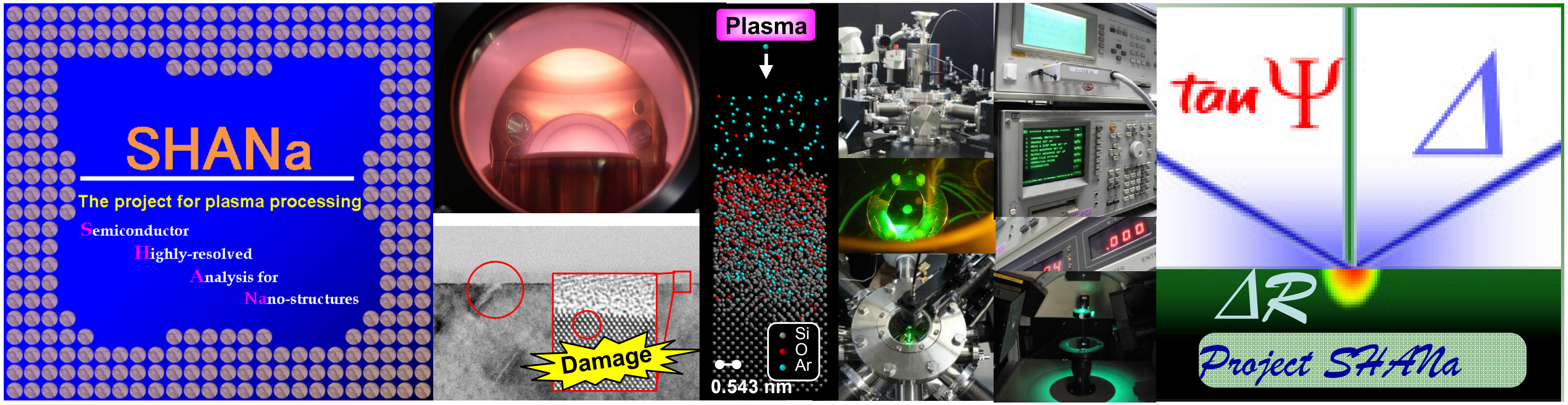
Plasma-Induced Damage in 3D Structures behind Device Scaling

K. Eriguchi, Y. Takao, and K. Ono
Kyoto University, JAPAN

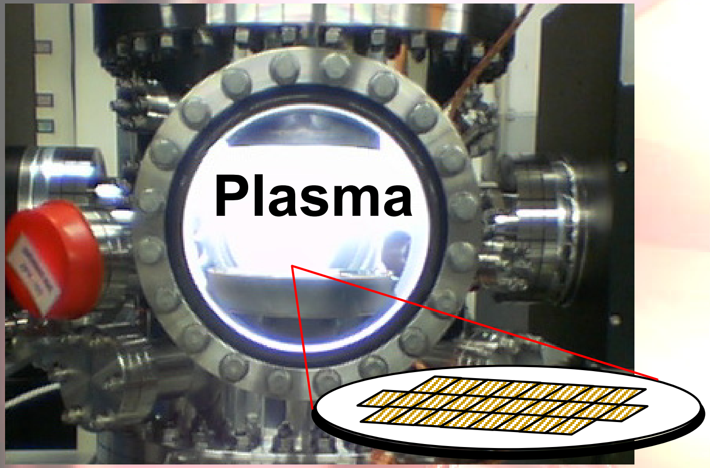
Acknowledgements: This work was partly supported by JSPS and STARC project in Japan.



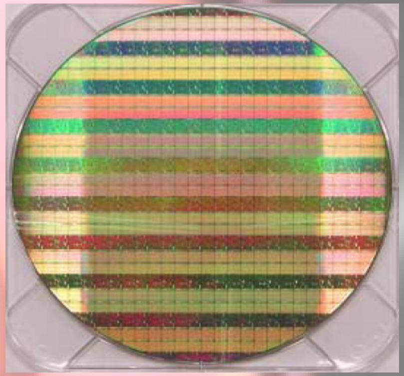
Outline

1. Introduction – Plasma-Induced Damage (PID)
2. A Scenario for PID in Scaled 3D Structures
    - 2-1 PID Models – Straggling & Sputtering
    - 2-2 Molecular Dynamics Simulation
    - 2-3 Electronic State of Defect
3. PID Prediction in 3D Structure
4. Summary

Plasma-Induced Damage (PID)

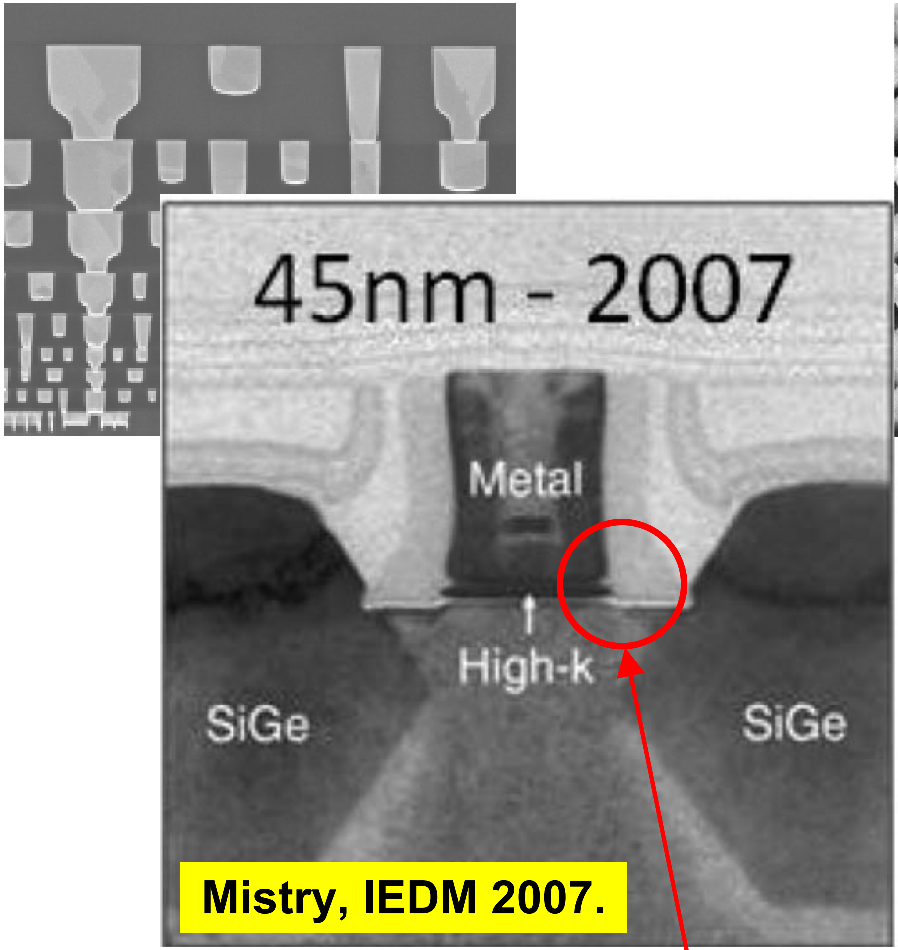


Performance
Reliability
Yield
Variability

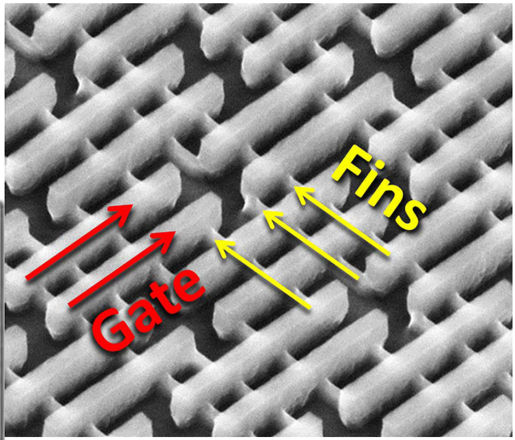


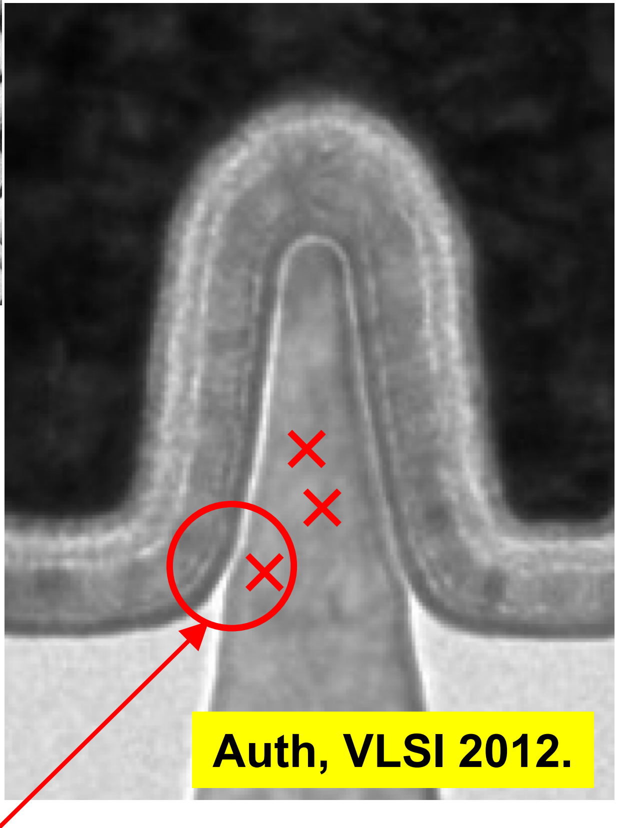
PID naturally does not scale!!

PID behind the scaling



Mistry, IEDM 2007.



