Direct-Write Patterning of Marker-Free Nano Devices

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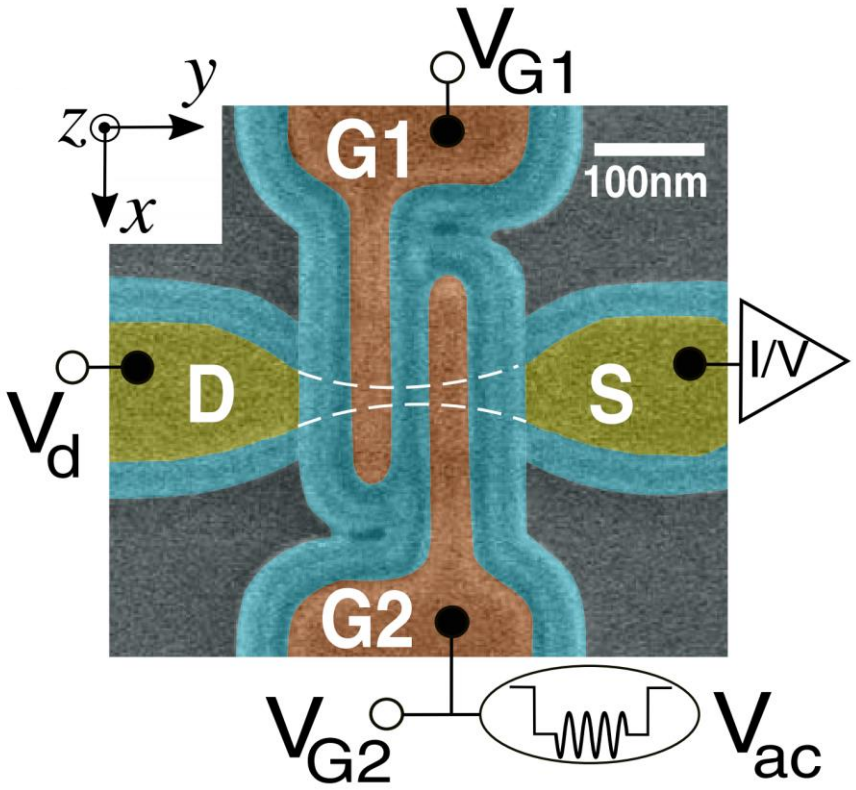
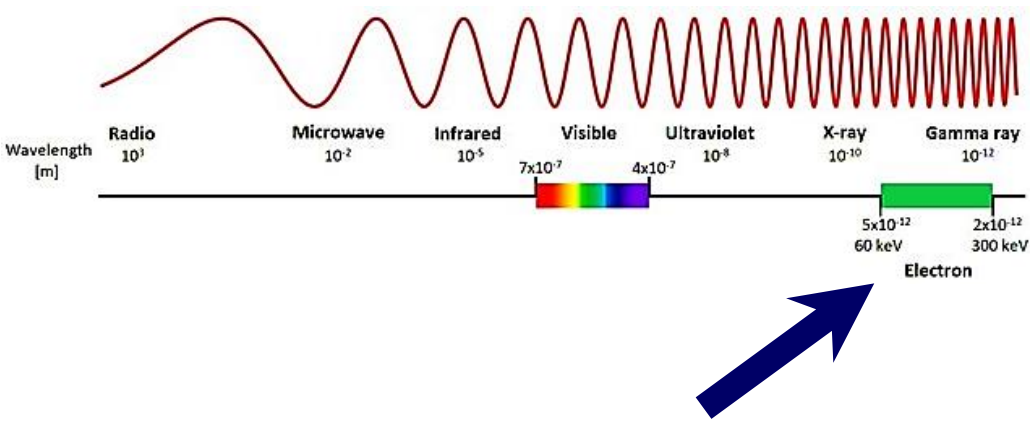
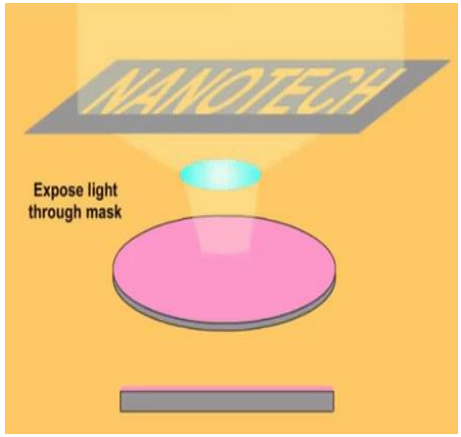


Crippa et al., *Phys. Rev. Lett.* (2018)

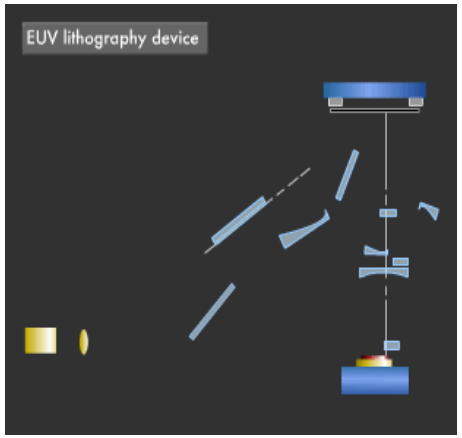
Background & Motivation

- Conventional optical lithography = ultraviolet **photon** exposure.
- Electron beam lithography = **electron** beam exposure.
- Ultimately, the *wavelength* of the energy being applied to a resist coating determines the feature size.
- It's possible to obtain 3-5 nm resolution with electron-beam lithography
  - Depends on your skill level (abstract).

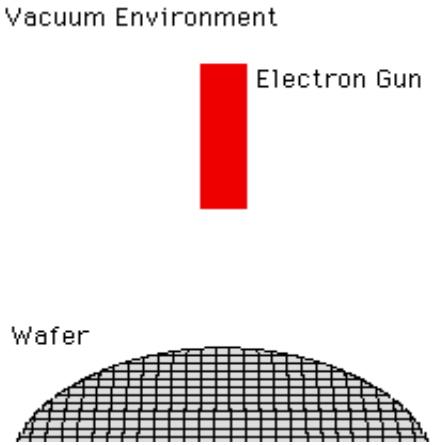




Maskless Ultraviolet Lithography



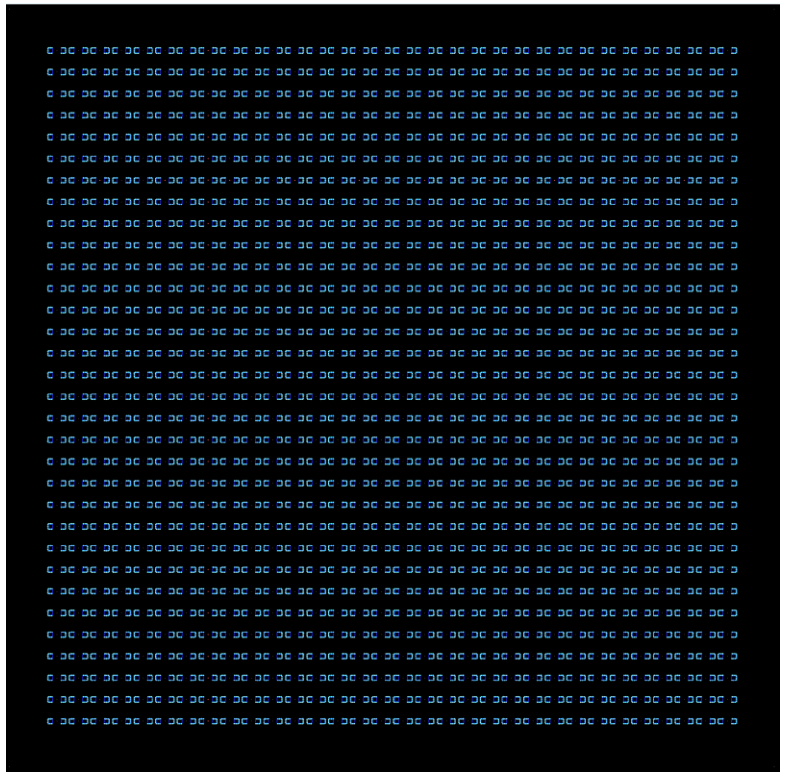
Maskless Extreme Ultraviolet Lithography

