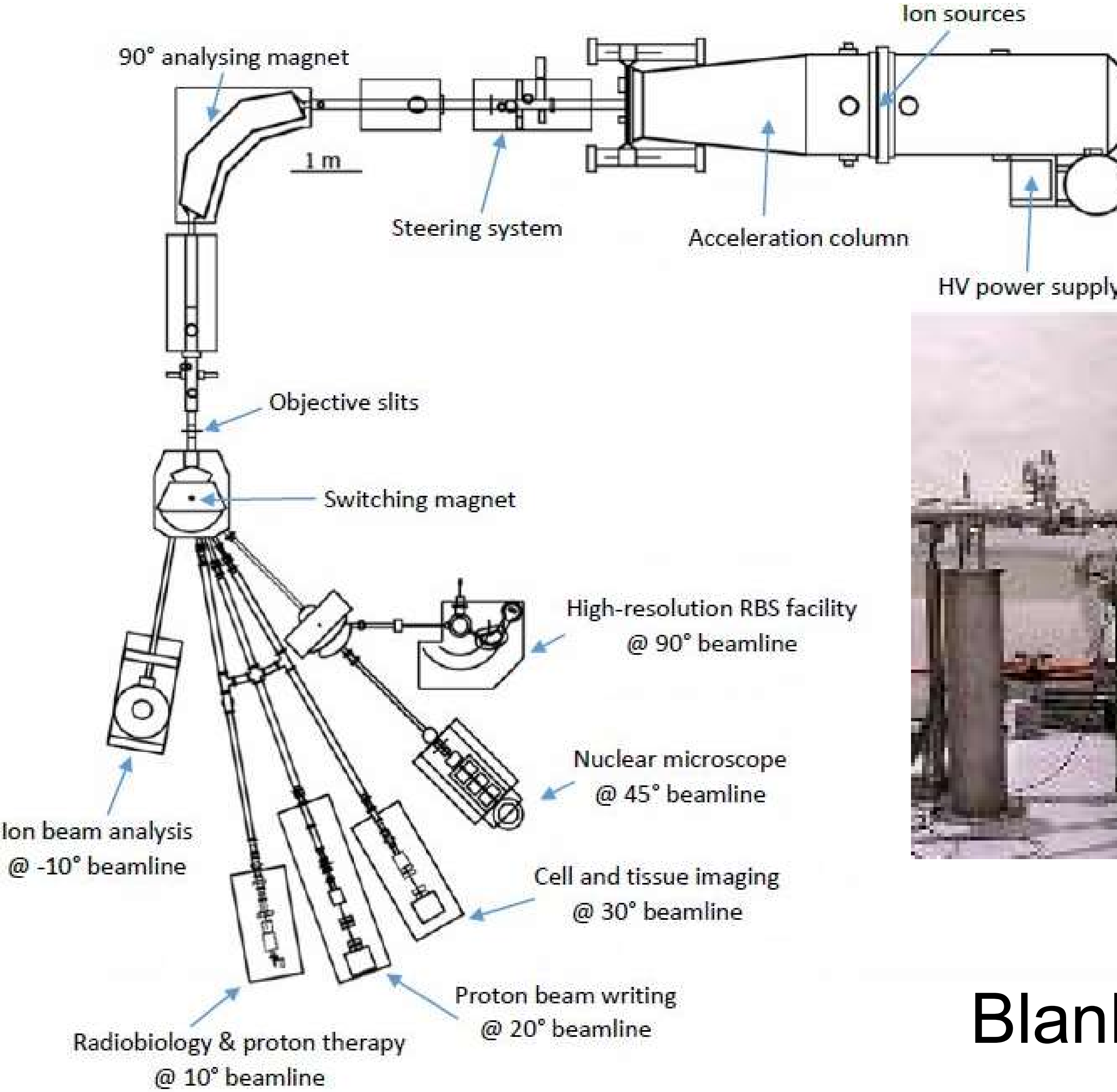
PC 3242 Part II

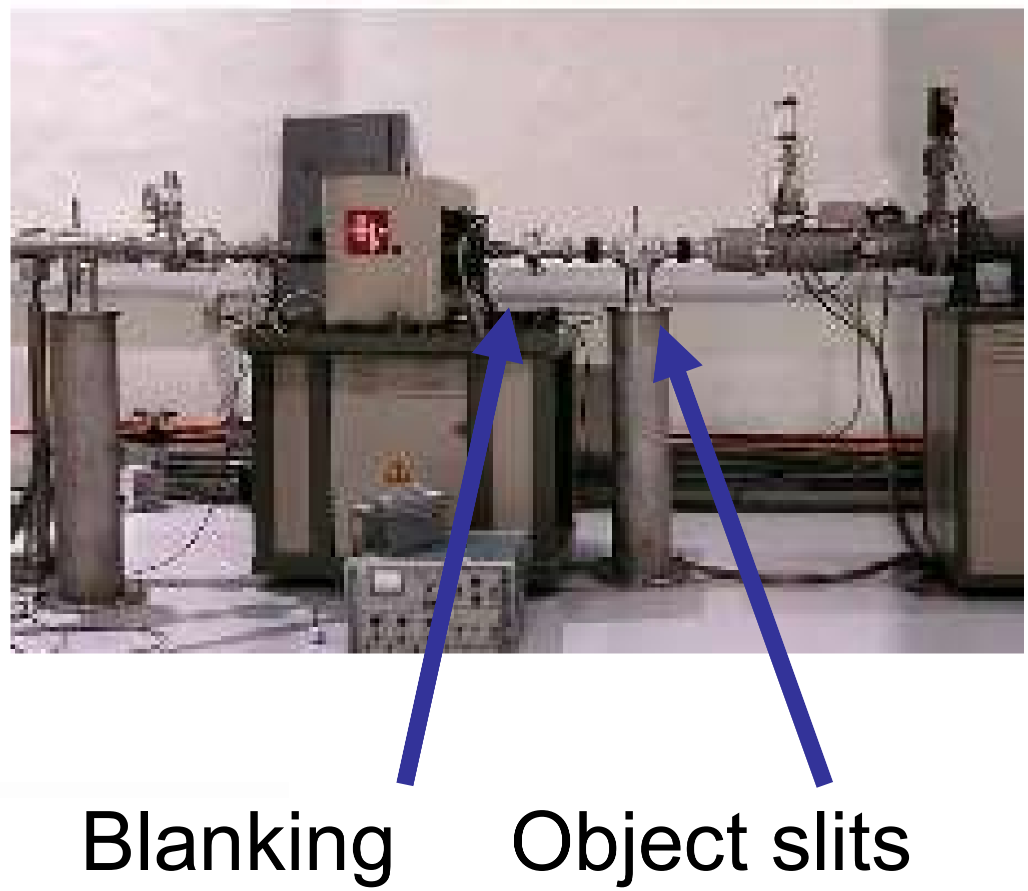
Topic	Text Book (Zhen Cui '05)	Lectures
Optical lithography	Chapter 2	1, 2 & 3
Electron Beam Lithography	Chapter 3	4 & 5
Focused Ion Beam Technology	Chapter 4	
Low Energetic Ions (keV)		6, 7 & 8
SIMS	Extra material provided	
FIB in Lithography	Chapter 4	
High Energetic Ions (MeV)	Extra material provided	8
RBS	Extra material provided	9
Light ions in lithography	Extra material provided	10
Etching	Chapter 7	10,11
Nano Imprint Lithography	Chapter 6	12
3DP Three Dimensional Printing	Extra material provided	13

