Ways to Fabricate Quantum Processor Chips

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UNIVERSITY OF MINNESOTA
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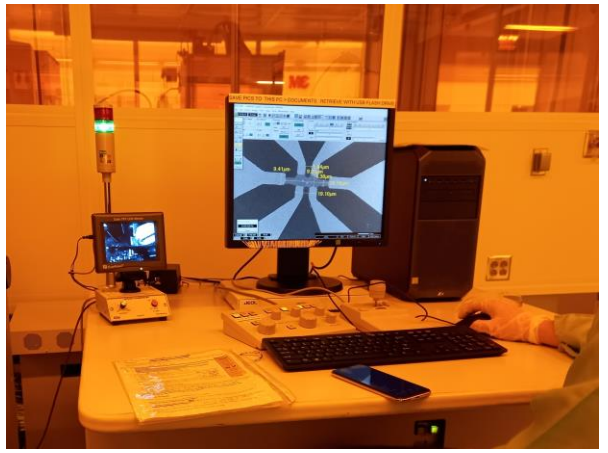
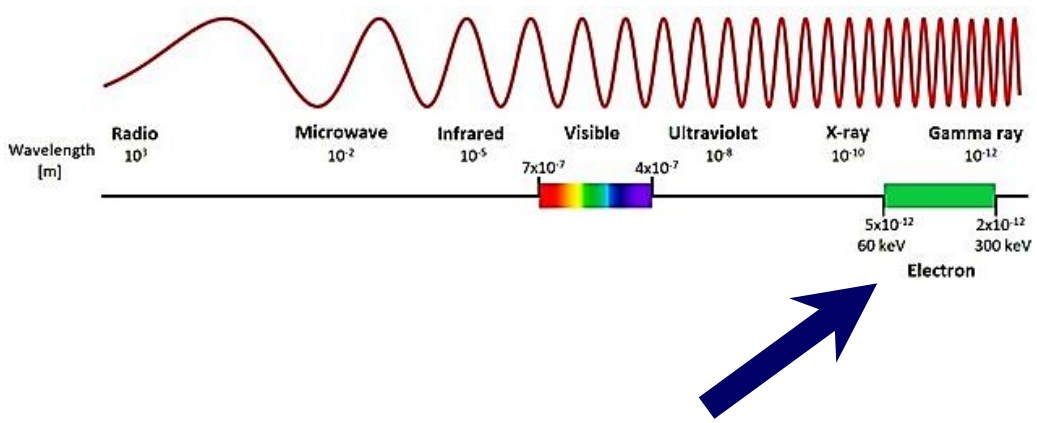
Table of Contents

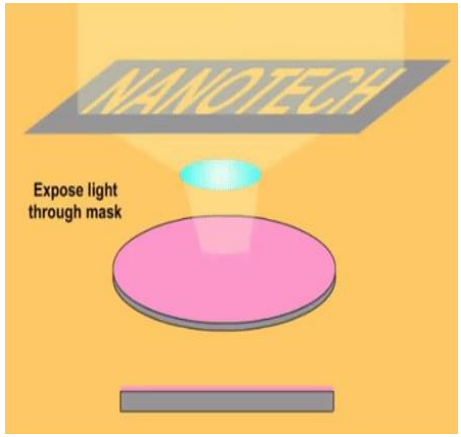


Scanning Electron Microscope from JEOL, *Onri Jay Benally* (2022)

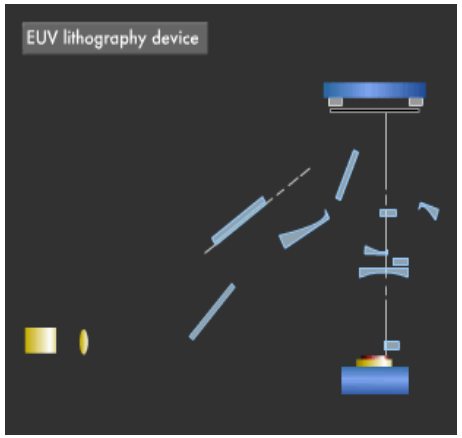
Background & Motivation

- 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).

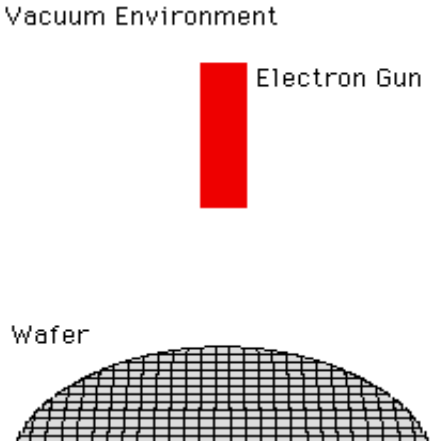




Maskless Ultraviolet Lithography



Maskless Extreme Ultraviolet Lithography



Maskless Electron Beam Lithography

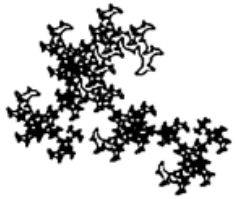
1. Venturi, *PhD Thesis* (2017)
2. Taken from: thumbs.gfy.com
3. Taken from: *Wikimedia Commons*

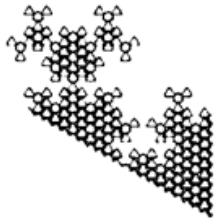
Geh., *ZEISS Group How Photolithography works* (2021)

Taxonomy of Plane-Filling Curves


G(1,1) norm 2 family


E(2,1) norm 3 family

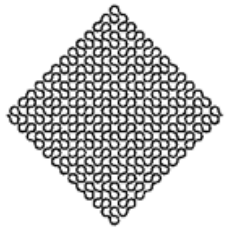

G(2,0) norm 4 family

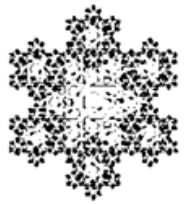

E(2,0) norm 4 family


G(2,1) norm 5 family


E(3,1) norm 7 family


G(2,2) norm 8 family


G(3,0) norm 9 family


E(3,0) norm 9 family

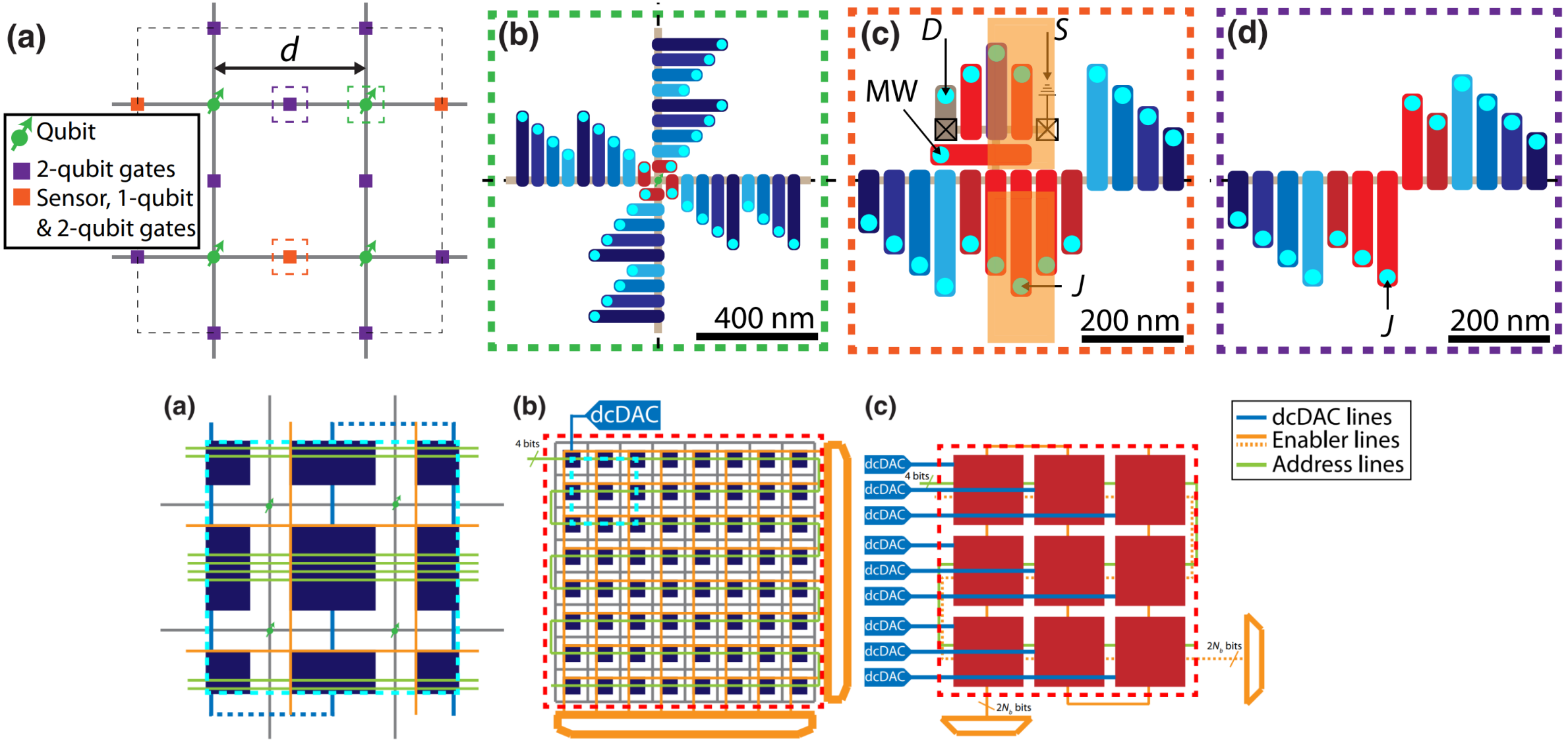

G(3,1) norm 10 family


E(3,4) norm 12 family


E(4.1) norm 13 family

1. Taken from: www.fractalcurves.com

Example of a Spin Qubit Array



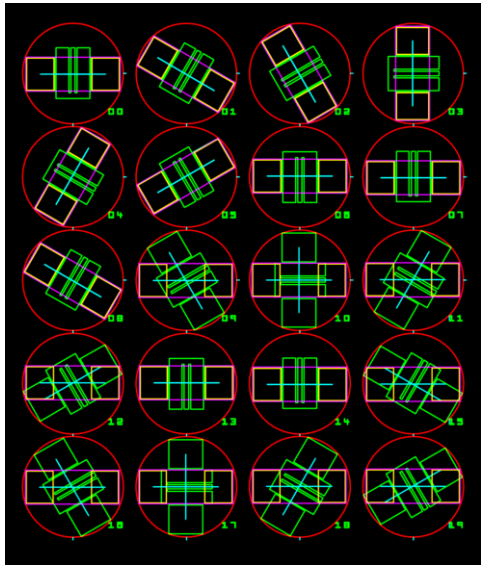
1. Boter et al., *Phys. Rev. Applied* (2022)

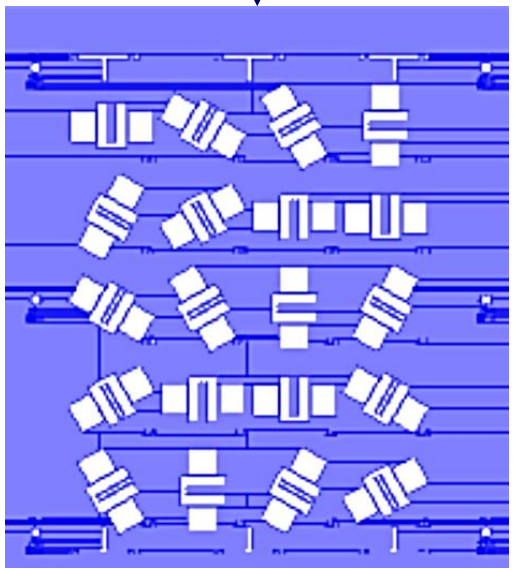
Design Process Flow

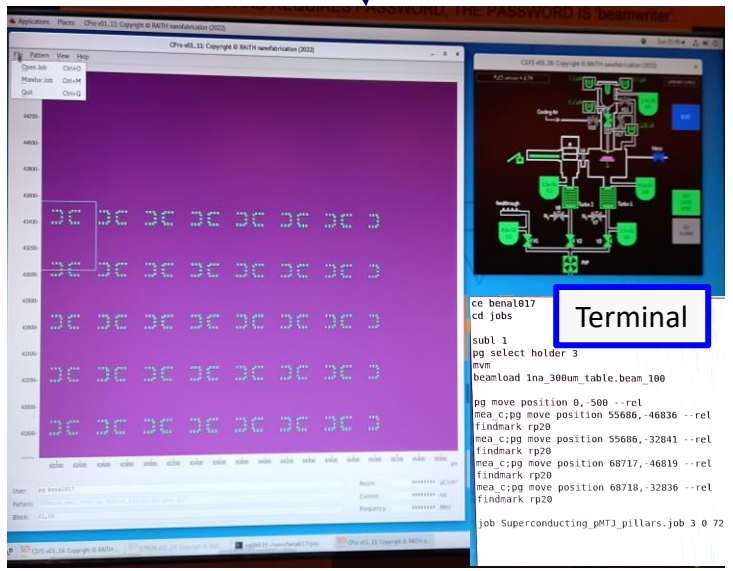
- Design file conversion is a bit extensive.
- CAD **DWG** → **DXF** → **GDS II** → **Beamer** → **GPF** → **CJOB** → **JOB File**

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

During final setup, machine actually uses this one.