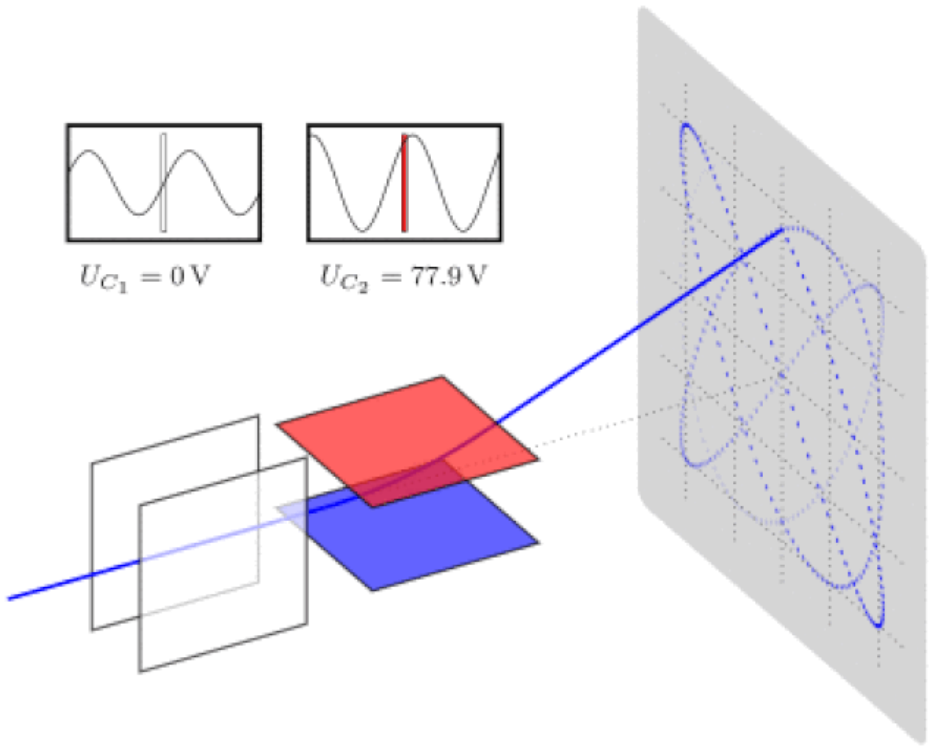


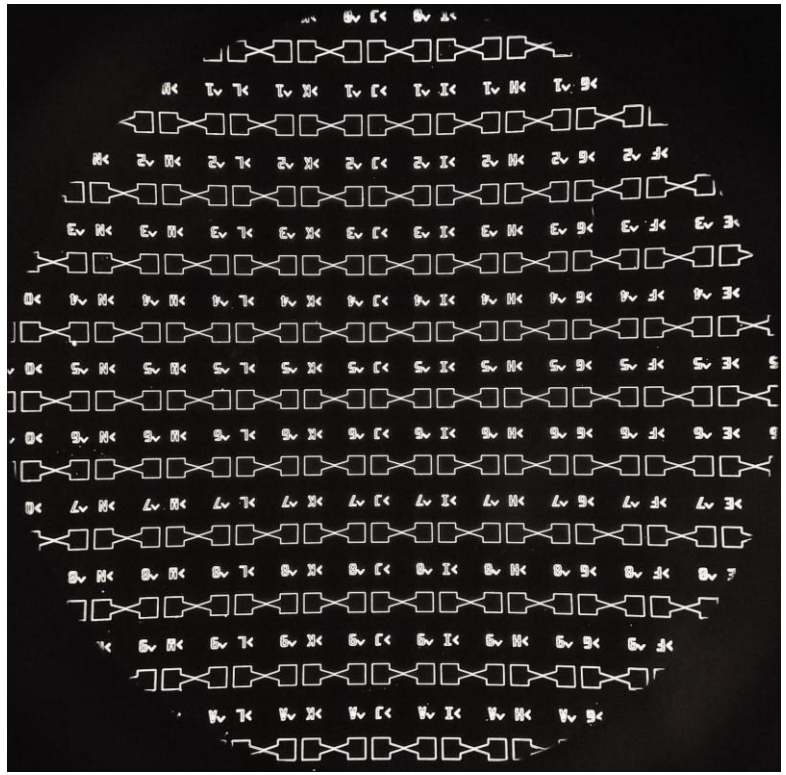
Maskless Electron Beam Lithography

1. Venturi, *PhD Thesis* (2017)
2. Taken from: thumbs.gfy.com
3. Taken from: *Wikimedia Commons*

Basic Principle of Electron-Beam Exposed Features

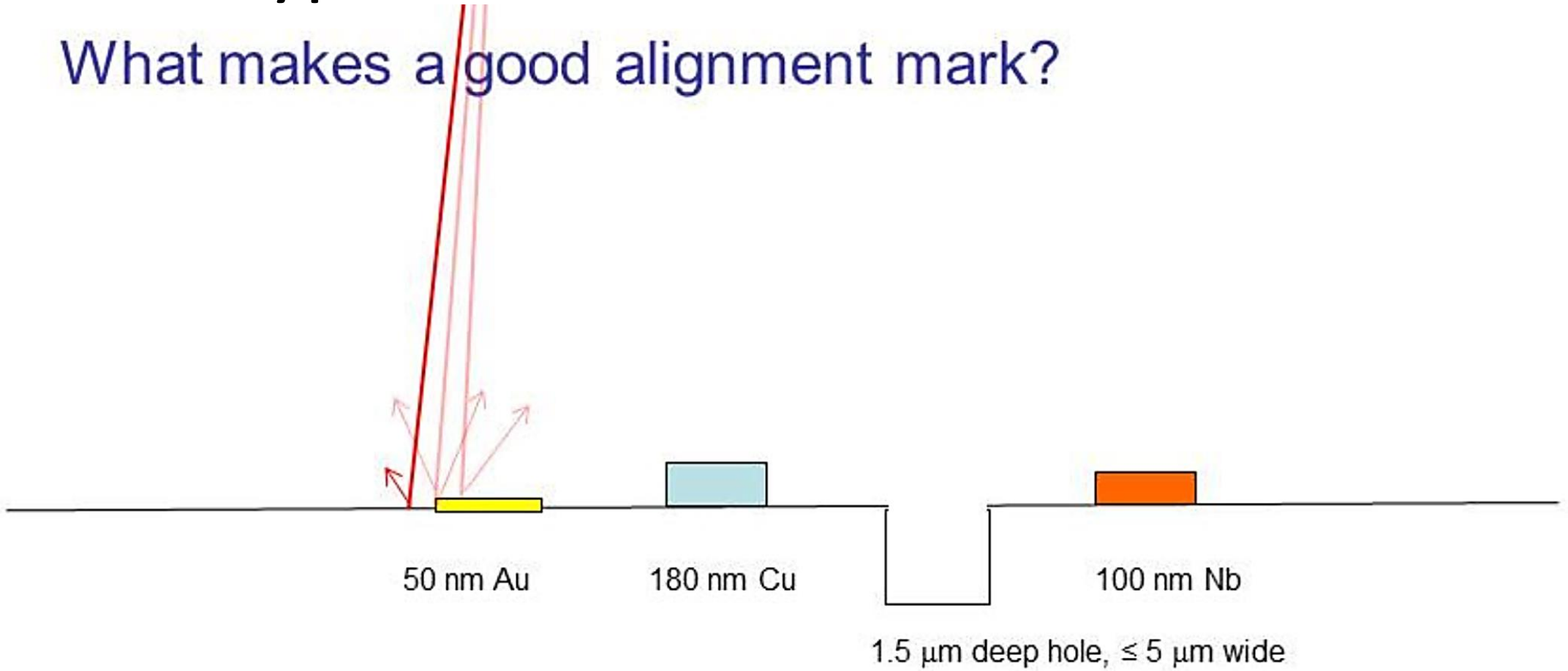






1. Taken from: Wikimedia commons

Typical Markers Used in E-Beam



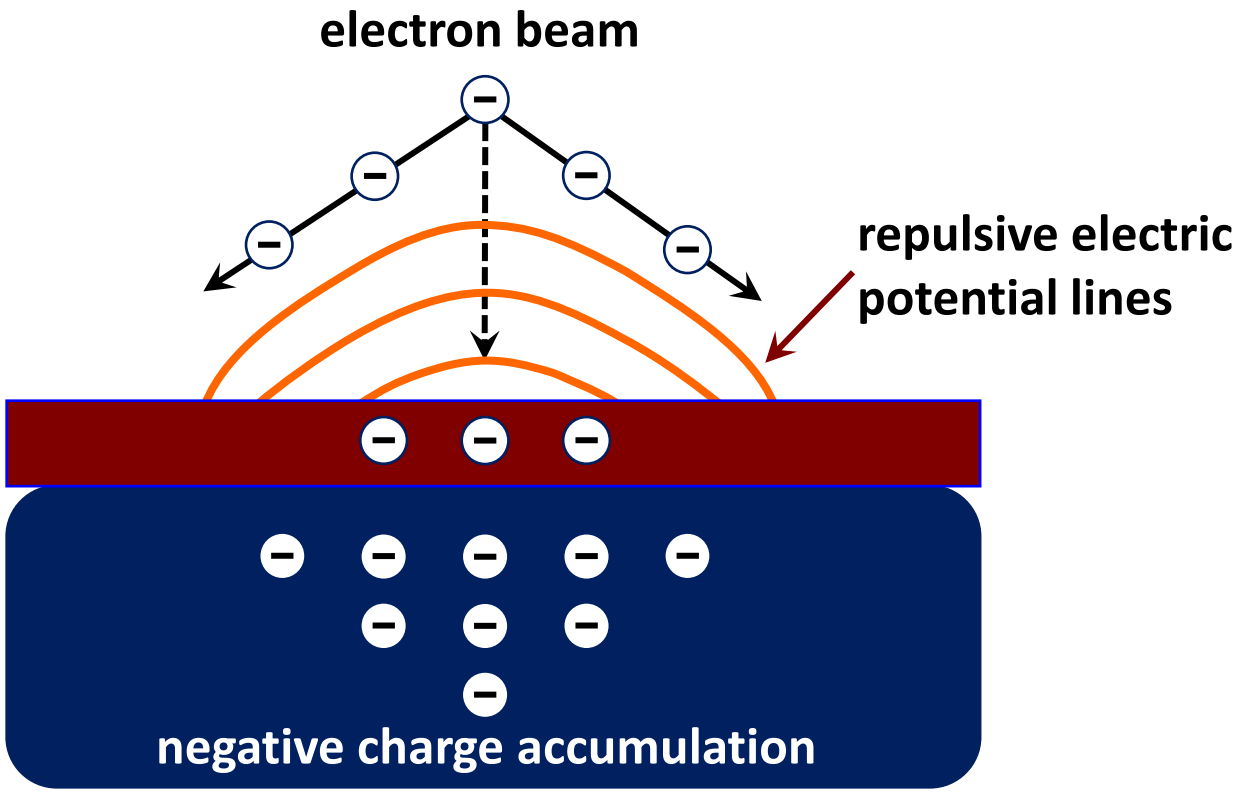
Marks are usually squares, 4 to 20 μm on a side.
Etched holes should be ≤ 5 μm wide.
Crosses can also be used, compatible with JEOL

* Taken from: nano.yale.edu

Equipment Advantages & Disadvantages

- Advantages:
  - Relatively high-resolution lithography.
  - Maskless procedure allows for indirectly importing AutoCAD drawings.
  - Fast design modification.
  - Vacuum environment leads to better control of contamination.
  - Markers can be avoided
- Disadvantages:
  - Vacuum environment required.
  - Charge build-up, even during SEM inspection.
  - Low throughput.
  - Proximity effects.

Equipment Advantages & Disadvantages



vs.

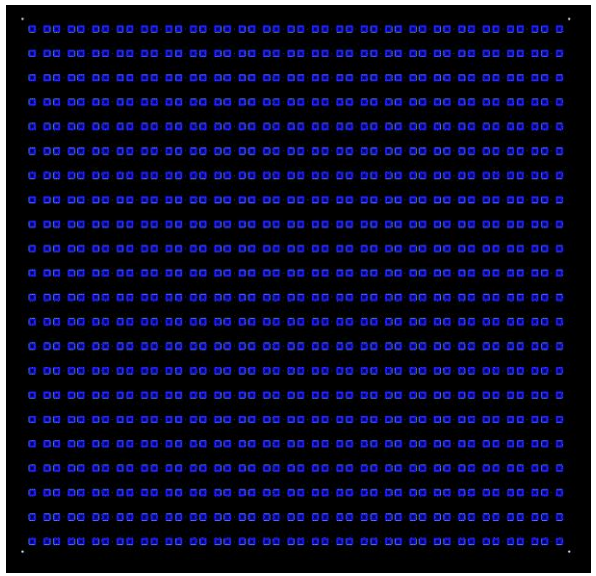
* Adapted from: nano.yale.edu

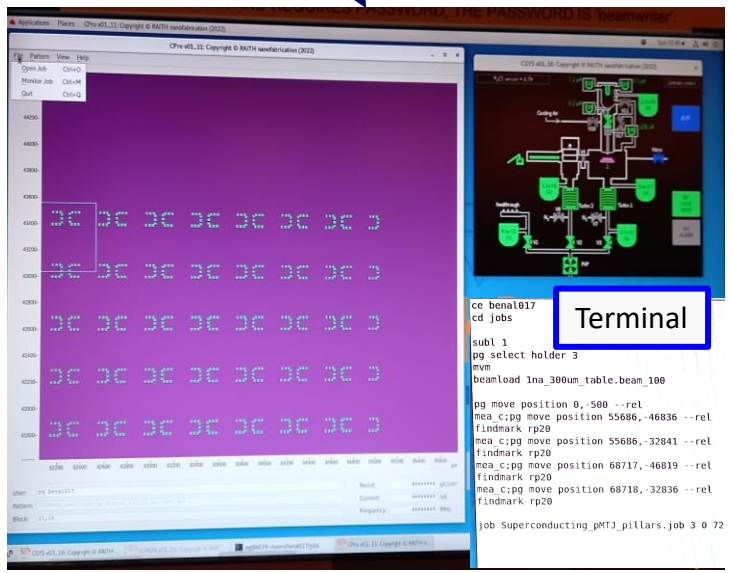
Design Process Flow

- Design file conversion is a bit extensive.
- CAD **DWG** → **DXF** → **GDS II** → **Beamer** → **GPF** → **CJOB** → **JOB File**

Additional Parameters (dosage, sub. size, etc.)