JA van Kan 2024

MeV Proton Lithography

Solid state non-moving parts accelerator

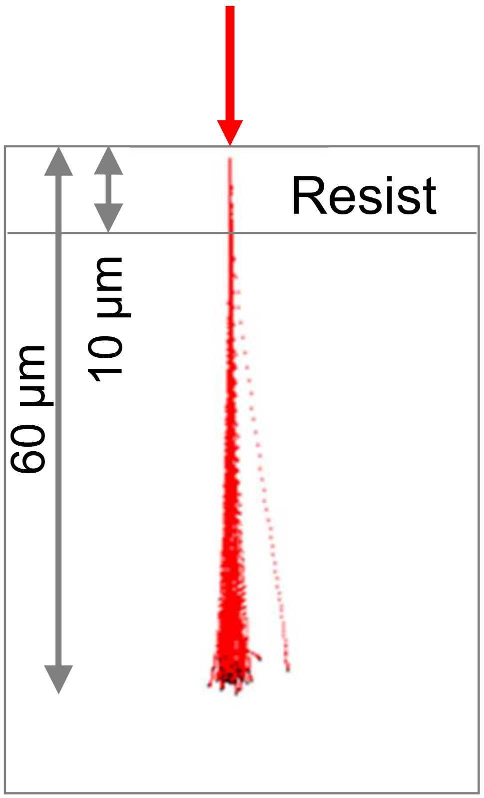




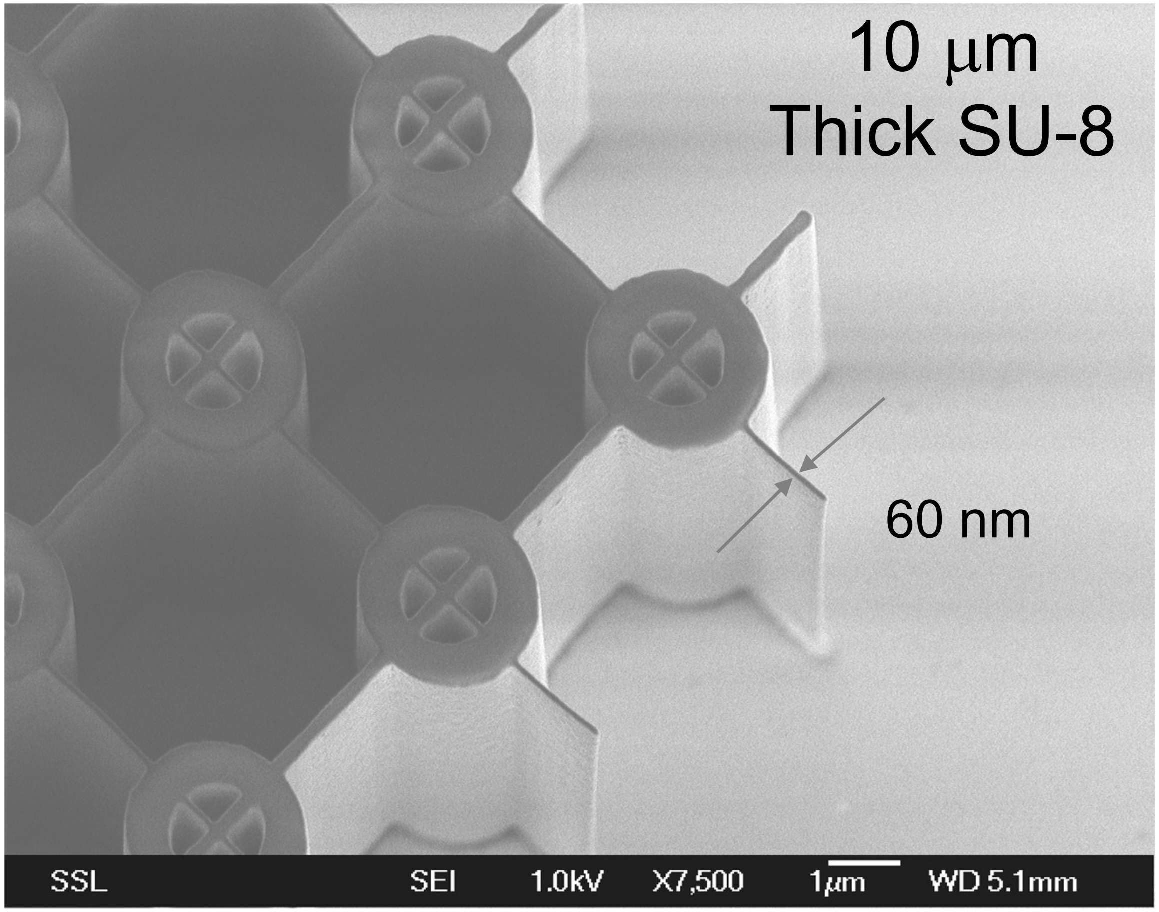
MeV Ions
Primary particle interaction with material

• Microprobes using MeV ion beams are difficult to focus because of the high ion mass
• However, once the beam is focused, it is this same property which prevents beam "blow-up", unlike focused keV electrons in a SEM
• Microprobes are very good at analyzing "thick" layers with high resolution

SRIM simulation
2 MeV Protons



2 MeV protons: Well defined path + Dose homogeneity



PBW fabricated 3D nanostructure demonstrating rigidity of the focused MeV proton beam

MeV Proton Lithography

Light / Electron / Proton Lithography

Photoresists can be exposed by:
Light (EM Waves), Electrons and Protons (ions)

The main difference:

- Photons: are absorbed, depositing all their energy at once, resolution limited by wavelength
- Electrons: gradual & full energy deposition + scattering within the photoresist
- MeV Protons: gradual energy deposition (δ-rays) + straight path through the photoresist (X-ray emission has smaller cross section and RBS even smaller)

For both Ions and Electrons if we use higher energy the required dose goes up (ie Resist becomes less sensitive); They go too fast less efficient electron excitation

Many transitions are excited by electron and proton beams. The dissociation energy for a C-C bond is 3.6 eV. Secondary electrons generated by primary ionizing radiation (electron/protons) have energies sufficient to dissociate this bond, causing scission.

MeV Proton Lithography

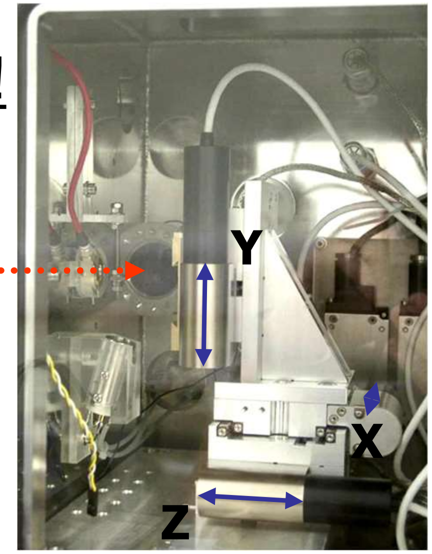
P-beam writing set-up

<u>CIBA Prototype PBW Exposure Chamber: Sub 100 nm system!</u>
<u>New system can reach sub 10 nm spot size!</u>

22.5° mirror with microscope for viewing and light detection

- Demagnification 228 x 60
- Exfo-Burleigh inchworm stage 1″ travel in X, Y or Z, 20nm closed loop.
- 1 MHz scanner,
- 2 MHz blanker