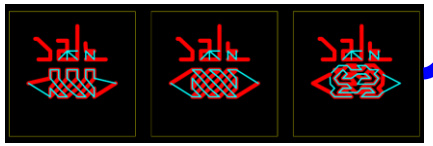


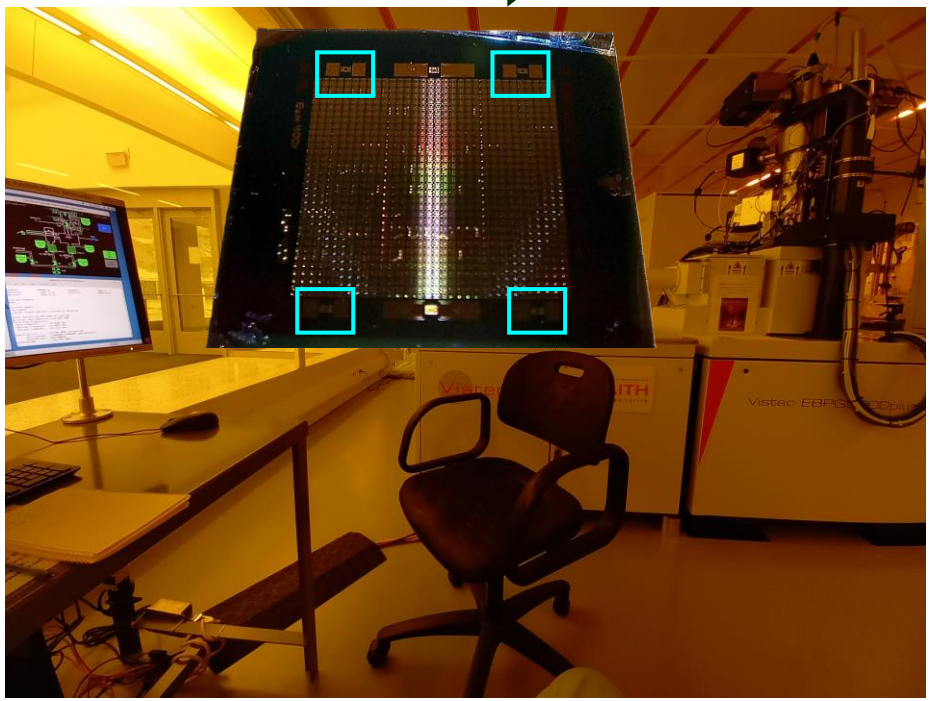


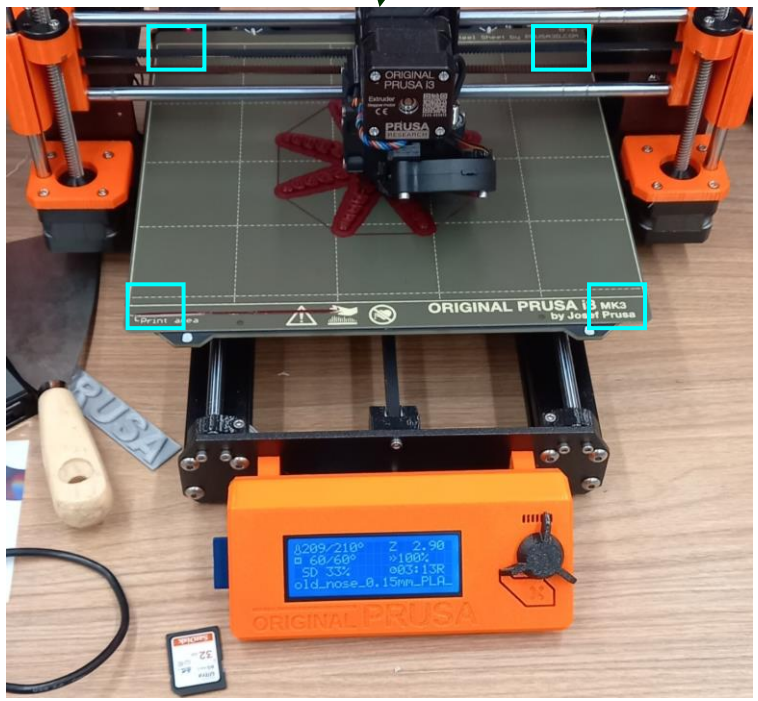


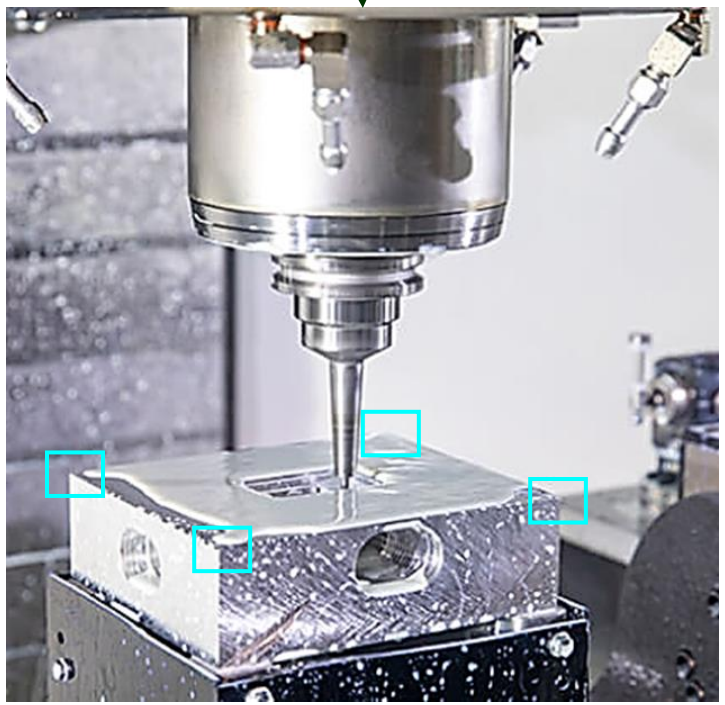
E-Beam vs. 3D Printing vs. CNC Machining

- Similarities:
  - Uses of a type of **G-code** or coordinate system.
  - Initial alignment procedure (reference points).
  - CAD **DWG** → **DXF** → "the **G-Code**".









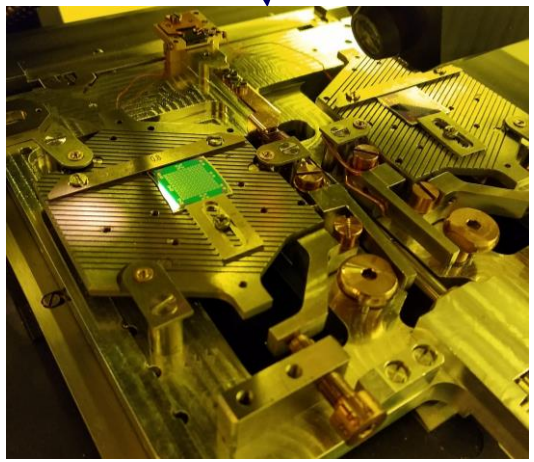
*E-Beam = Electron-Beam
**CNC = Computer Numerical Control
*3D = 3 Dimensional

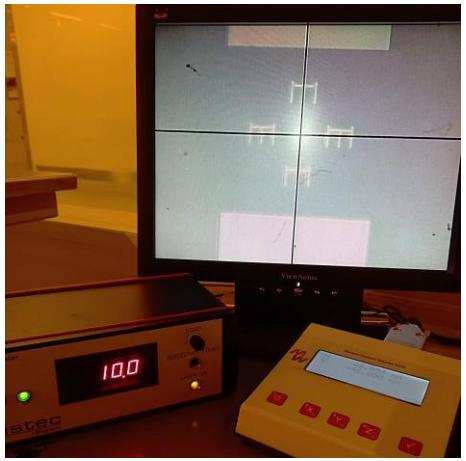
1. Taken from: howtomechatronics.com
2. Taken from: protolabs.co.uk

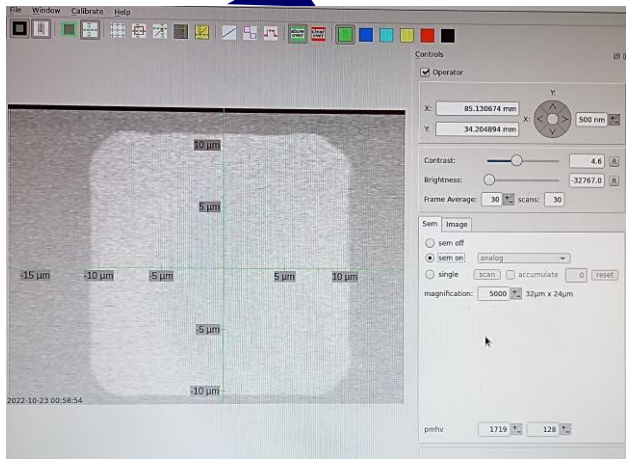
Maskless Direct Writing

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

(rp20)







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findmark rp20
mea_c;pg move position 55686,-32841 --rel
findmark rp20
mea_c;pg move position 68717,-46819 --rel
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mea_c;pg move position 68718,-32836 --rel
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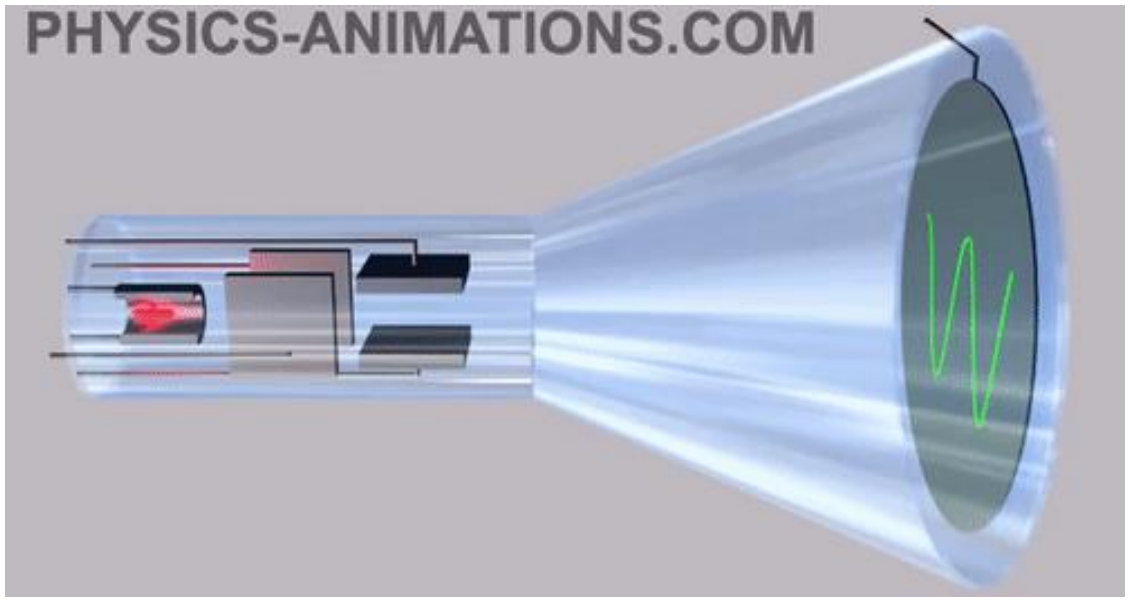
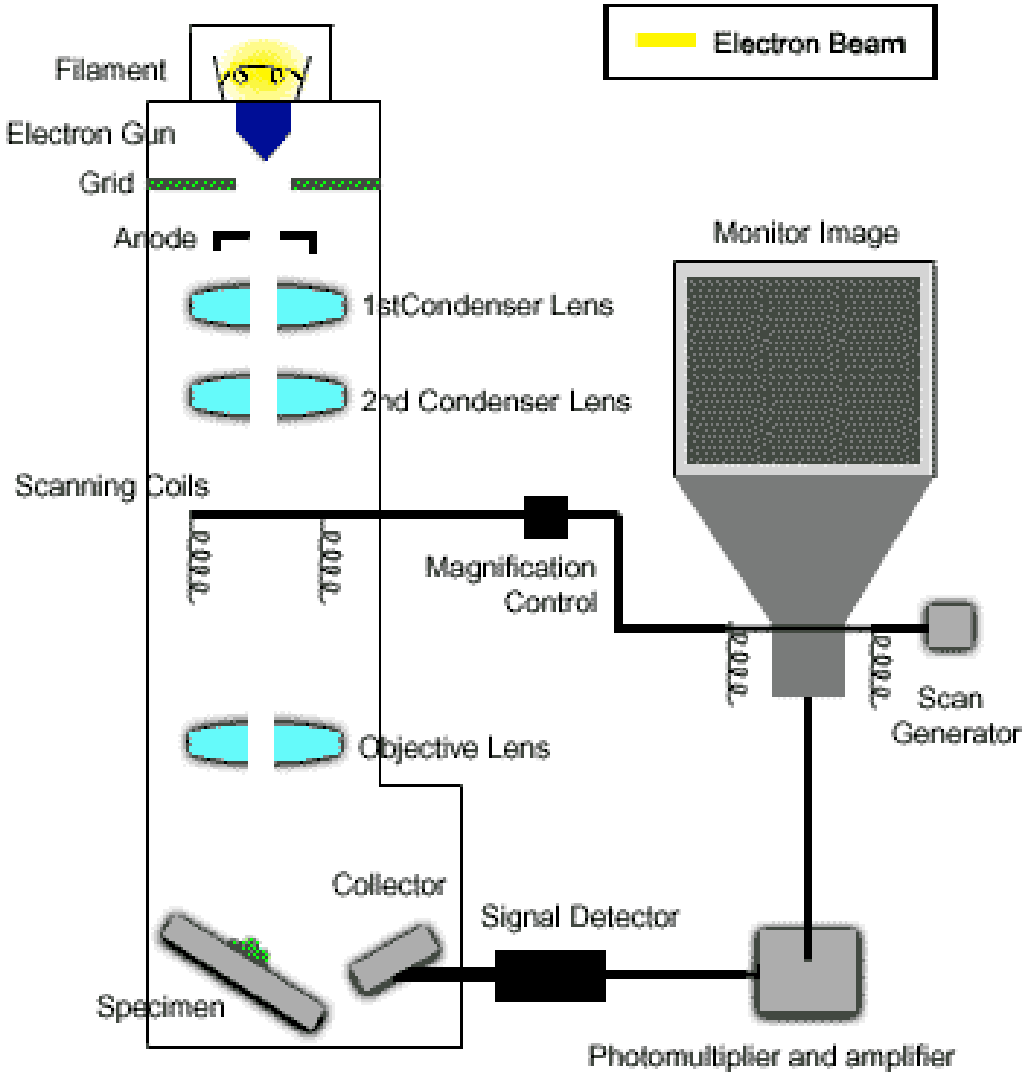
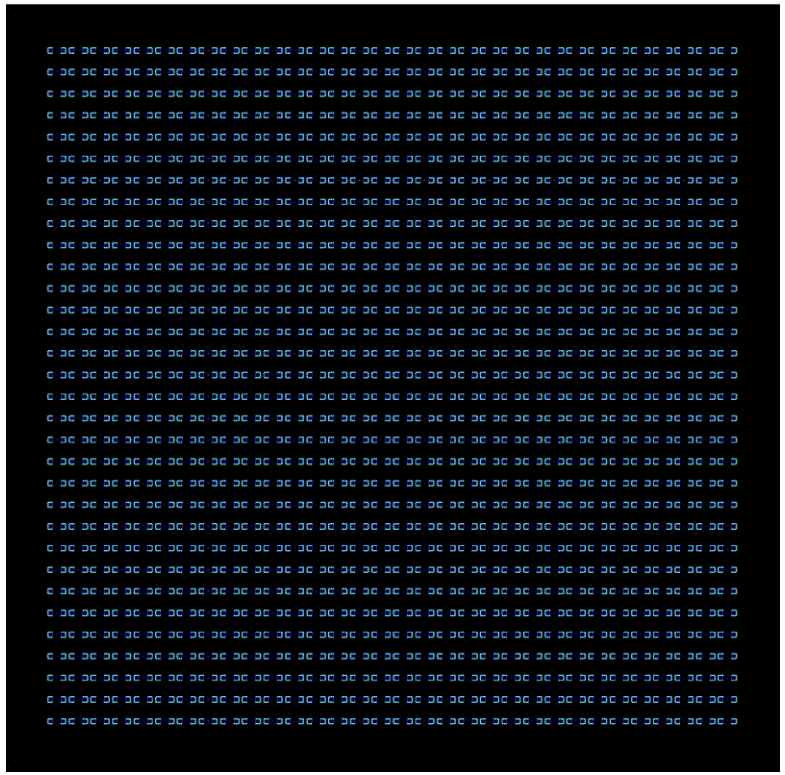
Bonus: Basic Operating Principle of Electron-Beam-Based Technology