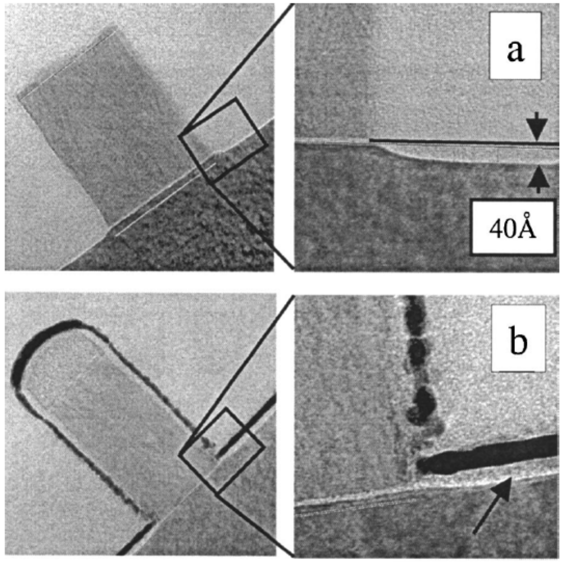


Auth, VLSI 2012.

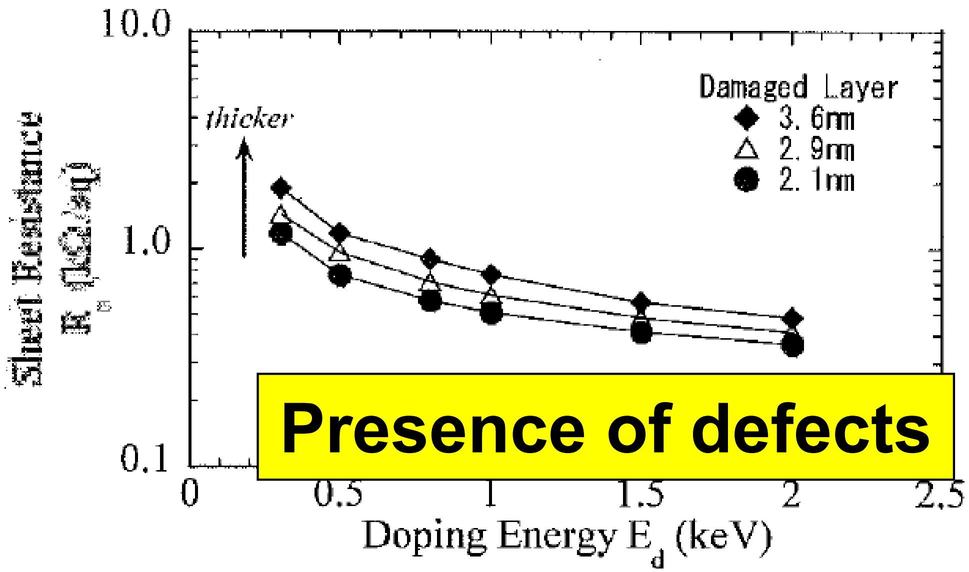
Plasma-Induced Physical Damage (PPD)

Power consumption increase & Operating speed down!!

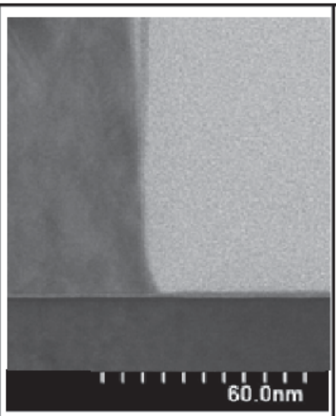
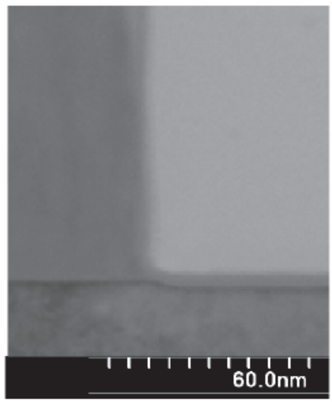
Previous reports on PID



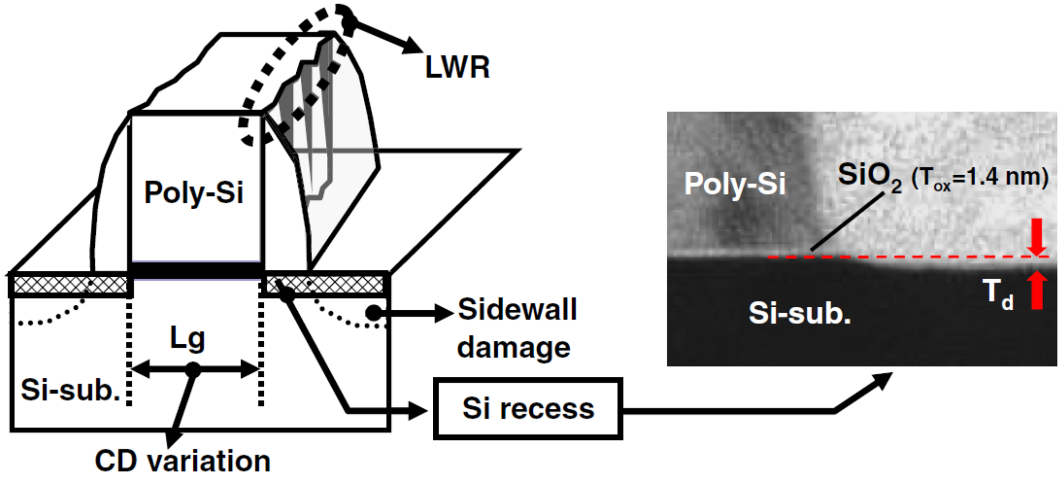
S. A. Vitale and B. A. Smith: JVST B 21 (2003) 2205.



H. Kokura et al., Proc. Symp. Dry Process, 2005, p. 27.

Poly-Si Profile		
Etching Step	(a) Before OE (after ME)	(b) After OE
Si recess	No-Si recess 0.0nm	1.9nm

N. Yasui et al.: Proc. Symp. Dry Process (2007) 195.



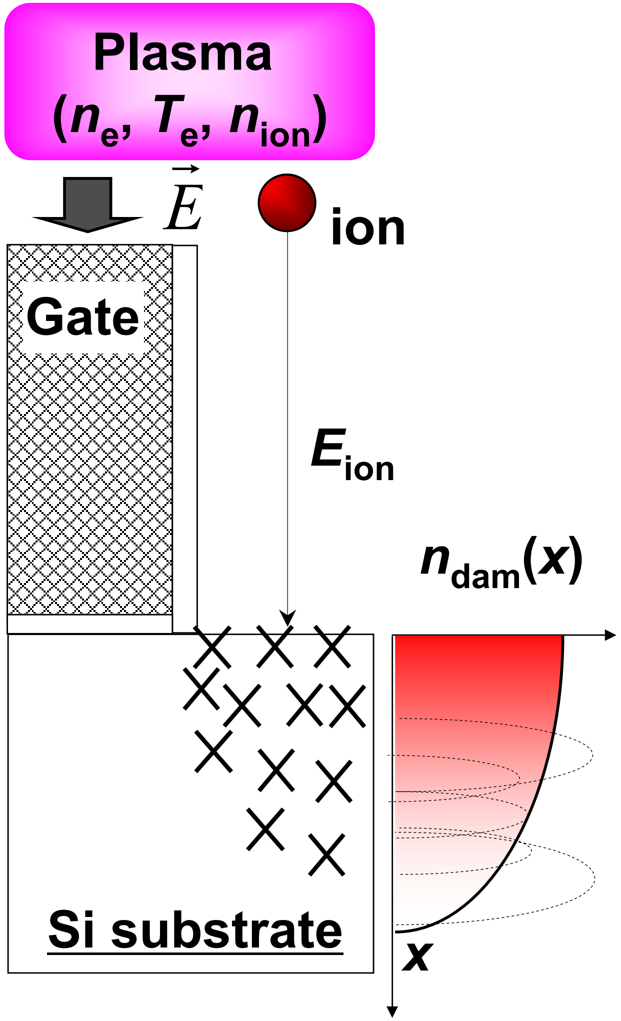
T. Ohchi et al.: Jpn. J. Appl. Phys. 47 (2008) 5324.

Outline

1. Introduction – Plasma-Induced Damage (PID)
2. A Scenario for PID in Scaled 3D Structures
    2-1 PID Models – Straggling & Sputtering
    2-2 Molecular Dynamics Simulation
    2-3 Electronic State of Defect
3. PID Prediction in 3D Structure
4. Summary

PID Range Theory – Planar Device

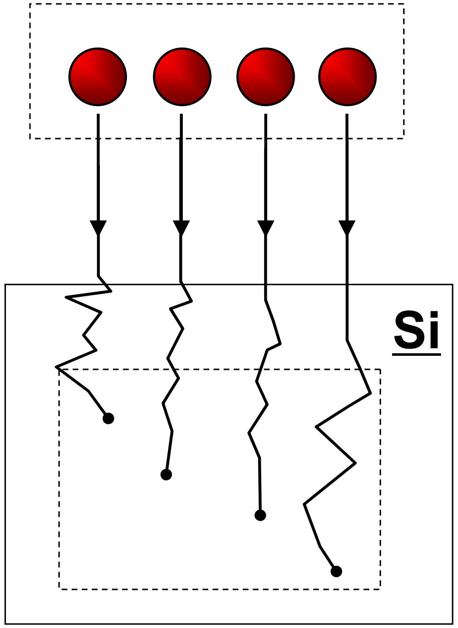
Project Range → Stopping Power



$$-\frac{dE_{\mathrm{ion}}}{dx} = n_0\, S_{\mathrm{d}}(E_{\mathrm{ion}}) = n_0 \int_0^{\infty} T(E_{\mathrm{ion}}, p)\cdot 2\pi\, p\,dp$$

