Editorial

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Toward full three-dimensional (3D) high volume fabrication

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Providing freeform full 3D fabrication on a large scale is the current technology trend (Figure 1) [1]. 3D fabrication is frequently discussed along with additive fabrication and next generation industrialization, where on-demand fabrication, or printing, of desired work pieces without expensive tooling from any imaginable material can be done on-the-spot and everywhere in the world. This bold vision needs to be proven first; however, 3D printing of essential parts has already replaced traditional fabrication. For example, the aviation industry is working hard on integrating 3D printing of metals and there are already 3D printed components in recent generations of airplanes [6]. Finally, we should not forget about the established sector of at home polymer 3D printing and the professional prototyping as well as functional device fabrication all being based on polymers.

When it comes to the smallest pieces that drive the evolution of our tech-society, namely nanoelectronic systems and microsystems, the visions for true 3D technologies at the micro and even the nanoscale are also bold. Quoting a pioneer in nanoimprint lithography (Stephen Chou, Princeton) [7]: "[…] *the commercialization of nanotechnology critically depends upon our ability to manufacture, if you want to use nanostructures commercially – you need to have the nanofabrication abilities*". It is as simple as that, and it is obviously true for 3D patterning. A very good candidate for high-resolution 3D printing and fabrication, even at the industrial scale, is femtosecond laser processing which makes use of non-linear optical effects to finally beat the diffraction limit by multi-photon lithography and stimulated emission depletion. Jonušauskas et al. and Stender et al. broadly discuss the technology in two review articles in this special issue. In the lab, of course, there are plenty of ideas and curiosities that might be realized with this technology being available already since the end of the last century. Applications may reach from photonic and mechanical metamaterials [8] all the way to photonic chip bonding [9] and smart mesoscopic objects and particles – just name it. On the industrial and applied scale, refractive and diffractive micro-optics play an important role. This has become very clear at the NIL Industrial Day 2019 in Aachen [http://www.nil-industrialday.org/]. Such optics are not new, however, new applications such as structured light applications and high-performing, light-weight optics for virtual and augmented reality wearables bring new challenges for traditional lithography. Now, techniques such as multilevel and grayscale patterning will become even more interesting. Especially using direct writing methods such as grayscale laser, electron or ion beam lithography allows for fabricating optical elements with challenging specifications for the field of view, illumination homogeneity and photon efficiency. Some of the major potential techniques in the field are covered in this special issue, including an excellent review on electron beam grayscale lithography by Unno et al. All these techniques have in common that they seem very laborious on the first look and might for that reason still live an abandoned life in niche applications waiting for the killer-application. It might be knocking on our doors just this moment. In addition, pattern transfer and high-volume replication is required to bring most of the valuable, original polymer or resist patterns into more durable and end-user friendly materials.

This special issue wants to motivate more industrial researchers to use the exceptional potential we have today with the integration of such 3D techniques into design and into fabrication flows. 3D lithography is just another lithography method in our toolbox. Let us make use of it.

Another key technique is required to help in accessing the high-volume fabrication and multiplication of original patterns realized with the mentioned 3D techniques. Here, we come back to the initial quote borrowed from nanoimprint lithography – a technique which also originally peaked in attention at the end of the last century as next generation lithography techniques for semiconductor

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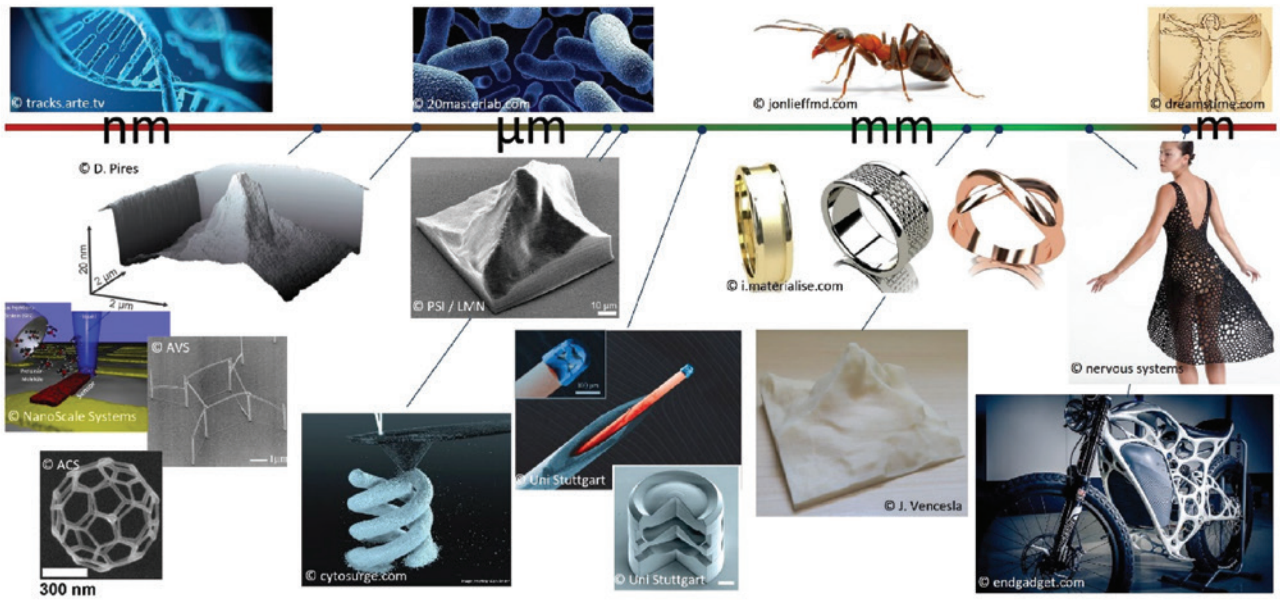

Figure 1: 2.5D and 3D patterning across scales: While desktop 3D printing in the millimeter- and centimeter-range has become state-of-the art technology, printing at the meter-scale especially for non-polymeric materials is ready but understanding resulting component properties, e.g. for layered metals pieces, is still an important research question. On the micrometer-scale, some interesting methods have evolved from laboratories and are about to enter industrial readiness, e.g. direct laser writing and printing based on multi-photon absorption (© PSI/LMN permission by Elsevier [1]). This technology is highly interesting for the optical industry because, e.g. multi-level micro-lenses aare possible that are very difficult to achieve with any other method (© University of Stuttgart permission by Nature Photonics [2]). At the nanometer-scale, current printing speeds are extremely slow considering the volume throughput. However, focused electron or ion beam-based deposition is an intrinsically 3D capable nanotechnology and it is worth following its future development (© NanoScale Systems, AVS [3], ACS [4]). Scanning probe methods are currently among the highest resolution concepts being available for 3D patterning (© D. Pires permission by AAAS [5]).

technology and which is currently becoming the method of choice for many photonic fabrication flows. We see a huge potential of such mechanical replication techniques in multiplying 3D – or more precisely 2.5D – surface topographies to redeem the potential of complex pattern origination. To achieve commercially successful 2.5D topography patterns – i.e. diffractive optics – we need to have one true method for origination and one true method for replication. This special issue tries to give a good overview on some important technologies.

However, new concepts are required for mass fabrication of true 3D structures such as metamaterials realized by femtosecond laser processing. So far, replication of undercut structures, etc. do not work well except for some limited undercuts [10] and some smart lab "curiosities" [11]. We hope that someone is inspired by this special issue to bring a new disruptive technology – nothing is impossible. Exploiting parallelization of multiple-beams is a good start for massive direct fabrication.

Not to forget that we have with scanning probe lithography and electron or ion beam-induced deposition true nanoscale techniques for 2.5D and 3D. While imprint-based replication is already in place for scanning probe-based pattern origination and large area speed up in massive tip parallelization might begin to lab prototypes soon, replication of fine structures made from 3D-deposited metals [4] are waiting to be discovered. The same is true for an industrial application of such structures. However, even in research and basic science large volume fabrication of such metal nanoscale 3D structures would be nice to have.

We hope you will enjoy reading this special issue and that it will inspire your work.

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Editors

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