PHOTOMASK

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Atomic force microscope integrated into a scanning electron microscope for fabrication and metrology at the nanometer scale

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ABSTRACT

An integration of atomic force microscopy (AFM) and scanning electron microscopy (SEM) within a single system is opening new capabilities for correlative microscopy and tip-induced nanoscale interactions. Here, the performance of an AFM-integration into a high resolution scanning electron microscope and focused ion beam (FIB) system for nanoscale characterization and nanofabrication is presented. Combining the six-axis degree of freedom (DOF) of the AFM system with the DOF of the SEM stage system, the total number of independent degree of freedom of the configuration becomes eleven. The AFM system is using piezoresistive thermomechanically transduced cantilevers (active cantilevers). The AFM integrated into SEM is using active cantilevers that can characterize and generate nanostructures all in situ without the need to break vacuum or contaminate the sample. The developed AFM-integration is described and its performance is demonstrated. The benefit of the active cantilever prevents the use of heavy and complex optical cantilever detection technique and makes the AFM integration into a SEM very simple and convenient. Results from combined examinations applying fast AFM-methods and SEM-image fusion, AFM-SEM combined metrology verification, and tip-based nanofabrication are shown. Simultaneous operation of SEM and AFM provides a fast navigation combined with sub-nm topographic image acquisition. The combination of two or more different types of techniques like SEM, energy dispersive x-ray spectroscopy, and AFM is called correlative microscopy because analytical information from the same place of the sample can be obtained and correlated [1]. We introduced to the SEM/FIB tool correlative nanofabrication methods like field-emission scanning

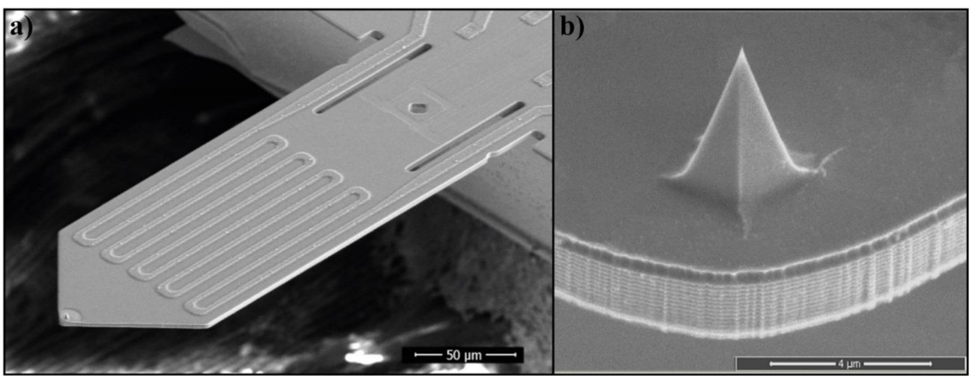

Figure 1. a) Active-AFM-SPL cantilever (scale bar 50μm) with integrated piezoresistive readout-force sensor and thermomechanical transducer and silicon tip. b) SEM image of 5.7μm silicon tip used for FN-electron emission and imaging. The thermomechanical transducer is shaped in the form of a meander made from Al/Mg alloy [12]. Four piezoresistors which form a Wheatstone bridge are placed at the base of the cantilever [9-13].

TAKE A LOOK INSIDE:

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Editorial

Change is Good!

Frank E. Abboud, Intel Mask Operation

When COVID-19 first surfaced in December 2019, little was known about the nature of the virus and the impact it would have on the world. The events of the past ten months have shaken us to the core and forever changed our normal. The entire world economy has reshaped to cope with the virus. Some industries flourished while others met their early demise. People and industries that were able to accept the change and rapidly adapt the new reality emerged stronger, wiser, and more valuable to stakeholders.

As a member of the SPIE Photomask Steering committee, I watched and participated in many debates regarding how to hold the yearly SPIE Photomask/EUVL conference in the age of COVID-19. I was impressed by the courage and methodical approach the BACUS/EUVL members and conference chairs demonstrated to deal with our new normal. It is their duty to provide a safe and healthy environment for the conference attendees while maintaining high standards for quality papers, keynote speakers, panel discussions and vendor sessions. Undoubtedly, stepping out of box to rethink how to uphold these standards and keep everyone safe proved no easy task. This year's virtual conference, however, showed all of us that unforeseen challenges can be opportunities to learn and creatively solve problems.

There were numerous high points of the conference, and I wanted to reflect on some of those and share my experience as well as the experiences of others.

