# Damage Control by Cluster implantation and heated implantation

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# Ion implantation technologies for defect suppression

1. Cluster ion implant
2. Low temp implant

Thick and fine amorphous, Clear regrowth

3. Heated implant

Less damages, Enhancing dynamic annealing

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# Ion Implantation Systems for Damage Control

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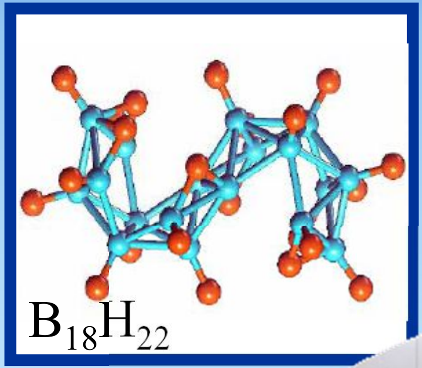
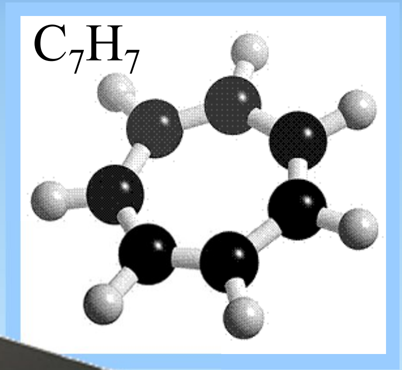
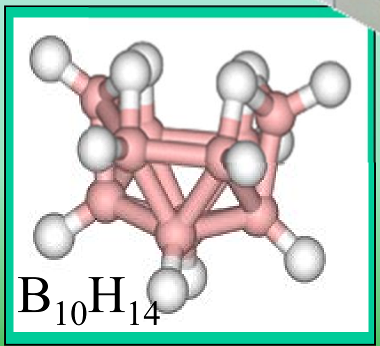
# Cluster ion implanter CLARIS



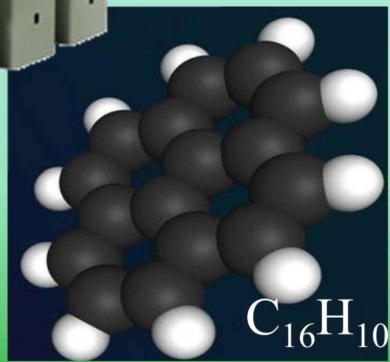
$B_{18}H_{22}$



$C_7H_7$



$B_{10}H_{14}$



$C_{16}H_{10}$

- ❑ High current with precise beam control
- ❑ Ultra shallow junction formation
- ❑ High activation
- ❑ Diffusion suppression
- ❑ Damage engineering
- ❑ Strain engineering

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# Cold ion implantation

## CLARIS

Precise beam control with high current
0.2 – 7keV with Cluster B
0.24 – 10.5keV with Cluster C

## EXCEED

High productivity medium current tool
More than 550 tools installation
3 – 750keV with EX3000AH
3 – 960keV with EX9600A

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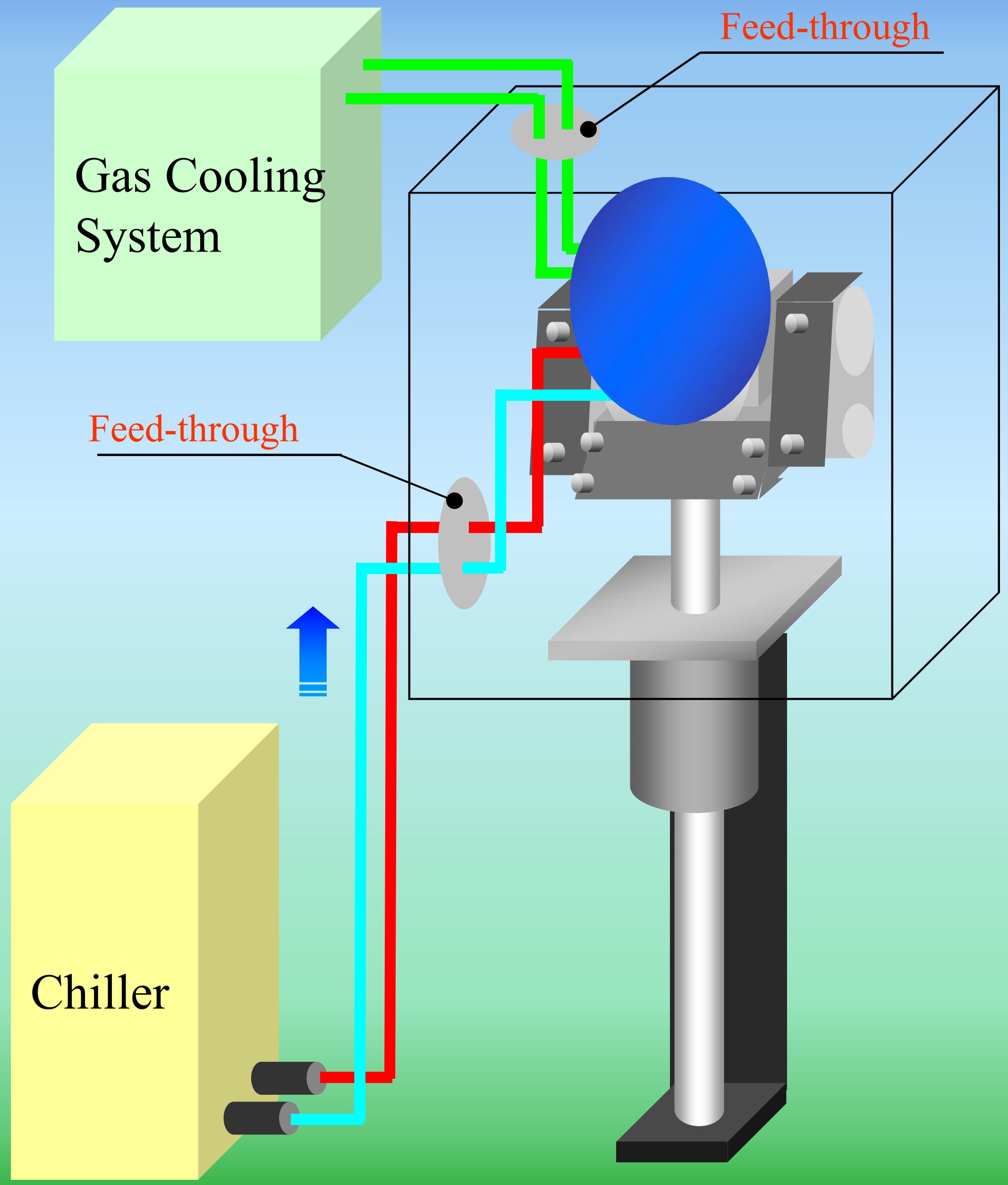
# Cold implant system