T: energy transfer
p: impact parameter

Potential-model-dependent

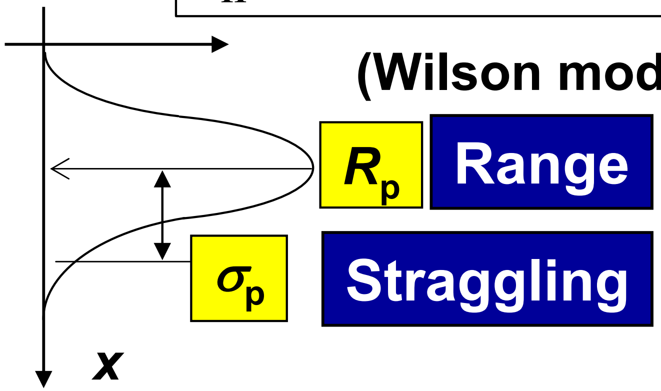


low energy limit

ε: reduced energy

$$s_{\mathrm{n}}(\varepsilon) \rightarrow 0.5B\varepsilon^{1-\alpha}$$

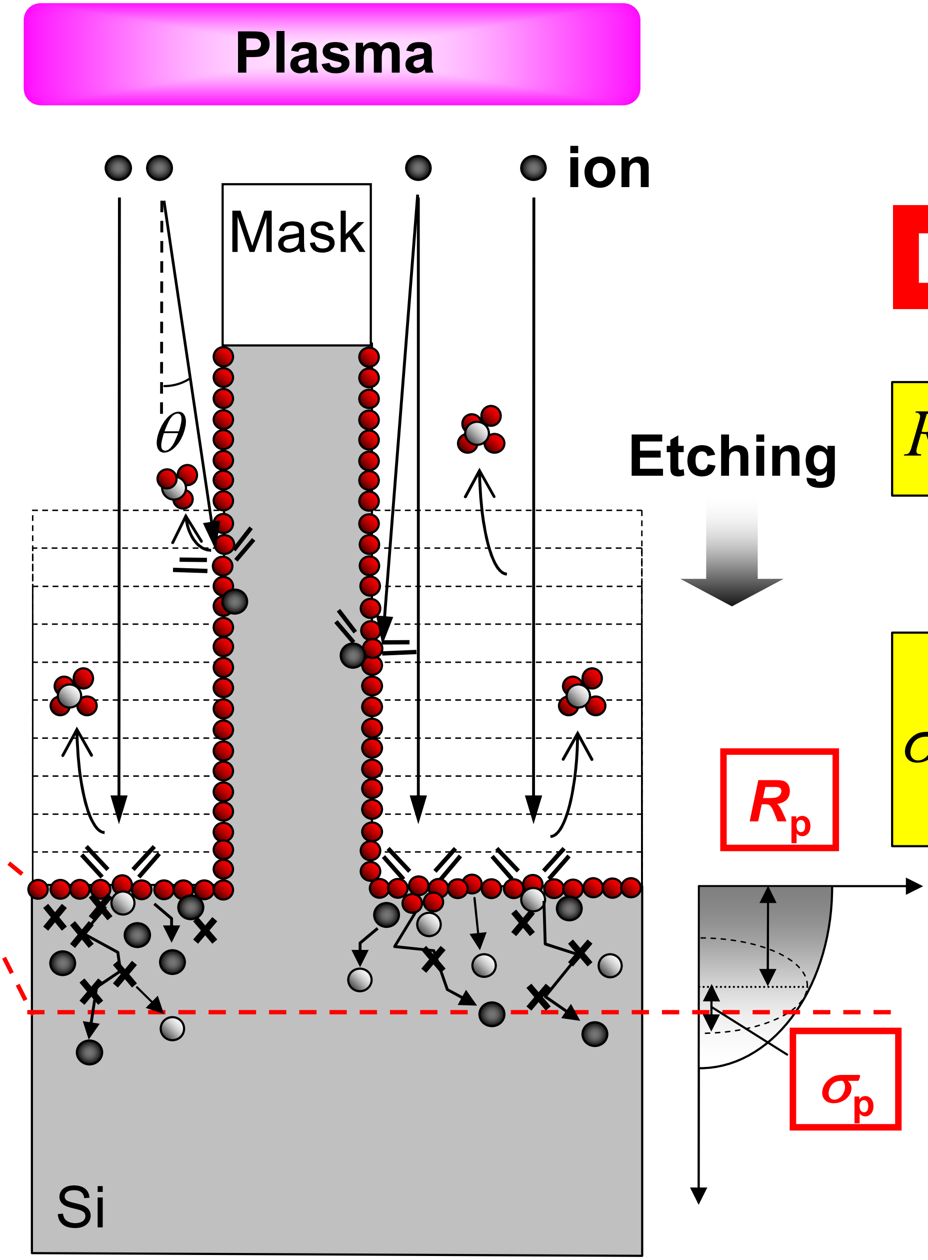
(Wilson model: α ~ 0.3)



N. Bohr: Mat. Fys. Medd. K. Dan. Vidensk. Selsk. 18 (1948).
J. Lindhard et al.: Mat. Fys. Medd. K. Dan. Vidensk. Selsk. 33, 1 (1963).
G. Moliere: Z. Naturforschung A2, 133 (1947).
W. D. Wilson et al.: Phys. Rev. B 15, 2458 (1977).

PID Range Theory – Planar Device

- ● ion
- ○ Si
- 🔴 radical



Damaged layer

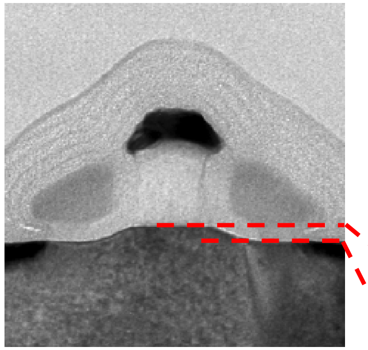
$$R_p = A_{\mathrm{ion}} \cdot (E_{\mathrm{ion}})^{\alpha}$$

(Eriguchi et al.)

$$\sigma_p = \sqrt{\frac{2}{3}\frac{\sqrt{M_{\mathrm{Si}}M_{\mathrm{ion}}}}{M_{\mathrm{Si}}+M_{\mathrm{ion}}}}R_p$$

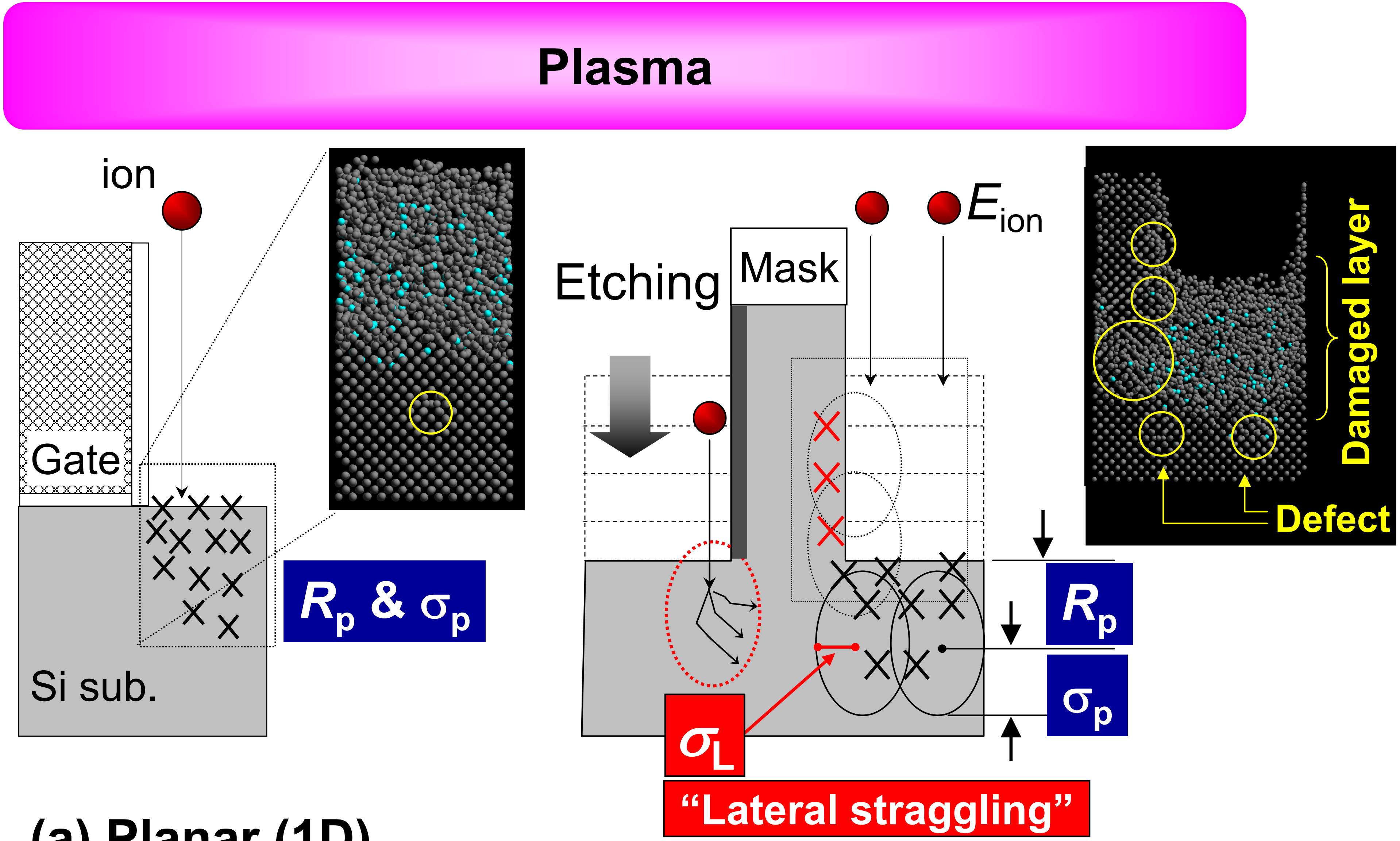
(LSS Theory)

