2007.08.30 ICIS2007@Jeju, Korea

Highly charged ion beam applied to lithography technique

Sadao Momota
Kochi University of Technology

高知工科大学
KOCHI UNIVERSITY OF TECHNOLOGY

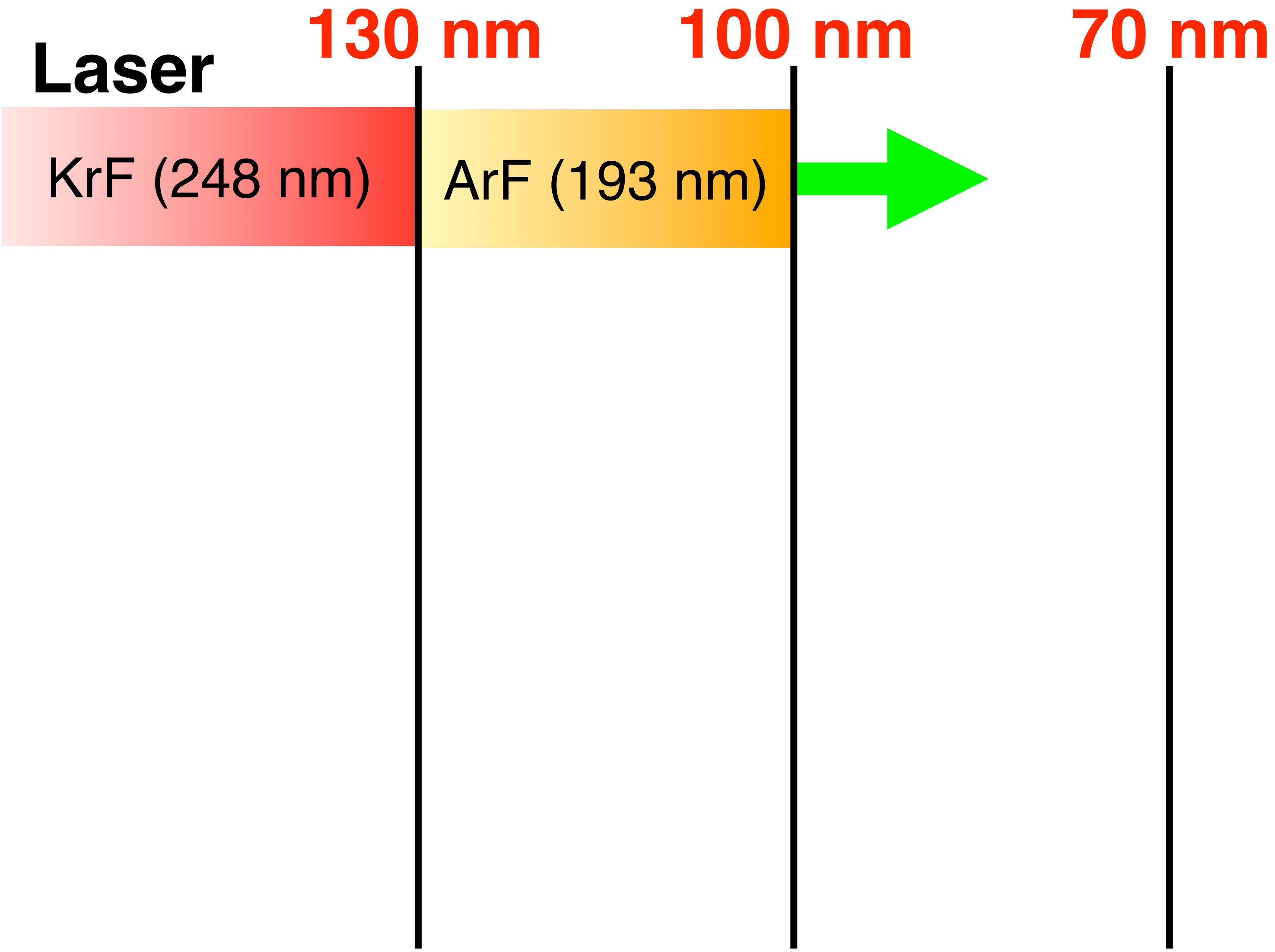
Contents

- Objective
- Principle of IBL
- Application of HCI beams to IBL
- HCI beam facility
- Experimental results
- Discussion
- Conclusion

Objective

Design rule of LSI

- Integration of 2D pattern



Laser

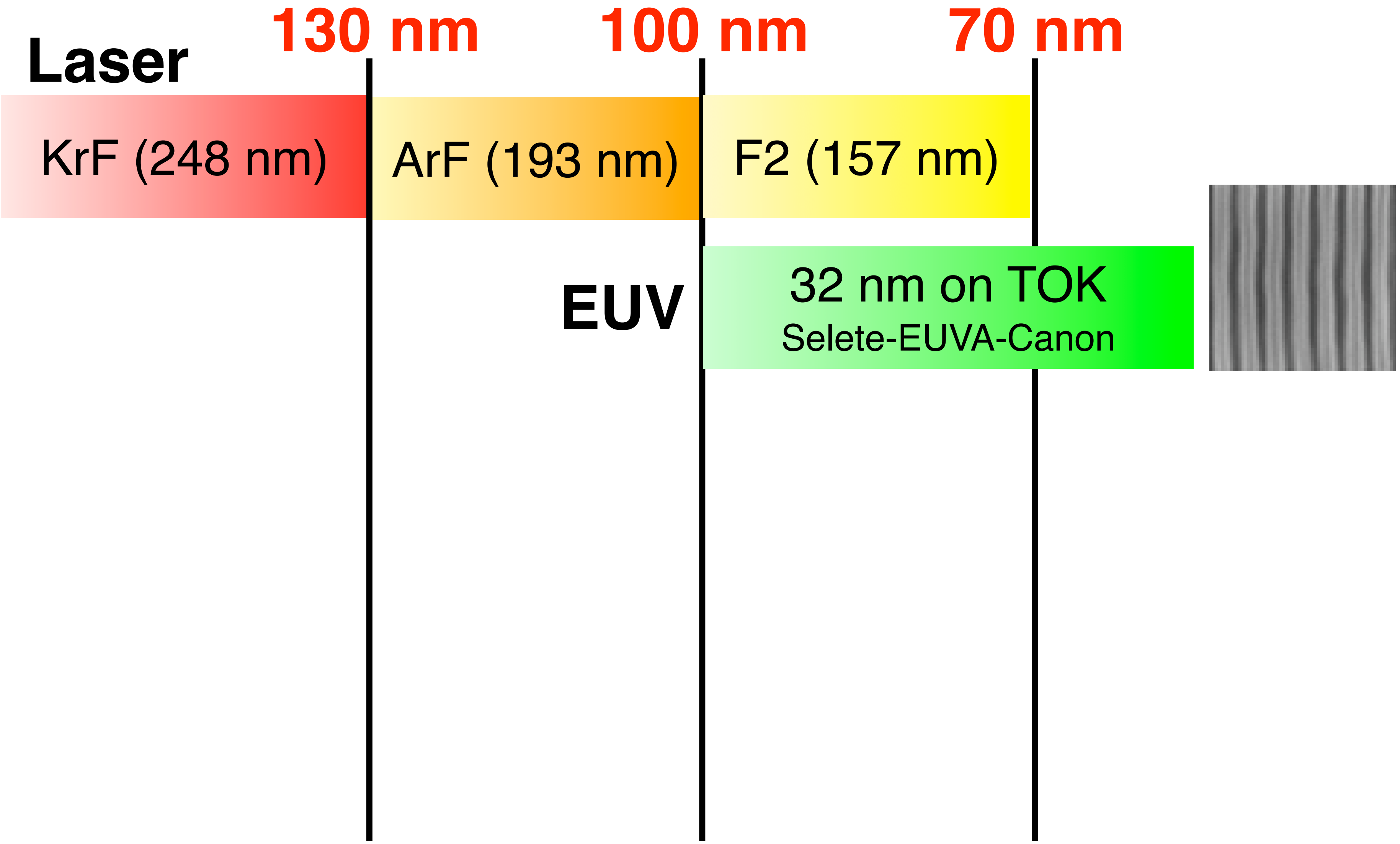
130 nm **100 nm** **70 nm**

KrF (248 nm)

ArF (193 nm)

Design rule of LSI

- Integration of 2D pattern



Laser

130 nm

100 nm

70 nm

KrF (248 nm)

ArF (193 nm)

F2 (157 nm)

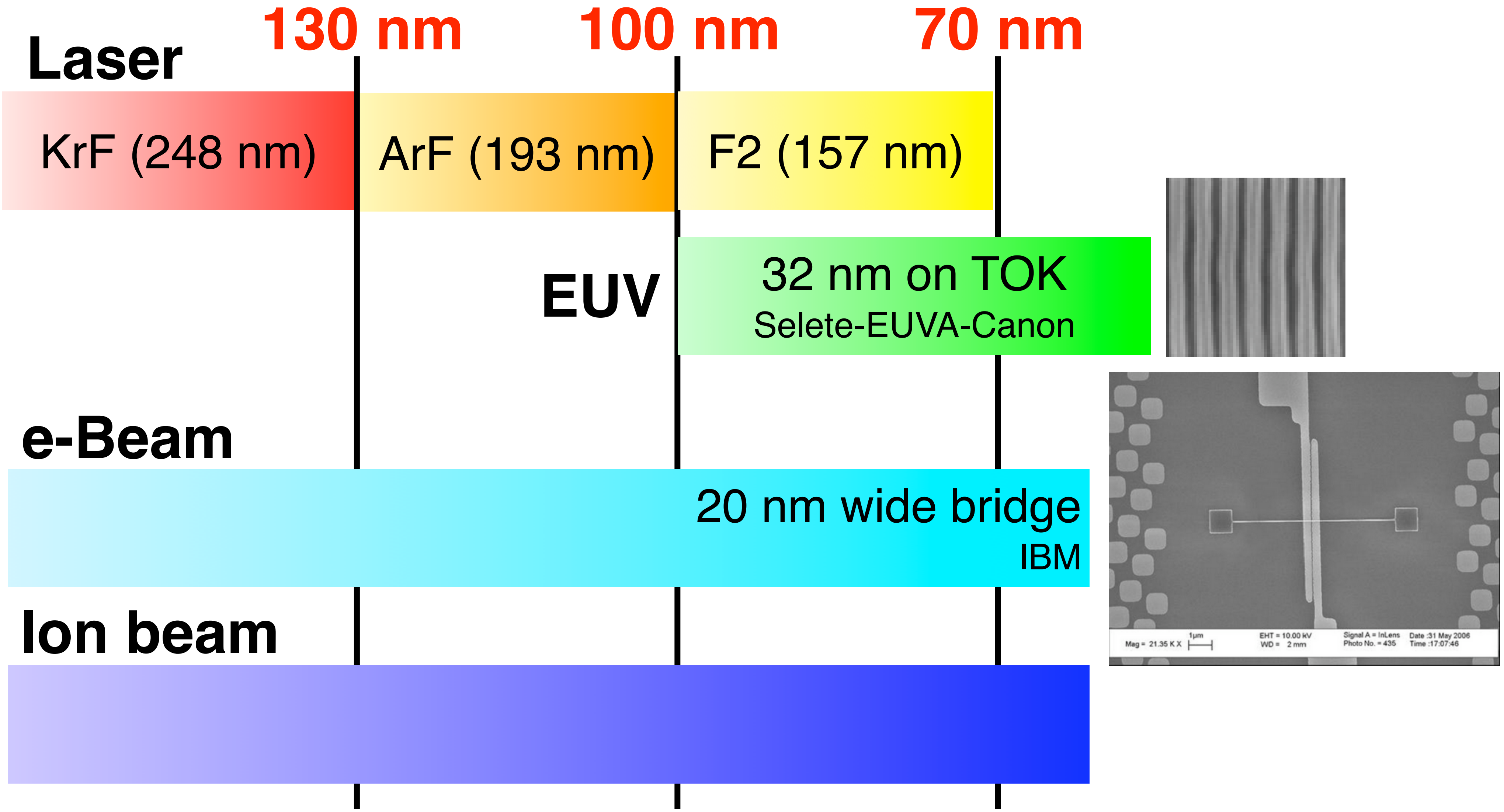
EUV

32 nm on TOK

Selete-EUVA-Canon

Design rule of LSI

- Integration of 2D pattern



Laser

130 nm **100 nm** **70 nm**

KrF (248 nm)

ArF (193 nm)

F2 (157 nm)

EUV

32 nm on TOK

Selete-EUVA-Canon

e-Beam

20 nm wide bridge

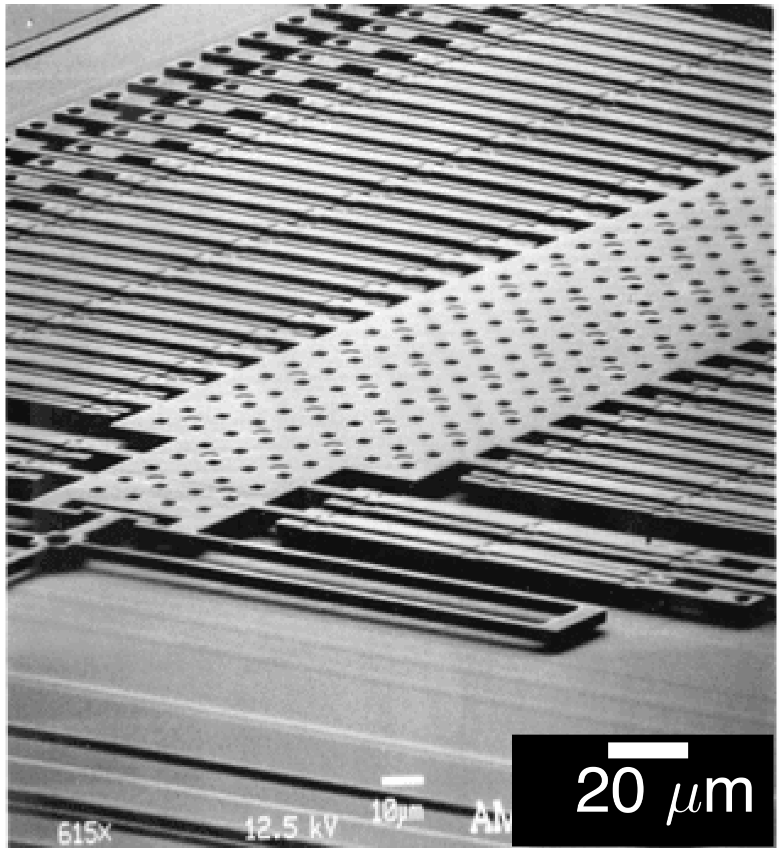
IBM

Ion beam

Applications of 3D micro-nano structures

- MEMS
  Micro Electro Mechanical System
- Optical device
- Mold
- Biochip
- Micro-machining tool

3-Axis Accelerometer



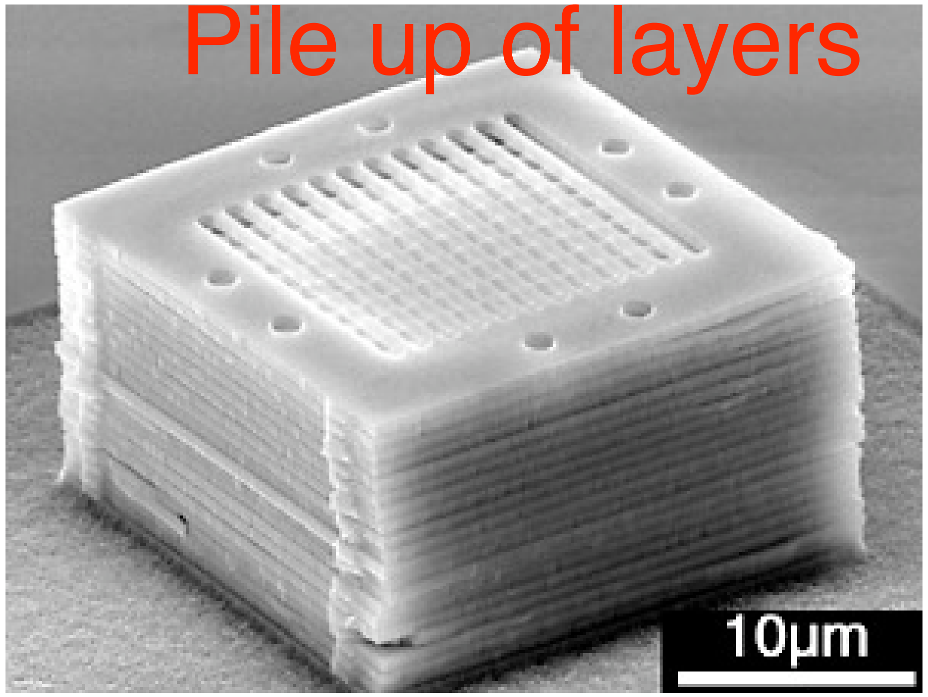
Analog Devices Co.

Applications of 3D micro-nano structures

- MEMS
  Micro Electro Mechanical System
- Optical device
- Mold
- Biochip
- Micro-machining tool

Photonic crystal

Pile up of layers



National Inst. for Material Science

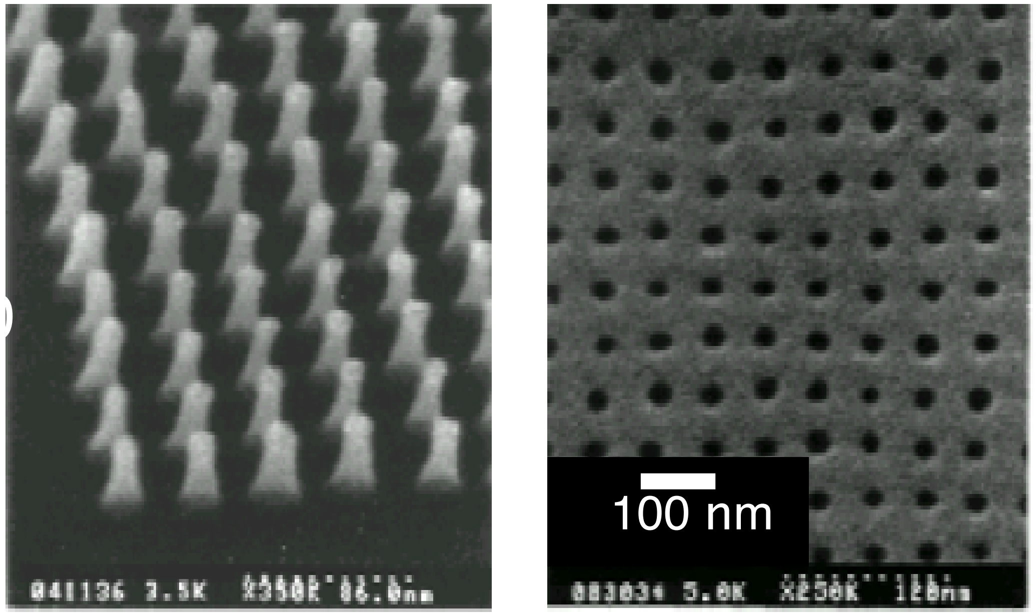
http://www.nims.go.jp/jpn/news/nimsnow/Vol4/2004-03/05.html

Applications of 3D micro-nano structures

- MEMS
  Micro Electro Mechanical System
- Optical device
- Mold
- Biochip
- Micro-machining tool

Pattern transfer

SiO_2/Si → PMMA



10nm diam. & 60nm pitch

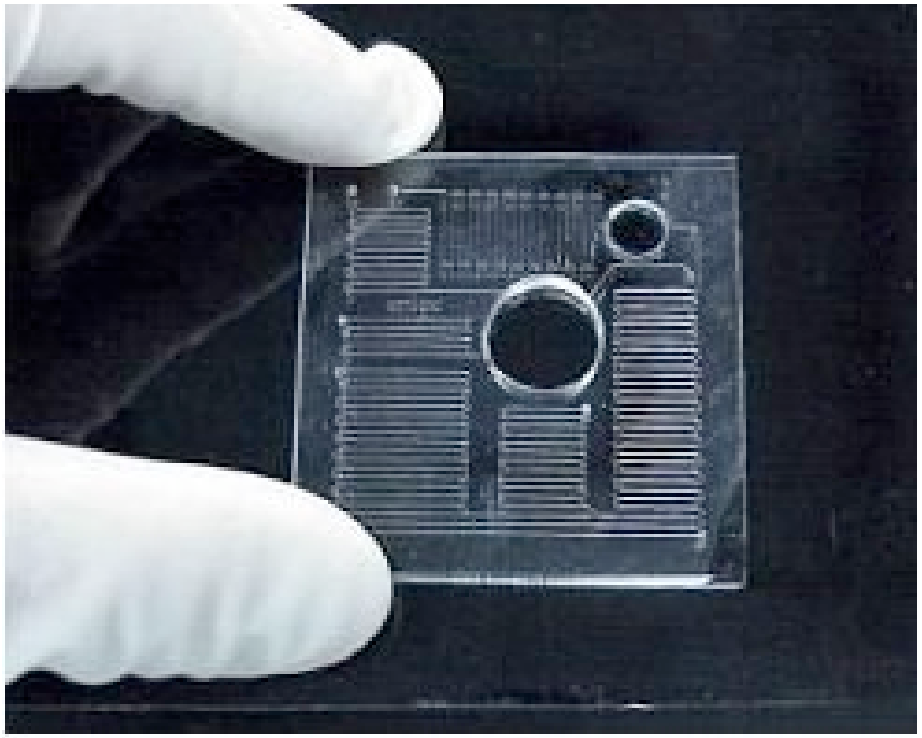
S.Y. Chou et al.

J. Vac. Sci. Technol., B15(1997)2897

Applications of 3D micro-nano structures

- MEMS
  Micro Electro Mechanical System
- Optical device
- Mold
- Biochip
- Micro-machining tool

Micro inspection chip

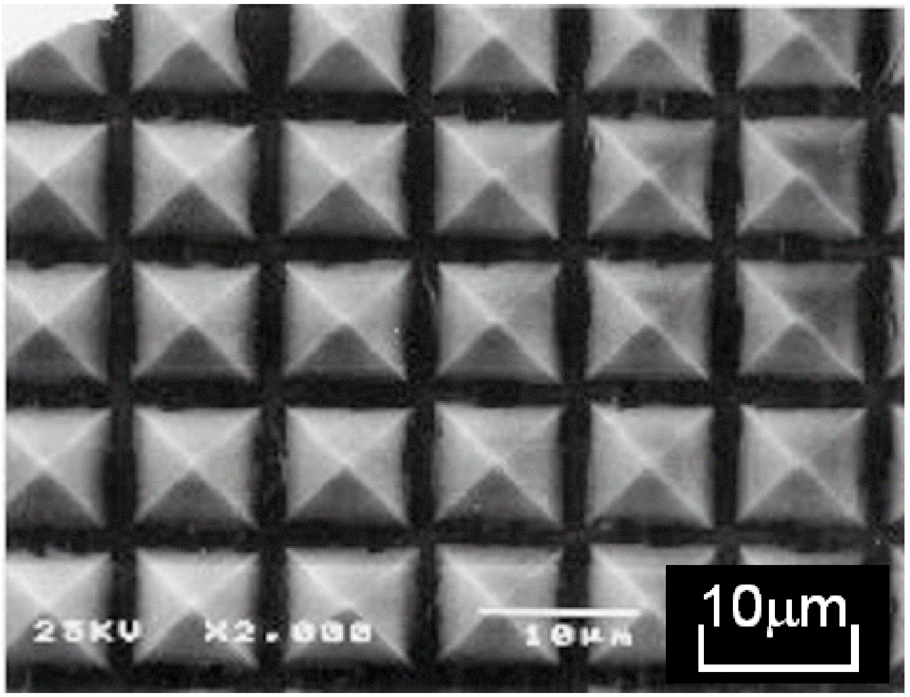


Hitachi, Ltd.

Applications of 3D micro-nano structures

- MEMS
  Micro Electro Mechanical System
- Optical device
- Mold
- Biochip
- Micro-machining tool

Diamond array tool



Morita Gr. (Toyama Univ.)

