HEIDELBERG INSTRUMENTS

New generation of thermal scanning probe lithography

Exploring paths for scale-up and automation with the NanoFrazor

September 16th, 2024

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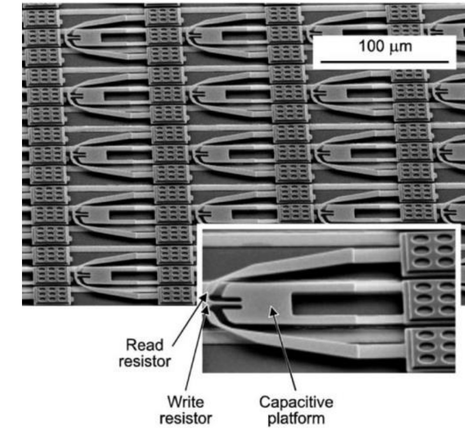
NanoFrazor by Heidelberg Instruments Nano

- NanoFrazor commercial since 2014 (SwissLitho AG)
- SwissLitho joined Heidelberg Instruments in 2018
- ~20 employees in Zurich on NanoFrazor technology

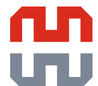
The next generation NanoFrazor: modular, flexible, and 10 times faster!

Origin Of Technology



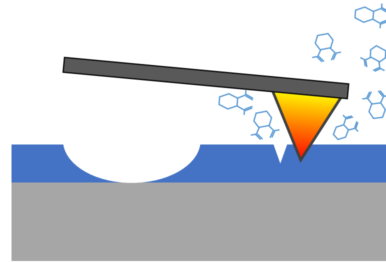
IBM Millipede (1995 – 2007)

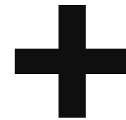
IBM Research Zürich



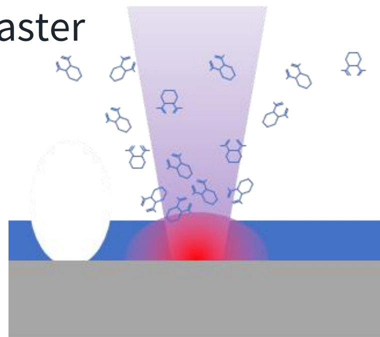
Principle of the NanoFrazor Technology

- Writing
  - Thermal probe sublimation
    - 10 nm sharp tip
    - Fast and accurate deflection

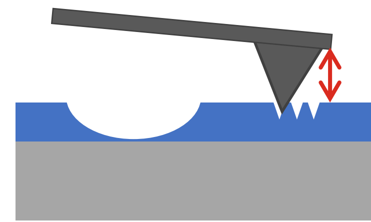




- Direct Laser sublimation
  - Micrometer resolution
  - 100x faster

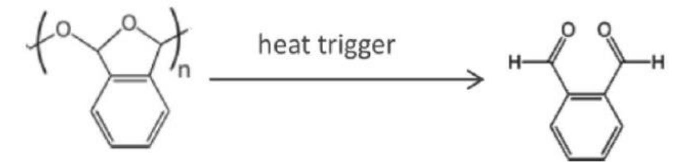


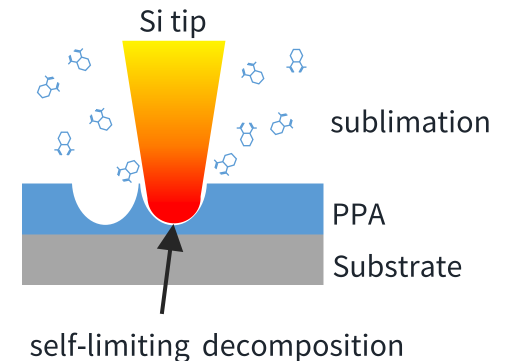
- Reading
  - In-situ high-speed imaging
    - Inspection
    - Metrology
    - Overlay & Stitching



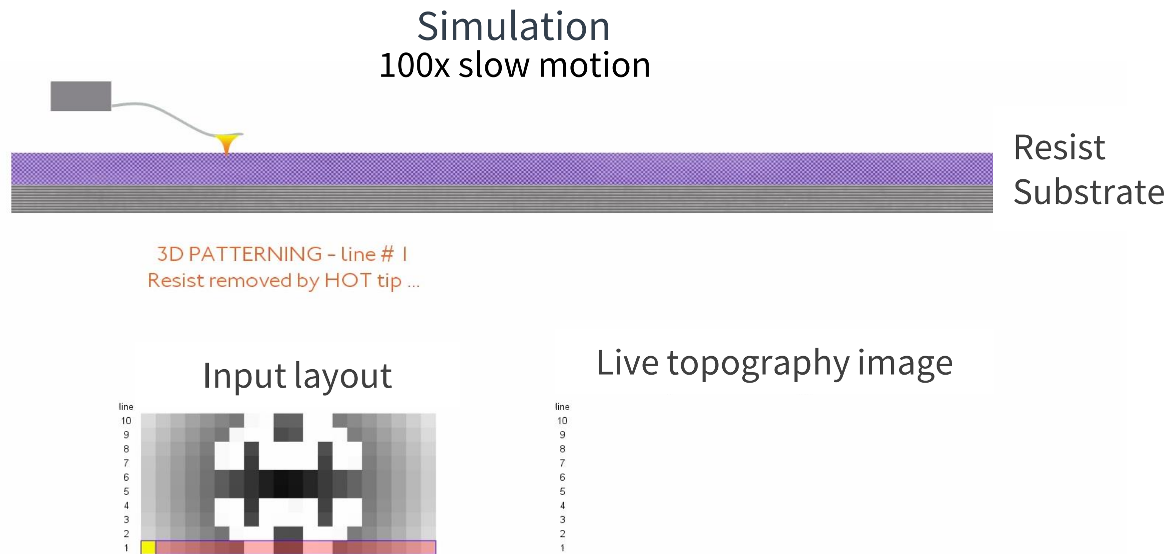
- Unique distance sensor
  - Level plane & autofocus
  - Drift corrections
  - Other calibrations

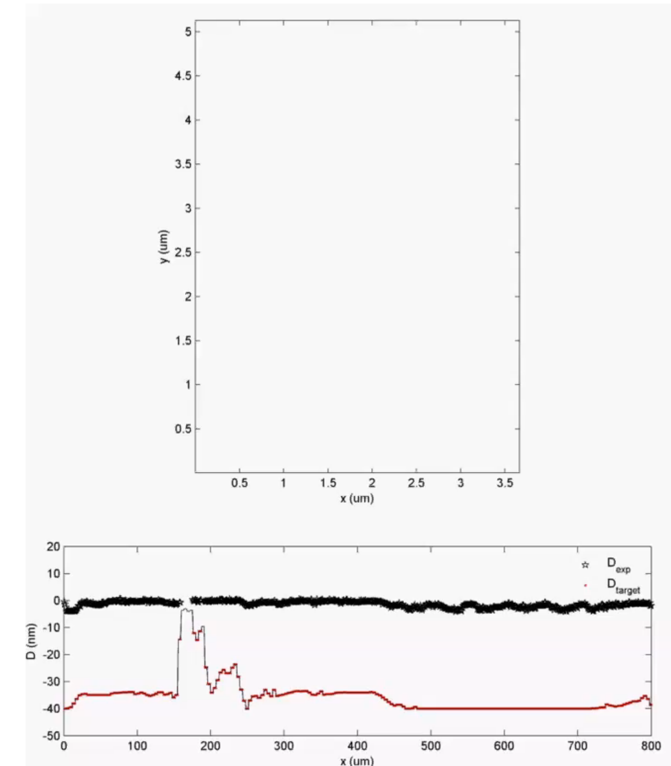
- Thermally-sensitive resist (PPA)
  - PPA resist decomposes upon heating by the tip
  - Endothermic decomposition reaction prevents spread of heat
  - No proximity corrections necessary





Closed-Loop Lithography: Patterning & Imaging



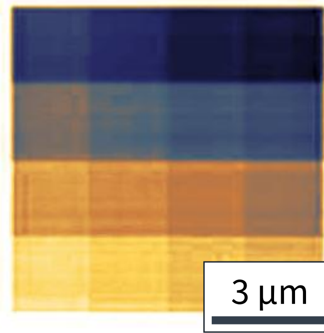


R. Garcia et al. Nat Nano 9, 577-587 (2014)

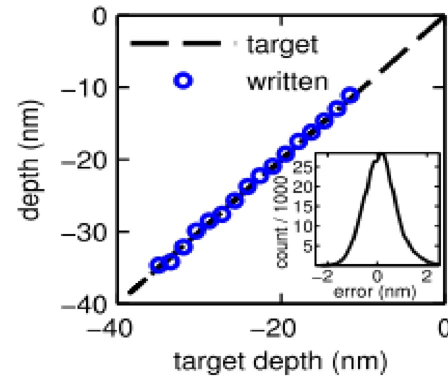
- Simultaneous reading and writing of nanofeatures
- Real-time patterning, imaging, and feedback
- Online adaption of patterning every few milliseconds
- No separate metrology necessary after lithography

NanoFrazor High-Resolution Grayscale Lithography

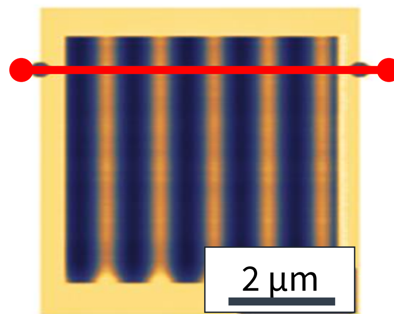
Single nanometer accuracy



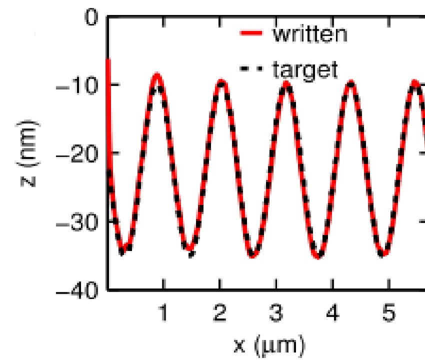
Discrete levels (1.5 nm)
Rawlings et al, Sci. Rep., 2017



