The future of nanofabrication

News and impressions from the 4th Thermal Probe Workshop in Zurich

Heated nanoscale tips are emerging for a wide variety of applications. The so called "Thermal Probes" are particular exciting for nanofabrication since the commercialization of the "NanoFrazor Technology" in 2013 by the company SwissLitho.

The rapidly growing community for thermal probe research met again in Zurich to attend the annual Thermal Probe Workshop. SwissLitho and IBM Research co-organized the event for the 4th time and invited researchers from all over world to present their newest results using thermal probes. The quality and the diversity of the shown applications reached a new level and everyone could actually feel the enormous impact the community is about to create on the progress and future of nanotechnology.

Keeping the tradition of previous workshops, the event kicked off with a historical review. Prof. Elisa Riedo, one of the pioneers of using thermal probes for lithography, delivered a definitive overview talk on the history and the variety of applications of thermochemical scanning probe lithography. Her numerous examples, all published in high impact journals, included e.g. local crystallization to form ferroelectrics, grafting of protein patterns, or local reduction of graphene oxide. Following that introduction, several speakers presented more recent ideas on thermochemical modifications using the *NanoFrazor* technology.

Thermochemical Patterning

Samuel Zimmermann, the 3rd place winner of last year workshop's *Young Researcher Idea Competition*, showed how he realized their pro-

posed idea for combined topographical and fluorescent security features using special glassy supramolecular films. His demonstration of reprogrammable nanostructures with tunable fluorescence left quite an impression on the audience.

Another highlight was the talk by Dr. Edoardo Albisetti from CUNY Advanced Science Research Center. His novel concept of using the heated tip to non-destructively create magnetic nanostructures in a single step could be quite promising for fabricating magnonic and spintronic devices. He pointed out that such nanostructures are not only reconfigurable and precisely tunable, but are also quite robust against external fields. Additionally, he showed favorable initial results for propagating spin waves in his structures.

Dr. Annalisa Calo showed yet another idea on how the heatable tip can be used for patterning. She managed local doping of 2D semiconductor materials like MoS_2 flakes in varying gas atmospheres. Her preliminary results on fabricating MoS_2 diodes and transistors were rather encouraging. In addition to an increased mobility, the doping also helps considerably to reduce contact resistance in such devices.

3D Patterning

Accurate 3D patterning is one of the unique capabilities of the NanoFrazor technology and justifiably so, an entire session was dedicated to this topic. Dr. Robert Kirchner, a well-known expert on 3D nanopatterning started off the session by making a clear statement on the increasing requirements of 3D nanostructures in the industry sector. For example, future augmented reality devices could heavily rely on accurate 3D nanopatterning. Though not yet a user of thermal probes, Dr. Kirchner showed his own impressive work on 3D patterning and polishing, which is state-of-the-art on what is currently possible with conventional techniques such as E-Beam Lithography.

Dr. Colin Rawlings gave an overview talk updating the audience about recent developments on the NanoFrazor 3D closed-loop lithography. He showed that it is indeed possible to fabricate patterns with a depth resolution below 0.7 nm. This unprecedented accuracy was applied for the first-time for the realization of *photonic molecules* which are coupled microcavities for quantum networks. The obtained measurements of such photonic molecules matched incredibly well with the simulations. Dr. Rawlings was obviously excited on the impact this recent breakthrough could have in the respective quantum community.

The accurate 3D nanostructures written by the NanoFrazor into the polyphthalaldehyde (PPA) polymer can be amplified to have depths of a few micrometers by etching them into *Si*. This was already demonstrated in last year's workshop by Dr. Yuliya Lisunova from EPFL Switzerland. This year, she showed that the roughness of such 3D *Si* structures can be kept below 1 nm even after the etching process. To accomplish this, she developed a smart polishing process using a sacrificial polymer layer.

Dr. Simon Hettler from Karlsruhe Institute of Technology showcased beautiful 3D nanostructures in his talk on 3D phase plates. His idea of using the NanoFrazor for the fabrication of complex 3D phase plates earned him the 2nd place in last year's *Young Researcher Idea Competition*. He realized a variety of 3D phase plates in *SiN* membranes and presented the corresponding beam shapes generated in his TEM at Karlsruhe. This approach will allow simple aberration corrections and the generation of angular orbital momentum beams in TEMs.

High resolution device fabrication

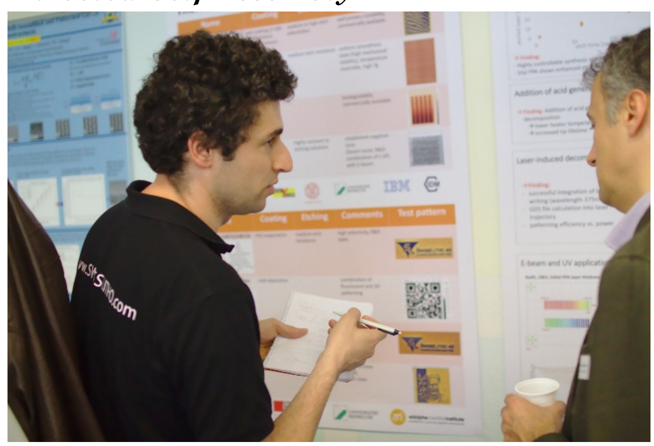
Device fabrication using the high resolution and overlay capability of the NanoFrazor is the most commonly used application of the NanoFrazor and was the central focus in several talks. Pattern transfer is usually required for device fabrication and Dr. Tero Kulmala from SwissLitho summarized the various pattern transfer techniques that have been developed for NanoFrazor lithography. He pointed out the particularities of the processes and presented various new ideas to simplify the high resolution etch processes. He invited the community to join such development work since he is convinced that an active collaboration among all NanoFrazor users on such processes would be beneficial for everyone involved.