During final setup, machine actually uses this one.

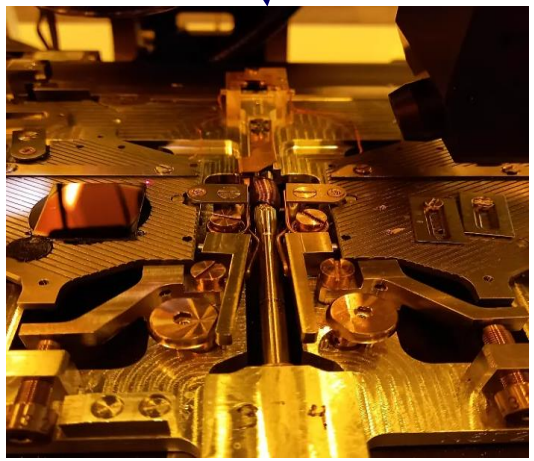


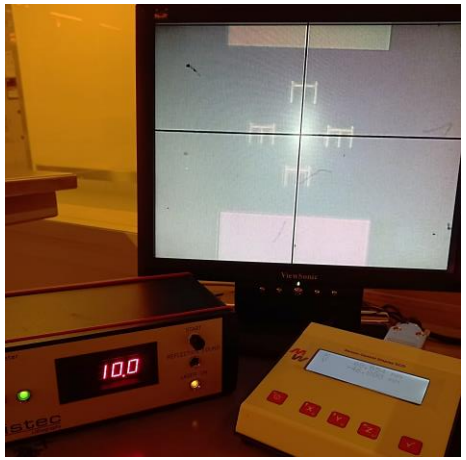


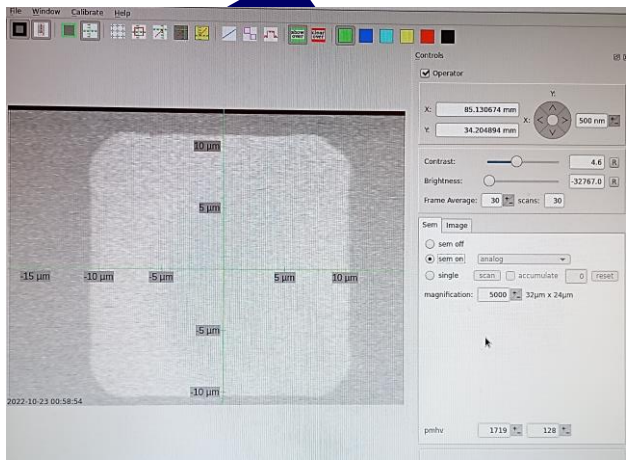
Maskless Direct Writing Using “Joyplus”

- Doses:
  - For relatively larger features (**pads** & **stripes**): 450 µC/cm^2.
  - For smaller features (**pillars**): 825-875 µC/cm^2.
- Basically:
  - Locate 4 Points → SEM-Aided ‘Marker’ Location → Record Final Marker Position → Confirm & Write!

(joyplus)





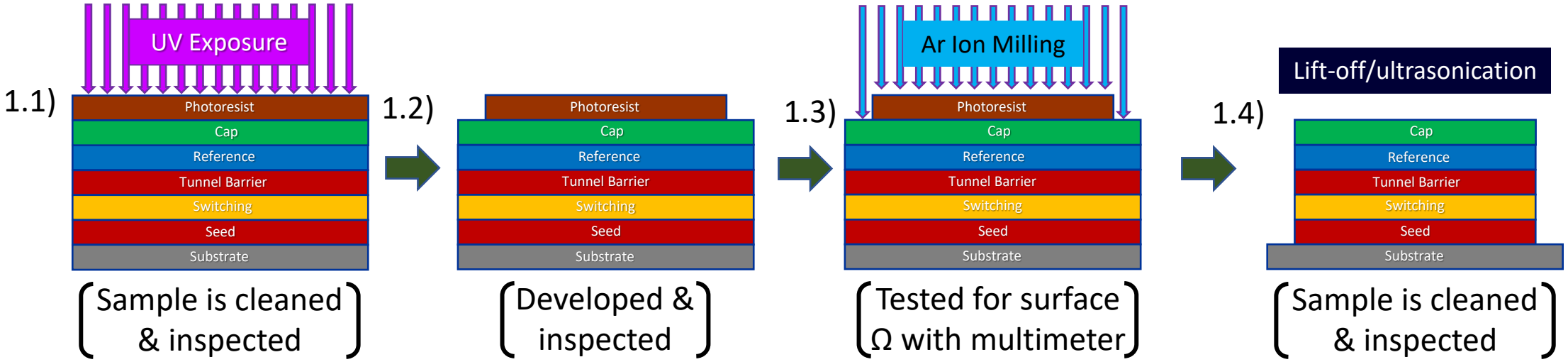


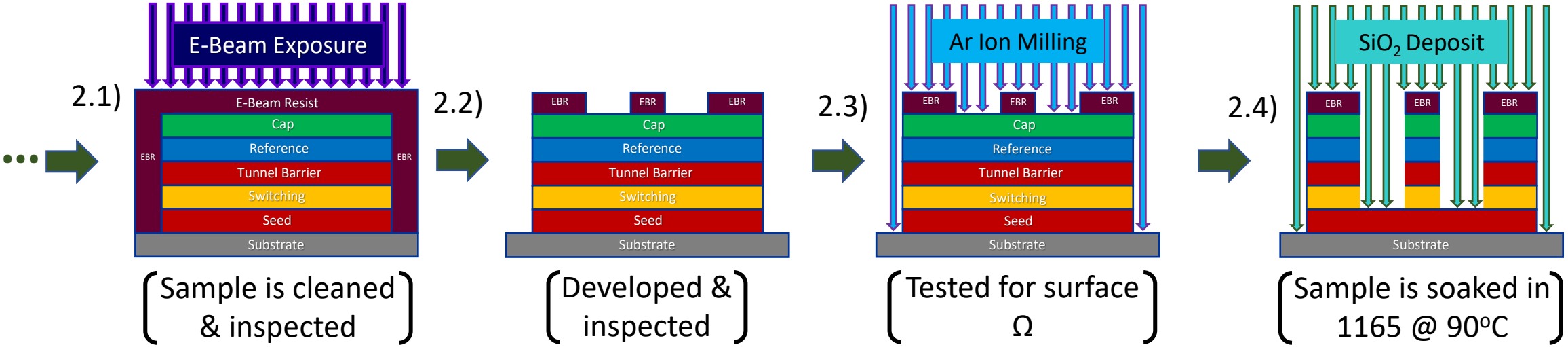
```
ce benal017
cd jobs

subl 1
pg select holder 3
mvm
beamload 1na_300um_table.beam_100

pg move position 0,-500 --rel
mea_c;pg move position 55686,-46836 --rel
findmark rp20
mea_c;pg move position 55686,-32841 --rel
findmark rp20
mea_c;pg move position 68717,-46819 --rel
findmark rp20
mea_c;pg move position 68718,-32836 --rel
findmark rp20

job Superconducting_pMTJ_pillars.job 3 0 72
```

Basic Flow Summary of “Joyplus” for E-Beam

- Enter relative coordinates >> locate desired marker reference points >> record real coordinates found >> enter (pg move position) of real coordinates >> type (joyplus) >> confirm real coordinates of marker locations by inspecting SEM scan >> press Enter.
- You may now continue with job file locations and other parameters for stage selection >> copy-paste job command into teminal >> press Enter >> watch 1st few steps of exposure >> Done!

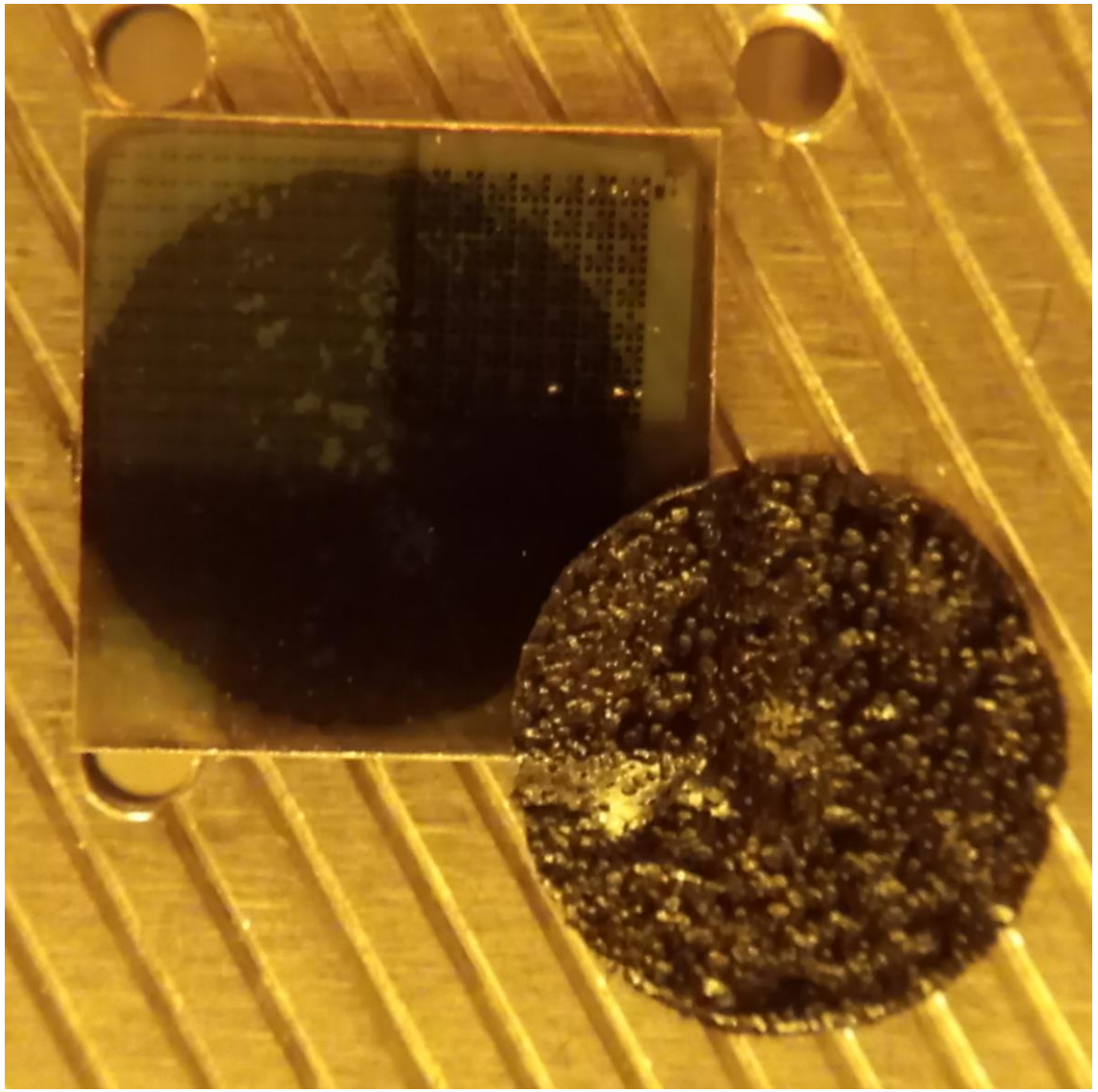
Randomized Example of Standard Fabrication Flow