- Insitu-cooling (Stable!)
- Batch cooling & warming (Quick & Reliable!)
- Closed cycle cooling

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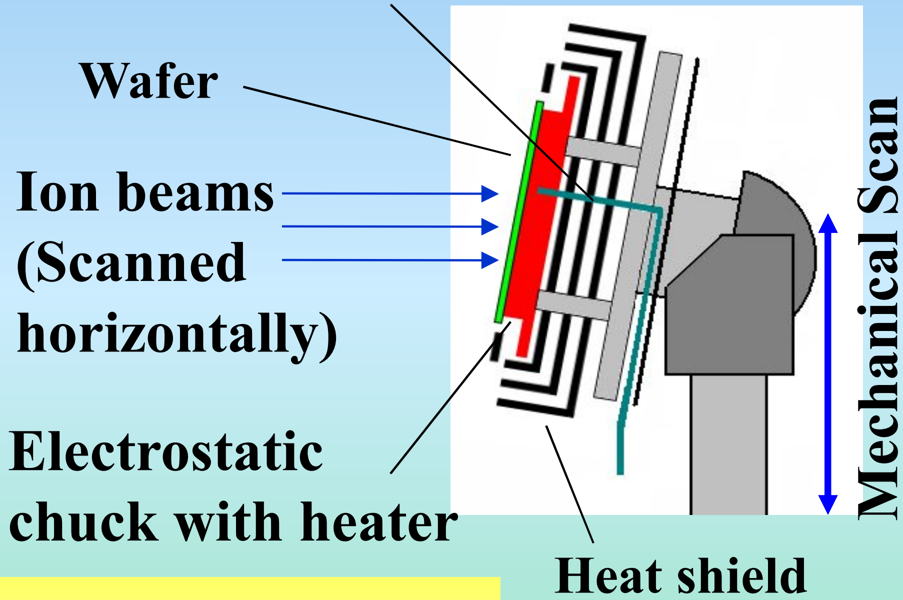
# High temperature ion implanter IMPHEAT

## High Temperature Platen

**Temperature Controlled by TC and feedback**




Temperature: up to 500°C
Energy: 3 – 960keV
Species: Al, P, B, N, etc.
High Current Al beam
Mass production tool for SiC devices

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# Damage Control with Cold and Cluster ion Implantation

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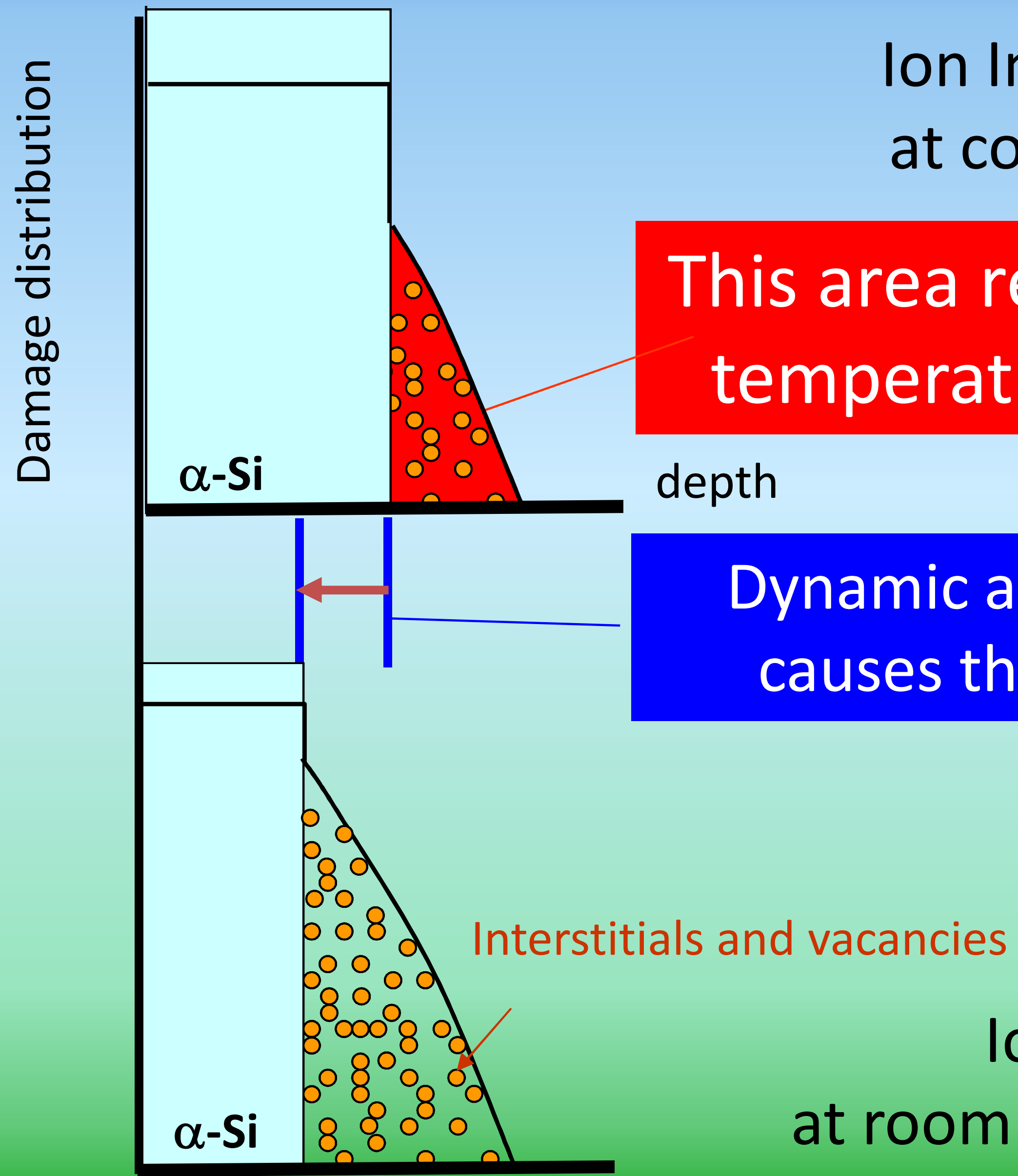
# Damage control mechanism with cold implant




