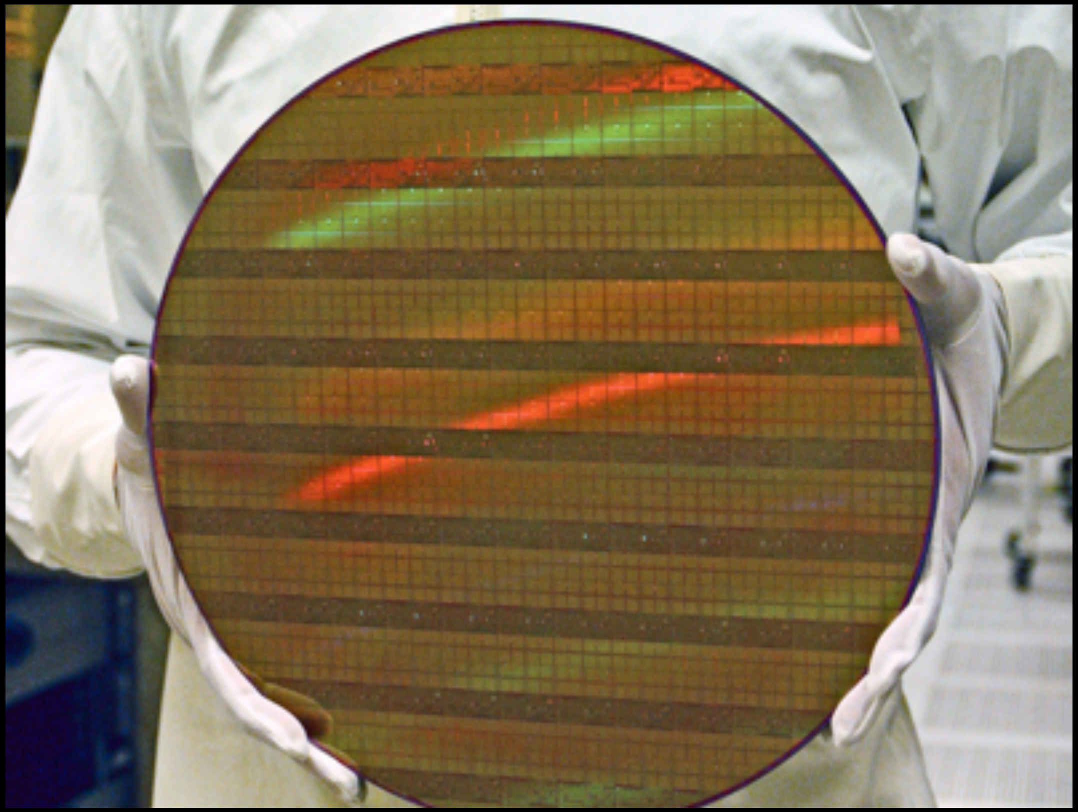
Highly charged ion beams applied to fabrication of Nano-scale 3D structures

Sadao MOMOTA
Kochi University of Technology

Prospect of microscopic structures

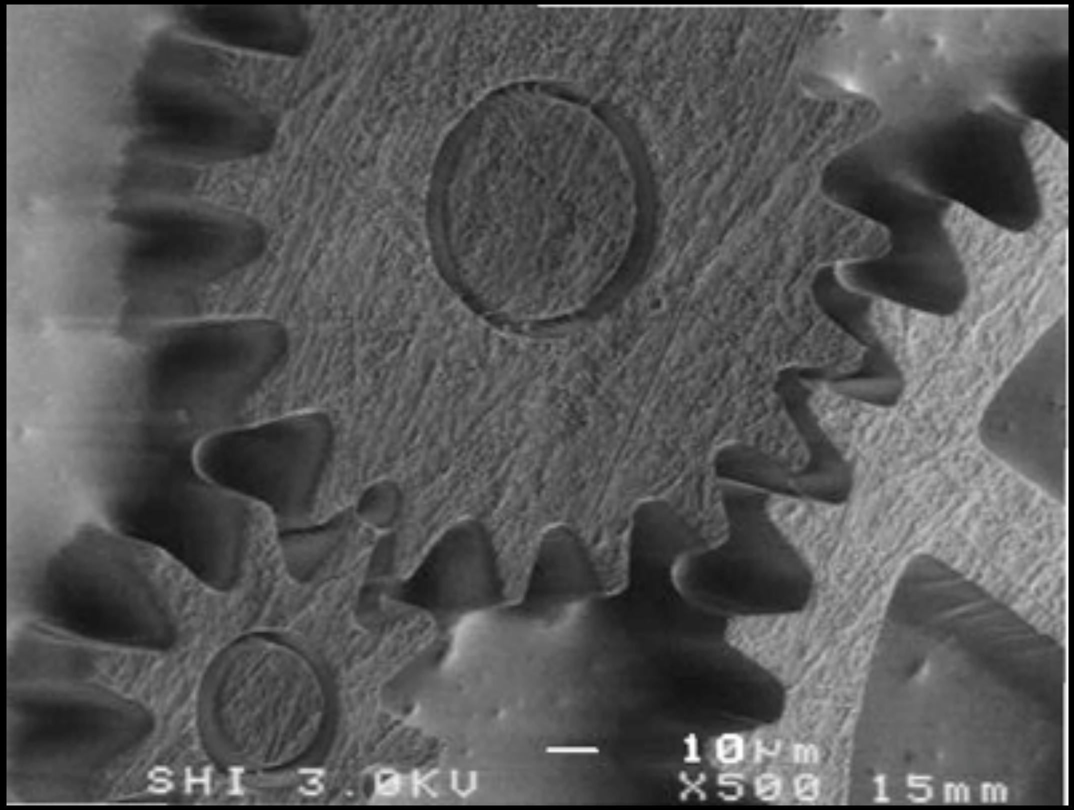
2D

Semiconductor



3D

Ex. MEMS



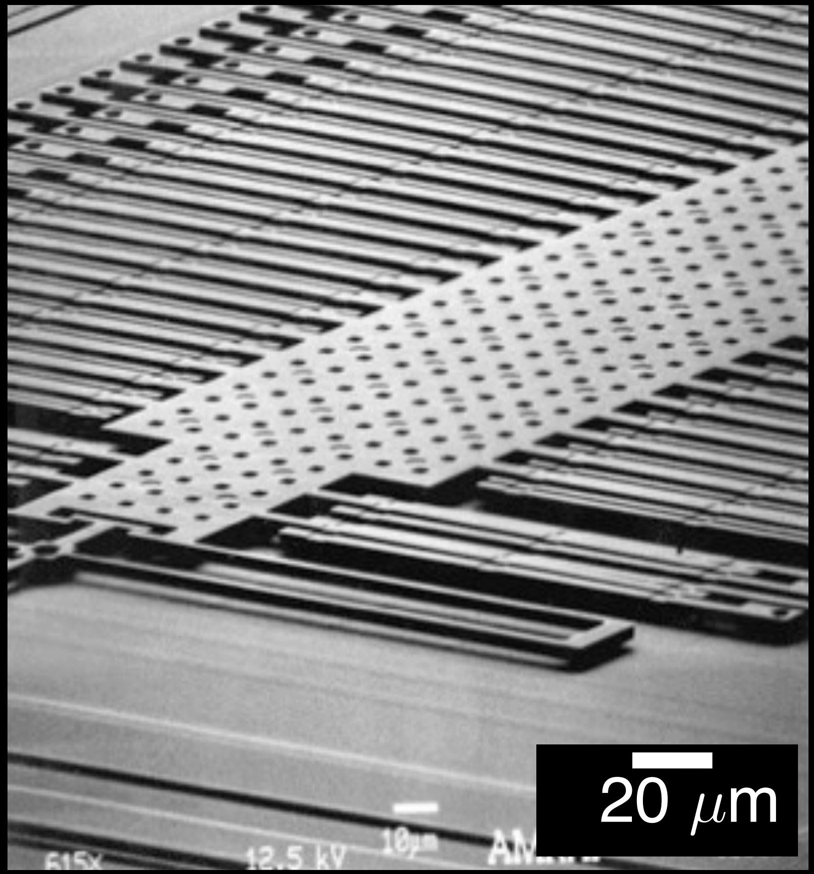
http://www.rise.waseda.ac.jp/proj/sci/S98S08/j-S98S08.html

Application of 3D structures

- MEMS

  Micro Electro Mechanical System
- Biochip
- Mold

ex. 3-Axis Accelerometer



Analog Devices Co.

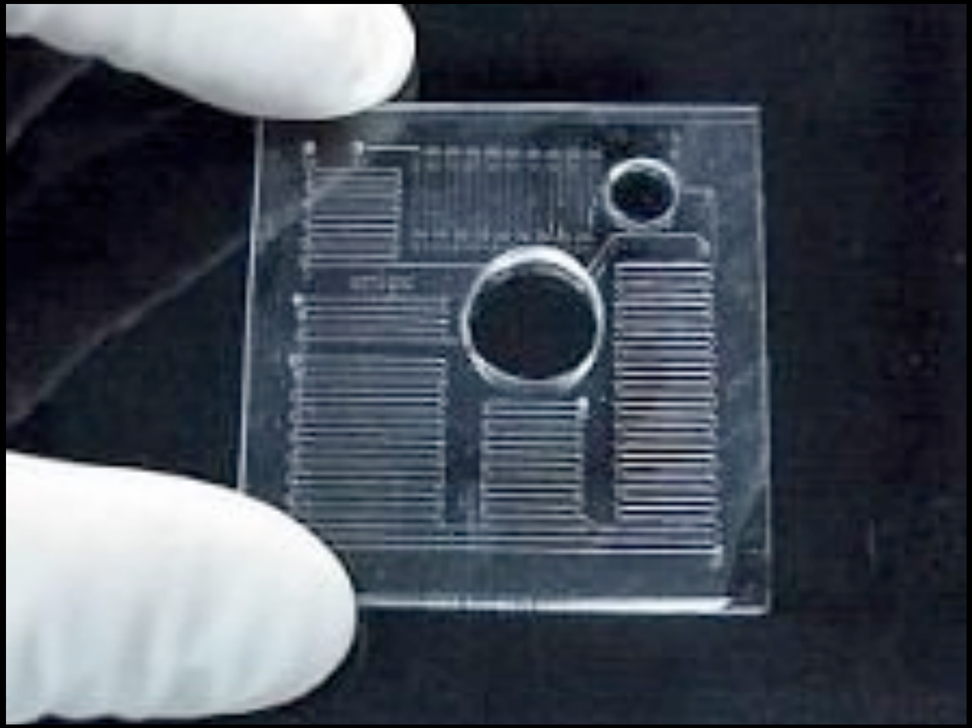
Application of 3D structures

- MEMS

  Micro Electro Mechanical System

- Biochip
- Mold

ex. Micro inspection chip



Hitachi, Ltd.