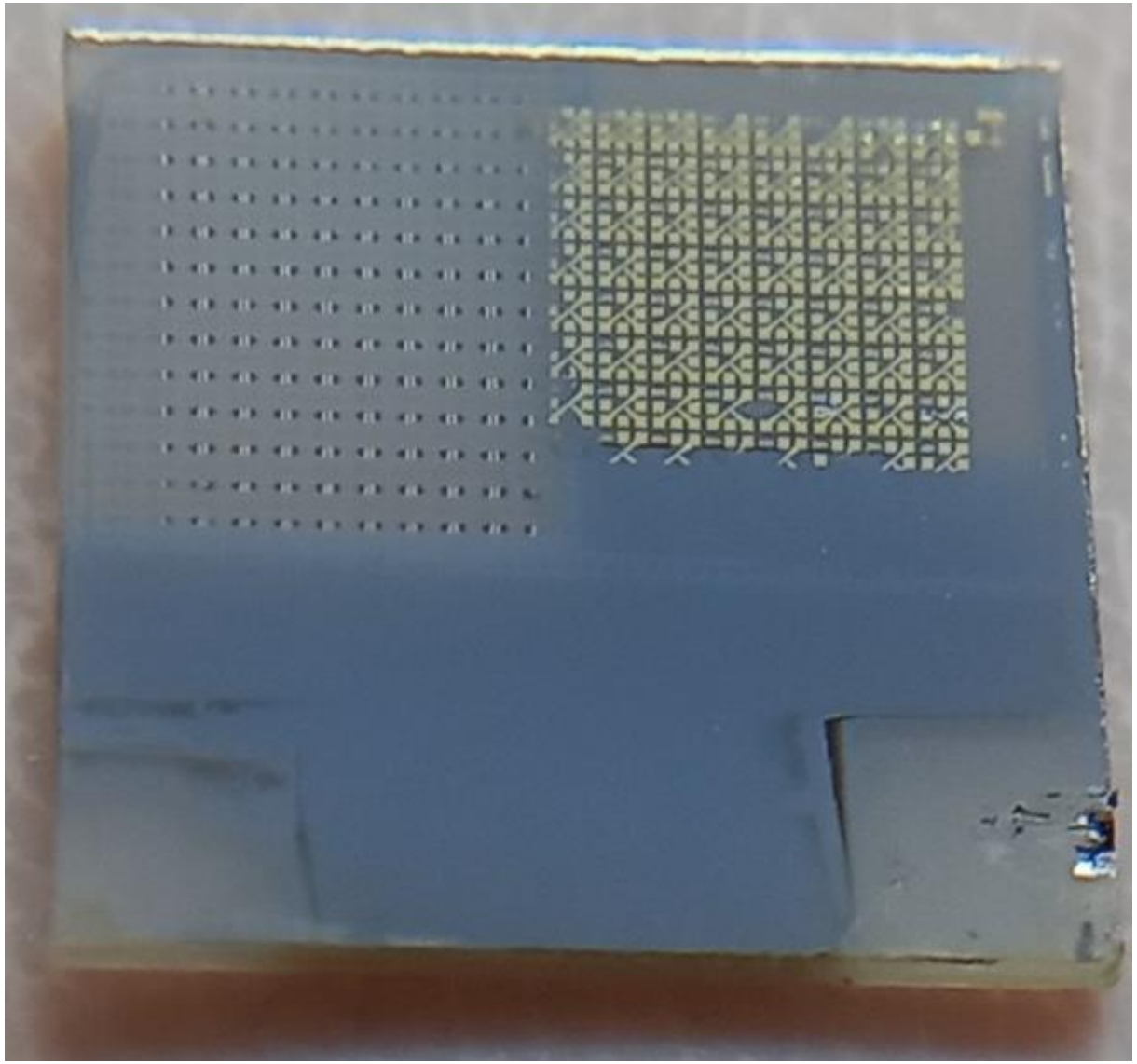




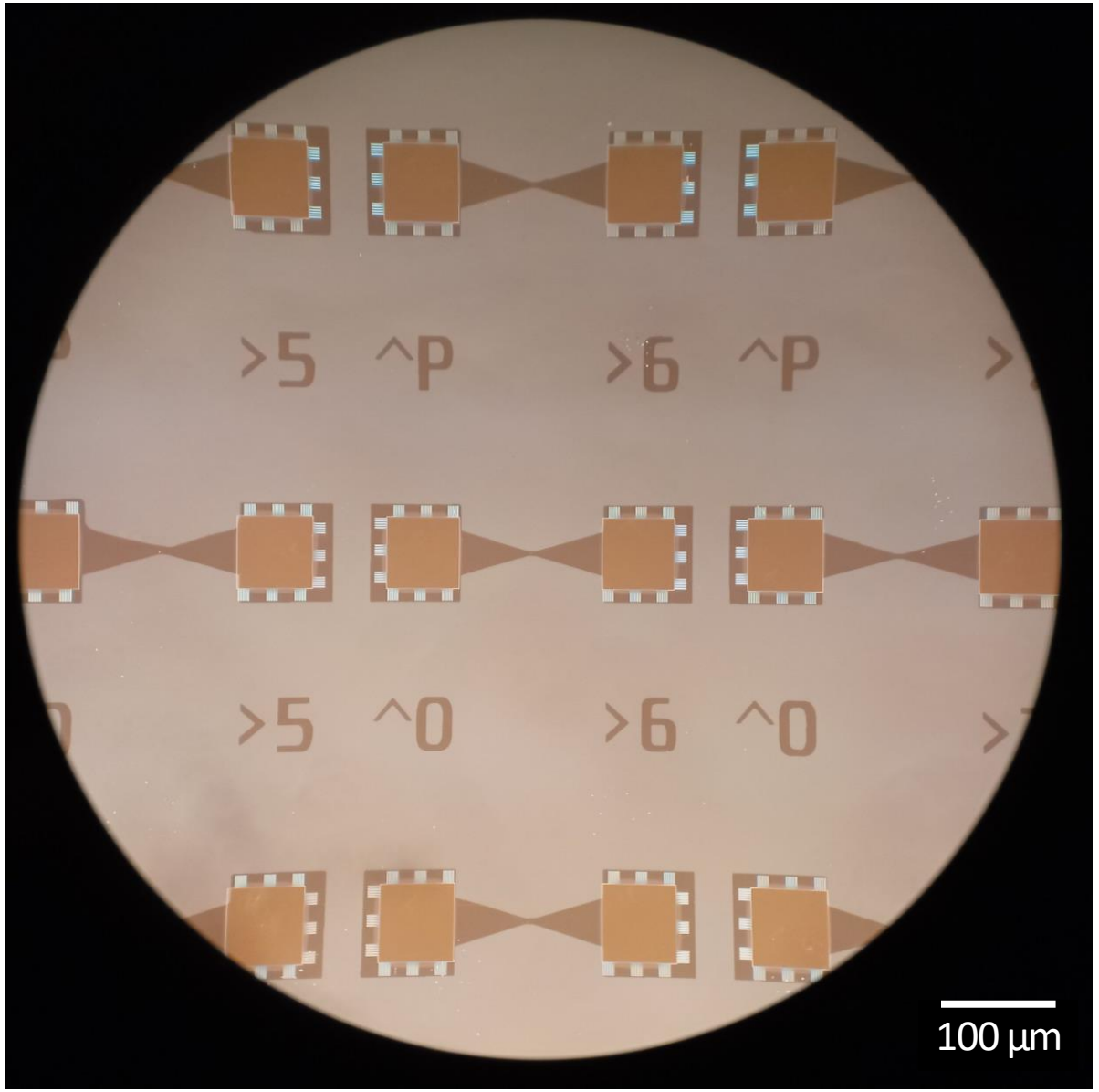
*PR = Photoresist ***EBR = Electron-Beam Resist
** Ω = Resistance