Ion Implantation
at cold substrate

This area remains even if the temperature is zero Kelvin

Dynamic annealing during implant causes thinner amorphous layer

Ion Implantation
at room temperature substrate

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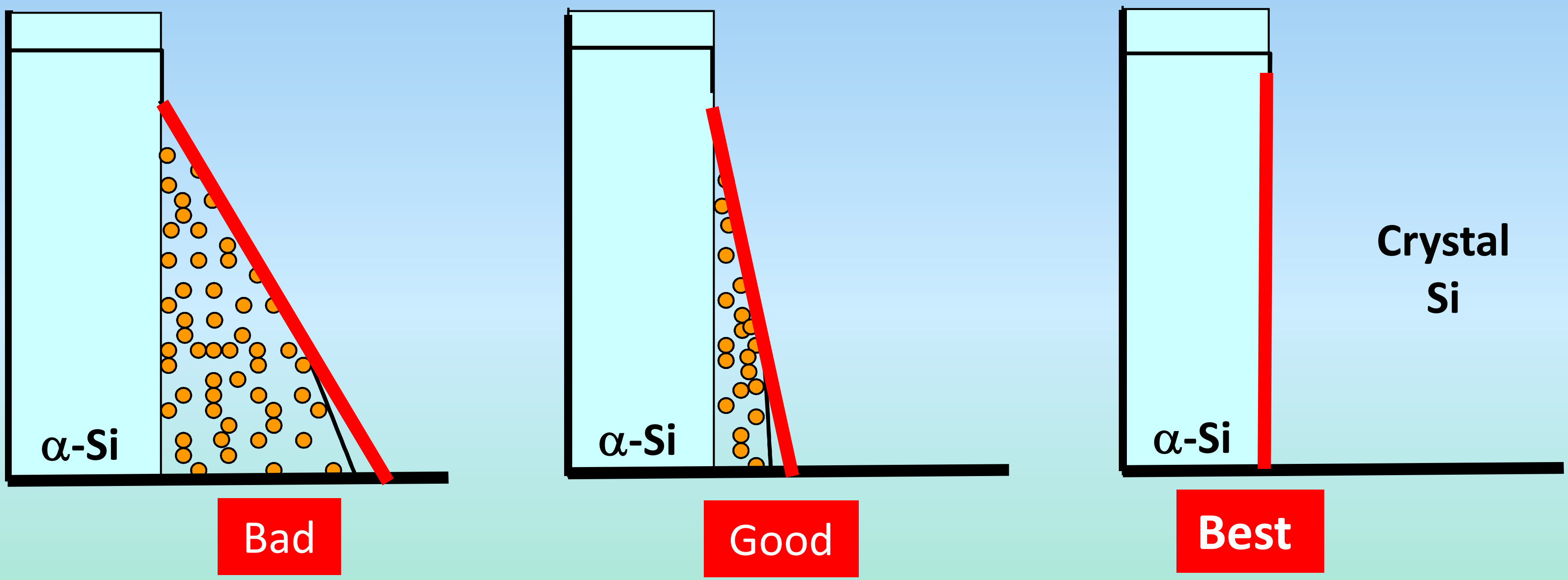
# Ideal implant for eliminating EORDs

Focus on a/c interface abruptness

Delta profile




a/c interface abruptness

To eliminate EORD not only thicker amorphous layer but also good a/c interface abruptness is required, ideally delta profile is the best.