$$d_V \rightarrow R_p + \sigma_p$$



ex. Si Recess

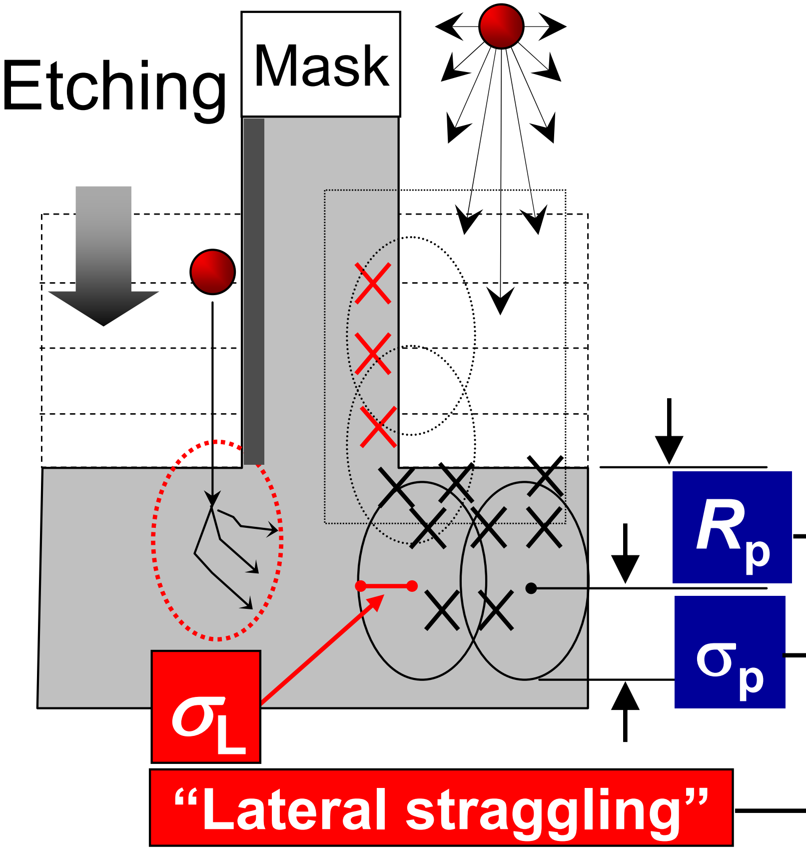
PID Range Theory – "Straggling"



(a) Planar (1D)

(b) Fin-structured (3D)

PID Range Theory – "Straggling"



$$R_{\mathrm{p}} = A_{\mathrm{ion}} \cdot (E_{\mathrm{ion}})^{\beta}$$

(Eriguchi et al.)

$$\sigma_{\mathrm{p}} = \sqrt{\frac{2}{3}\frac{\sqrt{M_{\mathrm{Si}} M_{\mathrm{ion}}}}{M_{\mathrm{Si}} + M_{\mathrm{ion}}}} R_{\mathrm{p}}$$

(LSS Theory)

$$\sigma_{\mathrm{L}} = K \cdot \sigma_{\mathrm{p}}$$

(Furukawa et al.)

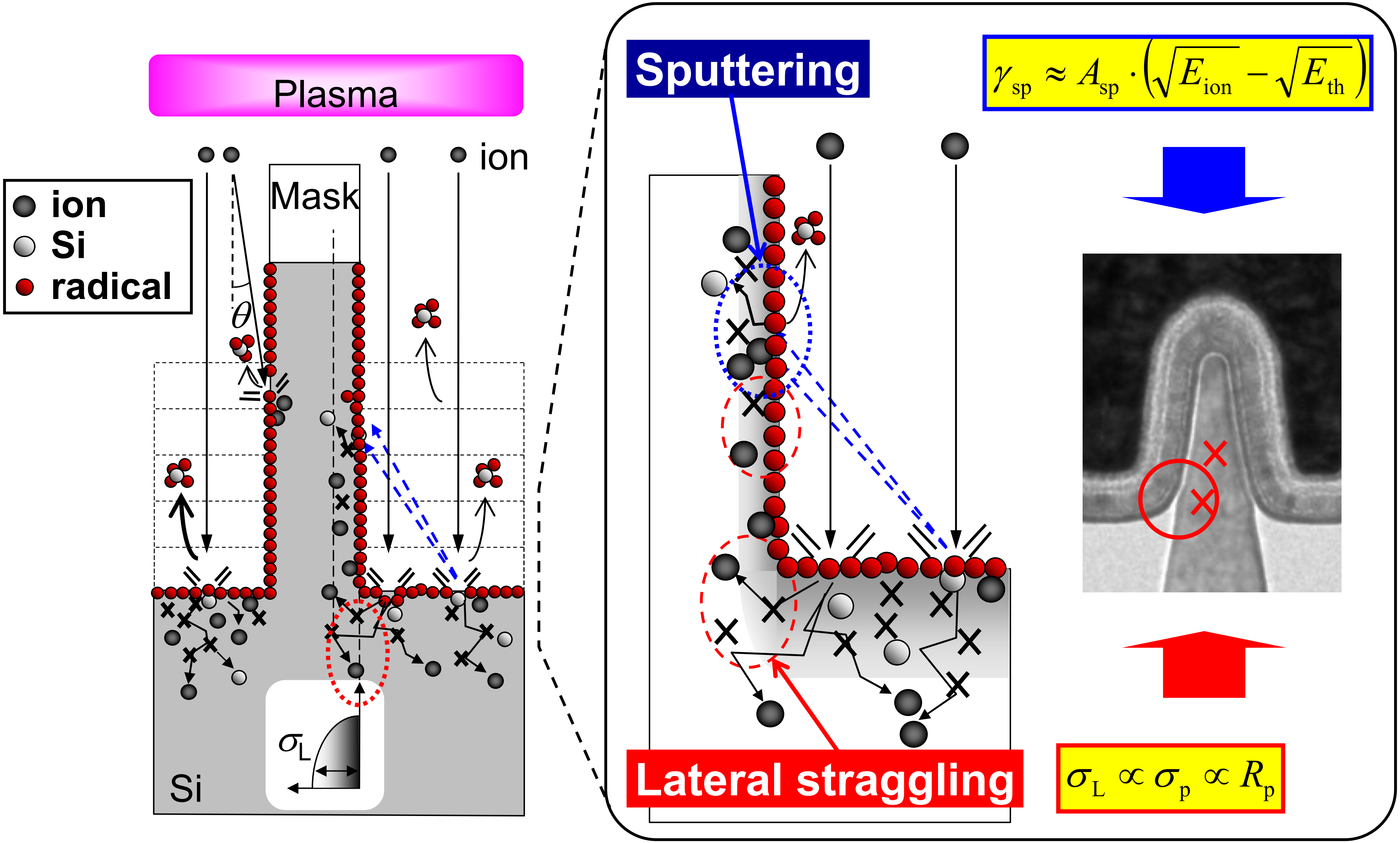
$$\sigma_{\mathrm{L}} = B_{\mathrm{ion}} \cdot \sqrt{\frac{2}{3}\frac{\sqrt{M_{\mathrm{Si}} M_{\mathrm{ion}}}}{M_{\mathrm{Si}} + M_{\mathrm{ion}}}} (E_{\mathrm{ion}})^{\beta}$$

(1) Lateral straggling depends on M_{ion}, E_{ion}, and Si–ion potential.

(2) Sidewall etching mechanism is governed, not only by direct ion impact & deposition, but also by THIS STRAGGLING, σ_L!

→ Damaged layer thickness ~ $R_p + \sigma_p$ (planar), σ_L (3D)

PID Model – 3D Device



$$\gamma_{\mathrm{sp}} \approx A_{\mathrm{sp}} \cdot \left(\sqrt{E_{\mathrm{ion}}} - \sqrt{E_{\mathrm{th}}}\right)$$

$$\sigma_{\mathrm{L}} \propto \sigma_{\mathrm{p}} \propto R_{\mathrm{p}}$$

Outline

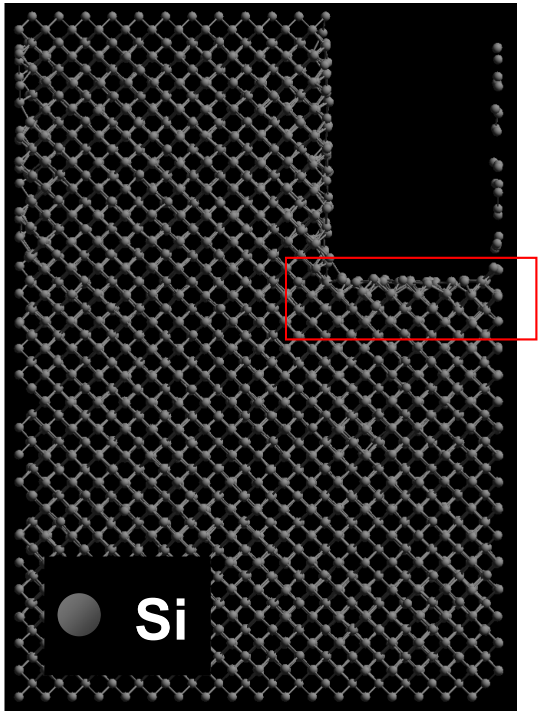
1. Introduction – Plasma-Induced Damage (PID)
2. A Scenario for PID in Scaled 3D Structures
    2-1 PID Models – Straggling & Sputtering
    2-2 Molecular Dynamics Simulation
    2-3 Electronic State of Defect
3. PID Prediction in 3D Structure
4. Summary