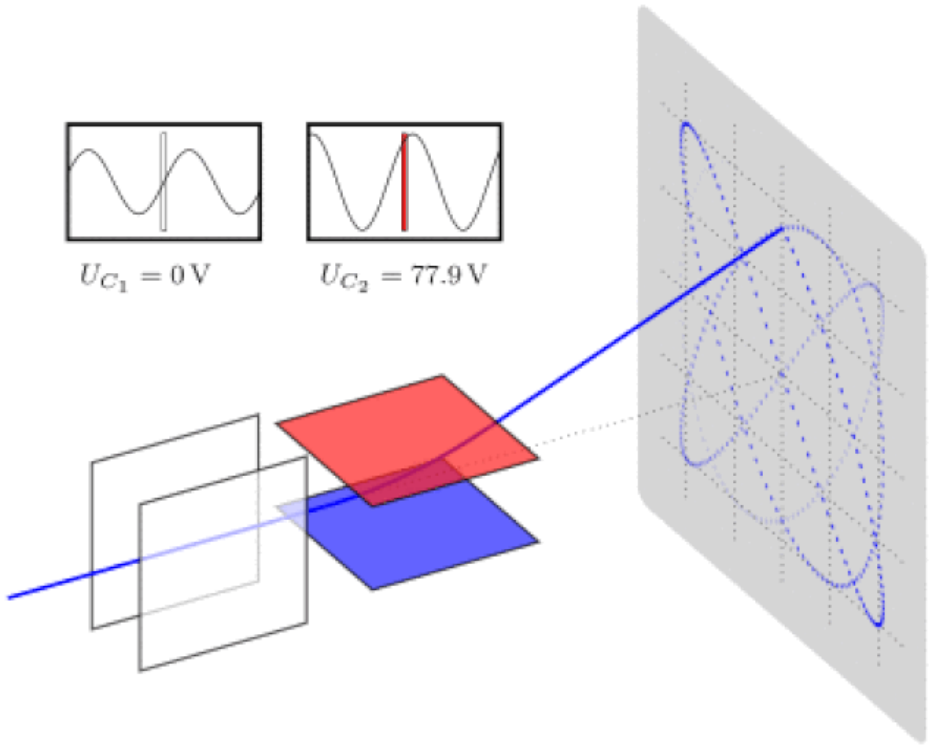


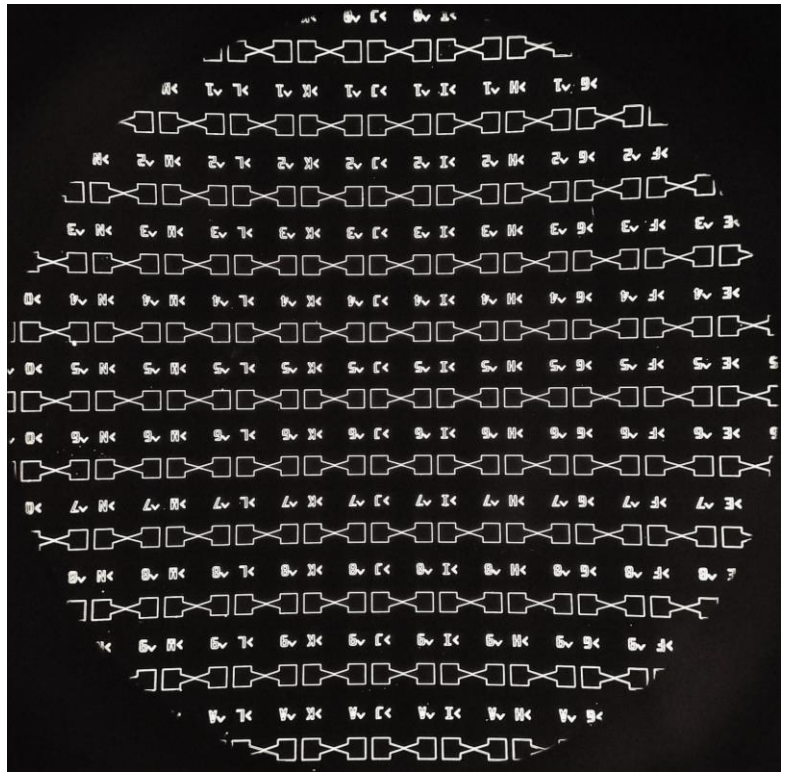


1. Taken from: *Wikimedia Commons*
2. Taken from: makeagif.com

Basic Operating Principle of Electron-Beam Exposed Features

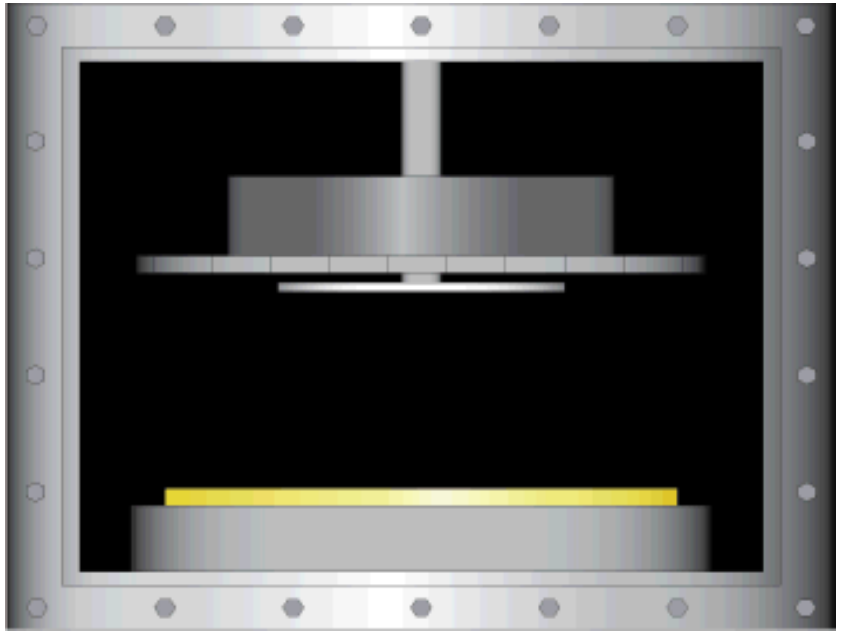




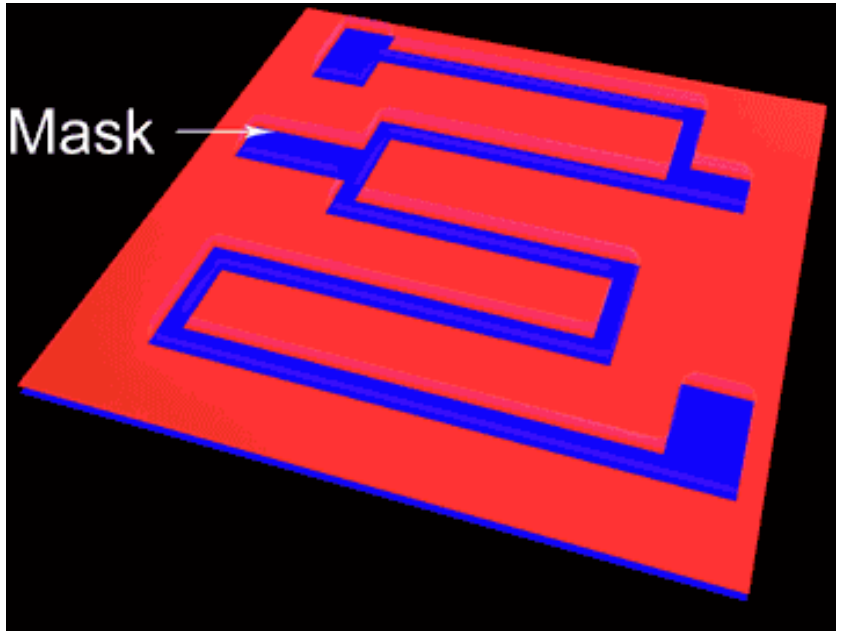


1. Taken from: Wikimedia commons

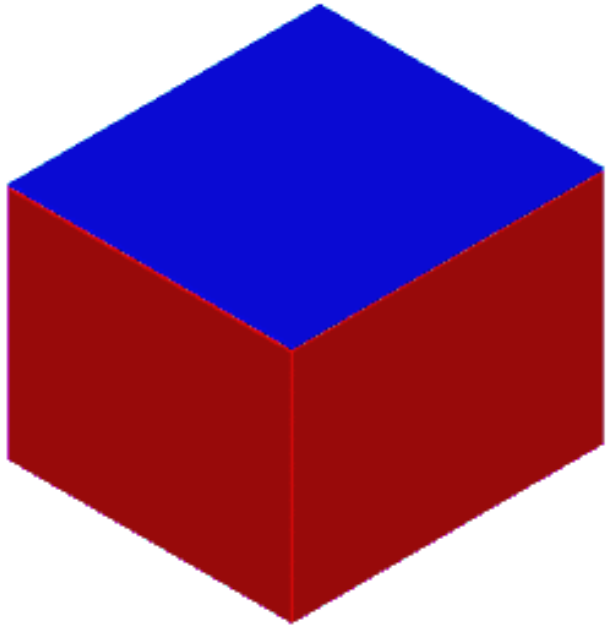
Material Deposition & Etching



For depositing or growing materials



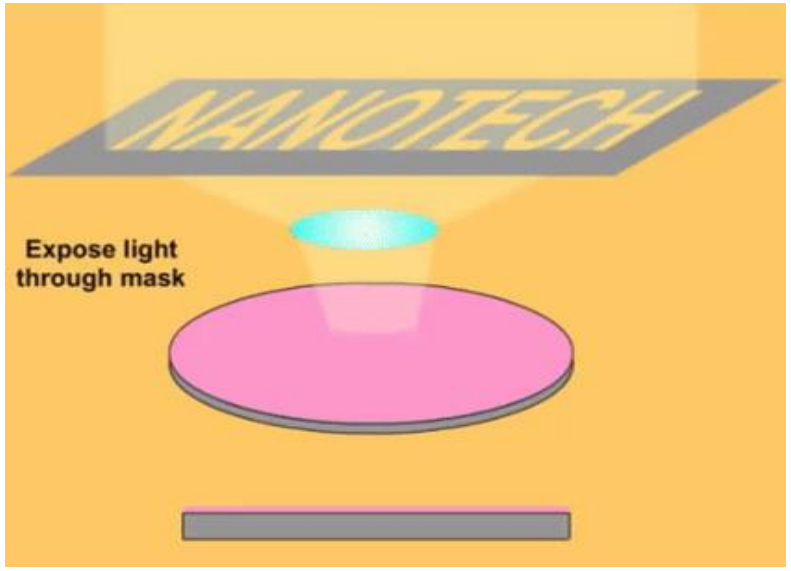
For removing or etching materials



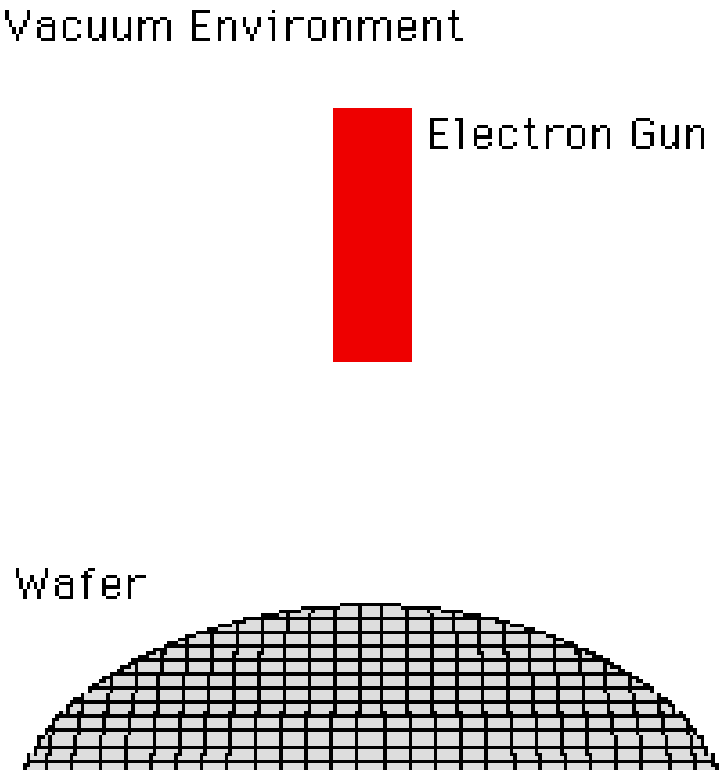
Result

1. *AJA International Inc.*
2. Taken from: tenor.com
3. Taken from: Wikimedia commons