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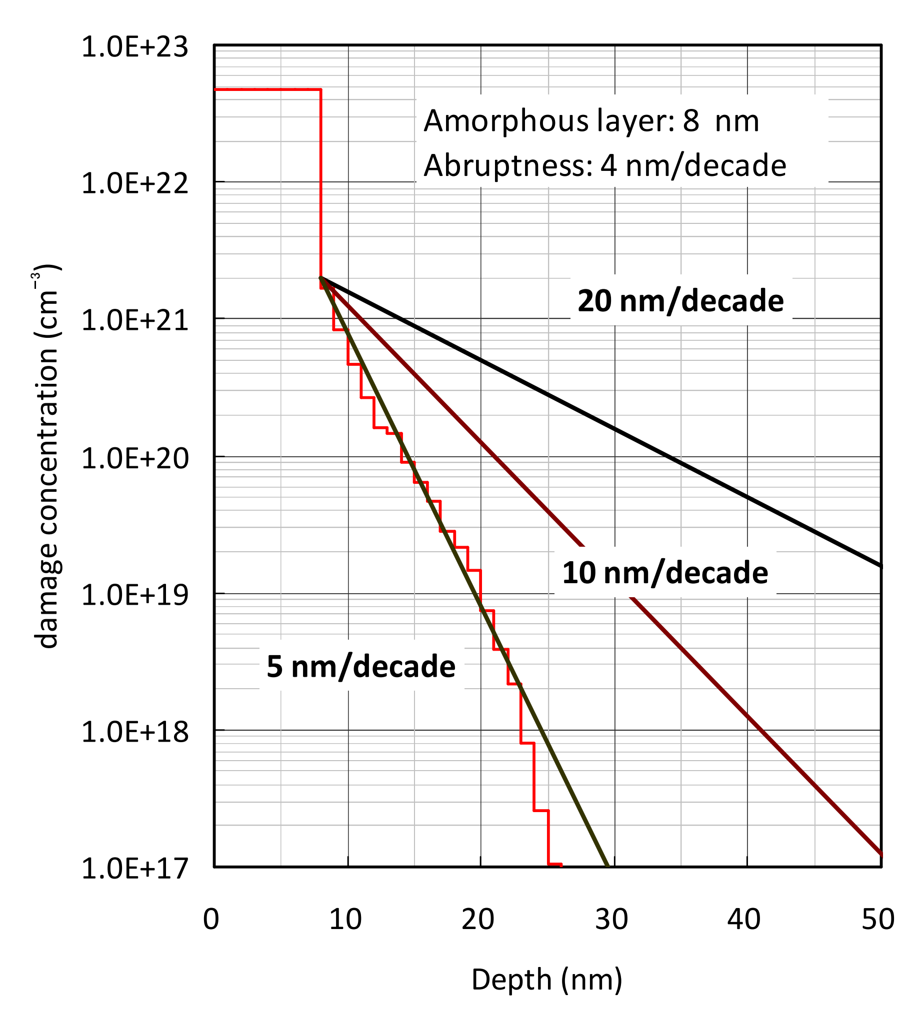
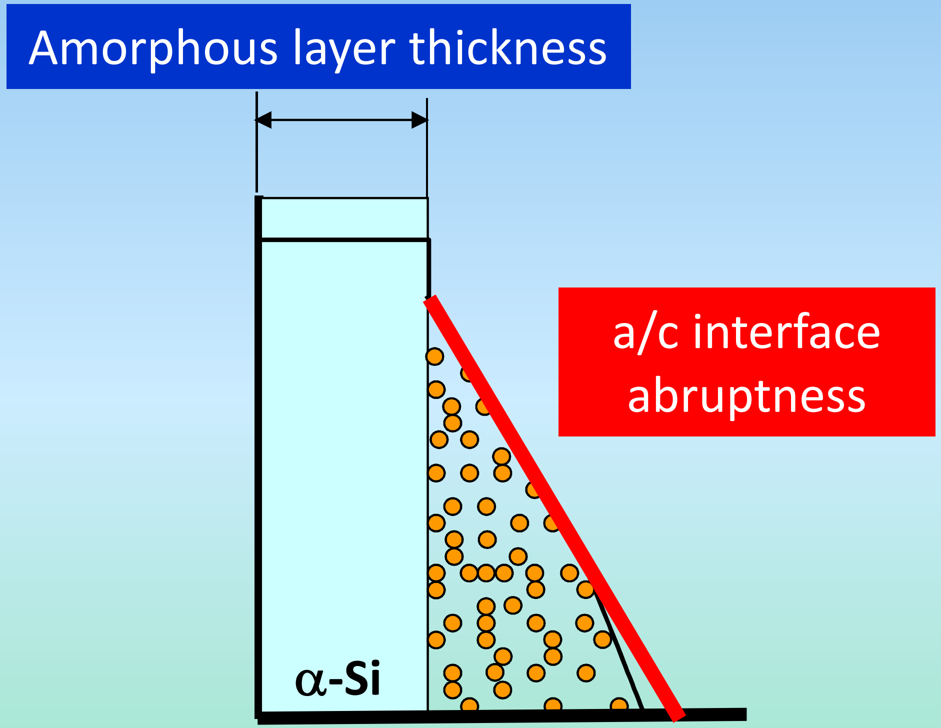
# Damage simulation by Crystal TRIM

## Amorphous layer thickness
## a/c interface abruptness




Crystal trim
Dr. Matthias Posselt,
Institute of Ion Beam Physics and Materials Research,
Helmholtz-Zentrum Dresden-Rossendorf,

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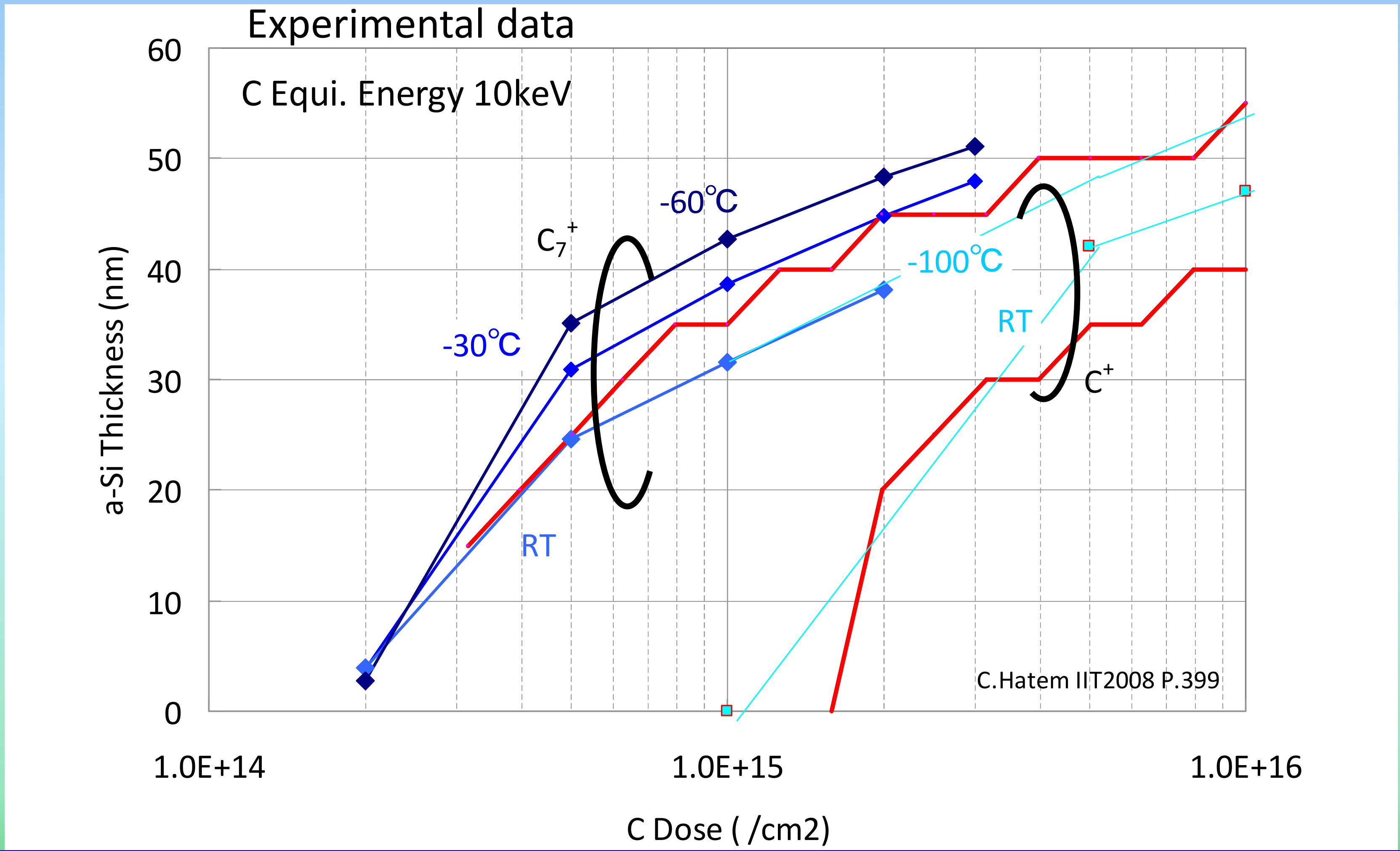
# Amorphous layer thickness