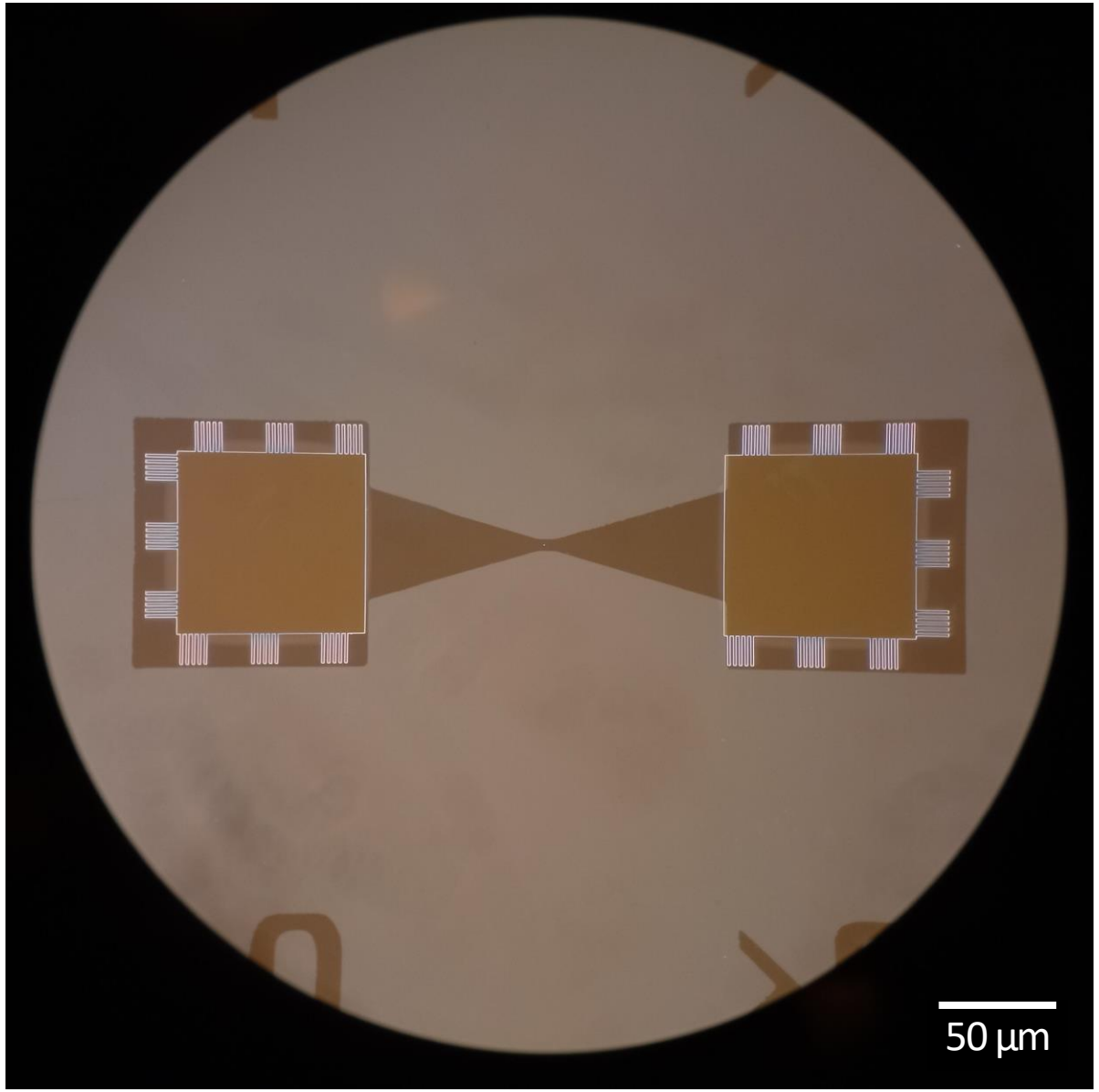
Nano Magnetic Tunnel Junction Results



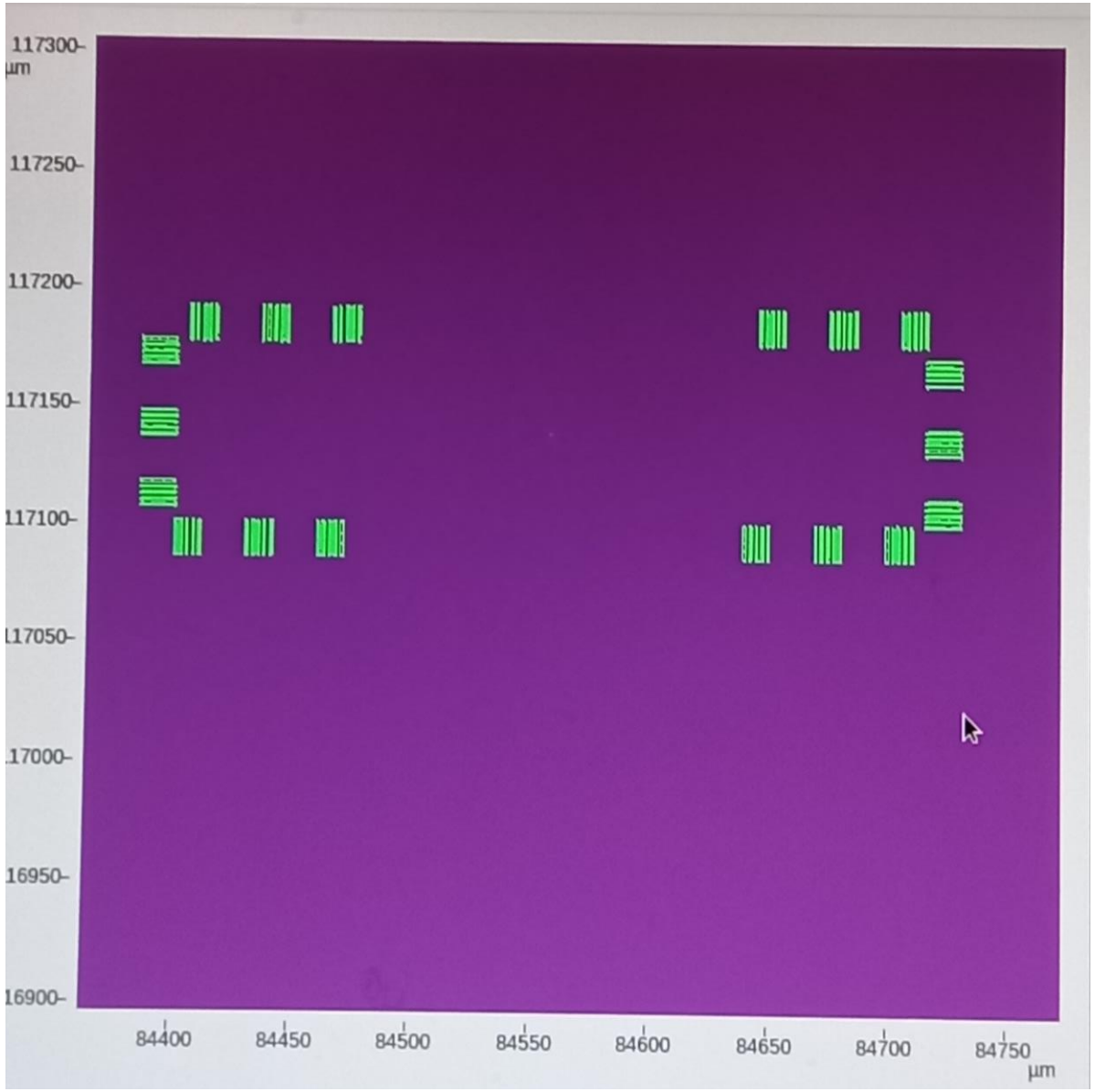


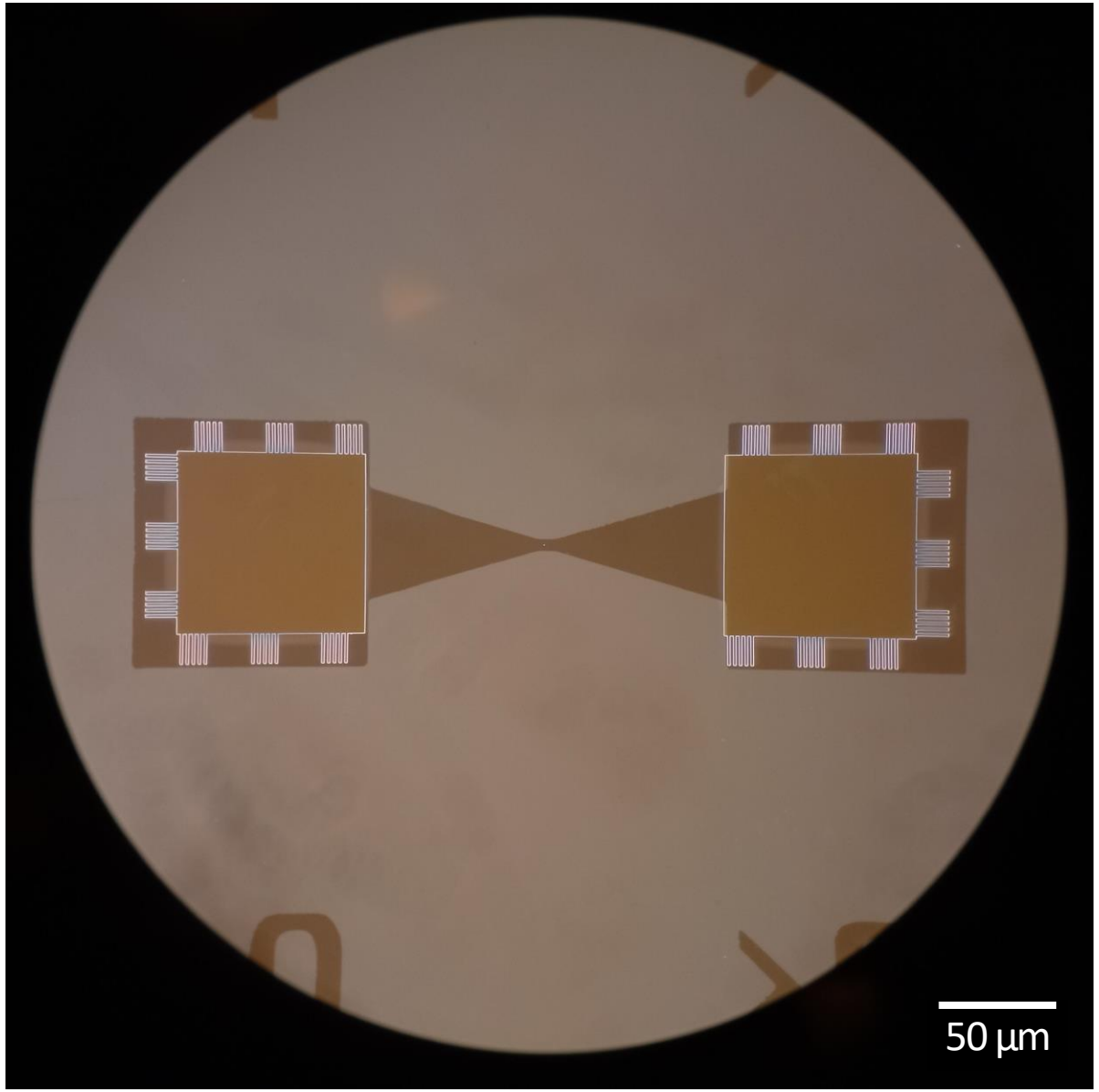
Nano Magnetic Tunnel Junction Results



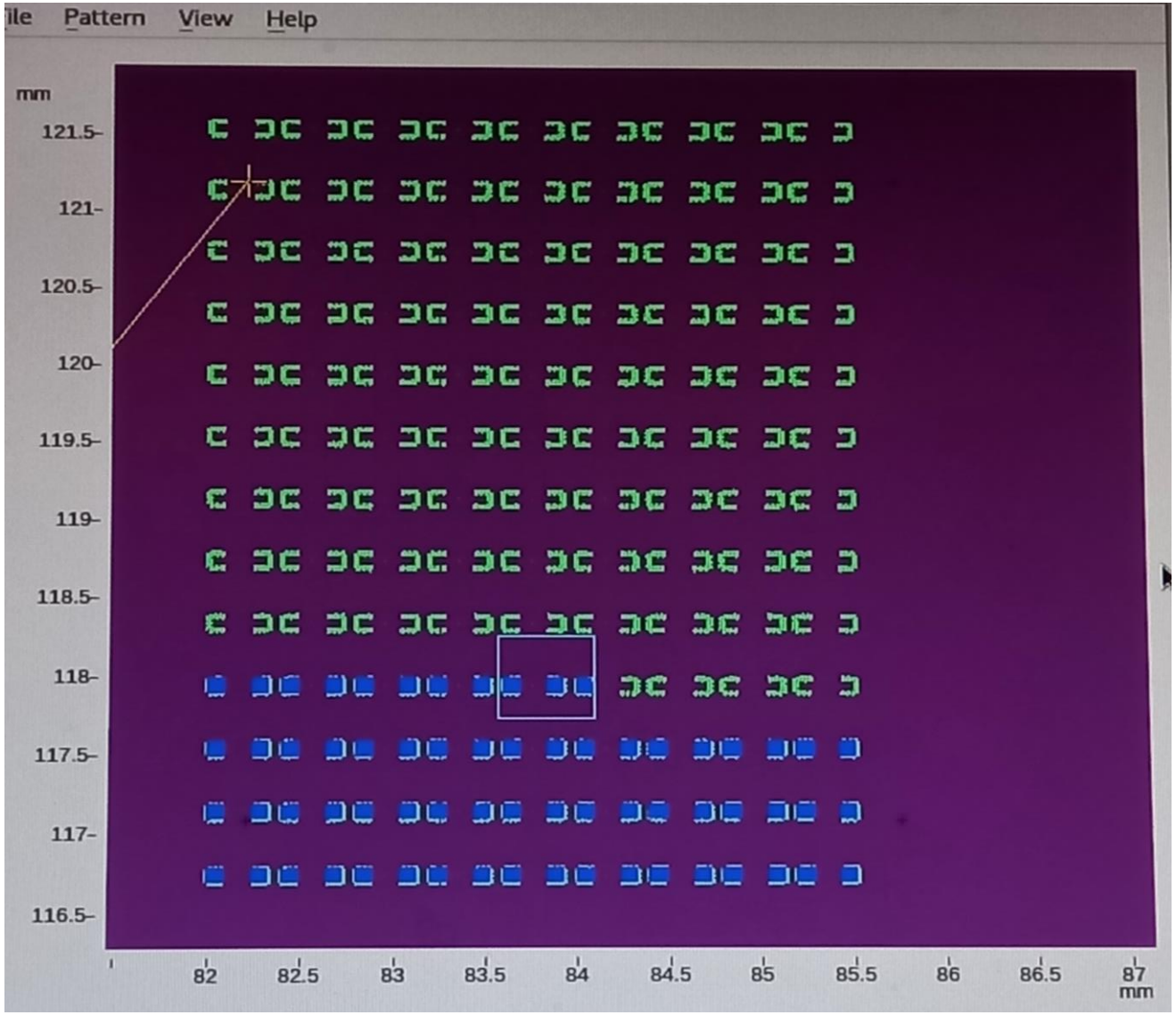


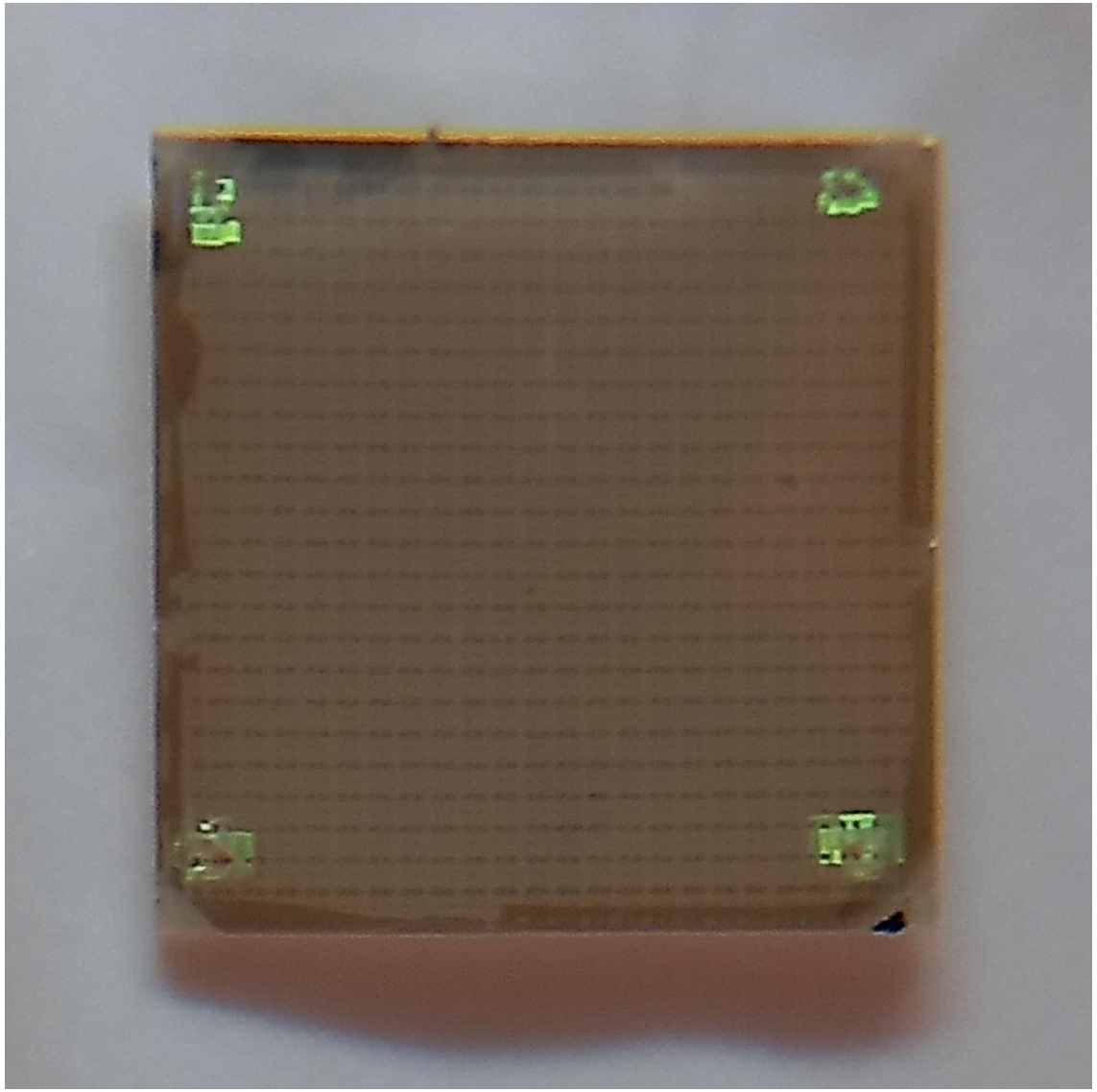
Nano Magnetic Tunnel Junction Results



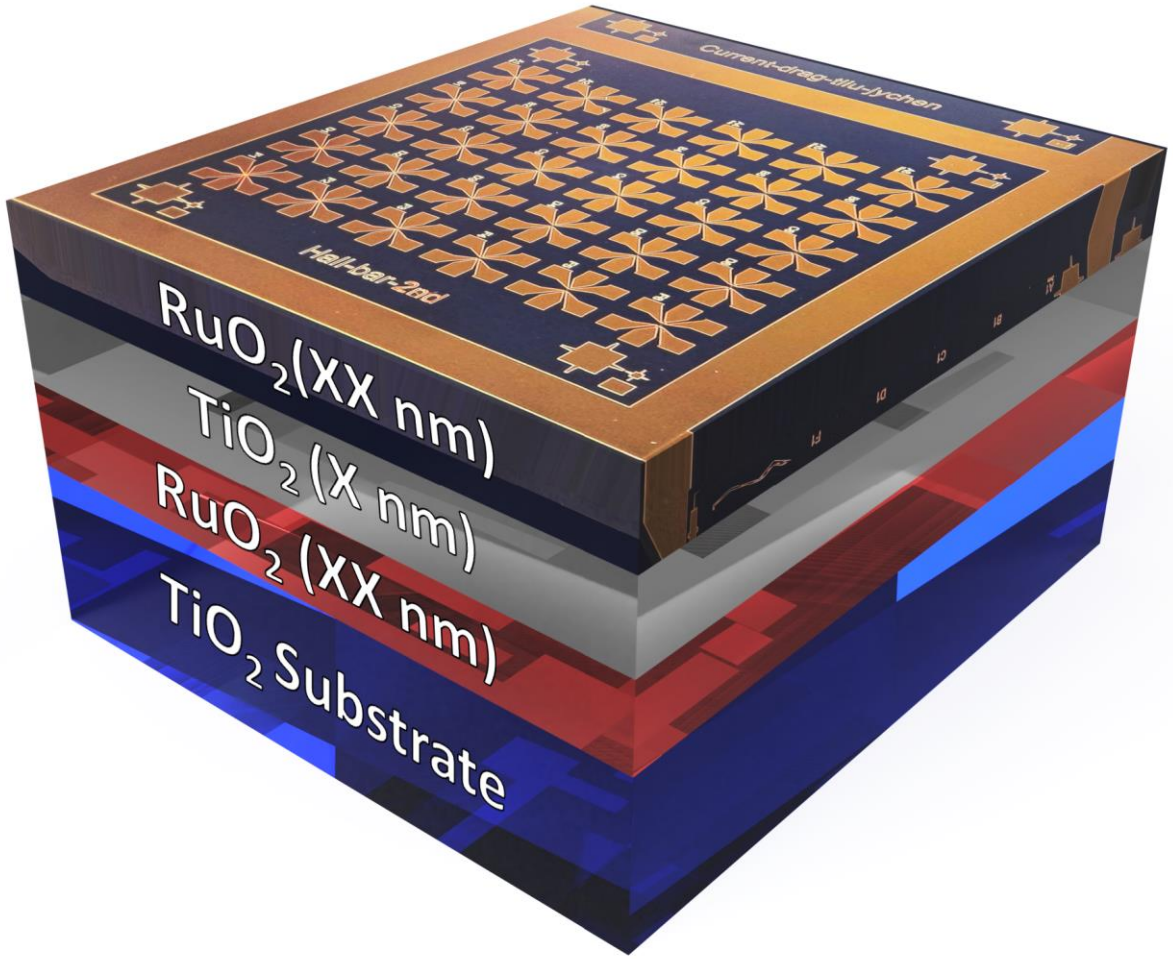


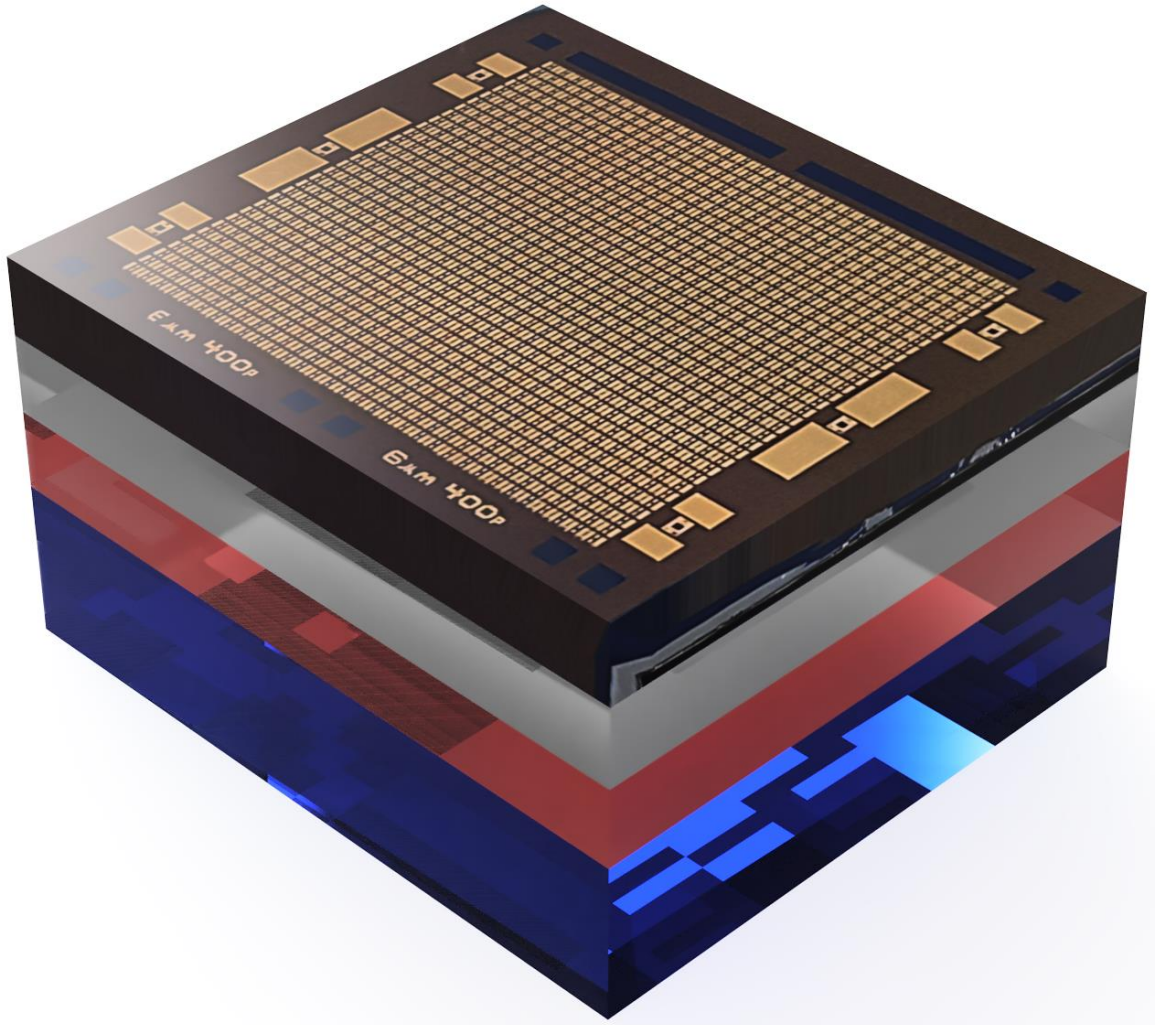
Nano Magnetic Tunnel Junction Results