Feasibility of IBL to fabricate 3D structures

- Ion range controlled by beam energy
  - $E \propto V$
- Small lateral straggling
- High reactivity
  - *Large energy deposition in materials*

Goal of this research

Fabrication of 3D nano-scale structure

Application of HCI to IBL technique

⇓

- Efficient fabrication
- Controllability/Enhancement of fabrication depth

compared with conventional IBL

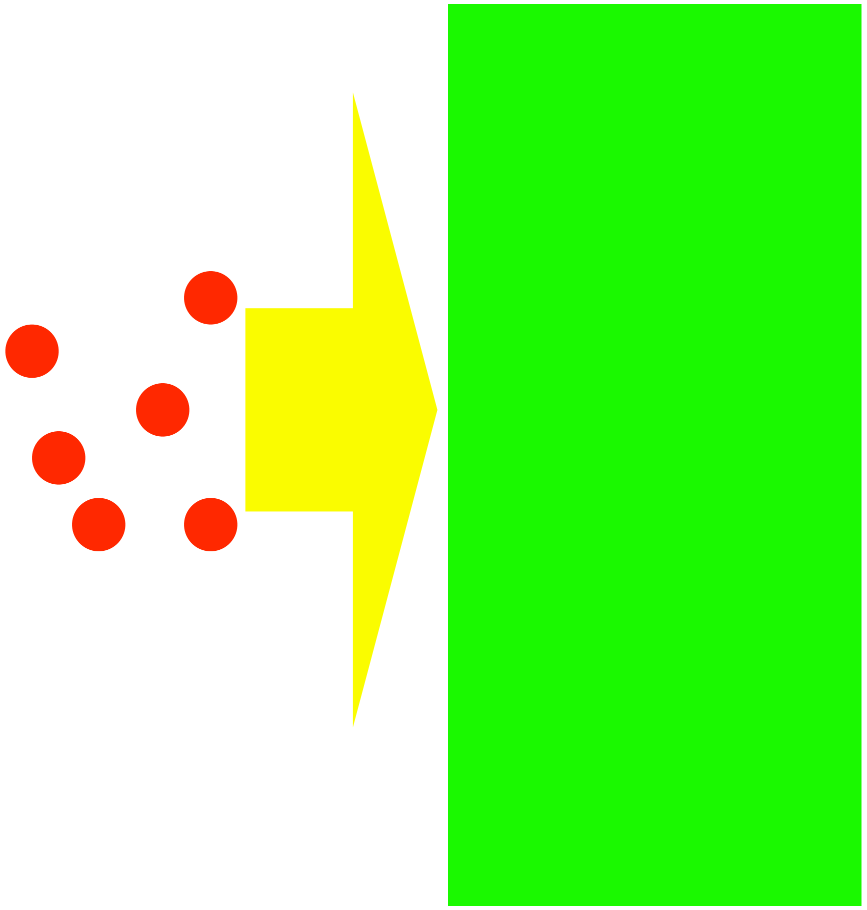
Principle of IBL

Exposure process

- Irradiation of ion beam
  - Mask or FIB
- Irradiation effect
  - Implantation of impurities
  - Change in chemical structure / component

    Crystal ⇔ Amorphous

    Polymer ⇔ Monomer

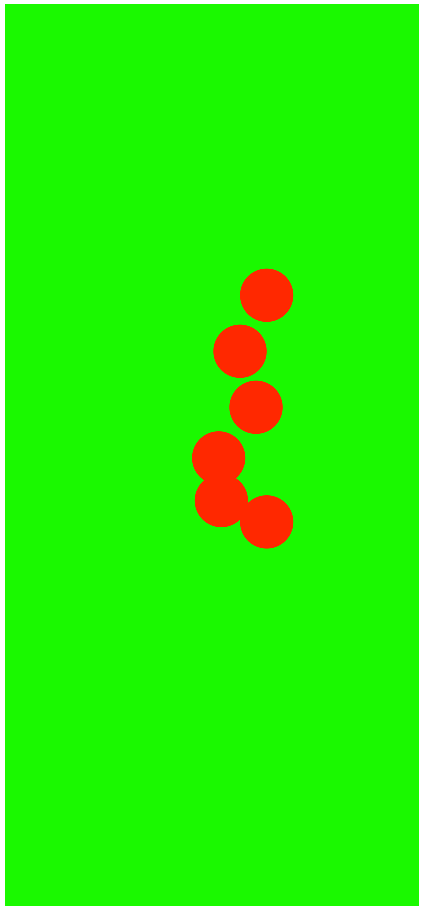


Exposure process

- Irradiation of ion beam
  - Mask or FIB
- Irradiation effect
  - Implantation of impurities
  - Change in chemical structure / component

    Crystal ⇔ Amorphous

    Polymer ⇔ Monomer

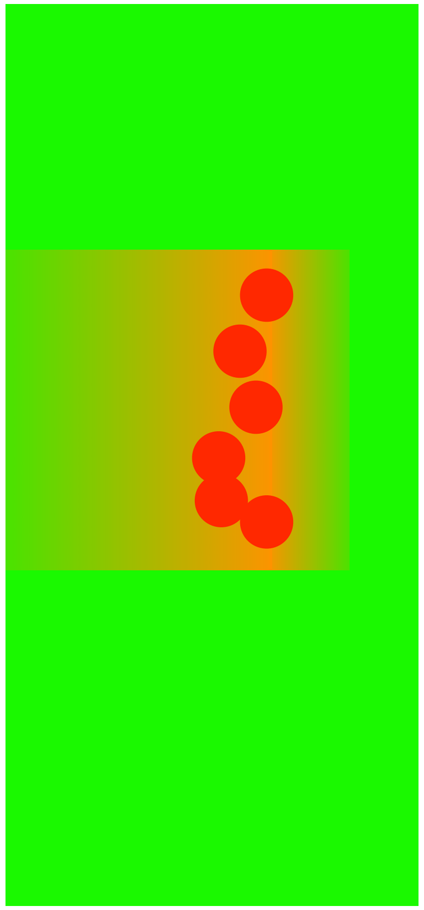


Exposure process

- Irradiation of ion beam
  - Mask or FIB
- Irradiation effect
  - Implantation of impurities
  - Change in chemical structure / component

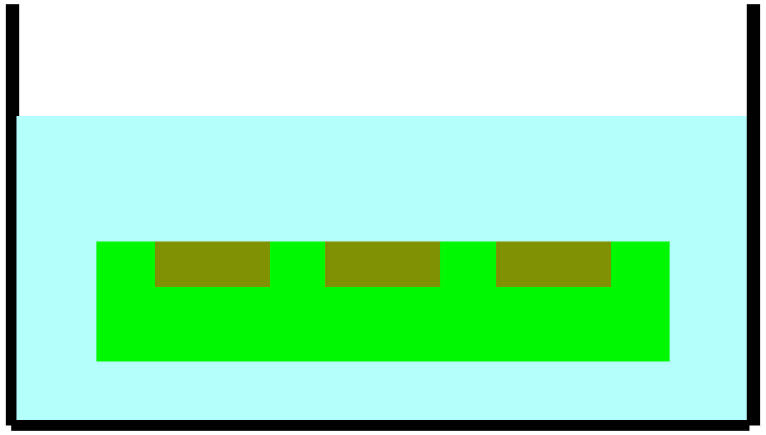
    Crystal ⇔ Amorphous

    Polymer ⇔ Monomer



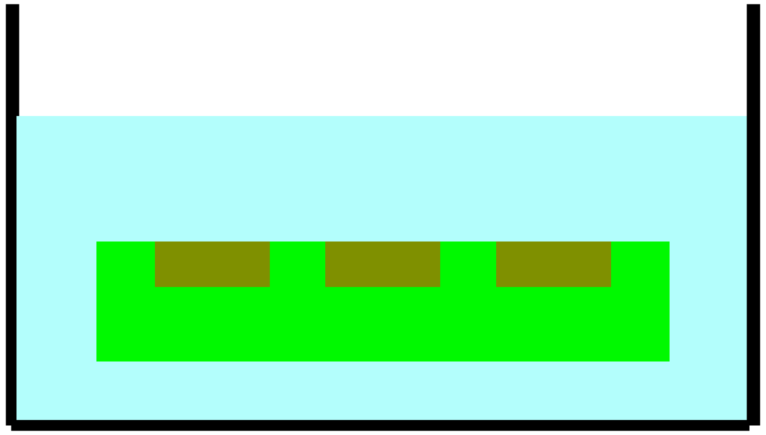
Development process

- Etching by chemicals
  - Wet / Dry
- Difference in etching rate caused by
  - Impurity
  - Change in chemical structure / component
- Fabricated structure
  - Concave : positive
  - Hillock : negative



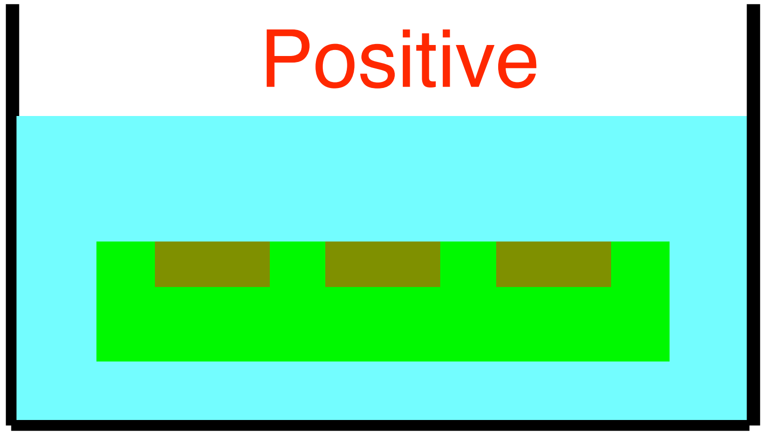
Development process

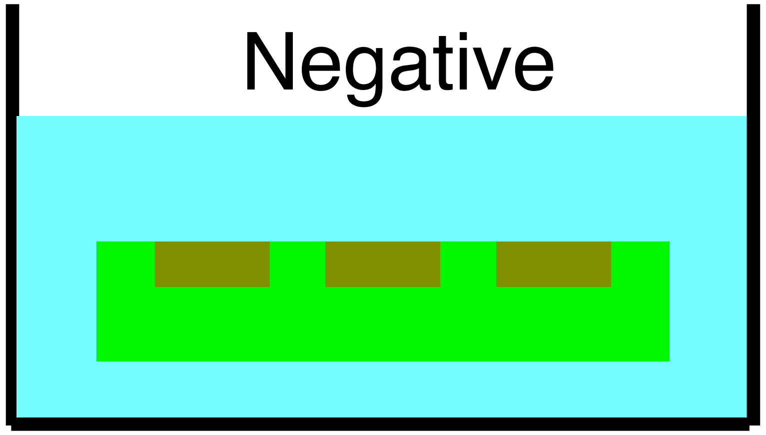
- Etching by chemicals
  - Wet / Dry
- Difference in etching rate caused by
  - Impurity
  - Change in chemical structure / component
- Fabricated structure
  - Concave : positive
  - Hillock : negative



Development process

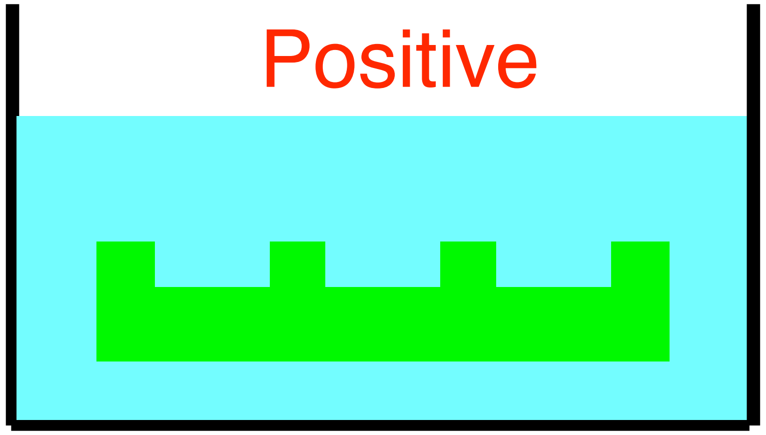
- Etching by chemicals
  - Wet / Dry
- Difference in etching rate caused by
  - Impurity
  - Change in chemical structure / component
- Fabricated structure
  - Concave : positive
  - Hillock : negative

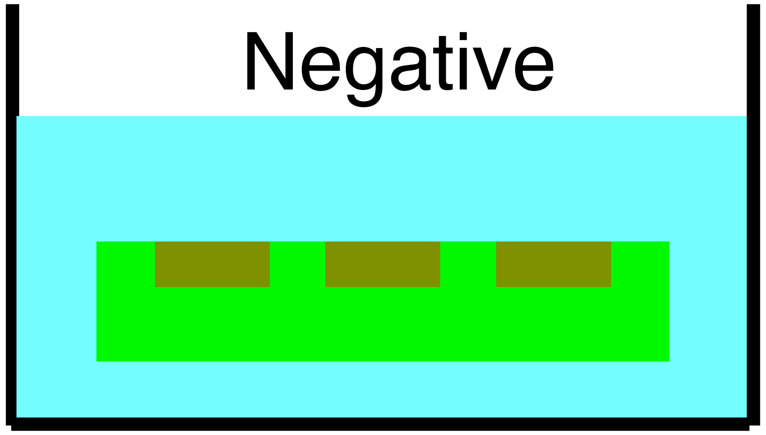




Development process

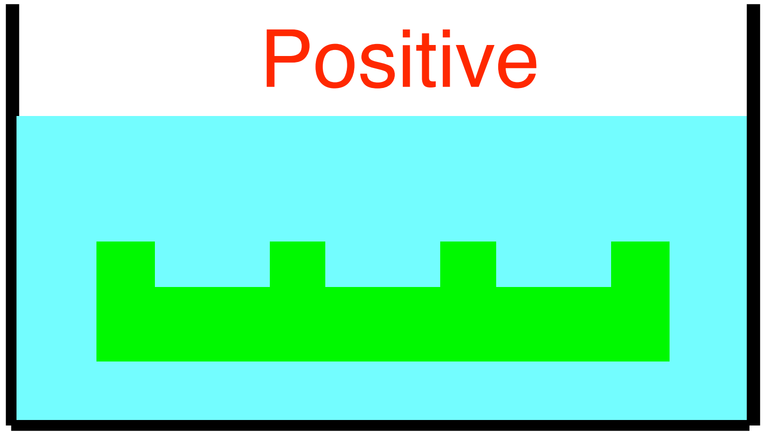
- Etching by chemicals
  - Wet / Dry
- Difference in etching rate caused by
  - Impurity
  - Change in chemical structure / component
- Fabricated structure
  - Concave : positive
  - Hillock : negative

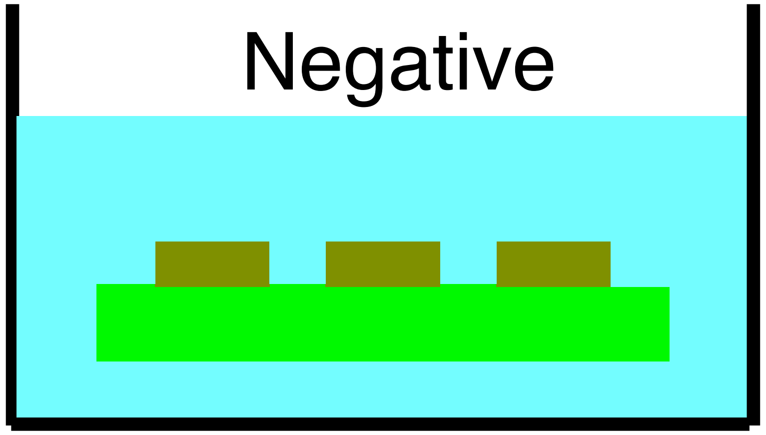




Development process

- Etching by chemicals
  - Wet / Dry
- Difference in etching rate caused by
  - Impurity
  - Change in chemical structure / component
- Fabricated structure
  - Concave : positive
  - Hillock : negative





Application of HCI beams to IBL

Why HCI beam?

Why HCI beam?

- Availability of HCI sources
  - ECRIS, EBIS, Laser IS

Why HCI beam?

- Availability of HCI sources
  - ECRIS, EBIS, Laser IS
- Expected advantages to use HCI

  compared with singly charged ion

Expected advantage to apply HCI beams

Expected advantage to apply HCI beams

- Efficient fabrication
  - *High reactivity of HCI beams in materials*

Expected advantage to apply HCI beams

- Efficient fabrication
  - *High reactivity of HCI beams in materials*
- Controllability/Enhancement of fabrication depth $\Leftarrow \boldsymbol{E \propto qV}_{\mathrm{Acl.}}$

compared with conventional lithography technique

Unique phenomena induced by HCI beams

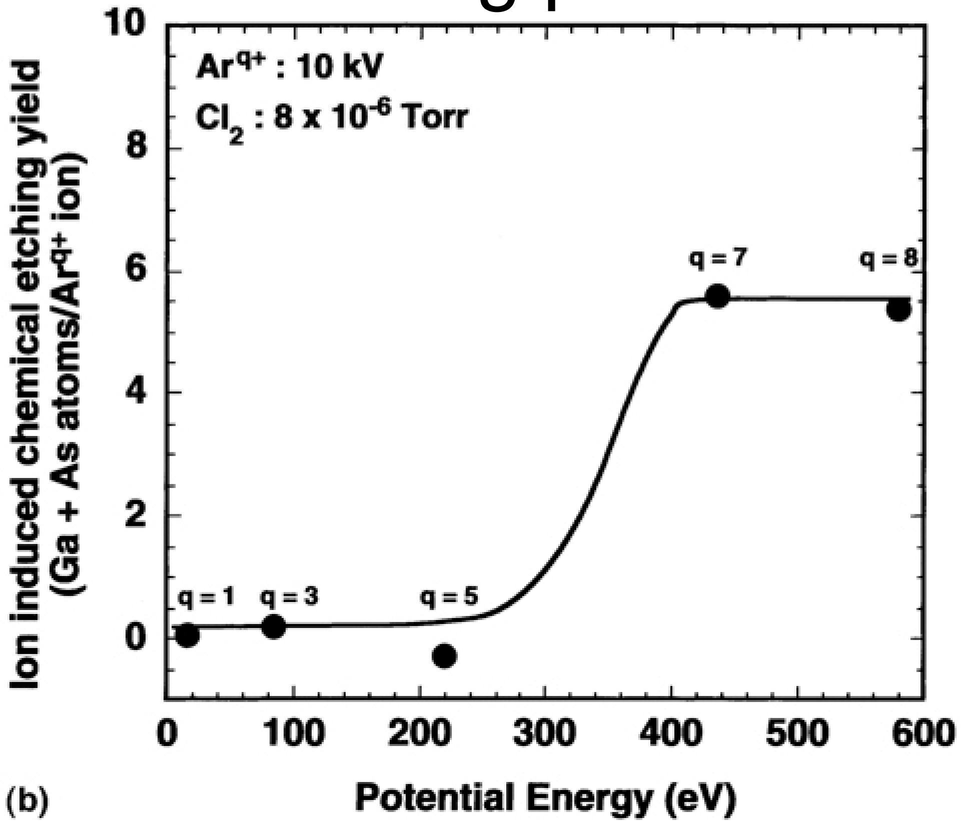
- Enhancement of *dE*
- Pot. emission
- Hollow atom
- Local modification
- Coulomb explosion

  etc.

Unique phenomena induced by HCI

- Enhancement of *dE*
- Pot. emission
- Hollow atom
- Local modification
- Coulomb explosion
  etc.

Enhancement of dry etching process



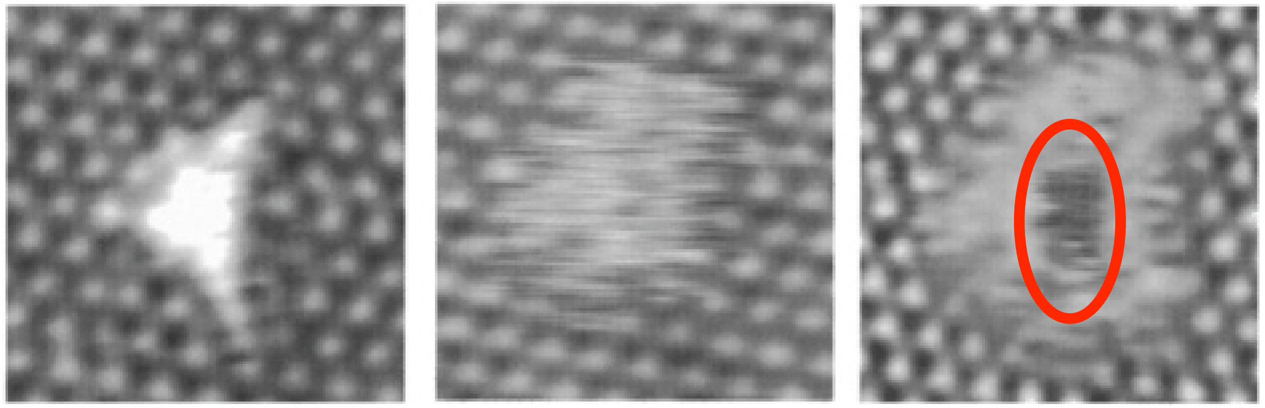
Mat. Sci. Eng. B74 (2000) 40 T. Meguro et al.

Unique phenomena induced by HCI

- Enhancement of *dE*
- Pot. emission
- Hollow atom
- Local modification
- Coulomb explosion

etc.

Creation of nano-diamonds in HOPG



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

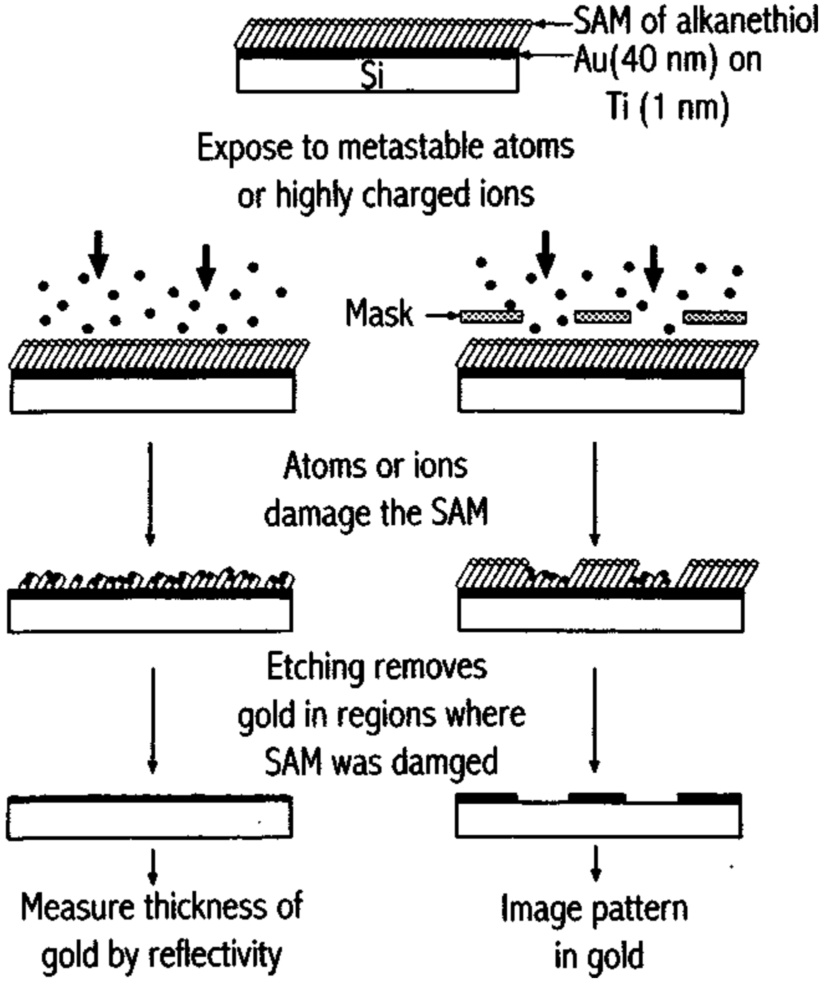
$sp_2 \rightarrow sp_3$

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

IBL of self-assembled monolayers

Xe^{44+} from EBIT at NIST(11x10^6 ions/s)

- Exposure :
  Xe^{44+} (350keV)
  Ar^* (~0.1 eV)
- Development :
  Remove Au in irradiated region
- Measurement :
  Loss of reflectivity



L.P. Ratliff et al.Appl. Phys. Lett. 75 (1999) pp.590

IBL of self-assembled monolayers

Xe^{44+} from EBIT at NIST(11x10^6 ions/s)

- Exposure :
  Xe^{44+} (350keV)
  Ar^* (~0.1 eV)
- Development :
  Remove Au in irradiated region
- Measurement :
  Loss of reflectivity

	$E_{pot.}$ (keV)	Dose (ions/cm^2)
Xe^{44+}	51.3	1.3x10^{11}
Ar^*	0.012	6.6x10^{15}

L.P. Ratliff et al.Appl. Phys. Lett. 75 (1999) pp.590

IBL of self-assembled monolayers

Xe^{44+} from EBIT at NIST(11x10^{6} ions/s)

- Exposure :
  Xe^{44+} (350keV)
  Ar* (~0.1 eV)
- Development :
  Remove Au in irradiated region
- Measurement :
  Loss of reflectivity

	E$_{\text{pot.}}$ (keV)	Dose (ions/cm^{2})
Xe^{44+}	51.3	1.3x10^{11}
Ar*	0.012	6.6x10^{15}

x 4400 **x 1/50000**

2D pattern

L.P. Ratliff et al.Appl. Phys. Lett. 75 (1999) pp.590

IBL of PMMA

Xe^{44+} from EBIT at NIST(11x10^6 ions/s)

- Exposure :
  Xe^{44+} (210keV) on PMM
- Dev
  Ren
  irrad
- Measurement :
  SEM, AFM

"... the method demonstrated here can be extended deep into the submicrometer range."

J.D. Gillaspy et al., J. Vac. Sci. Technol. B16 (1998) pp.3294

IBL of PMMA

Xe^{44+} from EBIT at NIST(11x10^{6} ions/s)

- Exposure :
  Xe^{44+} (210keV) on PMM

"... the method demonstrated here can be extended deep into the submicrometer range."

- Dev
  Ren
  irrad
- Measurement :
  SEM, AFM

	$E_{\text{pot.}}$ (kV)	Dose (ions/cm^2)
Ga^{1+}	0.006	6x10^{11}

J.D. Gillaspy et al., J. Vac. Sci. Technol. B16 (1998) pp.3294

Goal of this research

Fabrication of 3D nano-scale structure

- Efficient fabrication
  - *High reactivity of HCI beams with materials*
- Controllability/Enhancement of fabrication depth
  - *Controlled by V and q*
  - *Application of larger q*

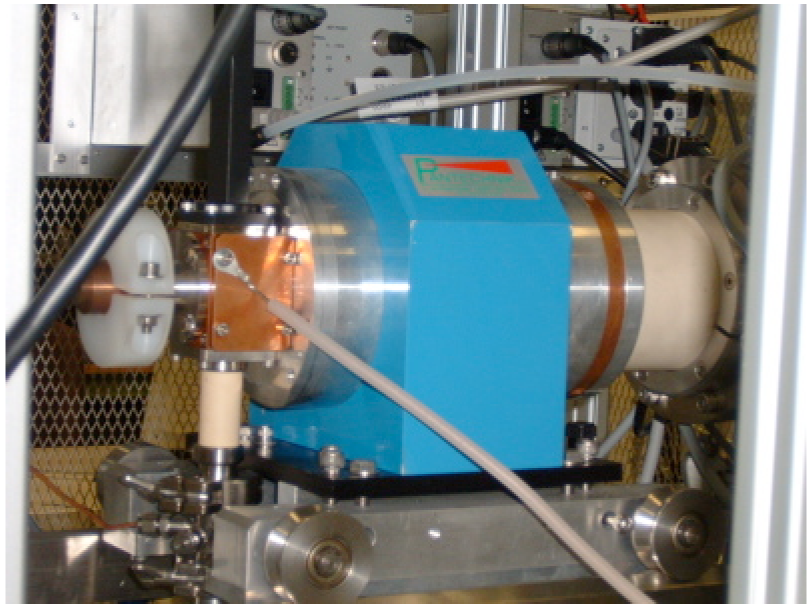
HCI beam facility

Production of HCI beams

- 10GHz-NANOGAN
  - P_{RF} = 0~80 W
  - $V_{Ext.}$ = 0~30 kV
- $V_{Acl.}$ = 0~100 kV
- Compact install

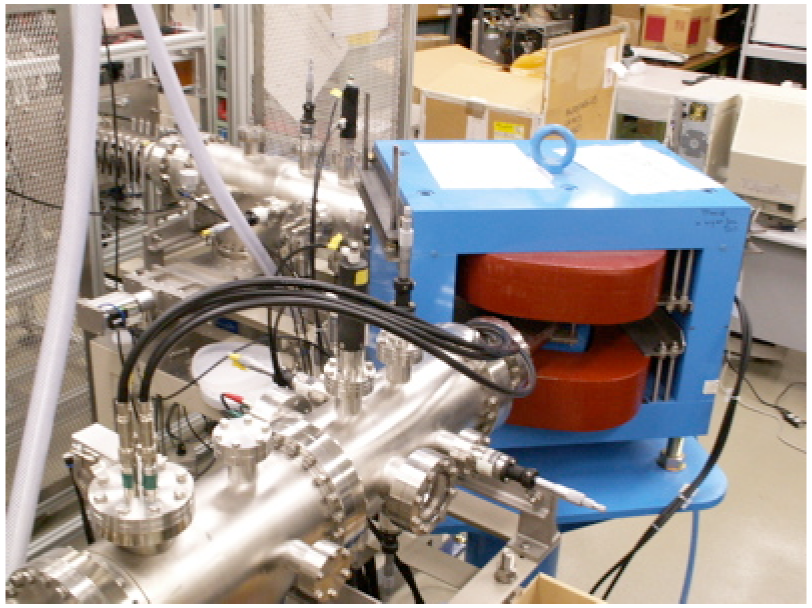
ECRIS and acceleration system installed in *L*~1 m.

