Very High Sensitivity Mask DUV Transmittance Mapping and Measurements Based on Non Imaging Optics

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ABSTRACT
A key feature of a photomask is the transmission (Tr) property of its many surfaces. Typical advanced 6” masks have 4 surfaces: back side Quartz (Qz), front side pattern, inside pellicle and outside pellicle. In addition to the surfaces themselves, the bulk of the transparent materials- fused silica, fluoropolymers, and MoSi shifter stacks, have specific optical Tr properties which contribute to the total Tr properties of the mask. Surface coating materials such as Cr of varying thicknesses and Anti-Reflective (AR) coatings also contribute to the total Tr of the photomask.

Overall the wafer printed pattern fidelity to the design depends both on the physical size of the etched lines and spaces and on the Tr properties of the spaces and of the coating material in the lines. The high MEEF values reported in advanced litho processes are most probably affected among other factors by mask Tr properties which may significantly deviate from their ideal Tr values.

Factors which may contribute to transmission deviations include contamination on any of the surfaces due to haze growth, contamination by metal and oxide ions absorbed in the Qz and adsorbed on the Qz surface during mask manufacturing, photochemical degradation of the pellicle and fused silica substrates, degradation of absorber thickness (particularly MoSi) due to clean processes, and more.

Accumulated contributions of all those factors can give rise to transmission variations of up to several percent. It is well known that every percent of exposure dose change may result in 1-2nm CD change on wafer depending on exposure and process conditions.

All of the above factors raise the need for an advanced transmission measurement system that will...
No Longer Looking for the Perfect Reticle

Paul Luehrmann, Director, Applications Development ASML

I am no longer looking for the perfect reticle. I will explain.

The exposure tool is the heart of the litho process. At least I like to think of it that way. Increasing NA and decreasing wavelength has enabled much of Moore’s Law. More recently, illumination control and water immersion have kept us continually shrinking. Being an experienced (i.e. OLD) lithographer, I remember my first production fab where 6 inch wafers were patterned using 1X Perkin-Elmer scanners and 5X GCA 6300 steppers. Even then, I have always had the desire to have “Perfect Reticles”. Perfection in my case, can be defined as “zero errors” allowing me to eliminate one source of variation and to concentrate on reproductive patterning. Perfect reticles for printing 1 micron lines were definitely easier than today’s 45nm product masks. OPC at 1 micron was as simple as adding “hammerheads” at the ends of lines. DFM wasn’t even a dream yet.

Jumping forward, today’s reticles are driven by the need for sub-wavelength printing. DFM (Rule based retargeting; Model based OPC; Model based verification; etc.) seeks to match the reticle to the desired printed device pattern. Paraphrasing Lars Liebmann (IBM) from his recent SEMICON West TechXPOTS session: “if you do DFM right, it simplifies things. Having designers, mask makers, exposure tool builders, and process engineers understanding their connectedness has lead us to be Practically Perfect Patterning People. In the past, each of these groups could have developed their products almost independently. Now they are mutually dependent.

Today’s world requires an understanding across each of these areas. This connectedness is best seen each February at the SPIE Advanced Lithography symposium in San Jose. The same engineers may listen to one paper in an EDA session, then slip out to see an immersion litho paper in a parallel session. At the break, they may be talking to photoresist supplier or process tool provider before going into a metrology session on the latest mask characterization methods. At the end of the day, many are spending their evening in the BACUS Panel Discussion. All this, done to increase their understanding and to drive improvements towards perfection in their work.

Somewhere along this path, I lost my desire for perfect reticles. This was driven by three things. The first involved improvements in reticle inspection and metrology. The second involves the ability of modern scanners to use this reticle fingerprint data and compensate for it during the imaging process. And the third involves increasing costs with minimal gain.

Reticule qualification besides giving a quality judgment of the mask, it also brings with it a vast amount of data. By looking to this data, one can observe typical signatures based on process, equipment and starting material. Having these known, they can be used to improve the mask manufacturing process. They can also be used to feed-forward into the exposure tool. The scanner has the flexibility to correct at wafer level, but can also correct for across the exposure field variations. While not being able to correct for all variations, the scanner can help drive printing errors down. The result is improved printing uniformity leading to better device performance. Using this data in feed-forward mode has the parallel benefit of reducing the cycle-time needed for getting new reticles into use and qualified. The cost – benefit is to put effort into actions that yield results (Low Hanging Fruit) instead of trying to globally fix everything at once.

