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Monterey Marriott
Monterey, California, USA

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2017

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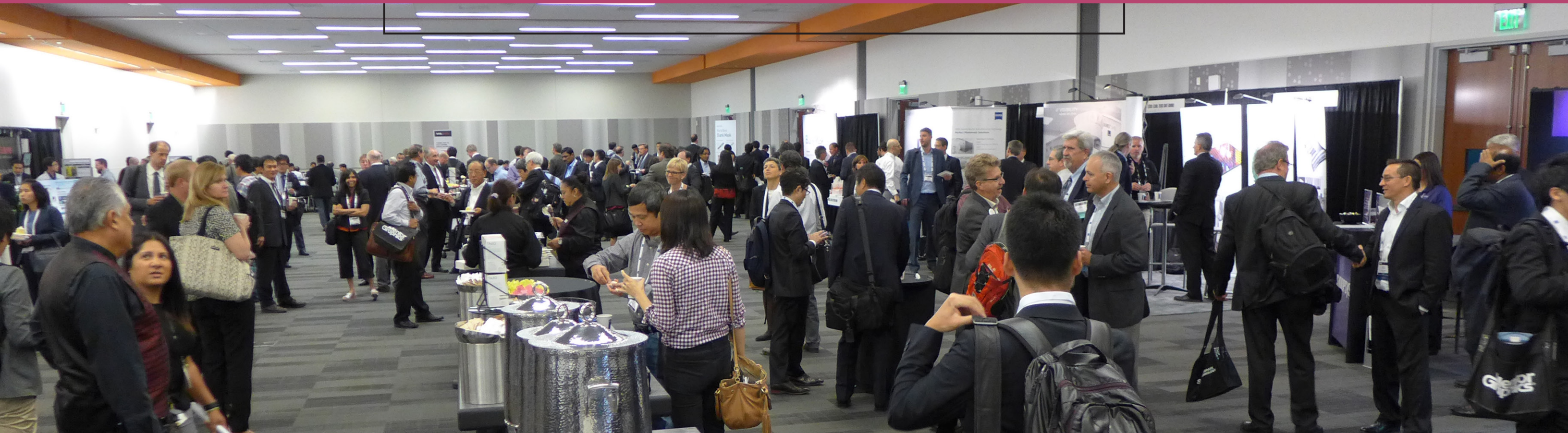

Conference 10450: International Conference on Extreme Ultraviolet Lithography

Monday - Thursday 11–14 September 2017

Part of Proceedings of SPIE Vol. 10450 International Conference on Extreme Ultraviolet Lithography 2017

10450-1, Session E1

EUV readiness, insertion opportunities, and challenges for logic and memory *(Keynote Presentation)*

Gregory R. McIntyre, IMEC (Belgium)

No Abstract Available

10450-2, Session E2

EUV lithography industrialization progress *(Invited Paper)*

Roderik van Es, ASML Netherlands B.V. (Netherlands)

This presentation will provide an overview of the industrialization of EUV Lithography, including the latest data on imaging, overlay, defectivity and source power/ productivity.

The focus of the presentation will be on the NXE:3400B scanner, ASML's fifth generation EUV lithography tool intended for the sub 10 nm volume production

Furthermore the ASML roadmap, NXE:3300B and NXE:3350B field data and field performance data will be shown

10450-3, Session E2

EUV single patterning for logic metal layers: achievement and challenge

Ryoung-Han Kim, Werner Gillijns, Youssef Drissi, Jae Uk Lee, Darko Trivkovic, Victor M. Blanco Carballo, Stephane Larivière, Rudi De Ruyter, Morin Dehan, Gregory R. McIntyre, Ling Ee Tan, IMEC (Belgium)

imec's investigation on EUV single patterning insertion into industry 5nm-relevant logic metal layer is discussed. Achievement and challenge across imaging, OPC, mask data preparation and resulting wafer pattern fidelity are reported with a broad scope.

Best focus shift by mask 3D of isolated feature gets worse by the insertion of SRAF, which puts a negative impact on obtaining large overlap process window across features. imec's effort across OPC including SMO and mask sizing is discussed with mask rule that affects mask writing. Resist stochastic induced defect is identified as a biggest challenge during the overall optimization, and options to overcome the challenge is investigated. For mask data preparation, dramatic increase in the data volume in EUV mask manufacturing is observed from iArF multiple patterning to EUV single patterning conversion, particularly by the insertion of SRAF. In addition, logic design consideration to make EUV single patterning more affordable compared to alternative patterning option is be discussed.

10450-4, Session E2

EUV mask manufacturing readiness in the merchant mask industry

Michael Green, Yohan Choi, Young M. Ham, Henry H. Kamberian, Christopher J. Progler, Photronics, Inc. (United States); Shih En Tseng, Tsann-Bim Chiou, Junji Miyazaki, Jason J. Shieh, Sang-In Han, Alek C. Chen, ASML Technology Development Ctr. (United States)

As nodes progress into the sub-7nm regime, extreme ultraviolet lithography (EUVL) becomes critical for all industry participants interested in remaining at the leading edge. One key cost driver for EUV in the supply chain is the reflective EUV mask. As of today, the relatively few end users of EUV consist primarily of integrated device manufactures (IDMs) and foundries that have internal (captive) mask manufacturing capability. At the same time, strong and early participation in EUV by the merchant mask industry should bring value to these chip makers, aiding the wide-scale adoption of EUV in the future. For this, merchants need access to high quality, representative test vehicles to develop and validate their own processes. This business circumstance provides the motivation for merchants to form Joint Development Partnerships (JDPs) with IDMs, foundries, Original Equipment Manufacturers (OEMs) and other members of the EUV supplier ecosystem that leverage complementary strengths. In this paper, we will show how, through a collaborative supplier JDP model between a merchant and OEM, a novel, test chip driven strategy is applied to guide and validate mask level process development. We demonstrate how an EUV test vehicle (TV) is generated for mask process characterization in advance of receiving chip maker-specific designs. We utilize the TV to carry out mask process "stress testing" to define process boundary conditions which can be used to create Mask Rule Check (MRC) rules as well as serve as baseline conditions for future process improvement. We utilize Advanced Mask Characterization (AMC) techniques to understand process capability on designs of varying complexity that include EUV OPC models with and without assist features (AFs). Through these collaborations, we demonstrate ways to develop EUV processes and reduce implementation risks for eventual mass production. By reducing these risks, we hope to expand access to EUV mask capability for the broadest community possible as the technology is implemented first within and then beyond the initial early adopters.

10450-5, Session E3

Classification and printability of EUV mask defects from SEM images

Wonil Cho, Micron Technology, Inc. (United States); Vikram L. Tolani, Masaki Satake, KLA-Tencor Corp. (United States); Daniel Price, Paul A. Morgan, Daniel Rost, Micron Technology, Inc. (United States)

EUV lithography is starting to show more promise for patterning some critical layers at 5nm technology node and beyond. However, there still are many key technical obstacles to overcome before bringing EUV Lithography into high volume manufacturing (HVM). One of the greatest obstacles is manufacturing defect-free masks. For pattern defect inspections in the mask-shop, cutting-edge 193nm optical inspection tools have been used so far due to lacking any e-beam mask inspection (EBMI) or EUV actinic pattern inspection (API) tools.

The main issue with current 193nm inspection tools is the limited resolution for mask dimensions targeted for EUV patterning. The theoretical resolution limit for 193nm mask inspection tools is about 60nm HP on masks, which means that main feature sizes on EUV masks will be well

beyond the practical resolution of 193nm inspection tools. Nevertheless, 193nm inspection tools with various illumination conditions that maximize defect sensitivity and/or main-pattern modulation are being explored for initial EUV defect detection. Due to the generally low signal-to-noise in the 193nm inspection imaging at EUV patterning dimensions, these inspections often result in hundreds and thousands of defects which then need to be accurately reviewed and dispositioned. Manually reviewing each defect is difficult due to poor resolution. In addition, the lack of a reliable aerial dispositioning system makes it very challenging to disposition for printability.

In this paper, we present the use of SEM images of EUV masks for higher resolution review and disposition of defects. In this approach, most of the defects detected by the 193nm inspection tools are first imaged on a mask SEM tool. These images together with the corresponding post-OPC design clips are provided to KLA-Tencor's Reticle Decision Center (RDC) platform which provides ADC (Automated Defect Classification) and S2A (SEM-to-Aerial printability) analysis of every defect. First, a defect-free or reference mask SEM is rendered from the post-OPC design, and the defective signature is detected from the defect-reference difference image. These signatures help assess the true nature of the defect as evident in e-beam imaging; for example, excess or missing absorber, line-edge roughness, contamination, etc. Next, defect and reference contours are extracted from the grayscale SEM images and fed into the simulation engine with an EUV scanner model to generate corresponding EUV defect and reference aerial images. These are then analyzed for printability and dispositioned using an Aerial Image Analyzer (AIA) application to automatically measure and determine the amount of CD errors. Thus by integrating EUV ADC and S2A applications together, every defect detection is characterized for its type and printability which is essential for not only determining which defects to repair, but also in monitoring the performance of EUV mask process tools.

The accuracy of the S2A print modeling has been verified with other commercially-available simulators, and will also be verified with actual wafer print results. With EUV lithography progressing towards volume manufacturing at 5nm technology, and the likelihood of EBMI inspectors approaching the horizon, the EUV ADC-S2A system will continue serving an essential role of dispositioning defects off e-beam imaging.

10450-6, Session E3

Actinic inspection of programmed defects on arbitrary patterns

Iacopo Mochi, Patrick Helfenstein, Yasin Ekinci, Dimitrios Kazazis, Paul Scherrer Institut (Switzerland); Shusuke Yoshitake, NuFlare Technology, Inc. (Japan); Rajeev Rajendran, Paul Scherrer Institut (Switzerland)

Actinic pattern inspection on EUV reticles is considered an essential tool for the implementation of EUV Lithography in high volume manufacturing, nevertheless there is currently no long-term solution available for it. The main challenges for any mask defect inspection platform are resolution and throughput. The reflective-mode EUV mask scanning lensless imaging microscope (RESCAN) is being developed to provide actinic mask inspection capabilities for defects and patterns with high resolution and high throughput, for node 7 and beyond. We have already demonstrated the ability to detect amplitude defects on periodic structures, and here we will report on our progress on defect detection on random, logic-like patterns.

RESCAN is based on a two-step approach: a first defect detection scan is carried out to generate a low-resolution map of the defects on the reticle. Once the defect location is known with a accuracy of few micrometers, a second scan is performed to localize the defect with sub-nm precision. The defect detection is performed scanning the reticle with a coherent EUV beam and recording the diffraction patterns with designed NA. The diffraction patterns are compared to simulated ones as in "Die-to-Database Inspection" or to data previously collected over a pattern in neighbor die as in "Die-to-Die Inspection" to detect the presence of defects. This is relatively easy to do for periodic patterns where it is sufficient to look for small discrepancies from a constant diffraction pattern. For logic-like patterns the ideal diffraction pattern is rapidly varying across the sample and discriminating the contribution of a small random defect is therefore more challenging. To test the limits and to demonstrate the potential of RESCAN, we developed a test sample with different kinds of programmed defects embedded in logic-like random patterns. The defects' size ranges from 200 nm to 25 nm on mask. We will produce a map the programmed defects using a die to die approach and we will perform an image reconstruction of the detected defects to determine their position with the maximum possible precision.

Finally, we describe the status of the RESCAN platform, its recent upgrades in terms of optics, detector NA and speed and we will outline our plans towards the development of a standalone actinic pattern inspection tool for EUV reticles.

10450-7, Session E4

Measurement of through-focus EUV pattern shifts using the SHARP actinic microscope

Obert R. Wood II, Yulu Chen, Pawitter Mangat, GLOBALFOUNDRIES Inc. (United States); Kenneth A. Goldberg, Markus P. Benk, Lawrence Berkeley National Lab. (United States); Bryan S. Kasprowicz, Henry H. Kamberian, Jeremy McCord, Photronics, Inc. (United States); Thomas I. Wallow, ASML Brion (United States)

Extreme ultraviolet (EUV) lithography with reflective photomasks continues to be a potential patterning technology for high volume manufacturing at the 7 nm technology node and beyond. Because EUV reflective masks must be illuminated at an oblique angle in order to separate incident and reflected light, their complicated coating structure gives rise to a variety of 3D mask effects. This paper presents experimental data on the through-focus relative pattern-shift between contact holes in a dense contact-hole array and a surrounding pattern of lines and spaces by analyzing images of these patterns captured with the SHARP actinic microscope in Berkeley.

A through-focus series of 17 actinic images of these patterns were recorded at 200 nm step size (equivalent to 25 nm on wafer scale). The actinic images were analyzed by separating them into three parts, contacts, horizontal lines and vertical lines. Centroids for all contacts were determined by a weighted zoning algorithm. The lines were decomposed into multiple segments and centroids were extracted for each segment before a linear fit was performed to determine the line position. The process was repeated for 7 of the through-focus images near best focus and the values for the relative shift of the contacts with respect to the lines were determined and plotted in the figure (on the right).

Since the EUV mask was illuminated at 6° to the mask normal, the image shift in the orthogonal (vertical) direction should be exactly zero. The data in the figure shows that the experimental values in the vertical direction are decidedly non-zero. Possible reasons for the discrepancy between simulation and measurement could be a) the method used to locate the contact hole centroids needs improvement, and b) the zone plate lenses in the actinic microscope have larger than expected aberrations. The experimental values for pattern shift in the figure are ~3x larger than the values predicted in the simulation. Even so, the experimental measurements plotted in the figure are believed to provide an upper limit to the relative pattern shift due to EUV 3D mask effects.

10450-8, Session E4

EUV Infrastructure: EUV photomask backside cleaning

Bruce Fender, Dusty Leonhard, Applied Materials, Inc. (United States); Hugo Breuer, Applied Materials BV (Netherlands); Jack Stoof, Applied Materials B.V. (Netherlands); My-Phung Van, Rudy J. M. Pellens, Reinout Dekkers, Jan-Pieter Kuijten, ASML Netherlands B.V. (Netherlands)

Due to electrostatic chucking of the backside of EUV masks, backside cleanliness in EUV lithography is an important factor. Contamination on the backside can cause damage to reticle (e-chuck), cross-contaminate to the scanner or cause local distortions in the reticle. Cleaning of the masks offers a solution to reduce the defectivity level on reticles. However, repeated cleaning on masks is known to have an impact on absorber, CD and reflectivity. Ideally, cleaning should occur without any alterations to the critical features on the front side of the mask. With the introduction of pellicles for EUV, there could be an additional drive for backside-only cleaning.

In this work the GuardianTM Technology is introduced that enables backside cleaning without any cleaning impact on the reticle front side through a protective seal at the outer edge of the mask. The seal protects the front side during the backside clean. The cleaning process encompasses a single-sided pre-clean oxygen plasma treatment of the mask surface, followed by sonic cleaning, and ending with a rinse and dry step. Separating the mask backside from front side enables:

• Backside cleaning without any cleaning impact on features on the mask front side.

• The isolation allows an aggressive cleaning of the backside to ensure defect removal.

• Processing of reticle with studs on the front side. This prevents unnecessary actions of stud removal and removal of the remaining glue after stud removal and subsequent gluing of the studs after cleaning.

Just before chucking of a reticle, the defectivity level on the mask is initially inspected with an in-scanner reticle backside inspection tool. The GuardianTM cleaning process is able to remove the vast majority of the cleanable defects that could impact scanner performance. Post GuardianTM clean interferometric microscope defect review reveals the remaining defects > 25-μm-PSL are ~78% are indent/damage and 11% are defects with insignificant height to impact scanner performance or cleanliness.

10450-9, Session E4

EUV mask flatness compensation strategies and requirements for reticle flatness, scanner optimization and E-beam writer

Christina Turley, Jed Rankin, Xuemei Chen, GLOBALFOUNDRIES Inc. (United States); Katherine Ballman, Christopher Lee, Thomas Dunn, Corning Tropel (United States)

High volume manufacturing with extreme ultraviolet (EUV) lithography requires mask induced overlay errors of less than 1.5nm for the N7 node. The use of electrostatic chucking and reflective optics causes the reticle backside flatness and reticle thickness to directly affect the placement of the pattern at wafer through both in-plane (IPD) and out of plane distortions (OPD). The minimization of reticle flatness alleviates some of the image placement distortion caused by the reticle's shape, however to be within the image placement error budget, N7 EUV blanks must have flatness <16nm p-v. With the manufacturing challenges associated with generating such flat blanks, compensation may be an option for imaging improvements; such methodologies will likely be essential for EUV to meet the stringent image placement and overlay specifications needed for high volume manufacturing (HVM).

Numerous compensation approaches can be utilized to minimize flatness related image placement errors including write compensation of the reticle, feed forward of reticle flatness data to the scanner corrections, and high-order empirical scanner corrections. This study investigates the benefits and limitations of each of these approaches, and seeks to better define which types of errors can be compensated and which will need further reticle flatness development in order to meet N7 and N5 specifications. Additionally, attention is given to the reticle's shape as it relates to the limitations to the depth of focus required within the scanner systems. Utilizing an array of substrates and blanks from different vendors, we provide an assessment on which type of compensation method is most effective for addressing the various topographies for each specific reticle, and further explore for which node such schemes may be necessary.

This investigation seeks to provide a guide for the industry to work towards the implementation of functional tolerances related to both the compensation scheme used in manufacturing, and the reticle's resulting non-correctable flatness (residual).

10450-11, Session E5

Efficient simulation of EUV pellicles

Peter Evanschitzky, Fraunhofer-Institut für Integrierte Systeme und Bauelementetechnologie IISB (Germany)

The paper presents a new simulation model for the efficient simulation of EUV pellicles. Pellicle membranes including additional coatings, pellicle deformations and particles on the pellicle can be considered. The model is integrated into the Fraunhofer IISB lithography simulator Dr.LiTHO enabling the efficient application of the new model in combination with all other models of the Dr.LiTHO tool to extensive lithography simulations and studies.

Furthermore, a simulation study on the printing impact of pellicles on lithographic performance data of high NA anamorphic EUV systems is presented. Typical illumination conditions, mask stacks and mask features are considered in the study. The impact of the pellicle thickness and material stack, of pellicle transmission variations, of pellicle deformations like wrinkles and of pellicle particles with different sizes on typical lithography measurements like CD, best focus, NILS, telecentricity, position, contrast and threshold to size is investigated.

For the computation of aerial images of EUV lithography systems a combination of rigorous electromagnetic field (EMF) simulations and imaging simulations based on Fourier optics are used in the Fraunhofer IISB lithography simulator Dr.LiTHO. Although the pellicle belongs to the mask, the combination of the pellicle simulation with the mask simulation could not be realized in practice. The problem results from the different size dimensions of typical pellicle particles and mask features and the fact that different boundary conditions, typically periodic boundaries for mask features and isolated boundaries for pellicle particles, have to be combined. This combination could not be realized with sufficient accuracy and acceptable simulation times. Therefore, the pellicle model is based on properly designed pupil filters representing all pellicle and particle properties to be investigated. The filters are combined with an adapted image simulation. Due to the double transition of the EUV light through the pellicle two different models for the pupil filter computation have been developed: On model for the forward light propagation from the source to the mask and one model for the backward light propagation from the mask to the entrance pupil of the imaging system. Furthermore, for the accurate representation of pellicle particles a specific model has been developed which is able to combine the different size dimensions of particles, of the entrance pupil and of the illumination source. Finally, some specific assumptions on the light propagation make the pellicle model independent from the illumination source and speed up the simulations significantly without introducing an important error. The consideration of a pellicle typically increases the overall image simulation time only by a few seconds on a standard personal computer.

10450-48, Session P1Tue

Key components development progress updates of the 250W high-power LPP-EUV light source

Takayuki Yabu, Yasufumi Kawasuji, Tsukasa Hori, Takeshi Okamoto, Hiroshi Tanaka, Yukio Watanabe, Tamotsu Abe, Takeshi Kodama, Yutaka Shiraishi, Hiroaki Nakarai, Taku Yamazaki, Noritoshi Itou, Takashi Saito, Hakaru Mizoguchi,

Takuya Ishii, Kenichi Miyao, Tatsuya Yanagida, Gigaphoton Inc. (Japan)

We have been developing CO2-Sn-LPP EUV light source, which is the most promising solution for the 13.5 nm high power light source for high volume manufacturing, which enables <7 nm critical layer patterning for semiconductor device fabrication. This source is composed of unique and original technologies such as; high power CO2 laser with 15 nanosecond pulse duration, solid-state pre-pulse laser with 10 picosecond pulse duration, highly stabilized droplet generator, a precise laser-droplet shooting control system and debris mitigation system using a magnetic field.

In this paper, a development progress update of key components of our 250W CO2-Sn-LPP EUV light source is presented. We developed multi-line short pulse CO2 laser oscillator and high gain traverse flow CO2 laser amplifier in cooperation with Mitsubishi Electric Corporation. The higher gain amplifiers realize higher output power with a shorter laser pulse at the same time. More than 20kW of CO2 laser output power and 15 nanosecond pulse duration with 100 kHz was achieved. The irradiation of target with pre-pulse prior to CO2 laser irradiation enabled high CE of over 4%. The solid-state pre-pulse laser with different wavelength from CO2 laser's and shorter pulse duration can achieve higher conversion efficiency because it can produce optimum tin expansion state. The solid-state pre-pulse laser is characterized by 1.06μm wavelength, pulse duration of 10 picoseconds (FWHM), and average output power of >100 W. The improved droplet generator can create smaller size and position-stable droplets suitable for longer operation times due to reduced generation of tin debris. ~20 um diameter droplets and position stability of less than +/- 5 μm was achieved. Improved laser-droplet shooting control system was also developed. The system has several shooting control loops for ensuring positional and temporal shooting accuracy of ?m and ns levels to synchronize the droplets and lasers. The improved metrology system also contributes to an improvement of shooting accuracy. The magnetic tin mitigation system maximizes the lifetime of the EUV collector mirror. Strong magnetic field traps the tin ions and promotes exhaust of tin debris outside of the vessel, so EUV collector mirror is protected from reflectivity degradation by tin debris deposition. Shooting error is also one of issues that enhance generation of debris leading to mirror contamination. The new, more accurate laser-droplet shooting control system contributes to reduce degradation of EUV mirror reflectivity.

We are now constructing a new high power HVM LPP-EUV source with >25kW CO2 driver laser featuring the amplifier system made by Mitsubishi Electric. At the conference we will report the performance of the new system and updated data of old systems.

10450-49, Session P1Tue

Investigation of secondary plasma formation in EUV sources

Gianluca A. Panici, Dren Qerimi, David N. Ruzic, Univ. of Illinois at Urbana-Champaign (United States)

The formation of parasitic or secondary plasmas in EUV sources is investigated in detail. As dense, high temperature plasma travels through ambient gas, energy transfer and ionization events occur that create a cold plasma that lingers after the dissipation of the initial plasma. In the case of a pulsed device this cold plasma has a lifetime that is orders of magnitude greater. This parasitic plasma can affect critical functions in the source ranging from debris mitigation to metrology.

An XTS 13-35 DPP EUV source was utilized to investigate the secondary plasma formation due to the photons, ions and electrons of the initial plasma. A simulation was developed in COMSOL to predict secondary plasma density and determine understanding of formation mechanisms. The simulation results including radial, axial and pressure scans are presented.

Experiments measuring the initial plasma interactions with ambient gas were performed in the XTS 13-35 source. Time-resolved measurements of electron densities as well as photon attenuation allow for accurate evaluation of dominant particle interaction mechanisms between initial plasma particles and ambient gas. Radial, axial and pressure profiles for these time-resolved measurements are presented and compared to simulation results.

10450-50, Session P2Tue

A study of EUV resist sensitivity by using metal materials, part 2

Atsushi Sekiguchi, Litho Tech Japan Co., Ltd. (Japan)

Studies are currently being carried out on developing a method for improving EUV resist sensitivity by enhancing EUV light absorption. The approach applied involves adding metals having high EUV light absorption to the resist polymer to increase secondary electron emission, enhance PAG reactivity, and improve acid generation efficiency [1]. One of our past studies confirmed that adding HfO2 nanoparticles improves EUV resist sensitivity [2].

Therefore, this time, it was not polymer, and it used high metal containing PAG by the absorption of the EUV light and it reviewed whether or not further sensitivity improvement was possible. It added metal containing PAG to the EUV resist of the acrylic fiber base and it exposed in EUV in NewSUBARU and it evaluated a sensitivity measurement and Transmittance or transmissivity.

As a result, it found that it was possible to sensitize in using metal containing PAG.

10450-51, Session P2Tue

Defectivity and CD uniformity improvement in resist coating and developing process in EUV lithography process

Yuya Kamei, Takahiro Shiozawa, Tokyo Electron Kyushu Ltd. (Belgium); Shinichiro Kawakami, Hideo Shite, Hiroshi Ichinomiya, Masashi Enomoto, Tokyo Electron Kyushu Ltd. (Japan); Kathleen Nafus, Tokyo Electron Kyushu Ltd. (Belgium); Philippe Foubert, IMEC (Belgium)

Extreme ultraviolet lithography (EUVL) technology is getting closer to high volume manufacturing phase every year. In order to enhance the yield in EUV lithography process, further improvement of defectivity and CD uniformity is required at the moment.

In our previous report in 2017, we have exhibited the defectivity reduction by applying our new rinse and dispense system to a 24nm contact hole (CH) pattern. On the basis of the knowledge received through that evaluation, further study for improvement of the defectivity will be investigated in this paper.

Also, CD uniformity control is a very crucial factor toward EUVL manufacturing phase. CD variations are comprised of several components such as shot to shot CD uniformity, within shot CD uniformity and local CD uniformity. Improvement of each component is studied with process optimization and latest technologies.

10450-52, Session P2Tue

EUV resist development at NewSUBARU in University of Hyogo

Takeo Watanabe, Shota Niihara, Shohei Nagata, Masahiro Watanabe, Daiki Memezaki, Tetsuo Harada, Univ. of Hyogo (Japan)

Extreme ultraviolet lithography (EUVL) is most promising lithographic technology for HVM of semiconductor devices. EUV lithography will be used in HVM around 2018 or 2019.

One of the technical issue of EUVL for HVM is development of EUV resist which can achieve was the high resolution, high sensitive, low line edge

roughness (LER), and low outgassing, simultaneously. In this issue, the significant achievement are the high sensitivity to maintain the wafer lithographic throughput to reduce the device production cost, and low LER to grantee the electronic characteristics of electronic device.

At Laboratory of Advanced Science and Technology for Industry, University of Hyogo, the EUV interference lithography, the resist and pellicle outgassing tool, the highly accurate resist sensitivity measurement, the resist and pellicle absorption coefficient measurement, and the resist fundamental chemical reaction analysis are prepared at the beamlines of the NewSUBARU synchrotron light facility. In addition, the 1st principle calculation method applied for the chemical structure analysis of the polymer resist material is introduced.

Since EUV interference lithographic tool is developed for the sub-10 nm resist patterning to evaluate such as resolution and LER by the patterning benefit avoiding of lack of the imaging optics aberration and mask error, the resist material property itself can be evaluated.

In-situ ellipsometry is adopted to the outgassing evaluation tool, not only outgassing species but also carbon contamination real-time growth can be measure during EUV exposure using high power EUV light generated by 10.8-m-long undulator.

Since the resist absorption coefficient accurate measurement is significant to design and achieve the EUV high sensitive resist materials including metal resist, for the accurate measurement of EUV resist materials, the resist coating method of the direct resist-coating on a photodiode is developed. The high stable and cheap photodiode is employed in this method.

Since soft x-ray absorption spectroscopy is powerful tool to analyze the EUV chemical reaction occurred in the EUV resist system, the analysis results of the chemical reaction using this tool could be feedback for the studying the achievement strategy of the high sensitive EUV resist development.

As results, the significant and highly accurate EUV resist evaluation and measurement of the resolution, sensitivity, outgassing, and chemical reaction, which were prepared at one facility might be powerful for the fundamental study to develop the conventional and novel EUV resist material system toward HVM EUV lithographic technology to transfer into the production line. These resist evaluation and measurement are opened for the users in world wide.

The recent results will be presented at the symposium.

10450-53, Session P2Tue

Development of the negative-tone molecular resists for EB/EUVL having high EUV absorption capacity, and molecular design method

Takashi Sato, Tomoaki Takigawa, Yuta Togashi, Takumi Toida, Masatoshi Echigo, Mitsubishi Gas Chemical Co., Inc. (Japan); Tetsuo Harada, Takeo Watanabe, Univ. of Hyogo (Japan); Hiroto Kudo, Kansai Univ. (Japan)

We are developing the resist materials for EUVL. Resists for EUVL are required of high sensitivity for high throughput of the lithographic process, and for reducing a shot noise to improve a roughness. So it is necessary that resist materials are ionized by absorbing EUV and emit more secondary electrons.

In previous report, we reported the development of the new materials containing the elements having high EUV absorption capacity. We have demonstrated that our materials have high EUV absorption coefficient.

In this report, we report more examination about the EUV absorption.

In the measurement of the EUV absorption, we measured the materials formed on PD instead of the materials formed on the silicon wafer. Therefore, we were able to measure the EUV absorption coefficient by good precision.