ICIS2003 : S. Momota et al.,
Rev. Sci. Instrum., 75(2004), pp.1497 - 1498



Separation of HCI beams

- Rigidity analysis
  - $\theta = \pi/4$ rad
  - $B\rho = 0 \sim 0.33$ T·m
- Ions
  - $\mathrm{Ar}^{1+} \sim \mathrm{Ar}^{9+}$

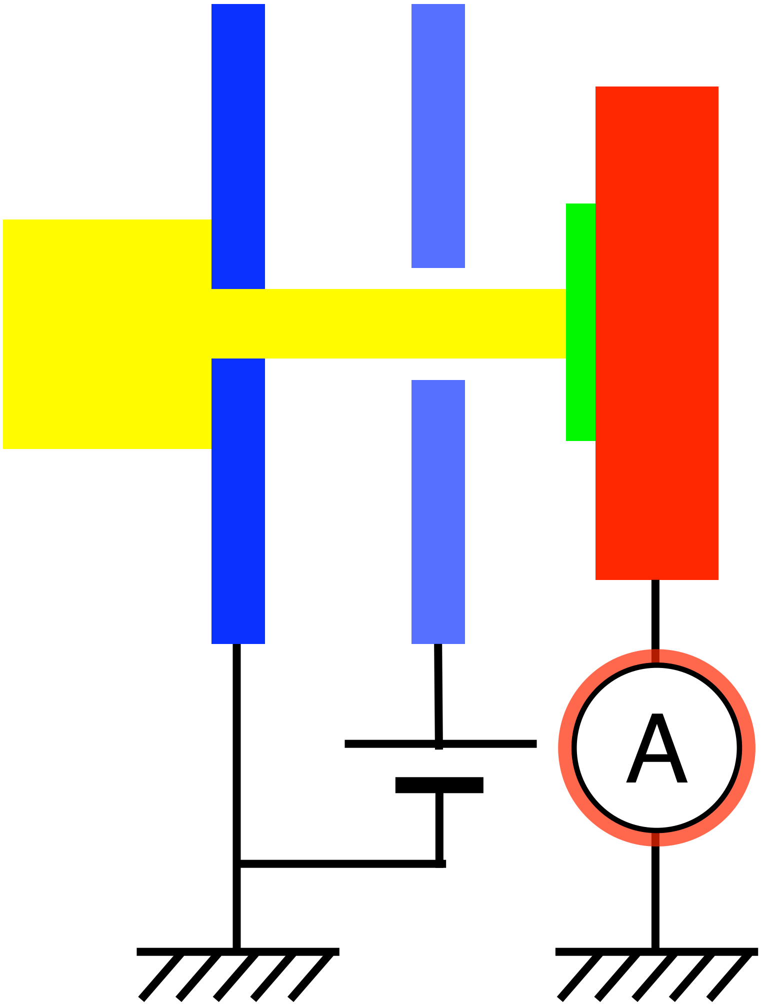


Irradiation of HCI beams

- Stencil mask
    - Cu
- On-line current monitor
    - Collimator
    - Secondary electron suppressor
    - Current integration

Irradiation of HCI beams

- Stencil mask
  - Cu
- On-line current monitor
  - Collimator
  - Secondary electron suppressor
  - Current integration

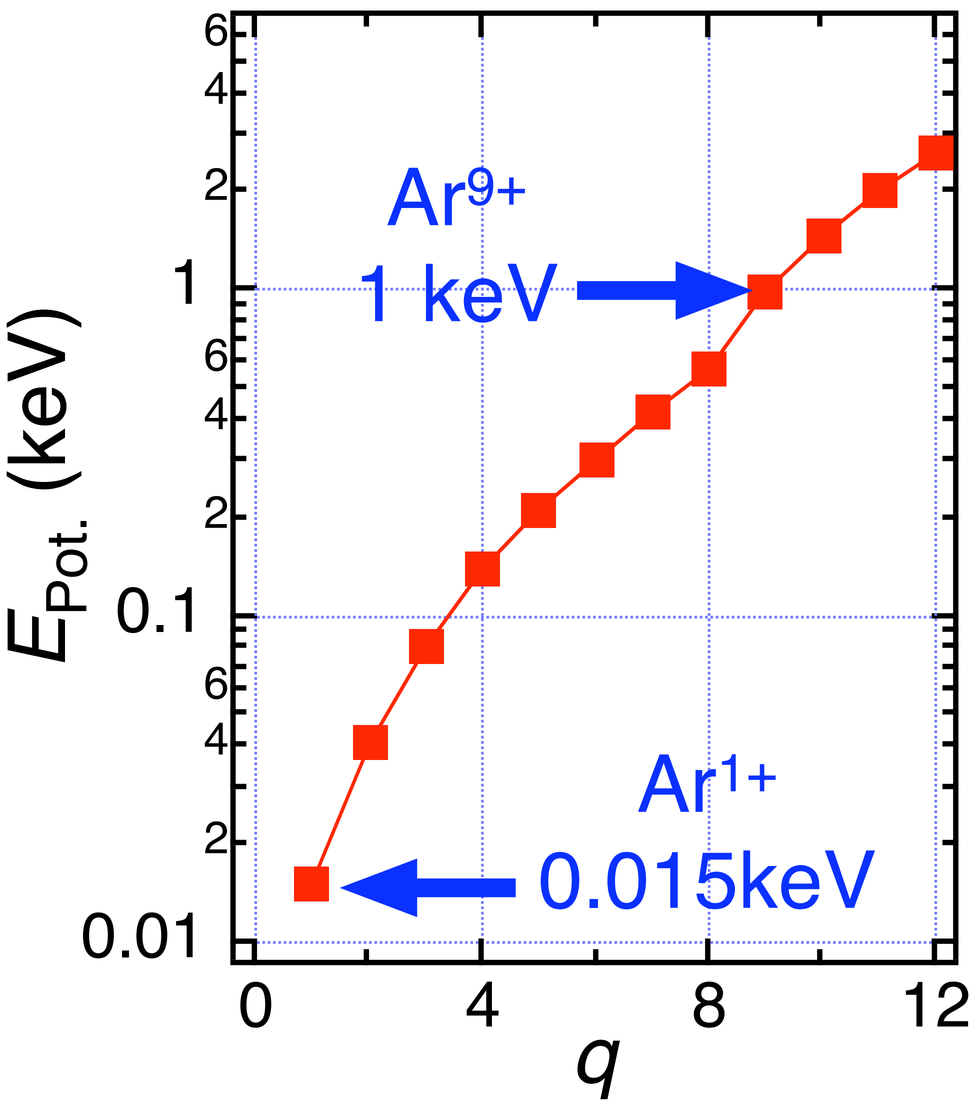


Experimental results

IBL on SOG

- Irradiation of Ar^{q+}
  - q = +1~+9
  - 80~240 keV
  - Cu-Mask (43×43 μm)
- Wet etching
  - BHF (HF, NH_4F)
- Surface profile
  - Optical microscopy
  - Profilometer

$E_{Pot.}$ of Ar ions



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

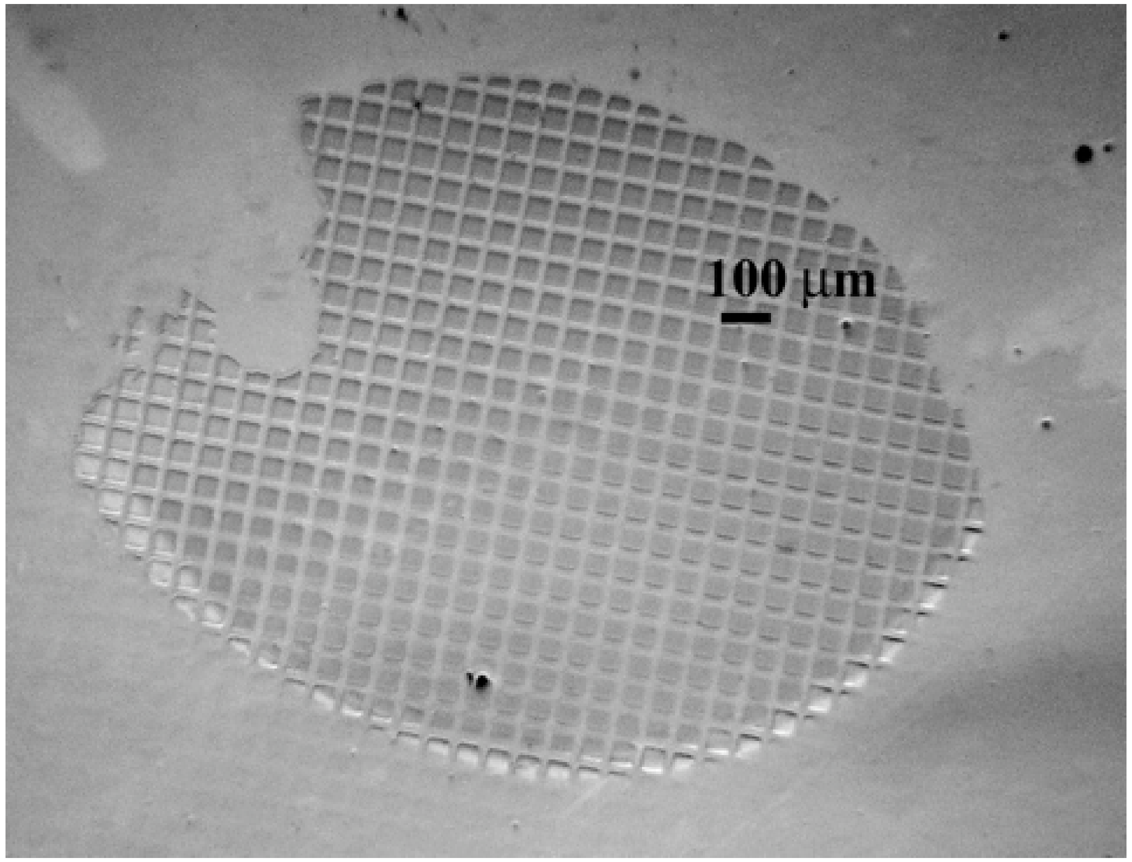
IBL on SOG

- Irradiation of Ar^{q+}
  - q = +1~+9
  - 80~240 keV
  - Cu-Mask (43×43 μm)
- Wet etching
  - BHF (HF, NH_4F)
- Surface profile
  - Optical microscopy
  - Profilometer

IBL of SOG

- Irradiation of Ar^{q+}
  - q = +1~+9
  - 80~240 keV
  - Cu-Mask (43×43 μm)
- Wet etching
  - BHF (HF, NH_4F)
- Surface profile
  - Optical microscopy
  - Profilometer

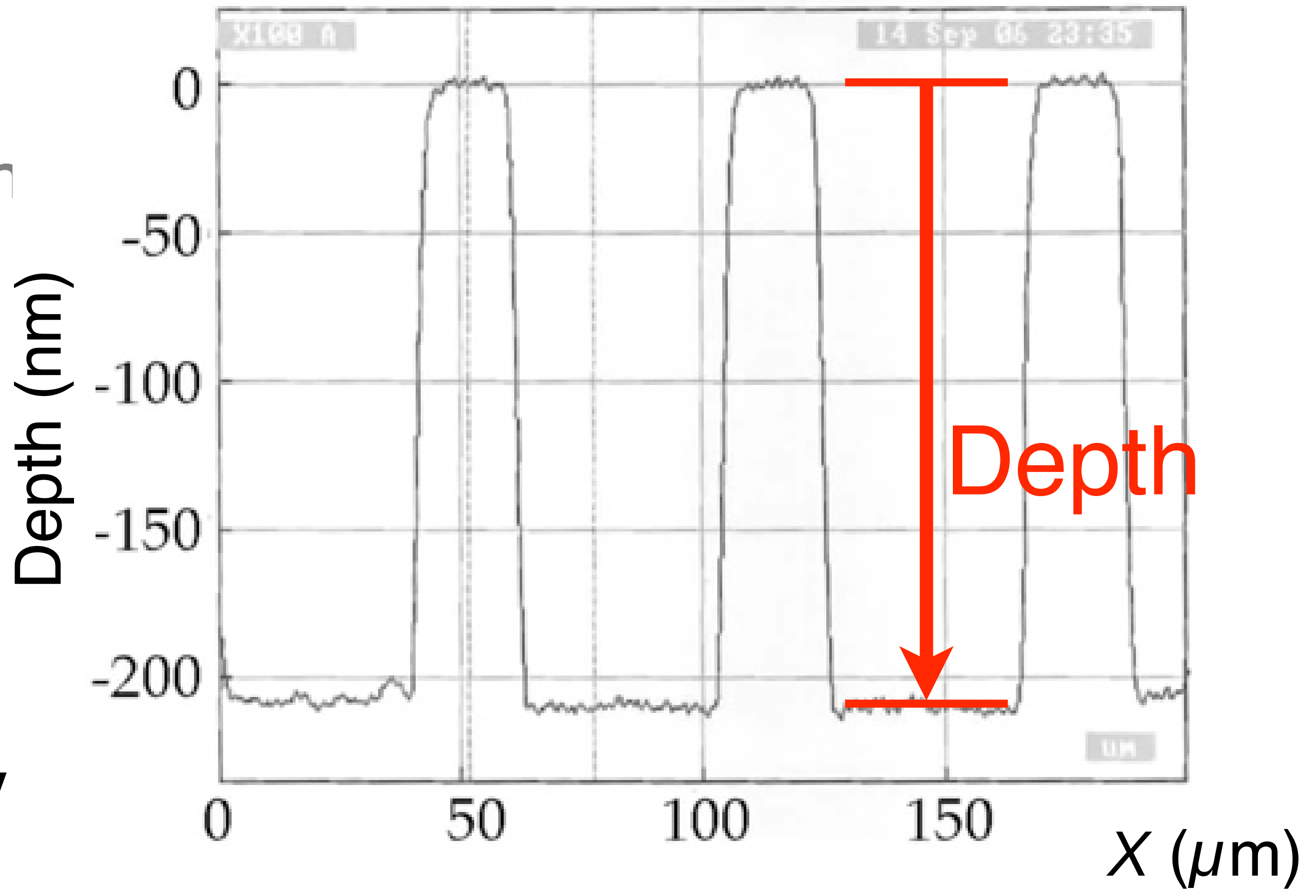
Optical micrograph



IBL of SOG

- Irradiation of Ar^{q+}
  - $q = +1 \sim +9$
  - 80~240 keV
  - Cu-Mask (43×43 μm
- Wet etching
  - BHF (HF, NH_4F)
- Surface profile
  - Optical microscopy
  - Profilometer

Profile observed by Alpha step



IBL on Si

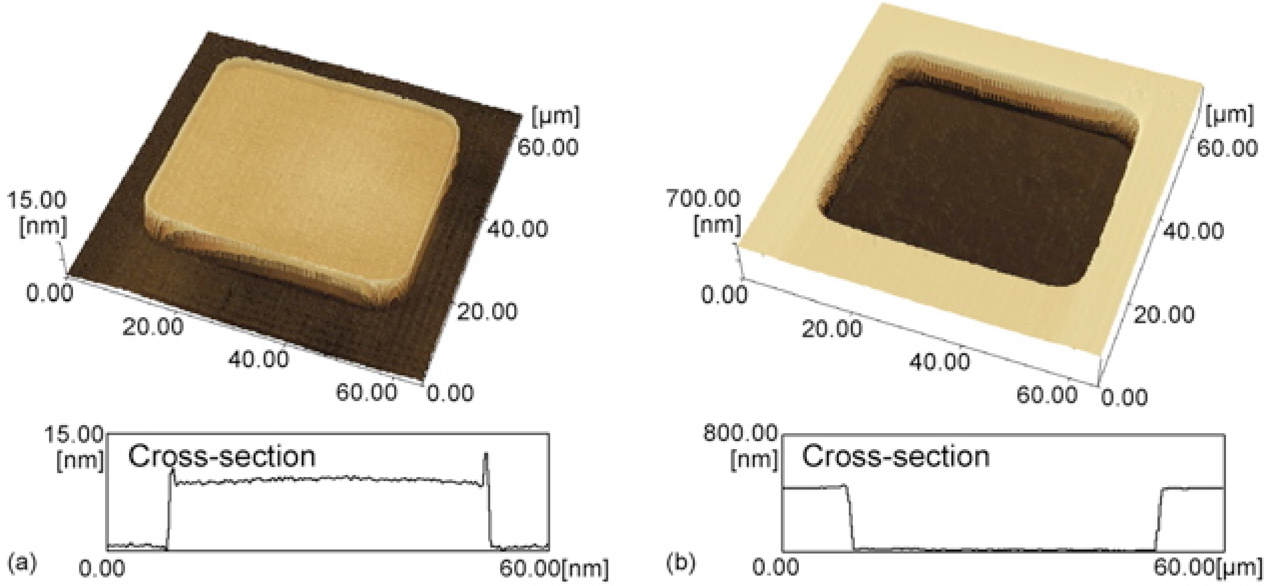
- Irradiation of Ar^{q+}
  - q = +1~9
  - E = 40~540 keV
  - Cu-Mask (43×43 μm)
- Etching
  - 46mass% HF
- Surface profile
  - AFM

IBL on Si

- Irradiation of Ar^{q+}
  - $q = +1\sim9$
  - $E = 40\sim540$ keV
  - Cu-Mask (43×43 μm)
- Etching
  - 46mass% HF
- Surface profile
  - AFM

Ar^{4+}

240 keV, 1.3×10^{15} ions/cm^2



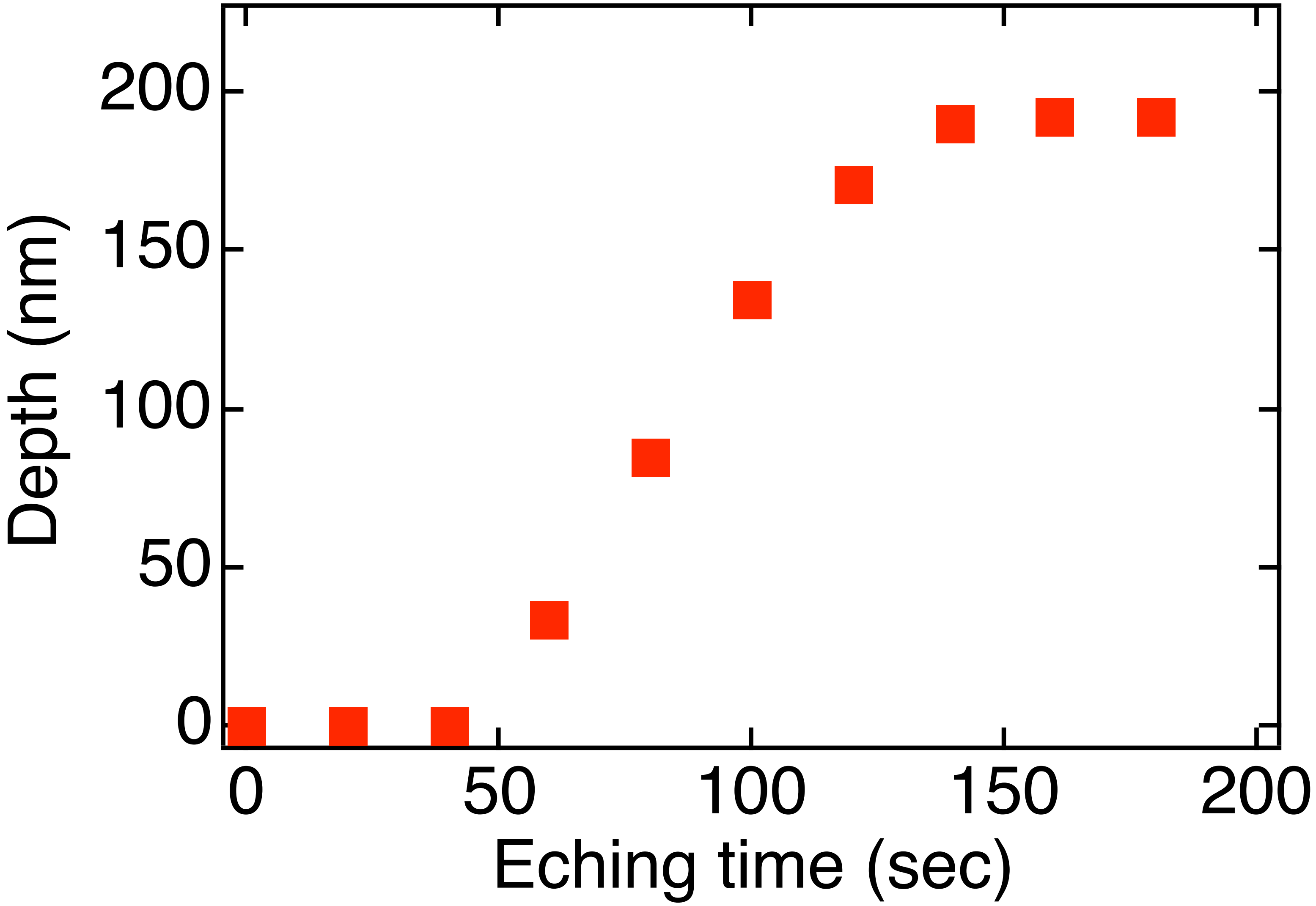
$T_{\text{etch.}}$ = 0 min.

$T_{\text{etch.}}$ = 120 min.

