The Abdus Salam
International Centre
for Theoretical Physics

2359-13

Joint ICTP-IAEA Workshop on Physics of Radiation Effect and its Simulation for Non-Metallic Condensed Matter

13 - 24 August 2012

Ion beam lithography - I

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Ion beam lithography - I

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ICTP-IAEA Workshop, Trieste, 13-24 August 2012

Outline

Introduction

- Ion-matter interaction
  - → MeV ions
  - → keV ions
- Ion-beam lithography
  - → conventional techniques
  - → MeV ions
  - → keV ions

Case studies

- MeV ion beam lithography
  - → resists
  - → silicon
  - → other materials
  - → single ion tracks
- keV ion beam lithography
  - → FIB milling
  - → FIB-assisted deposition
  - → Helium-ion microscope

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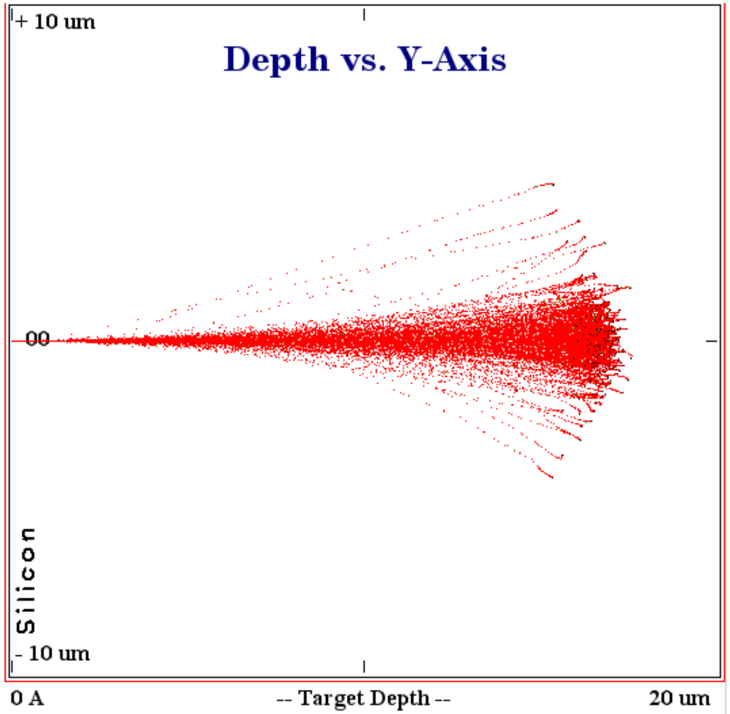
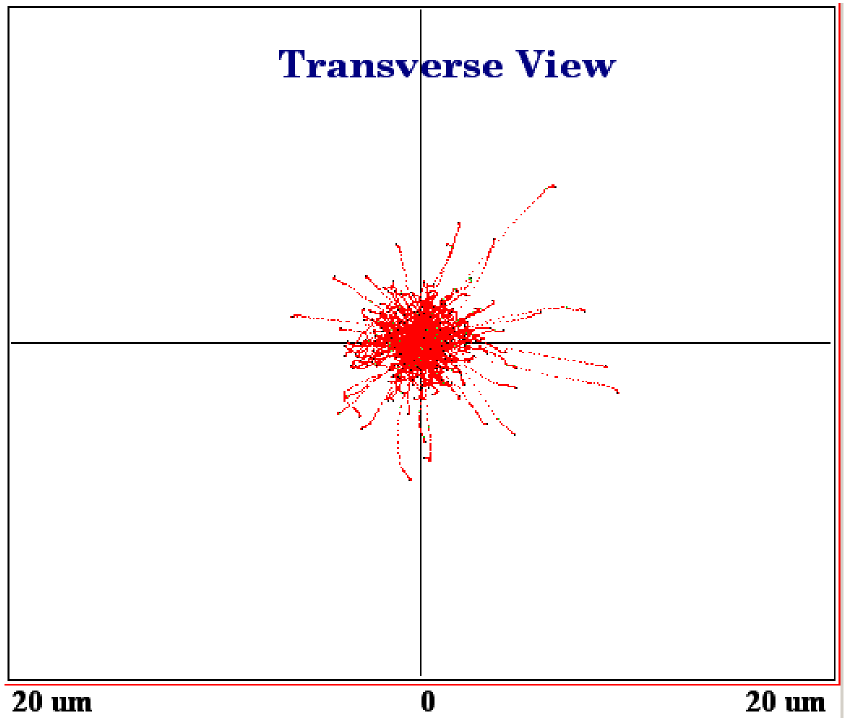
Ion-matter interaction: MeV ions

1 MeV H^+ in Si

Longitudinal trajectory



Lateral trajectory

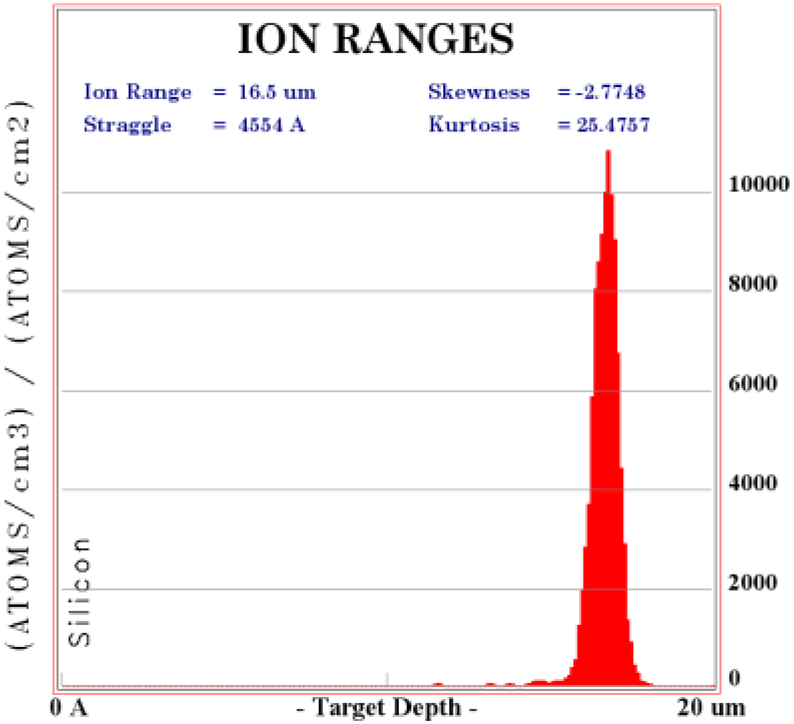


@ : SRIM Monte Carlo code

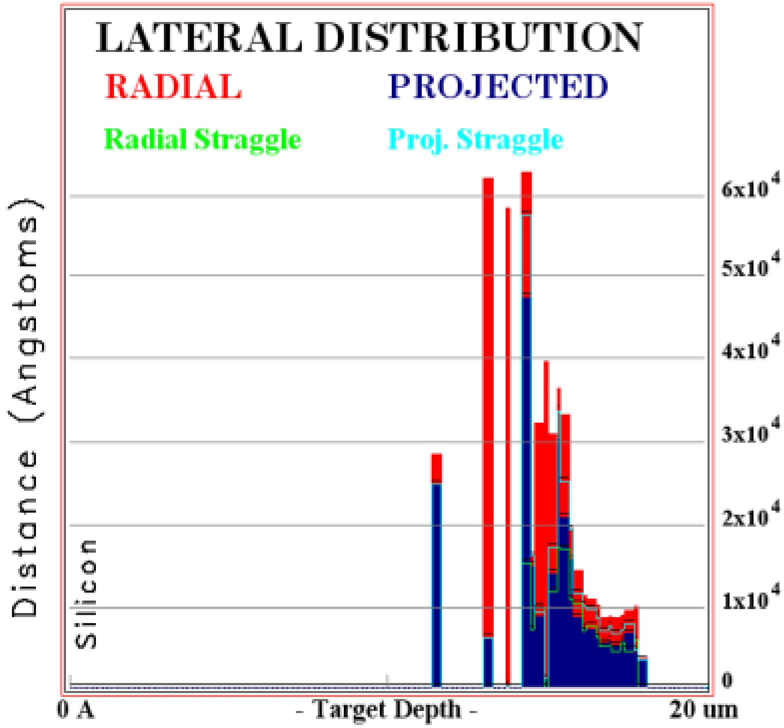
Ion-matter interaction: MeV ions

1 MeV H^+ in Si

Longitudinal range



Lateral range

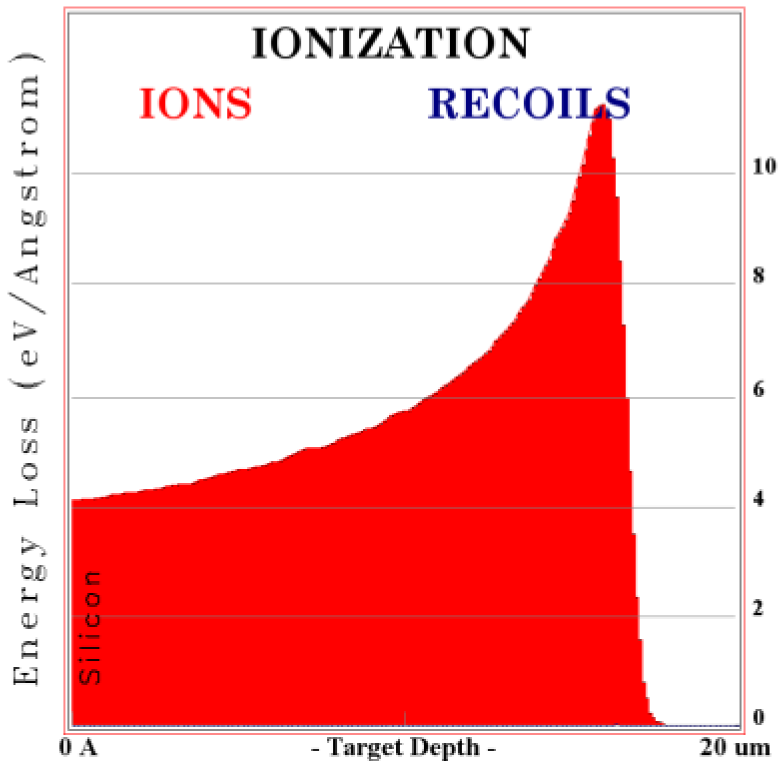


@ : SRIM Monte Carlo code

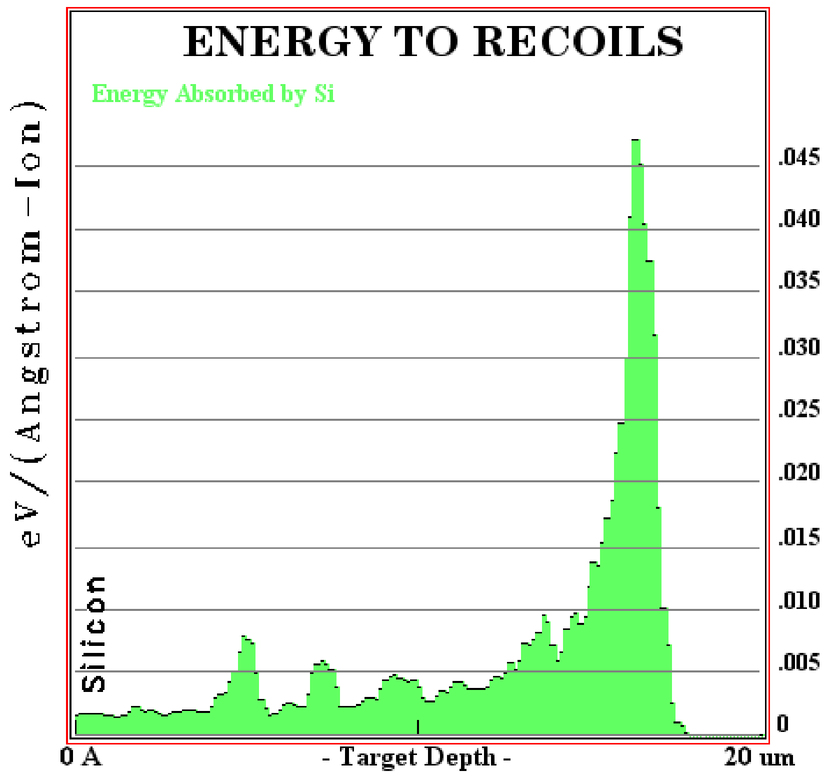
Ion-matter interaction: MeV ions

1 MeV H^+ in Si

Electronic energy loss



Nuclear energy loss



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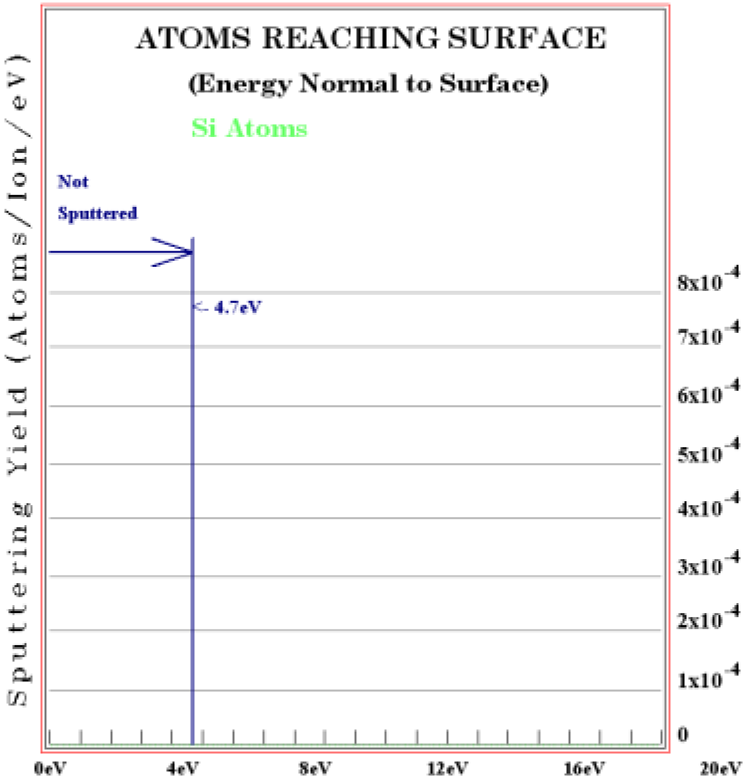
Ion-matter interaction: MeV ions

1 MeV H^+ in Si

Sputtering yield: ~0 atoms / ion



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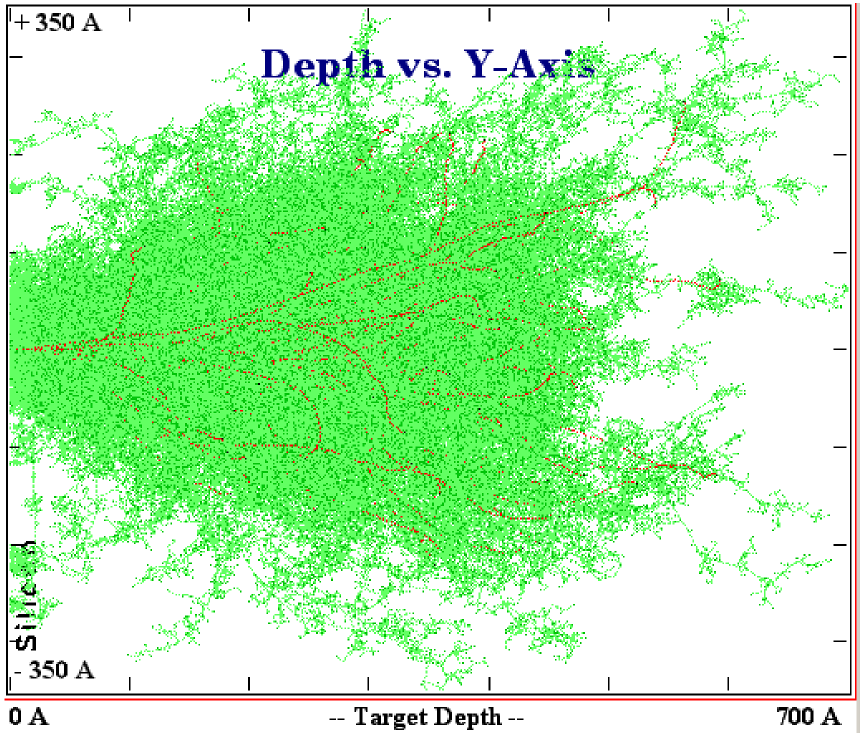
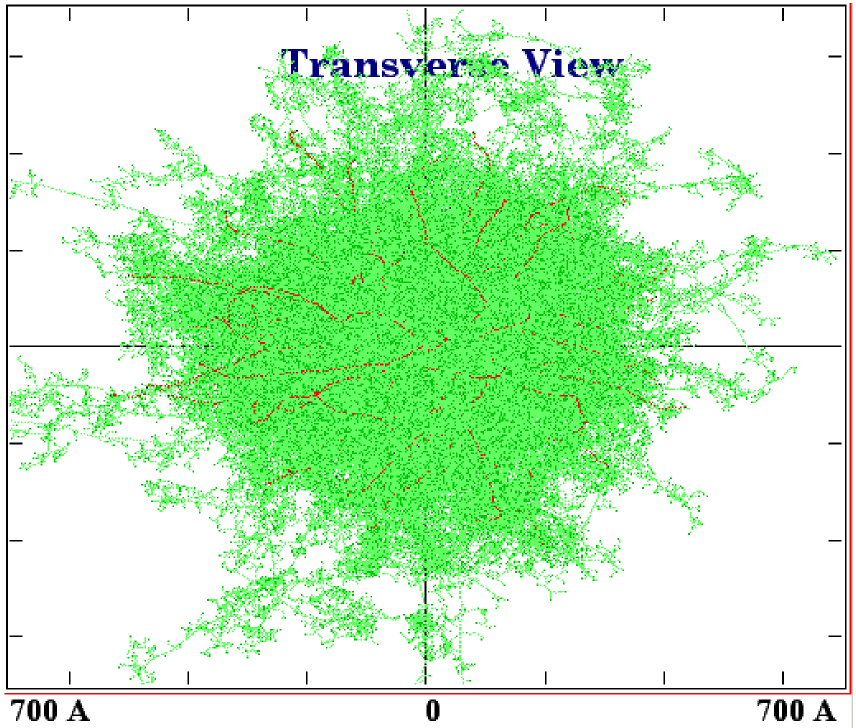
Ion-matter interaction: keV ions

30 keV Ga^+ in Si

Longitudinal trajectory



Lateral trajectory



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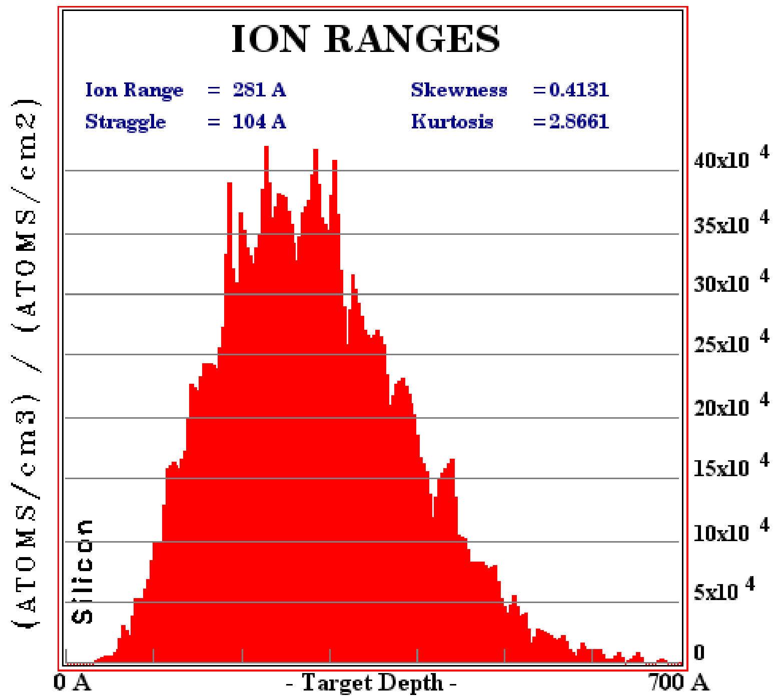
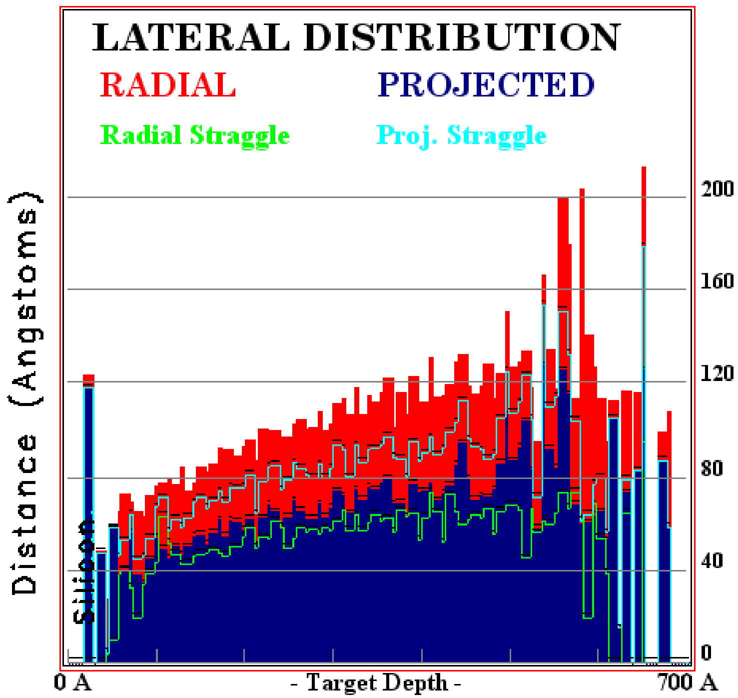
Ion-matter interaction: keV ions

30 keV Ga^+ in Si

Longitudinal range | **Lateral range**



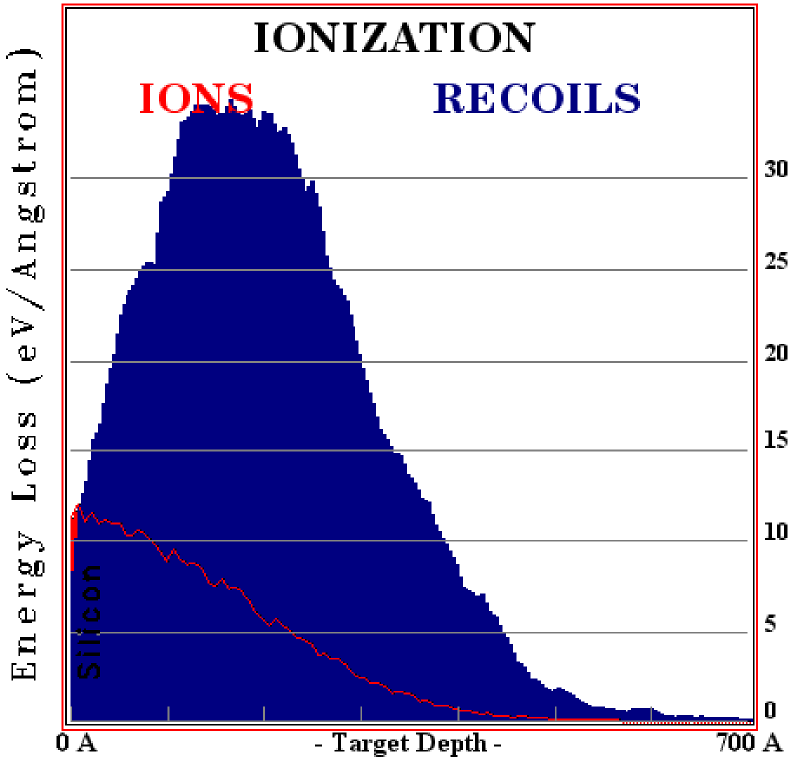


@ : SRIM Monte Carlo code

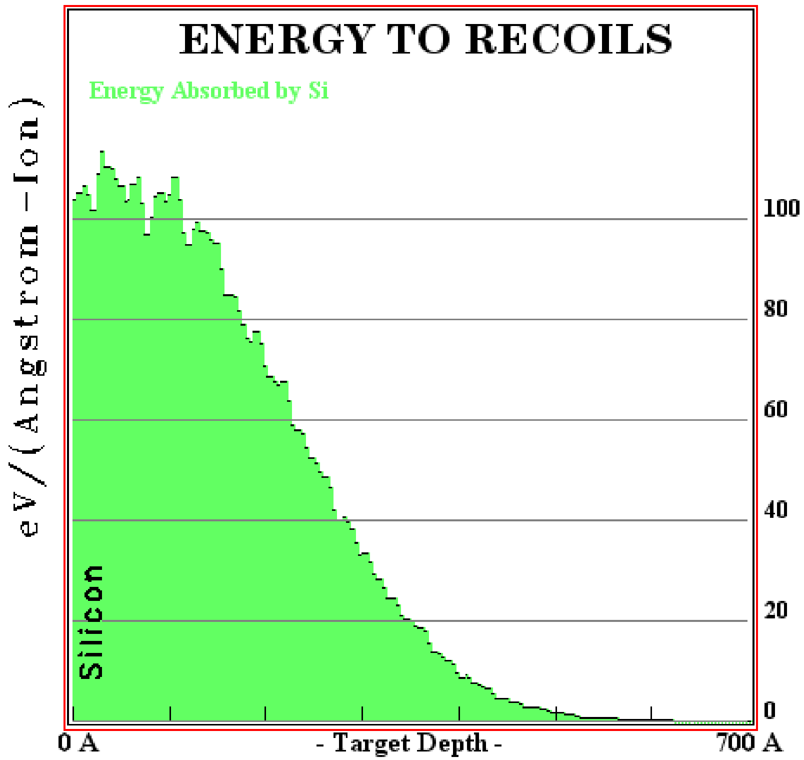
Ion-matter interaction: keV ions

30 keV Ga^{+} in Si

Electronic energy loss



Nuclear energy loss



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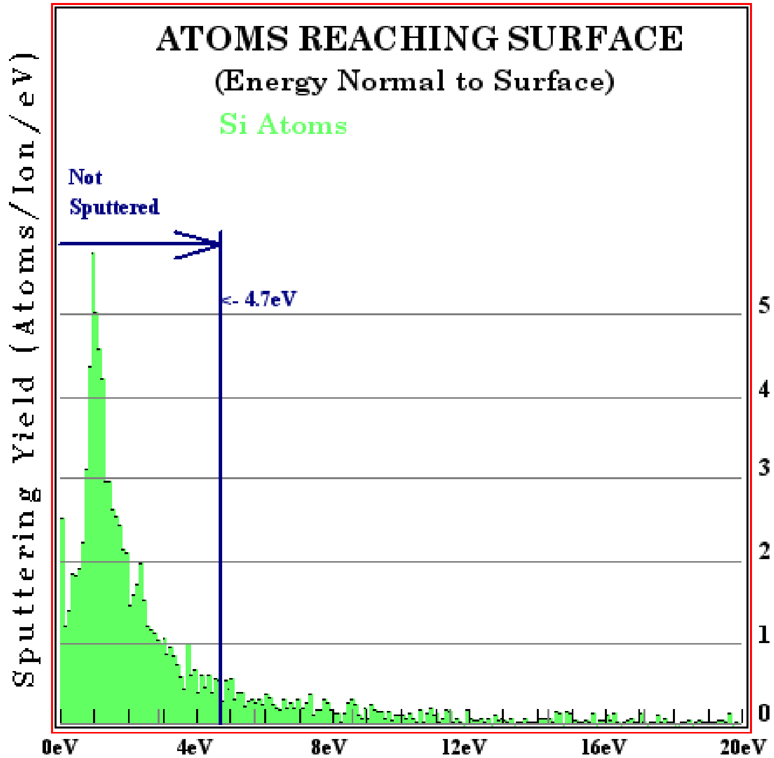
Ion-matter interaction: keV ions

30 keV Ga^{+} in Si

Sputtering yield: ~2.17 atoms / ion



@ : SRIM Monte Carlo code

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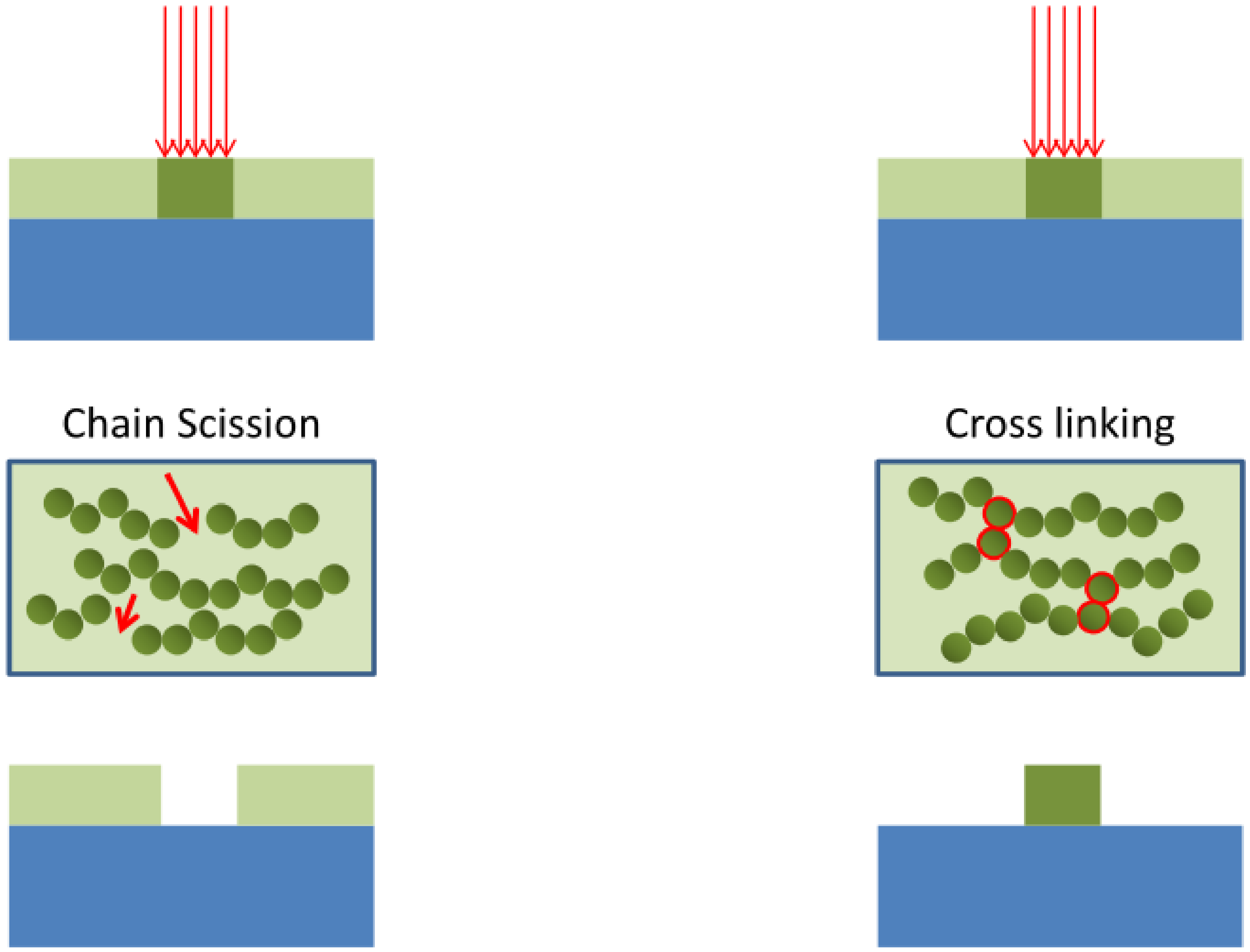
Conventional lithography techniques

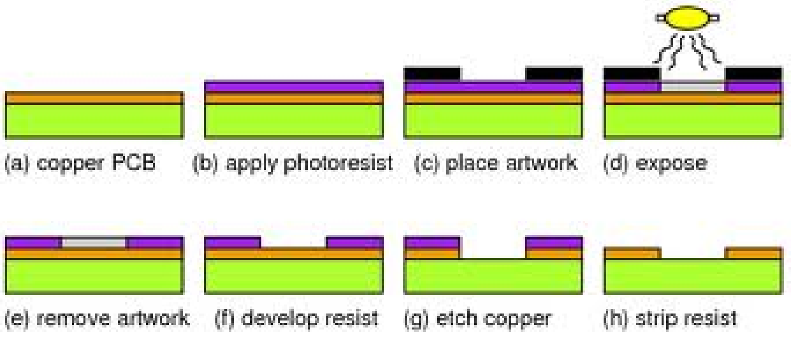
Lithography in positive and negative resists



Conventional lithography techniques

Photolithography

schematics



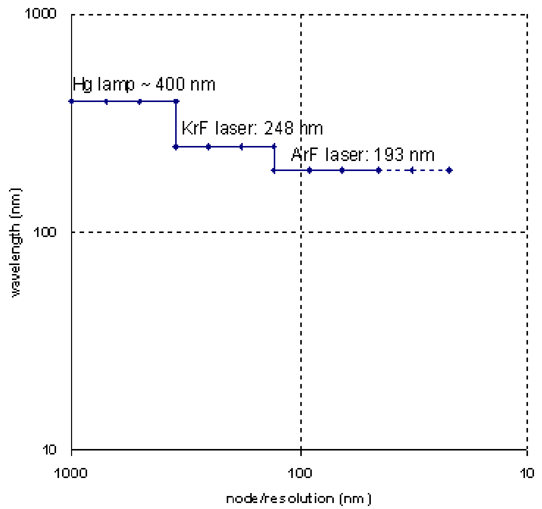
mask aligner (λ=365 nm)

photoresists: **PPMA, PMGI, SU-8, etc.**

very-large-scale integration (VLSI)

minimum feature size: $ND = k_1 \cdot \frac{\lambda}{NA}$

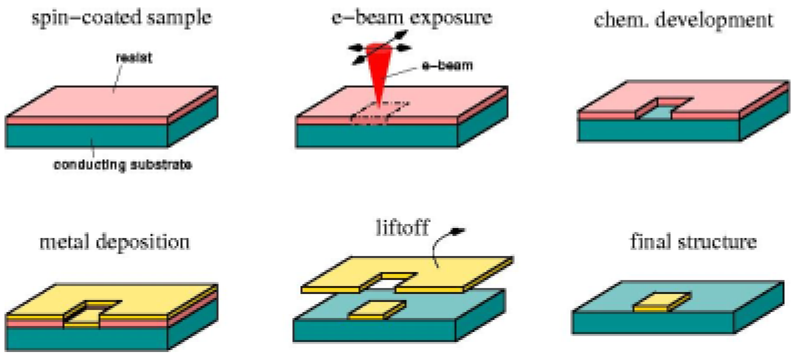
depth of focus: $D_f = k_2 \cdot \frac{\lambda}{NA^2}$



Conventional lithography techniques

Electron-beam lithography

schematics

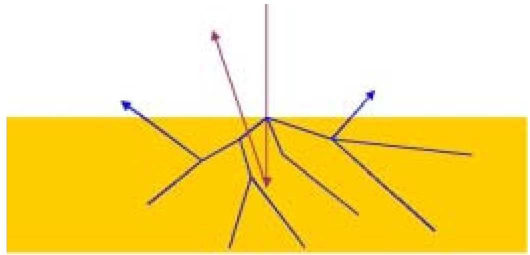


electron beam lithograph (SEM)

direct-write mask-less process

resists: ZEP-520, PMMA

resolution: e-beam size (~nm)
<u>**beam-target interaction**</u>



other issues: scattering
proximity effects
charging

best resolution: 30-60 nm

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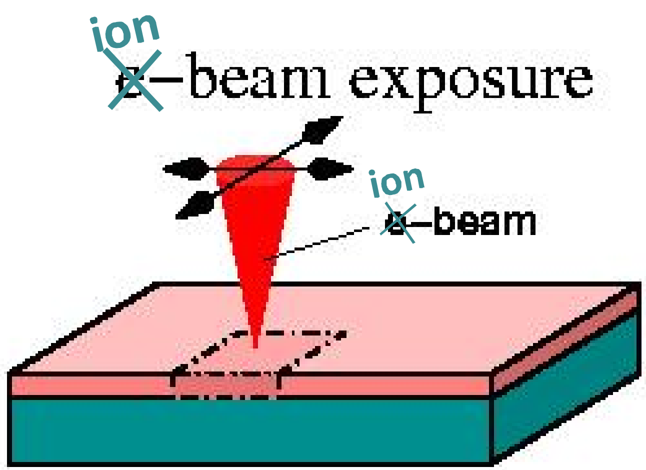
Ion-beam lithography: MeV ions



as for EBL:

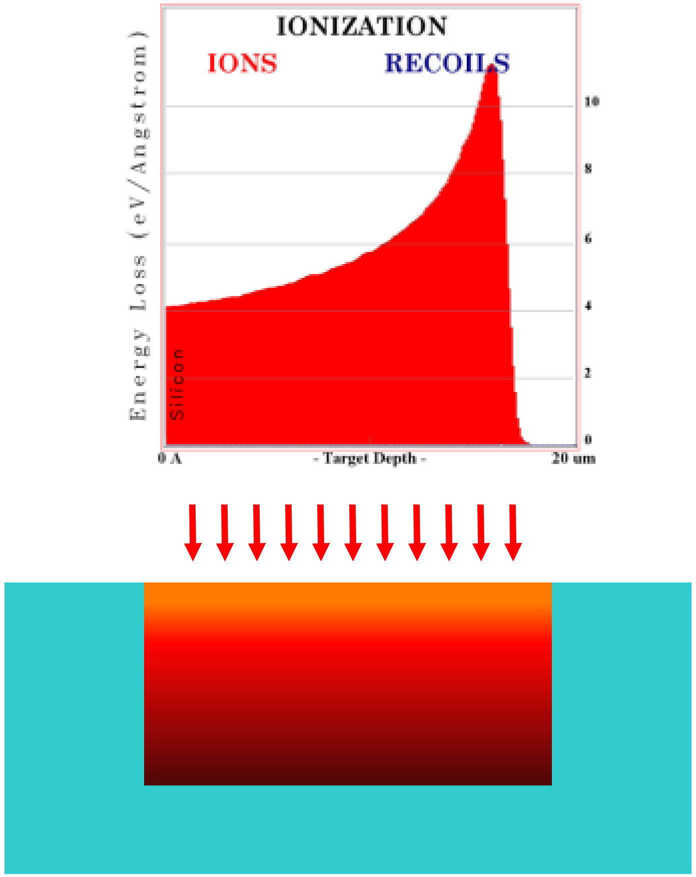
- scanning focused/collimated beam
- mask-less direct writing
- typical EBL resists

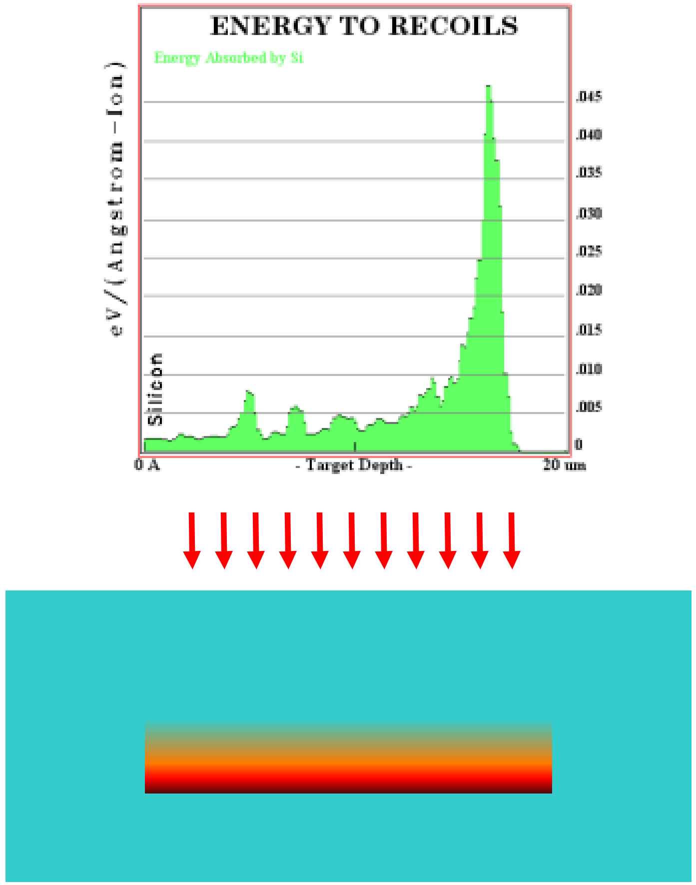
Processes

- ion implantation (doping, luminescent centers, …)
- change in chemical reactivity in a latent image
- local modification of physical (electrical, optical, magnetic, …) properties

Ion-beam lithography: MeV ions

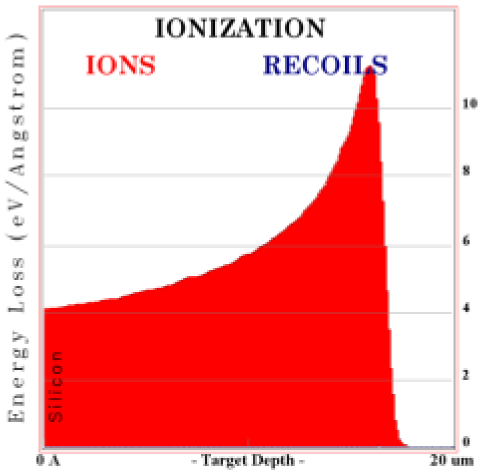
Tools
- **electronic interaction: ionization → chemical modification**
- **nuclear interaction: damage → structural modification**

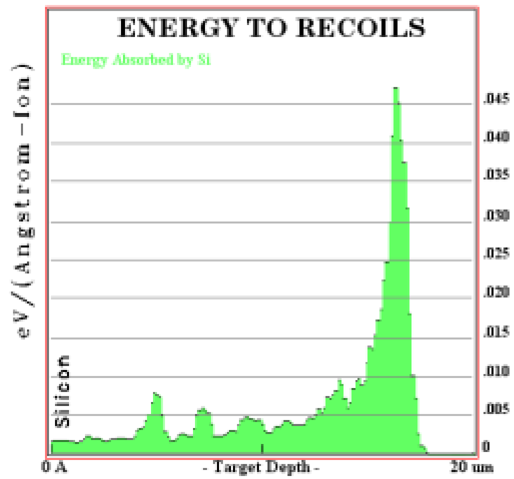


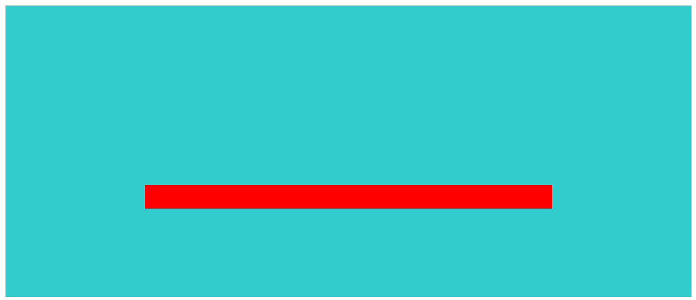


Ion-beam lithography: MeV ions

Tools
- **electronic interaction: ionization → chemical modification**
- **nuclear interaction: damage → structural modification**

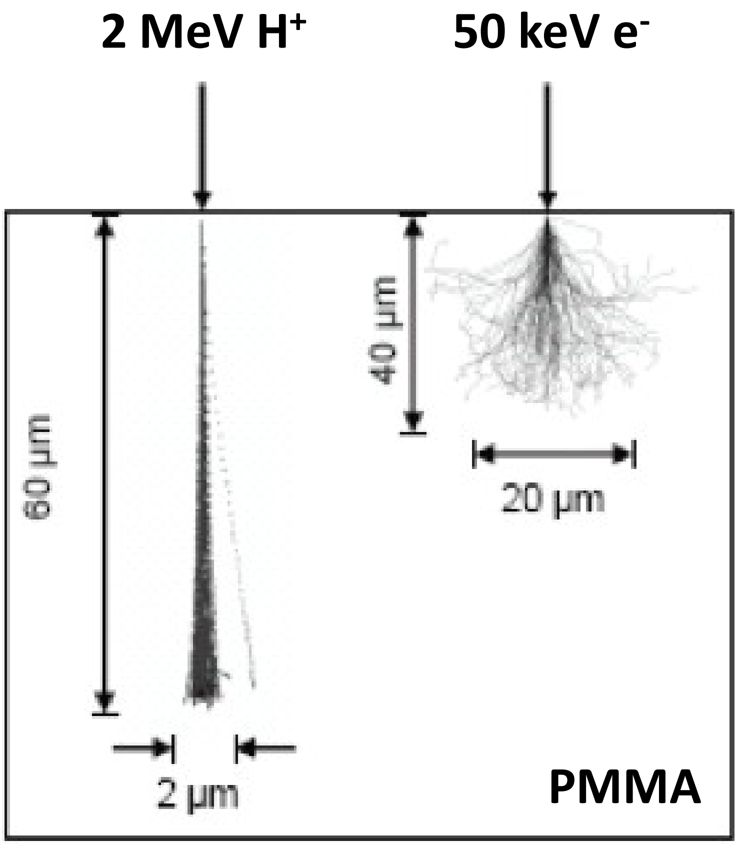






Ion-beam lithography: MeV ions

Key issue: beam-target interaction

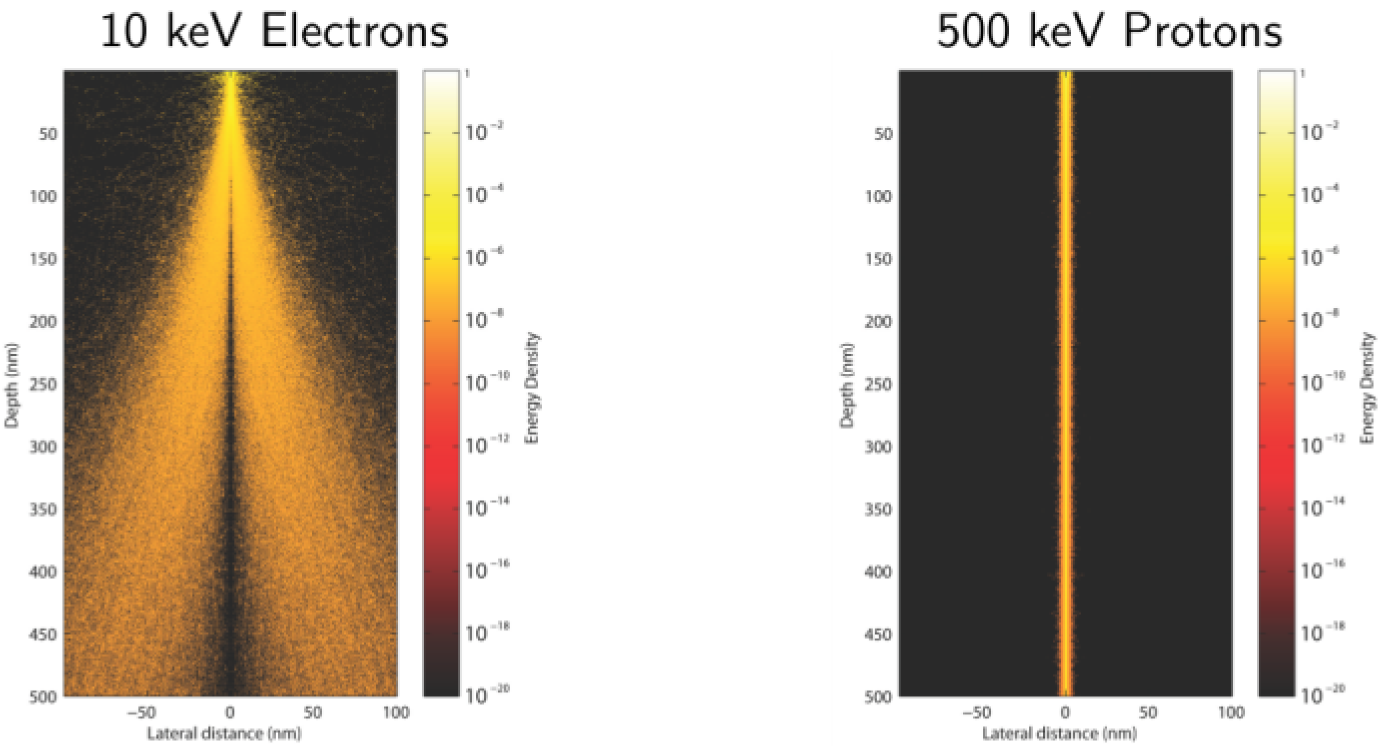


- ~nm beam focusing
- low lateral straggling
- low longitudinal straggling
- tunable penetration depth (ion energy & species)
- lower emission of high-energy secondary electrons (*δ rays*): no proximity effects

Ion-beam lithography: MeV ions

Beam-target interaction:
particularly relevant in shallow regions

in PMMA



@ : DEEP Monte Carlo code

Ion-beam lithography: MeV ions

Unique capabilities offered by IBL

High penetration depth	→	High aspect-ratios
Low lateral straggling	→	Smoothness in lateral features
Low longitudinal straggling	→	Multi-level structures
Focusing, no proximity effects	→	High resolution
End-of-range peak	→	Depth resolution
Structural modification	→	Functionalization of physical properties

Ion-beam lithography: MeV ions

Proton beams: ideal in terms of: focusing
penetration profile

⇓

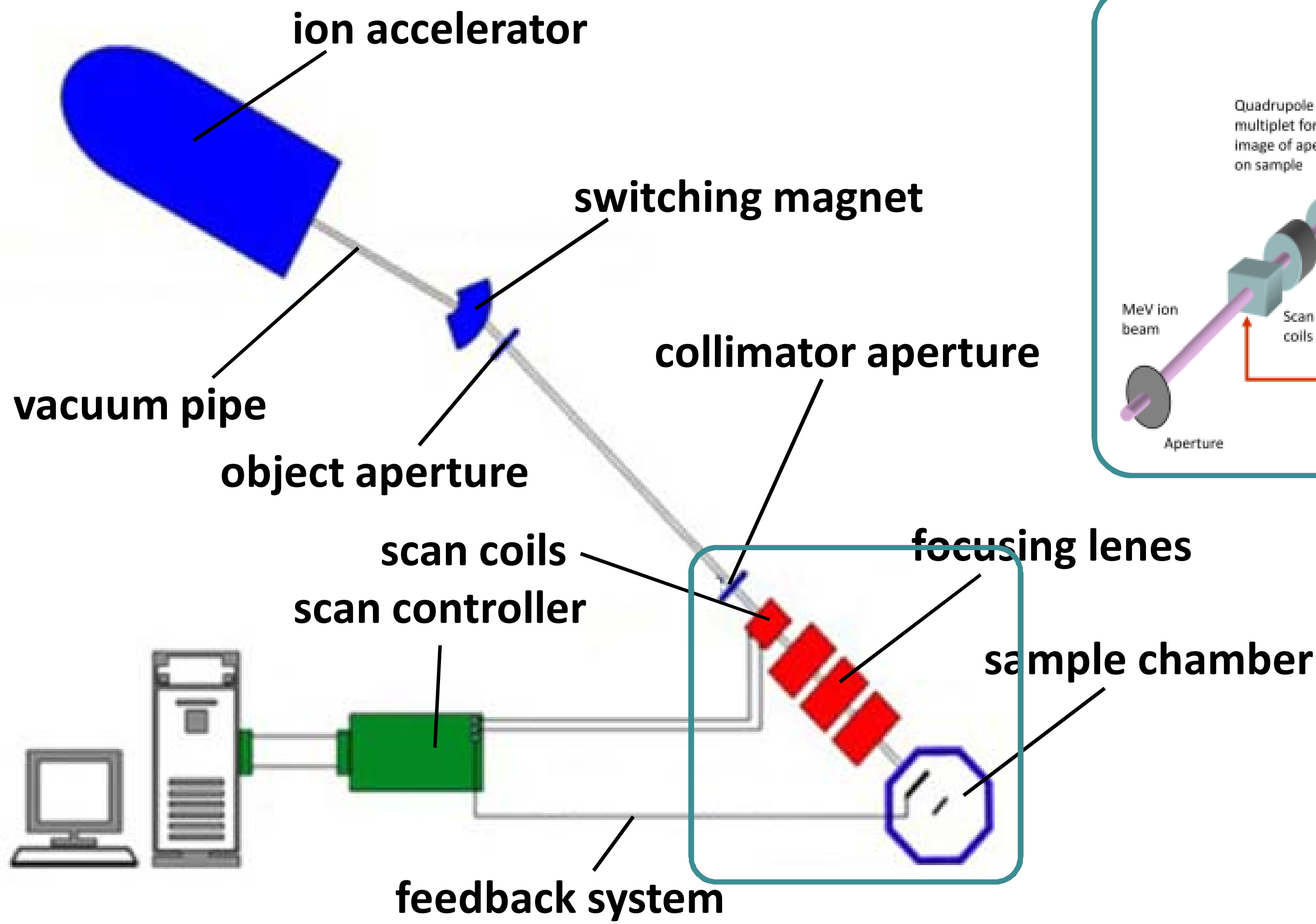
Proton Beam Writing (PBW)

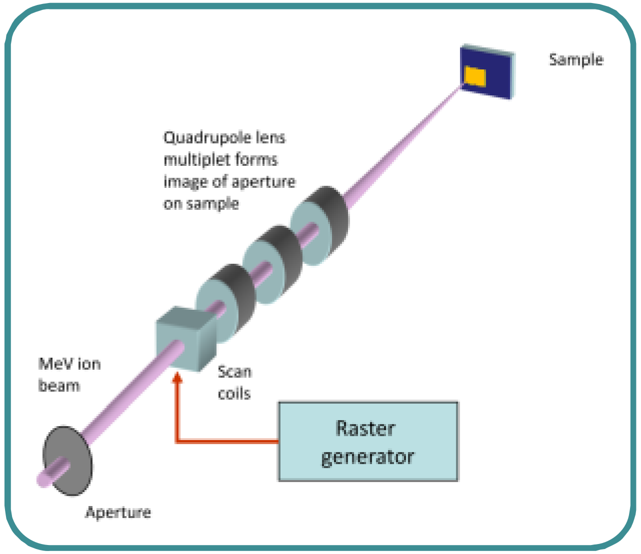
P-LIGA (Proton – Lithographie, Galvanoformgung, Abformung: Proton – Lithography, Electroplating and Molding)

In several specific applications, other ions species (He, C, N, O, Si, Ar, Br, Au, …) were employed

Ion-beam lithography: MeV ions

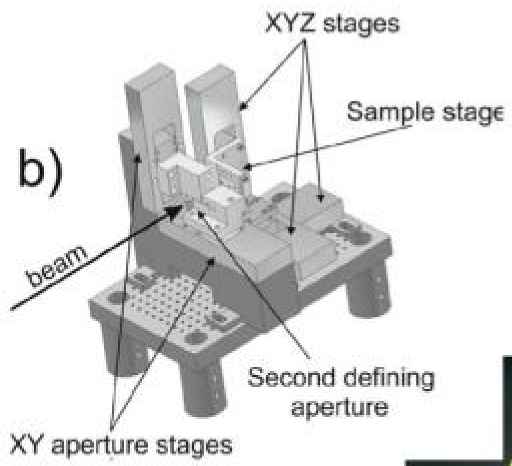
Scanning μ-beam system

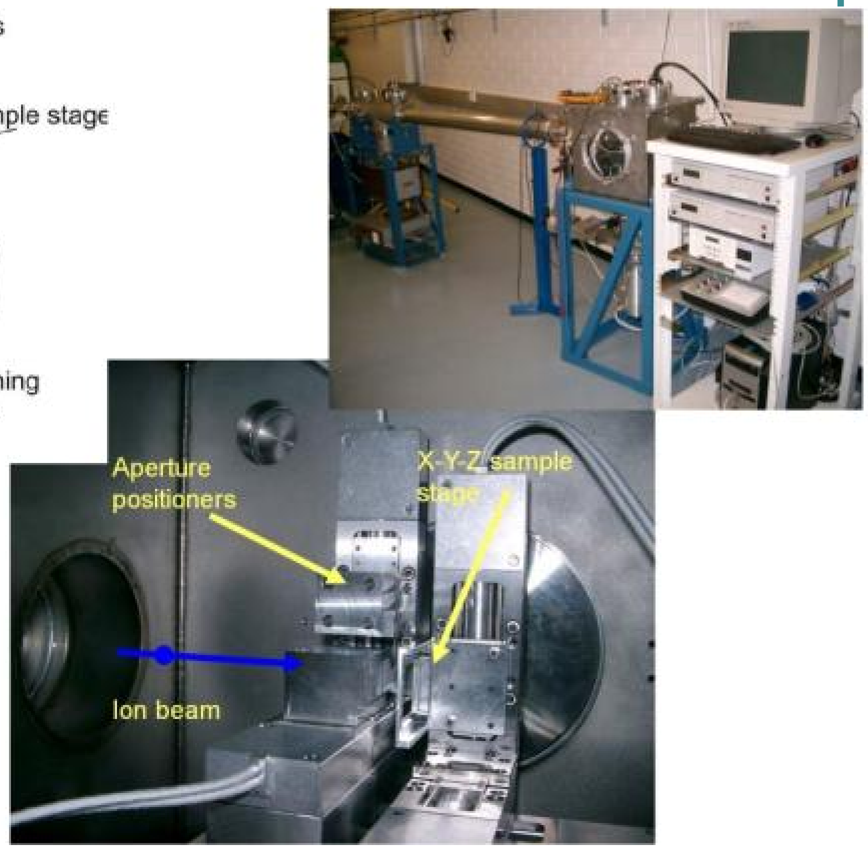


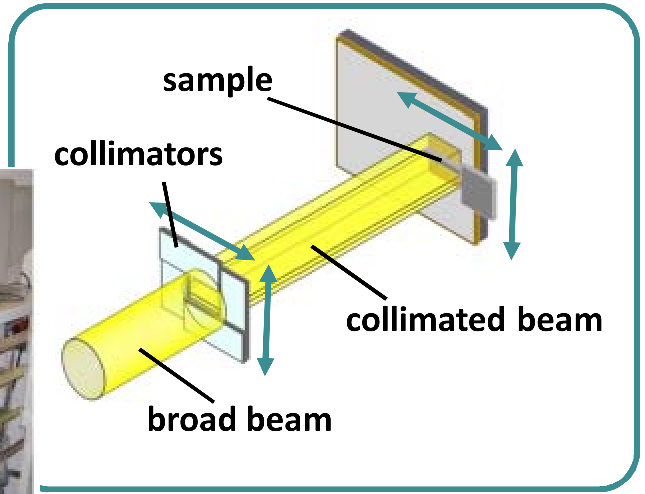


Ion-beam lithography: MeV ions

Programmable aperture system







Ion-beam lithography: MeV ions

Ion projection system

ELSEVIER

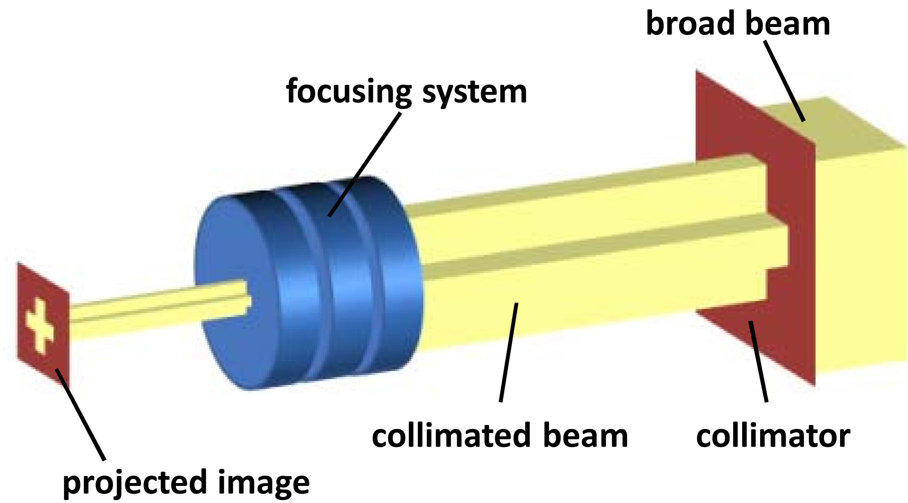
Microelectronic Engineering 41/42 (1998) 257–260

MICROELECTRONIC ENGINEERING

High Energy Implantation by Ion Projection

J. Meijer and A.Stephan

Physik mit Ionenstrahlen
Ruhr-Universität Bochum, 44780 Bochum, Germany



Ion-beam lithography: MeV ions

Proximity mask system

ELSEVIER

Nuclear Instruments and Methods in Physics Research B 132 (1997) 430–438

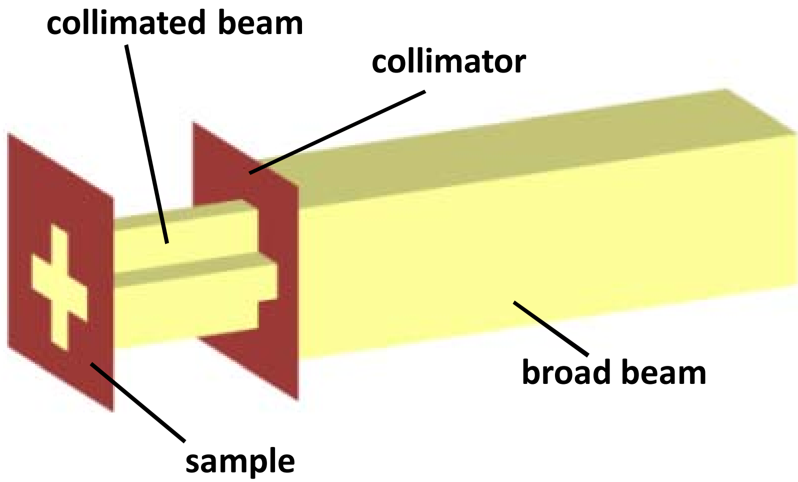
NIM B
Beam Interactions with Materials & Atoms

Deep light ion lithography in PMMA – A parameter study

F. Schrempel *, W. Witthuhn

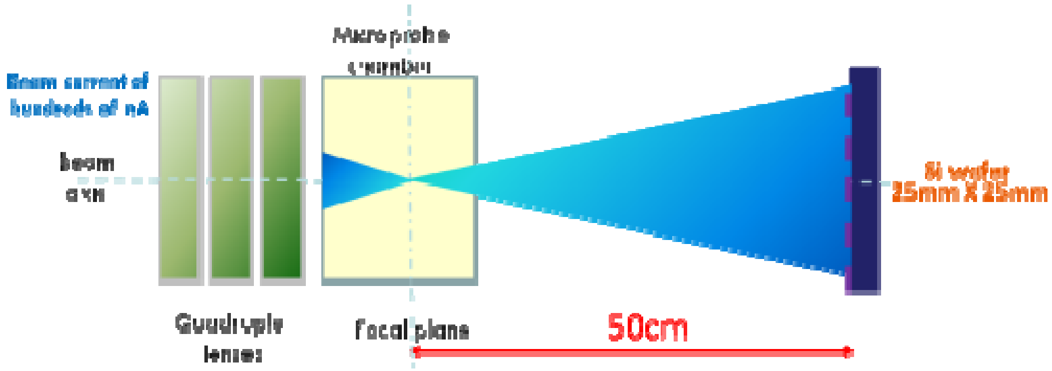
Institut für Festkörperphysik, Friedrich-Schiller-Universität Jena, Max-Wien-Platz 1, D-07743 Jena, Germany

Received 3 March 1997; revised form received 4 June 1997



Ion-beam lithography: MeV ions

Contact mask system



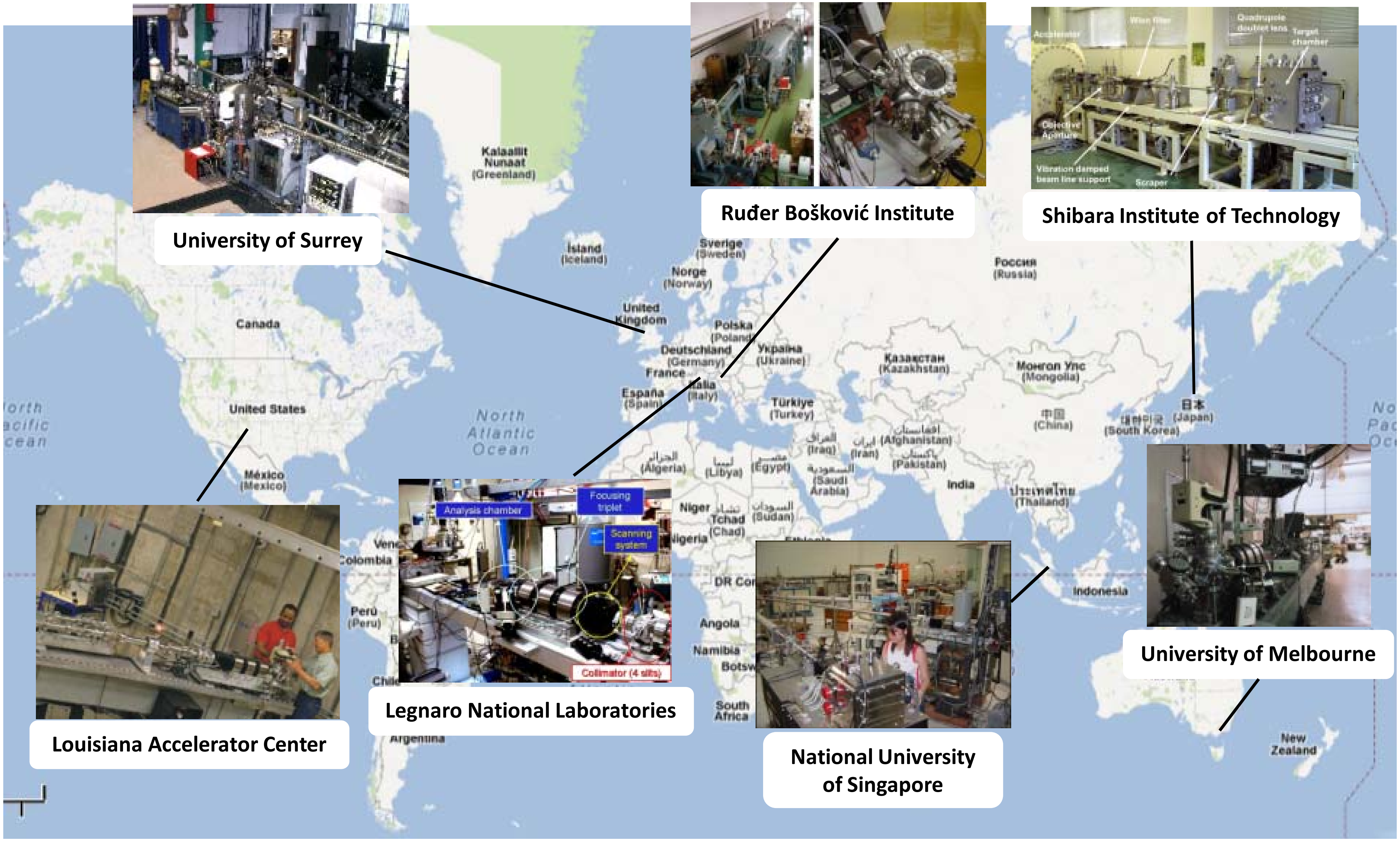
Ion-beam lithography: MeV ions

Scanning beams vs masks

Scanning beam systems	Mask-based systems
:-) Fast pattern definition	:-(Slow pattern definition
:-(Serial & slow irradiation	:-) Fast & parallel irradiation
:-) High resolution	:-(Mask scattering & heating
:-(Limited scan field	:-) Broad scan field

Ion-beam lithography: MeV ions

(*Some of the many*) MeV-IBL setups around the world



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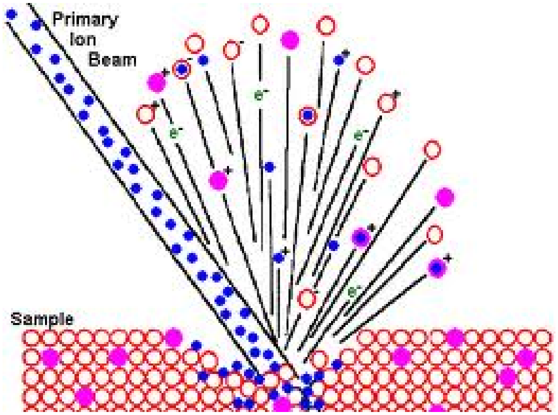
Ion-beam lithography: keV ions

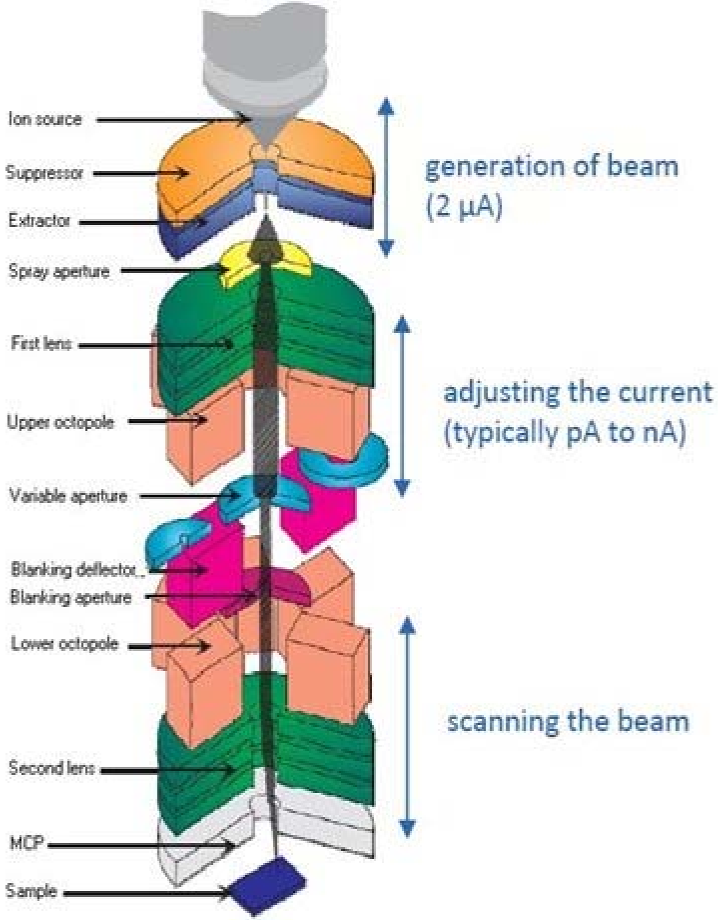
Focused ion beam (FIB) direct milling

schematics



typical FIB setup

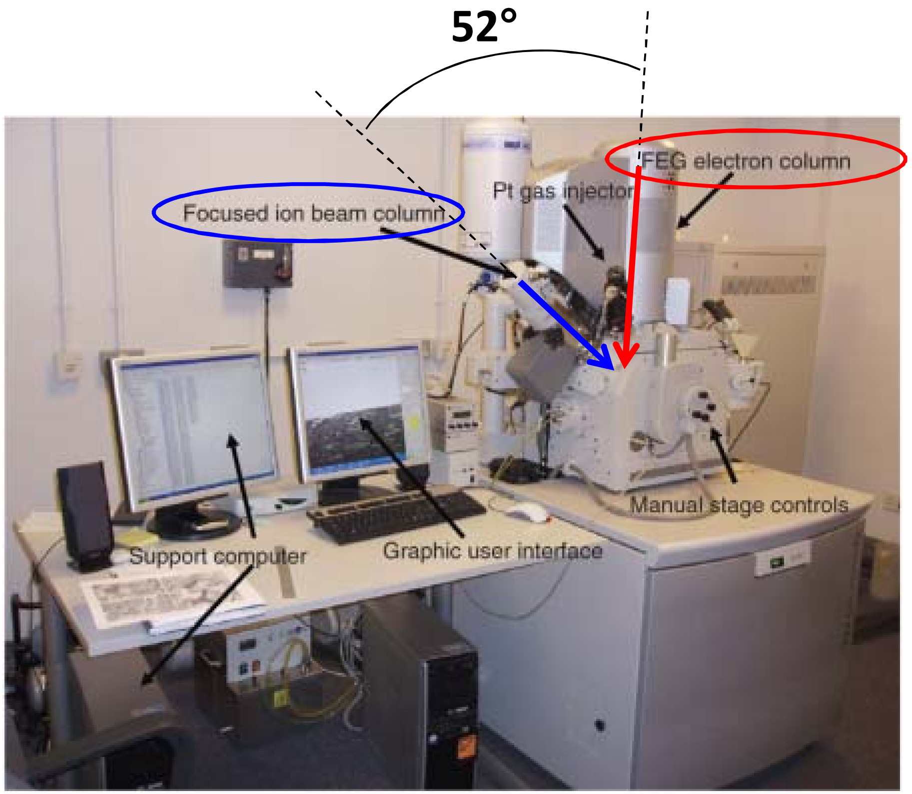
FIB column

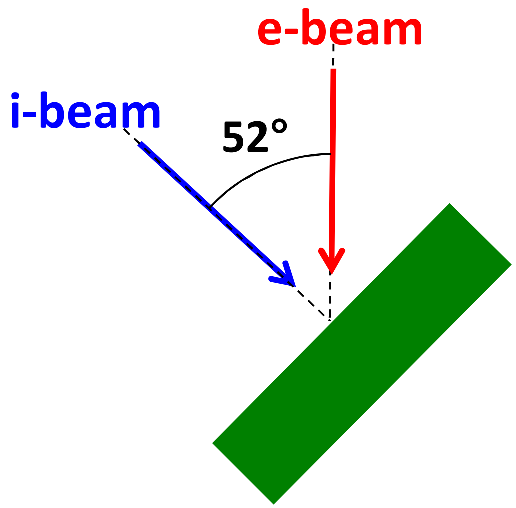


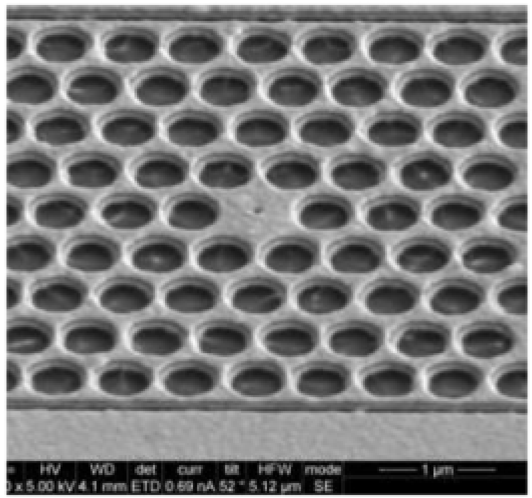
Ion-beam lithography: keV ions

Focused ion beam (FIB) direct milling

Dual beam systems





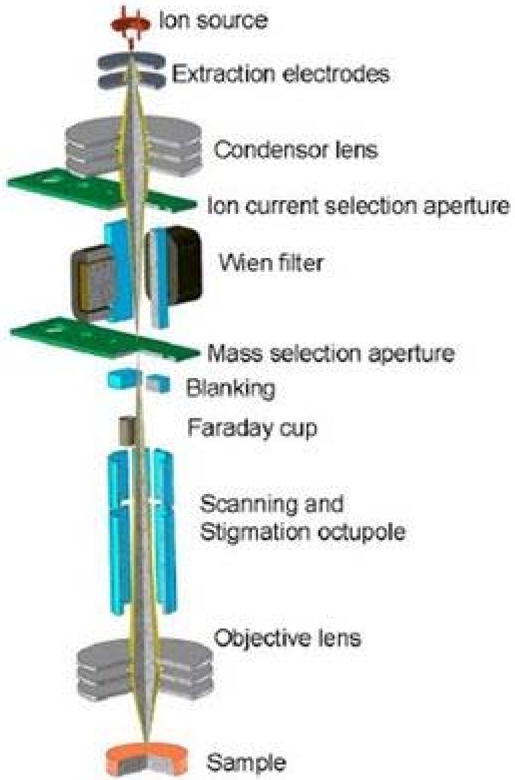


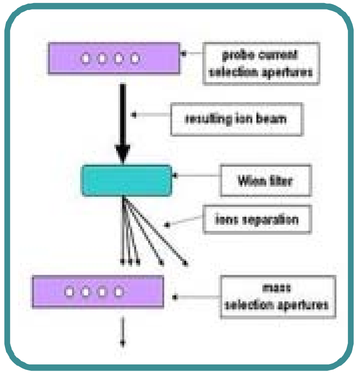
Ion-beam lithography: keV ions

FIB: key issues

Range of ion sources

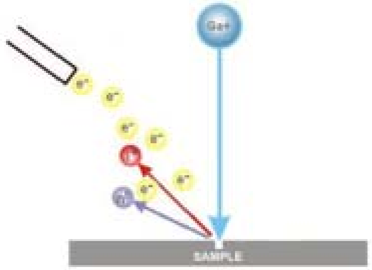
Wien filter setup





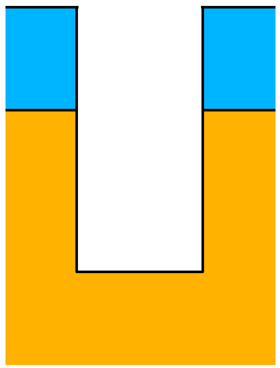
Sample charging

Sample coating and/or electron flooding

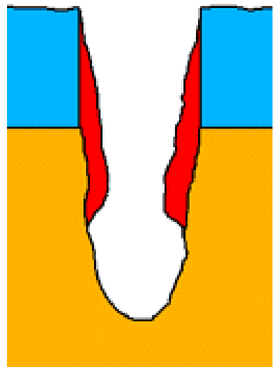


Material redeposition

Enhanced etching, limiting aspect ratio



ideal case

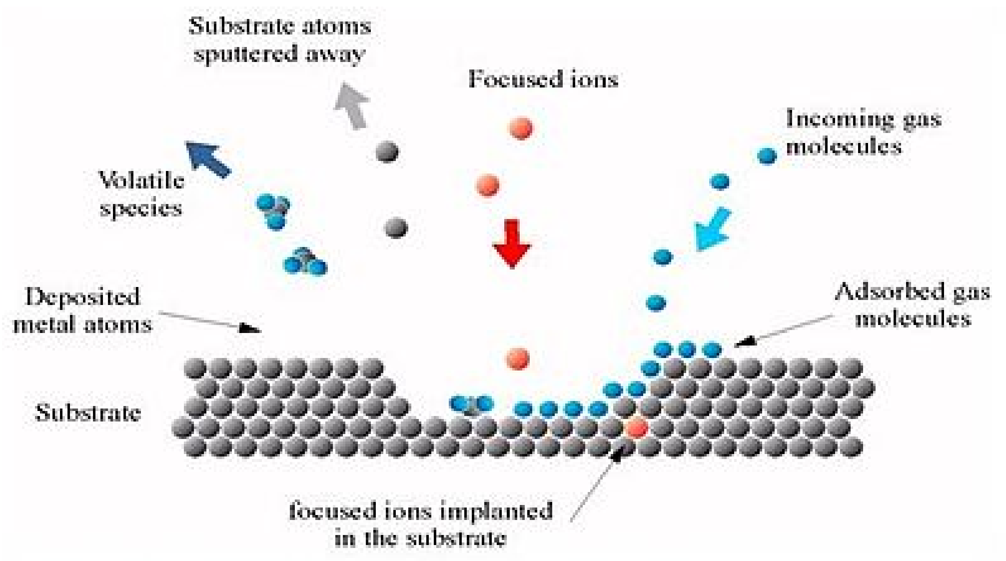


real case

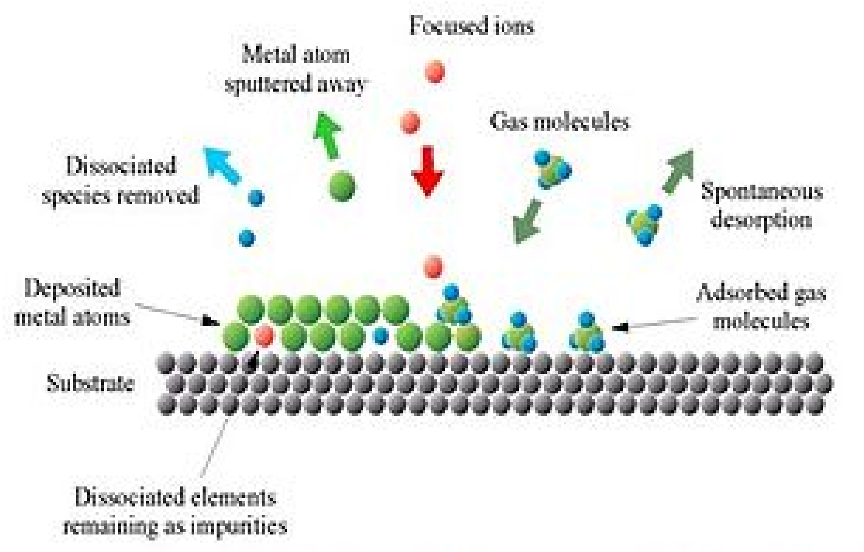
Ion-beam lithography: keV ions

Other FIB processes

Gas-assisted FIB etching



Gas-assisted deposition



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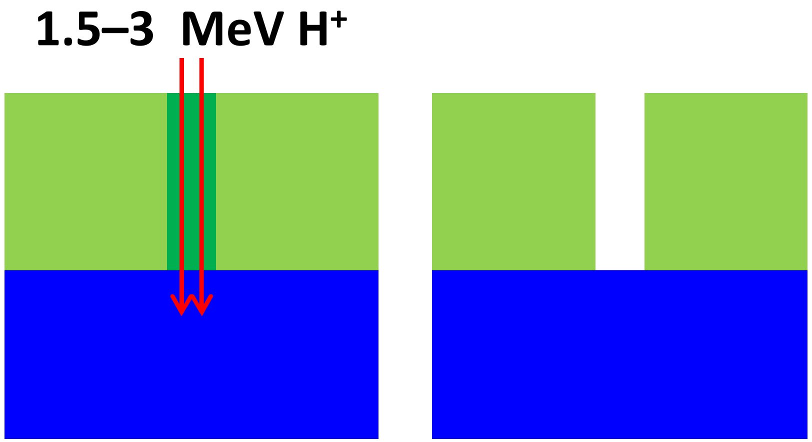
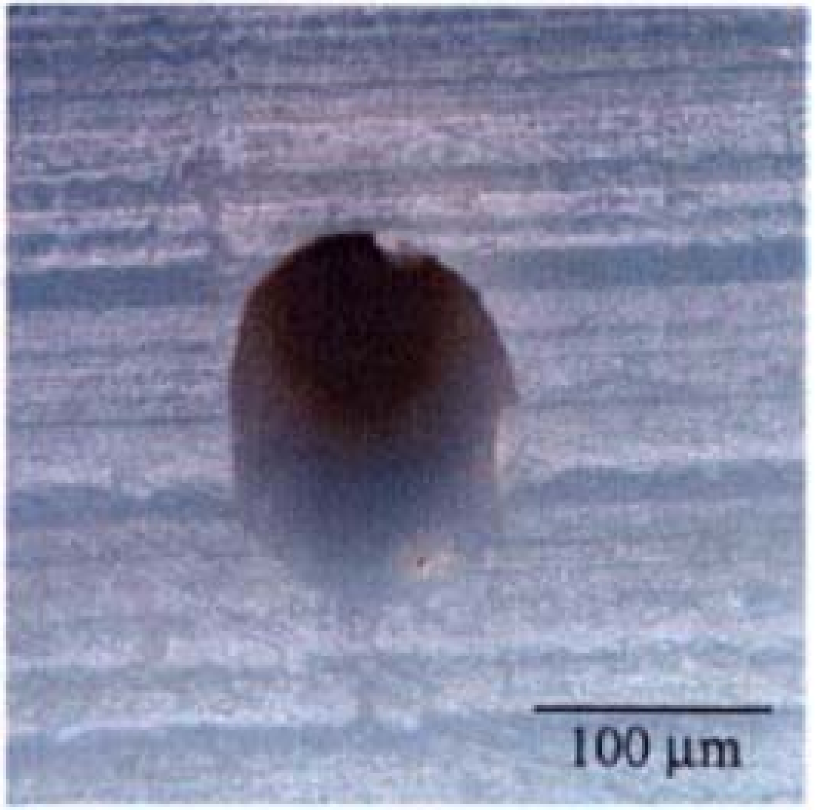
MeV Ion-beam lithography: resists

Material	Type	Fluence (nC/mm^2)	Smallest structure (μm)	Reference
PMMA	Pos.	80-150	0.03	Singapore[1]
PMGI	Pos.	150	1.5	Singapore[2]
SU-8	Neg.	30	0.06	Singapore[3]
HSQ	Neg.	30	0.02	Singapore[4]
TiO_2 (Sol-Gel)	Neg.	8000	5	Singapore[5]
WL-7154	Neg.	4	0.8	Singapore[5]
TADEP	Neg.	300	0.28	Singapore[6]
DiaPlate 133	Neg.	10	10	CAFI[7]
ADEPR	Neg.	125-238	5	Debecen[8]
ma-N 440	Neg.	200	0.4	Leipzig[9]

MeV Ion-beam lithography: resists

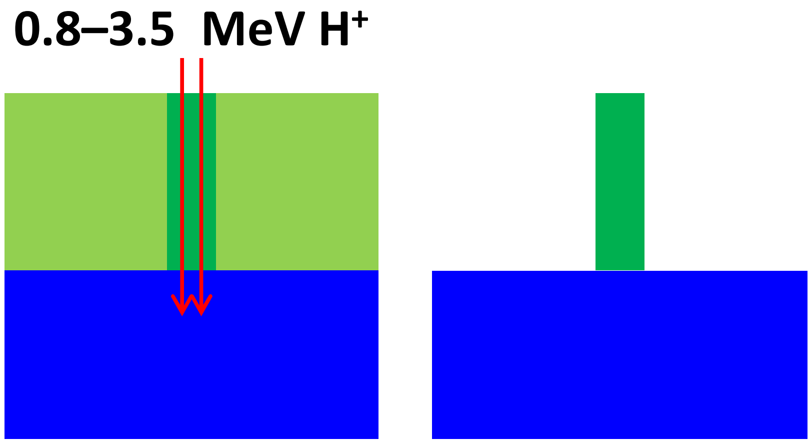
Positive process: polytetrafluoroethylene (PTFE)

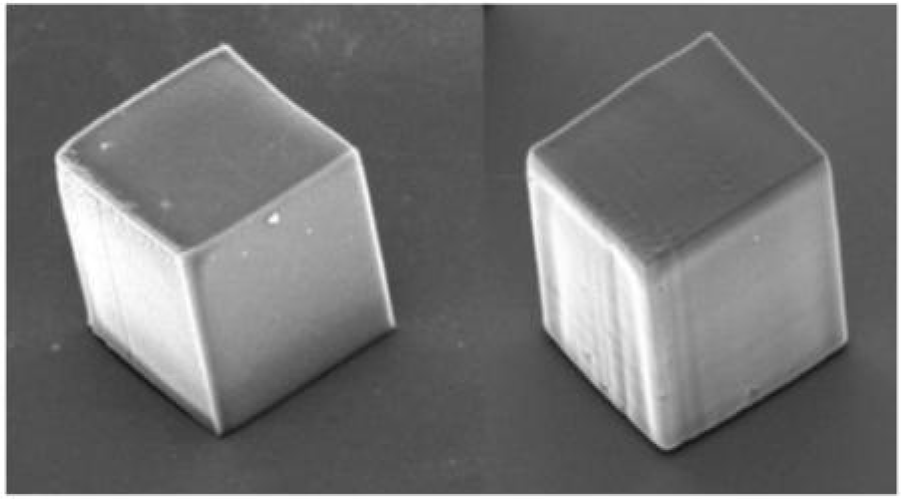




MeV Ion-beam lithography: resists

Negative process: SU-8, DiaPlate 133

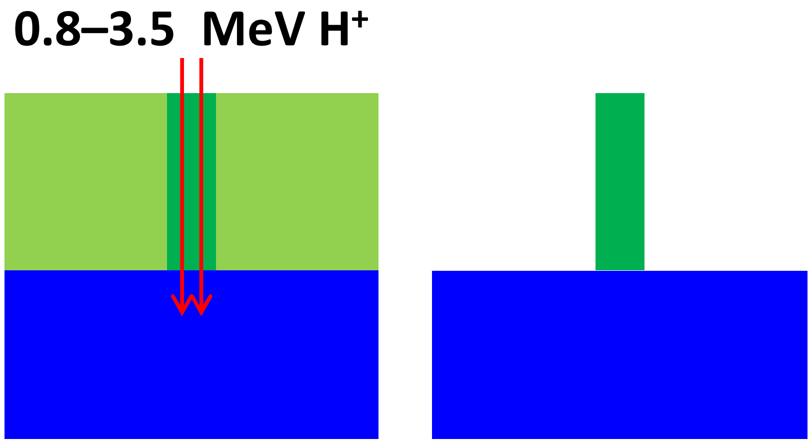


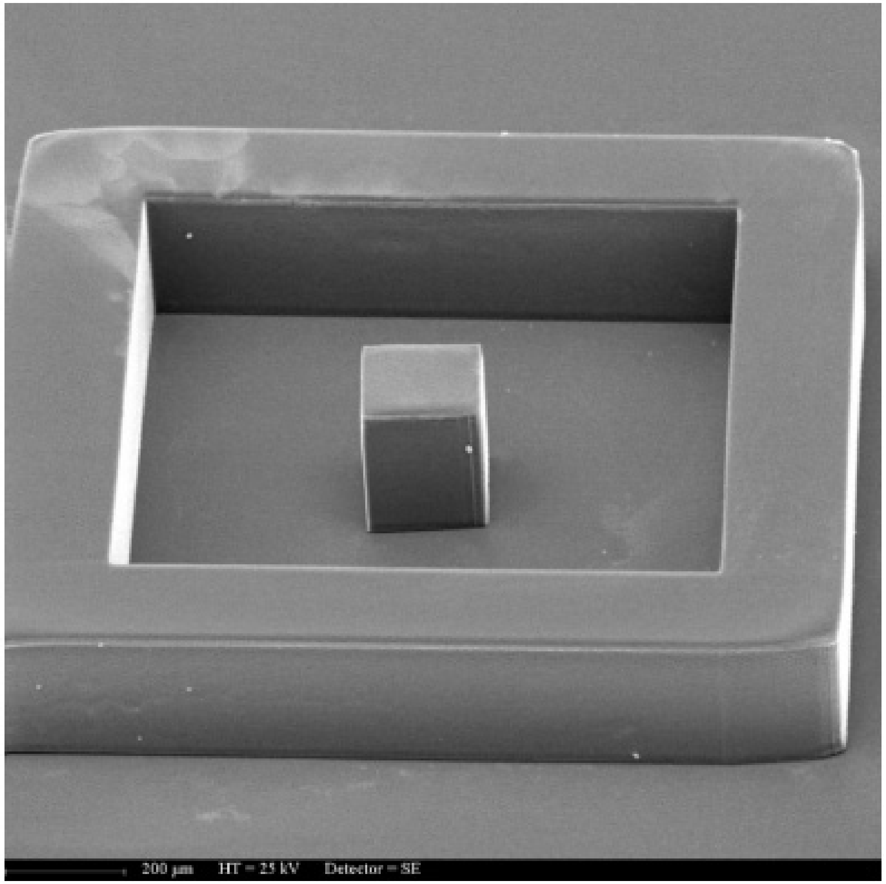


SU-8 DiaPlate 133

MeV Ion-beam lithography: resists

Negative process: SU-8, DiaPlate 133

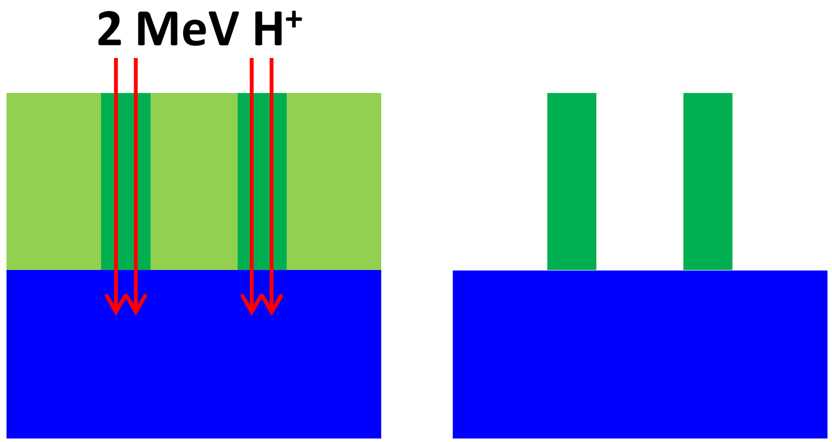


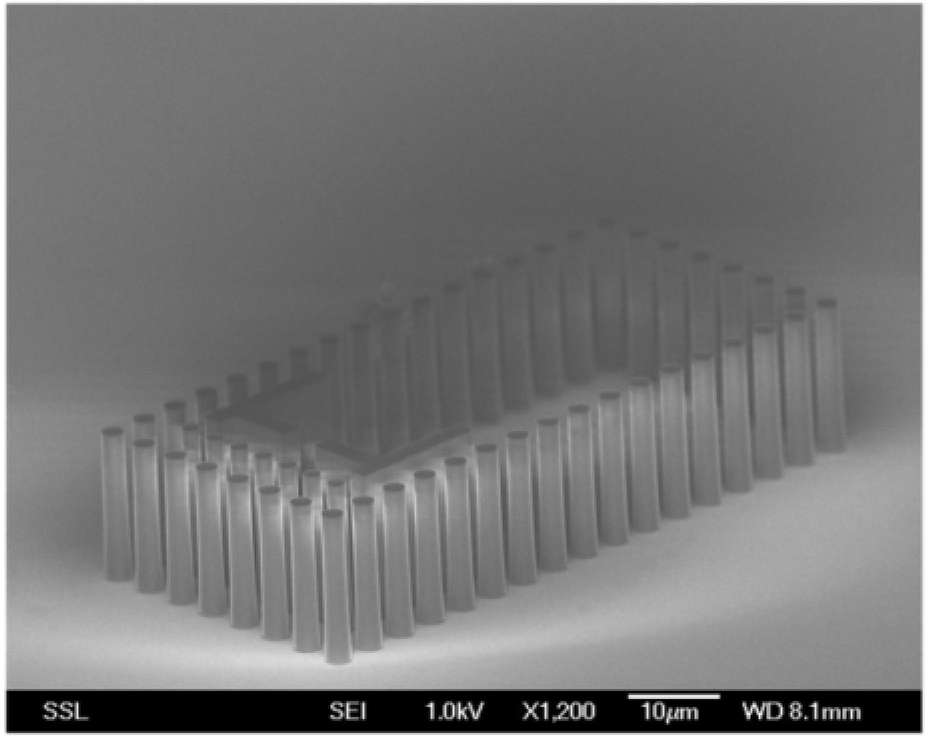


SU-8

MeV Ion-beam lithography: resists

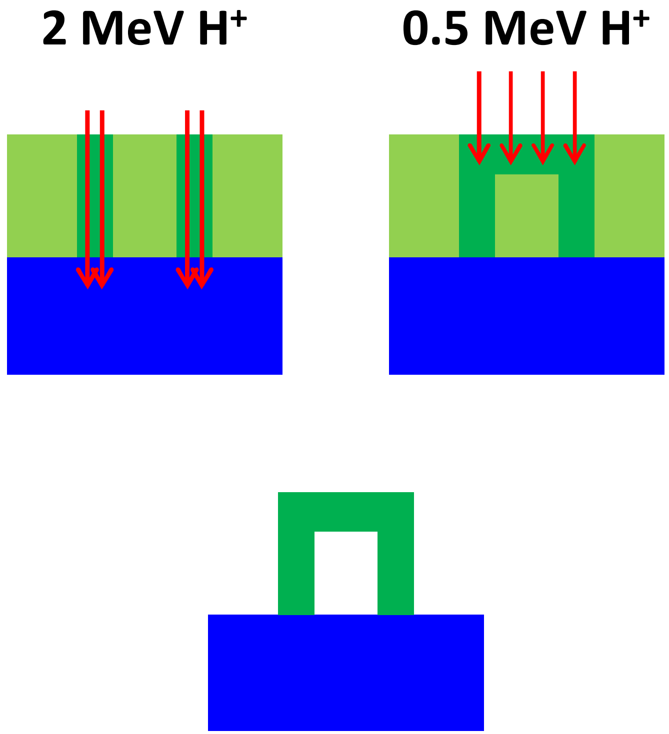
High-aspect-ratio structures

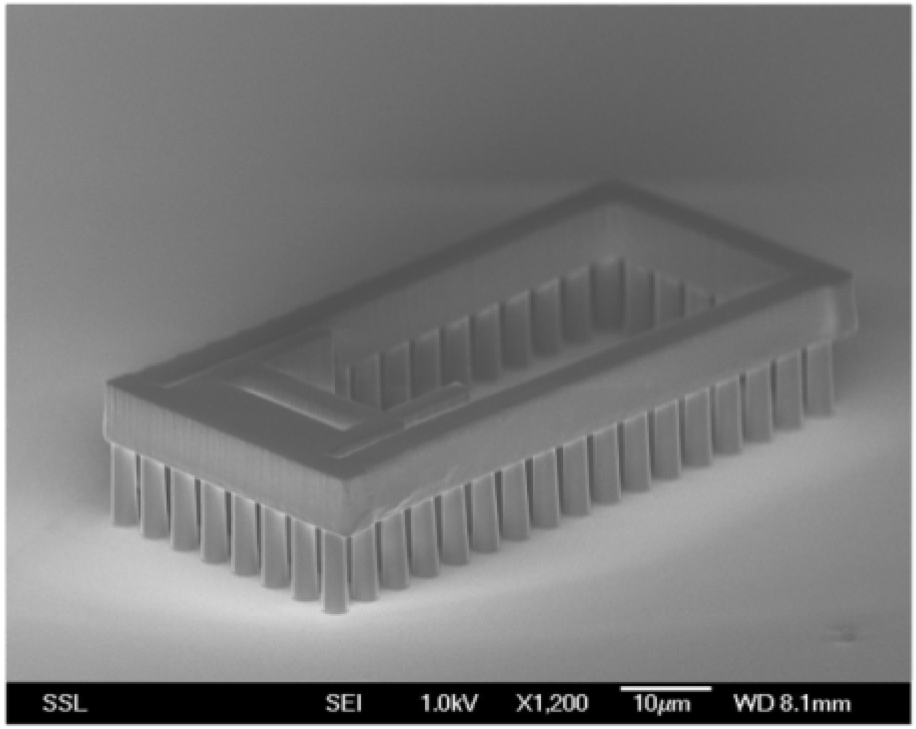




MeV Ion-beam lithography: resists

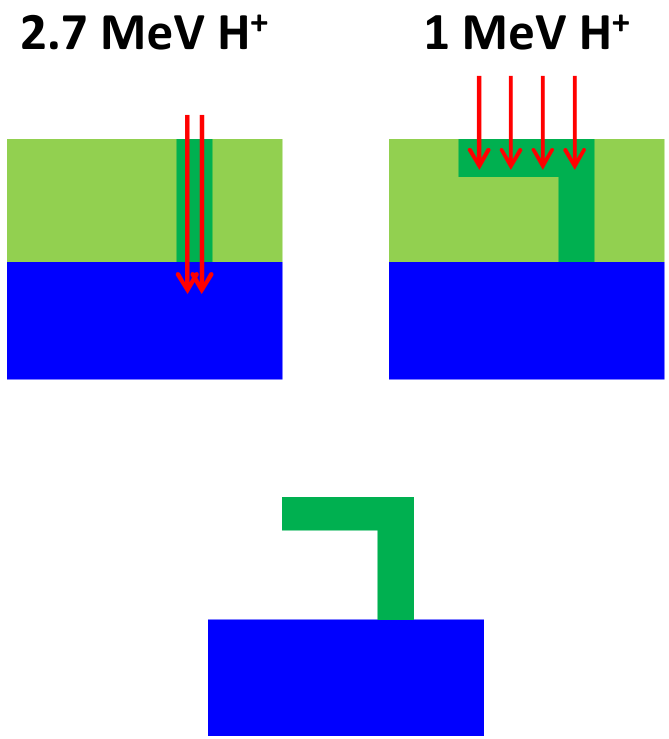
Three-dimensional structures

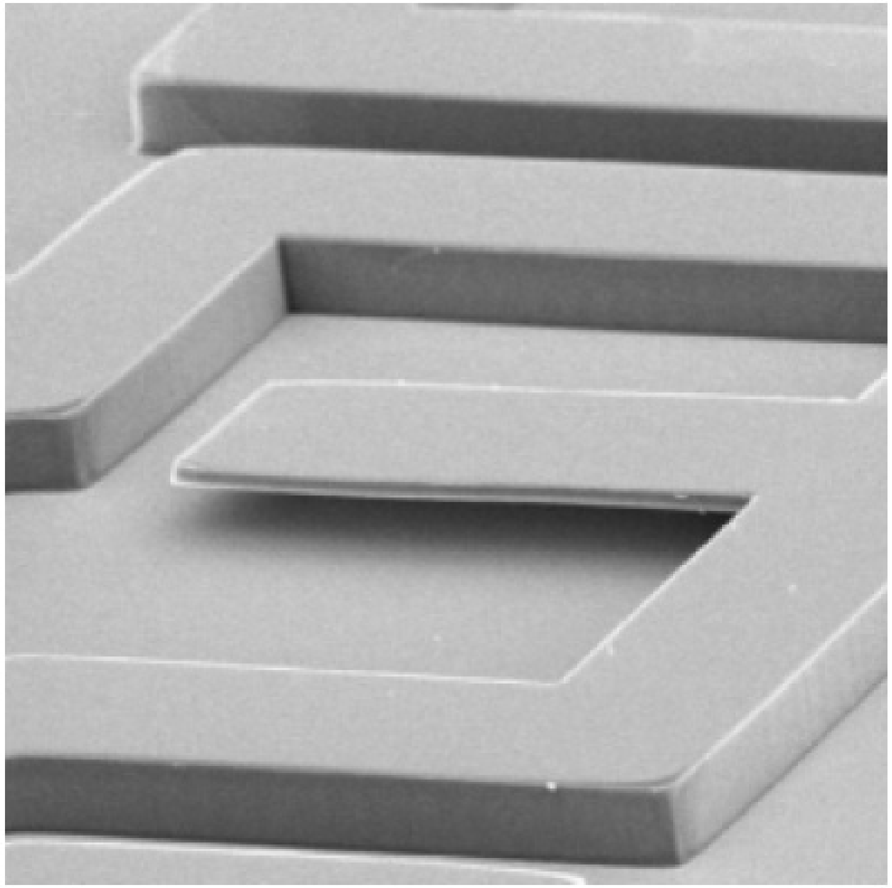




MeV Ion-beam lithography: resists

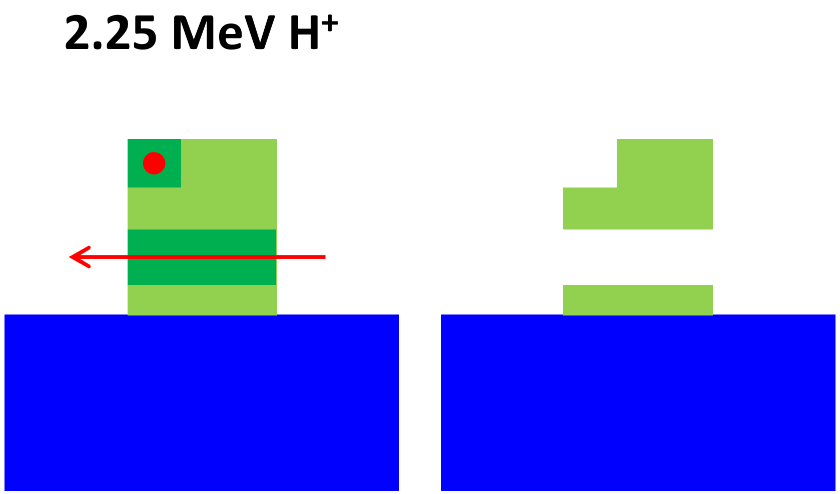
Three-dimensional structures

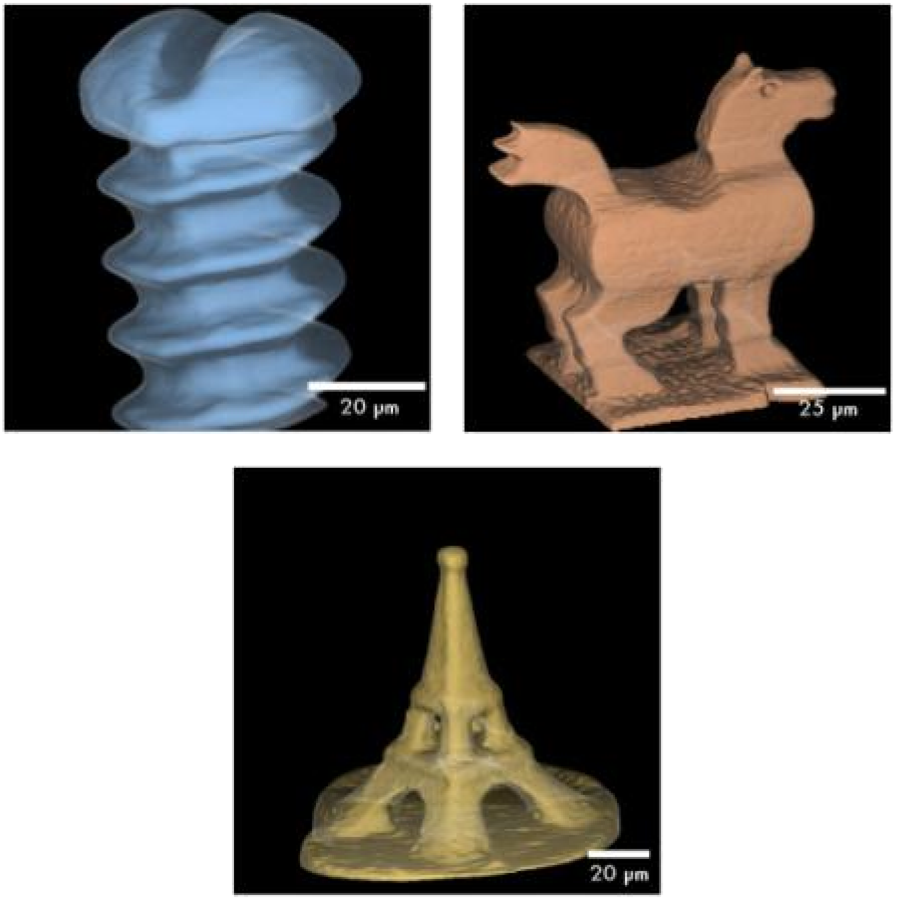




MeV Ion-beam lithography: resists

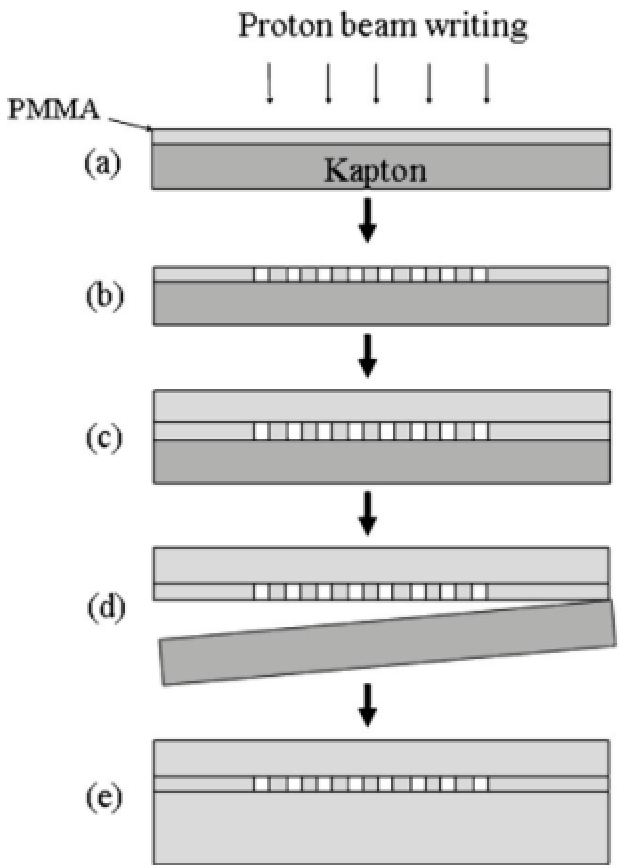
Three-dimensional structures



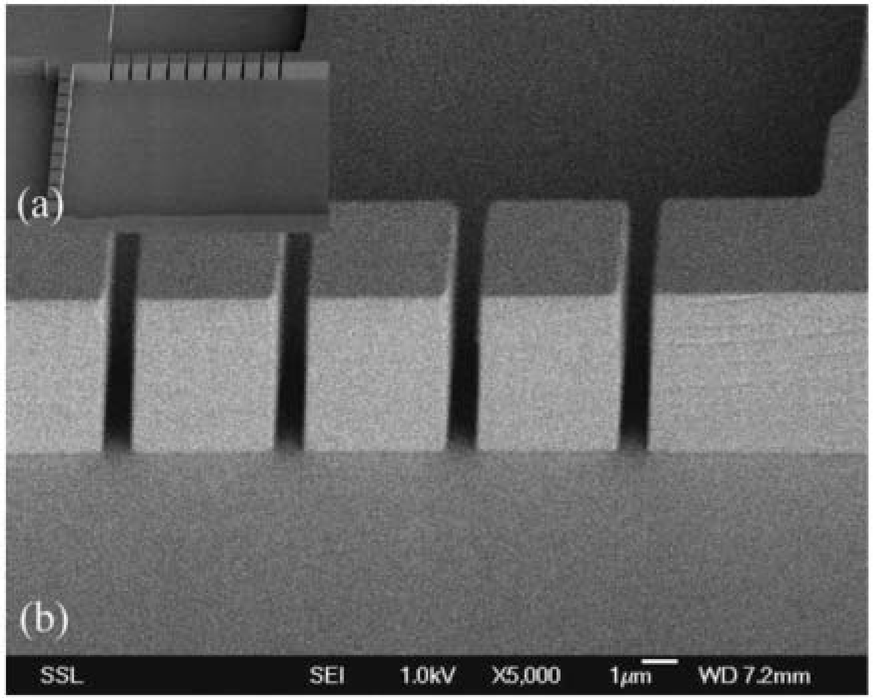


MeV Ion-beam lithography: resists

PMMA-on-PMMA microchannels

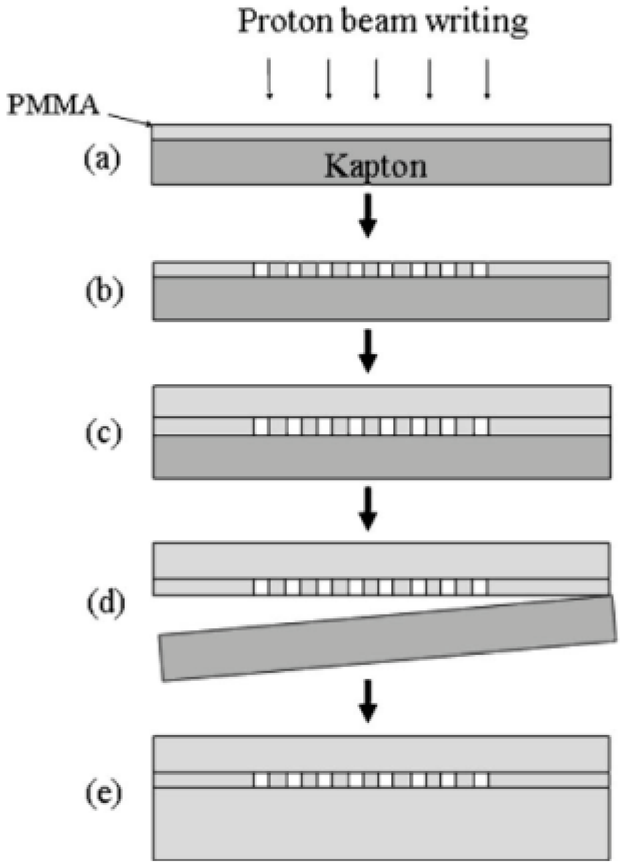


thermal bonding process

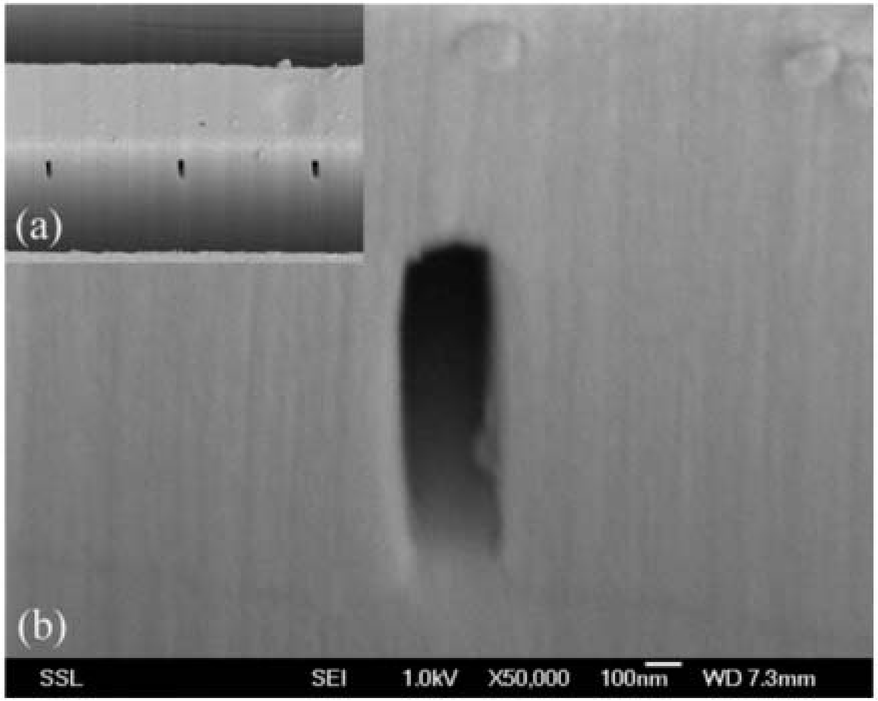


MeV Ion-beam lithography: resists

PMMA-on-PMMA microchannels

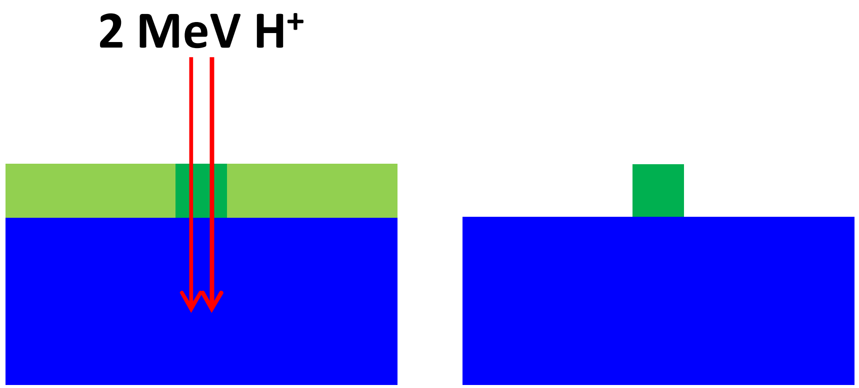


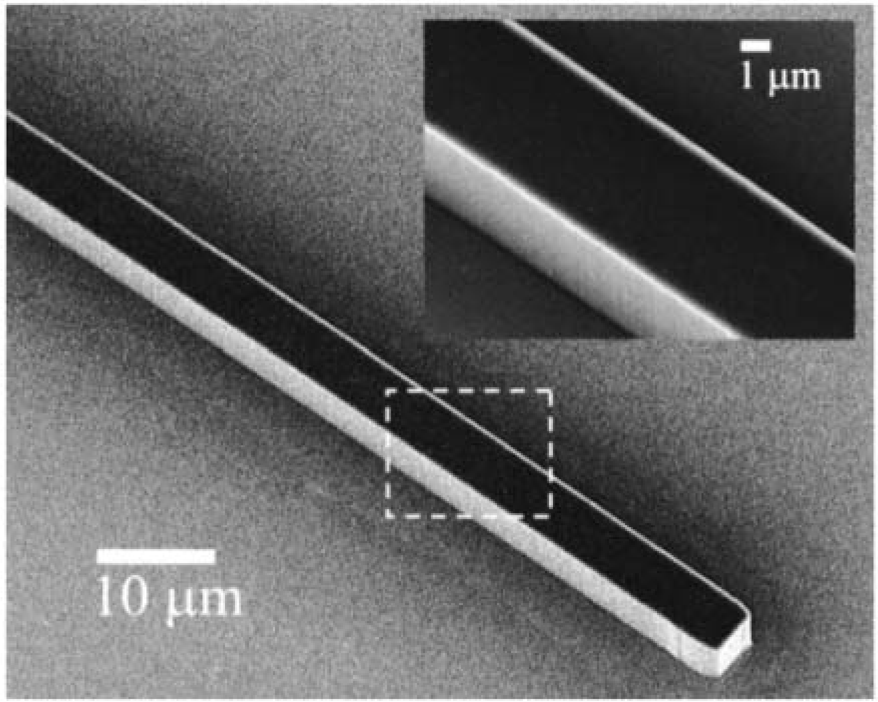
thermal bonding process



MeV Ion-beam lithography: resists

Low-loss optical waveguides in polymer

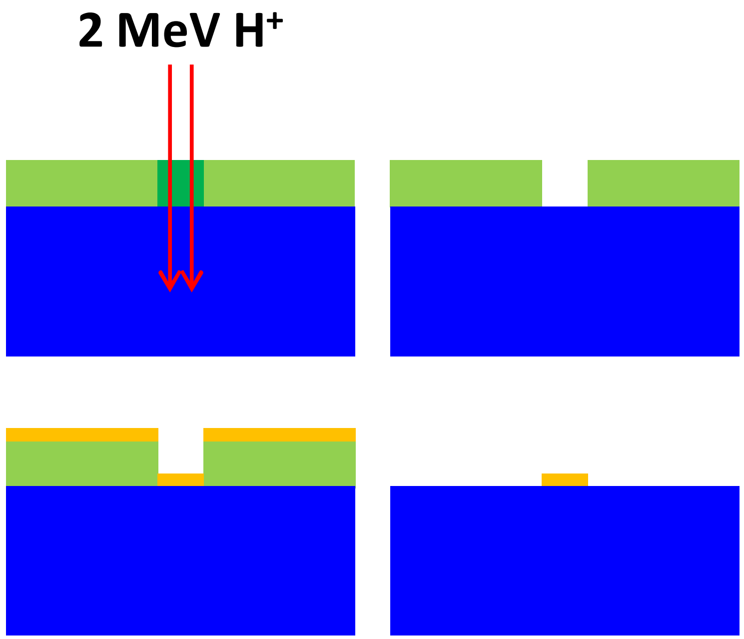


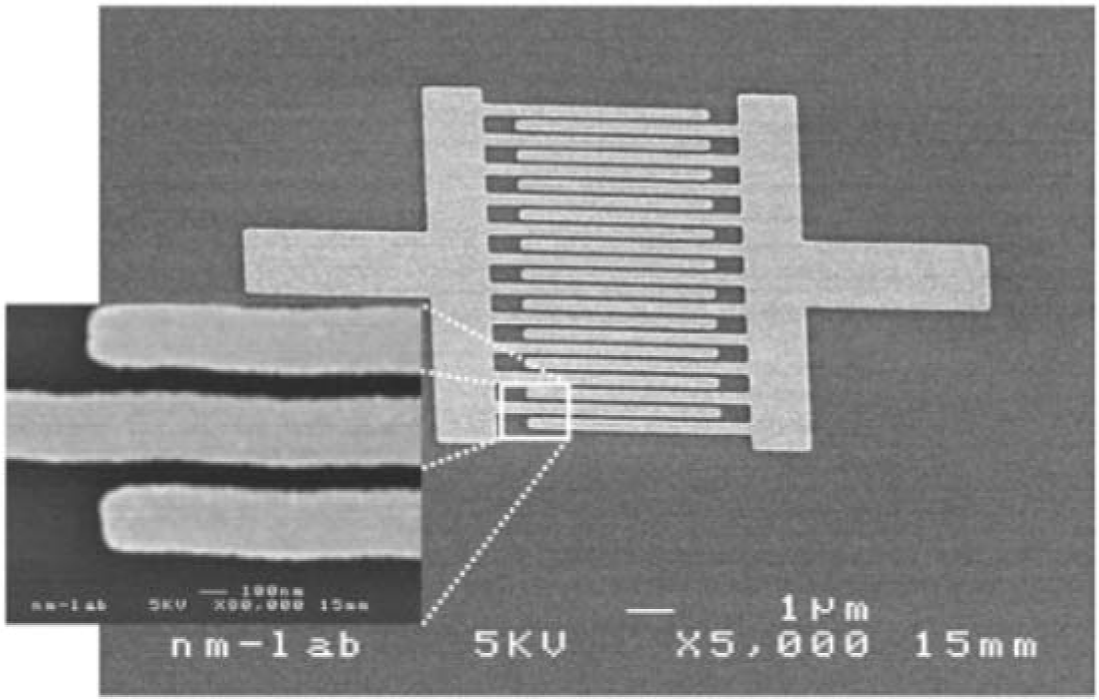


key fabrication issue: lateral smoothness

MeV Ion-beam lithography: resists

Metallic nano-electodes with lift-off method

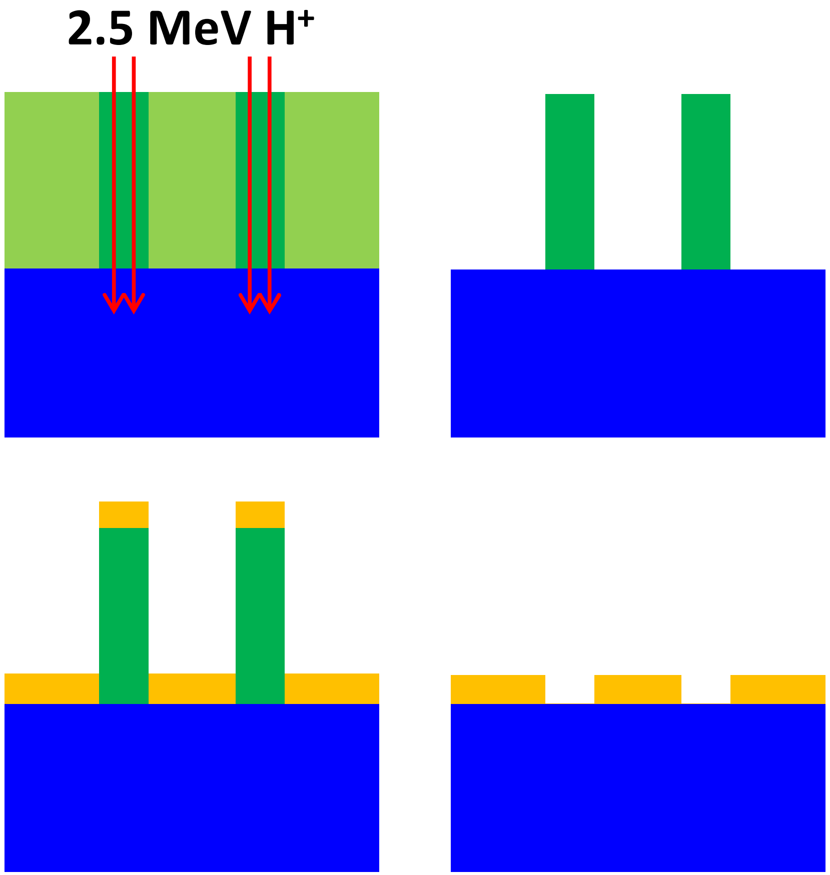


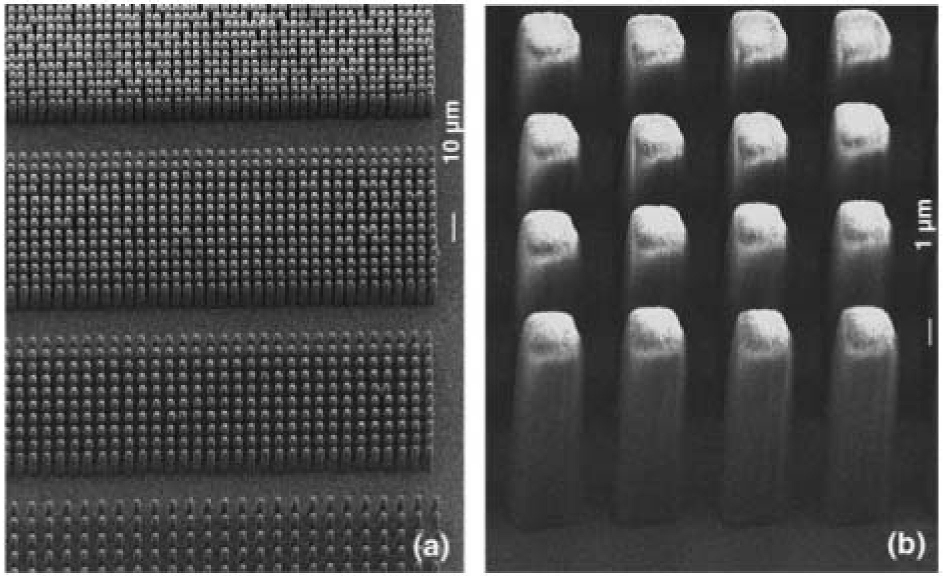


- SiO_2
- impressed PMMA
- PMMA
- Ti/Au

MeV Ion-beam lithography: resists

Metallic micro-grids



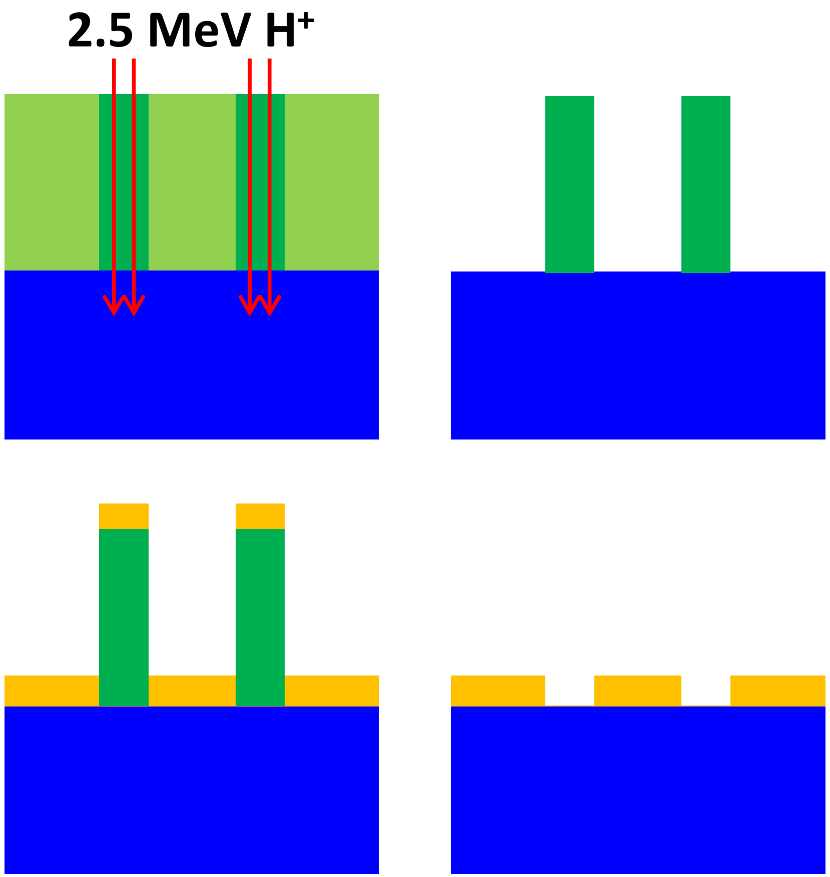


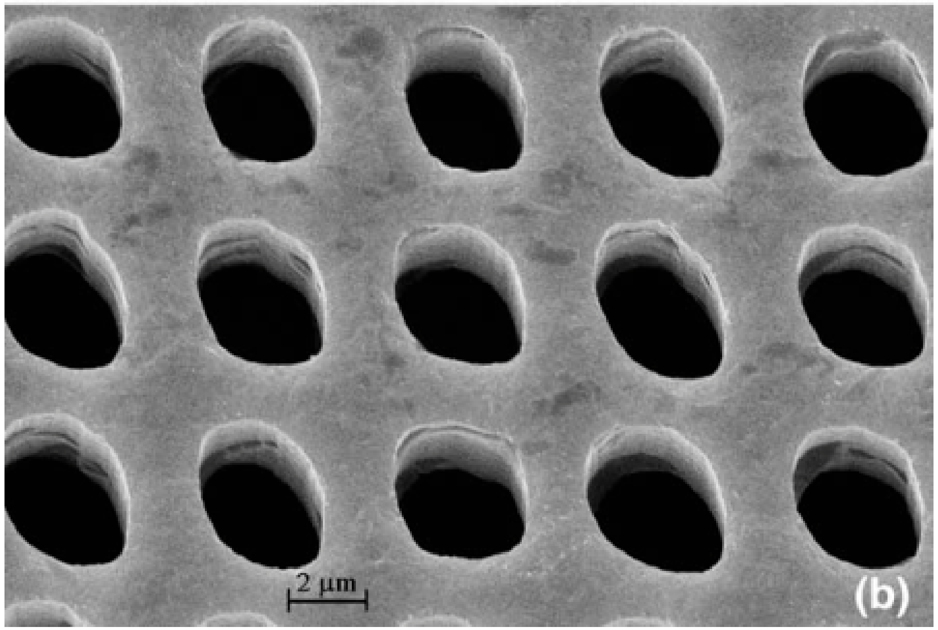
SU-8 pillars

@ : Lund Institute of Technology, Sandia National Laboratory

MeV Ion-beam lithography: resists

Metallic micro-grids



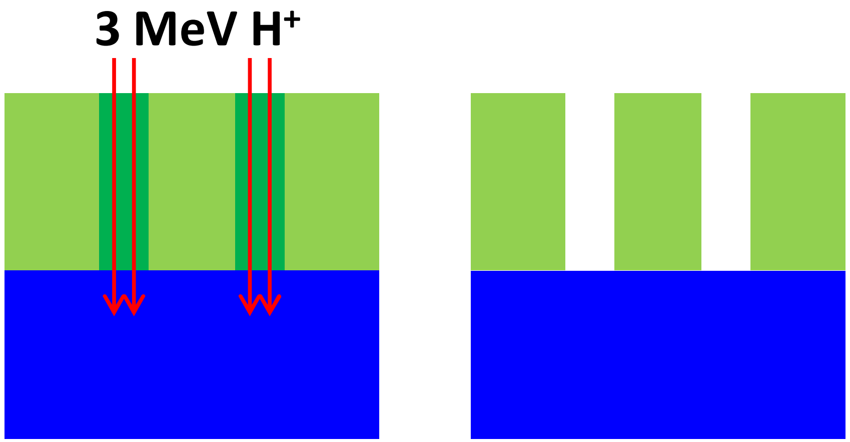


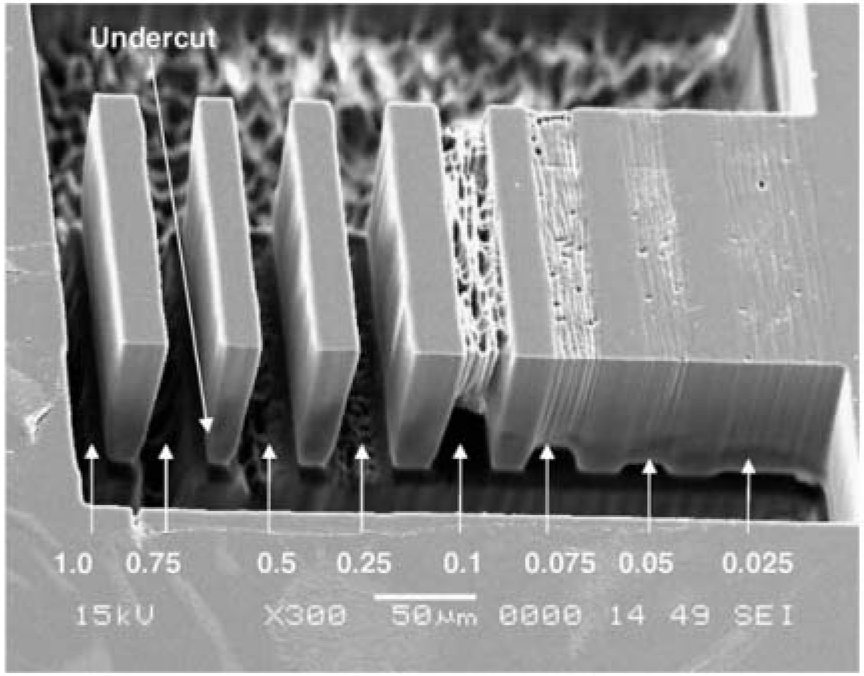
Au grid

@ : Lund Institute of Technology, Sandia National Laboratory

MeV Ion-beam lithography: resists

High-aspect-ratio microfluidic channels

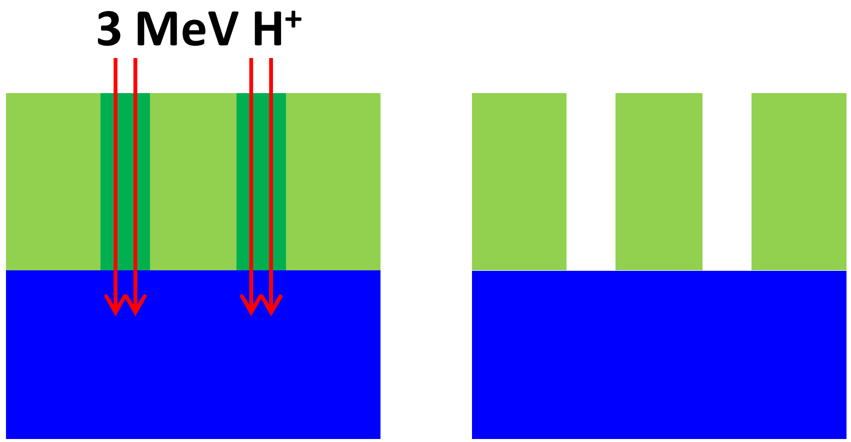


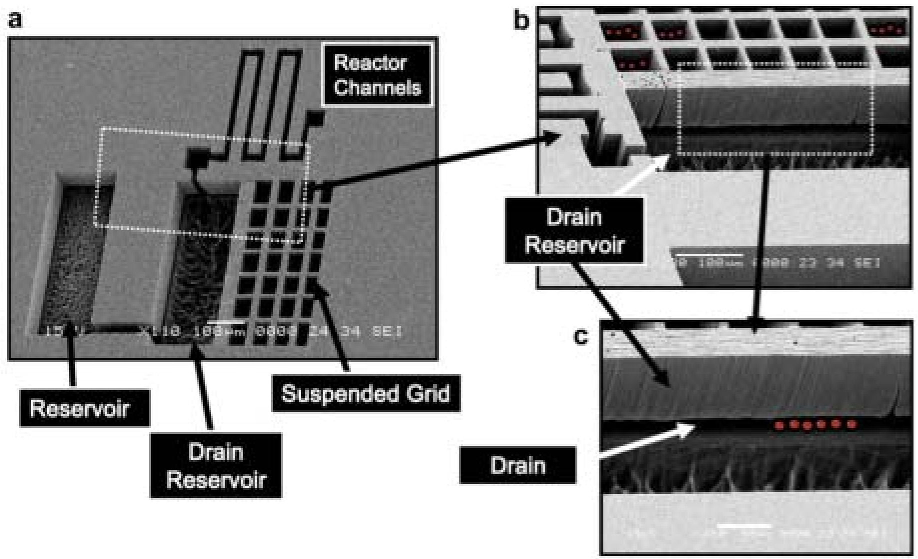


fluence study

MeV Ion-beam lithography: resists

High-aspect-ratio microfluidic channels

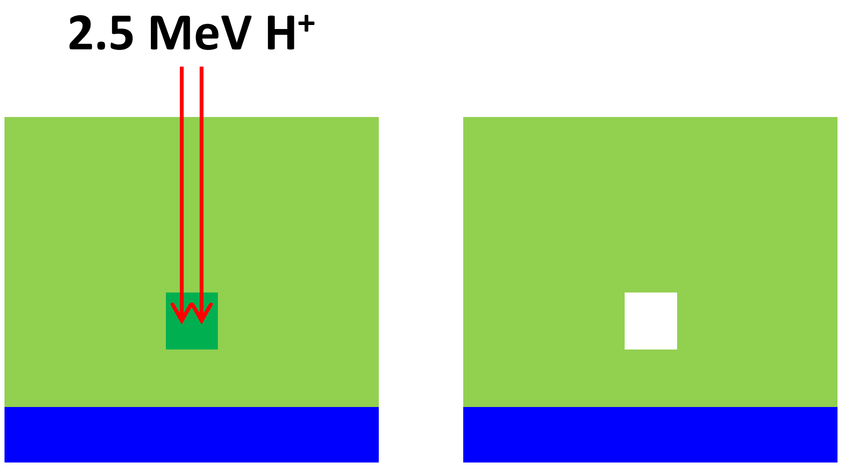


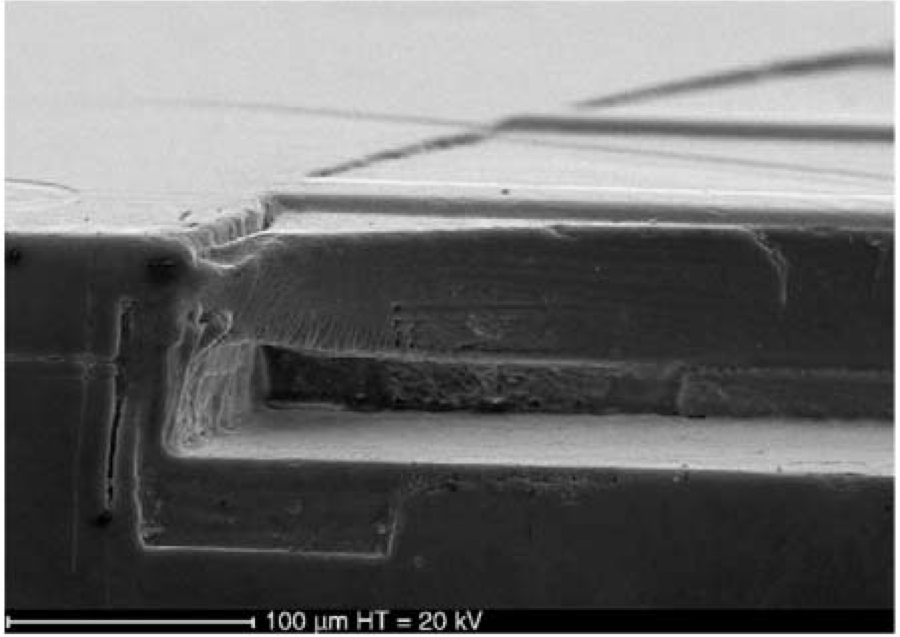


final structures

MeV Ion-beam lithography: resists

Buried microfluidic channels





Outline

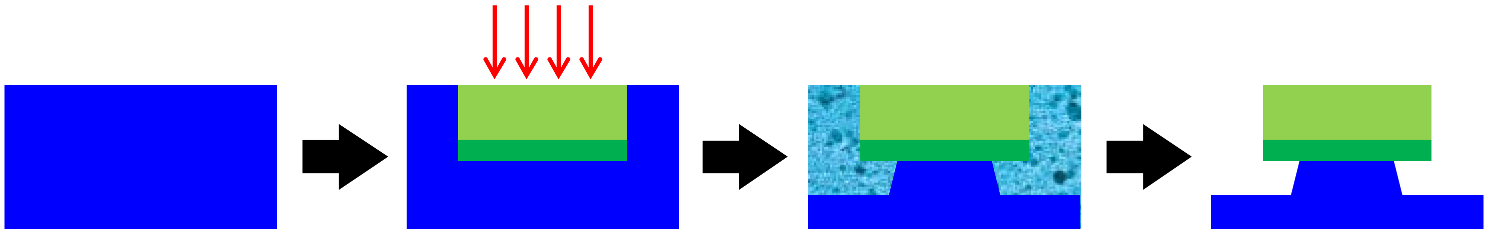
Introduction

- Ion-matter interaction
  - → MeV ions
  - → keV ions
- Ion-beam lithography
  - → conventional techniques
  - → MeV ions
  - → keV ions

Case studies

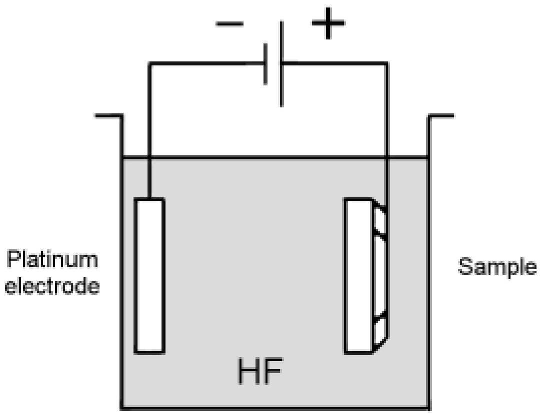
- **MeV ion beam lithography**
  - → resists
  - **→ silicon**
  - → other materials
  - → single ion tracks
- keV ion beam lithography
  - → FIB milling
  - → FIB-assisted deposition
  - → Helium-ion microscope

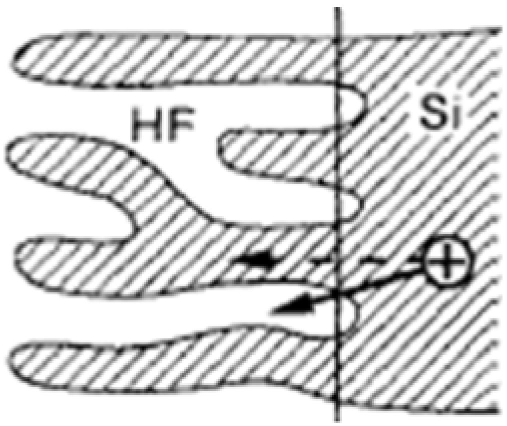
MeV Ion-beam lithography: Silicon

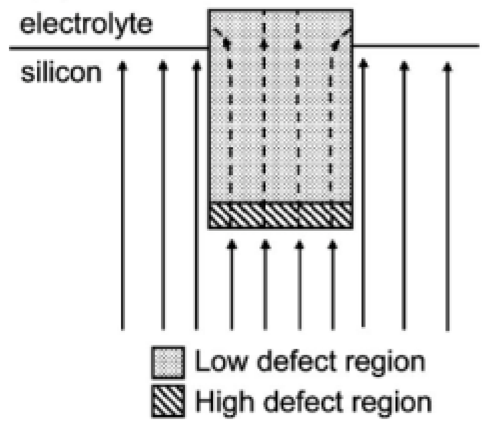


- Si sample
- MeV ion implantation
- electrochemical etching in HF
- wet chemical etching in KOH

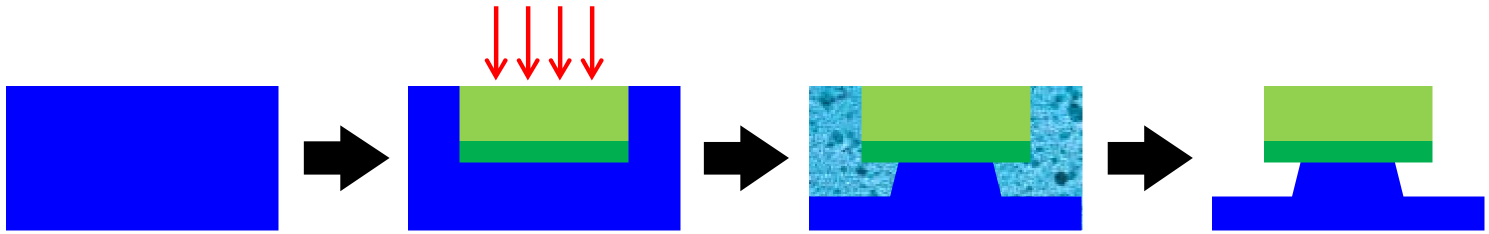
pristine Si | heavily damaged Si | lightly damaged Si | porous Si







MeV Ion-beam lithography: Silicon



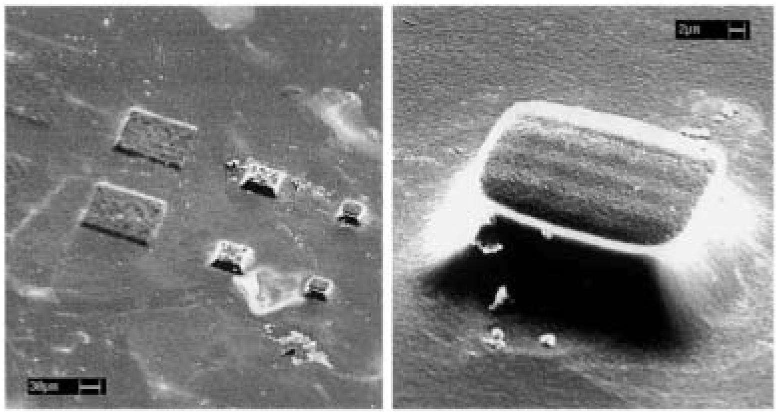
- Si sample
- MeV ion implantation
- electrochemical etching in HF
- wet chemical etching in KOH

pristine Si

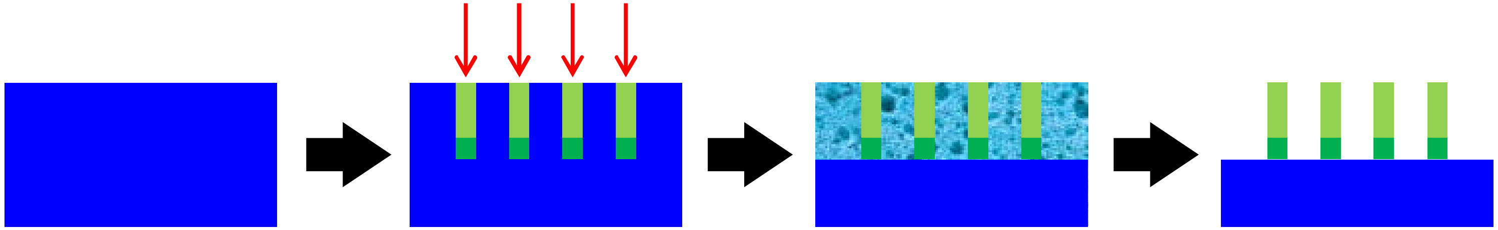
heavily damaged Si

lightly damaged Si

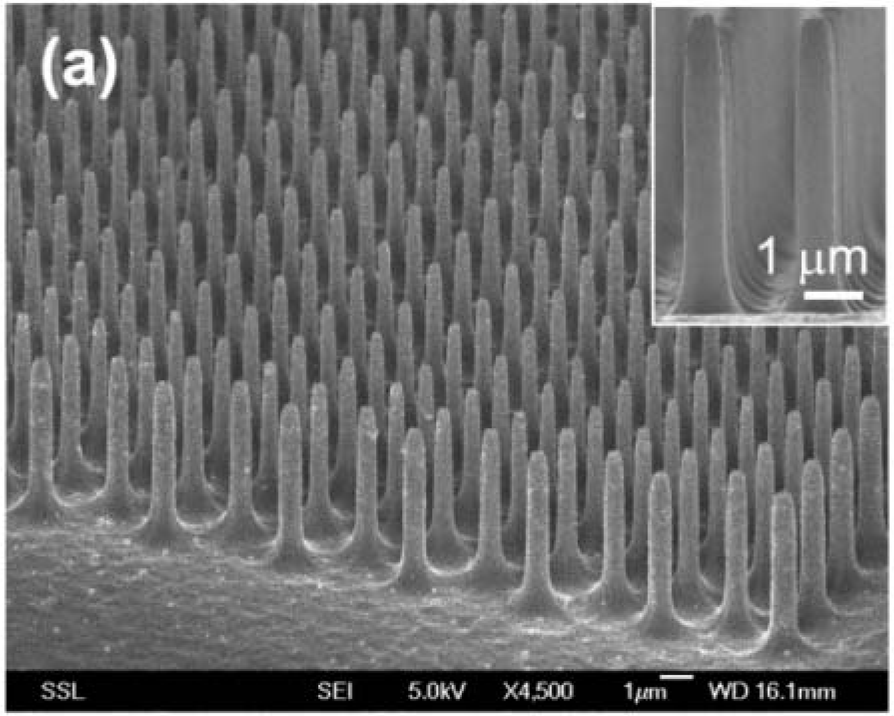
porous Si



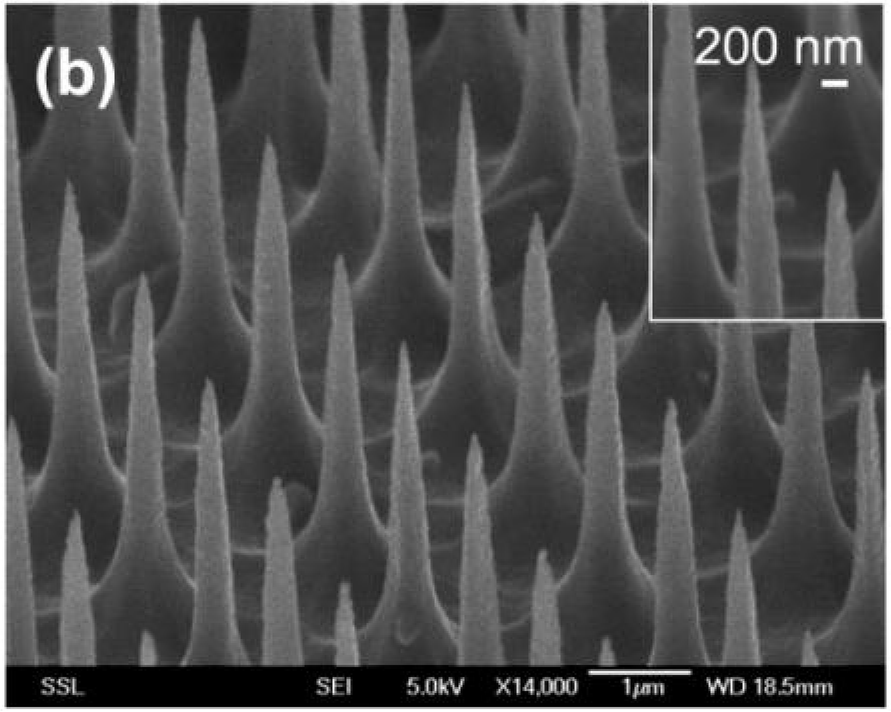
MeV Ion-beam lithography: Silicon



Micro-rod arrays

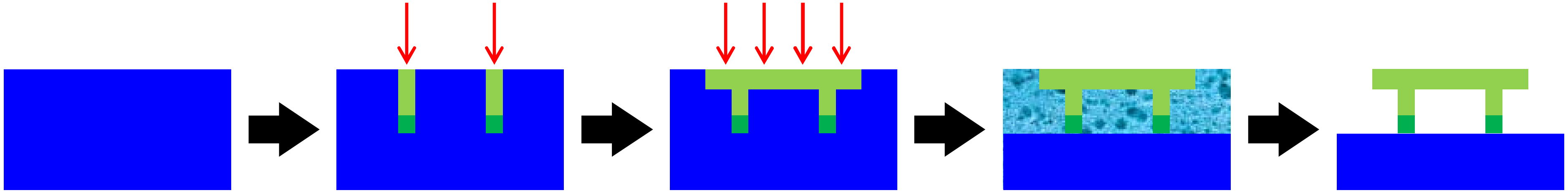


non-channeling implantation

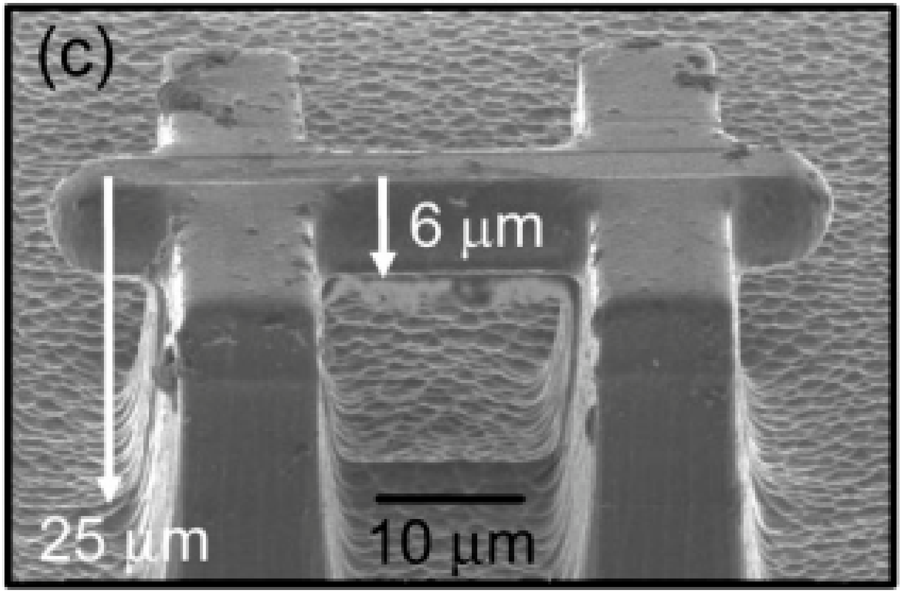


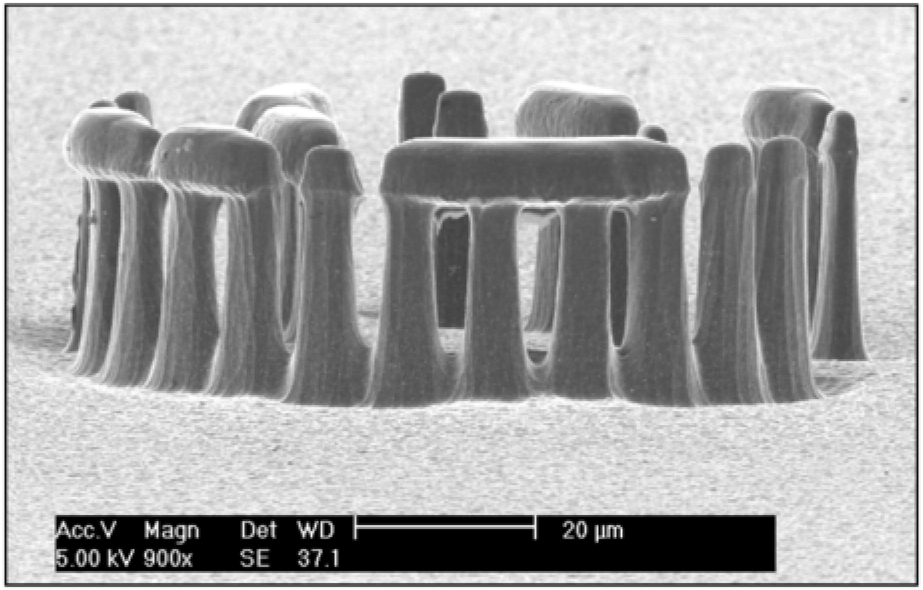
channeling implantation

MeV Ion-beam lithography: Silicon

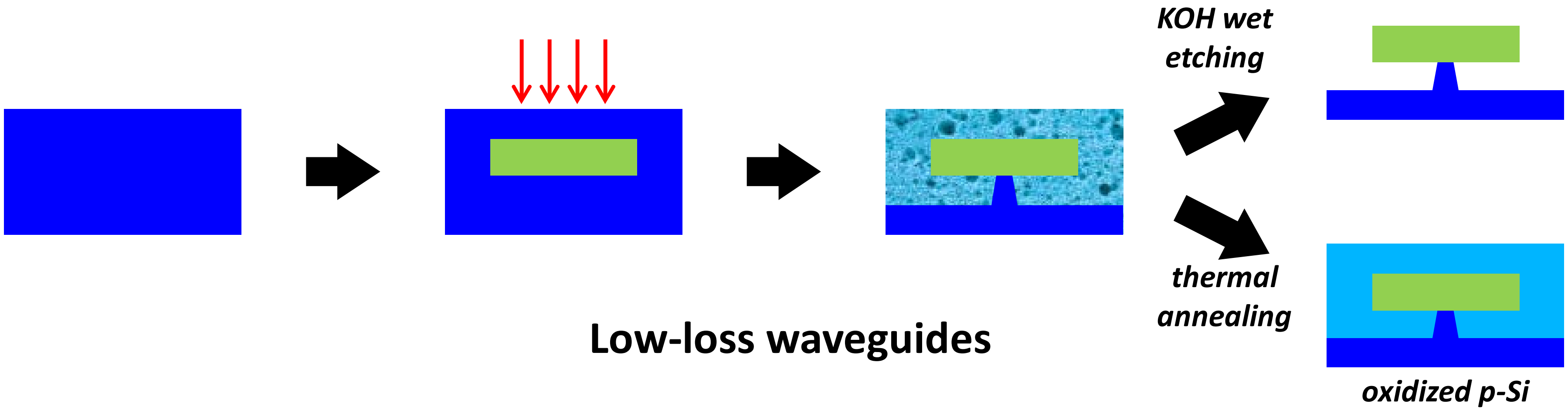


Three-dimensional structures

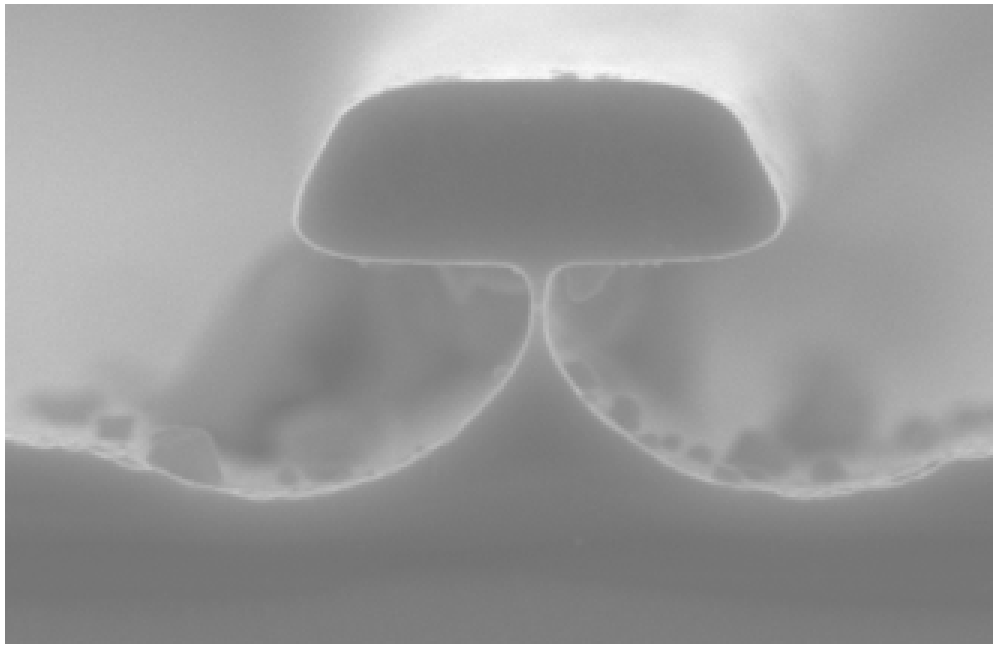


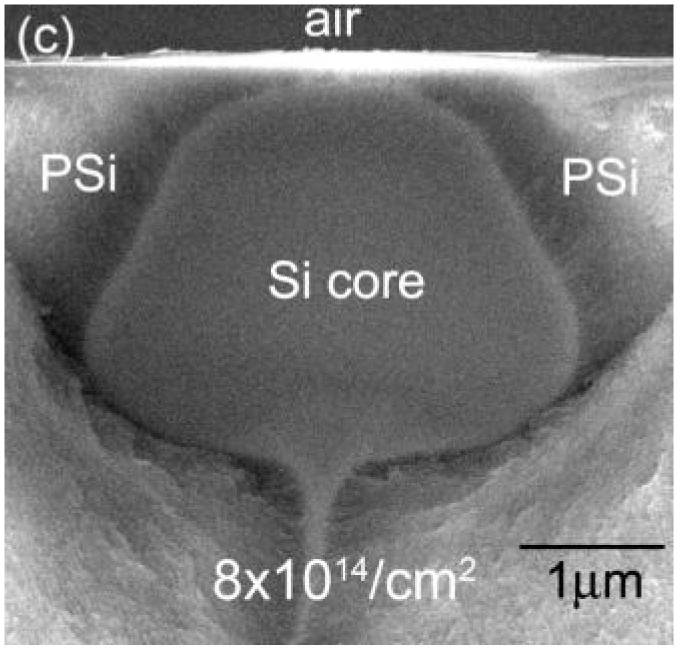


MeV Ion-beam lithography: Silicon

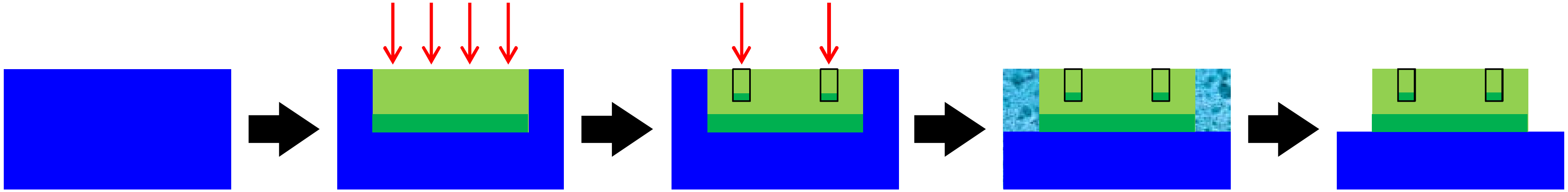


Low-loss waveguides

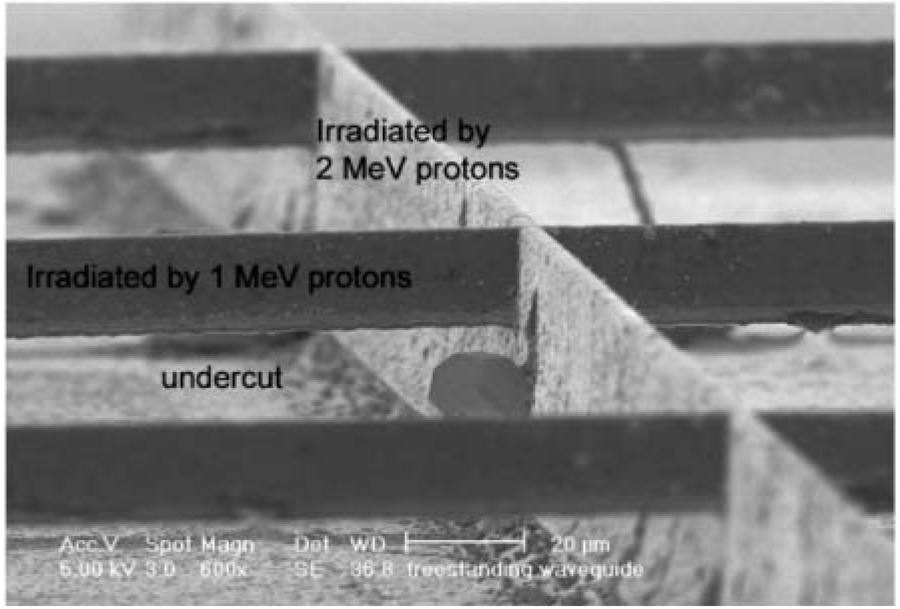


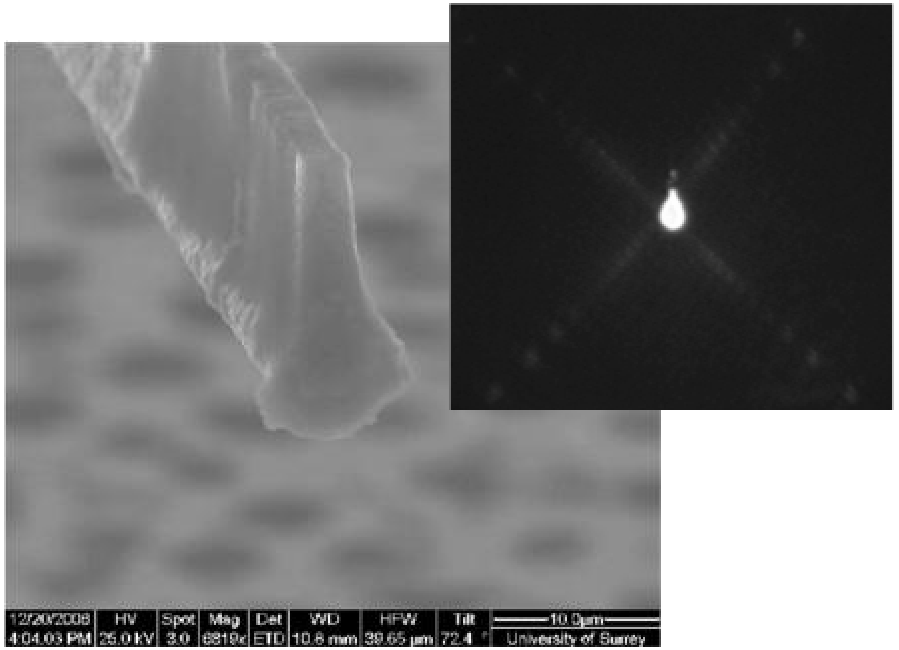


MeV Ion-beam lithography: Silicon

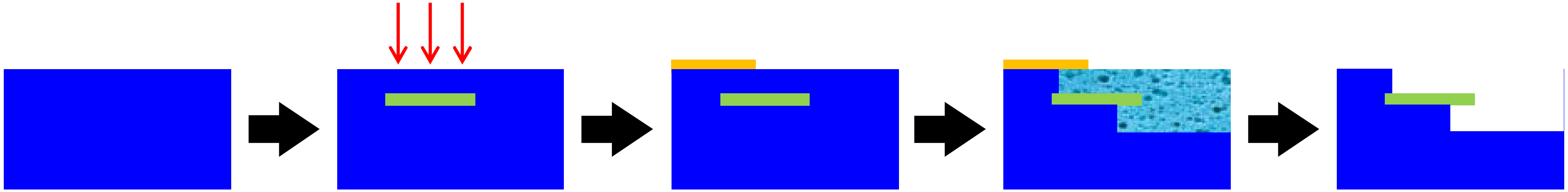


Free-standing waveguides

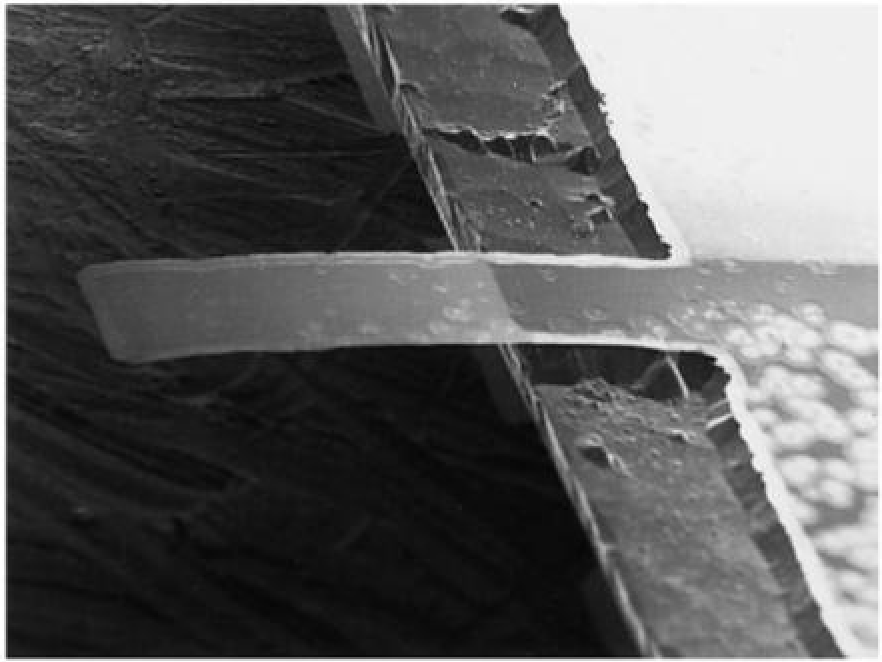




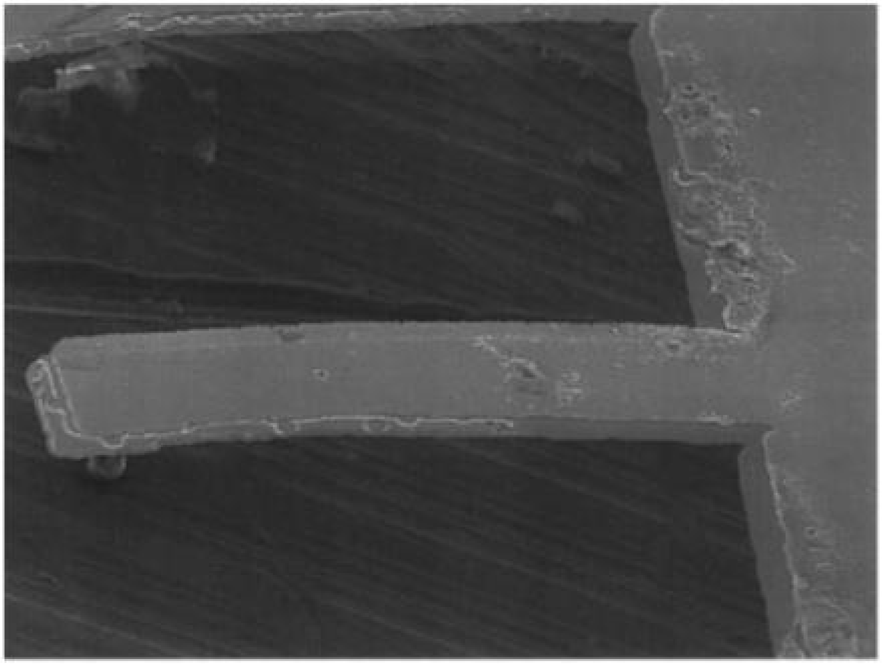
MeV Ion-beam lithography: Silicon



Cantilever MEMS structures



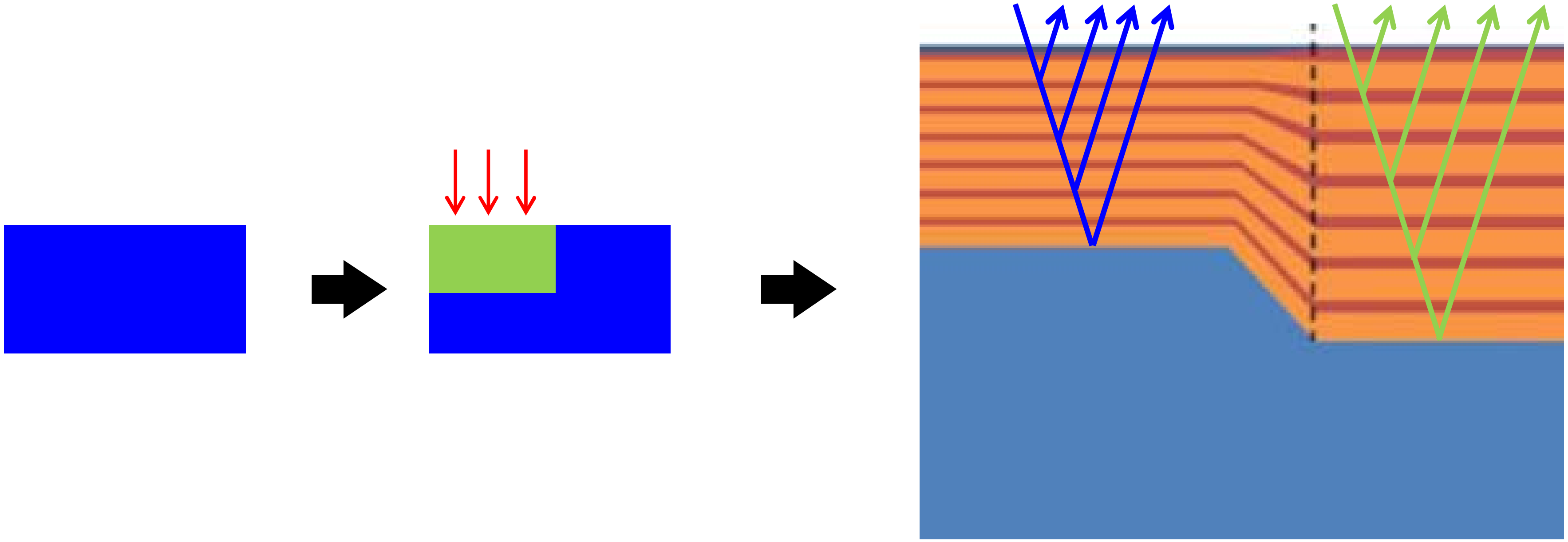
single layer (2.1 MeV Au)



double layer (2.1 MeV Au, 1.5 MeV C)

MeV Ion-beam lithography: Silicon

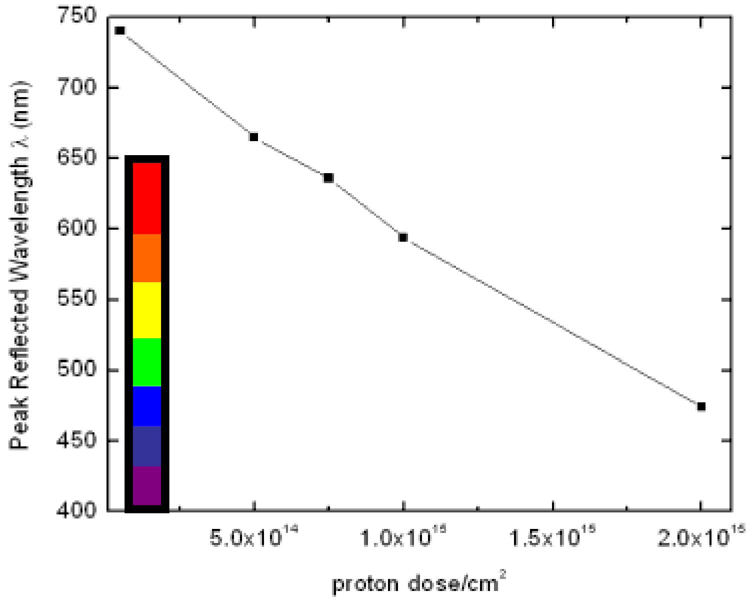
Bragg reflector

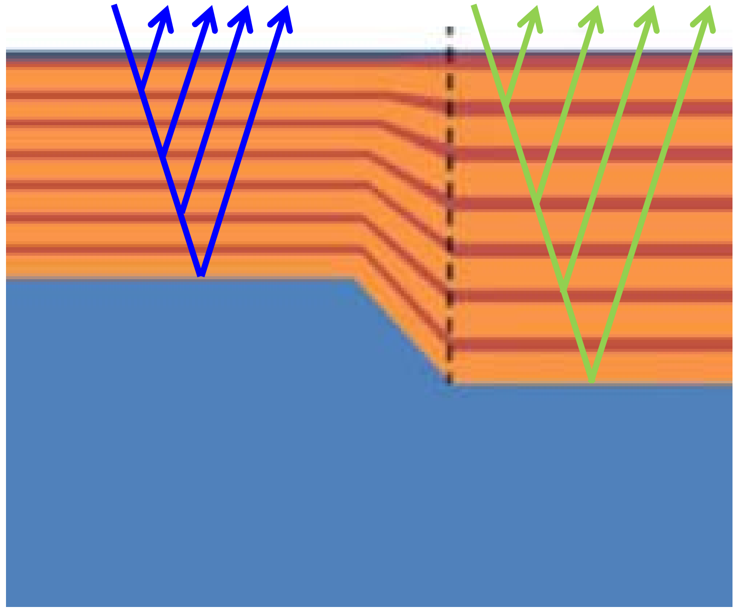


- electrochemical etching in HF at different currents → different porosity → different refractive index (1.2 – 3)
- electrochemical etching in HF at alternating currents → alternating layers of different refractive index
- Bragg law: $n \cdot \lambda = 2 \cdot d \cdot \sin(\theta)$

MeV Ion-beam lithography: Silicon

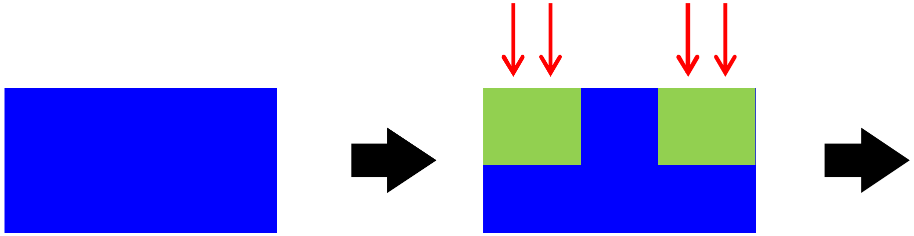
Bragg reflector

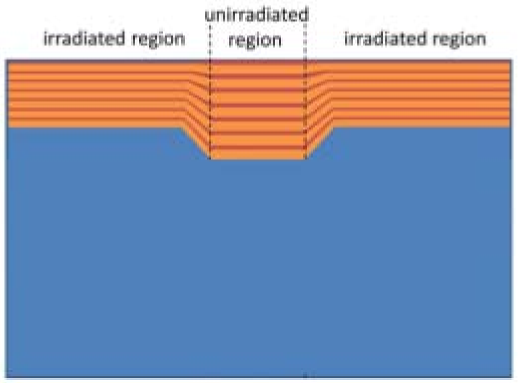




- electrochemical etching in HF at different currents → different porosity → different refractive index (1.2 – 3)
- electrochemical etching in HF at alternating currents → alternating layers of different refractive index
- Bragg law: $n \cdot \lambda = 2 \cdot d \cdot \sin(\theta)$
- different fluence → different refractive index modulation

MeV Ion-beam lithography: Silicon

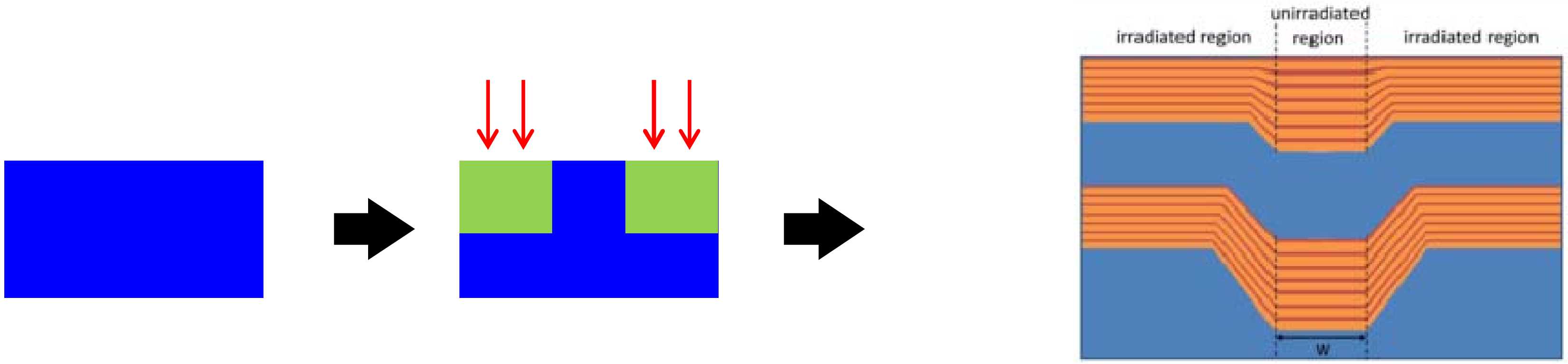




- electrochemical etching in HF at variable current
- modulation of the refractive index (1.2 – 3)

Bragg-cladding bulk waveguide

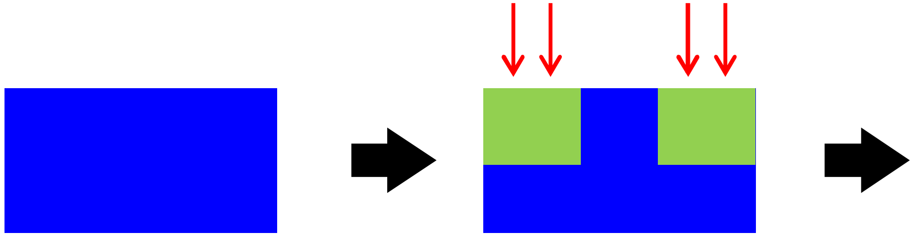
MeV Ion-beam lithography: Silicon

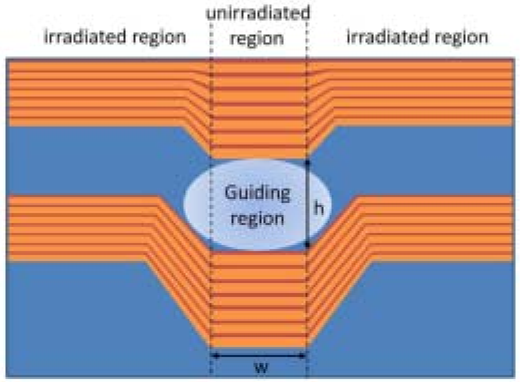


• electrochemical etching in HF at variable current
• modulation of the refractive index (1.2 – 3)

Bragg-cladding bulk waveguide

MeV Ion-beam lithography: Silicon





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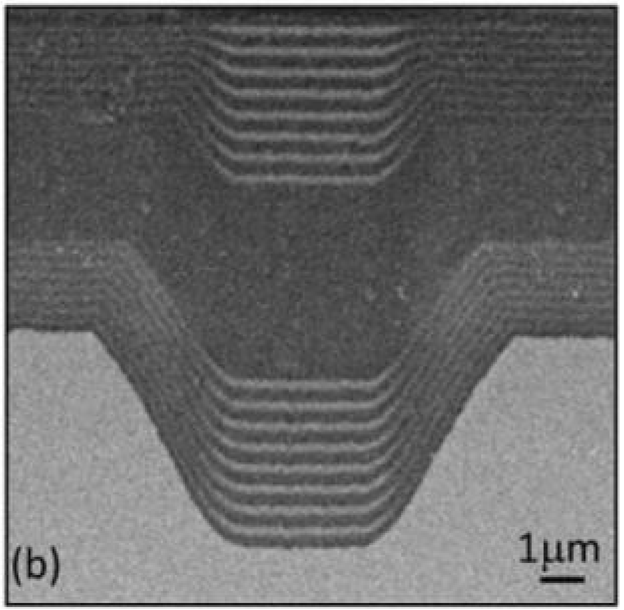
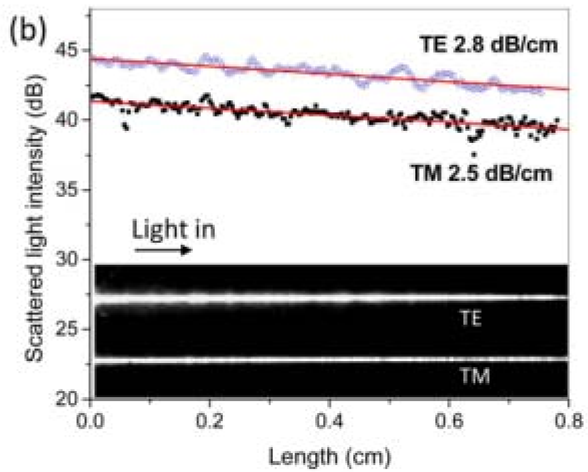
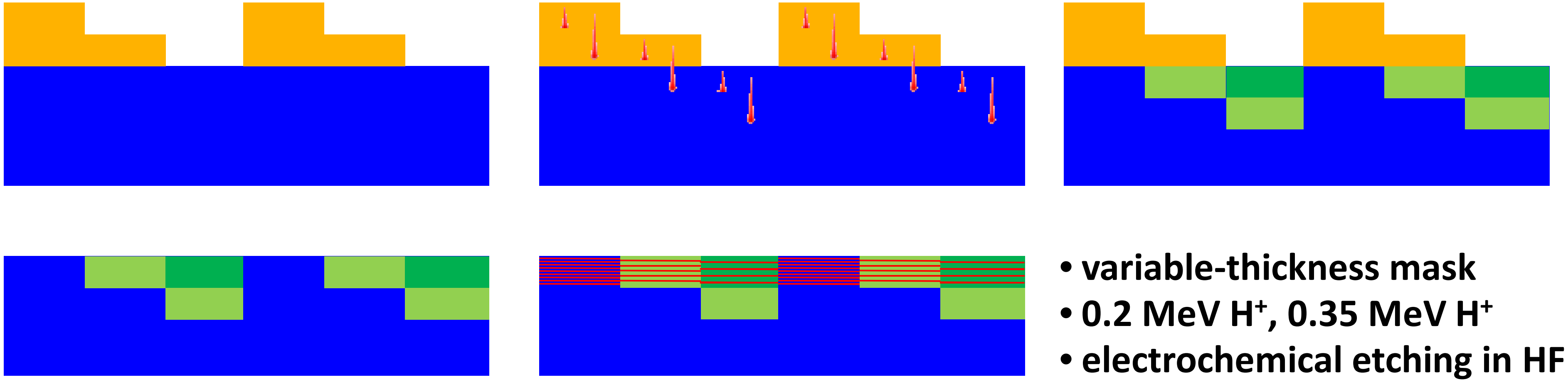
Bragg-cladding bulk waveguide



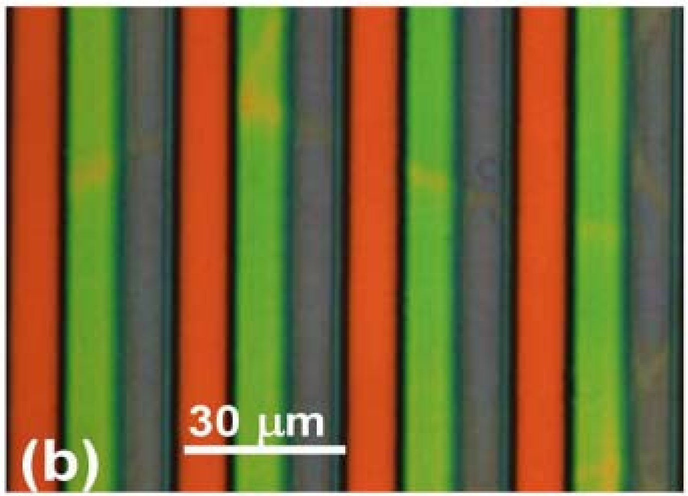


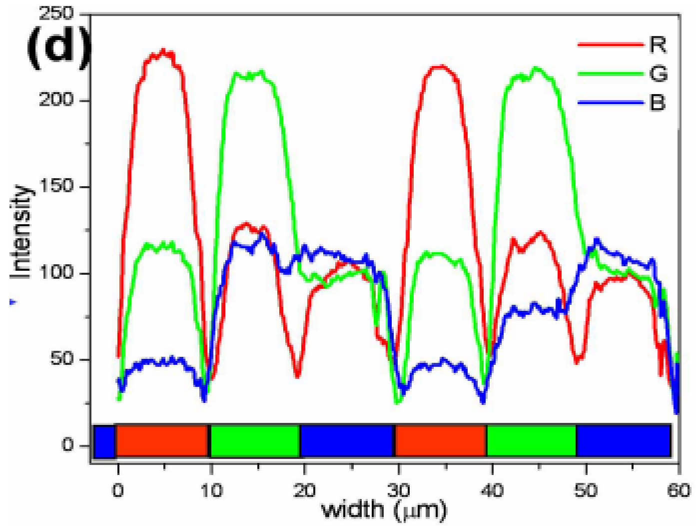
MeV Ion-beam lithography: Silicon



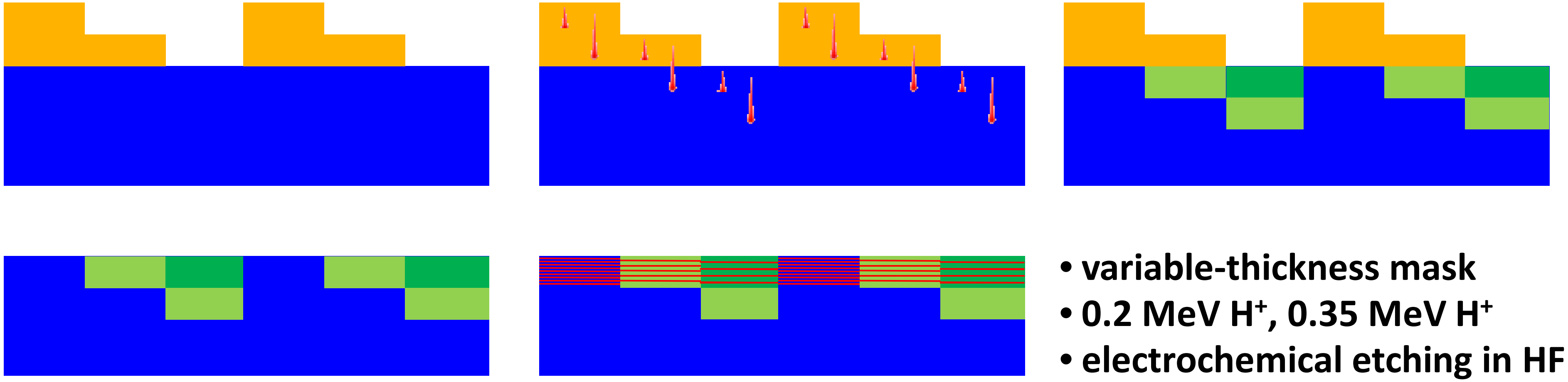
- variable-thickness mask
- 0.2 MeV H^+, 0.35 MeV H^+
- electrochemical etching in HF

Local modification of the refractive index → Distributed Bragg reflector



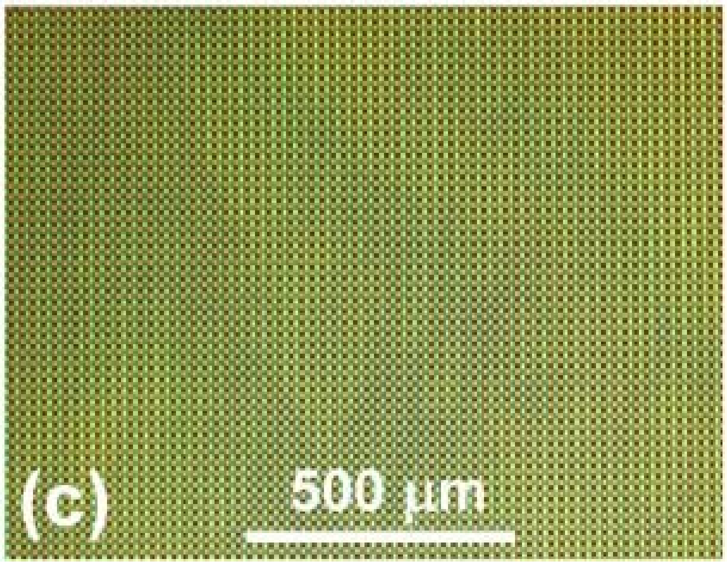


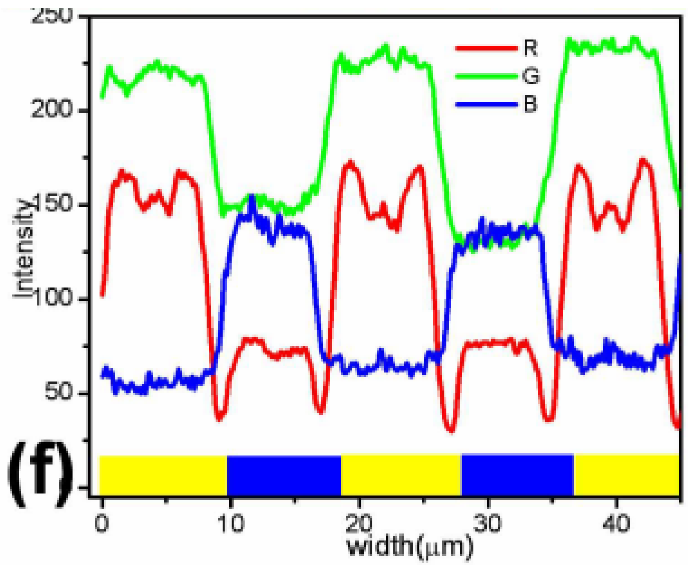
MeV Ion-beam lithography: Silicon



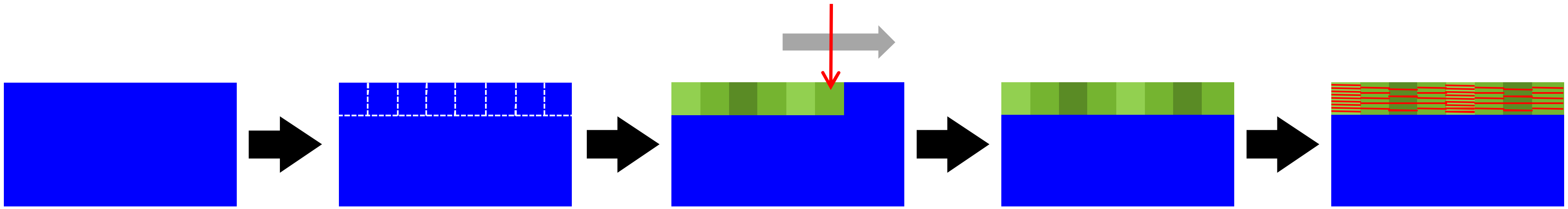
- variable-thickness mask
- 0.2 MeV H^+, 0.35 MeV H^+
- electrochemical etching in HF

Four implantation energies, 2-D mask geometry → Pixel array





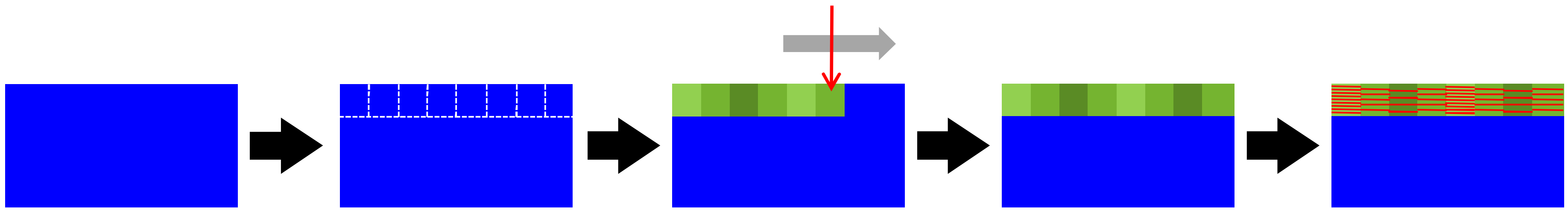
MeV Ion-beam lithography: Silicon



Refractive index modulation with a scanning microprobe

“The Red Armchair”, Picasso (1931)

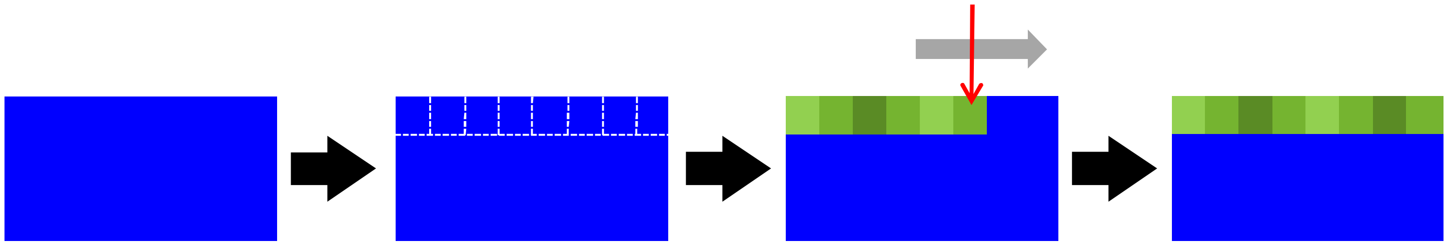
MeV Ion-beam lithography: Silicon



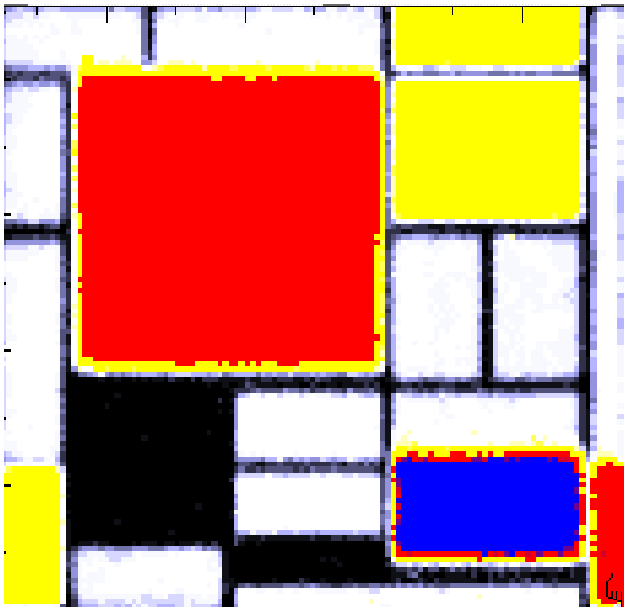
Refractive index modulation with a scanning microprobe

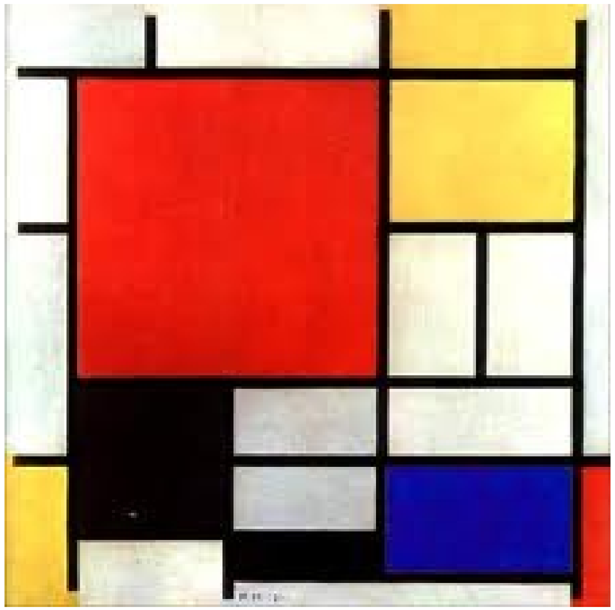
“The Dance”, Matisse (1910)

MeV Ion-beam lithography: Silicon



Charge Collection Efficiency modulation with a scanning microprobe





P. Mondrian

Outline

Introduction

- Ion-matter interaction
  - → MeV ions
  - → keV ions
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  - → conventional techniques
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  - → keV ions

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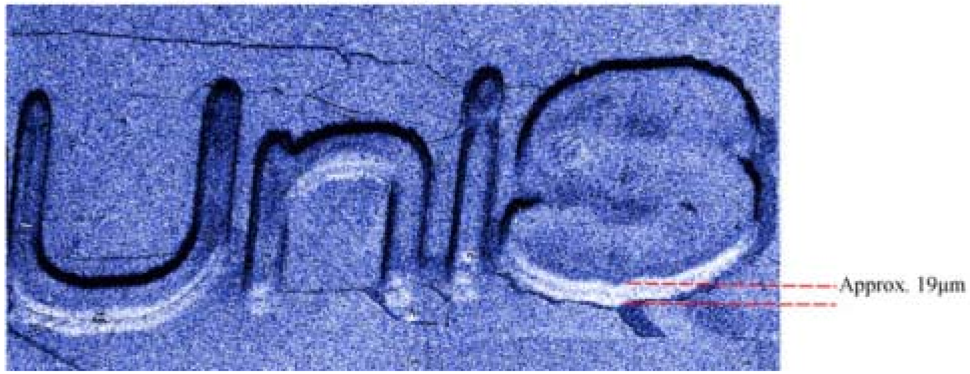
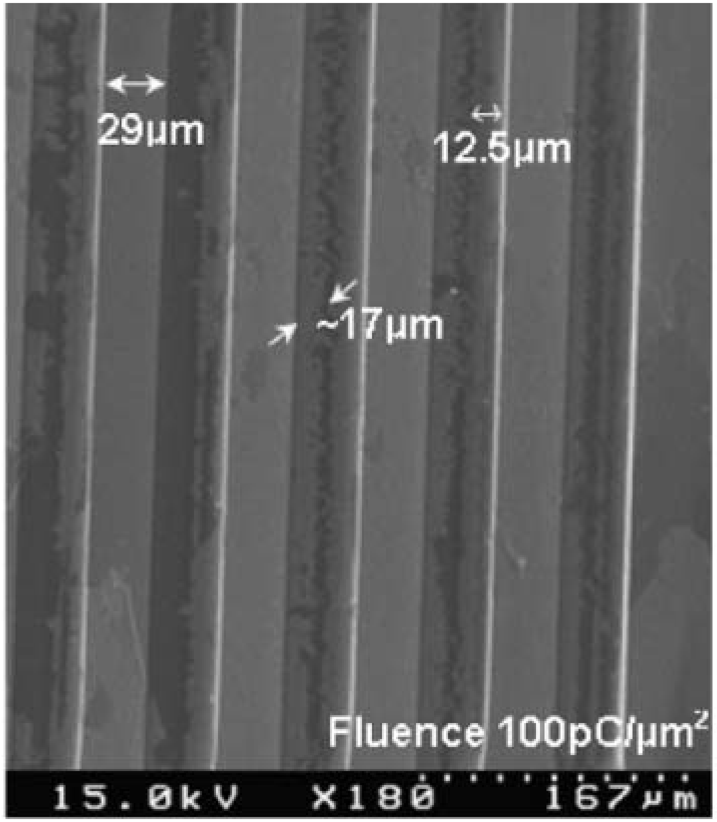
- **MeV ion beam lithography**
  - → resists
  - → silicon
  - **→ other materials**
  - → single ion tracks
- keV ion beam lithography
  - → FIB milling
  - → FIB-assisted deposition
  - → Helium-ion microscope

MeV IBL: Other materials

Gallium Arsenide

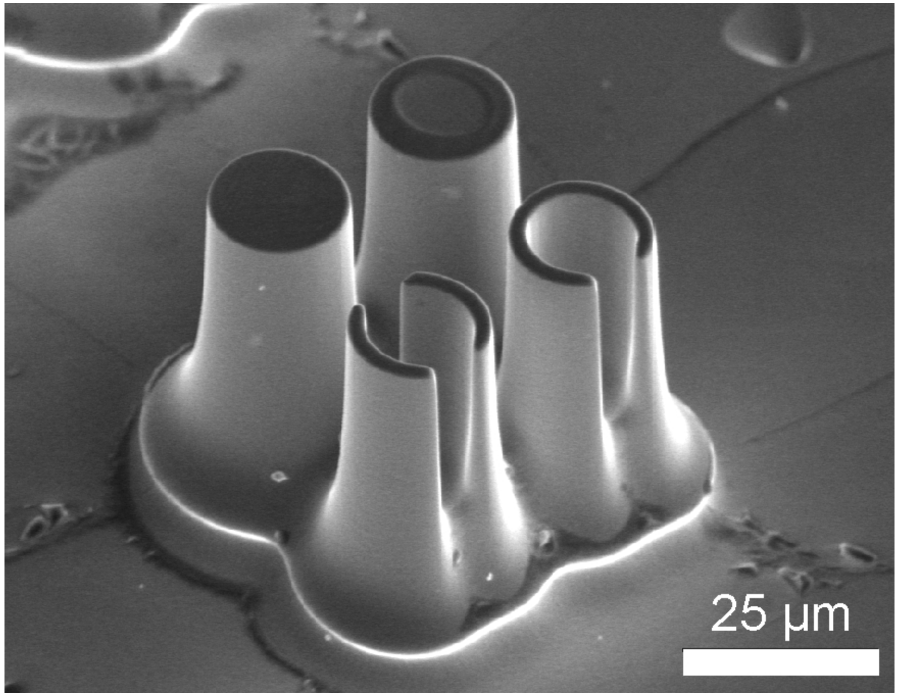


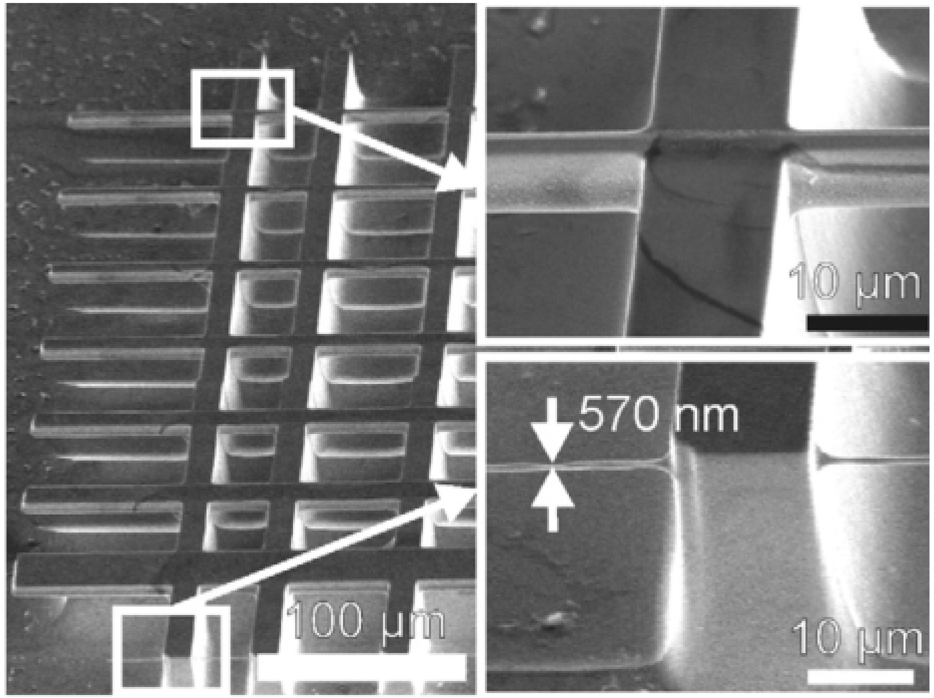


Negative process based on the modulation of the material sensitivity to reactive ion etching

MeV IBL: Other materials

Indium Phosphide

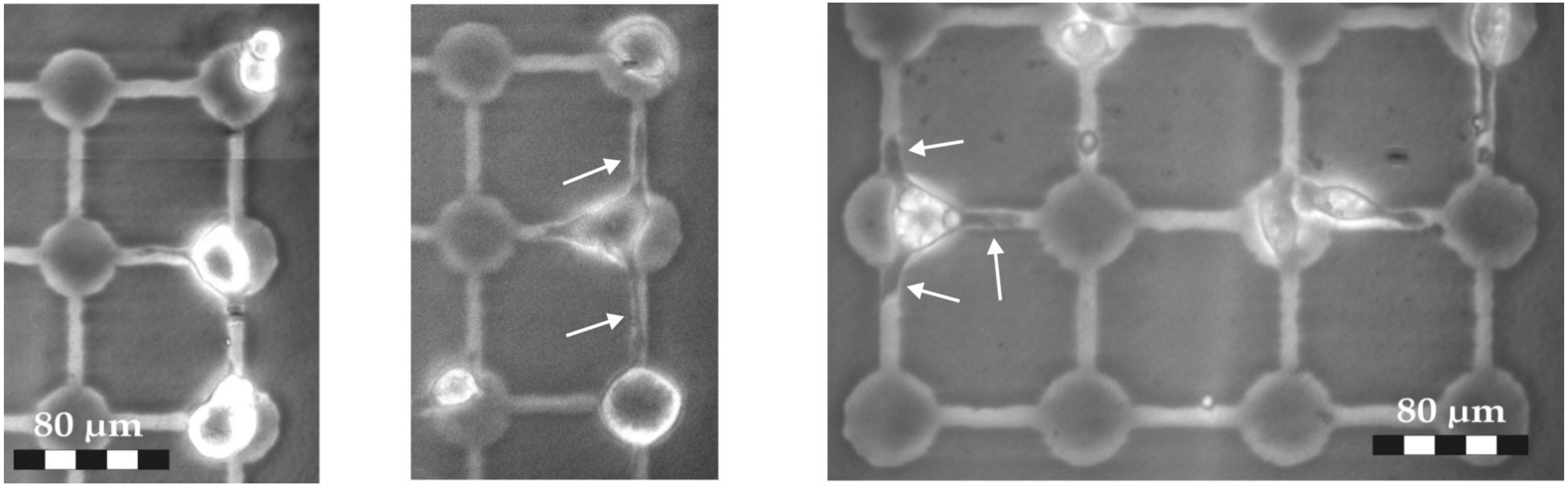




Negative process based on the modulation of the material sensitivity to electrochemical etching (→ Si)

MeV IBL: Other materials

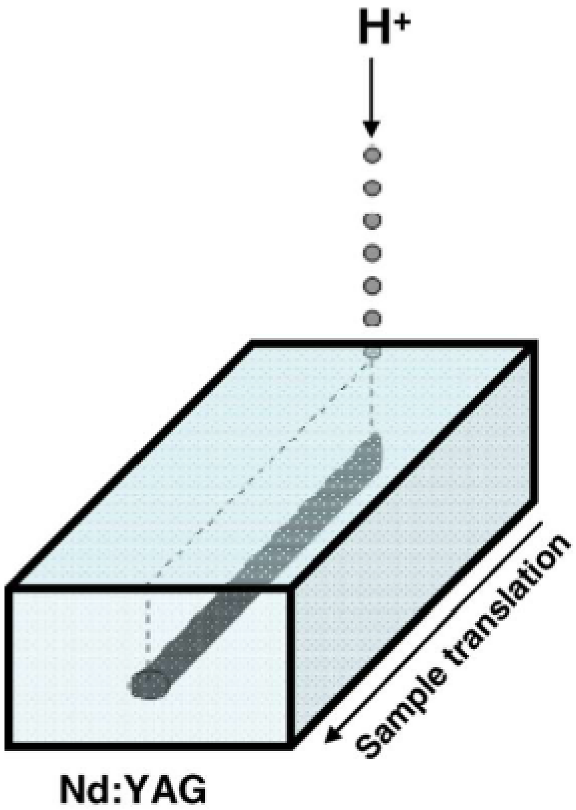
Agar gel

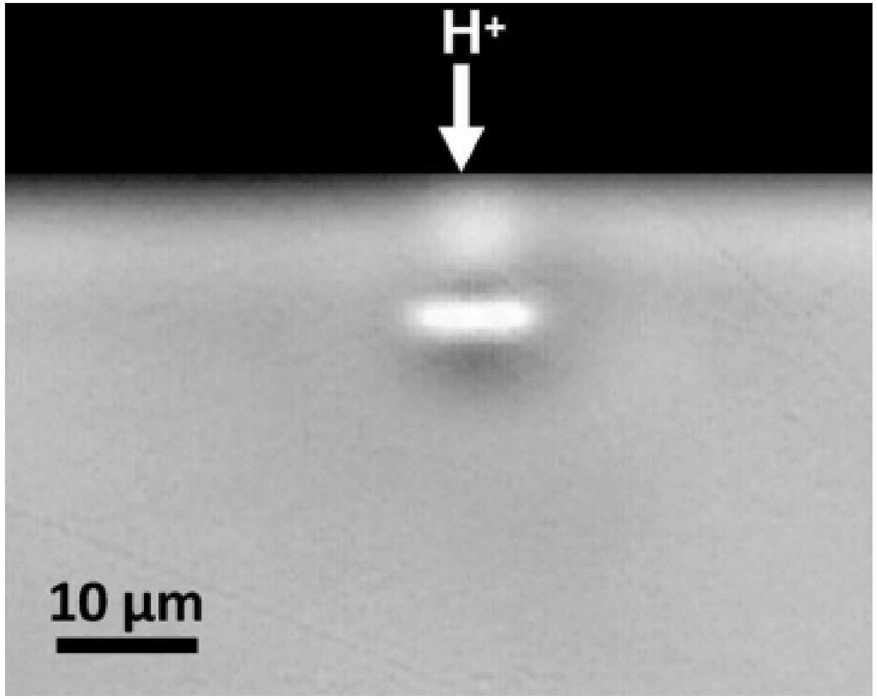


Positive process with 2.25 MeV H^+ ions
Agar-free regions: cell adhesion on underlying Petri dish

MeV IBL: Other materials

Nd:YAG

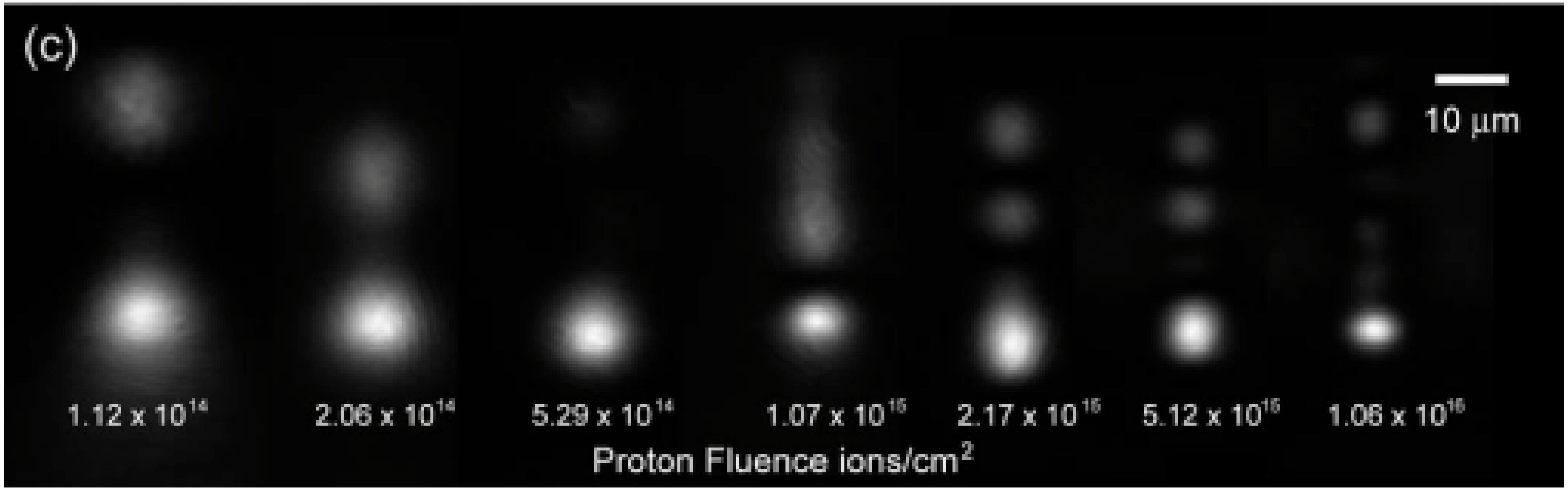




Modulation of the refractive index by H^+-induced damage

MeV IBL: Other materials

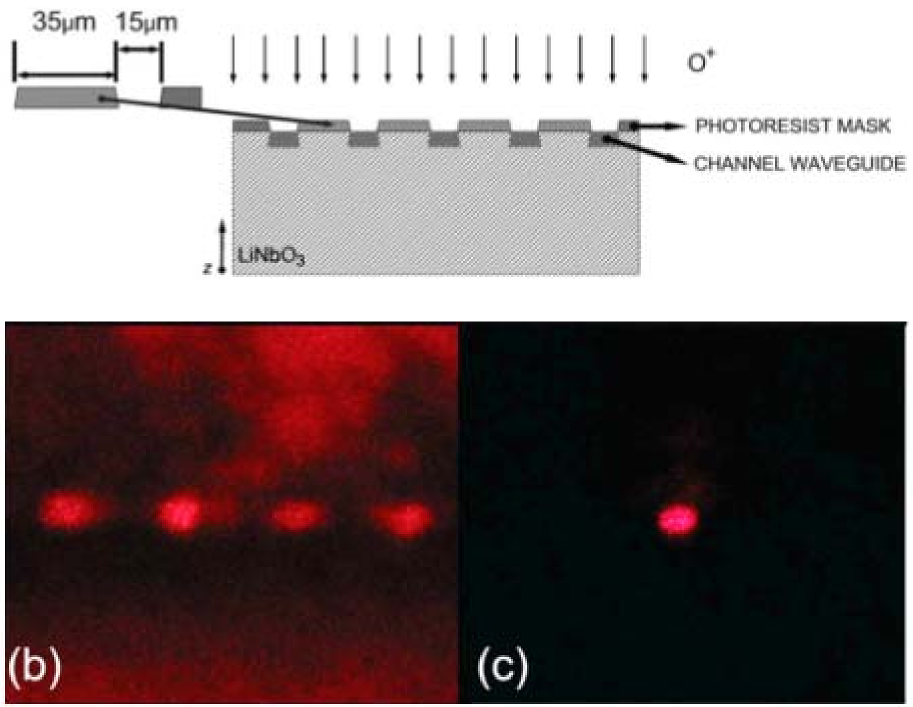
Photo-sensitive glass (Foturan^{TM})



Modulation of the refractive index by 2 MeV H^+-induced damage

MeV IBL: Other materials

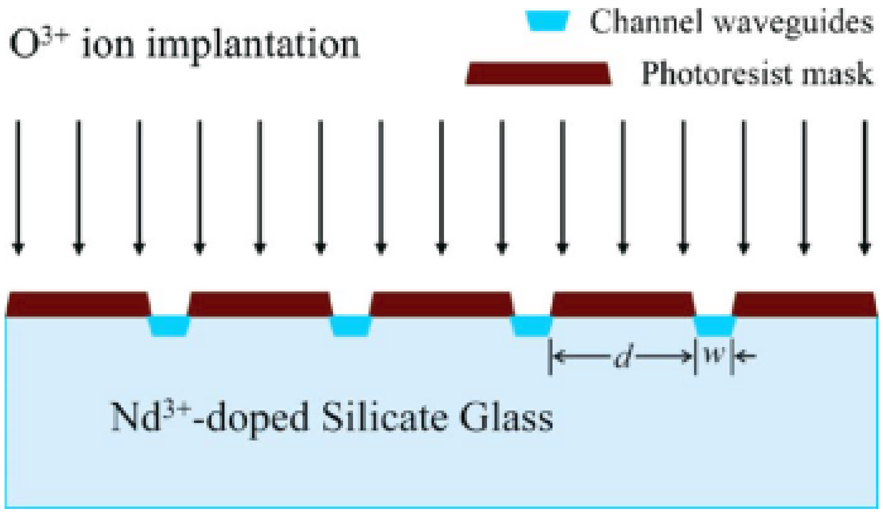
$LiNbO_3$ (*non-linear optics applications*)



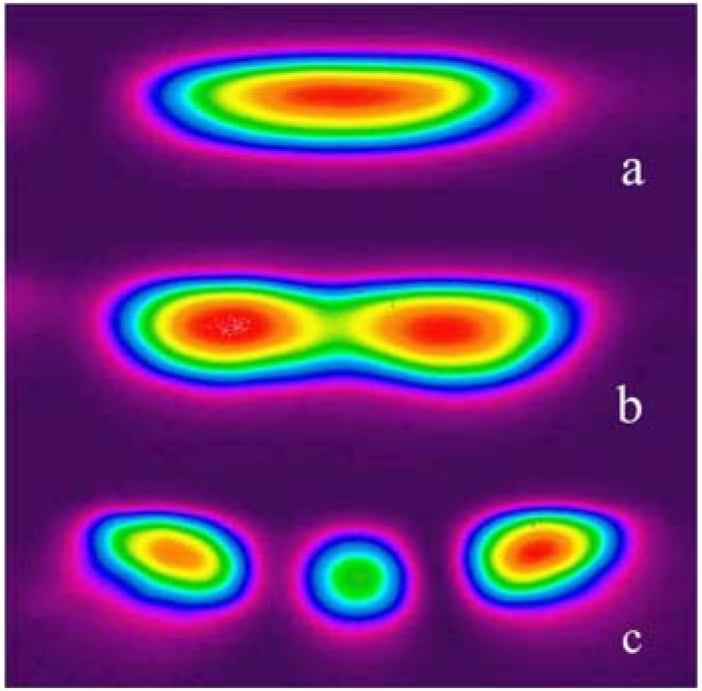
Modulation of the refractive index by 1.6-2.2 MeV O^{3+} induced damage

MeV IBL: Other materials

Nd3⁺-doped SiO_2



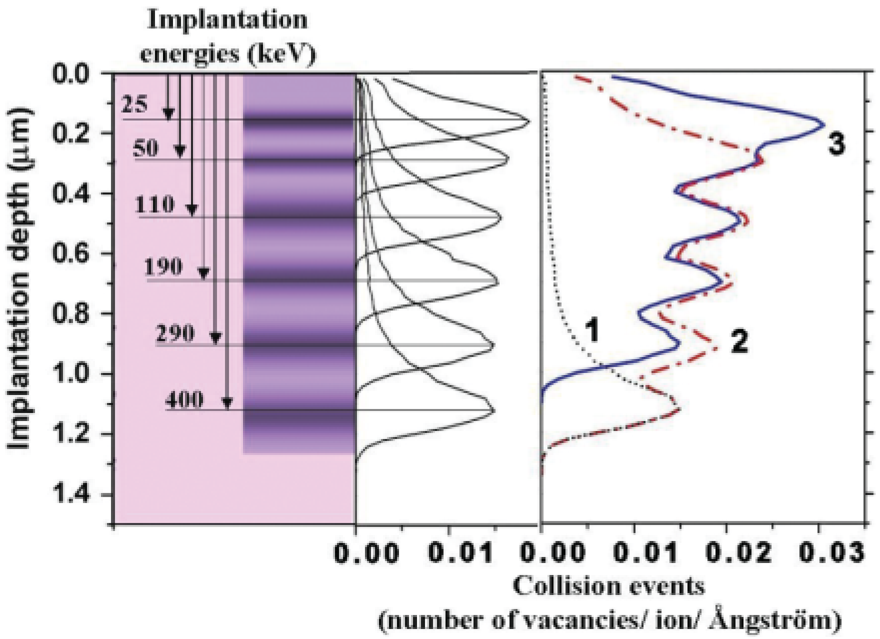
FEM simulation

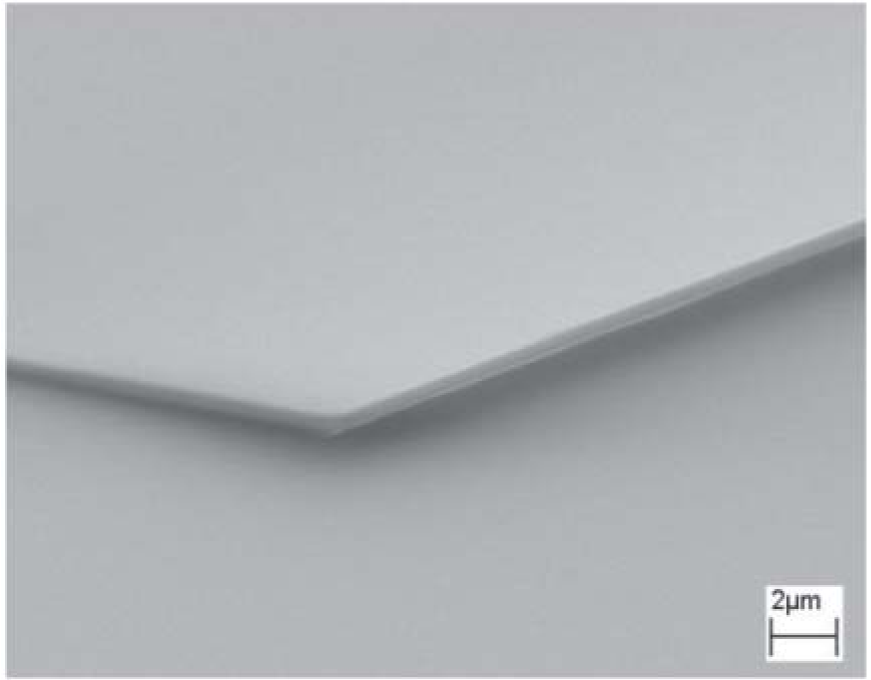


Modulation of the refractive index by 6 MeV O^{3+} induced damage

MeV IBL: Other materials

Sapphire





Lift-off in sapphire based on He$^+$ ion implantation

Positive process based on change in reactivity to wet chemical etching

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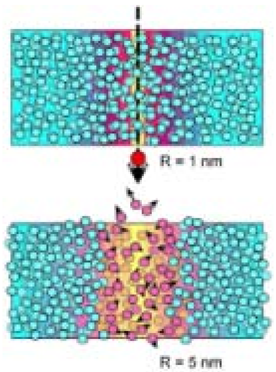
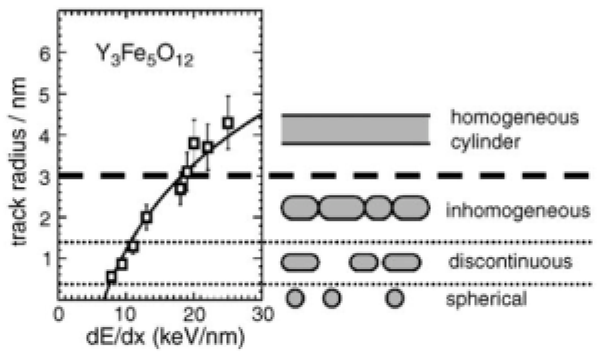
  - → Helium-ion microscope

MeV IBL: Single ion tracks

- Tool: single Swift Heavy Ions (SHI)
- Instantaneous & localized release of energy in the material { thermal spike / coulomb explosion }
- Spike: ∅ ~ 10 nm, L ~ $10^1 - 10^2$ µm → high aspect ratio (up to $1:10^4$) nano-wires
- Ideal samples: organic polymers
  high electrical & thermal resistivity → semiconductors, insulators
  crystals: transition to an amorphous phase
- Tracks: overlapping lumps of modified material: dE/dx → continuous/discontinuous tracks

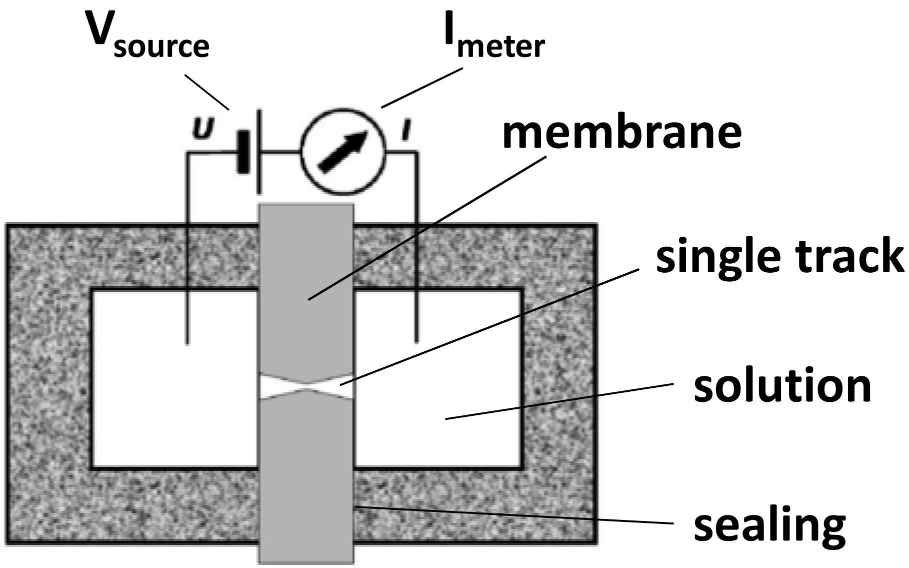




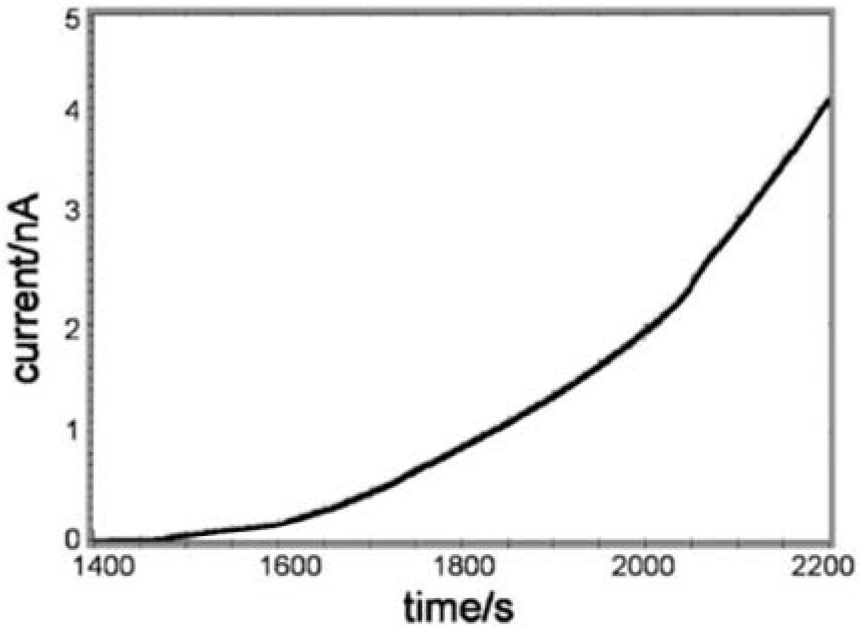
@ : Centre de Recherche sur les Ions, le Matériaux et la Photonique (CIMAP)

MeV IBL: Single ion tracks

Track etching



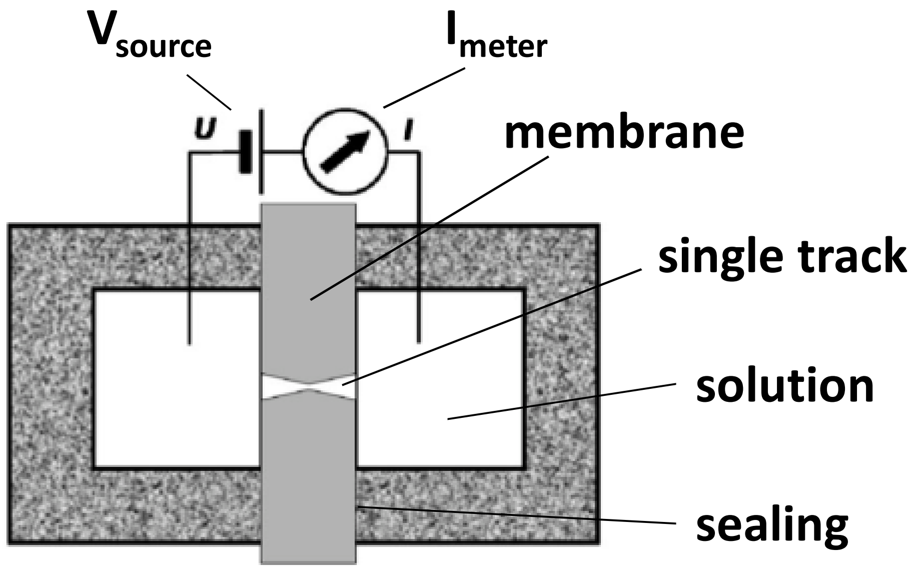
Electrolytic cell



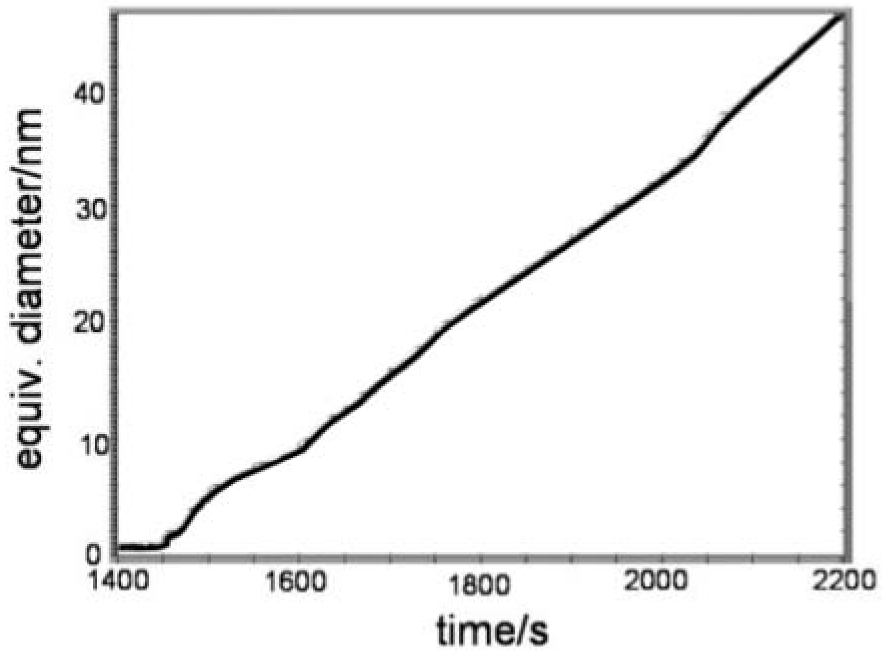
- Current flowing through a 30-µm-thick polycarbonate membrane with 5 tracks
- Solution: ~2.5 M NaOH + 5% methanol
- Applied voltage: 0.5 V
- Quadratic increase after breakthrough

MeV IBL: Single ion tracks

Track etching



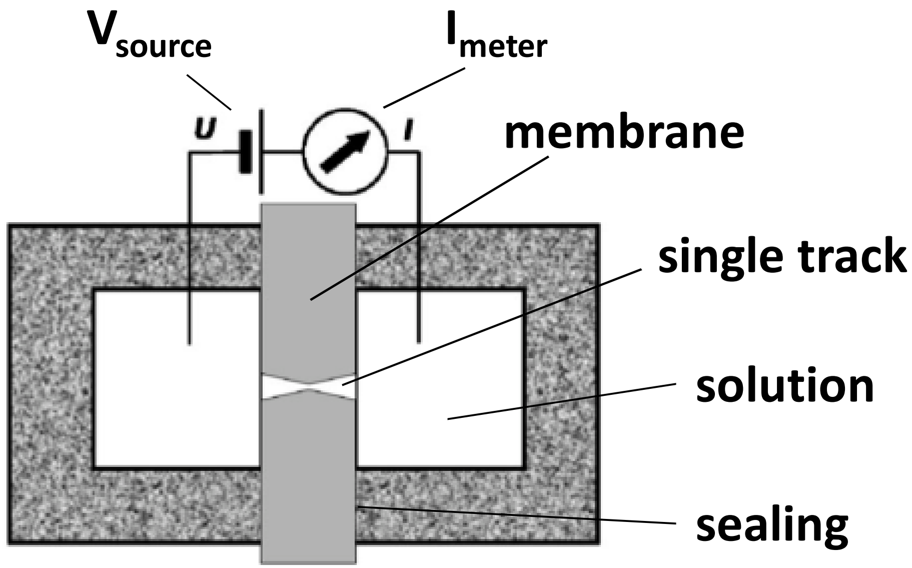
Electrolytic cell



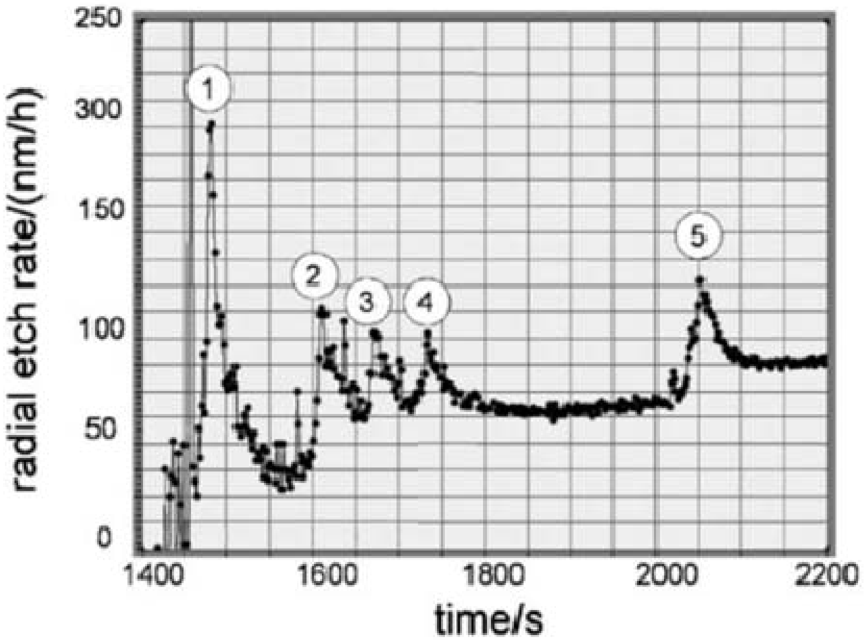
- Equivalent pore diameter vs.time
- Linear increase after breakthrough

MeV IBL: Single ion tracks

Track etching



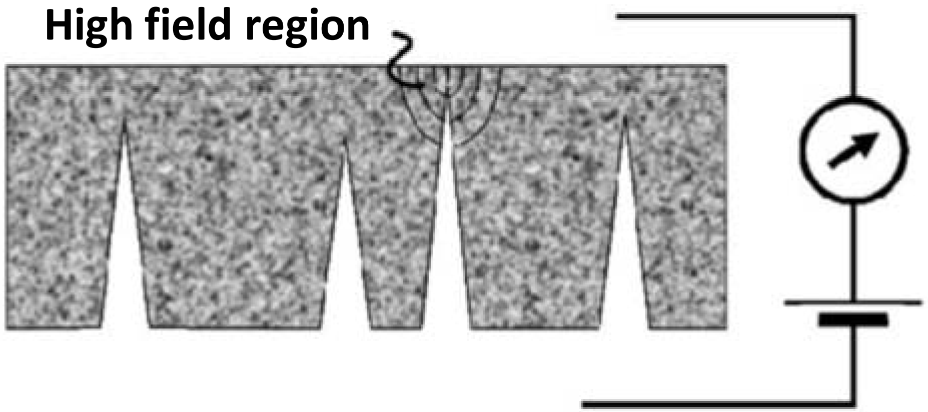
Electrolytic cell



- Radial etch rate vs. time
- 5 peaks corresponding to the 5 tracks

MeV IBL: Single ion tracks

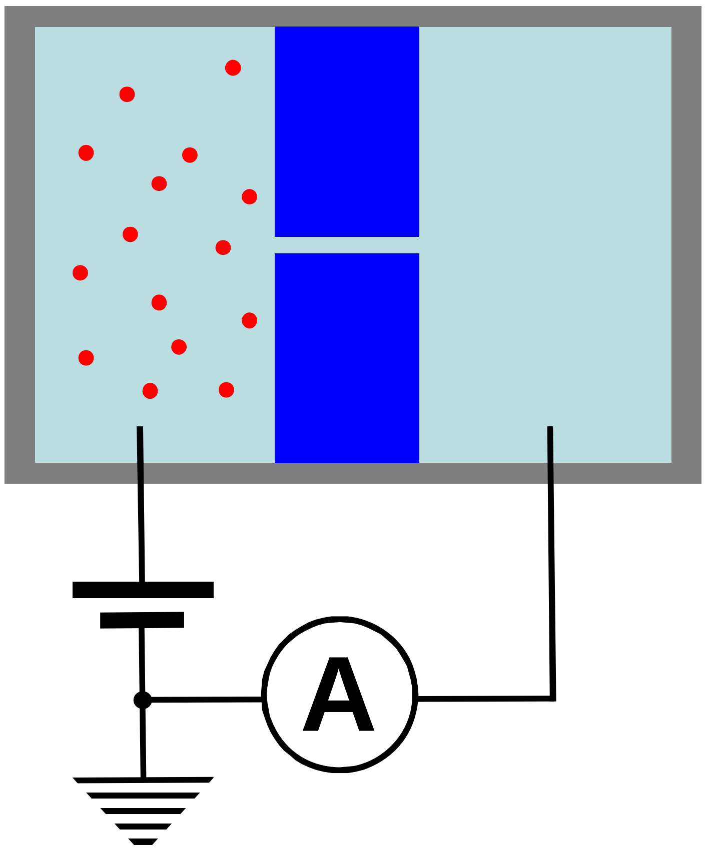
Tip enhanced electric field

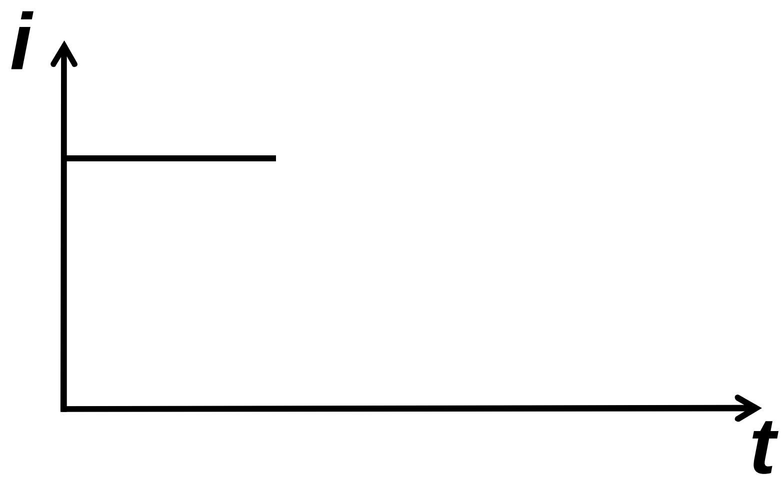


- Increasing etching rate as the residual thickness decreases
- Tracks develop in sequence

MeV IBL: Single ion tracks

Porous membranes
for counting and seizing cells, molecules and nanoparticles





MeV IBL: Single ion tracks

Porous membranes
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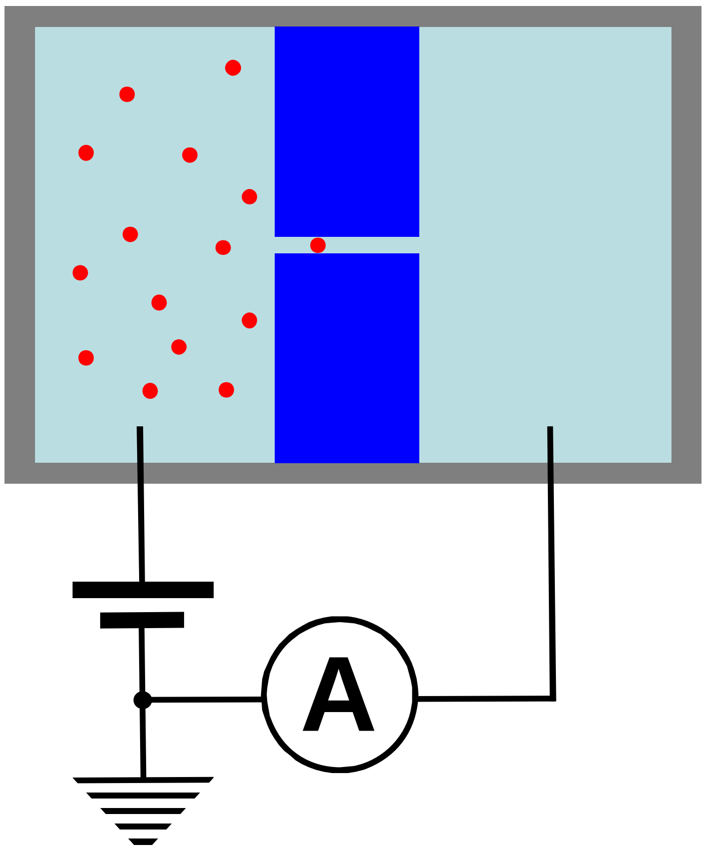

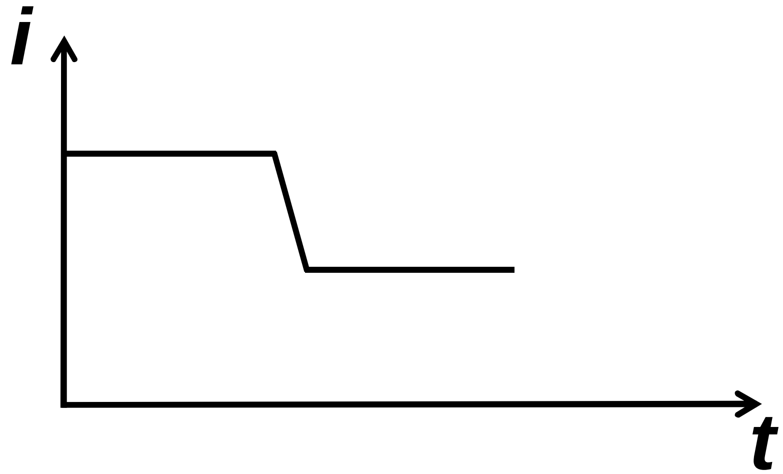

MeV IBL: Single ion tracks

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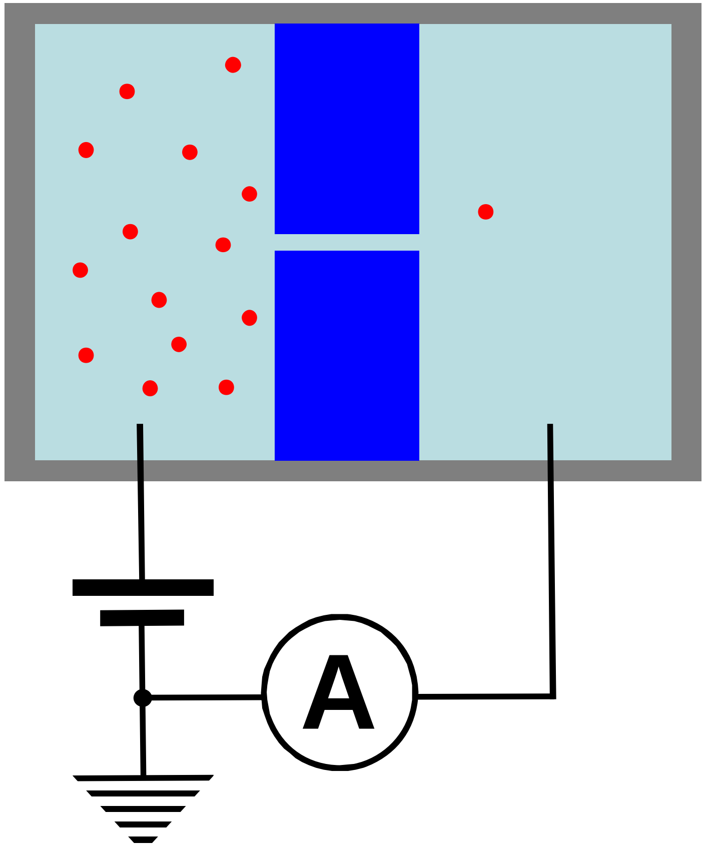
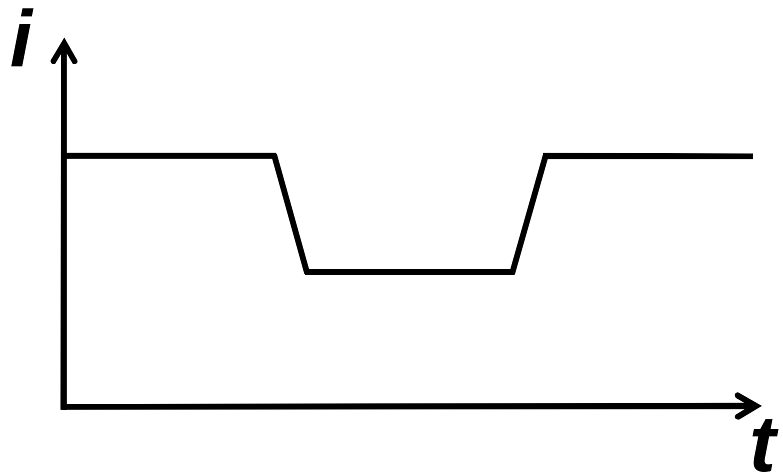
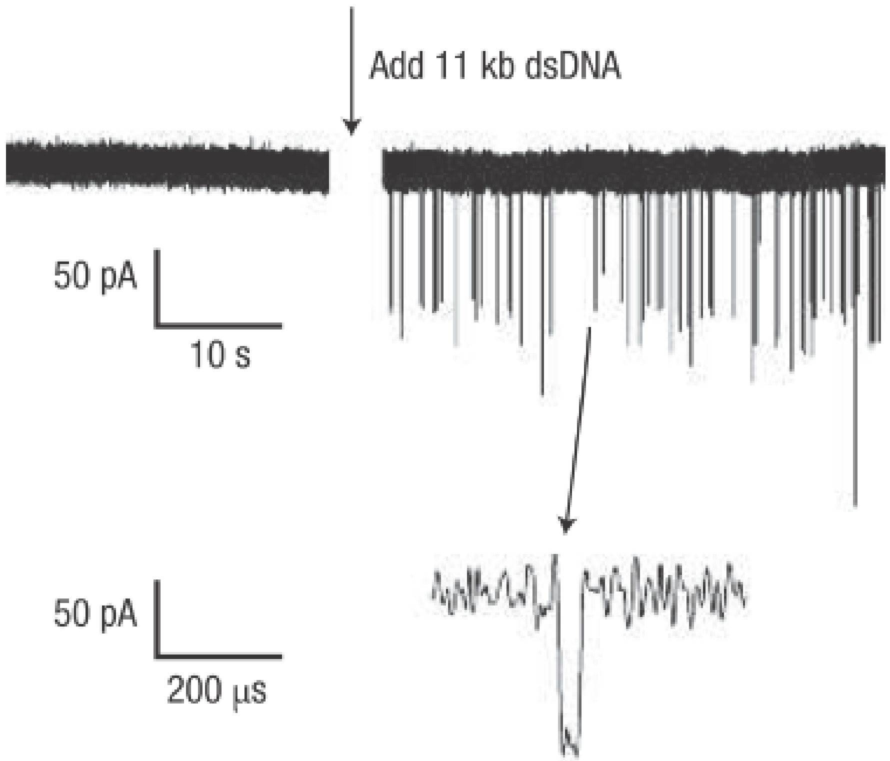




MeV IBL: Single ion tracks

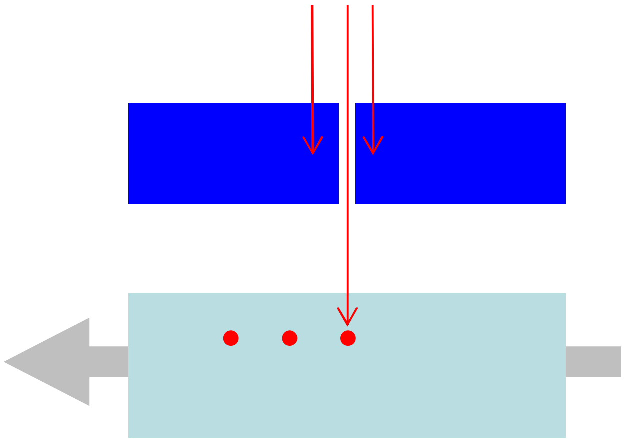
Porous membranes for detection of DNA strands

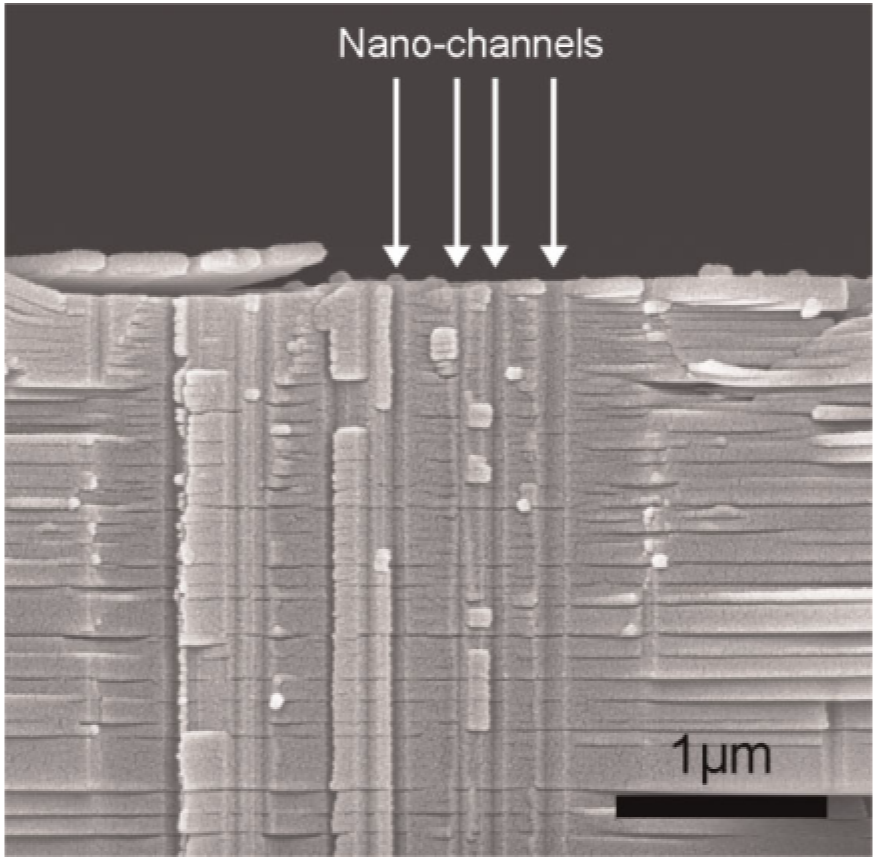


Spike duration → length of the DNA strand

MeV IBL: Single ion tracks

Mica nano-masks for high-resolution single ion implantation





MeV IBL: Single ion tracks

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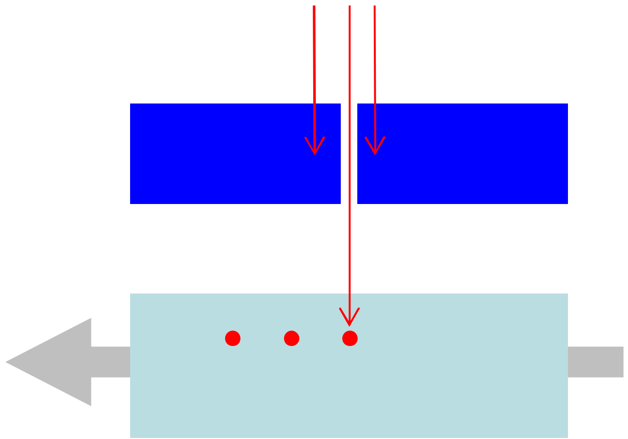
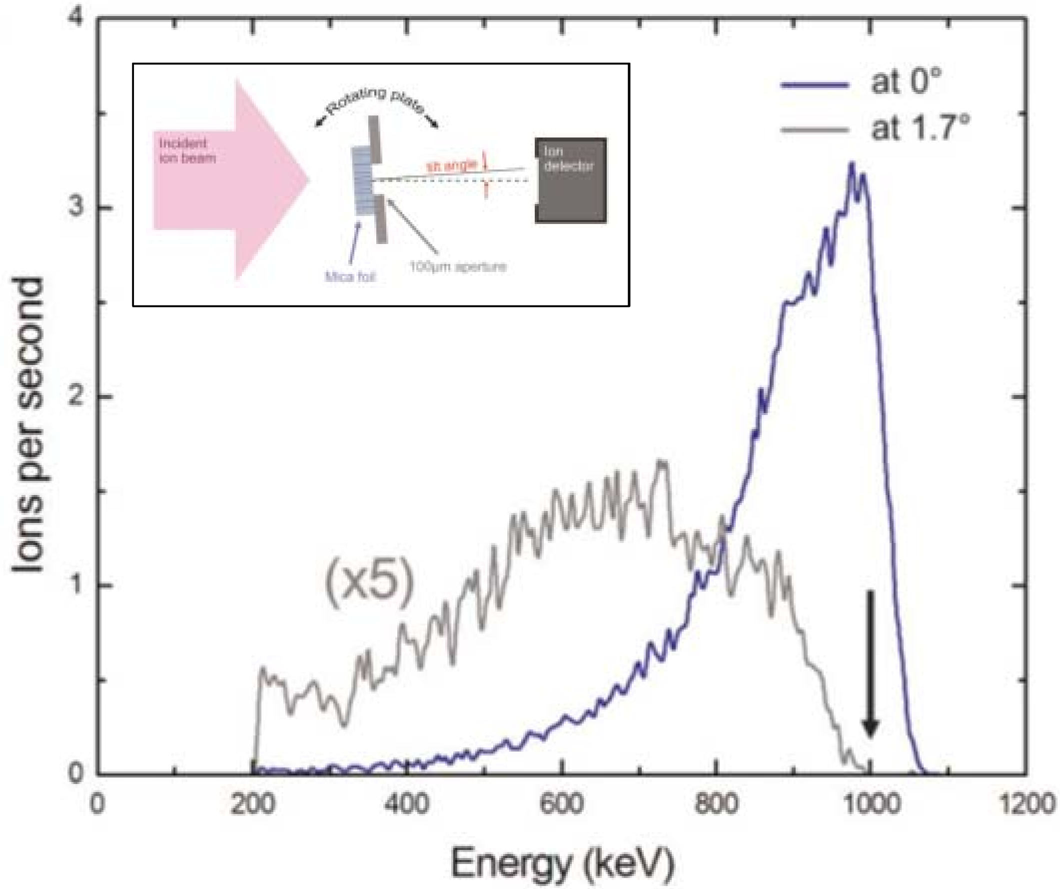


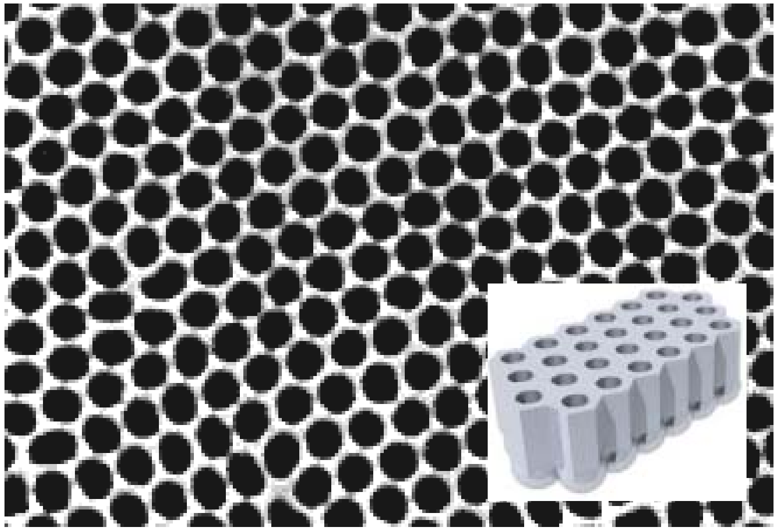
Single 1 MeV N^+ ion implantation



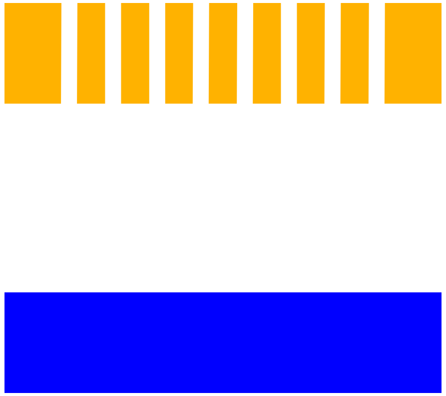
MeV IBL: Single ion tracks

Ordered nanopores in TiO_2 by SHI implantation through a porous anodic alumina mask

Porous Anodic Alumina (PAA)



anodic oxidation of Al in presence of acidic electrolytes



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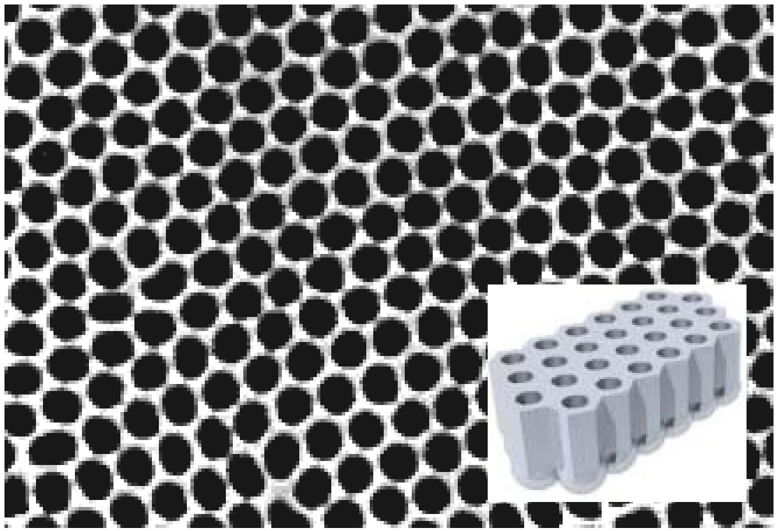