According to this measurement, our materials showed EUV absorption capacity of 2.4 times in comparison with a PHS as a common resist material for KrF lithography.

In addition, we examined a method to predict EUV absorption coefficient by an elementary composition. There were materials not corresponding between an actual EUV absorption coefficient and EUV absorption coefficient calculated from the elemental mass absorption coefficient.

Therefor, by measuring the density of materials, and considering it, we confirmed that EUV absorption coefficient and EUV absorption coefficient calculated from the elemental mass absorption coefficient were correspond with.

As above, we confirmed that we could predict the EUV absorption coefficient from the constituted elements and the density of materials.

10450-54, Session P2Tue

Actinic tools for EUV photoresist characterization in research and production

Rainer Lebert, Christoph Phiesel, Thomas Missalla, Christian Piel, RI Research Instruments GmbH (Germany); Sascha Brose, Serhiy Danylyuk, Chair for Technology of Optical Systems, RWTH Aachen Univ. (Germany); Peter Loosen, RWTH Aachen Univ. (Germany); Larissa Juschkin, Chair for Technology of Optical Systems, RWTH Aachen Univ. (Germany); Klaus Bergmann, Jochen Vieker, Fraunhofer-Institut für Lasertechnik (Germany)

EUV lithography is ramping up for volume production. EUV photoresists remain a key component to be optimized for

resolution, yield, sensitivity and line width roughness for exploiting performance of scanners for next generation production.

Much of the cutting edge EUV photoresist research and development is for the time being still accomplished at R&D and pre-production scanners. However, when EUVL will be in mass production there is a need for of more economic stand-alone tools at the suppliers. Within the portfolio of actinic EUV tools RI can offer a variety of solutions for resist characterization.

- Inband EUV dose controlled, calibrated open frame exposer: Our dose controlled, calibrated open frame exposer has first been shipped in 2004 and allows for determination of dose-to-clear for the resist. This tool is expected to be needed for supplier's batch quality control in production.

- Measurement solutions for EUV absorbance of photoresists: EUV absorption power of photoresists is assumed one key property for optimization of sensitivity and shot noise.

With the EUV-Lamp, a compact low cost EUV source for laboratory, concepts for handling thin resist layers for transmission measurements and our EUV-SPEC spectrograph or applying the "effective EUV inband qualification" concept from our pellicle tool, we can realize effective lab tools tailored to customer needs.

- Actinic EUV interference printer with demonstrated 28 nm hp contact-hole arrays over 1 x 1 mm_2 : With the EUV laboratory exposure tool (EUV-LET) of our research partners at RWTH-TOS - based on the achromatic Talbot effect - 28 nm half-pitch contact-hole arrays over areas of 1 x 1 mm_2 have been demonstrated. The theoretical resolution limit for the achromatic Talbot lithography of 10 nm half-pitch is mainly resist-limited. High aspect ratio transmission masks for 21 nm and 14 nm half-pitch structures are available to further analyze the practical resolution limit of the method. This makes the approach extendable for the resist characterization beyond N7 node.

- EUV power exposer with up to 1 W/mm_2 average intensity: Using our strongest lab sources of more than 40 W EUV in-band emission focused to < 1 mm_2 actinic EUV spots generates a test environment resembling peak and average powers as targeted for future scanner generations. This may be of interest for resist power qualification but also for the test of other elements like DGLs, pellicles and masks.

Experimental results, extrapolation and options are presented.

10450-55, Session P2Tue

EUV process improvement with novel litho track hardware

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Currently, there are many developments in the field of EUV lithography that are helping to move it towards increased HVM feasibility. Targeted improvements in hardware design for advanced lithography are of interest to our group specifically for HVM metrics such as LWR improvement, dose reduction processes, and defect density reduction. Of course, our work is focused on EUV process steps that are specifically affected by litho track performance, and consequently, can be improved by litho track design improvement and optimization. In this work we are building on our experience to provide continual improvement for HVM metrics achieved with a standard EUV process by employing novel hardware solutions on our SCREEN DUO coat develop track system. Although it is preferable to achieve such improvements post-etch process we feel, as many do, that improvements post-patterning are a precursor to improvements after etching. We hereby present our work utilizing the SCREEN DUO coat develop track system with an ASML NXE:3300 to improve aggressive dense L/S patterns.

10450-56, Session P3Tue

Extreme-ultraviolet pellicle at 500 W source power by thermal stress analysis

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The extreme-ultraviolet (EUV) pellicle can protect the mask from defects. However, the EUV pellicle can be easily deformed due to high absorption of EUV wavelength. Therefore, the high emissivity metallic material should be coated on the both sides to lower the stress and extend the life time of EUV pellicle. In our previous work, the thermal stress of the silicon pellicle with metallic Ru coating was shown to have ~ 30 MPa at 250 W source power. However, in order to realize 3-nm node or below high volume manufacturing (HVM), 500 W+ source power is required. There are three well reported EUV pellicles, so that we estimated these three cases of pellicles at 500 W. The thermal stress of the p-Si based B4C coated pellicle was 52.6 MPa with 92% EUV transmission. This shows that the thermal stress is increased to nearly double compared to the lower 250 W case. However, if we consider the ultimate tensile stress of the p-Si, which is in the range of 1~2 GPa, this amount of thermal stress increase not affect the life time seriously. The second case of the pellicle is graphene based B4C coated pellicle. The thermal stress for this combination of the pellicle is shown 137.9 MPa with 82% EUV transmission. This thermal stress is also much lower compared to tensile strength of the graphene (130 GPa). Last case we considered is 5 layer pellicle based on silicon core. The 2 nm of Ru and 0.5 nm SiO2 is coated on both sides. We used SiO2 for the surface coverage of the Ru. The result shows 32.6 MPa with 89% transmission. This result also shows the thermal stress is very small compared to silicon tensile strength. Our result shows that the metallic coated pellicles are also usable at 500 W EUV source power.

10450-57, Session P3Tue

Compositional pellicle characterization by EUV reflectance and transmittance measurements

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The authors present studies on the characterization of pellicles with a lab-based spectroscopic reflectometer operated in the EUV spectral range from 9 to 17 nm. The tool can, in its original purpose of design, perform spectroscopic measurements of reflectance under variable incidence angles of grazing illumination. Additionally, it can now perform spectroscopic measurements of transmittance for thin membranes <100 nm.

Pellicles for EUVL need to be characterized in a variety of aspects in order to ensure maximum actinic transmittance, maximum homogeneity in actinic transmittance and their thermal and mechanical stability. To ensure a sufficient performance, a full investigation of the pellicle membrane parameters is desirable. A means to determine important parameters such as thickness, surface roughness, density and chemical composition is presented in this work.

The reflectometer, the tool used for the investigations in this work, can perform spectroscopic measurements of reflectance of membranes and bulk materials as well as transmittance measurements of thin membranes with a thickness <100 nm. It operates spectroscopically in the wavelength range from 9 to 17 nm and the incidence angle of illumination is adjustable from 5° to 12° grazing for the reflectance measurements. It is lab-based through the use of an EUV-radiation source based on a gas-discharge plasma whose instabilities are accounted for by permanent reference monitoring during measurements. This together with the use of a calibrated reference sample allows to determine reflectivities with an accuracy <1%.

The tool can be used to collect an abundance of photometric data on the membranes. In the classical mode of operation, the tool can obtain spectroscopic reflectance data under different incidence angles of illumination. Additionally, a new operational mode has been implemented in the tool to spectroscopically measure the transmittance of thin membranes in the same spectral region. By using this type of multi-dimensional data set for a specific membrane, one can fit membrane parameters to it with high accuracy, such as thickness and surface or volume roughness.

The determination of dimensional parameters of a membrane such as thickness or surface roughness by reflectometric of ellipsometric techniques requires a sufficient knowledge of the optical constants of the materials under investigation. Angularly resolved reflectance spectra together with transmittance spectra of samples of well-defined thickness within the same tool enable a fit-based reconstruction of the optical constants with high unambiguity.

The goal of the studies to demonstrate the applicability of the presented metrology technique, angularly-resolved spectroscopic reflectometry in the EUV, to pellicle characterization in the context of development and quality control. Exemplary measurements on selected thin membranes are performed and the extendibility of the tool for spatially resolved surface scanning is demonstrated.

10450-58, Session P3Tue

Search for multi-stack EUV pellicle membrane for EUV non-actinic mask inspection

Sung-Gyu Lee, Hanyang Univ. (Korea, Republic of); Sumi Hur, Chonnam National Univ. (Korea, Republic of); Hye-Keun Oh, Hanyang Univ. (Korea, Republic of)

Extreme-ultraviolet (EUV) lithography with wavelength of 13.5 nm is the most promising candidate for sub-1x nm patterning. In order to maintain a defect-free mask, the use of EUV pellicle has been suggested. The EUV pellicle consists of a very thin single film due to its strong absorption of EUV light. However, the very thin membrane of EUV pellicle has a mechanical stability issue, so that a multi-stack structure for EUV pellicle stacked by several thin films was suggested.

The defect inspection of mask can use both actinic and non-actinic inspection system. However, EUV masks cannot be inspected by using actinic inspection system because there is no commercial EUV wavelength inspection systems available yet. Moreover, EUV pellicle must be removed

if EUV mask is inspected by non-actinic inspection system. Thus, inspection procedure of EUV mask is very inefficient, whereas optical mask inspection can be quickly done with optical pellicle due to high inspection wavelength transmission. Therefore, novel EUV pellicle membrane that is possible to inspect EUV mask without EUV pellicle removal in non-actinic inspection system is needed.

In order to optimize the EUV pellicle membrane that has a potential for through-pellicle inspection, we calculated DUV (a wavelength of 193 nm) transmission with various materials. Figure 1 shows the result of DUV transmission for material candidates as pellicle membrane by incident angle and polarization. The solid line and dotted line represent the DUV transmission for s-polarized light (s) and p-polarized light (p), respectively. As can be seen Fig. 1, graphene and nitride have much larger DUV transmission compared to crystalline-silicon. It is obvious that the graphene- or nitride-based pellicle have the potential for EUV mask inspection without pellicle removal since the Si-based pellicle is opaque to DUV wavelength. Based on these results, we believe that optimal multi-stack combination of EUV pellicle membrane has a high DUV transmission as well as EUV transmission and it would make better performance with respect to fidelity of through-pellicle inspection compared to well-known multi-stack EUV pellicle membranes.

10450-59, Session P3Tue

Thermo-mechanical behavior analysis of extreme-ultraviolet pellicle cooling by H2 flow

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Extreme-ultraviolet (EUV) lithography is next generation technology for achieving 1x nm patterning and beyond. To protect EUV mask from contaminations, EUV pellicle is required.

In order to use the pellicle in EUV lithography system, critical problems related to pellicle damage must be solved.

One of critical problems is the pellicle lifetime reduction by heat load during the exposure process. During repeated exposure process, the thermal stress of the pellicle will be saturated. We simulated silicon-based pellicle that has a high thermal conductivity to determine thermo-mechanical property change by H2 gas flow cooling.

Actually, the cooling system by H2 flow is applied to reduce internal temperature of scanner during the EUV exposure process. If the pellicle is also placed in the H2 environment, the temperature of the pellicle will be decreased by H2 flow. Due to decreased temperature, the thermal stress of the pellicle will be also reduced, so that the lifetime of the pellicle would be extended. We calculated how much temperature and thermal stress of silicon-based pellicle is decreased with various H2 gas conditions.

We also compared the thermo-mechanical properties of various pellicles in the H2 environment. So that we try to find which properties of the material affect to decrease the temperature and to maximize the lifetime of the pellicle through comparison of thermal stress.

10450-60, Session P3Tue

Lifetime impact on residual stress of extreme-ultraviolet pellicle

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Extreme ultraviolet (EUV) lithography is the next-generation technology. In EUV lithography, pellicle is used to protect EUV mask from some particles. However, since the pellicle is very thin, it can be affected easily on its manufacturing process or the exposure process.

Pellicle has residual stress from its manufacturing process. The residual stress is made by difference of the thermal expansion coefficient and Young's modulus between each layer. Also deposition temperature and the evaporation cause different residual stresses. If residual stress is large, the pellicle is expanded outside. On the other hand, if residual stress is negative, the pellicle is contracted inside. Thus considering the impact of residual stress, we should suggest EUV pellicle condition which has lower total stress that includes thermal stress.

Residual stress is calculated differently depending on the thickness and types of substrate, core and capping material. If residual stress has negative value, total stress is decreased and the durability of pellicle is increased. We also try to get the range of total stress by applying maximum and minimum deposition temperature. This can minimize the impact of residual stress and can reduce the total stress. Thus, we can increase the lifetime of pellicle.

10450-61, Session P3Tue

Mechanical break-down caused by external force for extreme ultraviolet pellicle

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Extreme ultraviolet (EUV) lithography is the next lithography technology by using 13.5nm wavelength to accomplish smaller patterns. Some particles located on the mask can cause serious problem in the EUV lithography. The pellicle should be used to protect the mask from various contaminations. However, the pellicle can be damaged from various external forces caused by transporting from the chamber after production to scanner since the pellicle is extremely thin. In order to prevent breakage of pellicle, we demonstrated the effect of external forces that can be generated in the shipping process.

The external forces include the pressure generated by the impact of object, the pressure exerted by the pellicle when it is dropped, and the acceleration to the top, bottom, left, and right. First, to know about pressure range and deformation due to pressure, we calculated the pressure corresponding to the height when pellicle was dropped. Due to this pressure, we analyzed the deformation of pellicle by finite element method (FEM). The higher the height, the greater the pressure received by the pellicle. The greater deformation according to that pressure causes the greater probability of breakage. Also, we investigated the characteristics of the pellicle how much the deformation can be varied with or without pod. From these results, we try to find out proper pressure range without any damaging on the pellicle, and we will compare various pellicle structures that have been suggested.

10450-62, Session P3Tue

Wrinkle formation analysis in extreme-ultraviolet pellicle

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Extreme ultraviolet (EUV) lithography is a next-generation lithography technology for fabricating smaller integrated chips. However, EUV lithography still has many problems such as source power and defect control for applying to high-volume manufacturing. One of problems is defect control, so that the EUV pellicle is required to protect EUV mask from contaminations. The EUV pellicle should be extremely thin thickness because an absorption rate is high in almost all material due to short wavelength. For this reason, EUV lithography needs extremely thin pellicle that should be nanometer thin. The thin thickness of EUV pellicle is easy to be deformed as wrinkle and deflection during the manufacturing and exposure process due to structural problems. In addition to this, EUV pellicle can be also deformed by thermal and mechanical problems. The deformation of EUV pellicle can break the pellicle. Even if the EUV pellicle is not broken, the deformation can change a transmission of EUV pellicle. The variation in transmission induces a critical dimension (CD) variation on the wafer. For this reason, the influence of deformation during the exposure process should be studied.

In this paper, a wrinkle of the EUV pellicle caused by the acceleration of 100 m/s2 during the exposure process is calculated with the finite element method. In this case, the wrinkle of EUV pellicle is occurred in a non-uniform wrinkle with full size (150 x 120 mm2) and 50-nm thick pellicle. The local tilt angle of the wrinkle should be less than 300 mrad which was suggested by ASML. Furthermore, the deformation caused by thermal problem and external force should be also studied with various materials for EUV pellicle because the EUV pellicle structure has not yet been determined. Therefore, various structures for EUV pellicle were considered and non-uniform and uniform wrinkles caused by mechanical and thermal deformation were calculated. From this study, we expect to suggest a proper EUV pellicle in the EUV lithography.

10450-63, Session P3Tue

Thermo-mechanical distortion caused by particle defect on extreme ultraviolet pellicle

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Extreme ultraviolet (EUV) lithography is the most promising next generation lithography technologies for achieving 1x nm patterning and beyond. To protect the EUV mask from contaminations, the EUV pellicle is required. However, there are still critical issues for EUV high volume manufacturing (HVM). During exposure process, particle defects placed on EUV pellicle can lead to pellicle deformation due to absorbed EUV light, so that thermal stress is increased and finally, the EUV pellicle will be broken. Therefore, the temperature distribution changed by particle defects needs to be studied to increase the pellicle lifetime.

Multi-stack EUV pellicle is consist of core (central) and capping layers. The capping layers of EUV pellicle have to robust thermal resistance by radiating heat. However, various defects occurred in the scanner can placed on top of the capping layers and can reduce emission of the capping layers. According to Intel's data, more than 1000 particle defects with a size of 5 μm were detected. Based on the 5 μm defect size, we compared maximum thermal stress of well-known pellicle structures (suggested by ASML and SAMSUNG) with finite element method (FEM). Due to the high emissivity of the Ru capping layer, the lifetime of the ASML pellicle is longer than the lifetime of the SAMSUNG pellicle. We calculated temperature distribution and thermal stress caused by particle defects of various materials. As a result, we found that thermal stress increased by particle defects was proportional to Young's modulus and thermal expansion coefficient but was inversely proportional to the emissivity.

The materials of pellicle and defect inside scanner are varied. In order to robust thermal resistance of EUV pellicle, we also tried to find the optimal structure of pellicle depending on the materials of various particle defects. We tried to optimize multi-stack membrane of EUV pellicle in terms of the extending the lifetime during exposure process and to determine critical defect material that caused the greatest thermal stress.

10450-64, Session P4Tue

EUV laser interaction and ablation of metals and dielectrics

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We present an overview of our systematic studies of the surface modifications resulting from the interactions of plasma EUV laser and soft x-ray free electron laser (SXFEL) pulses with materials, such as gold (Au), copper (Cu), aluminum (Al), and lithium fluoride (LiF), were investigated. We show experimentally the possibility of the precise nanometer size structures (~10–40 nm) on their surfaces by ultra-low (~10–30 mJ/cm2) fluencies of single EUV laser and SXFEL pulse. Comparison experimental results with the atomistic model of ablation, which was developed for the single EUV laser shot interaction with dielectrics and metals, is provided. Theoretical description of surface nanostructures is considered and is shown that such structures are formed after laser illumination in a process of mechanical spallation of ultrathin surface layer of molten metal. Spallation is accompanied by a strong foaming of melt, breaking of foam, and freezing of foam remnants. Those remnants form chaotic nanostructures, which are observed in experiments. Our measurements show that electron temperature of matter under irradiation of EUV laser was lower than 1 eV. The model calculation also predicts that the ablation induced by the EUV laser can create the significant low electron temperature. Our results demonstrate that tensile stress created in LiF and metals by pico-second EUV laser pulse can produce spallative ablation of target even for drastically small fluencies, which open new opportunities for material nano processing.

10450-65, Session P4Tue

Contrast matching of line gratings obtained with NXE3XXX and EUV-interference lithography

Zuhal Tasdemir, Iacopo Mochi, Paul Scherrer Institut (Switzerland); Karen Garrido Olvera, Marieke Meeuwissen, Oktay Yildirim, Rolf Custers, Rik Hoefnagels, Gijsbert Rispens, ASML Netherlands B.V. (Netherlands); Michaela Vockenhuber , Dimitrios Kazazis, Yasin Ekinci, Paul Scherrer Institut (Switzerland)

As the technology gets more and more mature, it becomes even more possible to go to smaller features. Although downscaling allows for faster processing along with more power efficiency thus lower cost, there are some issues to be addressed before going into high-volume manufacturing. These issues can be divided in two groups: device related and resist related ones. In this study, we aim to come up with a method to compare the data sets done by EUV scanner at ASML and EUV-IL setup at PSI. This work provides a guideline for the accurate reporting of the results obtained from both EUVL exposures at ASML and PSI.

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10450-66, Session P4Tue

Coater/developer based techniques to improve high-resolution EUV patterning defectivity

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Extreme ultraviolet lithography (EUVL) technology is one of the leading candidates under consideration for enabling the next generation of devices, for 7nm node and beyond. As the focus shifts to driving down the 'effective' k1 factor and enabling the full scaling entitlement of EUV patterning, new techniques and methods must be developed to reduce the overall defectivity, mitigate pattern collapse, and eliminate film-related defects. In addition, CD uniformity and LWR/LER must be improved in terms of patterning performance. Tokyo Electron Limited (TEL) and IBM Corporation are continuously developing manufacturing quality processes for EUV.

In this paper, we review the ongoing progress in coater/developer based processes (coating, developing, baking) that are required to enable EUV patterning. We will discuss our work for defect mitigation, with a special emphasis on defects related to film coating processes and developer processes, as well as the optimization results of CD uniformity and LWR/LER.

10450-67, Session P4Tue

Impact of aberration with various illumination systems and minimizing critical dimension difference through optical proximity correction

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EUV is possible to make sub-lxnm patterning. However aberrations affect the patterning errors. To show the impact of aberrations with each target CD, we optimized the illumination system without any aberration. We chose the illumination system conditions that had high DoF and the best image quality and compared the effect of aberration. We also tried OPC to compensate .

10450-68, Session P5Tue

Development of EUV phase imaging microscope for mask-3D-effect and defect evaluation

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In EUV lithography, reflection EUV phase of the mask is very critical to printing result. An EUV mask has 3-dimensional (3D) structure, which is reflective type and consists of glass substrate, reflective Mo/Si multilayer, and absorber pattern. This 3D structure affects the reflection phase, which would cause focus shift and pattern shift. In addition, the phase is very sensitive to the substrate shapes, because the mask is reflection type and EUV wavelength is quite short. As the result, shallow structure on the substrate is also printable as a defect, which is bump or pit structure or a particle in the multilayer. Thus, review tool for EUV phase imaging is very important.

We have developed EUV phase-imaging microscopes of coherent EUV scatterometry microscope (CSM). CSM is a simple microscope without objective. EUV phase and intensity image are reconstructed with diffraction images by ptychography. In this study, we will report observation result of actual defects on a mask blanks by the focused-type CSM. We successfully observed small defect with small diameter of 30 nm or shallow depth of 1.4 nm. In addition, we will also report the other standalone CSM result of pattern observation, which employed a high-harmonic-generation EUV source. Phase and intensity image of line patterns were well reconstructed by ptychography.

These result shows high capability of CSM for EUV mask reviewing, which system will be used in factory, such as mask shops and semiconductor fabrication plants.

10450-69, Session P5Tue

Improved throughput rate for HVM EUV mask and blank inspection with a droplet-based LPP EUV light source

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At the Applied Laser Plasma Science (ALPS) facility at the Laboratory for Energy Conversion (LEC) at ETH Zurich droplet-based laser produced plasma sources with the application in actinic blank and mask inspection are the main research focus. EUV sources with high brightness and stability are necessary to guaranty the throughput rate for HVM EUV mask and blank inspection applications. High cleanliness of the EUV emission and system availability are additional stringent requirements.

A dual axisymmetric EUV power measurement setup is used to measure the EUV source emission at 31°, 60°,75° and 90° towards the laser axis on a pulse to pulse basis. The measurements are combined with pulse-to-pulse laser power, droplet positional stability, timing stability and droplet size data. Thus the angular dependency of the EUV emission is quantified in regions for both a normal and gracing incident collector setup. The combination of the measurement data is used as a basis to define specifications for laser and droplet parameters guarantying a homogeneous and isotropic EUV power emission.

The high pulse-to-pulse reproducibility and stability of the plasma shape required for actinic mask inspection is verified by imaging the plasma source with an ICCD camera in combination with a YAG:Ce scintillator screen. The scintillator screen is coated with a Zirconium layer to ensure a narrow bandpass frequency in the EUV range and thus enabling EUV power emission visualization at nanosecond time scales.

Furthermore the long term EUV plasma positional stability and EUV source brightness is assessed with the addition of a soft x-ray pinhole camera. The long term source size, brightness and positional stability is directly correlated to the laser power, droplet positional stability and temporal stability.

The combination of all measurement data is used to define specific droplet-based EUV light source operational points of improved stability and brightness to meet the stringent requirements of actinic mask and blank inspection applications. The droplet-based LPP EUV source is further automated to run in the newly specified EUV power optimized regions to increase the throughput rate and availability for HVM EUV mask and blank inspection applications. Hence data showing the overall improved system reliability and decreased cost-of-ownership will be presented.

10450-70, Session P5Tue

Applications of RCWA on EUV mask optics

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The oblique illumination in EUVL system combined with relative thick absorber layer of EUV mask introduces many new challenges for mask simulation, like azimuthally asymmetric phase deformation, shadowing effects and secondary scattered field. Besides, these effects result in the ineffectiveness of the Hopkins approach and require new method for mask diffraction computation.

A 3D RCWA algorithm is implemented to perform rigorous computation of lights diffracted by the EUV masks. It can be used to address problem like conical diffraction from a crossed grating , i.e, the model can account for any 2D structure under any incident angle and polarization configuration. The reflectivity of a EUV mask can only be optimized for a single angle of incident due to its nature of Bragg reflectors. Therefore, the angle dependency of the reflectivitty of the EUV mask multilayer mirrors is

simulated and analyzed at first . Then, several special mask topographies are designed and simulated to fully analyze the various effects mentioned above. 1D gratings in different orientations with respect to chief ray is used to analyze the shadowing effects. Effective shadow width, effective height of absorber are researched together with the impacts of various parameters like grating pattern size, placement with respect to illumination arc on shadowing effects. The dot and small square patterns are used to analyze the asymmetric phase deformation. The asymmetries of diffraction phase distribution are analyzed by classification into different categories. Besides, the telecentricity error and contrast loss are studied by analyzing the unbalanced 0th and 1st diffracted order, which results from the absorber edge blocking effect for larger diffracted angle and reflectivity variation for different angles. Densely paired double lines are used to analyze the secondary scattered field.

Furthermore, a fast version of the rigorous 3D algorithm is demonstrated to reduce the computational time. The fully 3D RCWA algorithm is implemented for all possible scenarios with all possible incident angles, polarization and structures of 2D layers. However, if the diffraction is restricted for certain incident plane or certain grating structures (uniform in 1 or 2 directions), the 3D RCWA can be simplified greatly while the simulation time reduced dramatically. By proper decomposition, the 3D RCWA model is dissected into multiple 2D and 1D ones, after independent simulations, the results from these simpler models will be superposed back to construct the final results. An error will be induced during this process, thus error analysis between the fast algorithm and the rigorous algorithm for certain patterns are conducted to ensure the accuracy and for further improvement of the algorithm.

10450-82, Session P5Tue

Mitigating the impact of EUV mask flatness on pattern placement

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Current EUV reticles have a surface non-flatness in the order of several tens of nanometers. Reticle non-flatness not only impacts focus but also pattern placement, via two mechanisms

For the 16 nm node (ASML NXE3350) the maximum allowed non-flatness over the Image Field area is 16 nm for both the reticle front side and backside (reticle bow removed). For the 13 nm node this requirement is tightened to 8 nm.

Current champion non-flatness data shows 20-30 nm. The first order impact of mask non-flatness on pattern placement at wafer level can be described by Δx,y ~ ΔZreticle/40 nm. This means that the champion reticles contribute roughly 0.5- 0.75 nm to pattern displacement.

It is not known whether the required improvements to flatness can be made, due to potential engineering and manufacturing limitations. The ASML EUV system offers pattern placement improvement via intra-field High Order Process Corrections (iHOPC), but cannot counteract the impact of the highest orders of non-flatness.

A proposal to improve the pattern placement performance of the exposure system is to feedforward the pattern displacement due to the non-flatness to the reticle e-beam writer. Main requirement is the accurate prediction of the impact of the non-flatness on pattern displacement.

We will show that one can predict, with sufficient accuracy, the impact of reticle surface non-flatness on pattern placement, taking into account interaction between the reticle and the reticle chuck of the exposure system such as the contribution of back- and front side flatness to the non-flatness of the pattern area.

10450-71, Session P6Tue

Integral inband EUV reflectometry: Supplementing spectral reflectometry with fast full area mapping on masks and blanks

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EUV-Lithography is preparing for high volume production. For actinic component qualification for EUVL as mask blanks, masks, pellicles or optics, spectral reflectometry is a well established technique. The measurements yield spectral reflection curves from which the key SEMI parameters maximum reflectivity (Rmax), spectral bandwidth (FWHM) and central wavelengths (CWL50) are derived. This method is used in various variants at both storage ring beamlines and stand-alone laboratory tools.

The key quality figures of merit for the supply chain and life cycle of EUV masks, however, are the effective yield when the component is used with an EUV scanner and its homogeneity – i.e. the spatial variation. These figures are usually judged indirectly from the knowledge of Rmax, CWL50 and FWHM, where the efficiency is mainly proportional to Rmax when the spectral reflectance distribution and its central wavelength are similar to those of the scanner.

With conventional spectral reflectometry, only a few spots of around 1 mm square sizes are recorded from which homogeneity is extrapolated. Hence, only fractions of few mm? from the total mask quality area of around 20.000 mm^2 are really assessed. This is due to time limitations – because the measurement of one spectral reflectance curve takes some time; at best around 10 seconds.

Our EUV mask reflectometer EUV-MBR which has measuring spots of 100*250 μm^2 - but still high throughput of one scan from 12 to 15 nm in less than 20 seconds – is sensitive to small length scale variations and defects. Such features are usually overseen by conventional approaches of one mm? averaged spot measurements. Those variations may reach 0.5 % in Rmax and a few pm in CWL50.