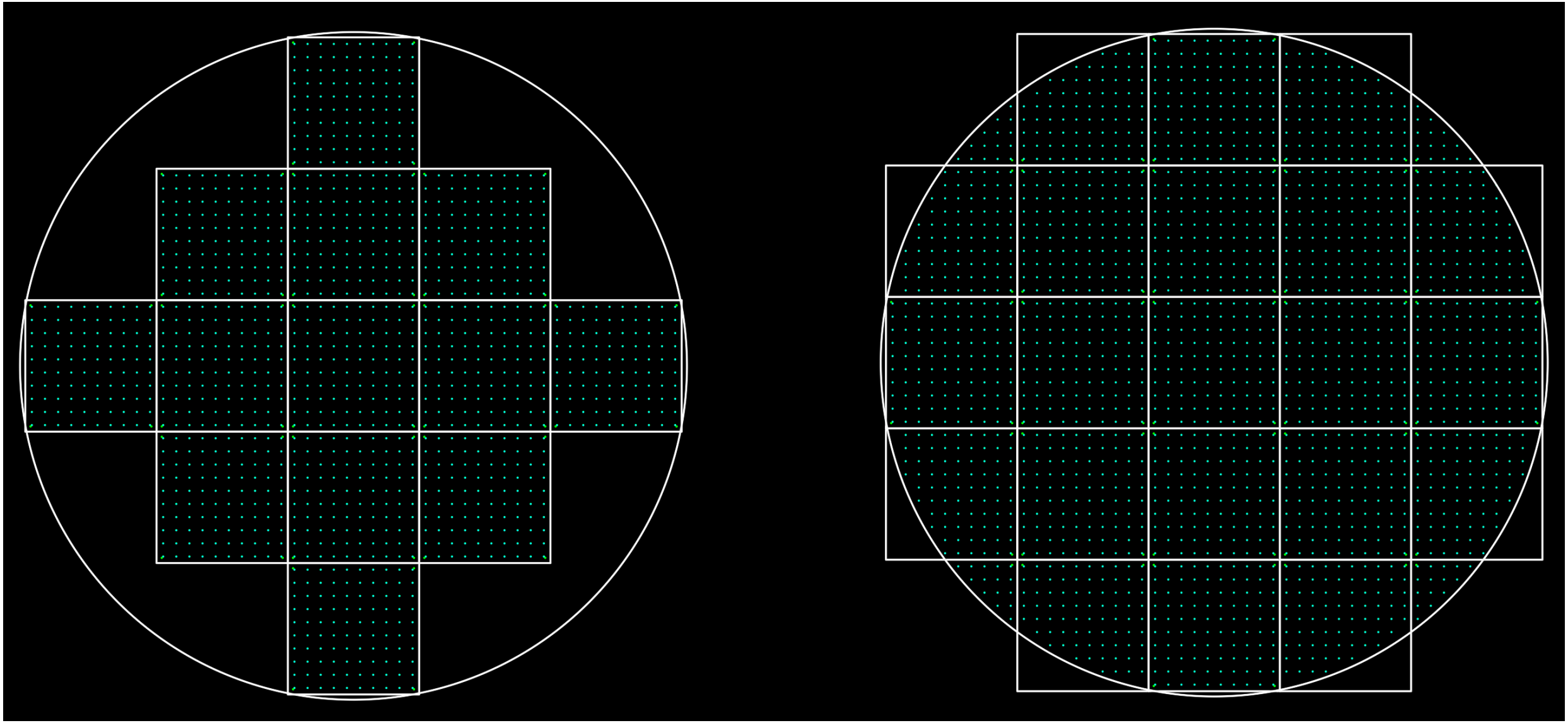


Magnetic Device Rendering Results





Double Squares Array Success (No Markers)



Green Lithography Methods

Table 1. The cost comparison among egg white, silk protein, organic and polymer resists

Type	Material	Source	Cost
EBL positive resist	Poly(methyl methacrylate)	EM Resist Ltd. [a]	1.49 [$ mL^{-1}]
EBL negative resist	Hydrogen silsesquioxane	Meryer Chemical Technology [b]	25.17 [$ g^{-1}]