Application of 3D structures

- MEMS

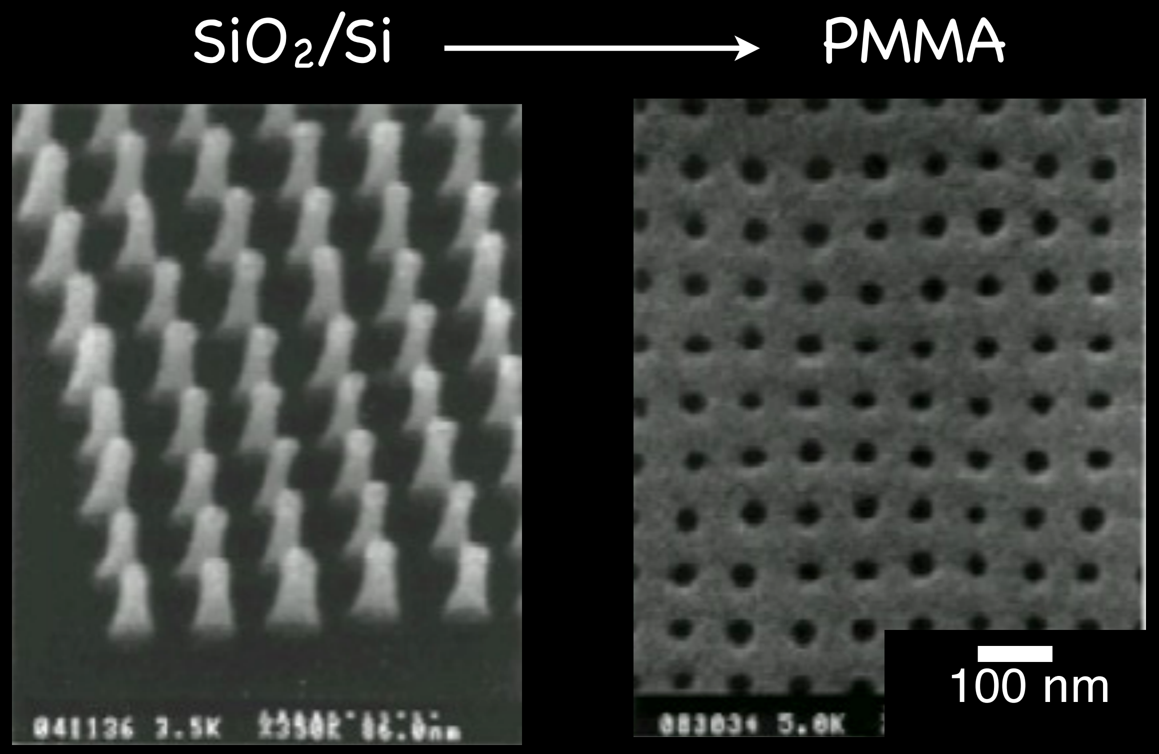
  Micro Electro Mechanical System

- Biochip

- Mold

ex. Pattern transfer

10nm diam. & 60nm pitch



S.Y. Chou et al.
J. Vac. Sci. Technol., B15(1997)2897

To be developed

Fabrication process with

1. High precision/controllability in vertical direction
2. Efficient and simple process
3. Small-size facility

Hopeful candidate

Ion beams

because

1. Small angular struggling
2. High reactivity
3. Controllable range

Hopeful candidate

Highly Charged Ion (HCI) beams

Hopeful candidate

Highly Charged Ion (HCI) **beams**

because of

- ✓ remarkably high reactivity
- ✓ extension of Rp

Hopeful candidate

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↓

IB litho. & swelling process

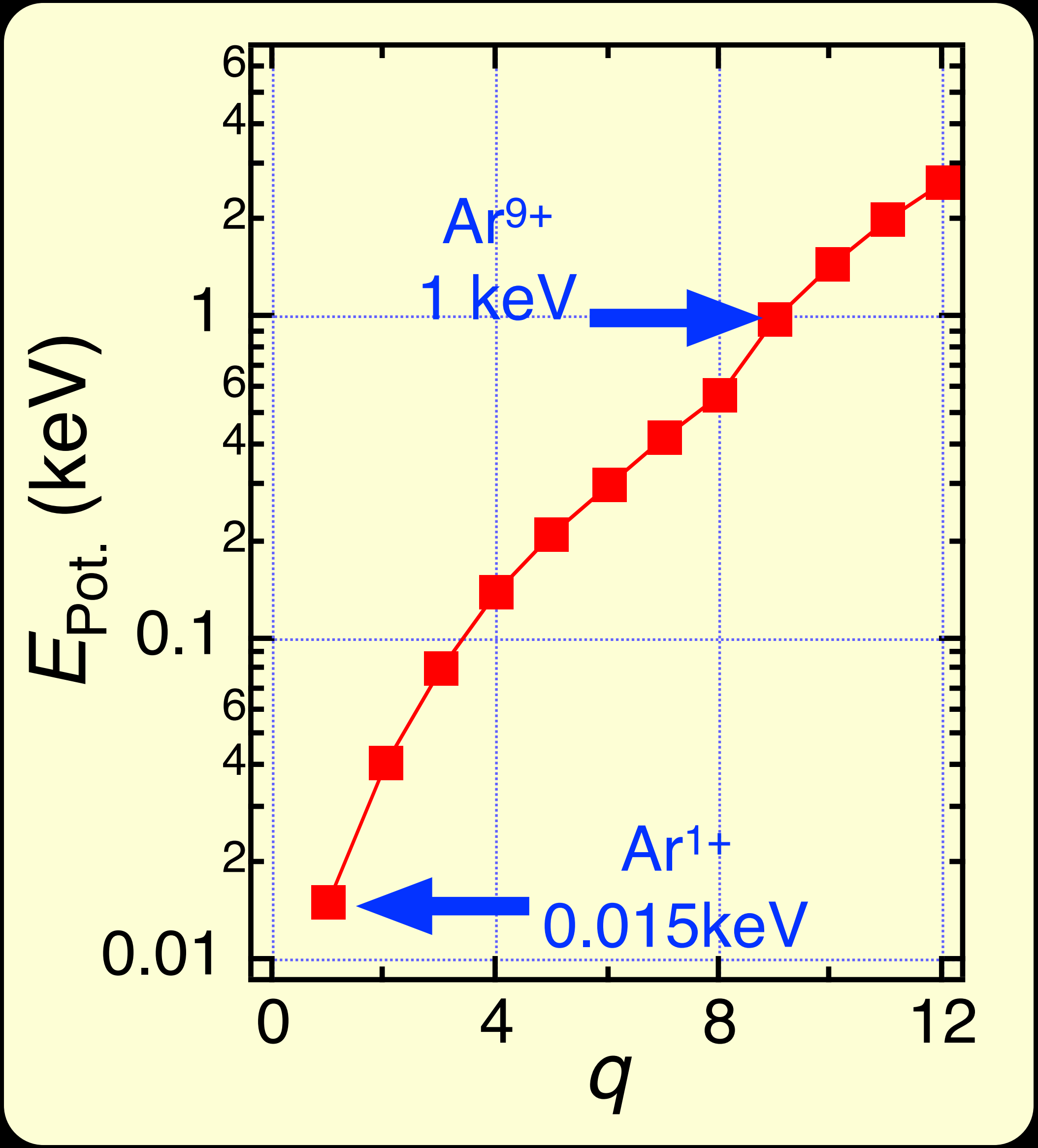
Energy of HCI beams

$$E = E_{\mathrm{kin.}} + E_{\mathrm{Pot.}}$$

- Kinetic energy

  $E_{\mathrm{kin.}} \sim q$

$E_{\mathrm{Pot.}}$ of Ar ions



http://www.dreebit.com/en/highly_charged_ions/data/

Energy of HCI beams

$$E = E_{\mathrm{kin.}} + E_{\mathrm{Pot.}}$$

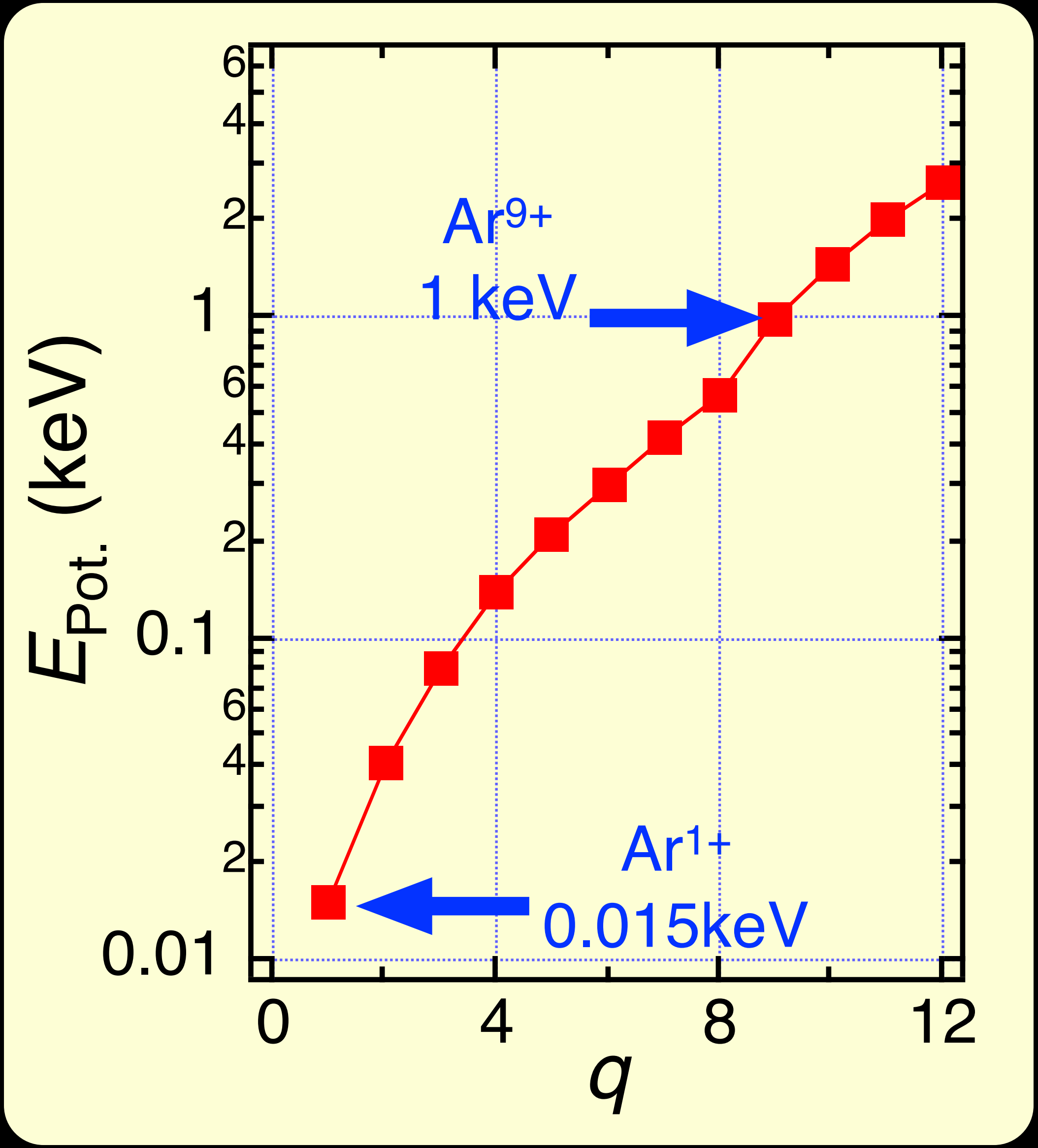
- Kinetic energy

  $E_{\mathrm{kin.}} \sim q$

- Potential energy

  $E_{\mathrm{Pot.}} \sim q^{2.8}$

$E_{\mathrm{Pot.}}$ of Ar ions

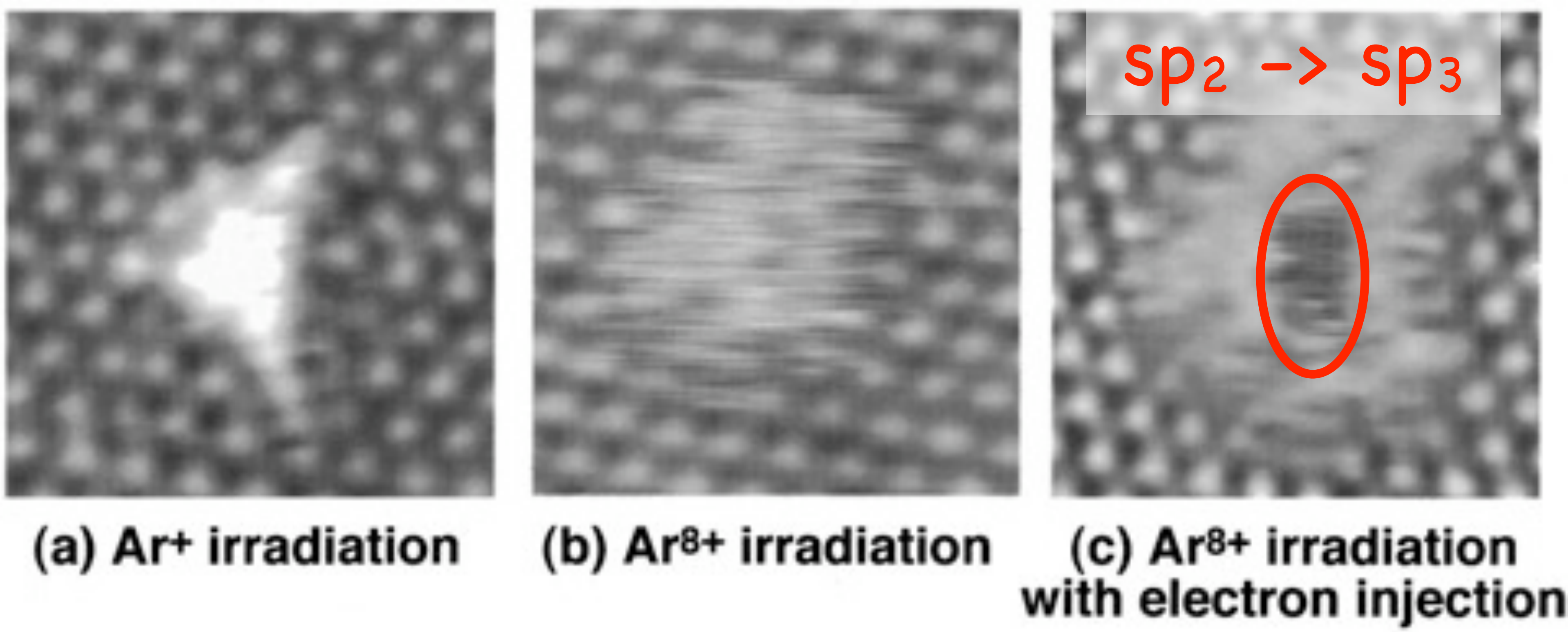


http://www.dreebit.com/en/highly_charged_ions/data/

Enhanced irradiation effect

- Additional energy deposition

ex. Nano-diamonds created in HOPG



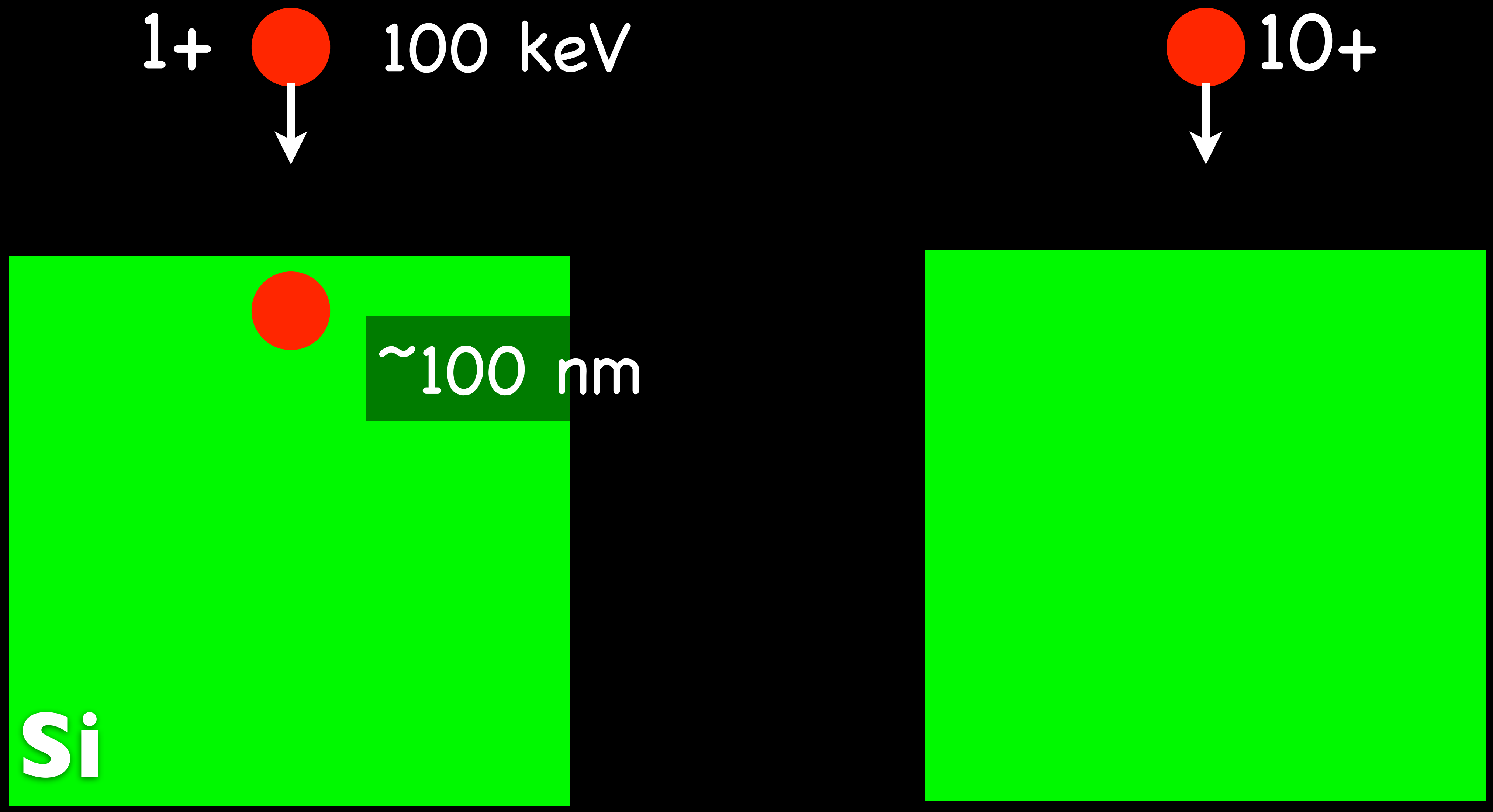
(a) Ar+ irradiation (b) Ar^{8+} irradiation (c) Ar^{8+} irradiation with electron injection

Appl. Phys. Lett. 79 (2001) pp. 3866, T. Meguro et al.

Extension of R_p

- Higher accelerability

ex. $^{40}\mathrm{Ar}^{q+}$ on Si, V=100 kV



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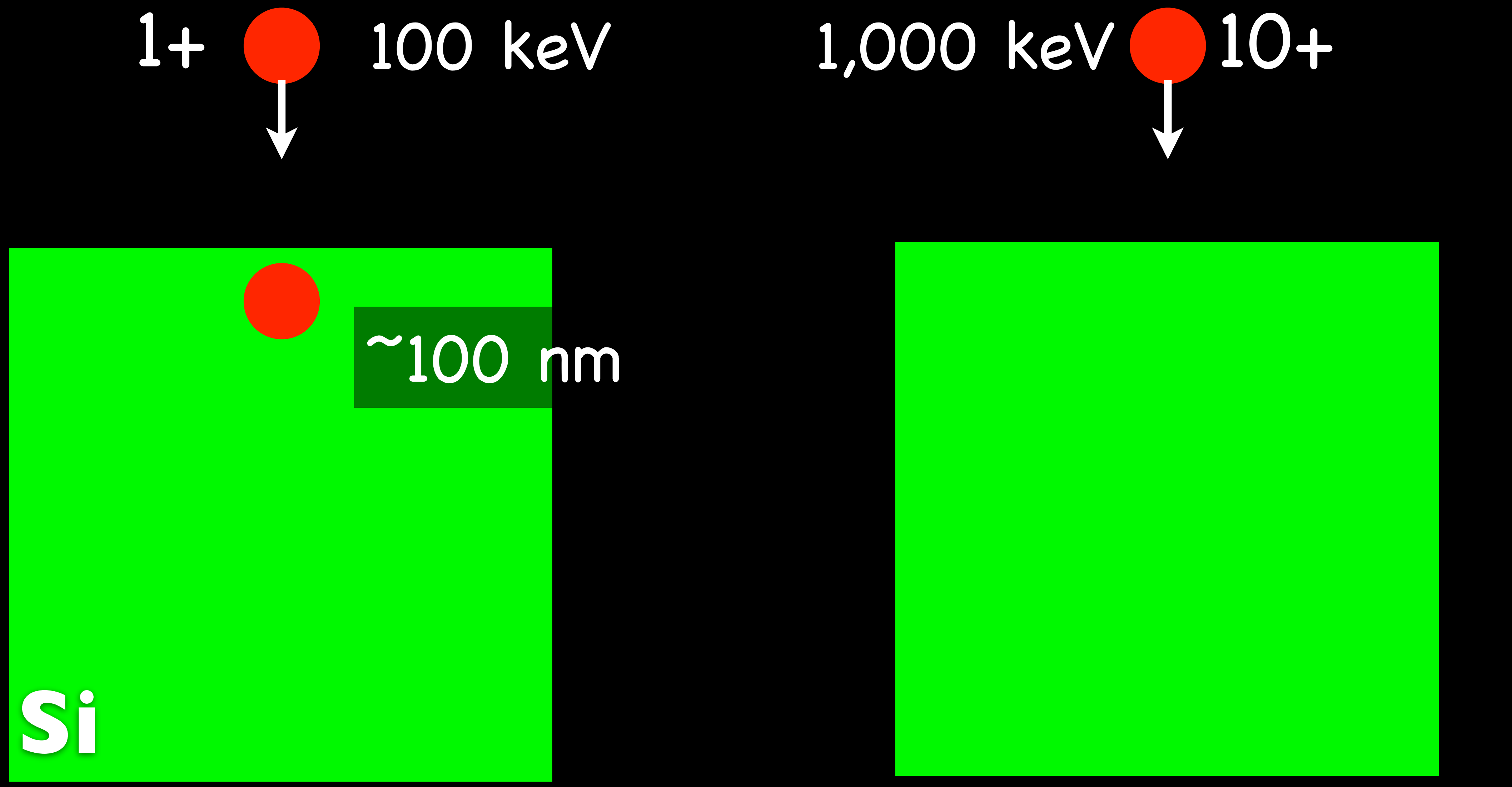

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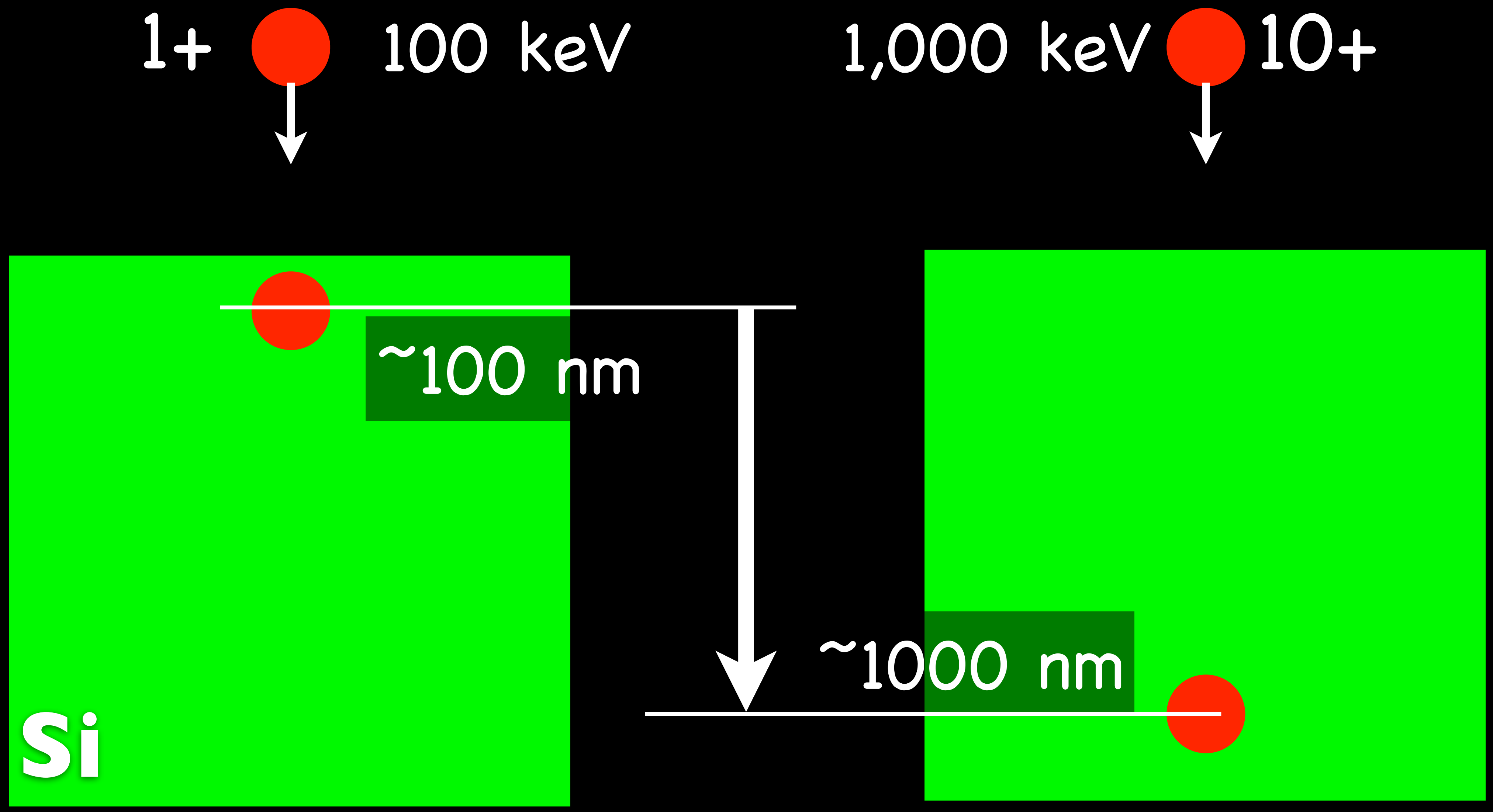