Crystal trim simulation result. A layer with over $2x10^{21}cm^{-3}$ damage density is defined as amorphous layer




**Experimental result and crystal-Trim simulation result show a good agreement. Crystal trim can estimate the amorphous layer thickness**

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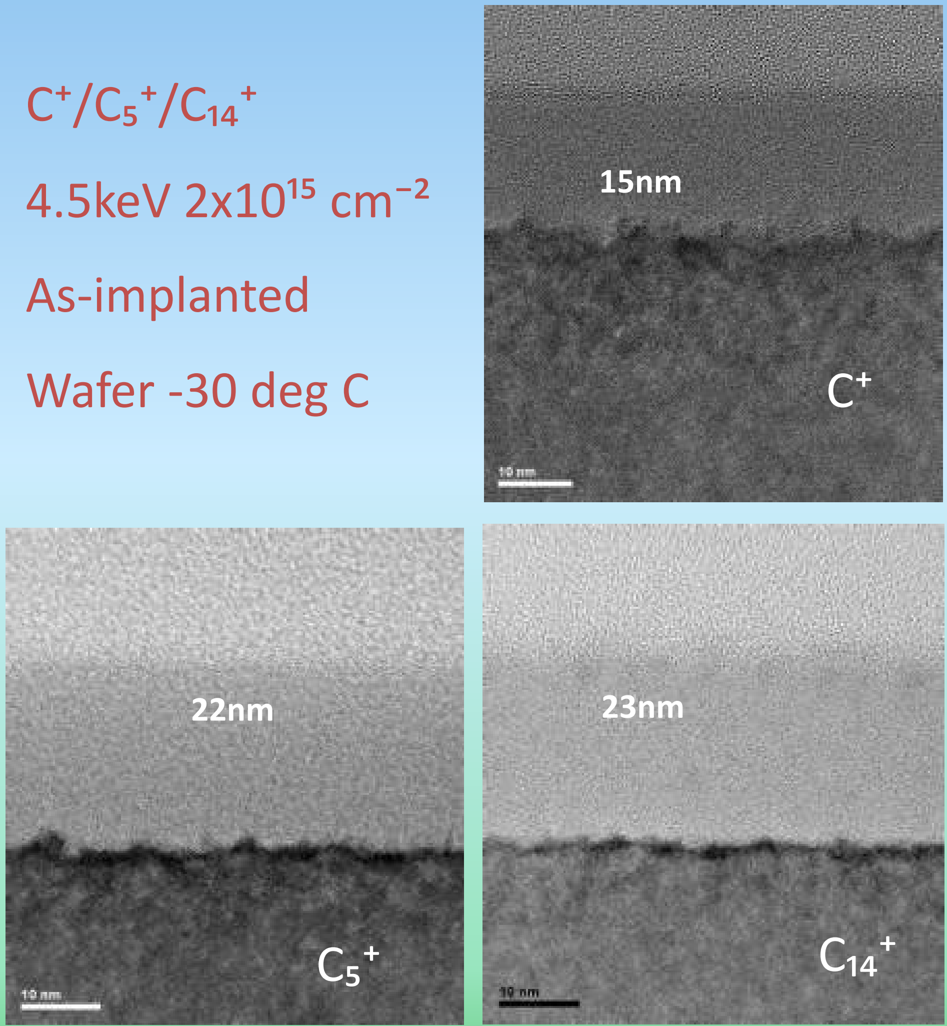
# Cluster size dependence on a/c interface abruptness