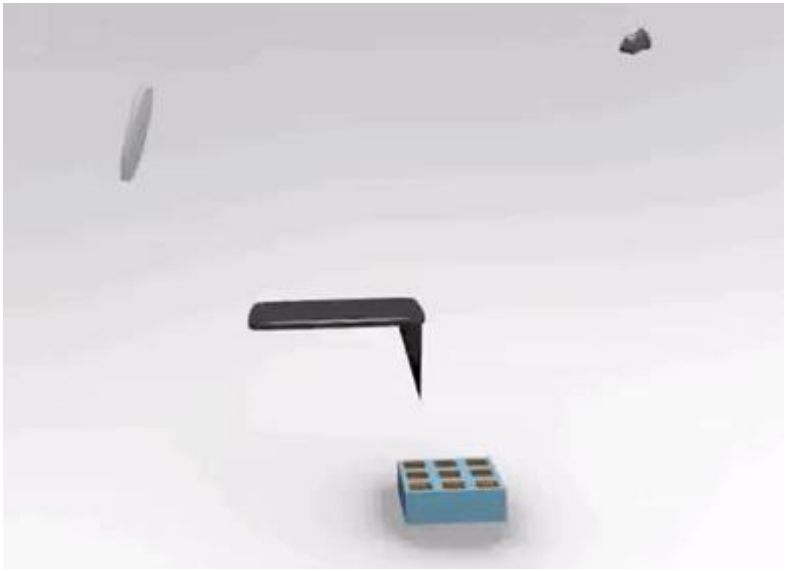
3 Examples of Lithography Systems



Ultraviolet Lithography



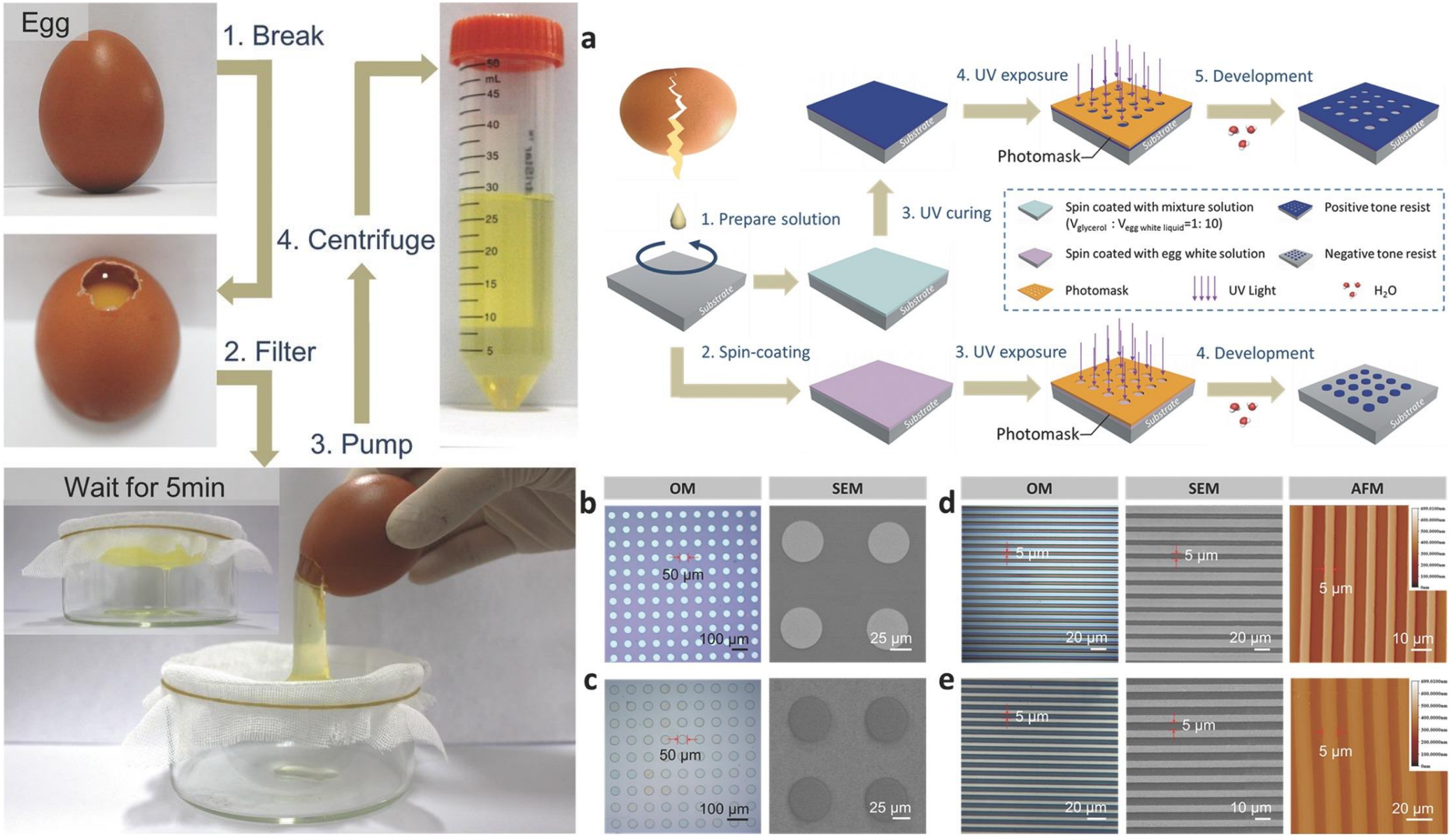
Electron Beam Lithography



Scanning Probe Lithography

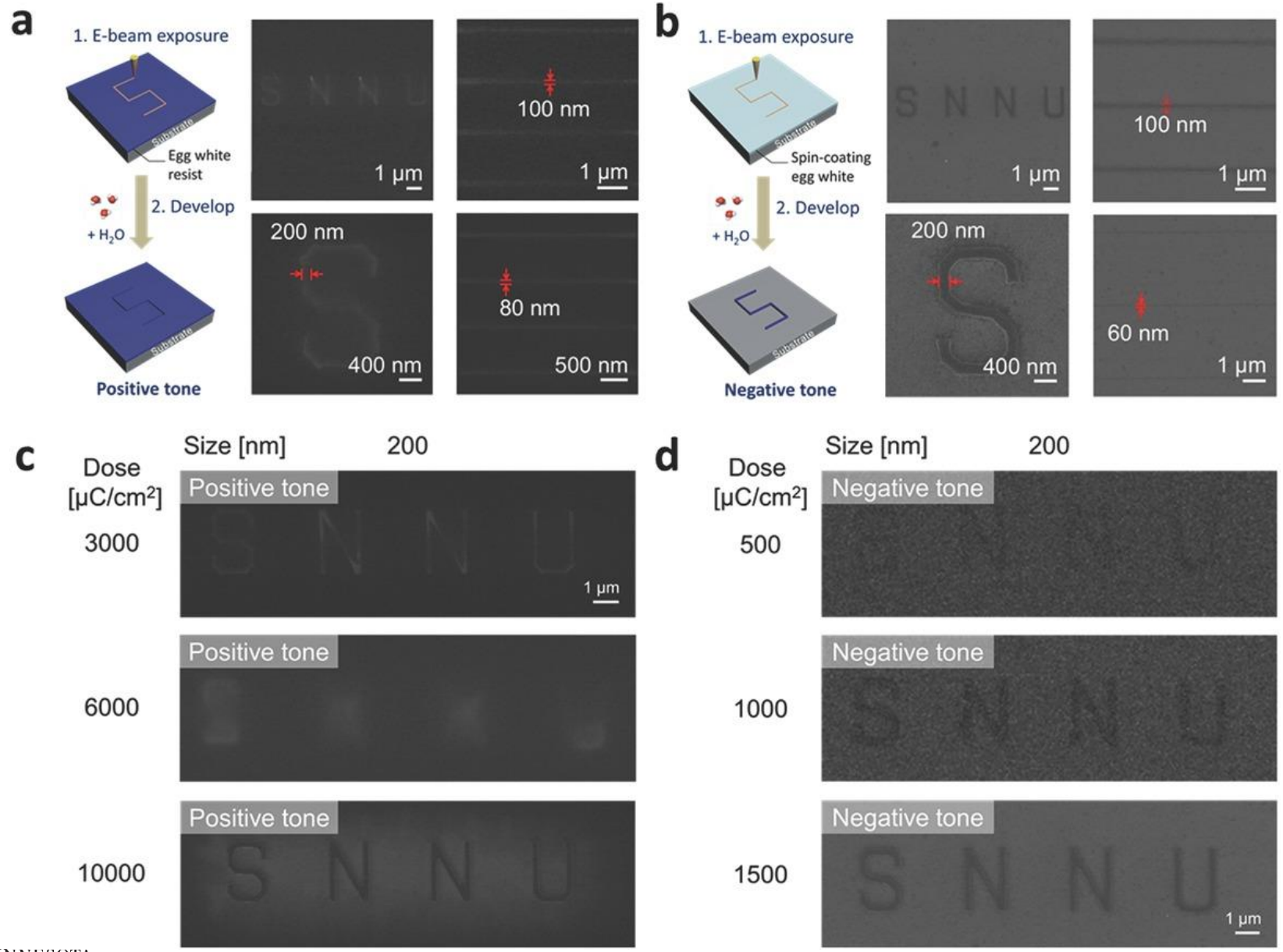
1. Taken from: thumbs.gfy.com
2. Taken from: wikipedia.org
3. Taken from: web.cecs.pdx.edu

Green Lithography Methods



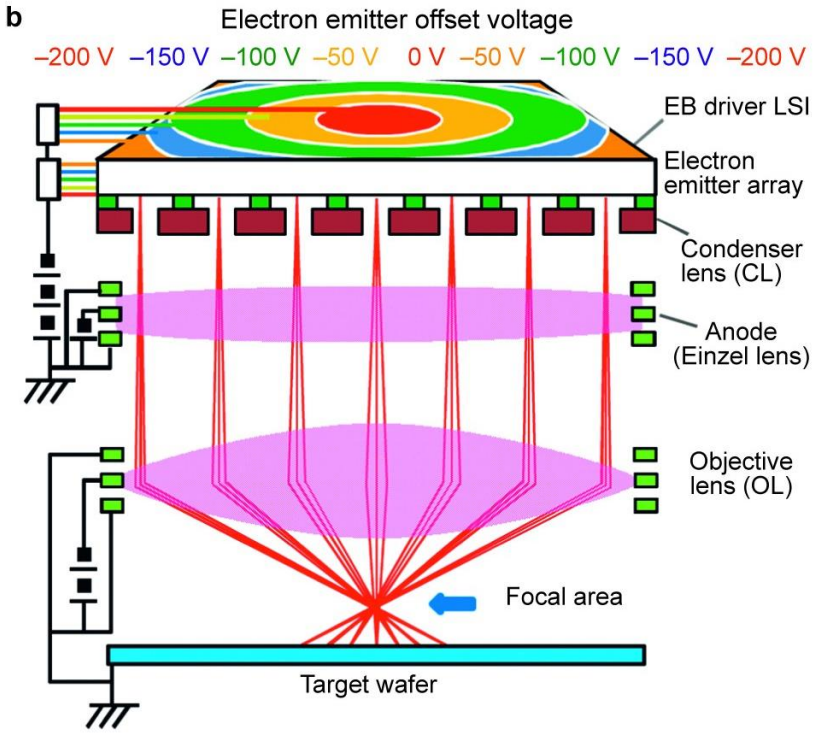
1. Jiang et al., *Advanced Materials Interfaces* (2022)

