Scaling up nanodevice fabrication with parallelized multi-tip thermal scanning probe lithography

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Device fabrication in the nanoscale requires high resolution patterning of complex, often arbitrary, structures with high fidelity; excellent overlay accuracy between layers, handling of underlying topographies, and realistic throughput. An additional challenge, especially for photonic structures, metasurfaces and biomimicry, is the size of designs and large number of elements in the designs. We present layout handling and high resolution, high throughput thermal scanning probe lithography (t-SPL), utilizing the NanoFrazor from Heidelberg Instruments, to address these challenges. T-SPL is a direct-write nanolithography method that employs an ultrasharp thermal tip to generate and inspect nanoscale structures[1]. Through precise localized thermal stimulus, this unique technique enables high-resolution, damage-free patterning with the capability of performing direct physical and chemical modification of materials[2]. With integrated automation, markerless alignment, and a closed-loop feedback mechanism, the NanoFrazor adeptly addresses complex fabrication challenges across diverse fields such as quantum nanoelectronics[3], nanophotonics[4], and nanobiosystems[5].

The first multi-tip version of the NanoFrazor, the Decapede (see Figure 1), allows for scaling up the areas that can be patterned at a time and speeding up the writing process by up to a factor of 10 while maintaining resolution. By parallelizing the tips, we were able to reduce overhead time, achieving simultaneous patterning of ten designs on the same surface. This scale up facilitated uninterrupted patterning of photonic sieves, metalenses and bionano-arrays.

In this talk, we will present successfully implemented use-cases of Decapede patterning, with a focus on nanophotonics applications. We will show how the multi-tip was used to create a photonic sieve, seen in Figure 2, via a rapid single indentation mode of patterning. The patterned single dots were then transferred into pillars etched in silicon, through a series of standard microfabrication steps. In another example, we will showcase how the multi-tip patterned a metalens spanning a total area of 690 µm x 690 µm, with a total of 2 million high-resolution rectangular elements, etched 300 nm deep into Si, as seen in Figure 3.

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[1] S. T. Howell et al., *Microsyst. Nanoeng.* **6** 21 (2020).
[2] E. Albisetti et al., *Nature Reviews Methods Primers* **2** 32 (2022).
[3] L. Shani*, J. Chaaban* et al., *Nanotechnology* **35** 255302 (2024).
[4] N. Lassaline et al., *Nature* **582** 506-510 (2020).
[5] X. Liu et al., *Advanced Functional Materials* **31** 2008662 (2021).

Figure 1: (left) NanoFrazor in-situ microscope showing the Decapede over a resist-coated substrate, writing features in both 2D high-resolution and in grayscale. (right) Simulated image of the Decapede patterning different features, alongside the integrated laser writehead.

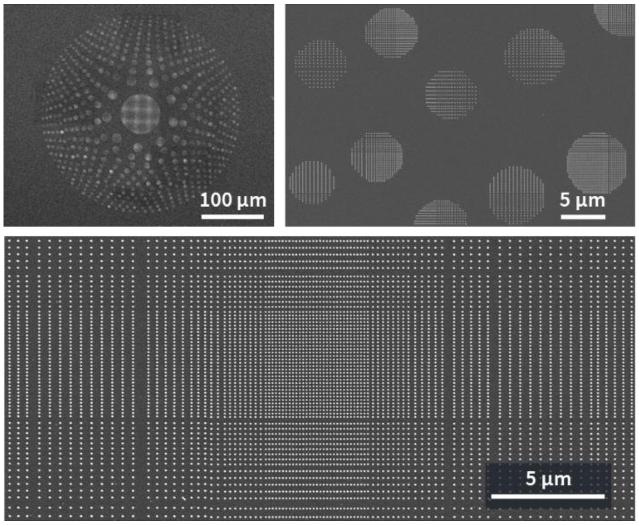

Figure 2: SEM images of the final photon sieve with structures following a bisinusoidal distribution. The structures were created by single tip indentations with a pitch of 75 nm, and then etched 200 nm deep into Si.

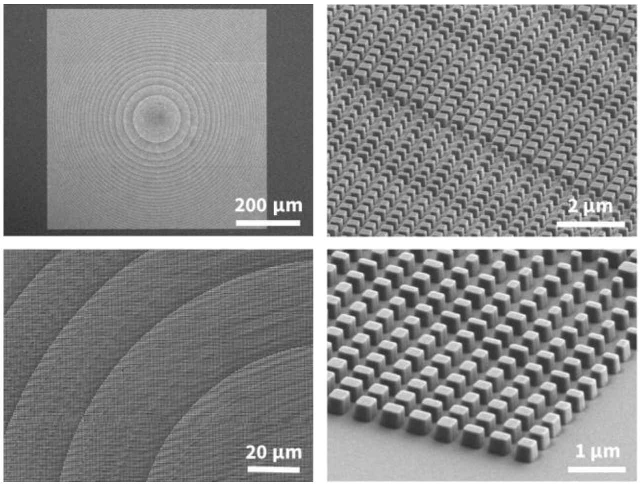

Figure 3: SEM images of the full metalens (top left), and close-ups of its individual components, highlighting the Nanofrazor decapede's large-area high-resolution patterning capability.