UV positive resist	2,3,4-Trihydroxybenzophenone	Sigma-Aldrich	3.68 [$ g^{-1}]
UV negative resist	Poly(vinyl cinnamate)	Sigma-Aldrich	45.88 [$ g^{-1}]
Silk resist	Fibroin silk solution	Advanced BioMatrix [c]	12.75 [$ mL^{-1}]
Egg white resist	Egg white solution	Local Supermarket	0.37 [¢ mL^{-1}]
	Glycerol	Sigma-Aldrich	0.45 [$ mL^{-1}]

a) http://www.emresist.com/webshop/pmma-product-details.php

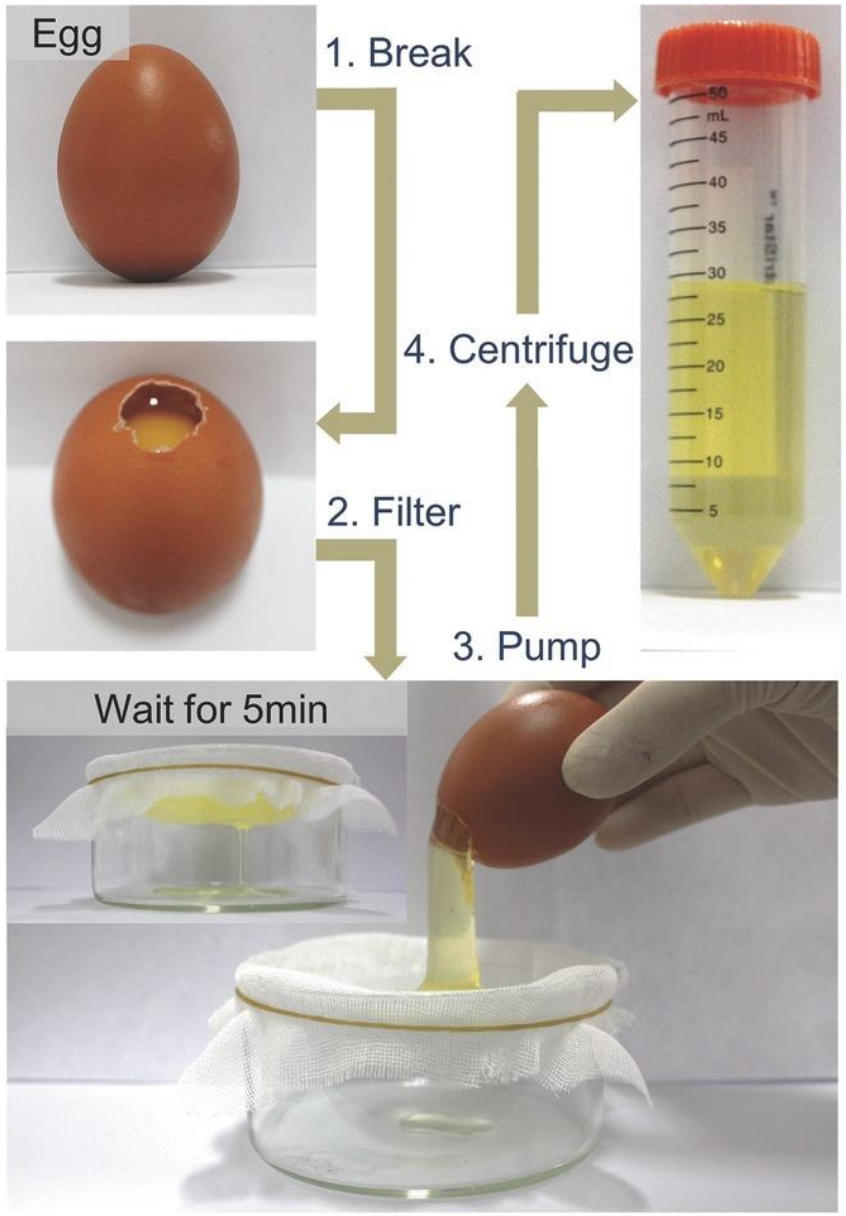
b) http://www.meryer.com/cn/products/detail.aspx?ProID=19970