Hillock structure

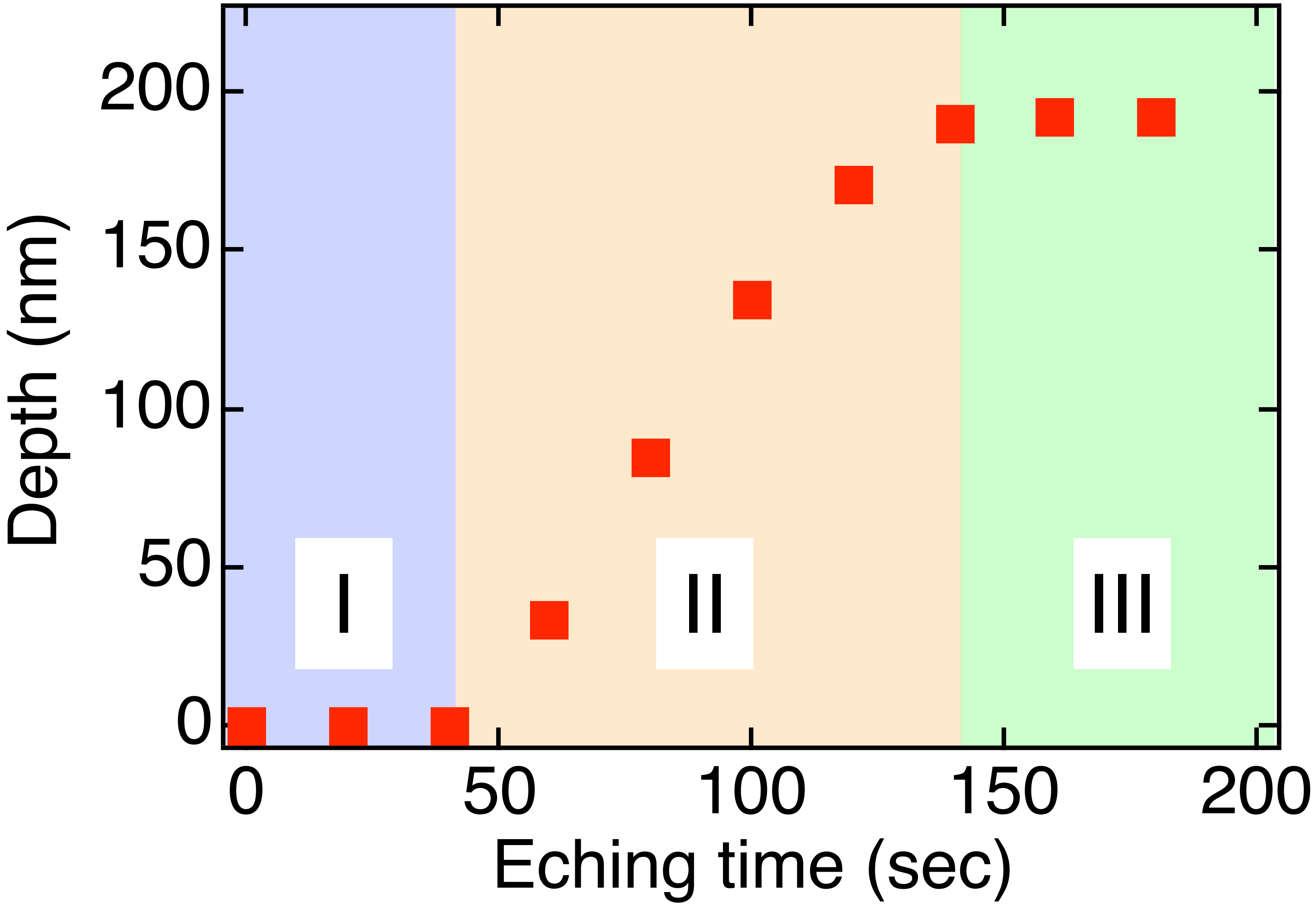
Etching process of SOG

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



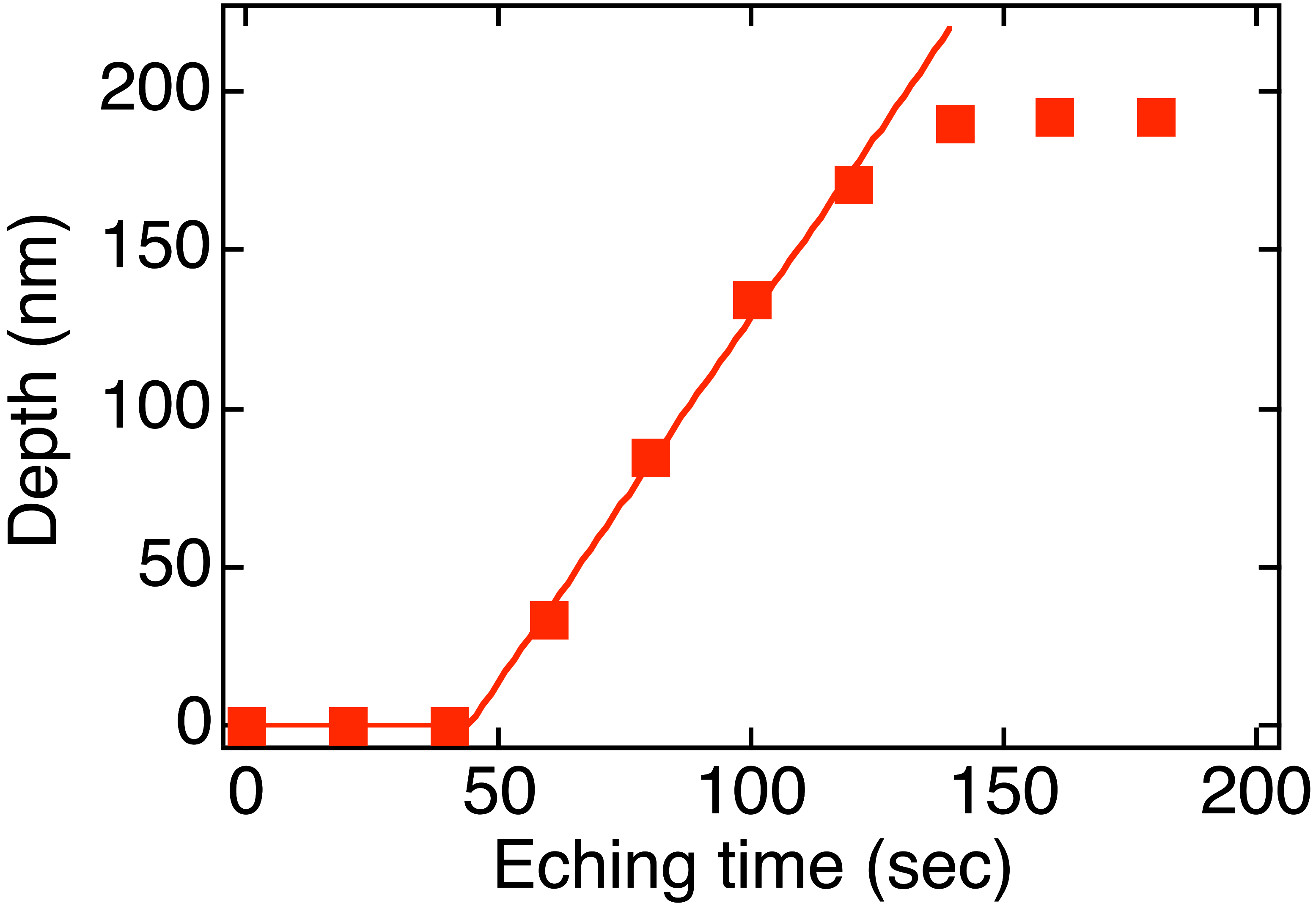
Etching process of SOG

- Ar^{1+}: 90 keV, 6.3x10^{13} ions/cm^2



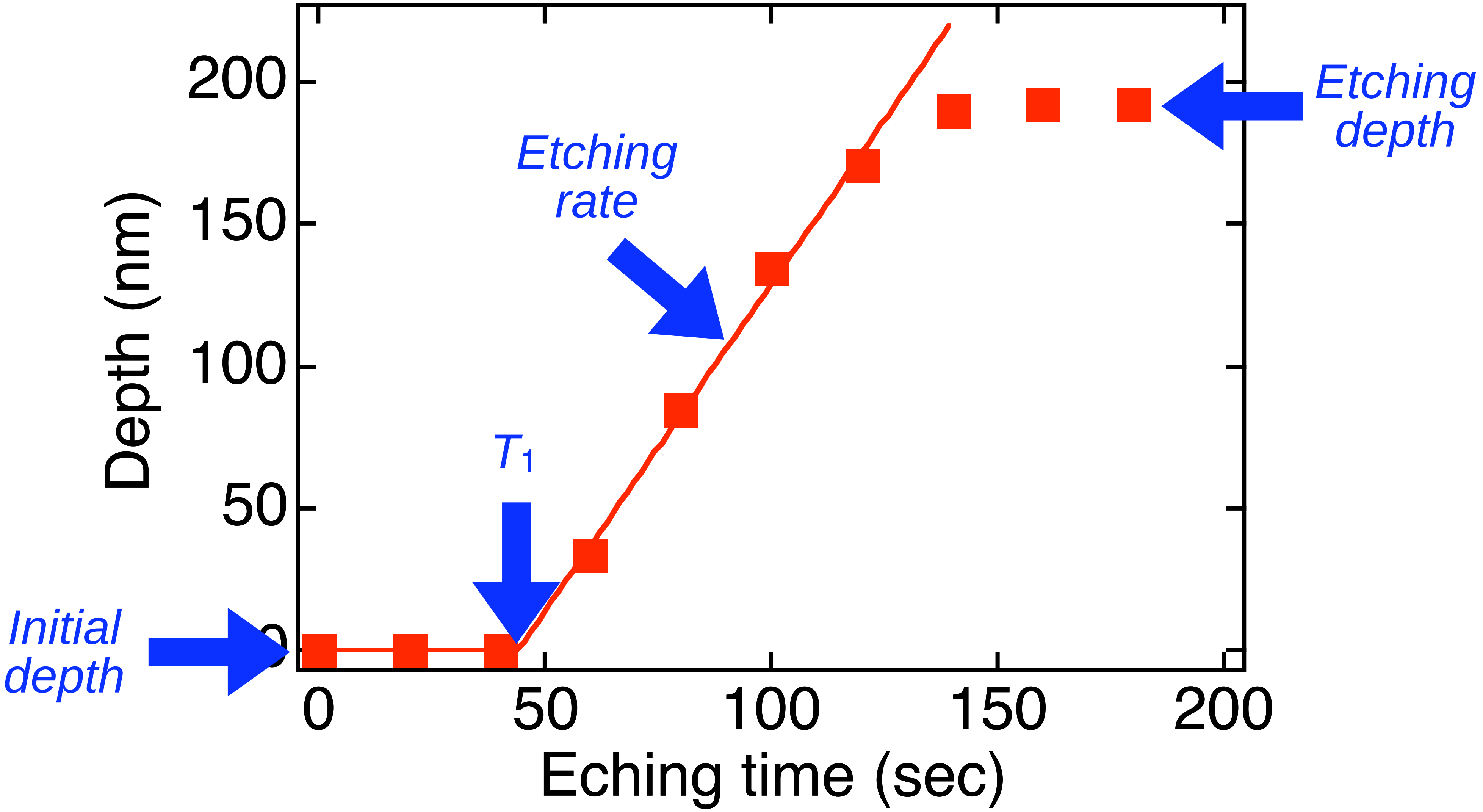
Etching process of SOG

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



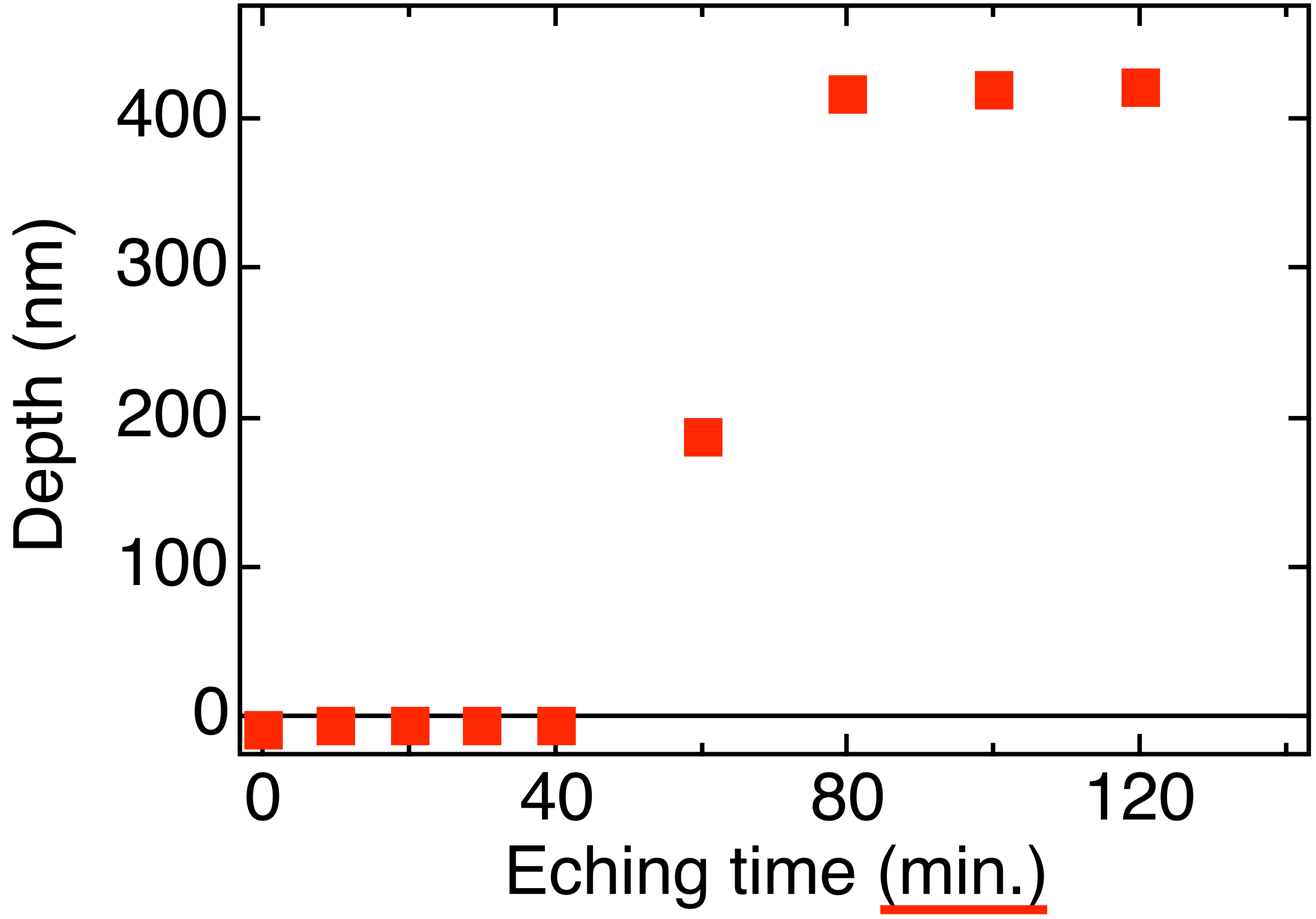
Etching process of SOG

- Ar^{1+}: 90 keV, $6.3x10^{13}$ ions/cm^2



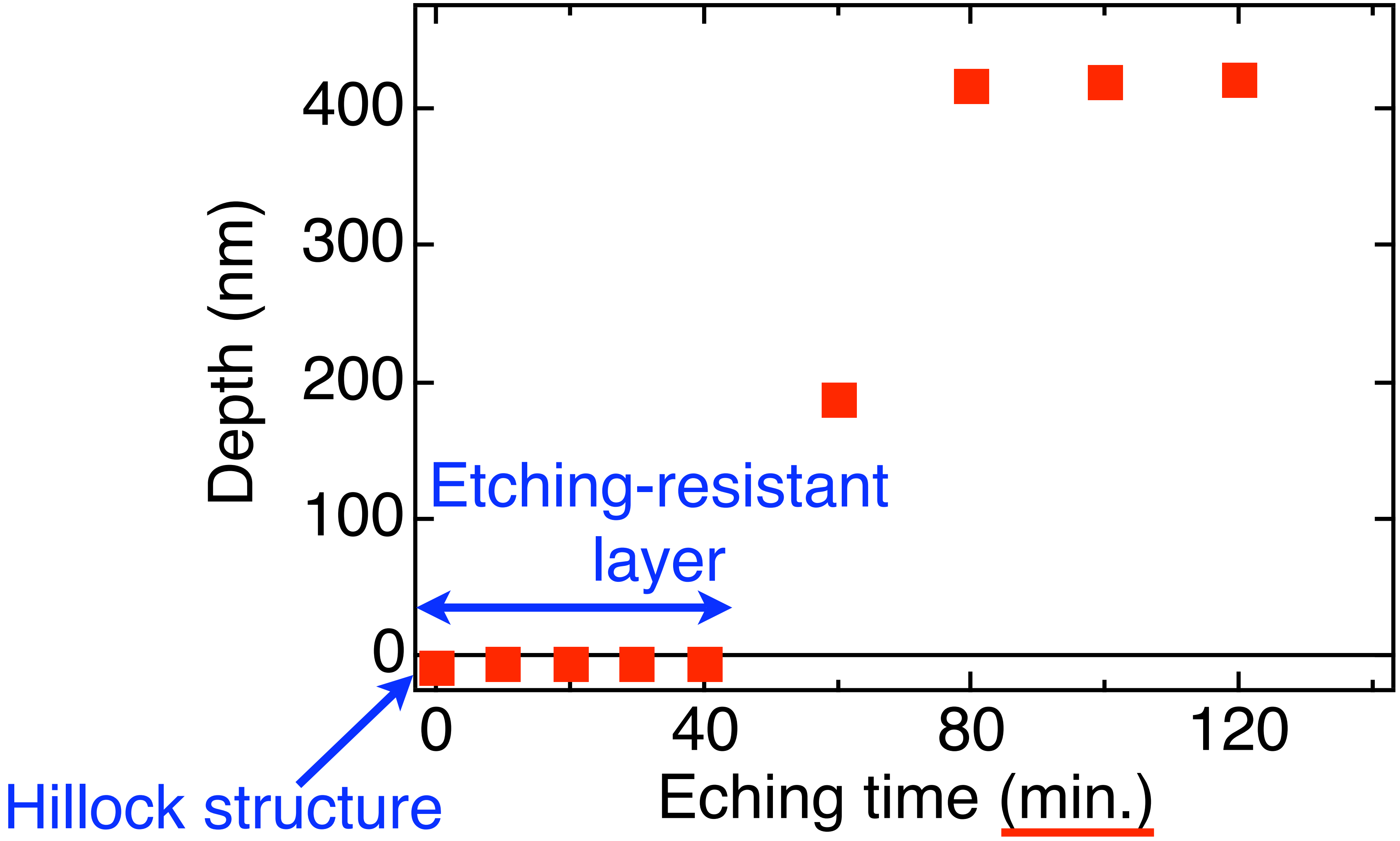
Etching process of Si

- Ar^{4+}: 240 keV, $1.3x10^{15}$ ions/cm^2



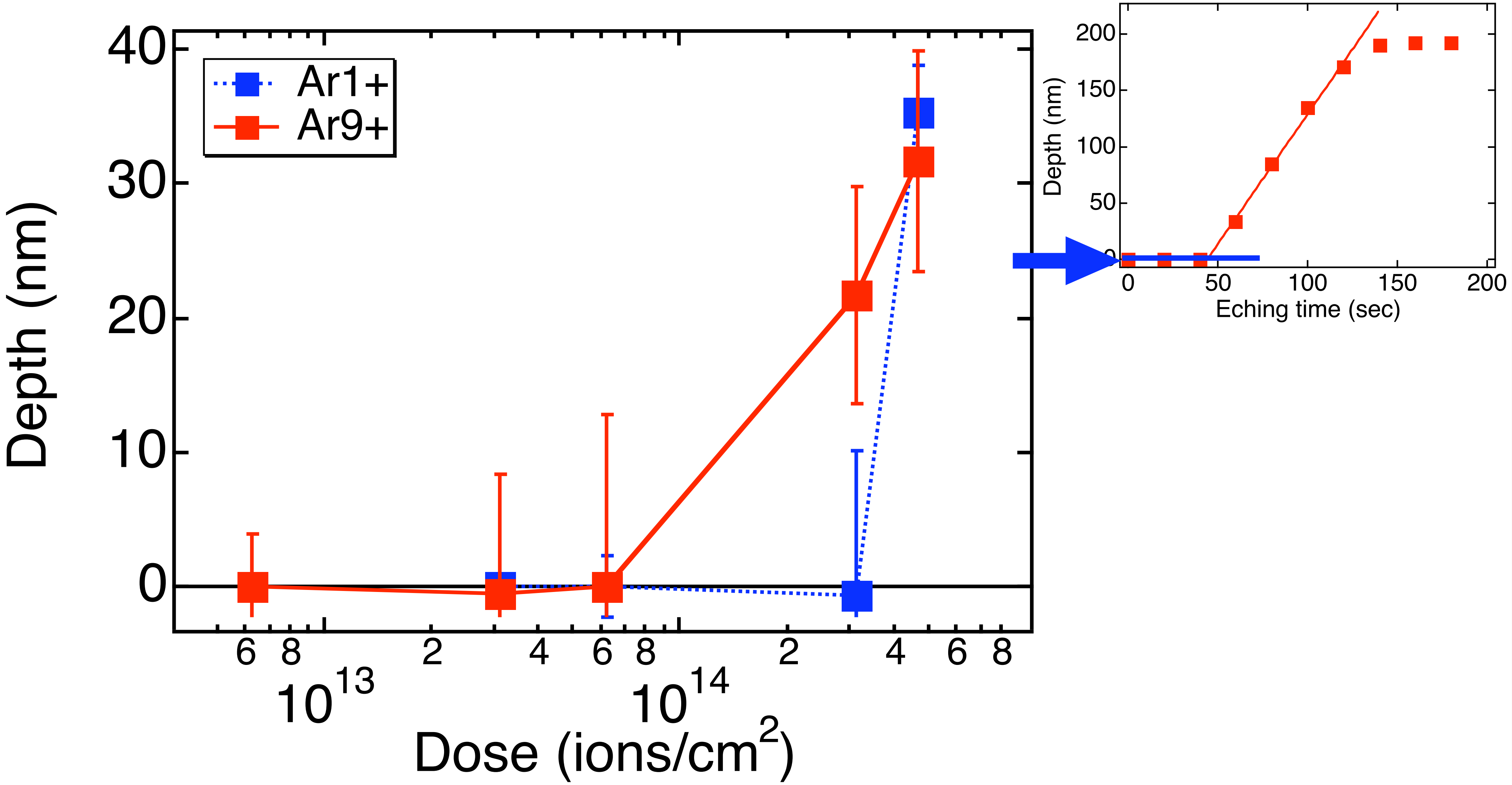
Etching process of Si

- Ar^{4+}: 240 keV, 1.3x10^{15} ions/cm^2



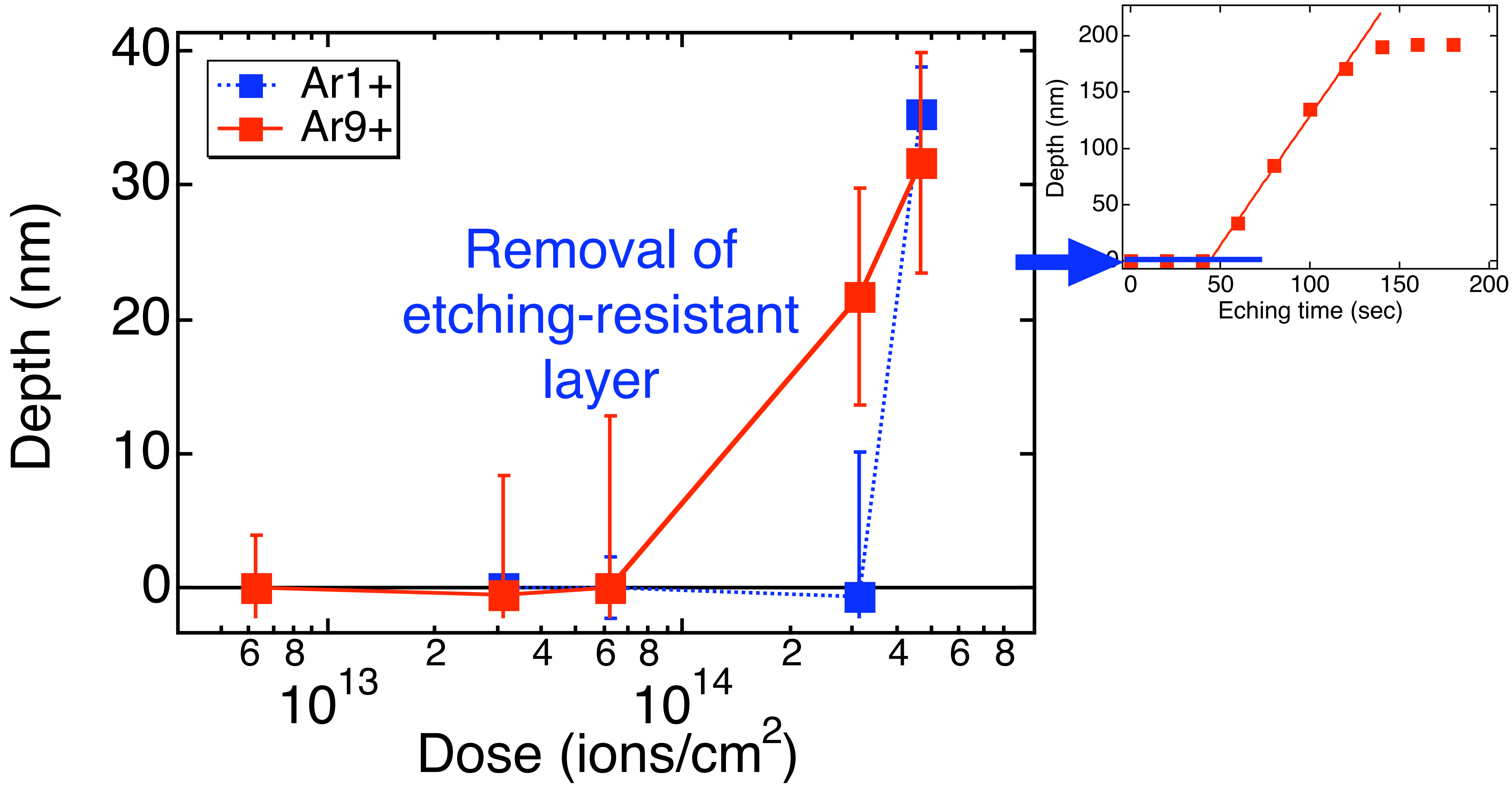
Sputtering of SOG

- Fabrication of concave structure



Sputtering of SOG

- Fabrication of concave structure



Removal of etching-resistant layer

Protrusion of Si

- Fabrication of hillock structure

Dose dep.

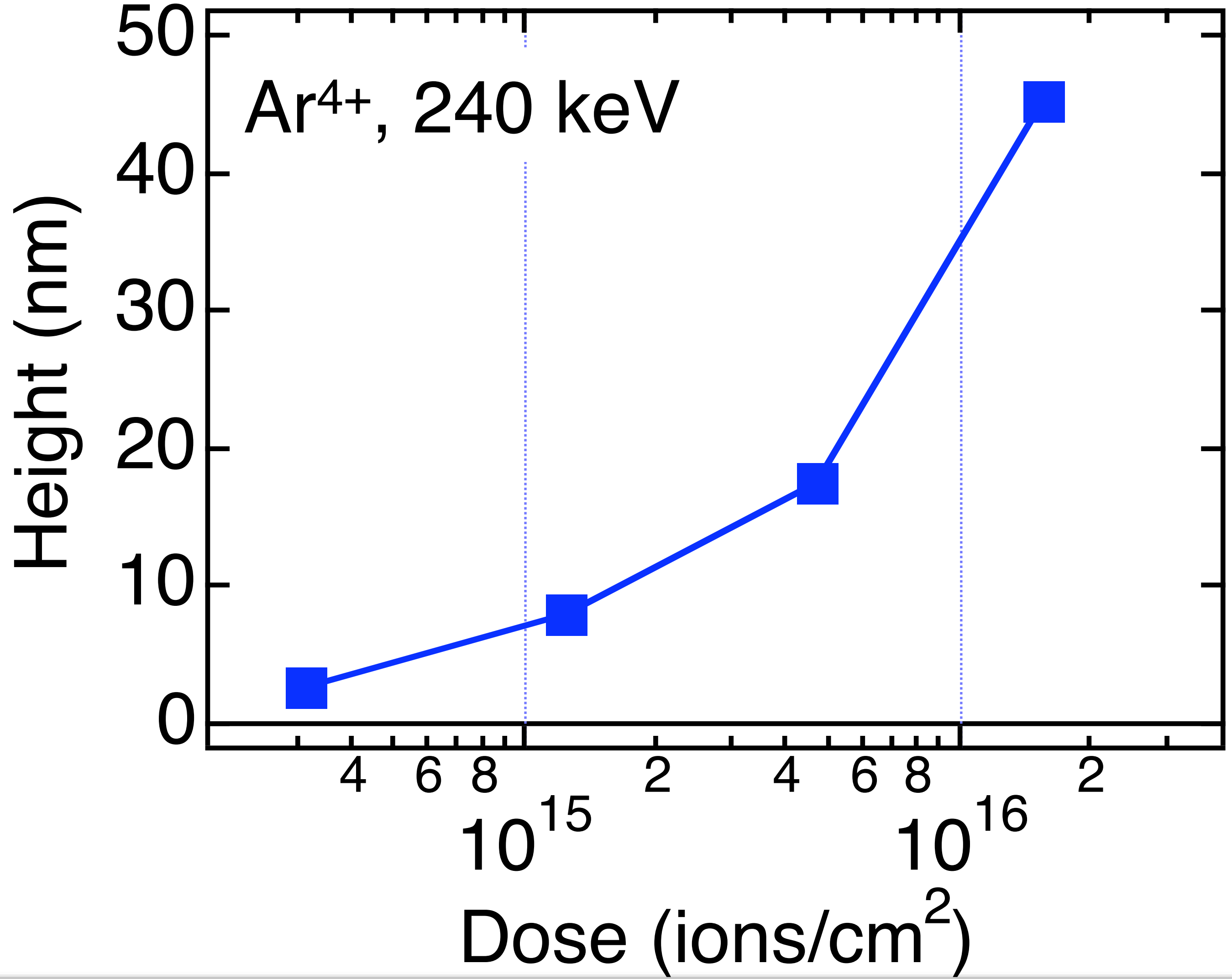
Increase with dose.

E dep.

Increase with *E*.

q dep.

Not depend on *q*.



Protrusion of Si

- Fabrication of hillock structure

Dose dep.

Increase with dose.

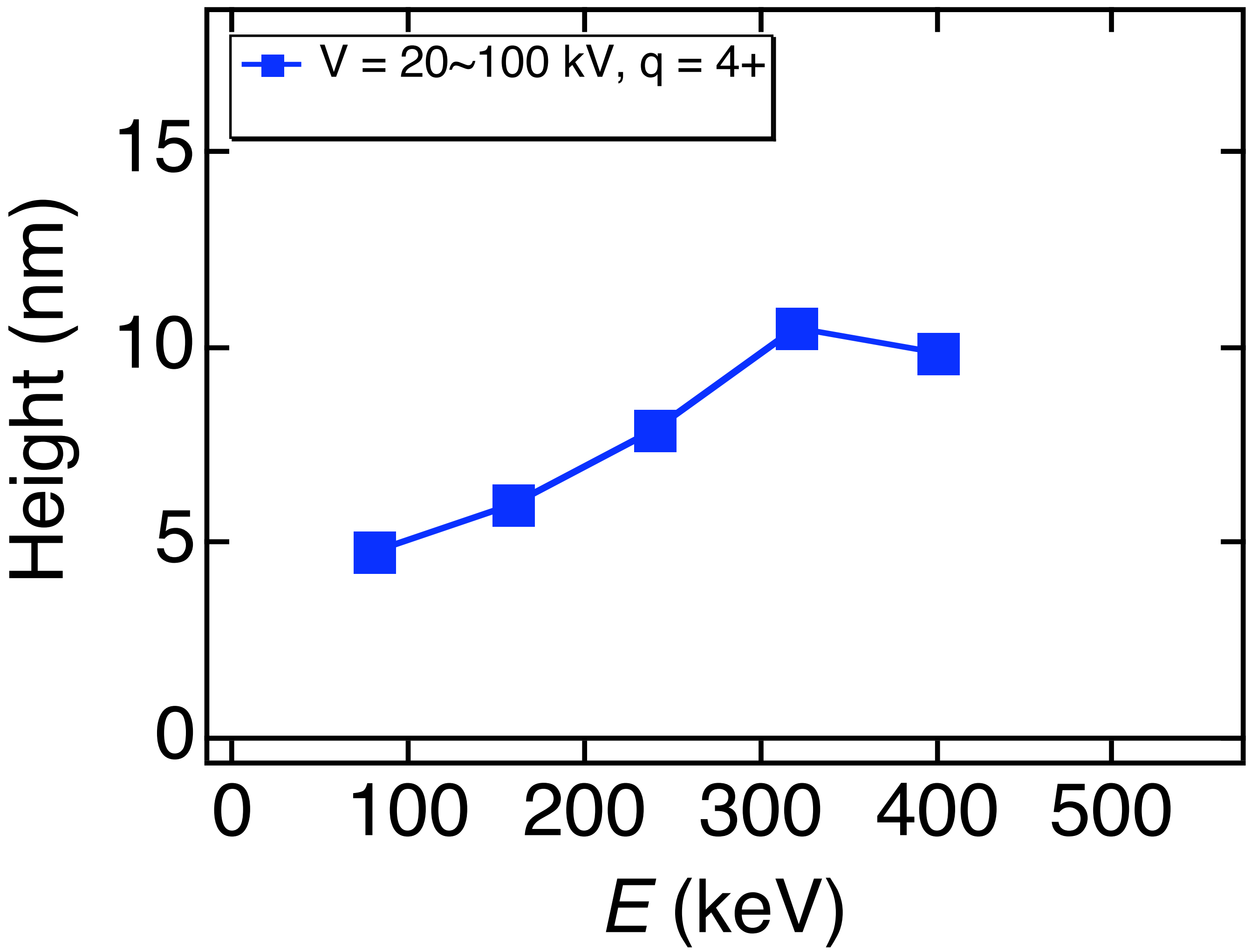
***E* dep.**

Increase with *E*.