This leads me back to why I am no longer looking for the perfect reticle. Instead of driving errors to zero at high cost and diminishing return, I propose driving errors to the maximum correctability. This will result in the best possible printing performance.
In addition to being able to measure Tr at a sensitivity better than 0.5%, a Tr measurement tool should have the following properties:

1. Full blank automatic coverage ability.
2. Short MAM time. MAM <1s (>3600 points/hr) is a realistic demand.
3. Flexibility to compromise between sensitivity and MAM time for high and low resolution measurements.
4. Auto loading in better than class 1 clean air (any soft defect contamination will contribute to Tr loss).
5. Low CoO

The measurement solution - Galileo™
Pixer Technology has developed a Tr measurement tool for masks and blanks. Galileo™ can measure both patterned masks for purposes of haze monitoring and clear blanks for purposes of Qz Tr profiling.

Pixer Galileo transmission measurement tool for blanks and masks can measure very low transmission variations within a clear blank and therefore assist a blank maker or a mask shop in assessing the mask transmission properties at the required accuracy and sensitivity.

The advantages of the Galileo solution for mask blank measurements:

• Energy based measurement with non imaging optics.
• MAM time <1s allows 3600 measurement points in 1 hr. TAT (Turn Around Time) of a typical mask is 0.5 Hr.
• Sensitivity at MAM time of 1s is better than 0.02% (Sensitivity depends on integration time which affects MAM time)
• Spot size FWHM 600um. Allows fast, large area coverage.
• 100% of active area covered in 3 hours. Advanced sampling algorithms allow reliable blank Tr mapping in <30 min.
• Auto loading in better than class 1 clean air (any soft defect contamination will contribute to Tr loss).
• Very low CoO- the DUV light source has life time of >2000 hours. No expensive consumables, gasses or dangerous collimated beams of DUV radiation.

TARGET
The target of the study was to measure the residual transmission profile of different quartz (Qz) blanks and masks after different processes in order to identify, and possibly quantify, the contribution of different processing steps on the CDU of the mask.

Continues on page 4.
To be a tool measurement artifact.

In order to visually judge the blank Tr signature we present each measurement as a Tr map.

In order to quantify the significance of the Tr signature we correlated the original and rotated Tr maps. The closer the correlation coefficient is to 1 or the higher coefficient square value R², the more significant is the Tr signature.

In cases that no real Tr signature was detected the correlation factor was close to zero.

**Principles of Non Imaging Optics compared to Imaging Optics**

**Imaging optics** technology requires a one to one correspondence between object and image. Figure 2 shows the principle of imaging optics.

All points are distinguishable in their coordinates and intensity level (grey-levels).

In order to execute a transmission measurement with imaging optics, a group of points within the field of view needs to be averaged to obtain its grey-level value.

Typical dynamic range is 256 (²) grey-levels, which together with typical CCD noise (imaging camera detection system) results in accuracy levels of >0.5%.

For patterned masks, and in particular for contact-holes mask, CCD dynamic range and intensity levels are so low in transmission mode, that accuracy deteriorates to unacceptable levels.

In imaging systems, the field of view is generally limited to less than 100μ at DUV, and averaging is limited to a few hundreds of pixels where there is no absorber (clear area), and therefore computation time is long.

Imaging optics require very high, full field illumination uniformity, and even the best diffraction limited design cannot fully compensate for source non uniformities and optical fabrication errors. This by itself adds more than 0.5% to the error budget.

Finally, even high quality state of the art imaging systems can not measure transmission with accuracy better than ~ 1%

**Non-imaging optics** technology does not need averaging of pixels since a CCD is not used. Instead, wide band DUV irradiance from source to target is directed through the measured mask onto a fast wide band detector. Figure 3 shows the principle of non imaging optics.

By fast averaging of very strong signals (thanks to the wide band source) and a very fast, sensitive and stable detection system, the dynamic range of the measurement is more then three orders of magnitude larger than in the imaging optics case.

Transmitted energy averaging is done on a large field, typically 0.5mm, and local non uniformities of the source and other optical component aberrations in the optical path are irrelevant, so accuracy levels can reach 0.1% even on a densely patterned mask.