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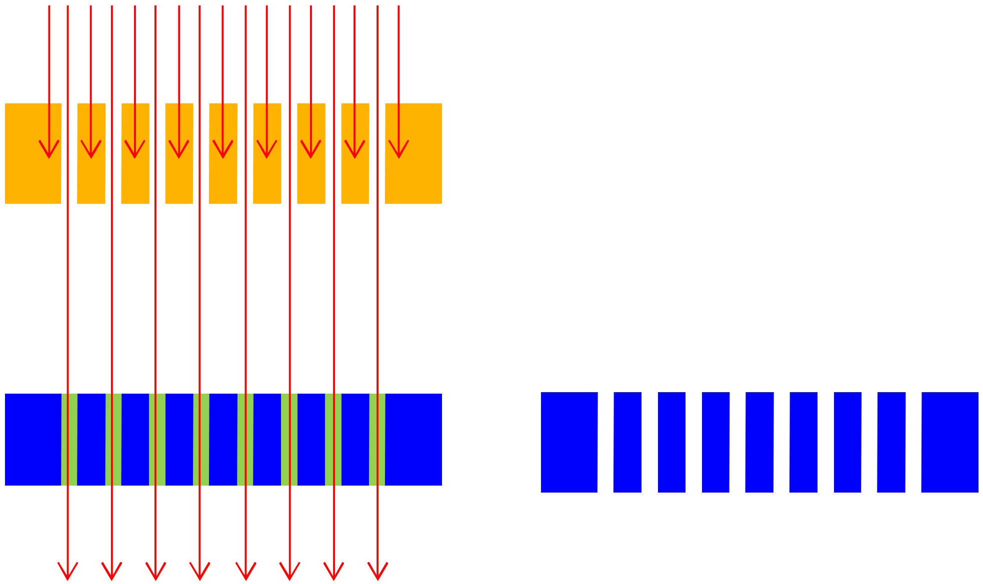

- **Broad implantation of 25 MeV Br^{7+} ions**
- **Wet chemical etching in HF**

@ : Material Science Institute of Madrid

MeV IBL: Single ion tracks

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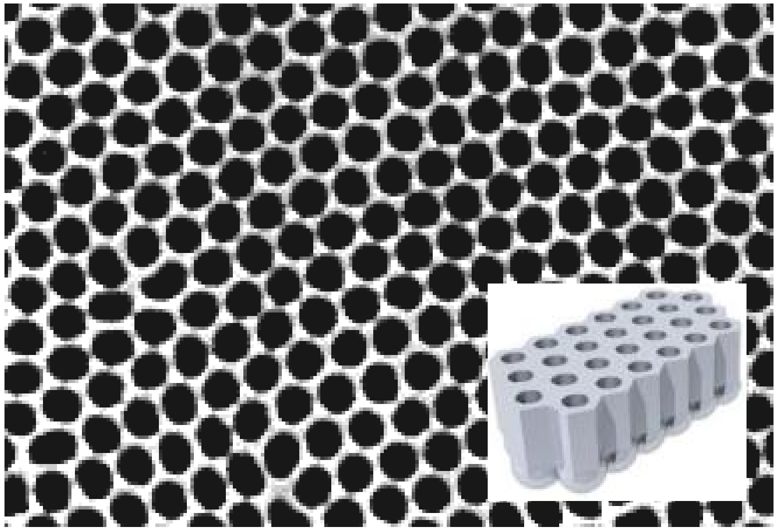

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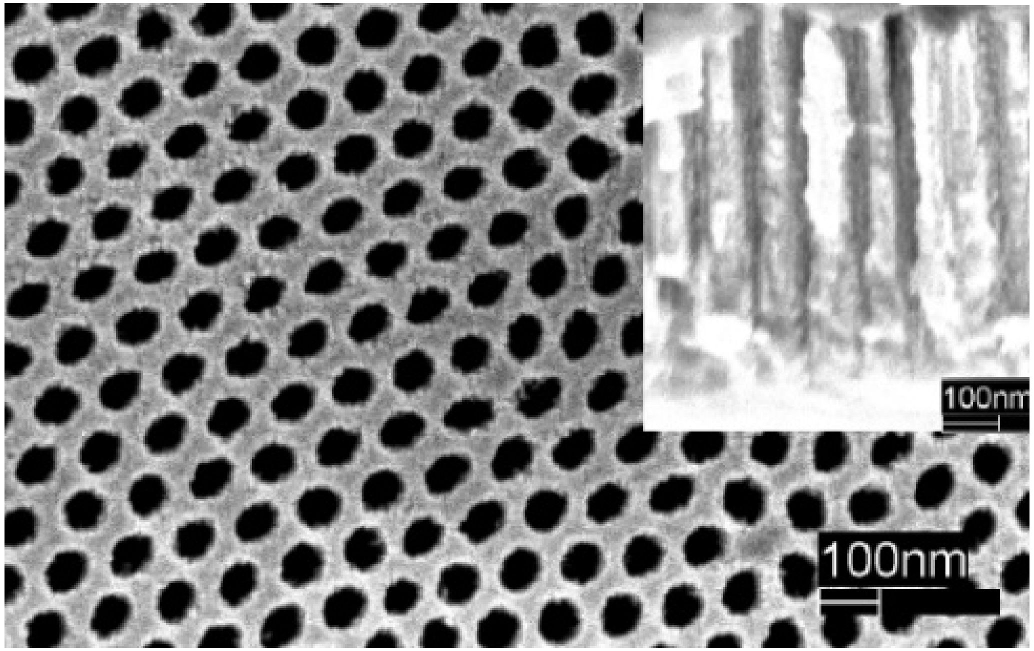

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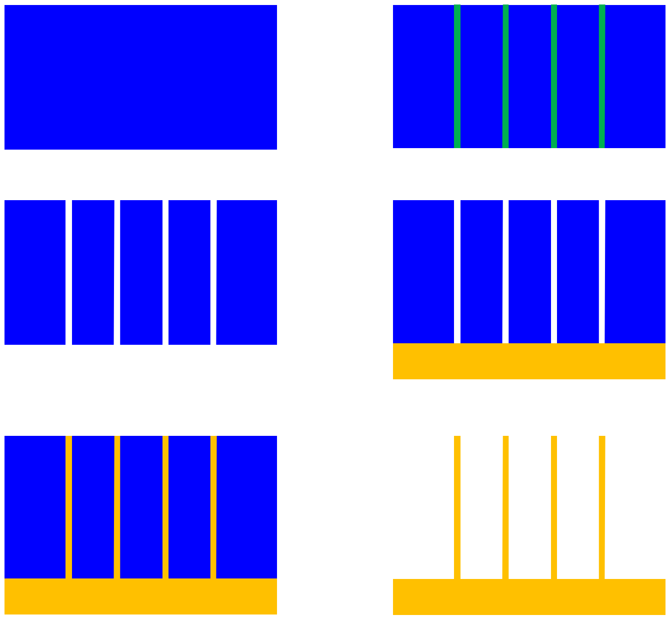
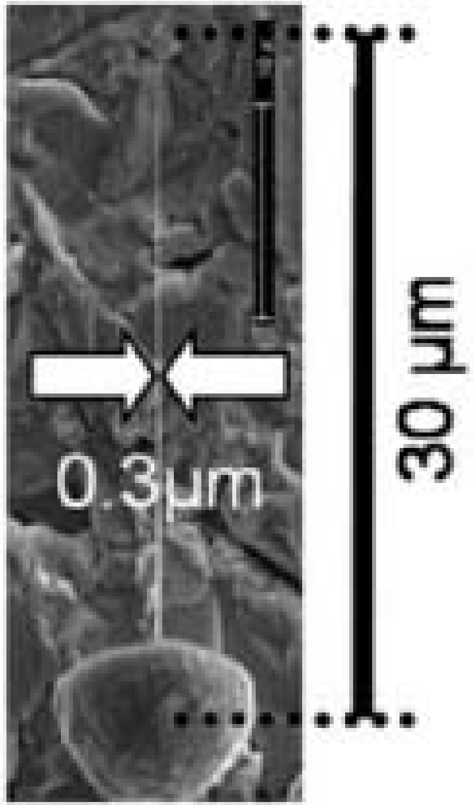
MeV IBL: Single ion tracks

Templates for nanowires growth



- Single ion tracks
- Electrochemical etching
- Metal deposition
- Metal electro-deposition



1:100 Cu nanowire

@ : Gesellschaft für Schwerionenforschung, Darmstadt

MeV IBL: Single ion tracks

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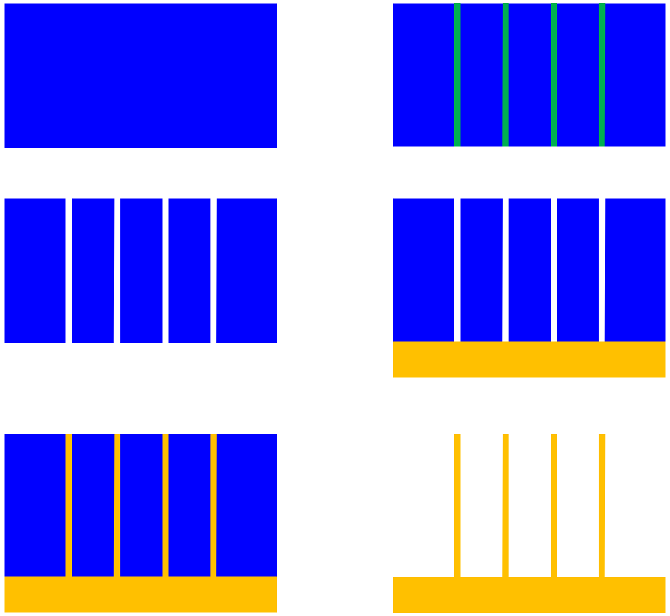

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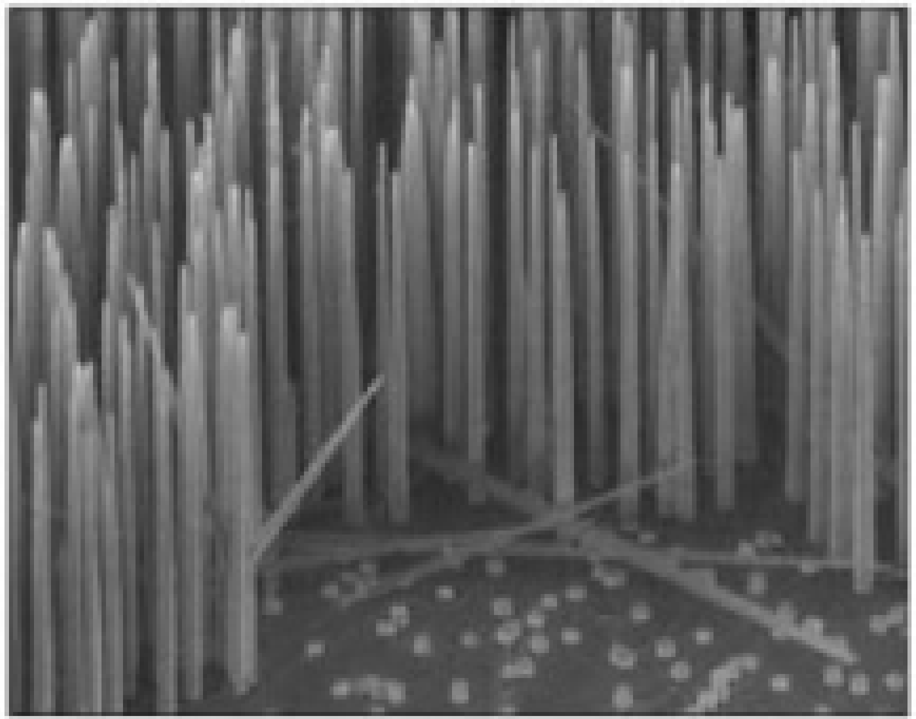
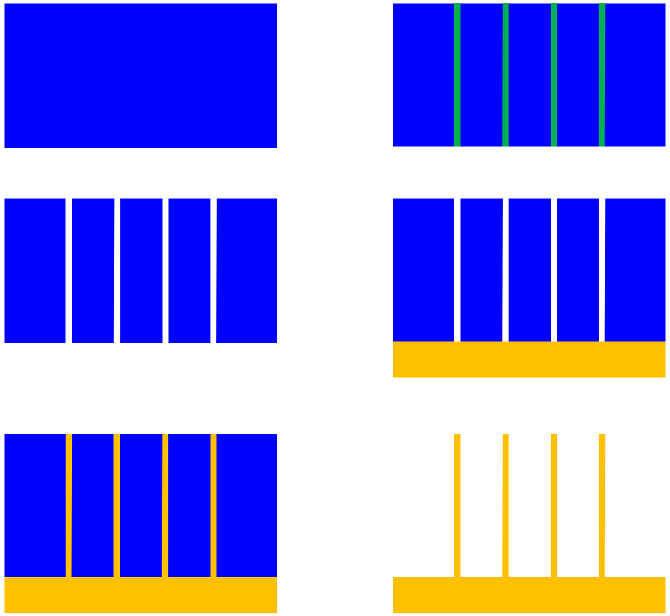


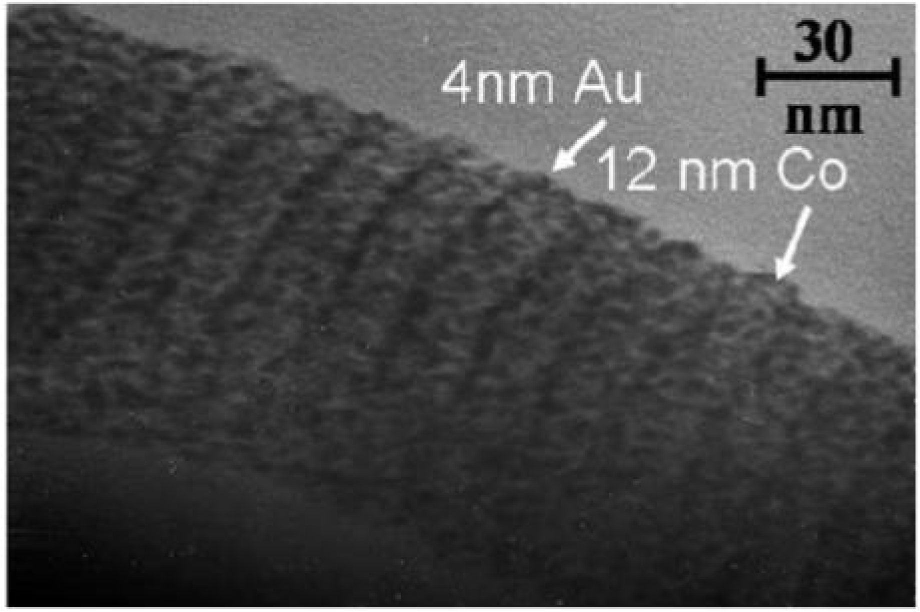
Nanowire array

tip-enhanced electro-deposition

MeV IBL: Single ion tracks

Templates for nanowires growth





- Single ion tracks
- Electrochemical etching
- Metal deposition
- Modulated electro-deposition in a mixed electrolyte

Compositionally modulated nanowire
(→ magnetometry, spintronics, …)

@ : Acreo Research Institute & Seagate Technology

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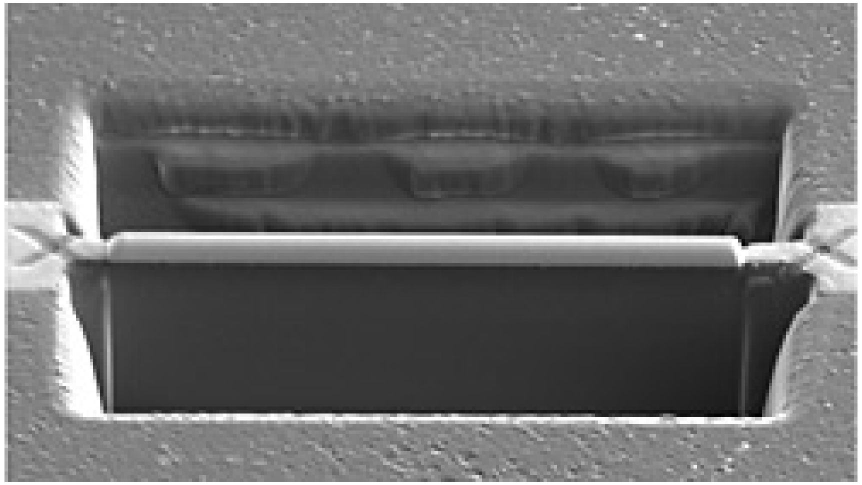
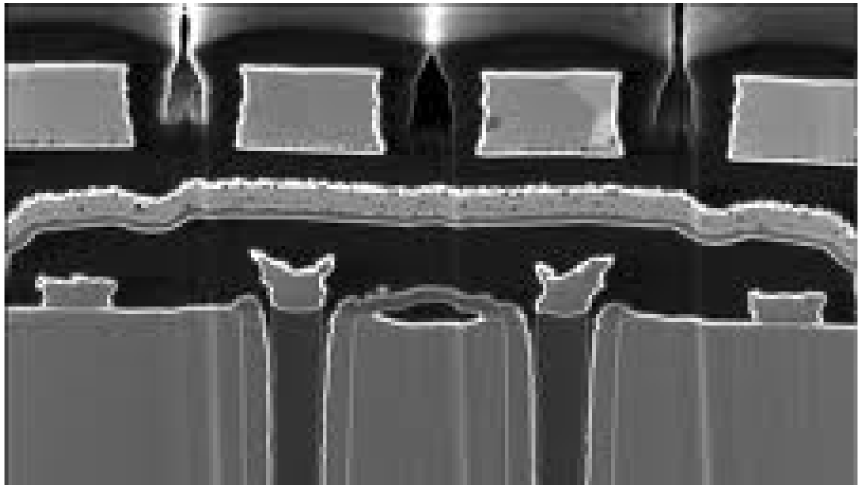
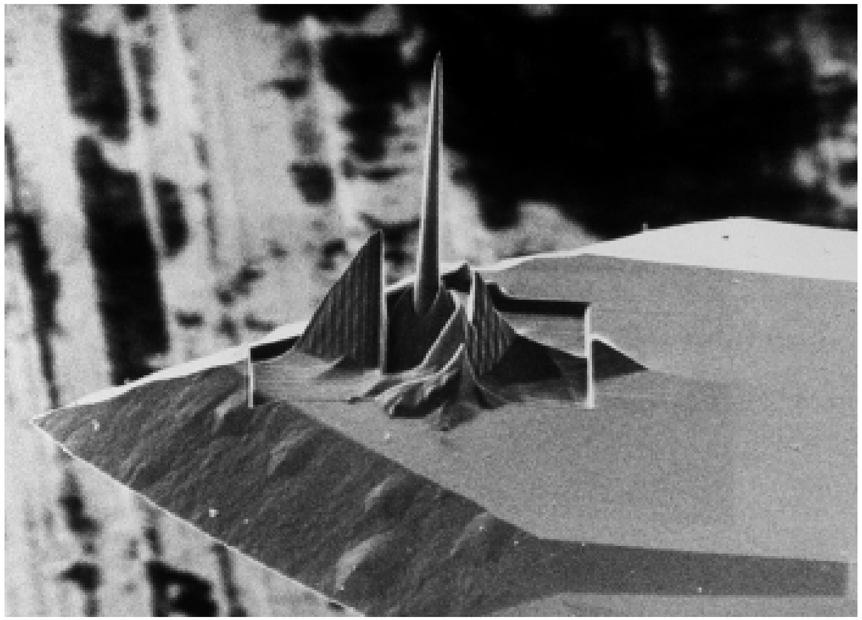
keV IBL: FIB milling



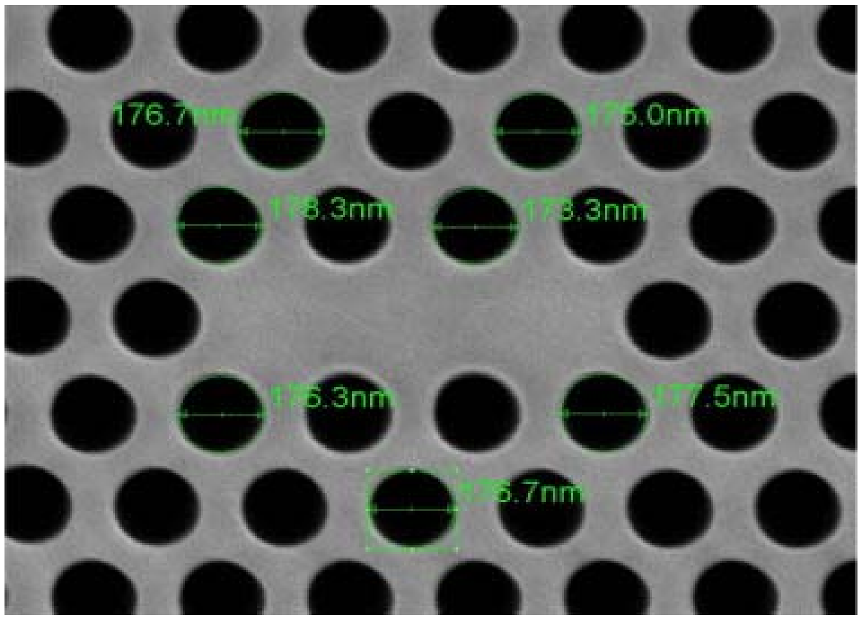
TEM sample preparation



Devices cross-sectioning



Nano-tips



Photonic crystals

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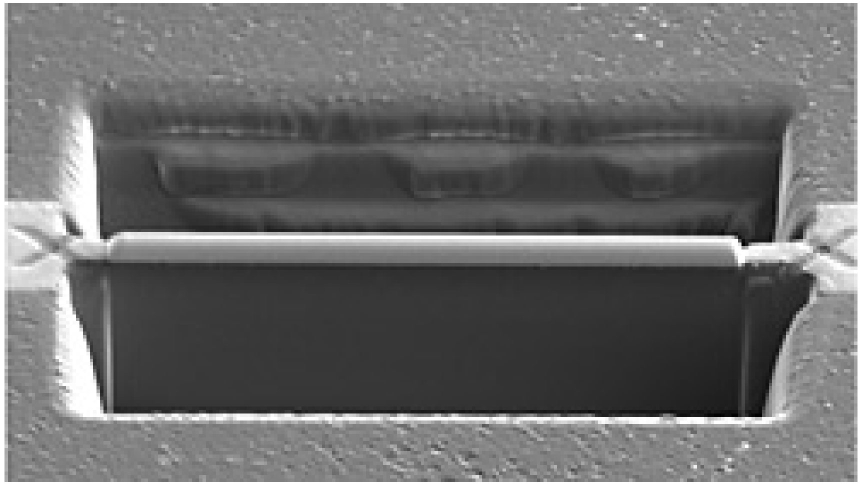
keV IBL: FIB-assisted deposition



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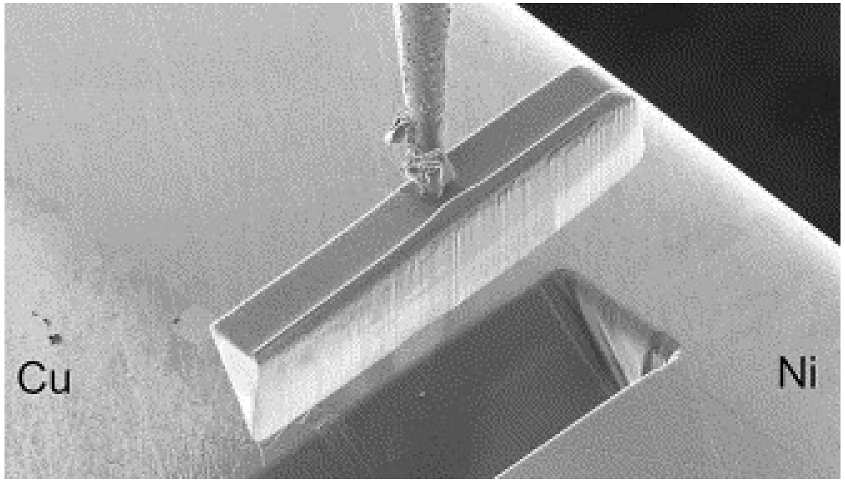
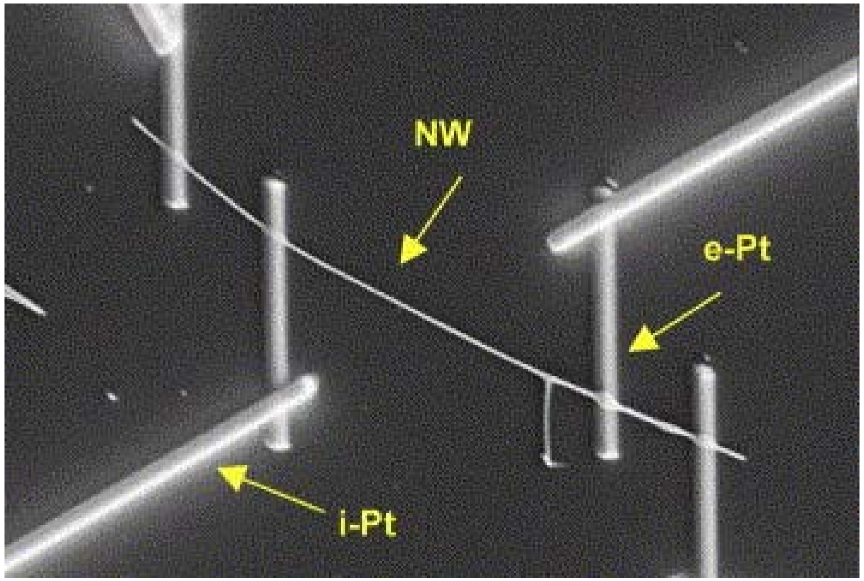
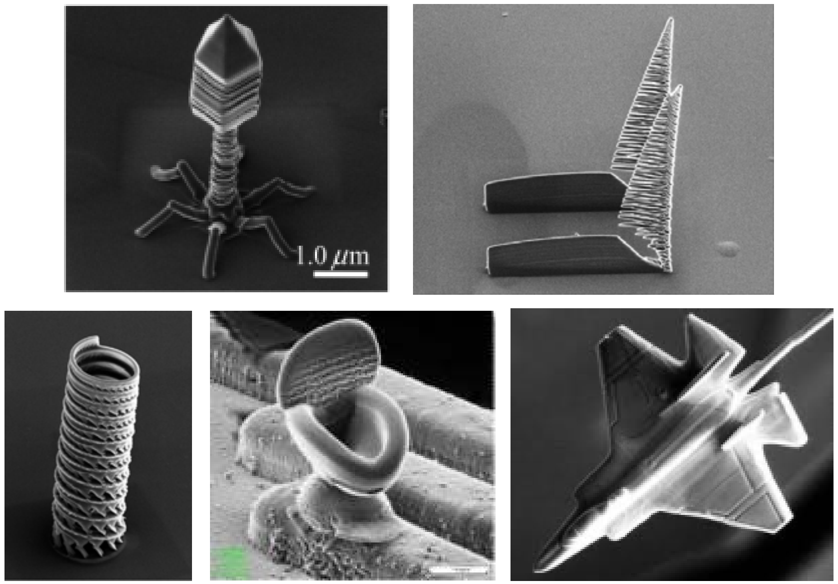


Cross-section lift-out



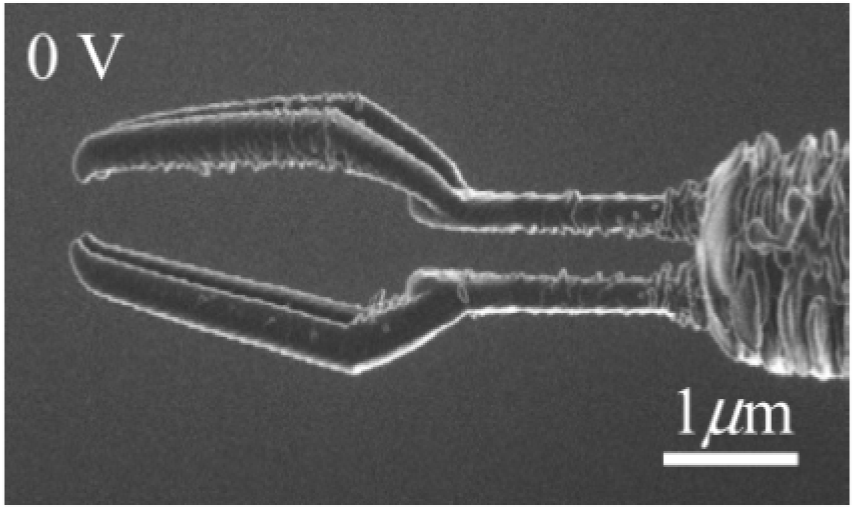
Nano-contacting

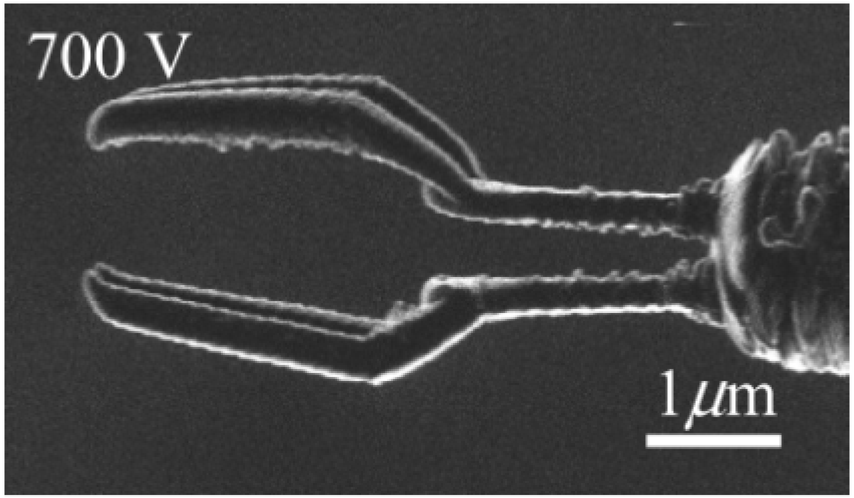


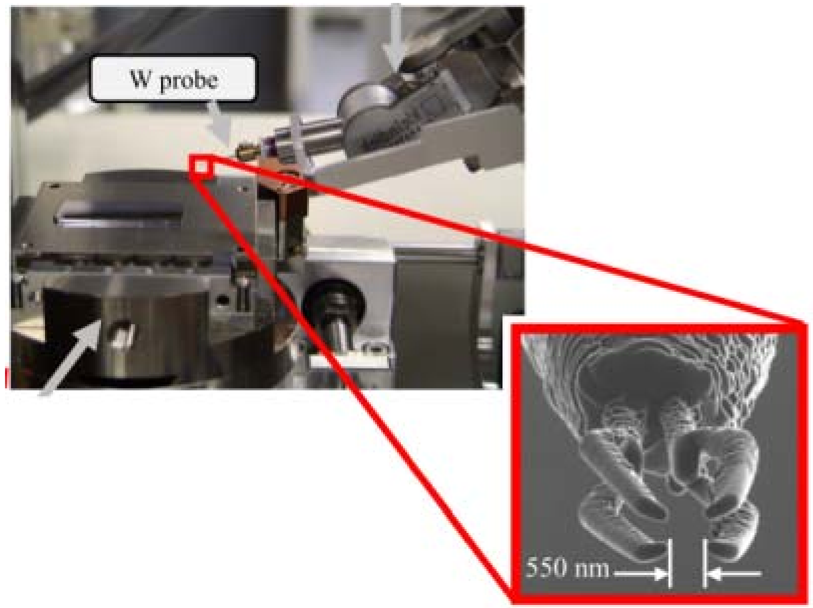
Advertising stuff

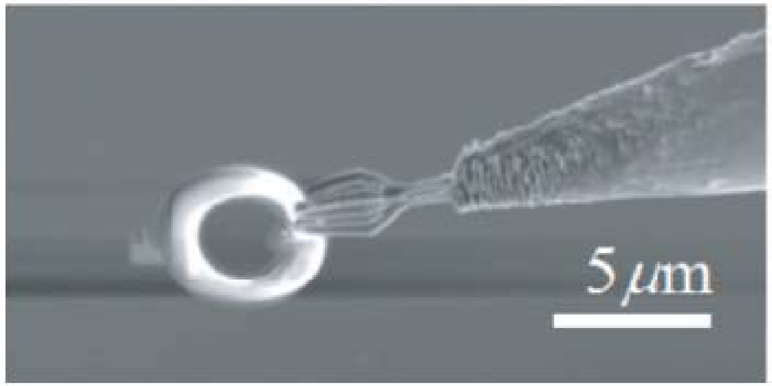
keV IBL: FIB-assisted deposition

Nanoelectromechanical devices with DLC deposition









@ : School of Engineering – University of Tokio

Outline

Introduction

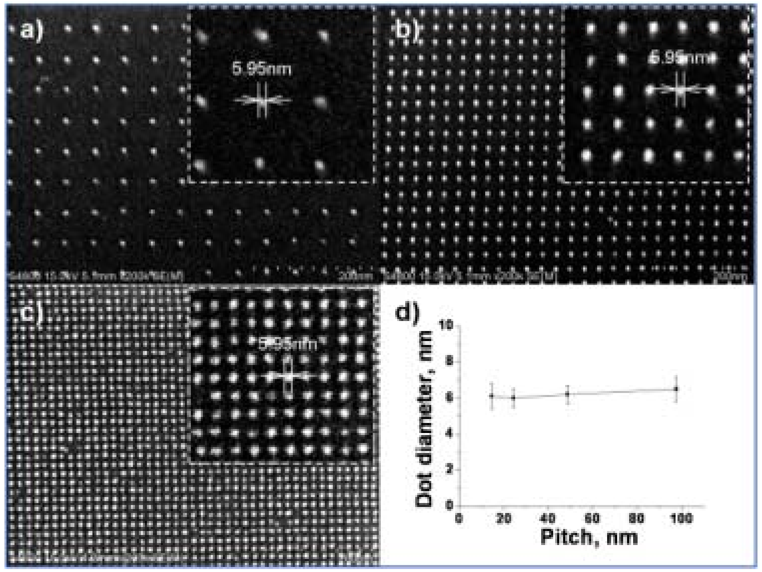
- Ion-matter interaction
  - → MeV ions
  - → keV ions
- Ion-beam lithography
  - → conventional techniques
  - → MeV ions
  - → keV ions

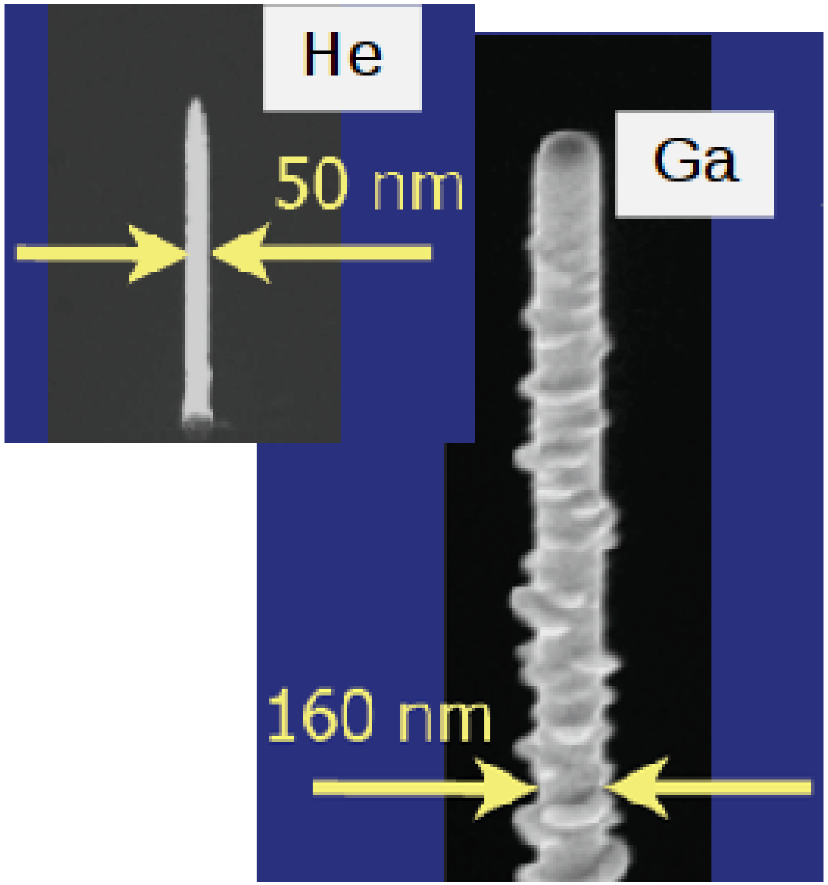
Case studies

- MeV ion beam lithography
  - → resists
  - → silicon
  - → other materials
  - → single ion tracks
- **keV ion beam lithography**
  - → FIB milling
  - → FIB-assisted deposition
  - → **Helium-ion microscope**

keV IBL: Helium Ion Microscope

- Smaller De Broglie wavelength
- Higher secondary emission yield → lower current
- Higher resolution





@ : Carl Zeiss SMT

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- CIBA – National University of Singapore
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- Ion Beam Analysis Center – CAFI
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- Kavli Institute of Technology – Delft University
- LIBI – Ruđer Bošković Institute
- LIPSION – University of Leipzig
- Louisiana Accelerator Center – The University of Louisiana
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