Exposure Chamber



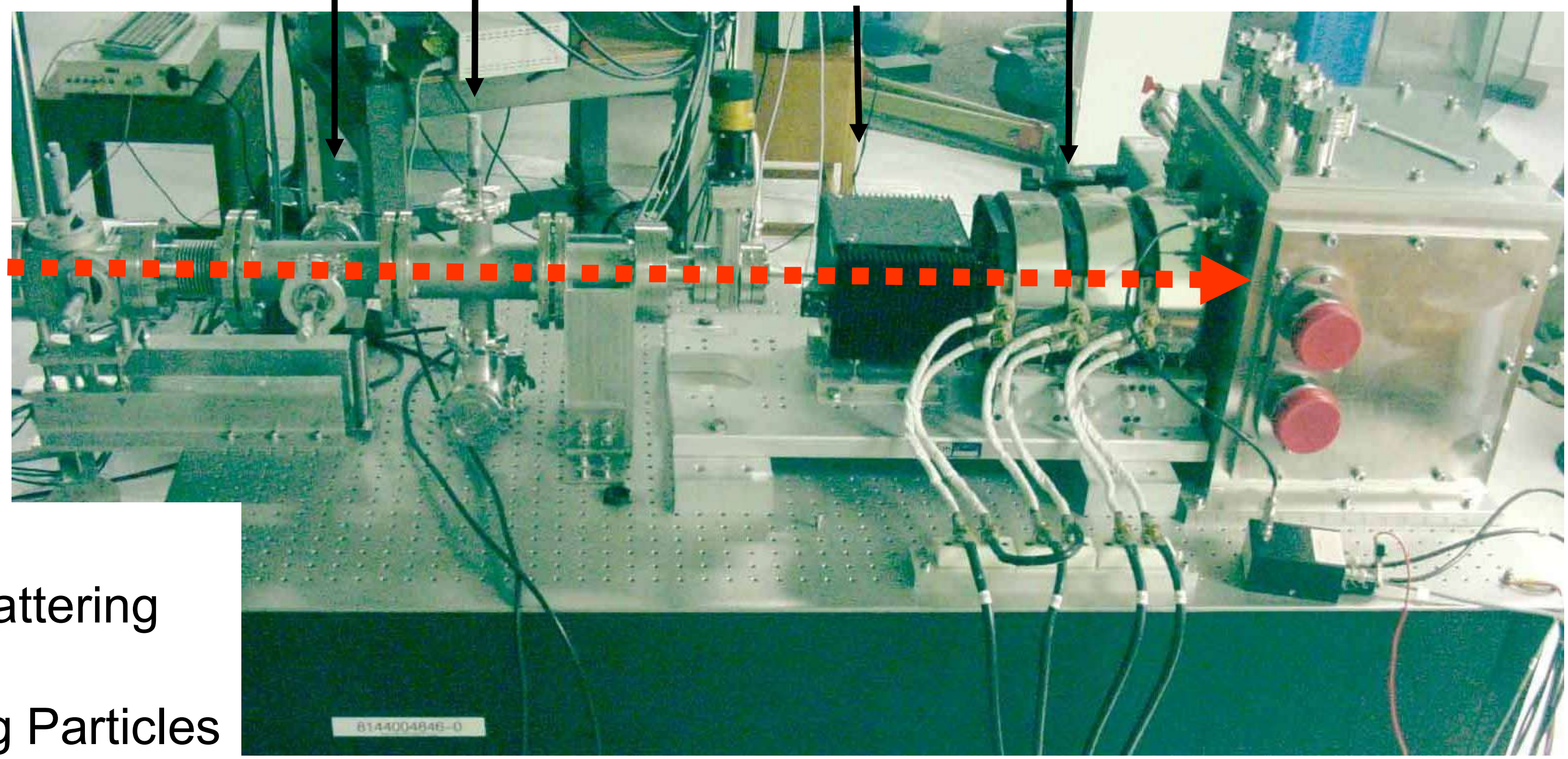
Focused Proton beam

Electrostatic scan

Y X

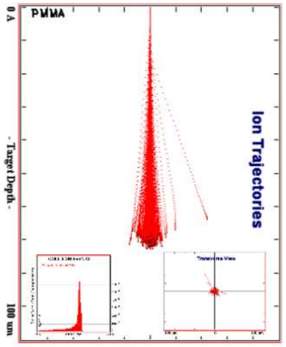
Magnetic scan

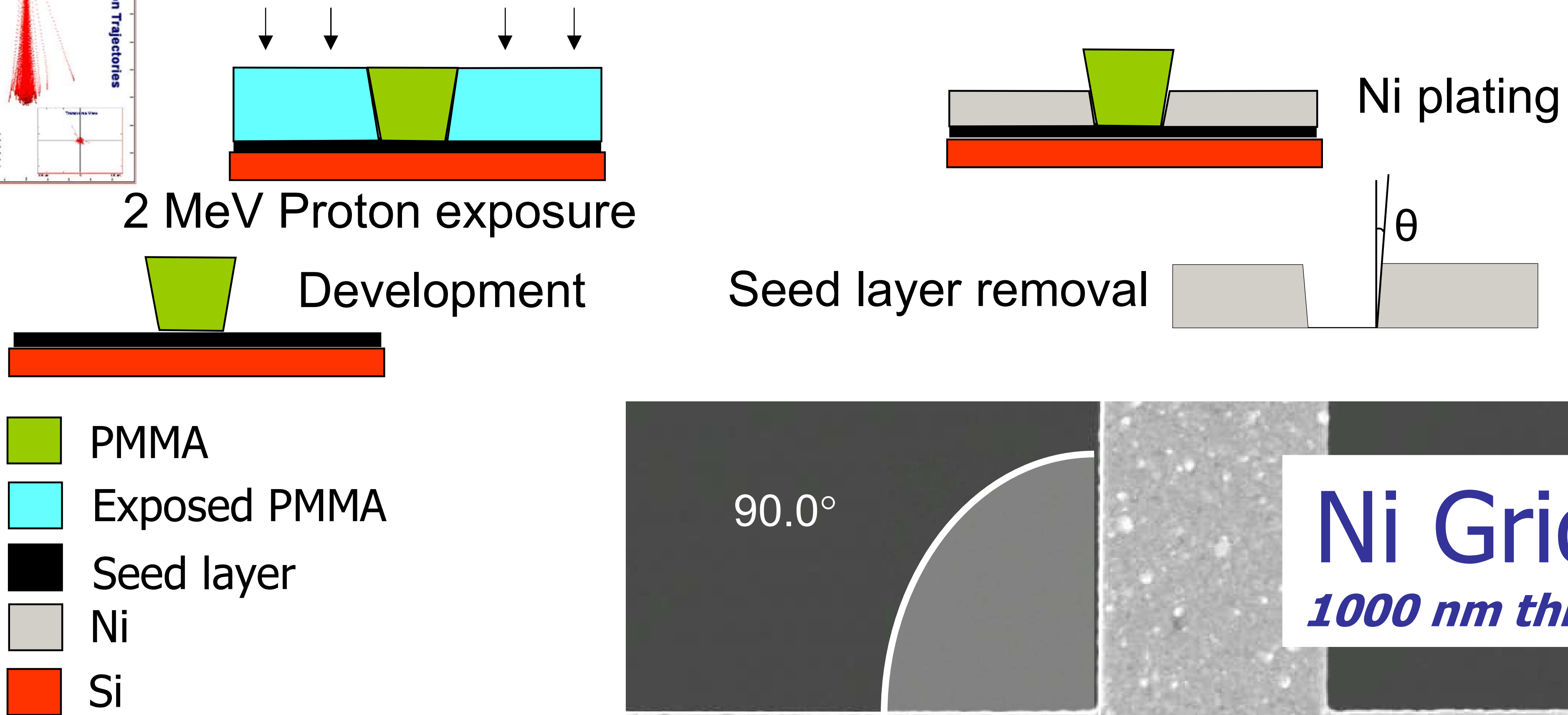
Focusing lenses

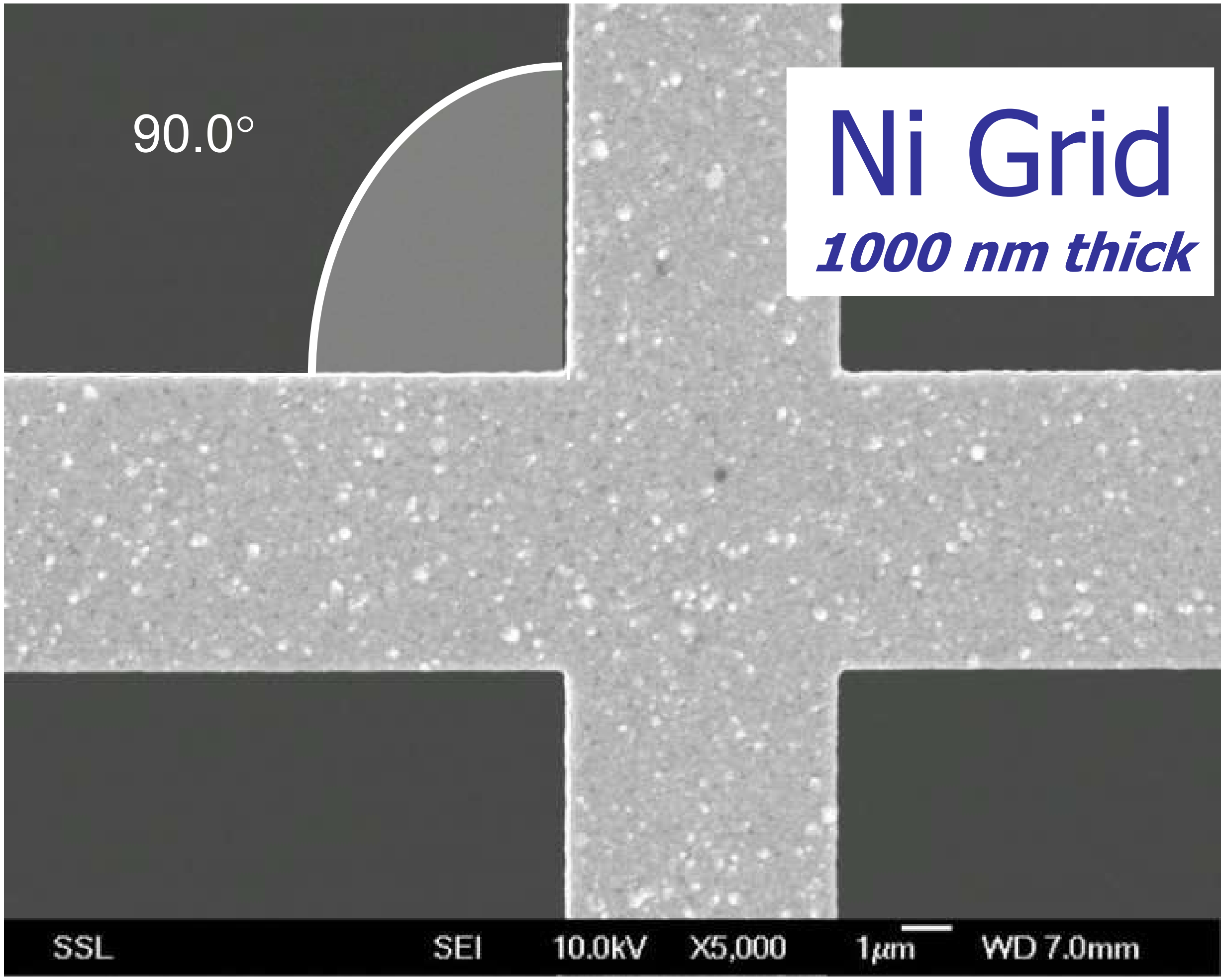


<u>Diagnostics</u>
Rutherford back scattering
Electron detector
Pin Diode Detecting Particles

MeV Proton Lithography





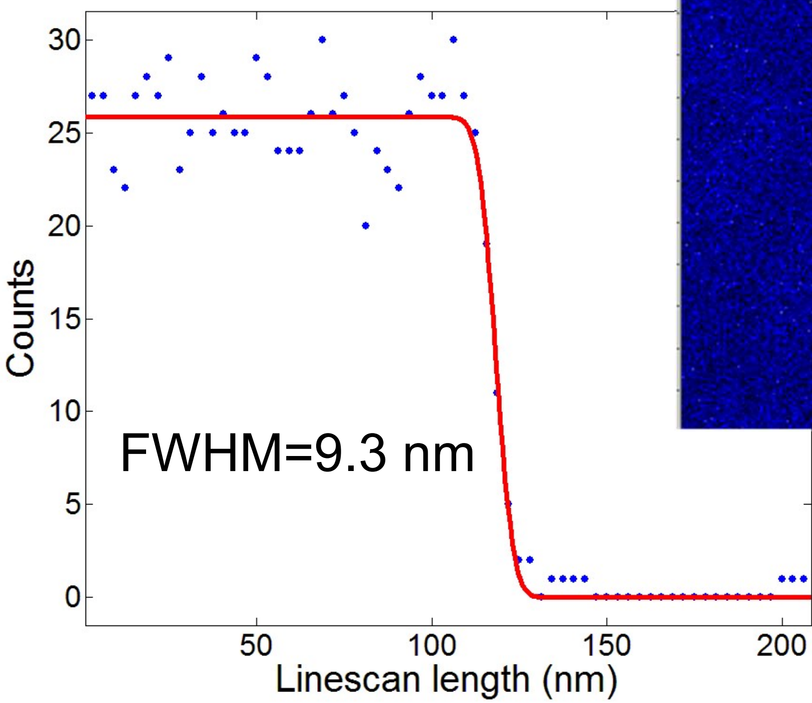


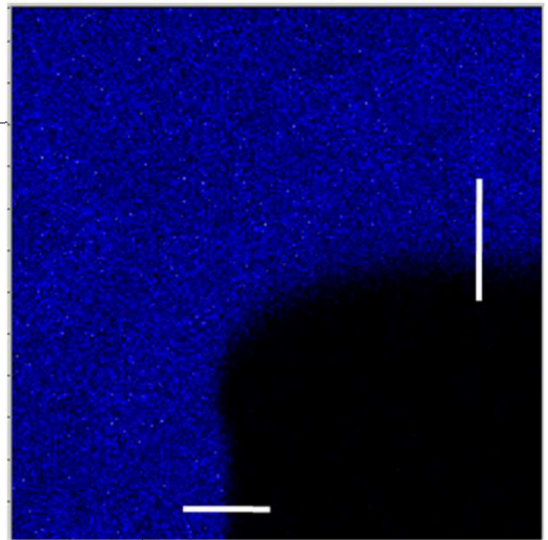
Using SRIM you can calculate the side wall angle θ (~ 0.2°) of this Ni grid assume we have spin coated 2 µm thick resist.