Simulation scheme

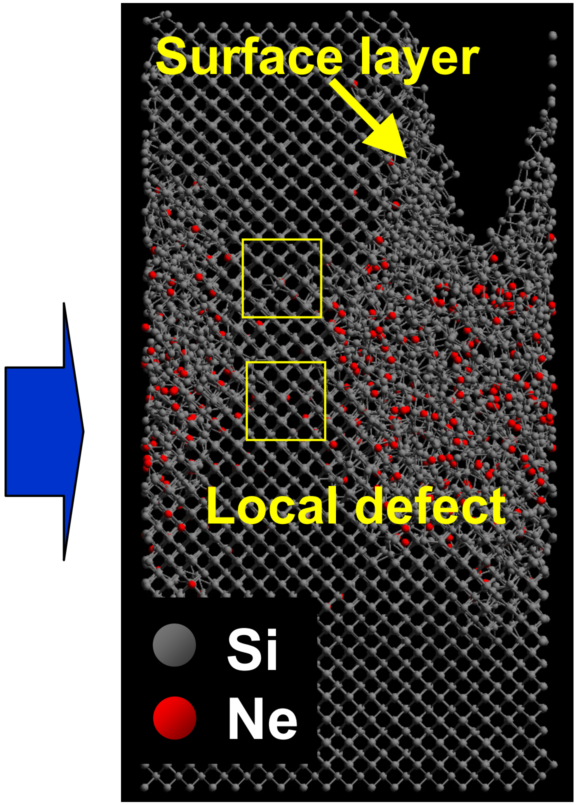
Classical Molecular Dynamics (Ohta and Hamaguchi, JVST 2001.)

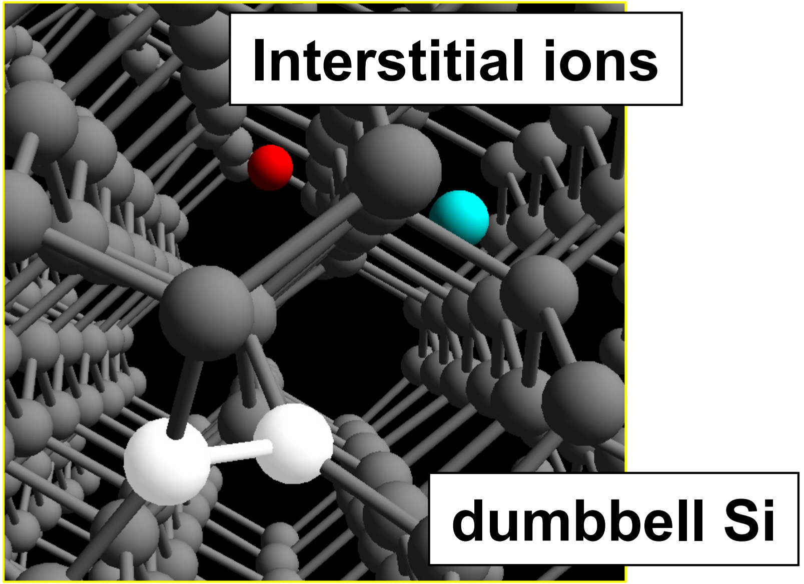
Si–Si, Cl, O: Stillinger–Weber Phys. Rev. B, Vol.31, No.8, (1985), pp. 5262-5271