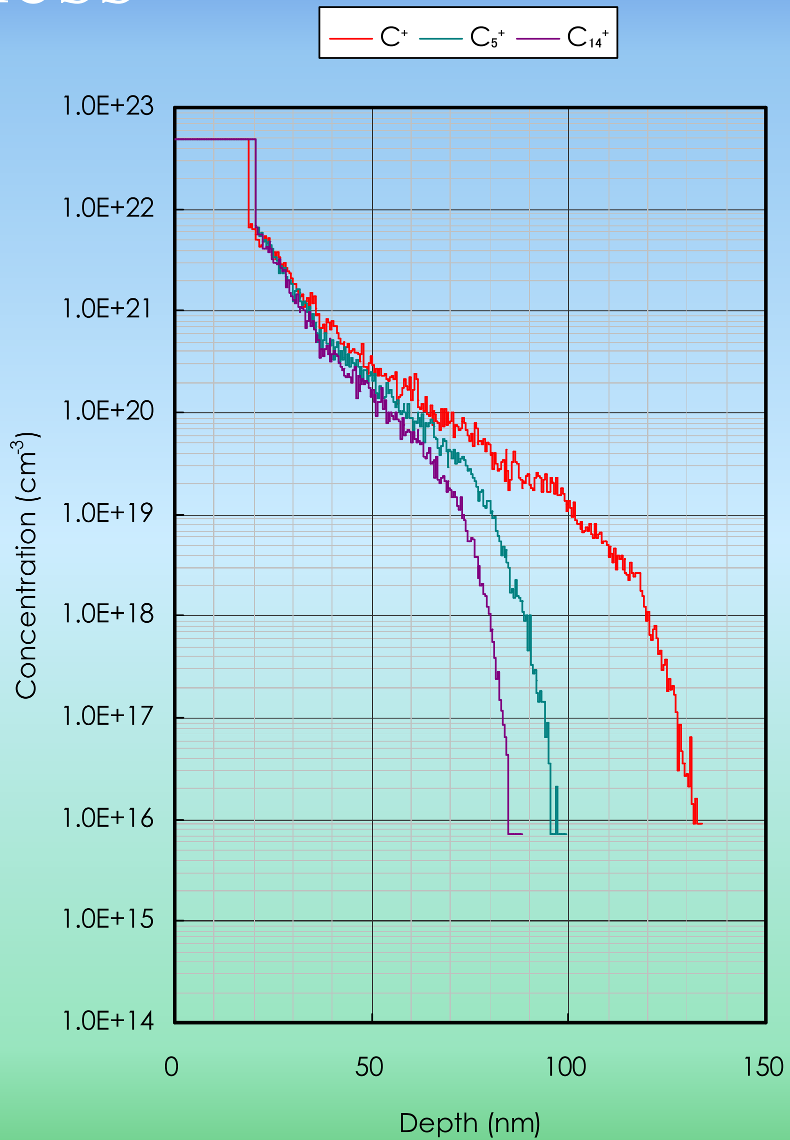
$C^+/C_5^+/C_{14}^+$

4.5keV $2\times10^{15}$ $cm^{-2}$

As-implanted

Wafer -30 deg C




**Crystal-Trim can estimate a/c interface abruptness**

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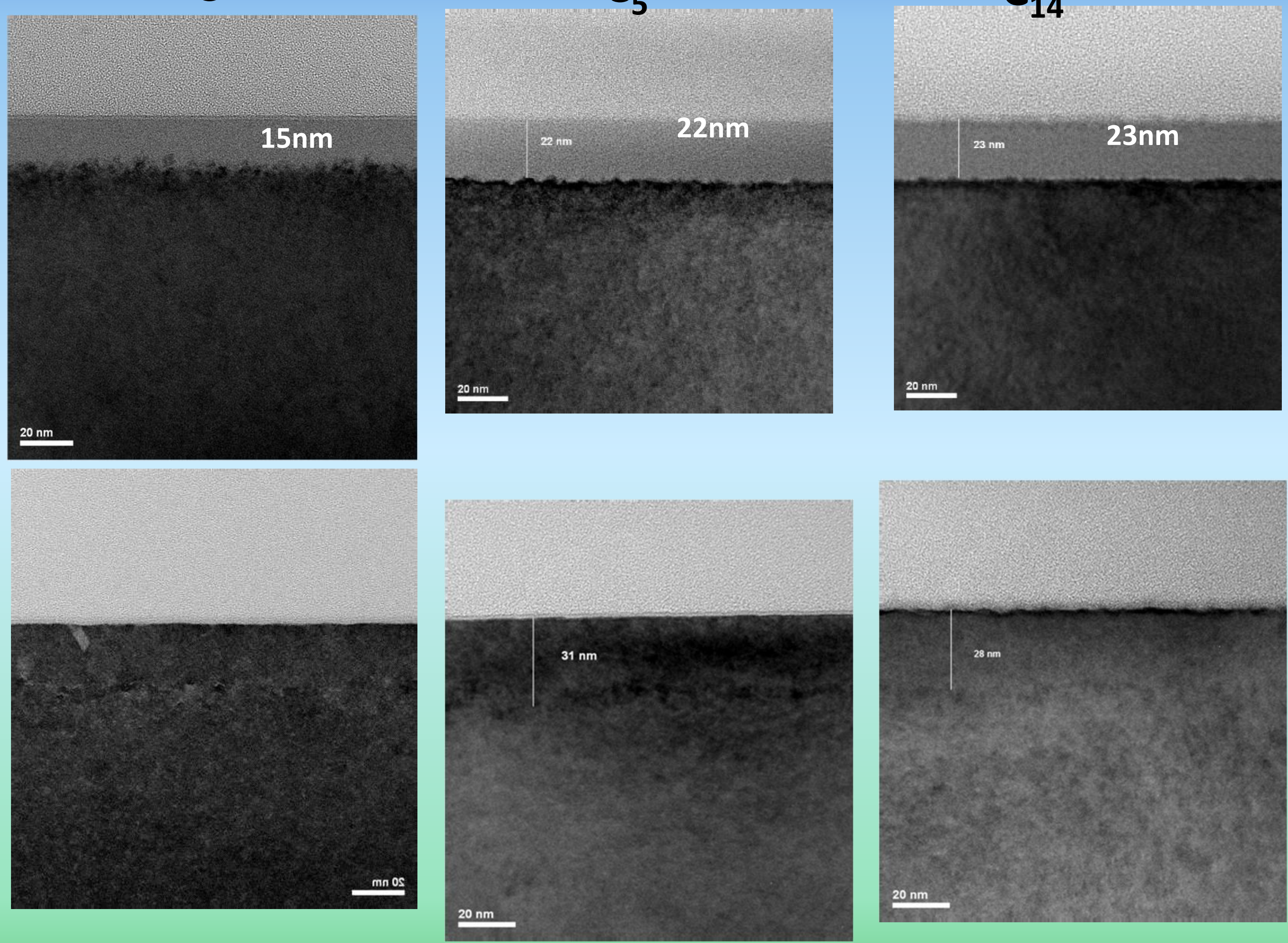
# EORD reduction with a/c interface abruptness

| | $C^+$ | $C_5^+$ | $C_{14}^+$ |
|---|---|---|---|
| As-implanted | 15nm | 22nm | 23nm |
| After RTA 800°C 10sec | | | |