***q* dep.**

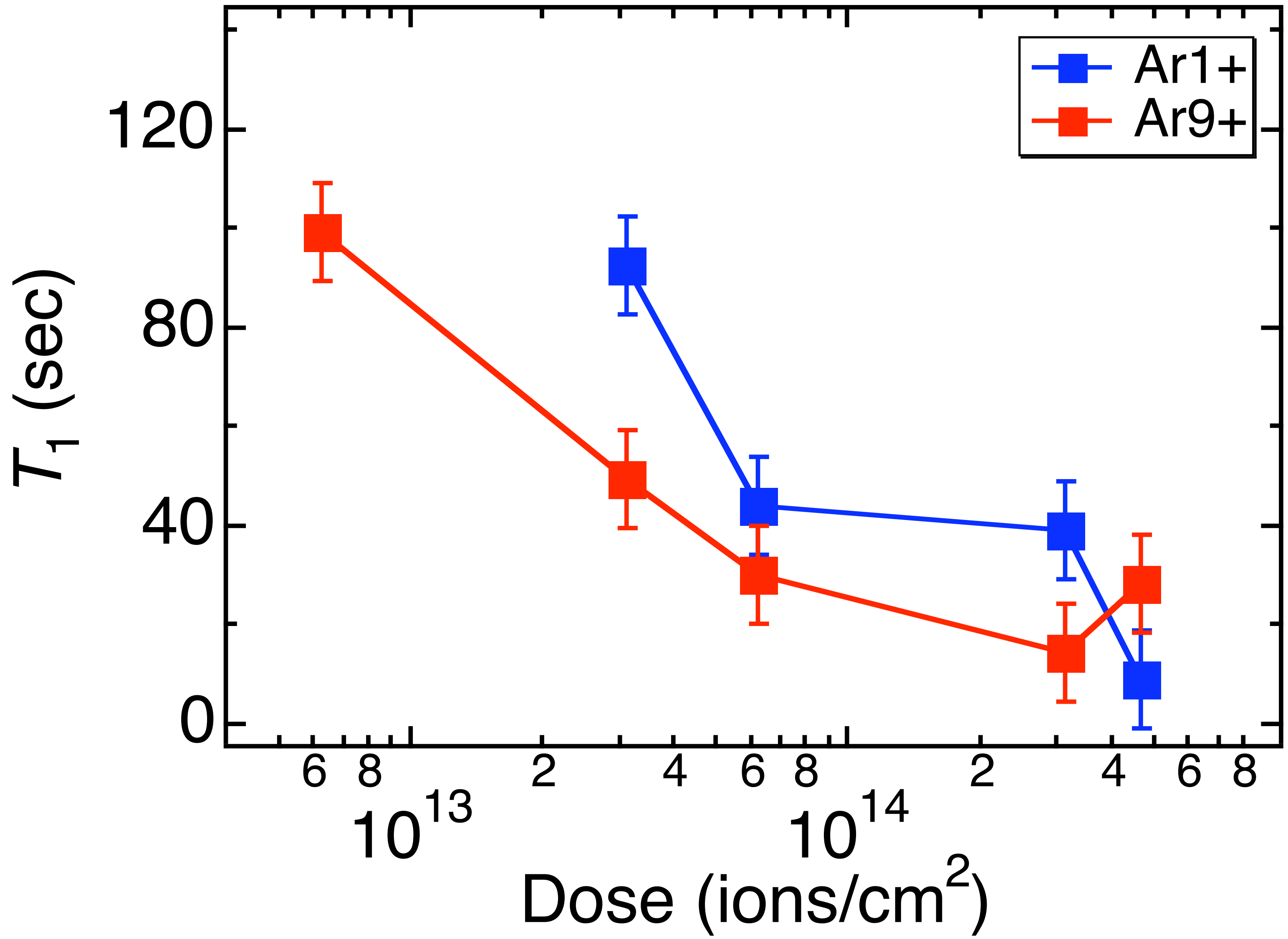
Not depend on *q*.