Noble gases: Wilson et al. Phys. Rev. B, Vol.15, No.5, (1977), pp. 2458-2468



Starting material

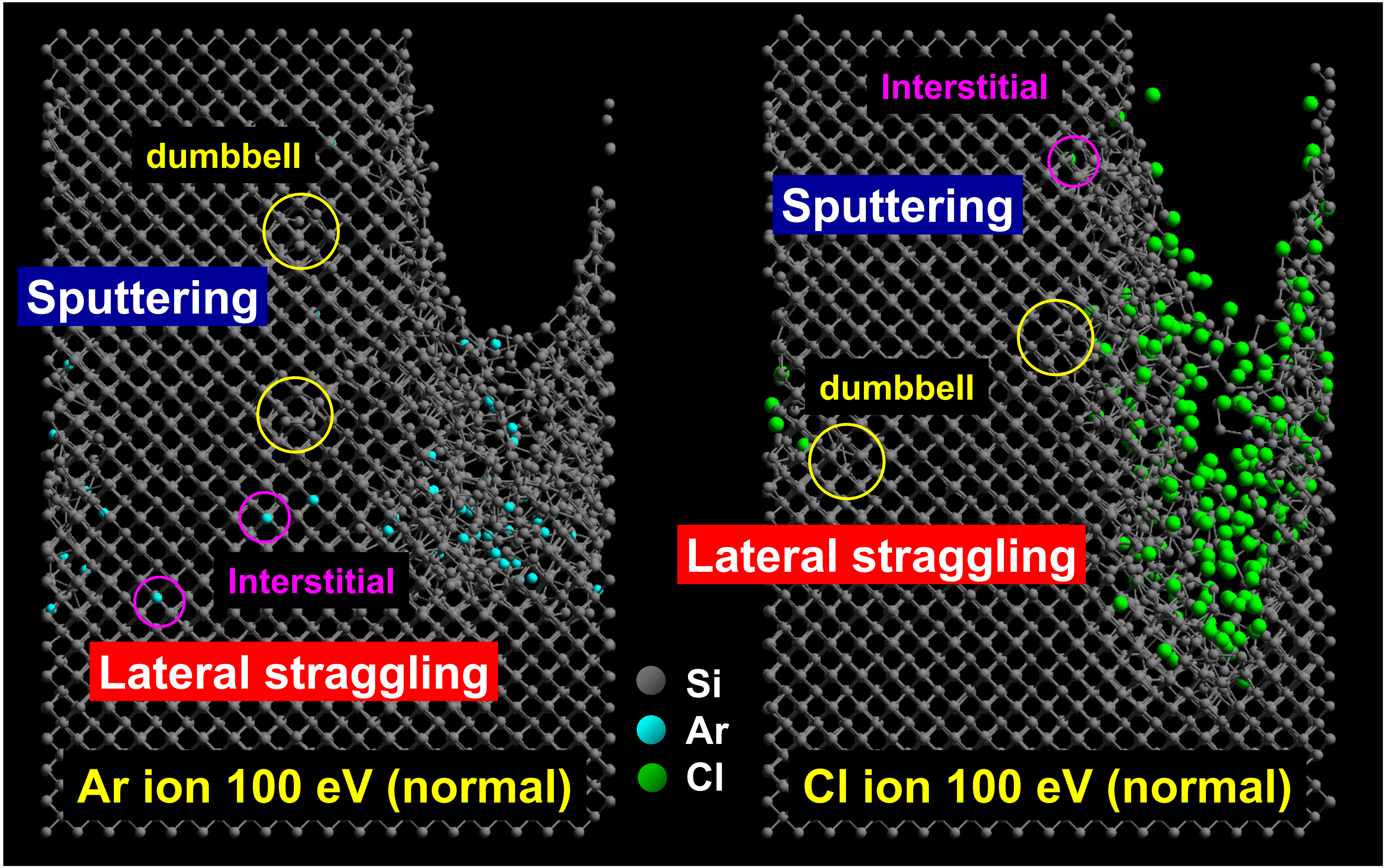




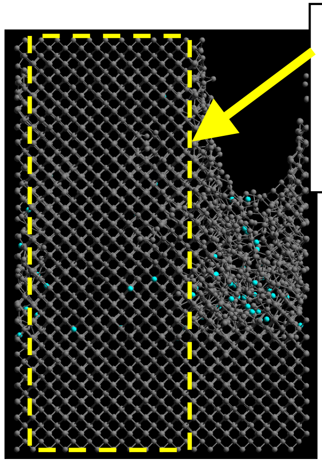
Defect analysis by

Density Functional Theory

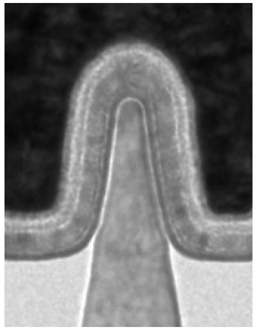
MD prediction results in Fin

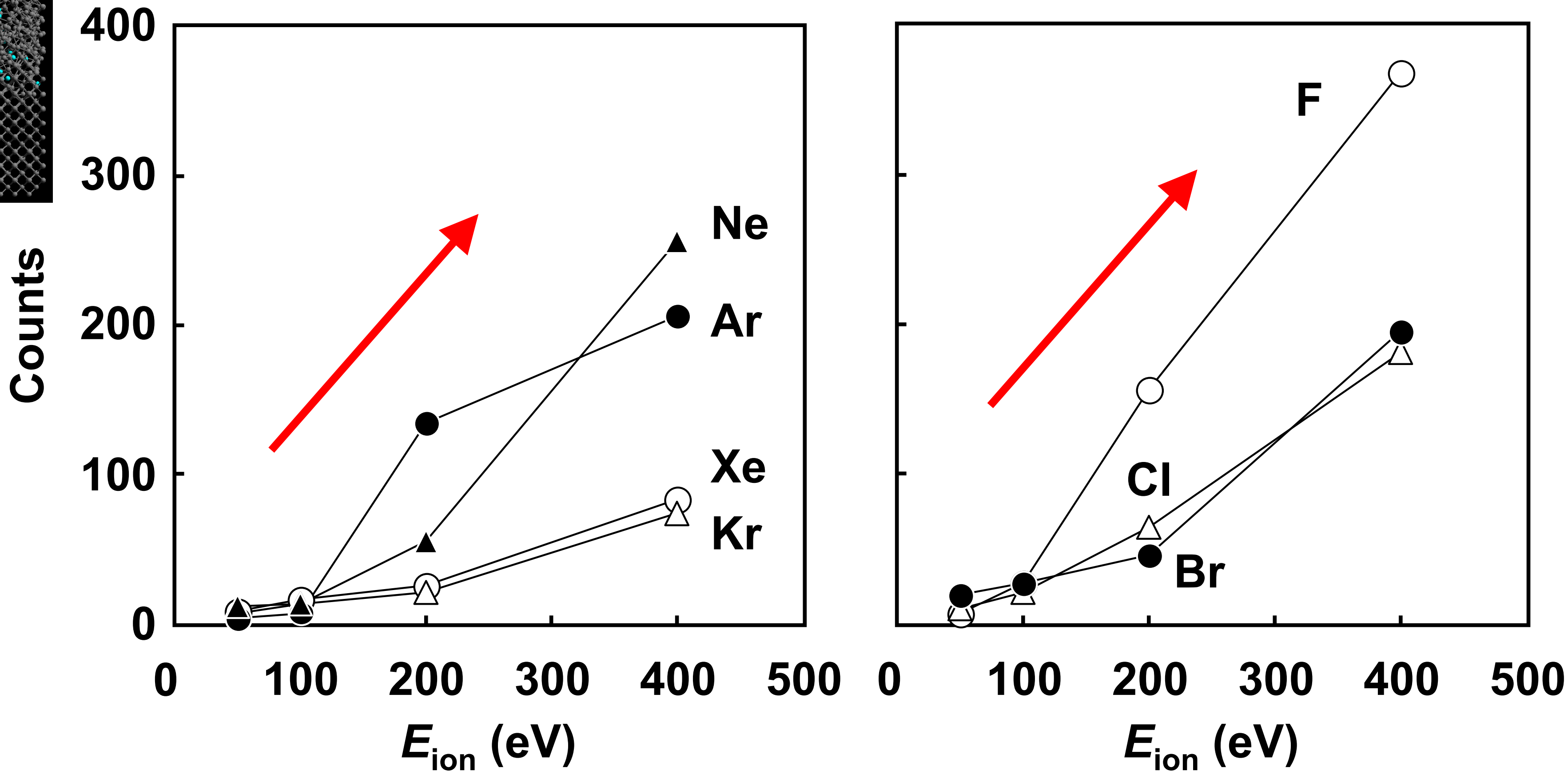


Defect creation in Fin



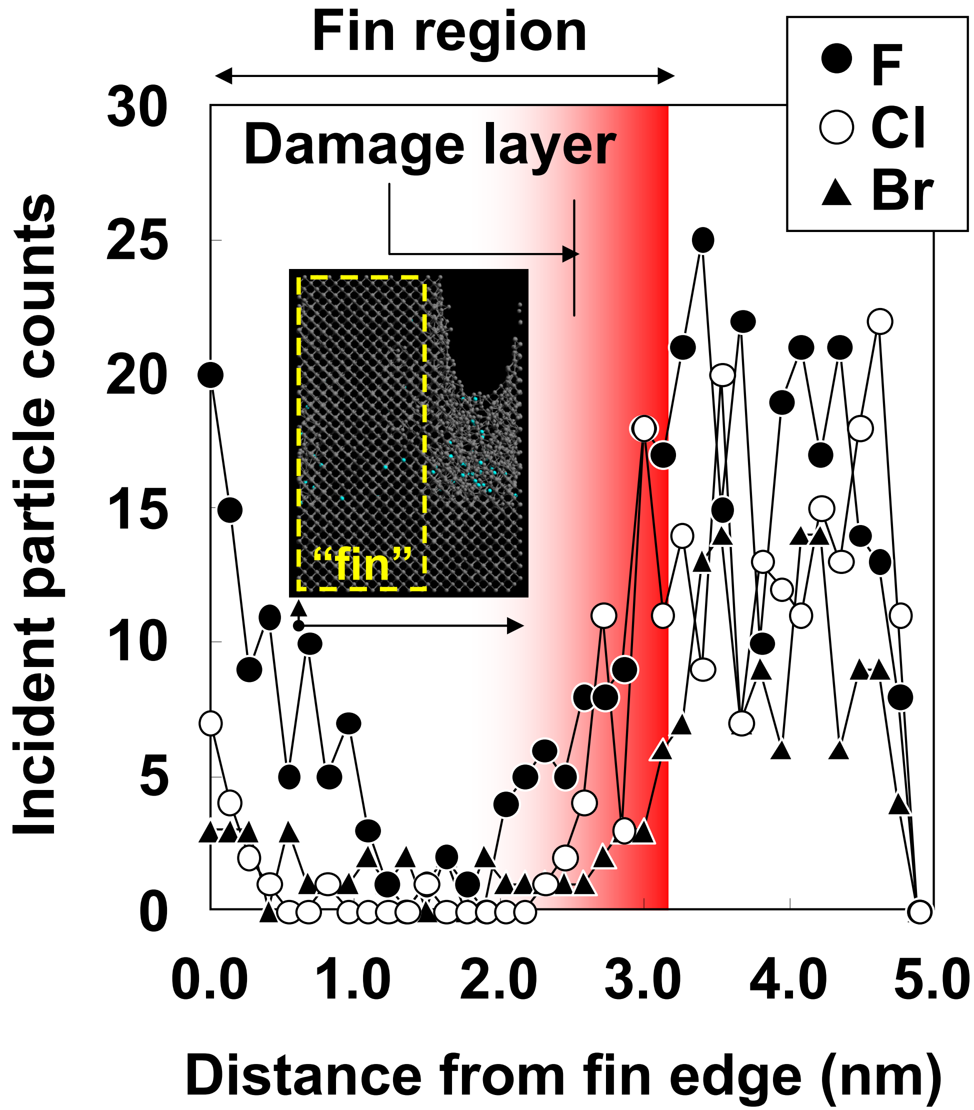
Counting the defects in this region one by one in accordance with the bond order and length.

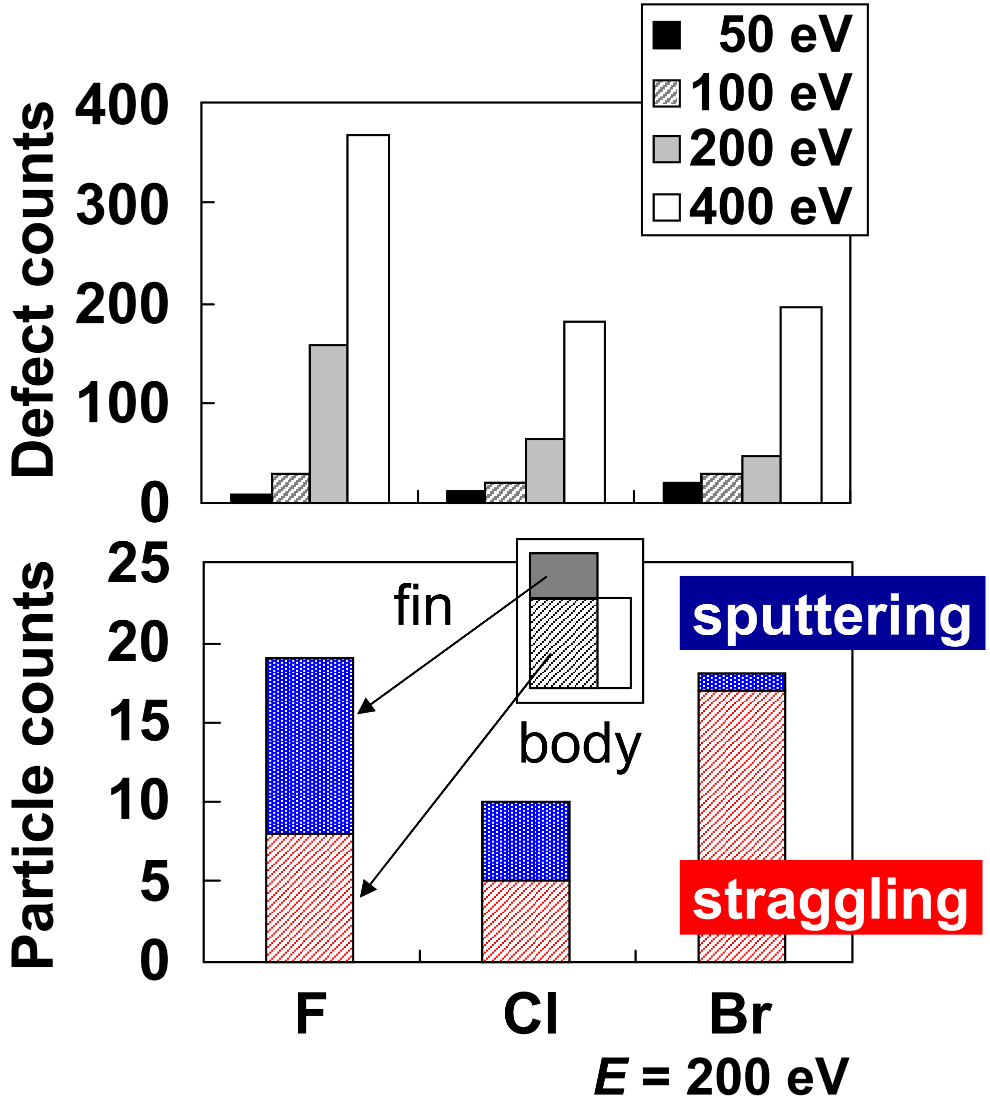




An ion with lighter mass and higher incident energy → larger damage

Defect creation in "Fin"





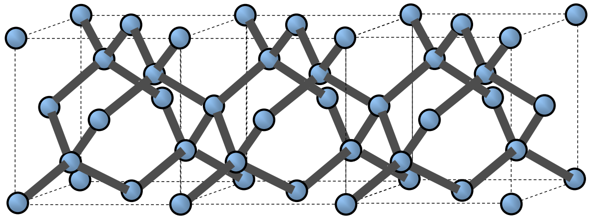
Both "sputtering" and "straggling" are responsible for PID in 3D.