- ❑ $C^+/C_5^+/C_{14}^+$ 4.5keV 2E15 at -30°C as-impl and after RTA 800°C 10sec
- ❑ Less EOR defects with better a/c interface abruptness

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# Cluster ion size effect

| Energy | | | Dose |
|---|---|---|---|
| 1 keV | $C^+$ | $\equiv$ | $2\times10^{15}\ cm^{-2}$ |
| 2 keV | $C_2^+$ | $\equiv$ | $1\times10^{15}\ cm^{-2}$ |
| : | : | : | |
| 5 keV | $C_5^+$ | $\equiv$ | $4\times10^{14}\ cm^{-2}$ |
| ⋮ | ⋮ | ⋮ | |
| 14 keV | $C_{14}^+$ | $\equiv$ | $1.4\times10^{14}\ cm^{-2}$ |

Si

Tilt 0 deg / Twist 0 deg

**Equivalent energy and equivalent dose are same**

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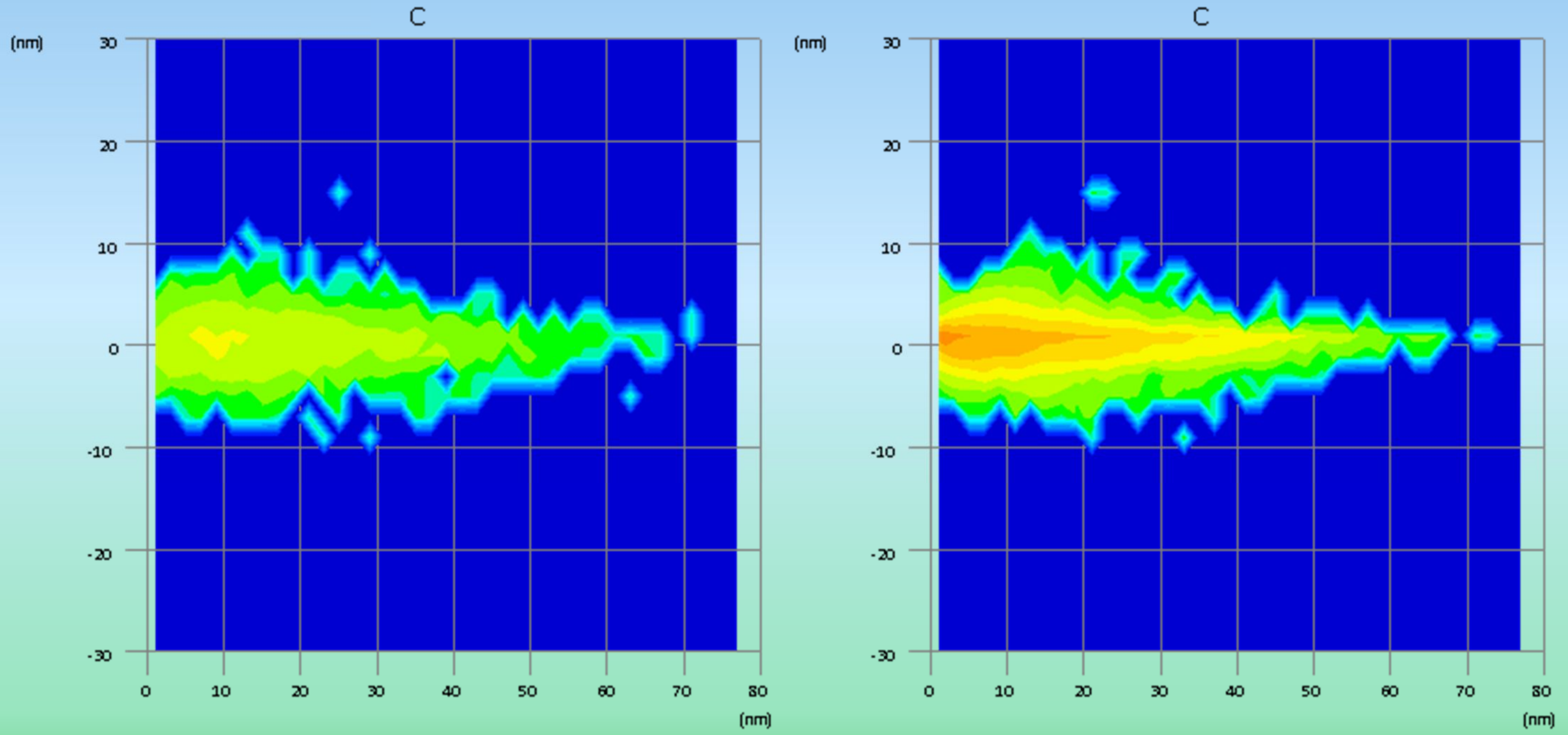
# a/c interface abruptness as a function of cluster

## □ 2 dimension carbon profile and damage profile

1.0 keV (equivalent) $2x10^{15}$ $cm^{-2}$ tilt 0 twist 0




Carbon profile

Damage profile

Larger cluster ions make tighter and abrupt damage distribution.