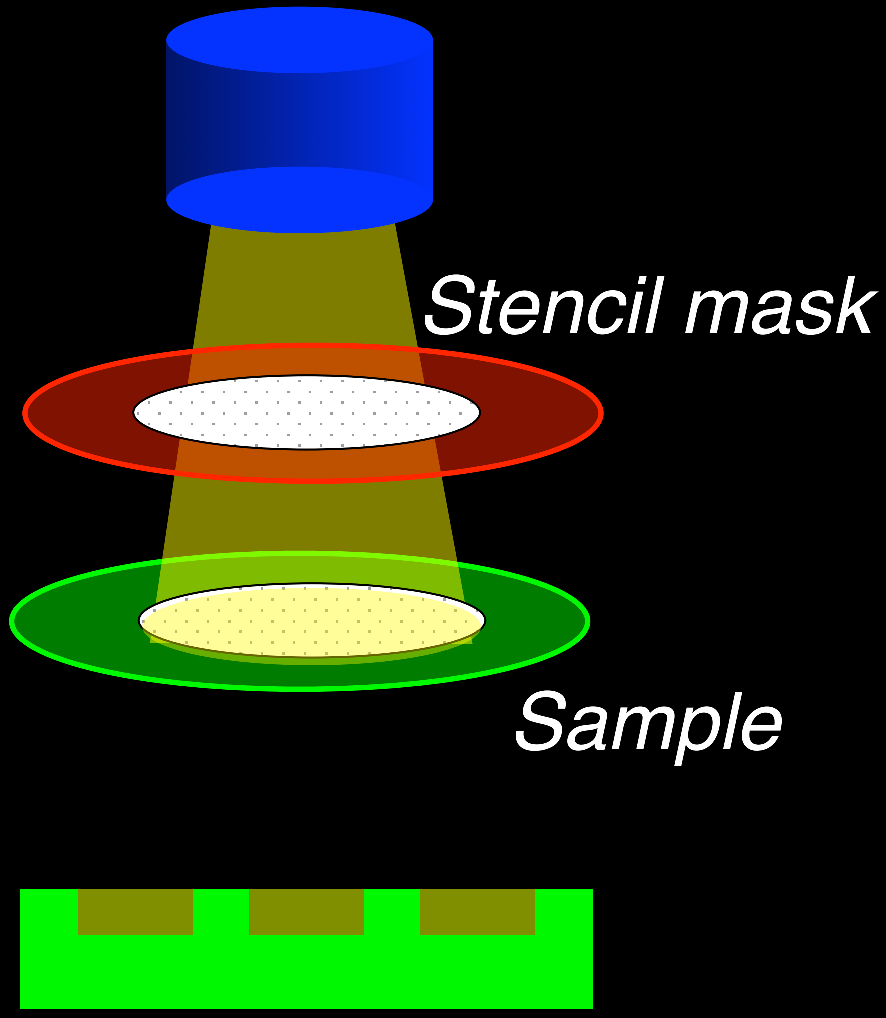
IB lithography

- Irr. of Ar-beam

  Modification of material

- Etching by BHF/HF

  Difference in etching rate



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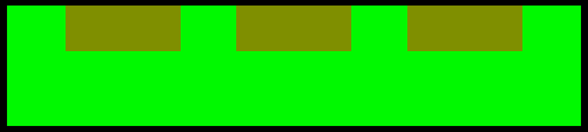

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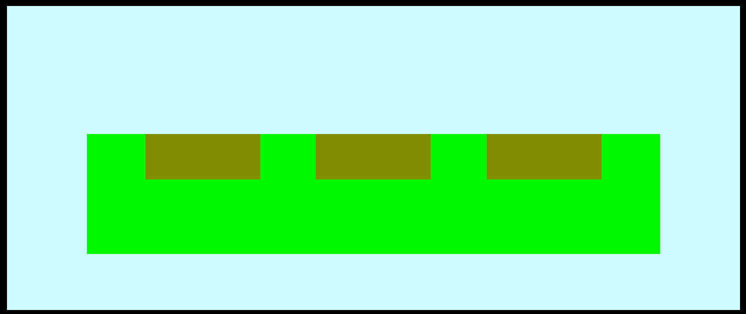

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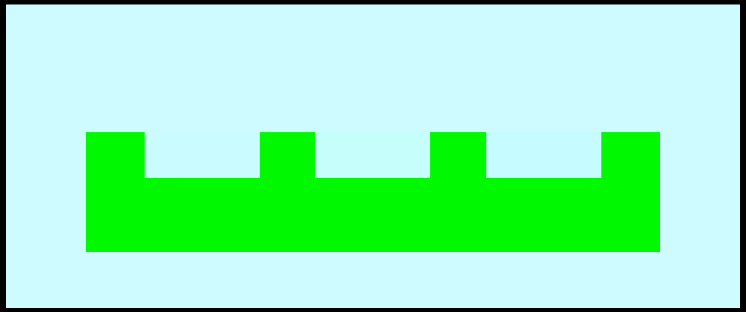
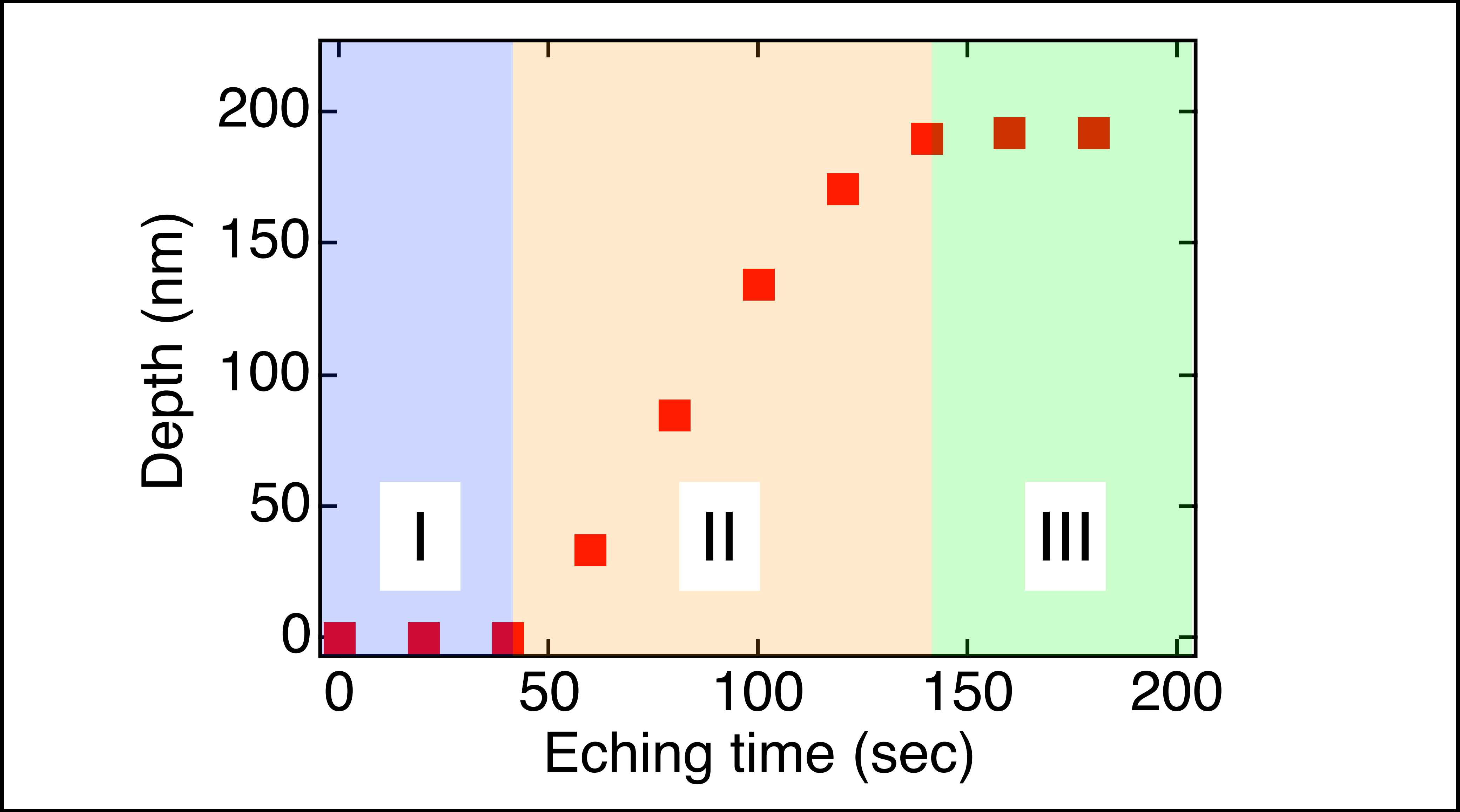


Etching process of SOG

- Ar^{1+}: 90 keV, 6.3×10^{13} ions/cm^2



Rev. Sci. Instrum. 79 (2008) 02C302, S. Momota et al.

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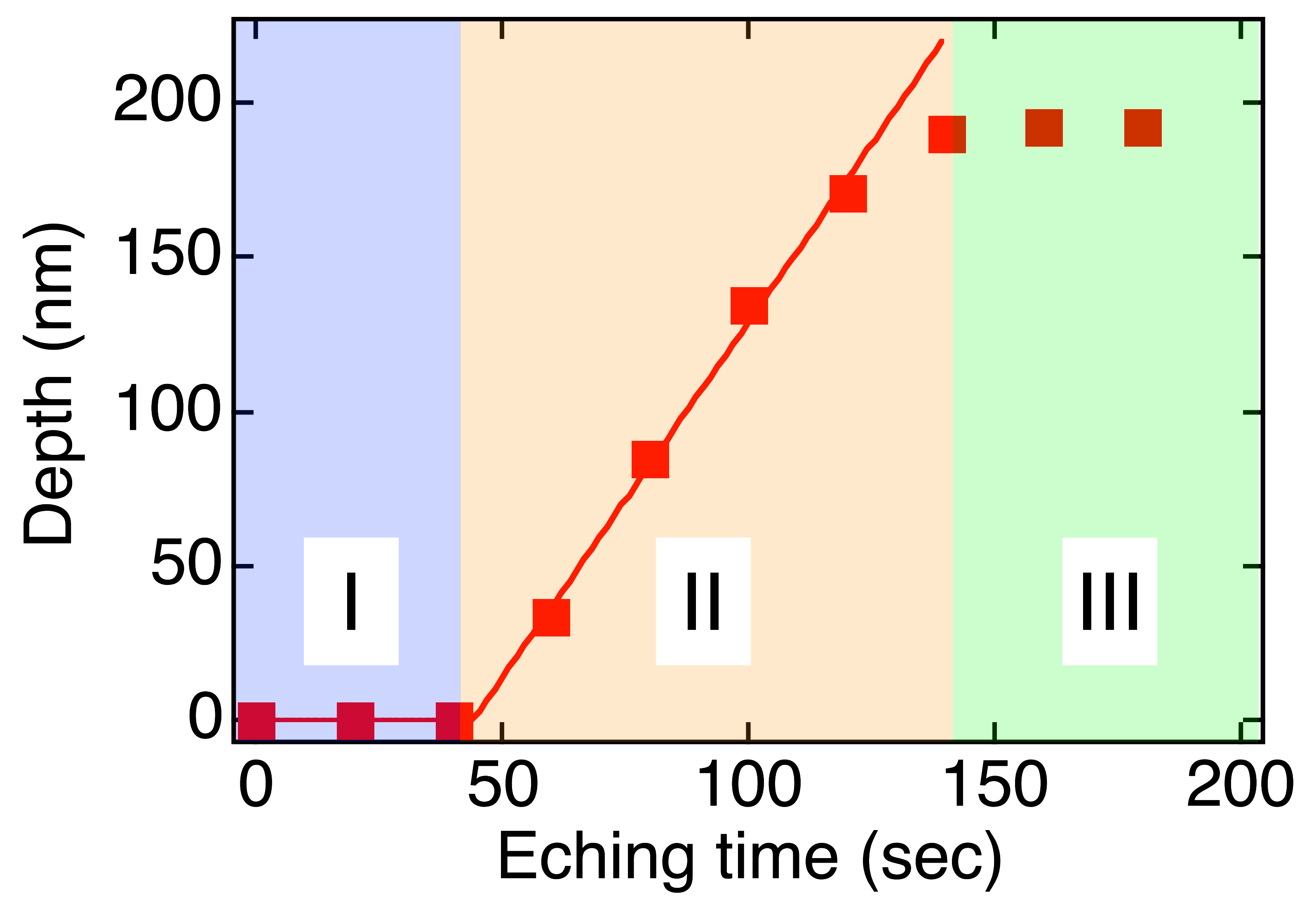

Rev. Sci. Instrum. 79 (2008) 02C302, S. Momota et al.

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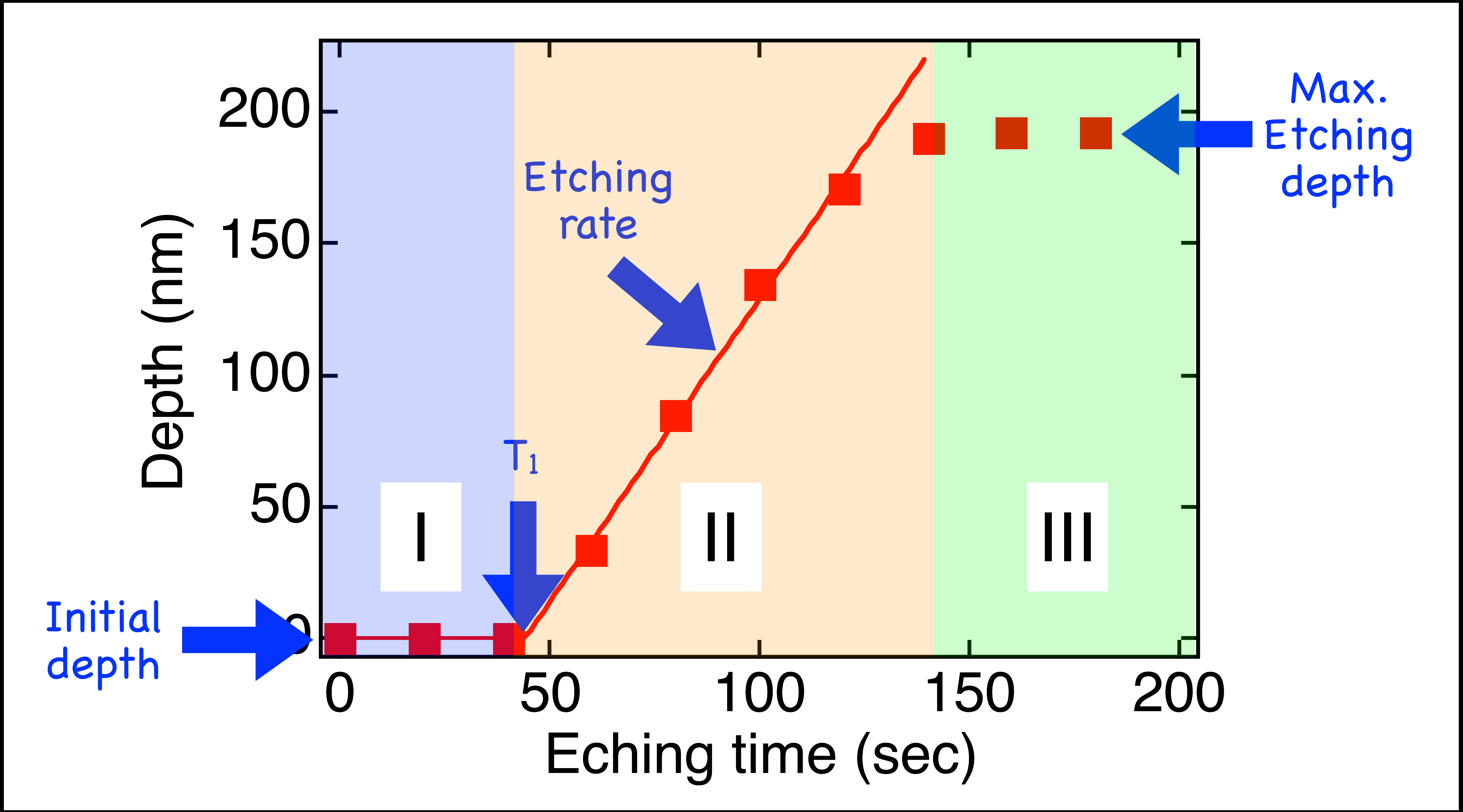
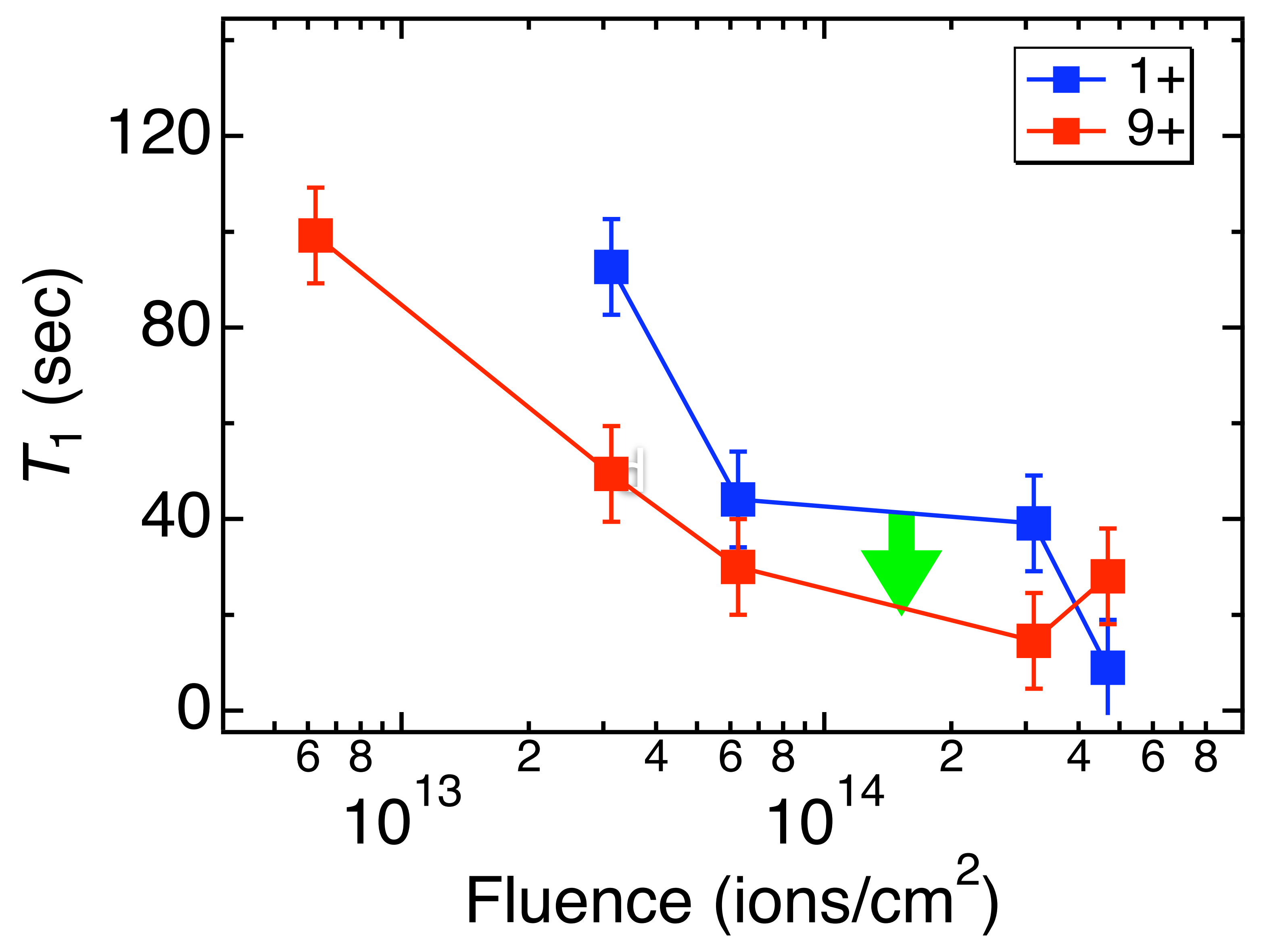
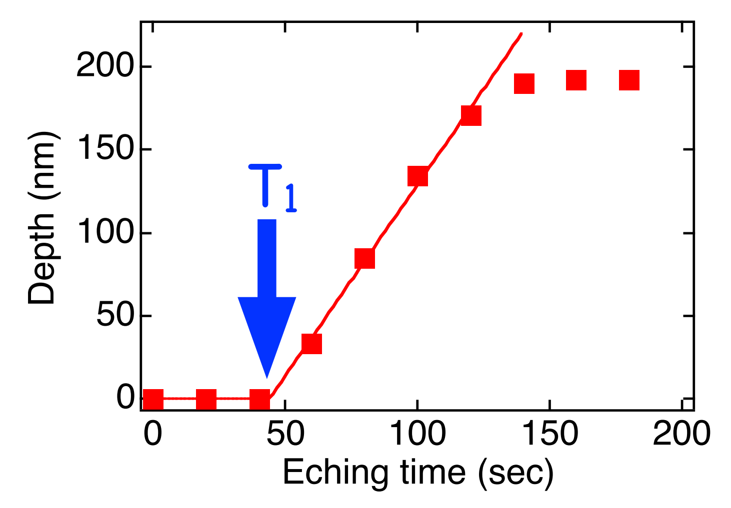


Rev. Sci. Instrum. 79 (2008) 02C302, S. Momota et al.

Reduction of etching time

- $Ar^{1+,9+}$, E = 90 keV

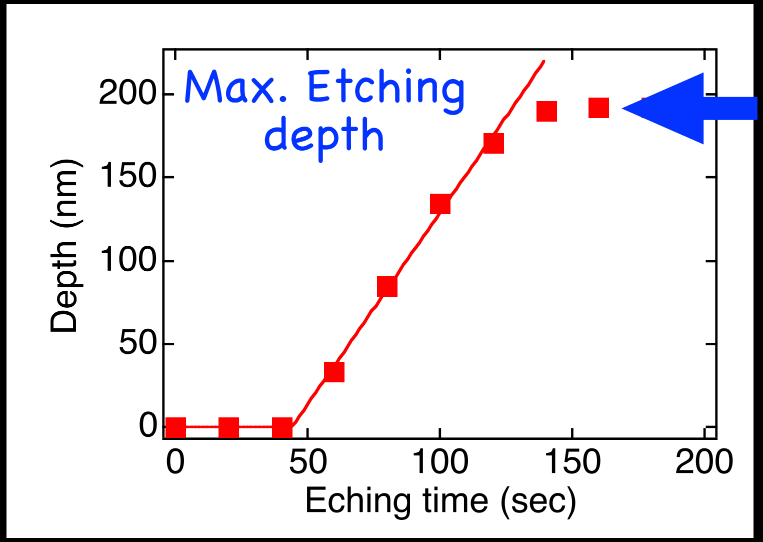




Rev. Sci. Instrum. 79 (2008) 02C302, S. Momota et al.

Enhanced fabrication depth

- $Ar^{1+,9+}$, E = 90 keV



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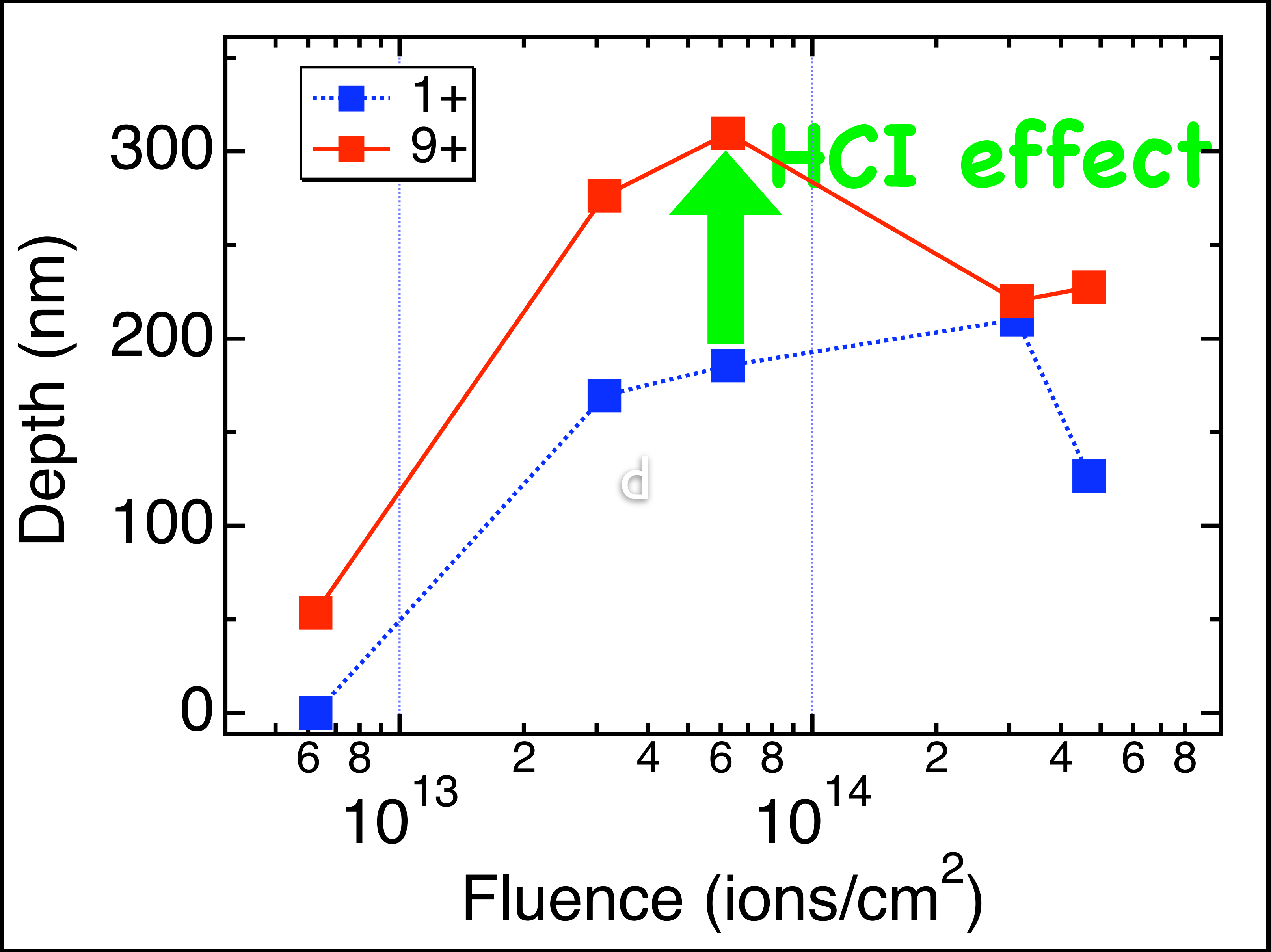
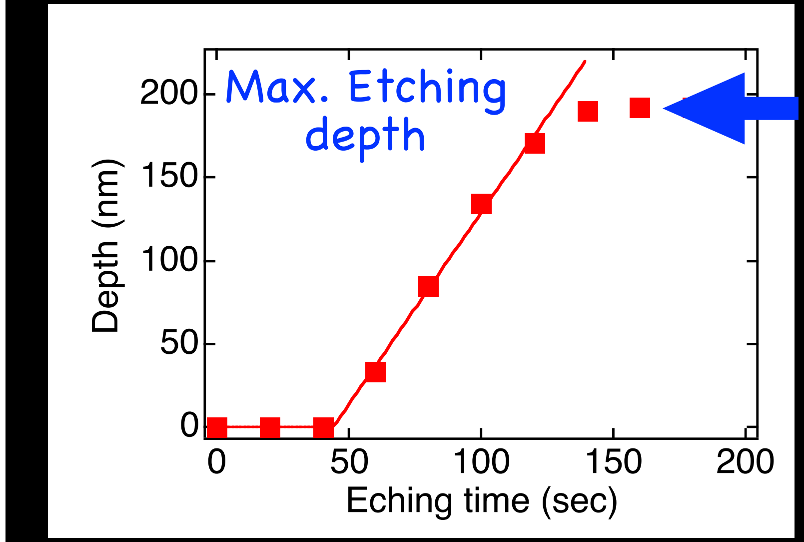




Rev. Sci. Instrum. 79 (2008) 02C302, S. Momota et al.

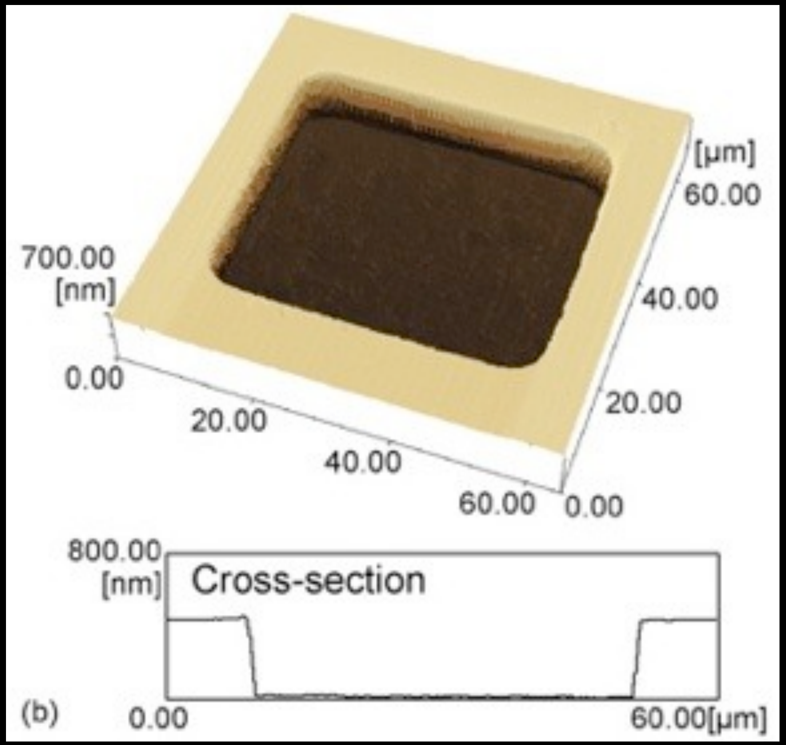
In case of Si

Irradiation of Ar^{q+}

- V = 60 kV
  E = 60 ~ 540 keV
  1+ 9+
- Cu-Mask (43×43 μm)

Ar^{4+}

240 keV, 1.3×10^{15} ions/cm^2

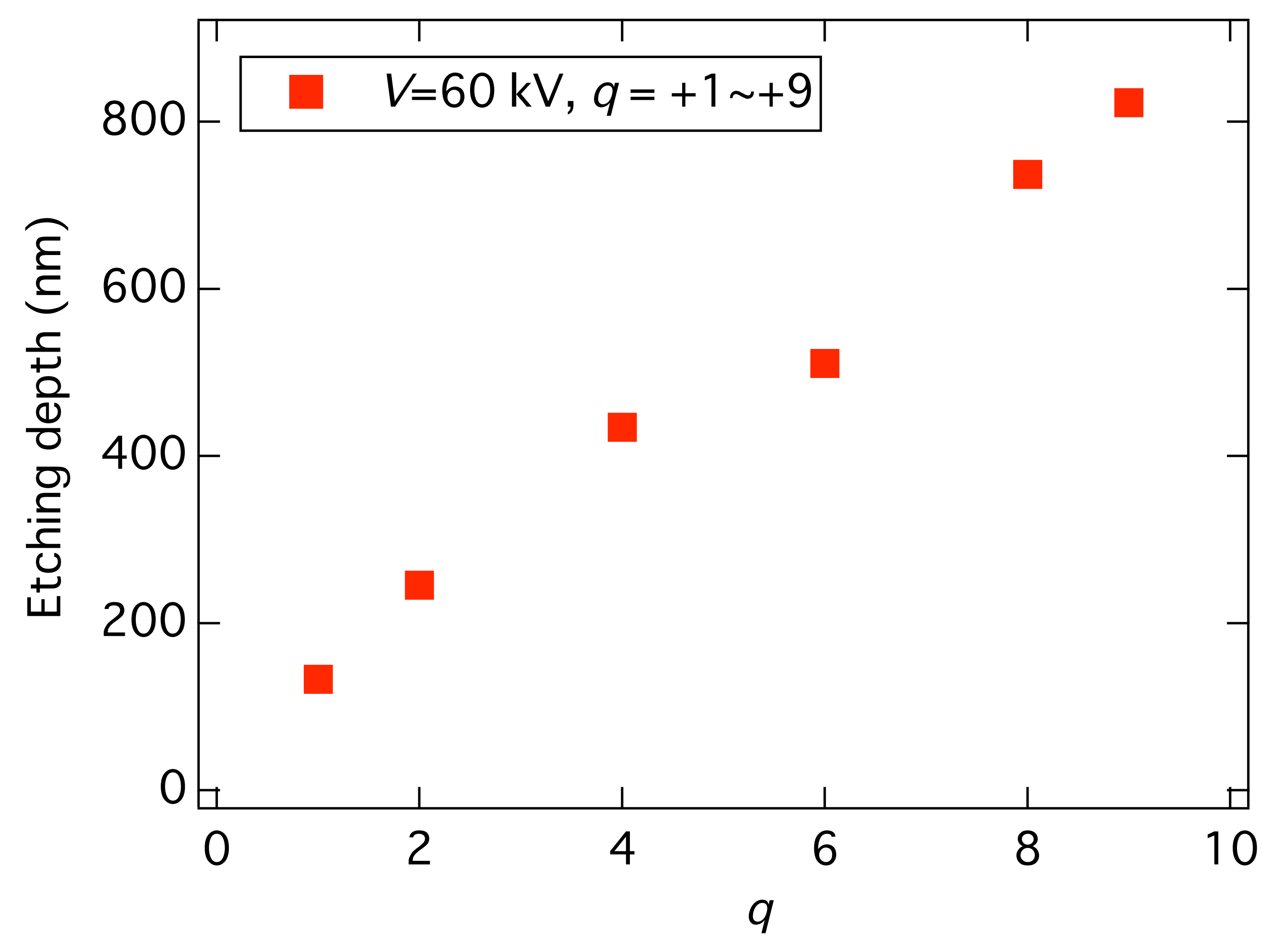


120 min. in 46 mass% HF

Appl. Surf. Sci. 253 (2007) pp. 3284, N. Kawasegi et al.

Enhanced etching depth

- $Ar^{1\sim9+}$ on Si



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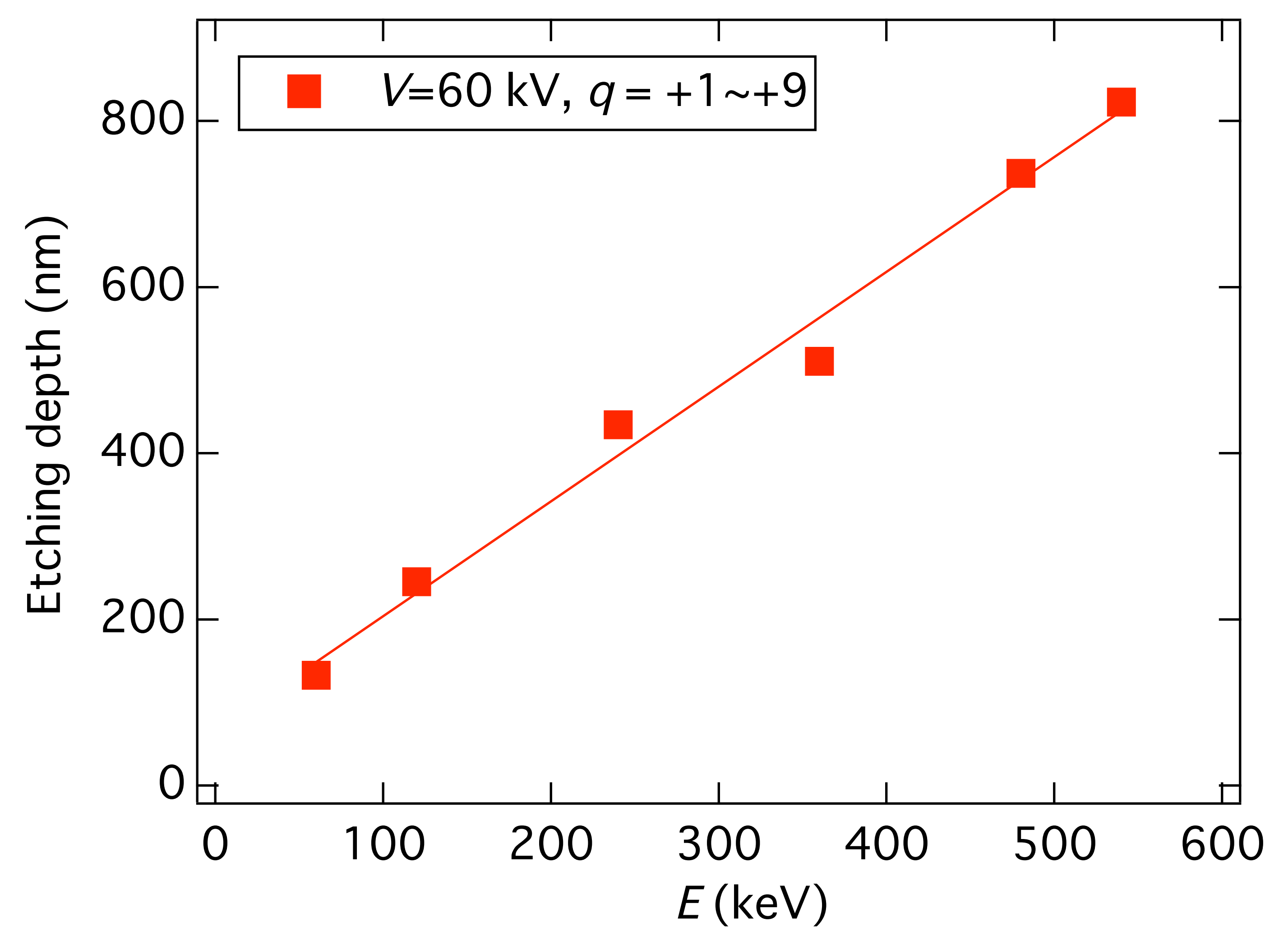

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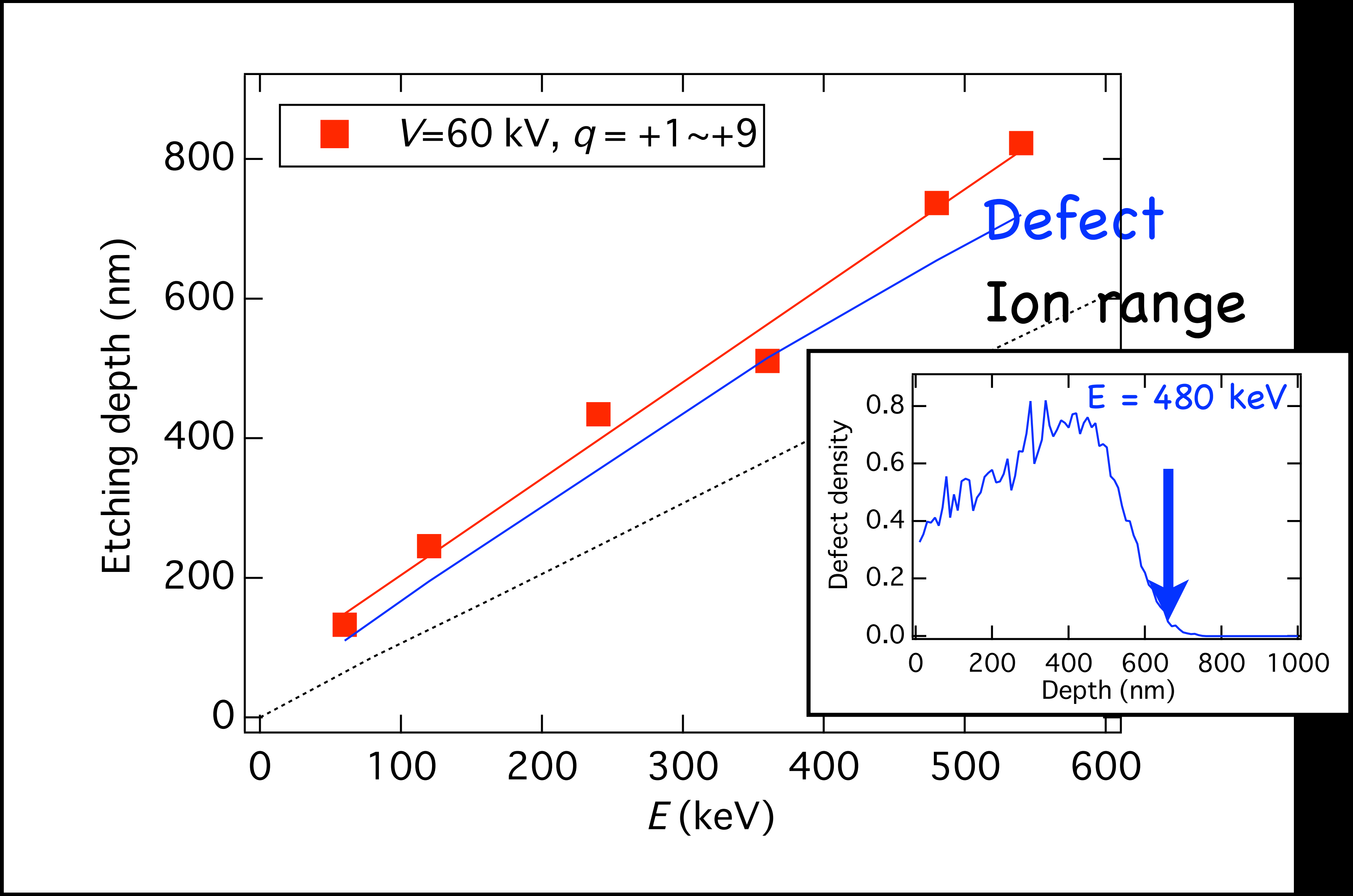
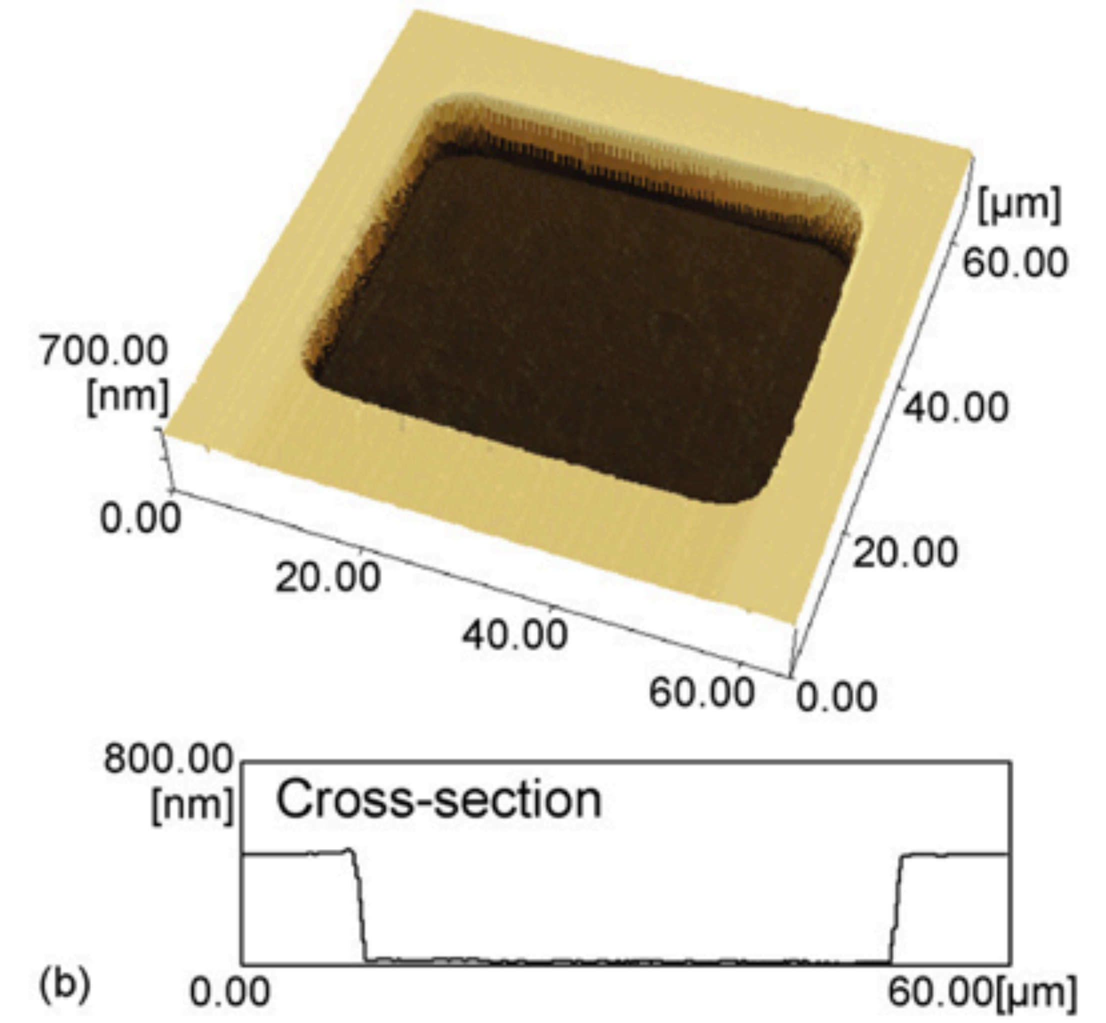


Rev. Sci. Instrum. 79 (2008) 02C302, S. Momota et al.

Just first step

1st step

2nd step



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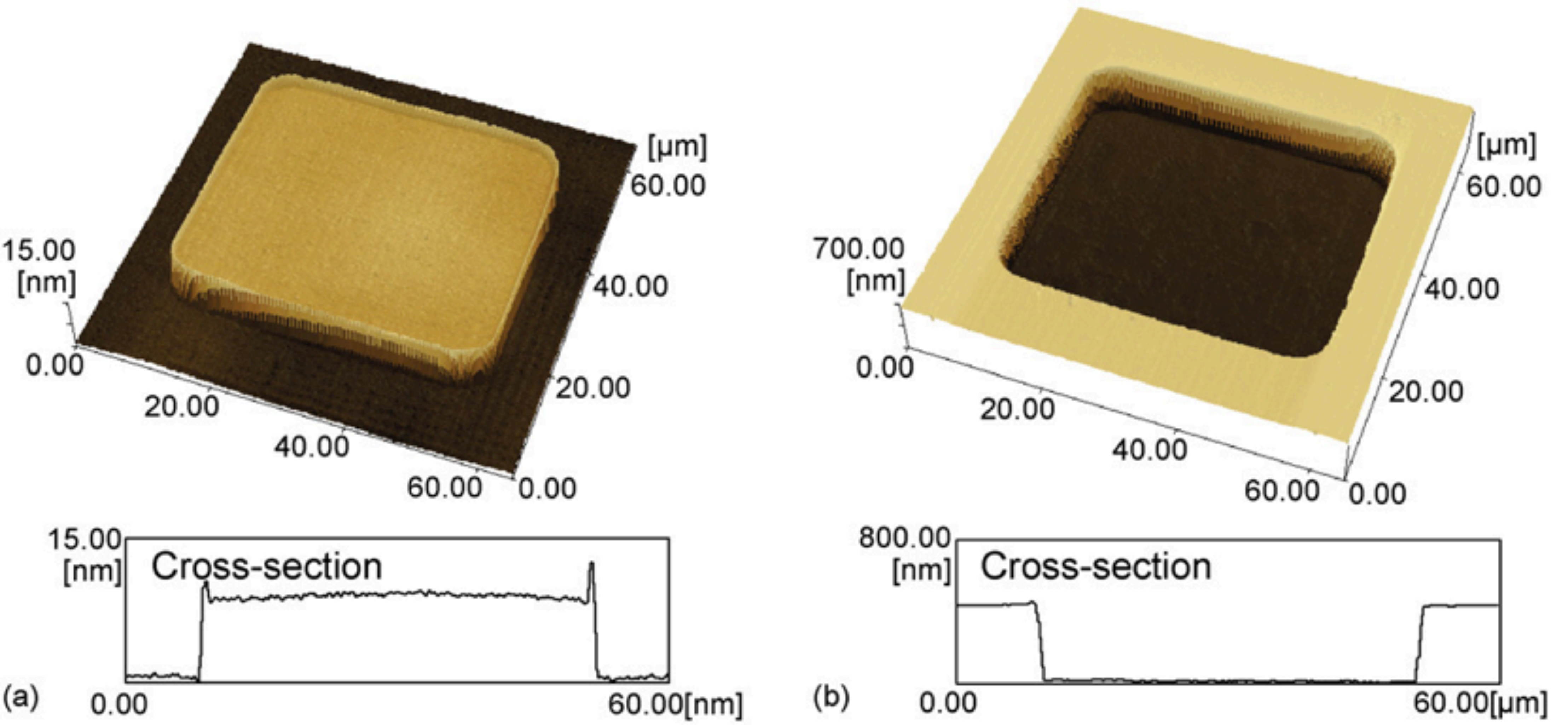
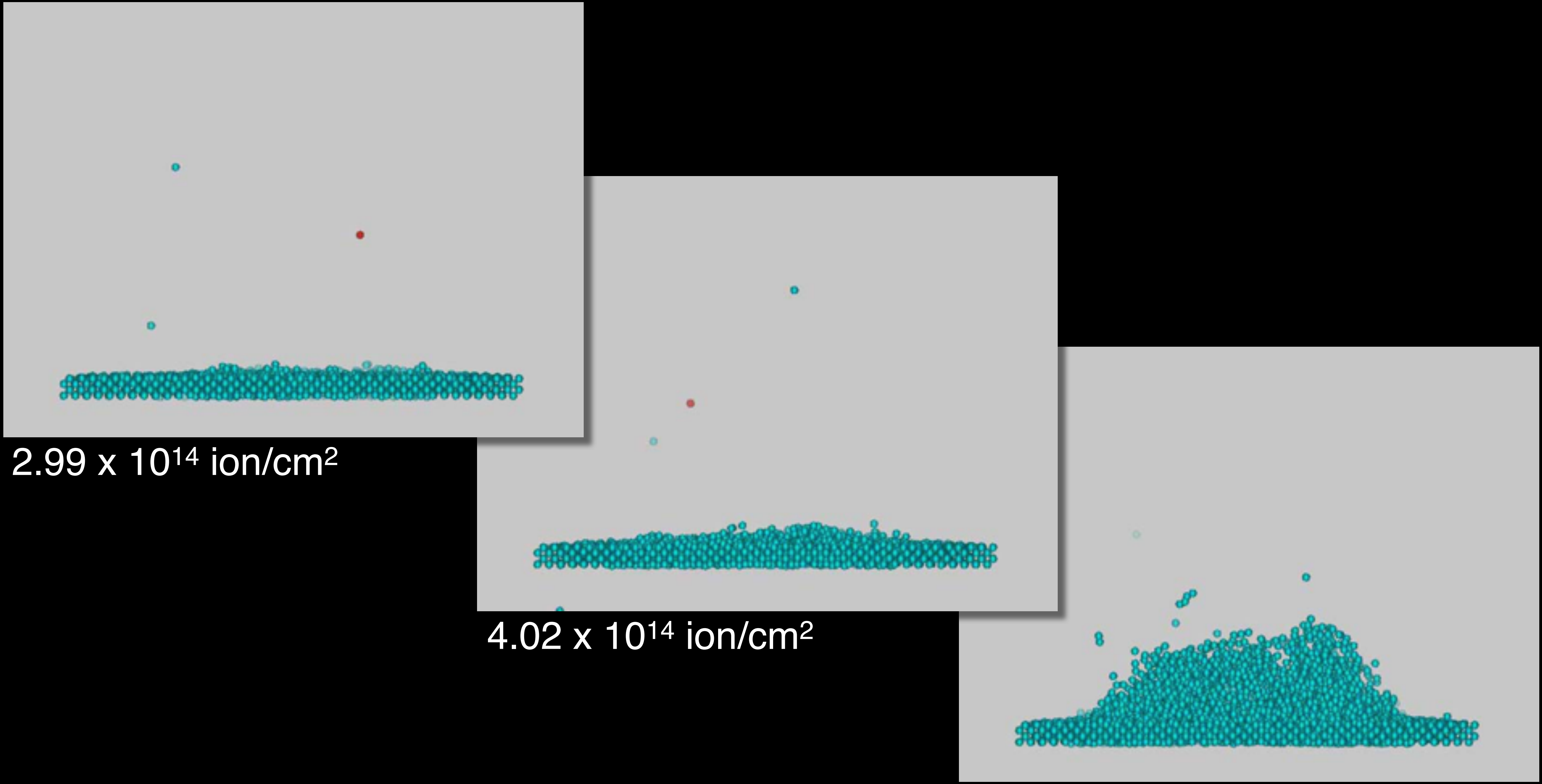


Appl. Surf. Sci. 253 (2007) pp. 3284, N. Kawasegi et al.

Growing swelling structure

– MD simulation J. Appl. Phys. 106 (2009) 044910, S. Satake et al.



2.99×10^{14} ion/cm^2

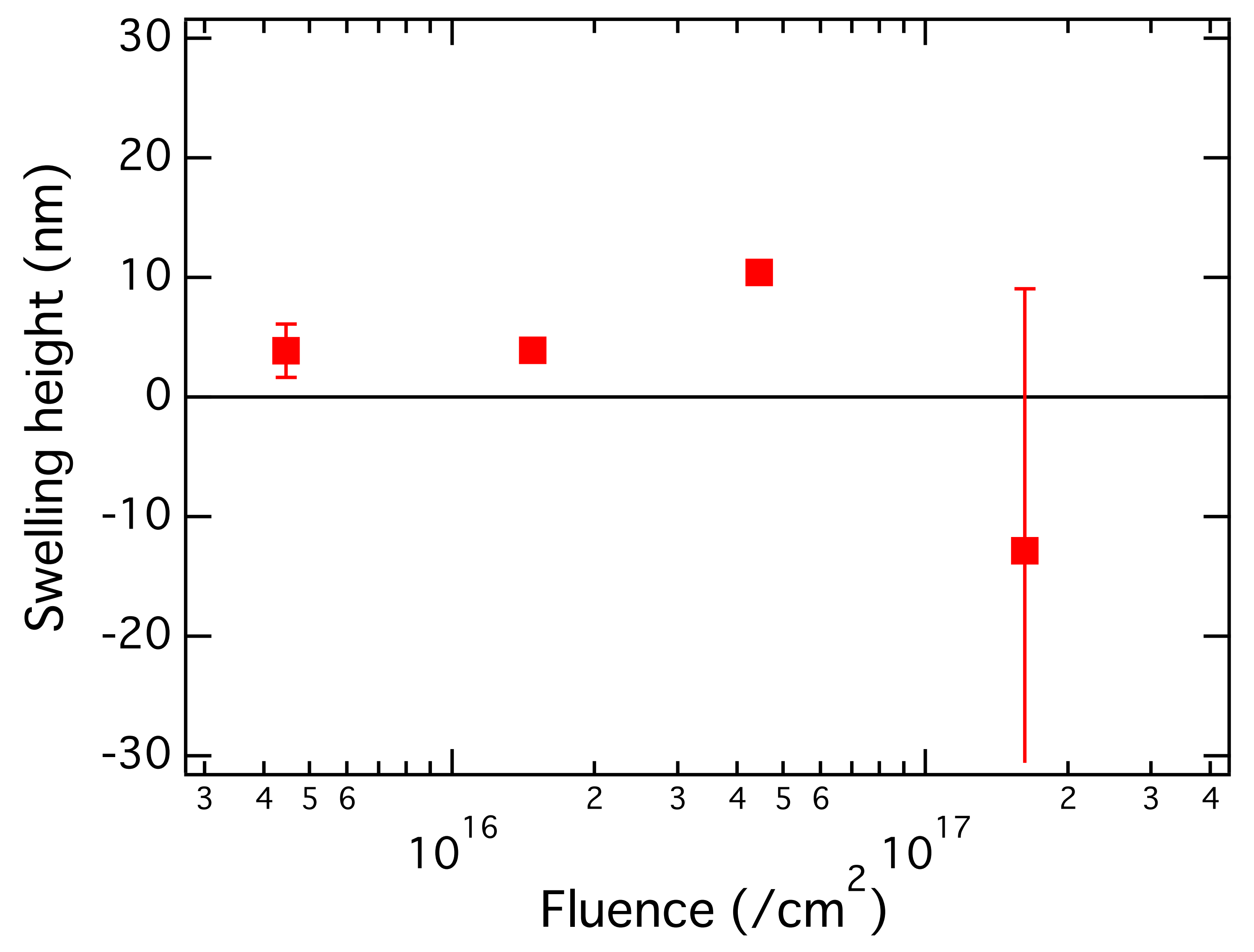
4.02×10^{14} ion/cm^2

6.52×10^{14} ion/cm^2

Growing swelling structure

- Experimental results

- Ar^{1+}(50 keV) on Si



Growing swelling structure

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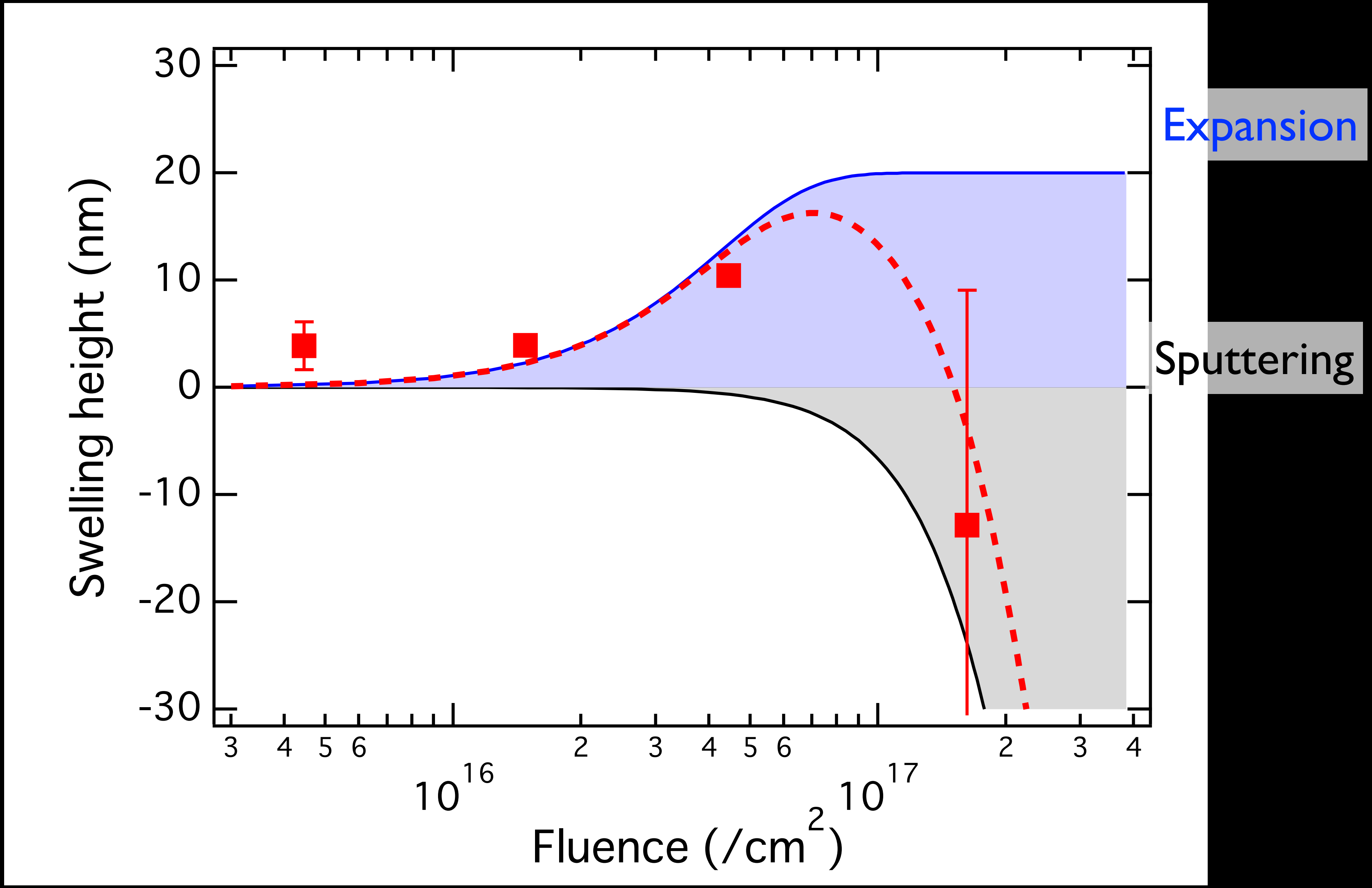
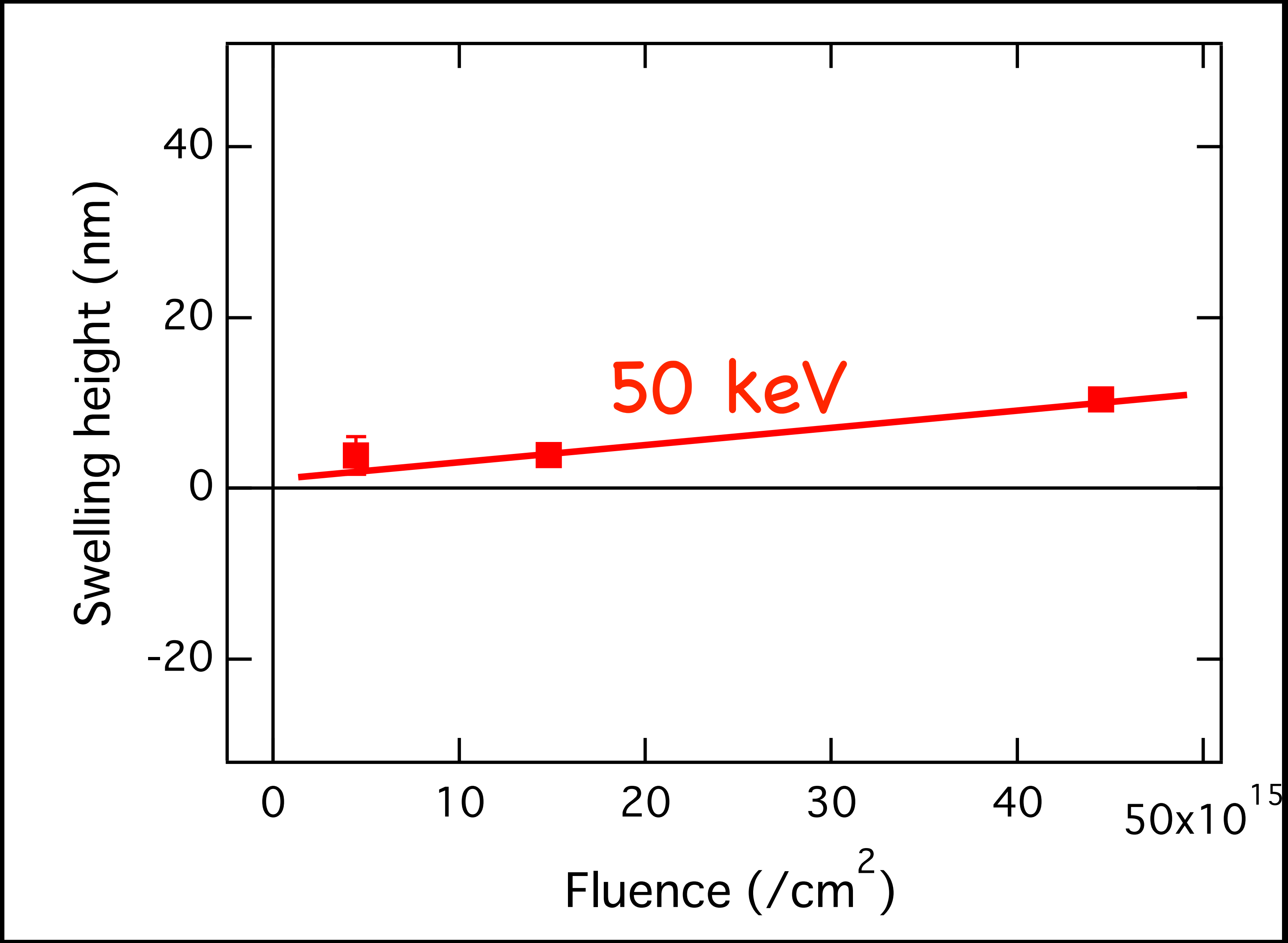


S. Momota, Nano-S&T, Oct. 23-26, 2011 @Dalian, China

Energy dependence

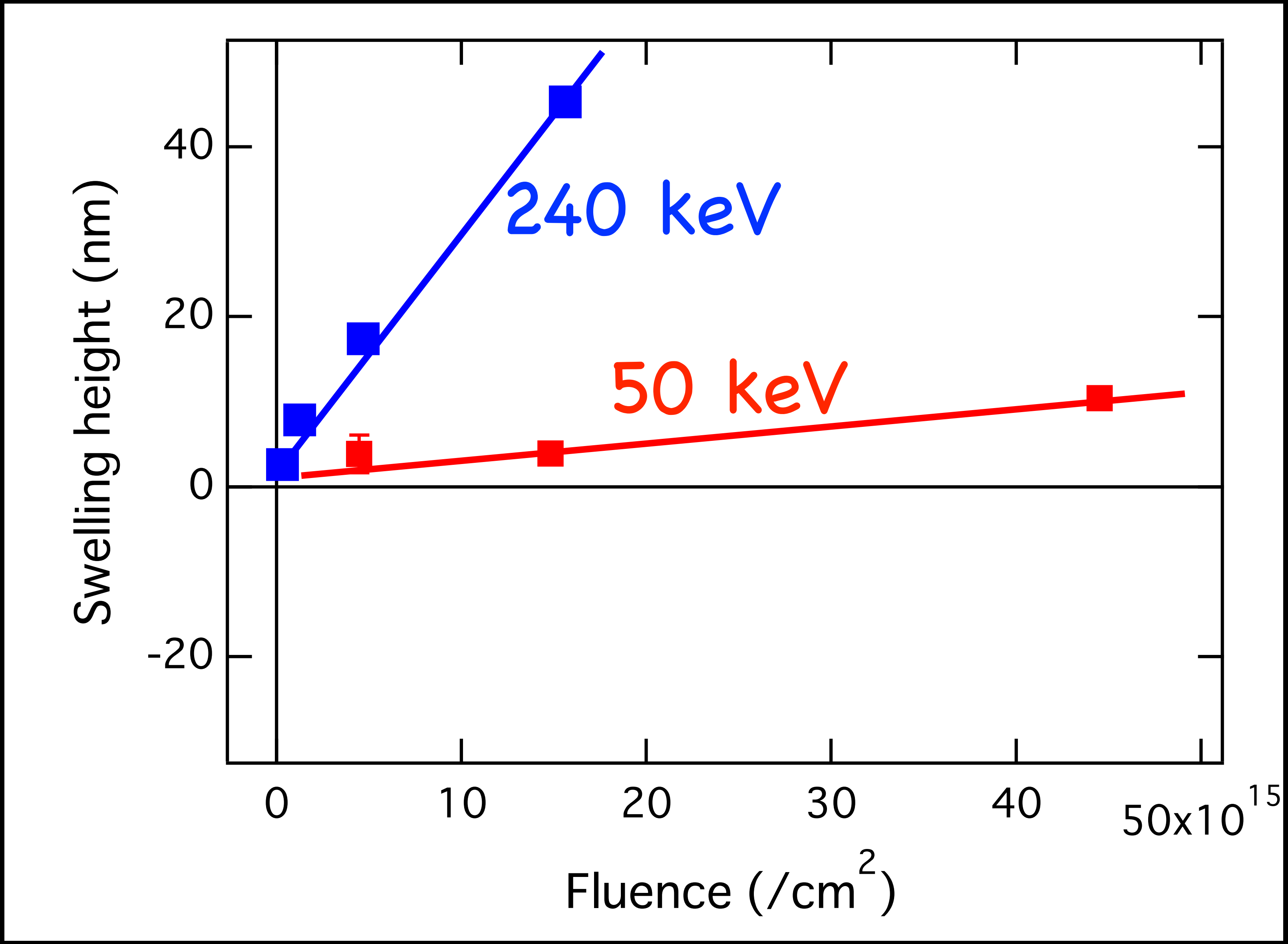
- Ar^{q+} on Si



to be published in J. Nanosci. and Nanotech., S. Momota et al.

Energy dependence

- Ar^{q+} on Si



to be published in J. Nanosci. and Nanotech., S. Momota et al.

Control of swelling height

Expansion rate × Depth of expanded layer

Fluence
Element

Energy = q x V

Conclusions

Possibility of HCI beams

examined

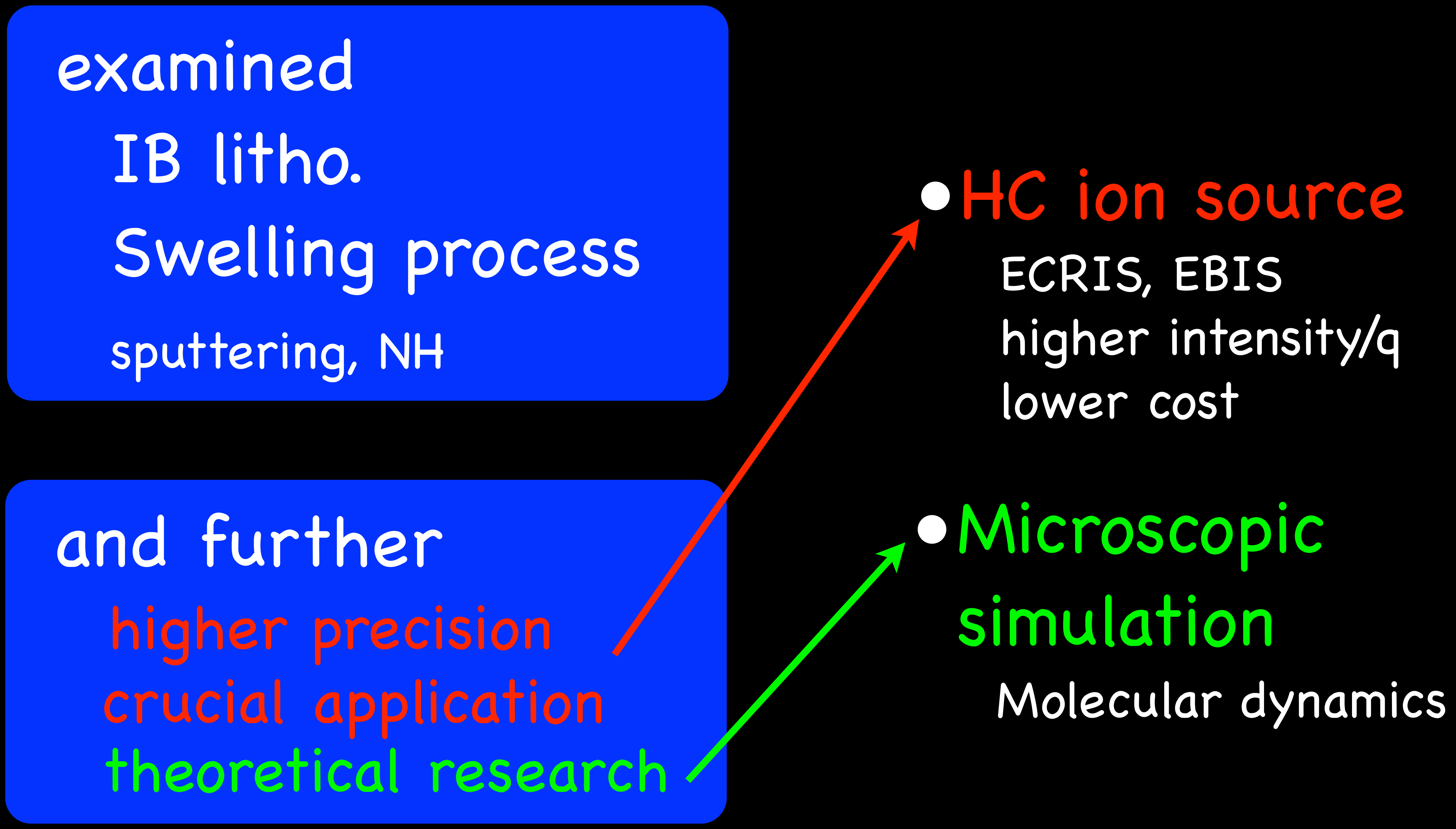
- IB litho.
- Swelling process
  - sputtering, NH

and further

- higher precision
- crucial application
- theoretical research

Conclusions

Possibility of HCI beams



examined

- IB litho.
- Swelling process
  - sputtering, NH

and further

- higher precision
- crucial application
- theoretical research

- HC ion source
  - ECRIS, EBIS
  - higher intensity/q
  - lower cost
- Microscopic simulation
  - Molecular dynamics

Collaboration with

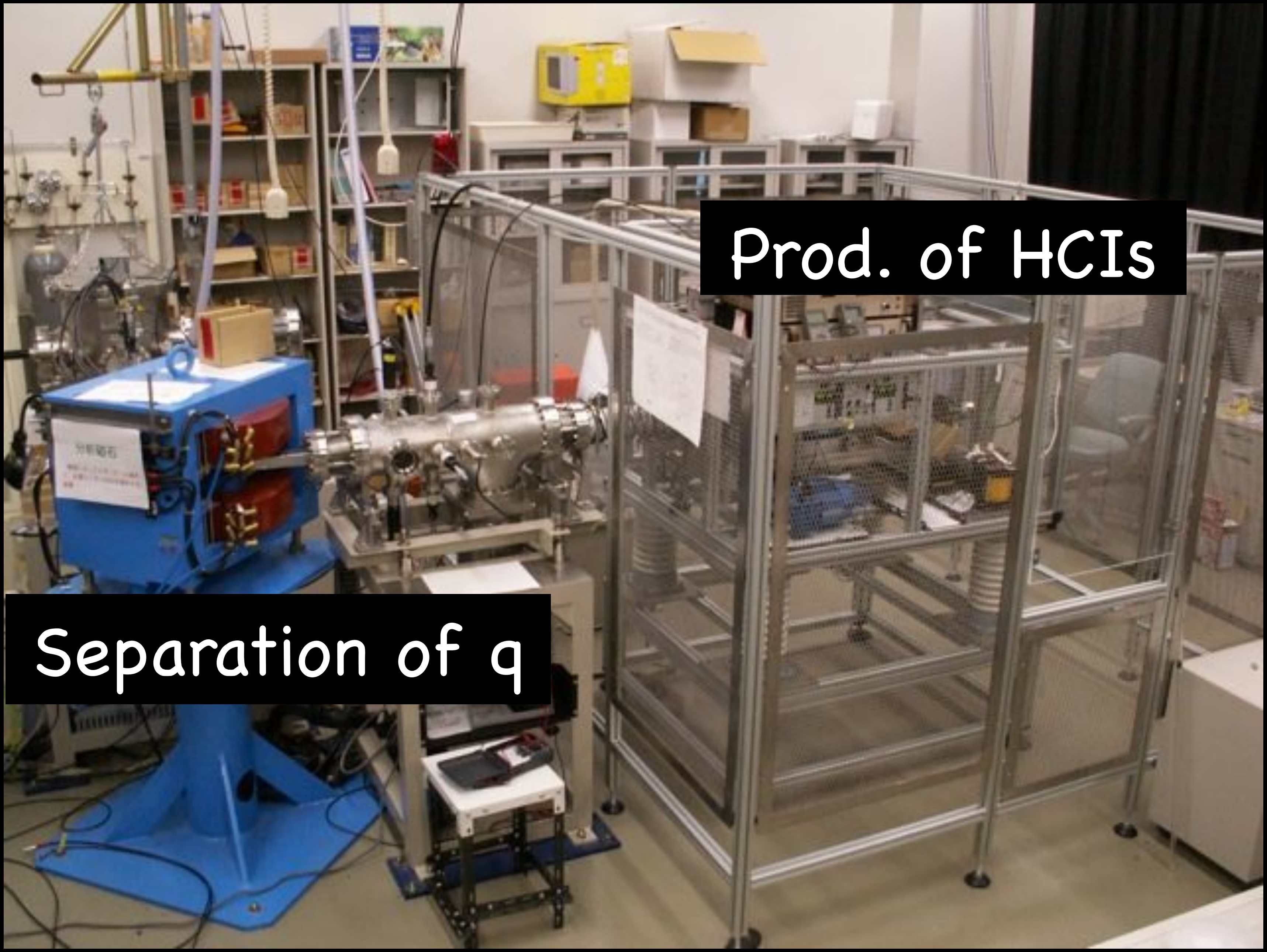
Tokyo Univ. of Sci.

Toyoma Univ.

Thank you for your attention.

Appendices

HCI beam facility

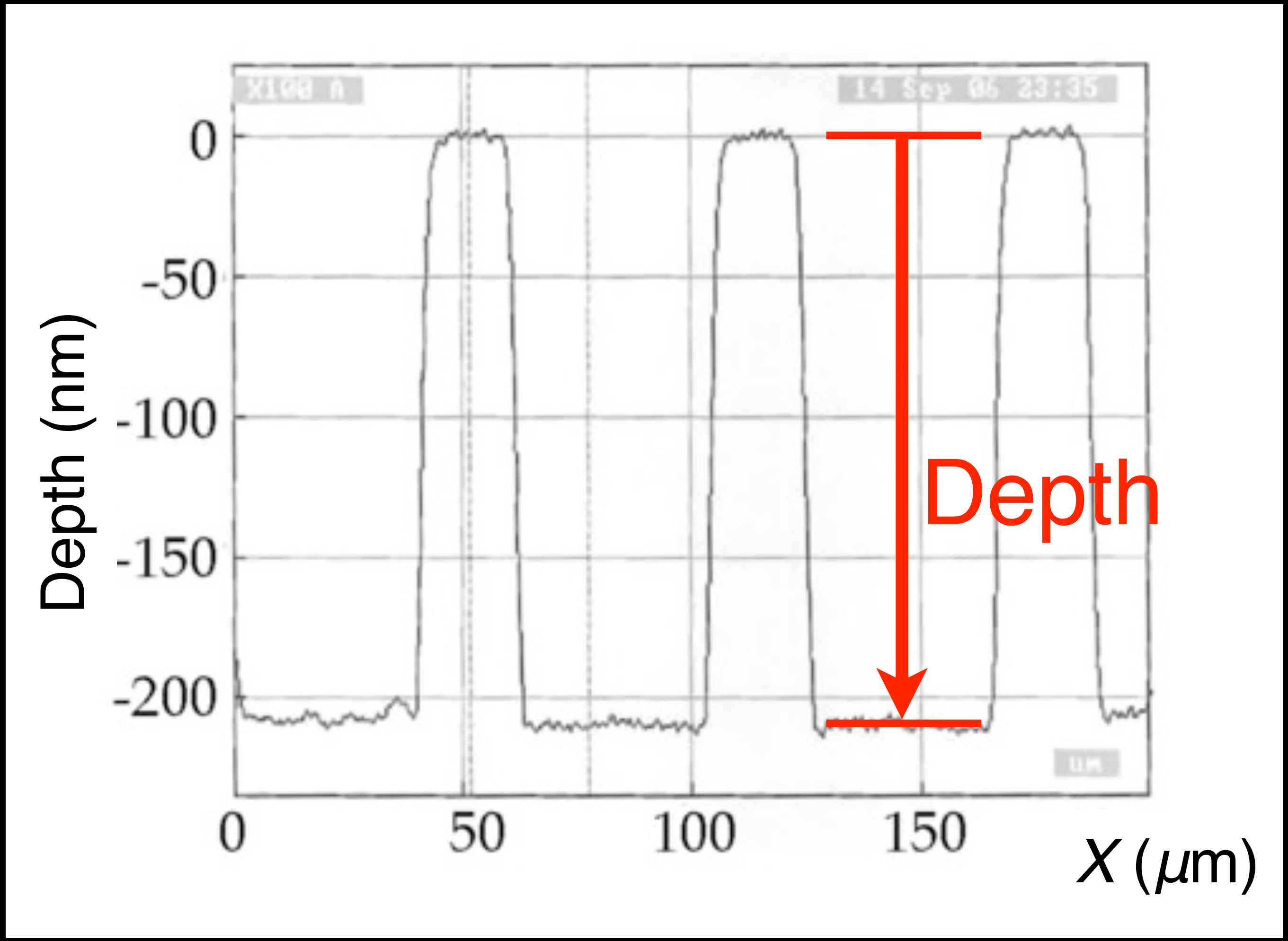


Rev.Sci.Instr. 75(2004) pp. 1497, S. Momota et al.

In case of SOG

- Irradiation of Ar^{q+}
  - q = +1~9
  - 90 keV
  - Cu-Mask (43×43 μm)
- Wet etching
  - BHF (HF, NH_4F)
- Surface profile
  - Optical microscopy
  - Profilometer

Surface profile



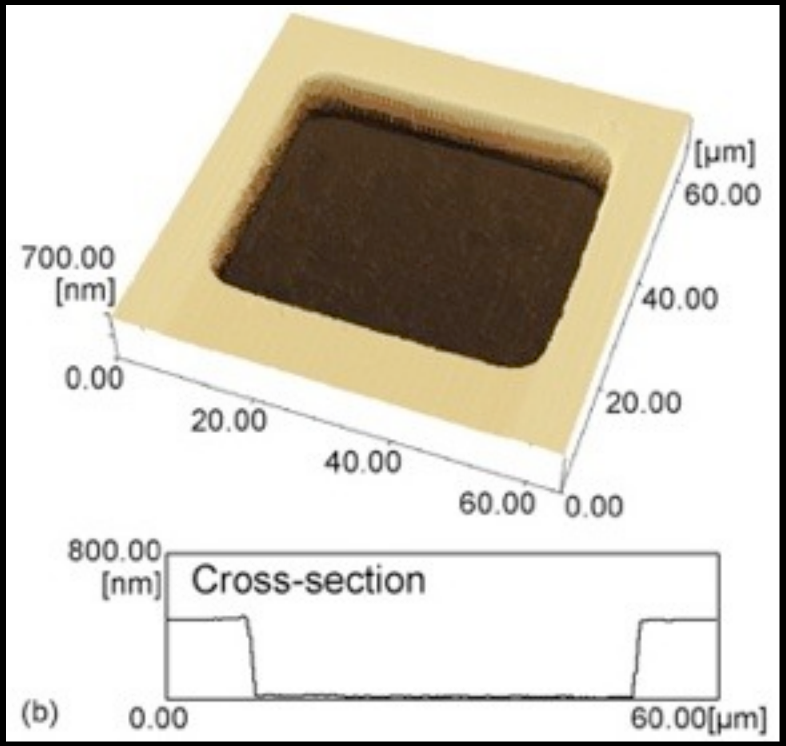
observed by Alpha step

In case of Si

- Irradiation of Ar^{q+}
  - q = +1~9
  - V = 60 kV
E = 60~540 keV
  - Cu-Mask (43×43 μm)
- Etching
  - 46mass% HF
- Surface profile
  - AFM

Ar^{4+}

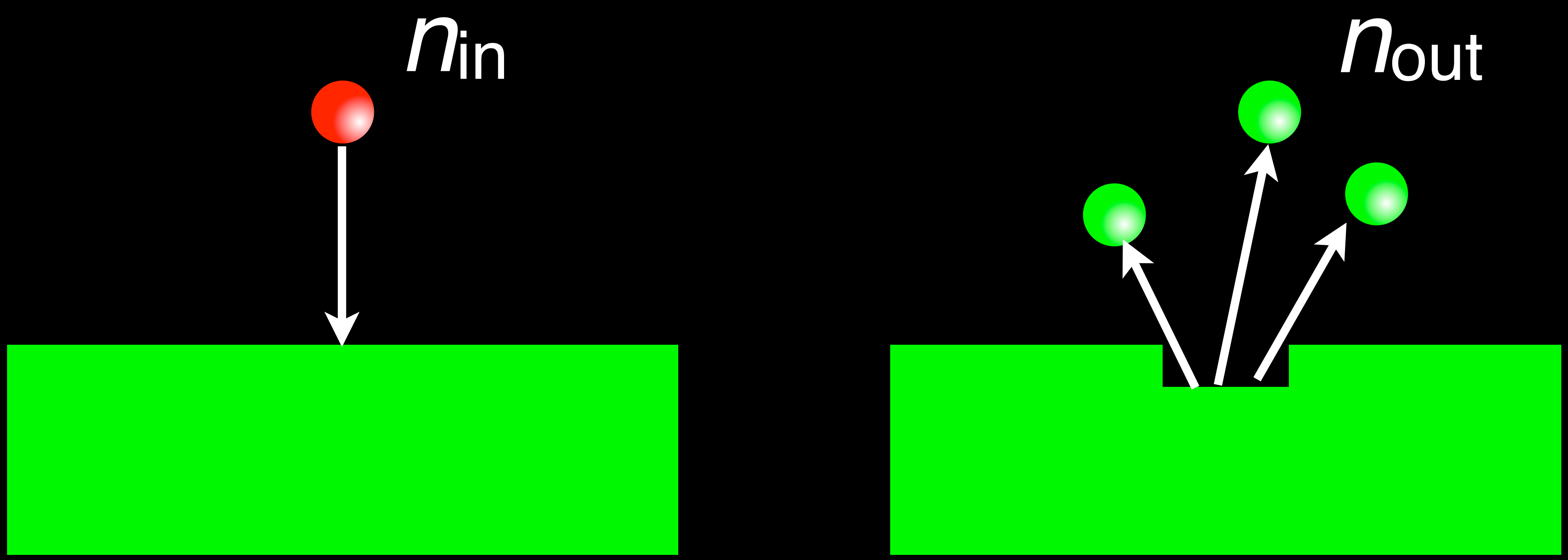
240 keV, 1.3×10^{15} ions/cm^2



$T_{etch.}$ = 120 min.

Appl. Surf. Sci. 253 (2007) pp. 3284, N. Kawasegi et al.

Sputtering rate



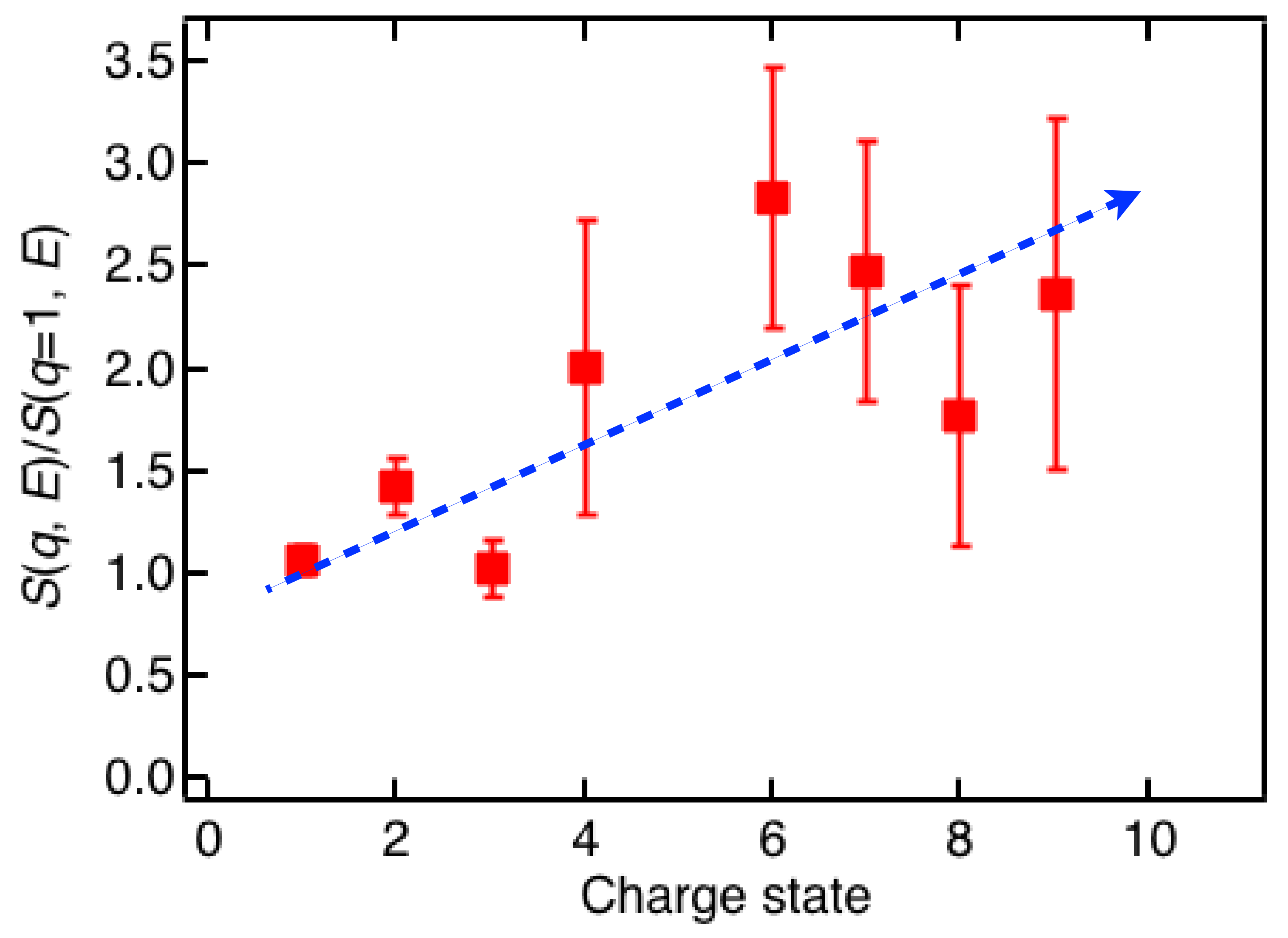
$$S = \frac{\text{Emitted atoms}}{\text{Irradiated ions}} = \frac{n_{out}}{n_{in}}$$

Measurement of S

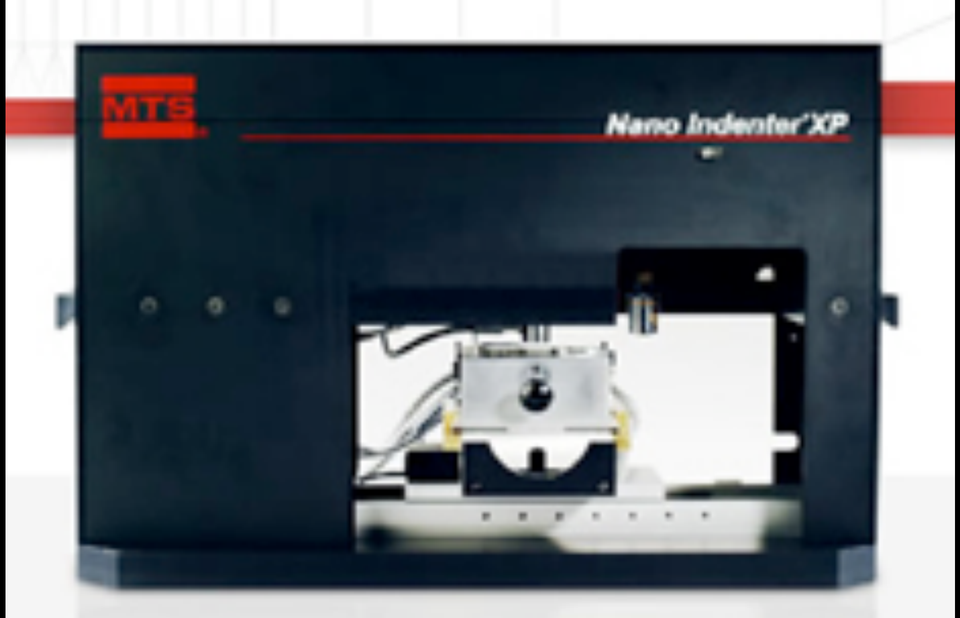
1. Irradiation of Ar^{q+}
    - $q = +1 \sim 9$
    - 100 ~ 900 keV
    - Number of irradiated ions (A)
2. Meas. of mass before/after irradiation
    - Number of sputtered Ag atoms (B)

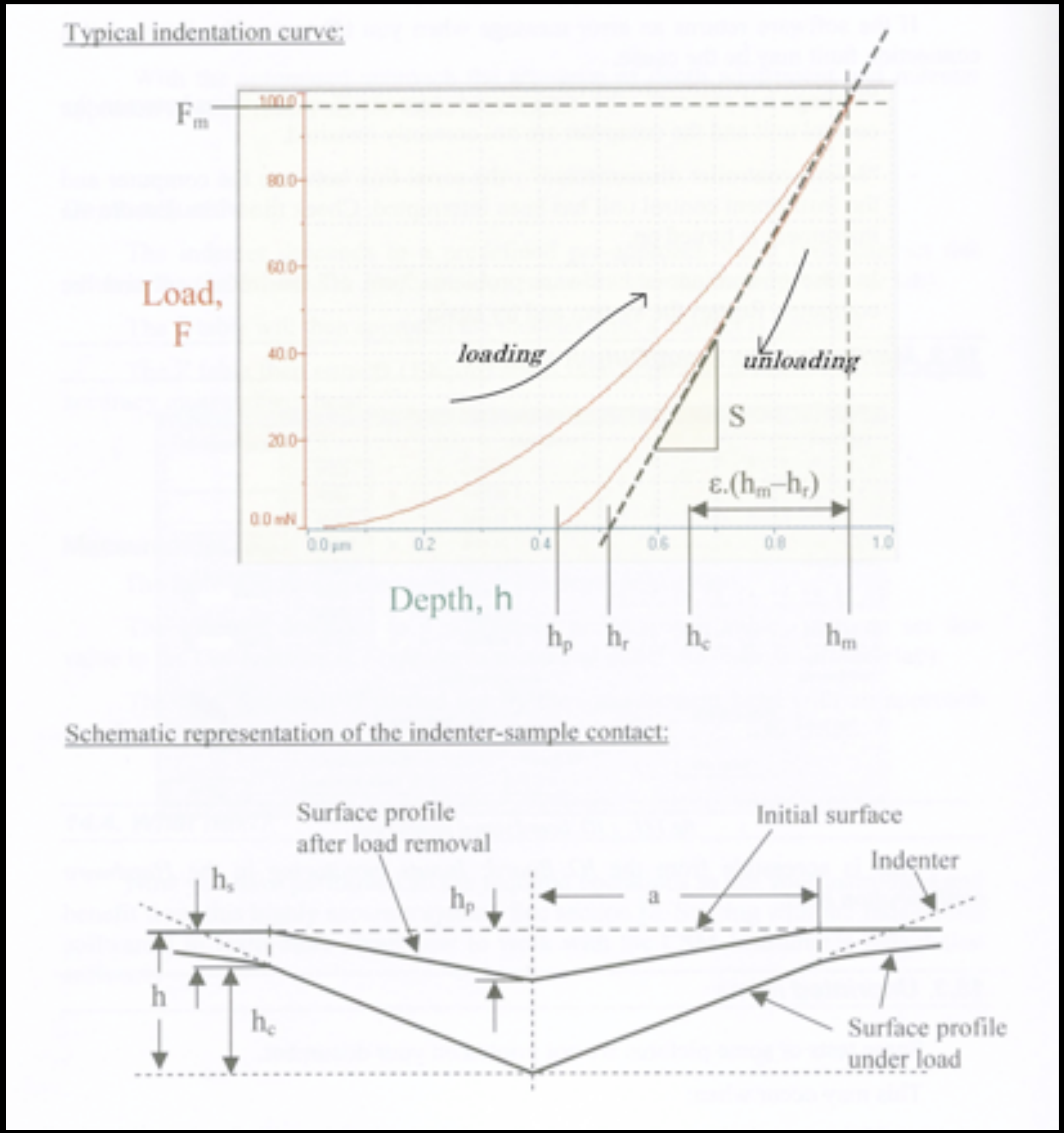
$$S = \frac{(B)}{(A)}$$

Sputtering rate vs. q



Nano hardness



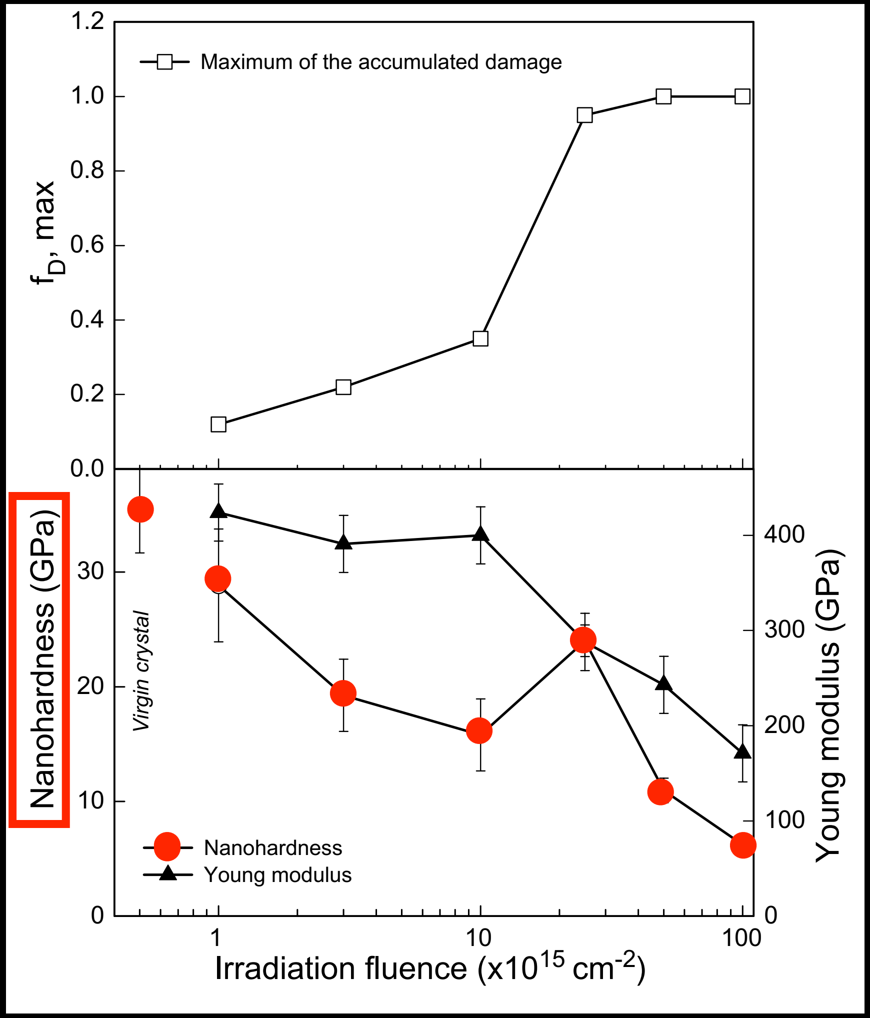


Mod. of mechanical properties

- IB-induced modification of crystal structure
  →Nano-hardness
  Young modulus etc.