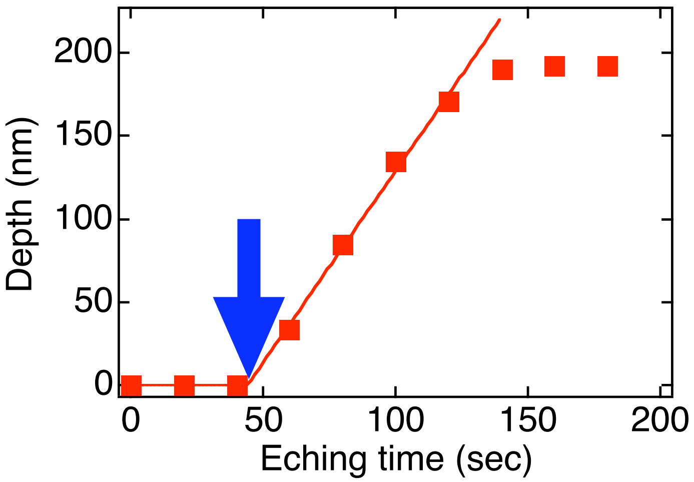
Ar^{4+}, 1.5×10^{15} ions/cm²



T_1 of SOG

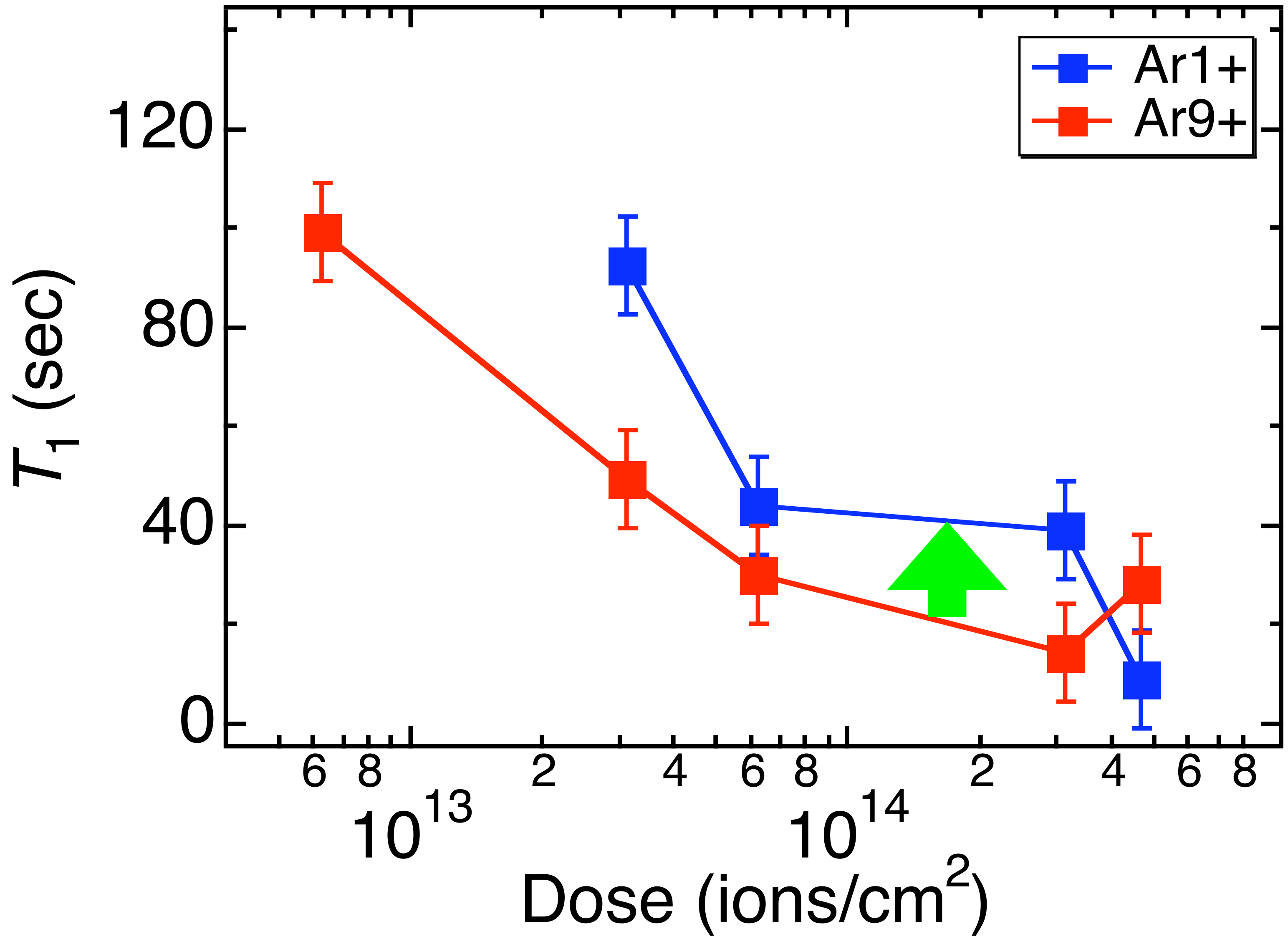
- Ar^{q+}, E = 90 keV

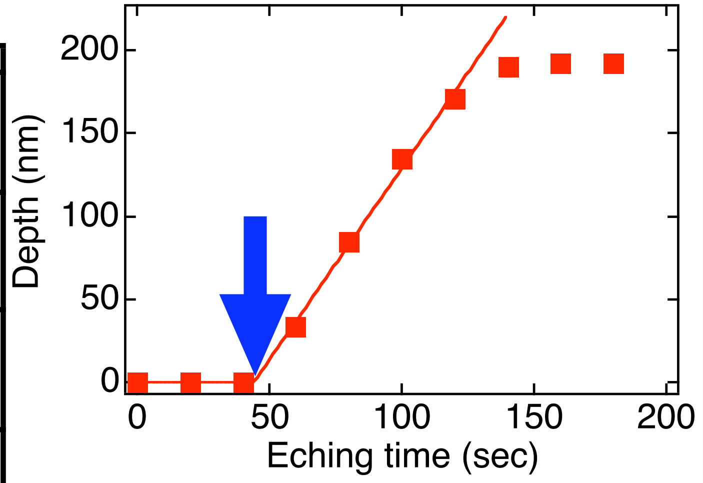


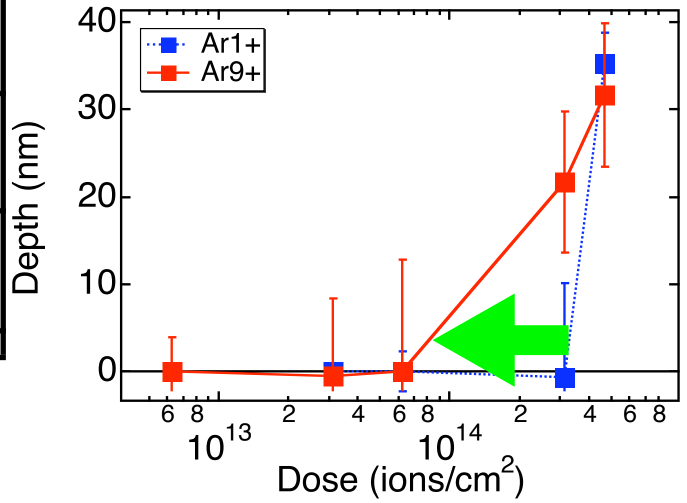


T_1 of SOG

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

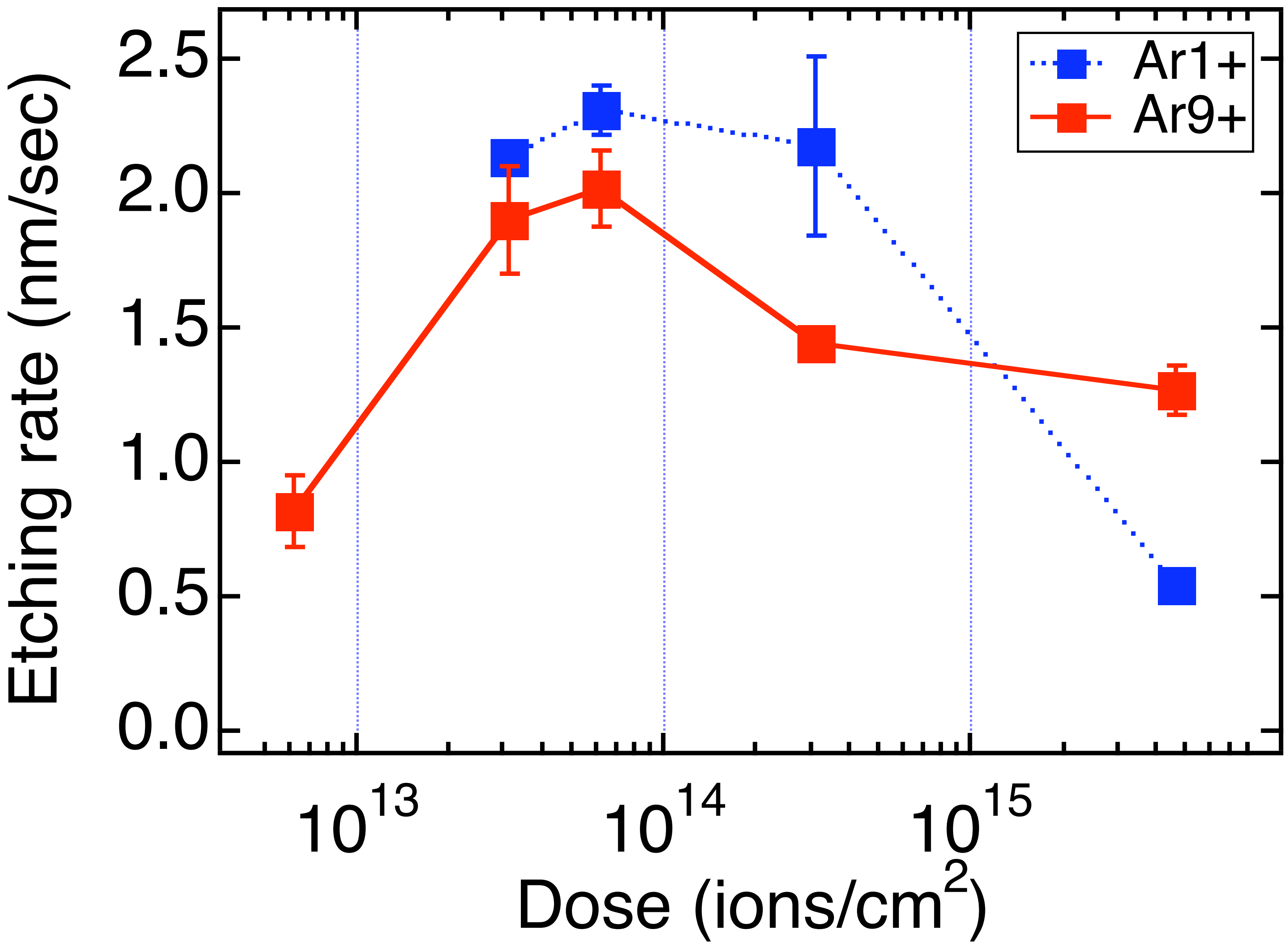


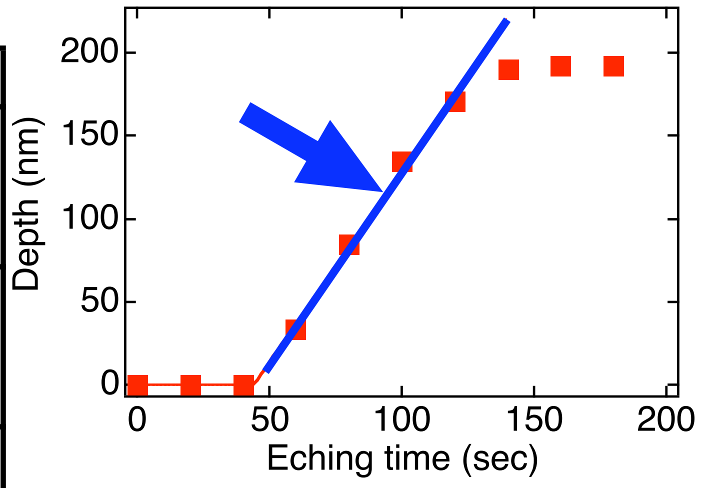




Etching rate of SOG

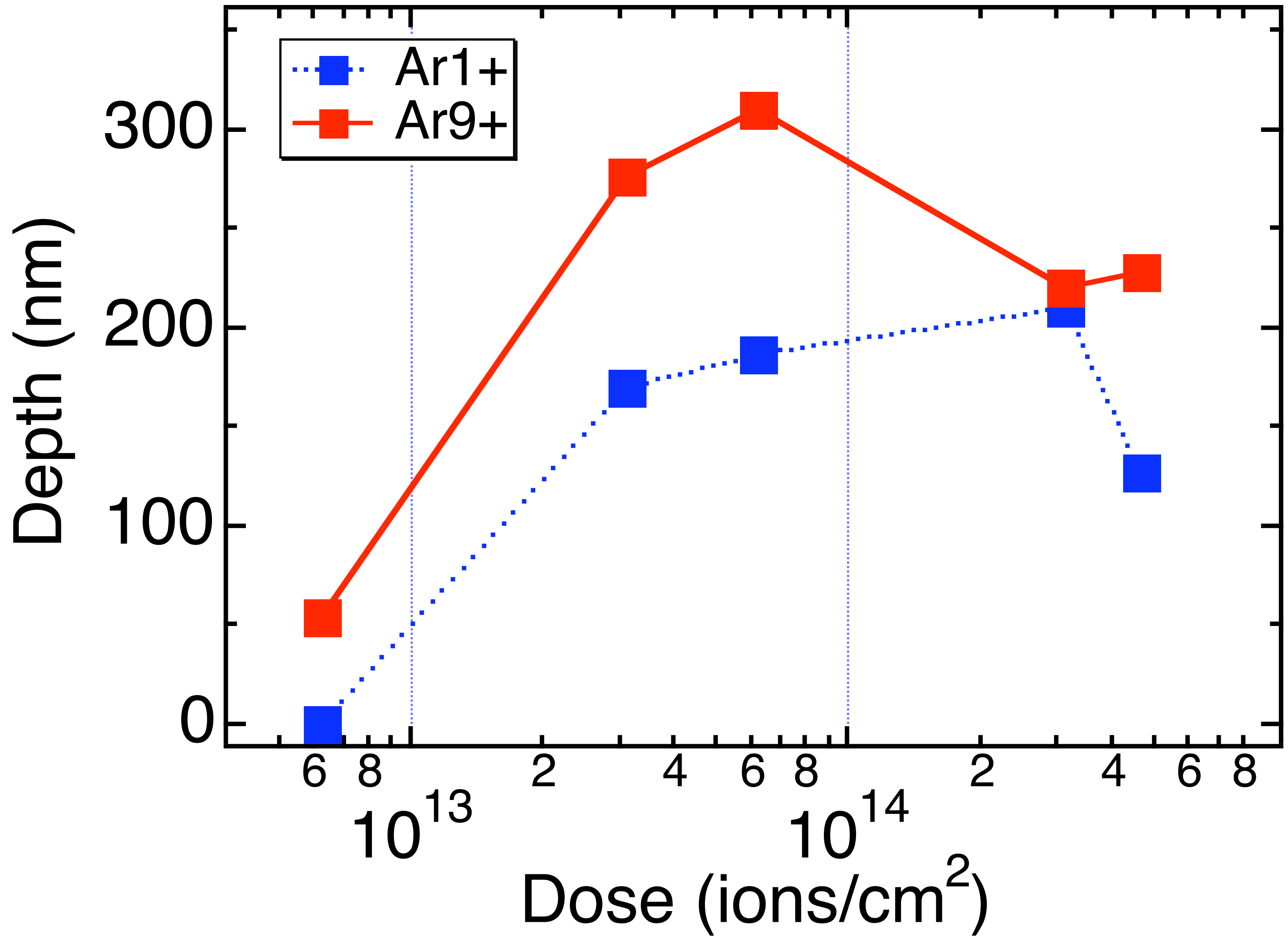
- Ar^{q+}, *E* = 90 keV

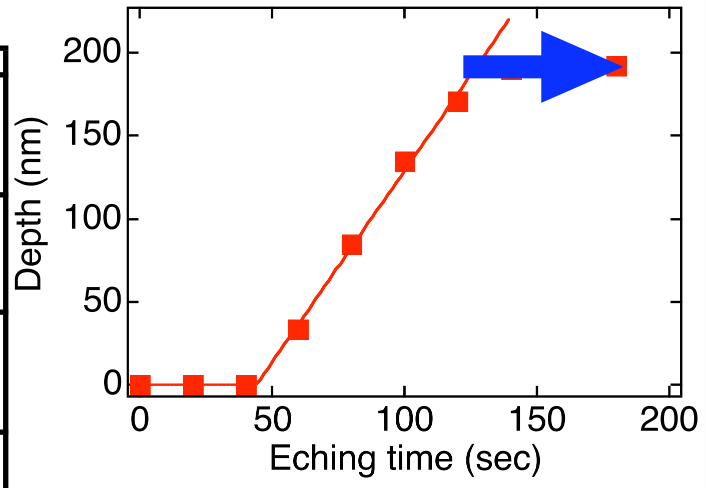




Etching depth of SOG

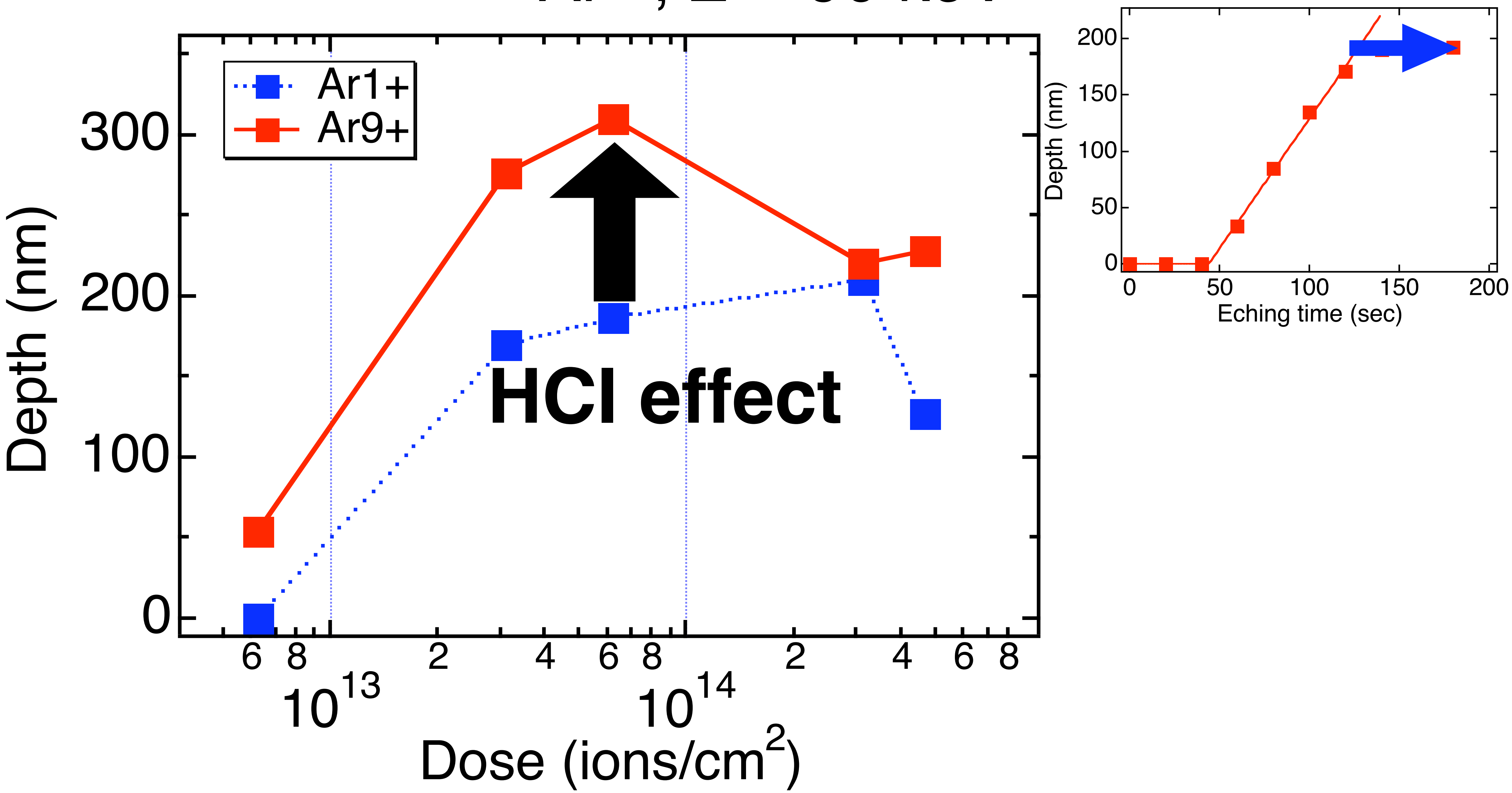
- Ar^{q+}, $E = 90$ keV





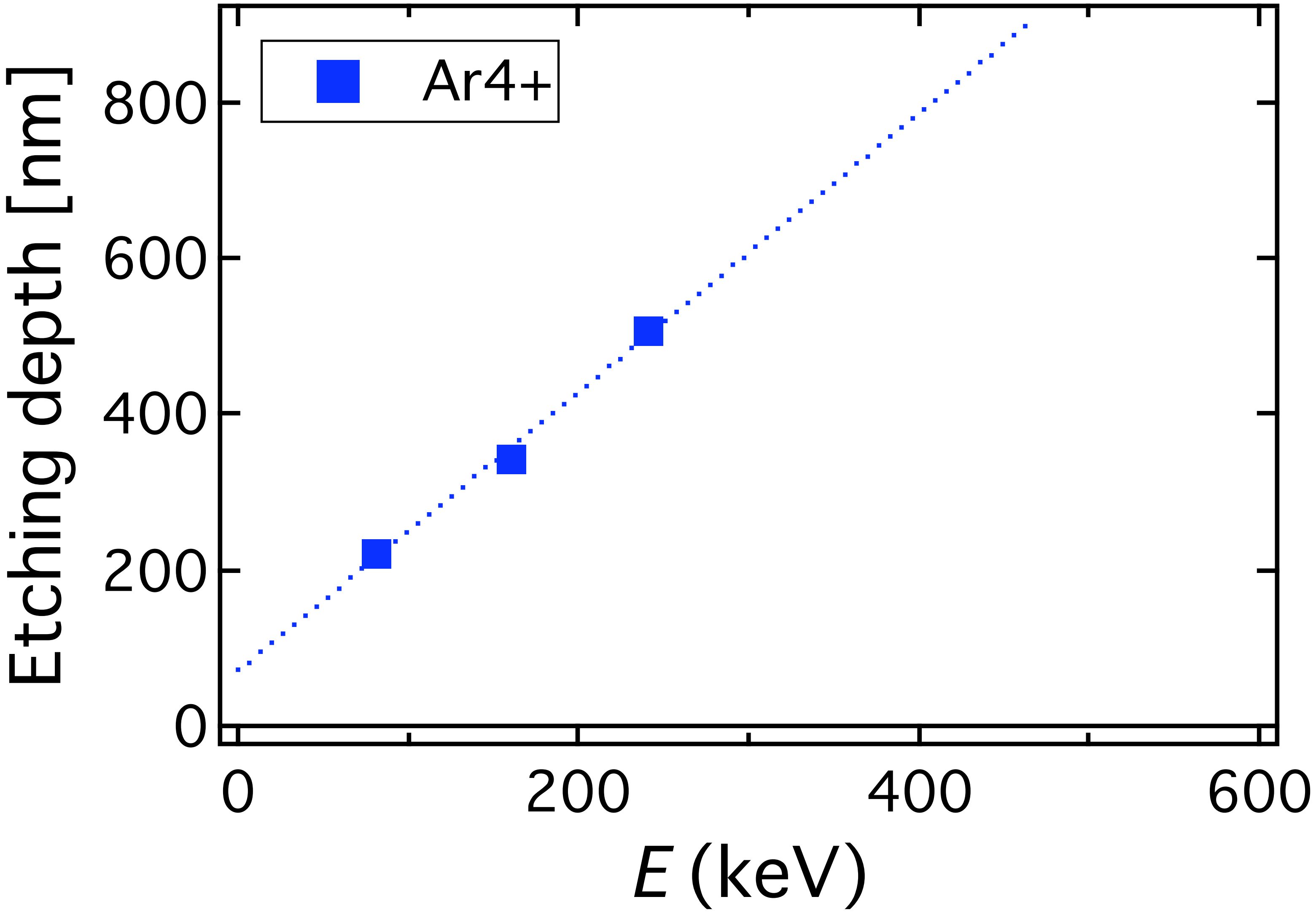
Etching depth of SOG

- Ar^{q+}, E = 90 keV



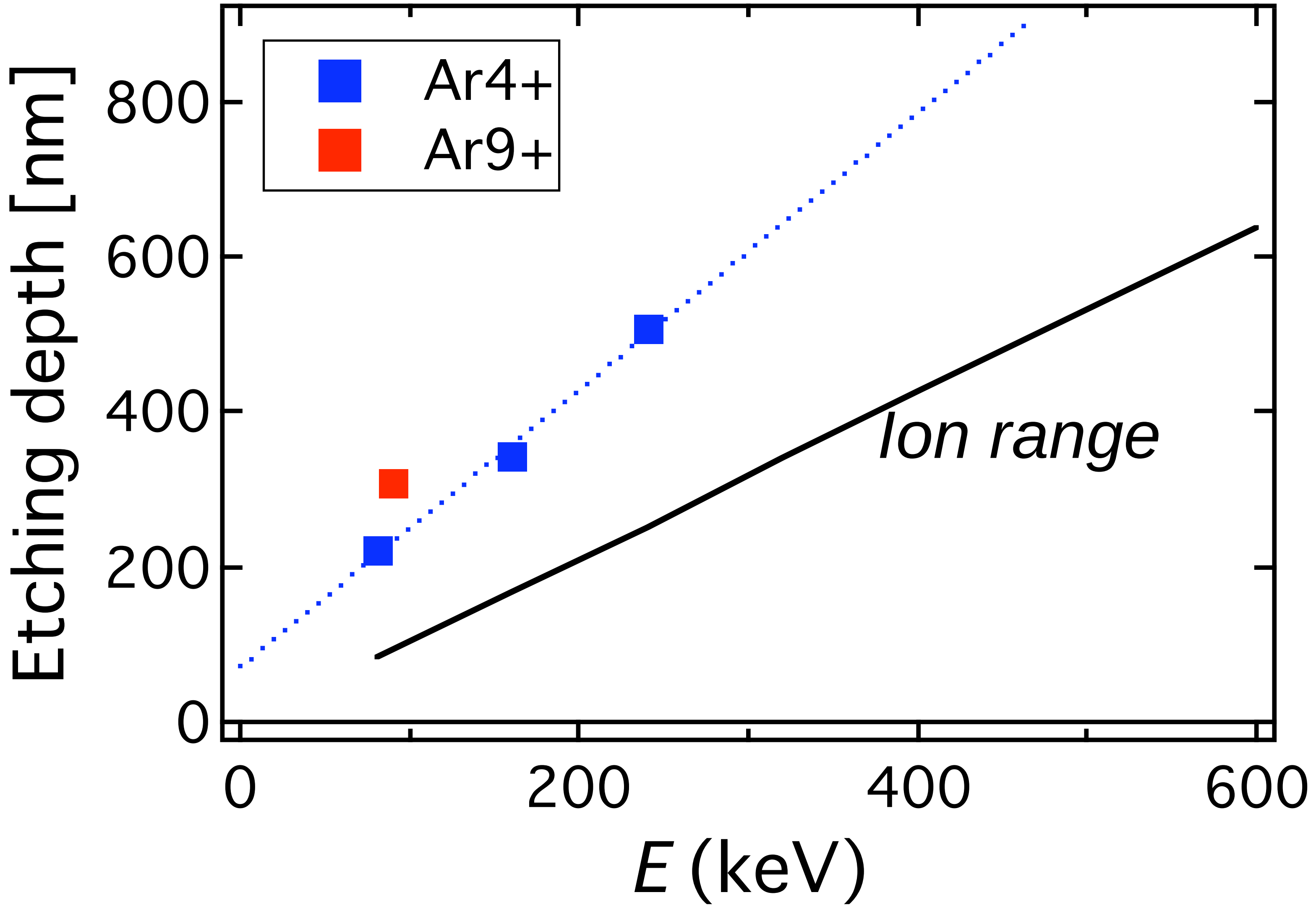
Etching depth of SOG

- Ar^{4+} on SOG



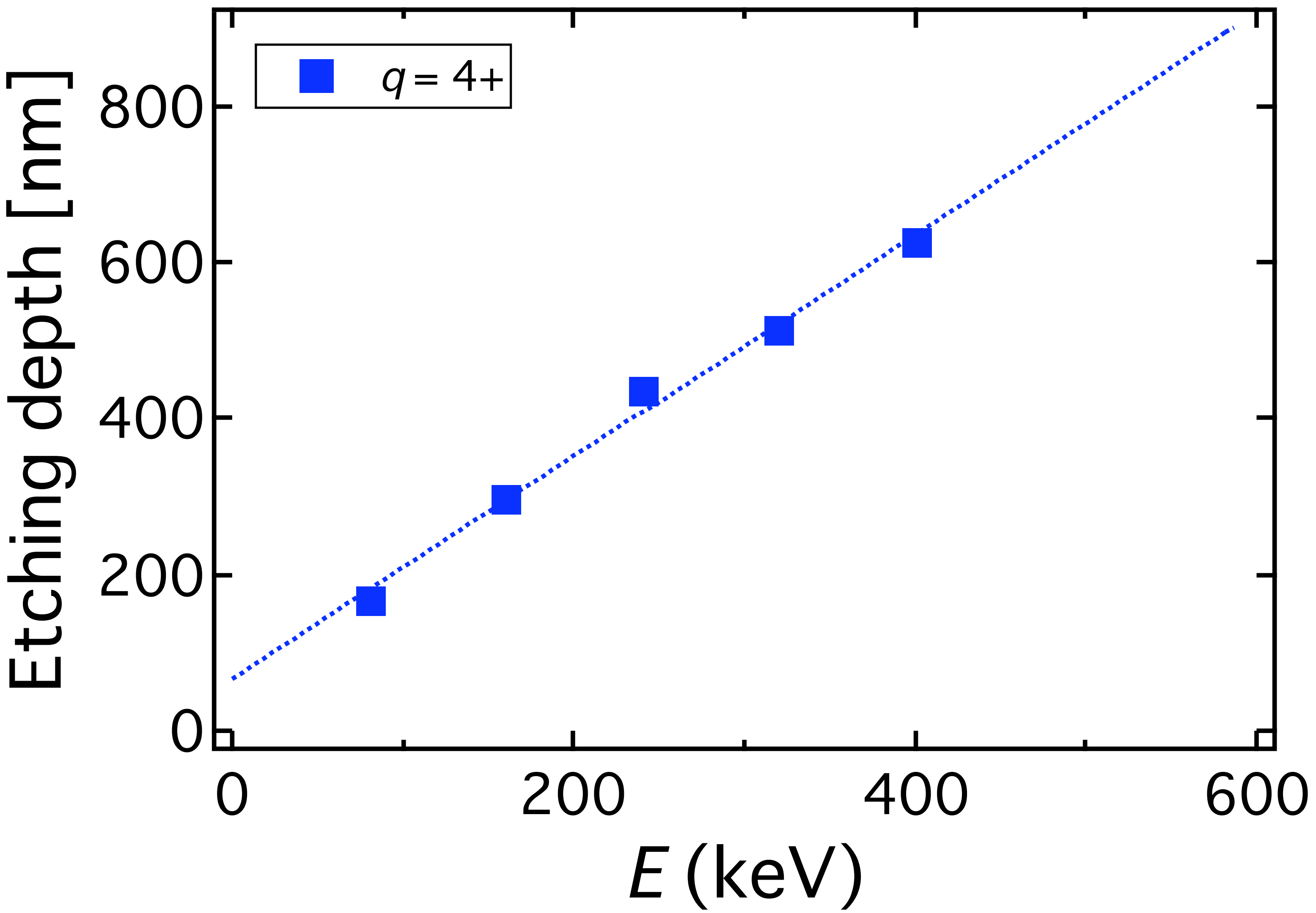
Etching depth of SOG

- Ar^{4+} on SOG



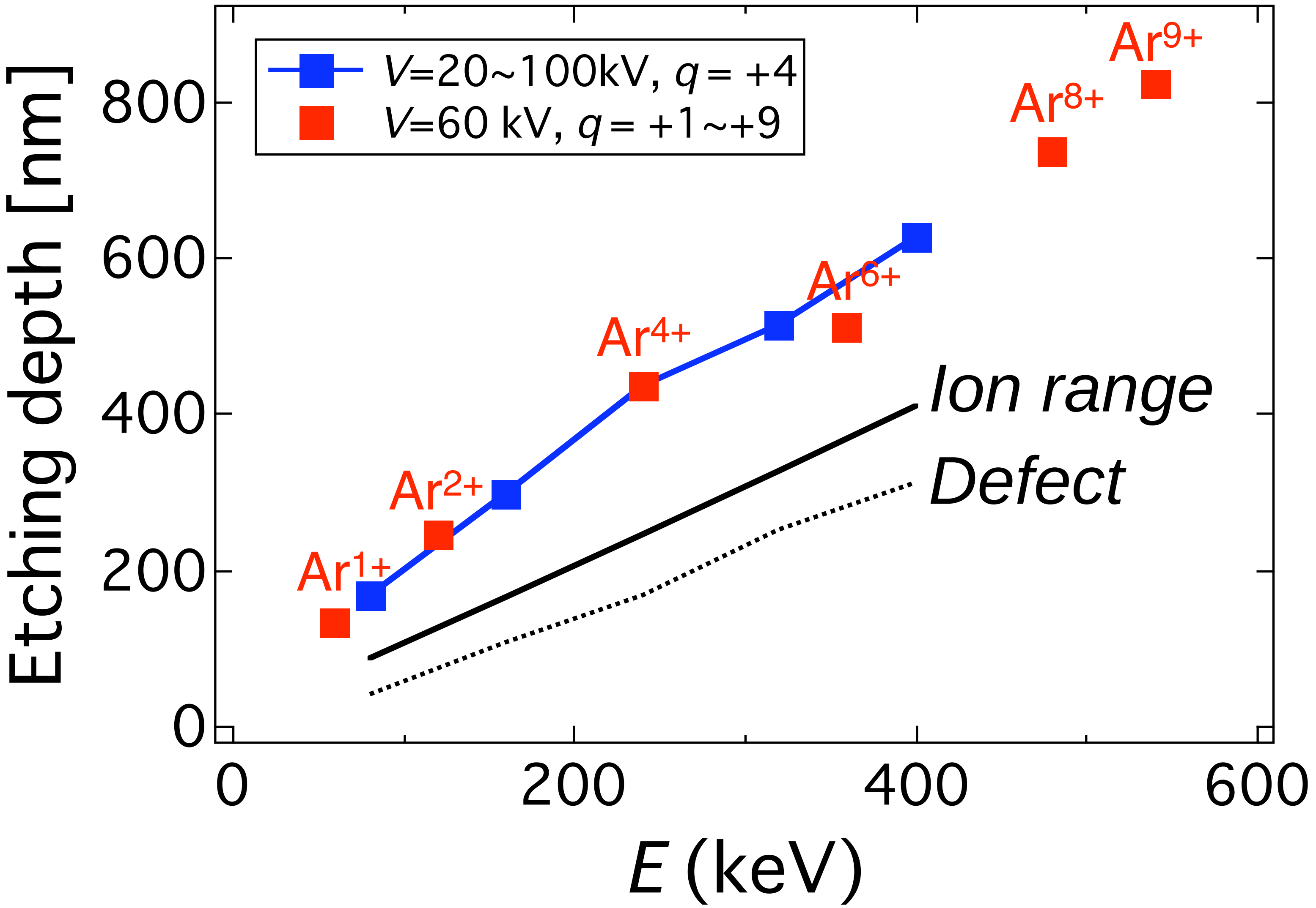
Etching depth of Si

- Ar^{4+} on Si



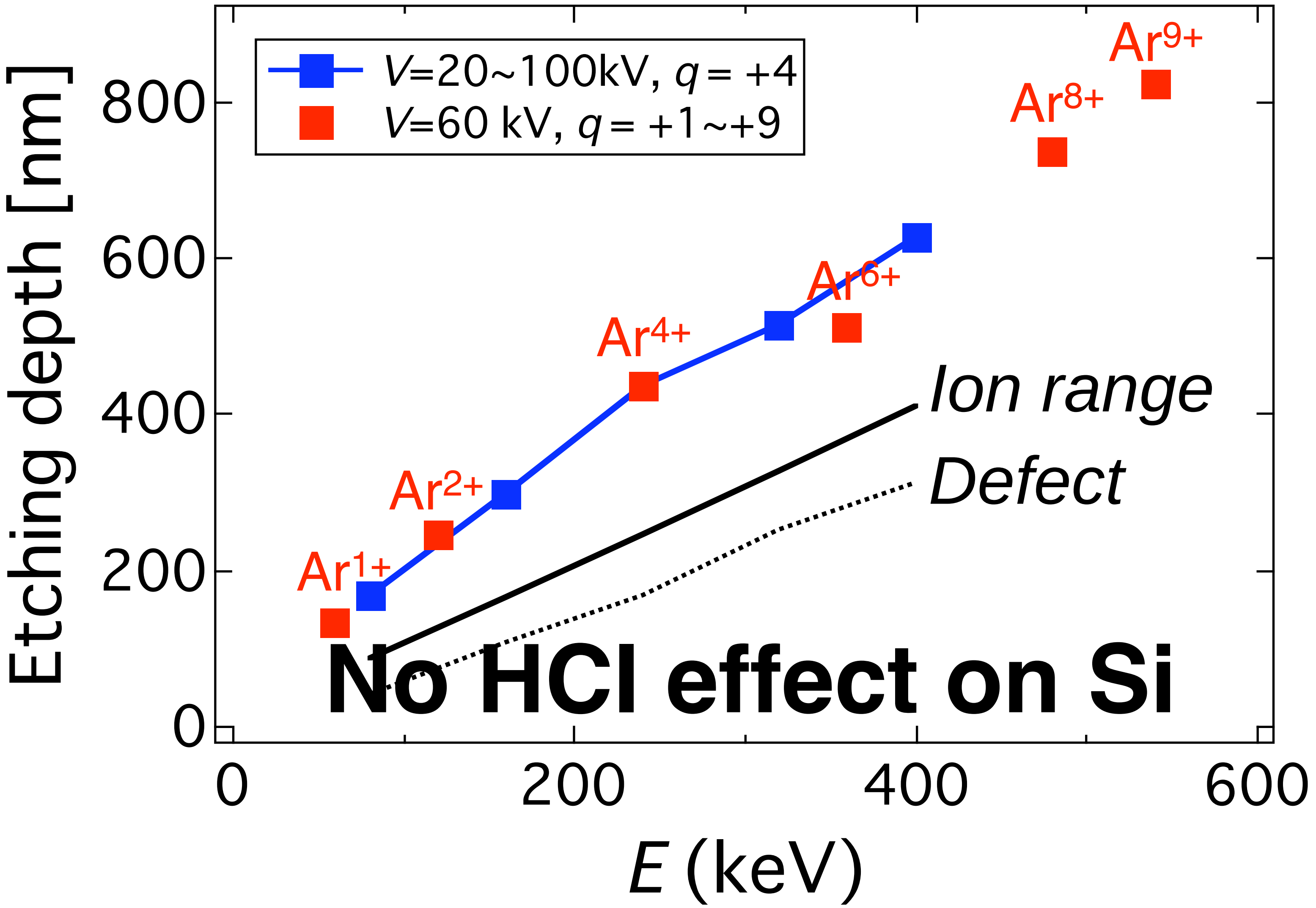
Etching depth of Si

- Ar^{q+} on Si



Etching depth of Si

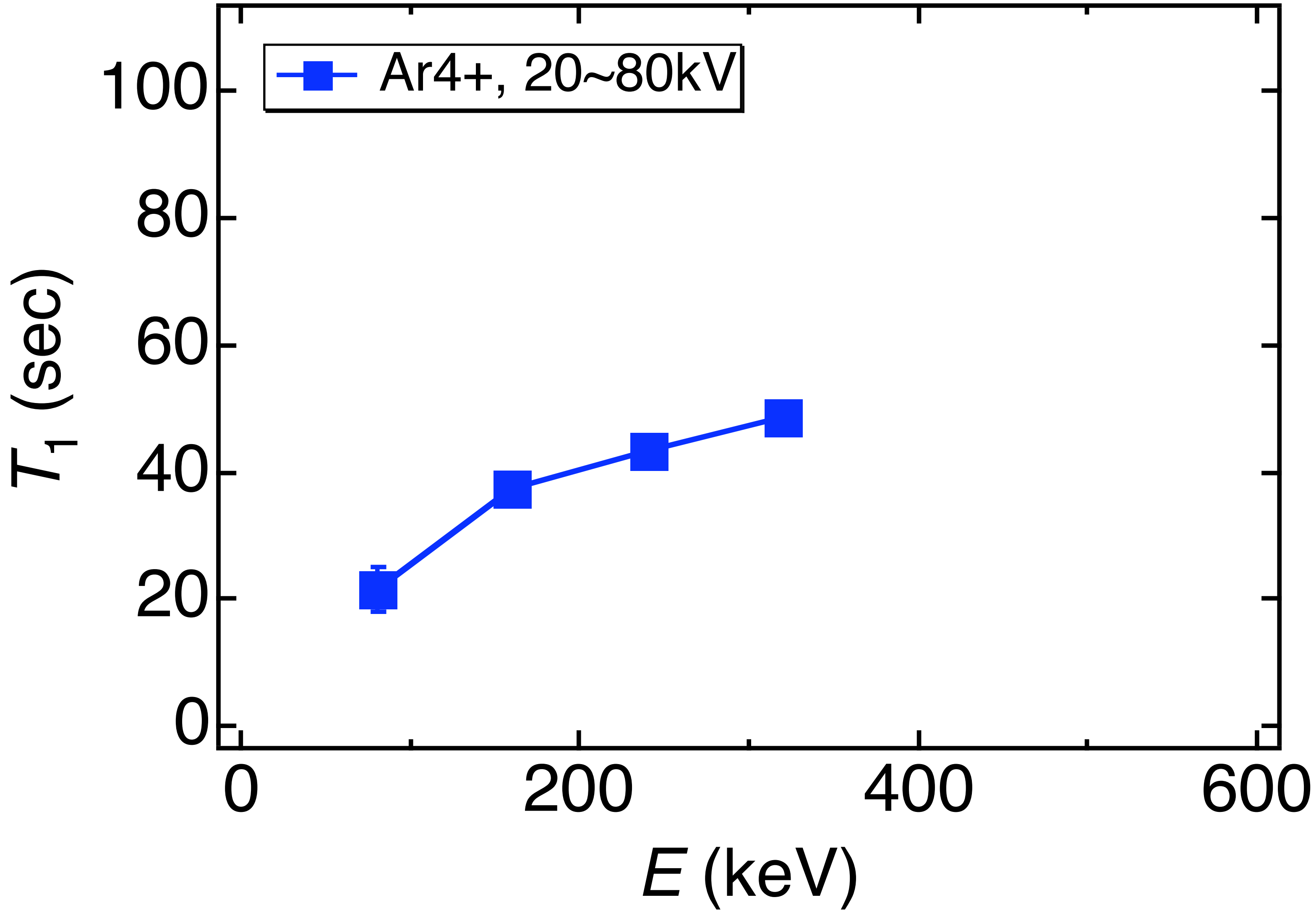
- Ar^{q+} on Si



No HCI effect on Si

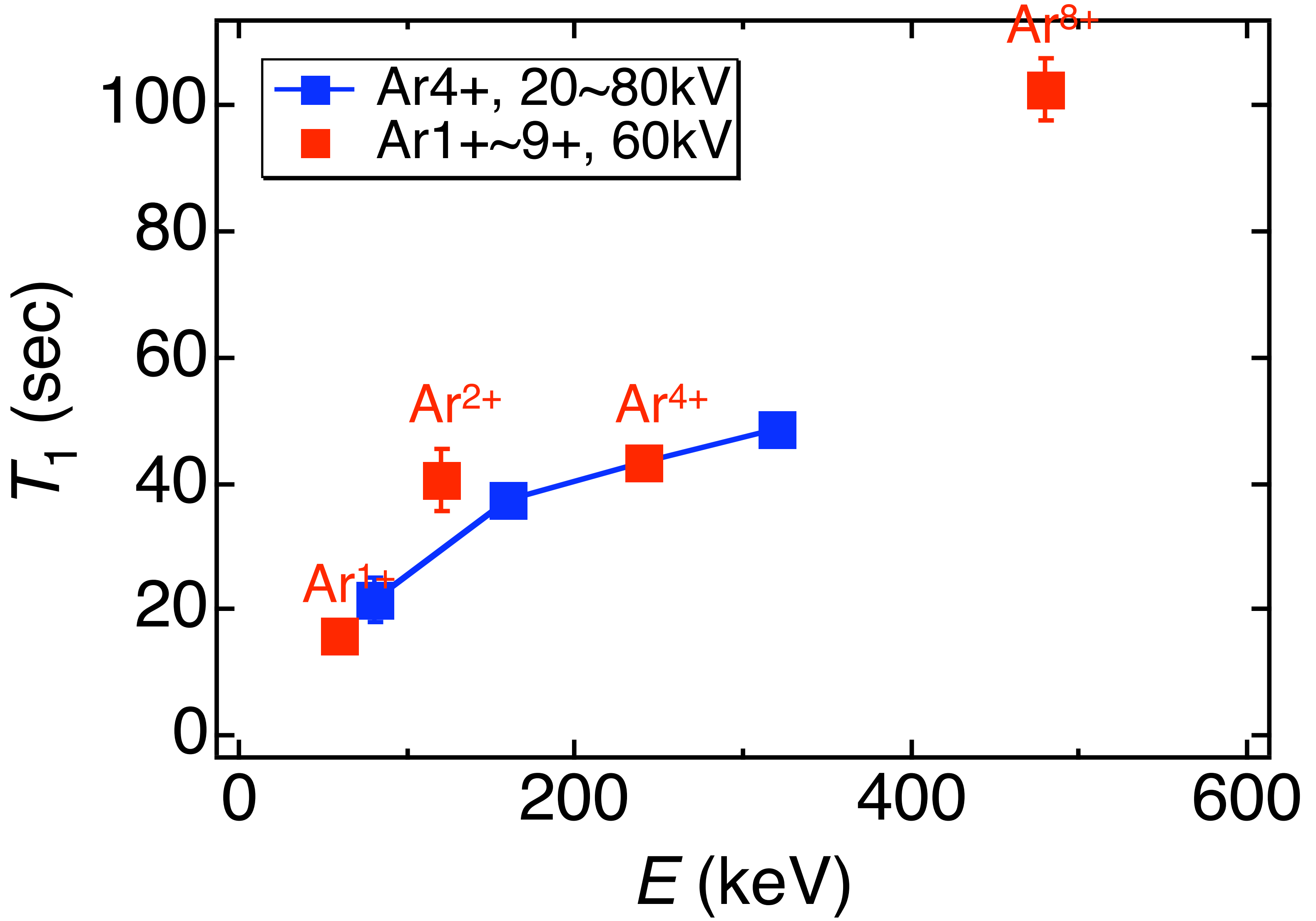
T_1 vs. E : Si

- Etching start time increases with$E$.



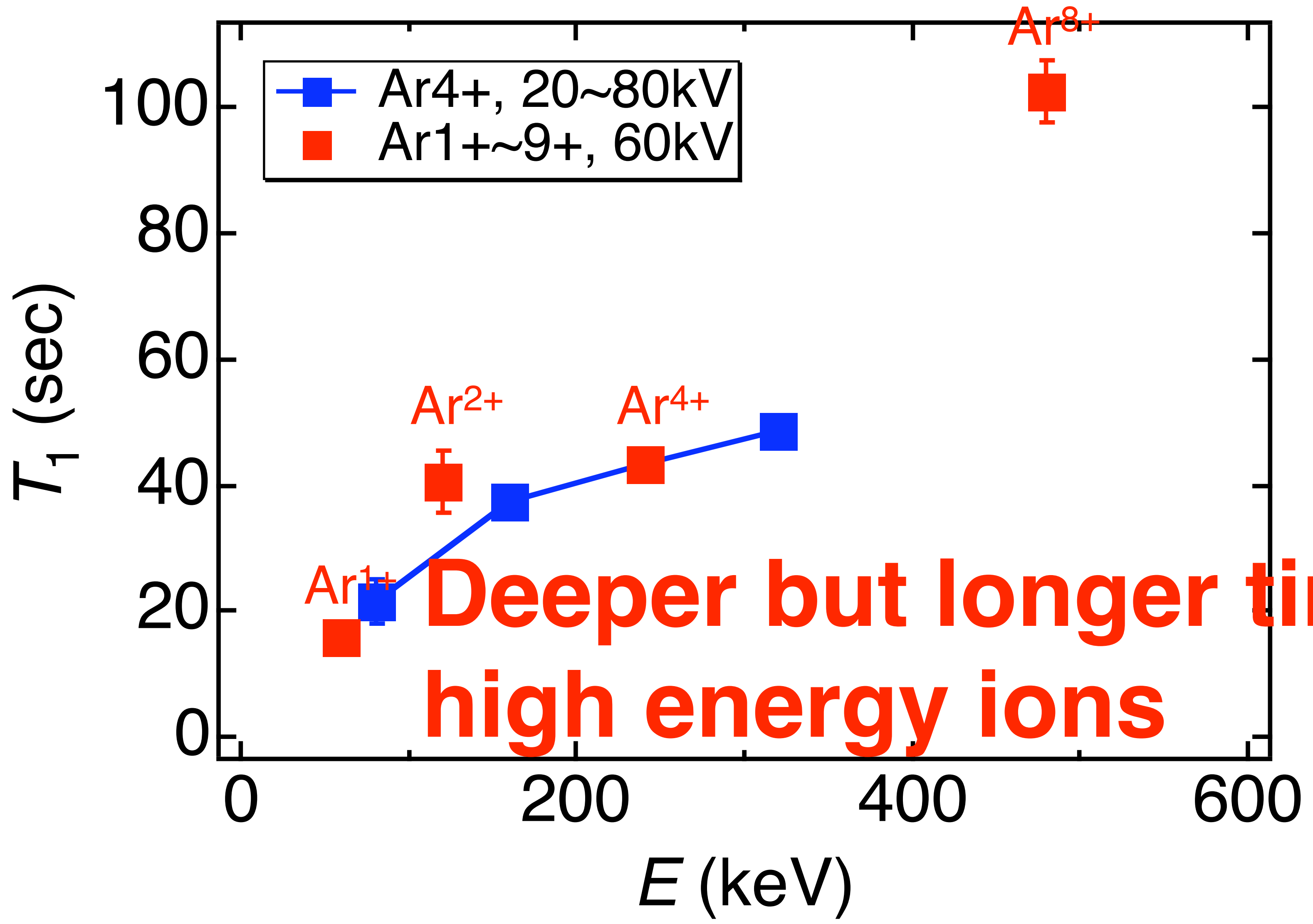
T_1 vs. E : Si

- Etching start time increases with*E*.



