PHOTOMASK

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PUV19 - 3rd Place Winner Best Poster

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 thermo-mechanically 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 probe

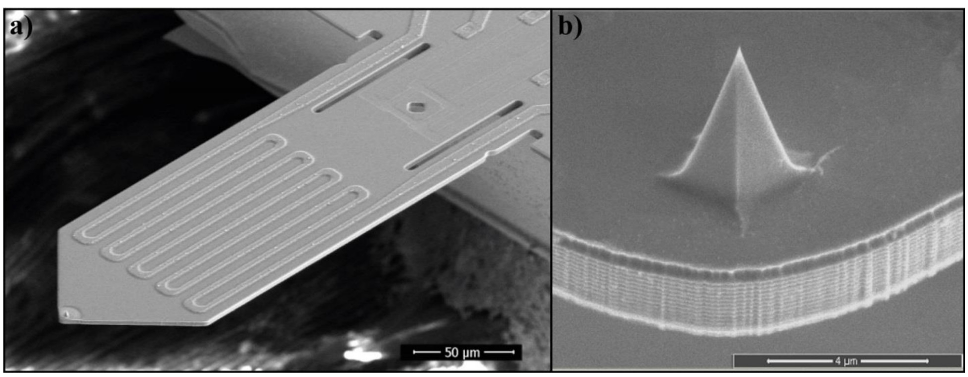

Figure 1. a) Active-AFM-SPL cantilever (scale bar 50μm) with integrated piezoresistive readout-force sensor and thermomechanical transducer and silicon tip. b) SEM image of 5.7μm silicon tip used for FNelectron emission and imaging. The thermomechanical transducer is shaped in the form of a meander made 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

The Opportunity of a Lifetime: Life without F2F

Artur Balasinski, Infineon Technologies

It is hard to discuss technical issues in cold blood when all these issues run the risk of becoming irrelevant in the light of the developments on the health front. So instead of not noticing the elephant in the room, i.e., COVID-19, perhaps it is better to acknowledge its impact.

We are surprised that we are surprised. Close interactions of human beings, on a massive scale, must have eventually led to the transmission of contagious microcells attached to them. It was inevitable in the past; it would be likely inevitable in the future. Just like until September 11, 2001, no one thought an aircraft can fly into a tall building. Well, it happened. We should make the best lemonade out of this lemon-like situation.

It is interesting how our industry at large does not sound alarmed with the lack of F2F (face-to face) interactions. Semicon West goes virtual on an upbeat note. When I just opened a paper about constrained innovation https://semiengineering.com/constrained-innovation/ in the EDA industry, I was expecting to find a lot of words about the COVID. Nope. By contrast, the constraint is coming from the boiled frog effect: the chips are designed in outdated ways. We need more startup-style ideas.

Giants of intellect did not need many peer interactions. Theoretical breakthroughs are often accomplished in solitary confinements, not at wine and beer poster sessions. Sure, it feels good to exchange random ideas, but gains are made by consistent effort, not by the conference high-life. Many societies fell into the trap of feeling good about themselves only to be bypassed by the ones who stayed off the beaten path and worked harder. One key factor is to be able to focus on a task for an extended period of time. Here, off-site gatherings used to have the advantage, due to the uninterrupted time at the conference activity. Alas, working remotely put an end to this. There is not a meeting where people are not busily working on their laptops instead of listening to the proceedings. So the question is, can one self-confine at an isolated location at home and make progress. It may be not easy, but it is certainly not unthinkable.

It is our opportunity of a lifetime to move on without the F2F. Develop a conference formula not in the style of the Congress of Vienna but one that would move us forward two centuries onwards. Examples:

- Small group meetings
- Pre-recorded best-quality presentations with live comments
- Unlimited display of the data (well, limited by the confidentiality).

No one would stop you from grabbing a beer (from your own fridge). The conference chair may pick a movie about tourist attractions in the area of your choice and have a live feedback. You may be able to negotiate with your employer a few extra days of vacation to actually go there on your own, given how much time would be saved.

We are just starting. Think of your own ideas. In the end, it is just the brain power that matters.