Both those aspects, need for mapping mode and higher sensitivity to short length scale variations in reflectance triggers the demand of full mask blank inspection with reflectometry.

With our pellicle transmission tool, we recently have first applied “effective EUV inband qualification” for the industrial supply chain. Employing the same concepts, we now can offer EUV inband mapping reflectometry, which is in its measuring principles emulating the throughput when the sample is used in the scanner, as a new metrology technique for EUV mask blanks.

“Effective EUV inband qualification” can qualify an area of > 20*20 mm? with a typical 13.5*13.5 μm^2 pixel resolution. This technics is very robust and fast when applying a beam for the measurement, which is spectrally filtered (e.g. from e.g. Xenon EUV emission of a lab source) to 2 % spectral bandwidth. With such an “inband EUV beam”, the efficiency of the sample is recorded with respect to quality factors throughput and homogeneity “as the scanner sees it”. While this technique is quite straight forward with lab sources, it may require very special installations at storage ring beamlines.

As Rmax, CWL50 and FWHM quantification are still indispensable for established supply chain communication, we propose combining the spectral and the mapping mode into one tool.

10450-72, Session P6Tue

Extreme-ultraviolet lithographic optical projection system design method using Code V lens module and generalized Gaussian constants

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The optical lithography process usually starting with wafer preparation, then photoresist coating, pre-exposure bake, exposure, post-exposure bake, etching, and then finishing with metrology. During the exposure stage, a mask of the pattern to be transferred is first illuminated by a light source, then through a projection system images the pattern onto the photoresist coated wafer. This projection system is the heart of optical lithography, and largely determines the performance of the lithography process, as well as attainable resolution.

Of the possible ways to improve resolution, decreasing the wavelength is the only possible way to continue the trend. However short wavelengths, currently at 13.4 nm (EUV), are highly absorbed in propagation mediums, and projection systems consisting entirely of reflective mirrors become a necessary. This study takes the approach of analysing the optical system in two subsystems, separated by the aperture stop in between. The optical requirements for a lithography system were explored, as well as its relation to the optical properties of the two subsystems, accomplished through the use of the generalized Gaussian constants (GGC). Since the conception of the GGC, it has seen almost exclusive use in designing zoom lens systems. However, the GGC in general, and its foundation the Gaussian bracket, is a powerful tool in particular in the analysis of complex optical systems, one such as an optical lithographic tool.

In the study, optical system properties critical to EUV lithographic tools are first analyzed and expressed in terms of the GGC. The properties of particular interests are the image telecentricity, system magnification, and object-image conjugate. However, one particular property, that the paths of light within the optical system must not be obstructed by the mirrors themselves, this obstruction condition is not analyzed using GGC, but is dealt with using an optimizer algorithm instead. The system GGC obtained are expanded to a system which now consists of the front subsystem, the aperture stop, then the rear subsystem. The resultant GGC for the two subsystems are then converted back into optical system properties, now for two subsystems.

At this point, one capability of the optical design software Code V becomes particularly useful, the lens module function. Code V is capable simulating, a virtual lens system, of which it calls a lens module. The lens module is able to behave as if it were an actual lens system with physical elements, given the desired optical properties. In this work, a Monte-Carlo random walk code is written for Code V and used in combination with the Code V lens module, using the optical system properties relations above to ensure that critical properties for lithographic tools are maintained, as the algorithm resolves the mirror obstructions.

The subsystem optical properties of the obstruction resolved system can now be used obtain the actual lens data, that is, the mirror curvatures and separations between each subsequent mirrors. The detailed four-mirror design is a proof of concept of the design method, and a more complex eight-mirror design demonstrates the capacity for higher design complexity.

10450-73, Session P6Tue

Irradiation damage test of Mo/Si, Ru/Si, and Nb/Si multilayers using coherent EUV lasers

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The short-pulse coherent EUV laser pulses can make damages on an extreme ultraviolet (EUV) multilayer mirror and several materials. In order to utilize intense x-ray pulse sources for EUV litography, it is important to study the damage mechanism caused by x-ray irradiation.The irradiation damage tests for Mo/Si, Ru/Si and Nb/Si multilayer were carried out using coherent EUV lasers with picosecond and femtosecond pulse. The created damages were observed by a scanning electronic microscopy and atomic force microscopy. These observations show that the damage size of Nb/Si multilayer is smaller than the others and indicates that Nb/Si multilayer is superior than the other multilayers for high fluence EUV irradiation.

10450-74, Session P6Tue

High-radiance LDP source for mask inspection and beam line applications

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High-throughput actinic mask inspection tools are needed as EUVL begins to enter into volume production phase. One of the key technologies to realize such inspection tools is a high-radiance EUV source of which radiance is supposed to be as high as 100 W/mm^2/sr. Ushio is developing laser-assisted discharge-produced plasma (LDP) sources. Ushio's LDP source is able to provide sufficient radiance as well as cleanliness, stability and reliability. Radiance behind the debris mitigation system was confirmed to be 120 W/mm^2/sr at 9 kHz and peak radiance at the plasma was increased to over 200 W/mm^2/sr in the recent development which supports high-throughput, high-precision mask inspection in the current and future technology nodes. Our current focus is to improve the system availability and short- and long-term performance stability. Long-term operation tests are being carried out to assess and improve the system availability. In order to evaluate the performance stability more in detail, a high-magnification camera of which magnification is greater than 7 was introduced. By tuning the source parameters, Ushio's LDP source can be used not only in mask inspection abut also in beam line application that exposes samples at high intensity. Ushio's USE3315E source has recently been installed on the beam line at the customer site. Source performances were evaluated through the acceptance tests.

10450-75, Session P6Tue

A new objective for EUV-lithography, EUV-microscopy, and two-dimensional x-ray imaging

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This paper describes a new objective for EUV lithography, EUV-microscopy, and 2D x-ray imaging, which similar to the well-known Schwarzschild objective consists of two concentric, convex and concave, spherical reflectors. Its essentially new feature is that it satisfies the Bragg condition for the wavelength of interest at every point on the surfaces of both reflectors [1], which would be spherical multi-layer structures with a uniform 2d-spacing, in the case of EUV radiation, and spherically bent crystals, in the case of x-rays Thanks to this new feature, it is possible to obtain two-dimensional EUV or x-ray images from a large area, at once. The advantage for EUV lithography would be that an entire mask could be imaged onto a wafer, at once, and that a scanning of the mask by a narrow beam of EUV radiation – which is being used with present systems because the Bragg condition can only locally be satisfied - would no longer be necessary.

[1] M. Bitter, K. W. Hill, P. C. Efthimion, Patent: US 2015/0055755 A1

10450-76, Session P6Tue

High-precision MoSi multilayer coatings for radial and 2D symmetric designs on curved optics

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The development of industrial infrastructure for EUV lithography requires a wide array of optics beyond the mask and the scanner optics, which include optics for critical instruments such as exposure testing and actinic inspection. This paper will detail recent results in the production of a variety of high-precision multilayer coatings achieved to support this development. It is critical that the optical designs factor in the capabilities of the achievable multilayer gradients and the associated achievable precision, including impact to surface distortion from the added figure error of the multilayer coating, which adds additional requirements of a specific shape to the period distribution. For example, two different coatings may achieve a ±0.2% variation in multilayer period, but have considerably different added figure error.

Part I of the paper will focus on radially-symmetric spherical and aspherical optics. Typical azimuthal uniformity (variation at a fixed radius) achieved is less than ±0.005nm total variation, including measurement precision, on concave optics up to 200mm diameter. For highly curved convex optics (radius of curvature less than 50mm), precision is more challenging and the total variation increases to ±0.01nm total variation for optics 10-30mm in diameter. Total added figure error achieved has been as low as 0.05nm.

Part II of the paper will focus on multilayer designs graded in two directions, rather than radially, in order to accommodate the increased complexity of elliptical, toroidal and hyperbolic surfaces. In most cases, the symmetry of the required multilayer gradient does not match the symmetry of the optical surface, and this interaction must be countered via the process design. Achieving such results requires additional flexibility in the design of the deposition equipment, and will be discussed with several examples in the paper, such as the use of variable velocity of an inline substrate carrier in conjunction with a shaped target aperture to produce ±0.03nm total variation on an off-axis elliptical surface.

10450-77, Session P6Tue

Laser produced plasma EUV sources for high-volume manufacturing: Performance, availability, and power scaling

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In this paper, we provide an overview of various technologies for scaling laser-produced-plasma (LPP) extreme-ultraviolet (EUV) source performance to enable high volume manufacturing. We will show improvements to source architecture that facilitated the increase of EUV power from 100W to 250W, and the technical challenges for power scaling of key source parameters and subsystems. Finally, we will describe current power-scaling research activities and provide a perspective for LPP EUV sources towards 500W.

10450-78, Session P6Tue

Characterization of EBL2 EUV exposure facility

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TNO has built EBL2; a facility for EUV exposure testing and surface analysis. EBL2 is capable of testing EUV optics, EUV photomasks, pellicles, and other components under controlled conditions. EBL2 is capable of generating conditions relevant to EUV scanner and source operation at all foreseen source power nodes. This enables life time testing of EUV optics, reticles and pellicles under conditions which are not yet available to industry, helping the industry to prepare for HVM production.

EBL2 consists of an EUV beam line coupled to an X-ray Photoelectron Spectroscopy system by an automated sample handler. The full system accepts standard EUV photomasks, with or without pellicles. Smaller samples can be handled using sample holders with generic interfaces. Performance of the XPS was reported earlier [Proc. SPIE 99840R].

The EUV beam line consists of an EUV source, collector module, and exposure chamber. The EUV source is a Sn-fueled Laser-assisted Discharge Plasma source [Proc. SPIE 97760L]; the collector module consists of two mirrors with an intermediate focus, and is capable of defocusing the EUV light to match the desired intensity [Proc. SPIE 998520]. The exposure chamber contains the chuck for EUV exposures, an in-situ imaging ellipsometry system, and a gas inlet and monitoring system. The chuck contains the thermal control system, as well as EUV metrology.

EBL2 reached first light in December 2016 [Proc. SPIE 1014356]. The system has since been subjected to extended qualification testing. The current contribution reports on the results of this testing. Topics investigated focus on the prerequisites for achieving a realistic and controlled EUV exposure: handling and position control, thermal management, a relevant gas environment, and EUV irradiation and metrology. Also, first trial exposures will be reported. An outlook for further work will be presented.

10450-79, Session P6Tue

Recent developments in EUV pellicle and mask metrology for high volume manufacturing

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EUV Lithography is poised to enter HVM in the very near future. One of the principal challenges in the EUVL implementation for HVM is the availability of necessary particle free at wavelength metrology tools. Since the company's inception in 1999, EUV Tech has pioneered the development of EUV Metrology tools.

EUV Tech recently developed a EUV Pellicle inspection tool to measure EUV pellicle transmission and thermal absorption. This tool provides key measurement information for the qualification of a photomask for use in a EUV Scanner. Recent results from measuring a variety of candidate EUV pellicles will be shown to highlight the measurement performance of the tool.

EUV Reflectometry provides key measurement information for the qualification of a photomask for use in a EUV Scanner. The data is useful for a variety of users across the EUV photomask development lifecycle.

Recently EUV Tech has delivered several HVM EUV Reflectometers which provides at-wavelength EUV metrology of a photomask with a high precision beamline and an ultra-clean reticle transfer system. These tools are currently in use at production EUV mask shops.

This paper will discuss the measurement performance and data output of the tool, the uses within the photomask development lifecycle, our R&D program and roadmap to minimize particle adders in our EUV Reflectometer

and the ongoing efforts to improve the reflectivity and wavelength, precision and accuracy required to qualify the EUV masks for future processing nodes.

10450-80, Session P6Tue

The EUV pellicle transmission qualification tool

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EUV lithography volume is ramping up for production in 2018. EUV pellicles are considered a corner stone for insertion. Making them ready in time imposes challenges also on actinic metrology tools. EUV pellicles are envisioned as a solution to reduce the impact of particle contamination on the front side of reticles. The pellicle is a thin film (≈ 50 nm) placed above the patterned surface of a reticle. Particles that would have otherwise landed on the patterned side of a reticle will now land on the pellicle. Because they are such out of focus their impact on the imaged pattern is strongly reduced. For making pellicles usable in EUV scanners, they must undergo several qualifications for supplying reproducible quality.

Within RI Research Instrument's approach of supporting EUV mask infrastructure with actinic metrology, we have developed a dedicated tool for EUV pellicle transmission qualification (EUV-PTT) using "effective inband EUV measurement" concept.

For "effective EUV inband qualification" the emission of a lab EUV source is spectrally filtered to about 2% band width of inband EUV around 13.5 nm central wavelength. For the EUV-PTT we use our own product EUV-Lamp operated with Xenon at less than nominal power rating. The used spectral distribution resembles that of the EUV scanner – especially as out of band radiation is efficiently blocked. Such the measurement emulates the performance of the pellicle "as in the scanner". Hence this technique is more directly addressing the real use than e.g. integrating or extrapolating spectral transmission curves usually recorded at beamlines at storage rings.

With the "effective EUV inband qualification" concept the pellicle transmission is recorded with respect to quality factors throughput and homogeneity "as the scanner sees it". It may be noted that while this techniques is straight forward and robust with lab sources, it may require special instrumentation at storage ring beamlines not readily available.

This concept is highly efficient with compact metrology sources like the EUV-Lamp. Acquisition of a single images qualifying about 20*20 mm^2 on the pellicle with 13.5*13.5 μm^2 pixel resolution is possible with less than 100 source pulses – i.e. less than 5 seconds even with a source at reduced power of 25 Hz repetition rate.

Of special importance for the quality of the measurements is monitoring the beam power such that images can normalized to the applied dose. With our E-Mon pulse energy monitor we apply a solution being used since 2000 in the developments of discharge sources for metrology and high volume manufacturing.

For qualifying a full pellicle e.g. 7 x 9 = 63 images are recorded. Final result is compiled from raw frames, monitor information and condensing to "quality pixels" (e.g. 200 * 200 µm?). Ultimate precision is achieved with stitching algorithms using overlap information and reference spots of 100 % transmission. The total acquisition process is accomplished in less than 45 minutes. Slow vacuum loading and unloading – necessary for extreme handling care with the delicate samples - consumes another 30 minutes.

First images of full sized pellicles show sensitivities to variations in the range of better 0.05 %, precision of better 0.1 % and accuracy better 0.2 %, with a spatial resolution of 30?m2.

10450-81, Session P6Tue

EUV-LET: Exposure tool for high-resolution resist characterization by interference lithography

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High resolution nanopatterning techniques are in high demand not only in science and research, but also in in lithographic industry for resist characterization. The quality of the resist pattern is directly linked to the quality of the aerial image that is utilized for the exposure of the photoresist. Approaches that are based on interference effects can provide very homogeneous intensity modulations over large areas. The intensity modulation in the mask-based interference approaches is defined only by the transmission mask and the source emission properties since there are no additional optical elements necessary. For the required transmission masks interference effects can lead to easier fabrication requirements since mask defects can be compensated and structure sizes on wafer is typically smaller than those on masks.

The realized EUV laboratory exposure tool (EUV-LET) is based on the achromatic Talbot effect which is an effective method when broadband emission is used. The exposure tool consists of a discharge-produced plasma source, high-efficient phase-shifting masks and the high-precision wafer stage. By positioning the wafer in sub-50 µm distance to the transmission mask the contrast of the provided intensity modulation is maximized. Since all diffraction orders contribute to the intensity modulation, a high throughput is achieved with typical exposure times of several seconds. Scalable single exposure fields of several square millimeters can be achieved and repeated to cover even larger areas.

The transmission masks are the key element of this approach and need to be fabricated for each target half-pitch size. Efficient fabrication of the masks has been achieved by minimizing the required number of process steps. Optimized parameters for the electron beam lithography of polymers on an ultrathin membrane lead to high-aspect ratio mask structures. Polymer thickness is optimized to achieve maximum diffraction efficiency providing sufficient aerial image contrast at the exposure distances.

With theoretical resolution limit for the achromatic Talbot lithography of sub-10 nm the technology is viable for the resist characterization beyond N7 node. With the available photoresists and mask fabrication technology we already demonstrate 28 nm half-pitch contact-hole arrays over areas of 1 x 1 mm?. High aspect ratio transmission masks for 21 nm and 14 nm half-pitch structures are also fabricated to further analyze the practical resolution limit of the method.

In this paper we present the details of the mask fabrication process together with the latest exposure results of the EUV-LET, describing an effective patterning tool that can be used directly at the facilities for the characterization of photoresists for the upcoming lithography generations.

10450-12, Session E6

Source optimization in EUV lithography driven by fundamental and physical diffraction considerations

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Source optimization is a very fundamental task for a lithographer. By optimizing the incidence angels at the reticles the combined diffraction behavior of mask and projection lens can be modified. As such off-axis illumination was a key enabler over the last 20 years to push the k1 value and thus resolution in optical lithography from k1=0.5 to k1 below 0.3. For simple test structures, as we will use in this study, the diffraction pattern consists of a limited number of diffracted orders with which will

be (partially) captured by the projection optics. Without Mask 3D effects, the illumination source optimization tries to maximize the amount of light captured by the projection lens. This often leads to very strong off-axis illumination. The symmetry off the pattern is reflected in the source shape: a rectangular contact hole leads to quadrupole type illumination, a staggered CH arrangement leads to hexa-pole illumination.

In EUV lithography the same arguments hold. However, there are a couple of fundamental differences compared to the early fundaments of source optimization that will alter the behavior:

• The chief ray angle will lift the symmetry with respect to the azimuthal angle in the illumination pupil. Therefore we expect the pupil to be (slightly) asymmetric and top and bottom part of the illumination pupil has different intensity.

• The multi-layer reflectivity changes the intensity in the diffraction orders, leading to very strong intensity effects for given incidence angles for some features (e.g. two trench arrangements). This leads to a strong preference for certain incidence angles and fine structure in the pupil.

• The mask 3D effects lead to very strong phase effects and this results in shifts of the aerial image per incidence angle. To avoid Mask 3D fading, it is best to use only one incidence angle. In the exposure tool this leads to illumination settings centered around sigma=0 ("small conventional and small annular")

We will study the diffraction behavior for a number of simple test-structures: two-trench, rectangular and staggered contact holes, semi-random contact holes. For the Contact Holes, we will derive the optimum illumination shape by source optimization with respect to contrast in the aerial image. The aerial image contrast drives the local CDU for Contact Holes and the Line width Roughness for grating type structures. The source shape we arrive at can be understood by looking at the phase and intensity effects in the diffracted orders. This methodology is very instrumental to study the interaction of Mask 3D effects and projection optics

These "optimum source shapes" are thus the theoretical limit for one single structure and when optimizing for one single parameter namely aerial image contrast. The derived sources show 10..20 % increased contrast, lower dose to size and improved illuminator efficiency compared to the source shapes chosen by traditional arguments. Furthermore the optimum source shape does not fully reflect the symmetry of the lithography pattern anymore.

10450-13, Session E6

Performance and characteristics of the NXE:3400 optical system enabling sub-10nm node lithography

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The optical train is a key sub-system of each lithography scanner. The single patterning resolution limit of a scanner is determined by the characteristics and performance of its imaging system consisting of illumination and projection optics. The most relevant performance parameters of the illumination system are the maximum achievable setting flexibility, off-axis imaging capability (sigma) and pupil fill ratio (PFR). The projection optics key drivers numerical aperture (NA), aberration level, and stray light determine resolution limit and image quality of the scanner. In EUV lithography, optimizing aerial image contrast and image overlay is of particular importance to achieve the required resolution and edge placement performance of the scanner because stochastic effects degrading the initial image as e.g. resist blur and photon shot noise are still comparably strong.

In this paper, we present an overview on the new features of the NXE:3400 EUV optical system designed to improve resolution limit, contrast and overlay performance of the NXE:3400 scanner. The illumination system features a novel design based on a large number of switchable facetted mirrors which enables an unprecedented setting flexibility and reduced pupil fill ratio. Furthermore, the off-axis imaging capability of the illuminator has been extended to the full NA which in combination with the reduced PFR improves the single patterning resolution limit of the NXE:3400 by approximately 20% down to 13nm. In addition, by exploiting the increased flexibility of the 3400 illumination system, we demonstrate the ability to further correct for 3D mask effects, and excellent matching to the NXE:3350 system. The projection optics features a NA of 0.33 with significantly reduced aberration level as compared to the precedent 3350 projection optics. In particular, the non-correctable errors impacting scanner overlay, and the wavefront RMS impacting image contrast have been substantially reduced. Keeping the design concept, the improvements have been implemented such that a seamless matching to the 3350 projection optics is guaranteed.

Finally, we present NXE:3400 printing results to verify the imaging performance of the NXE:3400 optical system in resist. NXE:3400B wafer prints demonstrate excellent and consistent imaging performance across several systems in line with the discussed improvements of the optical train.

10450-14, Session E6

Addressing EUV masks registration challenges through closed loop correction

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EUV lithography is expected to become a critical enabling technology in the short and mid future of high end IC manufacturing. Although much effort is going into process and manufacturing challenges and inroads are being made in the industry, some process residuals will still exist with the move to HVM and among them will be the mask registration errors and the on product overlay (OPO).

The PROVE® system is the state of the art high end registration metrology tool capable of measuring both DUV as well as EUV masks. The ForTune® EUV utilizes an ultra short pulse laser to modify the mask substrate in order to correct registration errors and bring the mask into specification. Combining the metrology capabilities of the PROVE® with the corrective capabilities of the ForTune® EUV allows a closed loop solution in which the registration metrology data is utilized to feed forward the correction job needed to be applied over the mask in the ForTune® EUV.

This paper investigates the ability to improve mask registration on EUV masks using closed loop feedback between the PROVE® and ForTune® systems. Initial registration data from an EUV mask is measured by the PROVE® and utilized to both calculate the mask tuning job as well as predict the improvement prior to actual procession. After carrying out the registration correction on the ForTune® EUV, the EUV mask is again measured on the PROVE® to evaluate the ForTune® EUV process

The registration is measured with the PROVE® and the data is utilized by the Advanced Tuning Center, a FAVOR® solution, to prepare the job for the ForTune® EUV correction.

10450-15, Session E6

Single element and metal alloy novel EUV mask absorbers for improved imaging

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Current EUV mask technology uses Ta-based metallic absorber layer, on

top of a reflective multilayer mirror. Multiple studies have shown that the optical constants and the required 50-70nm thickness of Ta-based metallic absorber at EUV wavelength, do not offer an optimal wafer image, and, for example, produce images with pitch and illumination dependent best focus shifts for patterns at Foundry N5 dimensions. Alternative metal absorbers with higher absorptivity than Ta, such as Ni and Co have been proposed and, in simulation, show improved imaging at <40nm thickness.

The replacement of a Ta- absorber by a new type of metal is a formidable task for the mask industry. A novel absorber must not only meet the criteria for improved imaging, but also must meet the required material properties that make it compatible with different steps in mask blank and subsequent mask manufacturing, such as a controlled deposition technique, availability of a patterning process for mask patterning, and be compatible with mask inspection, repair, and cleaning.

We have started an experimental evaluation of the properties of thin metal Ni and Co films, and alloys of Ni, considering imaging performance and mask manufacturability. Rigorous lithographic simulations are used to screen potential absorber materials for their imaging properties at Foundry N5 dimensions, and find optimal thickness. The microscopic structure of the thin films was determined using X-ray, X-SEM and X-TEM techniques, and optical constants were measured using ellipsometry at EUV wavelength. Towards mask manufacturing, patterning performance, and resistance to typical mask cleaning chemicals was evaluated experimentally.

Standard deposition of Ni and Co metals yielded polycrystalline thin films, that prove difficult to pattern using a traditional etch process. In addition, Co films were found to be affected by standard mask cleaning chemistry. Hence, if Ni and Co are required as new mask materials, also novel patterning techniques will have to be used, that may be additive rather than subtractive. To illustrate this, we show promising performance for area selective Co deposition techniques.

To identify new materials, that have better properties towards manufacturing than single-element Ni and Co, we have started the evaluation of metal alloys, at different elemental ratios. This allows to combine Ni with an element that has refractive index closer to 1, or with an element that has even higher absorptivity. The films of metal alloys have been characterized in a similar way as the single element metals, so that they can be compared to single element metals as suitable materials for mask manufacturing.

10450-16, Session E6

Individual multilayer reflectance in an EUV reticle

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The Extreme Ultraviolet reticle is a multilayer system ideally comprised of 40 alternating layers of molybdenum and silicon. The real reticle situation is not ideal, instead $MoSi_2$ regions are found between each Mo and Si layer in the reflector. Reflectance differences arise as the Si, Mo, and $SiMo_2$ proportions change. The material proportions are not necessarily constant throughout the reflector stack which results in reflectance variations. Small variations in the mask reflectance resulting from material proportion differences can impact CD formation and uniformity on the wafer.

The exact impact of a material variation on wafer CD is dependent on many factors. One factor is the depth in the mask stack at which the variation is found. Previous studies have demonstrated that multilayer variations at different multilayer locations produce imaging effects that are CD and pitch dependent . This study proposes to quantify the contribution of each multilayer set (1 through 40) to the intensity used to form the wafer pattern. This will be accomplished by computationally placing absorbers and transmitters into the stack, then measuring output intensities as well as final wafer CDs. It will provide a better understanding of material variation impacts in the mask multilayer.

10450-17, Session E7

Unraveling the role of secondary electrons upon their interaction with photoresist during EUV exposure

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The interaction of 91.6eV EUV photons with photoresist is very different to that of optical lithography at DUV wavelength. In the latter, the photons interact with the resist in a molecular way (for example the photon directly interacts with the photo acid generator (PAG), which leads to a deprotection reaction on a polymer), while at EUV the high energy photons interact with the matter on atomic scale, resulting in the generation of secondary electrons. It is believed that these secondary electrons in their turn are responsible for chemical modification and lead to switching reactions that enable resist dissolution. However, details of the interaction are still unclear, e.g. which chemical reaction an electron with a given energy can initiate.

In this work we have developed a method to measure the chemical interaction of the secondary electrons with the EUV resist. The method is based on E-gun exposures of photoresist with low energy electrons (range ~1eV to ~90eV) . The chemical interaction is then measured by Residual Gas Analysis (RGA), since this can monitor in-situ which and how much reaction products are generated. In this way a 'chemical yield' can be quantified as function of electron energy.

This method has been successfully applied to understand the interaction of secondary electrons on the traditional CAR materials. This was done by using advanced EUV model CAR samples consisting of polymer only, polymer+PAG, and polymer+PAG+quencher. It was found that low-energy electrons down to ~1eV can activate PAG (and quencher), which can lead to polymer deprotection. However it was also observed that electrons of energy ~15eV and higher can lead to polymer deprotection even in absence of PAG. In addition, these higher energy electrons seem to generate also side-reactions on the polymer chain that could lead to cross-linking.

In this work we will describe the investigation method of the electron-resist interaction by RGA, and report on the above mentioned understanding of how secondary electrons interact with the CAR material. Furthermore, we extend the investigation to novel EUV resist platforms such as metal-organic and nano-particle EUV photoresists. It is expected that the understanding gained from analysis of electron-resist interaction could help in optimizing future resists towards their use in EUV high volume manufacturing.

10450-18, Session E7

Secondary electron interactions of chemically amplified EUV photoresists

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Chemically amplified extreme ultraviolet (EUV, ~13.5 nm) photoresists are typically comprised of a photoacid generator (PAG) in a polymer matrix. During the photolithographic process, a photoresist is exposed to EUV photons; it is believed that electrons and holes generated during exposure are the major source of acid production between resist components. It has been shown that more easily reduced PAGs have higher acid yields within the same polymer matrix. This correlation of reducibility vs. acid yield should be consistent between PAGs regardless of the polymer matrix.

This work investigates PAG reducibility compared to acid yield for several PAGs contained in various polymer matrices. Reduction potentials of PAGs are determined through cyclic voltammetry and electrolysis. An acid indicator, coumarin 6, and an established outgassing technique are used to determine the number of acids generated for low energy (80 eV) electron exposures for given polymer matrices. These results are compared to analogous EUV exposures.

10450-19, Session E7

A novel route to EUV resists design: Fundamental understanding of chemical processes

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New resists are needed to advance EUV lithography. Tailored design of efficient photoresist is impossible without fundamental understanding of EUV induced chemistry. Resists incorporating high cross-section elements efficiently utilize EUV photons via radiation absorption by core-level electrons, resulting in emission of primary electrons. However, this is only an initial step in the process. Auger emission, molecular fragmentation, and subsequent electron-resist interactions are also critical. Understanding all these steps is crucial to harness all the deposited energy for improved patterning results.