The SPIE BACUS/EUVL 2020 as a Digital Forum was organized smoothly and, as a first-time online conference, I would say it was a great success. The program keynote address by Martin van den Brink at the Plenary session set the tone for a great outlook on the mask industry. Despite it being early morning in Europe (between 1 and 3 AM) the live presentation was clear, with vivid images and an energetic speaker telling us about future trends in view of the path to EUV-PSM and High-NA Masks.

The live panel discussion on "How has COVID-19 Uniquely Affected Our Business" was highly engaging and debated whether we are on vacation or if there is absolutely no second mask vacation.

The SPIE Digital Library allowed for easy viewing of the outstanding oral and poster presentations. And the best part: at no charge!

On the EUV technology trend, it was reported that the ASML NXE3400B/C are being used in HVM lithography for 7nm and 5nm logic with a high adoption rate with about 62 scanners delivered! My view is that the switch to EUV is already in place for high-end layers.

Work on EUV resist continues to show experimental 9nm and 12nm lines. Mask making remains at center stage. Increased image contraction and reduced 3D effects were highlighted, along with the long-standing blanks and absorber defects reduction efforts. EUV pellicles were also not forgotten! The new target now is 90% transmission as the industry is getting more comfortable with EUV pellicle usage. Post-pellicle mask inspection and wafer print check continue to be hot topics.

On student participation: Even in the event of difficult pandemic situation, research by students in the world related to photomask and lithography go on, as indicated by the number of presentations and posters (11 total with students from US, Japan, China, South Korea, the Netherlands, and Germany) which is similar to "normal" years. There does not seem to be any significant impact to the research and training of future scientists and engineers for our industry. This reiterates the point made in the panel discussion 'The Mask Industry Did Not Miss a Single Beat.'

The general sessions were full or technological and eye-popping results from various companies and institutions. A few statements made by the participants:

"I have to say, overall, I was pleased with the conference. The fact that I can see the videos on my own time and yet participate in the live sessions was a great combination. We should probably keep the video recording as an option even after COVID-19." Attendees echoed each other's overwhelmingly positive comments about the conference, some of which are included below.

"The logistics were fantastic! The SPIE logistics team did a marvelous job in facilitating the event and making the new technology easy to use."

"What I missed were the interactions with others. There is nothing more assuring than looking a fellow mask maker in the eye along with a firm handshake! Suppliers, customers, colleagues and friends - we all share the same common goals, face similar issues, and collaborate to progress the mask industry and the EUV technology. Oh, let me not forget... I did miss the entertainment!"

One of the most important take-aways from this year's SPIE BACUS/EUVL conference is that we remain a community that is not limited by our past, but together rises to creatively adapt to the unprecedented challenges brought on by the pandemic and succeed in doing so. I would like to thank everyone for their hard work and participation in making the 2020 conference an amazing experience and hope that we can all appreciate that great things can still come out of difficult times.

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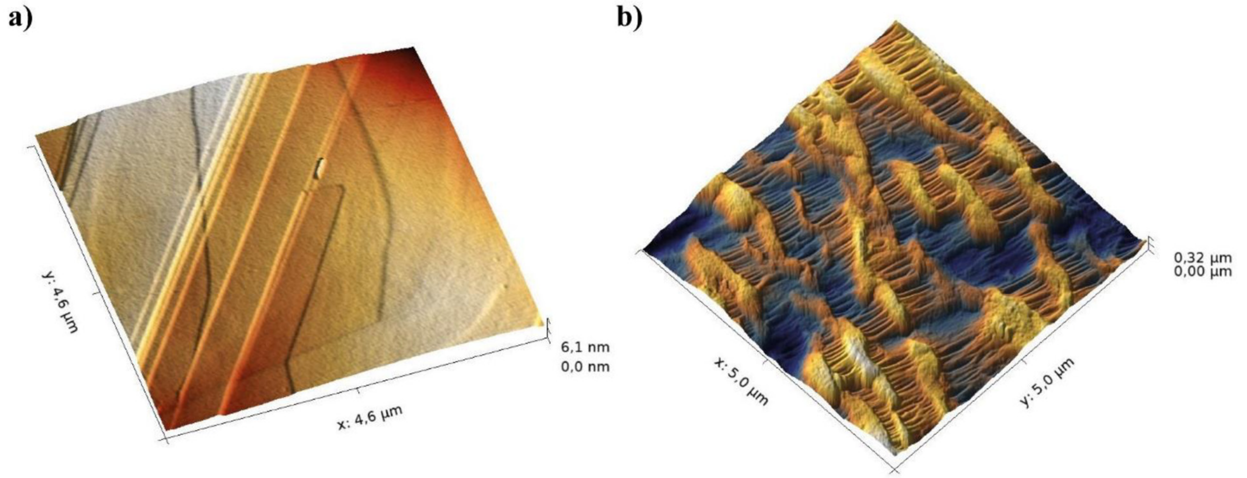

Figure 2. a) Atomic force microscope topography image of HOPG, indicating single atomic steps obtained with thermomechanically actuated piezoresistive cantilever. b) Topography AFM image of Celgard® polypropylene battery separator membrane. The image is demonstrating the performance of the active cantilever technology. The well-defined delicate structures of the topography image proof the exceptional performance of the AFM.

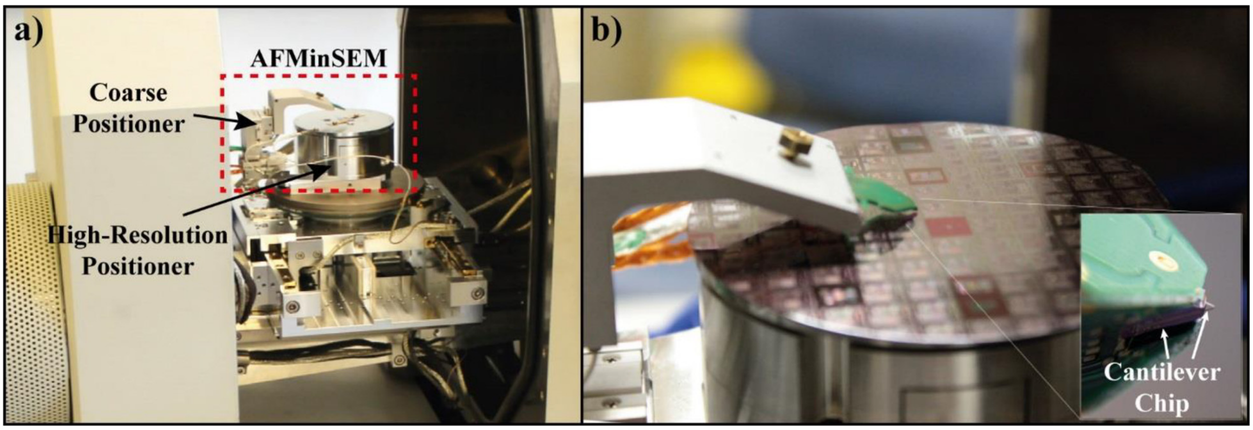

Figure 3. a) Optical image of the AFM system integrated in a dual beam SEM/FIB microscope. b) The AFMinSEM system can be operated at ambient condition. The installation and deinstallation of the tool into a SEM chamber takes not more than 5 minutes.

probe lithography, tip-based electron beam induced deposition, and nanomachining/nanoidentation.

1. Introduction

The atomic force microscope can be integrated with scanning electron microscope instruments as an increasingly capable and productive characterization tool with sub-nanometer spatial resolution. An AFM and a SEM are routinely applied techniques for high-resolution surface research. The force interaction of the AFM-cantilever tip with the surface is detected due to bending of the cantilever. The detected interaction measured optically or piezoresistive is used as feedback signal to control and maintain a constant force gradient between the cantilever tip and surface. In this context, a wide spectrum of research issues requires essentially a combination of both methods in order to gain the required surface/material information. Various studies have underpinned that demand and one of the first attempts combining AFM and SEM in an integrated system was presented which have shown an atomic resolution image of HOPG done by an AFM in SEM chamber [2-6]. Fukushima et al. presented a sample stage of the AFM module which have been equipped with remote controlled piezoelectric actuators enabling a three degree of freedom positioning with sub-nanometer resolution in a millimeter movement range [7]. Mick et al. presented a tilt-able setup using the SEM stage [8]. Today, the most popular technique measuring the AFM cantilever deflection is the optical read-out. Since a laser and photodetector unit is associated with that, a precise and for every cantilever individual mechanical alignment of the optical read-out system is required. Here, especially the limited space as well as the additional mass, which has to be carried, is a demanding design aspect.

The self-sensing and self-transduced cantilever, so called "*active*" cantilever, allow an easier system integration and substantial a) decrease in the scanning head mass [8–10]. Based on this cantilever, the AFM microscope provides a better controllability, significant higher imaging speeds with the potential of critical dimension (CD)-metrology automation.

In this paper, the concept and novel results obtained with the AFMinSEM are shown. A six-axis AFM system has been developed and integrated into a high resolution SEM/FIB system, allowing nanoscale analysis, nanomanipulation, and scanning probe lithography [11]. Combined nanoscale fabrication cases are presented. The AFMinSEM allows to combine scanning probe-based nanofabrication and metrology with conventional electronbeam- or ionbeam-based nanomachining and

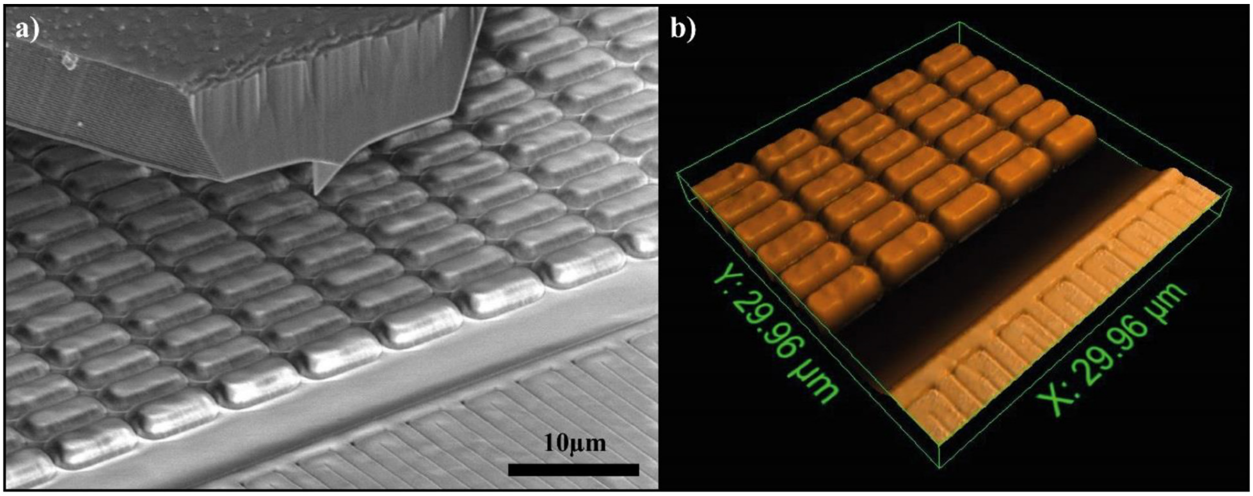

Figure 4. Simultaneous operation of the AFM and SEM. The direct view on the AFM-tip and its position makes the navigation of the tip over the sample and control of the imaging area very convenient. a) SEM image showing the cantilever while scanning. b) Recorded 3D AFM topography image of the structure. The measured height is about 1.5µm in total.

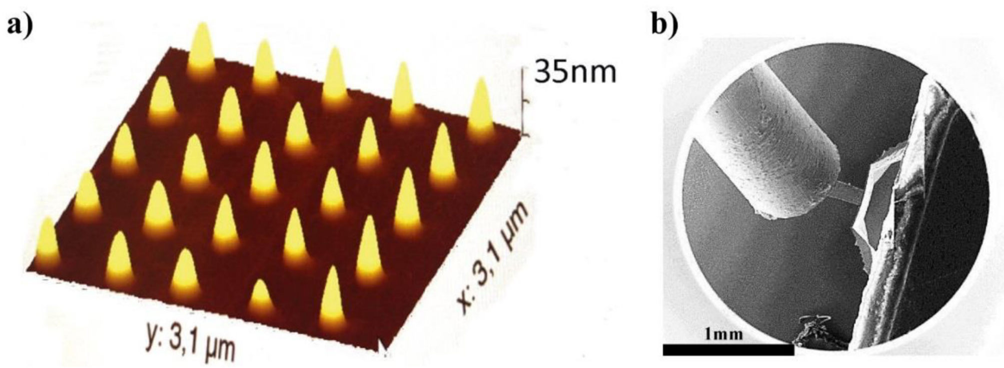

Figure 5. Generation of small platinum dots using field-emitted low energy electrons (<50eV) in the EBID process. a) AFM image of the dots using the same cantilever like before for deposition. b) SEMview on the cantilever and gas injector supplying the precursor (MeCpPtMe3).

analysis tools such as EDX without any modification of the main instrument (FIB-/SEM-system).

2. Piezoresistive Cantilever with Thermomechanical Actuator for Operation in Vacuum

The implementation of piezoresistive sensing and thermomechanically transduced cantilevers is offering unique capabilities beyond a standard AFM using optical read-out. The benchmarks for active cantilevers are routinely atomic resolution and high speed imaging. In this paper, we would like to substantiate the advantages in context of high vacuum operation in a SEM chamber. Four piezoresistors are arranged in an integrated Wheatstone bridge configuration to remove the influence of temperature variations. The advantage of piezoresistive cantilevers is not only the electrical readout but also the capability for an integrated transduction. The multilayer structure composed of thin-films forms the thermomechanical actuator, in which thermal expansion of cantilever layers occurs due to joule heating. Different coefficients of thermal expansion between the layers are introducing mechanical stress, which leads to deflection of the cantilever. By that way, the displacement of the cantilever tip can be precisely controlled by the dissipated electrical power in the embedded metallic resistor layer (Al/Mg alloy).

The main benefits of thermomechanical transduction are the small size, the precise excitation of the cantilever at its resonance, and the fast deflection of the cantilever at lower frequencies. For contact mode, a quasistatic deflection of the cantilever induces a DC-offset signal diagonally across the piezoresistive Wheatstone bridge. Keeping this signal constant by a feedback loop regulating the Z-piezoscanner, a contact mode topographic image is directly obtained. The achieved resolution in vertical (Z) direction is below 0.1nm, and measurement bandwidth is up to 1kHz in contact mode. In non-contact mode, the cantilever is excited at its resonance frequency, achieving a Z-resolution below 0.1nm as well. Furthermore, the thermomechanical transduction can be also used to drive the cantilever in higher eigenmodes.

For navigation and coarse positioning, a small motorized XYZ-stage based on piezoelectric stick-slip actuators is used. This enables to move the cantilever in an area of 18mm x 18mm x 10mm with a resolution of about 1nm. For metrology and nanofabrication, where high-resolution and position accuracy is needed, a bottom XYZ-scanning unit featuring capacitive closed loop sensors is used.

Another benefit of the tool is the non-invasive character of the featured mechanical design. The AFMinSEM can be installed in almost all commercial FIB/SEM-systems without the need for additional modifications of the vacuum chamber, therefore the warranty of the FIB/SEM-system is not affected at all. Moreover can the tool also be used as a regular AFM working at ambient conditions. Hence, the AFMinSEM can be removed from the vacuum chamber within a couple of minutes and can still be

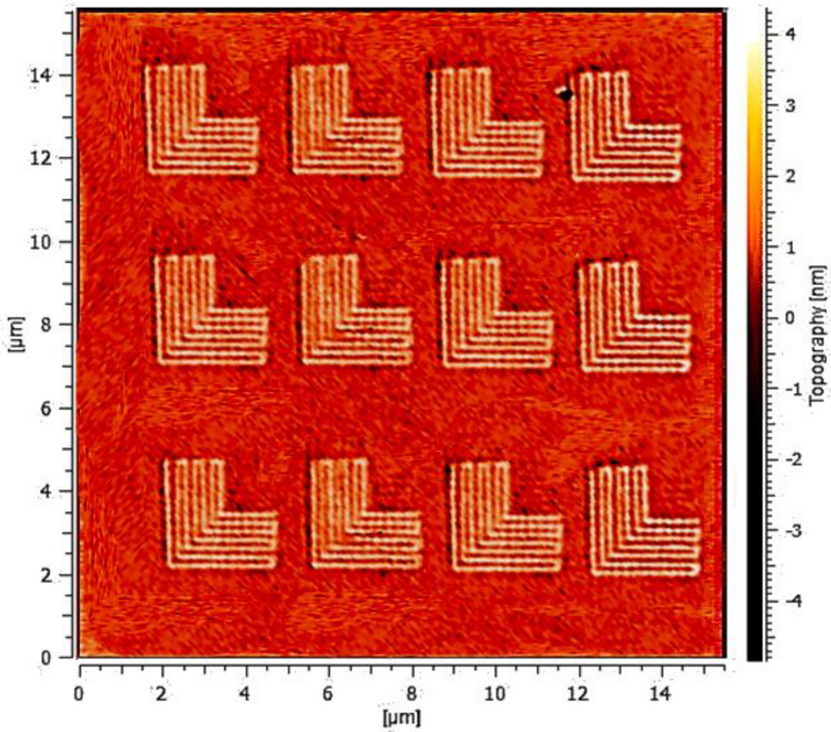

Figure 6. AFM image of FE-SPL test features taken after development in xylene. Negative tone features are inspected and measured switching the AFMinSEM in imaging mode. All lines (45nm half-pitch) were written with a bias voltage of 40V and exposure dose of 100nC/cm.

used for metrology and nanofabrication as a stand-alone system, while simultaneously keeping the FIB/SEMsystem vacant for other work.

3. AFMinSEM Applications

The AFMinSEM tool has been used usually for correlative microscopy. We extend the field of applications to: (1) Tip-Based Electron Beam Induced Deposition (TB-EBID) (2) nanomachining/indentation, and (3) Field-Emission Scanning Probe Lithography (FE-SPL). The all-inone integration of an AFM with a SEM provides versatile capabilities well surpassing a stand-alone instrument and may be used for fabrication of atomic scale devices that would otherwise not be possible. In the follow we will present examples of these applications.

(1) The AFMinSEM is used successfully for Tip-Based Electron Beam Induced Deposition (TB-EBID). The fast switching from AFM mode in field-emission mode with low energy electrons (<50eV) from the cantilever-tip serve allows to deposit nano-features with high precision. The tool can be used for studies of factors that control the properties of the deposition such as the electron-gas interactions for different precursors, the effects of gas pressure, and the temperature of the substrate. By now, parasitic deposition effects on the tip during the TB-EBID or FE-SPL have not been observed.

(2) The AFMinSEM setup is used for high-resolution Scanning Probe Lithography based on Field Emission (FE-SPL) [14-17]. The FE-SPL technology employs exposure with low energy (20–100eV) electrons field emitted from ultra-sharp diamond tips (typical radius 30nm) placed in close proximity to a resist-covered specimen. The same cantilever-tip is used for AFM imaging and lithography (to "write and read"). FE-SPL is cost-effective, mask-less nanolithography capable for (a) closed-loop operation; (b) sub-10nm lateral resolution; (c) lower implementation cost; (d) ambient or vacuum operation; (e) a simplified means of delivering exposure electrons without column or optics requiring optimization; (f) high-overlay accuracy and stitching; and use mix-and-match scheme. The operation scenario of FE-SPL is based on a vector scan scheme where the SPL-tip is directly addressed to the areas to be exposed. A strong advantage of using FE-SPL for mix-and-match lithography is the ability to overlay the high-resolution pattern with high overlay accuracy. The following example exhibits exposure of 16nm thick calixarene-resist on silicon (Figure 6).

(3) The ability of AFMinSEM to quickly and easily track diamond-tip milling with sub-nm Z resolution provides a convenient method for milling and indentation at the nanoscale. The AFM-tip can be formed using focused ion beam. Hemispherical and conical tips with radius of 30nm can be used as milling tool or indenter [18, 19]. If the diamond tip is hard-pressed into the surface of a material under moderate loads, a very well defined plastic indentation is formed with very little cracking around the edges. The scratching can be used for micro-hardness and friction measurements. The scratching process there is superposed a milling action. The local mechanical load facilitates the material to flow plastically and even with inelastic materials there is often evidence of milling. The nano-indentation with the AFMinSEM can be used to test the hardness of micro-objects with extremely smaller dimensions. The tool can potentially repair a lithographic mask using either a nano-milling or a deposition step with the low energy TB-EBID mode. The integrated piezoresistive read-out is used as closed loop for the determination of the load force under considering the spring constant of the active cantilever [16]. The XY-scanning stage is used to get the tip in a desired position and to control the machining path of the tip. The tip of the active cantilever can work as a nano-knife and due to its precise position control it can be employed for nanomachining and manipulation of nanoscale objects. Figure 7 shows the AFM image of machined grooves in an 80 nm thick chromium film. The active cantilever is equipped with a single crystal diamond-"knife"-tip. The machining trajectory is generated by a FPGA-based pattern generator.

4. Conclusions and Outlook

A versatile and compact AFM setup integrated into a SEM has been developed. We have demonstrated four techniques using the versatile AFMinSEM, TB-EBID, FE-SPL, nanomachining. The all-in-one integra-

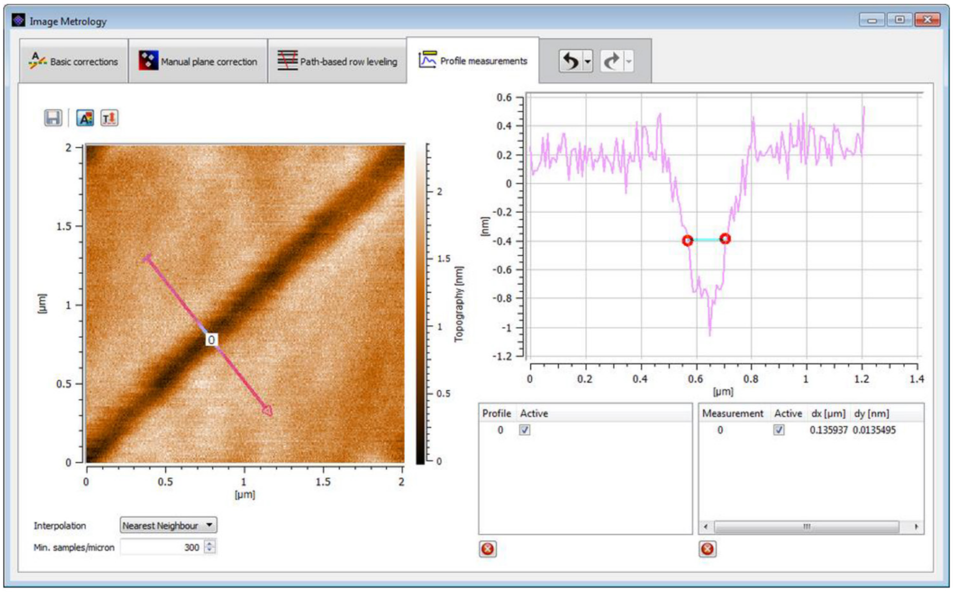

Figure 7. AFM image and cross section of a groove (depth ≈1nm) machined into an 80nm thick chromium film using an active cantilever equipped with a single-crystal diamond tip.

tion of an AFM with SEM provides versatile capabilities well surpassing a stand-alone instrument and may be used for construction of atomic scale devices that would otherwise not be thinkable. The AFMinSEM is a cutting-edge correlative microscopy and nanofabrication tool, which ensures investigations and nanofabrication by several techniques of the same area of a sample simultaneously.

The AFMinSEM makes a combination of electron, ion, FE-SPL, TB-EBID, nanomachining, nanoindentation, and other methods (EDX, WDX) without any modification of the main instrument possible and is offering a high-speed correlative analysis and nanofabrication with sub-nm resolution. The combination of all these methods provides a completely new instrument. Thus, it provides for the first time the capabilities of a stand-alone instrument with the capabilities of nondestructive three-dimensional tip-based metrology and nanofabrication into the combined SEM/FIB tool. We describe all these methods and present examples of the results obtained. The FE-SPL with AFMinSEM as a direct writing method has the advantage of high resolution, high overlay accuracy, and the ability to create lithographic features without a mask. The AFMinSEM can potentially repair a lithographic mask using either a nano-milling or a deposition step with the low energy TB-EBID mode. The AFMinSEM is a cutting-edge correlative microscopy tool, which ensures investigations and nanofabrication by several techniques of the same area of a sample simultaneously. We have demonstrated that self-sensing self-actuating cantilevers (active cantilevers) equipped with diamond tips are a versatile toolkit for fast imaging and emerging nanofabrication. Active cantilever sensors employed in AFM in SEM have enormous potential in quality and process control.

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Industry Briefs

Imec Demonstrates CNT Pellicle Utilization on EUV Scanner

Jade Liu, IMEC Press Release
October 6, 2020

LEUVEN (Belgium) — Imec, a world-leading research and innovation hub, announced promising results in extreme ultraviolet (EUV) reticle protection. Multiple full-field CNT-based pellicles were mounted on reticles and exposed in the NXE:3300 EUV scanner, demonstrating the successful fabrication and scanner handling. The tested pellicles had a single-pass EUV transmission up to 97%. The impact on imaging was low and correctable based on critical dimension (CD), dose, and transmission measurements.

Developing an EUV pellicle is challenging, since 13.5nm light is absorbed by most materials. In addition, stringent thermal, chemical, and mechanical requirements must be achieved. “Imec has leveraged partners in the semiconductor industry, materials companies and fundamental research to develop an innovative EUV pellicle design with potential to survive scanner powers beyond 600 Watts,” said Emily Gallagher, principal member of technical staff at imec. “We have seen tremendous progress in carbon nanotube membrane development in the past year and, based on strong collaborations with our partners, are confident it will result in a high-performance pellicle solution in the near future.”