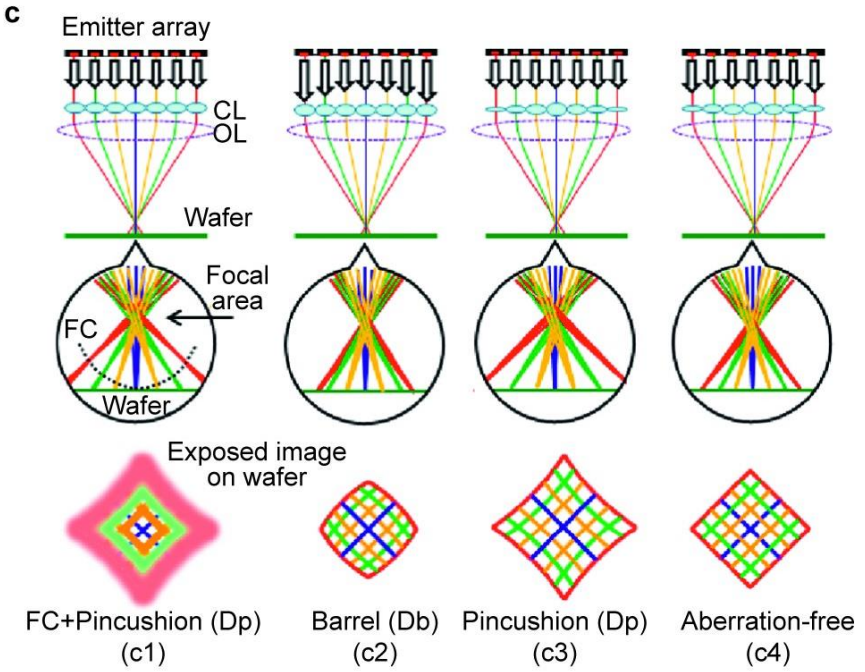
Green Lithography Methods

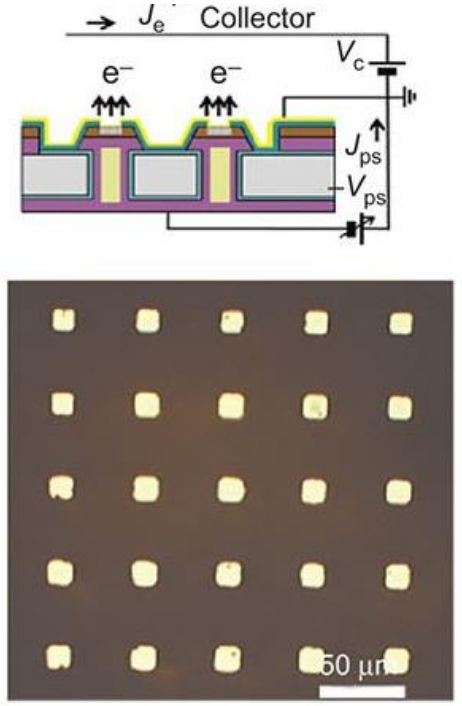


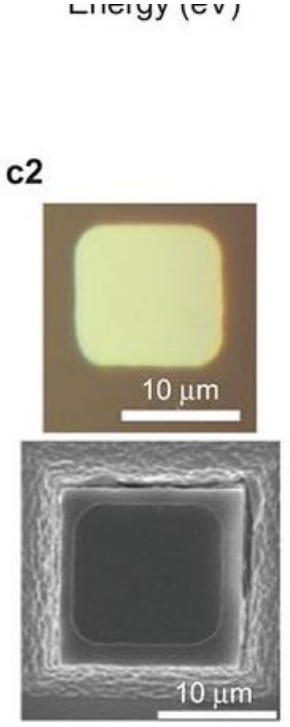
1. Jiang et al., *Advanced Materials Interfaces* (2022)

Multi-Beam Direct-Writing



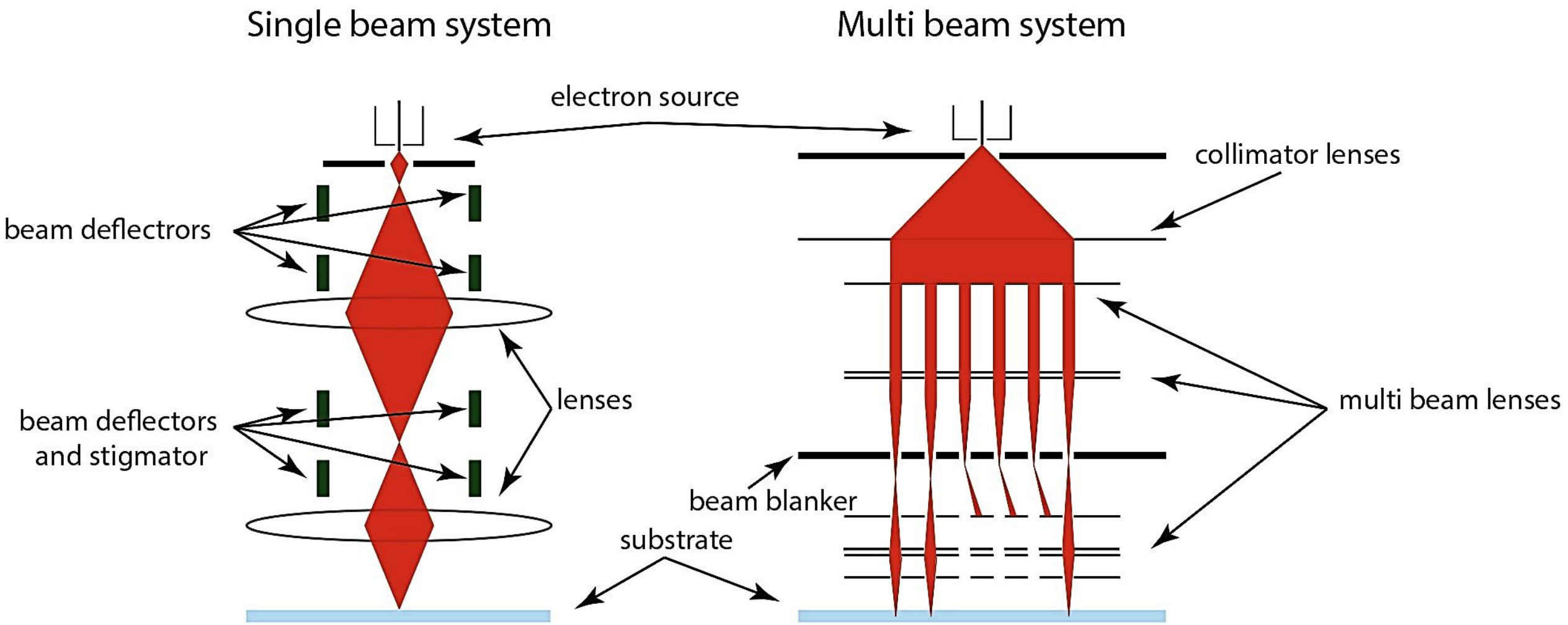






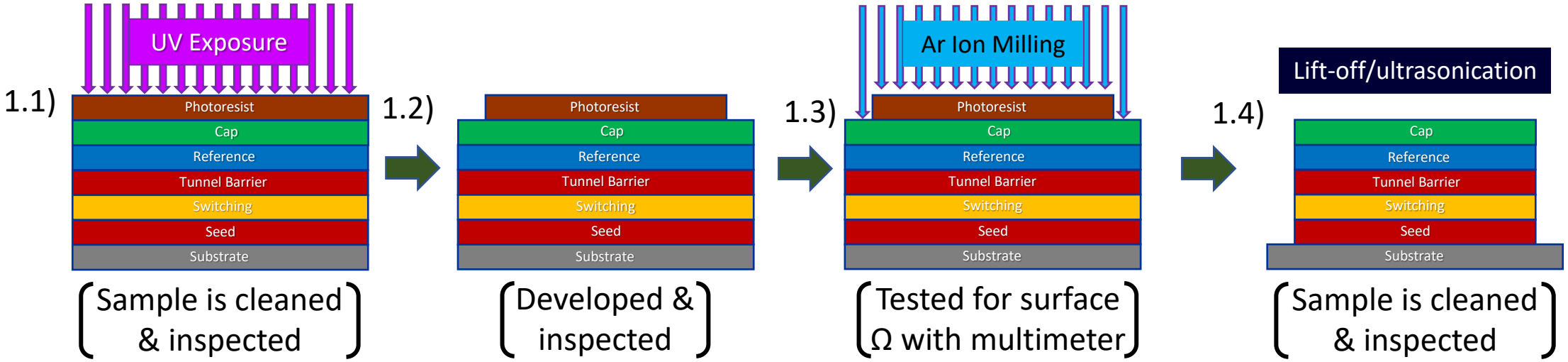
1. Zonnevylle et al., *Microelectronic Engineering* (2014)
2. Esashi et al., *Nature: Microsystems & Nanoengineering* (2015)

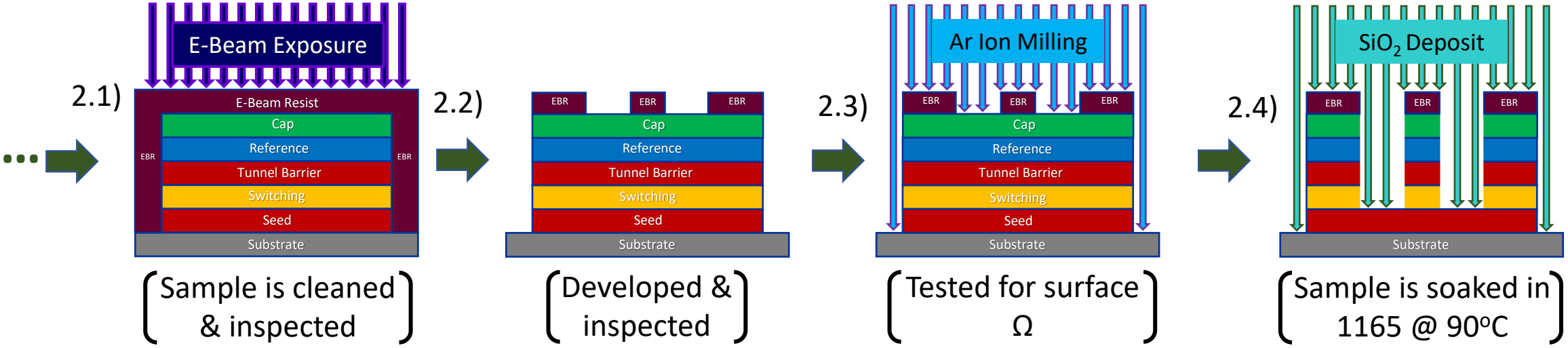
Multi-Beam Direct-Writing



1. Zonnevylle et al., *Microelectronic Engineering* (2014)
2. Esashi et al., *Nature: Microsystems & Nanoengineering* (2015)

Generic Example of Standard Fabrication Flow



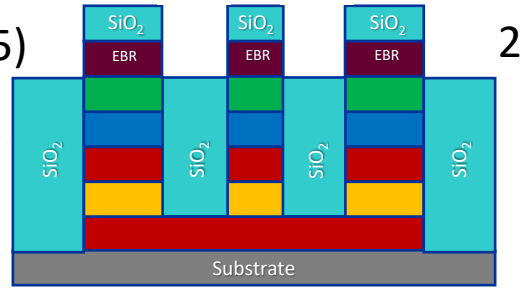


*PR = Photoresist ***EBR = Electron-Beam Resist
** Ω = Resistance

Randomized Example of Standard Fabrication Flow

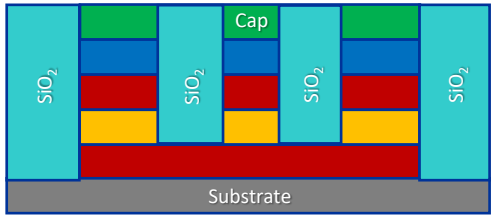
Lift-off/ultrasonication

2.5)



Sample is cleaned & inspected

2.6)



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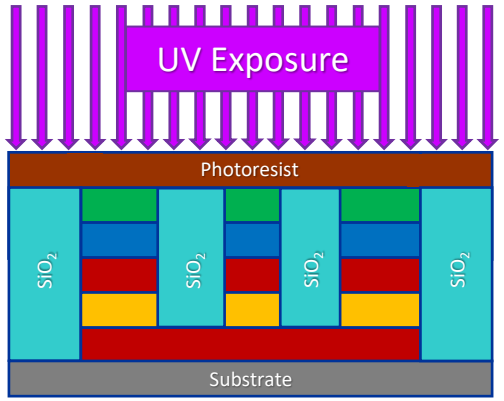
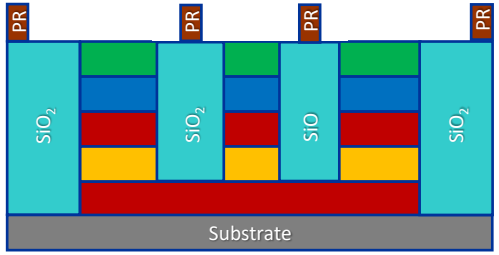


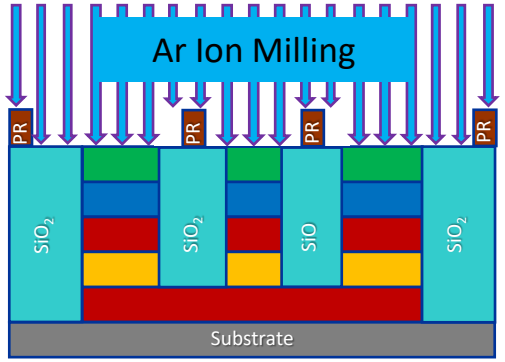
Sample is cleaned & inspected

3.2)



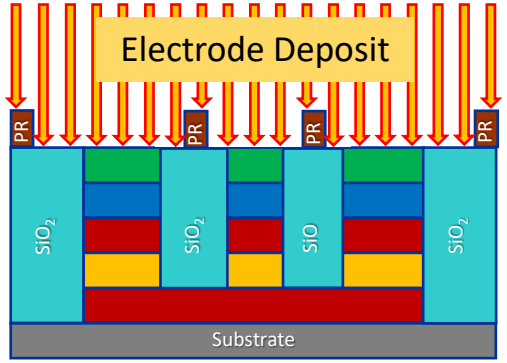
Developed & inspected

2.5)