MeV Proton Lithography

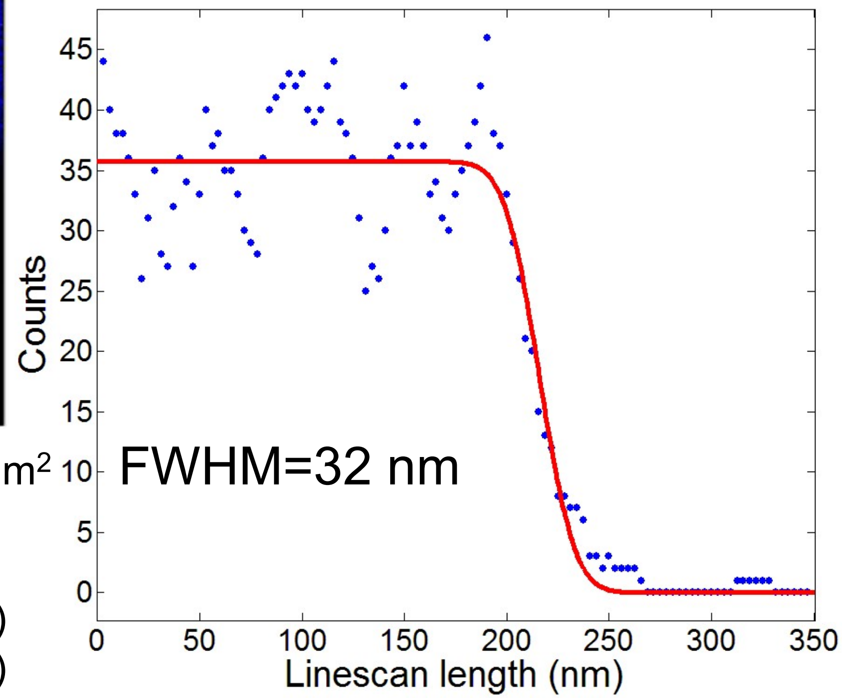
STIM map and line scan of Ni grid

X line scan





Y line scan

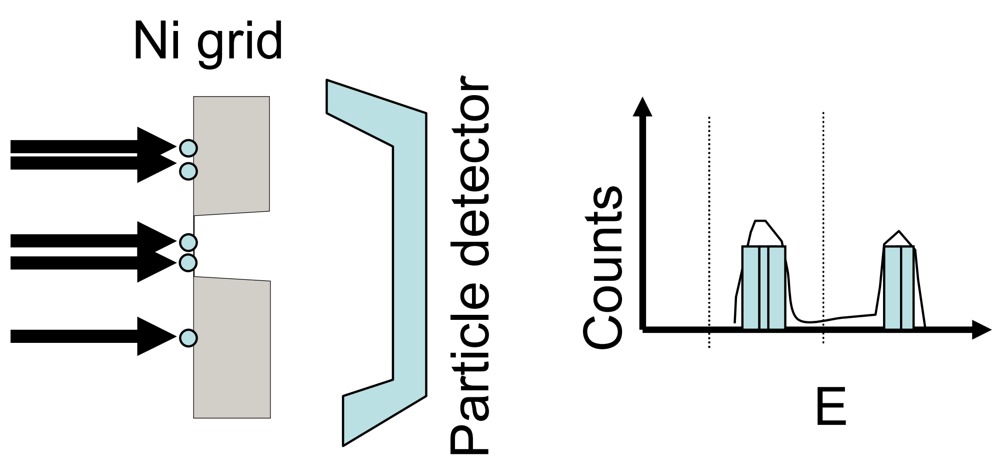


Scan size 0.8×0.8μm^2
Scan 20 frames
Fitting data:
Adjacent 4 lines (X)
Adjacent 6 lines (Y)