error (1σ): 0.69 nm

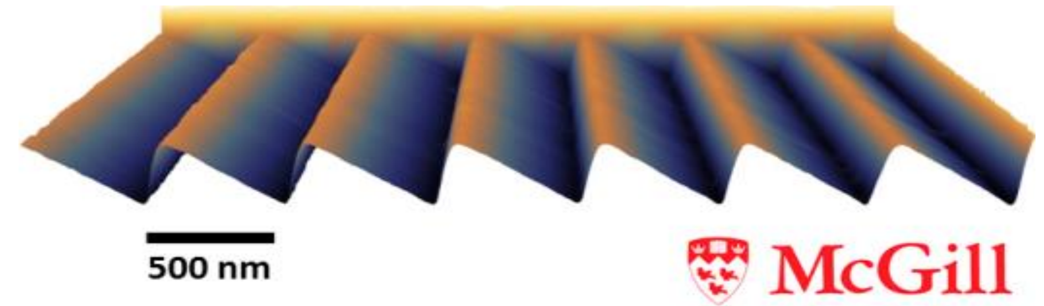


Continuous sine wave

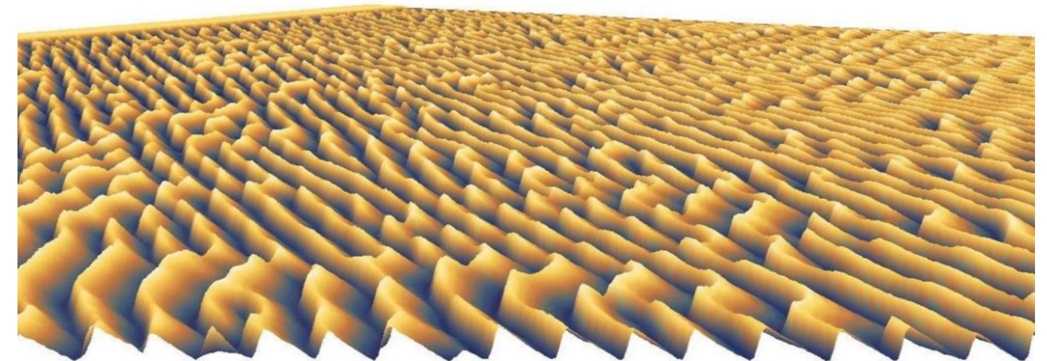


error (1σ): 0.85 nm

Grayscale high-resolution patterning examples



Blazed grating in PPA, Ristic et al, OSA Tech Digest, 2015

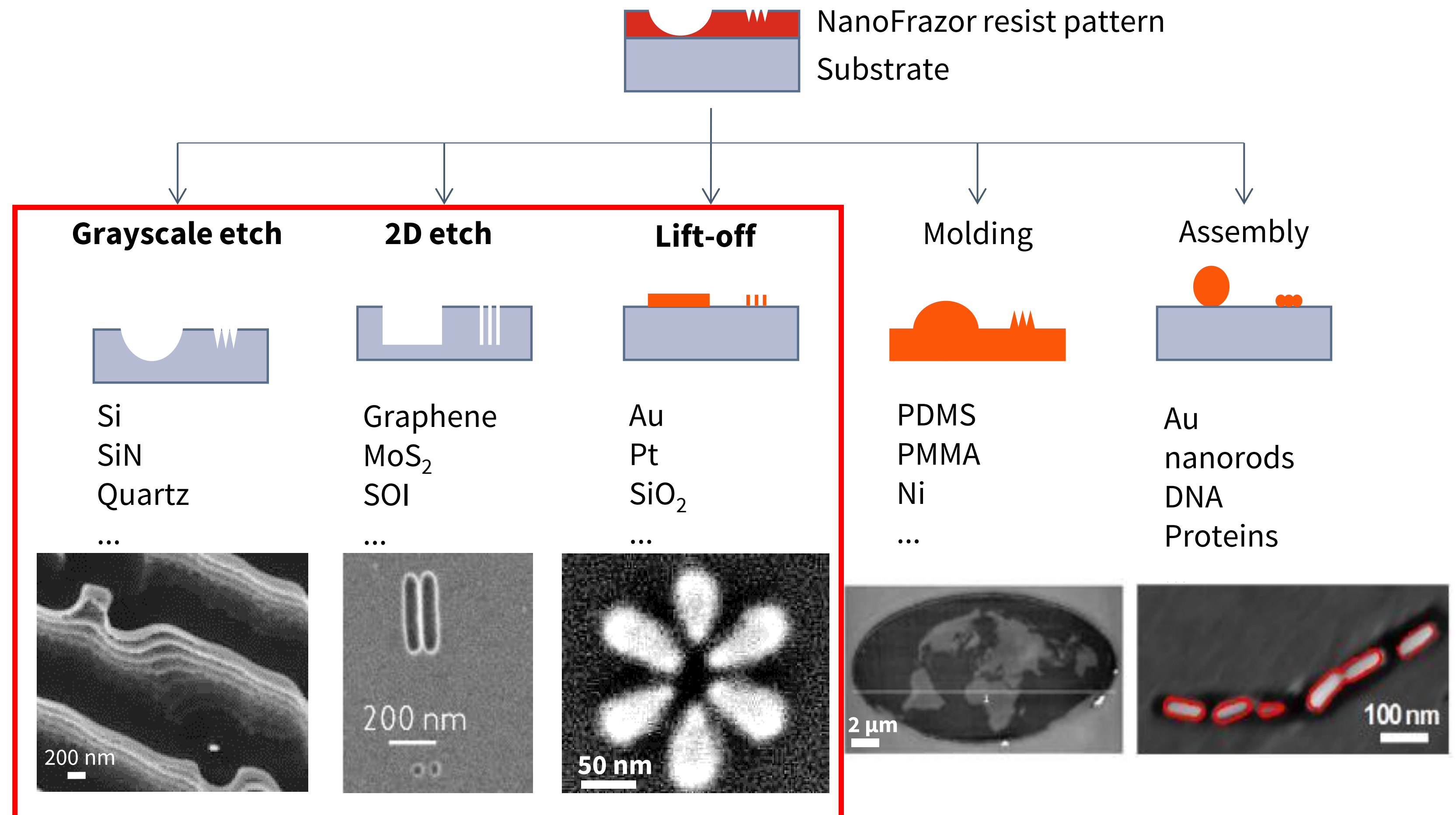


3D hologram in PPA, Kulmala et al, SPIE Adv. Litho., 2018

Pattern Transfer Overview

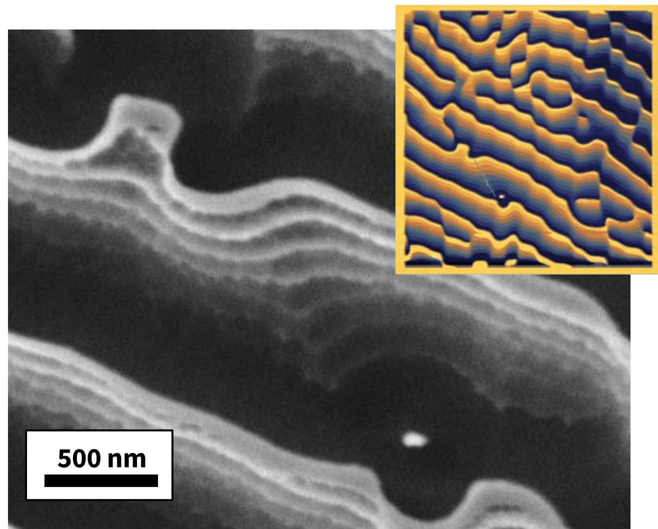
- Transfer the NanoFrazor pattern into **almost any material of choice**
- NanoFrazor patterns are **compatible** with a **wide range of standard transfer processes** and beyond*

*Howell *et al.*, **Nature Micro Nano** 2020, Thermal Scanning Probe Lithography - A Review



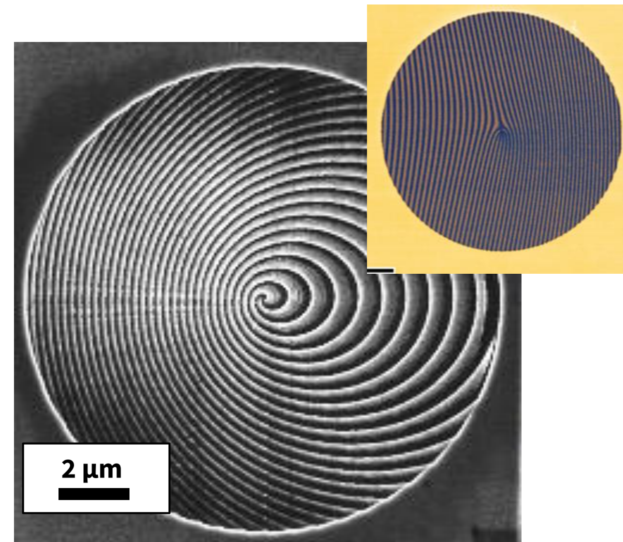
Sub-nm Grayscale Precision Enables new Possibilities Novel Applications in Photonics

Hologram in Si (700 nm deep)



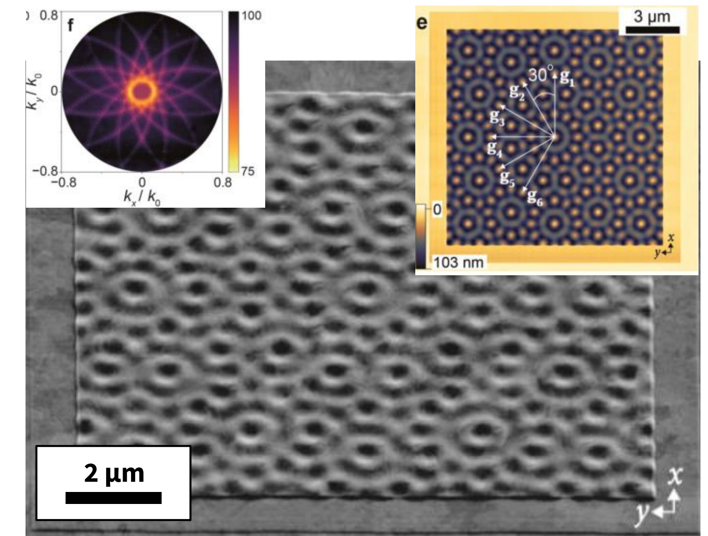
Kulmala *et al.*, SPIE, 2018

Phase Plates in SiN membranes



Hettler *et al.*, Micron, 2019

Optical Fourier Surfaces

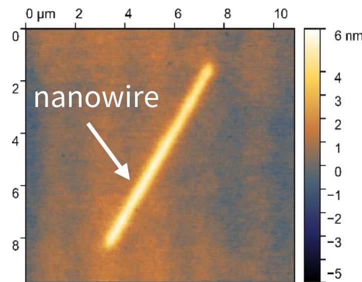


Lassaline *et al.*, Nature, 2020

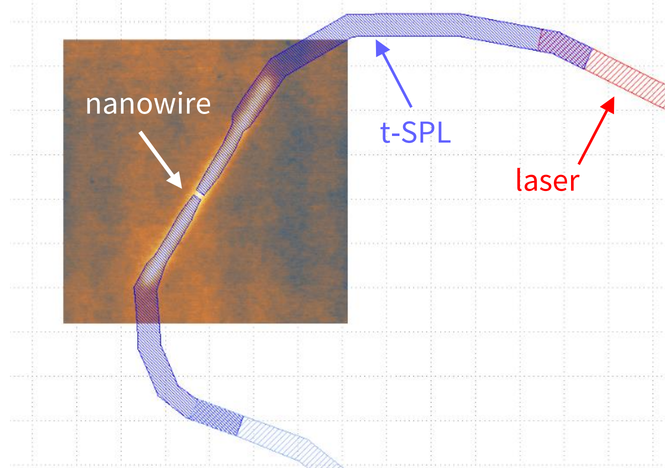
Markerless Overlay Principle

Inside the NanoFrazor:

In-situ reading of 70 nm nanowire buried under 300 nm resist

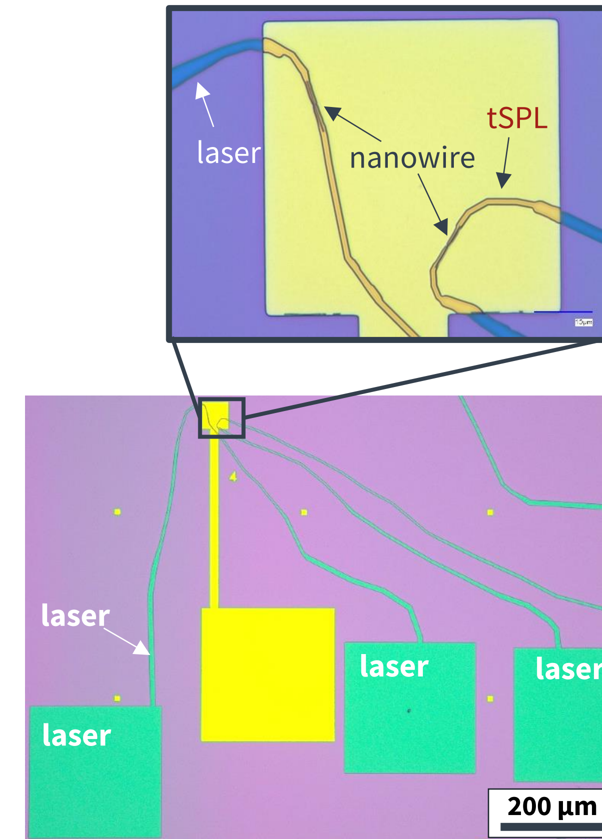


Place design pattern directly on topography image



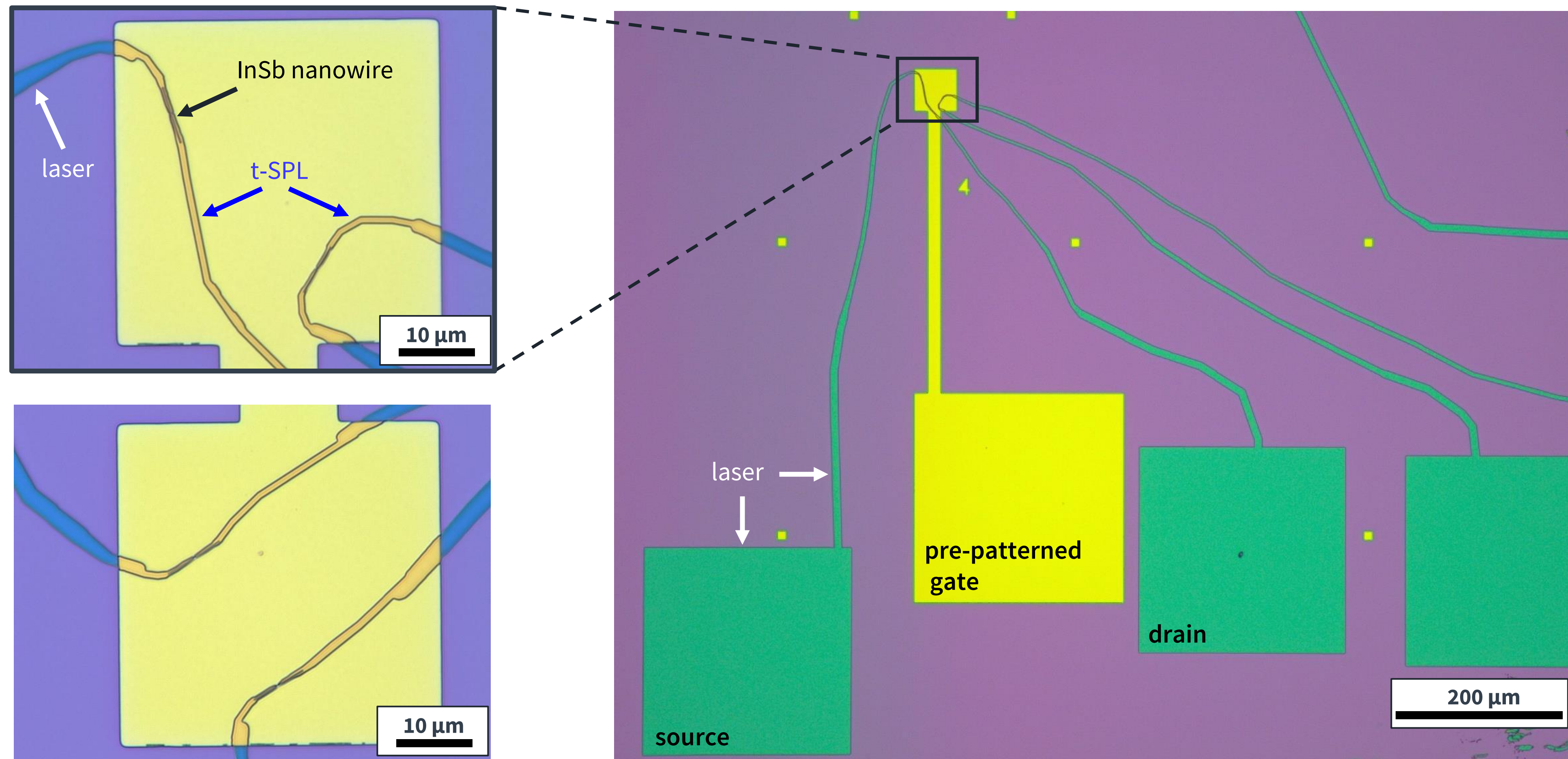
tSPL and laser patterning into the resist

Optical microscope images of nanowire design after patterning of tSPL and laser contacts.



Markerless Overlay, as seen in the NanoFrazor software

t-SPL and Laser Lithography for patterning InSb nanowire-based quantum devices

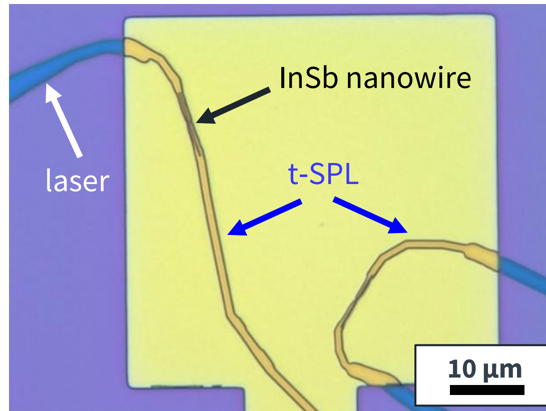


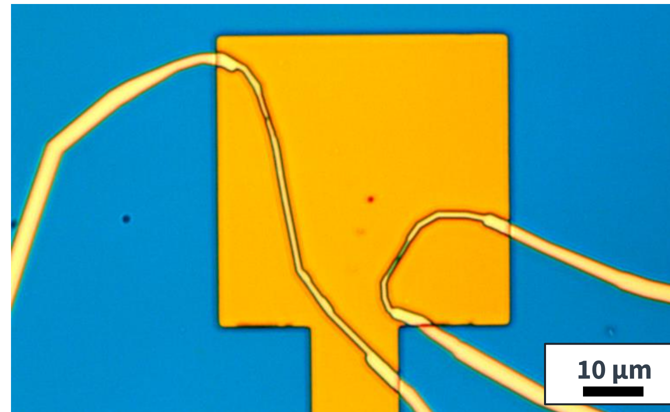
Optical microscope images after NanoFrazor t-SPL and laser patterning of source and drain electrode lines and pads.

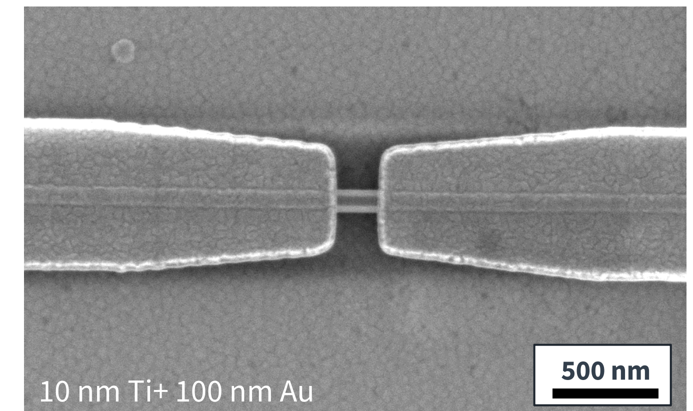
Shani*, Chaaban* *et al.*, Nanotechnology, 2024

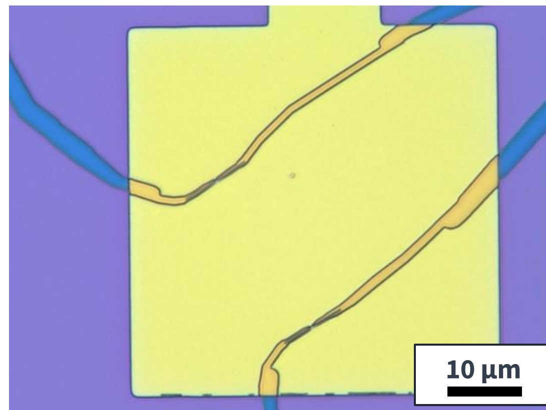
Markerless Overlay – NanoFrazor patterning of source and drain on InSb Nanowire

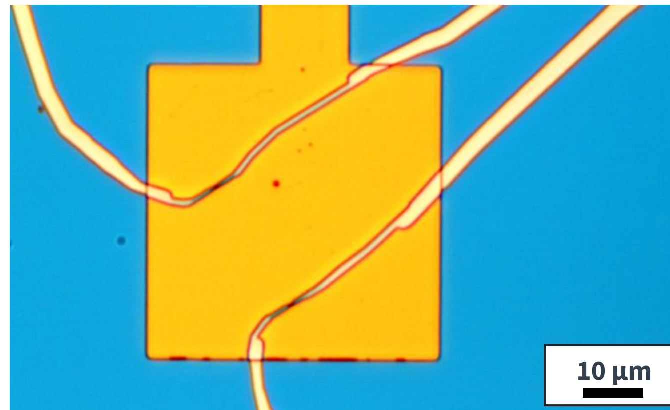
After NanoFrazor patterning | After metallization and lift-off | SEM of nanowire and t-SPL contacts