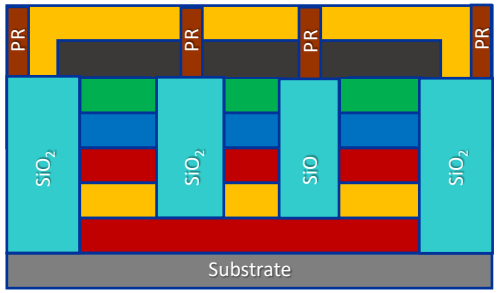


Etched immediately before deposition

2.6)

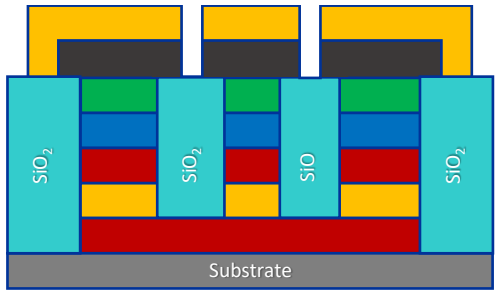


3.1)



3.2)

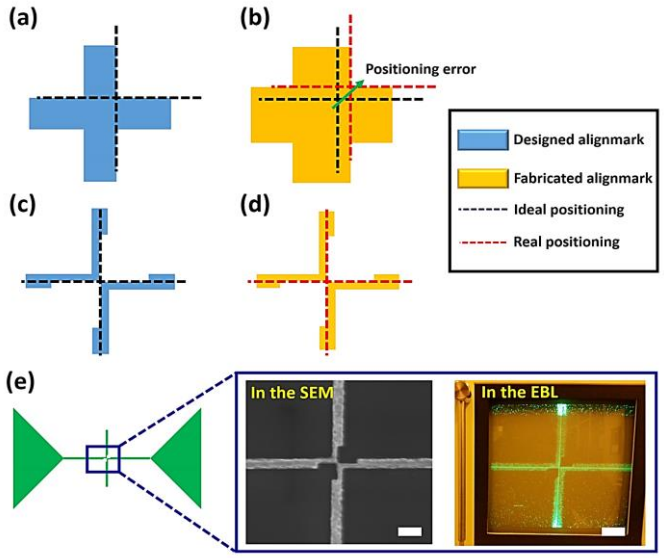
Lift-off/ultrasonication

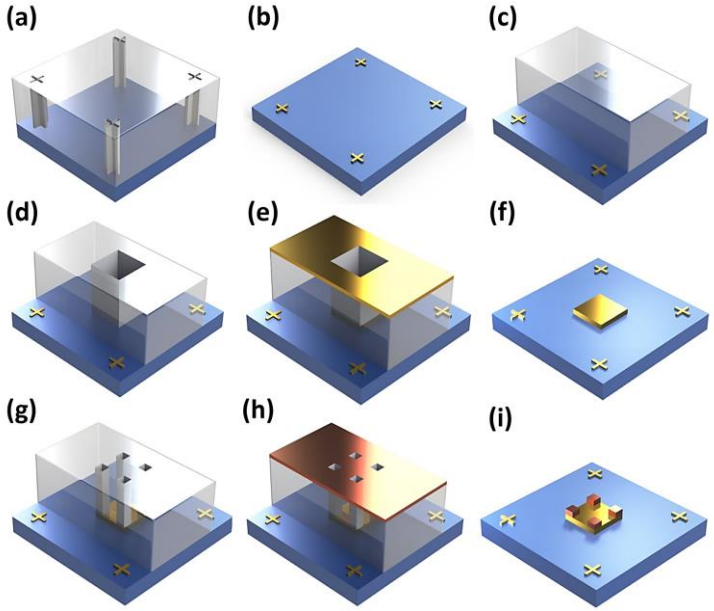


Device is cleaned & inspected

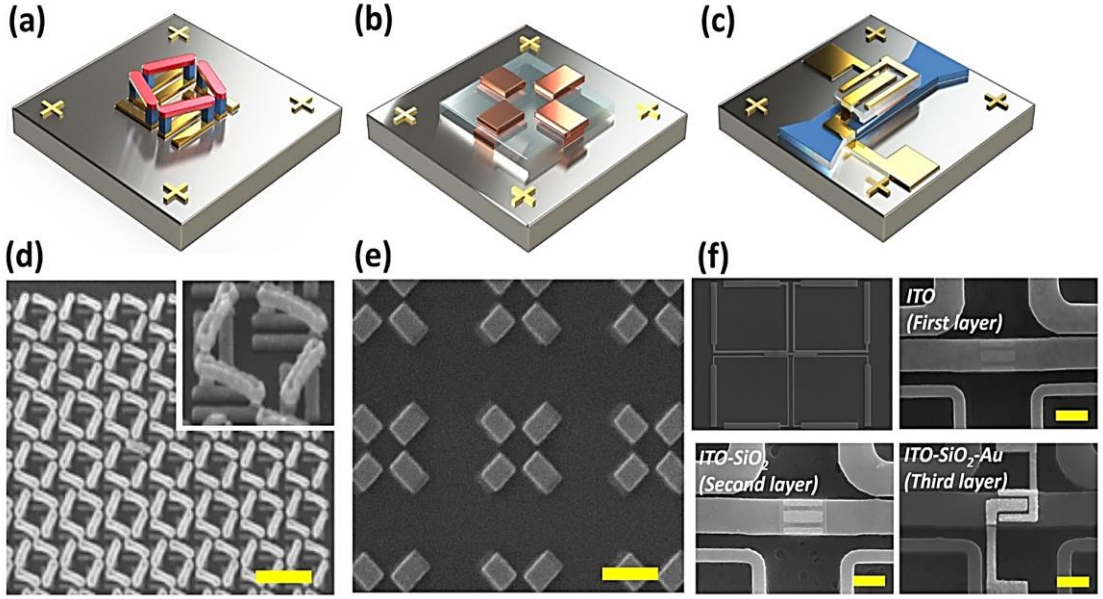
*PR = Photoresist ***EBR = Electron-Beam Resist
** Ω = Resistance

Example of Overlay Nanostructures Fabricated with E-Beam





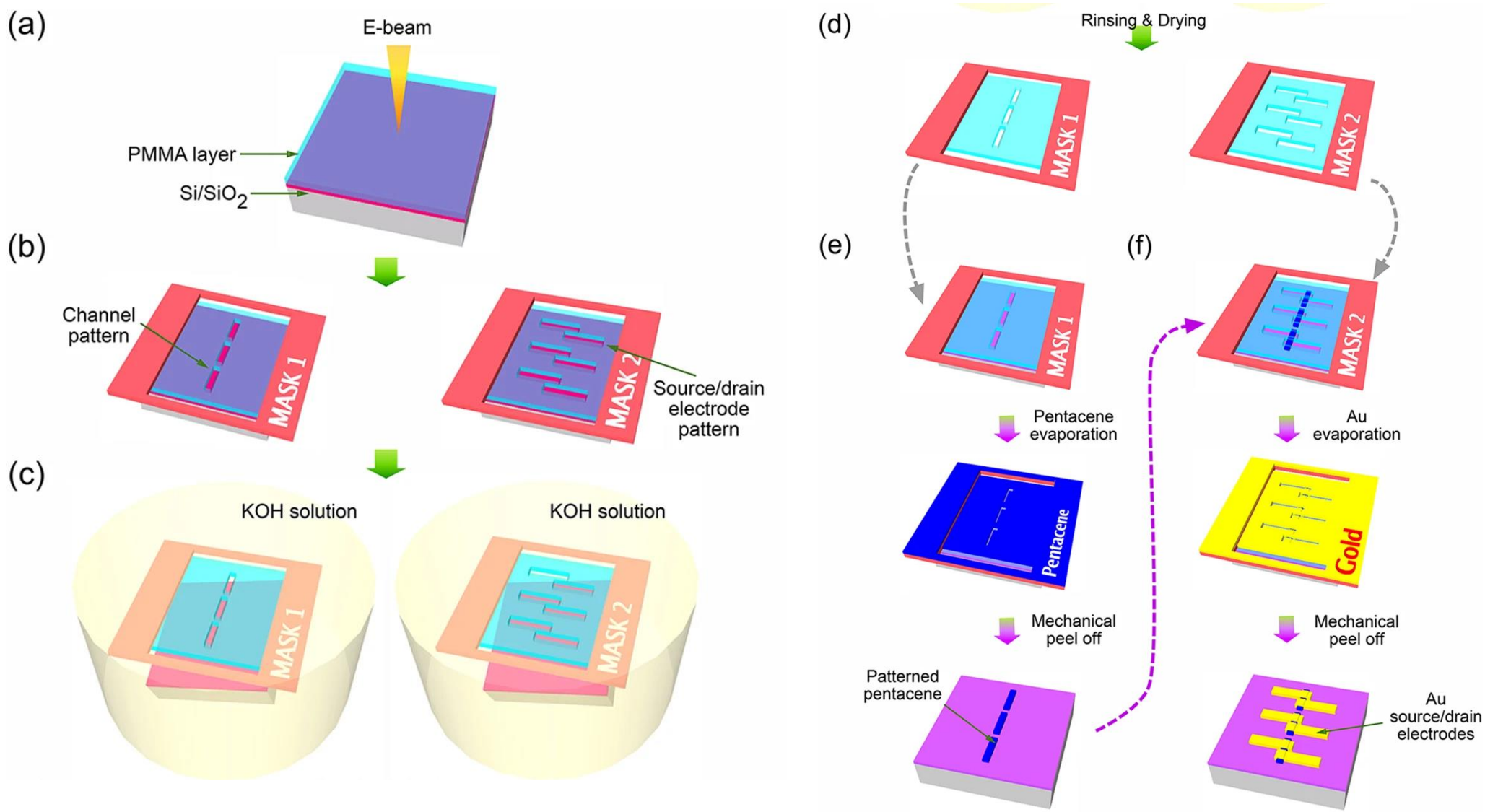
(100 nm scale bars)



(500 nm scale bars)

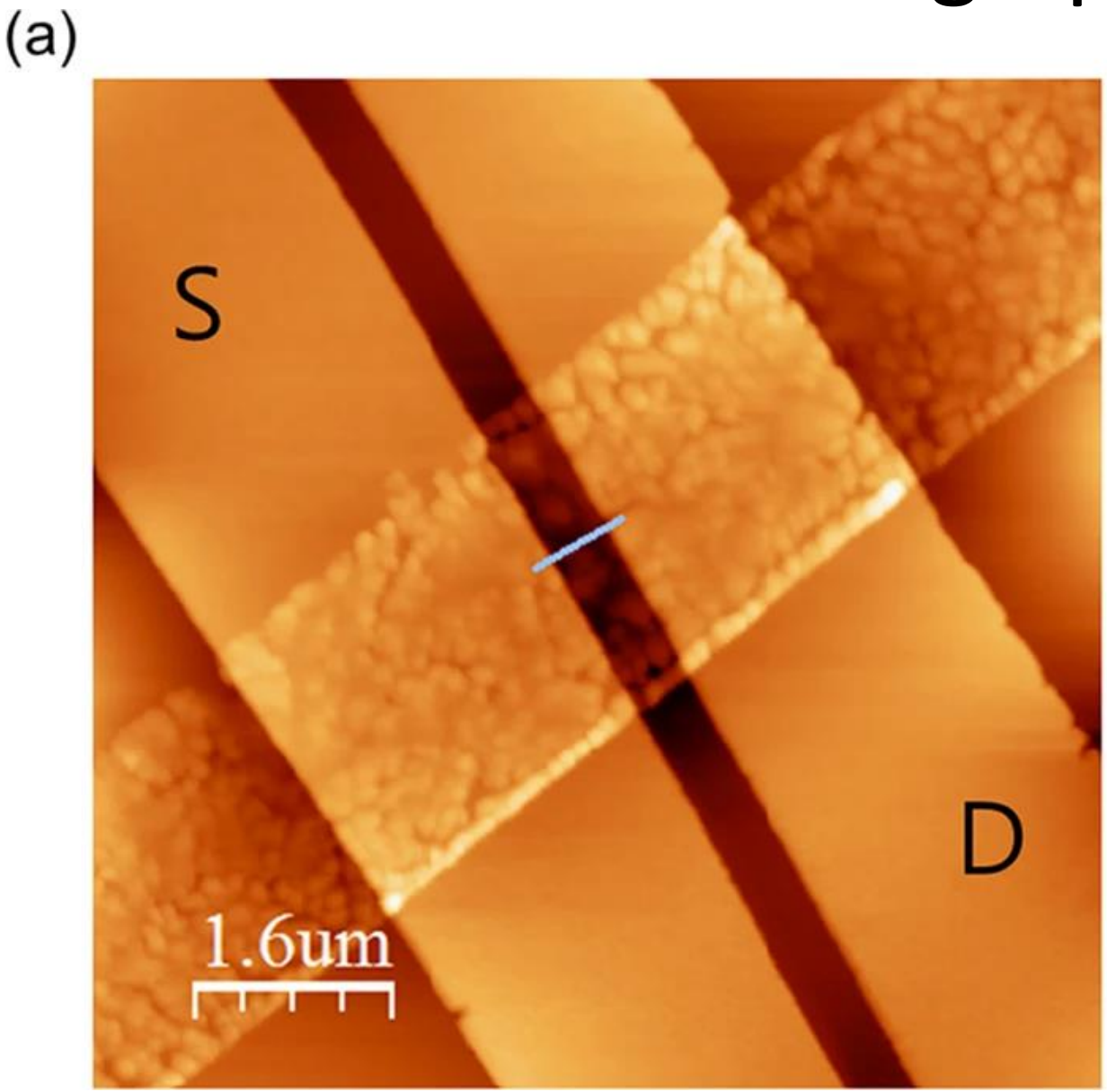
1. Yoon et al., *Nature Scientific Reports* (2017)