Sub 10 nm resolution in X

STIM image over edge in the new Ni grid

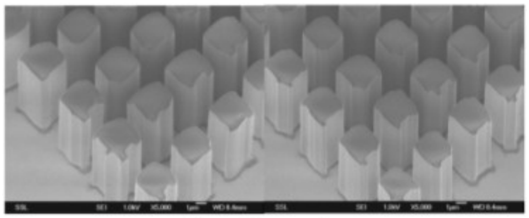
1 MeV protons 23,000 p/s



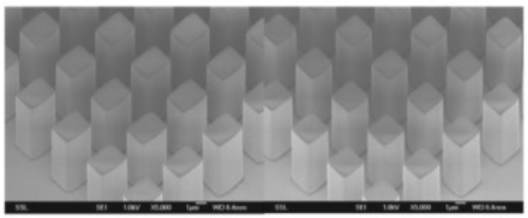
MeV Proton Lithography

Process steps

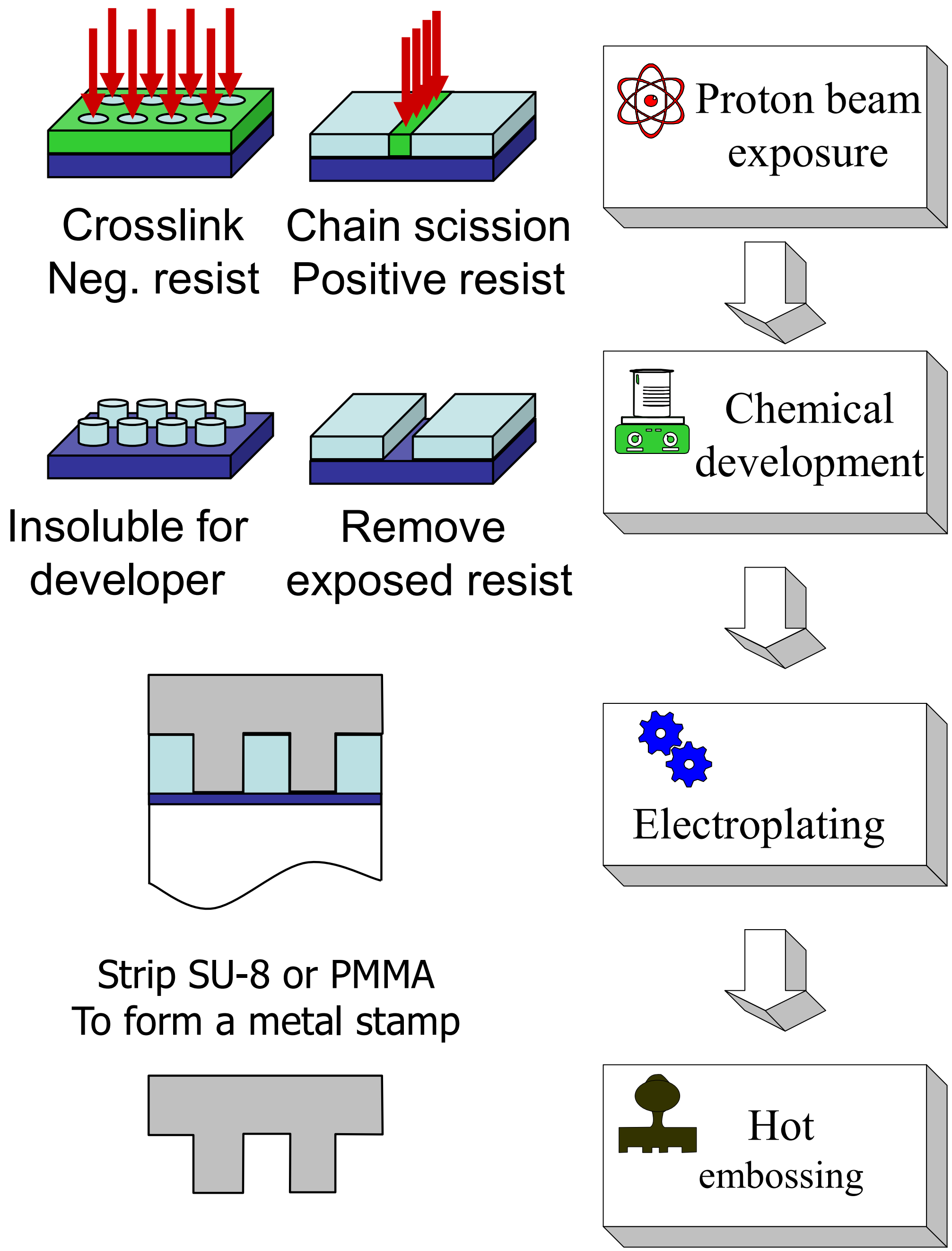
SU-8 or PMMA
Ni
Seed layer



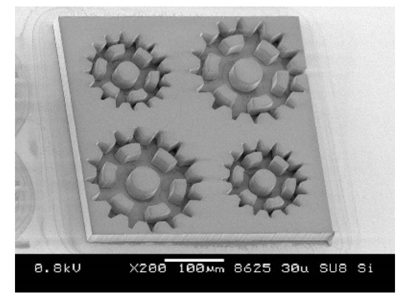
Magnetic scanning



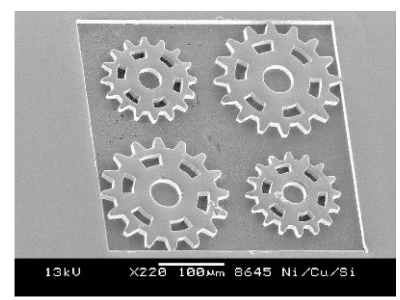
Electrostatic scanning



Imprinting NIL



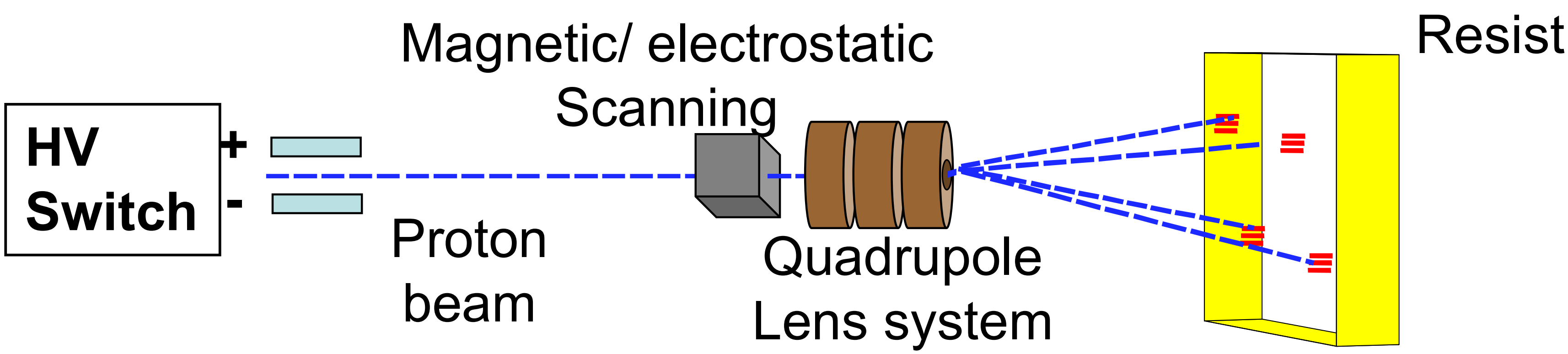
SU-8 mold for plating



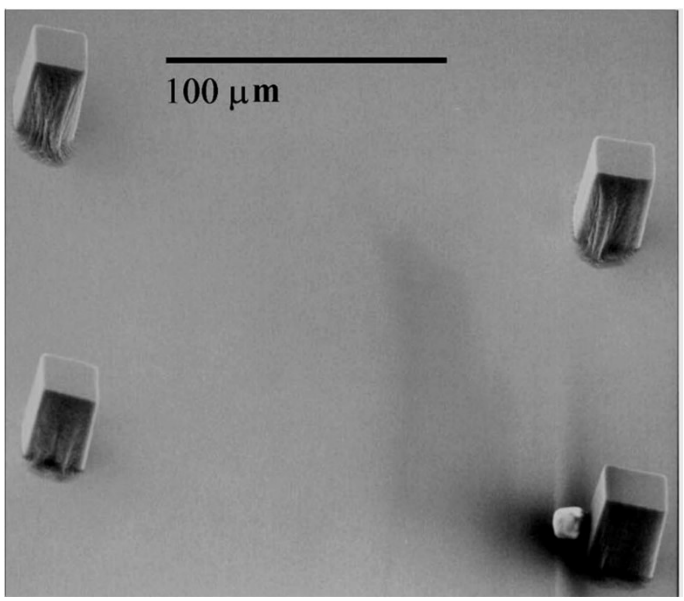
Ni structure

MeV Proton Lithography

Beam blanking



No Blanking



MeV Proton Lithography

Proton Beam Writing

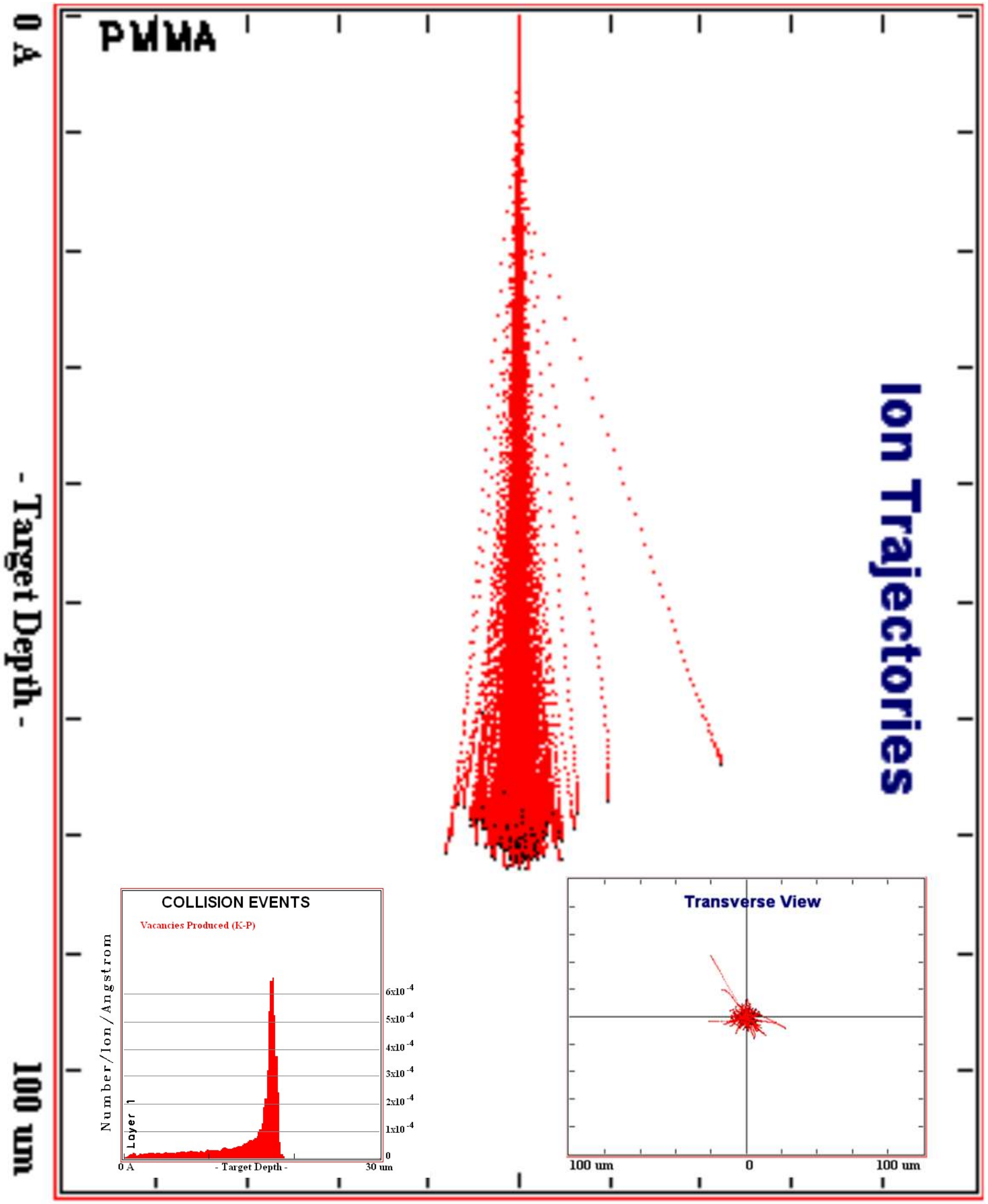
In both **proton beam writing** and **electron beam writing**, the primary particles produce secondary electrons, and it is the secondary and induced δ-rays electrons that contribute to developing the resist material this is very important in p-beam writing

Any calculations into how small we can fabricate a structure in resist material should therefore also consider the production of secondary electrons

Also in optical lithography the breaking of bonds through photons is in the same energy range:
$E=hf$ Take λ = 300 nm, ➔ $E = 6.6\times10^{-19}$ J = 4.1 eV