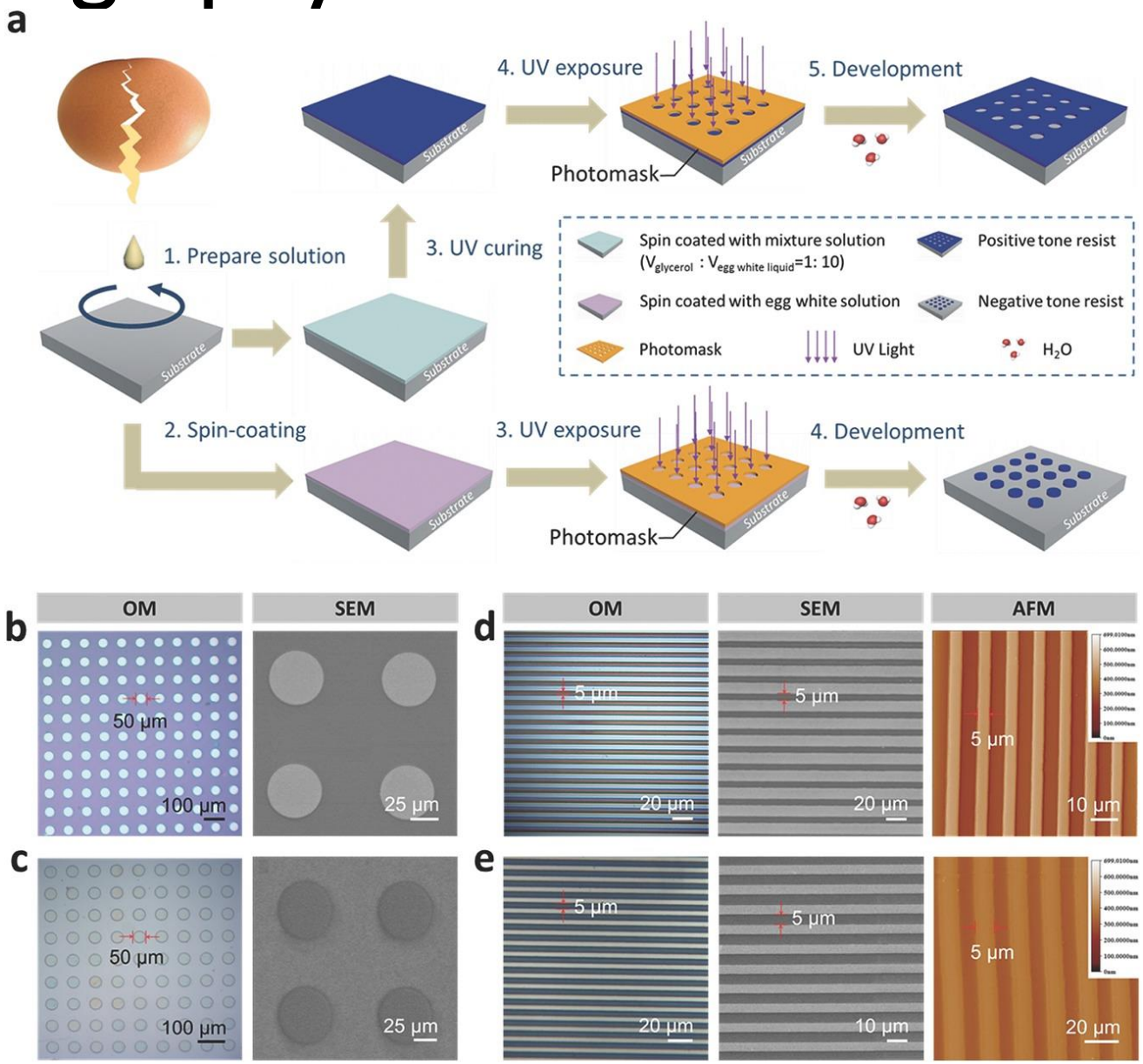
c) https://www.advancedbiomatrix.com/fibroin-silk-solution-2/fibroin-silk-solution/?gclid = CPr09dDGqdACFZclvQodcVcKEA.

***Resolution limit was verified at 15 nm.**

1. Jiang et al., *Advanced Materials Interfaces* (2022)

Green Lithography Methods





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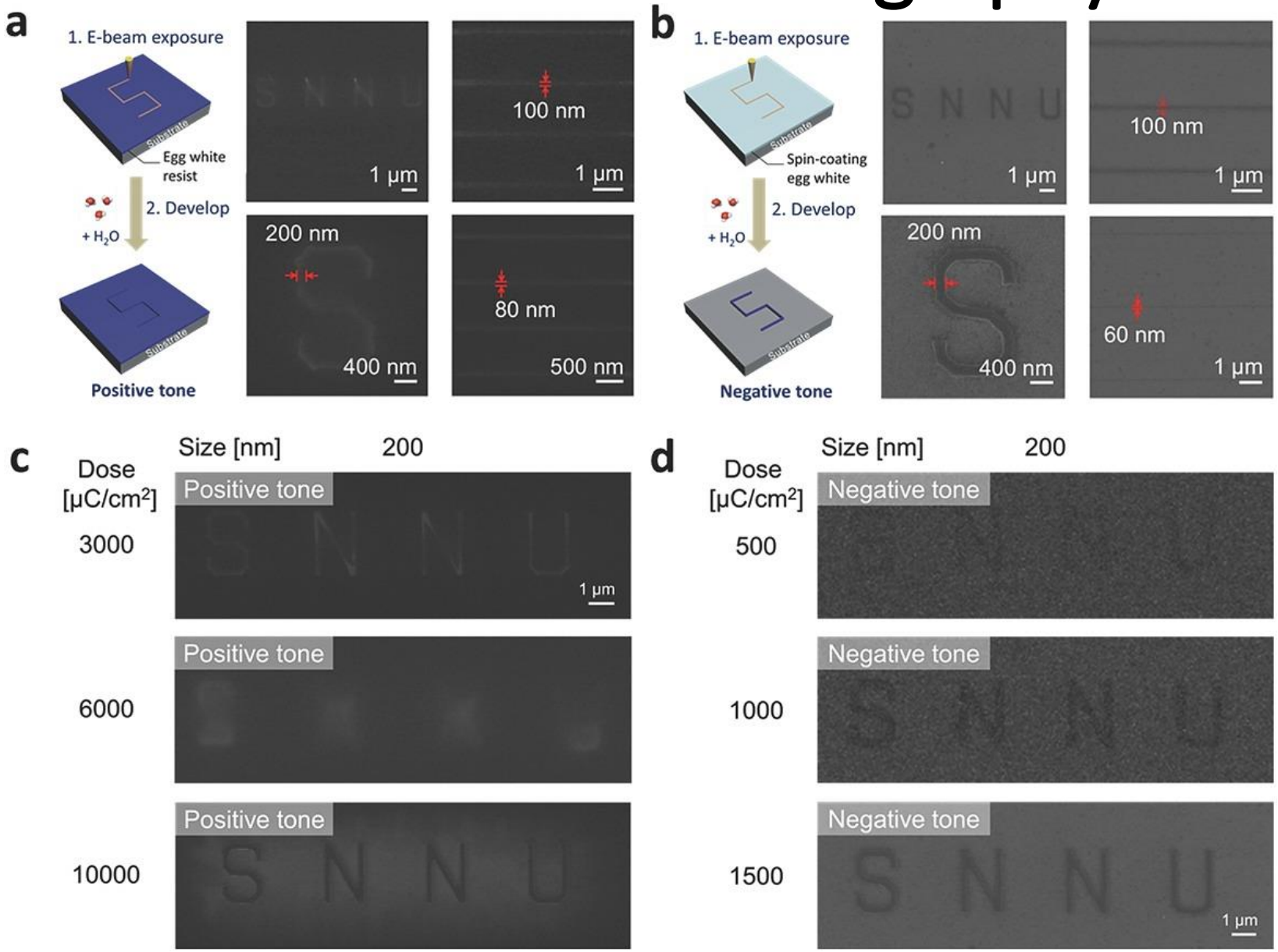
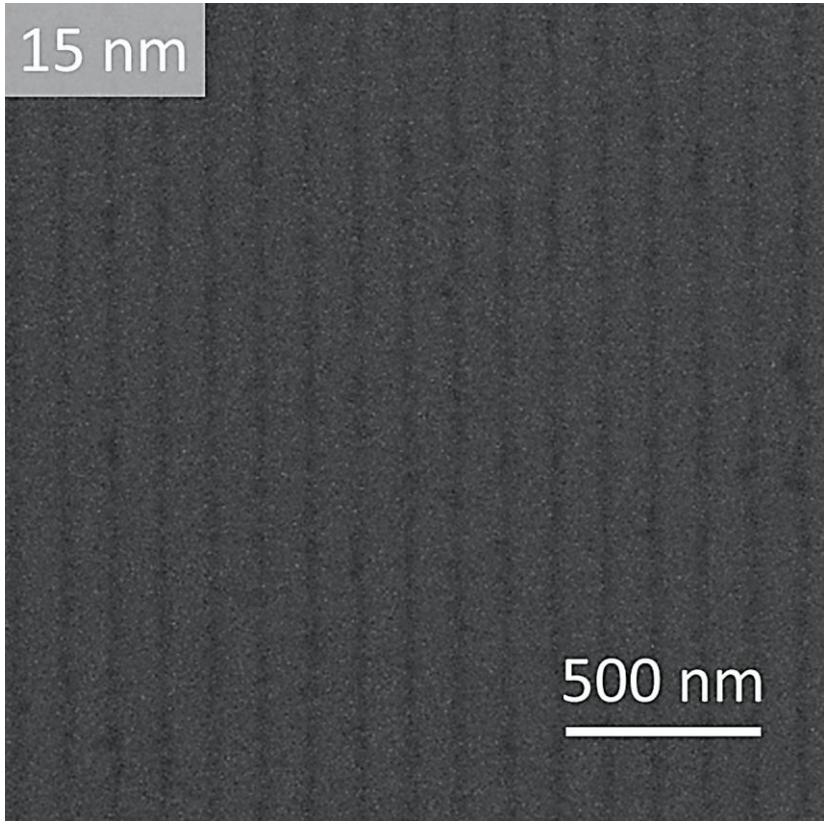
Green Lithography Methods





***Alternative name for egg white resist: albumen**

1. Jiang et al., *Advanced Materials Interfaces* (2022)

Summary

- Electron-beam lithography can provide repeatable/ modifiable design steps.
- The stage setup can be taped to reduce charge build up.
- Operation of design can be automated with Python code if needed in Beamer.
- Green lithography can be used to reduce cost as an experimental electron-beam resist.
- A repository will be made available on marker-free electron-beam patterning.