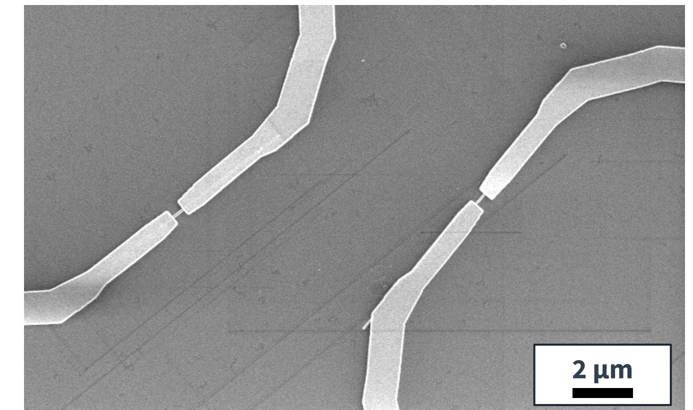








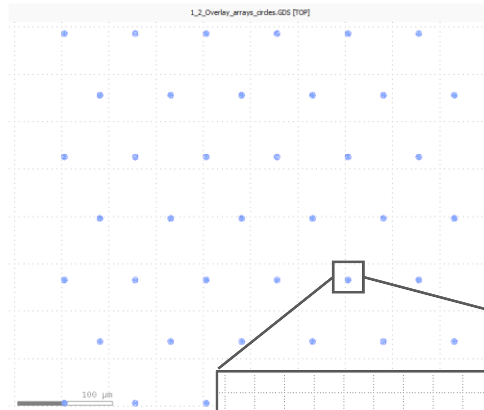


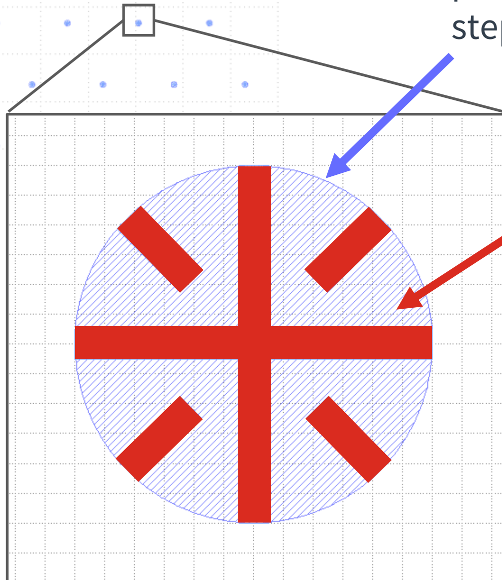


Shani*, Chaaban* *et al.*, Nanotechnology, 2024

From manual to automated overlay

GDS Design: array of pillars

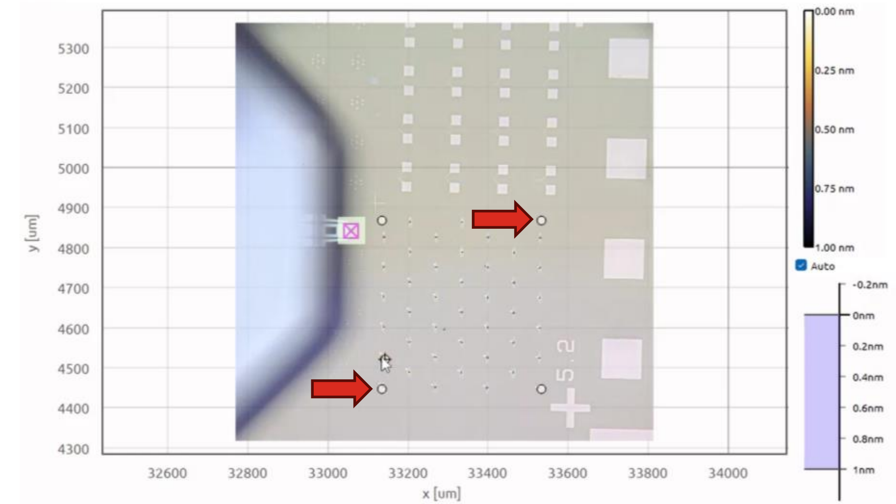




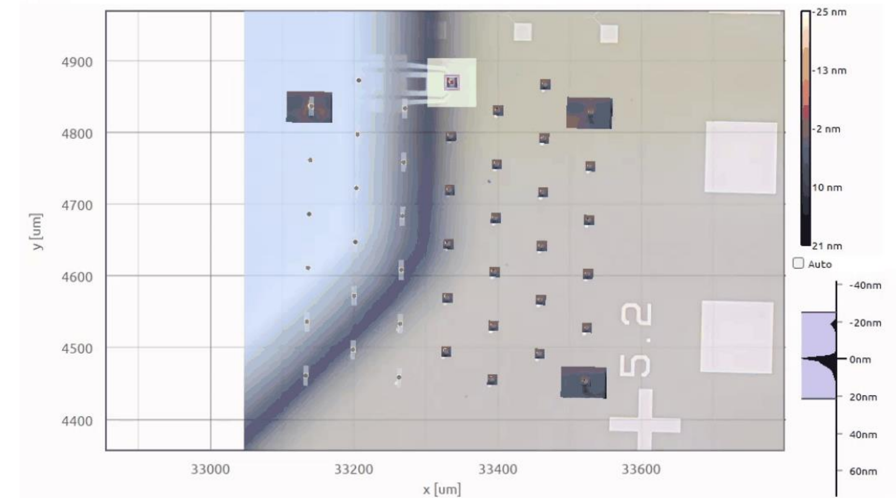
Pillar made with previous lithography step

Cross that needs to be precisely aligned on the pillar

Single-step manual alignment to adjust rotation

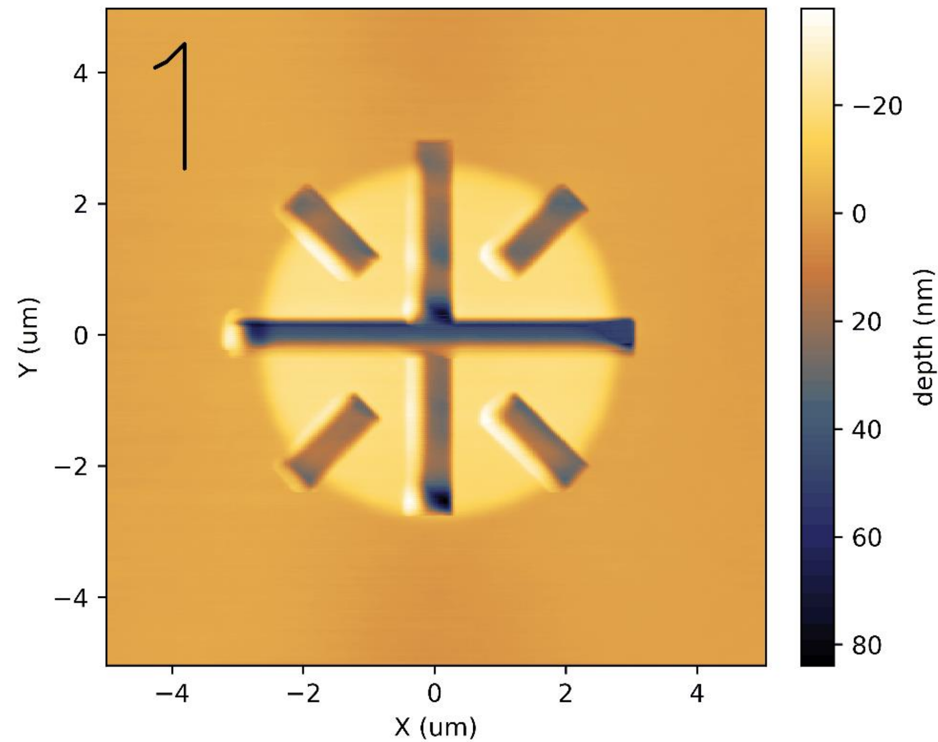


Automated markerless alignment of all features

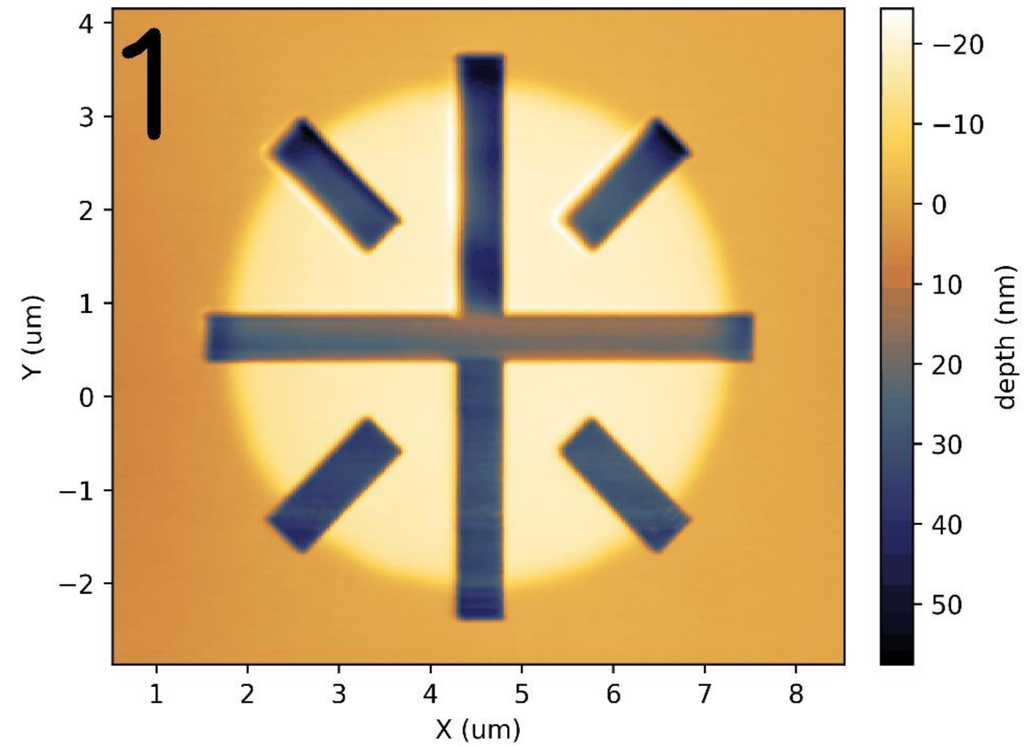


Results!

Without automatic overlay



With automatic overlay

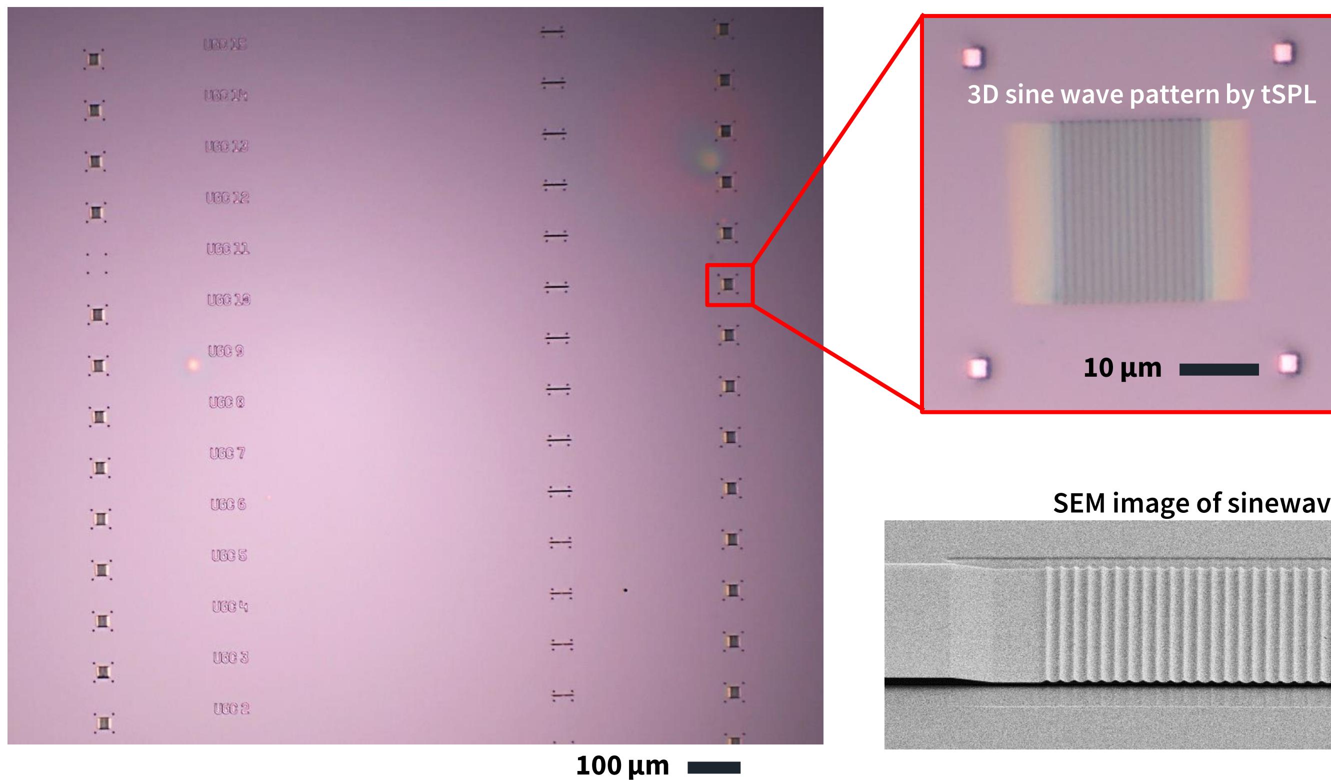


Overlay accuracy < 25 nm

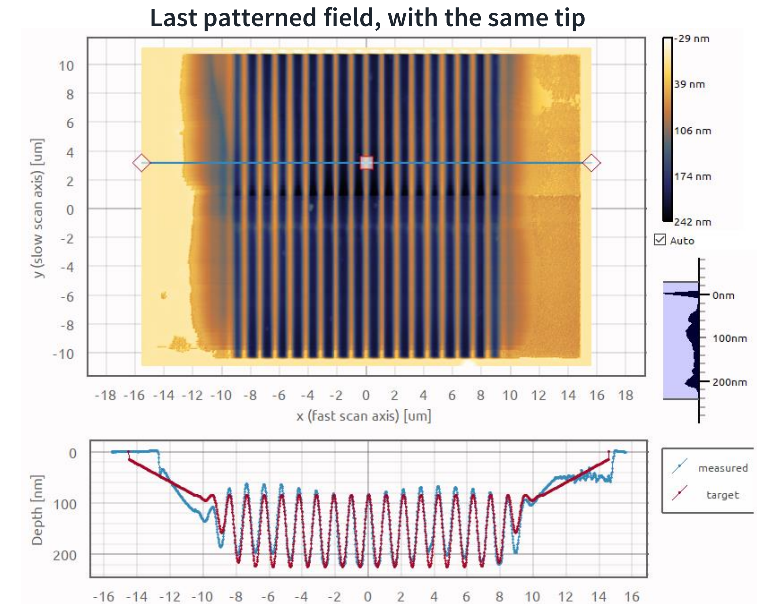
Automated overlay of grayscale sine waves