Although non imaging optics compromise image fidelity by allowing all scrambled angles of illumination to pass through the target and to be detected, with a proper non imaging optical design there is a large gain in energy transmission which leads to dramatic improvements in SNR and measurement time.

Thanks to the large spot size which averages DUV Tr over 0.6mm (FWHM) and very short MAM time, the whole measurement process throughput is very high, and a full mask can be mapped in less then one hour with unmatched accuracy.

**EXPERIMENTAL**

**Experimental conditions**

All 7 blanks were measured twice, at 0 and 90 deg rotation

All measurements done at the same conditions:

- Total scanned area- 130 X 130mm
- Measurement grid 53 X 53 points, pitch 2.5mm
- MAM time < 1S per point
- Total measurement time <40 min
- Normalization to air every 5 min
- Spot size FWHM 0.6mm

Figure 4 shows the blank measurement layout

**Experiment sequence**

In the first phase 3 blanks were measured. A regular virgin fused silica blank, a special low birefringence (LBF) high flatness virgin blank (both from the same vendor) and a reclaimed MoSi blank that had all its coating stripped and cleaned. Figures 5 a, b and c show the TRU maps of the blanks.

In the 2nd phase four special masks were prepared in order to identify the possible affects on transmission of two different etching processes (dry and wet) and two different metal coatings (Cr and MoSi).

Figures 6 a, b, c, d, show the TRU maps of these blanks

**Results**

Phase 1: Standard, LBF and reclaimed blanks are shown below

**Table:**

<table>
<thead>
<tr>
<th>Blank Type</th>
<th>Mean Tr %</th>
<th>Range %</th>
<th>Std Dev 1σ</th>
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<tbody>
<tr>
<td>Standard (Virgin)</td>
<td>92.0580</td>
<td>0.0087</td>
<td>0.0158</td>
</tr>
<tr>
<td>LBF (Virgin)</td>
<td>92.0565</td>
<td>0.0087</td>
<td>0.0158</td>
</tr>
<tr>
<td>Reclaimed</td>
<td>92.0303</td>
<td>0.0597</td>
<td>0.0097</td>
</tr>
</tbody>
</table>

Figure 5a. A regular virgin blank displays a relatively strong radial and tilt (marked with dashed line) Tr signature which rotates with the mask.

Figure 5b. A special LBF virgin blank displays a very low (<0.05%) Tr range with no detectable signature which rotates with the mask. The horizontal bands are tool measurement artifacts at the limit of a detectable signal.
Phase 2: Cr and MoSi dry and wet etched are shown.

Figure 5c. The reclaimed blank displays a very high (>0.25%) Tr range with a significant signature including a large 15mm cold spot (circled).

Figure 6a. The wet etched Cr mask displays a high (>0.1%) Tr range with a very significant ($R^2=0.85$) radial and tilt signature.

Figure 6b. The dry etched Cr mask displays a significant (>0.05%) Tr range with a significant ($R^2=0.43$) radial and tilt signature. Some horizontal lines are visible due to measurement artifacts.
DISCUSSION

1. The first phase of the experiment did not look at real masks but rather at the Qz properties either directly after production or after stripping and reclaiming. It is very easy to determine that the high special quality blank (Figure 5b) provides the best total transmission (92%) as well as the most flat transmission profile in terms of range and standard deviation (Stdv). Since there is no detectable signature that rotates with the blank we assume it has an extremely flat Tr profile. This kind of blank will not contribute a significant CDU error due to the Qz properties.

2. The standard virgin blank (Figure 5a) has at least 4 times higher range of Tr and Stdv than the LBF blank and displays a very significant signature. This high range is typical of many virgin blanks from all vendors which we have tested (not shown in this paper) and we believe it to be representative of a typical blank, and not the worst case. Some virgin blanks show >0.5% range of Tr. The 0.13% range of the standard virgin blank will contribute ~0.2nm CDU error to the mask.

3. The reclaimed mask (Figure 5c) shows a very large range of 0.25%. About half of this range is attributable to a large cold spot with low Tr. This cold spot is not a surface cleanable contamination but rather some embedded contamination, presumably due to the stripping process. It is interesting to note that if the cold spot is removed the residual Tr range is 0.1%, very similar to the range of a standard virgin blank.