In this work, we present recent results of multimodal experimental approaches to study photoresist materials. To build our grasp of EUV photochemistry from the ground up we aim for understanding the whole variety of processes happening after absorption of an EUV photon by a single building block of resist material – a resist molecule. Model photoresist constituent molecules functionalized with halogen atoms, are isolated in the gas phase and exposed to tunable EUV radiation from the Advanced Light Source, Berkeley Lab and the direct processes are investigated by photoelectron spectroscopy and photoionization mass spectrometry. We quantify the performance of several candidate molecules in terms of photoemission cross-sections and electron yield per primary photoionization event. We demonstrate that some prototype resist molecules can emit several (photo- and Auger) electrons after single EUV photon absorption. Following the electron emission, the atomic relaxation leads to the molecule fragmentation, which also depends on the halogen functionalization. Secondary electron-driven reactions are studied by tunable electron impact ionization and dissociative electron attachment mass spectrometry. We demonstrate that even very low kinetic energy electrons may lead to the molecule dissociation.

While gas-phase studies do provide insight into the primary EUV photon or electron induced events in the individual resist molecules, we seek to understand these processes in the condensed phase as this is where industrially relevant processes will occur. We discuss techniques allowing for generation of resist nanoparticles of different morphology, representing either condensed resist or a substrate coated by a resist film. The same techniques, as applied to investigate resist's building blocks, are used to study the condensed resist material, connecting our understanding of the fundamental phenomena from each isolated molecule to the solid state system.

10450-20, Session E7

The effect of resist film depth inhomogeneity on the lithographic performance of metal-based resist materials

Julius Joseph S. Santillan, Toshiro Itani, EUVL Infrastructure Development Ctr., Inc. (Japan)

The development of metal-based resist materials continues to be actively researched in preparation for high volume manufacturing with extreme ultraviolet lithography (EUVL). Metal-based resist materials have the potential for their high sensitivity to EUV light (λ=13.5nm). These materials also exhibit high etching resistance, allowing application at thinner film thicknesses (an advantage as EUVL moves to more stringent targets). Champion results have shown that fine patterning (in terms of resolution and line edge roughness) is possible. However, it is apparent that such patterning capabilities come at the price of lower resist sensitivity. Thus, significant research work remains on how to take advantage of these characteristics.

In this presentation, investigative studies utilizing new/alternative measurement techniques were performed to further understand the characteristics of metal-based resist materials. These investigations utilize the EIDEC standard metal resist (ESMR1), a metal-based material (composed of ZrOX cores and methacrylic acid (MAA) shells) coated on silicon wafer at 30nm thickness. The ESMR1 can resolve 17-nm lines at a high sensitivity of 7mJ/cm2 and a line width roughness (LWR) of 5.6nm. For this material, LWR and post-coating delay (PCD, change in sensitivity after a certain delay time after coating) are issues that need to be pursued.

To provide possible pointers in resolving this issue, the material composition/distribution was analyzed utilizing Gas Cluster Ion Beam (GCIB) combined with Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS). This method allows the depth profiling of the resist film through the combination of surface analysis (TOF-SIMS) and etching (GCIB), alternately performed. This method was customized for application in metal-based resists.

Preliminary results have successfully shown the depth profile of the ZrOX metal core and MAA shells from film surface to bottom. The concentration of metal cores was found to remain constant from resist film surface to bottom. However, shell components were observed to be relatively abundant at the resist film surface compared to the film bottom. Such inhomogeneity is crucial as the presence (or absence) of shell components affect the solubility of the resist film to developer solution (typically Butyl Acetate). A decrease in shell components at the bottom of the film explains the presence of scumming (from early reports) in unexposed areas of patterns resolved. This inhomogeneity also suggests non-uniformity in film solubility that in effect, can influence LWR. Further investigations using the same material also show the effect of PCD on the film's chemical depth profile. Experiments were done comparing the resist film right after coating to another measured after a PCD of 24 hours. Results showed an overall decrease of more than 50% in shell components throughout the film depth. This decrease in total concentration of shell components explains the effect of PCD, which in this case affects the solubility of the resist film. These, and other measurement results on metal-based resist characterization will be discussed in detail during the symposium.

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10450-21, Session E7

Sensitization and reaction mechanisms of metal resist used for extreme ultraviolet lithography

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The performance of chemically amplified resist is approaching its physical limit with the reduction of feature sizes due to the acid diffusion needed for the solubility change of resist polymer. The line edge roughness (LER) of chemically amplified resists rapidly increases in the sub-10-nm-half-pitch region when the half-pitch is decreased. Also, the stochastic defect (pinching and bridges) generation is a significant concern for the high resolution patterning with high throughput. To solve these problems, the increase of the density of resist films is an important factor. In this study, the radiation-induced reactions in metal resist were investigated. The metal resist is attractive for sub-10 nm fabrication because of its high density property. For the improvement of metal resist, understanding of the details of sensitization and reaction mechanisms is important. The resist used consists of zirconia metal oxide core and methacrylic acid ligand. Using the

metal resist, line-and-space patterns were fabricated in the exposure dose range of 7-17 mJ cm-2. The dependences of resist patterns on half-pitch and exposure dose were analyzed. The sensitization and reaction mechanisms of metal resist are discussed.

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10450-22, Session E8

High resolution lithography using a multi-trigger resist

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As the minimum lithographic feature size continues to shrink, the development of techniques and resist materials capable of high resolution (R), high sensitivity (S) and low line edge roughness (L) has become increasingly important for next generation lithography. However, the issue represents a fundamental trade-off in lithography (the RLS triangle) and it is difficult to overcome. Addition of quenchers in chemically amplified resists reduces the acid diffusion length and improves the line edge roughness and increases the resolution of the patterned features, but decreases the sensitivity, and impacts on material stochastics increasing the line edge roughness. One current approach to boost the sensitivity in organic resists has been the addition of metals by incorporating organometallic complexes or metallic clusters in the resist, but again this can impact the line edge roughness.

In this study we will introduce and explain the multi-trigger mechanism concept employed in our system. This enables high sensitivity without the need for additional metallic components in the resist, but also incorporates a quenching behaviour in to the chemistry to improve resolution. The standard material consists of a proprietary molecule – xMT, together with a crosslinker and a PAG. EUV light generates photoacids, as with a traditional chemically amplified resist, but the response of the resist matrix implements a logic-type function. Where two resist molecules are activated by two acids, in close proximity to each other, then the resist molecules will react catalytically and subsequently release both acids. When a resist molecule encounters a single acid in isolation then it will hold on to the acid, without itself reacting, thus removing the acid from the reaction. This behaviour allows a high sensitivity response at a certain dose threshold, but turns the resist response off much more quickly (as a second order reaction) as the dose decreases, leading to sharper lines and lower line width roughness.

We present results where the xMT molecular structure was modified to create enhanced versions of the standard resin that will offer higher cross-linking capability, better mechanical strength to reduce the LER and ultimately higher resolution. The impact of high Z additives was also evaluated. The materials were patterned in electron beam lithography at 100 kV and also using EUV lithography at the Paul Scherrer Institute in Switzerland, and their lithographic properties were analyzed in comparison with our standard resist. Dense line and spaces at 14nm and 16nm half pitches were patterned, and results show with a dose to size of 25mJ/cm2 with LER of 3.3nm at 16nm half pitch with an enhanced version. The same half pitch is patterned at a dose of 17mJ/cm2 when a high Z additive is introduced, but with a higher LER value. Results from the MET are also presented. Isolated pillars and holes with a diameter of 25nm, and line and space patterns at 11 nm half pitch have been patterned using ebeam lithography in the enhanced xMT resist.

10450-23, Session E8

DDR process and materials for NTD photo resist in EUV lithography

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We developed the novel process and material which can prevent the pattern collapse issue perfectly. The process was Dry Development Rinse (DDR) process, and the material used in this process was DDR material. DDR material was containing siloxane polymer which could be replaced the space area of the photo resist pattern. And finally, the reversed pattern would be created by dry etching process without any pattern collapse issue.

This novel process was useful not only in positive tone development (PTD) process but also in negative tone development (NTD) process. We newly developed DDR material for NTD process. Novel DDR material for NTD consists of special polymer and it used organic solvent system. New DDR materials showed no mixing property for NTD PR, so fine pattern of NTD PR could be filled by DDR materials then tone reverse could be achieved by dry etching process.

Tone reverse was successfully achieved by combination of NTD PR and DDR process keeping good pattern quality in EUV lithography. Reversed pattern below hp 14nm was obtained without any pattern collapse issue, which couldn't be created by just using normal NTD process.

Reversed contact hole could be obtained in NTD-DDR process at 24nm hole size. Reversed C/H made by NTD pillar showed good LCDU compared to PTD C/H. In addition, reversed C/H at 20nm hole size could be achieved in NTD-DDR process.

In DDR process, enough etch back is important to obtained fine reversed pattern with lower roughness but long etch back time caused degradation of the reversed pattern. Then etch back time was evaluated with NTD PR and DDR material. Reversed C/H showed minimum LCDU when short etch back time was applied, however degradation of LCDU was observed when long etch back was applied. LCDU of reversed C/H made by NTD-DDR process was 3.2nm. On the other hands, LCDU of normal C/H made by PTD process was 3.5nm, so reversed C/H from NTD pillar showed better LCDU than PTD C/H when suitable etch back was applied.

10450-24, Session E8

Recent progress of CAR materials for EUV lithography

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Extreme ultraviolet (EUV) lithography is considered to be the most effective strategy for realize 7 nm generation manufacturing and beyond. A key factor for the realization of EUV lithography is the choice of EUV resist material that is capable of resolving below 15-nm half pitch with high sensitivity. Chemical Amplified Resist (CAR) using positive-tone development (PTD) is still one of the strongest candidates for EUV lithography. Recently, some researchers have reported concerns on the limitations in the performance of CAR materials. Consequently, there is a critical need for new chemistry and development of new resist materials. However, new resist materials still have lots of concerns for manufacturing, such like a non-CAR materials including metal resist. Therefore, CAR materials are still most important items for EUV lithography manufacturing.

We've been developing negative-tone imaging (organic solvent development) with EUV exposure (EUV-NTI) for a long time. EUV-NTI has advantages for line-width roughness (LWR) due to their low swelling and dissolving smoothly. New EUV-NTI performances will be shown and also process condition progress will be updated.

Also, the basic study will be reported, which is high absorption unit including materials for improving stochastic effect.

We report herein recent progress of CAR materials, both positive-tone and negative-tone for EUV lithography.

10450-25, Session E8

Unbiased roughness measurements in EUV lithography

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Stochastic-induced roughness continues to be one of the major concerns for EUV lithography. Stochastic effects can reduce the yield and performance of devices in several ways:

• Within-feature roughness can affect the electrical properties of a device, such as metal line resistance and gate leakage;

• Feature-to-feature size variation caused by stochastics (also called local CD uniformity, LCDU) adds to the total budget of CD variation, sometimes becoming the dominant source;

• Feature-to-feature pattern placement variation caused by stochastics (also called local pattern placement error, LPPE) adds to the total budget of PPE, sometimes becoming the dominant source;

• Rare events in the tails of the distributions of errors are more probable if those distributions have fat tails, leading to greater than expected occurrence of catastrophic bridges or breaks;

• Decisions based on metrology results (including process monitoring and control, as well as the calibration of OPC models) can be poor if those metrology results do not properly take into account stochastic variations.

For these reasons, proper measurement and characterization of stochastic-induced roughness is critical. Unfortunately, current roughness measurements (such as the measurement of linewidth roughness or line-edge roughness using a critical dimension scanning electron microscope, CD-SEM) are contaminated by large amounts of measurement noise caused by the CD-SEM. This results in a biased measurement, where the true roughness adds in quadrature with the measurement noise to produce an apparent roughness that is larger than the true roughness. Further, these biases are dependent on the specific CD-SEM tool used and on its settings. Prior attempts at providing unbiased roughness estimates are proving inadequate for many of today's applications due to the smaller feature sizes and higher levels of SEM noise.

In this study, a new technique for producing unbiased estimates of roughness parameters will be used to investigate the impact of roughness in EUV lithography. It is based on the use of an analytical model for SEM scattering behavior that predicts linescans for a given feature geometry. Run in reverse, an Inverse Linescan Model can be used for edge detection in such a way that SEM noise can be adequately measured and statistically subtracted from the roughness measurement, thus providing unbiased estimates of the roughness parameters. In turn, these unbiased roughness measurements will be used to make predictions about within-feature roughness, LCDU, LPPE, and catastrophic failures for devices features at the 7-nm node.

10450-26, Session E8

The update of resist outgas testing for metal containing resists at EIDEC

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The metal containing resist is one of the candidates for high sensitivity resists. EIDEC has prepared the infrastructure for outgas testing in hydrogen environment for metal containing resists at High Power EUV irradiation tool (HPEUV). We have experimentally obtained the preliminary results of the non-cleanable metal contamination on witness sample using model material by HPEUV [1]. The metal contamination was observed at only the condition of hydrogen environment. It suggested the generation of volatile metal hydrides by hydrogen radicals. Additionally, the metal contamination on a witness sample covered with Ru was not removed by hydrogen radical cleaning. The strong interaction between the metal hydride and Ru was confirmed by the absorption simulation.

Recently, ASML announced a resist outgassing barrier technology using Dynamic Gas Lock (DGL) membrane located between projection optics and wafer stage [2], [3]. DGL membrane blocks the diffusion of all kinds of resist outgassing to the projection optics and prevents the reflectivity loss of EUV mirrors. The investigation of DGL membrane for high volume manufacturing is just going on. It extends the limitation of material design for EUV resists. However, the DGL membrane has an impact for the productivity of EUV scanners due to the transmission loss of EUV light and the necessity of periodic maintenance. The well understanding and control of the outgassing characteristics of metal containing resists may help to improve the productivity of EUV scanner. We consider the outgas evaluation for the resists still useful.

For the improvement of resist outgas testing by HPEUV, there are some issues such as the contamination limited regime, the optimization of exposure dose to obtain the measurable contamination film thickness and the detection of minimum amount of metal related outgas species generated. The investigation and improvement for these issues are ongoing. The updates will be presented in the conference.

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10450-27, Session E9

Actinic EUV scatterometry for parametric mask quantification

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In DUV lithography, scatterometry enables precise measurement of mask dimensions such as the pitch, linewidth, and sidewall-angle of periodic patterns. However, substantial differences in the optical properties of DUV and EUV masks, such as angular sensitivity and mask 3D effects, makes simply extending existing technologies difficult. Using the EUV reflectometer at Lawrence Berkeley National Labs Center for X-Ray Optics with tunable wavelength and illumination angle, we explore how to extend scatterometry to EUV masks, with particular emphasis on using rigorous simulations and experimental data to quantify the accuracy of sensitive measurements such as sidewall-angle.

Mask scatterometry at EUV wavelengths has benefits but also poses challenges that are not present at DUV wavelengths. The benefits come primarily from using the same wavelength as lithography; due to the severe sensitivity of the multilayer mirror to wavelength, the diffraction patterns obtained at DUV wavelengths from EUV masks would be both highly attenuated and substantially distorted. However, stronger mask 3D effects and the sensitivity of the multilayer to angle of illumination add extra levels of complexity to modeling the spectra of EUV masks that are not present in traditional DUV masks.

We use rigorous FDTD (Finite Difference Time Domain) imaging simulations of patterned EUV multilayer masks to generate a library of spectra including gratings with a range of orientations, pitches, line widths, absorber heights, and side-wall angles under a wide range of illumination wavelengths and angles. We then perform SVD-based dimensionality reduction to find an efficient representation, or dictionary, for the spectra. Using this low-dimensional dictionary, we determine the sampling requirements, i.e. which measurements (angles and wavelengths of illumination) are necessary to measure all parameters of interest to a specified accuracy. We finally acquire experimental spectra of known mask features on the EUV reflectometer

using different illumination conditions, and use the dictionary to recover the underlying dimensions of the features.

10450-28, Session E9

EUV mask roughness can recover litho-tool aberrations

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Speckle from an EUV mask adds to the line edge roughness of the final image in resist, so is typically minimized for better critical dimension control. However, the roughness of the mask can also be utilized constructively, for probing the pupil function of an aerial imaging system or a lithography scanner. The spectrum of the speckle image generated from an EUV mask blank encodes the system aberrations under a weak scattering approximation. We show that the properties of EUV masks are suitable for achieving a good balance between weak scattering and speckle contrast. Using this concept, we demonstrate in-situ experimental recovery of field-of-view dependent aberrations from blank areas of an EUV mask.

EUV masks are naturally rough at the scales seen by 13.5 nm light, creating weak diffused light that fills the entire pupil of the imaging system. Additionally, since most materials are only weakly scattering at soft X-ray wavelengths including EUV, the scattered light acts as a perturbation on the background illumination, recombining with it interferometrically to encode the pupil phase in the final speckle. We present an algorithm based on the phase contrast transfer function to use illumination angle diversity for extracting the pupil phase from the measured speckle spectrum at the camera plane. However, since the contrast transfer function is a linearization of the image intensity in terms of the object phase, it relies on the mask being a weak phase object. The exact properties of the EUV mask roughness needed for the linearization to apply are described. Measurements on the SHARP EUV microscope at the Lawrence Berkeley National Lab on mask blanks shows them to be weakly scattering, while still providing sufficient speckle contrast for aberration estimation. Additionally, the method can be used to probe aberrations across the field-of-view, using the speckle in any blank area of the mask for single-shot in-situ recovery of imaging system aberrations. While the method is shown to work on speckle from an aerial imaging tool, an extension to resist images of speckle from lithography scanner tools is being evaluated. This uses surface profile measurements of the speckle captured as the latent image on the exposed resist (before develop) to quantify aberrations in the lithography tool, under actual operating conditions. The recovered aberrations allow for high resolution reconstruction of the mask image in aerial imaging tools, or for compensating scanner aberrations using source-mask or pupil optimization techniques.

10450-29, Session E9

Evaluating mechanical characteristic of SiNx EUV pellicle membrane

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Various materials and structures have been studied to improve the mechanical and thermal properties of extremely thin membrane of EUV pellicle. We are developing pellicle membranes based on silicon nitride because silicon nitride is known to be stronger than silicon (e.g., Young's modulus of bulk material: ~300 GPa vs. ~150 GPa). Mechanical strength is required to guarantee the durability under mask stage acceleration and venting/pumping process. However, it is difficult to characterize the mechanical properties of nano-scale membrane such as Young's modulus, Poisson's ratio and fracture strength.

In this paper, mechanical properties of silicon nitride membranes with thickness less than 50nm were characterized by bulge test, tensile test and nano-indentation. Specially-designed 'push-to-pull device' was used to obtain stress-strain curve of silicon nitride membrane with 1.54 μm width and 2.45 μm length, and the Young's modulus of ~93GPa and tensile strength of 3.2GPa were obtained. Bulge-test were performed on silicon nitride membrane with 1 x 1 cm2 size, and the deformation of membrane induced by pressure load was monitored by laser displacement sensor with 0.1 ?m resolution. And the data points were fitted to the theoretical equation modified for square membrane and the Young's modulus of ~ 200 GPa was obtained. This value is higher than the one obtained by tensile test but lower than the bulk value. The detailed explanation of experimental data will be discussed during the presentation.

10450-30, Session E10

The future of EUV lithography: enabling Moore's Law in the next decade

Jan van Schoot, Kars Troost, Frank Bornebroek, Rob van Ballegoij, Sjoerd Lok, Peter Krabbendam, Judon Stoeldraijer, Erik Loopstra, Jos P. Benschop, Jo Finders, Hans Meiling, Eelco van Setten, ASML Netherlands B.V. (Netherlands); Bernhard Kneer, Bernd Thuering, Winfried Kaiser, Tilmann Heil, Sascha Migura, Carl Zeiss SMT GmbH (Germany)

While EUV systems equipped with a 0.33 Numerical Aperture lenses are readying to start volume manufacturing, ASML and Zeiss are ramping up their activities on a EUV exposure tool with Numerical Aperture of 0.55.

The purpose of this scanner, targeting an ultimate resolution of 8nm, is to extend Moore's law throughout the next decade.

A novel, anamorphic lens design, capable of providing the required Numerical Aperture has been investigated; This lens will be paired with new, faster stages and more accurate sensors enabling Moore's law economical requirements, as well as the tight focus and overlay control needed for future process nodes.

The tighter focus and overlay control budgets, as well as the anamorphic optics, will drive innovations in the imaging and OPC modelling.

Furthermore, advances in resist and mask technology will be required to image lithography features with less than 10nm resolution.

This paper presents an overview of the target specifications, key technology innovations and imaging simulations demonstrating the advantages as compared to 0.33NA and showing the capabilities of the next generation EUV systems.

10450-31, Session E10

Optical proximity correction for anamorphic extreme ultraviolet lithography

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The next generation of extreme ultraviolet (EUV) lithography scanners are expected to use anamorphic optics, instead of the traditional isomorphic lens systems. Specifically, the reduction factor from mask to wafer in the scan direction of the system will be larger than in the direction perpendicular to the scan. Therefore, the mask scale pattern for the anamorphic system is a distorted version of the wafer pattern, while it is a simple scaled version of the wafer pattern for an isomorphic system. This distortion adds new complexity to the mask data preparation process. New techniques to handle this complexity are discussed in this work

The effect of this hardware change on each component of the optical

proximity correction (OPC) software, and each step in the OPC flow, is investigated. When necessary, solutions to new problems are demonstrated, and verified by rigorous simulation. But, the convention of doing all layout processing and simulation at the wafer scale is maintained.

Additions to the OPC model include accounting for the optics, mask electromagnetics, and mask manufacturing. The Hybrid Hopkins Abbe (HHA) method is still applicable, but the incident angles of the illumination on the mask will depend on the anamorphic system. Also, additional direction dependent factors must be added to the Hopkins formulation. The Domain Decomposition Method (DDM) is also still valid, but the corrections signals must now be rastered based on the orientation dependent mask scale feature sizes. The established practice of "corner chopping", which replaces 90 degree corners with 45 degree edges to model the physical rounding of the mask, must be updated because a 45 degree edge in the wafer pattern does not correspond to a 45 degree edge on the mask.

The correction algorithm is updated to include awareness of anamorphic mask geometry for pattern fragmentation and mask rule checking (MRC). In many cases, the anamorphic system will improve the ability of OPC to converge on a solution because the wafer scale mask dimension limits will be reduced in the scan direction.

OPC verification through process window conditions is enhanced to test different wafer scale mask errors ranges in the horizontal and vertical directions. Accounting for a uniform mask bias error correctly will reduce the sensitivity to mask errors in the scan direction.

The effects of the anamorphic system on fracturing the post-OPC mask design to produce the mask writer input will also be discussed.

10450-32, Session E10

Edge placement error control and Mask3D effects in high-NA anamorphic EUV lithography

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To enable cost-effective shrink at the 3nm node and beyond, and to extend Moore's law into the next decade, ASML is developing a new high NA EUV platform. The high NA system is targeted to feature a numerical aperture (NA) of 0.55 to extend the single exposure resolution limit to 8nm half pitch. The system is being designed to achieve an on-product-overlay (OPO) performance well below 2nm, a high image contrast to drive down local CD errors and to obtain global CDU at sub-1nm level to be able to meet customer edge placement error (EPE) requirements for the devices of the future.

It is well known that EUV scanners employ reflective Bragg multi-layer mirrors in the mask and Projection Optics Box (POB) to project the mask pattern into the photoresist on the silicon wafer. These MoSi multi-layer mirrors are tuned for, amongst others, maximum reflectivity, and thus productivity, at 13.5nm wavelength. The angular range of incident light for which a high reflectivity at the reticle can be obtained is limited to ~ +/- 11o, however at 0.55NA the maximum angle at reticle level would extend up to 17o in the critical (horizontal) direction and compromise the imaging performance severely. To circumvent this issue a novel anamorphic optics design has been introduced, which has a 4x demagnification in the X- (vertical) direction and 8x demagnification in the Y- (horizontal) direction, as well as a central obscuration in some of the POB mirrors.

In this work we will show that the EUV high NA anamorphic concept can successfully solve the angular reflectivity issues and provide good imaging performance in both directions. A number of unique imaging challenges in comparison to the 0.33NA isomorphic baseline are being studied, such as the impact of the central obscuration in the POB and Mask 3D effects at increased NA that seem most pronounced for the Vertical direction. These include M3D induced contrast loss, non-telecentricity and BF shifts across slit. We will explore the solutions needed to mitigate these effects and to offer high quality imaging to be able to meet the required EPE performance in both orientations.

10450-33, Session E10

Next-generation EUV lithography productivity

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Beyond EUV insertion to high-volume manufacturing, the extendibility of the technology is dependent on the cost scaling advantages of high-NA or multi-patterning EUV lithography. Several concerns have been raised regarding the cost and lithographic feasibility of high-NA, including resist performance, productivity, depth of focus, mask infrastructure and field utilization/stitching capability. The intrinsic requirement of half-field exposures for high-NA lithography drives a necessary investigation on reduced field utilization verses stitching performance of the separate half fields. Furthermore, the additional mask for full fields dies will drive additional cost, complexity and overall overhead as compared to EUV NA 0.33 double patterning or other self-aligned technique. Here, the implication to EUV throughput capacity is analyzed within the context of the 7/5/3 nm technology nodes, specifically considering field utilization and scanner productivity as a function of source power and resist dose.

10450-34, Session E10

Taking a SHARP look at mask 3D effects

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Mask 3D effects are an area of active research in EUV mask technology. Mask-side numerical aperture, illumination, feature size and absorber thickness are key factors modulating mask 3D effects and affecting printability and process window.

The SHARP High numerical aperture Actinic Reticle review Project is a synchrotron- based, EUV mask microscope. Owing to its versatile architecture, SHARP has applications both in process development and advanced photomask research. Recent upgrades in flux, cleanliness and position accuracy enable our users to do defect imaging, printability assessment and repair verification on production-level photomasks.

SHARP is designed to emulate current and prospective future generations of EUV scanners, including anamorphic systems at 0.55 NA. The tool uses Fresnel zoneplate lenses as imaging optics. With 100s of lenses installed in the tool, the user can select a variety of isomorphic and anamorphic mask-side numerical apertures. High mask-side NA enables the study of mask-related properties of future nodes of EUVL, not accessible to 0.33 NA systems. SHARP's lossless Fourier-Synthesis illuminator produces arbitrary pupil fills, including pixelated sources, gray-scale sources and sources with a low fill factor and correspondingly high spatial coherence. Custom sources, obtained from computational source optimization or source mask optimization can be used with SHARP to record image data to complement simulation results.

Variable mask-side numerical aperture and flexible illumination make SHARP a powerful instrument for the study of mask 3D effects. We show an application example, comparing mask 3D effects for a standard Tantalum Nitride absorber and a thinner, 40-nm Nickel absorber. Data is presented for 0.33 4xNA and anamorphic 0.55 4x/8xNA. The influence of different illumination settings on mask 3D effects is discussed.

Funding for SHARP operations and upgrades is provided by Intel. General EUV infrastructure at Berkeley is funded through the EUREKA program. This work is performed by University of California, Lawrence Berkeley National Laboratory under the auspices of the U.S. Department of Energy, under Contract No. DE-AC02-05CH11231.

10450-35, Session E11

High-power LPP-EUV source with long collector mirror lifetime for high volume semiconductor manufacturing

Hakaru Mizoguchi, Takashi Saitou, Taku Yamazaki, Gigaphoton Inc. (Japan)

We have been developing CO2-Sn-LPP EUV light source which is the most promising solution as the 13.5nm high power light source for HVM EUVL. Unique and original technologies such as; combination of pulsed CO2 laser and Sn droplets, dual wavelength laser pulses shooting and mitigation with magnetic field have been developed in Gigaphoton Inc.. We have developed first practical source for HVM; "GL200E" 1) in 2014. We have proved high average power CO2 laser more than 20kW at output power cooperate with Mitsubishi electric cooperation2). Pilot#1 is up running and its demonstrates HVM capability; EUV power recorded at111W average (117W in burst stabilized, 95% duty) with 5% conversion efficiency for 22hours operation in October 20163). Recently we have demonstrated, EUV power recorded at113W in burst stabilized (85W in average, 75% duty), with 5% conversion efficiency during 143hours operation. Also the Pilot#1 system recorded 64% availability and idle time was 25%. Availability is potentially achievable at 89% (2weeks average), also superior magnetic mitigation has demonstrated promising mirror degradation rate (= 0.5%/Gp) above 100W level operation with dummy mirror test.4).

Reference

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4) Hakaru Mizoguchi, et al: " High Power HVM LPP-EUV Source with Long Collector Mirror Lifetime", EUVL Workshop 2017, (Berkley, 12-15, June, 2017)

10450-36, Session E11

Challenges to realize the EUV-FEL high-power light source for HVM system

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It is important to develop the high power EUV light source up to 1 kW to realize the 3nm node, which is expected to be in production at 2023-24. To this end, an energy recovery linac (ERL)-based free electron laser (FEL) must be a most promising candidate, so that our group has done some feasibility studies from the view point of accelerator technology. In order to realize the EUV-FEL high power light source, it is also important to recognize the demand of end users and related problems on the FEL light source. Last year, we attended many conferences and workshops to learn these items and also we organized one day workshop "EUV-FEL Workshop" at Tokyo. You can find the presentation materials in a website of http://pfwww.kek.jp/PEARL/EUV-FEL_Workshop/presentaions.html.

One of the most important requirements is to reduce the size of the EUV-FEL system. The total system size is about 200 m (L).x 20 m (W) at our current design of the EUV-FEL with 160m linac, where the acceleration energy and current are 800 MeV and 10 mA, respectively. However, we had comments from semiconductor industry that it is too long to install the light source in a usual LSI Fab, so that we have to find out solutions to reduce the length of the accelerator systems to ~100 m. To this end, there are following several challenges.

1) Increasing the field gradient of the superconducting RF (SRF) cavity to reduce the total length of the linac.

2) Higher Q to reduce the RF loss in higher field gradient SRF cavity.

3) Reduction of the acceleration energy by introducing shorter period undulator.

4) Double loop accelerator system, in which the electron passes through a same linac twice and accelerated up to twice energy or accelerating cavities are placed on both loop sides.

The R&D directions of the above challenges on accelerator technologies will be presented.

10450-37, Session E11

A concept for a 1 kW EUV source for lithography based on FEL emission in a compact storage ring

Michael Feser, Ronald D. Ruth, Rod Loewen, Lyncean Technologies, Inc. (United States)

EUV has long been hailed as the next generation lithography technology. Its adoption into high volume manufacturing (HVM), however, has been delayed several technology nodes due to technical issues, many of which can be attributed to the EUV source performance. Today's EUV lithography scanners are powered by laser produce plasma (LPP) sources. They have issues with power scaling beyond 300 W, reliability and contamination. Free Electron Lasers (FELs) have been considered as an alternative EUV source. Advantages of accelerator based sources are the maturity of the accelerator technology, lack of debris/contamination, and ability to provide high power. Industry turned away from this technology because of the requirement to feed up to 10 scanners from one linear FEL to make it economically feasible, the large footprint, and generation of radioactive byproducts. All of these issues are overcome in the presented concept using a compact storage ring with steady-state FEL lasing action. At 1 kW output power, comparable cost and footprint to an LPP source, this source is ideally suited for use on a single scanner and promises reliable, contamination free operation. FEL action in the storage ring is sustained by operating the FEL well below the saturation regime and preserving the equilibrium low emittance and energy distribution of the ring.

10450-38, Session E11

Improved cost-of-ownership for a droplet-based LPP light source for HVM EUV mask and blank inspection

Markus Brandstätter, Marco M. Weber, Duane Hudgins, Jeremy Nickol, Flori Alickaj, Reza S. Abhari, ETH Zürich (Switzerland)

Key components for the EUV mask infrastructure include actinic AIMS and pattern inspection, which are crucial for the introduction of EUV lithography into HVM. The usage of pellicles further substantiates the need for actinic light sources. EUV light sources with a high availability and brightness are required to increase the throughput for AIMS and pattern inspection systems.

The first bounce EUV collection optics are subject to harsh debris fluxes in the form of ions, neutrals and droplet fragments comprising the lifetime of the light source. Enhancing the debris mitigation reduces the reflectivity decay and therefore improves the light source cost-of-ownership (CoO).

Key to optimize the debris mitigation strategy is the assessment and quantification of the detrimental plasma debris. In the present work, the high kinetic energy particles including ions and neutrals generated from the laser irradiated droplet target are resolved spatially and temporally for an intermediate pressure regime. The implications of the ion and neutral flux on the collection optics are discussed in this work. By providing fresh targets in the form of micro-meter sized droplets to the droplet irradiation position, a certain variability of the droplet position with respect to the laser

focal area is inherent. By actively changing the droplet position with respect to the laser focal area with a control system the influence on ion and EUV propagation direction is studied in this work.

Finally, the long term LPP source operation is assessed. The debris mitigation system is enhanced employing a three-layer strategy demonstrating an increased source cleanliness for a GI collector configuration. Results from a sample exposure test for EUV reflection degradation of the first collector optics and the impact on the CoO will be presented.

10450-39, Session E11

Study of ion enhanced Sn removal by surface wave plasma for source cleaning

David N. Ruzic, Gianluca A. Panici, Dren Qerimi, Univ. of Illinois at Urbana-Champaign (United States)

A hydrogen plasma cleaning technique to clean Sn (tin) off of EUV collector optics is studied in detail. The cleaning process uses hydrogen radicals and ions (formed in the hydrogen plasma) to interact with Sn-coated surfaces, forming SnH4 and being pumped away. This technique has been used to clean a 300mm-diameter stainless steel dummy collector optic, and EUV reflectivity of multilayer mirror samples was restored after cleaning Sn from them, validating the potential of this technology.

This method has the potential to significantly reduce downtime and increase source availability. Thus, an investigation into the fundamental processes governing Sn removal has been performed. These experiments have shown that the Sn etch rates scale with hydrogen ion energy at the surface. Incident ions upon the surface impart energy that weakens the Sn-Sn bond allowing the chemical etch by hydrogen to proceed at a faster rate. Due to this the plasma is able to be in a reactive ion etch (RIE) regime. Results showing etch enhancement due to ions in this particular chemistry, including threshold energy, are shown.

A concern for plasma based methods is the implantation of high energy hydrogen ions into the MLM, reducing reflectivity and possibly blistering. With a surface wave plasma (SWP) this concern is alleviated somewhat because of lower ion energies. Surface wave plasmas have lower electron temperatures than conventional sources in the range of 1 to 3 eV. In addition, SWP sources result in plasma densities on the order of 1011-12 cm-3, allowing for greater utilization of ion etch enhancement. Experiments measuring electron density and hydrogen radical density over large areas have been conducted and the results from these measurements are presented. Pressure has also been varied to illustrate the effect between etching with radicals and RIE etching with ions included. Etch rate radial profiles over pressures ranging from 30 mTorr to 1.3 Torr have been measured with peak etch rates of 94.9 ± 4.6 nm/min at 250 mTorr.

10450-40, Session E12

imec's iN5 BEOL patterning development

Waikin Li, Ming Mao, Stefan Decoster, Sandip Halder, Gayle Murdoch, Monique Ercken, IMEC (Belgium)

The imec N5 logic device platform aims for 24nm pitch for first metal level (M1) and a subsequent metal (M2) patterns with minimum pitches of approximately 24nm to 28nm.These 1D pitch requirements are technically feasible by using well established 193i SAQP processes. With this metal grid design, however, the tightest center-to-center (C2C) distance for block and via layers will require 34nm. It's considered to be the key challenge to the enablement of a single exposure process with the 0.33NA EUV scanner. Moreover, mask rule check (MRC) constraints literally make the edge placement error (EPE) performance suffer greatly in dense layout arrays such as those found on the SRAM cells.

In this paper, we will present the evaluation result of several EUV patterning schemes on a series of DOE designs for pattern fidelity assessment, their process challenges, and limitations. A new patterning scheme will be recommended to meet the BEOL Design rule and IMEC logical scaling roadmap on track.

10450-41, Session E12

EUV exposure tool stability at IMEC

Vinayan Menon, Raul Pecharroman-Gallego, Lieve van Look , Eric Hendrickx, IMEC (Belgium); Andre van Dijk, ASM Belgium N.V. (Belgium); Tom Lathouwers, ASML (Belgium)

Source challenges have prolonged EUVL insertion into high volume chip production. Though recent years have seen much faster pace mitigation of key detractors.

In meantime ASML's first production platform NXE3300B continues to positively support imec's core Advanced Lithography Program and Advanced Patterning Center.

This presentation discusses source instability challenges addressed that impacted availability & power under UP2 configuration. Collector degradation caused illumination pupil pixel loss but remained within expected levels.

Long term exposure tool monitoring data indicates production sustainable capability for EUV dose variability & CDU. Lens aberration, focus & overlay issues unique to EUV addressed will also be discussed.

10450-42, Session E12

Investigation on post process for improving EUV resist performance

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ArF immersion has long been the mainstream lithography of high volume manufacturing due to delay of Extreme Ultraviolet(EUV) technology. EUV is the most desirable technology as substitute for multiple patterning based on ArF immersion lithography if suitable productivity is provided. Recently many significant results lately have been reported in EUV tool such as the progress of source power and availability on schedule of ASML, but lots of improvements are still required for the implementation of EUV lithography on high volume manufacturing. Among them, it is especially important to attain high sensitivity resist without degrading other performance.

In this paper, we evaluated various EUV resist for device implementation and tried to improve their performance through process optimization and some post process such as EUV specific rinse, chemical trimming in track, and so on. Finally characteristics and possibility of each post process will be reviewed and discussed.

10450-43, Session E12

EUV local CDU healing performance and modelling capability towards 5nm node

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Extreme Ultraviolet Lithography (EUVL) is considered as a primary imaging solution satisfying the aggressive scaling requirements in high-volume

manufacturing (HVM) of future generation integrated circuits. Furthermore, other advantages such as the integration simplicity, cost reduction and design rule mitigation make the EUV technology preferred option for imaging of 2D features in the 5nm node and beyond while 1D gratings remain patterned with spacer techniques.

Local CD uniformity (local CDU) and line edge roughness (LER) have big contributions to the Edge Placement Error (EPE) budget (1) which is closely related to the device yield. The local CDU improvement in litho requires novel resist materials, contrast optimization with SMO and high exposure dose, the latter is a challenge for EUV productivity. Other improvement techniques are needed, and the post-litho contact hole healing (2) is discussed here as a possibility to meet after-etch (AE) local CDU specifications using a resist with relevant throughput in HVM.

In this work, we will demonstrate local CDU performance improvement forN5 Via pattern after litho and etch using the novel EUV resist with 30mJ/cm2 dose-to-size. Local CDU, contact edge roughness (CER) and Local Placement Error (LPE) of the contact holes resembling in local EPE, will be characterized. The key parameters of local variability such as stochastics, systematic and metrology noise will be addressed as well to understand a nature of the local effects better.

The EPE metric estimates the worst errors on the production wafer which impacts the final device yield. So the holistic patterning optimization and computational EPE assessment (3) require the local EPE prediction functionality. In this work, litho and etch local CDU, LPE and local EPE prediction accuracy will be investigated and discussed using ASML Tachyon Stochastic EPE model (4) for the N5 use case .

The CD healing process (2) has complex etch proximity effects. Previous work indicated the imperfections in the models introduce significant additional errors in EPE budget (3) and not accurate computational EPE assessment and corrections (e.g. in Tachyon LMC and OPC). We will demonstrate the prediction accuracy of Tachyon AE model for this etch proximity behavior.

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(3) Jan Mulkens, Michael Hanna, Bram Slachter, et al., “Patterning control strategies for minimum edge placement error in logic devices”, Proc. SPIE 10145, Metrology, Inspection, and Process Control for Microlithography XXXI, 1014505 (March 28, 2017)

(4) Stephen Hsu, Rafael Howell, Jianjun Jia, et al., “EUV Resolution Enhancement Techniques (RETs) for k1 0.4 and below”, Proc. SPIE 9422, Extreme Ultraviolet (EUV) Lithography VI, 94221I (March 16, 2015)

10450-44, Session E12

Roadmap Evolution: From NTRS to ITRS, From ITRS 2.0 to IRDS

Paolo A. Gargini, Stanford Univ. (United States)

The semiconductor industry has benefitted from roadmap guidance since the mid-60s. The roadmap anticipated and outlined the main needs of the semiconductor industry for decades and identified future challenges and possible solutions. This methodology allowed the removal of multiple “red brick walls”. The NTRS and the ITRS constituted primarily a “bottom up” approach as standard microprocessors and memories where introduced at a blistering pace barely allowing time for system houses to integrated them in their products. The advent of Foundries and Fabless companies has transformed the electronics industry into a “top down” driven industry. The International Roadmap for Devices and Systems sponsored by IEEE is addressing the requirements and needs of the new ecosystem of the electronics industry.

10450-45, Session E13

Single-nm resolution techniques with DDR process and materials

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EUV lithography has been desired as the leading technology for 1x or single nm half-pitch patterning. However, the source power, masks and resist materials still have critical issues for mass production. Especially in resist materials, RLS trade-off has been the key issue. To overcome this issue, we are suggesting Dry Development Rinse Process (DDRP) & Materials (DDRM) as the pattern collapse mitigation approach. This DDRM can perform not only as pattern collapse free materials for fine pitch, but also as the etching hard mask against bottom layer (spin on carbon : SOC). In this paper, we especially propose new approaches to achieve high resolution around hp1X nm L/S and single nm line patterning. Especially, semi iso 8nm line was successfully achieved with good LWR (2.5nm) and around 3 times aspect ratio. This single nm patterning technique also helped to enhance sensitivity about 33%. On the other hand, pillar patterning thorough CH pattern by applying DDRP also showed high resolution below 20nm pillar CD with good LCDU and high sensitivity. This new DDRP technology can be the promising approach not only for hp1Xnm level patterning but also single nm patterning in N7/N5 and beyond.

10450-46, Session E13

Development of amorphous silicon based EUV hardmasks through physical vapor deposition

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Extending extreme ultraviolet (EUV) single expose patterning to its limits requires more than photoresist development. The hardmask film is a key contributor in the patterning stack that offers opportunities to enhance lithographic process window, increase pattern transfer efficiency, and decrease defectivity when utilizing very thin film stacks. This paper introduces the development of amorphous silicon (a-Si) deposited through physical vapor deposited (PVD) as an alternative to a silicon ARC (SiARC) or silicon-oxide-type EUV hardmasks in a typical trilayer patterning scheme. PVD offers benefits such as lower deposition temperature, and higher purity, compared to conventional chemical vapor deposition (CVD) techniques.

In this work, sub-36nm pitch line-space features were resolved with a positive-tone organic chemically-amplified resist directly patterned on PVD a-Si, without an adhesion promotion layer and without pattern collapse. Pattern transfer into the underlying hardmask stack was demonstrated, in order to evaluate patterning metrics related to resolution, pattern transfer fidelity, and film defectivity for PVD a-Si compared to a conventional tri-layer patterning scheme. Etch selectivity and the scalability of PVD a-Si to reduce the aspect ratio of the patterning stack will also be discussed.

10450-47, Session E13

Fabrication and performance of transmission engineered molybdenum-rich phase structures in the EUV regime

Farhad H. Salmassi, Weilun Chao, Eric M. Gullikson, Julia Meyer-Ilse, Patrick P. Naulleau, Lawrence Berkeley National Lab. (United States)

For applications in the Extreme Ultraviolet (EUV) region, phase-shift structures play an important role in pushing the throughput and performance of optical systems. While EUV optical elements are typically designed and fabricated for use in reflection, there are important applications in transmission as well where phase shift structures can provide substantial throughput gains. Examples are EUV microscopy and interferometry using gratings or zone plates. In the EUV regime, few materials offer a better combination of phase shift and absorption properties than molybdenum (Mo), however, drawbacks for Mo include crystalline growth complicating the etch process, and ease of oxidation which leads to diminished performance with time.

Here we develop a fabrication process for transmission optical elements made of an engineered molybdenum-rich film on free-standing silicon membranes and show the performance of these phase structures in the EUV regime. We chose the fabrication of simple binary gratings of 72nm half pitch (Fig. 1) in order to establish a baseline for performance. We further addressed the oxidation concerns for Mo by developing a process to passivate the surface using atomic layer deposition (ALD) to coat a thin and conformal layer of silicon nitride while incurring minimum throughput loss. The gratings were measured for efficiency in three stages of fabrication at Lawrence Berkeley Laboratory's Advance Light Source (Beamline 6.3.2) in Berkeley California (Fig. 2). The first measurement was prior to ALD passivation, the second measurement was immediately after passivation, and the third measurement was performed after exposure of the gratings to UV ozone used as an accelerated oxidation test. The conformal coating of silicon nitride was effective in passivating the surface of Mo features. The measurement results show that we were able to achieve a grating efficiency of approximately 18% in the 1st and -1st orders (compared to 8% possible with a conventional absorber grating on Si membrane). The results also demonstrate the effectiveness of the ALD passivation process in mitigating oxidation effects with minimal effect on performance.

Conference 10451: Photomask Technology

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10451-1, Session P1

Extending the Era of Moore's Law *(Keynote Presentation)*

Tsu-Jae King Liu, Univ. of California, Berkeley (United States)

No Abstract Available

10451-2, Session P1

2017 Mask maker survey conducted by the eBeam Initiative *(Invited Paper)*

Aki Fujimura, D2S, Inc. (United States); Jan Willis, Brian J. Grenon, eBeam Initiative (United States)

Captive and merchant mask makers participated in an anonymous survey in the summer of 2017 to capture the profile of the mask industry for the period of July 2016 through June 2017. A mask industry survey has been conducted for the 15th time in the past 16 years. Sematech ran the mask industry survey for 13 years through 2013. In 2015-2017, the eBeam Initiative invested in reviving a subset of the survey called the Mask Maker Survey. This year the results and analysis will be presented during the main program of the Photomask Conference.

The eBeam Initiative's third Mask Maker Survey in 2017 covers a number of questions related to the profile of the mask industry, from overall number of masks to pattern generation type. The survey addresses questions about data preparation, writing and delivery times. Mask yields and returns are captured along with a new question on the usage of mask process correction (MPC) by ground rules. The eBeam Initiative also conducts an annual Perceptions Survey of mask industry luminaries. That survey result will be presented at the eBeam Initiative's annual reception co-located at the Photomask conference.

10451-3, Session P2

Manufacturing challenges for curvi-linear masks *(Invited Paper)*

Christopher A. Spence, Quan Zhang, ASML Brion (United States); Vincent Shu, ASML US, Inc. (United States); Been-Der Chen, Stanislas Baron, ASML Brion (United States); Yasuko Saito, Brion Technologies KK (Japan); Masakazu Hamaji, Shuichiro Ohara, Nippon Control System Corp. (Japan); Katsuya Hayano, Naoya Hayashi, Dai Nippon Printing Co., Ltd. (Japan)

To achieve the ultimate in resolution and process control from an optical (193i 1.35NA) system it is desirable to be able to exploit both Source and Mask degrees of freedom to create the optimal Illumination and Mask for any given set of patterns that comprise a photomask. For illumination it has been possible to create an illumination system that allows for almost no restrictions in the location and intensity of points in the illumination plane (ref Flex-Ray). For masks it has been harder to approach the ideal continuous phase and transmission mask that one would ideally like to have. Mask blanks and processing requirements have limited us to binary (1 and 0 amplitude, or 1 and -0.25 amplitude (6% attenuated PSM) or Alternating PSM (1, 0 and -1 amplitude) solutions. Furthermore, mask writing (and OPC algorithms) have limited us to Manhattan layouts for full chip logic solutions.

Recent developments in the areas of mask design and newly developed Multi-Beam Mask Writers (MBMW) now mean that masks are no-longer limited to Manhattan geometries. In this paper we consider some of the manufacturing challenges for these curvi-linear masks. Specifically we consider:

1) Process benefits for various curvi-linear mask designs at wafer level

2) Challenges in implementing a complete end-to-end MDP flow including OPC, MPC and fracturing

3) Challenges in defining and implementing Mask Rule Checks on non-Manhattan layouts in OPC and in mask inspection

10451-5, Session P2

VSB fracture optimization for mask write time reduction

Lei Sun, Synopsys, Inc. (United States)

Mask Data Preparation (MDP) takes IC layout data and decomposes ("fractures") complex polygons into rectilinear and trapezoidal figures suitable for mask writers. For rectilinear polygons, the total of decomposed figures from a given polygon is bounded mathematically in terms of the polygon's reflex vertices count. However, such geometric-based decomposition algorithms can be further optimized by considering parameters associated with VSB mask writers. This paper describes our efforts to reduce mask write time while maintaining CD quality by further optimizing the underlying algorithms. The optimization results are statistically analyzed with variation of different shot sizes and sliver sizes. Case study is also conducted to explore how sliver size specification impacts both shot count and fracturing quality.

10451-6, Session P3

Adopting rigorous verification flow in fabrication of silicon photonic devices

Siti Noor Aisyah B. Yahya, Mogana S. Sathisivan, Silterra Malaysia Sdn. Bhd. (Malaysia); Chuanhai Li, Synopsys (Singapore) Pvt., Ltd. (Singapore); Jinhua Pei, Yu Chen, Synopsys (Shanghai) Co. Ltd. (China)

Lithography simulation plays an invaluable role in the field of advanced process development and optimization. Lithography simulation effectively minimizes the experimental engineering effort and the number of short-loop experiments, resulting in accelerated process development, considerable cost-savings, and a faster time-to-market. Therefore, it is important to adopt a rigorous verification flow that accurately models the impacts of lithographic process on the drawn layout designs to determine the wafer data dimensions of the fabricated devices. This paper investigates how rigorous models simulate the lithographic process on the drawn layout data to determine the dimensions of wafer data for device fabrication. In our case, we report the application of an advanced lithography simulation tool provided by Synopsys, Sentaurus Lithography (also known as S-Litho), to predict the fabrication imperfections of silicon photonic devices during the lithography process. Sentaurus Lithography provides all the modeling capabilities necessary to enable engineers to make precise and reliable predictions of the performance of lithography processes and strategies during the design preparation. Resist calibration has been performed, with both FEM CD and resist profile simulation results matching well with the wafer results for the design rule patterns. Our model calibration result is acceptable, and SEM overlay proves that the simulation contours agree with the wafer images for the design rule test patterns. Throughout this report, we demonstrate the benefits of lithography simulation for the fabrication of the photonic devices using a rigorous verification flow.

10451-7, Session P3

An efficient tool to rewrite a VSB12 format jobdeck for any target VSB12 machine

Juan L. Olate, Synopsys, Inc. (Chile)

NuFlare has several VSB mask writers which read in patterns in the VSB12 format. Each type of machine has restrictions over the input VSB12 chips they can read; mainly the file-size of input files. MDP software tools - which are used to convert the customer's layout designs into VSB12 format files - can generate VSB12 chips for a given VSB12 machine model. However, the generated VSB12 chip might not be compatible for printing in other VSB12 machine models other than the one specified. This is very inconvenient for some mask manufacturers, as it hinders the flexibility of their processes. They might require to write a previously generated VSB12 chip in a different machine model than the originally specified one. This paper presents a tool that can rewrite VSB12 jobdeck files to be compatible with a different VSB12 machine model than originally intended. It generates the new VSB12 jobdeck in a time considerably shorter than refracturing it with a MDP tool and comparable to just file copying it.

10451-8, Session P3

Full-chip GPU-accelerated curvilinear EUV dose and shape correction

Ryan Pearman, Oleg Syrel, Harold R. Zable, Ali Bouaricha, Mariusz Niewczas, Bo Su, Linyong Pang, Aki Fujimura, D2S, Inc. (United States)

With both 193i multiple patterning and EUV technologies, the constraints on the mask manufacturability are becoming increasingly stringent. The necessity for understanding curvilinear shapes implicitly in design (for ILT and EUV) or OPC correction (corner-rounding effects) along with new multi-beam mask writing systems mean the mask manufacturers are at an inflection point: whether the mask shapes are described as curvilinear targets or complex rectilinear targets, the actual mask shapes after exposure are curvilinear and must be accounted for correctly for wafer lithography. We present a GPU-accelerated intrinsically curvilinear mask data preparation system, compatible with both VSB and multi-beam systems, that is capable of full-ship simultaneous shape and dose correction using arbitrary (non-Gaussian) kernels for model shape and dose effects..

10451-9, Session P3

CLMPC: curvilinear MPC in a mask data preparation flow

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The value of non-Manhattan, or in other words, curvilinear mask shapes for wafer lithography has been demonstrated. Inverse Lithography Technology (ILT), introduced in 2006 [1] provides an improved process window compared to conventional OPC which is based on rectangular shapes. However, curvilinear mask shapes have not yet been widely adopted so far due to the cost and cycle time of the higher computational load of curvilinear OPC as well as unacceptable mask write times for curvilinear shapes using available vector shaped beam (VSB) mask writers. Due to the architecture of VSB writers, the curvilinear data has to be approximated by rectangular shots, or a combination of rectangular and right triangle shots. To maintain acceptable fidelity to the input layout the number of shots needs to be so large that mask write times become unacceptably long, easily exceed 24h or more. Shot count can be reduced through simplifications of the mask shapes, however it has been demonstrated through simulation that the more the simplified structure deviates from the ideal curvilinear structure, the smaller the lithography process window [2] with the magnitude of the process window reduction somewhat dependent on mask corner rounding [3]..

With the advent of raster based Multi-Beam Mask Writers (MBMW), the write time problem has been solved since the mask write time on MBMWs does not depend on mask shapes or mask data complexity [4]. In addition, generating full chip ILT masks is becoming computationally feasible with high performance compute clusters of 20-30 thousand CPU cores typically used for advanced node post tapeout flows.

Another reason for not adopting curvilinear mask shapes in the past was the lack of mask process corrections for such curvilinear mask shapes which often have CDs strongly affected by proximity effects. In this paper we present a solution to this problem, demonstrating a mask data preparation flow including mask process correction of curvilinear shapes. In the following we refer to this as CLMPC (CurviLinear MPC).

Correcting curvilinear shapes natively, i.e. not Manhattanizing the shapes internally which would inevitably introduce some approximations, is a mind shift for the mask data preparation world. Historically MDP tools are based on rectangular data representation and even for special semiconductor devices like wave guides or sensors the fractured output is often rectangular. With the introduction of CLMPC, the curvilinear OPC or ILT (Inverse Lithography) output can be corrected for mask errors while maintaining the curvilinear nature of the shapes.

In this paper we will present challenges and solutions for a curvilinear MDP flow including the use of model-based MRC.

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10451-10, Session P4

Machine learning for mask/wafer hotspot detection and mask synthesis *(Invited Paper)*

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Machine learning is a powerful computer science technique that can derive knowledge from big data and make predictions/decisions. Since nanometer integrated circuits (IC) and manufacturing have extremely high complexity and gigantic data, there is great opportunity to apply and adapt various machine learning techniques in IC physical verification and physical design. In this talk, I will first give an introduction on machine learning, and then discuss several case studies in various applications, including mask/wafer hotspot detection, and machine learning based optical proximity correction (OPC) and sub-resolution assist feature (SRAF) insertion. I will further discuss some challenges and research directions.

10451-11, Session P4

Machine learning of IC layout "styles" for Mask Data Processing verification and optimization

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Practical machine learning (ML) techniques are being deployed, at an accelerated pace, in an expanding set of application domains. The

newsworthy examples in games strategy, image recognition, automated translation and autonomous driving are only the tip of the iceberg of a massive revolution in industrial manufacturing. Semiconductor IC design and manufacturing are also starting to see a number of ML applications, albeit of limited scope. In this work we present both a novel computational tool for ML of physical design layout styles (constructs, patterns) and also a general technical framework for the implementation of ML solutions across the design to mask to silicon chain.

ML applications derive their mathematical foundations from Computational Learning Theory, which establishes "learning" as a computational process. The quantitative characterization of the learnability space and its associated Vapnik-Chervonenkis, (VC) dimension, is therefore a pre-requisite of any meaningful ML application. Various types of geometric constructs in the 3D Euclidian space of physical design layouts provide an ideal learnability domain. Specifically, the entire set of generalized Design Rules, silicon retargeting, Optical proximity Correction (OPC), post-OPC verification (ORC) and mask manufacturing constraints (MRC) can be demonstrated to be in a learnable set. This means that, given a suitable feature extraction model, classifiers systems can be built to perform data analytics and optimization, with a quantifiably higher performance (in terms of speed and scale) than any of the currently used engineering-based heuristics. Additionally layout styles, particularly the ones generated by Place-and-Route (P&R) tools and even manual layout for custom blocks are amenable to automated learning (and subsequent parametric-space optimization).

Two complete examples in the Design to Mask flow, for advanced technology node applications will be used to validate the ML methodological framework and to illustrate extendibility to other areas, such as process and fab flow optimization.

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10451-12, Session P4

Impact of feature extraction to accuracy of machine learning based hotspot detection

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Machine learning based hot spot detection is an emerging area in verification of mask and layout design. The machine learning approach is expected, in recent complex designs, to resolve problems like false errors generated by conventional rule-based verifications and to reduce the prohibitive computing cost of simulation based verifications. The problem in developing a practical application seems to be the lack of accumulation of domain knowledge. Many machine learning based verification systems have been reported, but the research seems still necessary for practical application. Lack of domain knowledge seems to cause inefficient trial and error in the development of the system. In this paper, we have investigated properties inherent in the feature extraction of the hot spot detection, developed the several types of feature extraction codes and done comparison studies.

In usual machine learning based tools, the code consists of feature extraction, learning and inference parts. Feature extraction is used with both learning and inference as a front end of the codes. Experiences indicate that the extraction methods suitable for application domains are as important as learning and inference algorithm itself for detection accuracy.

Proposed feature extraction methods and the implementation will be described in detail. The implemented extraction methods are based on two scanning algorithms namely orthogonal scan and spiral scan. Both scan algorithms can scan and evaluate features of all graphical objects in a subject region called clip by different orders. The feature extraction code scans the clip, extract feature quantities like geometrical dimensions and relations with adjacent figures, and makes vectors of the feature quantities for the learning and inference parts.

Evaluation have been done by combination of the feature extraction code and a standard Support Vector Machine(SVM) using a set of bench-mark data1. SVM is one of the standard machine learning software and provides good results relatively easy. Excellent results have been obtained in comparison with reported results2. Accuracy by the described method reached up to 98.4% by the standard optimization tool.