- Automatic overlay functionality used to align and pattern 45 grayscale sinewave gratings across markers on a 1.4 x 1.4 mm^2 sample
- Substrate: SOI chip coated with a thick PPA layer of ~225 nm

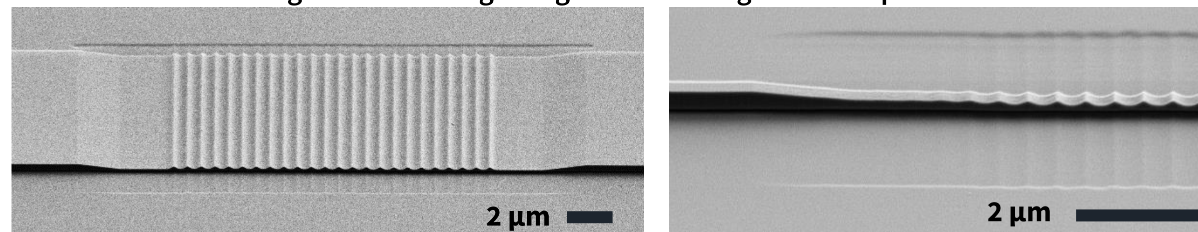
Optical microscope images after automatic overlay of 45 sine waves patterns across sample area of 1.4 x 1.4 mm^2



Last patterned field, with the same tip



SEM image of sinewave gratings in a Si waveguide after pattern transfer



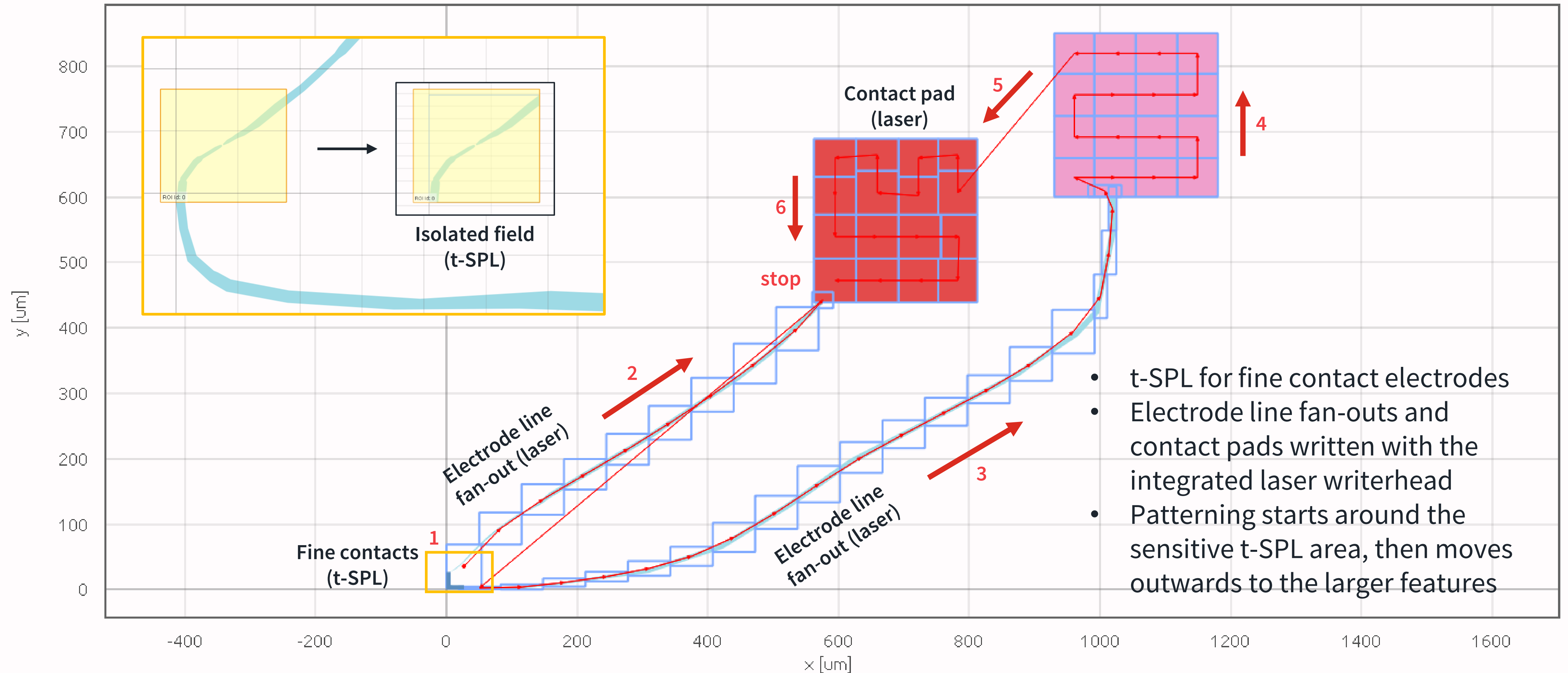
Daniel Petter, Yannik Glauser, Nolan Lassaline, ETH Zurich

How do we handle large and complex layouts in a smart manner?

Partnering up with GenISys

- Implement an existing importer (GenISys BEAMER engine) within the NanoFrazor software
- Enable use of advanced GenISys functionalities through the NF software, notably:
    - Fields creation modes: Fixed, Floating and Follow-Geometry
    - Ordering of fields
    - Region selection and application of local rules
- With the new functionalities, create new applications and NanoFrazor workflows

Tackling Large(r) Designs with Smart Splitting



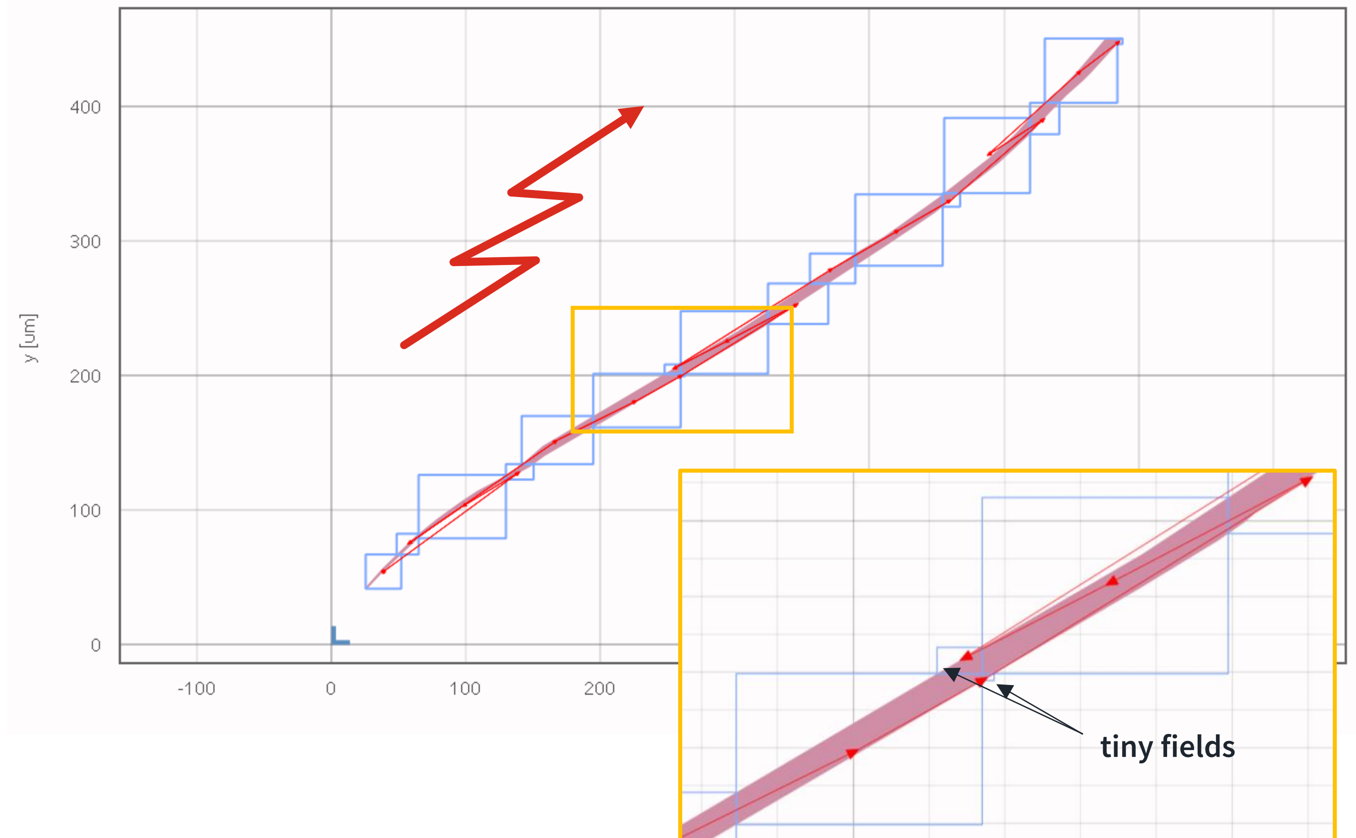
- t-SPL for fine contact electrodes
- Electrode line fan-outs and contact pads written with the integrated laser writerhead
- Patterning starts around the sensitive t-SPL area, then moves outwards to the larger features

Field ordering in an electrode line

- Elongated, diagonal layout (purple)
- Thin red arrows show order of fields (blue)

Option 1: **Fixed Fields**

- Default field ordering, before *GenISys* integration
- Patterning goes back and forth between fields, tiny fields appear
- Number of fields: **17**
- Patterning time: **28 min**



Field order needs to be manually rearranged

- 0,1,2,3,… → 0,3,2,1,4,5,9,8,7,10,…
- Tedious and time-consuming (**> 5 min**)