T_1 vs. E : Si

- Etching start time increases with*E*.

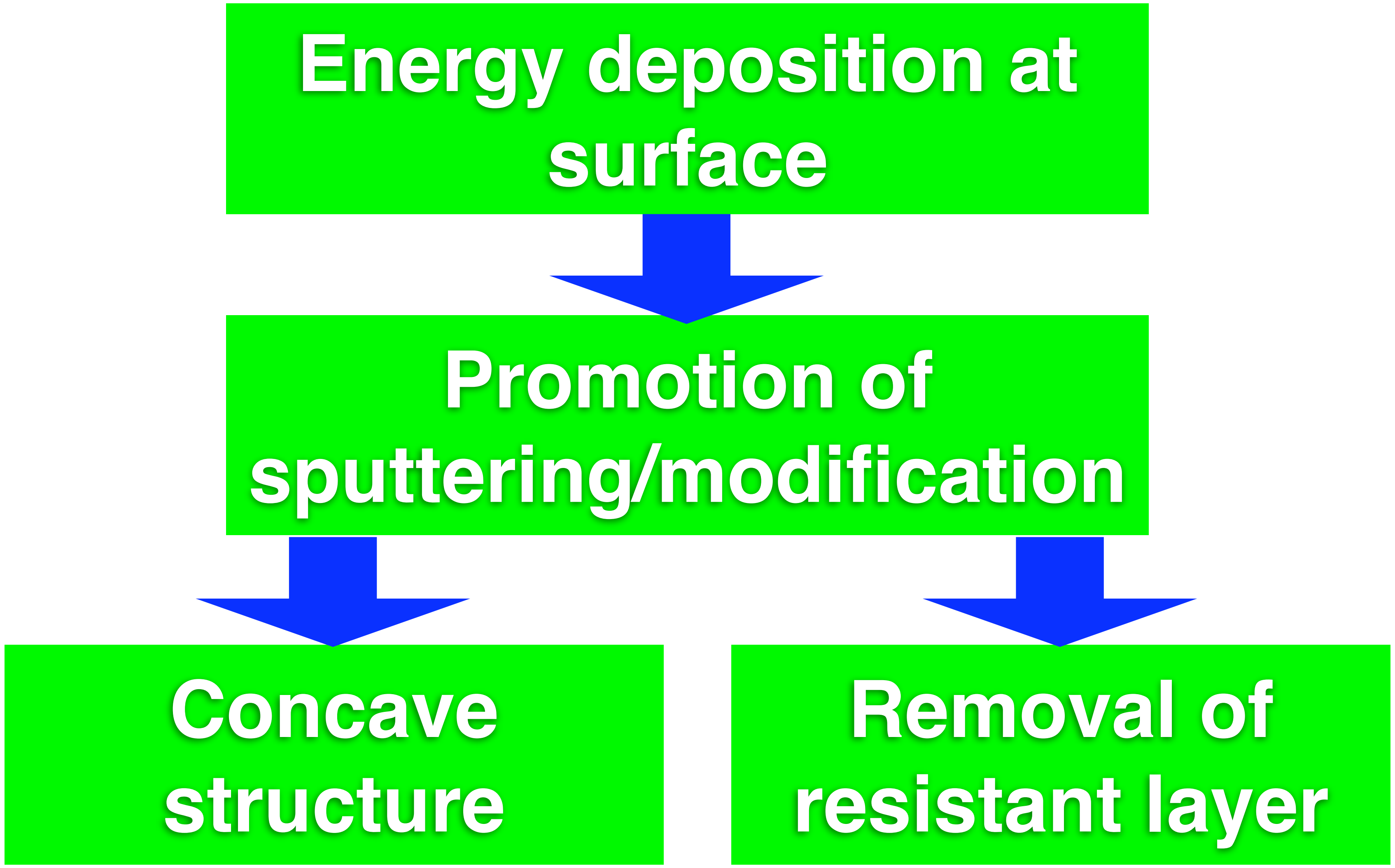


Deeper but longer time with high energy ions

Discussion

Modification of surface: SOG

- Top surface : resistant layer for etching



Energy deposition at surface

Promotion of sputtering/modification

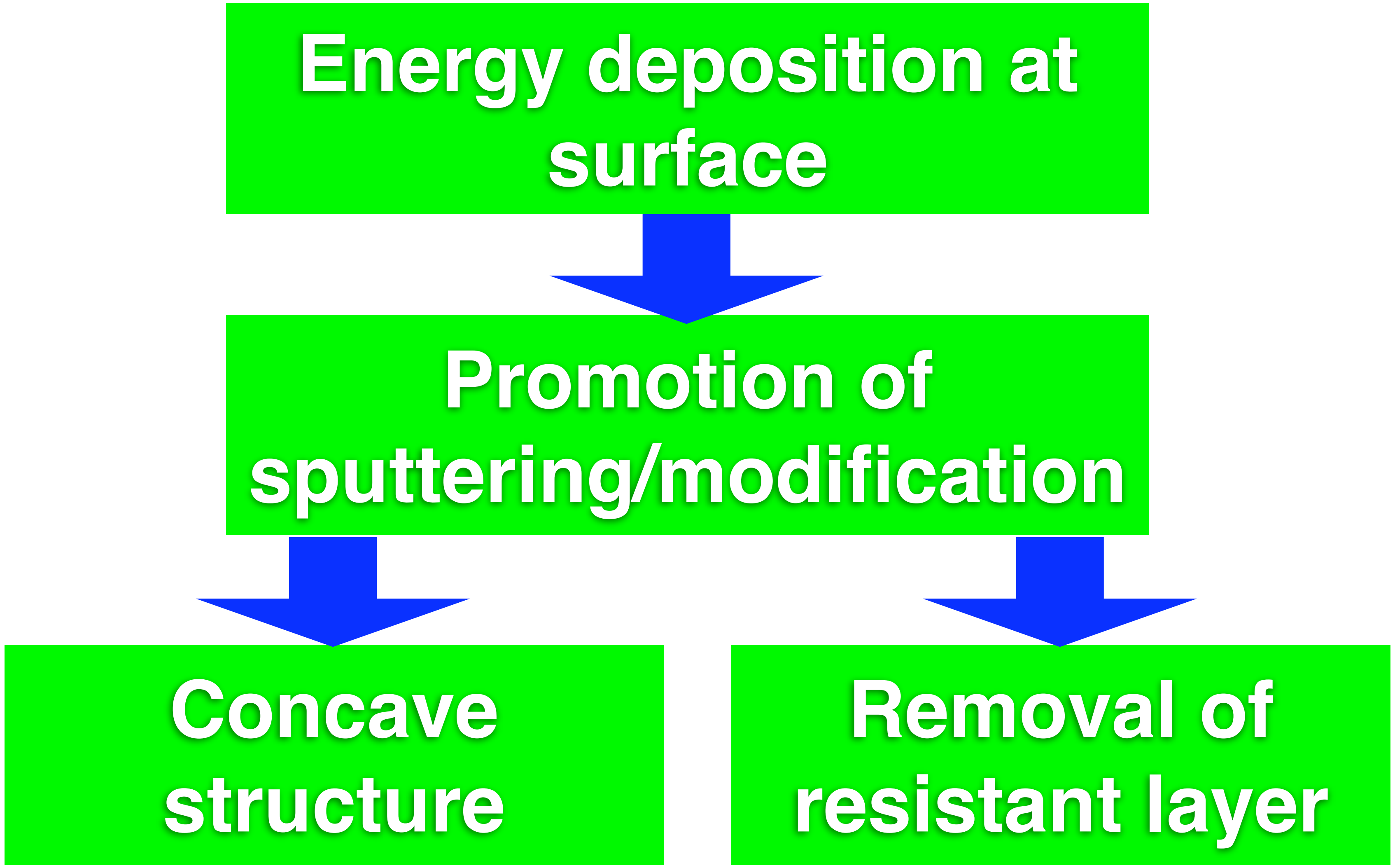
Concave structure

Removal of resistant layer

Modification of surface: SOG

- Top surface : resistant layer for etching

1+ ⇒ 9+



Energy deposition at surface

Promotion of sputtering/modification

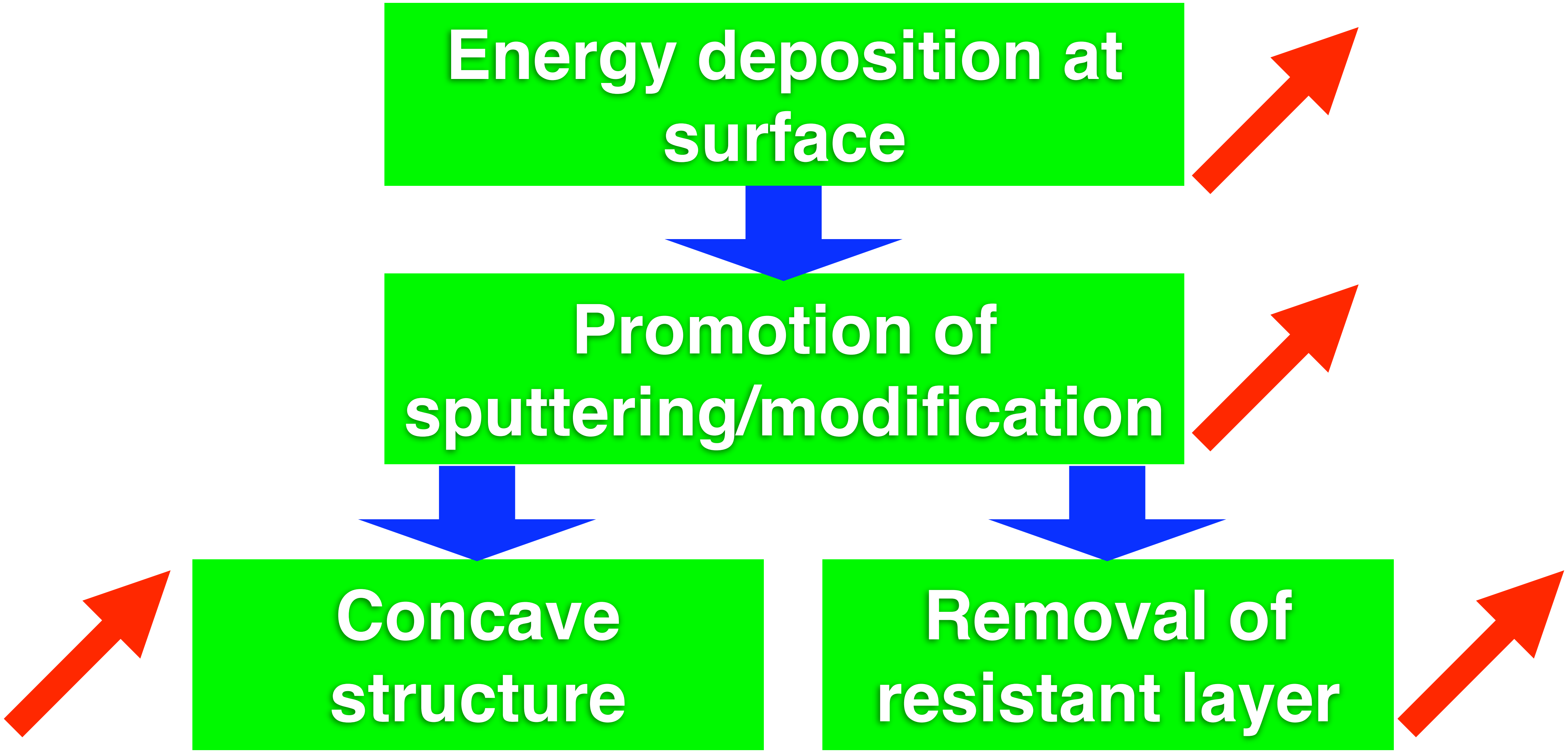
Concave structure

Removal of resistant layer

Modification of surface: SOG

- Top surface : resistant layer for etching

1+ ⇒ 9+



Energy deposition at surface

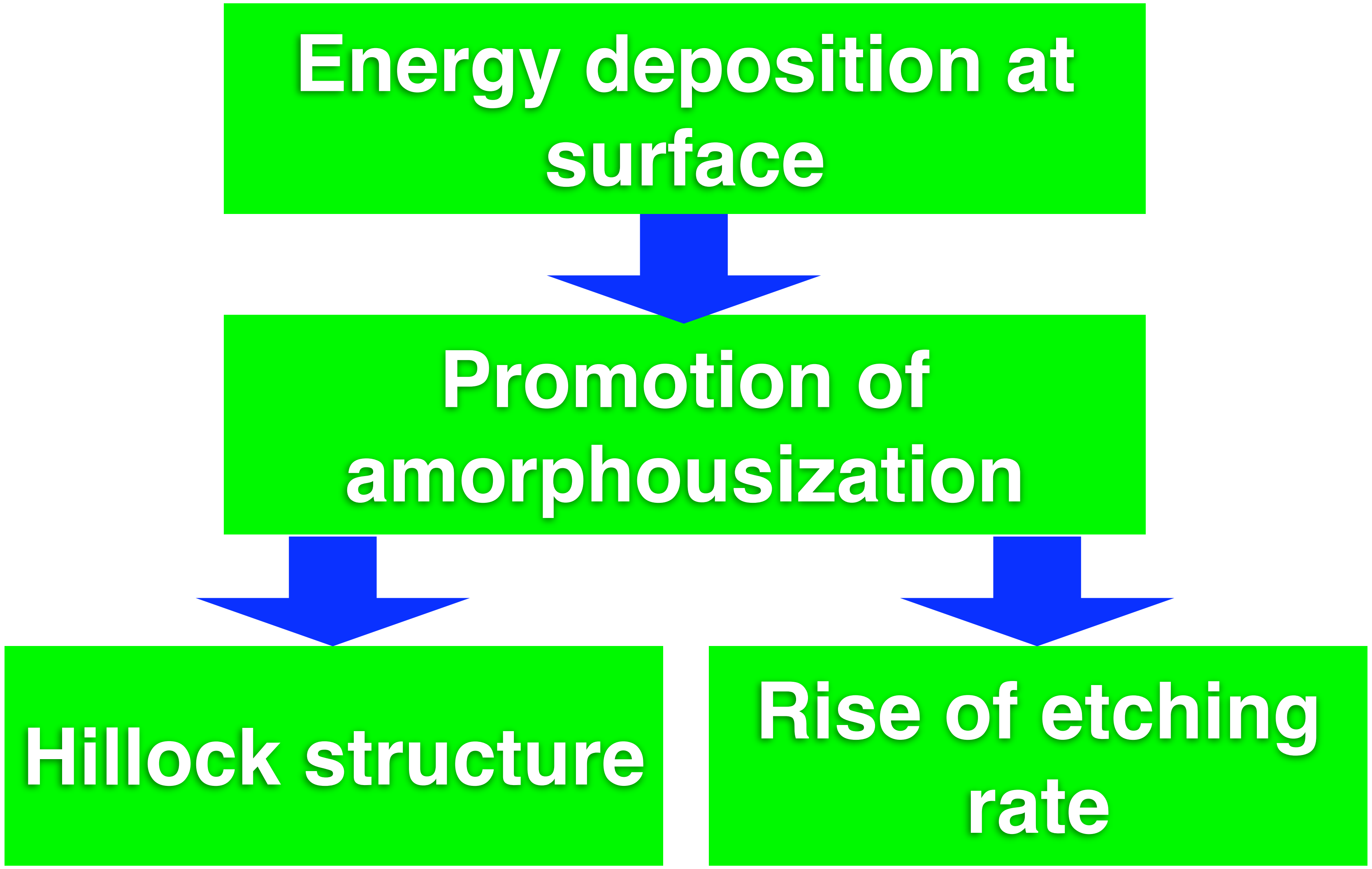
Promotion of sputtering/modification

Concave structure

Removal of resistant layer

Modification of surface: Si

- Top surface : resistant layer for etching



Energy deposition at surface

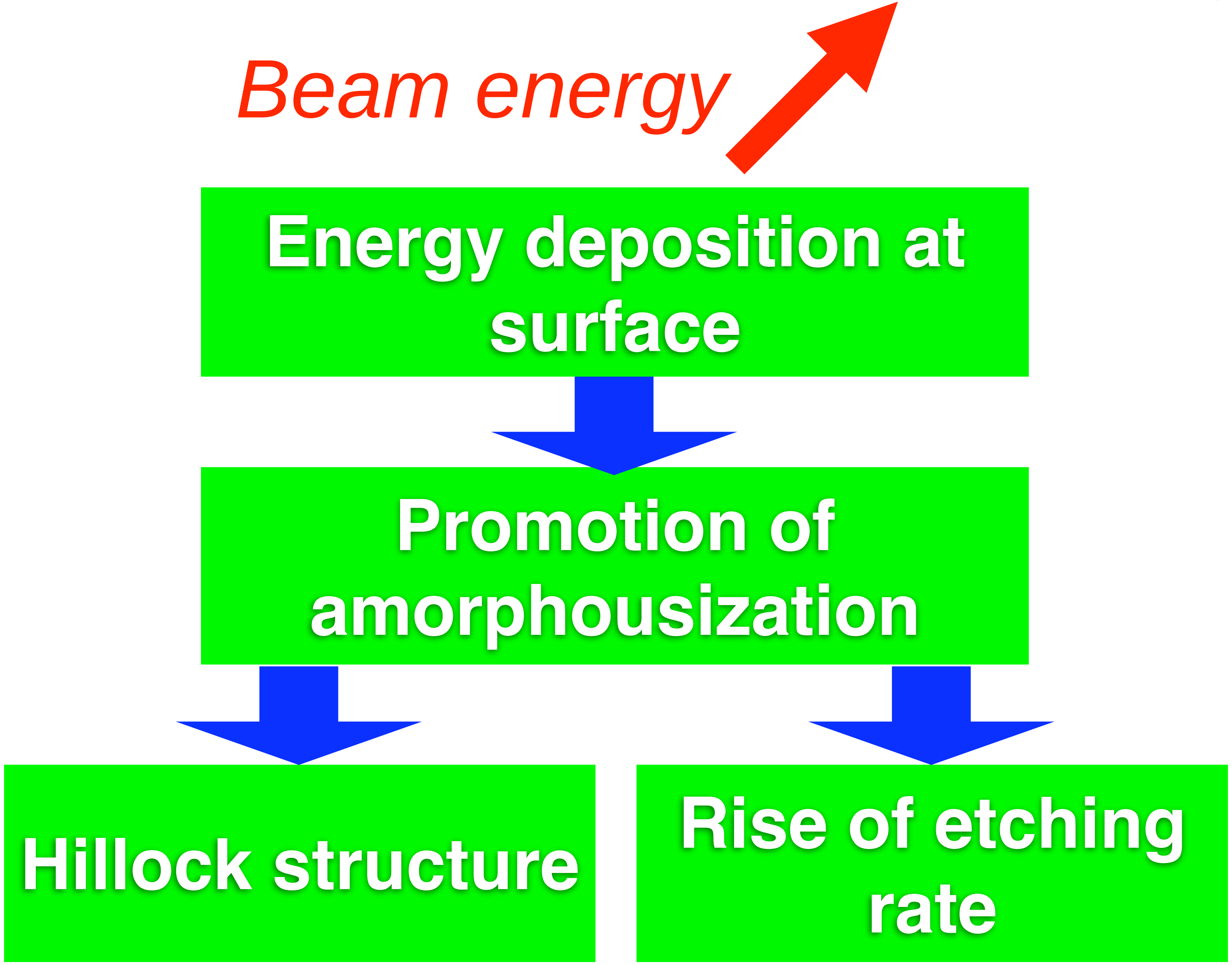
Promotion of amorphousization

Hillock structure

Rise of etching rate

Modification of surface: Si

- Top surface : resistant layer for etching



Beam energy

Energy deposition at surface

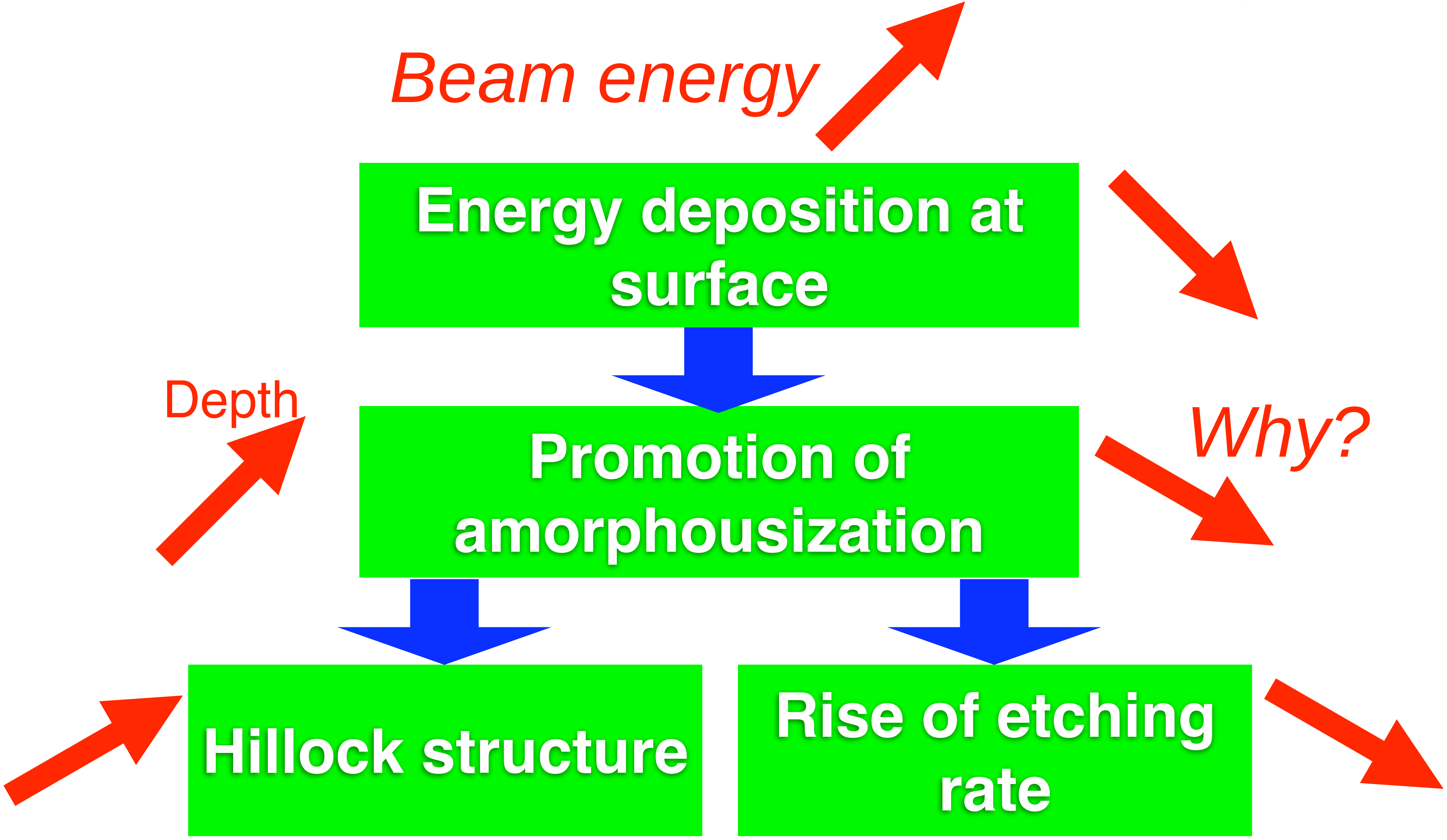
Promotion of amorphousization

Hillock structure

Rise of etching rate

Modification of surface: Si

- Top surface : resistant layer for etching



Beam energy

Energy deposition at surface

Depth

Promotion of amorphousization

Why?