Accuracy comparisons between several combinations of feature quantity extraction and scan methods have been made. The results indicated that the spiral scan based feature extraction stably gave better accuracy than another scan based method. This fact suggests that invariance to affine transformation is important for the feature extraction. Finally, this paper discusses about a relationship between accuracy of the detection and feature extraction methods, and preferable characteristics for feature extraction.

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10451-13, Session P4

Machine learning assisted SRAF placement for full chip

Jing Su, Quan Zhang, Weichun Fong, Dezheng Sun, Cuiping Zhang, Chenxi Lin, Shibing Wang, Been-Der Chen, Stanislas Baron, Rafael C. Howell, Stephen D. Hsu, Larry Luo, Yi Zou, Yen-Wen Lu, Yu Cao, ASML Brion (United States)

The Sub-Resolution Assist Feature (SRAF) is widely used for Process Window (PW) enhancement in computational lithography. Rule-Based SRAF (RB-SRAF) works well with simple designs and regular repeated patterns, but requires a long development cycle involving Litho, OPC, and DTCO engineers. Furthermore, RB-SRAF is heuristics-based and there is no guarantee that SRAF placement is optimal for complex patterns.

The Model-Based SRAF (MB-SRAF) technique to construct optimal SRAF using the guidance map is sufficient to provide a required process window with the 32nm node and below. It provides an improved lithography margin for full chip and removes the challenge of developing manually complex rules to assist 2D structures.

The machine learning assisted SRAF placement technique developed on the ASML Brion Tachyon platform allows us to push the limits of MB-SRAF even further. A Convolutional Neural Network (CNN) is trained using a Continuous Transmission Mask (CTM) that is fully optimized by the Tachyon inverse lithography engine. The neural network generated SRAF guidance map is then used to assist full-chip SRAF placement. This is different from the current full-chip MB-SRAF approach which utilizes a guidance map of mask sensitivity to improve the contrast of optical image at the edge of lithography target patterns. We expect that machine learning assisted SRAF placement can achieve a superior process window compared to the MB-SRAF method, with a full-chip affordable runtime significantly faster than inverse lithography. We will describe the current status of machine learning assisted SRAF technique and demonstrate its application on the full chip mask synthesis and how it can extend the computational lithography roadmap.

10451-68, Session P4

EMLC 2017 Best Paper: Splendidly blended: a machine learning set-up for CDU control

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As the concepts of machine learning and artificial intelligence continue to grow in importance in the context of internet related applications it is still in its infancy when it comes to process control within the semiconductor industry. Especially the branch of mask manufacturing presents a challenge to the concepts of machine learning since the business process intrinsically induces pronounced product variability on the background of small plate numbers.

In this paper we present the architectural set up of a machine learning algorithm which successfully deals with the demands and pitfalls of mask manufacturing. A detailed motivation of this basic set up followed by an analysis of its statistical properties is given. The machine learning set up for mask manufacturing involves two learning steps: an initial step which identifies and classifies the basic global CD patterns of a process. These results form the basis for the extraction of an optimized training set via balanced sampling. A second learning step uses this training set to obtain the local as well as global CD relationships induced by the manufacturing process.

Using two production motivated examples we show how this approach is flexible and powerful enough to deal with the exacting demands of mask manufacturing. In one example we show how dedicated covariates can be used in conjunction with increased spatial resolution of the CD map model in order to deal with pathological CD effects at the mask boundary. The other example shows how the model set up enables strategies for dealing tool specific CD signature differences. In this case the balanced sampling enables a process control scheme which allows usage of the full tool park within the specified tight tolerance budget.

Overall, this paper shows that the current rapid developments off the machine learning algorithms can be successfully used within the context of semiconductor manufacturing.

10451-14, Session P5

PMJ Panel Discussion Overview: Race for Volume Production: Who is closer to goal, EUVL or NIL?

Naoya Hayashi, Dai Nippon Printing Co., Ltd. (Japan)

This presentation is a summary of the panel discussion at PMJ2017.

10451-15, Session P5

PMJ Best Poster I: Fabrication of cylindrical micro-parts using synchronous rotary scan-projection lithography and chemical etching

Kaiki Ito, Yuta Suzuki, Toshiyuki Horiuchi, Tokyo Denki University (Japan)

Lithography onto cylindrical pipes is required for fabricating medical micro-parts and bio-devices. Electron or laser-beam writing methods have been researched. However, there is a problem in those methods that it takes a long time for delineating complicated patterns. To solve this problem, a new scan-projection exposure system was developed. In the new system, while a reticle is moved in the horizontal direction, a cylindrical pipe is rotated synchronously. An oblong slit was placed on the reticle to replicate patterns in a narrow almost flat area of the cylindrical pipe surface. The imaging performance was kept excellent because the pipe surface was exposed almost at the same height in the oblong slit area. And, all the reticle patterns were printed on the pipe surface during the one rotation of the cylindrical pipe through the slit. Adopting this exposure scheme, the total exposure time was kept almost constant without depending on the complexity of the reticle patterns.

After printing patterns on the surface of a SUS304 stainless-steel pipe, the pipe was chemically etched in an aqueous solution of ferric chloride. The resist patterns were used as etching masks. Caused by the undercut phenomena, mesh widths of etched pipes were slightly narrower than those of resist patterns. However, micro components were successfully fabricated by removing the resist patterns after the etching.

At first, stent-like patterns were printed on stainless-steel pipes with outer and inner diameters of 2.0 mm and 1.9 mm, respectively. The exposure field was 15 mm long in the pipe axial direction. The pipes were coated with a negative resist (tok, PMER N CA-3000PM) in 5 μm thick using the dip coat method. Because the pipes were undercut in the etching, resist patterns should be sufficiently wider than a tentative target mesh width of 200μm. For this reason, the stent-like patterns were printed using a reticle with 250 ?m wide mesh patterns. When the exposure time for rotating a pipe 360° was 30 s, formed resist pattern widths were 251± 30 μm.

Next, patterned pipes were chemically etched one by one in an aqueous solution of ferric chloride for 22min at 40-45°C. In order to uniformly etch the pipes, the etchant was constantly stirred using a propeller during the etching. The mesh widths obtained after the etching were 230 ± 30 μm. Therefore, it was estimated that the width reduction was caused by the undercut during the etching was approximately 20 μm.

Thus, stent-like meshed parts with 230?m fine mesh widts were successfully fabricated. It was demonstrated that the new method had a potential to be applied to fabrications of stent and other cylindrical micro-parts.

This work was partially supported by a Grant-Aid for Scientific Research (C) 26390040 from the Japan Society for the Promotion of Science.

10451-16, Session P5

PMJ Best Poster II: The capabilities of measuring cross-sectional profile for hole patterns in nanoimprint templates using small-angle x-ray scattering

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Nanoimprint lithography (NIL) is one of the highest potential candidates for next generation lithography in semiconductors. NIL is very useful technology for pattern fabrication in high resolution compared to conventional optical lithography. NIL technology makes use of replication from quartz templates. The cross-sectional profile of the template is directly transferred to the resist profile on a wafer. Accordingly, the management of the cross-sectional profile on the template pattern is much more important than on each photomask.

In our previous report, we had studied the performance of measuring cross-sectional profiles using grazing-incidence small-angle X-ray scattering (GISAXS). GISAXS has made it possible to analyze the repeated nanostructure patterns with a 2D X-ray scattering pattern. After various researches, we found the application is very effective in the method of cross-sectional profiling of sub-20 nm half-pitch lines-and-spaces (LS) patterns.

In this report, we investigated the capabilities of measuring cross-sectional profiles for hole patterns using GISAXS. Since the pattern density of hole patterns is much lower than that of LS patterns, the intensity of X-ray scattering in hole measurements is much lower. We optimized some measurement conditions to build the hole measurement system. Finally, the results suggested that 3D profile measurement of hole pattern using

GISAXS has sufficient performance to manage the cross-sectional profile of template. The measurement system using GISAXS for measuring 3D profiles establishes the cross-sectional profile management essential for the production of high quality quartz hole templates.

10451-17, Session P6

EUV mask readiness for HVM

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Currently, we are supplying defect-free EUV mask for device development. This was one of the biggest challenges in the implementation of EUV lithography for high volume manufacturing (HVM). It became possible to hide all multi-layer defects by using defect avoidance technique through improvement of blank mask defectivity and development of actinic blank inspection tool. In addition, EUV pellicle is also considered as a requisite to guarantee predictable yield. Both development of mask shop tools and preparation of EUV scanner for pellicle are going well. However, still membrane needs to be much improved in terms of transmittance and robustness for HVM. At the conference, EUV mask readiness for HVM will be discussed including blank defect improvement, preparation of actinic tools and pellicle development.

10451-18, Session P7

Actinic review of EUV masks: challenges and achievements in delivering the perfect mask for EUV production

Martin Dietzel, Renzo Capelli, Dirk Hellweg, Markus Bauer, Conrad Wolke, Grizelda Kersteen, Carl Zeiss SMT GmbH (Germany)

EUV Lithography is reaching the last milestones of its development towards implementation into semiconductor high volume manufacturing. A crucial element for inserting EUV into production line has been and still is the availability of defect free masks. In order to deliver defect free masks to the wafer fab, actinic imaging of potential defect sites is required to assess the printability behavior of such defects (defect disposition), infer the best repair and/or compensation strategy (defect repair), and to verify the effectiveness of the repair (defect review).

ZEISS and the SUNY POLY SEMATECH EUVL Mask Infrastructure consortium have developed such a EUV aerial image metrology system, the AIMS™ EUV, with the prototype tool regularly being used for customer measurement campaigns and the first system shipped to customer end of 2016.

AIMS™ EUV can qualify and quantify defect printability by fully emulating the illumination and imaging conditions within the lithography process, along with providing crucial information for the assessment of the best repair strategy. For this process to work reliably and effectively in the mask shop, the established AIMS™–MeRiT® closed loop mask repair solution comes to serve as standard workflow also within the EUV production chain.

In this paper, we provide an update on the program and the system qualification status. Achievements from two years of measurement campaigns on the prototype system by the EMI program participants will be presented along with an outlook on applications development supporting the future of EUV lithography.

10451-19, Session P7

DUV inspection beyond optical resolution limit for EUV mask of hp 1X nm

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With shrinkage of semiconductor device scale, the requirement for defect inspection tools becomes severer [1]. Deep Ultra Violet (DUV) inspection tools have been used for photomask and Extreme Ultra Violet (EUV) mask until hp 2X nm. And it is generally said that conventional DUV inspection tools are difficult to meet the requirement for EUV mask of hp 1X nm because of the insufficient resolution. Therefore, inspection tools with higher resolution such as using actinic wavelength or Electron Beam (EB) have been candidates. However, actinic pattern inspection has not been demonstrated so far, and EB inspection has low throughput compared to optical inspection tools.

In previous studies, it was shown that the newly developed optics and systems of DUV inspection tool by NuFlare Technology,Inc. (NFT), named SIRIUS?, has an availability for the Nano Imprint Lithography(NIL) template which is the same scale as a wafer[2],[3]. SIRIUS can detect 8 nm of pattern error defect and have 60 min of throughput per 26?33 mm square for NIL template of hp 26 nm Lines and Spaces(LS) pattern, even though the pattern on acquired image is not resolved.

In this paper, we evaluate the capability of SIRIUS for the EUV mask of hp 1X nm LS pattern which is also not resolved.

Firstly, the target defect size which causes 10% printed wafer Critical Dimension (CD) error according to ITRS standard was calculated. And the conventional NFT's DUV inspection tool for EUV mask of hp 1X nm LS pattern was evaluated. As a result, the sensitivity was the defect size which causes 40% printed wafer CD error with 120 min of throughput per 100?100 mm square.

Secondly, the SIRIUS for EUV mask of hp 1X nm LS pattern was evaluated. As for the sensitivity, Signal Noise Ratio (SNR) was better than the conventional one and the defect of the target size which causes 10% printed wafer CD error was able to be detected with inspection. However, if the inspection with SIRIUS for NIL template with an area of 26?33 mm square applies to the EUV mask with that of 100x100 mm square, 700 min of throughput is estimated. It is difficult to adopt for High Volume Manufacture (HVM). Then, the relationship of the light power and SNR was investigated. Consequently, it was confirmed that since DUV reflectance to EUV mask is higher than that to NIL template, it was possible to move the stage faster with adequate light power, without decreasing SNR. Therefore, the throughput using SIRIUS was able to be 120 min per 100?100 mm square which is the same as the conventional one.

From these results, it was demonstrated that the SIRIUS can detect the defect which causes 10% printed wafer CD error with 120 min of throughput per 100?100 mm square.

In summary, we confirm that the SIRIUS can be available for the EUV mask of hp 1X nm.

SIRIUS: Super Inspection Resolution Improvement method for UnreSolved pattern

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10451-20, Session P7

EUV reticle print verification with advanced broadband optical wafer inspection and e-beam review systems

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As the Extreme Ultraviolet (EUV) lithography ecosystem is being actively mapped out to enable sub-7nm design rule devices, there is an immediate and imperative need to clearly identify the EUV reticle (mask) inspection methodologies. The introduction of additional particle sources due to the vacuum system and potential growth of haze defects or other film or particle deposition on the reticle, in combination with pellicle uncertainty pose unique inspection challenges compared to 193i reticle.

EUV reticles are typically inspected with optical reticle-inspection tools. However, if there is a pellicle on the EUV mask that is non-transmissive to the optical wavelengths used in the reticle inspection tools, there is a need for alternate inspection methodologies based on inspection of printed wafers. In addition, due to the potential new defect mechanisms associated with the EUV reticle, fabs are looking for additional methods to re-qualify reticles in production which might involve printed wafer inspection. The printed wafer inspection methodology is referred to as “Reticle Print Verification” or “Reticle Print Check”. This paper discusses these alternate inspection methodologies that are being developed by KLA-Tencor in collaboration with IMEC using an advanced broadband optical inspection (390x) and e-beam review systems (eDR7280).

To conduct this study, a series of programmed defect patterns were generated on the EUV mask. This mask is then exposed by the EUV scanner and the pattern is printed on a short-loop EUV resist wafer. The wafer is then inspected with the broadband optical inspection tool to detect and filter the mask defects (repeaters) that are printed on the wafer. These repeater defects are then imaged by e-beam review tool to verify the capture rate of printed defects and assess the sensitivity of the optical inspection tool. Electro-magnetic simulations are also conducted to identify the optimal stack of the short-loop wafer to further enhance the optical inspection sensitivity to the EUV mask repeaters. The simulation study suggested the appropriate under-layer material and the stack thickness that can provide the best sensitivity for repeater defects. New EUV resist wafers are then printed with the optimized stack and inspected with the advanced broadband plasma optical wafer inspection tool. The printability of the repeater defects across the wafer are also investigated to assess the stochastic affects that are often seen with EUV. This study has shown that soft-repeaters (repeater defects that are not printed on every die) may exist and full-wafer inspection coverage is necessary for the detection of repeaters. An improvement of >3x Signal-to-Noise and up to 9x capture rate with the 390x inspection tool was observed with the new stack.

10451-21, Session P8

16hp EUV reticle inspection with a 193nm inspection system

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The current industry plan is for EUV Lithography (EUVL) to enter High Volume Manufacturing (HVM) in the 2019/20 timeframe at about the 16nm half-pitch node (16hp). Reticle quality and reticle defects continue to be a top industry risk. The primary reticle defect quality requirement continues to be defined as “no reticle defects causing 10% or larger CD errors on wafer”.

In 2013, KLA-Tencor reported on inspection of EUV reticles for the 22hp node using a 193nm wavelength inspection system; this report included both die-to-database (db) and die-to-die (dd) inspection modes. Results showed the capability to detect a wide variety of programmed and native reticle defects judged to be critical for the 22hp generation.

We have developed extensions to the 193nm inspection system for the typical 16hp EUV reticle defect requirements. These improvements include innovations in: resolution enhancement techniques, database modeling, defect detection, and throughput.

In this paper, we report on the latest data and results of this work, focusing on EUV reticle die-to-database inspection. Inspection results are shown using typical next generation EUV programmed defect test reticles from industry sources, as well as, typical full field product-like reticles. Results show significant defect detection improvements versus the prior generation inspection system.

We also report the results from a high throughput particle inspection mode developed for the front side of patterned EUV reticles. This mode is suitable for use in both mask shops and wafer fabs for reticle particle qualification (no poly-silicon pellicle in place – opaque at 193nm wavelength).

10451-22, Session P9

Pellicle films supporting the ramp to HVM with EUV

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EUV pellicles are needed to support EUV in high volume manufacturing. We demonstrate progress in cap layer design for increased transmission and infrared emission of the Polysilicon-film. EUV transmission of 90% and good emissivity for a fully capped pSi film is demonstrated, supporting the ramp to high volume manufacturing. We also discuss research on next generation EUV pellicle films. This includes metal-silicides and graphite. Next-gen film performance is compared to the current generation pSi film. These films are stable at higher operating temperature than pSi. Metal-silicides have the advantage of sharing a similar process flow as that of pSi, while graphite shows ultimate high temperature performance at the expense of a more complicated manufacturing flow. Capping layers are needed here as well and capping strategies are discussed for these film generations.

10451-23, Session P9

CNT EUV pellicle: moving towards a full-size solution

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Development of a pellicle membrane to protect the reticle from particles for EUV source powers beyond 250W is a subject of intensive research. Existing solutions for current EUV scanners, including p-Si or SiN, are not able to meet the requirements imposed by future high power scanners (1).

This paper presents free-standing carbon nanotube (CNT) film as a promising next generation pellicle material. Here we evaluate the properties of several types of free-standing CNT films composed of either single-walled or multi-walled CNTs in random or aligned configurations. For a thin film material to be a viable pellicle, several key requirements must be simultaneously fulfilled: high EUV transmission, thermo-mechanical strength and chemical resistance (EUV+H2).

We demonstrate that free-standing CNT film can have very high EUV transmissions even above 99%. Depending on the density and type of the

CNTs within the free-standing film, thermal emissivity can be varied over a large range (from 0.02 to >0.5). We can then calculate the maximum pellicle temperature at 250W EUV source power through the relation between the CNT film emissivity and transmission, which is expected to be below 600 C. A number of CNT pellicle coating options were explored with the main purpose of CNT film protection from the exposure to hydrogen radical/ion environment generated by EUV light. Coating optimization is required to maintain the optimal thermo-optical properties. Due to their porosity, free-standing CNT films demonstrate a clear mechanical advantage for pressure resistance and can tolerate pressure changes better than solid films. Other important pellicle properties including EUV transmission uniformity and scattering, as well as transmission at DUV for a through-pellicle inspection, will be discussed. Finally, the feasibility of a full-size pellicle based on free-standing CNT films, corresponding to an aspect ratio of pellicle length/thickness of >10^6, is demonstrated.

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10451-24, Session P9

Development of EUV pellicle for suppression of contamination, haze, and outgas generation

Yosuke Ono, Kazuo Kohmura, Atsushi Okubo, Daiki Taneichi, Hisako Ishikawa, Tsuneaki Biyajima, Mitsui Chemicals, Inc. (Japan)

In the existing DUV pellicle, haze generation risk on mask surface during DUV exposure exists due to the reaction of out gas in an exposure atmosphere. It is well known fact that outgas is generated not only from pellicle in itself but also by stray light being irradiated on adhesive parts.

As for EUV pellicle, problems of the exposure defect such as haze generation and reflectance reduction of mask will be anticipated because EUV has higher photon energy compared with DUV and diffusion of the outgas is promoted in high vacuum condition of EUV scanner.

In this study, similar to the pelliclized EUV mask structure was constructed?by using the full-size EUV pellicle frame stacked on a base plate which has similar component of the EUV mask surface, and dummy plate placed on the membrane side of the frame. Contamination growth behavior was examined by irradiating the EUV light to the base plate inside pellicle via EUV transparent membrane on dummy plate.

Adhesion of the contamination on base plate was observed in EUV irradiation area in the case of the pellicle sample using commercially available adhesive as the mask adhesive. So, general commercially available adhesives will not be suitable for mask adhesive of pellicle.

We found that generation of the contamination was not almost observed for pellicle sample with coated adhesive materials as the mask adhesive, which has both outgas suppressing and EUV light screening function. Coated adhesives for mask adhesive of pellicle, which keep the adhesive properties, will be suitable for fixing method to suppress the contamination growth during EUV exposure.

10451-25, Session P9

EUV optical characterization of alternative membrane materials for EUV pellicles

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Pellicles are an important part of the IC-manufacturing supply chain, keeping particles away from the imaging plane of the photomask to preserve wafer yield. EUV lithography poses new challenges on the pellicle membrane because the radiation must pass twice due to the reflective mask. Additionally, there are no transparent materials for EUV so the EUV pellicle must be extremely thin to keep the transmission high.

Present continuous-membrane pellicle solutions will not be sufficient for the source powers greater than 250W that are anticipated for HVM EUV lithography. A possible approach to maintain strength and high transmittance is to use nano-structured materials[1]. We report here on the EUV optical characterization of a variety of alternative membrane materials. The fine structure of etched holes or membranes made of carbon nano-tubes introduces interesting optical effects. We, therefore, not only address specular reflectance or transmittance by the optical characterization but also investigate spatial homogeneity at different length scales and off-specular diffuse scatter. We compare the respective optical properties of homogeneous reference membranes with etched membranes and carbon nano-tubes. Particularly the latter show a very high EUV transmittance of more than 95 % and are therefore considered as a highly promising candidate for alternative EUV pellicles.

[1] Emily E. Gallagher; Johannes Vanpaemel; Ivan Pollentier; Houman Zahedmanesh; Christoph Adelmann; Cedric Huyghebaert; Rik Jonckheere; Jae Uk Lee; Properties and performance of EUVL pellicle membranes. Proc. SPIE 9635, Photomask Technology 2015, 96350X (October 23, 2015); doi:10.1117/12.2199076.

10451-26, Session P9

Rigorous simulation of EUV mask pellicle

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Pellicles are stand-off membranes designed to prevent particle contamination on masks during extended usage in production environment[1]. While pellicles have been used in optical lithography for a long time, none of these solutions can support EUV lithography. As the industry is preparing insertion of EUV lithography into high volume manufacturing, significant research and development efforts on pellicles that are compatible with EUV masks have been made[2]. Currently the leading candidate for EUV pellicle membranes is either silicon nitride (SiNx) or carbon nanotubes (CNTs)[3], and a full-size SiNx pellicle has been fabricated and evaluated[4]. Because of the high EUV transmission required to minimize throughput reduction, pellicle membranes have to be made very thin and supporting structures are under consideration[5]. From the modeling perspective, aerial images have been calculated using full electromagnetic simulations when the EUV pellicle with supporting structures is placed on the mask[6]. The scenario of particles landing on pellicle is also analyzed[7]. The residual stress, thermal, and mechanical implications of pellicle in dynamic exposure conditions have been studied[8,9]. Pellicle protected EUV masks have been exposed in NXE scanners, and a slight increase in CDU has been observed[10,11].

We report here the integration of pellicle in the full flow of rigorous EUV lithography simulations. By handling the defocus elegantly, accurate and consistent aerial images can be obtained for arbitrary pellicle standoff distances, which would enable further rigorous resist simulations. In Fig. 1, we show the three scenarios considered for testing simulation accuracy. A vacuum layer is deposited on top of mask absorber (Fig. 1(b)) to specify the stand-off distance between pellicle and mask. Without the pellicle, this should give identical results to the standard case (Fig. 1(a)) if mask defocus is set correctly. After the pellicle is added (Fig. 1(c)), a decrease in image intensity is expected. Rigorous electromagnetic field simulations allow us to model various amounts of attenuation of incident and diffracted waves as they pass through the pellicle at different angles. Aerial image results in agreement with previous analysis are presented in Fig. 2. We also place a 5nm-radus circular Ni particle above the pellicle. As the distance between pellicle and mask is increased, we clearly observe diminishing impacts of the particle, both in aerial image and in resist profile (Figs. 3 and 4), as it is moving out of focus. We will further investigate dose-to-target variation

after pellicle insertion using calibrated EUV resist models, pellicle induced aberration under diversified source profiles, interplay between optical properties of add-on particles and pellicle stand-off distance, and image quality deterioration due to a pellicle deformed by heat or stress. We hope that our study could provide some theoretical insight into pellicle development and facilitate the insertion of EUV pellicle in high volume manufacturing.

10451-50, Session P9

In-fab reticle operations: paradigm shifts with EUV

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Reticle operations for 193nm optical lithography in a HVM (High Volume Manufacturing) wafer fab are well established and matured. Most of the reticle manufacturing, qualification and maintenance is handled in the mask house whereas only periodic quality checks are performed in the wafer fabs. Reticles are shipped back to mask house for repel and repair process. This standard process of record for 193nm optical reticle handling is not applicable on EUVL (Extreme Ultraviolet Lithography) reticles. Optical reticle qualification at mask house is ensured with advanced inspection and imaging validation using AIMS (Aerial Image Measurement System). However due to lack of manufacturing ready EUV actinic reticle inspection and AIMS, EUV reticles are qualified with wafer prints checks at the fab. Pellicles are mounted on optical reticles before shipping to wafer fab to secure against shipping & handling particle contaminants. EUV pellicles are not mature yet, thus reticles require unique handling and maintenance procedures at the wafer fab including cleaning, inspection and storage. EUV pellicles, once available, may not be transparent to currently available optical inspection systems; this will require pellicle removal for periodic reticle inspections which will necessitate the need of pellicle infrastructure in the fab. Unlike optical wafer scanners, EUV scanner is very sensitive to EUV reticle's backside contamination; this requires additional backside monitoring (inspection, etc.) and maintenance such as backside cleaning (with pellicle mounted on frontside). Numerous other differences between EUV and optical reticle features as well as equipment readiness will lead to a paradigm shift in the wafer fabs. This paper will detail and discuss these differences and present a solution to fill in interim gaps of in-fab EUV reticle operations to enable EUVL in an HVM foundry fab.

10451-48, Session P1Tue

Dark field technology for EUV mask blank inspection

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The current industry plan is for EUV Lithography (EUVL) to enter High Volume Manufacturing (HVM) in the 2019/20 timeframe at about the 16nm half-pitch node (16hp). Reticle quality and reticle defects continue to be a top industry risk. The primary reticle defect quality requirement continues to be defined as "no reticle defects causing 10% or larger CD errors on wafer".

Traditionally, mask shops and mask blank manufacturers have been using bright field confocal technology to perform mask blank qualification. However, due to more stringent defect requirements for EUV blank defects, and the difficulty in detecting and repairing any mask defects caused by a blank defect, the industry requires a new approach to detect defects to support 16 nm hp EUV manufacturing.

To meet these emerging requirements, we have developed a new dark field imaging system for photomask blank inspection. This system can be used in the blank manufacturing process to inspect the quartz blank, to inspect after film deposition, and to inspect the finished blank after resist coating. In the mask shop, the same system can be used to inspect an uncoated blank prior to resist coating, or to perform incoming inspection on a finished blank, prior to writing.

In this paper, we report on the initial results from this new system on a range of programmed defect blanks as well as production photomask blanks. Inspection results will be shown on a variety of substrates, both for EUV blanks as well as optical blanks.

10451-49, Session P1Tue

JUNGFRAU and COSAMI: Detector and source technologies for high-throughput EUV mask inspection

Rajeev Rajendran, Iacopo Mochi, Patrick Helfenstein, Aldo Mozzanica, Bernd Schmitt, Shusuke Yoshitake, Yasin Ekinci, Paul Scherrer Institut (Switzerland)

Actinic defect inspection on EUV reticles is one of the key technologies required for the insertion of EUV in high-volume manufacturing, but currently there is no working solution available for it. Recently we started the development of RESCAN, a lensless actinic defect inspection platform based on coherent diffraction imaging that has potential for current and future lithography nodes. Coherent diffraction imaging techniques rely on the collection and analysis of large amounts of diffraction spectra to detect the defect position, amplitude and phase. The advantages of a lensless approach are that it avoids the costs and technological challenges of high-NA EUV optics, and allows scalability for future nodes. However, the successful implementation of these techniques and their use in the mask metrology process flow requires that an accurate defect map of the reticle can be generated in a reasonable amount of time. In order to scan the full mask in 6 hrs with an illumination spot size of 40 ?m, the images have to be acquired at a rate of 2000 frames/sec and the photon flux must be enough to obtain a good signal-to-noise ratio. The two key components required to reach this goal are: a high frame-rate EUV image detector and a compact high brightness coherent EUV light source. Further, the signature of defects in the reciprocal space being orders of magnitude smaller in signal strength than the diffraction peaks of the patterns, the sensor must have a large dynamic range for sensitive defect identification. In this paper, we will describe the capabilities and the development status of two technological components of RESCAN that address these requirements – JUNGFRAU, the detector we chose for RESCAN and prototyped for EUV at PSI and COSAMI a high-brightness coherent EUV source that is being developed at PSI as a stand-alone solution for our defect inspection platform. JUNGFRAU offers a frame rate of 2 KHz and has a measured dynamic range of 10^6 photons in the EUV. We will also demonstrate the recent results we obtained and status with JUNGFRAU for fast defect detection and outline our future plans on COSAMI.