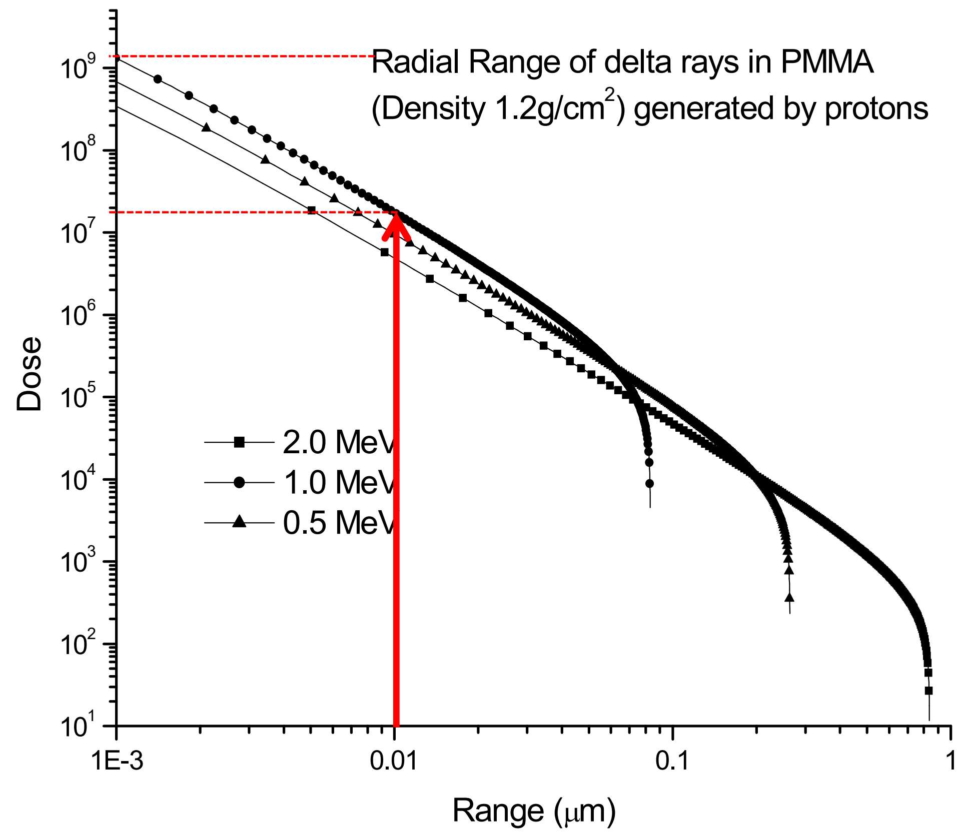
MeV Proton Lithography

Energy deposition



SRIM (Stopping and Range of Ions in Matter) www.srim.org

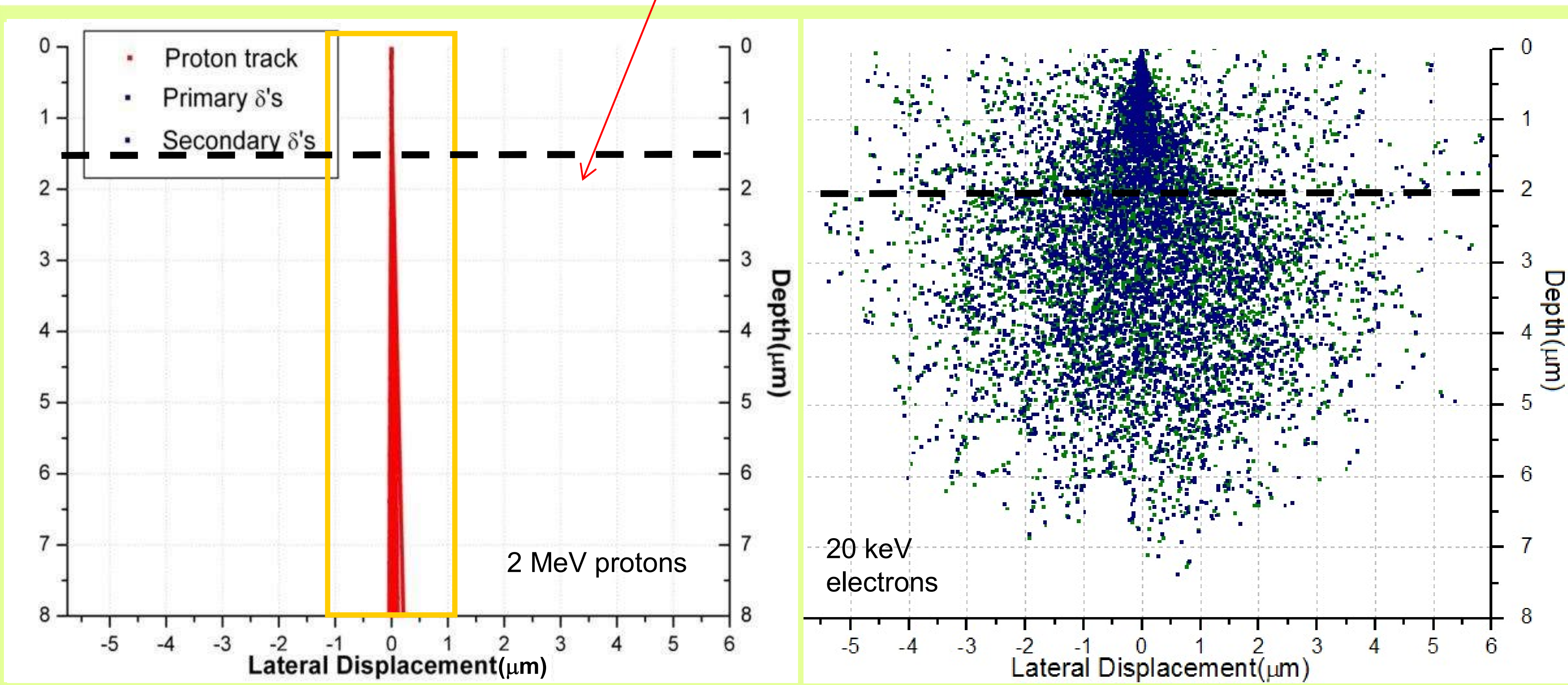
δ-ray is another word for secondary electron



Waligorski, M. P. R.; Hamm, R. N.; Katz, R. *Nucl. Tracks Radiat. Meas.* **1986**, *11*, 309.

MeV Proton Lithography

Comparing P-beam writing and E-beam writing



2 MeV Protons & 20 keV Electrons into 10 μ m PMMA (Spatial Map)

Red-primary protons: Blue-Primary electrons: Green-secondary electrons

MeV Proton Lithography

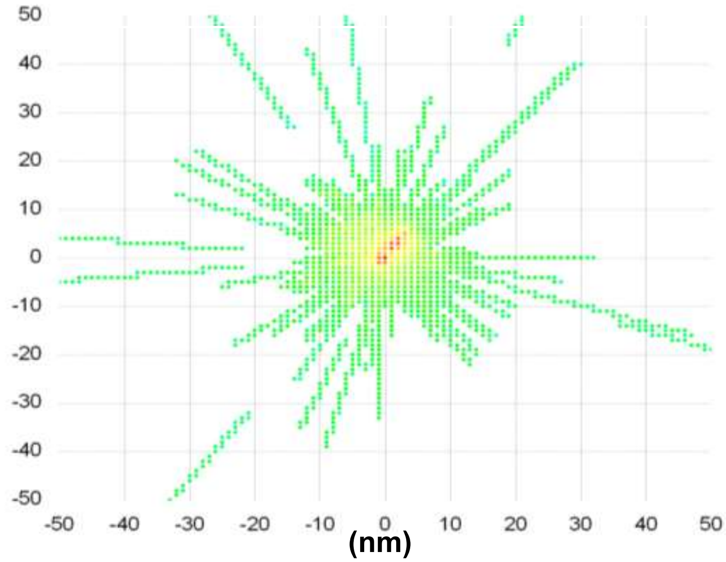
Energy deposition in 2 μm PMMA

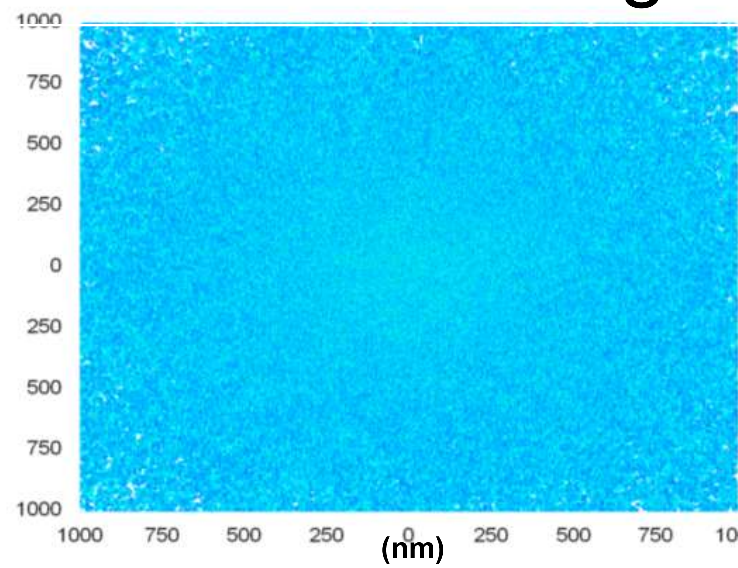
P-Beam ↔ E-Beam Writing

1000
2 MeV Protons

↕

100,000
20 keV Electrons





P-Beam **E-Beam**

Calculations using the Hansen - Kocbach – Stolterfoht (HKS) model show that the proton induced secondary electrons have low energies and therefore short range (ie minimal proximity effects):

In proton beam writing the energy deposition (and therefore the resist exposure) is contained within a 10nm radius in the first 2 microns of the proton path.

P-beam writing is potentially superior compared to E-beam writing!

A Monte Carlo study of the extent of proximity effects in e-beam and p-beam writing of PMMA
CNB Udalagama, AA Bettiol and F Watt, Nucl. Instr. and Meth **B260**, 384-389 (2007).

MeV Proton Lithography

Characteristics of MeV proton beams

A proton beam penetrates ‘deep’ into the sample (eg a 2 MeV proton beam will travel around 60μm into PMMA).

a) A proton beam will maintain a **straight path** (at least until the end of range, when it broadens).