- HCI beams enhances modification?

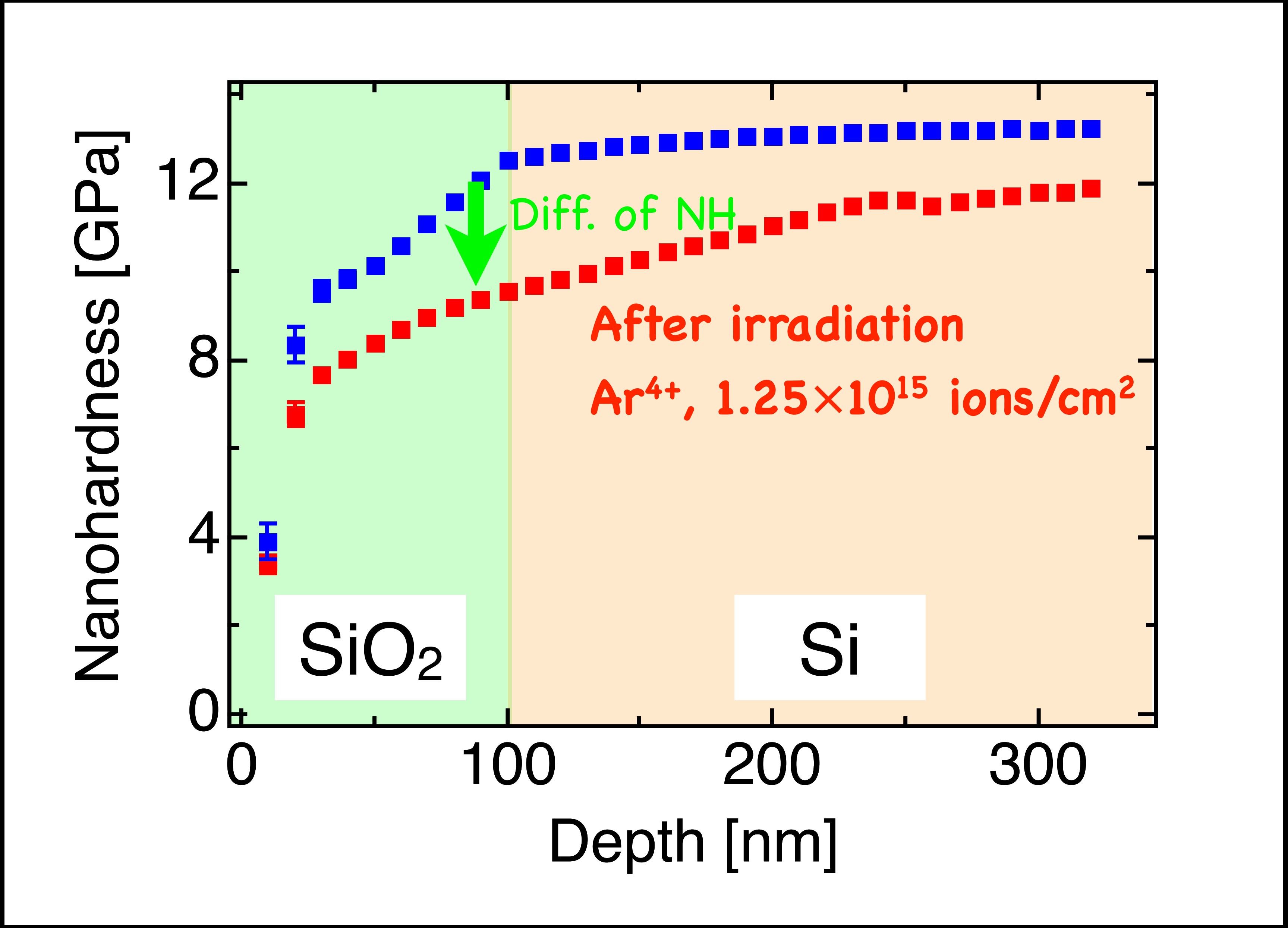
Ar-irradiated sapphire crystal



Nucl. Instr. and Meth. B 240 (2005) pp. 111,
J. Jagielski et al.

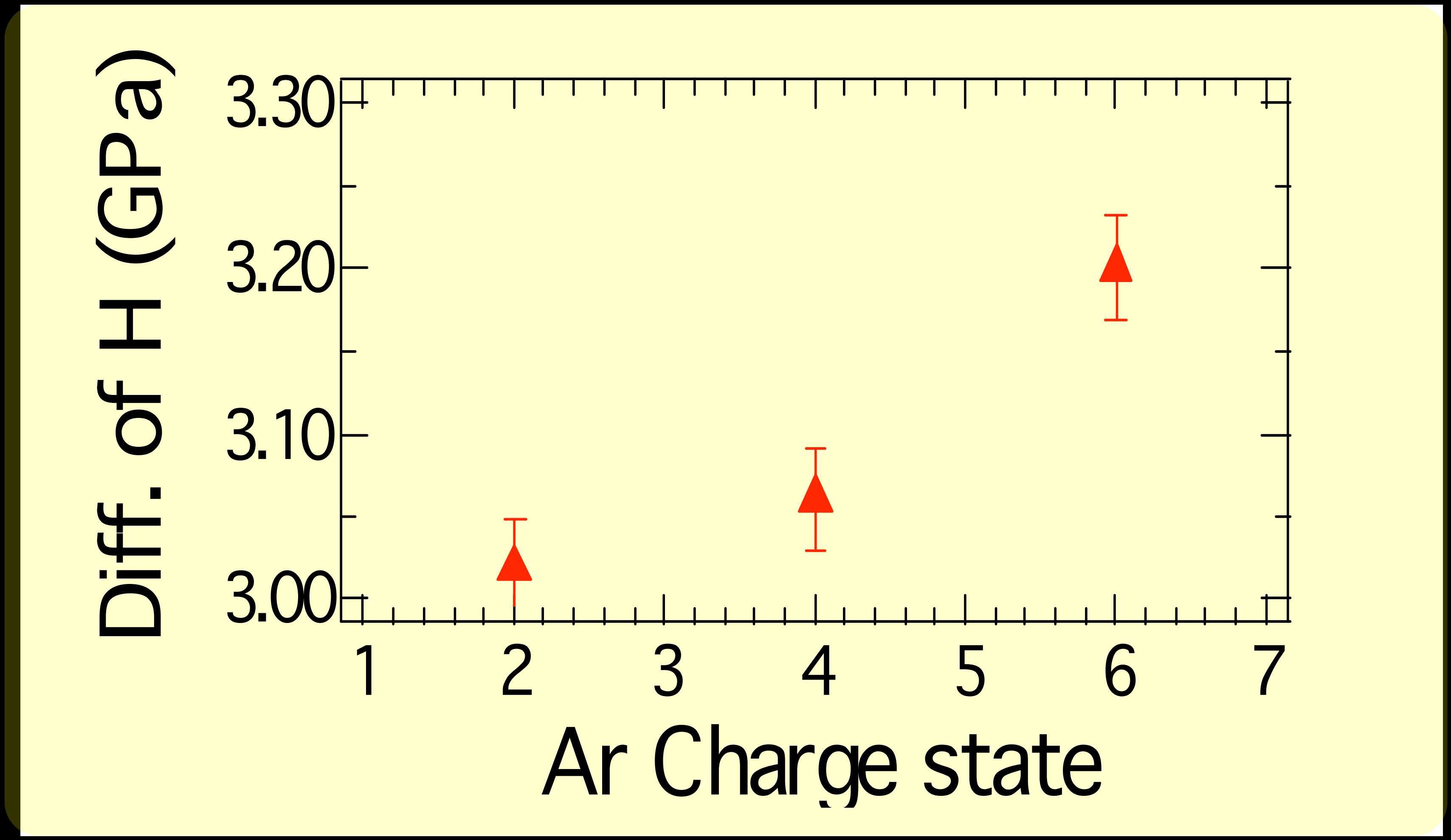
Softening of Si crystal

- Nano-indentation meas.



Ref. S.A. Pahlovy, Ph.D Thesis, Kochi Univ. of Tech., 2008

Charge state dep. of modification of NH



Ref. S.A. Pahlovy, Ph.D Thesis, Kochi Univ. of Tech., 2008

ECRIS (ECR ion source)

NANOGAN by PANTECHNIK

PANTECHNIK

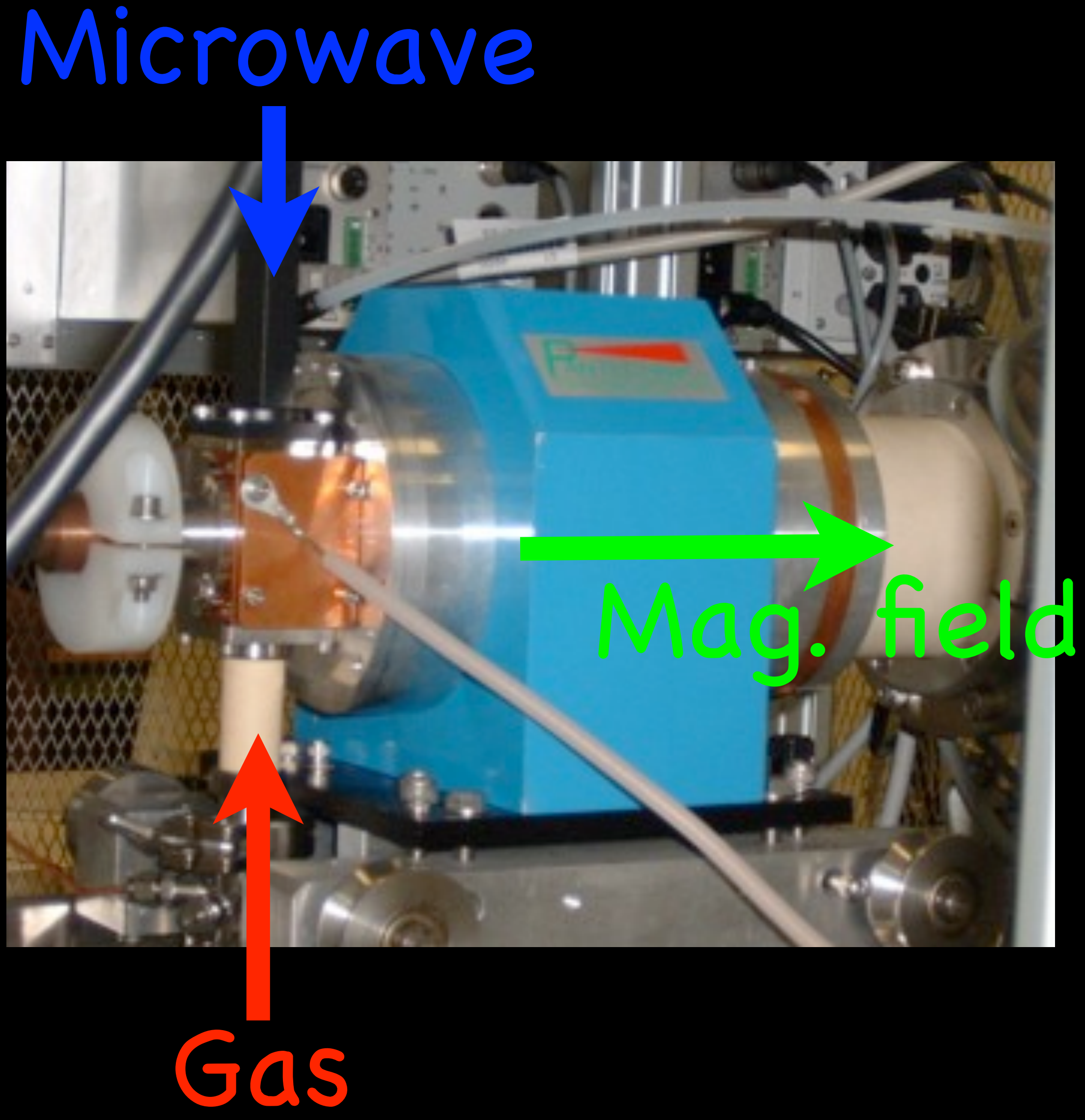
http://www.pantechnik.fr

- e^- with high E

  acceleration by ECR process

- confinement of ions

  Mirror mag. field



Ion source for HCIs : 2

EBIS (Electron beam ion source)

dresdenEBIS by DREEBIT

Electron & Ion Beam Technologies

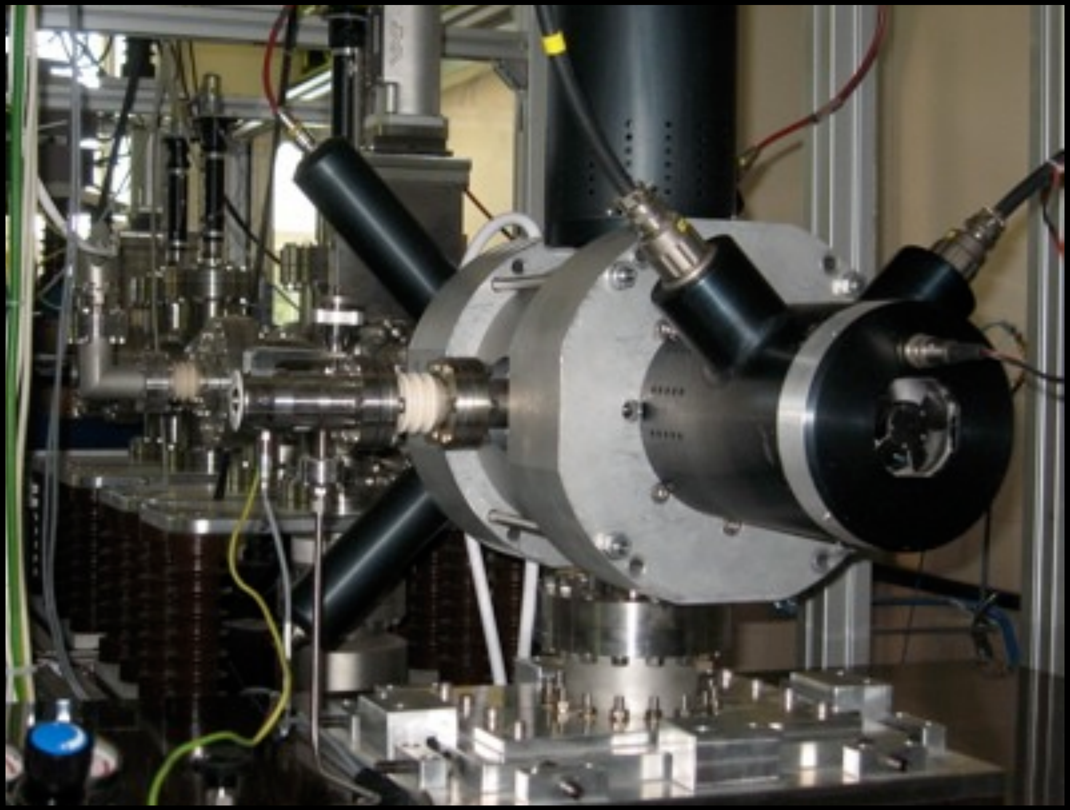
http://www.dreebit.com/

- e^- with high E

  e^--beam (~10μmφ, >10keV) produced by electron gun

- confinement of ions

  Trapped by ele. field induced by electrodes and e^--beam



Ion source for HCIs : 3

ILIS (Intense laser ion source)

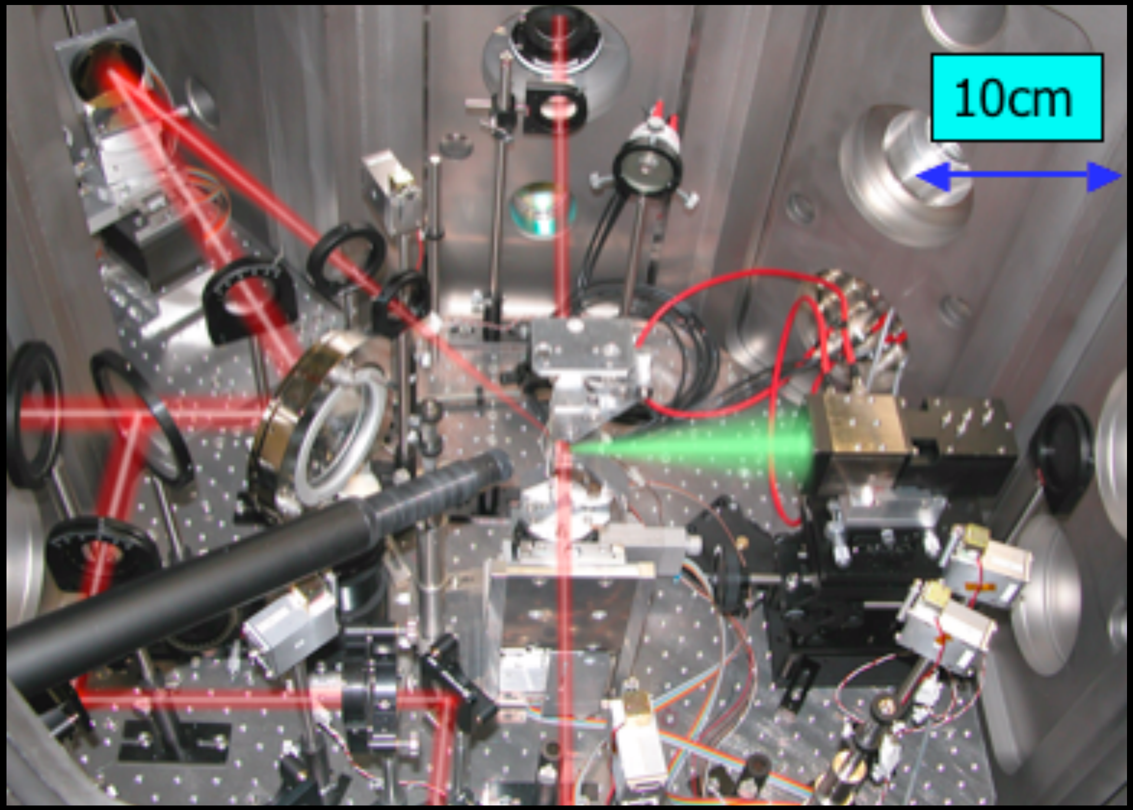
At present no industrial products,
but in future ...

- e^- with high E

  Heated by intense laser

- confinement of ions

  No fields for confinement because of high density of e^-



http://www2.gpi.ac.jp/JSPF/JAEA%20ion/JAEAion.html