10451-52, Session P2Tue

9-inch size binary Cr and PSM mask blanks statuses in 450mm wafer process (2017)

Noriyuki Harashima, Tatsuya Isozaki, Arata Kawanishi, Shuichiro Kanai, Hiroyuki Iso, Tatsuya Chishima, ULVAC Coating Corp. (Japan)

6-inch size (known as 6025QZ) binary Cr mask is widely used in the semiconductor lithography for over 20years. In the 450mm wafer process, high grade 9-inch size mask is expected. We have studied Binary Cr mask blanks and developed prototypes 9-inch size PSM KrF and ArF mask blanks.

This time we will explain these mask blanks statuses include in resist coating recently.

10451-53, Session P2Tue

Bottom layered phase-shift mask blanks for FPD

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In recent years, demands for fine pattern photomasks are incresing as the flat panel display (FPD) has become higher definition. Paticularly since organic light emission display (OLED) needs further fine pattern on the array side, photomasks which can form fine pattern are required.

Ulvac coating corporation have developed and reported phase shift mask blanks (PSMB) for forming fine and in-plane uniform distribution pattern for the first time in the world. In 2016, we have developed bottom layered PSMB with etching stop (ES) layer and reported its possibility.

The above-mentioned PSMB uses two kinds of etchant which are Cr etching solution and nitric etching solution.There is a demand for bottom layered PSMB that can formed by simple pattern process due to further process simplicity.

Since we have recently developed bottom layered PSMB which can be formed by simple pattern process, we report its structure, various characteristics and patterning process. In this technology we have possibility to reduce process steps and number of equipment as compared in the past.

10451-54, Session P2Tue

The deposition of the Cr binary film and attenuated phase-shift film on the FPD photomask substrate

Takashi Yagami, Yohei Takarada, Kento Hayashi, Takashi Ozawa, Nikon Corp. (Japan)

Nikon manufactures the FPD photomask substrate with Cr binary film. Our Cr binary film features the nearly orthogonal cross section shape and low reflectance @g~i line, both leading to good resolution.

In this study we introduce Cr binary film with higher performance. We refined the condition of the film deposition. As a result, the etching rates of AR layer and the light-shielding layer are strictly controlled, consequently the cross section shape is almost orthogonal after the wet etching process.?In addition, we can control the reflectance @g~i line by several percent and the thickness uniformity is excellent even in all over G10 area.

Furthermore, we are developing Cr Attenuated Phase-Shift film (Cr Att-PS film) that has stronger adhesion with resist than other Cr Att-PS film. As a result, the penetration of the etchant between the?film and the resist doesn't occur and the cross section shape is almost orthogonal after the wet etching process.

10451-55, Session P2Tue

Laser-scan lithography and electrolytic etching for fabricating mesh structures on stainless-steel pipes 100 μm in diameter

Hiroshi Takahashi, Toshiyuki Horiuchi, Tokyo Denki Univ. (Japan)

Fine cylindrical micro-components such as stents and micro-needles are required. Here, laser-scan lithography and electrolytic etching were investigated for opening many slits on tips of fine stainless-steel pipes with an outer diameter of 100 μm, a thickness of 20 μm and a length of 40 mm.

At first, a pipe coated with a positive resist (tok, PMER P LA-900) was exposed to a beam spot of violet laser with a wavelength of 408 nm (Neoark,TC20-4030-45) [1]. Linearly arrayed 22 slit patterns were delineated in every 90-degree circumferential direction by axially scanning and rotating the pipe. The pipe was intermittently moved, and exposed to the laser spot for a length of 170 μm by setting interval lengths of 100 μm. Thus, 88 slit patterns in total were delineated on the pipe surface.

Following the patterning, the pipe masked by the resist was electrolytically etched. The pipe was used as an anode and an aluminum cylinder was set as a cathode around the pipe. In the past research, aqueous solution of sodium chloride and ammonium chloride was used as the electrolyte [2]. However, all 17 investigated pipes were snapped during the etching or the removing of resist after the etching. It was clarified that the etching was especially concentrated at the chuck side, and pipes were snapped there caused by undercut. It was considered the current intensity distributed in the axial direction of the pipe, and the current intensity distribution caused the unevenness of the etching. For this reason, sodium chloride in the electrolyte was changed to sodium nitrate which was considered to improve the current intensity distribution. Effects of adopting sodium nitrate etchant were investigated by etching 7 pipes for 20 s applying 5 V to an electrolyte composed of water: sodium nitrate: ammonium chloride =100:5:5. As a result, concentration of etching at the chuck side was improved. All the pipes were not snapped, and all slits were opened almost homogeneously. Before the etching, sizes of 22x7 slits in a line were measured using an optical microscope (Arms system, LUSiS PA-20CU). The average width and length of the slits were 35.1 and 194.3 μm, respectively. In comparison, the average width and length measured at inner surfaces using SEM (JEOL, JSM-5510) after the etching were 14.8 μm (σ=2.1) and 211.4 μm (σ=4.2), respectively. The width and length measured at the outer surface were 25.8 μm (σ=4.7) and 174.8 μm (σ=13.4), respectively. The average edge roughness measured at the inner surface was 4.3 μm. It was demonstrated that aimed mesh structure was successfully fabricated.

This work was partially supported by Grant-in-Aid for Scientific Research (C) 26390040 from Japan society for Promotion of Science.

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10451-56, Session P3Tue

Automatic SRAF printing detection based on contour extraction

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Sub-resolution Assistant Feature(SRAF) printing detection is critical during SRAF model building. The current methodology of SRAF detection on Silicon wafer cost lots of human efforts on subjective judgement on SEM images. Therefore, the automation of robust SRAF printing classification is essential to improve detection accuracy and efficiency. A sensitive contour extraction on SEM images is a promising approach. In this paper, a database-independent contour extraction algorithm is used to detect the contours of printed SRAF structures. By area calculation and database comparison, SRAF feature printing classification can be made automatically. This flow has been demonstrated to correctly classify SRAF printing with consistent justification and avoid inconsistency in human judgement that may occur through time. With the new flow, both modeling cycle time and model accuracy of SRAF model could be greatly improved.

10451-59, Session P3Tue

Strategies on quantitative data preparation for OPC model calibration to reduce catastrophic failure at 7nm logic node

Hong Chen, Xtal Inc (United States)

The paper aims to establish systematic methodology and discuss the relevant strategies for data preparation to calibrate empirical OPC model with the effort of the least catastrophic failure. With 7nm technology node, the minimum dimension of line and space reported on the wafer is 18nm. Some papers[1] [2] reveal that the noise from Line-end roughness (LER) and Line-width roughness (LWR) could be even 25% as high as the feature size, which dramatically increases the probability to have "catastrophic failure" [1]. The common loop and the framework to build up an OPC empirical model will be reviewed first in this work to reflect this open issue and the solution is pursued to respond the desirability of the technology node. The emphasis of the strategies adopted from OPC modeling perspective is associated with the data collection and the data preparation beyond the very first step of pattern samplings.

As well-known in the semiconductor manufacturing field, the current dominant metrology technology to accomplish data collection is Critical Dimension (CD) Scanning Electron Microscope (SEM). Data from CD SEM could be presented either CDs at various height of the side wall or top-view contours and will be collected after the curtain process steps. Data preparation to calibrate an OPC model with the strong flavor from curtain process and process engineers is turning into the hardest part due to the fact that the strategies must be applied to reduce the probability of catastrophic failure. All the achievable information from CD SEM will be analyzed and compared to have in-depth insight of the significance of the patterns so as to make decision about the usage of the information before a customized OPC model is developed. The OPC model templates will be slightly touched to reflect the demands from the various manufacturing processes. The conclusions will be drawn finally from the above discussions and the strategies used to select the curtain trend data for the development of an OPC model is summarized with the mission to reduce the catastrophic failure at 7nm technology node.

10451-60, Session P3Tue

The impact of inconsistency in assist feature generation on OPC performance

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The speed and functionality requirements of advanced Integrated Circuits (ICs) always drive the reduction of the Critical Dimension (CD), therefore, the semiconductor industry is always required to develop ways to pattern smaller feature sizes.

Optical lithography is the industry leading approach for producing Integrated Circuits (ICs). Although it reached its theoretical physical limits years ago, but Resolution Enhancement Techniques (RETs) were a major factor extending the industrial use of optical lithography.

Different Resolution Enhancement Techniques (RETs) were invented, developed, and used over the years to overcome the printability limitation of optical lithography. Sub-Resolution Assist Features (SRAFs) are a very common RET strategy. SRAFs are patterns below the resolution limit that are intentionally placed on the optical reticle to enhance the printability of the main features but are not supposed to print.

The locations of the SRAFs need to be optimized in order to achieve the main feature printing enhancement goal. SRAF placement is done two ways: rule based SRAF placement and model based SRAF placement. In model based SRAF placement a numerical model is used to predict the optimal location for placing the SRAFs as well at their sizes, while in rule based placement a rule table is used for SRAF placement and sizes in order to enhance the IC patterns printability. Recently another step is used: SRAF Print Avoidance (SPA) step is done by a model that predicts the SRAF printability. SPA may change the SRAF solution if any of the SRAFs were found printing on the wafer.

Model generated assists have become widely used to enhance main feature printability; because the model based solution predicts the assist placement location compared to the rule based assist placement solution. One disadvantage of the model based approach is the possible inconsistency of the SRAF placement and SRAF size which may lead to inaccuracy in the main feature printing process.

In this work, the result of cases that have SRAF placement inconsistency will be presented. On silicon results of some of these cases will be shown to highlight the risk of a non-uniform SRAF placement. Some possible solutions will be explored.

The study is important to the OPC community as it highlight the extent of the risk in using inconsistent SRAF placement solution.

10451-28, Session P4Tue

Extension of advanced mask characterization techniques to 28nm logic technology through hot spot Investigation

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We have previously introduced the concept of Advanced Mask Characterization (AMC) which is a series of techniques that harmonize the mask and wafer processes resulting in wafer yield improvement. These methods were published previously with demonstrated positive impact on wafer yield in memory devices. AMC is especially beneficial for identifying the mask contribution to design points with unpredictable and/or narrow process margin, or hot spots. The synchronization of wafer and mask process conditions is a key output of AMC. We have demonstrated the ability to identify toggles in the mask or wafer process that can be optimized to improve wafer yield. The AMC toolkit includes lithographic simulation and various mask metrology methods applied to detect weak points in the design. Test plates are designed to study process variables and determine wafer hot spot behavior relative to each. The analysis of test plates is accomplished by using SEM contour based methodology. Contour based analysis has proven the critical points in the understanding of the correlation between mask characteristics and wafer performance. A Focus-Exposure Matrix (FEM) is used to evaluate and characterize process variable impact on wafer hot spot behavior, confirming previous lithographic simulations. By this method, the best process condition on both the mask and wafer sides can be identified and implemented resulting in wafer yield improvement. In this paper, we extend AMC concepts to a 28nm logic device with more complex shapes and more complicated optical effects than the previously published work on DRAM designs. We verify the criticality of contour-based hot spot analysis, determine whether AMC can define optimized process parameters, study their effects on hot spot behavior, and evaluate yield impact on these 28nm logic designs.

10451-29, Session P4Tue

Study of in-situ inspection for 10nm lithography mask and beyond

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In a photomask manufacturing process, Defect repair technology is an

exceedingly important topic for 193 immersion lithography and EUV lithography. The several repair tool based on SEM or FIB system improved repair process for any kind of Material, Defect type etc, there tool supplier reported status of Repair tool Development. However, High MEEF pattern e.g SMO-ILT, NTD and more complex patterns, require tighter repair spec and accuracy, it is especially big impact for productivity.

Therefore one of key Technologies for mask manufacture is Defect reduction and control for mask Yield. Photomask defect phenomenon is especially diversified e.g. developer, Dry Etcher, mask handling etc.We reported capability of In-Situ inspection system. We showed that tool development status , and standard spec.

In this paper, we will report capability of in-situ inspection system for mask Yield, defect control and next generation tool development status.

10451-61, Session P4Tue

Aerial image ORC checks and their correlation to wafer-edge yield limitation for metals: a study and an OPC resolution

Tamer Desouky, Yixiao Zhang, Mark Terry, Haizhou Yin, Muhammed Pallachali, Nicolai Petrov, Teck Jung Tang, Fadi S. Batarseh, Ahmed M. Khalil, Pietro Babighian, Rohan Deshpande, Deborah Ryan, Rao Desineni, Shweta Shokale, SangKee Eah, Feng Wang, Jiechang Hou, GLOBALFOUNDRIES Inc. (United States)

Lithography process variation as well as etch and topography have always been a stubborn challenge for advanced technology nodes, i.e. 14nm and beyond. This variability usually results in defects aggregating around the edge of the wafer and leading to yield loss. A very tight process control is the logical resolution for such issues, nevertheless it might not be possible, or it may slow down the whole design to silicon cycle time. Another degree of difficulty is detecting these defects in ORC and concluding an OPC fix. In this paper, we show that aerial image ORC checks could provide a very useful insight to these defects ahead of time, and that they correlate well with silicon defects highlighted by CFM scan. This early detection upstream enables us to conclude a generic OPC fix for such issues and also improves the total OPC process-window enhancement and eliminates these defects on silicon.

10451-62, Session P4Tue

Advanced process control based on litho-patterning density

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The reduction in critical dimensions (CD) and process control requirements at 14nm technology node, and below, present challenges for wafer-to-wafer and lot-to-lot variation. Most advanced process control (APC) approaches are based on product groups, but different product groups have different tuning parameter targets after etch. Because lithography pattern density varies between product groups, it is difficult, or impossible, to share a single APC thread to control the etch process.

This paper will introduce a new method to optimize APC into dynamic control using a specific, matched sub-set of design features as a reference. Pattern density was previously calculated by transmission and reflection (RT) ratio of the entire reticle, including the post optical proximity patterns. However, litho-patterning density differs from reticle RT ratio due to assist features and the difference between resist CD and reticle CD. Litho-patterning density can be obtained using an OPC litho-target consisting of main and dummy patterns only which closely resemble the final resist pattern density.

With dynamic control, product groups with different pattern density will have a similar tuning parameter targets that can be grouped together and allow feedback for improved and simplified process control.

10451-63, Session P4Tue

Improved testpatterns and coverage for complex SrAF to optimize 5nm and below OPC and mask patterning

Kevin Lucas, Synopsys, Inc. (United States); Marco Guajardo, The Univ. of Texas at Austin (United States); Hesham M. Abdelghany, Ahmed S. Omran, Synopsys, Inc. (United States)

Below the 28nm node the difficulty of using subresolution assist features (SrAFs) in OPC/RET schemes increases substantially with each subsequent device node. This increase in difficulty is due to the need for tighter OPC/RET EPE control through process window for smaller target patterns; the increased risk of SrAF printing with complex new photoresist materials (e.g., negative tone development materials) and more coherent illumination schemes; and also the increased difficulty of smaller SrAF CD and spaces for mask manufacture and inspection. Therefore, there is a substantially increased risk of SrAF placement methods adding an SrAF to the layout which will unknowingly violate manufacturability limits for EPE control, SrAF printing and/or photomask patterning. Much effort is being spent at fabs to optimize and reoptimize SrAF placement algorithms to avoid these issues. However, it has historically been difficult to predict SrAF placement issues for a design without actually running the exact SrAF placement recipe (and repeating that process multiple times during process development and production).

In this paper, we present results of our work to better pre-characterize designs and SrAF placement methods which are likely to become problematic for EPE control, SrAF printing and/or photomask manufacturability. We do this by extending previous methods for design pattern clustering and testpattern minimization to accurately incorporate advanced SrAF placement interactions. We first present results of our review of several possible algorithm choices for this application and give details about the algorithm we have chosen and its implementation using scientific programming methods. We next describe our approach to accurately extending previous testpattern minimization methods to cover complex layouts with SrAFs. We then provide examples and validation for practical applications including EPE control, SrAF printing risk and mask manufacturing/inspection. Finally, we summarize our work and learning.

10451-4, Session P5Tue

Mask process correction method comparison and study: CD-SEM box versus standard correction method

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With shrinking nodes, the error tolerances for mask CDs (Critical Dimension) becomes tighter and tighter since mask errors are passed on downstream and might even be amplified at wafer level. Therefore, high accuracy MPC (Mask Process Correction) models are imperative. Besides the mask model, the MPC algorithm for the input layout has a critical influence on mask

quality. This paper studies and compares two methods of MPC: a new method, introducing a correction algorithm based on the CD-SEM boxes is comparing to the standard method that measures edge placement errors only in the center of an edge. We discuss when the CD-SEM box correction method should be applied and demonstrate its influence on the correction accuracy of small CD patterns.

10451-40, Session P5Tue

Micro-defect repair assisted with contour-based 2D metrology

Irene Shi, Eric Guo, Max Lu, Semiconductor Manufacturing International Corp. (China); Izumi Santo, Holon Co. (Japan)

To deliver a defect-free photomask, is an essential step of mask manufacturing. EB (Electron-beam) repair is widely applied to deal with defects on photomasks, and has to cover etch and deposition capabilities without any pattern damage. However, mask repair is facing more challenges, with the shrinkage of minimum feature resolution for advanced technology nodes. Especially for micro defects at the edge of wafer printability specifications, differences between defect and reference may be tiny and hard to distinguish in visual or by existing methods on repair tools, so that it was difficult to start.

In this paper, a new approach named Contour-based 2D Metrology will be introduced as assistance for the repair processes of such challenging micro defects. Both CDSEM images of defect and reference are input for extracting; then contour-based patterns are overlapped for each other and compared with GDS as well, to describe quantitative differences for each micro area. Assisted with such rigorous and comprehensive data analysis, micro defects can be accurately positioned according to Aims Results and repair processes would be proceeding.

10451-64, Session P5Tue

Direct laser writing: virtual mask optimization for optical quality control artefact

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Grayscale lithography is an efficient way to fabricate 3D microstructures in the field of micro-electro-mechanical systems (MEMS) and micro-optics. We use direct laser writing (DLR) to create a layered staircase sample for bio-microscopic use. To minimize the number of experiments necessary for determining the laser system parameters and the height of the steps we used Design of the Experiment (DOE) together with a high resolution scanning white light interferometry (SWLI) based system as a 3D measurement device. A gray-scale mask featuring 42 patterns was developed and used to pattern a 6.2 μm thick positive tone photoresist. We utilized a Microtech LW405 laser writer with a 405 nm wavelength GaN laser. Our results show the potential of the SWLI-DOE approach as a tool to optimize gray-scale DLR lithography. This work is a step towards getting rid of slow SEM and AFM devices for quality control 3D MEMS production.

10451-65, Session P5Tue

Dual-line fabrication method in direct laser lithography to reduce the manufacturing time of diffractive optics elements

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To reduce the manufacturing time of DOEs (Diffractive Optics Elements) and POEs (Periodical Optics Elements), a new fabrication method in direct laser lithography is proposed based on the laser ablation phenomenon and the thermochemical effect of chrome. The basic mechanism of the proposed method and experimental results are also presented. It was found that when a 3x3 rectangular pattern is fabricated, the proposed method can reduce the total lithographic length by approximately 33%. The manufacturing time is reduced by nearly 52%. When fabricating a 1,000x1,000 rectangular pattern, the manufacturing time was reduced by more than 90%. The time reduction rate is drastically improved when the number of patterns is increased.

10451-66, Session P5Tue

Transparent and conductive backside coating of EUV lithography masks for ultra- short pulse laser correction

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Photolithographic masks especially for EUVL have to fulfill highest demands with respect to defectivity CD uniformity, mask flatness, and especially image placement (registration) as well as mask-to-mask overlay. These challenges require highly precise techniques for the production of extreme ultraviolet (EUV) masks. It is already known that an optical photomask can be modified in a controlled manner in order to correct image placement signatures by applying ultra-short laser pulses into the substrate by using the RegC system. This compensation occurs through multiphoton absorption of incident light from the backside of the mask. Applying this technology to EUV masks thus requires a backside coating sufficiently transparent at the wavelength of the ultra-short laser pulses.

On the other hand, an extremely careful handling and chucking of EUV mask is necessary in order to avoid as much as possible mechanical abrasion and the formation of particles, which may deteriorate the function of an EUV lithography system. In order to fulfill these handling requirements, EUV mask are held through an electrostatic chuck in the scanner. As the substrate of EUV masks is a dielectric, usually glass, or a semiconducting material, an electrically conducting layer has to be deposited on the backside in order to be able to hold the substrate with an electrostatic chuck. Therefore, in order to allow image placement correction by ultra-short pulse laser technology, the rear side coating has to be optically transparent and electrically conductive at the same time.

Ultrathin metals, their nitrides and oxides if sufficiently thin become transparent while still being electrically conductive. We will present results on backside coatings for lithography masks, especially for EUV applications, consisting of multilayer films made of ultrathin Cr, Cr nitrides and oxides having different compositions and thicknesses. Different compositions are obtained by varying the atmosphere during deposition. For example, during deposition of the Cr atoms on a substrate one can obtain different CrNy compositions by a proper ratio of N2 and Ar.

In the talk we will present our studies that confirm the possibility to achieve an optically transparent (transmission of 20-50%) and electrically conductive (sheet resistance of 50-200 ohm/sq.) backside coating for lithography masks with high mechanical resistance and durability, the latter attributes being tested also through abrasion, adhesion and scratching tests. We will also demonstrate pixel writing through such coating, enabling the technological path to correction and tuning of image placement on EUV masks.

We thank Carl Zeiss SMT for their collaboration in validating the proposed backside coating technology.

10451-27, Session P10

Mask capabilities, OPC solutions and, the MRC that binds them

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Introducing EUV lithography into high volume manufacturing requires various Resolution Enhancement Techniques (RETs). OPC software now supports EUV lithography, including slit-dependent Mask 3D (M3D) effects. In addition, Sub-resolution Assist Features (SRAFs) are being evaluated for use in low k1 EUV lithography. These SRAFs are on the order of 24 to 40 nm (4x) and thus challenging what is currently possible in mask manufacturing. Current mask making processes require the use of Mask Process Correction (MPC) to achieve the desired linearity and resolution. For mask designers, these limitations in mask manufacturing are expressed in Mask Rule Check (MRC) rules. In this paper, we study the chain of EUV model building, OPC and mask manufacturing.

In addition to CD control, there are other parameters that impact EUV imaging. We examined non-CD mask parameters such as Multi-Layers (ML) reflectivity and absorber sidewall profile. In the recent past, extensive simulation analyses were done to assess sensitivities of these parameters. We will close the loop by putting these simulations side-by-side with mask measurements.

We created an EUV OPC model calibration reticle and an EUV OPC verification reticle. With the current mask process, the minimum absorber dimension limits the dose range that can be selected. When evaluating the total chain of OPC, data prep, mask making and exposure, data volume is also an aspect that requires attention. The through-slit correction inevitably destroys some of the hierarchy and thus EUV mask data files are expected to be larger than DUV files. The file size of our verification reticle in our case was larger than 100GB. We found these file sizes strained the MPC throughput.

On the model calibration mask studied here, some 2,000 CD measurements of different feature types on the mask are correlated to about 20,000 measurements on the wafer.

In Figure 1 the ML reflection as function of angle is shown. We found a mismatch between simulation and measurement, which resulted in a simulated CD-offset between H and V lines of up to 0.5 nm for relevant 1-D features. This mismatch is currently under study.

This study identified a desire for smaller mask dimensions and capacity to efficiently handle large EUV mask data files.

10451-30, Session P10

Process window discovery from mask inspection for hotspot analysis and verification

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Patterning hotspots, i.e. yield limiters, slow down advanced node development and ramp. This problem is particularly acute for the back-end of the line (BEOL) layers with random 2D patterns.

There are established methodologies for prevention, detection, characterization and mitigation of hotspots; yet gaps remain. Hotspots are missed which translates to ballooning cost and time for node development.

A new technology verifies wafer patterning through process window from mask inspection images, before printing wafers. The mask is imaged at multiple focus settings; the phase and amplitude of the field at the mask are inverted from the mask images, and the phase and amplitude at the mask are used to simulate the 3-D lithography image in resist through process window.

This allows for early detection and ranking of hotspots; and distinguishes host spots caused by mask from hot spots caused by wafer processes. Advantages of this technology over existing OPC verification is twofold: 1) the 3D EM diffraction by the mask is inverted from mask inspector images without the approximations used in OPC models, hence model accuracy is higher, 2) mask manufacturing imperfections, e.g. CDU error, are included in the measurements. The results can be used in several ways including 1) Feedback to OPC teams to improve process window 2) feed forward to litho team for scanner adjustment, 3) feed forward to wafer inspection in the form of care areas to reduce time to result for wafer-based process window discovery.

To demonstrate the performance of mask-based hotspot verification, results from a joint project between UMC, PDMC and KLA-Tencor are presented. Hotspots from UMC's hotspot library are chosen and mask is imaged to predict wafer results. The results of HSV are correlated with wafer SEM data through focus-exposure matrix. Both 1D and 2D patterns are considered. The accuracy of predictions on 1D patterns through pitch and through focus shows an RMS of 1.9nm. For hotspots, HSV predicts scum at the bottom of trench for out of focus conditions and results are verified by SEM images. In addition, the similarity of Bossung curves between HSV and wafer data is shown.

10451-31, Session P10

Estimated mask contours: potential applications

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Potential applications include Manufacturing Rule Check (MRC): can be used to reduce false corner-to-corner violations. Ability to generate "ideal" mask contours can benefit Inspection and Metrology as well by providing more realistic bitmaps for fine alignment.

The key is ability to produce these contours with acceptable performance, which excludes usage of simulation.

10451-58, Session P10

Edge placement errors in EUV from aberration variation

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With several foundries/IDMs committed to using EUV to manufacture devices 7/5 nm nodes, success of EUVL will depend critically on the ability of manufacturers to meet extremely tight EPE budgets. EPE is affected by many different pieces of the process and it becomes important to identify and address all systematic sources of edge placement error. One major source of this error, which hasn't been given a lot of attention, continues to be the magnitude and variation of aberrations across the exposure field and between different scanners. EUV lithography is expected to have significantly higher level of aberrations than DUV due to the substantial drop in wavelength requiring tighter specifications on lens roughness, as well as a move to reflective optics producing double pass impact of surface roughness.

In addition, the variation in aberrations across the exposure field is an

example of systematic EPE that is correctible in OPC software and is only limited by the accuracy of the measured aberrations. Previous work [1] introduced Dynamic Model Generation, which allows for unique models for EMF, apodization, aberrations, etc to vary through the entire field and provides a capability to precisely and accurately model systematic field signatures. However, there are no known ways to address tool-to-tool aberration variation. Given foundries are expected to have multiple EUV tools for high volume manufacturing, the degree of tool-matching between different machines is expected to play a critical role to the success of EUV.

This work seeks to further the study by quantifying the simulated edge placement error on realistic 7 nm / 5 nm node designs resulting from a fleet consisting of multiple EUV tools, under the assumption of single mask for multiple tools and whether such assumptions are valid. Given the importance of tool-to-tool aberration matching in EUVL, this study investigates the amount of variation in tool-to-tool aberration that can be tolerated before foundries must consider “tool dedicated” OPC masksets. This study statistically analyzes different metrics such as PV bands, EPEs, imageshifts and worst case pinch/bridge checks to understand which single tool in the fleet should be best used in model calibration to generate the OPC mask shapes. In addition, an effort to rank relative quality of the verification solutions is investigated, to be used to tool allocation.

[1] Enabling Full Field Physics Based OPC via Dynamic Model Generation, M Lam et.al

10451-32, Session P11

Implementation of CDSEM contour extraction on OPC verification

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CDSEM metrology has been a powerful tool to obtain silicon data. However, as our technology node advances to 14nm and below, the CD measurement data from CDSEM cannot provide sufficient information for OPC verification (OPCV) and the related silicon verification. On the other hand, the abundant information from CDSEM images has not been fully utilized to assist our data analysis. In this context, contour extraction emerges to obtain extensive information from CDSEM images, especially for 2D structures. This paper demonstrates that contour extraction bridges the gap between the needs of 2D characterization and the limited capability of CDSEM measurement. The extracted contour enables automatic identification of litho-hotspots using OPCV tools, especially for non-CD related hotspots. Statistical silicon data extraction and analysis on complex geometries is viable with extracted contours. The silicon data can then be feedback to the evolution of non-CD OPCV checks, where simple CD measurement is inadequate. Effective CD can also be calculated from the obtained 2D information, with which Bossung curves can be built and provide complementary information.

10451-33, Session P11

Selective measurement of small metrology targets using CD-GISAXS

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To address the increasing requirements of the semiconductor industry for accurate measurement of the smallest features, new metrology tools based on X-ray scattering are being considered [1]. Critical Dimension Small-Angle X-ray Scattering (CD-SAXS) offers contact-free measurements with high statistical validity; however, the transmission of the X-ray beam through the wafer leads to high absorption and thus to long measurement times, making CD-SAXS in transmission mode too slow for metrology applications in high-volume manufacturing with current X-ray source intensities.