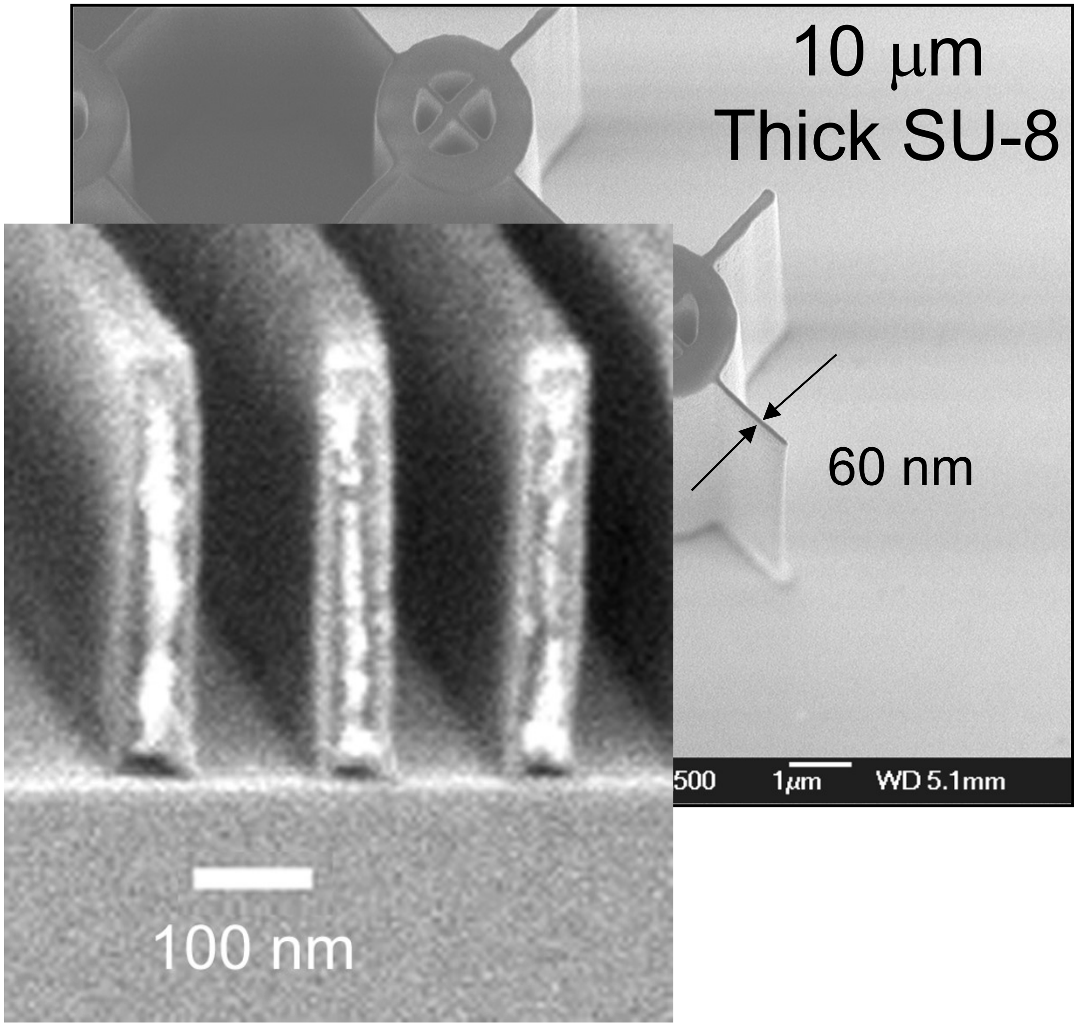
b) The **range of the proton beam depends on its energy**, therefore by changing the energy, multi-level structures can be fabricated.

c) The energy deposition (exposure) as the proton beam passes into the material is **almost constant with depth** (apart from an increase at the end of range). You can confirm this using SRIM.

d) The **proximity effects** (unwanted exposure due to secondary electrons) are **minimal**.

MeV Proton Lithography

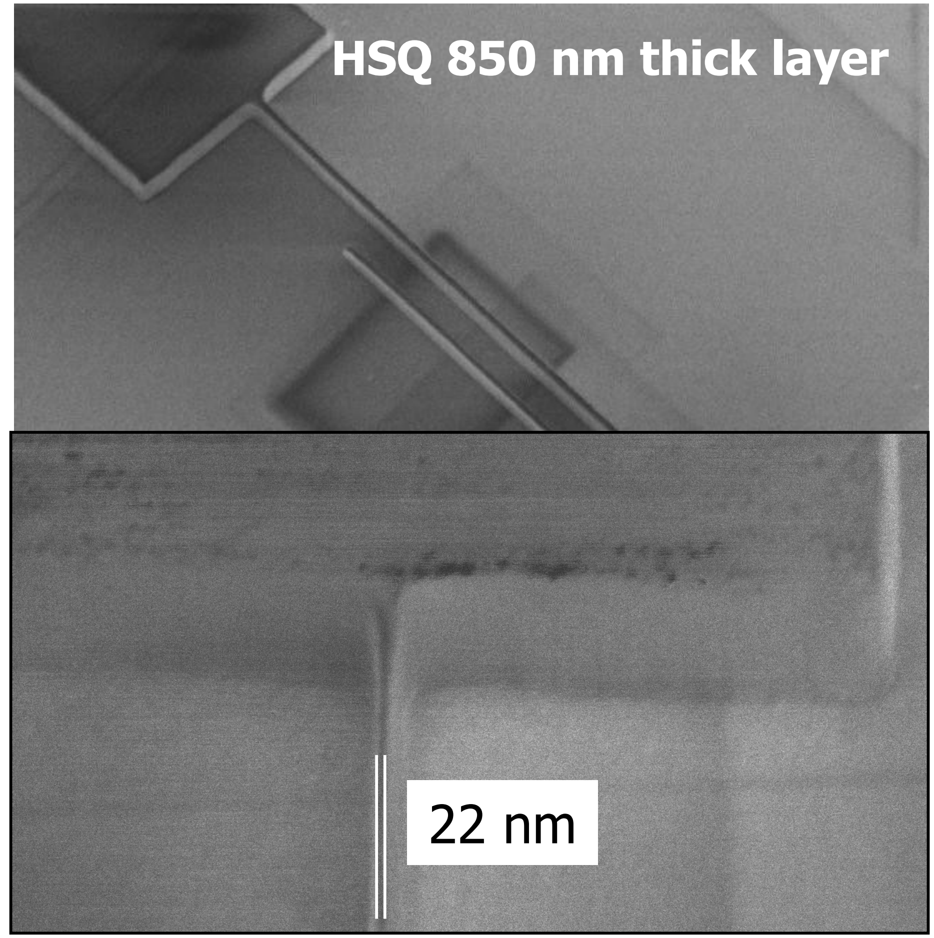
PBW High aspect ratio nanostructures



PMMA
50 nm wide lines

2003

Three-dimensional nanolithography using proton beam writing
J.A. van Kan, A.A. Bettiol, and F. Watt Appl. Phys. Lett., **83** (2003) 1629

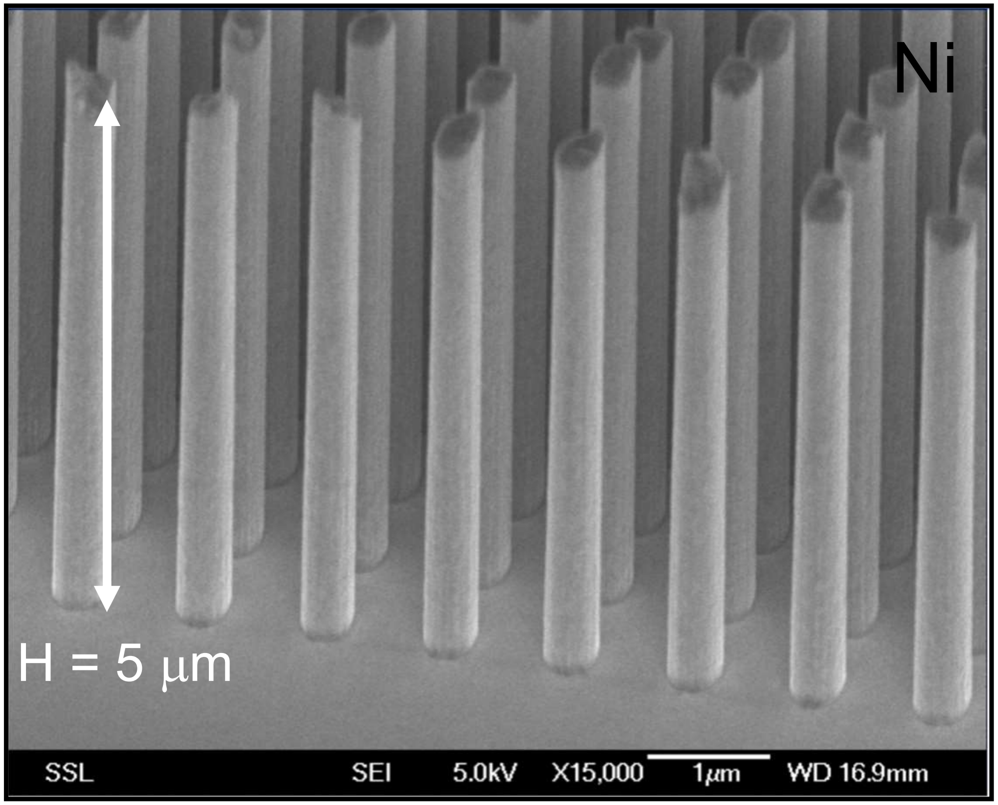


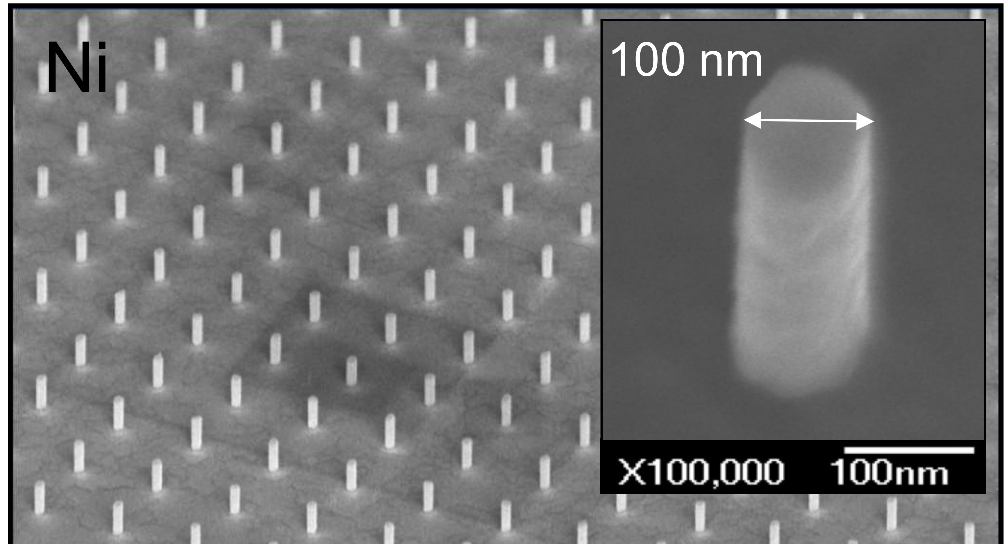
2006

Proton Beam Writing of Three-Dimensional Nanostructures in HSQ
J.A. van Kan, A.A. Bettiol, and F. Watt
Nano Letters Vol 6 (2006) 579-582