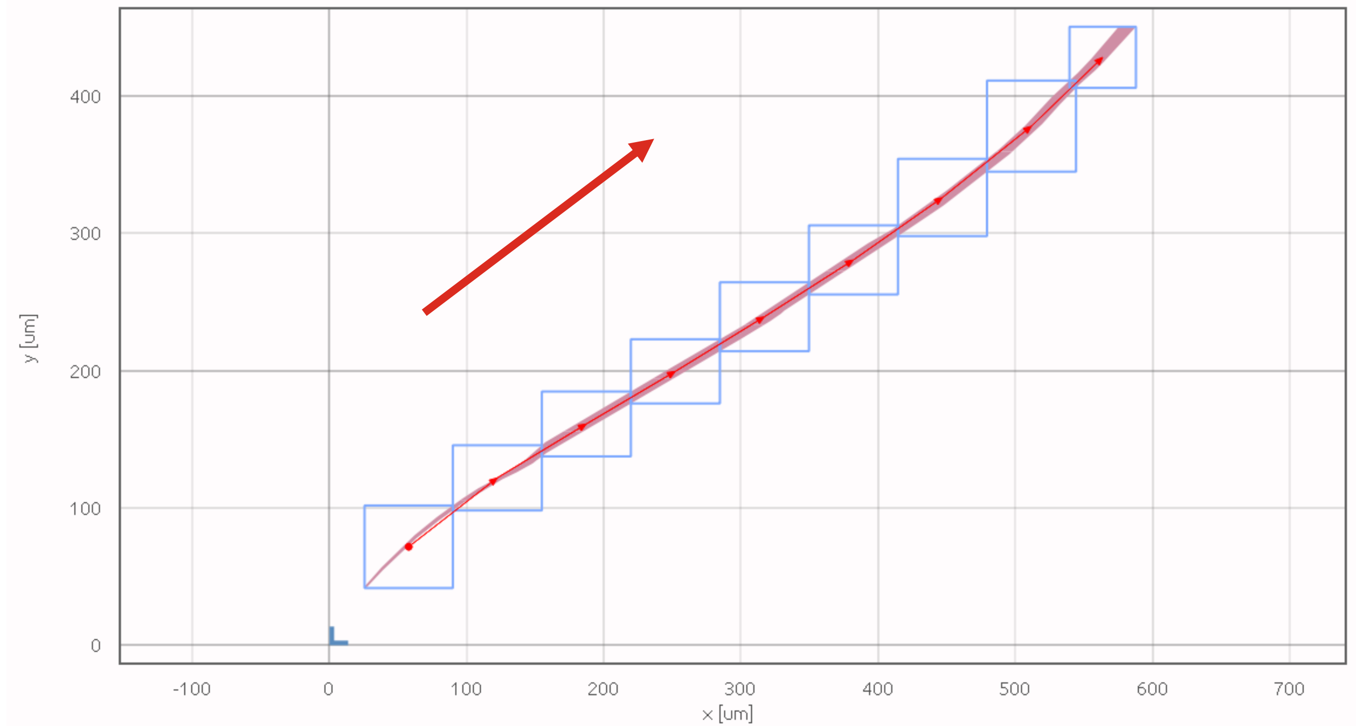
Field ordering in an electrode line

- Elongated, diagonal layout (purple)
- Thin red arrows show order of fields (blue)

Option 2: **Floating Fields**

- Fields are arranged logically, and automatically, here from bottom to top
- Eliminated tiny fields
- Number of fields: **9**
- Patterning time: **24 min**

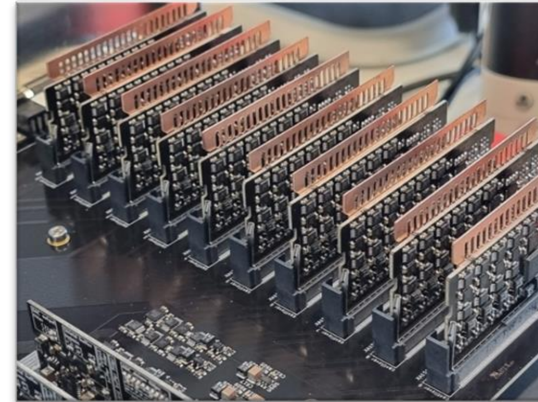
Fewer fields lead to shorter patterning times and more accurate stitching. No overhead due to manual ordering of fields!



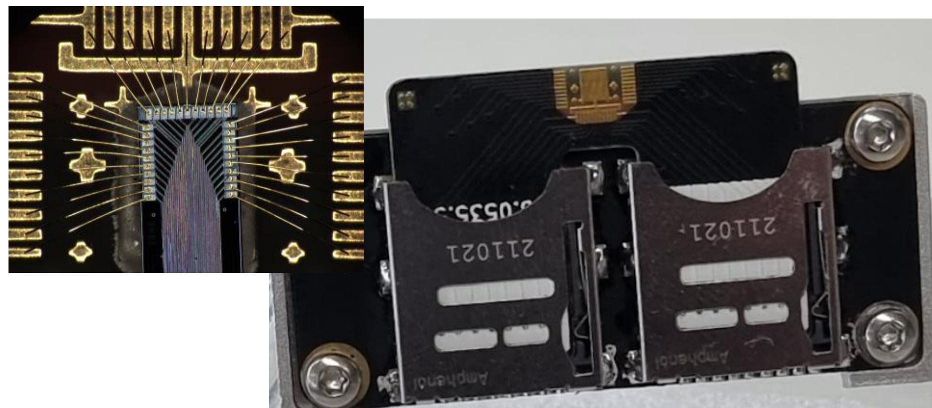
Tackling Parallelization

Arrays of Cantilevers - Fabricated Wafer Level

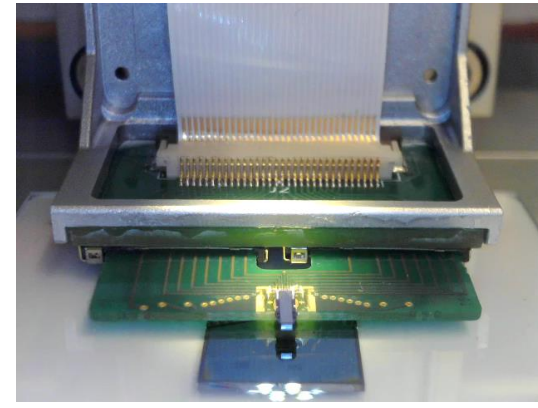
Electronics - Fast, Low Noise, and Scalable



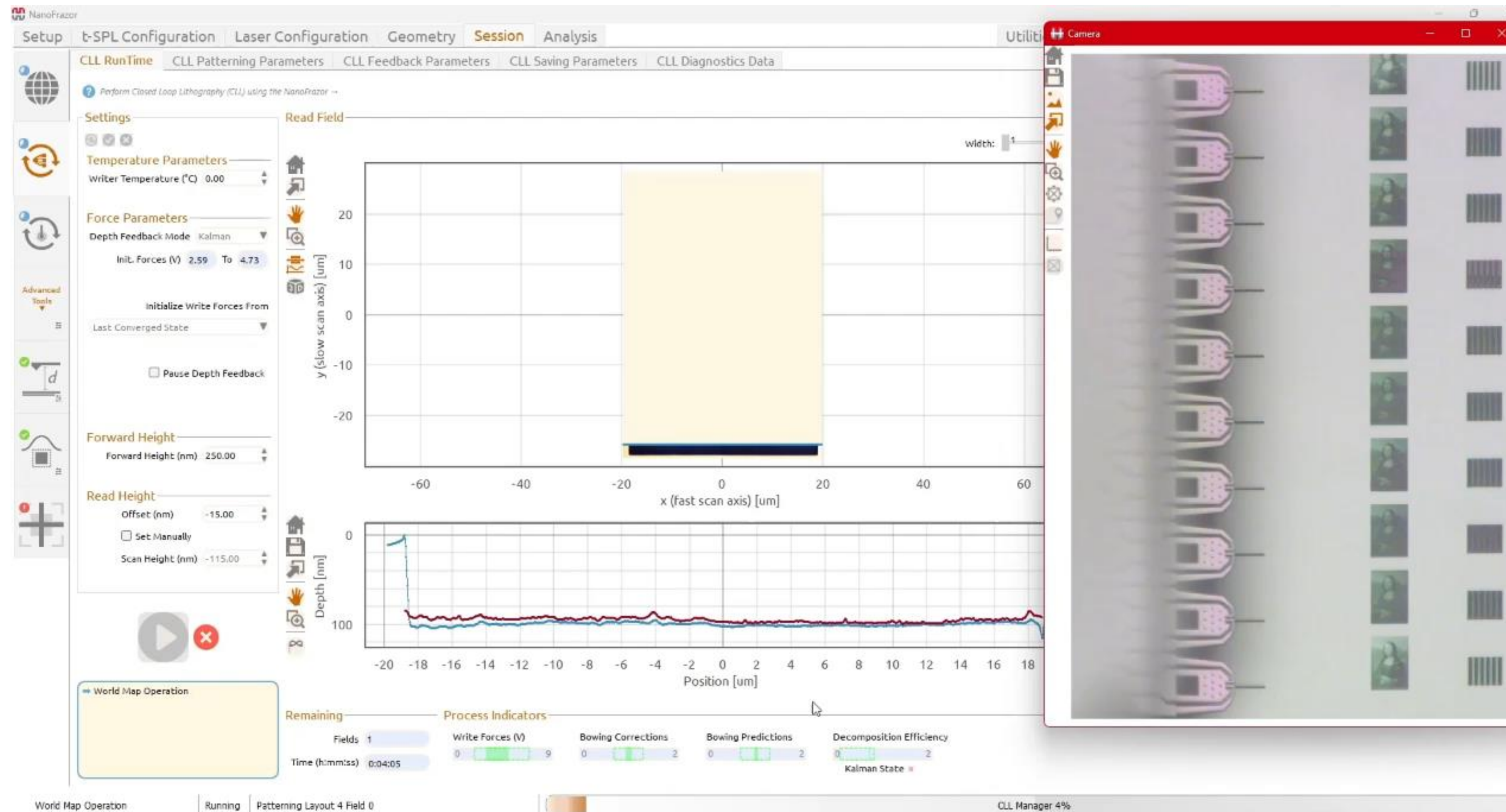
Packaging and Interfacing - Chip Level



Put It All Together!