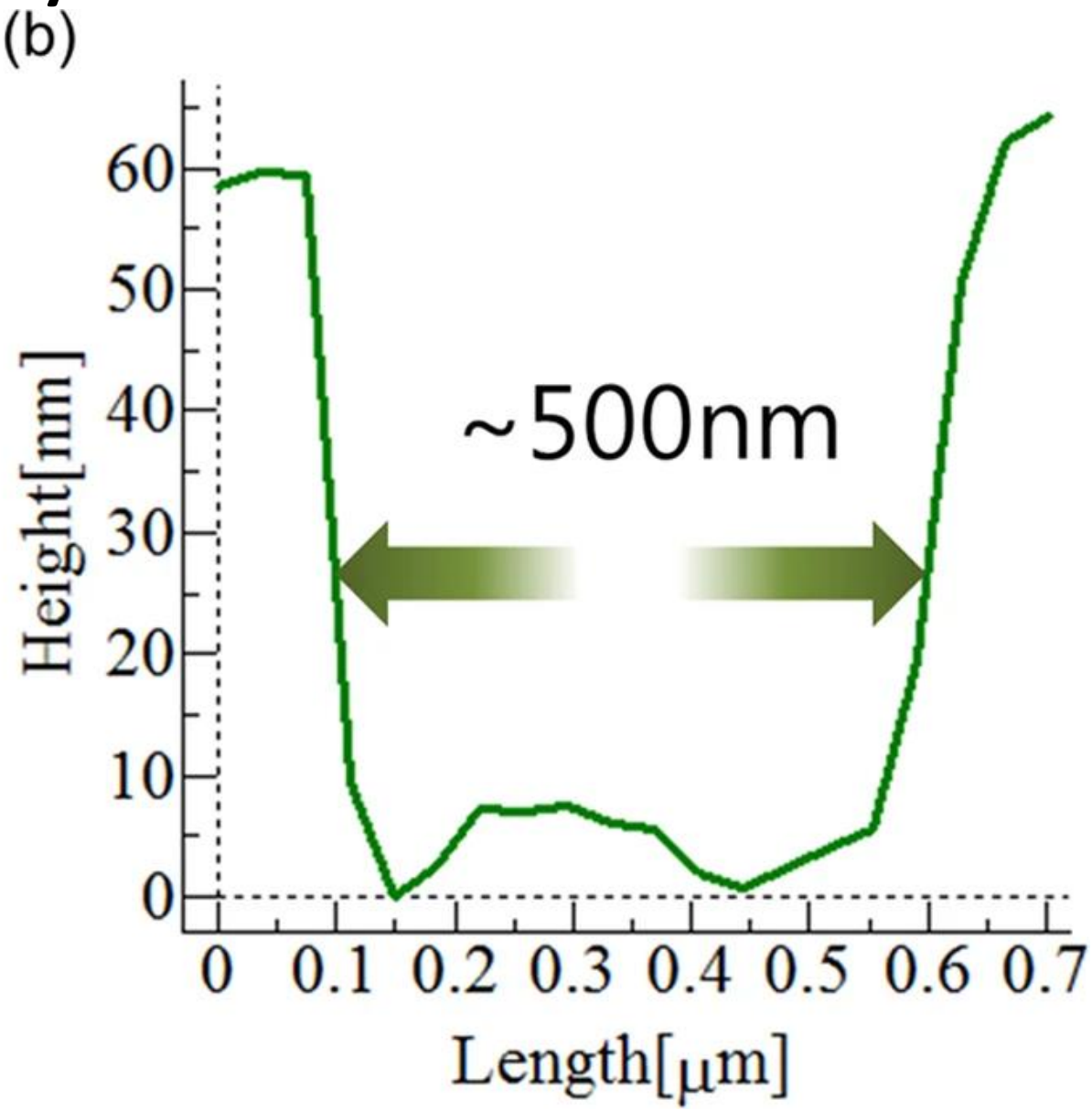
Shadow Lithography for Nanowires



1. Yun et al., *Scientific Reports* (2015)

Shadow Lithography for Nanowires

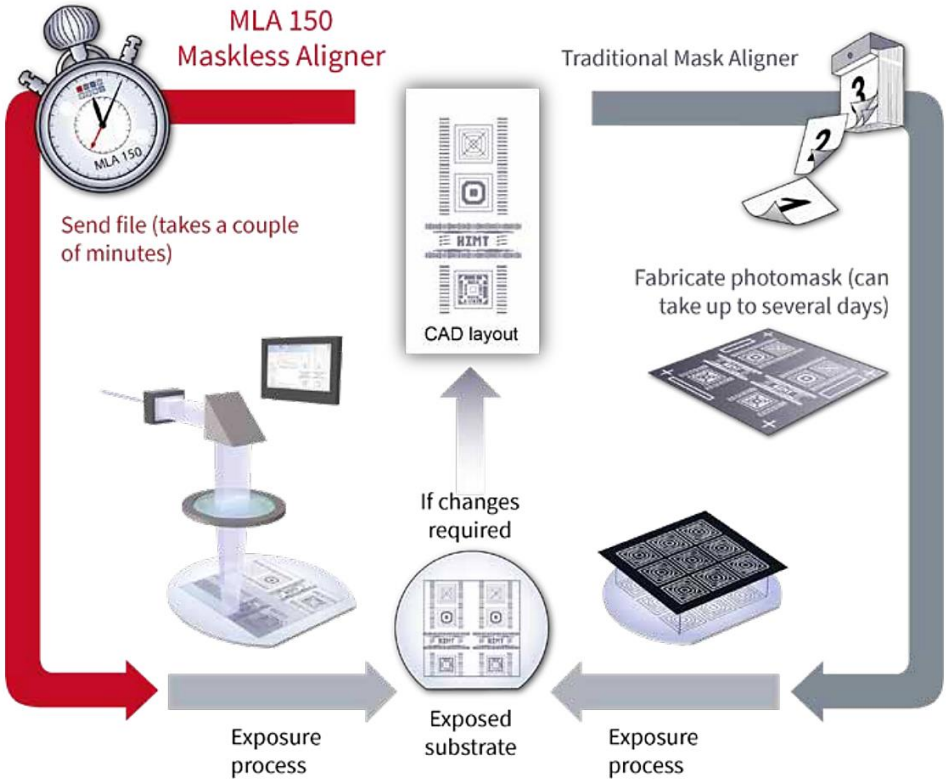


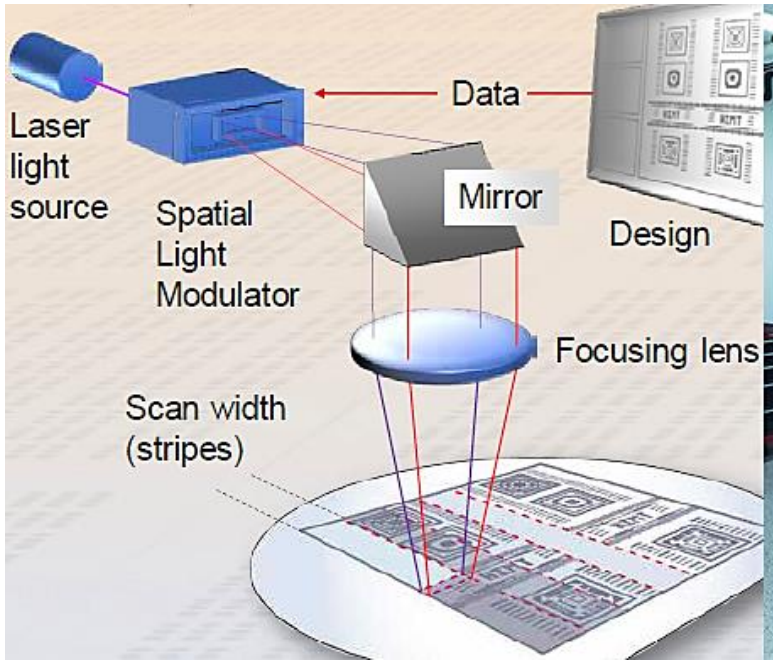


1. Yun et al., *Scientific Reports* (2015)

Heidelberg MLA 150 Maskless Aligner

- LASER wavelength = 375 - 405 nm
- 50 mm x 50 mm^2 = 4 min of writing time, 0.6 micron
- Large machine
- Compatible with all broadband UV photoresists

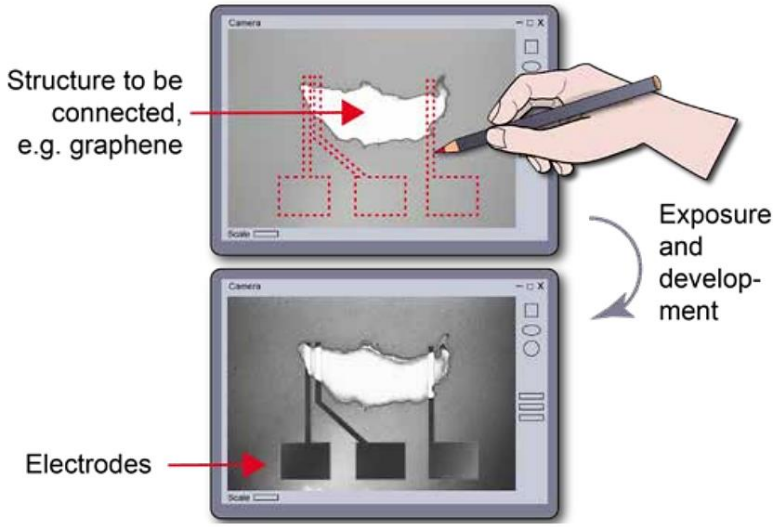


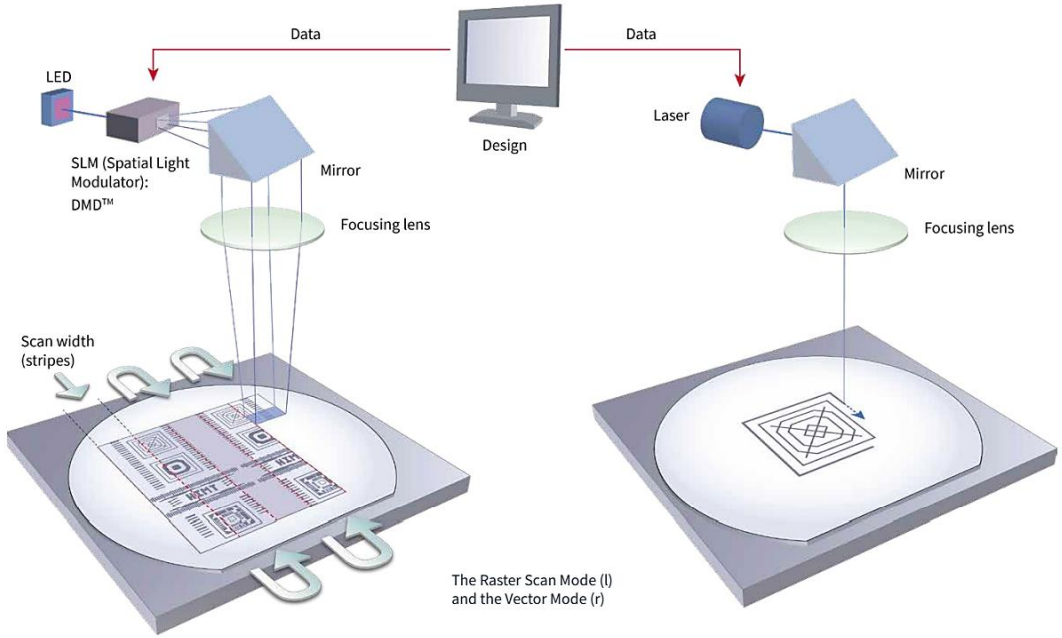


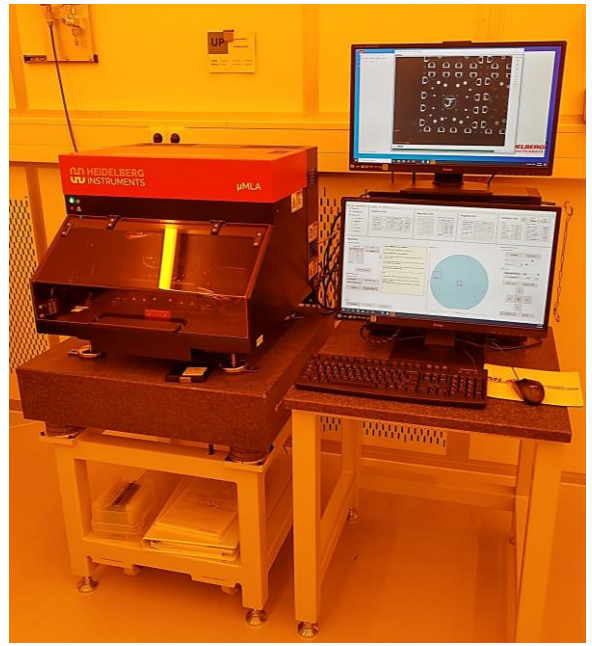
1. Heidelberg Instruments, *MLA150* (2021)

Heidelberg µMLA Maskless Aligner

- LASER wavelength = 375 - 405 nm
- LED wavelength = 365 - 390 nm
- Smaller machine
- Compatible with all broadband UV photoresists

