Ion microscopy
&
Ion beam lithography

Paolo Olivero

olivero@to.infn.it

Outline

Ion beam microscopy

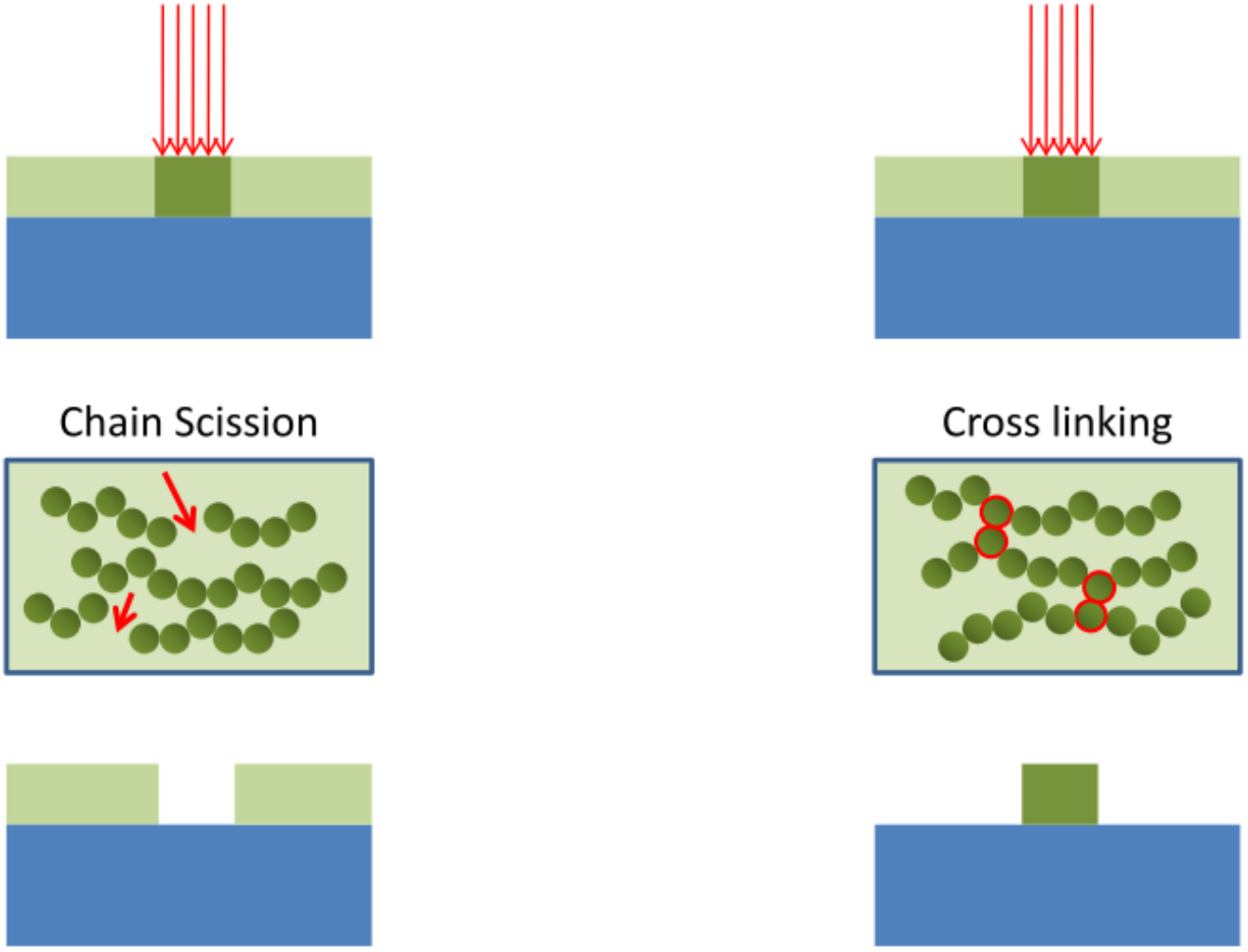
- Experimental features
  - → **focused ion beams**
  - → **acquisition systems**
- I-beam microscopy techniques
  - → **STIM, IBIL**
  - → **other μ-scopy techniques**

Ion beam lithography

- MeV ion beam lithography
  - → **resists**
  - → **silicon**
  - → **other materials**
  - → **single ion tracks**
  - → **single ion doping**

Conventional lithography techniques

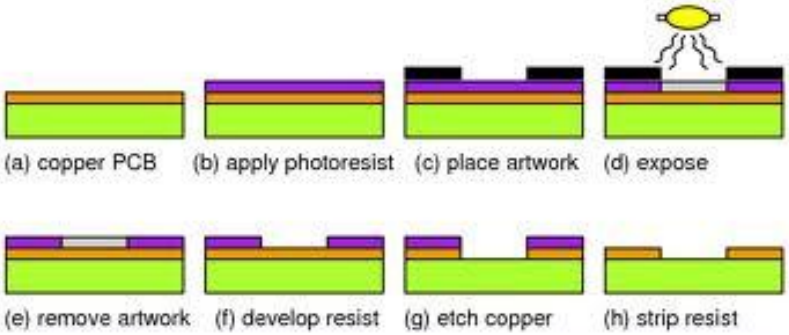
Lithography in positive and negative resists



Conventional lithography techniques

Photolithography

schematics



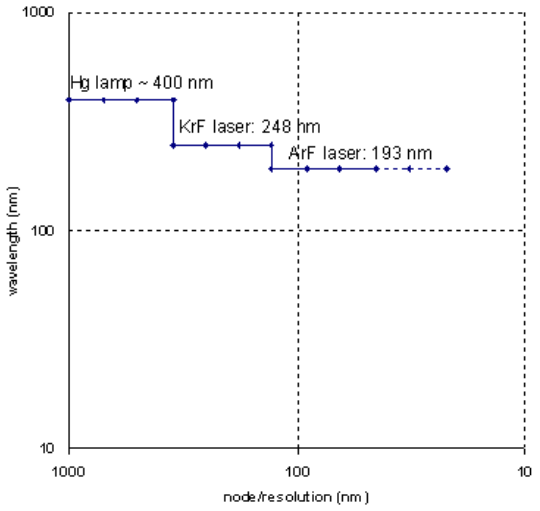
photoresists: PPMA, PMGI, SU-8, etc.

very-large-scale integration (VLSI)

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

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

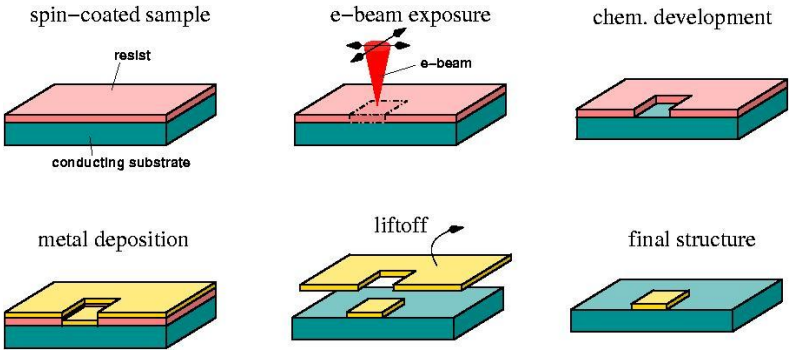
mask aligner (**λ**=365 nm)



Conventional lithography techniques

Electron-beam lithography

schematics

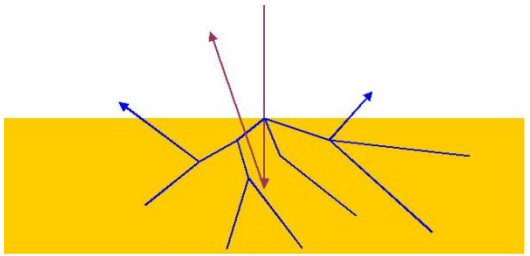


electron beam lithograph (SEM)

direct-write mask-less process

resists: ZEP-520, PMMA

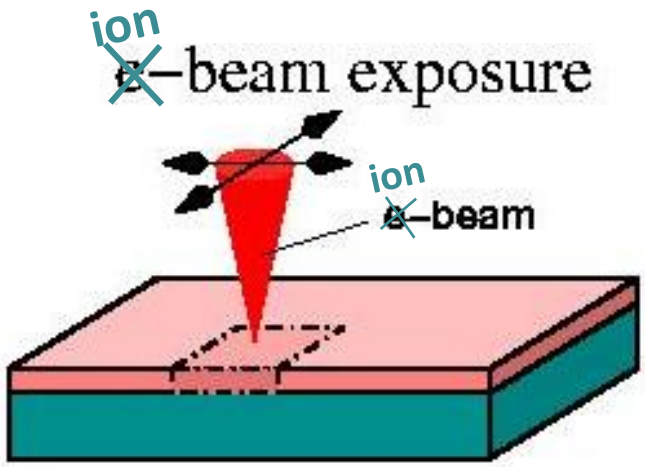
resolution: e-beam size (~nm)
<u>beam-target interaction</u>



other issues: scattering
proximity effects
charging

best resolution: 30-60 nm

Ion-beam lithography: MeV ions



as for EBL:

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

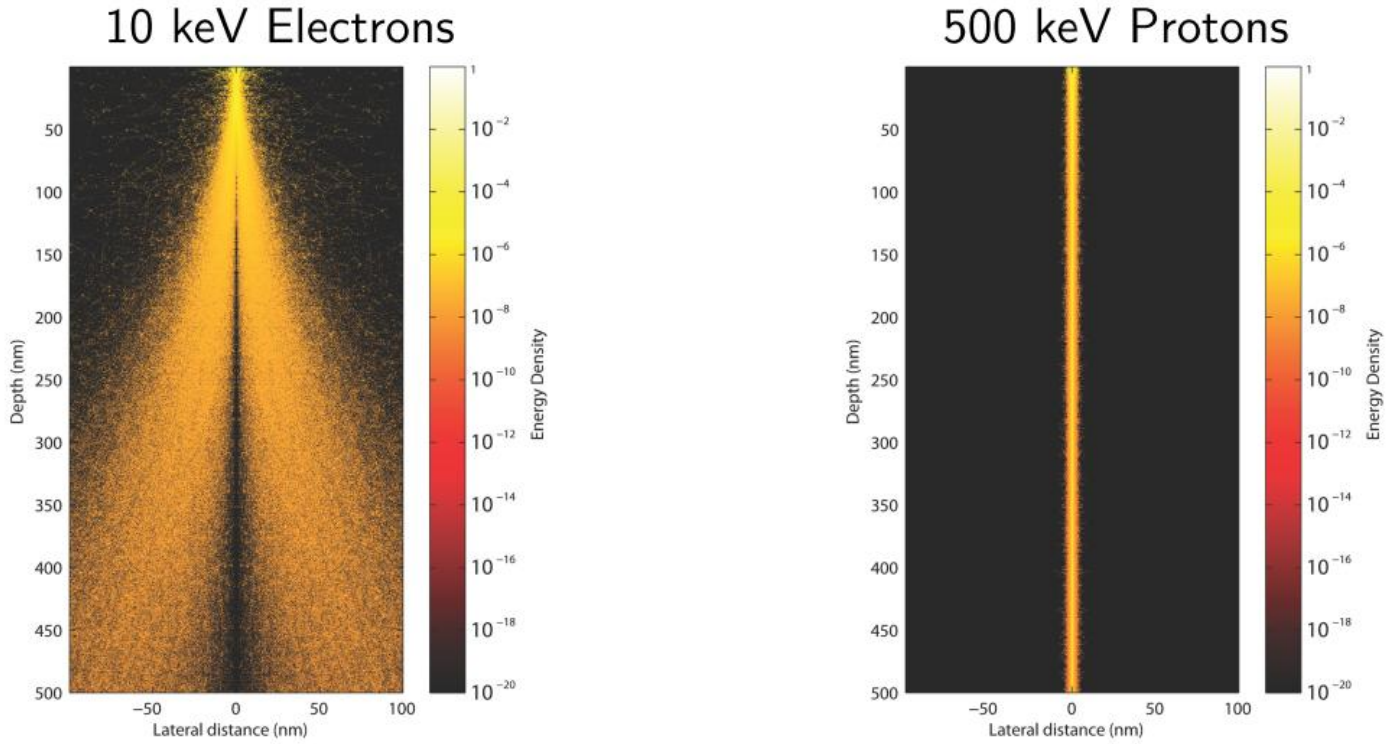
Processes

- **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

Beam-target interaction:
particularly relevant in shallow regions

in PMMA



@ : DEEP Monte Carlo code

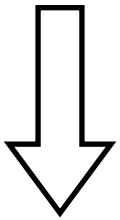
Ion-beam lithography: MeV ions

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



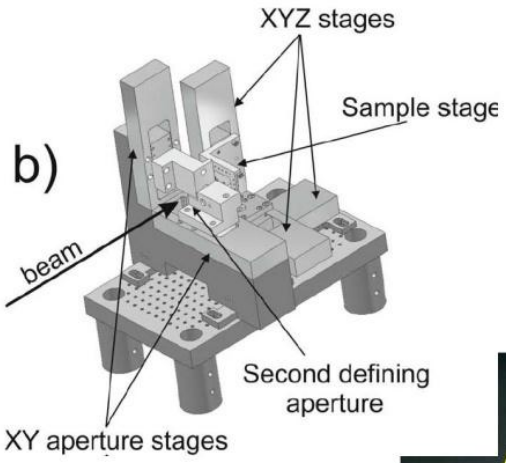
Proton Beam Writing (PBW)

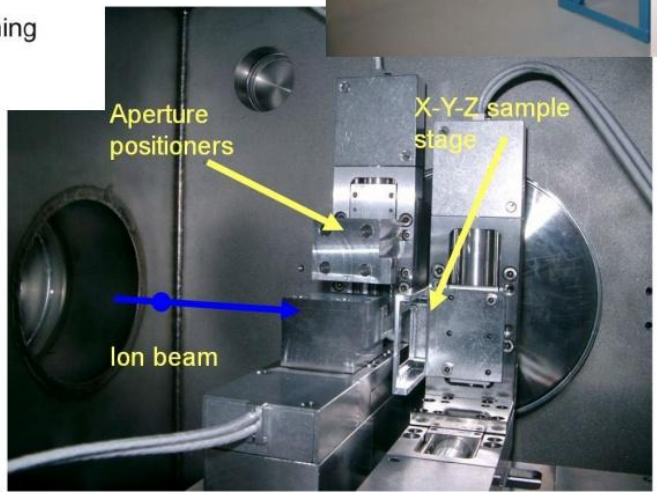
P-LIGA (Proton – Lithographie, Galvanoformgung, Abformung: Proton – Lithography, Electroplating and Molding)

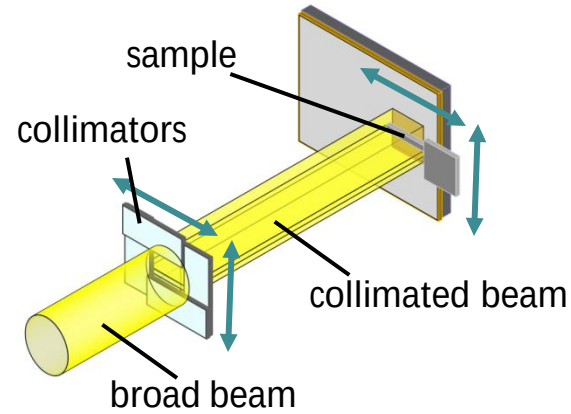
In several specific applications, other ions species (He, C, N, O, Si, Ar, **Br, Au, …) were employed**

Ion-beam lithography: MeV ions

Programmable aperture system







Ion-beam lithography: MeV ions

Ion projection system

ELSEVIER

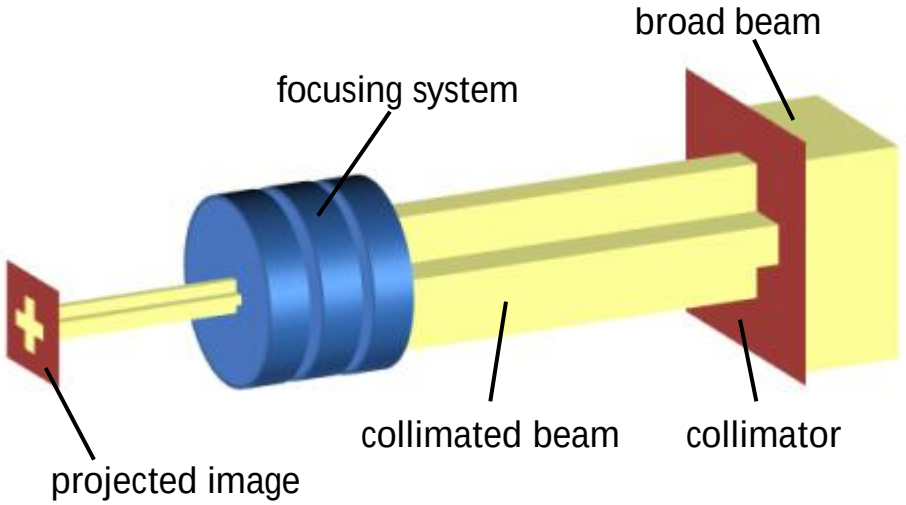
Microelectronic Engineering 41/42 (1998) 257–260

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

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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

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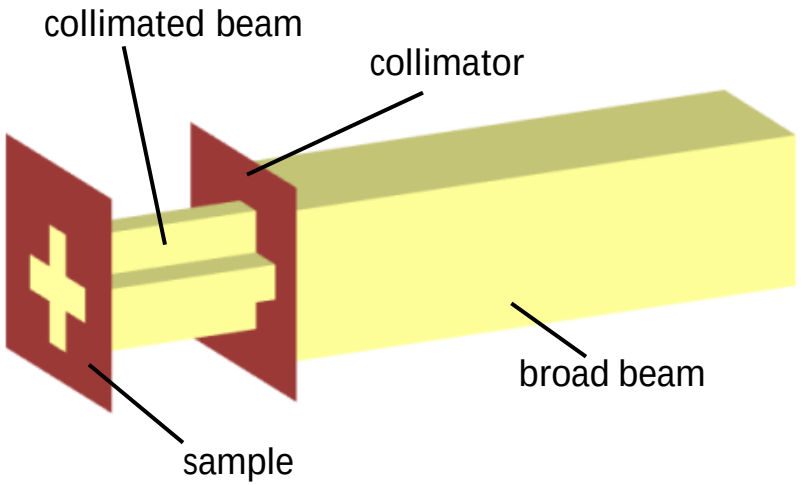
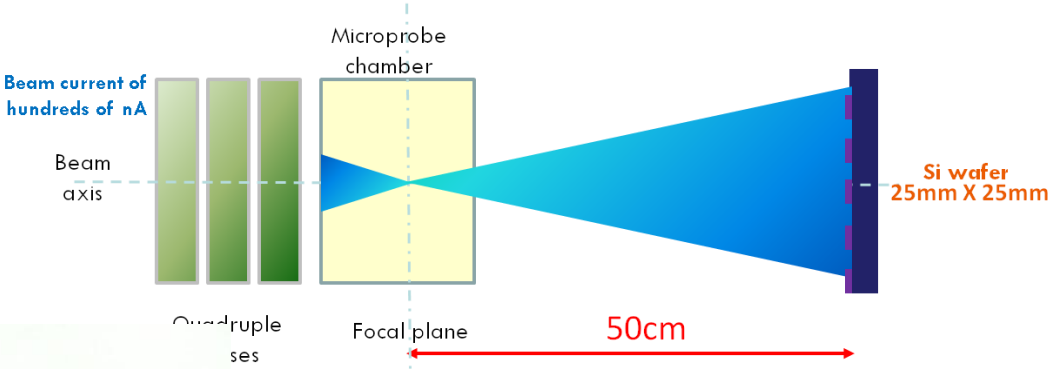
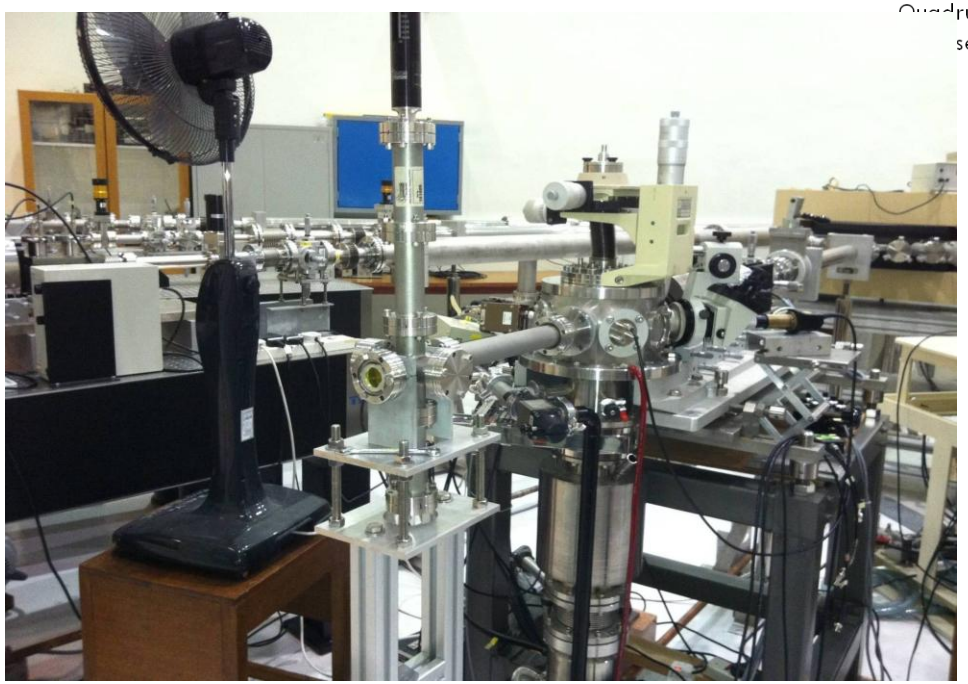


Ion-beam lithography: MeV ions

Contact mask system





Ion-beam lithography: MeV ions

Scanning beams vs masks

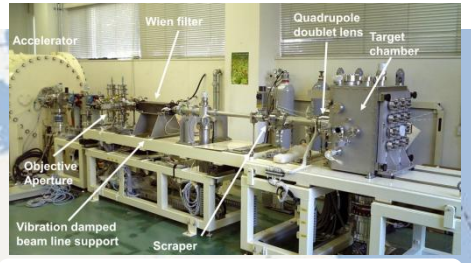
Scanning beam systems	Mask-based systems
:-) Fast pattern definition	:-(Slow pattern definition
:-(Serial & slow irradiation	:-) Fast & parallel irradiation
:-) High resolution	:-(Mask scattering & heating
:-(Limited scan field	:-) Broad scan field

Ion-beam lithography: MeV ions

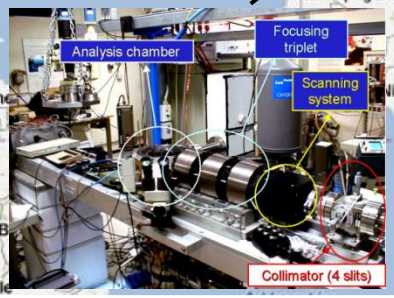
(Some of the many) MeV-IBL setups around the world

University of Surrey

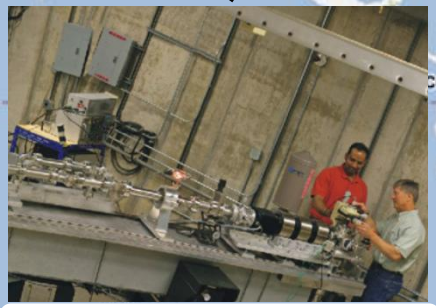
Ruđer Bošković Institute



Shibara Institute of Technology

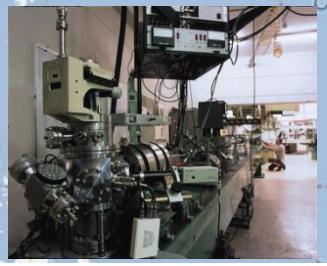


Legnaro National Laboratories



Louisiana Accelerator Center

National University of Singapore



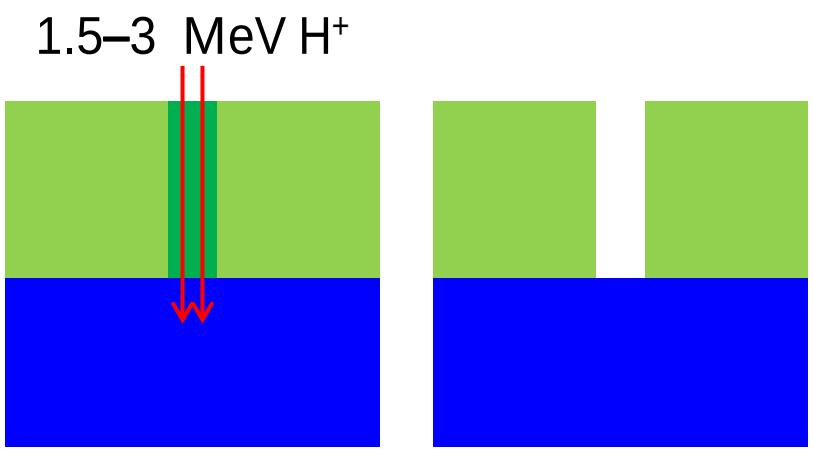
University of Melbourne

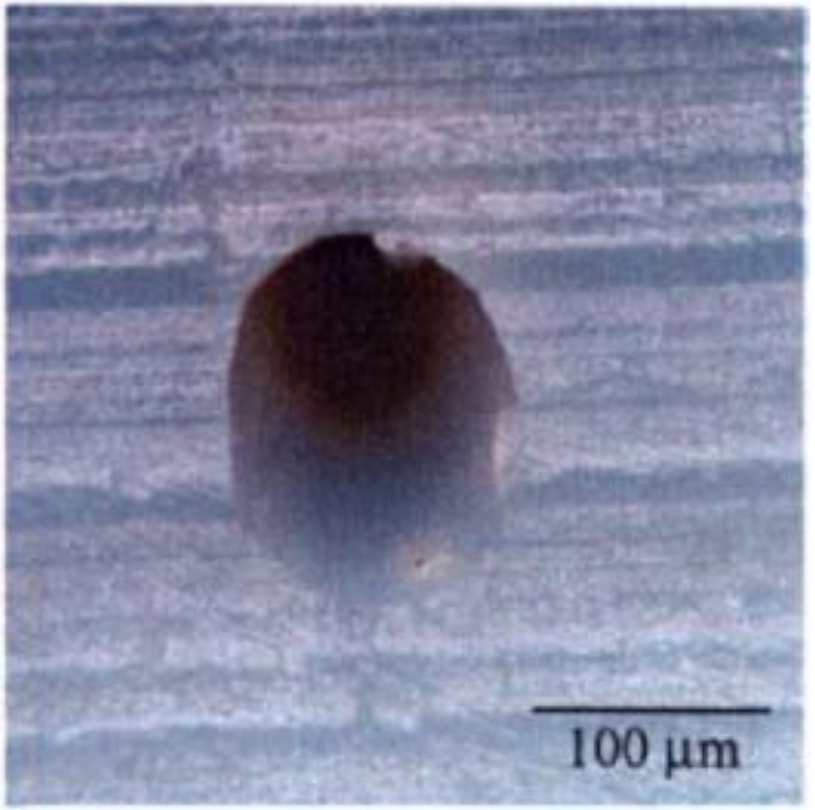
MeV Ion-beam lithography: resists

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

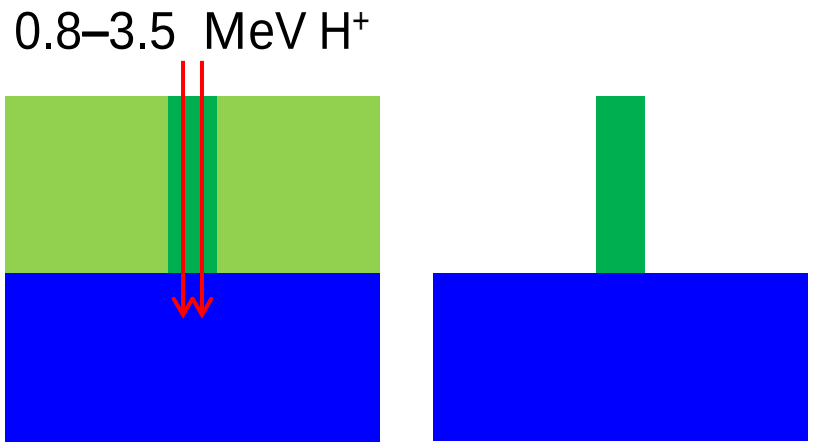
Positive process: polytetrafluoroethylene (PTFE)

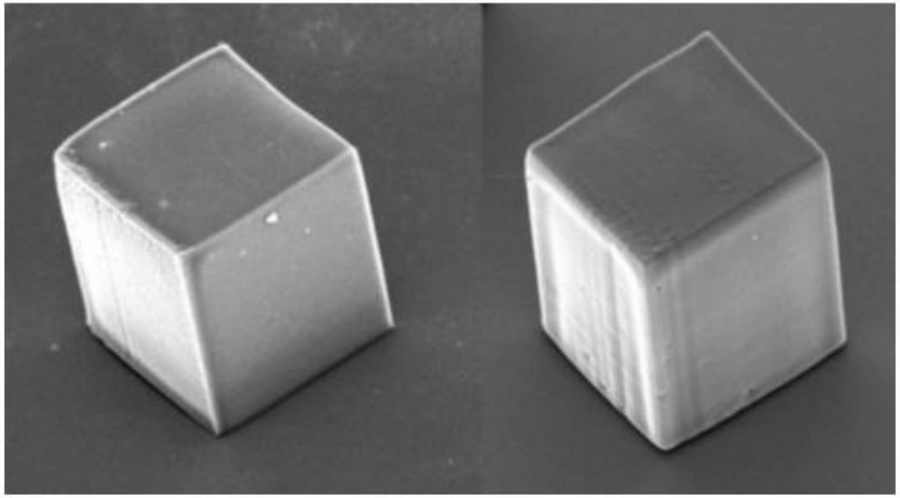




MeV Ion-beam lithography: resists

Negative process: SU-8, DiaPlate 133

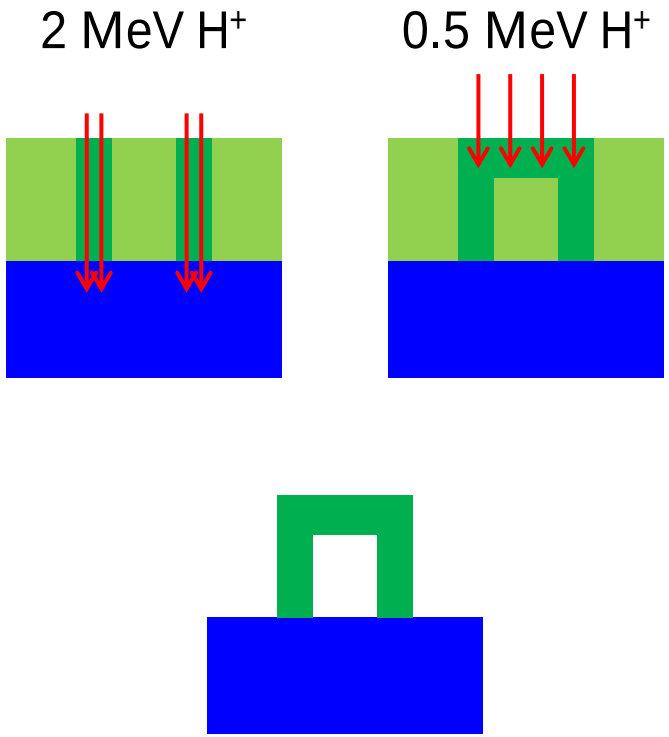


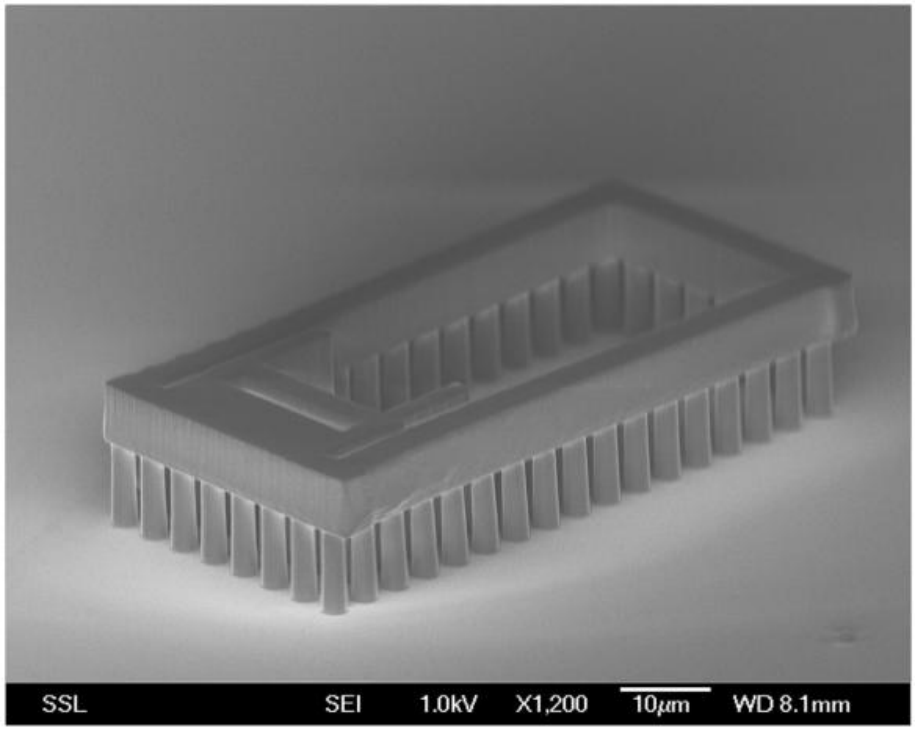


SU-8 DiaPlate 133

MeV Ion-beam lithography: resists

Three-dimensional structures

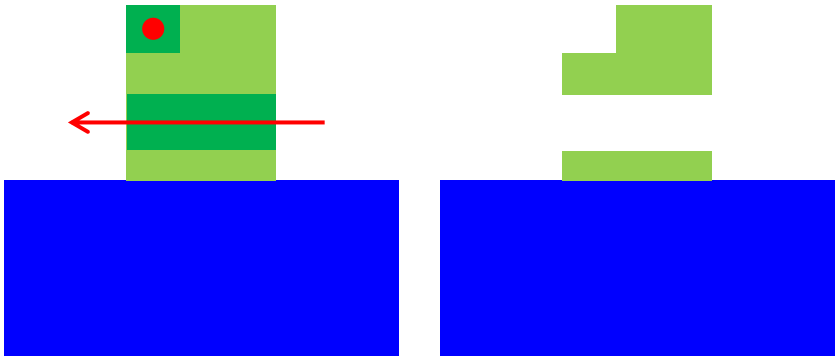


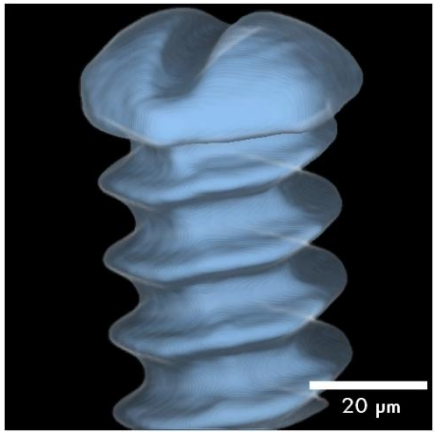


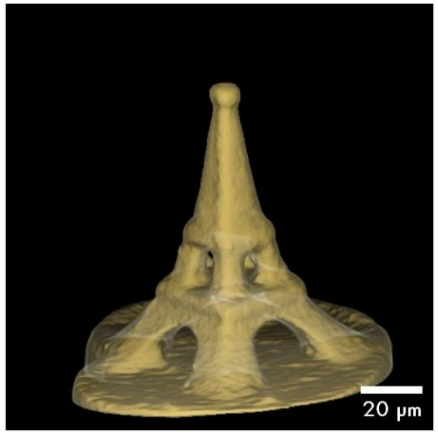
MeV Ion-beam lithography: resists

Three-dimensional structures

2.25 MeV H^+

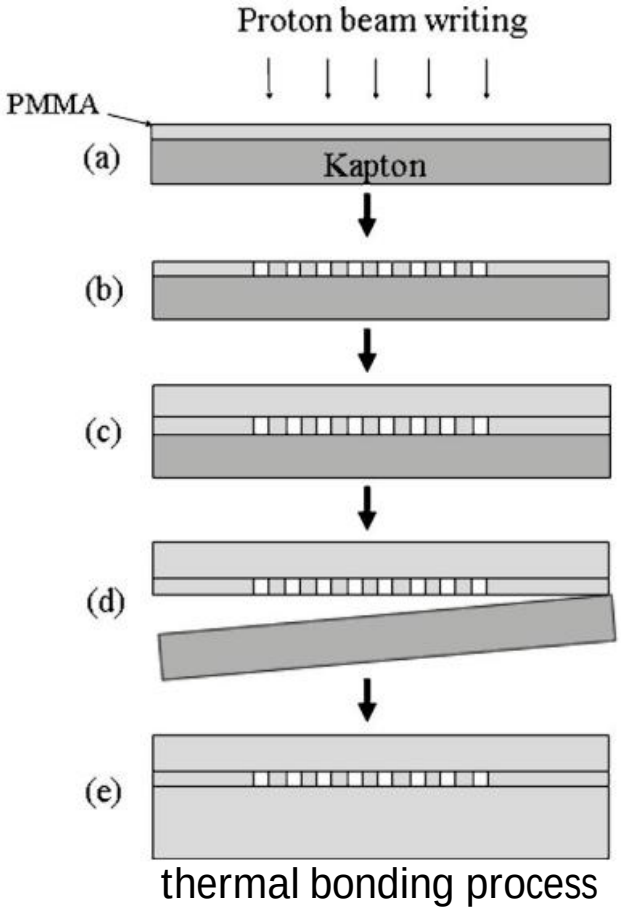




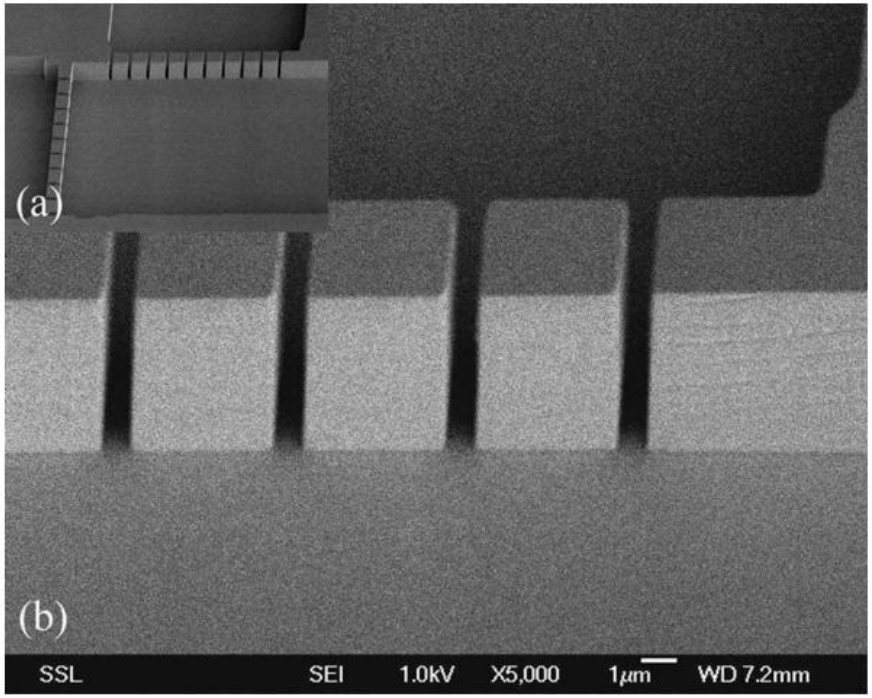


MeV Ion-beam lithography: resists

PMMA-on-PMMA microchannels



thermal bonding process



MeV Ion-beam lithography: resists

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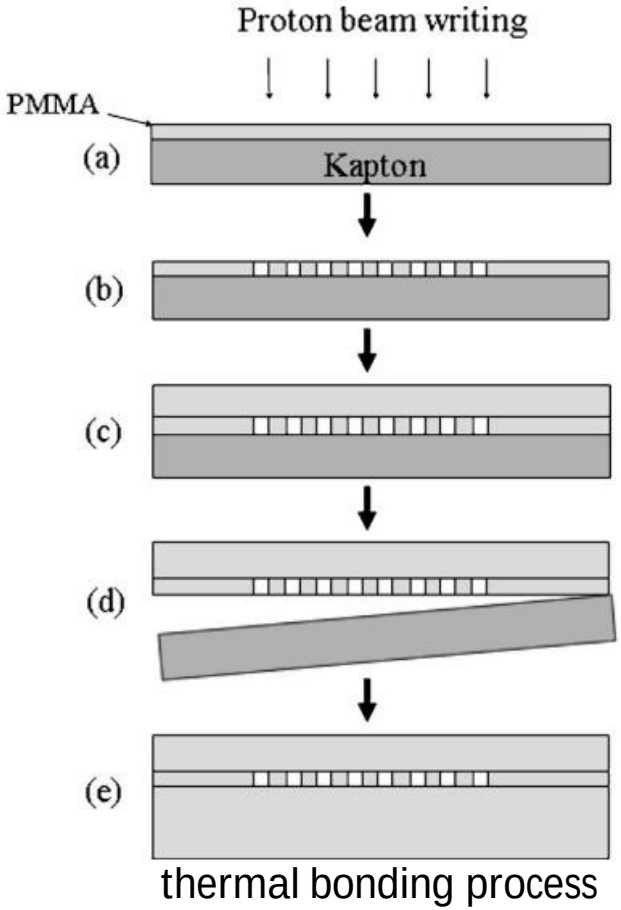

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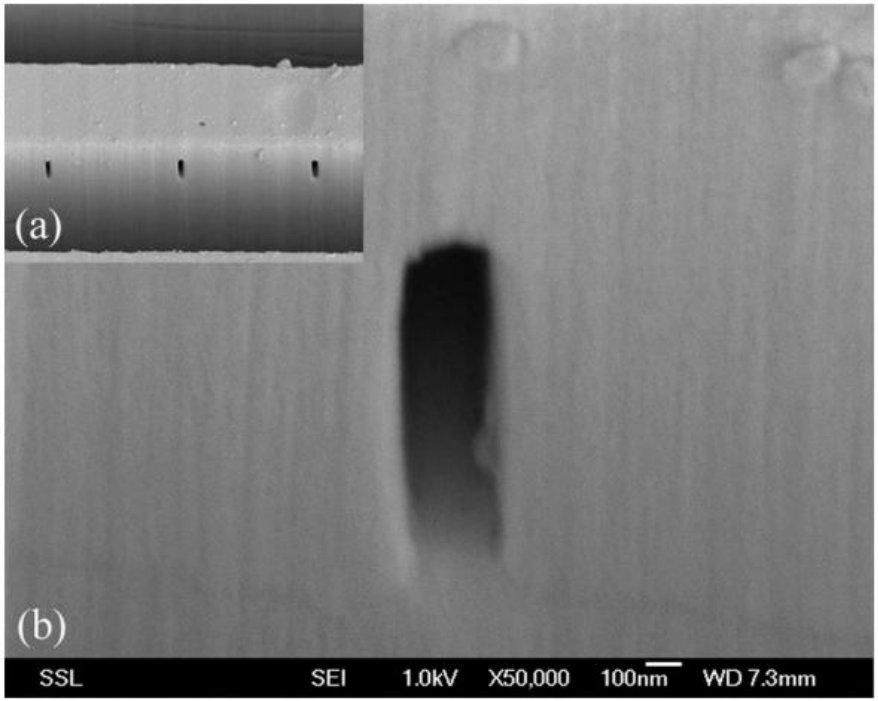
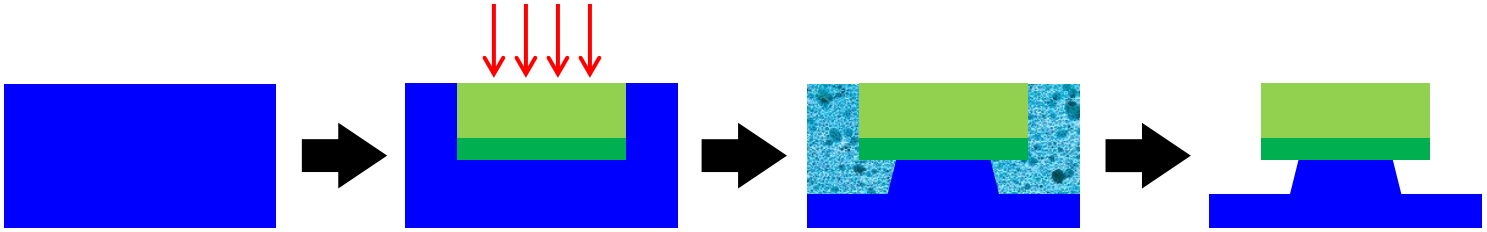


MeV Ion-beam lithography: Silicon



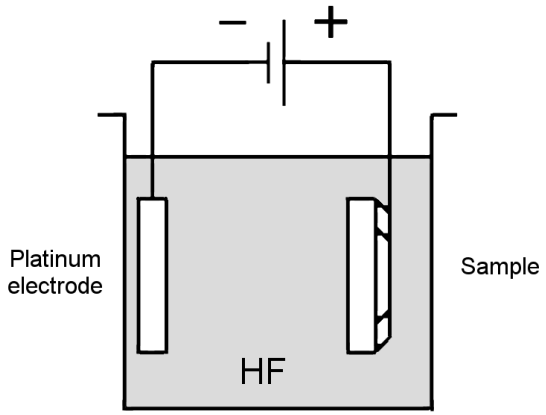
pristine Si

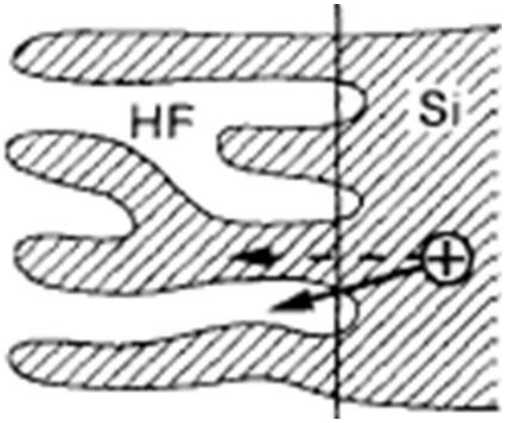
heavily damaged Si

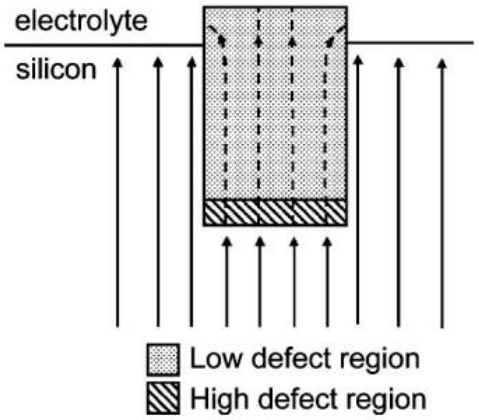
lightly damaged Si

porous Si

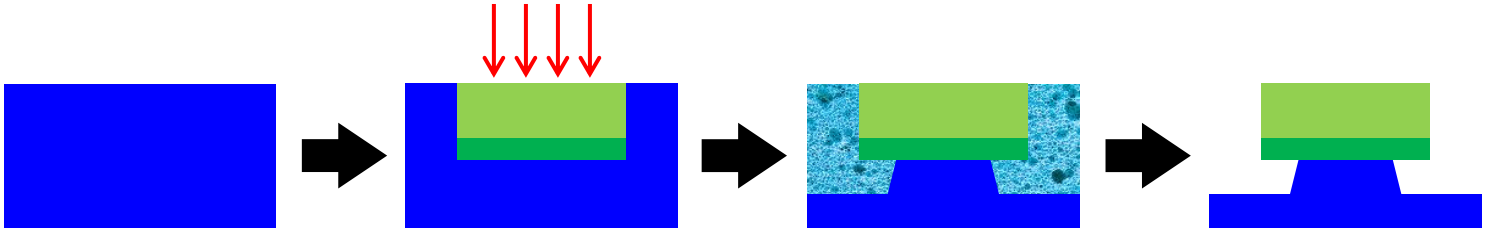
- Si sample
- MeV ion implantation
- electrochemical etching in HF
- wet chemical etching in KOH







MeV Ion-beam lithography: Silicon



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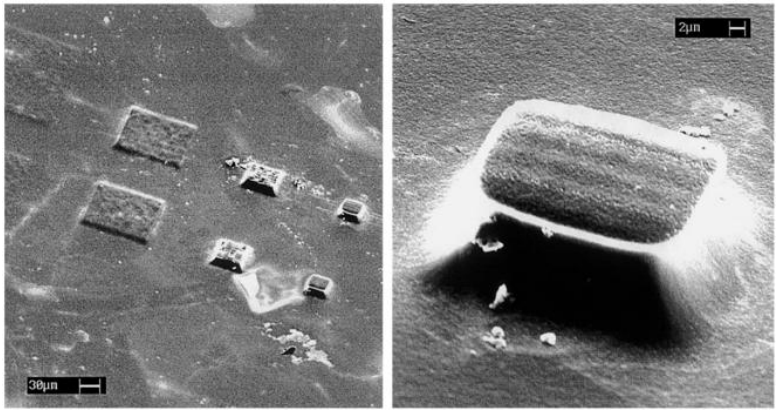
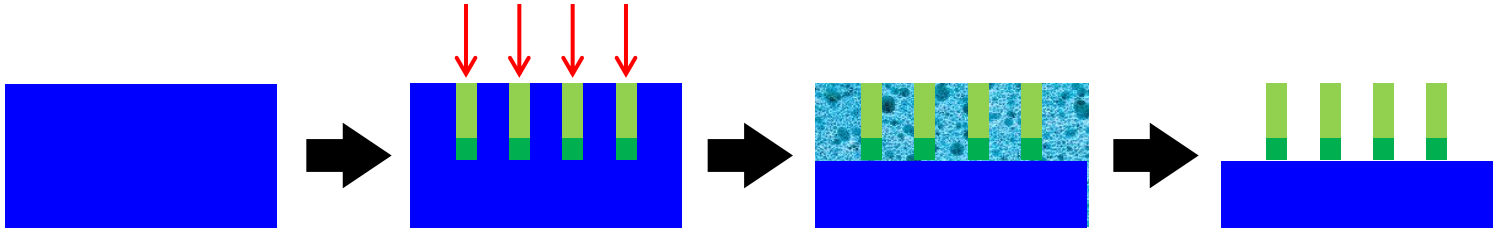
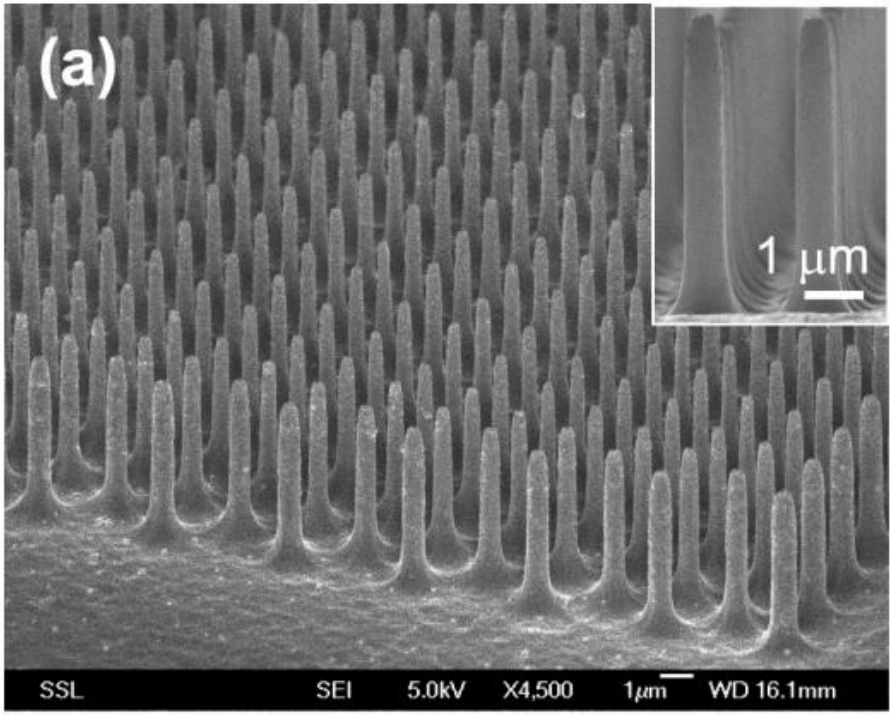


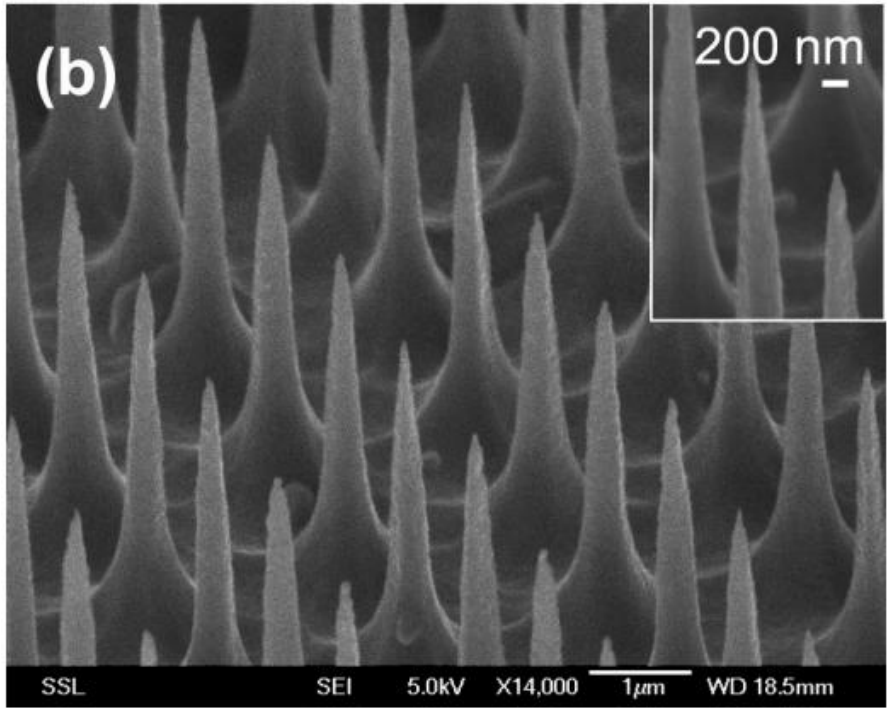
MeV Ion-beam lithography: Silicon



Micro-rod arrays

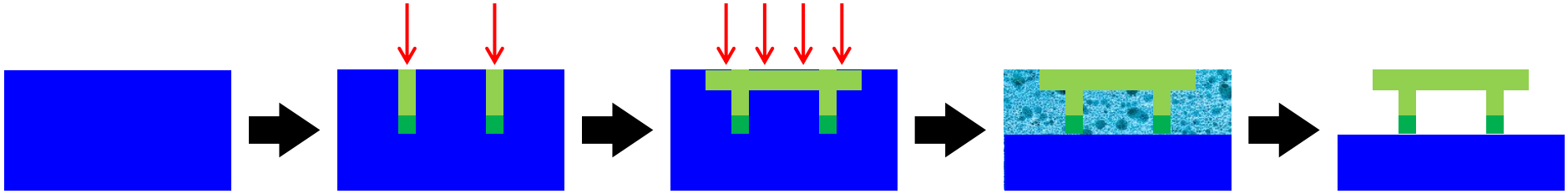


non-channeling implantation

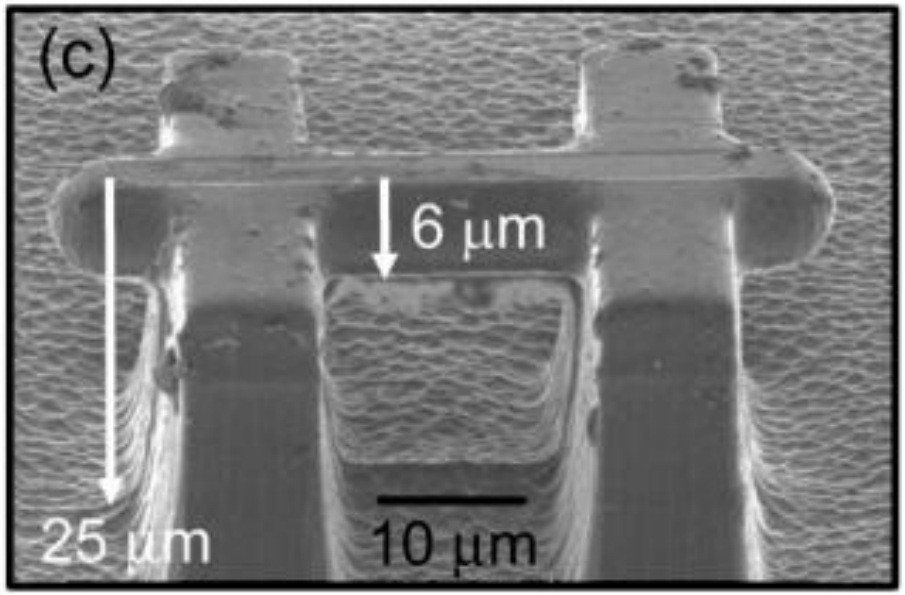


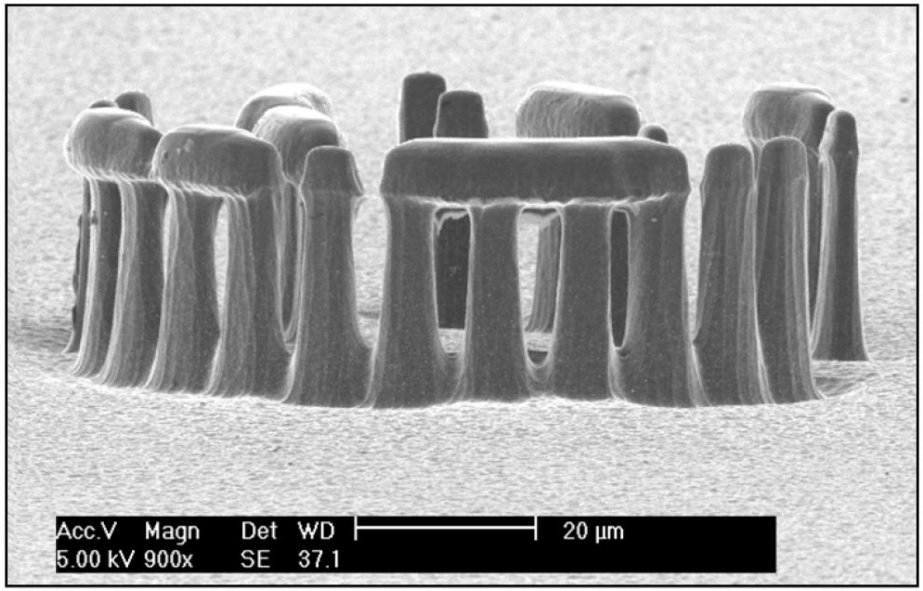
channeling implantation

MeV Ion-beam lithography: Silicon

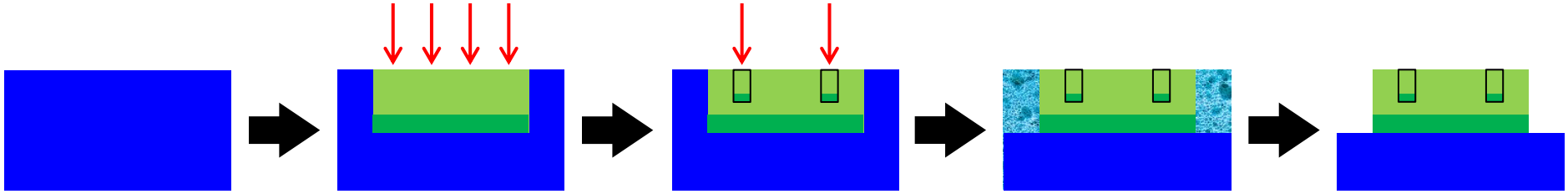


Three-dimensional structures

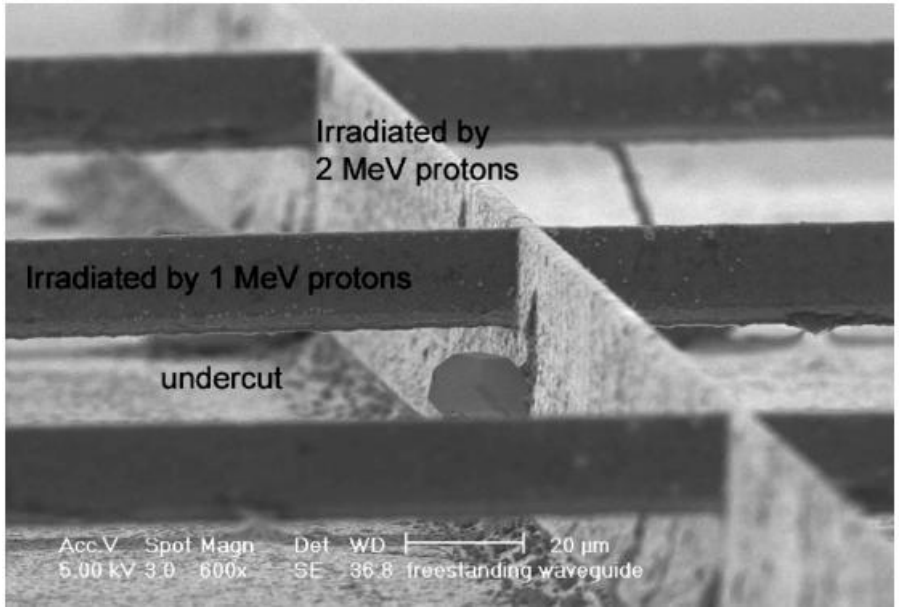


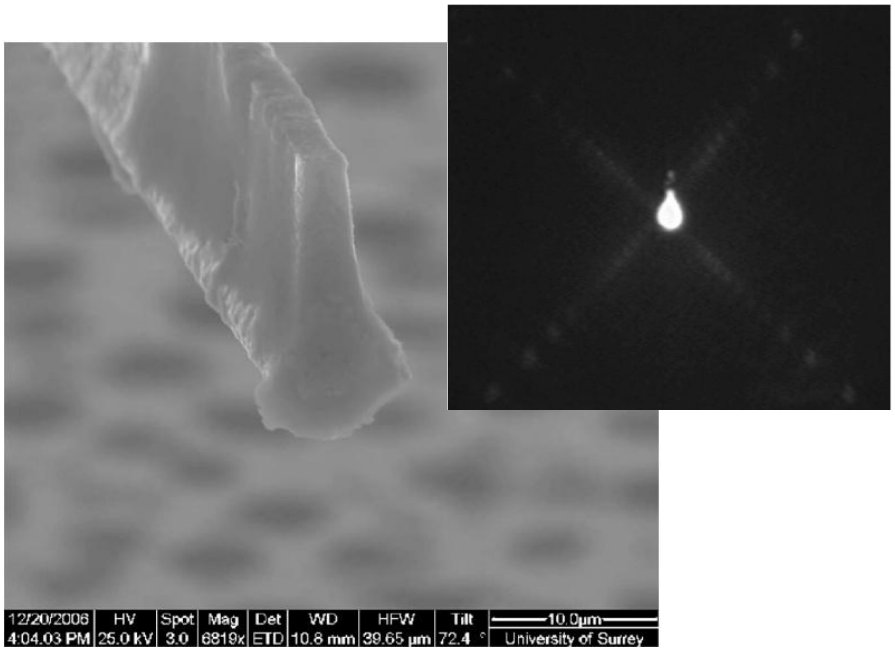


MeV Ion-beam lithography: Silicon

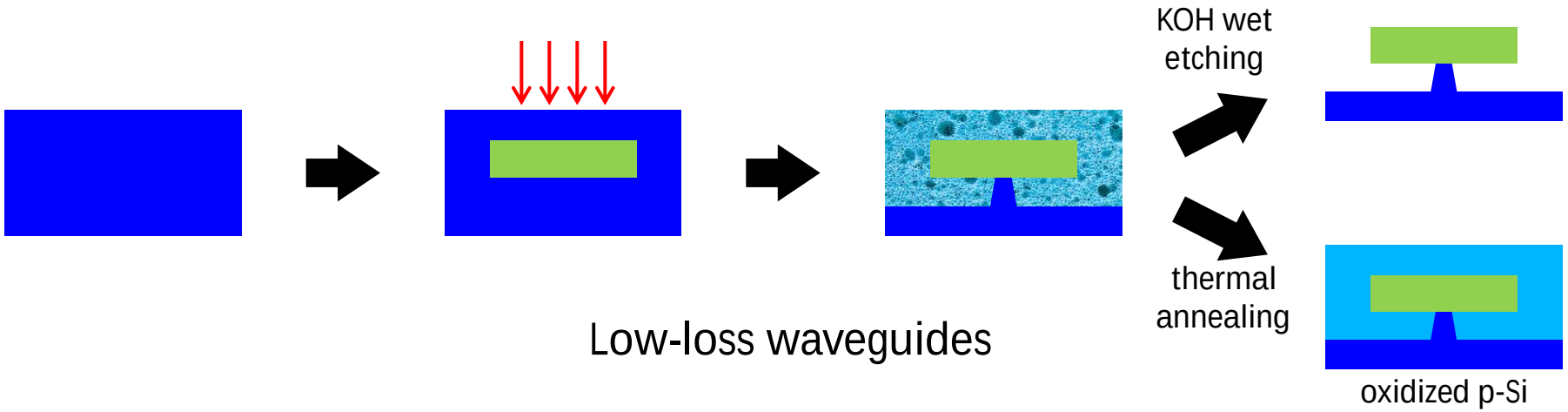


Free-standing waveguides

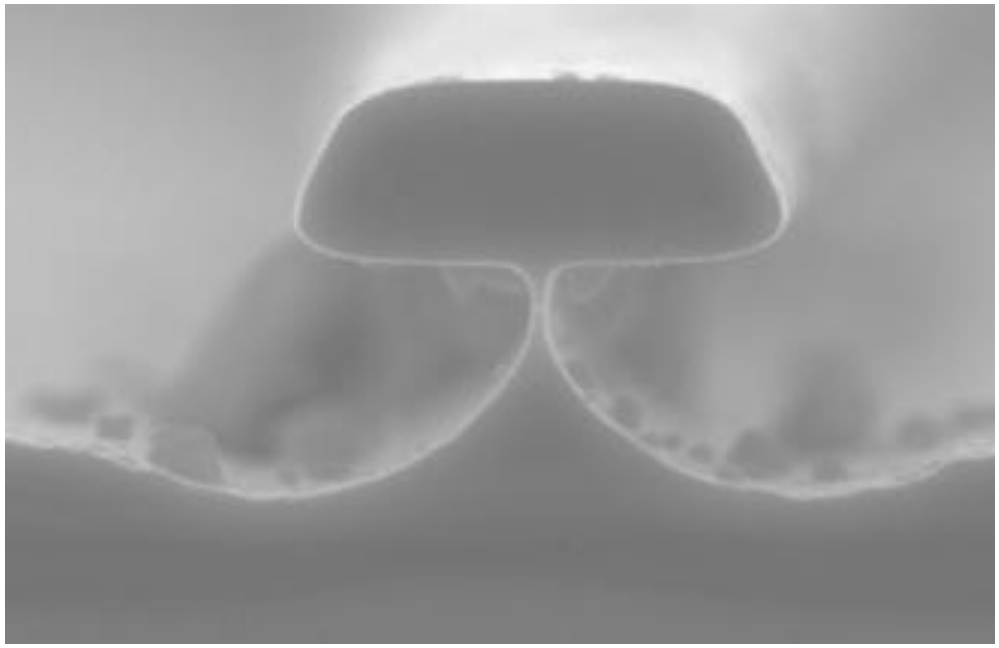


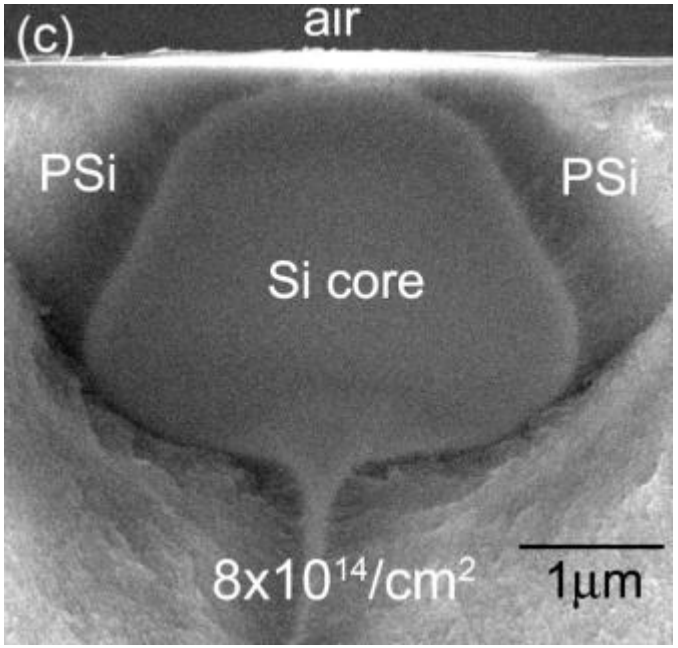


MeV Ion-beam lithography: Silicon



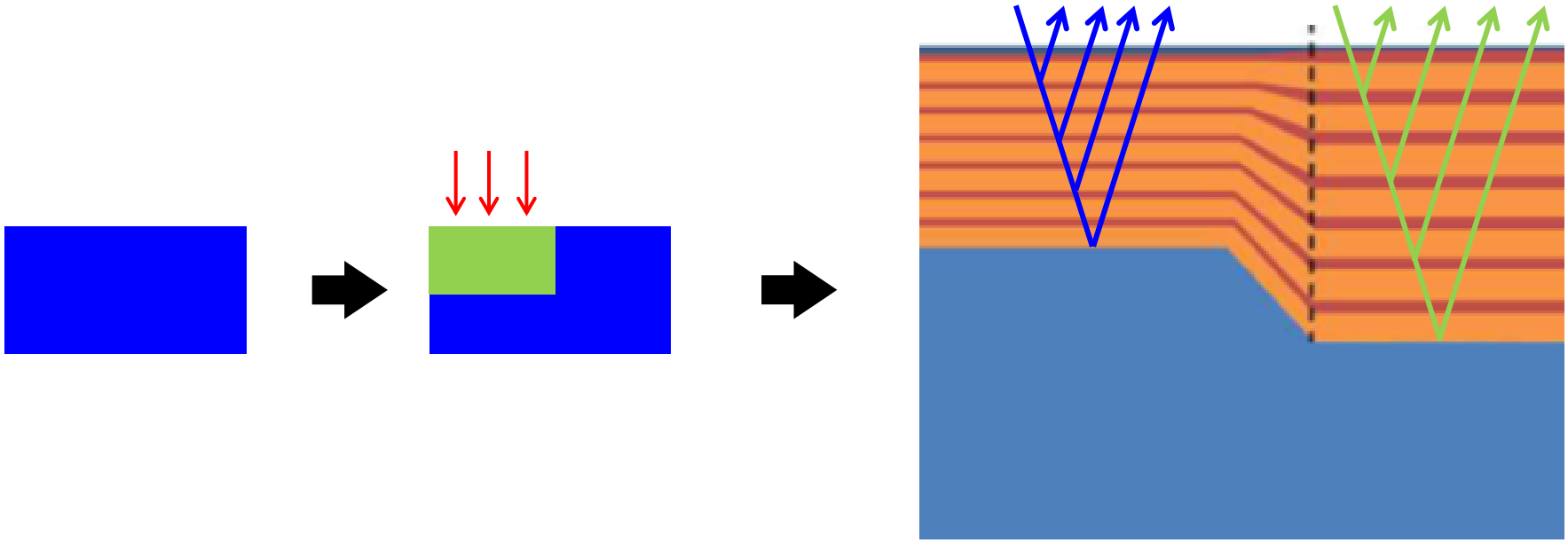
Low-loss waveguides





MeV Ion-beam lithography: Silicon

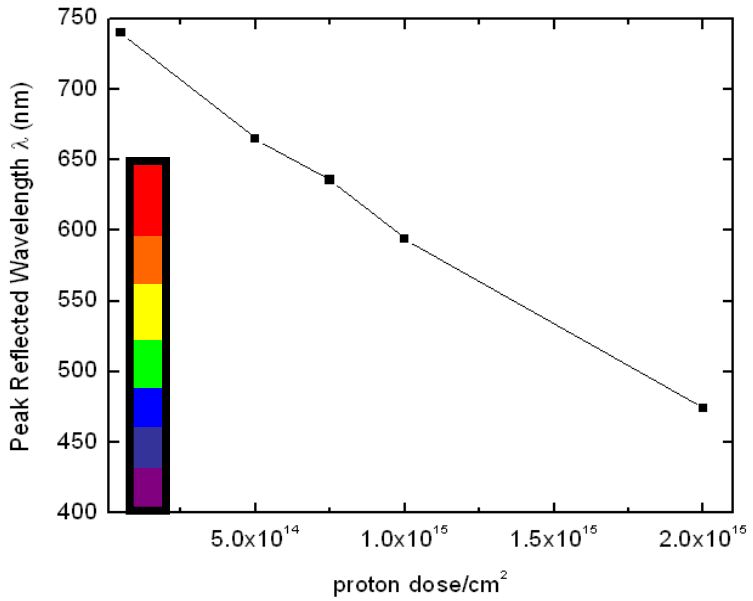
Bragg reflector

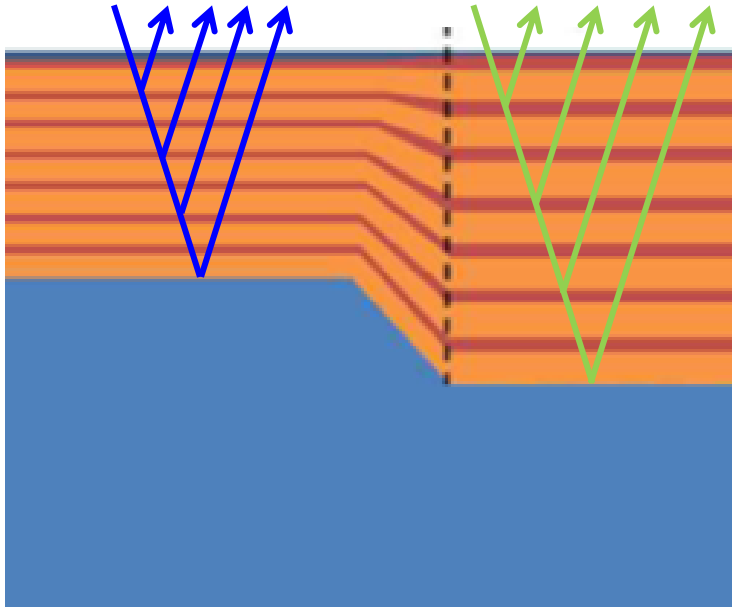


- **electrochemical etching in HF at different currents → different porosity →** different refractive index (1.2 – 3)
- **electrochemical etching in HF at alternating currents →** alternating layers of different refractive index
- Bragg law: $n \cdot \lambda = 2 \cdot d \cdot \sin(\theta)$

MeV Ion-beam lithography: Silicon

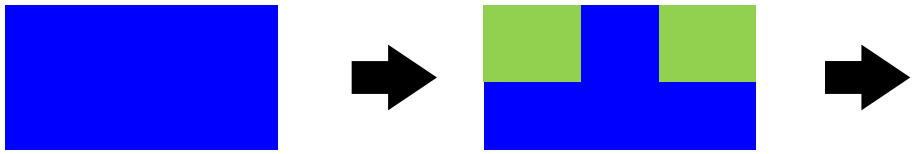
Bragg reflector

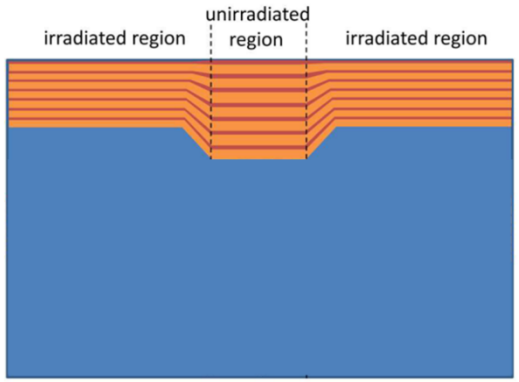




- **electrochemical etching in HF at different currents → different porosity →** different refractive index (1.2 – 3)
- **electrochemical etching in HF at alternating currents →** alternating layers of different refractive index
- Bragg law: $n \cdot \lambda = 2 \cdot d \cdot \sin(\theta)$
- **different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

MeV Ion-beam lithography: Silicon

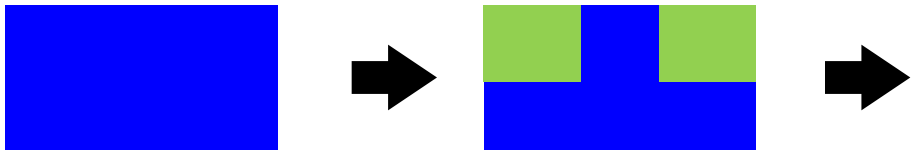


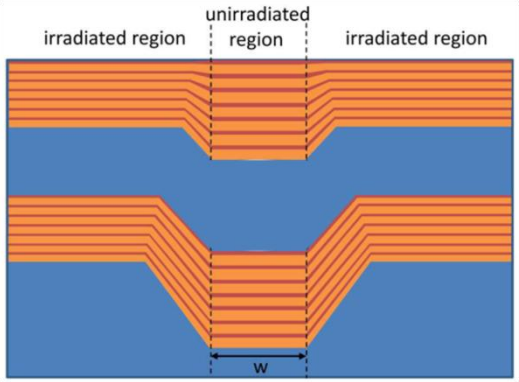


- electrochemical etching in HF at variable current
- modulation of the refractive index (1.2 – 3)

Bragg-cladding bulk waveguide

MeV Ion-beam lithography: Silicon





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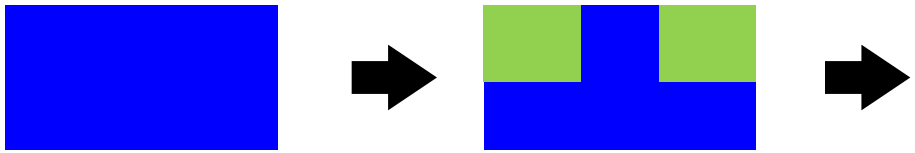
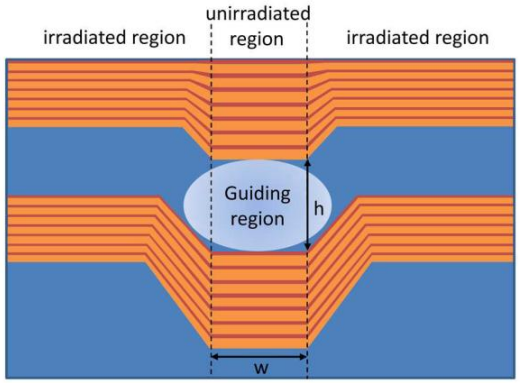
Bragg-cladding bulk waveguide

MeV Ion-beam lithography: Silicon





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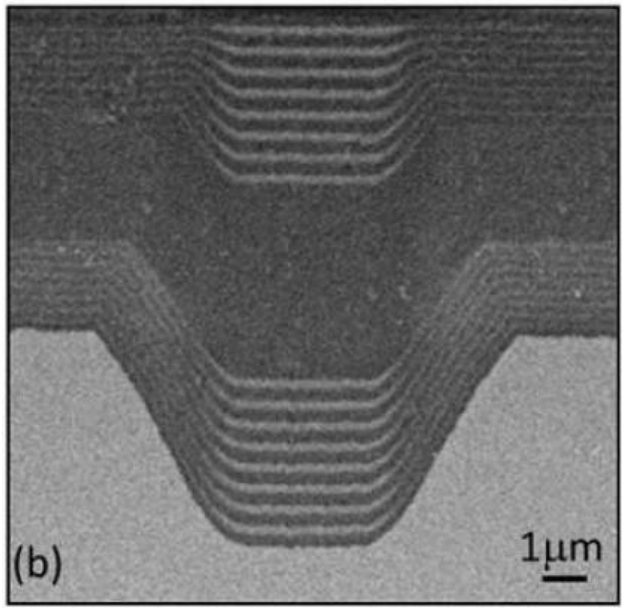
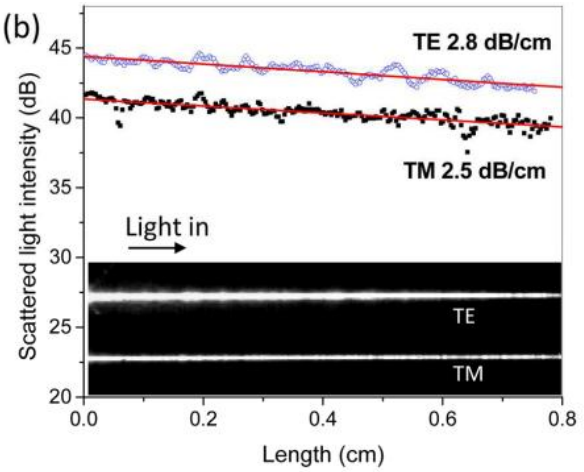
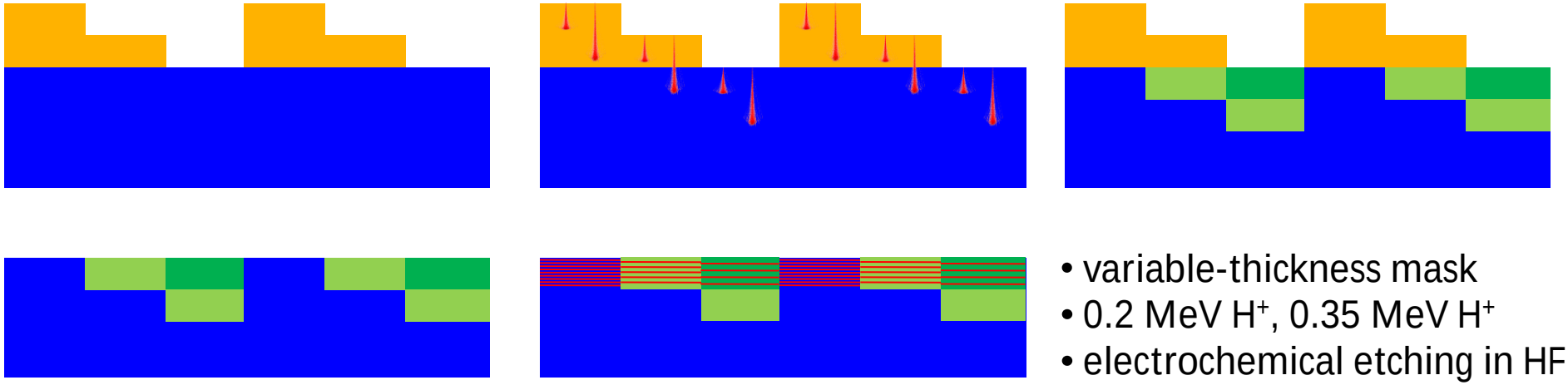
Bragg-cladding bulk waveguide



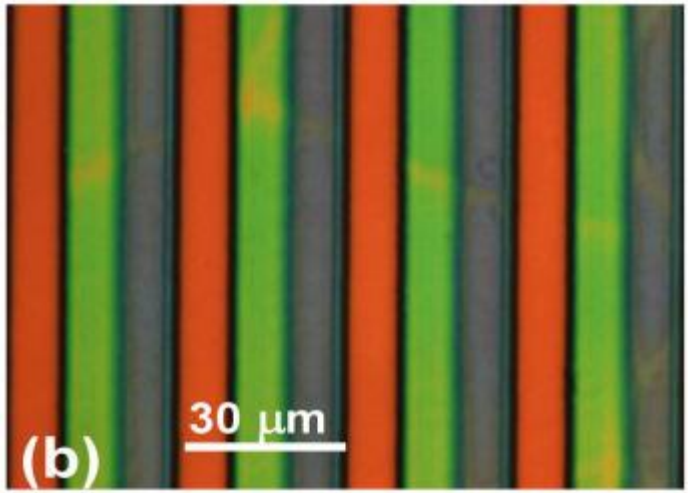


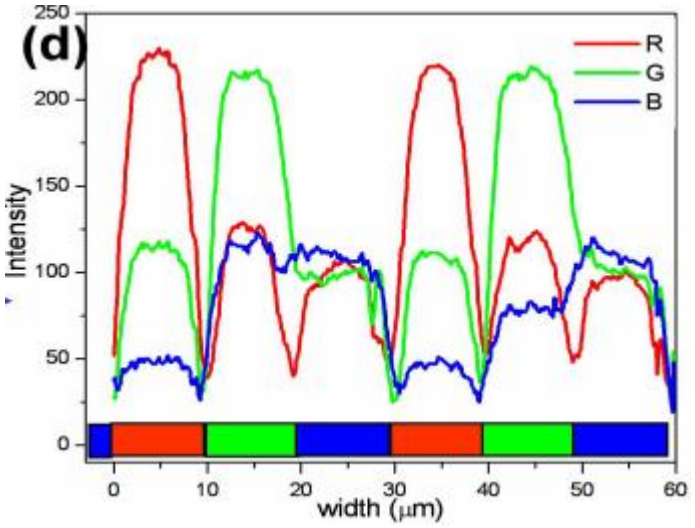
MeV Ion-beam lithography: Silicon



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

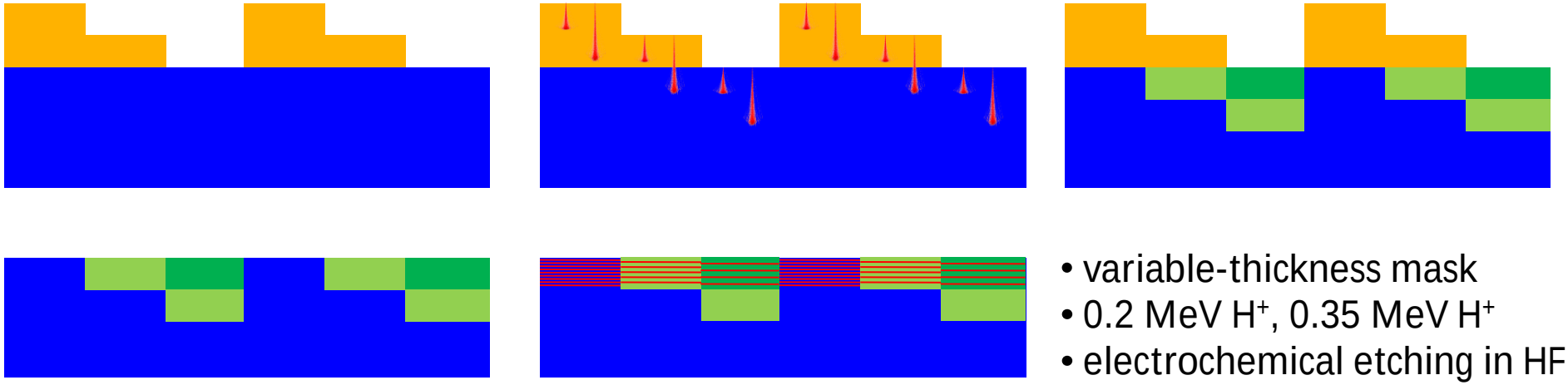
Local modification of the refractive index → Distributed Bragg reflector





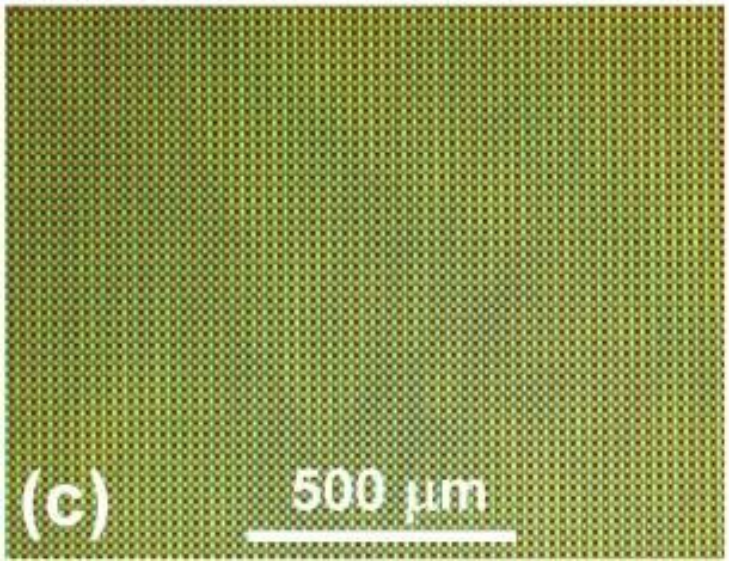
@ : CIBA – National University of Singapore

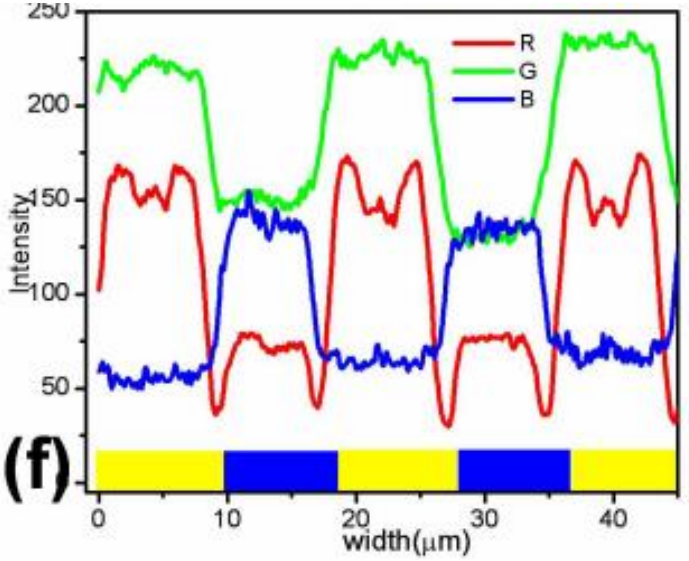
MeV Ion-beam lithography: Silicon



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

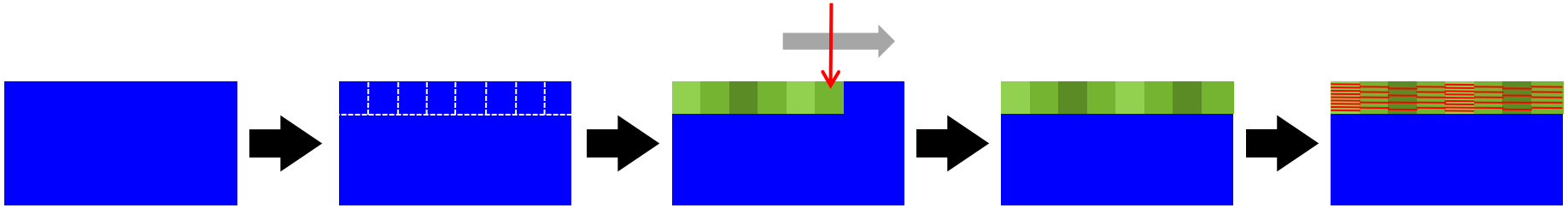
Four implantation energies, 2-**D mask geometry → Pixel array**





@ : CIBA – National University of Singapore

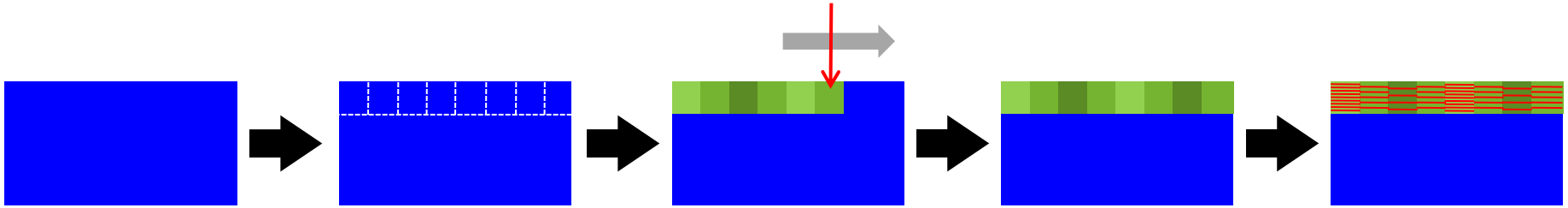
MeV Ion-beam lithography: Silicon



Refractive index modulation with a scanning microprobe

“The Red Armchair”, Picasso (1931)

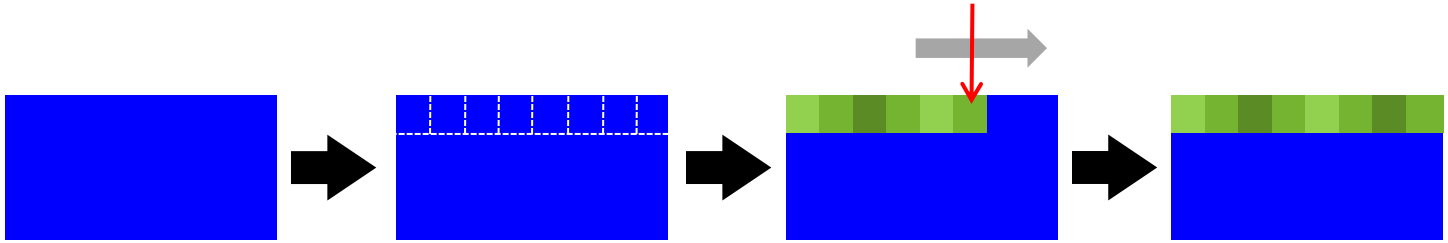
MeV Ion-beam lithography: Silicon



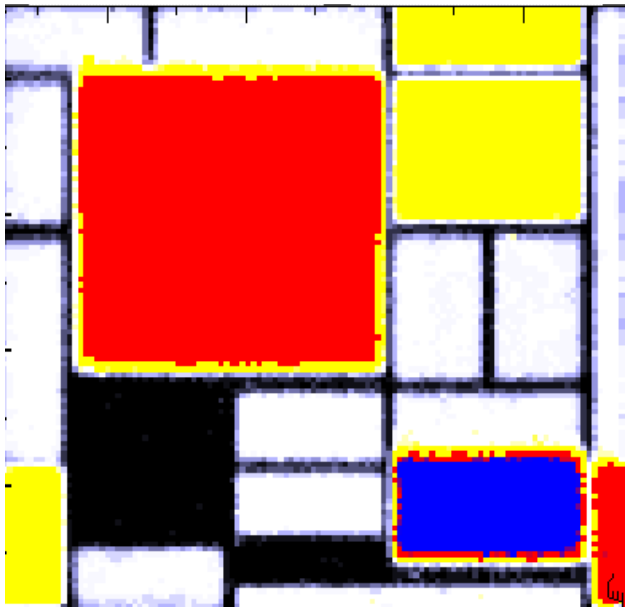
Refractive index modulation with a scanning microprobe

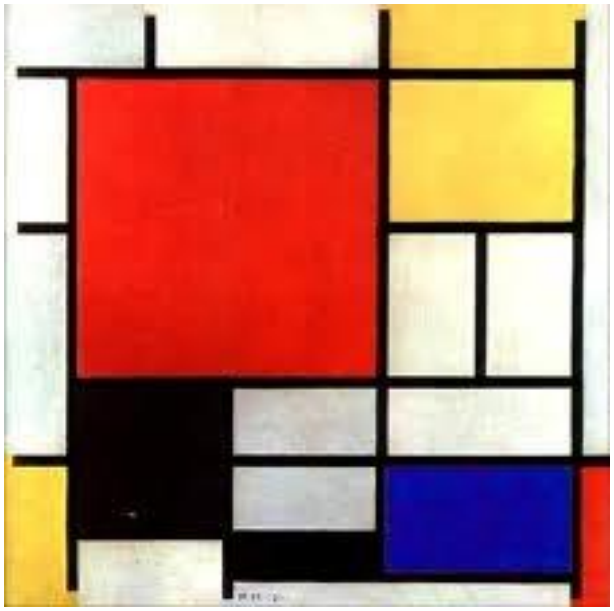
“The Dance”, Matisse (1910)

MeV Ion-beam lithography: Silicon



Charge Collection Efficiency modulation with a scanning microprobe

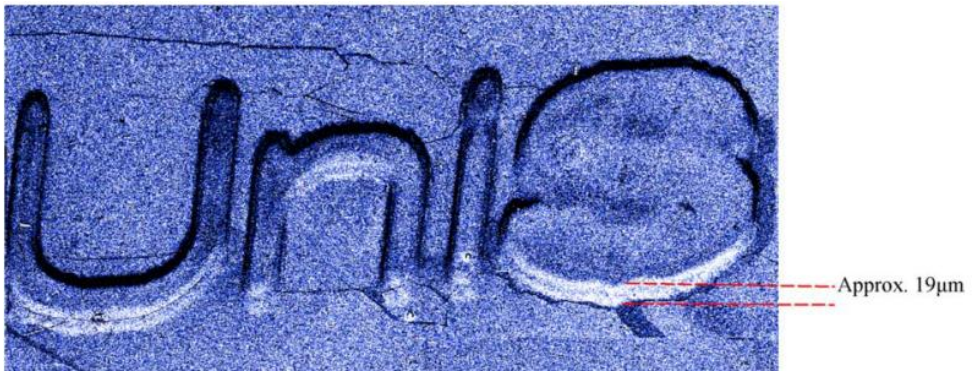


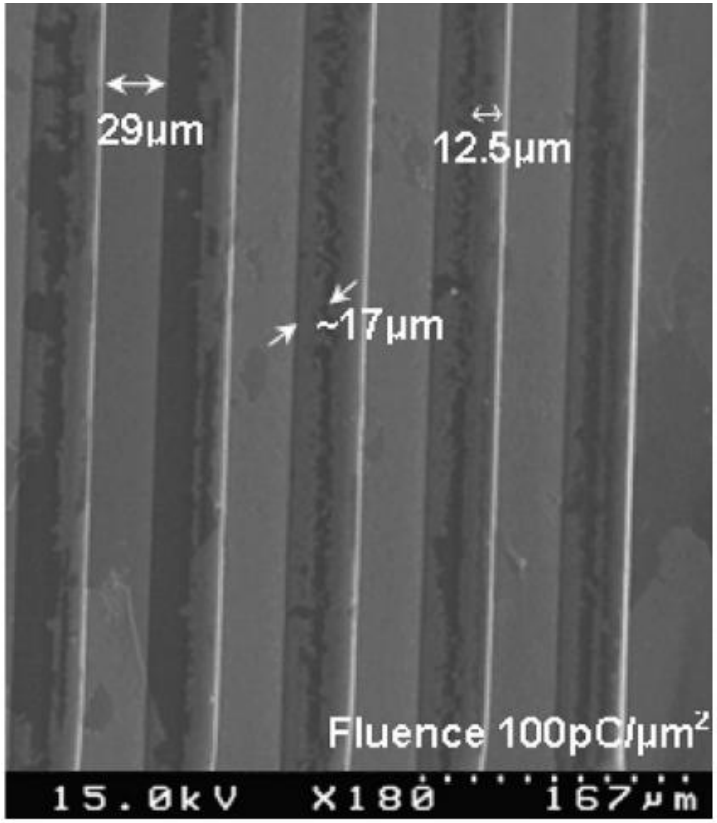


P. Mondrian

MeV IBL: Other materials

Gallium Arsenide

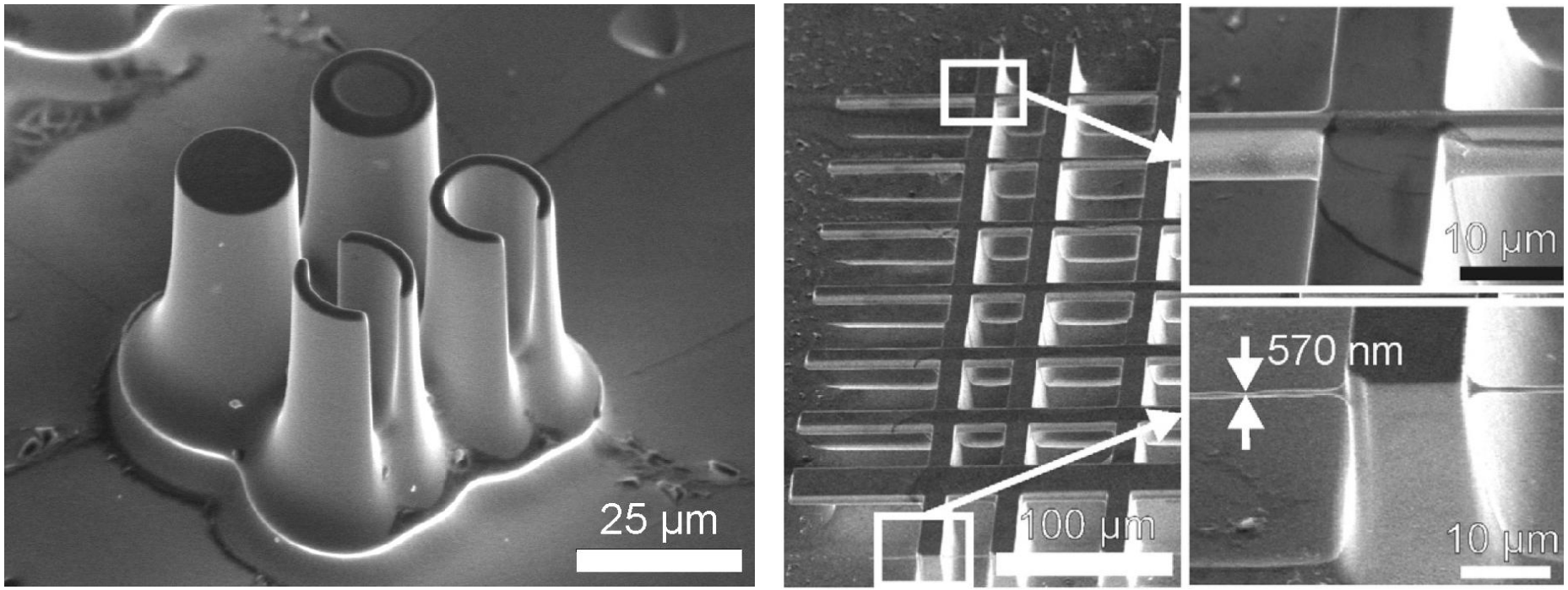




Negative process based on the modulation of the material sensitivity to reactive ion etching

MeV IBL: Other materials

Indium Phosphide

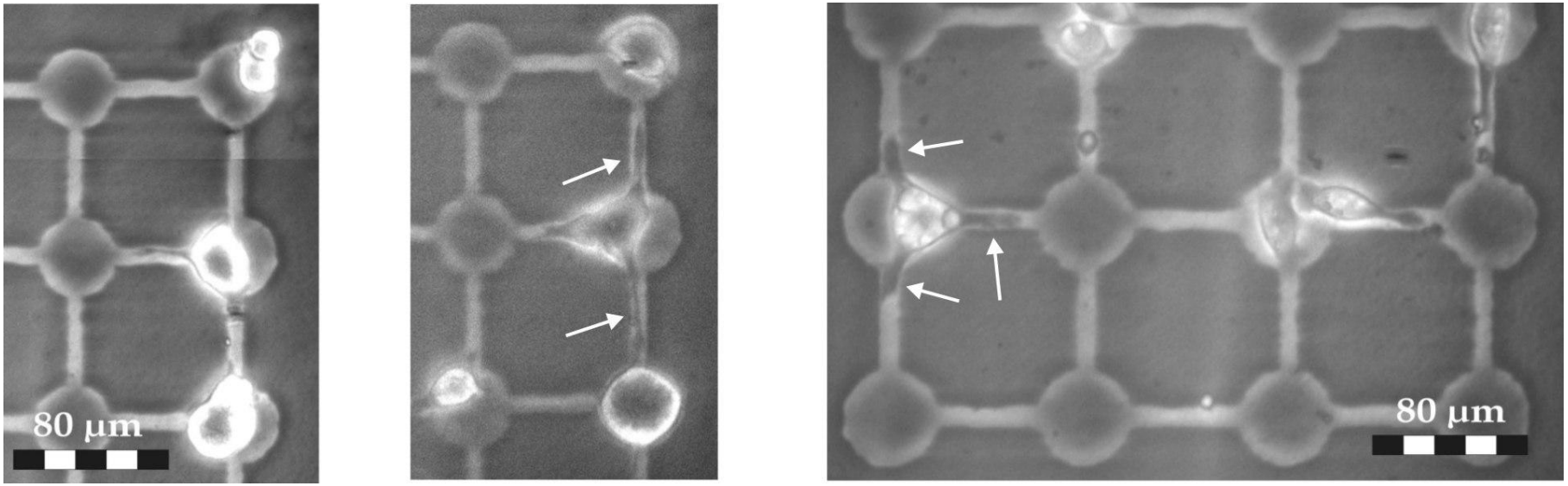


Negative process based on the modulation of the material sensitivity
to electrochemical etching (→ Si)

@ : LIPSION – University of Leipzig

MeV IBL: Other materials

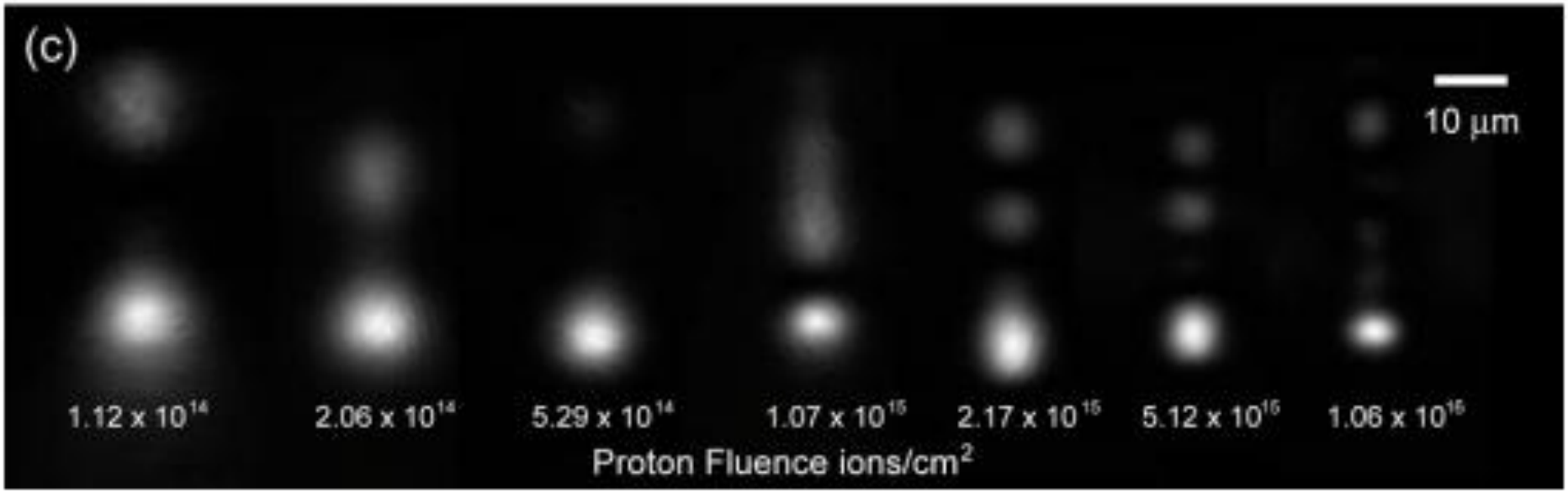
Agar gel



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

MeV IBL: Other materials

Photo-sensitive glass (Foturan™)

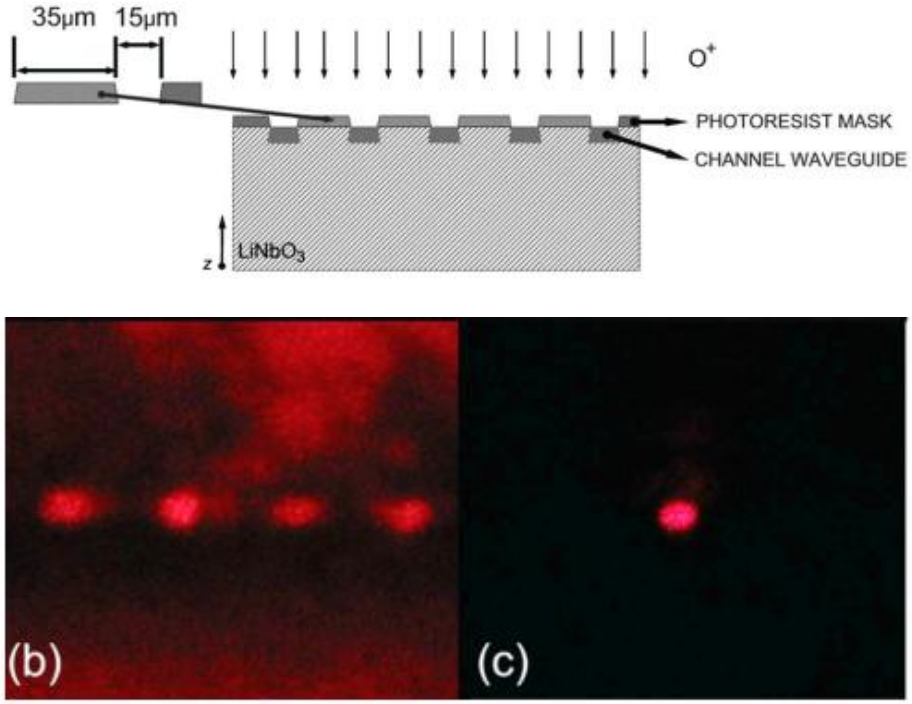


Modulation of the refractive index by 2 MeV H^+-induced damage

@ : CIBA – National University of Singapore

MeV IBL: Other materials

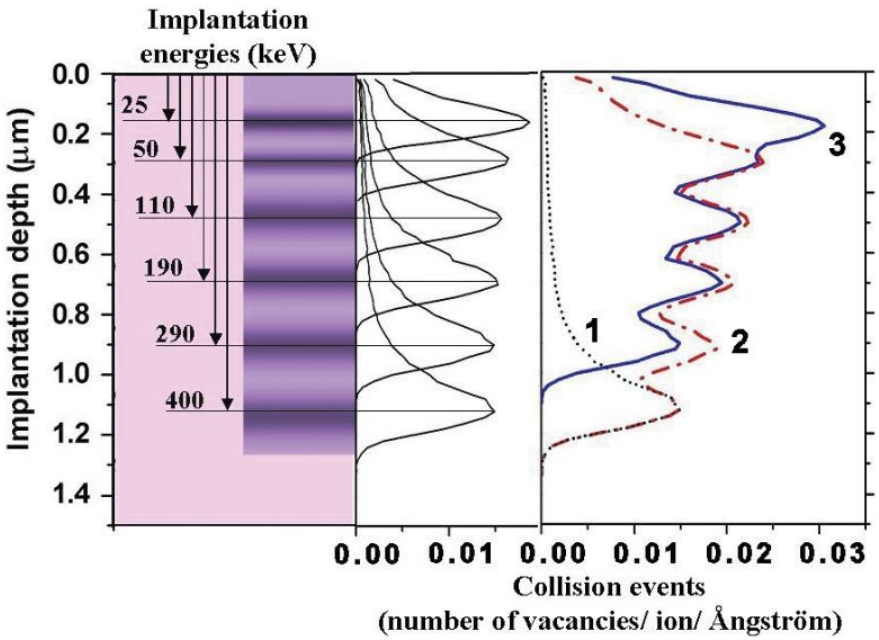
$LiNbO_3$ (non-linear optics applications)

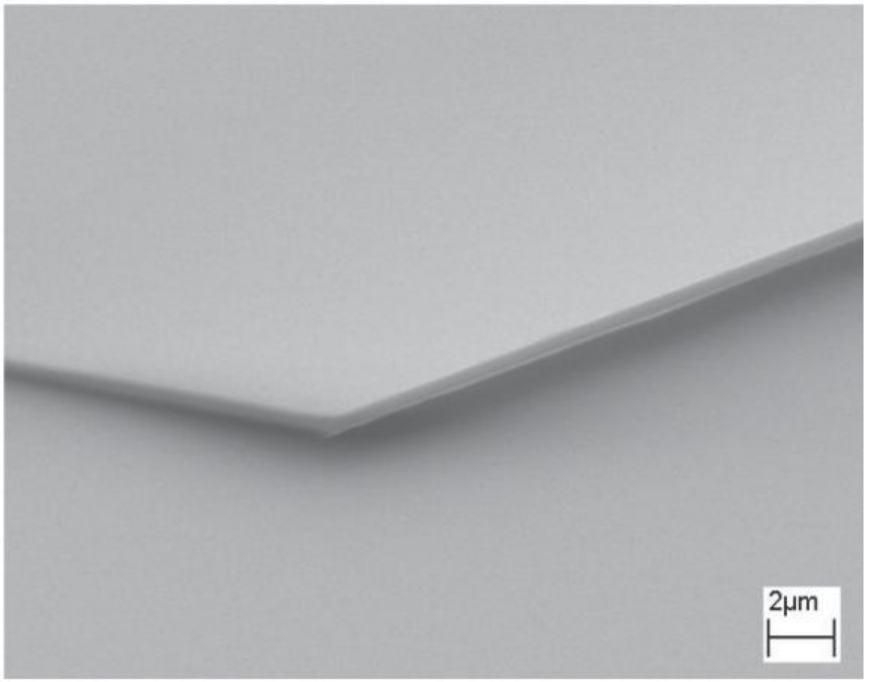


Modulation of the refractive index by 1.6-2.2 MeV O^{3+} induced damage

MeV IBL: Other materials

Sapphire



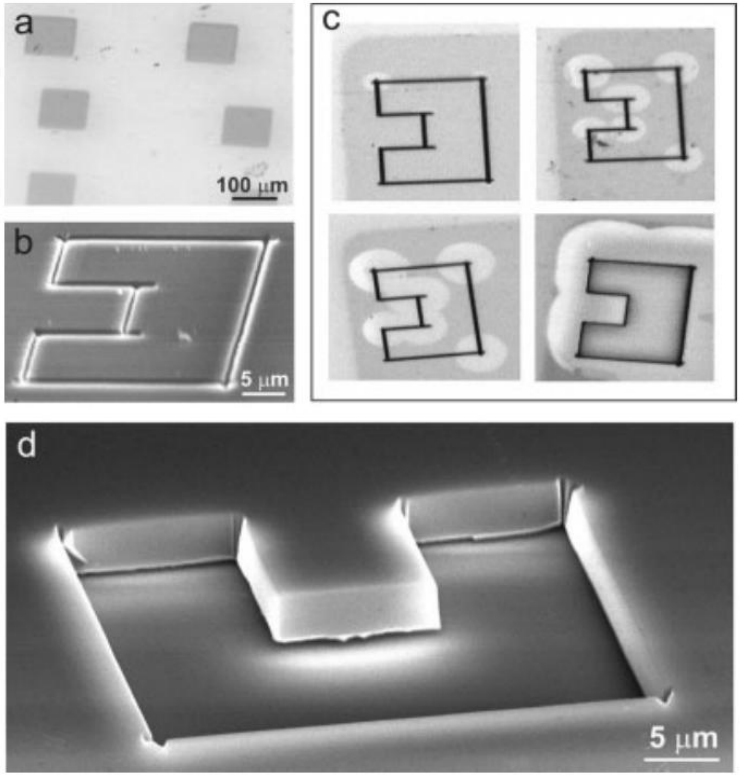


Lift-off in sapphire based on He^+ ion implantation

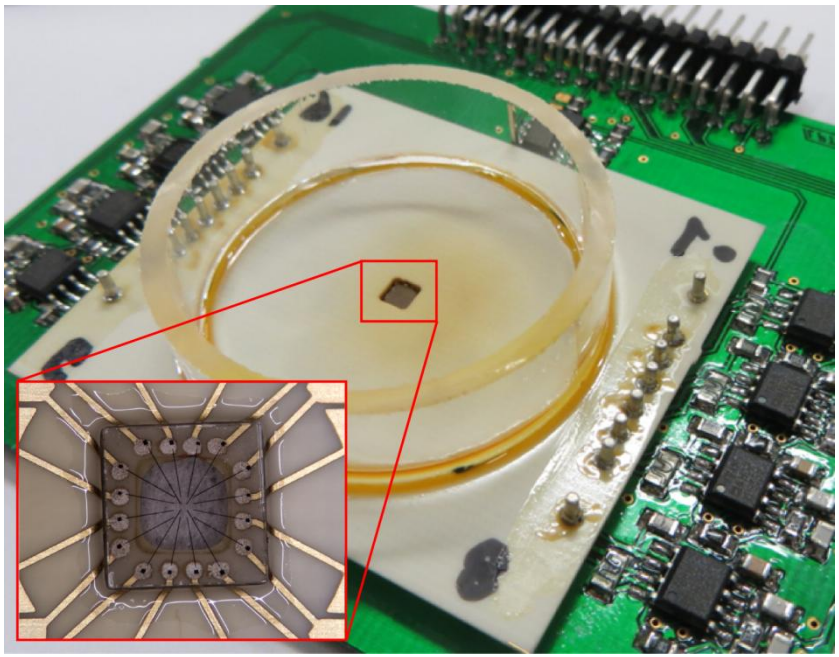
Positive process based on change in reactivity to wet chemical etching

MeV IBL: Other materials

Diamond



FIB-assisted lift-off technique



Direct ion-beam writing
of electrically conductive graphitic structures

@ : University of Melbourne, University of Torino

MeV IBL: Single ion doping

"Conventional" ion implantaton:
Statistical/macroscopic approach
Fluence = # · $10^{\#}$ ions cm-2

↓

"Single ion" implantation
Deterministic, single-particle approach
# of implanted ions per step = 1, 2, 3, …

Motivations

- Miniaturization in integrated devices: the number of dopants per active area is fast approaching the ~10 range → **variability in devices operation**
- Development of quantum computers: single dopants in semiconductors = qbits encoders

MeV IBL: Single ion doping

Experimental considerations

Ion beam source: significantly reduce the ion current and introduce beam-blanking functionalities

Deterministic doping: 3 main approaches:

1) statistical approach: post-selection of single implanted ions (not scalable)
2) detect the single-ion impact event with IBIC, secondary electron **emission, … (**requires high detection efficiency)
3) pre-determine the single ion implantation at the source level (requires high efficiency in the qbit creation)

Spatial resolution: 3 main approaches:

1) highly focused ion beam
2) collimated beams
3) masked samples

MeV IBL: Single ion doping

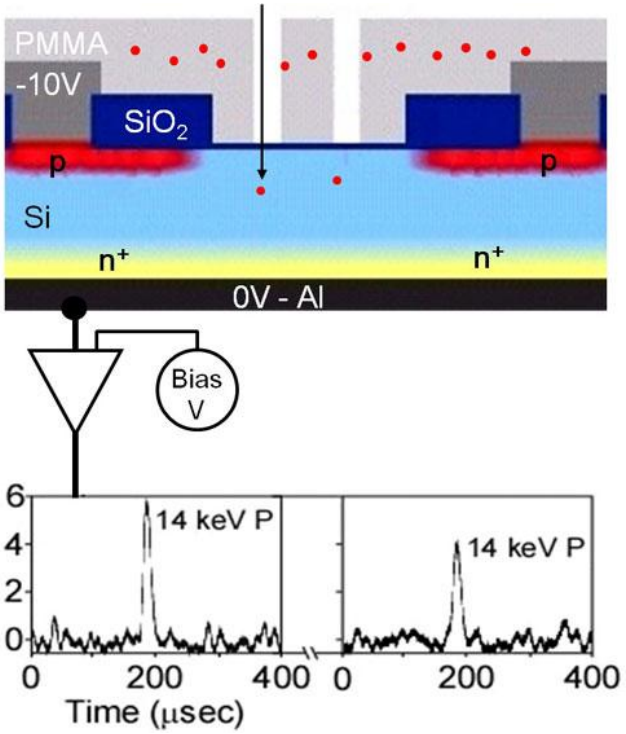
Examples

Single P implantation in masked & active Si substrates

Implanted ions: ~10 keV P (low lateral straggling)

Detection: IBIC signal in active substrate

Spatial resolution: masked sample



MeV IBL: Single ion doping

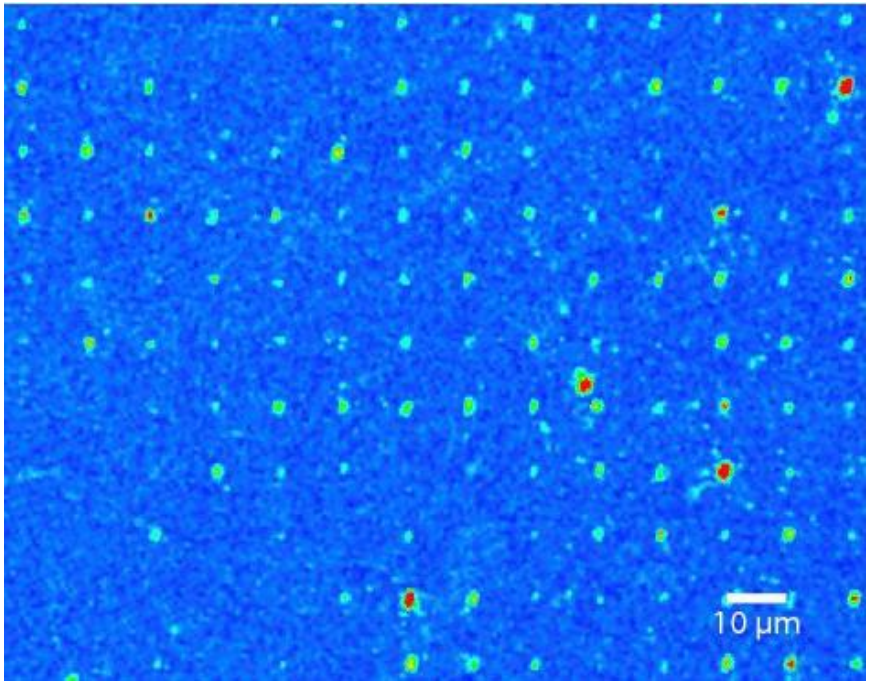
Examples

Creation of single optical centers in diamond substrates
by implantation of focused MeV N ions

Ion energy: ~1 MeV N (high lateral straggling, relatively high creation efficiency)

Detection: statistical approach, post-selection

Spatial resolution: focused ion beam (~ 1 µm)



Ref: Appl. Phys. A 83(2), 321 (2006)

MeV IBL: Single ion doping

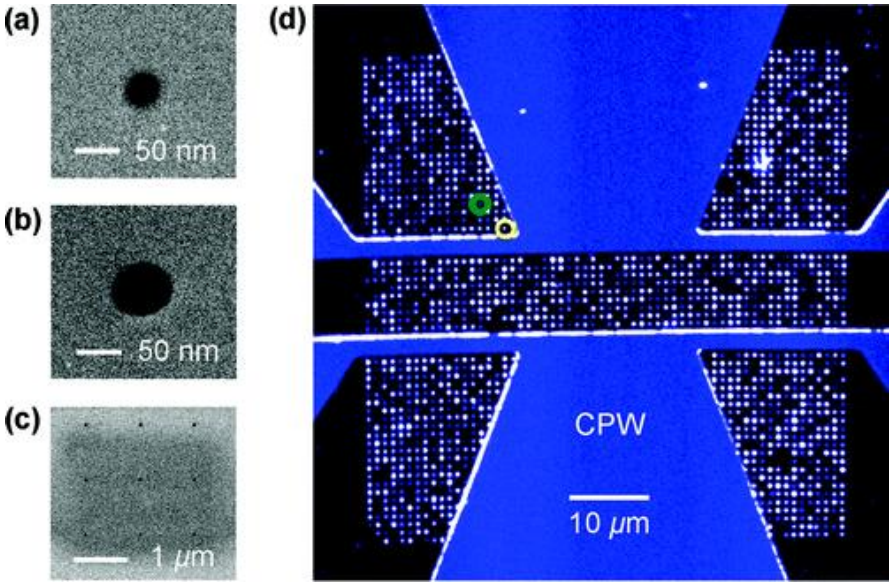
Examples

Creation of single optical centers in diamond substrates
by implantation of collimated keV N ions

Ion energy: ~10 keV N

Detection: statistical approach, post-selection

Spatial resolution: collimated ion beam (~50 nm)



Ref: Nano Lett. 10 (8), 3168 (2010)

MeV IBL: Single ion doping

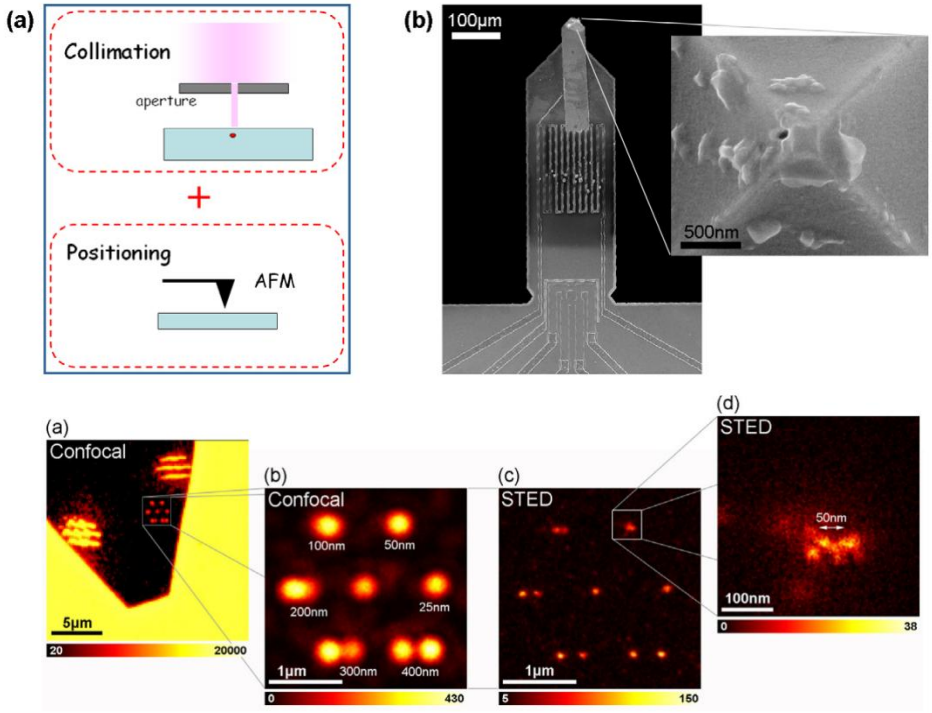
Examples

Creation of single optical centers in diamond substrates
by implantation of collimated keV N ions

Ion energy: ~10 keV N

Detection: statistical approach, post-selection

Spatial resolution: collimated ion beam through an AFM tip (~50 nm)

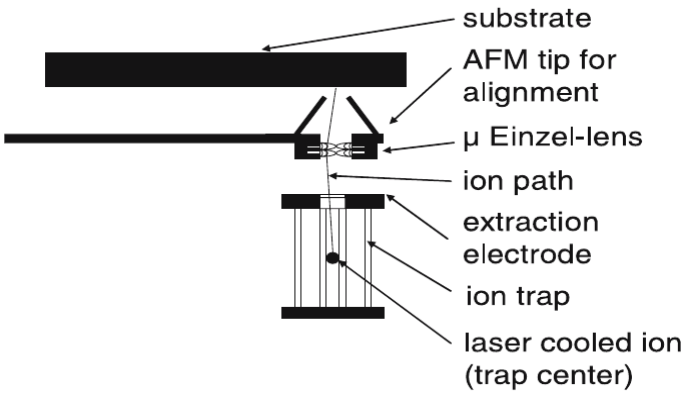


Ref: New J. Phys. 13, 035024 (2011)

MeV IBL: Single ion doping

Examples

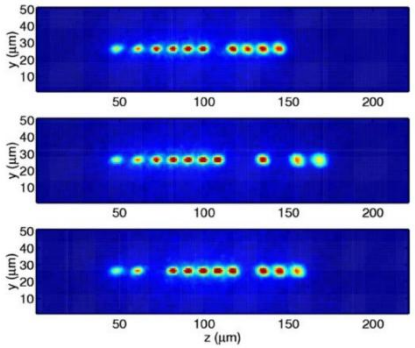
Creation of single optical centers in diamond substrates
by implantation of collimated keV N ions



Ion energy: ~10 keV N

Detection: single-ion emission from
laser-cooled ion trap

Spatial resolution: collimated ion
beam through an AFM tip (~50 nm)



Ref: Nano Lett. 10 (8), 3168 (2010)