BACUS N • E • W • S

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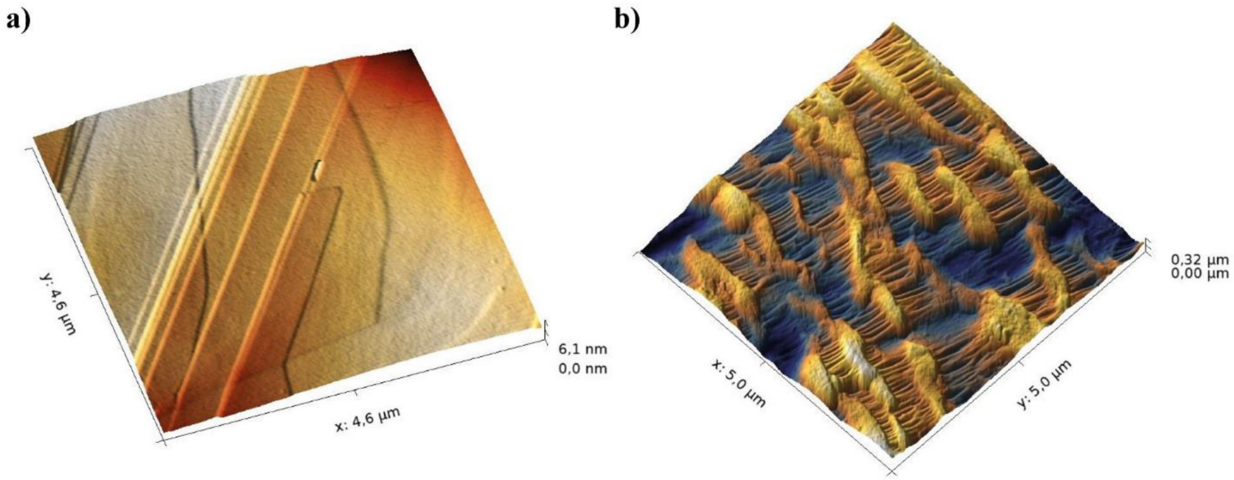

Figure 2. a) Atomic force microscope topography image of HOPG, indicating single atomic steps obtained with thermo-mechanically actuated piezoresistive cantilever. b) Topography AFM image of Celgard® polypropylene battery separator membrane. The image is demonstrating the performance of the active cantilever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

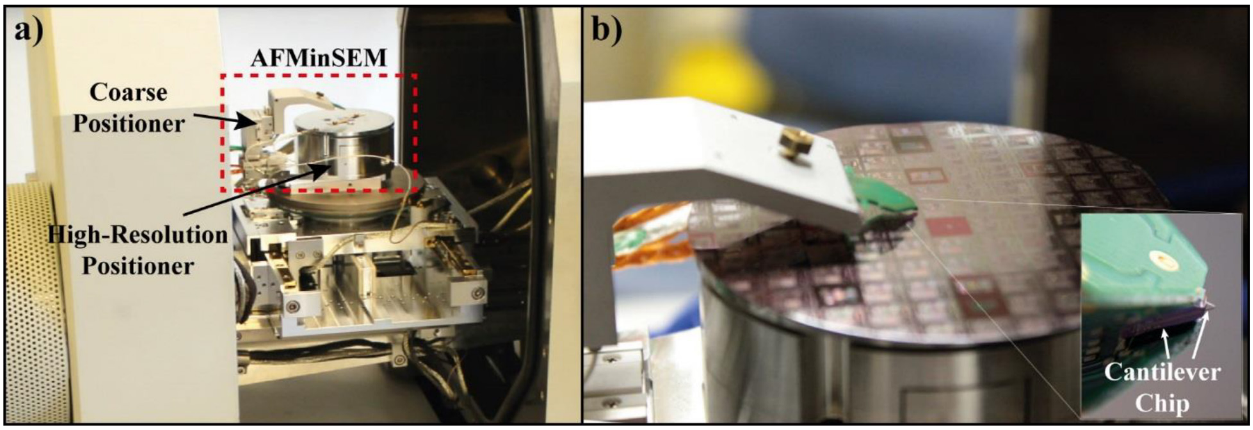

Figure 3. a) Optical image of the AFM system integrated in a dual beam SEM/FIB microscope. b) The AFMinSEM system can be operated at ambient condition. The installation and deinstallation of the tool into a SEM chamber takes not more than 5 minutes.

