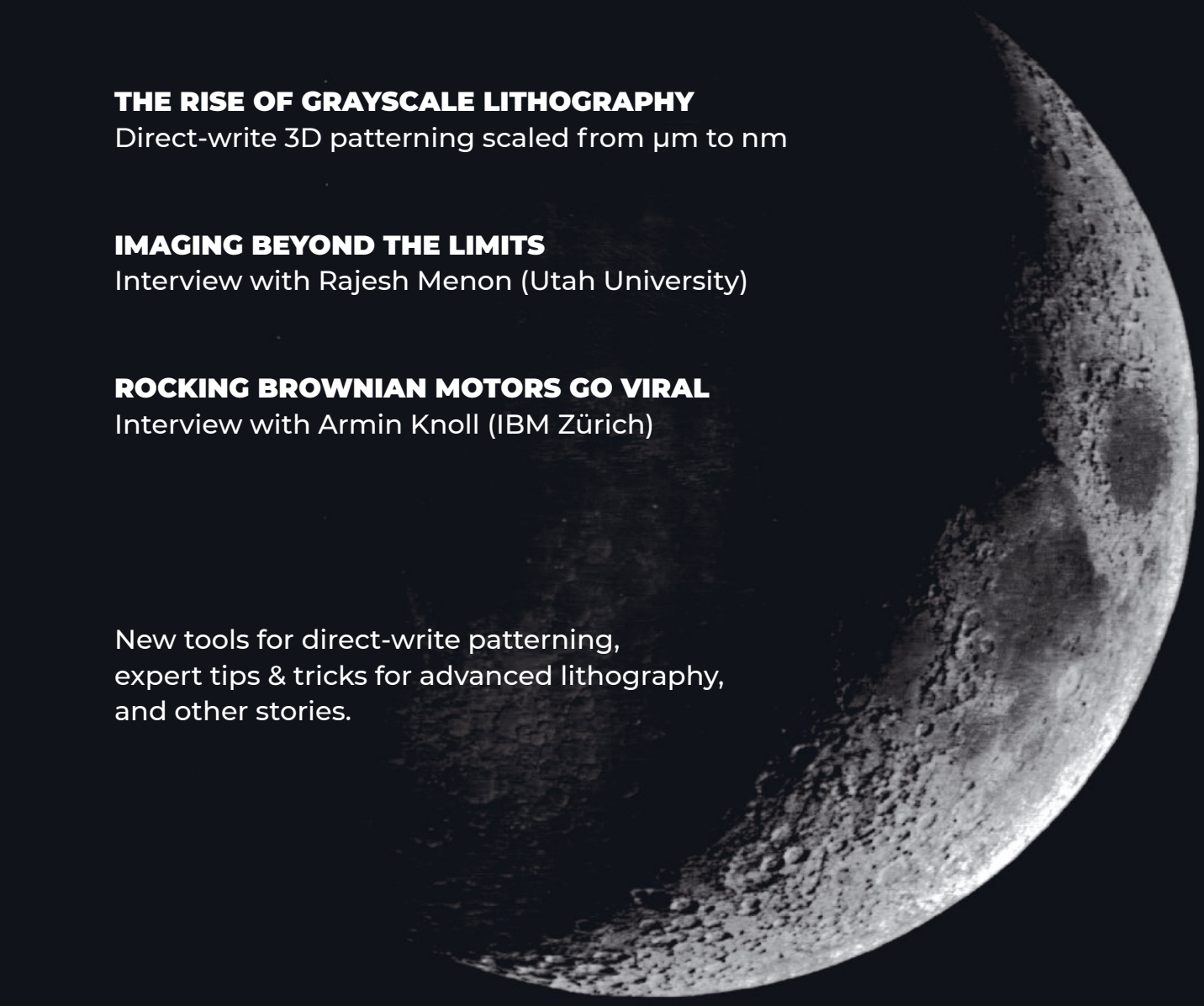
THE LITHOGRAPHER

GRAYSCALE LITHOGRAPHY ISSUE • JANUARY ‘20



THE RISE OF GRAYSCALE LITHOGRAPHY
Direct-write 3D patterning scaled from µm to nm

IMAGING BEYOND THE LIMITS
Interview with Rajesh Menon (Utah University)

ROCKING BROWNIAN MOTORS GO VIRAL
Interview with Armin Knoll (IBM Zürich)

New tools for direct-write patterning,
expert tips & tricks for advanced lithography,
and other stories.

5 µm

70.5 65.0 60.0 55.0 50.0 45.0 40.0 35.0 30.0 25.0 20.0 15.0 10.0 5.0 0.0

HEIDELBERG INSTRUMENTS

The power of direct writing

- Substrate size up to 120 x 120 mm
- Min feature size: down to 0.6 µm
- Max write speed @ 4 µm resolution: 100 mm^2/min
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- Frontside alignment
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µMLA

State-of-the-art maskless technology for entry-level R&D

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This is the first issue of a biannual topical magazine which we called The Lithographer. Heidelberg Instruments launched this project to share with you what we hold dear and what we know the best — emerging capabilities of the direct-write approach to micro- and nanofabrication in cleanrooms and at industrial production lines. The Lithographer will cover the state-of-the-art direct-write techniques: *e.g.* laser, e-beam and thermal scanning probe lithography (t-SPL), and other relevant technologies: software, resist chemistry, pattern transfer processes, etc. Leading scientists, micro/nanofabrication experts, and equipment manufacturers will share their know-how and outlook on these matters.

This issue is dedicated to grayscale, or 3D, micro- and nanolithography. We mention a few interesting papers published this year in *Research Highlights,* with a partial focus on t-SPL technique, an emerging method that enables nanofabrication not feasible with other techniques and with very versatile applications. We discuss the current state of affairs in direct-write grayscale lithography in *The Rise of Grayscale Lithography* and talk with a few experts about nanofluidics, nanophotonics and computational imaging. *Experts' Know-how* features some particulars of grayscale sample fabrication on micro- and nanoscale. We also present Heidelberg Instruments' new tool MLA300, a Maskless Aligner designed for industrial use.

Enjoy the magazine! Hopefully, you will find this issue interesting and useful.

Anya Grushina

The cover images are from the NASA's Apollo 11 mission. We chose them to highlight the 50-th anniversary of Moon landing that was celebrated as we began working on this magazine, and also to mark the first step of The Lithographer. The grayscale versions of these historical photographs were patterned and imaged by the NanoFrazor, a thermal scanning probe lithography tool from Heidelberg Instruments Nano (formerly SwissLitho).

THE LITHOGRAPHER

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Record-breaking 2D transistors

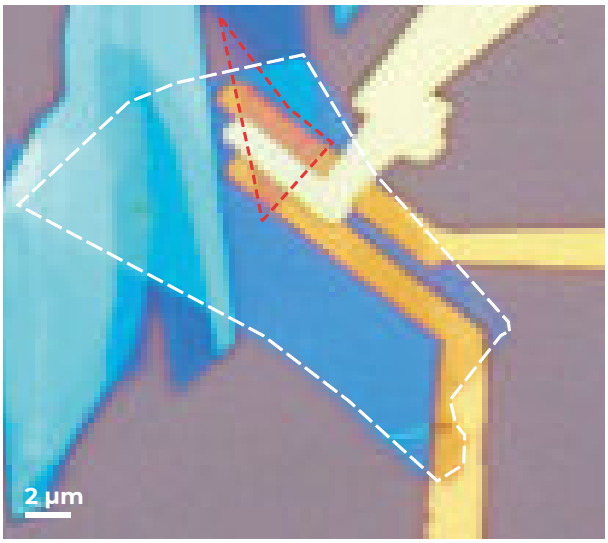
Nanofabrication of high-quality devices on two-dimensional materials is no easy task. A breakthrough result[1] from the group of Elisa Riedo at the NYU demonstrates the success of using thermal scanning probe lithography for sample fabrication. This approach will potentially make it easier to reach the subtle physics that is often masked by imperfect contacts on 2D materials.

A double-gated field-effect transistor on a single-layer MoS_2 flake shows exceptional quality:

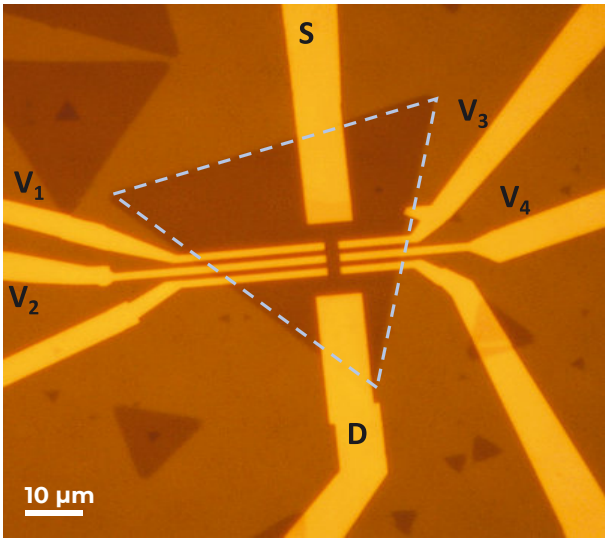
- Linear I-V curves even at low temperatures;
- Record-high on-off ratio of 109-1010;
- Ohmic contacts (vanishingly low Schottky barrier of ~0 mV);
- Very low subthreshold swing of 64 mV/dec.

Researhers have also presented a single-layer WS_2 device fabricated in a similar fashion and showing excellent characteristics.

Such device quality could be obtained thanks to the thermal probe-assisted nanofabrication. Local sublimation of the resist does not leave residues that are often problematic in devices fabricated with e-beam lithography by significantly reducing device performance. Non-invasive character of the patterning method helps to avoid charging of the gate dielectric, since no charged particles are used in the process.



Double-gated field-effect transistor on single-layer MoS_2 (red dashed line) with h-BN (white dashed line) as gate dielectric.



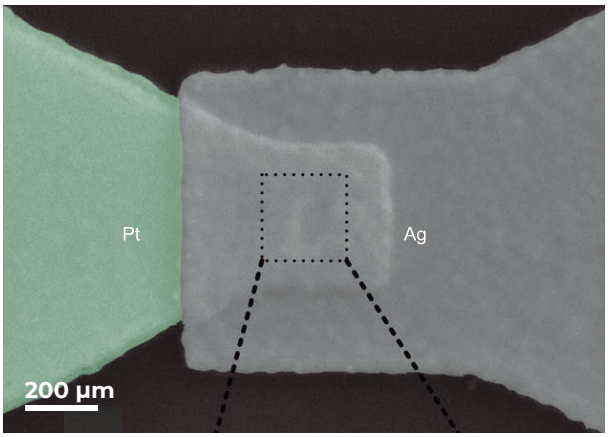
Field-effect transistor with a Hall bar on a single-layer MoS_2.

[1] X. Zheng *et.al.*, Nature Electronics v.2, pp. 17–25 (2019)

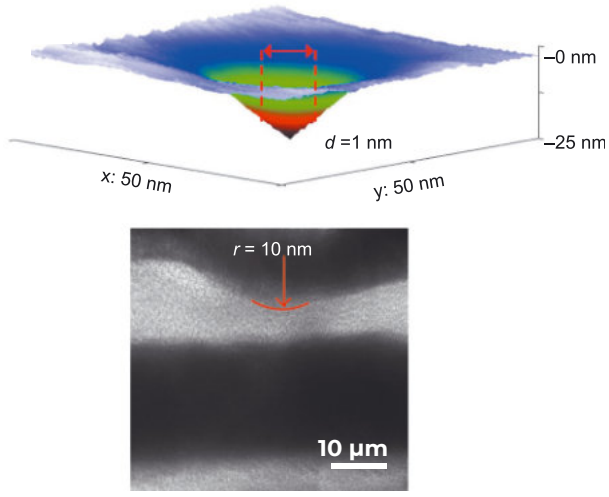
Atomic memristor

Electrochemical metallization cells (EMC), or conductive bridging random access memory (CBRAM), are very promising for non-volatile memory applications. EMCs usually consist of metal-insulator-metal layer stacks, where one metallic layer plays a role of an active electrode, and the other – of the inert one. To switch between different states, the cell electrochemically grows or dissolves a tiny metal filament between the electrodes. An atomic scale EMC[2] demonstrated by Juerg Leuthold's group at ETH Zürich features low switching voltage around 100 mV, operation speed in the nanosecond range, extinction resistance ratio as high as 6×10^5, reliable operation, and the possibility to achieve multi-level behavior.

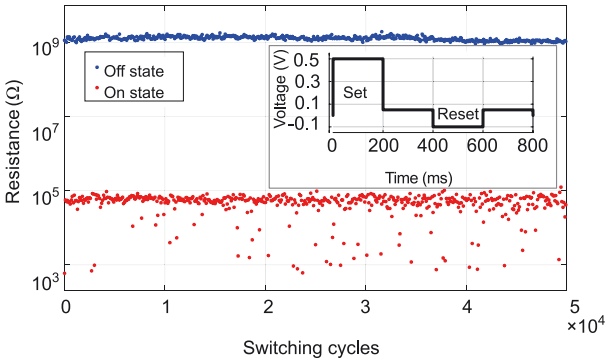
Such impressive performance at the atomic scale is achieved due to the device geometry: one of the electrodes (Pt) is flat, whereas the other one (Ag) is essentially a 3D tip about 10 nm in radius, creating a highly confined electric field in a few nm thick SiO_2 switching matrix. The tip geometry was defined in resist using an ultra-sharp heated tip and then transferred into the SiO_2 by reactive ion etching. The 1-nm distance between the electrodes was precisely defined using atomic-layer deposition. During switching, a few-atoms-long filament forms between the electrodes, acting as a conductive bridge. In such EMCs, filaments almost don't suffer from Joule heating, as they operate near the ballistic limit and most of the power dissipation occurs in the metallic electrodes and not the filament itself. Given the extremely compact footprint of the device, scaling up the amount of such EMCs would enable a very densely packed memory array.



Scanning electron microscope (SEM) image showing the top view of the atomic-scale ECM cell. The dashed area indicates the location of the sharp tip, (area with the darker contrast).



Atomic force microscope (AFM) image of the surface topology and Transmission electron microscope (TEM) image of the device cross-section. The tip radius is 10 nm, marked by the red dashed line.



Resistance of the on- and off-states for 50,000 cycles (only the first resistance in a group of consecutive 100 cycles shown on the plot). The inset: voltage sequence applied to the device.

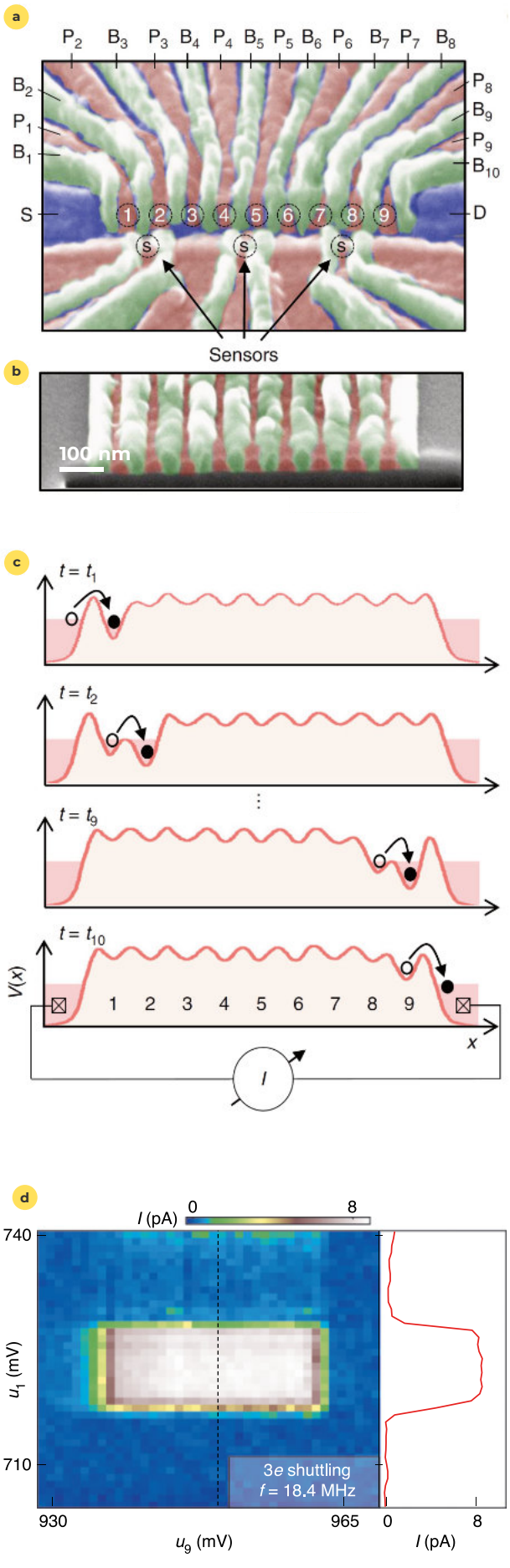
[2] B. Cheng *et.al.*, Communications Physics v. 2, 28 (2019)

"Bucket brigade" shuttle for electrons in a quantum dot array

Quantum dots are one of the promising candidate among various quantum systems that could constitute a quantum computer. Single-spin qubits implemented in a quantum-dot array would be very convenient for quantum operations due to well-defined physical properties. The most important challenges yet to overcome are reproducibility of quantum dot characteristics in an array and the performance robustness that would allow scaling up the system.

The group of Jason Petta from Princeton University has reached an important milestone in the quest for robust single-spin qubits[3]. The researchers shuttled an electron across a 9-quantum-dot array in ca. 50 ns — 3 orders of magnitude faster than the coherence time! — in a series of interdot exchange transfers. Moreover, this "bucket brigade" approach allows parallel high-fidelity shuttling of up to 3 electrons.

The quantum dot array was implemented in enriched Si and is also suitable for other III-V systems (GaAs, InAs, etc). These results overcome the constraint to only nearest-neighbor connectivity between qubits and offer a robust platform for scaling up the quantum dot arrays.



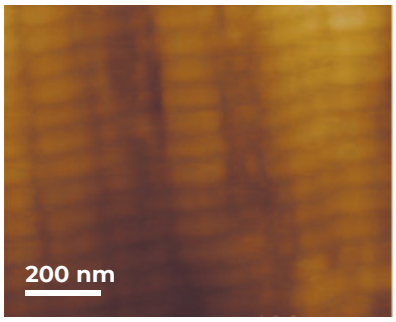
Si charge shuttle. a) False-color SEM image of a 9-quantumdot linear array (see circled numbers) with 3 proximal charge sensors (denoted with a circled 'S'). The potentials of the dots are controlled by the plunger gates (pink) while the tunnel barriers are controlled by the barrier gates (green). The source and drain gate electrodes are shown in blue. b) Tilted-angle cross-sectional SEM image of overlapping Al gates fabricated on a Si substrate. c) Illustration of the charge shuttling sequence showing the quantum dot confinement potential V(x) at 4 different times during the shuttling sequence. d) $I(u_1,u_9)$ during continuous 3-electron charge shuttling. A robust region of pumped current is observed. Right panel: a line-cut shows a stable plateau of pumped current.