4. The processed masks show a very distinct behavior. Ranking from best to worst in terms of contribution to Tr non-uniformity and therefore CDU error we can say that dry etch is "cleaner" than wet etch and MoSi is "cleaner" than Cr. The best performance mask (dry etch MoSi) has a Tr range which is smaller than the standard virgin blank. Therefore one can cautiously conclude that this process adds a very small Tr error if at all. Note that this is one experiment only with each type of mask and therefore the results need to be considered with caution until the experiments are repeated.
5. Regarding the Galileo transmission measurement we can see that the limit of SNR of the tool in its current configuration is around 0.05%. All samples with higher then 0.1% range show no significant bands. Samples with range below 0.04% show distinct bands. The conclusion is that although the sensitivity of the measurement is better than 0.05%, no reliable measurements can be taken below 0.05%.

6. Based on the results of this initial experiment we propose to use the Tr range as a principal metric for blank quality. In addition a visual assessment of the TRU map can provide more intuitive information regarding process effects. As verification for the significance of a measured signature, rotating the mask, repeating the measurements and calculating the R² correlation may provide additional confidence in the results. The Stdv does not seem as a very significant metric because it is less sensitive to local effects.

7. The Galileo non imaging Tr measurement system by itself has a sensitivity which is better that 0.01%. The main contribution to the reduced accuracy is tool induced systematic artifacts that show up as horizontal bands. We have identified the sources of these artifacts which are related to the normalization procedures of the tool. With such sensitive devices in the DUV range a very precise and sophisticated normalization procedure must be developed in order to mitigate artifacts due to environmental conditions. For example we have found that clean room air RH% and temperature fluctuations may have significant influences on the DUV transmission of the air in the optical path itself. Accordingly we are developing an improved system with a target of DUV Tr accuracy of 0.01%. Such a system will be able to measure significant TRU’s on all types of masks and blanks which are currently available or will be available in the foreseeable future.

8. A typical measurement recipe for blanks which will provide excellent resolution in terms of Tr Uniformity will have the following parameters:
   a. Active area 129 X 105mm (Max active field)
   b. Measurement grid pitch 3.0 X 3.0mm
   c. Total measurement points 1505
   d. Measurement time 25 min
   e. TAT including load align and unload <30 min

   The tool allows custom measurement and mapping recipes to be developed by the user. Different recipes for R&D and quality control can be developed.

9. Measurement of blanks and masks TRU profiles may be important for three types of users:
   a. Blank glass manufacturer as an R&D and quality control tool. The fast measurement during ~30 minutes for a typical map, may allow the raw material blank supplier to classify and bin the plates based on their total Tr and their Tr uniformity.
   b. The blank coater (Which is not always the virgin blank Qz maker) can use the tool for incoming raw material inspection and classification.
   c. The mask shop can use the tool for R&D of coating and etching processes and as quality control. In principle even a process for testing and qualifying reclaimed Qz blanks can be developed.

10. The Galileo tool can potentially be used for other transmission uniformity applications such as:
   a. Haze early detection in fabs
   b. Haze detection and analysis in mask shops pre and post haze clean
   c. Pellicle TRU contribution
   d. Mask CD uniformity

   These applications are under development and will be reported at later stages.

CONCLUSIONS

1. The new Galileo tool for high sensitivity Tr measurement can measure virgin Qz blanks and etch processed masks on clear areas with an accuracy of 0.05%. This level of sensitivity and accuracy is at least 10 times better than alternative transmission measurement techniques.

2. Virgin standard Qz blanks have a Tr uniformity (TRU) of ~ 0.1-0.2%.

3. High quality low BF high flatness blanks of the type we have tested have potentially a much better TRU than standard blanks, on the level of <0.05%.

4. Etched MoSi according to our experiment has potentially a better TRU than etched Cr.

5. Dry etching according to our experiment has potentially a better TRU than wet etching.

FUTURE DEVELOPMENT

Pixer is developing more applications for its unique DUV transmission tool, among them haze detection, mask CDU mapping for its CD control application (CDC200 tool) and more.
Industry Briefs

Double Patterning Battles Cost, Complexity

By Aaron Hand, Semiconductor International

In case you have not heard enough about double patterning, apparently, the subject is still hotly debated. Senior AMD Fellow Harry Levinson at Sokudo Lithography Breakfast Forum focused on its challenges as a technology positioned as the most promising one for 32nm patterning, and likely 22nm as well. While double patterning is indeed double the trouble, the industry generally agrees that it is needed to bridge the gap until the next wavelength change. The overlay or cost issues depend on the type of double patterning. As an example, spacer double patterning does not have overlay concerns because it has only one critical exposure, but the cost-of-ownership is considerably higher than other double patterning techniques and not all designs can benefit from this technology.