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

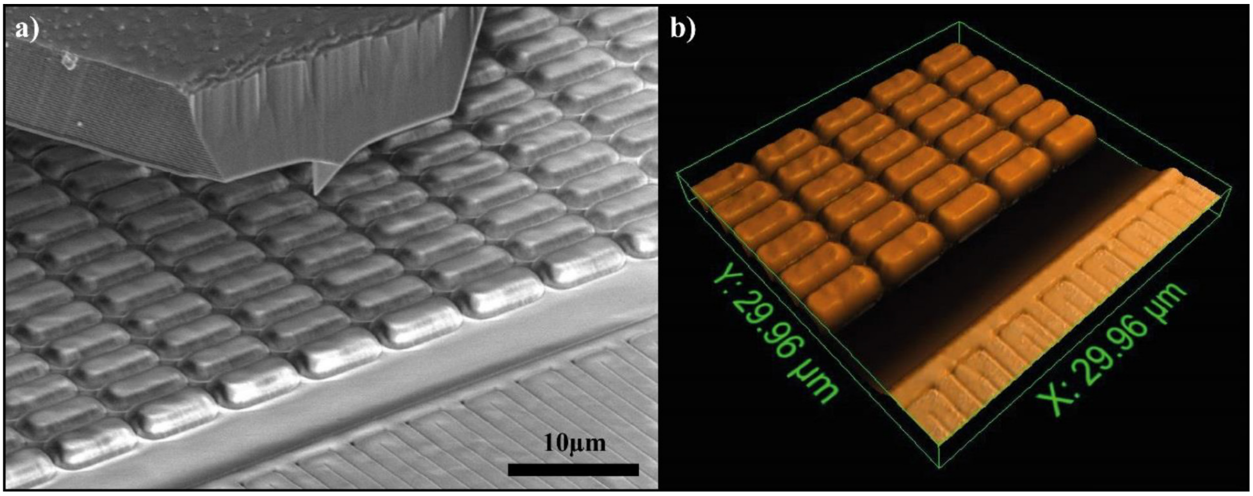

Figure 4. Simultaneous operation of the AFM and SEM. The direct view on the AFM-tip and its position makes the navigation of the tip over the sample and control of the imaging area very convenient. a) SEM image showing the cantilever while scanning. b) Recorded 3D AFM topography image of the structure.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

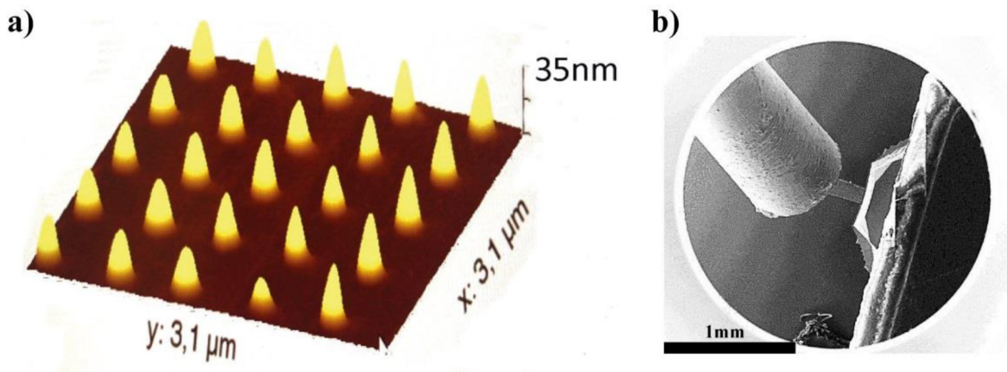

Figure 5. Generation of small platinum dots using field-emitted low energy electrons (<50eV) in the EBID process. a) AFM image of the dots using the same cantilever like before for deposition. b) SEMview on the cantilever and gas injector supplying the precursor (MeCpPtMe3).

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

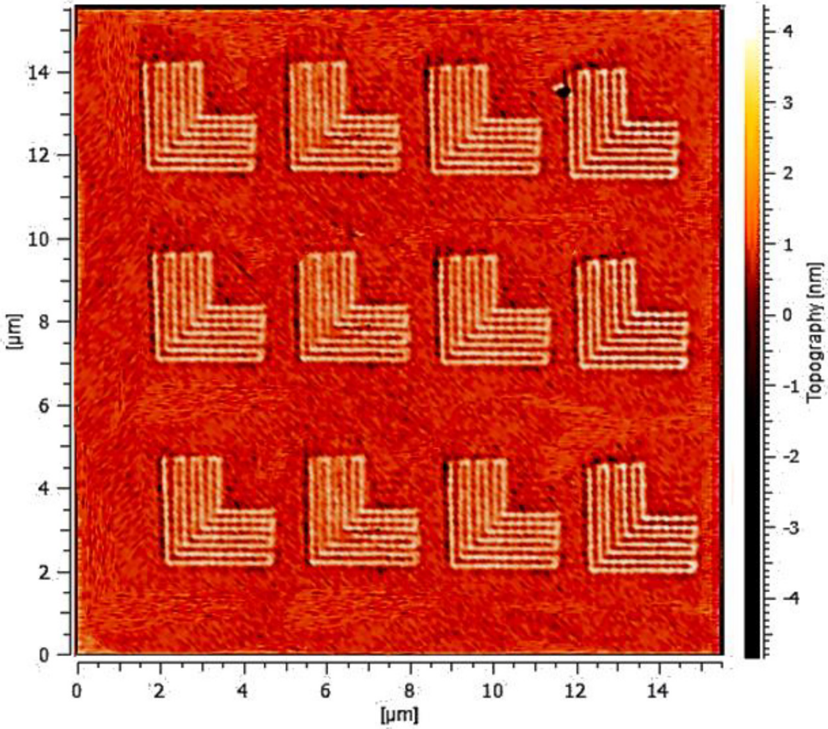

Figure 6. AFM image of FE-SPL test features taken after development in xylene. Negative tone features are inspected and measured switching the AFMinSEM in imaging mode. All lines (45nm half-pitch) were written with a bias voltage of 40V and exposure dose of 100nC/cm.