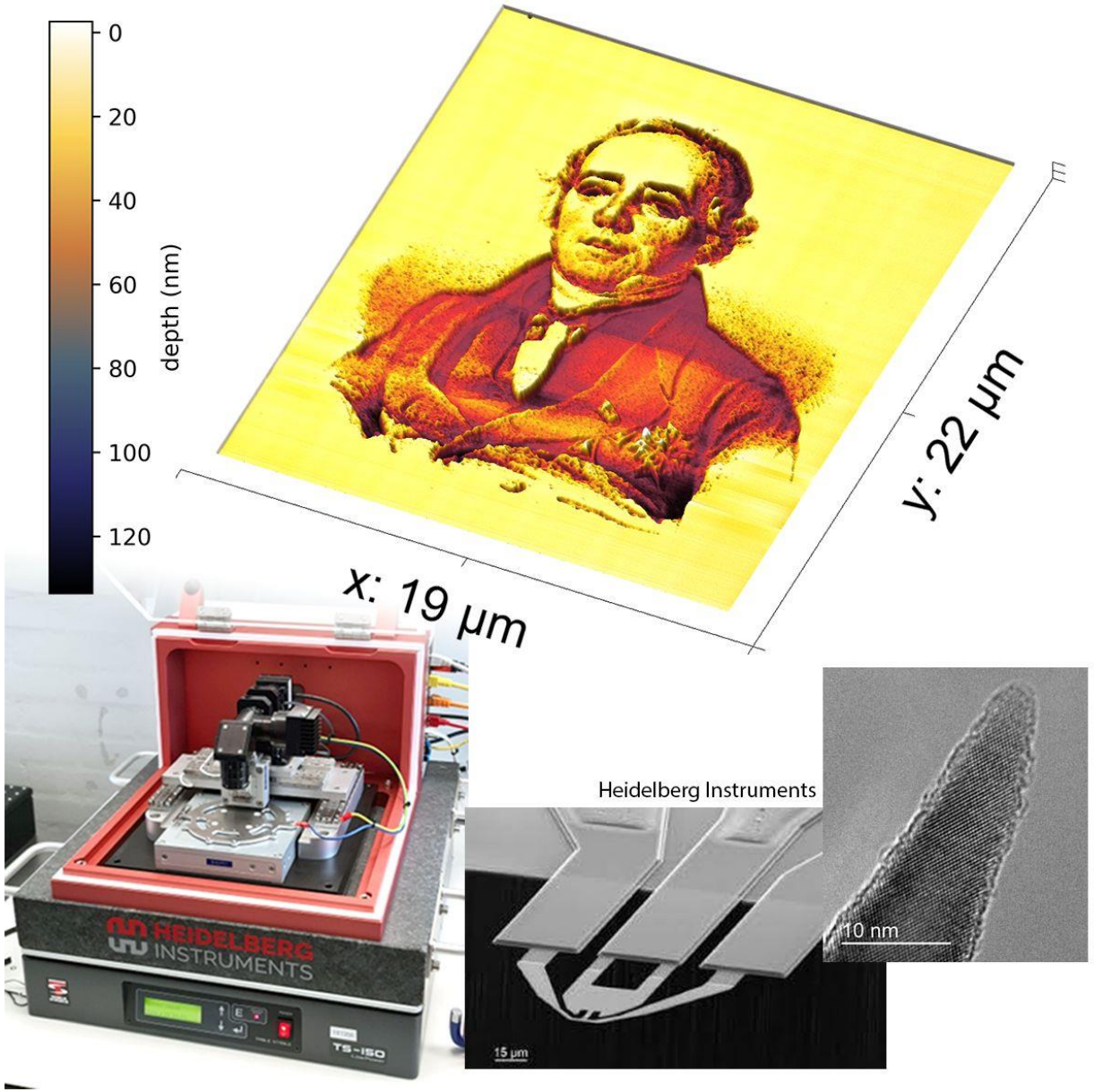






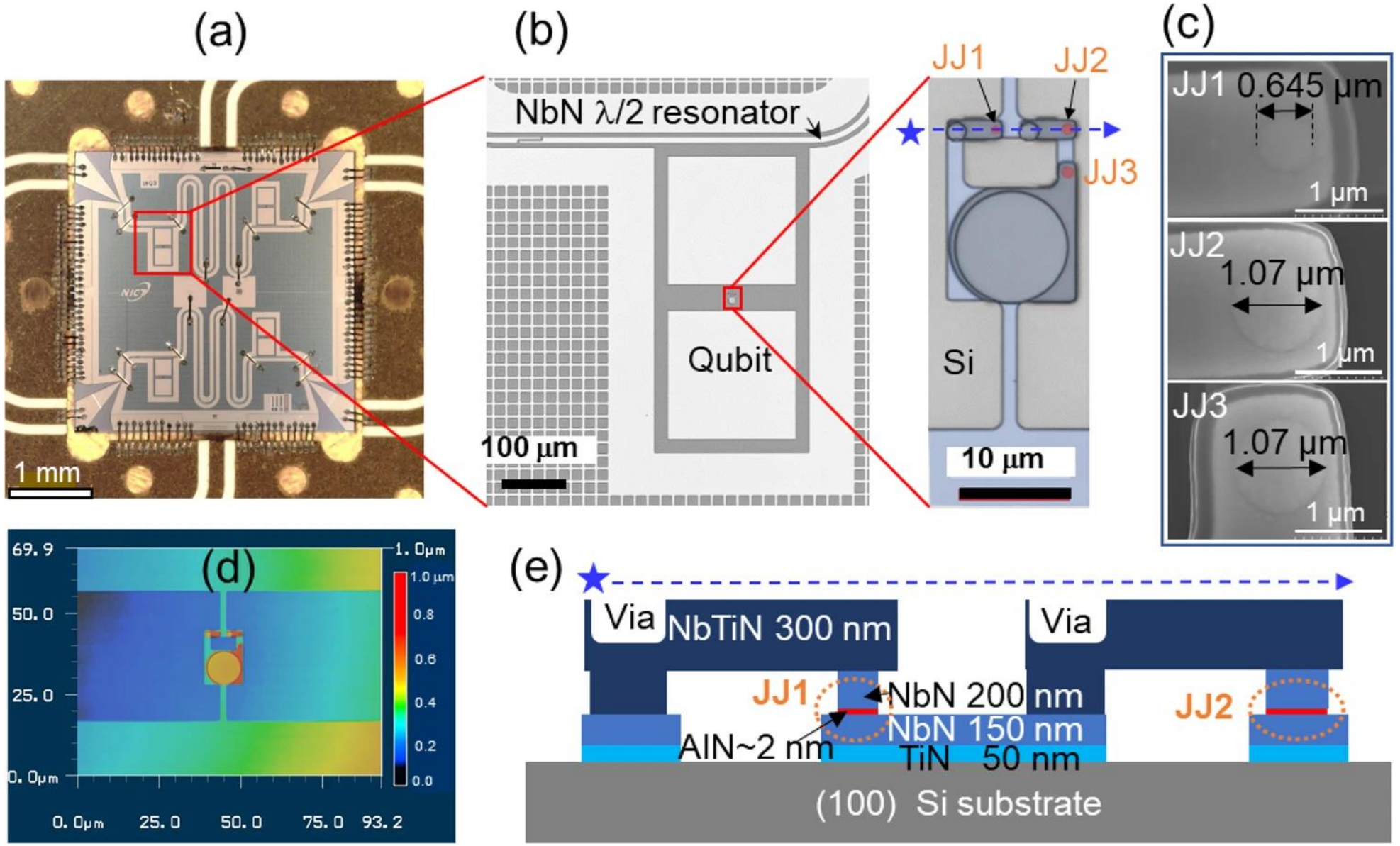
1. Heidelberg Instruments, *µMLA* (2021)

Scanning Thermal Probe Lithography for Custom Designs



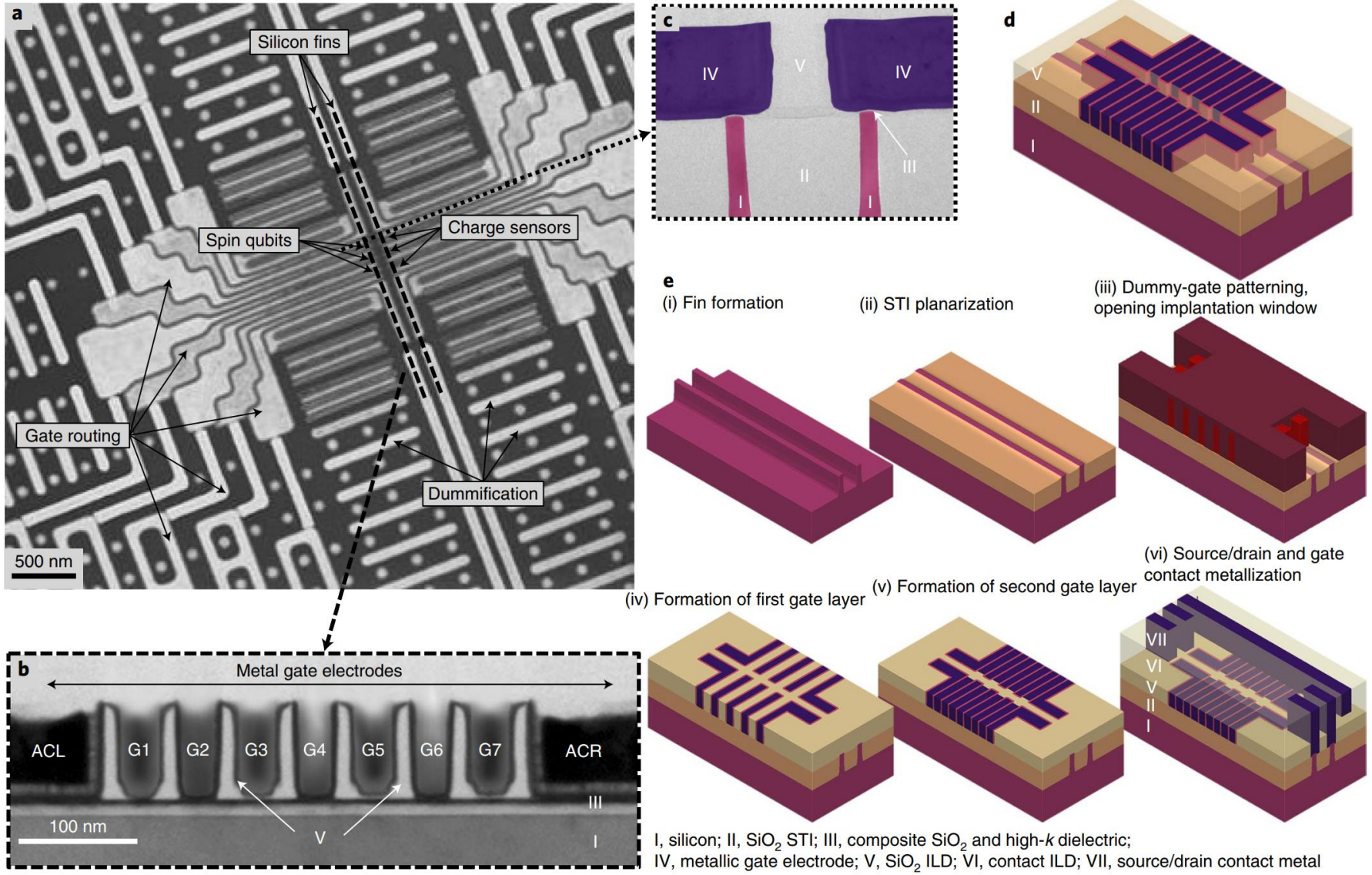
1. From: Technical University of Denmark-Physics & Heidelberg Instruments

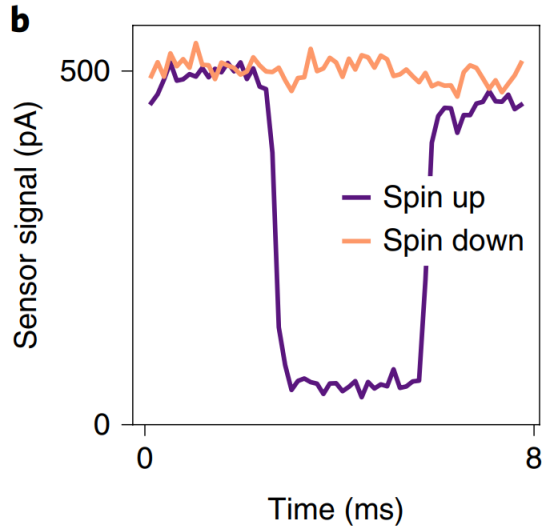
Superconducting All-Nitride Junctions

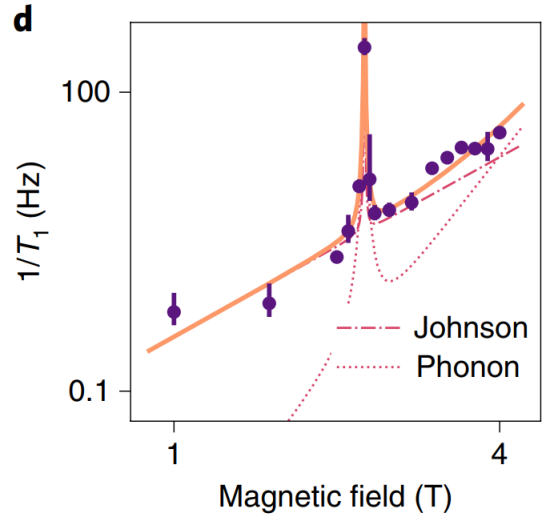


1. Kim et al., *Communications Materials* (2021)

Example of a Semiconductor Fab Spin Qubit







1. Zwerver et al., *Nature Electronics* (2022)

Summary

- Electron beam writing is a great tool for high-resolution nanopatterning.
- The direct write operation allows for complex design imports.
- The machine setup can be compared with CNC-based technologies.
  - More or less.
- If trained on the equipment, transferring skills to other maskless-based lithography systems is a little easier.
- Always watch out for charge build-up!
- Next week we will talk about hardware control & imaging.