Dr. Yu Kyuong Ryu Cho presented the results of one such collaboration between IBM and SwissLitho. She optimized and extended the well-established IBM hard mask etch process by appropriate consideration of the initial etch phase. This enabled obtaining magnificent TEM cross sections of 7nm wide *Si* lines with a half-pitch of below 14 nm. Dr. Yu presented an impressive variety of fabricated devices like *InAs* nanowire transistors and MoS_2 nanoribbon arrays which relied strongly on precise overlay capability. Furthermore, she also showed results on single electron transistors made in *Si* using mix-and-match lithography with a prototype of an integrated laser writer.

Another highlight of the workshop was the talk of young PhD student Bojun Cheng from ETH Zurich. He showed initial results on atomic

scale memristors fabricated with the NanoFrazor. The sharp NanoFrazor tip was used to overlay extremely sharp vertical *Ag* tips (< 10 nm) to very close proximity of bottom *Pt* electrodes. This allows tiny silver filaments to grow and break fastly in the thin matrix between the tip and the bottom electrode to form electrical contacts. His measurements of such resistive memory devices showed very high on-off ratios and low switching voltages. Moreover, this concept is very promising as switching can reach GHz frequencies and the switches can be packed in an extremely dense manner.

Directed Self-Assembly



This year's workshop also included a special session dedicated to Self-Assembly. Dr. Alex Liddle, one of the big names in the field of nanofabrication opened the session with some impressive results from NIST on the exciting possibilities of DNA origami. Using the right DNA sequences, predictable folding of the DNA strands can be achieved for generating impressively complex geometries.

Most of the contributions in the self-assembly session used the NanoFrazor to pattern guiding structures for molecules or nanoparticles.

Dr. Christian Schwemmer from IBM demonstrated that manipulation and assembly of nanoparticles and nanowires within nanofluidic channels is possible using accurate 3D patterns in PPA. His talk included a series of impressive videos on how the "wild" Brownian movement of tiny particles is controlled by the geometry of the patterned 3D nanostructures. This novel concept may become very useful for automated sorting of nanoparticles or proteins. Precise integration of functional chemically synthesized nanoparticles into devices is also possible, which was e.g. demonstrated with *InAs* nanowires.

Directed Self-Assembly (DSA) of Block Copolymers (BCP) is currently one of the hot topics in semiconductor industry to continue with Moore's Law. Steven Gottlieb from CSIC Barcelona used NanoFrazor lithography to fabricate high resolution guiding structures that proved to be very suitable for DSA of BCPs. Most importantly, they do not suffer from proximity effects that make conventional techniques like DUV or E-beam lithography extremely challenging for highly dense features. He used a smart combination of shallow topographical features (only 2 nm deep) and local chemical modification to assemble BCP with high resolution (10 nm) and high quality.

Nanoscale thermometry and analysis

The focus of the workshop was on lithography and nanofabrication; however, thermal probes can also be very exciting for surface material analysis and temperature mapping. Dr. Craig Prater from Anasys showed how his company has already been using thermal probes for years to measure softening temperatures of materials. Dr. Olivier Chapuis from CETHIL Lyon, gave an overview on scanning thermal microscopy and nanoscale thermal transport and opened a dedicated session on the topic.

Nico Mosso from IBM showed that it is actually possible to measure heat transport even through single *Au* atoms. Fabian Motzfeld's talk was more real world application oriented and showed how the NanoFrazor cantilevers can be used in vacuum to map the temperature distribution in active nanodevices with *mK* resolution. Artifacts that arise from the changing tip contact area during scanning of the topography can be elegantly corrected by an additional AC heating. Astonishingly, the bipolar AC voltage even allows to quantitatively separate Peltier and Joule heating in the devices.

Mass replication

The workshop finished with a presentation of Prof. Jens Gobrecht from PSI. His talk focused mainly on mass-replication of nanostructures and injection molding, which is used to make plastic parts in very high volumes. The NanoFrazor was used to make 3D nanopatterns in PPA on which *Ni* could be electroplated using a *Pd* seed layer. The so formed *Ni* shim was then replicated with high quality in PMMA by variothermal injection compression molding. This proof-of-principle experiment shows that the accurate 3D features made with the NanoFrazor can be cheaply replicated even by methods that people don't think of first when talking about nanotechnology.

The workshop was a big success and one could feel the excitement of the community concerning all the new possibilities that come forth by using thermal probes. The 70 participants from Europe, Japan, Korea, China, Australia and the US clearly enjoyed the nice atmosphere of the workshop and the sunset dinner cruise on lake Zurich. Most attendees already confirmed their participation in next year's workshop which will be again in Zurich on the 28th and 29th of March 2018.