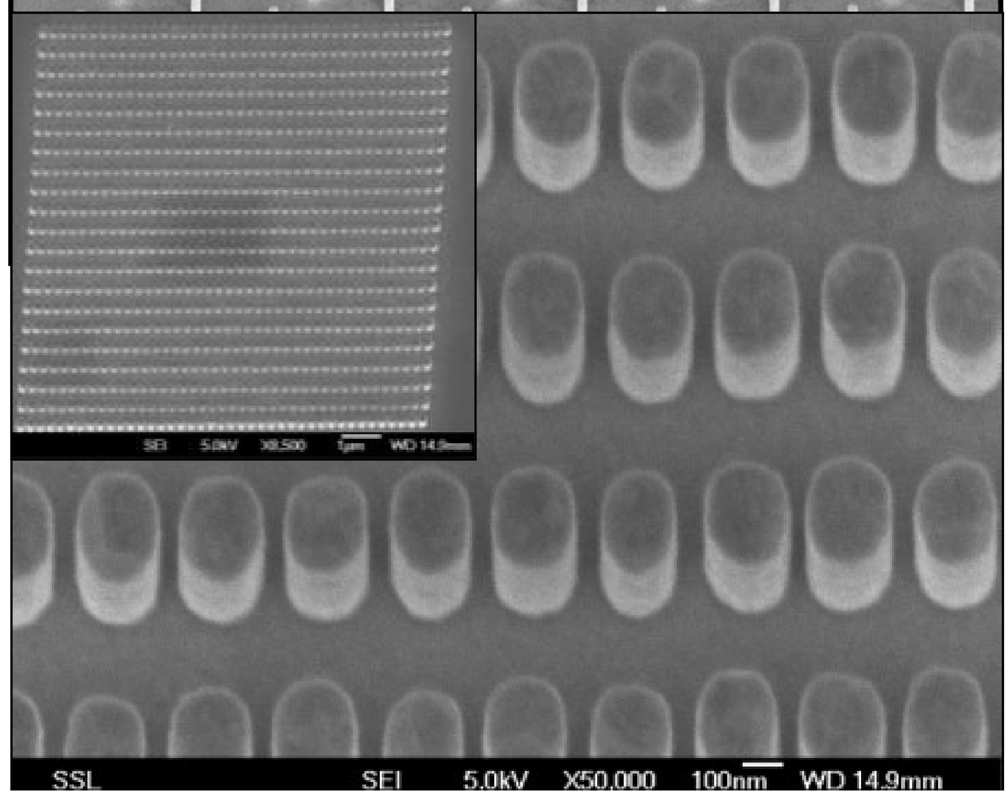
MeV Proton Lithography

High aspect ratio Ni nanowires





Aspect ratio:
Height/width of a structure

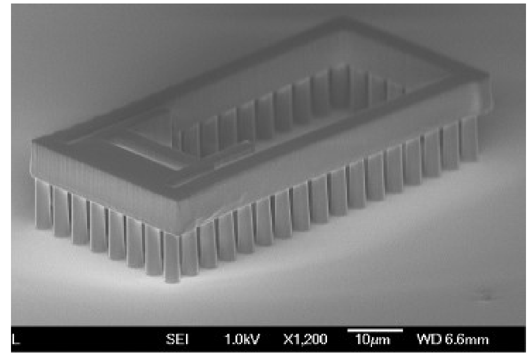


Au nano pillars
H = 700 nm
Gaps 35 nm

MeV Proton Lithography

Summary

- Small lateral straggling: vertical walls
- Virtually no proximity effects: High density
- Different ion energies: multi-layered structures



Multi level 3D structures fabri-cated in a single layer of SU-8 resist using 0.5 & 2 MeV protons

- 3D nano capability with high aspect ratio structures > 160
- One limitation is the low brightness of the proton source
  - I am now working on developing a high brightness ion source!

- No Proximity effects!

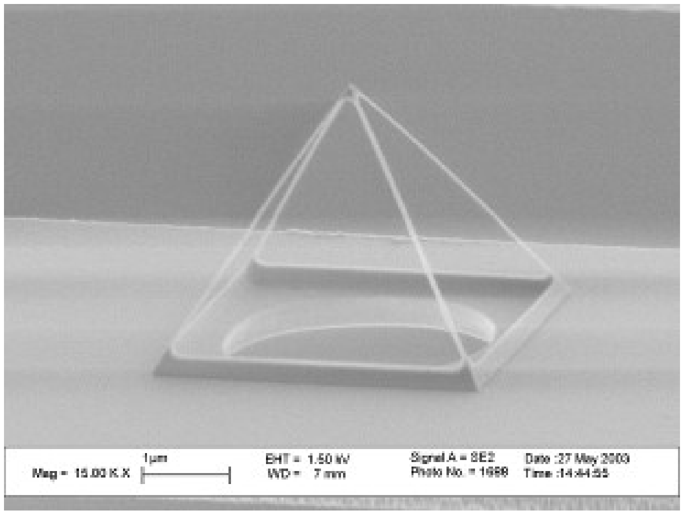
<u>Proton beam writing</u>: Great potential for 3D nano fabrication down to the 10 nm and below **<u>& Imaging of IC circuits via induced current.</u>**

No commercial machine yet:

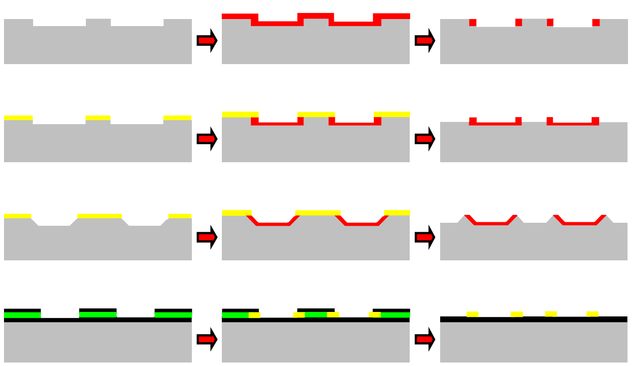
Singapore has great opportunity with NUS Patent

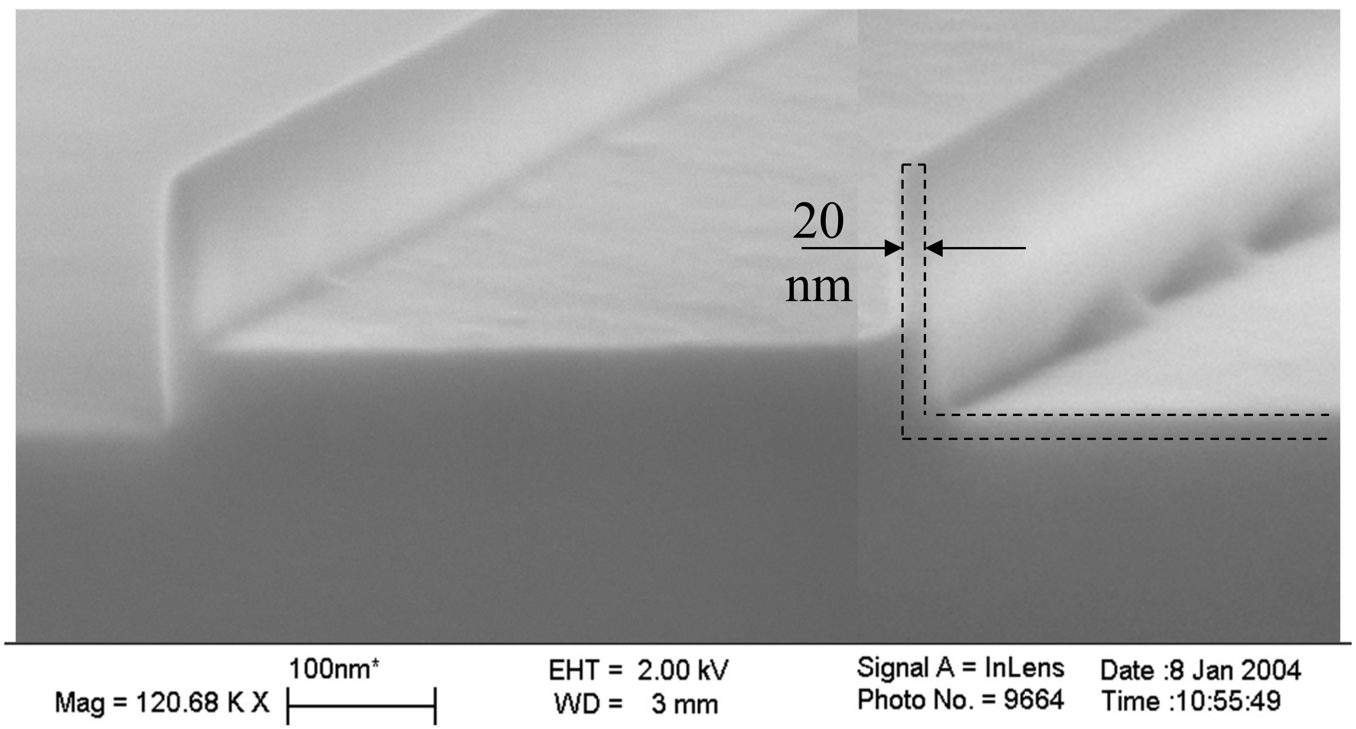
Etching

Reproduced from Twente university



2D nanobeams/nanostencil





Etching

Etching is the selective removal of deposited films.

✓ KOH to etch Si

✓ HF dip etch native oxide but not Si

More often: through a mask to leave a patterned film: