# Image reversal through NanoFrazor patterning and pattern transfer processes: from nanoholes to nanopillars

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The NanoFrazor uses thermal scanning probe lithography (t-SPL) for the simultaneous patterning and inspection of nanoscale structures[1]. The technology has proven its value as an enabler of novel ultra-high resolution nanodevices[2], as well as an asset for improving the performance of existing device concepts[3]. In doing so, the NanoFrazor is establishing itself as a direct-write nanolithography method for advanced nanofabrication, as well as a complementary extension to other mask-less nanolithography methods such as electron beam lithography (EBL).

A broad range of t-SPL applications[1] spanning from ultra-high resolution 2D and grayscale patterning, to chemical and physical modification of matter at the nanoscale have been demonstrated in the last few years. Applications such as critical areas of nanoelectronic and nanophotonic devices are gaining significance with advances in fabrication technology.[4] The key strengths of the NanoFrazor relevant for these applications include its nanometer-precise markerless overlay, and the ability to locally remove thermal resists or modify surfaces, while remaining non-invasive towards sensitive materials and free from proximity effects. The NanoFrazor tool also allows for the control of the line edge roughness of structures in an on-the-fly manner by adjusting the pixel size during patterning. In this work, the high-resolution patterning capability of the NanoFrazor is exploited to write arrays of nanoholes with diameters ranging from 30-200 nm as seen in Figure 1. Through a series of standard pattern transfer processes illustrated in Figure 2, an image reversal of the nanoholes is then performed to reveal arrays of silicon nanopillars with diameters ranging from 30-200 nm, as shown in Figure 3. Nanopillar fabrication is in particular interesting for flat optics and metasurfaces applications where a typical metalens can use an array of sub-100 nm diameter pillars to achieve the functionality of multiple refractive lenses.[5] Moreover, such an image reversal process is versatile and can be used for any arbitrary shape or pattern written with the NanoFrazor.

In this talk, I will present the background and unique capabilities of the NanoFrazor technology. I will also discuss a complete patterning and pattern-transfer solution based on t-SPL and standard semiconductor processes that allows for the image reversal of any written design. In particular, I will showcase how this NanoFrazor-based image reversal process can create nanopillars out of nanoholes.

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[2] M. J. Skaug et al., Science **359** (6383), 1505–1508 (2018).
[3] X. Zheng et al., Nature Electronics **2**, 17-25 (2019).
[4] N. Lassaline et.al., Nature **582** (7813), 506-510 (2020).
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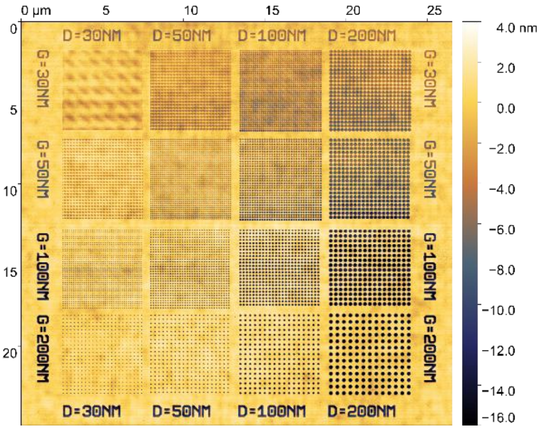


*Figure 1:* (a) In-situ NanoFrazor topography image of arrays of nanoholes patterned with different diameters *D* and gaps *G*.

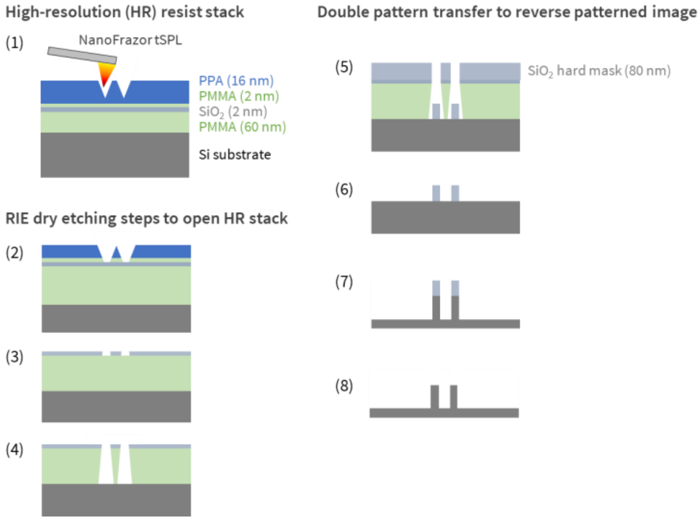


*Figure 2:* Cross-section schematics illustrating the pattern transfer steps required to perform an image reversal of the NanoFrazor patterns from nanoholes to nanopillars. (1) Resist stack used for NanoFrazor high-resolution (HR) patterning. (2)-(4) Reactive ion etching (RIE) dry etching steps for transferring the nanoholes patterns into the HR stack, starting with (2) a $O_2$ descum step to open the top thermal resist PPA and the 2 nm PMMA layer, then (3) a $CHF_3$ etch to open the 2 nm $SiO_2$ hard mask, (4) and a final $O_2$ etch step to etch open the PMMA underlayer.
(5) Evaporation of a 50 nm of $SiO_2$ hard mask layer. (6) Lift-off of the HR stack in acetone. (7) HBr dry etching of the Si substrate.
(8) BHF wet etching step to remove the SiO2 hard mask layer.

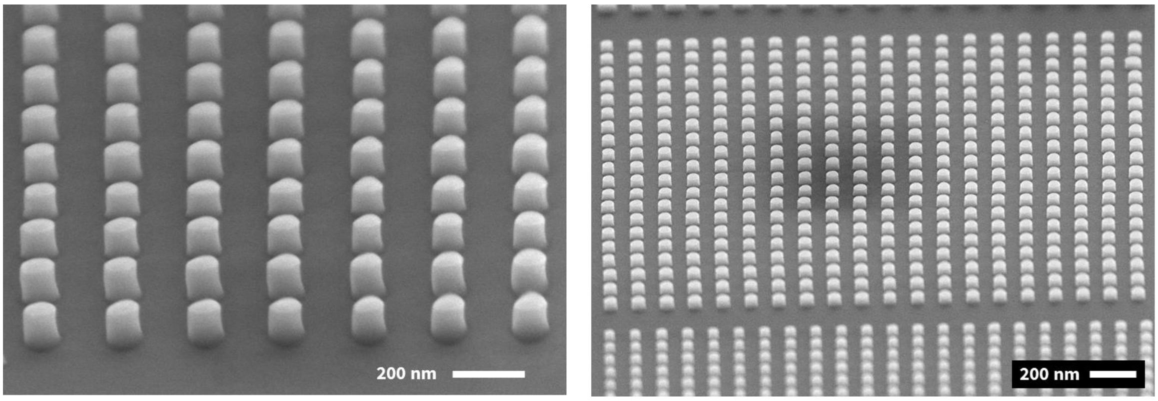


*Figure 3:* Tilted SEM images of 100 nm high silicon nanopillars with different diameters and spacings, obtained after the NanoFrazor image reversal process illustrated in Figure 2.