Outline

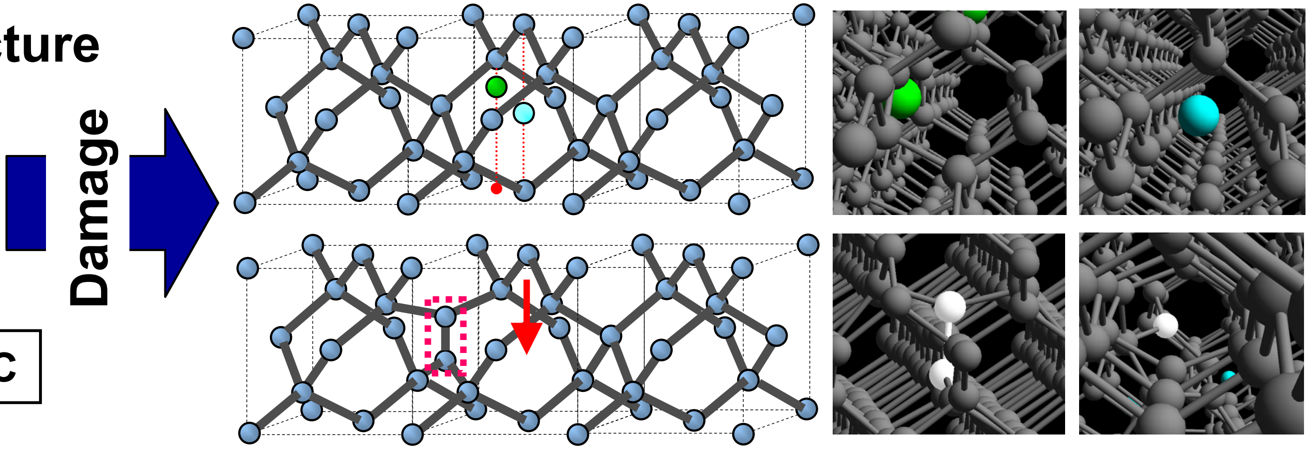
1. Introduction – Plasma-Induced Damage (PID)
2. **A Scenario for PID in Scaled 3D Structures**
    - 2-1 PID Models – Straggling & Sputtering
    - 2-2 Molecular Dynamics Simulation
    - **2-3 Electronic State of Defect**
3. PID Prediction in 3D Structure
4. Summary