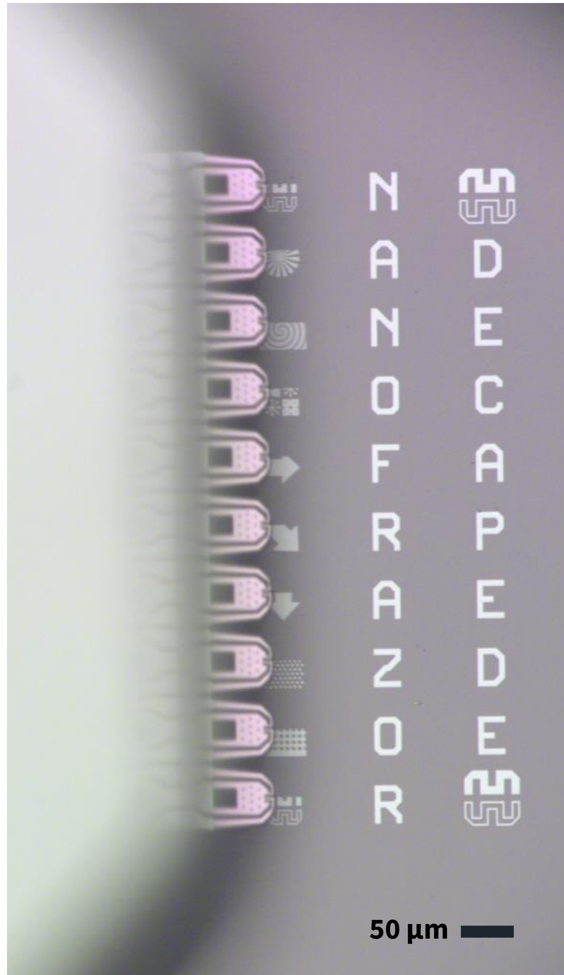


When everything comes together: writing with 10 tips in parallel

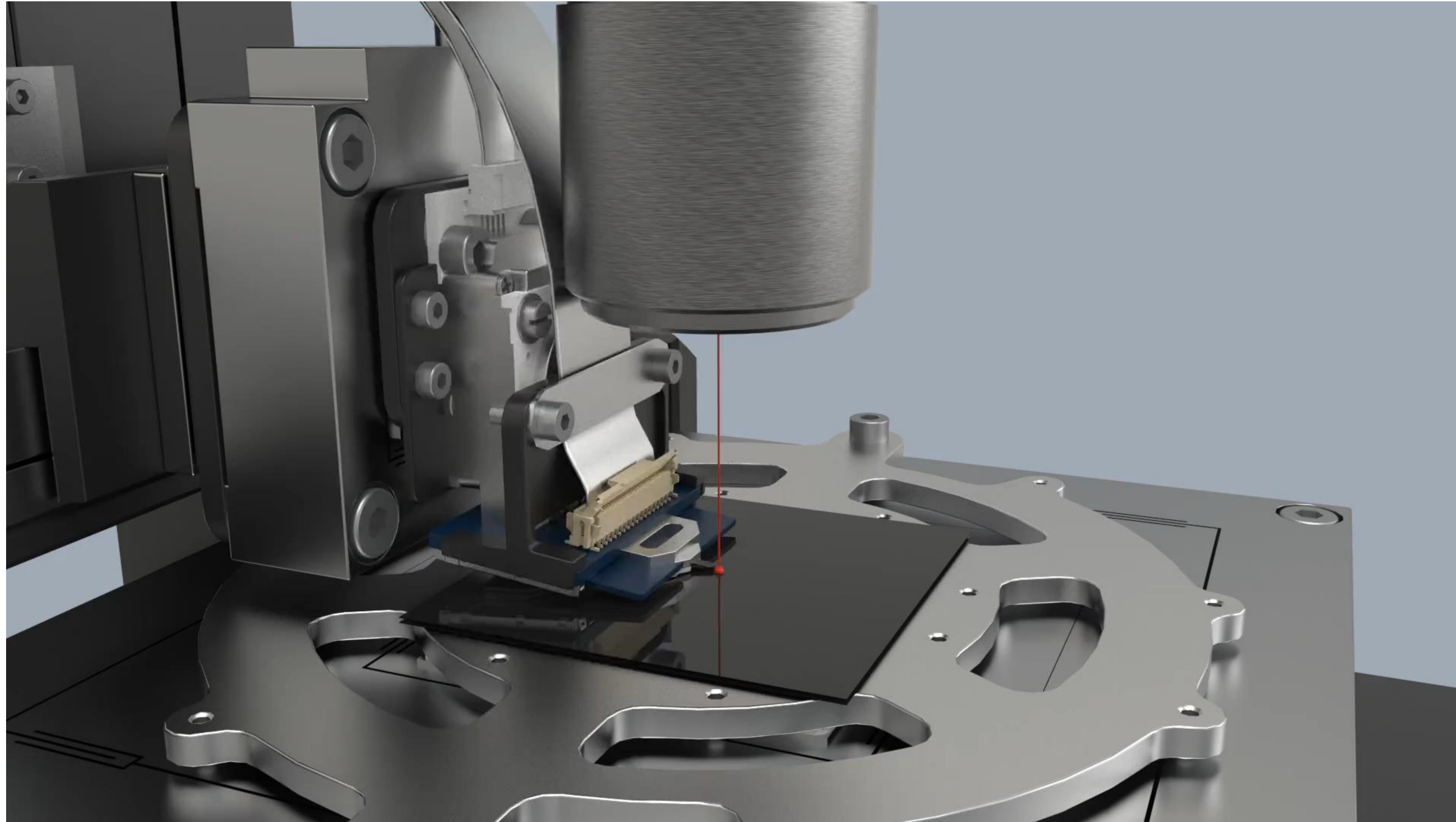


- Real-time video of 10 tips patterning the same arrow in parallel
- Each tip is independently biased (reader & writer)
- Patterning force across tip-sample for each tip is the same

The new NanoFrazor is here!

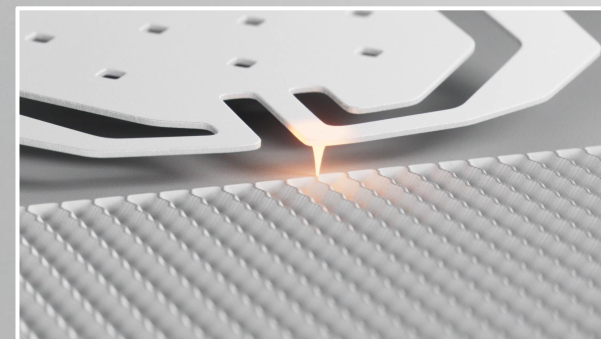


Providing More Flexibility



Providing More Flexibility

- Configurable for different applications, requirements and infrastructure
- Check out the configurator on **nanofrazor.com**, or speak with us!
- Visit us at **Booth 17** for a NanoFrazor demo!
- **Evening reception** celebrating 40 years of Heidelberg Instruments and the new NanoFrazor: Tuesday, September 17, 6 PM at the Bar à Tartines



Make Nano Possible

nanofrazor.com

Thank You!

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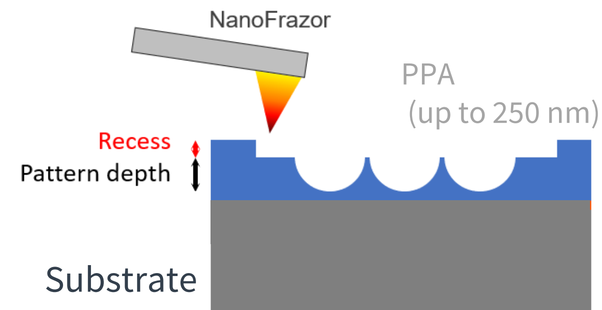
Pattern Transfer: Grayscale High-Resolution Etching

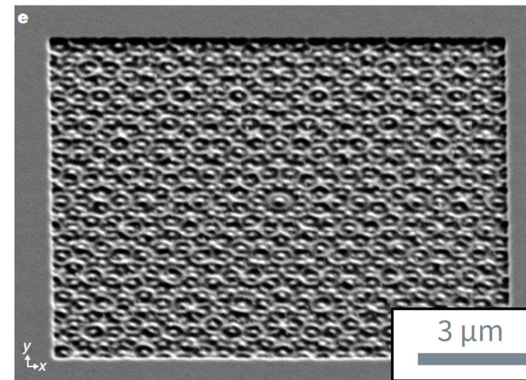
Process Flow



Dry etching
into substrate
RIE, ICP…

Key Features

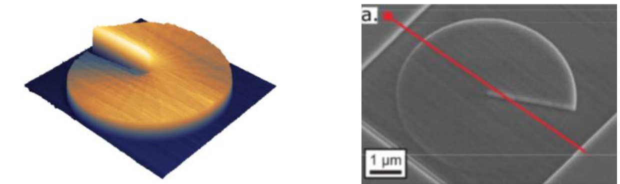
- Single nm vertical resolution
- Requires dry etching
- Compatible with soft molding and nanoimprint lithography (NIL)



SEM image of etched NanoFrazor pattern into Si
Lassaline *et al.*, Nature, 2020

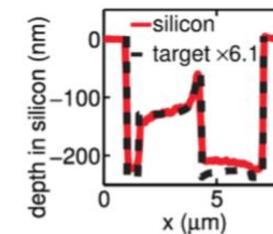
Examples

- Optical Fourier Surfaces
- Phase plate



NanoFrazor in-situ imaging of patterned PPA

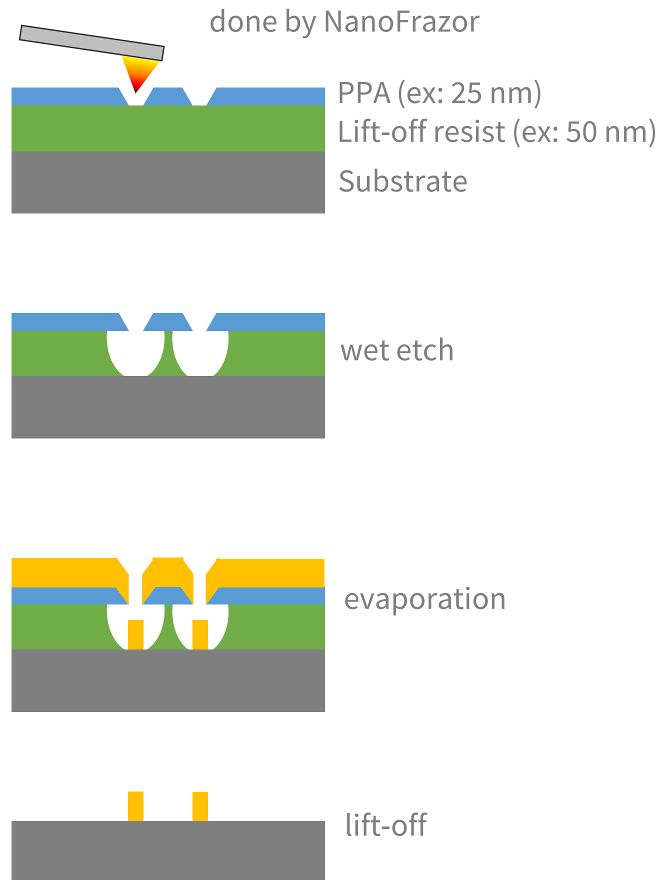
SEM image of etched NanoFrazor pattern into Si



AFM profile across phase plate
Rawlings *et al*, IEEE Transducers, 2017

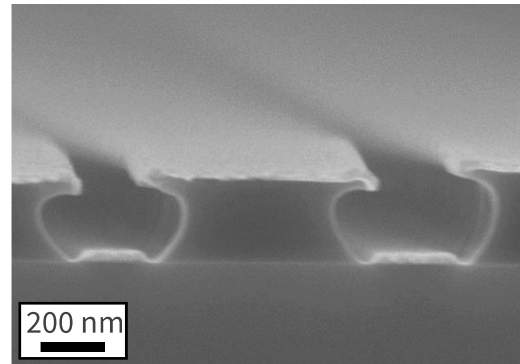
Bilayer Lift-Off

Process Flow

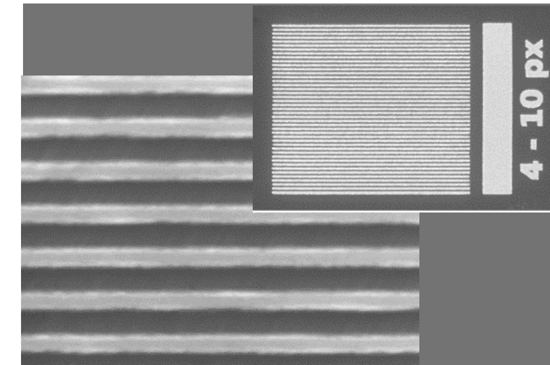


Key Features

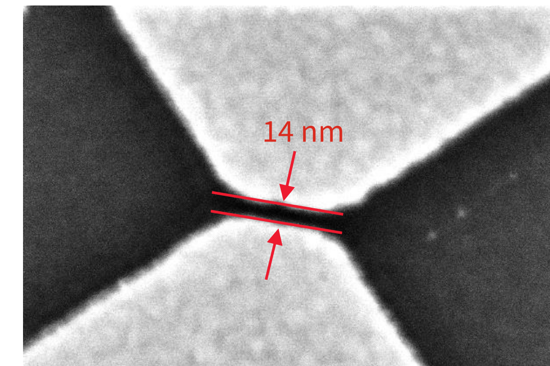
- Simple & fast process
- Limited feature density
- Resolution of 100 nm reproducibly achieved