[3] A.R. Mills *et.al.*, Nature Communications V. 10, 1063 (2019)

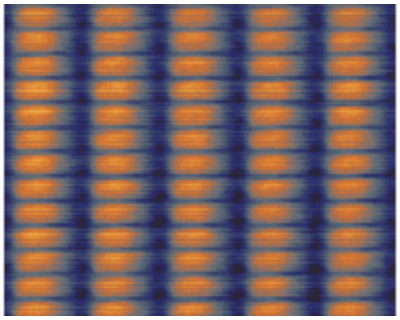
Biocompatible grayscale nanolithography

Can sell-culture substrates be easily patterned to reproduce biological tissues' nanostructures in a biocompatible material? Researchers from the City University of Hong Kong and from Melbourne Centre for Nanofabrication answer both of these questions with an affirmative.

Their pioneering work[4] demonstrates biocompatibility of polyphthalaldehyde (PPA), the workhorse resist for thermal scanning probe lithography: human mesenchymal stem cells adhere, spread and proliferate on the resist. Researchers also directly reproduced the surface topography of a bovine tendon section, producing a substrate on which cells differentiated just like they would on a native tissue. This proof-of-principle work means that tissue engineering research can be done on any desired surface topology with nm-resolution reproduced in PPA resist directly or in PDMS patterned with help of PPA master molds.



Native tissue (AFM)

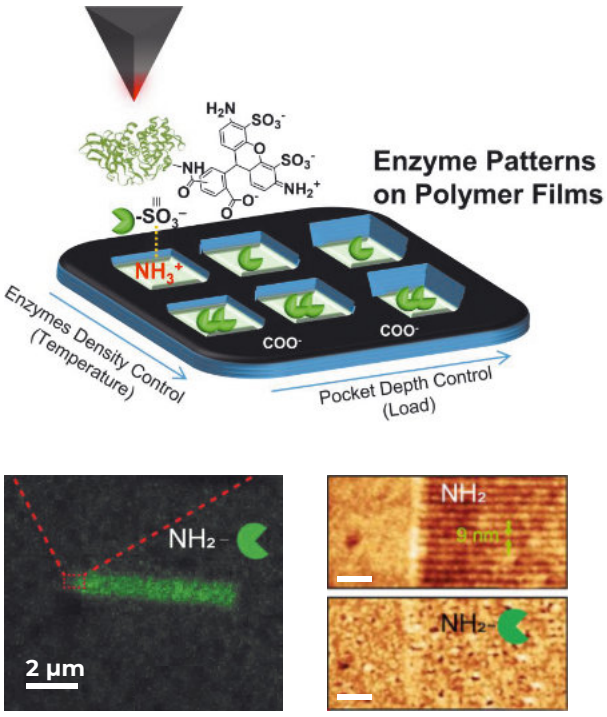


t-SPL pattern

"Reading" the topology of the native Achilles tendon and then reproducing it in PPA using 3D thermal scanning probe lithography.

Single-enzyme patterning

Fabrication of enzyme patterns with sub-10 nm resolution in a single lithography step[5] was shown by Elisa Riedo from NYU Tandon School of Engineering and her colleagues. They used thermal chemical conversion to locally deprotect amine groups along the side-chain of a methacrylate-based copolymer that selectively bind enzymes. This approach produces enzyme nano-gradients and patterns with the single-enzyme resolution. It can be used for single-molecule studies, biosensing and fabrication of bio-nanoreactors.



Top: Basic principle of enzyme patterning by thermal chemical conversion; Bottom: a pattern of enzymes with fluorescent markers, (left), and an AFM image of the area denoted by red dashed line after deprotection and binding (right).

[4] S.W. Tang et.al., ACS Appl. Mater. Interfaces 2019, 11, 21, 18988-18994

[5] X. Liu et.al., ACS Appl. Mater. Interfaces 2019, 11, 44, 41780-41790

The rise of grayscale lithography

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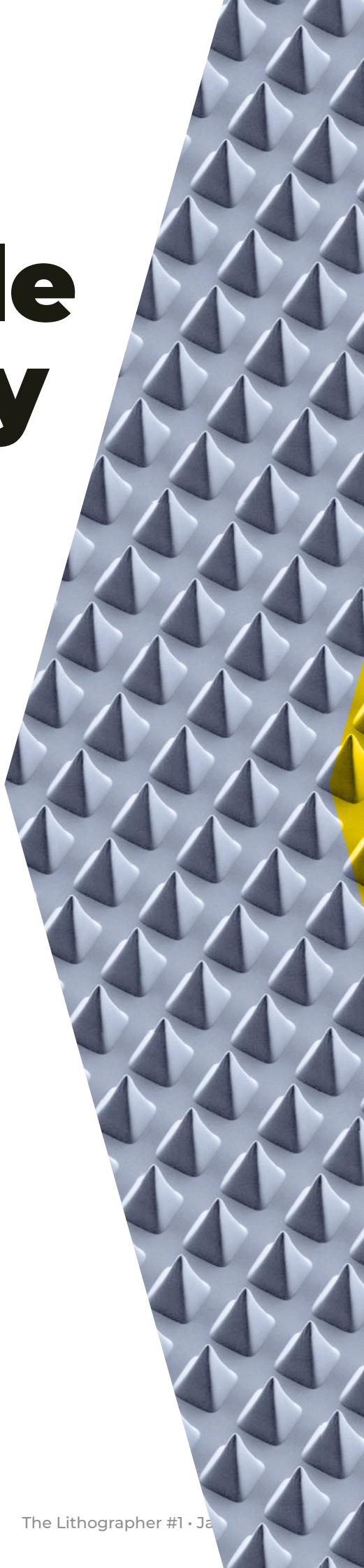
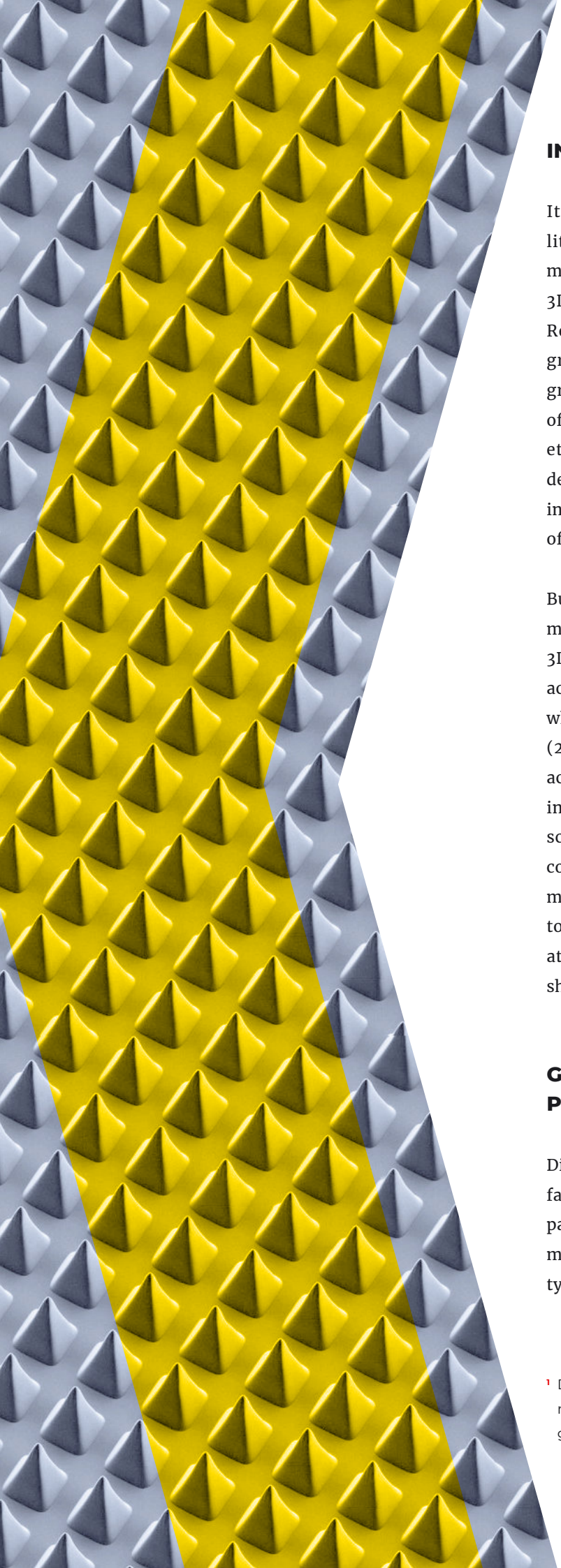
Technoparkstrasse 1, *8050 Zurich, Switzerland*

Grayscale lithography is used to produce three-dimensional (3D) structures on micro- and nanoscale. During the last decade, micro-optics, security features, biotechnology, high-density data storage, etc. created a significant market demand for such structures. Direct-write systems that use lasers and heated scanning probes can be used for high-precision grayscale micro- and nanolithography. Heidelberg Instruments pioneered the development of direct-write optical lithography tools both for research and industrial microfabrication. Now, together with SwissLitho, they also offer tools for thermal scanning probe lithography, enabling 3D nanolithography. At both the micro- and nanoscale, though, some challenges remain, mainly related to throughput. Ongoing R&D efforts and emerging new applications drive Heidelberg Instruments, SwissLitho and GenISys to join forces in order to meet the market demands for grayscale lithography today and in the future.





INTRODUCTION

It is hard to overestimate the importance of 3D lithography for current technology. It is used to make: Micro-lenses arrays for mobile cameras; 3D-patterned sapphire substrates for LEDs; Reflectors & diffraction optical elements; Blazed gratings for waveguides; Fresnel lenses; Holograms; Solar panels, Smart surfaces; IoT (Internet of things); AR/VR glasses; Medical devices; Sensors, etc. All these technologies drive the increasing demand for high-precision 3D micro-manufacturing, and also motivate the intensive R&D in the field of grayscale lithography.

Building up on the progress in semiconductor chip-making, photolithography can be used to create 3D[1] microstructures. The key challenge here is to achieve the desired resist profile with high accuracy while maintaining reasonable throughput. In binary (2D) photolithography, high throughput is usually achieved by using photomasks, which are replicated in the resist by large-area exposure to light. Grayscale photolithography, however, requires very complex masks in order to produce the required dose modulation. Such masks are difficult and expensive to make, and even with the correct mask, the fabrication process is hard to control and is limited in the shapes that it can produce.

GRAYSCALE DIRECT-WRITE PHOTOLITHOGRAPHY

Direct laser writing offers solutions to the obstacles faced in mask-based grayscale lithography. As compared to mask lithography, direct-write approach is more flexible, affordable and suitable for rapid prototyping, especially for complex 3D microstructures.

[1] Depending on conventions, grayscale, or 3D, microstructures are called 2.5D, as the possible pattern geometry is limited by the patterning method.

DWL series from Heidelberg Instruments is particularly well-suited for such tasks. Process and throughput of this technology saw a significant progress, but a few challenges still remain.

Proximity effects arise from the complex non-linear interactions of the resist with the light: Exposure of areas with higher dose lead to unwanted exposure in neighbouring areas. Large patterns and complex geometries require specialized software to account for proximity effects with sufficient accuracy. BEAMER from GenISys with its 3D-PEC module was specifically developed to correct for such proximity effects for e-beam lithography and grayscale photolithography[2].

Stitching errors can occur when moving from one write-field to another during exposure, compromising the quality of the resulting pattern. In case of grayscale lithography, stitching is particularly tricky; even with minimal stitching errors, the resulting pattern can suffer from unintentional additional exposure at the edges. The so-called 'n-over' approach remedies this issue. Original write-fields are substituted by n overlapping write-fields, and the intensity of each field is reduced accordingly. This way, potential errors at the edges are averaged away, and at high enough n (typically n = 4 or higher), no stitching errors can be detected in the resulting structures anymore. An obvious downside of the 'n-over' method is the n-fold sacrifice in throughput.

Resist thickness can also be a limiting factor for grayscale lithography. Binary structures can feature high-aspect ratio elements up to almost 1 mm with perfectly straight walls. At 405 nm – the laser wavelength used in DWL systems – the resist profile can be accurately reproduced only up to around 60 µm. Higher features can be achieved either by pattern amplification (using reactive ion etching, for example) or by using ancillary resist layers and optimization of etch parameters.

Finally, **throughput** is one of the key challenges, especially for industrial microfabrication. To suit the manufacturing processes for large (exceeding 1 m^2) substrates, the direct-write grayscale lithography must scale up. Next-generation grayscale lithography machines could rely on faster light modulators like digital mirror devices (DMD) or grating light valves (GLV) and implement parallel exposure. As of now, replication technologies such as nanoimprint lithography and injection molding are still required for high-throughput manufacturing of 3D microdevices.

DIRECT-WRITE APPROACH IS MORE FLEXIBLE, AFFORDABLE AND SUITABLE FOR RAPID PROTOTYPING

PUSHING THE VERTICAL RESOLUTION TO A SINGLE NANOMETER

3D-nanostructures are increasingly relevant in applications such as computer-generated holograms, 3D multi-mode waveguides and grating couplers, nanofluidic devices, and high-Q-factor

[2] "Experts know-how" on proximity effect corrections for complex grayscale structures using 3D-PEC is on p.36.

optical microcavities. 2-photon lithography can make true 3D structures, but it has very low throughput and its resolution is limited to ca. 100 nm. Nanometer vertical precision can be reached by other nanopatterning techniques: electron beam lithography, focused ion beam milling or focused electron beam induced deposition. However, it is a big challenge due to non-conducting substrates charging, proximity effects and sample contamination. Other limitations are that these methods are slow and costly.

Thermal scanning probe lithography (t-SPL) offers an alternative approach. An ultra-sharp heated probe 'writes' the structure line by line and retraces it in a cold regime like a high-speed AFM, immediately imaging the topography of the just-written pattern. t-SPL routinely achieves lateral resolution below 15 nm (record at 8 nm half-pitch) and vertical resolution of 2 nm[3]. A single tip can pattern more than 1000 fields of 10 × 10 μm^2 with a resulting error of the target depth below 1 nm (1σ) for each of the fields. For comparison, such overall error is close to the best expected roughness of a spin-coated polymer film.

The thermal resist typically used for t-SPL, polyphthalaldehyde (PPA), decomposes through an endothermic reaction. This process is highly localized, so no proximity effects are observed. Furthermore, since no charged particles are used, the substrate is not damaged or charged. Moreover, t-SPL is less expensive than other nanopatterning methods, mainly because it does not require any vacuum, special shielding, or high-voltage electron optics.

T-SPL ROUTINELY ACHIEVES LATERAL RESOLUTION BELOW 15 NM AND VERTICAL RESOLUTION OF 2 NM

WITH HIGH RESOLUTION COMES HIGH SCALABILITY?

The use of t-SPL is not confined to academic research. The 3D nanostructures produced by the t-SPL can be precisely replicated by pattern transfer from PPA resist into soft nanoimprint stamps or molded into a UV nanoimprint resist. Also, PPA resist with a 3D-nanoscale pattern can be electroplated with Ni. The resulting Ni shim can then be used to replicate 3D-nanostructures into PMMA by means of vario-thermal injection molding.[3]

Commercial tools for t-SPL are developed by SwissLitho AG (now known as Heidelberg Instruments Nano) under the name NanoFrazor. Currently, the NanoFrazor systems can only pattern using a single tip. There are a few ways to achieve larger throughput. MultiTip systems are already in development, targeting coverage of cm^2 areas without compromising the resolution. Mix&match with other techniques like laser lithography has been implemented as a Direct Laser Sublimation module for the NanoFrazor Explore, and it significantly increases the throughput when the pattern consists both of nano- and microstructures.

[3] "Experts know-how" on 3D nanopatterning with t-SPL is on p. 46.

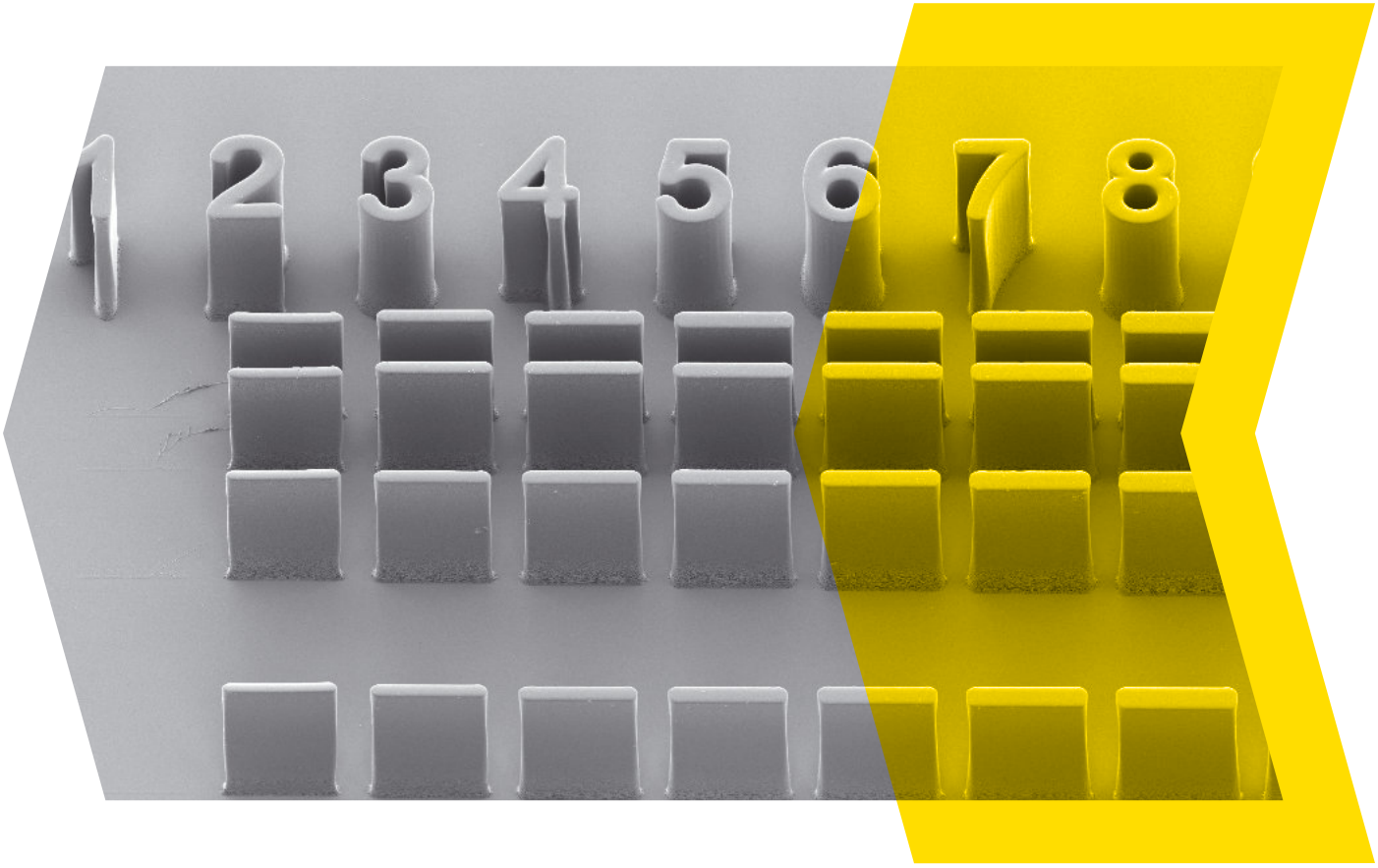
Maskless Aligners for industry

Steffen Diez, a recently appointed COO of Heidelberg Instruments, has seen the Maskless Aligners series from the initial idea conception to successful commercial release of 3 tools in the series: MLA150 optimized for R&D, table-top version (µMLA) and the recently launched industrial machine MLA 300.

Steffen, thank you for finding the time to talk about the MLA series. And congratulations for the launch of the MLA300 and your new role in the company! By the way, how did you begin at Heidelberg Instruments?

Thanks a lot. I started at Heidelberg Instruments in 2000 as a software engineer. We were only around 30 people at that time and the business was just starting to pick up. Over the years, I had the chance to look into almost every part of our company. I worked in Research and Development (R&D), led several projects, did benchmarking and customer demonstrations, and then switched to Technical Sales and Product Management. In 2012, after one-year stay in Japan, I was invited to join the Technical Board, a group of experts managing all technical aspects of our company. This was when we decided to develop the first Maskless Aligner (MLA150). A few years later, in 2017, I joined the executive team of Heidelberg Instru-

“MLA300 IS THE MOST ADVANCED TOOL WE HAVE EVER BUILT AND THE ONLY PRODUCTION-READY DIRECT-WRITE SOLUTION FOR INDUSTRIAL MICROFABRICATION”



ments together with Martin Wijnaendts and Konrad Roessler. After a recent Heidelberg Instruments restructuring, I am now the Chief of Operations.

So, why a Maskless Aligner?

We actually hit upon this idea during a customer visit in a multi-user cleanroom which housed one of our DWL 66 systems (a powerful direct-write lithography tool). That DWL was used to produce masks for several mask aligners in the same cleanroom, some of them already quite old. We thought that replacing the Mask Aligner by a maskless tool for R&D applications could be a good opportunity for us.

Even before we introduced the Maskless Aligner, direct writing was already a well-known technology in R&D. µPG 101 (our table-top direct writing tool) and the DWL 66 were installed in many facilities, but most of the time they were employed for producing photomasks instead of writing directly on wafers. And indeed, at that time our systems were optimized for photomask fabrication rather than for direct patterning of various substrates and photoresists. Even more critically, the exposure times were long as compared to a mask aligner. That was one of the biggest challenges we had to overcome with the MLA.

Tell us more about the development of the system. Which challenges did you face?

To develop the MLA technology, we used new MEMS-based optical modulators that just became available, and solid-state light sources to build new high-speed optical engines. This combination formed the core of the MLA and allowed us to significantly speed up the exposure. Apart from the exposure time, we also wanted to reduce the entire process runtime. Another important challenge we wanted to address is to improve usability and decrease user training time as much as possible: in facilities, where many users operate the tools, this is crucial. Taking all those requirements into account we set three main targets:

- Exposure time under 10 minutes for a 4″ wafer;
- Complete runtime including substrate loading and alignment under 30 minutes for a 4″ wafer;
- Training time of less than 1 hour to fully qualify as a user for system operation.

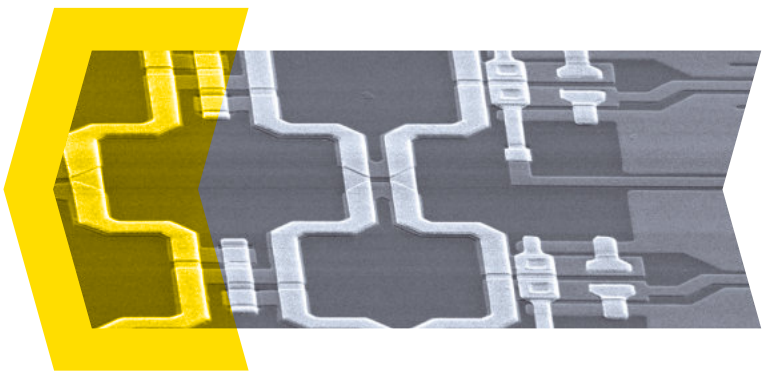
MLA owes its success to the clear vision of what we wanted to achieve and an outstanding, motivated development team. Based on the overall concept, the team implemented many ideas which transformed the vision into an exceptional tool, the MLA150.

What is so special about the MLA tools?
They were and still are the first and only tools which have become a real alternative for mask aligners in an R&D environment: They offer extremely high exposure speed; front- and backside-alignment; warpage compensation; high resolution and high accuracy; and the ability to expose on any substrate sizes from few-mm wafer pieces up to full 8" wafers.

When did you introduce the first system? Did you collaborate with any potential users to develop and test the tool?
The MLA150 was officially introduced with a big marketing campaign in May, 2015. After we developed the first working prototype, we decided to work together with a few selected users to evaluate and refine the tool. Main focus besides stability and bug-fixing was to optimize the usability of the system.

The first beta-site was established at the CMi (Center for MicroNanoTechnology at EPFL in Lausanne). This facility was already our long-term customer and it has an outstanding reputation. Philippe Fluckiger, the head of CMi, didn't hesitate to enter a collaboration after the concept of the MLA had been presented to him. The CMi team helped us a lot to optimize the user interface and eliminated most of the critical bugs. The second beta-site was in the group of Andreas Fleischmann and Sebastian Kempf from the Kirchhoff Institute of Physics in Heidelberg. They are world leaders in the research on SQUIDS, superconducting quantum interference devices that are used as low-temperature magnetic field sensors. Here, we focused on transferring multi-layer processes from their old mask aligner to our MLA. These applications have very demanding requirements for overlay accuracy, and we had to enhance the performance of our tool in many aspects even further to match the required specification. This was a very

MLA150 IS THE FIRST AND ONLY TOOL WHICH HAS BECOME A REAL ALTERNATIVE TO A MASK ALIGNER IN AN R&D ENVIRONMENT



An array of SQUIDs (superconducting quantum interference device) used for the readout of metallic magnetic microcalorimeters. These large arrays comprise up to 18 layers and submicron features. Image courtesy of the Kirchhoff Institute for Physics, Heidelberg University.

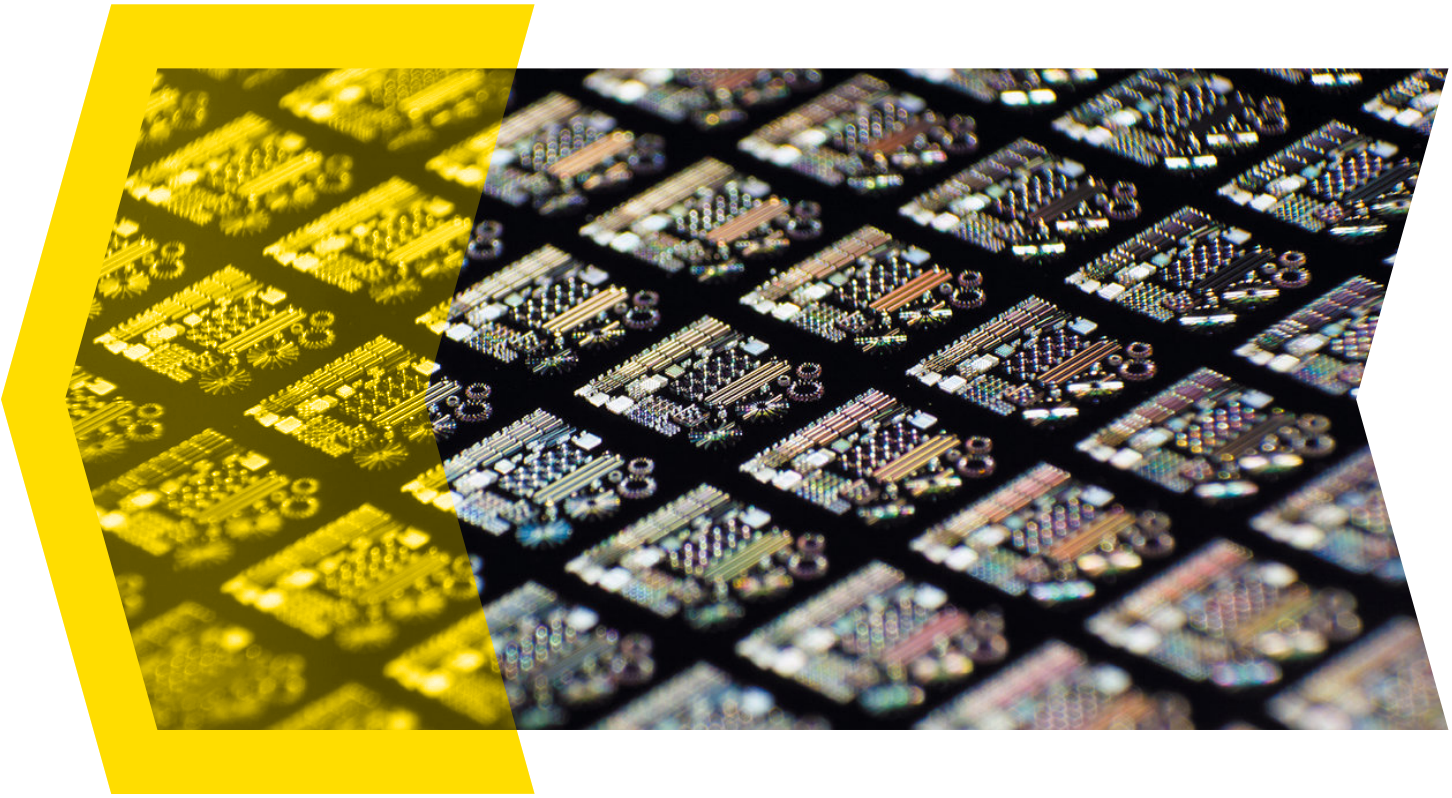
successful beta-site testing – we were even able to increase the yield for these particular sensors by a factor of three. Harvard/CNS served as the final beta-site. Jiangdong Deng, the CNS Lab Manager, has also already worked with us previously. I really appreciate the fruitful collaboration between the beta-site users and our R&D team. Almost all requests from users were efficiently implemented. Finally, all collaboration partners purchased the tool after the beta-site period ended: A clear sign that the MLA has become a mature product.

THE TOOL SPEAKS FOR ITSELF

Was MLA150 commercially successful?

In the beginning, it was not so easy to convince the customers that the MLA was a real alternative to mask aligners. Long-time users of traditional lithography hesitated — understandably so. Many times, we heard that mask aligners expose much faster. We insisted that the overall cycle time is a more important parameter, and this time is much shorter with the MLA compared to a mask aligner, especially taking into account the mask fabrication time (needed for the mask aligner). But the tool speaks for itself, and soon MLA150 gained a very good reputation, and the news spread. The R&D community in the USA has accepted MLA150 very fast, and eventually we saw more and more interest in Europe as well. Over the time, we implemented quite some extra features following our customers' requests.

MLA is attracting increasingly more attention from industrial companies as well. Most of them have special requirements which cannot be fulfilled by mask-based technologies, some just produce low volumes, others benefit from the low running costs of the maskless technology.



Did this interest motivate the development of the industrial MLA?

We planned to develop an industrial version of a maskless aligner back when we began working on the MLA concept. Due to limited R&D resources, we prioritized the work on the MLA150. This turned out to be a good choice, because we could fully develop the core technology and learn from our industrial MLA150 users what the tool really needed to improve in order to fulfil their requirements. The MLA150 is optimized for R&D: The software is designed for handling small lots and for easy tracking of project status, not for high-volume production. The exposure time is excellent for research applications, but it is not fast enough for commercial production. There was no automation, either.

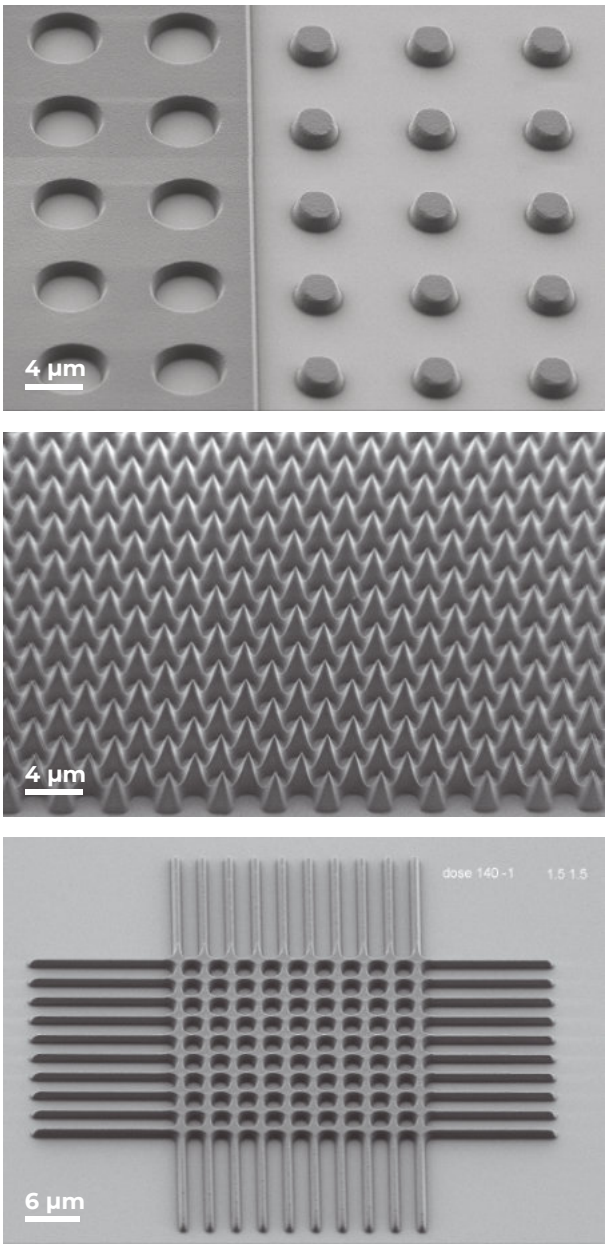
MLA300 is a completely new machine, so we could meet all the needs of our industrial customers, which extended far beyond just higher throughput:

- A massively increased throughput as compared to the MLA150;
- The MLA300 can be fully automated, including substrate handling and loading, and interfacing to manufacturing execution systems (MES);
- It is a fully integrated and modular machine with a minimal, yet flexible footprint. This concept simplifies service and allows a fast "plug and play" installation;
- The software interface and usability concept were developed with the help and feedback from a customer, this time from industry.

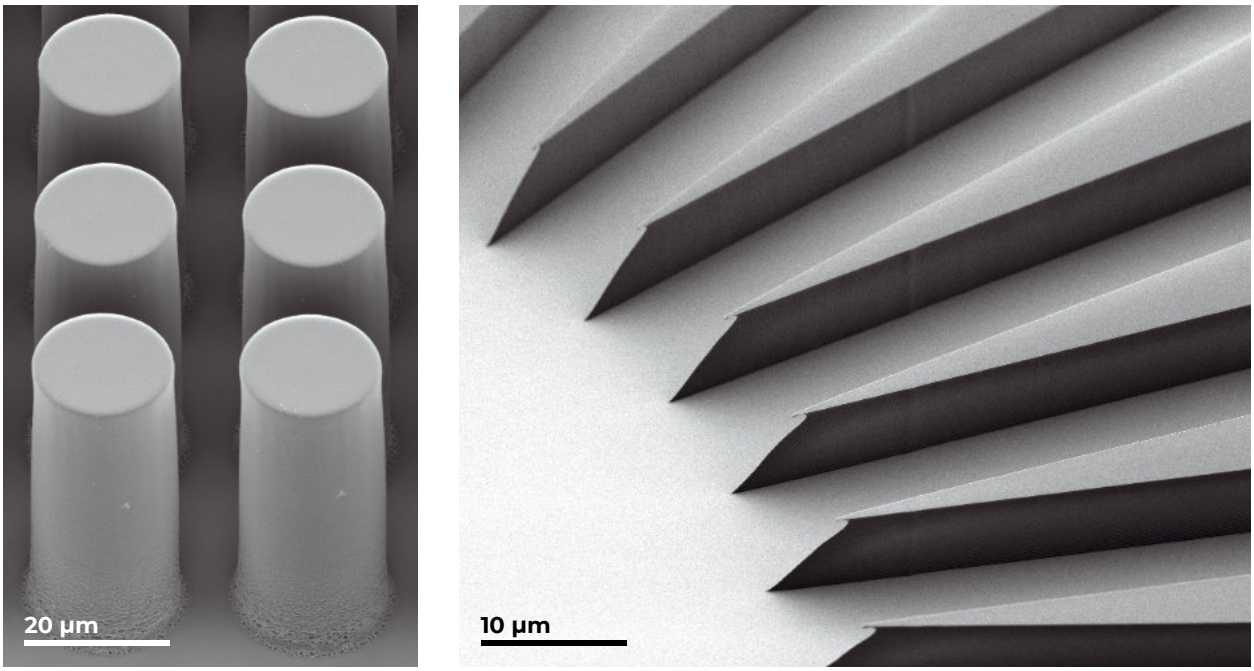
Our R&D team really pushed the limits of direct-write lithography. We are very proud of the MLA300. It is the most advanced tool we have ever built. It is unique in many ways, and it is also the only production-ready solution for industrial micro-fabrication currently available in the market.

What were the key design challenges?

After some calculations, we realized that we couldn't achieve the required speed with only one optical engine. So we embarked on one of our most demanding R&D projects ever: The development of a fully integrated optic module. Our optical designers and construction engineers created an opto-mechanical masterpiece. The MLA300 system is designed for the integration of up to four optic modules. It is even possible to integrate modules with different wavelengths or different resolutions. That means you can customize the MLA300 according to the specific application requirements in terms of resolution, write-speed and substrate handling.



SEM images of different structures written using MLA technology. Images courtesy of CMi (EPFL Center of MicroNanoTechnology)



SEM images of micropillars array and tapered structures patterned using MLA. Image courtesy: CMi (EPFL Center of MicroNanoTechnology)

What kind of applications can it be used for?
At the moment, we focus on applications where maskless lithography has a significant advantage, for example, warped substrates. Such deformations commonly occur in applications which use a stack of materials with different thermal expansion. The warpage can measure up to 300 µm. Our system is able to compensate warpage with the real-time autofocus system. Other niche applications demand a flexible adaption of the pattern, a requirement which is efficiently met by the MLA300 system. We aim to ultimately place the system in high-volume applications such as wafer-level packaging, MEMS fabrication, or LED production.

One of our customers has already begun using the MLA300 in a pre-production environment. We are now integrating the tool into their production line to make it their standard exposure machine.

Since the official launch of the MLA300 in November 2019, we have already received multiple orders for the system. The fast order intake confirms that the flexibility and superior exposure quality on challenging substrates is a large unmet need for industrial production customers.

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The power of direct writing

- Unmatched flexibility: Dynamic adjustments and compensations possible without delay.
- No mask procurement, handling, and storage expenses, no mask degradation.
- Unmatched uniformity and yield: Real-time autofocus follows substrate warp and corrugations.
- Our fastest Maskless Aligner with 1.5 µm min feature size:
  2.6 min for 100 x 100 mm,
  18 min for 300 x 300 mm.
- Low cost of ownership:
  No consumables and long-lifetime laser.
- Full automation ofloading, alignment and exposure

MLA300

Brings flexibility of maskless lithography to the production line

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Rocking Brownian motors go viral

Armin Knoll from IBM Zürich is working on rocking Brownian motors — nanofluidic cells with nanoscale ratchet-like surface structures. These devices can sort nanoparticles with down to 1 nm difference in radius, and are very promising for diagnostics and protein purification. Dr Knoll told The Lithographer about these nanofluidic devices and their future applications.

Hi Armin, thanks for finding time for an interview. First of all: what are rocking Brownian motors, and why are they called like that?

Let's begin with a Brownian motor definition. It was discovered in the 90's that biology uses so-called molecular motors to transport molecules in cells, for example to do cell division, to actuate muscles, and so on. When people studied the basic principles of molecular motors they also began trying to build artificial machines based on the same principles to do similar things — transport particles or other cargo along a guiding track. This is when the term Brownian motor was coined by Peter Hänggi, a Swiss physicist. Brownian motors are called so after Lord Brown who

discovered Brownian motion in 1827 — the thermal motion of particles in liquids. Temperature activates the movement of all molecules in the liquid, so what you actually see when these particles are moving around is the result of water molecules randomly bouncing off them. The energy input that makes them jiggle around is what you want to exploit in a Brownian motor, *i.e.* a device that uses Brownian energy to transport the particles inside the nanofluidic cell. On top of that, we have to do two things: create an energy landscape inside the Brownian motor and bring the system out of equilibrium. The Brownian motion enhances the properties of the motor.

Why is it rocking?

For a Brownian motor in a nanofluidic cell, we need to create an asymmetric energy landscape for the particles, sawtooth-like, for example. One way to make such a system is to switch the energy landscape on and off. When it's switched on, the particles will be drawn to the lowest point of the energy landscape, and when it is off, they will diffuse in all directions. When the potential is applied again, some particles will have moved closer towards the next minimum, so — because the energy landscape is asymmetric — in average you get transport of the particles. This implementation is called flashing Brownian motors.

Our implementation of a Brownian motor is different. We don't switch the landscape on and off but rather keep it static. Instead, we apply a zero-mean external force. It is applied in forward direction with the same magnitude and duration as in the backwards direction, so the force cancels to zero for the particles. It is the asymmetric potential that rectifies the motion of the particles, so they only go in the forward direction. And that is why they are called rocking: we rock the potential back and forth. The particles feel the applied force as a potential with a linear slope, which means that you tilt the potential to one side and then to the other side, and so on. That's where the name comes from.

What can such devices be used for?

First of all, Brownian motors transport the particles through liquids, and that's what they are used for in biology, too. The only prerequisite in our case is that the particles need to be charged. And if that is fulfilled the Brownian motor works with DNA, with proteins, gold nanoparticles, viruses — all this stuff can be transported.

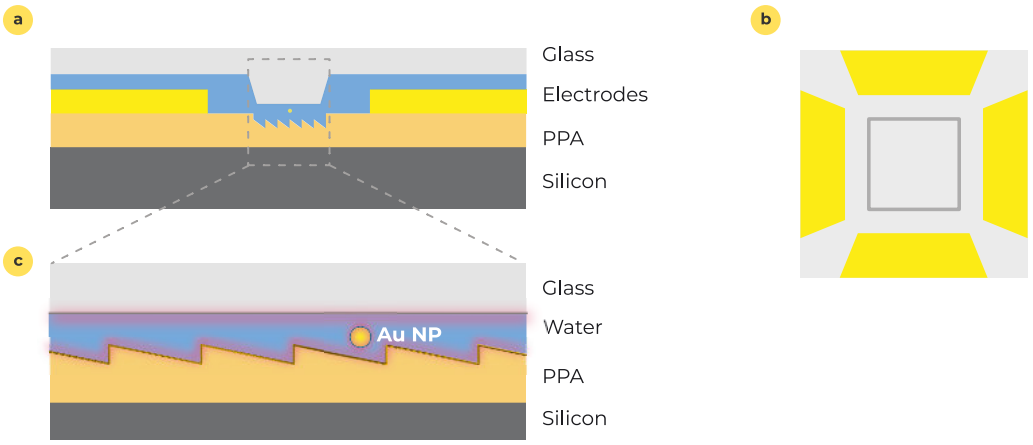
So the shape of the particles doesn't matter?

The size of the object needs to be smaller than the length of our sawtooth unit. Around half the size is a good number. Transporting large DNA molecules would be a problem, you would have to make really large ratchets. Small DNA molecules can be transported directly, but if DNA spans several teeth of the motor, it would get stuck.

IF YOU ARE REALLY ABLE TO MANIPULATE THE ENERGY LANDSCAPE YOU CAN MANIPULATE THE BEHAVIOUR OF THE PARTICLE

How did the idea of particle transport in liquid lead to sorting?

In 2010, we already had this nanofluidic project running, and since we have the capability to write very high-precision patterns, we were looking for applications. A paper from Madhavi Krishnan appeared more



Nanofluidic Brownian motor setup: a Schematic cross-section and top view of the nanofluidic slit. b The top view (not to scale) depicts the electrodes (yellow, spaced by ~1.2 mm) and the pillar in the center (width ~100 mm). c The ratchet topography in polyphthalaldehyde and the 60-nm gold nanoparticle, drawn to scale. The particle experiences a ratchet-shaped energy landscape due to the ion-cloud interactions (orange) between like-charged surfaces. The gap distance is d = 150 ± 1 nm.[1]

or less at the same time, where she showed that the geometrical recess of a surface can produce an energy landscape, at least a potential minimum. So, we thought it would be a nice fit to combine single-digit nanometer precision and the ability to generate potential energy landscapes. Energy always controls the behaviour of particles, and if you are really able to manipulate the energy landscape you can manipulate the behaviour of the particle.

A nice thing about lithography is that you really control all the energy barriers because you write them. When you know the energy barriers, you know the timing in the system, you can tune it from the top down. For Brownian motors, in our implementation at least, the particle transport strongly depends on the size of the particle because a bigger particle feels an amplified energy landscape. So, a larger particle rests closer to the interfaces of the nanofluidic channel, and therefore, the interaction energy amplifies exponentially. The energy landscape needs to be stronger than the thermal fluctuations, which is at least 3–4 k_BT. But you don't want it to be at 20-30 k_BT, because then you don't have sufficient force to tilt the energy landscape anymore. At around 5-10 k_BT, the transport works nicely. And now, if there are different-sized particles, the smaller ones might not see enough of the energy landscape, so they will not be transported, and the ones that are too big will get stuck. But there is a size range in which the particles will be nicely transported. When we built our motor it was clear that this would happen. Then, we designed a slightly more complicated device optimized to achieve very high efficiency in separating particles[1].

In one of your papers, you say that the theoretical limit of the size separation of the particles is 1 nm, in radius. Do you think you can achieve it? Actually, if you look at it theoretically, it can be even finer. But due to fabrication constraints set by the tools we have at our disposal you cannot be more precise than about 1 nm, so this is in the end where this limitation comes from. But also the physics "stops" at around this point. Even if you had a perfect device, sorting particles by 1 Angstrom would be very tough.

[1] Skaug et al., Science 359, 1505–1508 (2018)

Have you actually built such a system yet?
We are currently working on that. We have a few demonstrations now. They don't reach 1 nm yet but they are on the order of a few nanometers, and we should get down to 2 nm at least.

How do you engineer the energy landscape?
A basic motor geometry is very trivial, you just need a saw-tooth topography with linear profiles. We pattern them on the bottom of the nanofluidic cell, and the topography exponentially translates into the energy landscape. Actually, the resulting energy landscape is exponential, but this effect is not very strong. Ideally, the sawtooth slopes should be logarithmic to create linearly rising energy landscapes, but it doesn't make a big difference.

And what are the dimensions?
The dimensions depend on the concentration of salts in your solution. The more salt you have the lower will be the range of the interaction between particles and walls. We typically work with salt concentrations in the millimolar range, which gives you a size range of about 10 nm, and the tooth height should be on the order of a few times more, so we usually work with 20–30 nm high "teeth". It is important to explore the entire energy range. If a particle is too far from the surface it no longer "feels" its effect, so the energy will be flat. If the particle is close to the surface, however, then you see the right energy landscape, about 10 k_BT or so. So, we have to make sure we don't recess the topography too much.

How sensitive is the energy landscape to the precise topography?
During the motor operation 30 nm high topography features result in 10 k_BT energy landscape. Therefore, 1 nm of topography corresponds to approximately 0.3 k_BT. So, an error of 1 nm in your device produces 0.3 k_BT error in the energy landscape, which is acceptable because it's less than k_BT.

1-nm accuracy in the structure height is not trivial to achieve. How do you do it?
We use thermal scanning probe lithography (t-SPL), or NanoFrazor technology, and polyphthalaldehyde, the typical polymer resist for t-SPL, to write these landscapes. It is a well-established process for us. There are some tricks we have to use, of course. For example, when you put a piece of silicon with the polymer on top in water, the polymer floats off. We control the silicon-polymer interface by adding a cross-linked polymer in between. The cross-linked polymer attaches very firmly to the substrate, and the interface between our resist and the cross-linked polymer is very stable because both are hydrophobic. We can also use other methods to stabilize the stack, such as removing the oxide by HF treatment from the Si interface, or silanisation of the surface. But, typically, we work with crosslinking.

You also made a few videos of particles being sorted. It is fascinating that one actually see it! How do you detect what happens in the cell?
It was quite a tricky setup to build. Luckily, we could use the knowledge of other people to make it work. The two slides forming the nanofluidic cell are contacted by electrodes to apply the potential. We shine a laser onto

the system and record the interference of the light scattered by the particles and the substrate. In this way, we can detect very small particles with high frame rates of up to 1000 frames per second. Currently, the optical setup is quite large and complex but it could be reduced to a size of a small box with very simple parts.

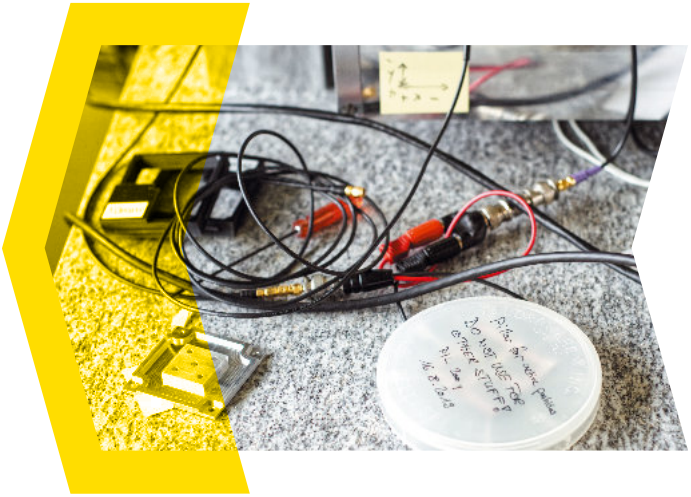
What are the current bottlenecks and the goals of this project?

We demonstrated that we can separate particles with a device just a few tens of microns in size, achieving a complete separation of populations within seconds. Then, we extrapolated which kind of devices we could make, which would be relevant for real-world applications. One could build devices that continuously separate the particles, for example. There would be input and output channels, and the output channels would deliver different particle sizes. Unfortunately, the throughput of such a device would not be very high. In order to get quantitative amounts of liquids, a lot of devices need to be stacked together, which is very complicated to manufacture.

A simple device, on the other hand, can already handle the detection of nanoparticles in liquids. Our target at the moment is to detect small viruses in water. We think that we can build a device that can detect attomolar concentrations of viruses within 1 hour. And that is interesting for surveillance of water samples: to check if they contain viruses. Since we can transport the viruses, we can also trap them locally so they cannot escape. We simply write a deep pocket and then they are trapped there. Then, it is easy to detect these viruses even without special markers on them. This way, we can realize markerless virus detection. And this would be a device that cannot be made/built with any other technology at the moment.

How expensive would it be?

If we make the devices as we do them now it would be quite expensive. But, in principle, the system is based just on a topography on a polymer surface so you could use nanoimprint lithography to replicate the devices. We will even try injection moulding. That would be really cheap. If we could make the devices by injection molding it would open a large use space. But we have to find out how to do it first.



Are you developing a high-throughput manufacturing method for such devices?

To replicate and scale up the devices? Of course. Thermal probe lithography can address small areas, and in order to manufacture for the big market we should find a way to replicate the nanostructures. This is a general problem – not just of our devices but of the nanolithography techniques that operate on small areas in general. Parallelized t-SPL wouldn't solve the problem with the throughput either. Engineering-wise, implementing a large number of cantilevers is a big effort. This approach will never reach the prices and costs of the cheap techniques: if injection molding works, you can never beat this price, there is no chance.

What are the other challenges of the project?

We would like to achieve particle sorting in bodily fluids. It would be extremely helpful for the doctors and the patients if our devices could detect viruses in bodily fluids like blood or sweat within a short time frame at attomolar concentrations. Then, it would be possible to immediately determine if there is a viral infection. However, the salt concentration is too high, so we would have to dilute the blood before we can test it. The other complication is that bodily fluids are very complex systems. They contain a wide range of different molecules and particles, and we are not sure how the motor will function in such conditions. We will have to find out how good our motors are at rejecting

these other things. In principle, as I said, the transport only works for certain object sizes (within a certain object size range), so it should be more or less robust. But if things start to attach and coat the surface, blocking becomes a problem. For this kind of applications there is still a long way to go.

Would it also be of interest for pharma industry to separate very small molecules and proteins, since it is not possible to separate nanoparticles scale by size?

After my presentations people often approach me with questions about separating proteins, for example. We plan to go in this direction soon. But at the moment, it is not completely clear how it is going to work. We would also need to work at reduced salt concentrations, which means the proteins would not be in their native environment. But, in some cases, it is not a problem, so people are interested in this approach. They want to purify and crystallize the proteins in order to study their structure. It would be a very nice use case for us if we were able to get quantitative information on the number of proteins separated from the residues and to extract them into a separate container.

A recent paper from your group shows reversal of the particle current direction[2]. Could you please tell a little bit about that?

The reversal of the transport direction in a motor is something that has been known for a long time, but nobody has done it for overdamped systems. Particles in fluids are heavily overdamped; if you would apply a force to a particle it would stop within less than a nanometer or so. It was not clear if the particle reversal would happen in such a system. It was predicted theoretically, and we thought we'd check our system, and indeed this current reversal happened at higher frequency. It has to do with how fast particles move in a potential. If you apply the force for too short a duration, so they cannot reach the next element, then they never jump forward but there is still a low probability for them to jump over the potential barrier in the back-

[2] C. Schwemmer et.al., Phys. Rev. Lett. 121, 104102 (2018)

[3] S. Fringes et.al., Nano Letters (2019) https://doi.org/10.1021/acs.nanolett.9b03687

ward direction. At some point, this probability is higher, and you get transport in the other direction.

The reversed particle current must be slower. Indeed, it is a factor of 30 slower than the current in forward direction. But, in principle, it could also be interesting for separation and sorting because it is also frequency and size dependent.

Do you have other applications in mind?
At the moment, we are focused on controlling the nanoparticles in nanofluidic cells because we think we have established something new, and we want to see what kind of applications we can get out of that. But we want to go beyond use for mere transport since we can also trap the particles, transport them to a compartment or specific locations[3], and increase their concentration for analysis or detection.

For virus detection, size separation is interesting because each virus family has its distinct and rather monodisperse size. So, knowing the size already gives you a hint about what kind of virus is there, and then you can still do DNA or RNA identification to really find out which specific virus from this family you have. But you would know if you have a family that might be dangerous. At the moment, the detection of viruses is based mostly on PCR[4], amplified DNA and RNA of viruses, so you always need to know what kind of virus you are dealing with. Otherwise, you have to do metagenomics — sequence all the DNA in the sample and then analyse it using bioinformatics tools. Currently, there's no method to operate directly.

So, here everything comes together: transport, size sorting and accumulation in a separate zone for detection. We are trying to establish a toolbox that we can operate with different nanofluidic systems and complement it with other things, for example, electric gates for steering transport, switching it on and off, and things like that. This is the main thrust of our work.

WE CAN SEPARATE PARTICLES WITH A DEVICE JUST A FEW TENS OF MICRONS IN SIZE, ACHIEVING A COMPLETE SEPARATION OF POPULATIONS WITHIN SECONDS

What is the outlook for this project?
We want to explore the limits in terms of particle size for interesting molecules like proteins. We also want to demonstrate that such devices can work with very small concentrations and still be able to detect the particles.

This small world seems to be largely unexplored. The field of metagenomics appeared 10–20 years ago. For example, in one study, people analysed 200 litres of sea water. They filtered and then sequenced it. And they found more than 5000 different viruses. More than 99% of them were not known at the time. There seems to be so much going on at this scale!

[4] Polymerase chain reaction (PCR) is used to copy a specific DNA segment billions of times in vitro. PCR is used to diagnose deseases, identify pathogens or match criminals to crime scenes.

Imaging beyond the limits

Many labs around the world are studying light-matter interaction at the nanoscale. The work of Rajesh Menon, an expert in micro/nanofabrication and photonics, and a Professor at the University of Utah, stands out for its scope and creativity. His team pushes photolithography and imaging beyond the diffraction limit, developing optical elements for photovoltaic systems and algorithms for computational imaging. Professor Menon has kindly agreed to tell us more about his research.

First of all, thanks for finding time for the interview. I hope I have described your research scope correctly. Would you like to highlight anything further?

Thank you for the interest. We are a team of scientists and engineers, who work on approximately 3 areas: Nanophotonics, Nanofabrication and Computational Imaging. Our goal is to combine these areas to enable applications that are not otherwise possible. To give you an example, we have recently shown that a single nanofabricated flat lens can be achromatic over a very large operating bandwidth (from the visible to the long-wave Infrared)[1], something which was generally thought to be impossible!

[1] P. Wang, N. Mohammad & R. Menon, Scientific Reports v. 6, Art.n. 21545 (2016)

That is really impressive! And how does the computational imaging come into play here?
Computational Imaging is very important now that we appreciate imaging as a form of information transfer. Another way to look at it; conventional cameras are anthropomorphic, but information doesn't have to be. This opens up enormous design spaces for new "non-human" cameras. For example, such cameras could be used where the hardware/software design implicitly includes privacy (like in the case of facial recognition) and no human may be in the data loop.

How did you arrive at this specific research area?
Most research projects arise from either solving problems that we face within existing projects, or while meeting with scientists from different areas, or simply from curiosity. For example, back in 2003, I had lunch with Stefan Hell (the 2014 Nobel Laureate in Chemistry), who was then discussing his technology on super-resolution optical microscopy. As a young scientist, I was inspired to take his ideas and apply them to optical lithography, which led me down a more than a 10-year productive research journey. At some other point, I was curious to see what a camera could "see" if we removed the lens from an image sensor. At that time, I was learning about the information theory of imaging. A very sharp undergraduate student took this project up over a summer and made very clever experiments to show that indeed imaging could be achieved.[2]

Speaking of students, how is your team organized? Where are your former students now, do you work with any of them?
We are a fairly decentralized and non-hierarchical team of scientists and engineers. The team workflow is more organic than strict, and it changes based on the problems that we are trying to solve. I should point out that we are heavy users of remote collaboration tools, such as Slack, Zoom, etc. We collaborate widely across disciplines (Computer Science, Math, Physics, Biology, Neuroscience, Materials Science, Chemistry, etc.) and also across the planet, as one person can't have sufficient expertise to tackle all these knowledge areas. The most fruitful collaborations happen when there are mutually aligned interests, naturally. Most of my former students are working in industry (including companies like Intel, Apple, Micron, etc.) and a few are in government or academia. I currently collaborate with two of them on projects in the field of micro- and nanophotonics.

I WAS CURIOUS TO SEE WHAT A CAMERA COULD "SEE" IF WE REMOVED THE LENS FROM AN IMAGE SENSOR

Your publications suggest a long history of maskless and sub-diffraction limit optical lithography. So here is a chicken-and-egg question: do microfabrication capabilities give you ideas for what kind of devices to make, or do

[2] G.Kim and R. Menon, Optics Express 26, 22826-22836 (2018)

you do have an idea for a device first, and find the way to make it with the tools at hand?

As a student, I was building the nanofabrication tools, and at that time applications were chosen to showcase the capabilities of the tools. Nowadays, this has flipped to some extent, so the device requirements come first. Part of the reason is that we have such a large palette of tools to choose from, of course.

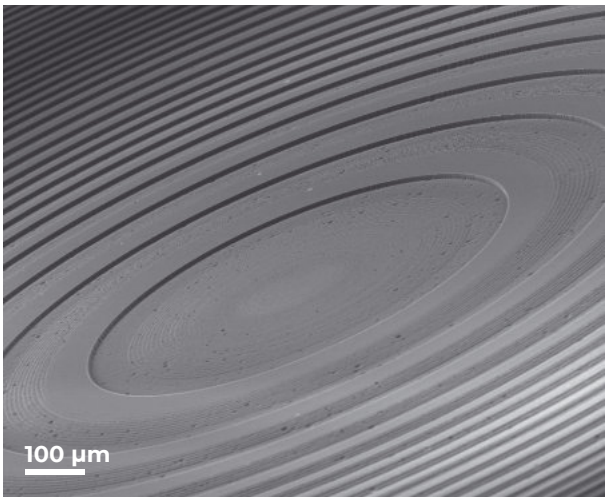
You are using a few interesting mix&match micro/nanofabrication methods. Can you tell a bit more about them?

With the amazing commercial developments in nanofabrication tools and processes, we are in a golden age of where we can dream up devices and get them made. So, we stand on the shoulders of all the giant engineers and scientists who have made this possible.

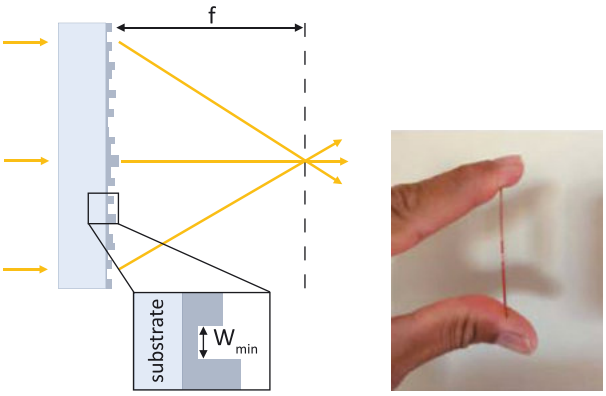
We work on two types of devices. First, those driven by system-level requirements that are technologically-speaking more mature, and typically fabricated using standard processes (sometimes mix & match). Second, the devices for which it is not clear what the best fabrication method is. Such devices, of course, require lots of experimentation and discussions with fabrication-/process experts. Nowadays, we use grayscale direct laser lithography, focused ion beam lithography, scanning electron beam lithography, nanoimprint lithography and contact photolithography.

You are pushing your direct laser lithography tool (µPG from Heidelberg Instruments) to the limit of its performance. What are the most special things you have used it for?

I am very fond of the µPG as its flexibility enables us to do very nice things. It is hard to select one of my favorites, but we have made lots of grayscale microstructures, such as flat lenses, broadband holograms, and many other micro-optics elements. We are still using it to make devices that have never been demonstrated before.



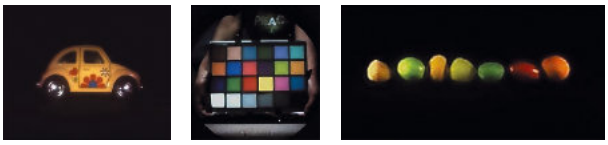
SEM image of a flat lense.



Schematic of a flat-lens comprised of concentric rings of varying heights, and a photograph of a fabricated lens.[3]

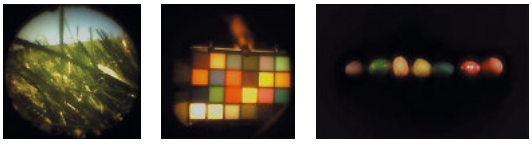
NA=0.05

LED Sunlight Halogen lamp



NA=0.18

Sunlight Sunlight Halogen lamp



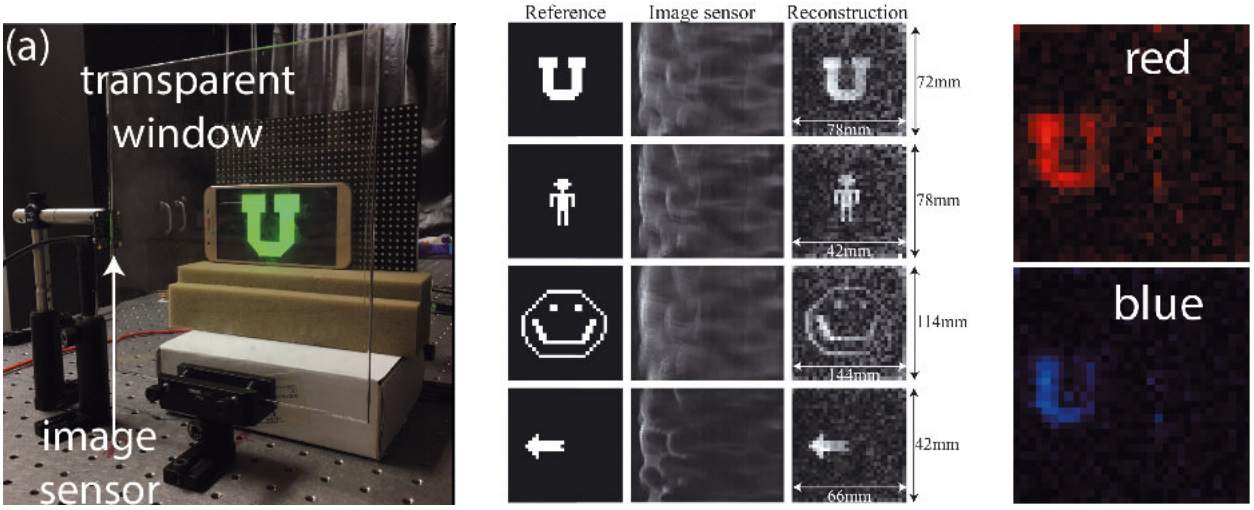
Raw images taken with a camera consisting of only a single flat lens and a conventional color CMOS sensor. An IR cut filter is placed in front of the lens for images taken under sunlight.[3]

[3] N. Mohammad, *et.al.*, Scientific Reports v. 8, art.n. 2799 (2018).

You also develop Absorbance-modulation-optical lithography (AMOL) and Patterning via Optical-Saturable Transitions (POST) photolithography techniques.[4] Have other research or industry labs adopted these methods yet?
These lithography methods are still under development. A lab at MIT is exploring AMOL and related approaches, as far as I am aware. AMOL, POST and other related techniques will hopefully get incorporated into commercial systems in the near future, but I don't have a good intuition for how long it will take to reach process maturity.

A few papers came out recently about your work with 3D micro-optical elements, specifically, flat lenses. What is so special about them?
These flat lenses, which we call multi-level diffractive lenses, are special for a few reasons. They allow efficient broadband imaging; image aberrations can potentially be corrected with a single lens; they are extremely lightweight, thin and could be manufactured at low cost. These devices arise from a simple, yet fundamental insight: In imaging, the sensor only records the intensity of light and ignores the phase. As a result, the phase distribution of light in the image plane can be considered as a free (unconstrained) variable. We showed that this insight leads to the fact that the ideal lens can have an infinite variety of solutions, not a single parabolic function, as is often taught in Optics textbooks. This large degeneracy of the lens phase-transmittance function enables new lens designs, such as a lens that is achromatic over a huge bandwidth[1], or a lens with an extreme depth of focus[5], as we also demonstrated recently. Such lenses can be used in thin cameras (security, consumer electronics, etc.), lightweight cameras (aerospace, UAVs), LIDAR, etc.

How difficult is it to fabricate them?
Ideally, we would fabricate a master containing the geometry of the flat lens design. Then, use low-cost replication technologies (like nanoimprint lithography), we could set up large volume manufacturing. The key fabrication challenges are resolution and scalability to larger areas. However, I should point out that these challenges are vastly easier to address for the flat lenses than in case of metalenses or other nanophotonic devices.



Left: A "see-through" lense-less setup; Center: Results from an LED array. Left column: Reference images placed on LED array. Center column: Raw data captured by image sensor (frame size = 640×480 pixels). Right column: Reconstructed images. The distance between the LED array and the window 150 mm. Right: recorded and reconstructed color images from an LED array[4].

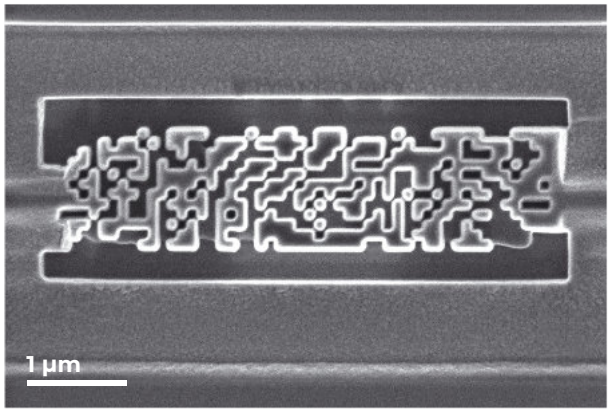
[4] A. Majumder et.al., OSA Continuum 2, 1754-1761 (2019)

Can you tell more about computer-aided brain imaging?

The motivation for this project is to gain insights into the mechanisms of normal cognitive functions such as how long-term memories are acquired and stored, and also to study various psychiatric conditions. We aim to record high-resolution videos from the deep part of an animal brain with as little trauma as possible. This technology, which we call "Computational Cannula Microscopy", involves surgically inserting a cannula (an optically transparent needle) into the brain of a mouse. The mouse is genetically engineered to express fluorescent cells, or they are transfected via a virus-based injection. Light is then piped into the brain to excite these cells. The emitted fluorescence is collected and piped back to the outside world via the same cannula. Since the cannula is not an imaging element, spatial details of the fluorescent cells are lost during this process. We developed algorithms to convert this "jumbled mess" into an image that can be distinguished by humans.[4]

IN IMAGING, THE SENSOR ONLY RECORDS INTENSITY OF LIGHT AND IGNORES THE PHASE

One of the main problems that all computational imaging technologies have to deal with is the impact of signal-to-noise ratio on image resolution and field of view. We now employ machine learning for this task. This project is a good example of a problem that requires both new algorithms and improved hardware (for example, nano- or micro-engineering the geometry of the cannula). In fact, we are just starting to 3D print customized cannulae. This is a very exciting area of research that combines input from computer scientists, neuroscientists and optical engineers.



An ultra-compact nanophotonic polarization rotator (S. Banerji, *et.al.*, arXiv preprint arXiv:1910.07928). Photonic functions can be encoded as subwavelength pixel distributions that are computationally optimized and we refer to these devices as digital metamaterials.

It would be very interesting to see how this project will develop! One final question: if you could fabricate any kind of micro- or nanodevice and did not care about difficulty, cost or time of production, what would it be?

Emergent behaviour is common in the natural world. Think about consciousness in our brain. I believe there is something similar that arises when a huge number of non-repeating photonic unit cells work together to create emergent macroscale photonic behaviour/properties. Such phenomena are extremely hard to explore due to the massive computational and also fabrication challenges. So, to explore such emergent photonic phenomena would be amazing if the fabrication and computational limitations could be overcome.

[4] G. Kim *et.al.*, Scientific Reports v. 7, Art.n.: 44791 (2017)

Experts' Know-how: Grayscale lithography of complex microstructures

Andreas Ludwig, Christian Pies, Heidelberg Instruments Mikrotechnik GmbH; Thomas Michels, Daniel Ritter, GenISys GmbH

INTRODUCTION

Grayscale lithography creates intensity gradients, which translate into a 3D[1] resist topography. Direct-write laser lithography is a fast, scalable and geometrically flexible approach to grayscale microstructures fabrication. It is suitable for both fast prototyping and large-area production of 3D microstructures for micro-optics – e.g. diffractive optical elements (DOE), micro-lenses, computer-generated holograms (CGH) – MEMS, microfluidics and many other applications.

The resulting topography is strongly influenced by geometry-dependent proximity effects, lateral development and non-linear dose dependence of the resist. Finding the optimal combination of these factors is a major challenge for grayscale lithography. It is usually addressed by iterative optimization of the gray value distribution (GVD[2]) until remaining deviations from the desired target topography are sufficiently small.

[1] Depending on conventions, grayscale or 3D microstructures can be called 2.5D, as the geometry is limited by patterning the surface.

[2] See the an application note on Grayscale lithography at https://heidelberg-instruments.com/en/media-info-center/downloads/applications-notes.html

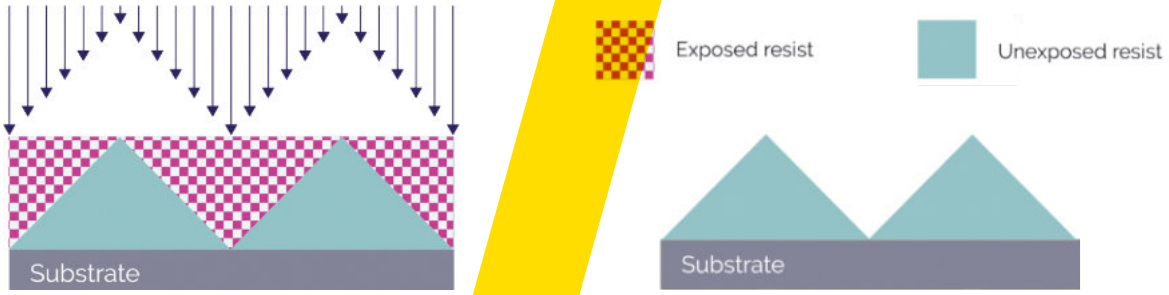


Figure 1: Schematic illustration of grayscale lithography. The photoresist layer is partially exposed by UV-light (top). During development, exposed resist is removed (bottom), resulting in a 2.5-dimensional topography.

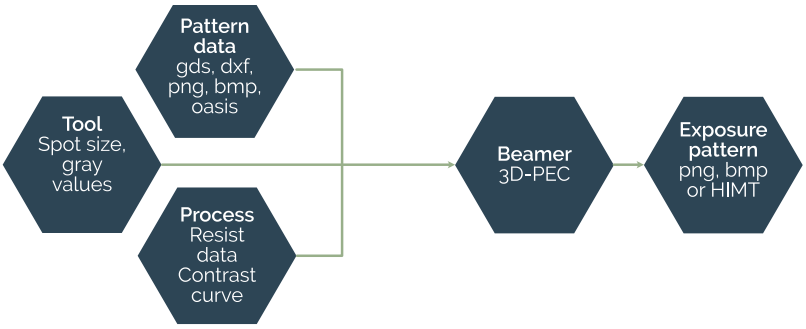
Although the iterative approach fits well for many common patterns, it requires a lot of experience in grayscale lithography from the system operator. Even long-term users have to carry out many time-consuming iterations of exposing, measuring and optimizing before obtaining a satisfactory result.

Furthermore, this approach is not suitable for complex patterns such as asymmetric lenses, freeform optics or diffractive optical elements (DOEs). A global solution provided by GVD tuning does not compensate deviations from the designed profile caused by local proximity effects – i.e. effects caused by the local surroundings of any given position in the pattern.

Both limitations of the iterative approach can be avoided by using numerical methods based on process modelling such as those implemented in 3D-PEC module of GenISys BEAMER software. This module takes into account the resist contrast curve, models the exposure and development and modifies the dose assigned to each pixel based on strength of proximity effects from its surroundings. Here, we present this powerful software solution for rapid and easy optimization of complex 3D microstructures.

GRAY VALUE DISTRIBUTION (GVD)
Relationship between gray value and exposure dose. On DWL systems, this relationship can be defined by the user. Nonlinear distributions can be used to compensate resist nonlinearities and proximity effects.

Iterative approach	BEAMER 3D-PEC
Keeps the design layout fixed.	Keeps dose of every gray value fixed.
Changes the dose assigned to every gray value based on previous tests.	Changes gray value of pixels according to the simulations based on the contrast curve.
⊕ More precise approach for simple and repetitive structures (e.g. micro-lenses).	⊕ Fast Requires only one test exposure for the contrast curve measurement.
⊕ Fine dose assignments possible for each gray value.	⊕ Universal: One contrast curve can be applied to any design.
⊖ Not possible to fully optimize patterns with complex non-repetitive designs.	⊖ Eventually reduced height resolution because of a limited number of gray values.
⊖ Testing can be very time-consuming.	⊖ Can be computationally intensive for non-repetitive designs.



Schematic of the working principle of the 3D-PEC module

SOFTWARE-BASED APPROACH: GENISYS BEAMER

GenISys BEAMER is a data preparation software for electron-beam and laser lithography. It is used for preparing a designed layout by using a set of comprehensive layout operation (e.g. Editing, Extraction, Healing, Biasing, Boolean Operation) and correction (PEC, OPC) for the exposure and generating the final exposure data for the e-beam or laser lithography tool.

3D Proximity Effect Correction, or 3D-PEC – one of the advanced features of this software – provides an alternative to the iterative optimization of the gray value distribution. It uses a three-dimensional-physics-based model of photoresist exposure and development to compensate for the proximity effect in grayscale exposures. The input includes tool-specific exposure parameters, the target design data and, most importantly, the resist contrast curve – the relation between the exposure dose and the resulting developed resist thickness. Based on these parameters, BEAMER assigns an individual gray value to each pixel of the pattern according to its local environment.

Depending on the application, the iterative or numerical approach is preferable. 3D-PEC is optimal for complex or irregular patterns, where the iterative approach may prove cumbersome. This is often the case for patterns containing irregular geometries, like lens arrays with varying radii of curvature or gratings with varying blaze angles. While each of these geometries needs to be treated separately in the iterative approach, 3D-PEC offers a global solution based on its underlying physical model.

The pattern	DOE-like structure, 16x16 square flats The shallow flats (black): 1 µm below the resist surface The deepest flats (white): 5 µm below the resist surface
Size of each flat	6.4 x 6.4 µm²
Grayscale	16 selected levels, 8-bit layout
Exposure	DWL 66+ with a 405 nm diode laser, Write Mode I and a 200 nm pixel grid[3]
Resist	10 µm thick layer of AZ4562
Development	AZ 826 MIF, 6 minutes

[3] This configuration does not exist in present DWL 66+ systems anymore. The Write Mode I uses the same write lens, but with a 100-nm pixel grid.

As gray value 0 always corresponds to zero exposure dose, it is recommended to not use this value in the design layout. This way, it is possible to introduce an offset between resist surface and final target structures.

EXAMPLE: OPTIMIZING A DIFFRACTIVE OPTICAL ELEMENT WITH BEAMER 3D-PEC

Here we present the grayscale pattern optimization process for a diffractive optical element using BEAMER 3D-PEC software and show the resulting microstructure.

Diffractive optical elements (DOEs) consist of square flats with different heights. The absolute accuracy of the final topography is paramount to the optical properties and the quality of the resulting device. To ensure a uniform target depth and sharp transitions from one flat to the next, the exposure dose close to edges and corners has to be modified individually for each flat. This cannot be solved by the iterative approach since the same dose assignment would be applied to all pixels within one flat and to all flats with the same gray value. In contrast, 3D-PEC changes the gray value of each pixel individually and thus is the more effective approach for this application.

STEP-BY-STEP PROCESS FLOW

1. SET UP THE BEAMER FLOW

The BEAMER graphical user interface has a modular, sequential design. Individual modules are simply dragged and dropped into the flow window and connected in the desired consecutive order.

A basic flow for 3D PEC correction consists of three modules:

Import. Imports the design bitmap (.bmp or .png) layout and converts design gray values into layers. With a slightly more complex flow, it is also possible to import true 3D objects in .stl file format, where the z-values are translated into layers.

3D-PEC. Corrects the data for three-dimensional process and proximity effects.

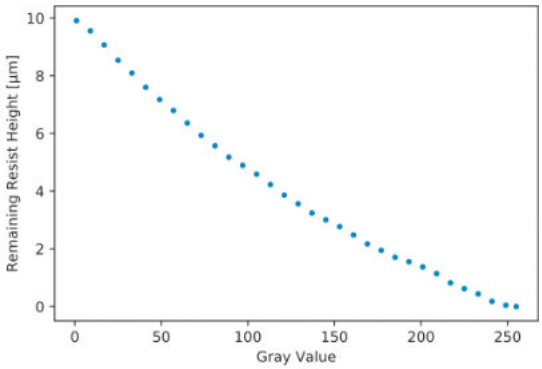


Figure 5: An example of the resist contrast curve for 10 µm-deep structures.

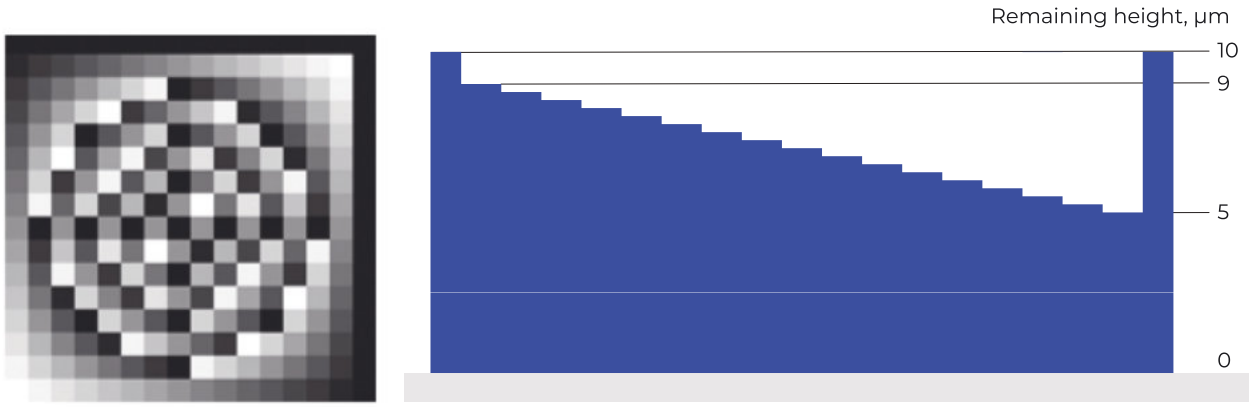


Figure 2 Left: .png layout of DOE structure; Right: target resist profile cross-section, lateral dimension not to scale.

Export. Exports the corrected data in the desired format, which can vary depending on the exact configuration of the tool.[4]

2. SET UP THE 3D-PEC MODULE

3D-PEC Module needs definitions of the exposure tool and resist parameters (laser beam size, the number of gray values in the system and optical parameters of the photoresist) as well as resist contrast curve and definitions of the layers and the dose class.

Resist Contrast Curve

A contrast curve (CC) correlates each exposure gray value to the depth it produces under given process conditions (base exposure dose, photoresist, developer, development time). This relationship can be derived from a simple test exposure with a pattern consisting of a set of squares, to each of which a different gray value is assigned to e. An example obtained in 10 µm of AZ4562 is shown in Fig. 5[5].

Layer Definition Table

The layer definition table defines the target depth of each layer (= layout gray value) in the photoresist. For convenience, this can be done in a simple text file, which can then be imported to the software. According to the specifications given above, the layer definition table would look like this:

```
# Layer     ,     Remaining Resist Height
1           ,     9
2           ,     8.98425
3           ,     8.96850
            [...]
255         ,     5
```

Dose Class Definition

As HIMT systems work with integer gray values only, it is recommended to specify an explicit list of all available gray values. These are normalized between 0 and 1 corresponding to the power of the laser between off and full power. For a system with 256 gray values, a text file as follows can be imported.

```
# Dose Class Definition
0.003921569
0.007843137
[...]
0.996078431
1
```

3. CORRECTED DATA OUTPUT

After running the 3D-PEC module (a calculation for such small structure takes a few seconds), the corrected dataset is finished and ready for exposure. Selec-

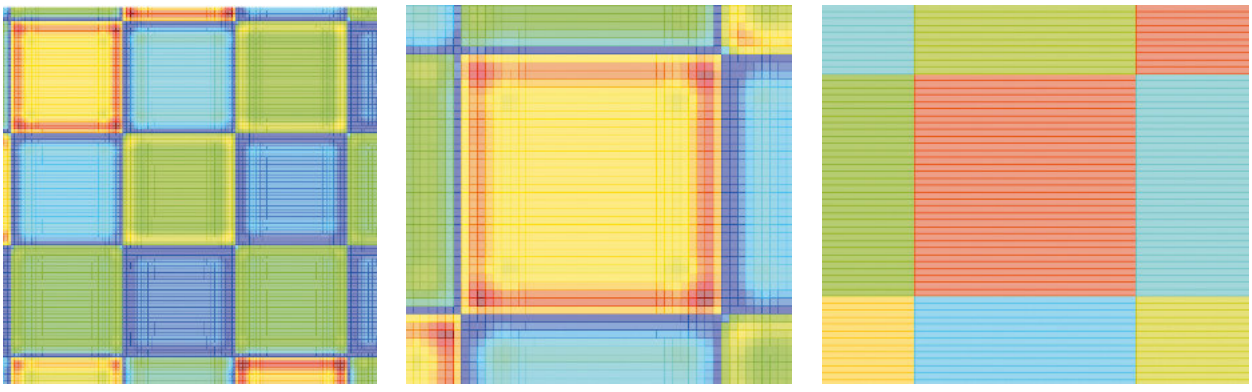


Figure 5: Corrected data output as seen from the BEAMER viewer (top images) and uncorrected data (bottom images). Exposure dose is color-coded, with warmer colors corresponding to higher exposure dose.

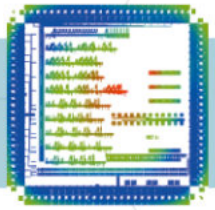
[4] Please refer to the BEAMER user guide for more detailed information.

[5] For more detailed information on how to measure a contrast curve, see an appendix to this application note at https://heidelberg-instruments.com/en/media-info-center/downloads/applications-notes.html.

GenISys
Advancing the Standard

Software for Advanced Lithography, Analysis & Metrology

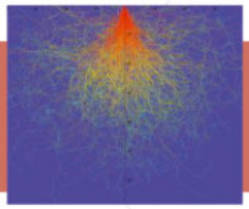
Electron and Laser
Beam Direct Write

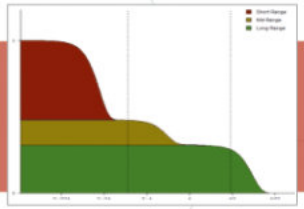


Paul Scherer Institute - Switzerland

BEAMER

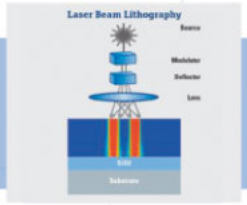
e-Beam Lithography
Monte Carlo Simulation
Process Calibration

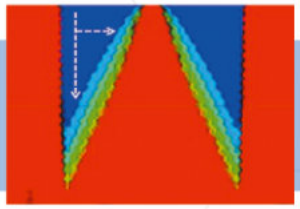




TRACER

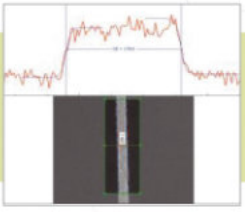
3D Lithography
Simulation Proximity,
Projection, Laser

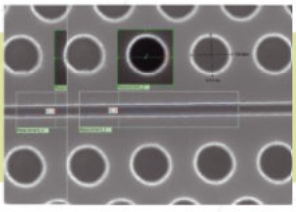




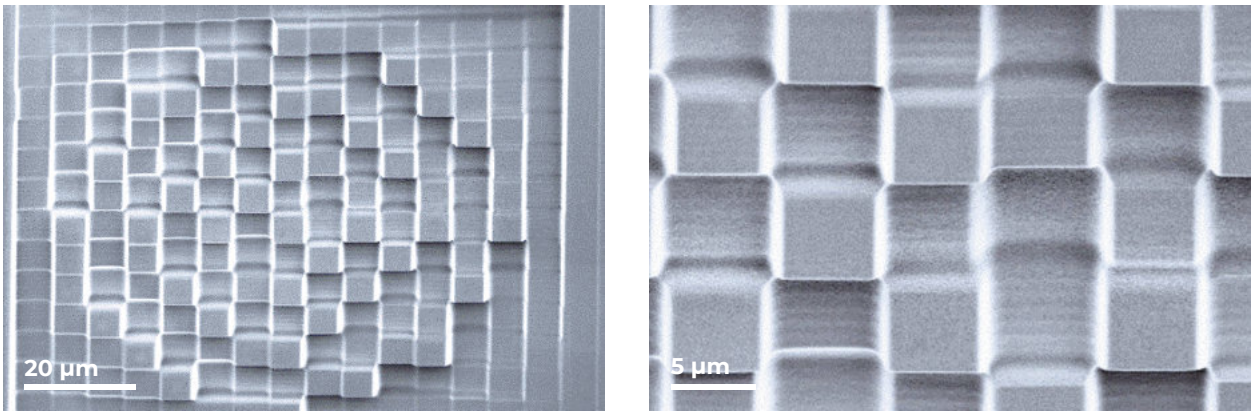
LAB

SEM Image Analysis
& Metrology





Pro SEM



Left: A tilted SEM image of the resulting DOE. Right: A zoom-in highlights the resulting topography and flats quality.

ted areas of this optimized dataset are shown in figure 5. The resulting gray values are represented in a color scale from blue (low GV) to red (high GV). The 3D-PEC correction breaks down the individual flats and modulates the gray value within each of them with respect to adjacent structures. In the vicinity of corners and edges, the gray value is either increased or decreased, depending on whether the next adjacent flat is exposed at a higher or lower dose. Individual flats are separated by single-pixel-wide lines of low gray values to ensure the highest possible contrast.

The resulting structure matches the specified target very well. Quality of corners, edges and sidewalls is very good with relatively little effort in determining the exposure parameters.

CONCLUSIONS

The complexity of grayscale patterns is increasing, and the iterative approach is no longer sufficient for 3D micropatterning that meets the specifications. The approach presented in this application note enables straightforward grayscale lithography even for complex irregular microstructures.

The BEAMER 3D-PEC module enables accurate fabrication of complex 3D structures with Heidelberg Instruments lithography systems.

- Easy-to-use software interface;
- Reasonably short computation time;
- Required input: a resist contrast curve and target definition;

Figure 7: Confocal image after the final exposure and development.

- Output files can be transferred to the HIMT exposure system automatically.

Heidelberg Instruments' processes and applications engineers have accumulated extensive know-how in optimization and fabrication of grayscale microstructures of various complexity. Advanced exposure sysems, established fabrication processes, and 3D-PEC capabilities enable fast prototyping and high-throughput fabrication of high-quality complex irregular microstructures.

HEIDELBERG INSTRUMENTS EXPERTS IN GRAYSCALE LITHOGRAPHY, DOMINIQUE COLLE AND ANDREAS LUDWIG TOLD THE LITHOGRAPHER ABOUT THEIR WORK.

Which tools and resists are you using?

AL: Our main workhorse is the DWL66+, very flexible tool for grayscale lithography. On the photoresist side, low-contrast positive-tone resists are required. I mainly use ma-P 1200G (micro resist technology) or AZ 4562.

What were the challenges you had to overcome to achieve reliable system performance?

DC: Over the past decade, I have seen (and taken part) in many improvements of the system. It went from 32 to 1024 available gray values, the software was improved, we developed strategies for efficient stitching and exposure optimization both by iterative approach and computations.

AL: As the photoresist layer is only partly exposed, grayscale laser lithography is very sensitive to stage vibrations, laser power instabilities and environmental influences, so a lot of effort went into making the system as stable as possible.

What are the current grayscale lithography capabilities of your setup?

The DWL66+ is capable of producing almost any 2.5-dimensional topography with structure heights between 1 and 60 µm. It has up to 1000 gray levels to guarantee extremely smooth surfaces with a roughness down to 10 nm. The minimum achievable feature size strongly depends on the target geometry and the resist thickness, but we can achieve down to 500 nm is possible for grayscale structures.

What are the biggest challenges still remaining?

AL: Exposure optimization, maximum achievable structure height and, of course, the throughput. We are working together with other companies to address current limitations: The BEAMER-software by GenISys is a very promising candidate for optimizing the exposures; Together with micro resist technology we are investigating how to structure layers beyond 60 µm thickness; And lastly, we aim to develop a new, significantly faster optical engine to make large-scale grayscale exposures feasible in the future.

Can you share a few tips with the readers?

DC: Try turning off the air flow of the Pneumatic Auto Focus (pAF) and using the optical AF instead. With this method, the resist will not dry while exposing, preserving its chemical properties, mainly the development rate. This trick would improve the repeatability of similar structures over long exposures.

Grayscale positive photoresist

series ma-P 1200G

C. Schuster, A. Voigt, G. Grützner
micro resist technology GmbH,
Köpenicker Str. 325, 12555 Berlin, Germany

Micro resist technology GmbH (MRT) develops, produces and supplies innovative photoresists, special polymers and ancillaries for micro- and nanolithography, and micro-optical applications. MRT's materials are used for key technological applications: microsystems, microelectronics, micro- and nano-photonics, life sciences, etc. Serving the global high-tech markets for more than 25 years, MRT products enable processes like UV, Laser, X-ray, and e-beam lithography, nanoimprint lithography, and associated patterning technologies.

MOTIVATION

Grayscale lithography creates 3D film profiles with gradually varying thickness[1], see Fig.1. The grayscale lithography is especially advantageous for the microstructures where reflow patterning[2] does not produce the desired result, e.g.:

- Applications with high structure density, where adjacent reflow patterns could merge;
- Complex shapes such as random microlense arrays;
- Additional patterns on bigger lenses;
- Microlenses with different heights, or patterns for diffractive optics;
- Other free-form profiles used for e.g. light-beam-shaping and steering, MEMS, MOEMS. etc.

Figure 1 Resist profiles produced by binary (left) and grayscale (right) lithography.

REQUIREMENTS TO PHOTORESISTS FOR GRAYSCALE TECHNOLOGY

A standard positive photoresist exhibits an inhibition at low doses, i.e. the solubility in the developer (translating into the remaining film thickness after development) increases only after the exposure to a certain minimum dose. Above this dose, a standard photoresist shows a very steep decrease in thickness after development, the resulting thickness depending on the exposure dose in a non-linear fashion (Fig. 2).

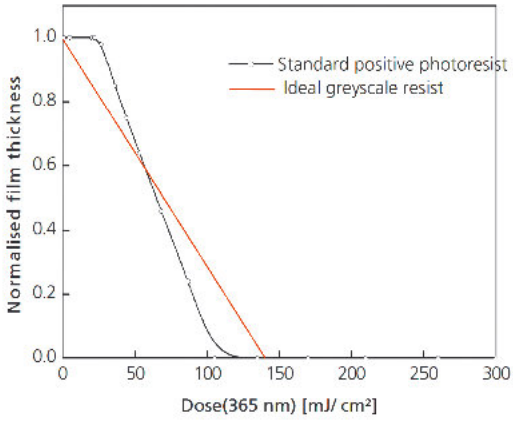


Figure 2: Response curves (normalized film thickness FT/FT_0 after development versus the exposure dose) of a standard binary positive photoresist and an ideal grayscale resist.

An ideal resist for grayscale lithography should have:

- A more linear response than a standard photoresist;
- A smaller contrast than that of standard binary resists to allow true grayscale response;
- Yet, the response curve should be sufficiently steep to avoid long exposure times;
- None or negligible initial solubility inhibition;
- Low residual absorption to enable exposure and development to the bottom even in very thick films.

Furthermore, due to the comparatively narrow process window, especially in grayscale mask lithography, the resist should have a high batch-to-batch reproducibility of the response curve.

Direct laser writing often uses high laser intensity during exposure, which can cause an „explosive“ N_2 release from the resist. A resist suitable for direct laser writing in grayscale mode should have a strongly reduced tendency for this kind of outgassing during exposure.

MA-P 1200G SERIES: MATERIAL SOLUTIONS FOR GRAYSCALE LITHOGRAPHY

Micro resist technology GmbH developed a series of special positive resists for UV grayscale lithography:

- ma-P 1215G – 1.5 µm thickness @ 3000 rpm
- ma-P 1225G – 2.5 µm thickness @ 3000 rpm
- ma-P 1275G – 9.5 µm thickness @ 3000 rpm
- ma-P 1295G_XP – an experimental product for very high film thicknesses (100 µm).

[1] Binary lithography, on the other hand, aims at fabricating structures with the steepest possible sidewalls.

[2] Reflow patterning is a common method used to make rounded patterns by letting binary resist structure begin to melt.

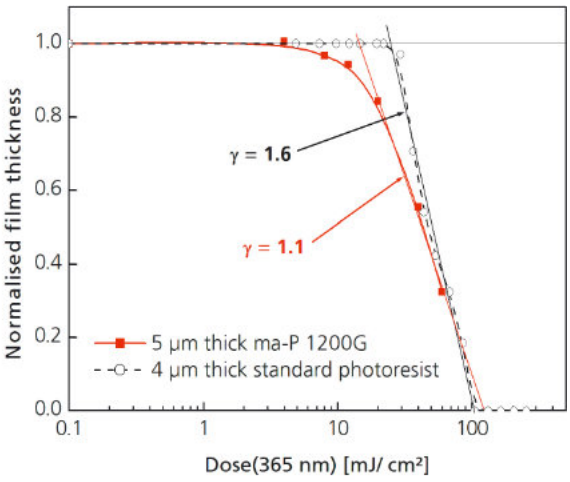


Figure 5: Contrast curves of 5 µm thick ma-P 1200G and of a 4 µm thick standard positive photoresist

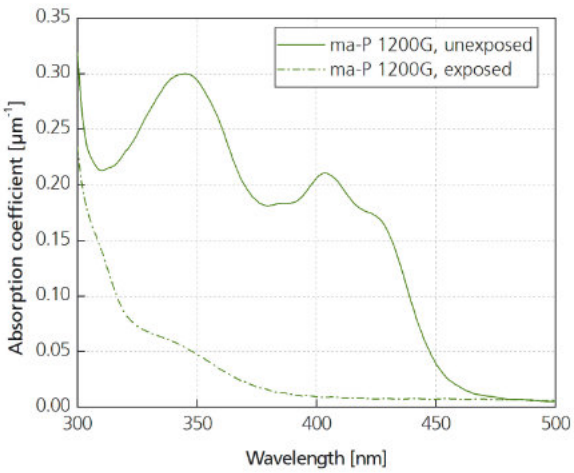


Figure 6: UV/vis absorption spectra of unexposed and exposed ma-P 1200G

Unique features of the ma-P 1200G series:

- Reduced contrast;
- Film thickness 1–60 µm in a single spin-coating step, 100–130 µm with ma-P 1295G_XP (single and double spin-coating);
- High-intensity laser exposure without outgassing;
- Reproducible grayscale pattern 50-60 µm deep;
- Up to 80 µm pattern depth in grayscale mode, up to 100–120 µm pattern depth (proven for binary lithography with a mask aligner);
- Aqueous alkaline development (TMAH for grayscale lithography, NaOH for binary lithography);
- Also well-suited for pattern reflow after standard binary lithography.

Figure 3: Grayscale exposure of thin film resist (FT ≤ 5 µm)

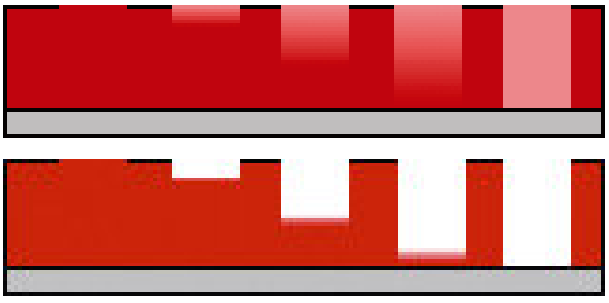


Figure 4 Top: Grayscale exposure of thicker resist films (FT ≥ 5 µm); Bottom: resist pattern after development.

PROCESSING OF MA-P 1200G RESISTS

Grayscale lithography on thin resists

In thinner resists with a film thickness < 5 µm, such as ma-P 1215G and ma-P 1225G, the penetration depth of the exposure light is higher than the film thickness. As a result, the dose variation directly

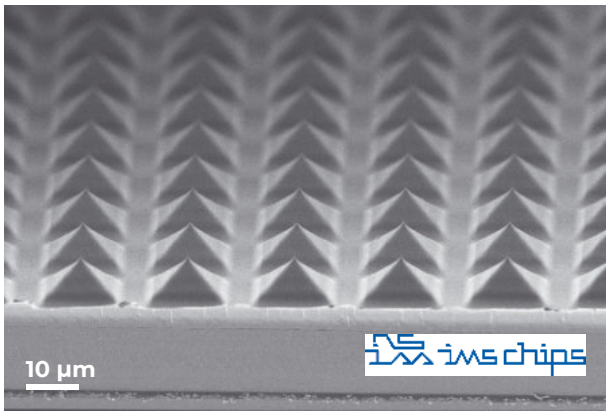


Figure 8: ma-P 1275G pyramid structure.Image courtesy of IMS CHIPS.

translates into the variation of photoactive compound conversion and of resist solubility in the developer (Fig.3 and 8).

The resulting resist profile has a smaller contrast as compared to the standard positive photoresist (Fig. 5). ma-P 1200G grayscale resists also have significantly less initial solubility inhibition (no or hardly any film thickness reduction with increasing dose).

Grayscale lithography on thick resists

The composition of ma-P 1200G was optimized to drastically reduce the outgassing caused by the high laser energy density, which makes this resist suitable for creating deep structures.

In thick resists with a film thickness >5 µm (ma-P 1275G and ma-P 1295G_XP), the penetration depth of the exposure light is smaller than the film thickness. Resist bleaching contributes to the variation of the exposure depth at different doses (see the UV/vis absorption of unexposed and exposed resist film in Fig. 6). The resulting gradient of the dissolution rate in z-direction also results in a resist gradient after development (Fig. 4).

The reduced resist contrast is still large enough for reasonable writing times. Recent tests demonstrated 80-µm-deep grayscale patterns obtained by direct writing at 405 nm using a DWL 66+ laser lithography system from Heidelberg Instruments.

PATTERN TRANSFER

Lithography is often followed by pattern transfer into the target materials. ma-P 1200G resists are compatible with:

- Metallization and electroplating;
- Etching;
- UV moulding (Fig. 9).

SUMMARY

Resists of the ma-P 1200G series allow reliable grayscale patterning of 1-60 µm thick films and have the potential to be used in even thicker films of up to 100-130 µm. They can be used for direct-write laser lithography to produce complex micro-scale shapes in a reproducible and straightforward way.

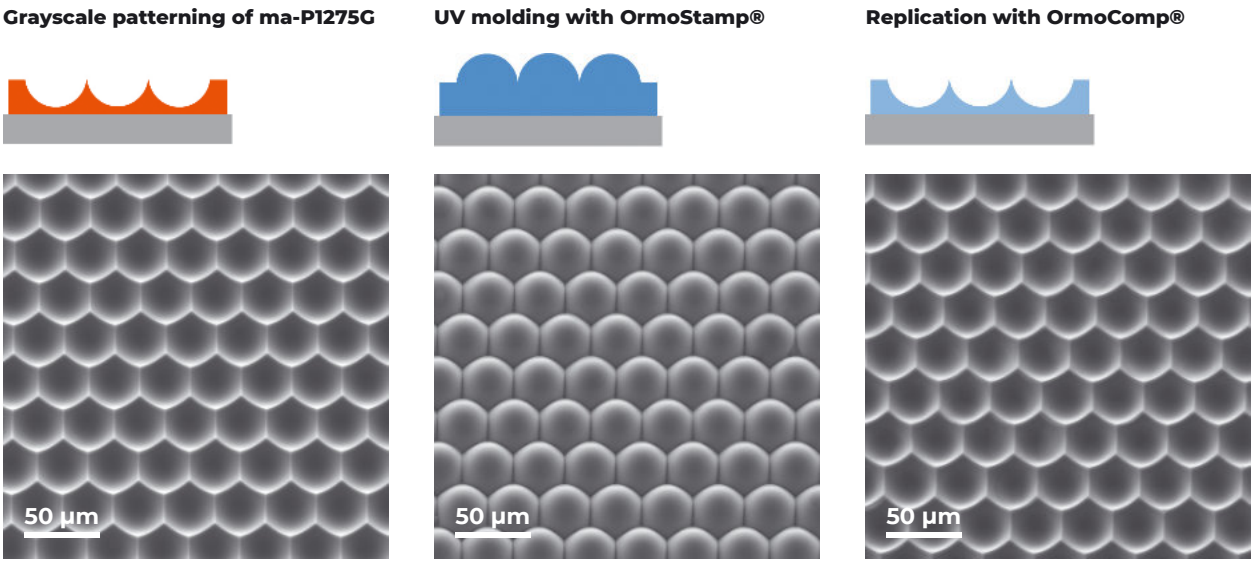
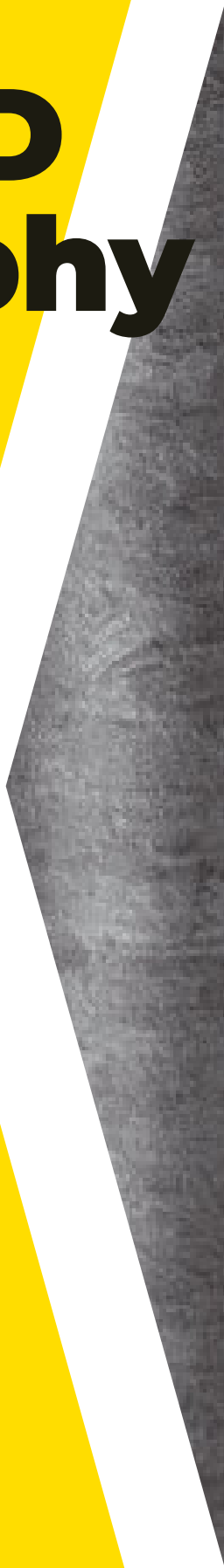


Figure 9: Pattern transfer of grayscale structures in ma-P 1275G by UV moulding with OrmoStamp® (left) to form a working stamp (center) and subsequently with OrmoComp® to form final concave lens structures (right).

Experts' Know-how:
Closed-loop 3D Nanolithography

A. Grushina, Heidelberg Instruments Nano
Technoparkstrasse 1, 8050 Zurich, Switzerland



More and more applications take advantage of 3-dimensional nanostructures. The surfaces are engineered with nanometer-precision and often require high surface smoothness. The NanoFrazor technology powered up with a Closed-Loop Lithography approach delivers unprecedented single-nanometer vertical precision. This process is compatible with pattern transfer by etching, as well as with several replication methods. So it enables new applications in photonics and nanofluidics. For example, single-nanometer accurate high-quality master templates for Nano-Imprint Lithography (NIL) have been demonstrated. Apart from its unrivalled depth accuracy, the NanoFrazor stands out from the competition (e-beam, focused ion beam), by being easier to use, non-invasive and more affordable.

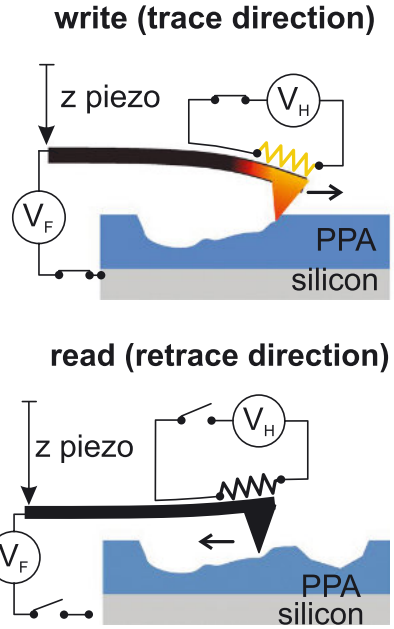
[1] Depending on conventions, grayscale, or 3D, microstructures are called 2.5D, as the possible pattern geometry is limited by the conical shape of the tip.

CLOSED-LOOP LITHOGRAPHY

The NanoFrazor patterns the substrate using a heated ultra-sharp tip. The same tip is used for in-situ imaging, the data from which is fed into our patented Closed-Loop Lithography algorithm. working principle of Closed-Loop Lithography (CLL) is shown on the schematics on the left. When moving forward in the trace direction, i.e. from left to right, the tip patterns the resist. When moving back in the retrace direction, the topography of the just-written line is read-out, recorded, and compared to the target profile.
Deviations from the target pattern are fed back to the settings of the patterning parameters to ensure the closest fit to the designed topography.
Closed-loop approach automatically accounts for:

- Deviations in the alignment between the sample and the scanning plane
- Drift in the vertical direction.

At the same time, the user obtains a topography image of the pattern as it is written. Based on the image, the user can choose to manually adjust the patterning parameters (such as temperature) or decide to abort the process. This is especially helpful for rapid prototyping and for exploring new processes, resists or critical structures.



250 nm deep sine profile etched in Silver, half-pitch 1.5 µm.

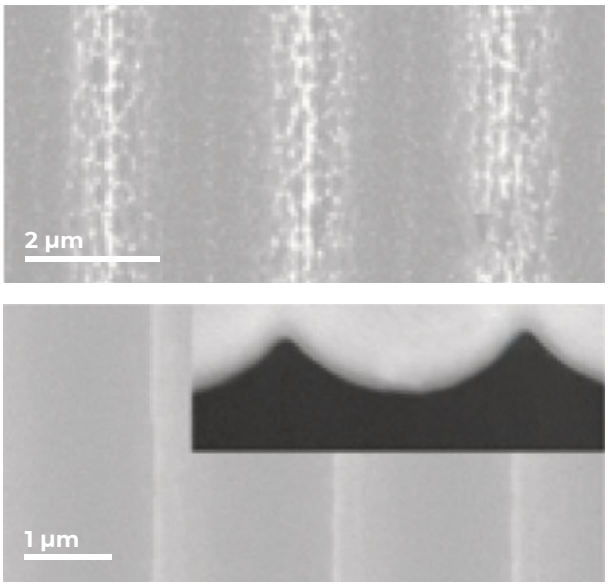
PATTERN TRANSFER

NanoFrazor technology and PPA resist are fully compatible with the most ubiquitous pattern transfer processes, such as lift-off, reactive-ion etching, and electroplating.

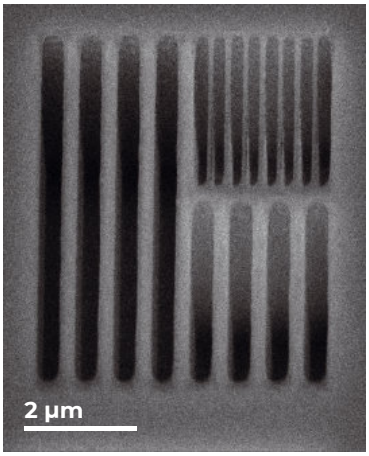
For many applications, transferring the 3D topography into a specific target material is a crucial step. The main challenges are in achieving minimal surface roughness[2] and the desired depth amplification[3].

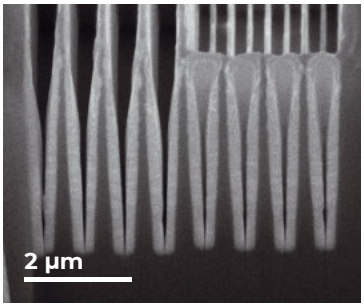
Our process and applications engineers, together with our customers and partners, have developed a broad selection of recipes for pattern transfer. A full collection of this wealth of know-how is available as a "Recipe book" from Heidelberg Instruments. Our experts are also happy to consult NanoFrazor users on most suitable processes to achieve their desired applications.

NanoFrazor lithography typically uses polyphthalaldehyde (**PPA**) as a thermal resist. Upon contact with the hot tip, PPA readily decomposes into volatile monomers. The sublimation reaction is very rapid and highly localized, making PPA perfect for grayscale nanolithography. PPA has proven to be compatible with various pattern transfer processes (see examples below).



High-accuracy t-SPL grating in Si polished by ion beam etching. Left: top view SEM image of the transferred t-SPL patterns in Si without smoothening step. Right: SEM images of a similar t-SPL pattern after polymer-assisted ion beam polishing, respectively. The inset shows an SEM cross-section after Pt deposition and FIB milling.





High-aspect ratio t-SPL nanopatterns fabricated in silicon using a 100 nm thick SiO_2 hard mask. Top: Tilted SEM image of the pattern transferred into Si at a complete SiO_2 mask layer transfer. Bottom: The cross-section of transferred SiO_2 pattern into Si after Pt deposition and FIB etching. A deep silicon etch narrows the silicon lines to 150 nm and 240 nm from the initial pattern size of 210 nm and 460 nm, respectively. At the conditions used, the larger patterns are 4 µm deep silicon and the narrow pattern is of 3.4 µm deep in silicon (not shown here). Tilt 52°.

[2] Lisunova et al, MEE 2018

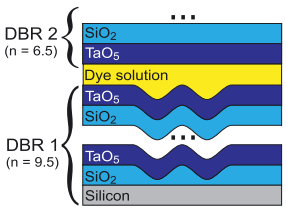
[3] Lisunova et al, Mic. Eng., 2017

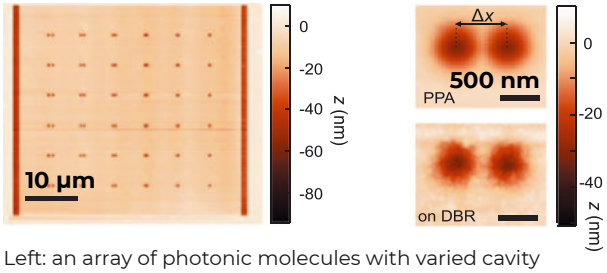
EXAMPLES

PHOTONIC MOLECULE

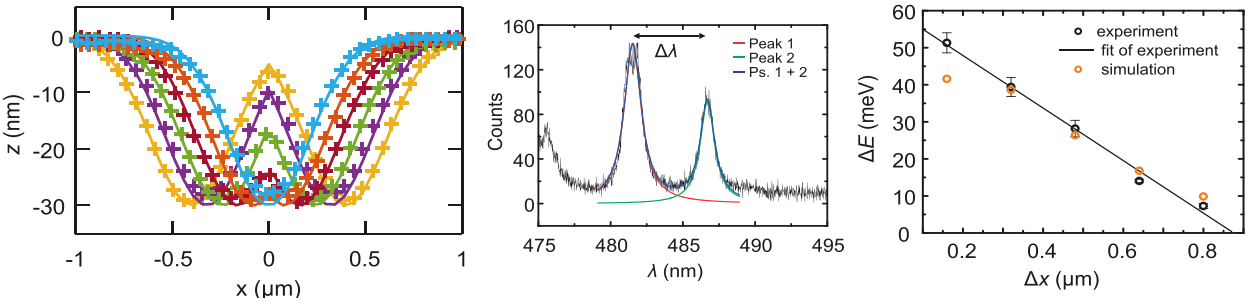
A so-called photonic molecule can be formed by coupling two zero-dimensional cavities through their evanescent fields. Such a system can be realized by placing two identical Gaussian cavitiess in SiO_2 within a small distance on the order of the visible light wavelength from each other, as a part of a distributed Bragg reflector. An optical cavity with a Gaussian shape is advantageous in comparison to a conventional "mesa" stack: a smooth profile provides significantly better light confinement, resulting in a ca. 200-fold higher Q-factor. The coupling between the cavities produces "bonding" and an "anti-bonding" modes, where the energy separation is set by the distance between the Gaussian cavities and crucially depends on the fabrication accuracy of the structures.[4]

Twin Gaussian cavities for a stack forming distributed Bragg reflectors, comprising a photonic molecule.





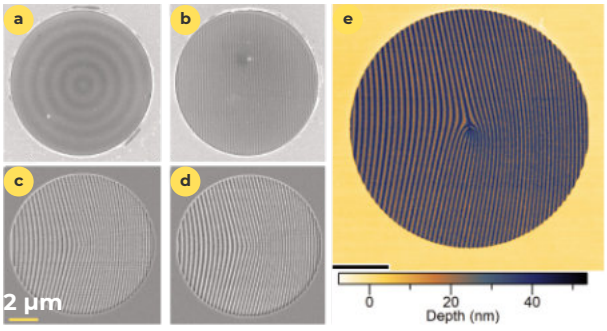
Left: an array of photonic molecules with varied cavity separation; Right: AFM image of the twin cavities in PPA and as a part of a DBR structure.



Left: average cross-scans taken with 160 nm step; Center: photonic molecule radiation spectrum with bonding and anti-bonding modes separated by ΔE; Right: ΔE as a function of distance between the cavities.

PHASE MASKS FOR ELECTRON MICROSCOPY

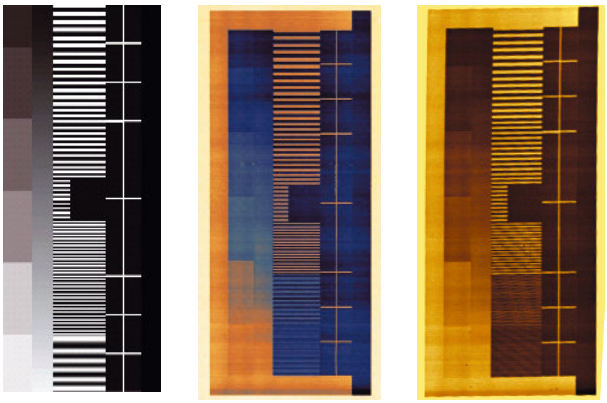
se masks can produce a Vortex or a Bessel electron beam for advanced studies on material properties. Such masks are typically thin Silicon Nitride membranes with a 3D profile. They are usually made using a focused ion beam, but this method has its limitations. Ions implant the Ga and induce defects in the mask, and it is hard to achieve optimal thickness and mask profiles. 3D capabilities of NanoFrazor lithography enable fabrication of superior phase masks[5] without implanted impurities.



Phase masks made in SiN membranes: a) On-axis Bessel beam; b) Off-axis Vortex beam; c-d) Off-axis Bessel beams; e) Phase mask pattern written in PPA, imaged using the NanoFrazor in-situ imaging mode.

[4] Rawlings et al., Scientific Reports 2017

[5] Hettler et.al, Micron, 2019

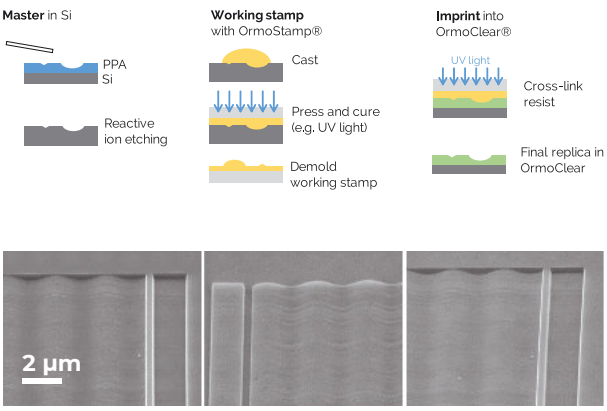


Design, NF stamp and sol-gel imprint done by SCIL (substrate conformal imprint lithography)

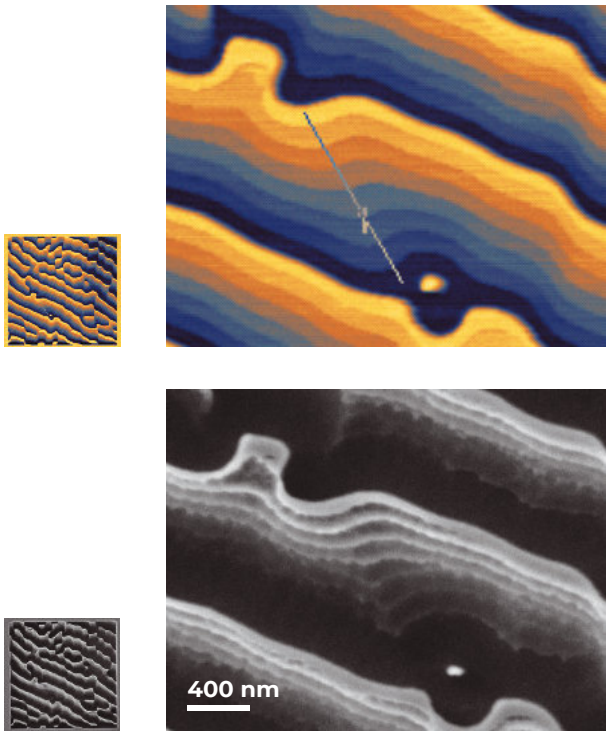
NIL AND SCIL MASTER STAMPS

Master templates made by NanoFrazor lithography are suitable for very accurate and fast replication of the patterns. This approach is compatible with commercially available production techniques, such as nanoimprint lithography or injecti

In some cases, the 3D-structures written with the NanoFrazor into PPA resist can be directly used as templates. But in most replication processes, suitable masters are made using one of the following approaches:



Top: Process schematic of using a hard Si template for nano-imprint lithography; Bottom: Replication of a Sine-wave pattern using this process. Image courtesy: Arne Schleunitz, Loic Jacob-Descombes from micro resist technologies.



A computer-generated hologram. Left: patterned PPA (depth 64 nm); Right: Pattern transfer into Si with x100 amplification (depth 700 nm); Pillar width 65 nm. Image courtesy of Prof. Jianwen Dong, Sun Yat-Sen University.

- Soft template stripping by casting PDMS materials on top of the 3D PPA pattern to form soft transparent working stamps for UV NIL processes.
- 3D etching (RIE) into the substrate (usually Si) to form a hard master template that is compatible with various replication techniques. The depth of the resist pattern can be amplified by the tech process (>100x demonstrated from PPA to Si)
- Electroplating of Ni can be done on PPA to form Ni shims that have been shown to be suitable for replication of 3D nanostructures in PMMA using injection molding.

All of these methods result in very high-quality replicas, where both the pattern fidelity and dimensions are accurately reproduced. Importantly, the area of the original pattern can be multiplied in a step-and-repeat process where the pattern from the master is imprinted several times in succession next to each other.

HEIDELBERG INSTRUMENTS

The power of direct writing

- Minimum structure size 15 nm
- 3D resolution 2 nm
- Wafer size up to 10 cm
- Mix & Match lithography: direct laser sublimation for microstructures
- In-situ high-speed AFM topography imaging, markerless overlay
- Non-invasive lithography for sensitive materials
- Heat modification of materials

NanoFrazor Explore

The first mix & match nanolithography tool

himt.de

Heidelberg Instruments and its new Nano division

February 2018: Heidelberg Instruments acquired 70% of the shares of the Swiss high-tech company SwissLitho AG.

This move marked the beginning of a new synergy. SwissLitho will now be called Heidelberg Instruments Nano. The companies are going to share not only the brand name, but also the website. On this occasion, Heidelberg Instruments revised company logo, website and corporate design.

Heidelberg Instruments, with more than 3 decades of expertise in direct laser writing, is an established power in the world of microfabrication. Direct-write laser lithography demands many sophisticated technological solutions, which Heidelberg Instruments have successfully implemented in their tools. Expanding the capabilities beyond the current smallest feature size of 300 nm, however, is more than just an engineering challenge, if the systems are to be still affordable to the university labs and research facilities. With NanoFrazor joining the laser lithography product family, Heidelberg Instruments can offer nanofabrication solutions to their customers as well.

Another bottleneck related to nanofabrication is low throughput. One possible solution for this problem is a so-called mix & match approach: a combination of nanopatterning for writing fine features and photolithography for coarser structures. Different techniques can be combined for this purpose, and it is typically done in separate fabrication steps. Since immediately after the merger, engineers from both companies began collaborating, Heidelberg Instruments now offers a unique DLS add-on module for the NanoFrazor Explore. DLS stands for Direct Laser Sublimation: a laser write-head is mounted on the NanoFrazor cantilever holder. This hybrid solution combines the best of two worlds in terms of resolution, throughput and flexibility. It makes so much sense, that DLS module is now a part of the default configuration for the NanoFrazor Explore.

Another direction, in which the tool development in both companies points, is industrial-scale production. There already are a few Heidelberg Instruments' tools designed specifically for industrial mask-making or for maskless production. These tools are particularly suitable for mid-range foundries and 3D, or grayscale, device manufacturing.

NanoFrazor, by microfabrication standards, has low throughput (comparable to e-beam in the ultra-high-resolution regime). Nevertheless, it proved handy for producing master stamps for nanoimprint technology, for example.

In order to further increase the throughput preserving the unique high-resolution patterning and imaging capabilities of the system, Heidelberg Instruments Nano is working on a prototype of a MultiTip add-on to NanoFrazor Explore, and on the NanoFrazor Professional system for writing larger-scale wafers, which is ready to go to the beta-testing stage.

SwissLitho has emerged in 2012 to commercialize the *NanoFrazor technology*, or thermal scanning probe lithography, originally developed at IBM Zurich in the framework of the *Millipede* project. Felix Holzner and Philip Paul, who worked on that project, founded *SwissLitho*. The company developed and produced two nanolithography systems, the flagship *NanoFrazor Explore* and its table-top version, *NanoFrazor Scholar*.

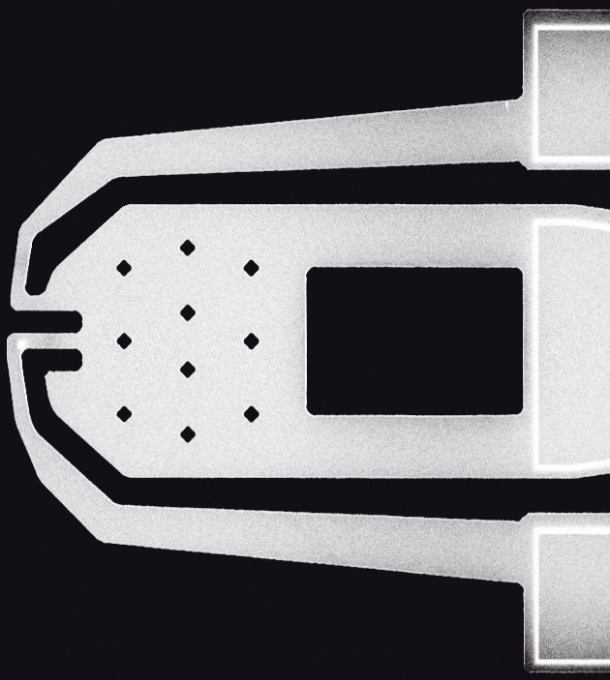
Conferences '20

Date	Location	Event name
2–6 Feb	San Francisco, CA, USA	Photonics West + AR VR MR
20–21 Feb	New York, NY, USA	Graphene4US
23–27 Feb	San Jose, CA, USA	SPIE Advanced Lithography
12–14 Mar	Singapore, SG	ICNRD
15–20 Mar	Dresden, DE	DPG Spring (Condensed Matter)
18–19 Mar	Zurich, CH	Thermal Probe Workshop
29 Mar – 2 Apr	Strasbourg, FR	SPIE Photonics Europe
20–24 April	San Diego, CA, USA	IEEE NEMS
28–30 Apr	Bilbao, ES	ImagineNano
28–30 Apr	Graz, AT	nanoFIS
5 May	Lausanne, CH	CMi Day EPFL
11–12 May	Berlin, DE	NIL Industry Days
19–23 May	Munich, Germany	11th International Conference on Quantum Dots
23–28 May	Houston, TX, USA	Surface Plasmon Photonics 10
26–29 May	New Orleans	EIPBN
2–5 Jun	Grenoble, FR	Graphene
2–3 Jun	Basel, CH	Swiss Nano Convention
14–17 Jun	Madison	UGIM
16–17 Jun	Berlin, DE	BioChip
22–24 Jun	Leuven, BE	EMLC
22–26 Jun	Poznan, PO	Physics of Magnetism

Date	Location	Event name
24–26 Jun	Hamburg, DE	NIBS Nanotech Baltic
1–3 Jul	London, UK	Condensed Matter & Quantum Materials
20–23 Jul	San Francisco, CA, USA	SEMICON WEST
28–31 Jul	Montreal, CA	IEEE Nano
23–28 Aug	Copenhagen, DK	EMC
24–28 Aug	Rennes, FR	Condensed Matter Days
Early Sep	*tbd*	Flatlands
6–9 Sep	Lecce, IT	Eurosensors
7–9 Sep	Paris, FR	NanOP
14–18 Sep	Leuven, BE	MNE
14–17 Sep	Warsaw, PO	EMRS Fall
16–17 Sep	Bochum, DE	GMM Workshop Micro-Nano Integration
21–25 Sep	Strasbourg, FR	Graphene Week
4–8 Oct	Palm Springs, CA, USA	MicroTAS
Oct	Changdu, CN	China MNE
20–25 Oct	Columbus, OH	AVS
25–28 Oct	Rotterdam, NL	IEEE Sensors
29–30 Oct	Dortmund, DE	NRW Nano
29 Nov – 4 Dec	Boston, MA, USA	MRS Fall
9–11 Dec	San Francisco, CA, USA	IEDM
17 Dec	Kolkata, IN	IWPSD

HEIDELBERG INSTRUMENTS
The power of direct writing

7th Thermal Probe Workshop



18–19th March 2020 • Zürich

This 2-day workshop has grown into a small conference with around 25 talks and 70–100 experts from a broad range of nanosciences, attending.

Registration and more information at tpw-zurich.com

Novel devices enabled by nanofabrication
2D materials, qubits, topological insulators, Josephson junctions

Advanced pattern transfer & materials
High aspect ratio structures and new materials

Thermochemical & additive manufacturing
Local conversion of materials and dip-pen nanolithography

Ultra-high-resolution patterning
Sub 20-nm nanofabrication and pattern transfer

Nanofluidics & nanomanufacturing
Lab-on-a-chip, engineering nano-landscapes, self-assembly

Large-area nanostructuring
Nanoimprint lithography, large nanostructures arrays

Nanoscale imaging & metrology
Advanced probe microscopy

Heated tips, MEMS & thermometry
New cantilever designs and thermal metrology

Industrial flash-session
Latest development in direct-write lithography tools and resists

Icons made by eucalyp and freepic from www.flaticon.com

THE LITHOGRAPHER, 1918

Lithograph

Childe Hassam, American, 1859–1935

45.7 x 31.1 cm (18 x 12 1/4 in).
Stone:
34.7 x 30.2 cm (13 11/16 x 11 7/8 in.)

Gift of Mrs Childe Hassam

1940.77

Culture: American

Period: 20th century

Classification: Works on Paper — Prints

Status: By appointment

5 µm
70.0 nm
60.0
50.0
40.0
30.0
20.0
10.0
0.0