Electronic structure of defect

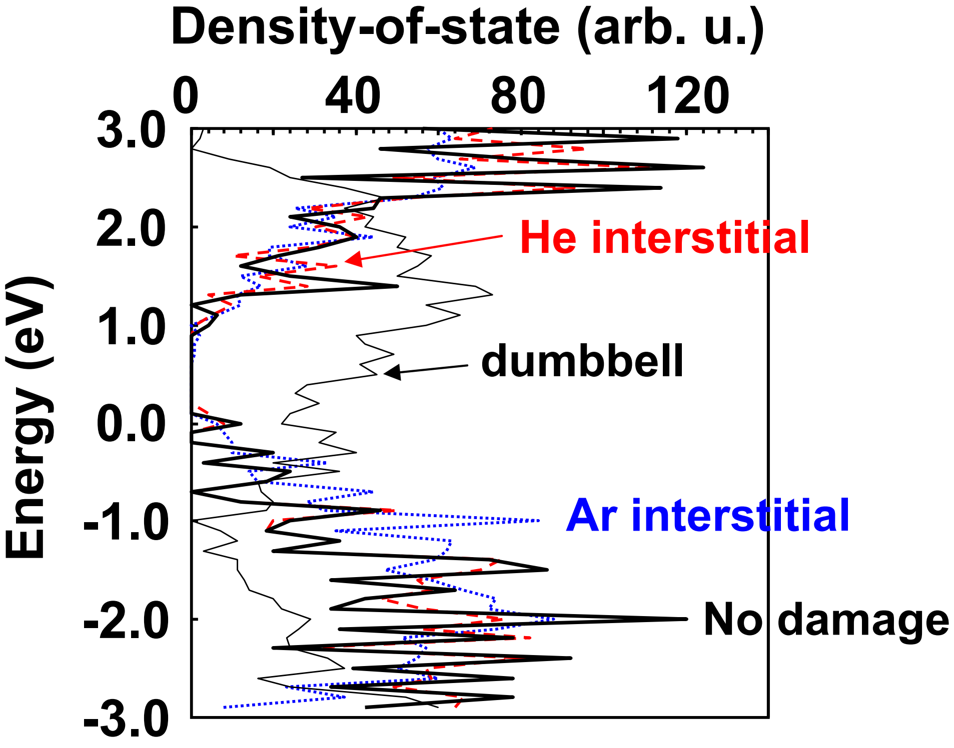
Original super-lattice structure

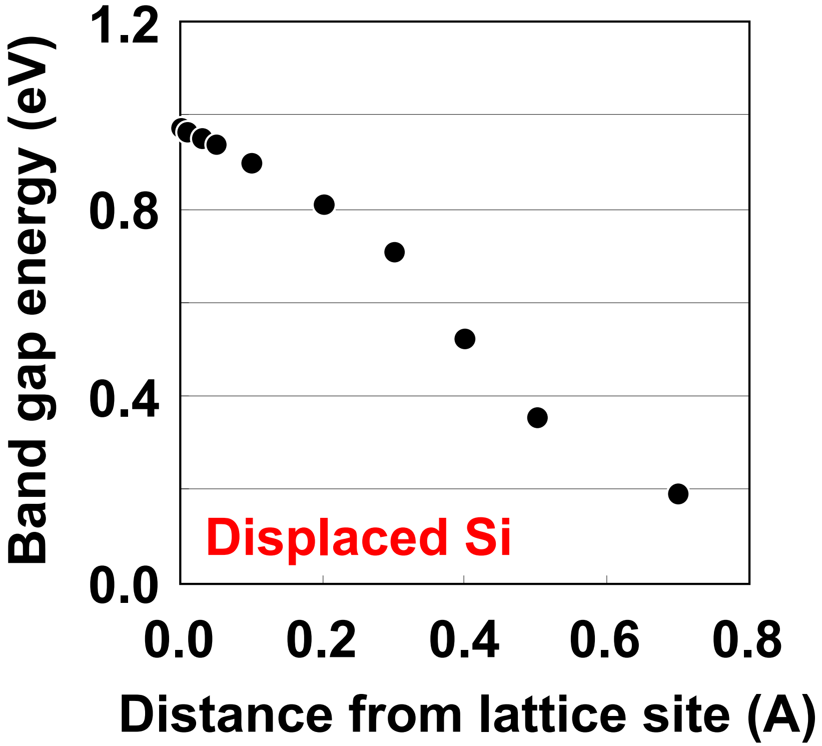


DFT: 6-31G with PBEPBE & PBC



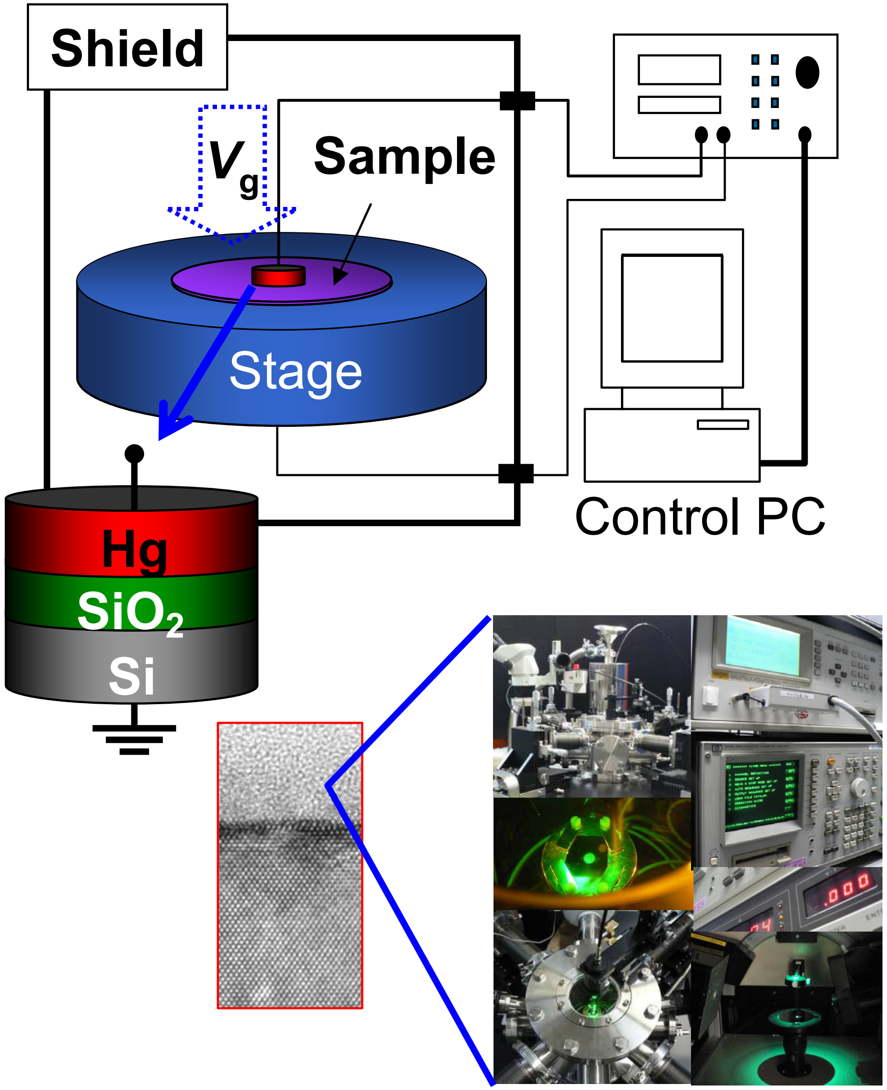
Displaced Si

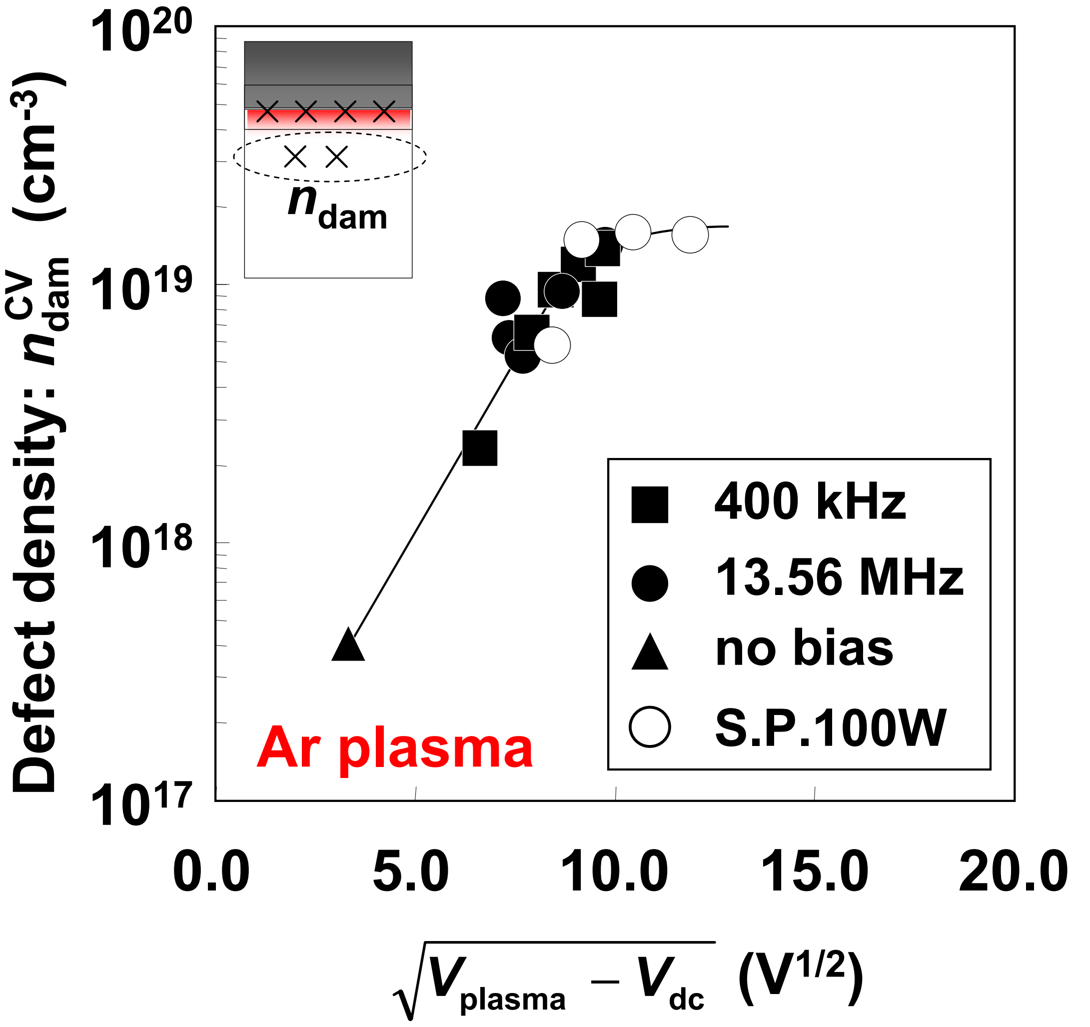




Experimental evidence

Eriguchi IEDM 2008 / Kamei Thin Solid Films 518 (2010) / Nakakubo AVS 2011





Defect Density ~ 10^{18} - 10^{19} cm^{-3}

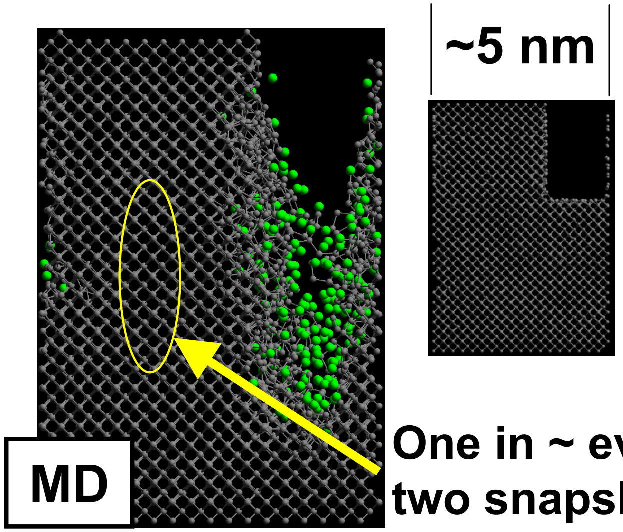
Outline

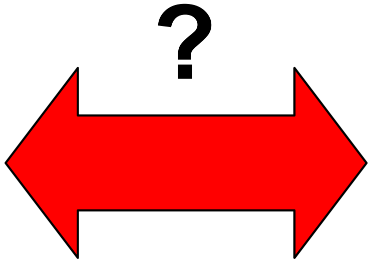
1. Introduction – Plasma-Induced Damage (PID)
2. A Scenario for PID in Scaled 3D Structures
   - 2-1 PID Models – Straggling & Sputtering
   - 2-2 Molecular Dynamics Simulation
   - 2-3 Electronic State of Defect
3. **PID Prediction in 3D Structure**
4. Summary

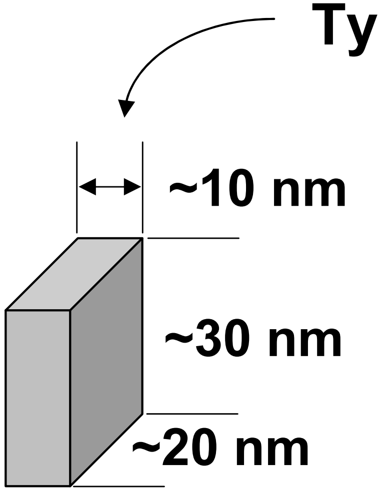
PID prediction in Fin-structure

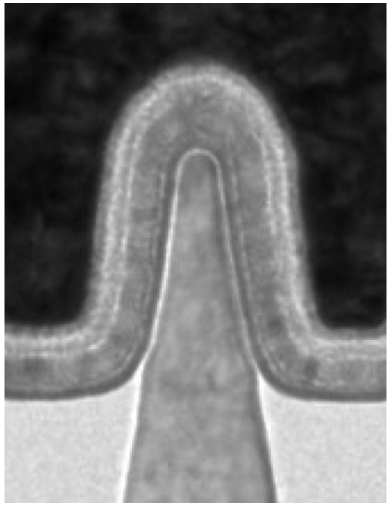
Assumption:
(1) PID is modeled by the present scheme.
(2) Surface damaged layer was stripped off.
(3) Latent-defect creation was uncorrelated.

Typical fin size









MD

One in ~ every two snapshots

PID Range Theory

$$P(n_{\mathrm{MD}} > 0) = \frac{n_{\mathrm{dam}}{}^{n_{\mathrm{MD}}} \cdot \exp(-n_{\mathrm{dam}})}{n_{\mathrm{MD}}!}$$

$$n_{\mathrm{dam}}(x)dx = \int_x^{\infty} \eta(E_{\mathrm{ion}}) \cdot n_{\mathrm{ion}} dy$$

Typical PID:
Ar 200 eV
n_p ~ 10^{11} cm^{-3}

Experiment in planar structure

Present Models

n_{dam} ~ 10^{18} - 10^{19} cm^{-3}

$$\sigma_{\mathrm{L}} = B_{\mathrm{ion}} \cdot \sqrt{\frac{2}{3}}\, \frac{\sqrt{M_{\mathrm{Si}} M_{\mathrm{ion}}}}{M_{\mathrm{Si}} + M_{\mathrm{ion}}} (E_{\mathrm{ion}})^{\beta}$$

$$\gamma_{\mathrm{sp}} \approx A_{\mathrm{sp}} \cdot \left(\sqrt{E_{\mathrm{ion}}} - \sqrt{E_{\mathrm{th}}}\right)$$

Outline

1. Introduction – Plasma-Induced Damage (PID)
2. A Scenario for PID in Scaled 3D Structures
    - 2-1 PID Models – Straggling & Sputtering
    - 2-2 Molecular Dynamics Simulation
    - 2-3 Electronic State of Defect
3. PID Prediction in 3D Structure
4. **Summary**

Summary

Plasma-induced damage in 3D structures were discussed.

(1) A new PID model was proposed on the basis of
- (A) lateral straggling at the etched surface and
- (B) bombardment of sputtered species at the sidewall.

(2) A model prediction and MD simulations suggest that both the lateral straggling and the sputtered particle bombardment will become responsible for PID in scaled 3D structures.

One should revise the views of plasma etching at the sidewall because the lateral PID is no longer negligible in ultimately scaled 3D devices.