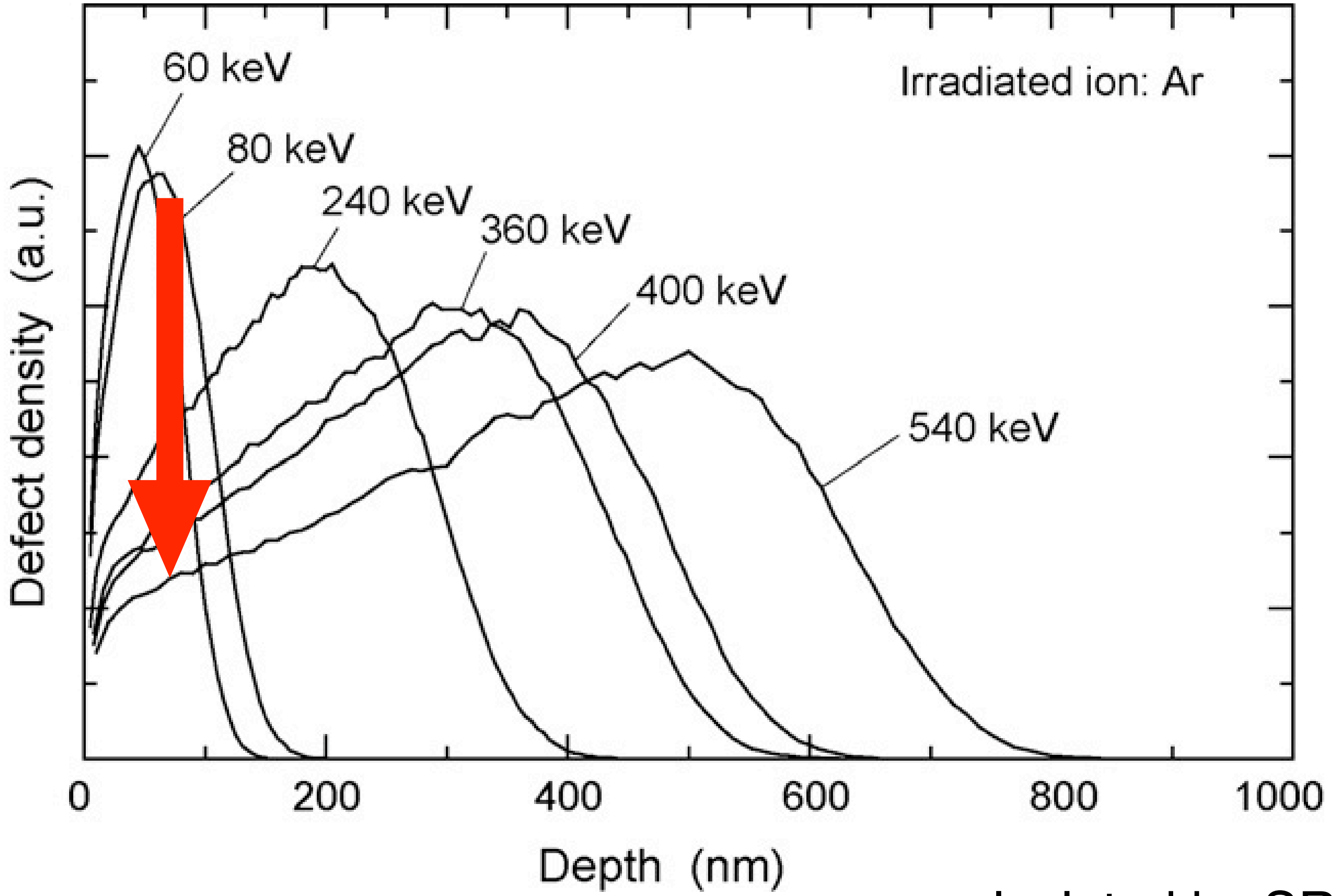
Hillock structure

Rise of etching rate

Because

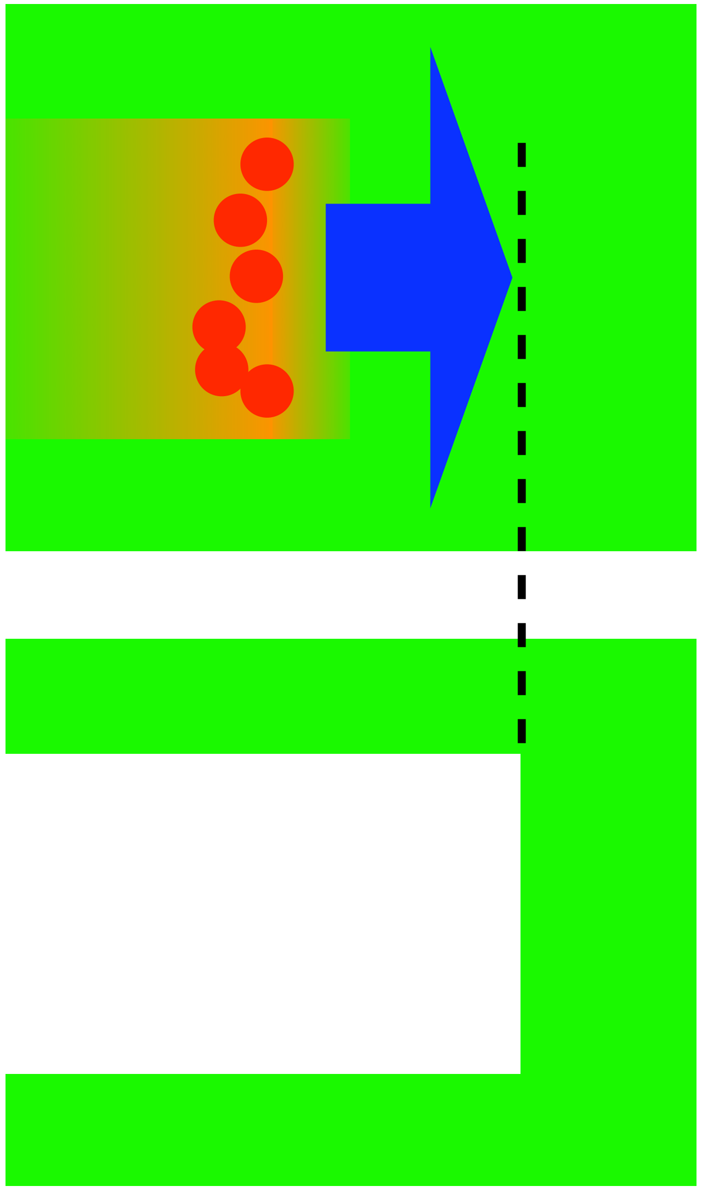
Reduction of energy deposition at surface

Defect density distribution in Si induced by Ar irradiation



calculated by SRIM

Modification of inside: SOG



- Etching rate
  - not depend on *q*
- Etching depth
  - anomalously deeper than ion range
  - increase with *q*

q dep. does not observed for Si.

Indirect irradiation effect

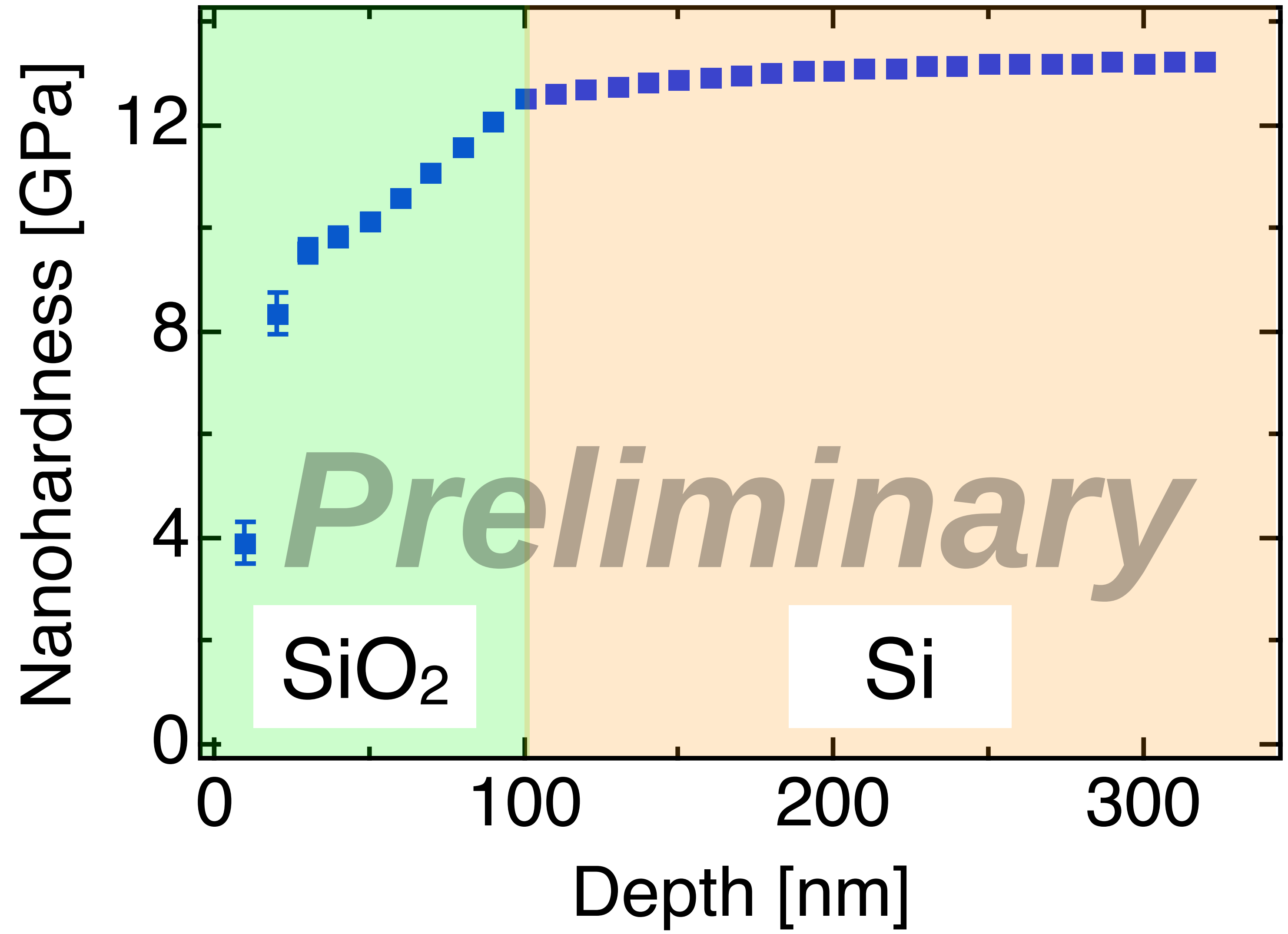
- Anomalously deep structural change
  - *Secondary e^-*
  - *Shock waves*
  - *Stress etc.*
- Remarkable for glasses

A. Deshkovskaya, Nucl. Instr. and Meth. in Phys. Res. B166-167 (2000) pp.511

HCI effect is material dependent.

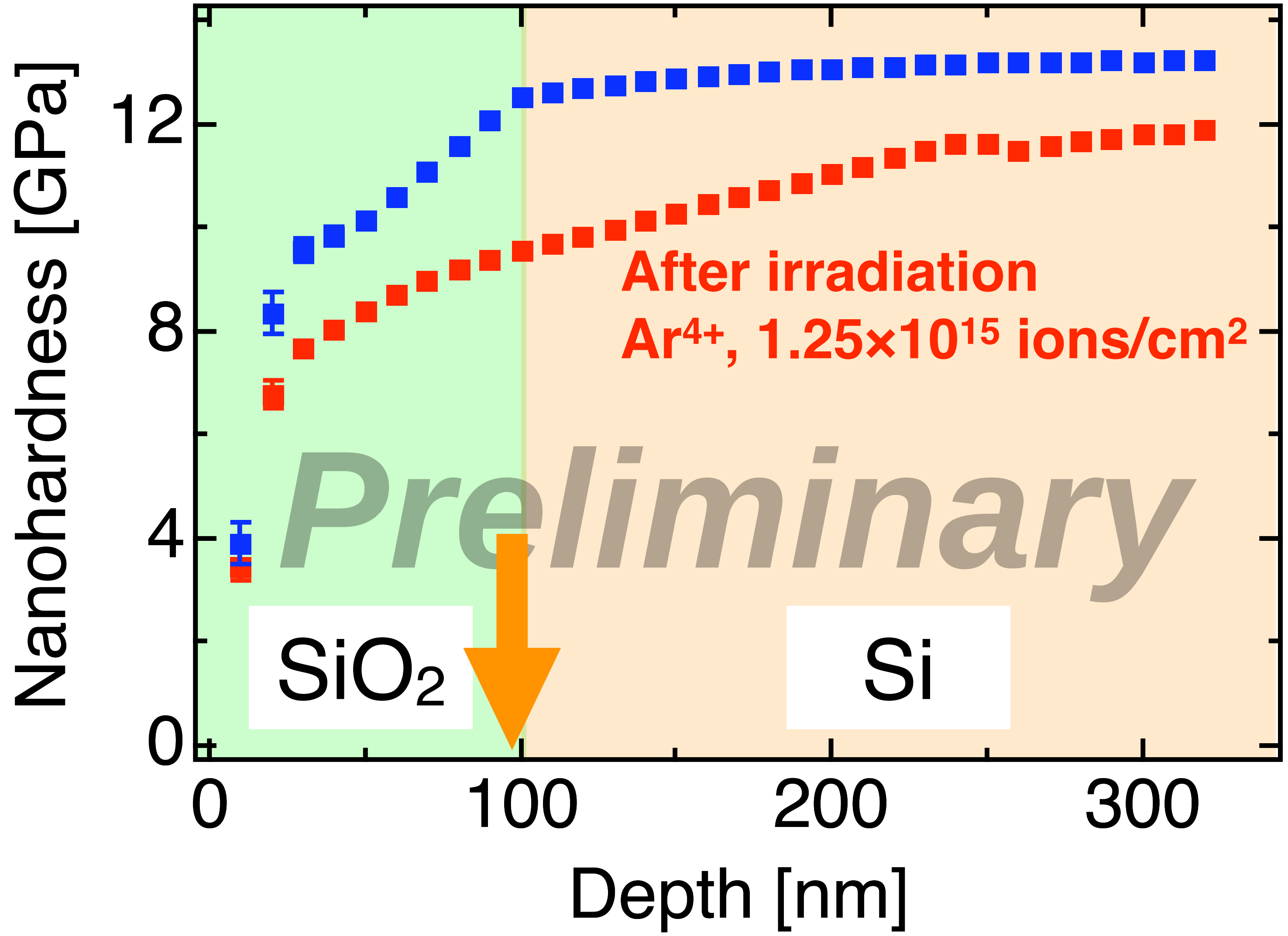
Modification of mechanical properties

- Nano-indentation meas.



Modification of mechanical properties

- Nano-indentation meas.



Conclusion

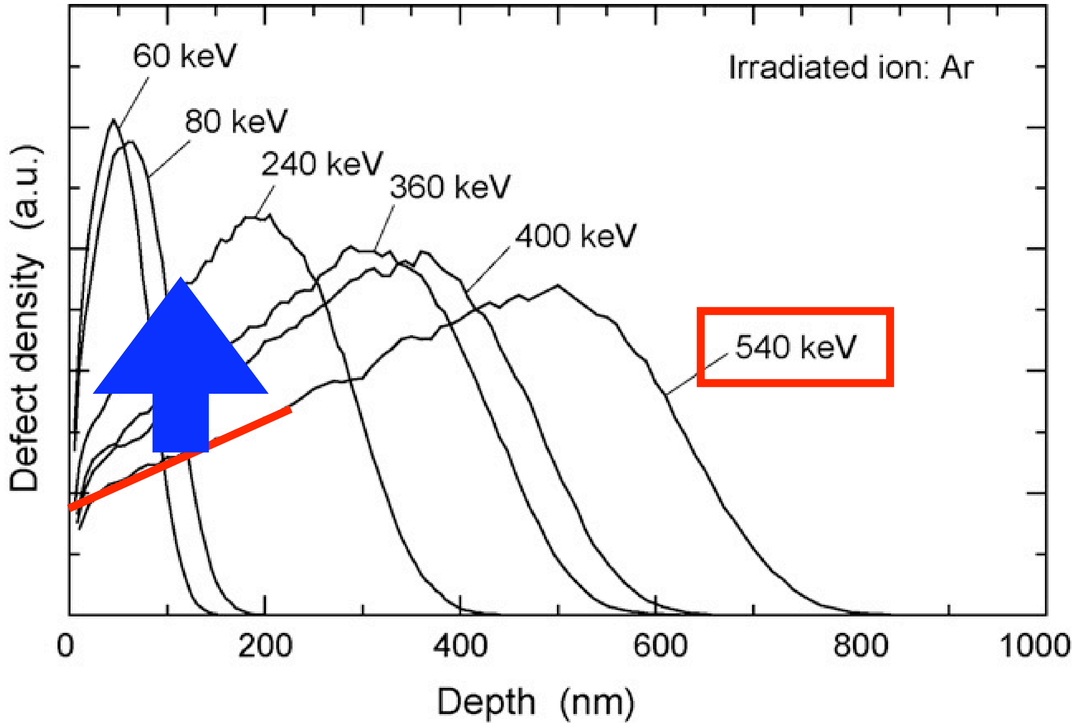
HCI effect on IBL

- HCI beams reduces etching time.
  - Reduction of T_1
- HCI enhances fabrication depth.
  - Anomalously deep structural change (Material dependent)
  - HCI beams
- Fabrication depth can be controlled.
  - ±10nm
  - V and q

For deep fabrication

- Energy deposition promotes fabrication.
- More energy deposition at surface.
  - Co-irradiation of low energy IB
  - Irradiation of HCI beams

Defect density distribution

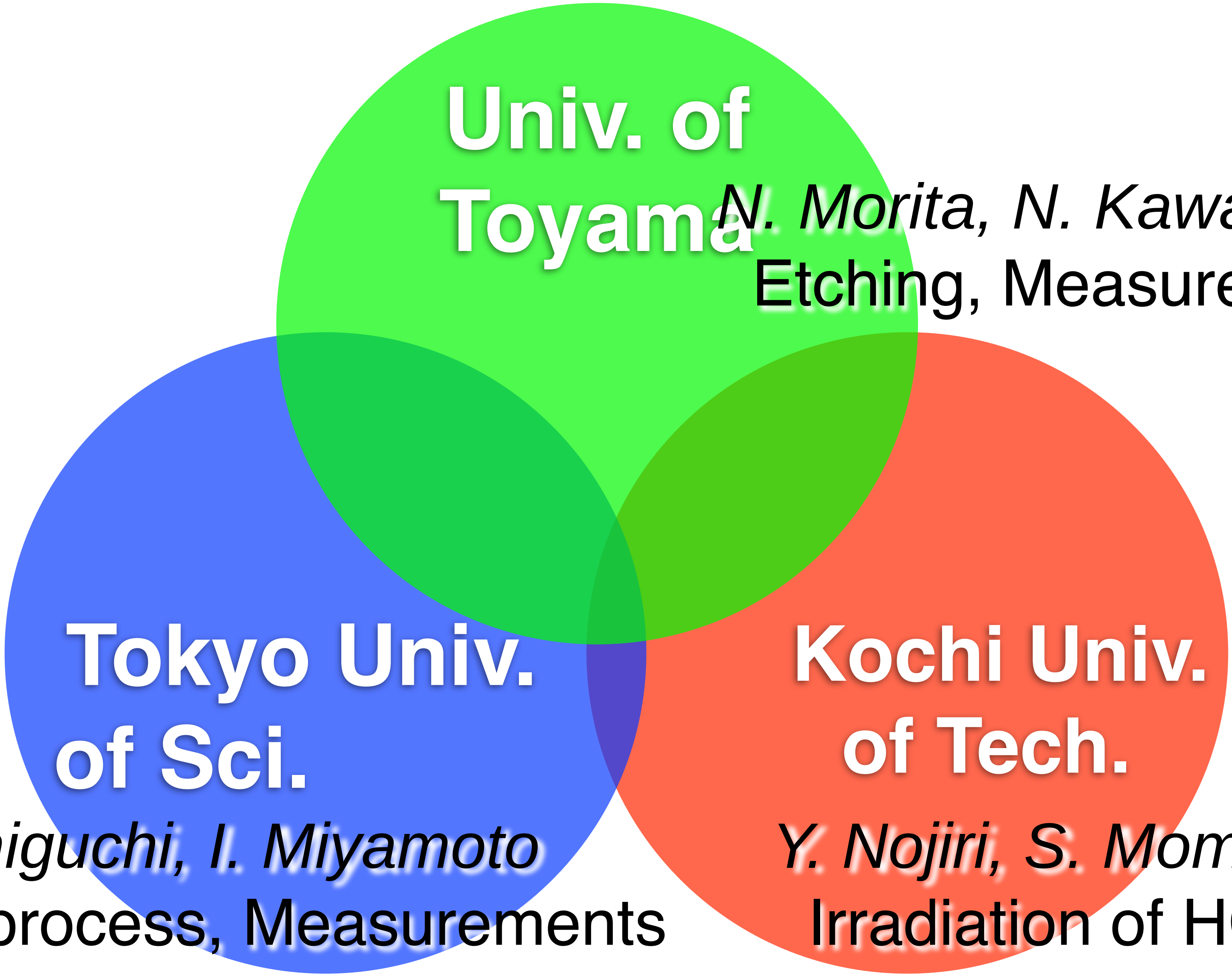


calculated by SRIM

Prospects

- Further development of IBL with HCI beams
  - Application of higher $E_{\mathrm{pot.}}$
  - Fabrication of unique structure
- Further development of ion source
  - More intense / more focused HCI beams

Collaboration



Univ. of Toyama

N. Morita, N. Kawasegi
Etching, Measurements

Tokyo Univ. of Sci.

J. Taniguchi, I. Miyamoto
IBL process, Measurements

Kochi Univ. of Tech.

Y. Nojiri, S. Momota
Irradiation of HCI beam

Collaboration

Univ. of Toyama

N. Morita, N. Kawasegi
Etching, Measurements

Tokyo Univ. of Sci.

J. Taniguchi, I. Miyamoto
IBL process, Measurements

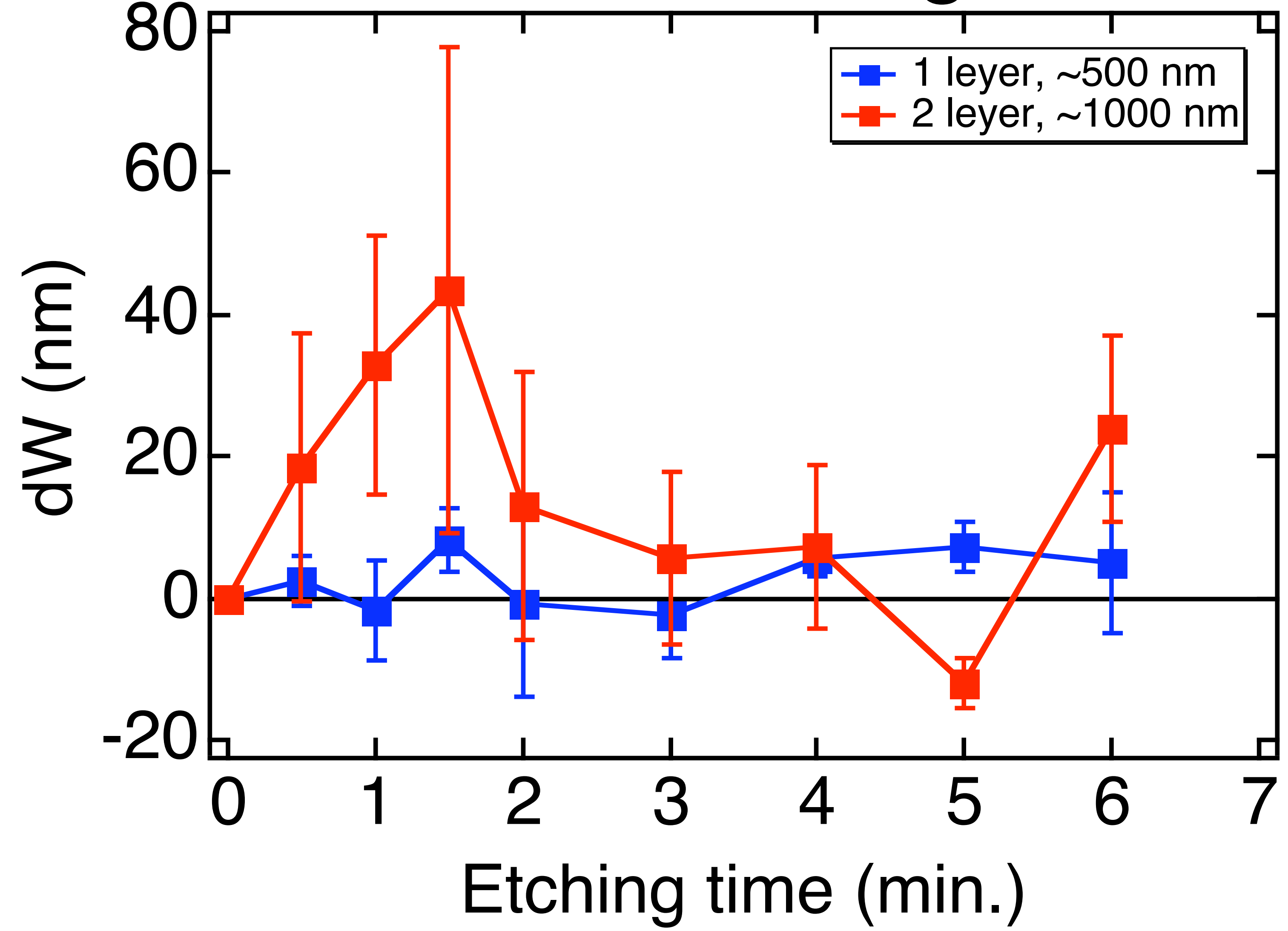
Kochi Univ. of Tech.

Y. Nojiri, S. Momota
Irradiation of HCI beam

Appendix

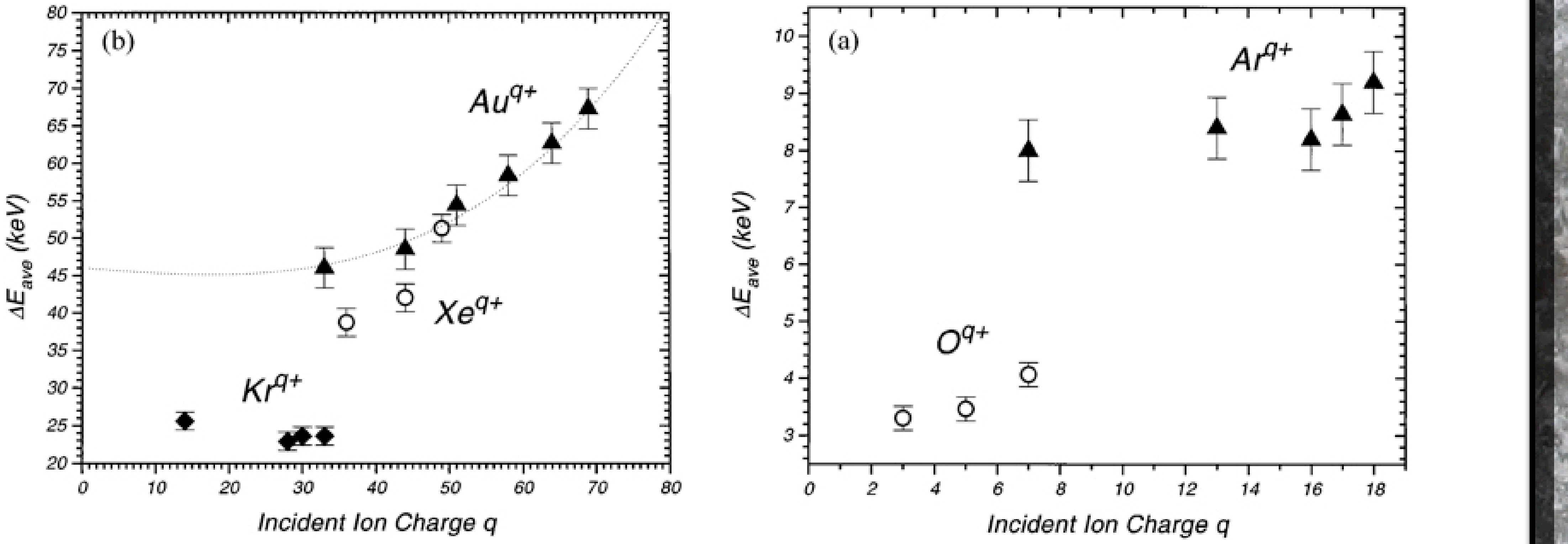
Change in thickness of SOG by etching process

- dW vs. etching time



Enhancement of E-loss

- *dE* of HCI beam in C-foil (~10 nm)



E = 35.5 ± 0.2 (^{16}O), 92.3 ± 0.6 (^{40}Ar),197.7 ± 1.0 (^{86}Kr), 312.4 ± 2.0 (^{136}Xe), and 454.4 ± 3 (^{197}Au) keV

T. Schenkel et al., Phys. Rev. Lett. 79 (1997) pp.2030