Examples



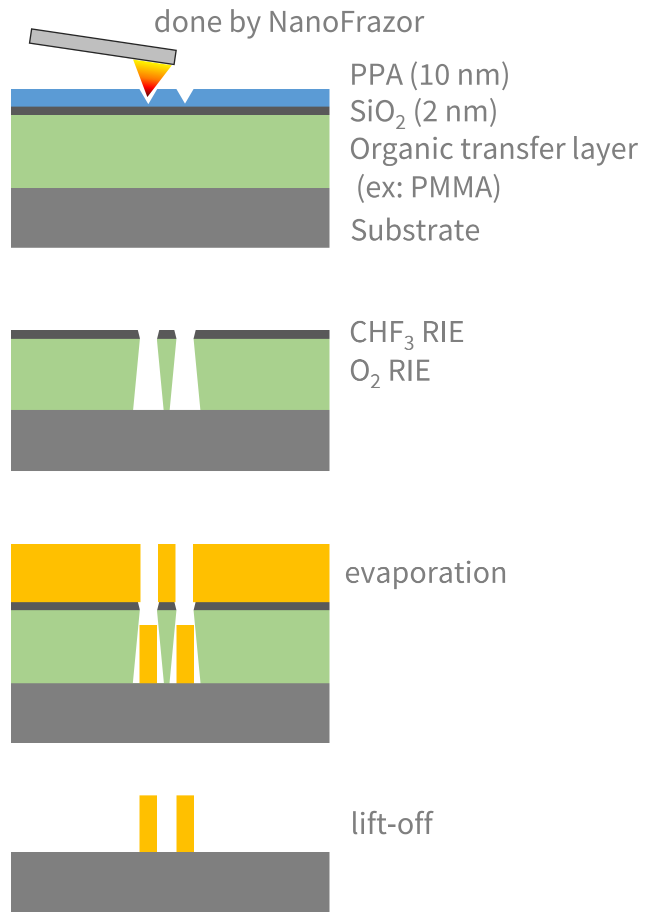
70 nm half-pitch lines in Pt



Small gaps easily possible (with limited length)

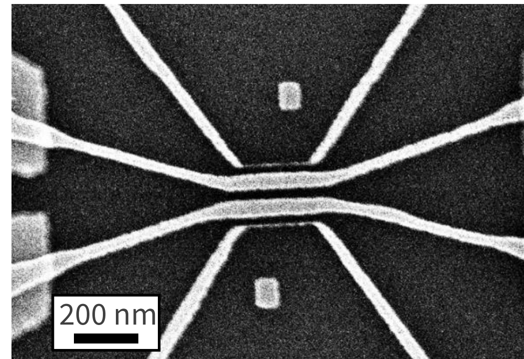
High-Resolution Lift-off

Process Flow



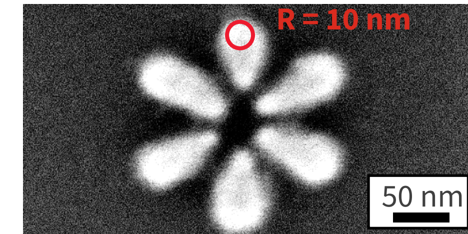
Key features

- High resolution
- High feature density
- Minimum structure size 20 nm
- Minimum lines and spaces 30 nm
- Requires dry etching

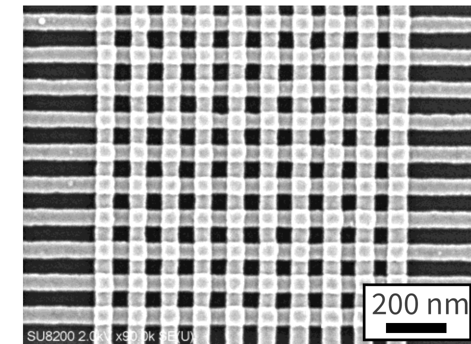


by Bojun Cheng, ETH Zurich

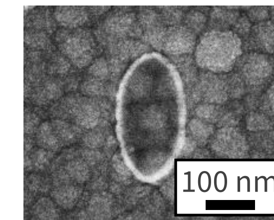
Examples



Plasmonic antennae (Au lift-off)



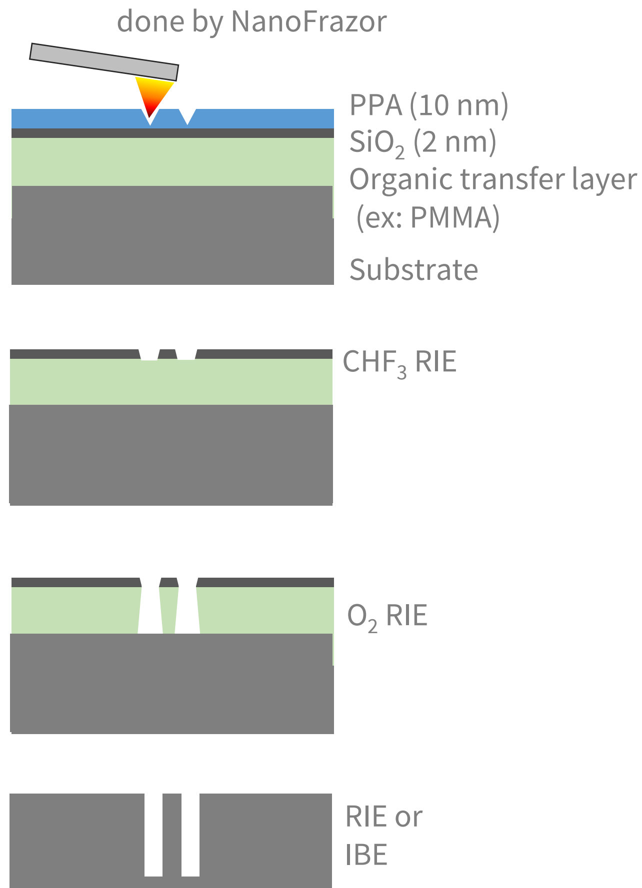
Metal electrodes (Au lift-off)



Magnetic ellipses (SiO2 lift-off)

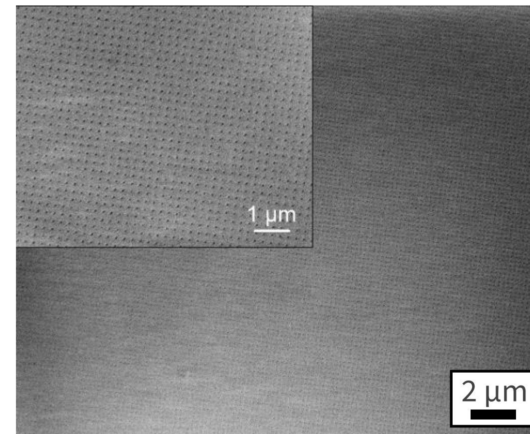
2D High-Resolution Etching

Process Flow



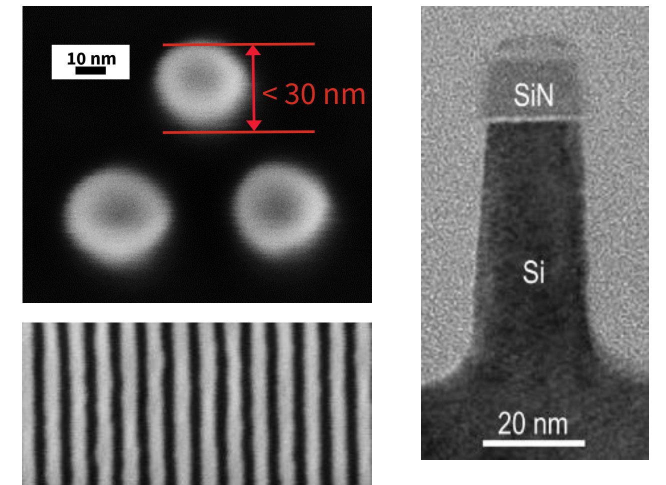
Key Features

- High resolution & feature density
- 25 nm half-pitch lines reproducibly achieved
- Good & tunable etch selectivities for various substrates



50 nm holes etched 1 µm deep in PMMA

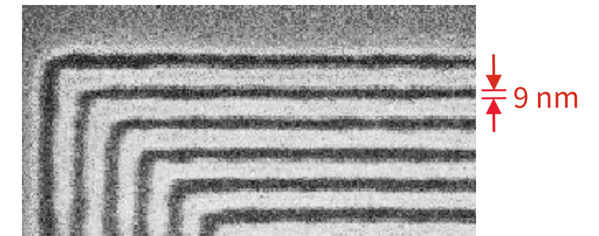
Examples



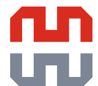
Ar Ion Beam Etching (IBE) of 20 nm Au

18nm

SIS process (Marneffe et al., imec)

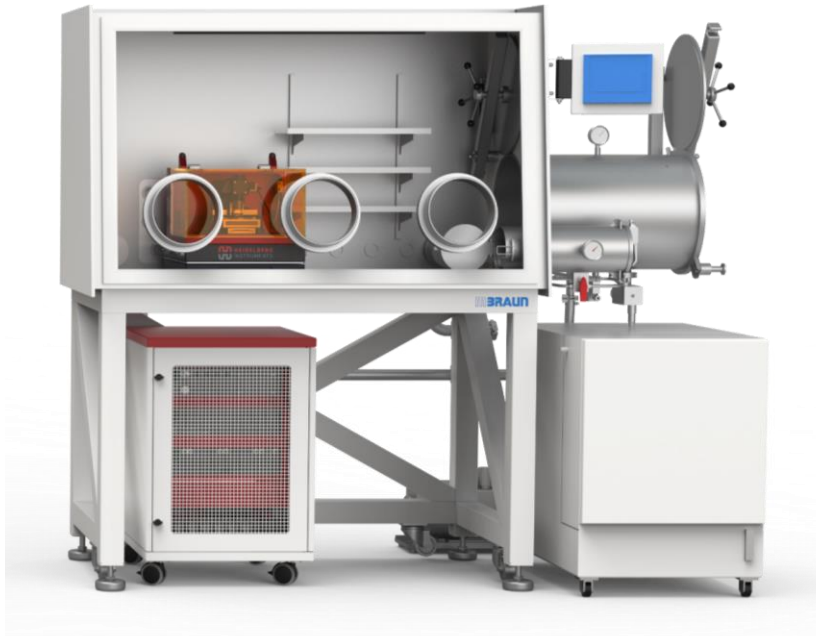


13.8 nm half-pitch etched into Si using RIE (Ryu et al., ACS-Nano, 2017)



NanoFrazor in a glovebox

- Customized glovebox, collaboration with MBraun
  - Reinforced frame and window for noise insulation
  - Validated feedthrough panel
  - Adjustable for Scholar, Explore (shown here), third party integration, and glovebox clusters



- Designed for user experience
  - Automation possibilities, workflows for inert atmosphere
  - Water-free fabrication processes for sensitive materials