Faster, surface sensitive measurements are enabled using a grazing incidence geometry at shallow incidence angles (CD-GISAXS), where total external reflection of X-rays close to the critical angle results in a large enhancement in the measured scattering signal. Relevant structural parameters like pitch, critical dimension, line height and even detailed line profiles can already be reconstructed from CD-GISAXS measurements. Despite these advantages, several problems need to be overcome to use CD-GISAXS as an in-line metrology tool. One of the main problems of CD-GISAXS is the large beam footprint on the sample resulting from the shallow incidence angles. Because the beam footprint of typically at least 0.5 mm x 10 mm is much larger than usual metrology targets and the surrounding structures contribute parasitic scattering, small metrology targets could not be measured using CD-GISAXS so far.

We show that despite the large spot size, CD-GISAXS measurements of small targets are possible. Using a conventional 0.5 mm x 0.5 mm X-ray beam with a beam footprint on the sample of 0.5 mm x 50 mm, we selectively measure the scattering of small metrology targets. On a sample with 40 μm x 40 μm grating targets with varying orientations, we select the measured targets based on their orientation with respect to the incident beam using the reciprocal-space description of scattering from rotated gratings. From 1360 targets in a field measured at once in the X-ray beam we measure the scattering of 3 targets alone. To demonstrate the versatility of our approach, we additionally select the CD-GISAXS signal of a single 15 μm x 15 μm rotated grating target in a randomized surrounding. With this technique, it is possible to separate the CD-GISAXS signal of rotated metrology targets from the scattering of the surroundings, as long as the surroundings have a predominant direction, which virtually all lithographically produced nanostructures have.

References:

[1] Benjamin Bunday ; Eric Solecky ; Alok Vaid ; A. F. Bello and Xintuo Dai “Metrology capabilities and needs for 7 nm and 5 nm logic nodes”, Proc. SPIE 10145, Metrology, Inspection, and Process Control for Microlithography XXXI, 101450G (March 28, 2017); doi:10.1117/12.2260870;

10451-34, Session P11

Off-line mask-to-mask registration characterization as enabler for computational overlay

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After the introduction of multi-patterning techniques like multiple Litho-Etch (LEn) steps and/or Spacer Assisted Double/Quadruple Patterning (SADP/SAQP), the amount of masks required to produce a semiconductor device increased significantly. The main reason was that a functional layer could no longer be exposed in one single litho step due to the elevated pitch requirements. Consequently, the required pattern had to be split-up and divided over multiple masks. One can imagine that this has put a huge constraint on the Mask-to-Mask on-product overlay requirements and control. It was already shown before that for LE2 use-case the Mask-to-Mask contribution is the second post (after the scanner) in the overall on-product overlay budget. In order to keep the on-product overlay within specification over time, the number of on-wafer overlay metrology steps inside the fab increased even more. Since more masks are used per layer, multiple combinations are now possible to measure and control both the intra-layer as well as the inter-layer overlay. As a consequence, the increasing number of metrology steps has resulted in a negative impact on the overall wafer/lot cycle time in the fab. It would be beneficial to fully characterize the Mask-to-Mask overlay off-line and apply computational overlay techniques to compute the on-wafer overlay. This enables smart metrology sampling to address and reduce the overall wafer/lot cycle time inside the fab.

In this work, we performed a correlation study between off-line Mask-to-Mask registration metrology and on-wafer measurements. The off-line overlay measurements were performed on a PROVE tool while the exposures and scanner readouts were performed on an ASML TWINSCAN™. Two ASML qualification (BaseLiner) masks were used for this purpose.

Extensive off-line registration measurements were performed on both reticles including the reticle alignment marks as well as the image field metrology features (gratings). We show an excellent correlation between the measurements on the PROVE tool and the on-wafer results reaching R2 > 0.92 and Max3σ of 0.45-nm and below. We identify and discuss the underlying contributors to the error budget enabling a further improvement between the Mask-to-Mask and the on-wafer overlay.

Since the results of this first investigation were so promising, the effect of a pellicle mounted on one of the masks was studied as well. The off-line Mask-to-Mask registration metrology was repeated and the resulting computational overlay has been compared with the on-wafer results.

10451-35, Session P11

Critical dimension sensitivity analysis of a MoSi photomask using actinic reflection scatterfield microscopy

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Achieving higher densities and smaller dimensions in semiconductor manufacturing technology requires continuous advances in measurement technology. Compared to other metrology techniques, optical metrology has had an important role in the industry because of its nondestructive character, higher speed, and relatively lower cost. A key challenge for optical methods is accurate dimensional measurement of ever-decreasing deep subwavelength feature sizes. Characterizing such features will require high measurement sensitivity with low uncertainties as well as high throughput.

Optical scatterfield imaging microscopy enables characterization of nanoscale features beyond the resolution limit with high sensitivity by analyzing far field images formed by light scattered from the features. Engineering of the illumination beam is essential for yielding high sensitivity in scatterfield imaging as the characteristics of the scattered light depend not only on the parameters of feature but also strongly on the condition of the incident light such as incident angle, angular intensity, polarization and partial coherence. The partial coherence factor, which is defined by the ratio between the illumination numerical aperture and the collection numerical aperture, is closely related to the measurement sensitivity, especially as scatterfield microscopy measurements can take an advantage of the sensitivity to geometrical changes that can be observed at the edges of multiple line structures. At these edges, overshoot and ringing may be observed that augment the geometrical sensitivity. Thus, tailoring of the illumination beam condition is crucial for increasing the capability of scatterfield imaging microscopy for the characterization of nanoscale features. The illumination beam shape can be accessed and controlled at a conjugate back focal plane (CBFP) of the objective lens by locating an aperture with a specific size and shape or by scanning a small aperture, yielding capability of manipulating the angular illumination beam at the sample plane for efficiently tailoring the scattered fields.

The National Institute of Standards and Technology (NIST) has developed a reflection scatterfield imaging microscope operating at an actinic wavelength λ = 193 nm for the characterization of nanoscale features on both wafers and photomasks. The tool is used to investigate the relationships between illumination conditions and critical dimension sensitivity for photomask. The illumination optics is designed to have a relatively large telecentric conjugate back focal plane to engineer angular illumination beam shape with enough resolution. A commercial catadioptric objective lens of NA 0.12 - 0.74 is used for illumination and imaging. Using this NIST 193 nm scatterfield imaging microscope, various illumination beam conditions are imposed upon multiple line array targets to investigate the sensitivity dependence of the illumination beam condition on the scatterfield image. Defocused multiple line edge profiles are obtained with respect to the illumination variations such as numerical aperture, polarization, and incident angle.

In this paper, we present a critical dimension sensitivity analysis with respect to various illumination conditions of the NIST 193 nm scatterfield imaging microscope for a MoSi photomask that has nominally 86 nm to 94 nm CD with 2 nm increments. Optimal configurations for improving sensitivity are reported.

10451-36, Session P11

Automated defect disposition with AIMS AutoAnalysis

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The ongoing trend to smaller structures and an increasing number of high MEEF features in the mask design makes defect disposition and repair verification more critical than ever. For AIMS™, as the standard method for defect disposition and repair verification the requirements are getting tighter. Additionally, the efforts required for defect disposition are steadily increasing. This trend is intensified by increasing pattern complexity due to advanced methods like massive OPC treatment and inverse lithography. As a result mask manufacturers are forced to find methods to increase again productivity and optimize the cost of defect disposition.

Smart solutions for automated defect treatment together with a high degree of tool integration play an increasing role in this challenge. With the FAVOR® platform ZEISS offers a set of software applications for mask manufacturers to deal with these challenges. As an example AIMS™ AutoAnalysis (AAA) provides fully automated analysis of AIMS™ aerial images. Due to direct connection and communication of AAA with the AIMS™ tool the image analysis runs in parallel to the image measurement process. A high degree of automation reduces human error influence and provides highly reliable results.

In the following paper a study is presented demonstrating the benefits of the implementation of AAA in production environment at Photronics Inc.. The study was carried out by analyzing defects in a production relevant pattern set, varying from simple to very complex pattern. Furthermore, the analysis capabilities of AAA have been compared with the capability of advanced operators and engineers. The performance of AAA is presented showing significant time saving in the defect disposition process as well as an overall increase in reliability of analysis results.

An outlook is given for further automation solutions.

10451-37, Session P12

Enhanced critical feature representation for fuzzy-matching for lithography hotspot detection

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Due to the continuous scaling down in the feature size of semiconductor process technology nodes, the industry is greatly challenged in terms of manufacturing and design. The challenge is due to the widening gap between the lithography capabilities that is still limited by the continued scaling of the feature size and the 193nm wavelength. To cope up with these challenges, many manufacturing-friendly design techniques are proposed and developed to detect the problematic design patterns. These problematic design patterns are called lithography hotspots. Detecting the lithography hotspots in the early stages are preferred to ensure high production yield at post silicon stage.

The classical way is to interpret all topological relations of edges within a layout pattern to design rules. This may generate huge number of design rules and induce tremendous locations reported by DRC, hence, make the analysis extremely difficult. On the other hand, few extracted rules may

also result in tremendous locations reported. Therefore, extracting only the critical design rules is our goal to ease the DRC and analysis.

The two main milestones that we have to maintain are: 1) a good representation model for modeling the topological extracted features; and 2) to select the critical feature from the selected representation and translate them to design rules. One of the state-of-art representation that satisfies the above two milestones and recently showed very promising results is Modified-Transitive-Closure-Graph (MTCG). Another advantage for our selection for the MTCG representation which has a leverage over all other representations is that there is a proved lemma states that the MTCG is compact for a given tiled pattern.

This paper proposes a new enhanced feature representation for fuzzy matching for lithography hotspot detection. The enhancement to the MTCG can be stated as adding specific Do-not-Care (DC) regions to filter out unwanted polygons. First, the DC regions are inserted into the space areas based on the input hotspot patterns. By this step, we are adding fuzziness to the hotspot pattern which will enhance the pattern matching detection. Second, we use the conventional MTCG for graph representation where spaces and blocks regions are represented by different graph node type. We represented our new DC regions in the graph using another new graph node type to be able to identify the DC regions from spaces and blocks regions in the hotspot pattern. Our technique is capable of reaching 88% success rates by 10% increase compared to the conventional MTCG with no impact on total run-time.

To mention, there is a proven theorem which states that the MTCG is unique for a given tiled pattern. Building on the uniqueness of MTCGs for any lithography hotspot pattern, this paper also introduces a new similarity-detection technique that detects hotspots of similar shapes with acceptable defined tolerance. This technique, besides MTCG, is able to reach 97.044% success rate with only 1.0287% increase in total run-time.

10451-38, Session P13

Characterization of acoustic cavitation from a megasonic nozzle transducer for photomask cleaning

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Megasonic agitation continues to be used in advanced EUV photomask cleaning processes. The trend to adopt higher frequencies is driven by the need to expand the cleaning process window and limit pattern damage. Despite its adoption, the effect of the acoustic field applied to the mask substrate remains unclear. Photomask cleaning is a dynamic process with many parameters that contribute to the particle removal efficiency and pattern damage. These include transducer type, transducer position, drive frequency, power setting, flow rate, chemistry, gas concentration, etc. To add to the complexity, when the acoustic waves from the transducer interact with a quartz mask the energy may reflect from, transmit through, or couple into the substrate.

An in-situ measurement of the acoustic field, as present at the feature location, is required to correlate acoustic parameters with cleaning performance. This presentation introduces a mask- shaped cavitation sensor capable of measuring the absolute pressure from the direct field, stable cavitation, and transient cavitation present at the surface. In contrast to previous work characterizing skirt-type transducers, this measurement instrument is sensitive to higher drive frequencies while withstanding concentrated pressure levels from nozzle transducers. Here, a megasonic system with dual nozzle transducers at 5 MHz and 3 MHz was evaluated.

The aim of the study is to better understand the acoustic properties from different types of transducers for process development and monitoring in the quest to correlate with photomask cleaning.

10451-39, Session P13

Advanced Photomask Chrome Etch: Selectivity without Sacrifice

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While the industry awaits the maturity of EUV technology, the current Cr etch solutions will need to be improved upon to keep up with market demand for smaller features and reticle resolution. Writing smaller features on a photomask with a typical Cr/PR stack of 200/50nm can have a negative impact on the integrity of the PR, resulting in product scrap.

Based on the current technology roadmap, there is an urgency to improve the Cr reticle pattern resolution capability today while EUV comes on line. Higher write resolution requirements necessitate the use of thinner resist layers which directly leads to a need for lower consumption of the resist during the etch process. Given the Cr layer thicknesses, this translates to a higher etch selectivity of the Cr layers to the resist.

In this work, we report on the findings of research conducted on a Plasma-Therm LLC Mask Etcher V® Advanced Cr tool. The test material was a 150mm X 150mm Quartz photomask with 160nm of chemically amplified resist on a 50nm Chrome layer. The etch results were measured and quantified using a variety of metrology tools like a Veeco X3D CD AFM, FEI Inspect F50 XSection SEM and KLA Tencor 8100 CD SEM.

The initial approach involved developing various process conditions using the current node hardware technology. A full factorial DoE with three factors (Pressure, ICP Power and Cl2/O2 Ratio) and one center point was performed. This approach yielded moderate improvements in selectivity but the tradeoff between selectivity and CD performance was not optimal.

A ranked, weighted criteria matrix was completed utilizing input from a cross functional team of engineers and market experts at Plasma-Therm LLC to narrow down the focus of the development program. Based on the final rankings, resist pretreatment and Ion/Neutral Control were identified as the primary approaches.

*Resist Pretreatment Experimental Set

Two unaltered PR plates were run using the process of record (PoR) and a baseline etch rate of 293Å/min was recorded. Two unetched PR plates were exposed to UV with no change in resist thickness/hardening. The fifth PR plate was exposed to NH3 (no plasma) and then etched using the PoR resulting in an etch rate of 275Å/min. The sixth PR plates was exposed to an N2 plasma and then etched using the PoR with only a slight decrease in etch rate at 281Å/min. The final plate was exposed to an NH3/N2 plasma and then etched using the PoR generating an increased etch rate of 300Å/min. With only marginal reduction in PR etch rate, experiment 5 at ~6%, repeats were tabled until further hardware testing could be pursued.

*Ion/Neutral Control Experimental Set

The Gen V ICP source was redesigned with multiple new features, with the primary area of focus being the introduction of an Ion/Neutral control concept. Specific parameters for the Ion/Neutral control were selected based on data gathered during previous studies. This was followed by a series of one factor at a time experiments to narrow down the process factors to be used in the next DoE. Out of that DoE, run 4 (full table can be provided) with 0% OE, medium %02, Low Press, High RF2/3 and a PR loss of 65nm (0.72 Cr:PR selectivity) showed the most promise.

Another series of one factor at a time experiments were performed around run 4 to narrow down the selection of the Ion/Neutral control. Runs 5 and 6 showed the most promise (full table can be provided) with 1.26:1 and 1.27:1 Cr:PR selectivity respectively. Run 6 was a repeat, but with 75% over-etch (~ industry standard for Cr etch). Run 5 exhibited a slight foot and good CD Bias at 6nm while run 6 produced no foot but increased CD Bias at 20nm. Both profiles had a >88° sidewall angle with no undercut. As a verification, the Ion/Neutral Control was removed and run 5 was repeated. Without the Ion/Neutral Control an unusable sloped profile with a large foot was generated.

The next series of tests performed were with a scale up in Cr loading and a scale down in OE. There was a 15.7% decrease in selectivity (1.08:1 Cr:PR)

moving from low to medium load. Run 2 had no foot and an average CD Bias of 19nm while run 4 produced almost not foot and good CD Bias at 7.5nm. Both profiles had a >88° sidewall angle with no undercut. The following data was collected from a repeat of the 50% OE medium load experiment above.

Initial PR Thickness - 1595Å

Over Etch - 50%

Final Cr + PR Thickness - 1385Å

Cr Thickness - 480Å

Final PR - 905Å

Selectivity (Cr:PR) - 1.04:1

CD Bias - 9nm

Profile - >88deg with no undercut

*Conclusion

The final data set above showed a >25% improvement in Cr to PR selectivity without sacrificing CD performance. This would have allowed for an initial resist thickness of 1100Å, thus greatly reducing the risk of collapsing the PR on top of an ever shrinking feature. Further experiments to line up CDU, Linearity etc. will need to be completed to finalize the process, but preliminary runs on test patterns show very little impact to the remaining critical specifications. With more room to explore, including the additional resist pre-treatments and adjustments in OE, advanced chrome development proves to be a viable solution to pursue while we wait on EUV to fully mature.

10451-42, Session P13

Multi-beam mask writer MBM-1000

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We have been developing a multi-beam mask writer MBM-1000 for N5 semiconductor production. The mask writing system is based on large area projection optics with blanking aperture array (BAA) for individual beam blanking and a single cathode capable of high-emission current to illuminate large area shaping aperture array. It inherits a mechanical platform from the latest variable shaped beam (VSB) mask writer EBM-9500 such as mask transfer system and holding mechanism, writing chamber, and tool base with mechanical stabilizer system. Air bearing/driving stage was introduced to improve reliability and low oscillation performance.

The MBM-1000 will be released in Q4 2017 and is under integration of modules for the final configuration and writing performance tuning. A high-volume manufacturing version of BAA with 300 Gbps TPT was fabricated to realize high writing throughput, and is under writing test. Writing evaluation of the MBM-1000 has been carried out by using an alpha tool at NuFlare Techonology.

The 1st beta system of MBM-1000 was shipped to a customer site in last March. In this paper, writing results from tool evaluation at NuFlare Technology and the 1st beta customer will be reported. Tool performance and readiness will be presented in detail.

10451-67, Session P13

Improving back end of line productivity through smart automation

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Smart automation is yet to be fully implemented in production for many industries, including semiconductor, despite recently receiving a large amount of global publicity. One specific area that can significantly benefit from smart automation is the back end of line (BEOL) in mask manufacturing where the implementation of data driven decision making and predictive analytics can completely revolutionize our current way of working. Apart from the hardware aspect, software must adapt to the current needs of connectivity which demand the ability to handle large amounts of data, have sufficient computational resources and execute tool-to-tool communication. These requirements call for flexible and expandable software applications that increase the productivity and efficiency of backend processes. Additionally, by incorporating automated systems, businesses benefit from the reduction or elimination of losses due to human error.

Given the number of human interactions within each step of the standard BEOL, such as inspection, cleaning, disposition/ review and repair, mask shops run a high risk of a mishap. Even by extensive measures such errors can be reduced but not completely avoided as their origin lies in human nature. The consequences can range from harmless slip-ups up to severe manufacturing impacts which finally can lead to an economic loss. These risk levels become further multiplied as both product and workflow become more complex due to the possible repetitive cycles in the repair steps.

These losses can be mitigated by the use of smart automated solutions that deliver a reduction in turnaround time (TAT) and overhead. More efficient use of operator expertise and cost reductions in data handling will improve mask shops productivity. Another issue that intelligent automation brings is efficient tool management. In a high volume manufacturing environment it can be challenging to maintain active monitoring of tools. Consequently, idle times and bottlenecks rob mask shops from achieving their highest potential in terms of cycle time and reliability in delivering on time products. Having the possibility to monitor the tool clusters enables efficient delegation of operations and facilitates the optimization of workflows.

The proposed model in this paper investigates the effects of defectivity complexity on the TAT in a mask shop. The inclusion of intelligent application solutions effectively address human error, bottlenecks and defect complexity reducing both TAT and TAT variability. Smart automation coupled with real time monitoring and decision making solutions help control the BEOL in a predictive manner. Therefore optimization of the BEOL workflow through intelligent automation leads to a mask production with a higher reliability and a higher market value.

10451-43, Session P14

Multi-beam mask writing ready to enter production

Elmar Platzgummer, IMS Nanofabrication AG (Austria)

No Abstract Available

10451-44, Session P14

Low-cost memory device fabrication using NIL by advanced template technologies

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Recently, the biggest value in Non-volatile memory was the reduction of bit cost by pattern shrinking with lithography progress. Due to the information explosion, the interest of the market is changing from the bit cost to power saving, latency and long term and huge volume memory applying SSD. The pattern shrinking is reaching a physical limit in device, by the causes of the inter-cell interference, for instance. The device structure is shifting from 2D to 3D. The requirement in lithography for Non-volatile memory device is changing from the higher resolution technology to reduction of process cost such as having higher productivity, manufacturing yield, reliability.

Therefore, in order to significantly reduce investment cost in lithography, nano imprint lithography (NIL) technology has aggressively been developed. The framework surrounding these pattern shrinking technologies has not been able to provide lower-cost semiconductor devices. Therefore, in

order to significantly reduce investment cost in lithography, nanoi mprint lithography (NIL) technology has aggressively been developed.

Over the past few years, Toshiba, with the support of Canon and DNP, has developed NIL technology for the application of advanced memory devices and succeeded in yielding working devices with the latest memory devices. We are in the process of verifying the fundamental technologies and the compatibility of NIL to the Si-fab and are now preparing the NIL technology for the production line. To be successful however, we must solve the unique challenges of NIL in defectivity, overlay accuracy, and productivity.

For any lithographic approach, nano-scaled defects and particles are quickly becoming one of the main contributors for yield losses. As a result, the challenge will be the management of the nano-scaled defects and particles. Nano defect management called NDM will be an enabler that drives to future lithographic solutions and methods. As applied to the development of the NIL infrastructure, NDM includes issues such as:

1) Advanced metrology and Inspection: As an example, electron beam inspection for wafer and imprint templates, including multi CD-SEM inspection.

2) Resist and material Innovation: Etching resistance improvement to reduce defects on the template and wafer.

3) Super clean tools and clean room environment: The cycle for mitigating defects and/or particles for all unit processes.

4) Cleaning technology: The process cycle includes inspections, clarification of root causes, countermeasures, and controls.

In specially, template innovation that requires mask infrastructure improvement such as EB writer, resist, inspection, etcher, and cleaning, will lead NIL evolution.

In this paper, updates of the nano imprint lithography applications to the semiconductor device, progress of nano imprint related technology by improvement of template technologies will be shown. Moreover, the role of in identifying these challenges and developing NDM solutions will also be discussed.

10451-45, Session P14

Development of an inkjet-enabled adaptive planarization process

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Nanoimprint lithography manufacturing utilizes a patterning technology that involves the field-by-field deposition and exposure of a low viscosity resist deposited by jetting technology onto the substrate. The patterned mask is lowered into the fluid which then quickly flows into the relief patterns in the mask by capillary action. Following this filling step, the resist is crosslinked under UV radiation, and then the mask is removed, leaving a patterned resist on the substrate. The technology faithfully reproduces patterns with a higher resolution and greater uniformity compared to those produced by photolithography equipment. Throughputs of 80 wph have been demonstrated, and mix and match overlay of 4.0nm 3 sigma has been achieved. The technology has already been successfully applied as a demonstration to the fabrication of advanced NAND Flash memory devices.

A similar approach can also be applied however to remove topography on an existing wafer, thereby creating a planar surface on which to pattern. In this paper, a novel adaptive planarization process is presented that addresses the problems associated with planarization of varying pattern density, even in the presence of pre-existing substrate topography. This process is called Inkjet-enabled Adaptive Planarization (IAP). The IAP process uses an inverse optimization scheme, built around a validated fluid mechanics-based forward model that takes the pre-existing substrate topography and pattern layout as inputs. It then generates an inkjet drop pattern with a material distribution that is correlated with the desired planarization film profile. This allows a contiguous film to be formed with the desired thickness variation to cater to the topography and any parasitic signatures caused by the pattern layout. This film is formed by the coercing action of a compliant mask (superstrate), which forces the drops to spread and merge and eliminates any bubble trapping. The strength of the IAP process is that it can be used to address topography issues for any lithographic method.

For advanced devices, planarization is a critical unit step in the lithography process because it enables patterning of surfaces with versatile pattern density without compromising on the stringent planarity and depth-of-focus requirements. In addition to nanoscale pattern density variation, parasitics such as pre-existing wafer topography, can corrupt the desired process output after planarization.

Chemical Mechanical Polishing is the industry standard, but the technique is subject to the dependence of material removal rate on the pattern density of material, leading to the formation of a step between high density and low-density regions on a wafer. The step shows up as a long-range thickness variation in the planarized film, similar in scale to pre-existing substrate topography that should have been polished away. Preventive techniques like dummy fill and spin coated resist films can be used to reduce the variation in pattern density, however these techniques increase the complexity of the planarization process and significantly limit the device design flexibility.

An initial test of the IAP process demonstrated that planarization could be achieved over dense 30nm half pitch features and semi-dense features with critical dimensions ranging from 750nm up to 3.50 microns, with planarization efficiencies exceeding 96%.

These results are a significant improvement over what can be achieved with spin-on films such as a spin-on carbon (SOC). To further test the process, a 20 mm x 20 mm CMP test mask with pattern sizes ranging from 180nm to 100 microns was used to pattern a 100nm thick oxide film on a 300mm silicon wafer. After SOC deposition, marginal planarization efficiency of 70% was achieved for the smallest features but fell rapidly to below 40% as feature size and pitch was increased. A first IAP layer was applied over the SOC, and planarization efficiency ranged from 93 to 98 percent. The small planarization excursions are a parasitic that can be attributed to shrinkage of the IAP resist, and after further drop compensation, the planarization efficiencies of better than 99% were realized.

In this paper, further preliminary results obtained using a step and repeat approach will be presented and the means for scaling the process will be discussed.

10451-46, Session P14

Progress in nanoimprint wafer and mask systems for high volume semiconductor manufacturing

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Imprint lithography is an effective technique for replication of nano-scale features. Jet and Flash Imprint Lithography* (J-FIL*) involves the field-by-field deposition and exposure of a low viscosity resist deposited by jetting technology onto the substrate. The patterned mask is lowered into the fluid which then quickly flows into the relief patterns in the mask by capillary action. Following this filling step, the resist is crosslinked under UV radiation, the mask is removed, and leaves a patterned resist on the substrate.

Previous studies have demonstrated resolution better than 10nm, making the technology suitable for the printing of several generations of critical memory levels with a single mask. Given that there are no complicated optics in the imprint system, the reduction in the cost of the tool, when combined with simple single level processing and zero resist waste leads to a cost model that is very compelling for semiconductor memory applications.

There are many other criteria that determine whether a particular technology is ready for manufacturing. With respect to the imprint stepper, both critical dimension uniformity (CDU) and line edge roughness meet

the criteria of 2nm. Overlay of 4nm, 3? has been demonstrated, and defect levels ~ 1.1/cm2 across 25 wafers has been achieved. Other criteria specific to any lithographic process include throughput, and for a four station cluster tool, a throughput of 80 wafers per hour has been reported.

On the mask side, there are stringent criteria for CDU, image placement (IP) accuracy and imprint defectivity. Semiconductor requirements dictate the need for a well-defined form factor for both master and replica masks which is also compatible with the existing mask infrastructure established for the 6025 semi standard, 6" x 6" x 0.25" photomasks.

In this paper, we review the advancements in both wafer and mask replication systems. To address high volume manufacturing concerns, a cluster approach will be used in order to meet throughput and cost of ownership requirements (CoO). The FPA-1200 NZ2C is a four station cluster tool, and the status of overlay, throughput, particle control and defectivity will be discussed. With respect to overlay, a High Order Distortion Correction (HODC) system has now been installed which applies heat input to the wafer on a field by field basis using a digital multi-mirror device (DMD), and defines a potential path for achieving overlay results of better than 3nm. The HODC system has already been applied to fields with K7, K11 and K17 distortions and to device wafers, generating residual errors as low as 1.5nm, 3sigma. Additionally, the FPA-1100 NR2 mask replication tool is introduced. Mask replication is required for nanoimprint lithography, and criteria that are crucial to the success of a replication platform include both particle control and image placement (IP) accuracy. The development status of feature resolution, IP accuracy, and defectivity will be covered. These topics, as well as others will be presented.

*Jet and Flash Imprint Lithography and J-FIL are trademarks of Molecular Imprints Inc.

10451-47, Session P14

Improvement of the template performance for contact-hole nanoimprint lithography

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Nanoimprint lithography (NIL) is one of the most promising candidates for the next generation lithography for semiconductor. The biggest impact of NIL is low lithography CoO. Direct NIL requires no SADP, SAQP or LELE and is cost effective compared to the ArF immersion or EUVL. In addition, NIL needs no optical proximity correction and 1D design rules. NIL can apply conventional 2D design rules and may realize chip shrinkage.

Templates which will be used for wafer process are fabricated by replicating the E-beam written high quality master template. Maintaining the quality of the master templates in replication process is very important. NIL technique is used for the template replication, and optimization of the nanoimprint process is the key as well as pattern transfer etching process after imprint. Defect quality is one of the most concerns for NIL templates. Nanoimprint specific defects will appear on the replicated templates. By analyzing the mechanism of the defect generation, we have succeeded to reduce the defect density drastically. Image placement is another focus of nanoimprint templates, especially for the next generation lithography. Template image placement degrades at replication because nanoimprint process produces physical stress on both substrates. Stress reduction is necessary for image placement improvement.

We have been developing not only L&S templates but also contact hole templates. We have succeeded to fabricate pillar array templates for contact hole on wafers, by replicating from the hole tone master template.

E-Beam writing for high density hole tone master can be an issue because of its high shot count and multi beam mask writing technique must be one of the solutions for hole tone master fabrication.

In this presentation, our development results on NIL template replication will be presented.

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