Toward Sustainable Economics of Artificial Intelligence

W. Victor Gao, EETimes
October 09, 2020

Recent technology and business media have given much coverage to the expanding use case of machine learning and artificial intelligence, but how much have they talked about economics of AI?

At the physical layer, more objects in our lives are embedded with sensors or are sensors, to record and quantify more of our physical world, creating vast data sets that make machine learning possible. At the application layer, growing compute power and model sophistication such as dimensionality reduction and manifold learning have helped data scientists tackle messier technical problems. Meanwhile, the pandemic has heightened the urgency and societal stakes to direct research insights toward practical problem-solving.

And yet as practitioners know well, AI/ML faces challenging economics because of data and model complexities. An underlying cause is entropy, the tendency of our natural world to become more chaotic over time. Another is the long tail: no matter how neatly a model accounts for a perceived cluster of data points, many still fall outside its explanatory power. Financially, these technical challenges impose a high level of recurring expenditures for modeling and training data generation, classified as operating expenses rather than capital expenditures.

Nvidia’s $40 Billion ARM Purchase Will Test Current M&A “Ceiling”

Source IC Insights
September 16, 2020

After nearly two months of negotiations, Nvidia this week announced a $40 billion agreement to buy ARM—the leading supplier of processor intellectual property (IP)—from financially struggling SoftBank in Japan. If approved, the deal would be the largest semiconductor acquisition in history. The acquisition, which is expected to take 18 months to complete, would top Avago’s 2015 deal to buy Broadcom for $37 billion, and SoftBank’s $32 billion purchase of ARM in 2016.

ARM’s technology generated $1.8 billion in 2019 and over $1.0 billion in the first half of 2020, but SoftBank decided to sell the business to help it climb out of huge losses from investments in technology startups. Nvidia’s move to own ARM and its near-total grip on central processor unit (CPU) technology in smartphones, tablets, and other portable systems has stirred debate and fears about access to new design cores and instruction sets used by dozens of mobile MPU suppliers. To quell concerns, Nvidia promised to maintain ARM’s ability to work independently with other IC companies, such as Qualcomm, Samsung, MediaTek, and Apple, which is expanding its use of ARM CPU technology for custom 64-bit processors beyond iPhones, iPad tablets, smartwatches, and other products to its Macintosh computer line (replacing Intel x86 MPUs).

While computer graphics leader Nvidia and cellphone IP leader ARM have grown their businesses by serving different customers and different applications for products, their paths have merged—especially in the exploding field of artificial intelligence (AI). Last decade, Nvidia parlayed its lead in graphics processing units (GPUs) to get a big jump in AI machine-learning applications for servers. It sees ARM’s IP and design-support software for low-power consuming system-on-chip (SoC) processors as a vehicle to quickly move its AI and machine-learning capability into a much wider range of systems. Nvidia executives also suggested that the ARM acquisition could result in a strong industry alternative to Intel’s dominance in central microprocessors for server computers.

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The BACUS Newsletter is the premier publication serving the photomask industry. For information on how to advertise, contact:

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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)
- Eligibility to hold office on BACUS Steering Committee

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Corporate Membership Benefits include:

- 3-10 Voting Members in the SPIE General Membership, depending on tier level
- Subscription to BACUS News (monthly)
- One online SPIE Journal Subscription
- Listed as a Corporate Member in the BACUS Monthly Newsletter

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CALENDAR

2021

SPIE Advanced Lithography
21-25 February 2021
San Jose, California, USA
www.spie.org/al

Photomask Japan
20-22 April 2021
Digital Forum
Japan
www.photomask-japan.org

The 36th European Mask and Lithography Conference, EMLC 2021
21-23 June 2021
Leuven, Belgium
www.emlc-conference.com/en

SPIE Photomask Technology + EUV Lithography
26-29 September 2021
www.spie.org/conferences-and-exhibitions/photomask-technology--extreme-ultraviolet-lithography

SPIE is the international society for optics and photonics, an educational not-for-profit organization founded in 1955 to advance light-based science and technology. The Society serves more than 255,000 constituents from 183 countries, offering conferences and their published proceedings, continuing education, books, journals, and the SPIE Digital Library in support of interdisciplinary information exchange, professional networking, and patent precedent. In 2019, SPIE provided more than $5 million in community support including scholarships and awards, outreach and advocacy programs, travel grants, public policy, and educational resources. **spie.org**

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You are invited to submit events of interest for this calendar. Please send to lindad@spie.org.