In fact, the choice of double patterning scheme is a game of trade-offs between process and material complexity. The standard litho-etch-litho-etch scheme uses materials available today, but it takes a big hit in throughput and process complexity. Litho-freeze-litho-etch, on the other hand, a great simplifier, allows the process to stay in the litho tool, but the idea is based on materials that are not yet available.

A lot of hope placed on the pattern freezing technique motivates several materials suppliers working on solutions. JSR Micro Mark Slezak presented the etch results at IMEC where they successfully patterned 32nm logic and contact holes. The idea of the technology is to image the first material, apply a freeze, and then put the frozen first resist through the subsequent steps. The trick is coming up with a frozen resist, immune to these steps. Although the freeze process puts more pressure on the materials, the fewer steps required in patterning can add up to significant savings.

Besides coming up with the right materials, there is a long list of requirements for the track systems as well. In some results, it was possible to optimize the resist and then preserve the first vertical lines well after horizontal lines were laid down and cured on the second layer.

Mask specifications: It’s not getting any easier

By Chris A. Mack, Microlithography World

Feature sizes, overlay errors, operating voltages, drive currents must scale in some fashion to enable the next generation of device technology. But not everything scales at the same rate. Some parameters (such as voltage) scale more slowly, while others (such as photomask dimensional uniformity) scale more quickly. Mask manufacturing specifications are scaling at a significantly faster rate than the minimum half-pitch of the device.

Over the last 10 years, half-pitch has shrunk by a factor of 4, while gate CDs have shrunk somewhat faster (almost a factor of 5). Thanks to OPC, however, the minimum (primary) feature size on the mask has shrunk faster still: by more than a factor of 6. But it is the critical dimension uniformity (CDU) specification for the mask that has scaled the fastest. Contact hole CDU specs have shrunk by a factor of 14 in the last 10 years, or more than 3x faster than the rate at which the minimum half-pitch has scaled. While everything in lithography becomes harder over time, mask-makers have earned more than their share of difficulties.

What happened to cause mask specifications to shrink significantly faster than wafer dimensions? There are three main reasons. In 2000, the industry discovered the mask error enhancement factor (MEEF), where a given percent change in mask CD results in a much higher percent change in wafer CD. As a result, mask CDU specifications shrank by a factor of 2-3 to compensate for MEEF (contact hole MEEF being the highest). By 2002, aggressive RET/OPC caused mask primary features to shrink faster than dimensions on wafer. By 2004, double exposure processes put a bigger burden on mask image placement.

How will these mask specification trends play out in the near future? MEEF is getting higher, so that we can expect mask CDU specs to continue to shrink significantly faster than wafer CD. Also, it is likely that some form of double patterning will become mainstream in the next few years. Depending on the flavor adopted, we could see a significant tightening of mask image placement specifications beyond the normal scaling (by up to a factor of 3). Masks have gotten much harder to make in the last 10 years, even relative to the difficulties in wafer lithography. More of the same is in store for at least the next five years.
Join the premier professional organization for mask makers and mask users!

About the BACUS Group

Founded in 1980 by a group of chrome blank users wanting a single voice to interact with suppliers, BACUS has grown to become the largest and most widely known forum for the exchange of technical information of interest to photomask and reticle makers. BACUS joined SPIE in January of 1991 to expand the exchange of information with mask makers around the world.

The group sponsors an informative monthly meeting and newsletter, BACUS News. The BACUS annual Photomask Technology Symposium covers photomask technology, photomask processes, lithography, materials and resists, phase shift masks, inspection and repair, metrology, and quality and manufacturing management.

Individual Membership Benefits include:
- Subscription to BACUS News (monthly)
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- Eligibility to hold office on BACUS Steering Committee

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You are invited to submit events of interest for this calendar. Please send to lindad@spie.org; alternatively, email or fax to SPIE.

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