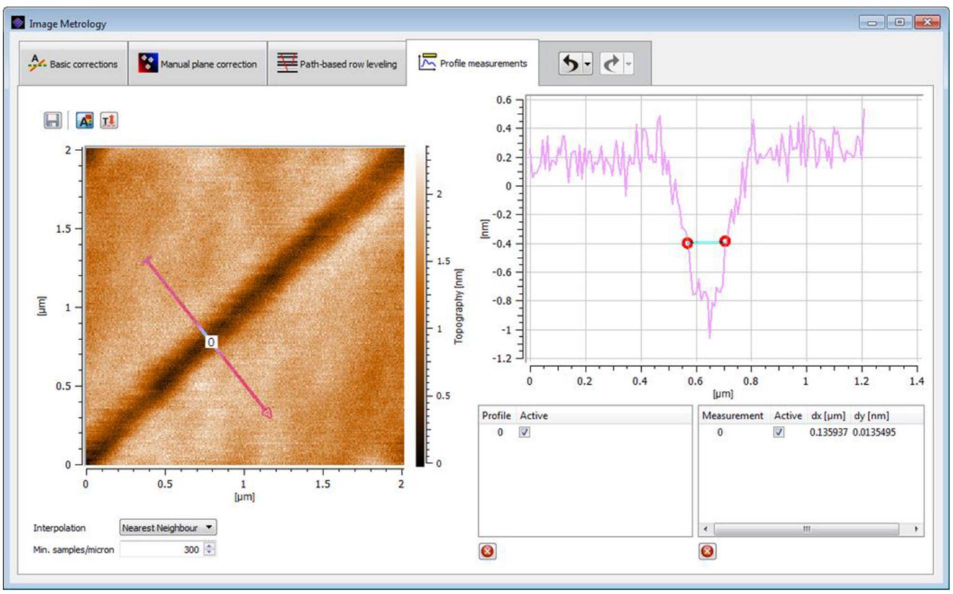

Figure 7. AFM image and cross section of a groove (depth ≈1nm) machined into an 80nm thick chromium film using an active cantilever equipped with a single-crystal diamond tip.

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 integration 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 nanomilling 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.

5. Acknowledgments

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Industry Briefs

SEMI World Fab Forecast Report Projects Record Equipment Spending in 2021

Despite COVID-19, our industry seems to be looking up into a solid 2021.

https://www.embedded-computing.com/home-page/semi-world-fab-forecast-report-projects-record-equipment-spending-in-2021

KPMG and GSA conducted a pulse survey that reflects a largely neutral to positive effect from COVID-19 on 5G, AI, and IoT.

https://advisory.kpmg.us/articles/2020/impact-of-covid-19-on-semiconductor-industry.html

TSMC to build a $12B megafab in Arizona for 5nm node, online in 2024

This news adds to the general momentum in our industry. Though there appears to be no announcement regarding whether there is a mask shop that will be built there, it is a major announcement nevertheless as it is the first time in a long time that a semiconductor fab is being added in US, particularly for a leading-edge node.

https://www.forbes.com/sites/willyshih/2020/05/15/tsmcs-announcement-of-a-us-fab-is-big-news/#39ebc4992340

NVIDIA announces A100 GPU with 78 TFLOPS tensor core performance

Delayed by COVID-19, with a keynote from his home, Jensen Huang (CEO) announced the long awaited A100 (Ampere architecture). It is an impressive system, continuing to be a full-reticle design as was the V100 before. The core computing chip in the system is built with 7nm technology at TSMC. Among the notable specs are 78 TFLOPS of Tensor performance (for deep learning inferencing), 1,555 GB/s bandwidth to 40GB of stacked memory, using up 400W of power.

Here's a good summary of the general specs:

https://www.techpowerup.com/gpu-specs/tesla-a100-sxm4.c3506

For those of you interested in chip technology, here's a different approach to deep learning that's also made at TSMC, announced last fall. There are many inferencing startups competing with NVIDIA, but this one uses wafer-scale integration.

https://www.pcworld.com/article/3432977/cerebras-systems-new-deep-learning-chip-is-as-big-as-your-keyboard-and-the-largest-ever.html

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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.

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CALENDAR

2020

SPIE Photomask Technology + EUV Lithography
20-24 September 2020
Monterey Conference Center and Monterey Marriott
Monterey, California, USA

2021

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

Photomask Japan
26-28 April 2021
Yokohama, Kanagawa, Japan
www.photomask-japan.org

The 36th European Mask and Lithography Conference, EMLC 2021
21-23 June 2021
Leuven, Belgium

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