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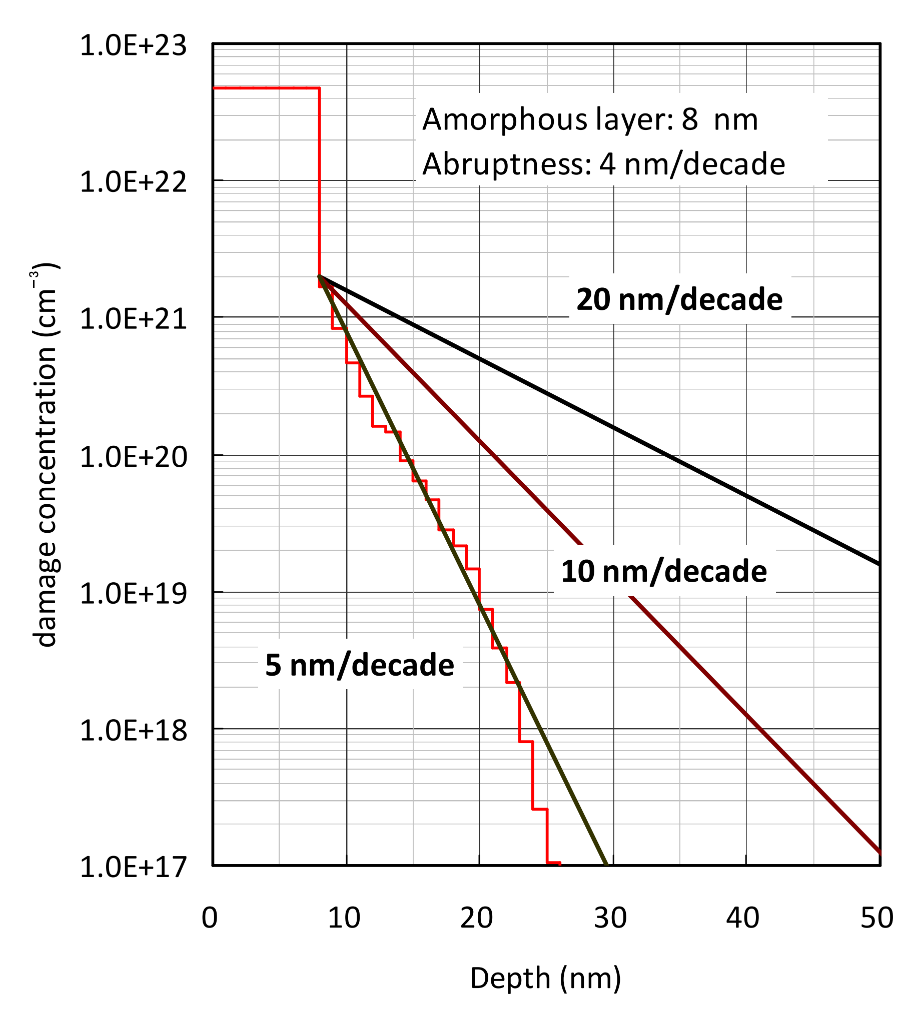
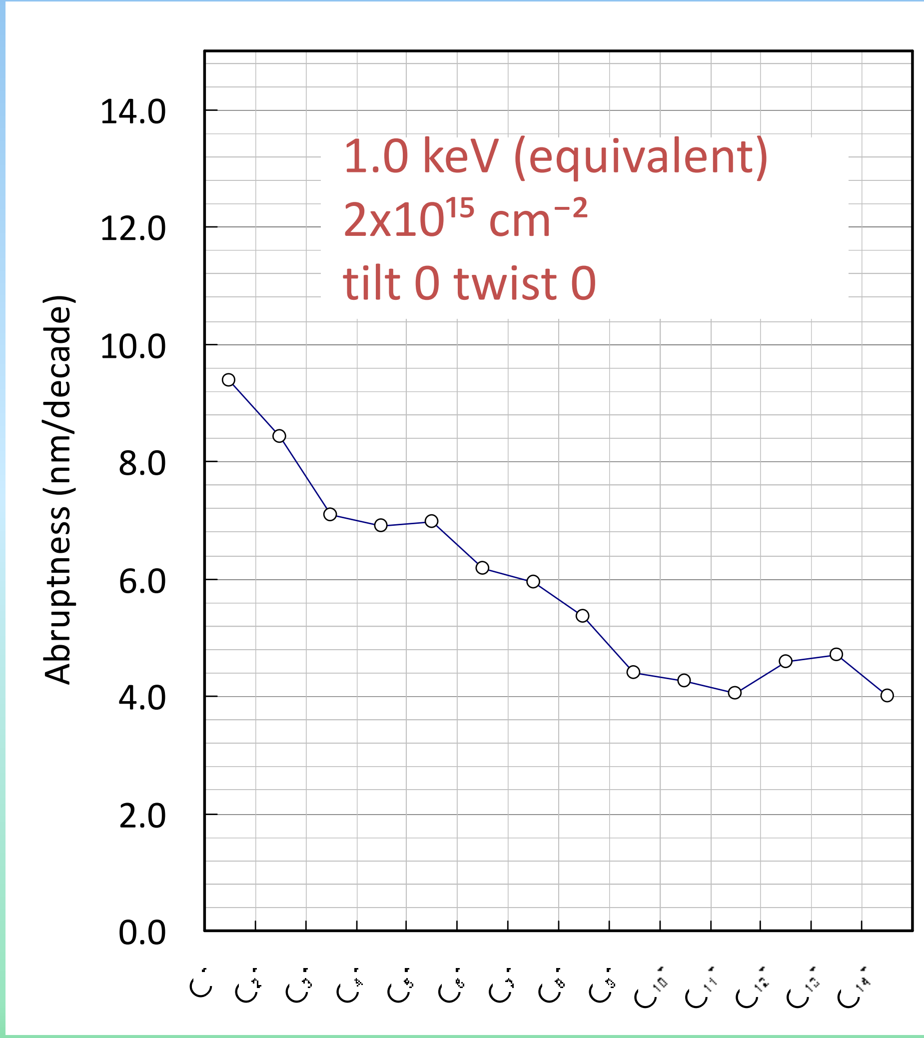
# a/c interface abruptness as a function of cluster size

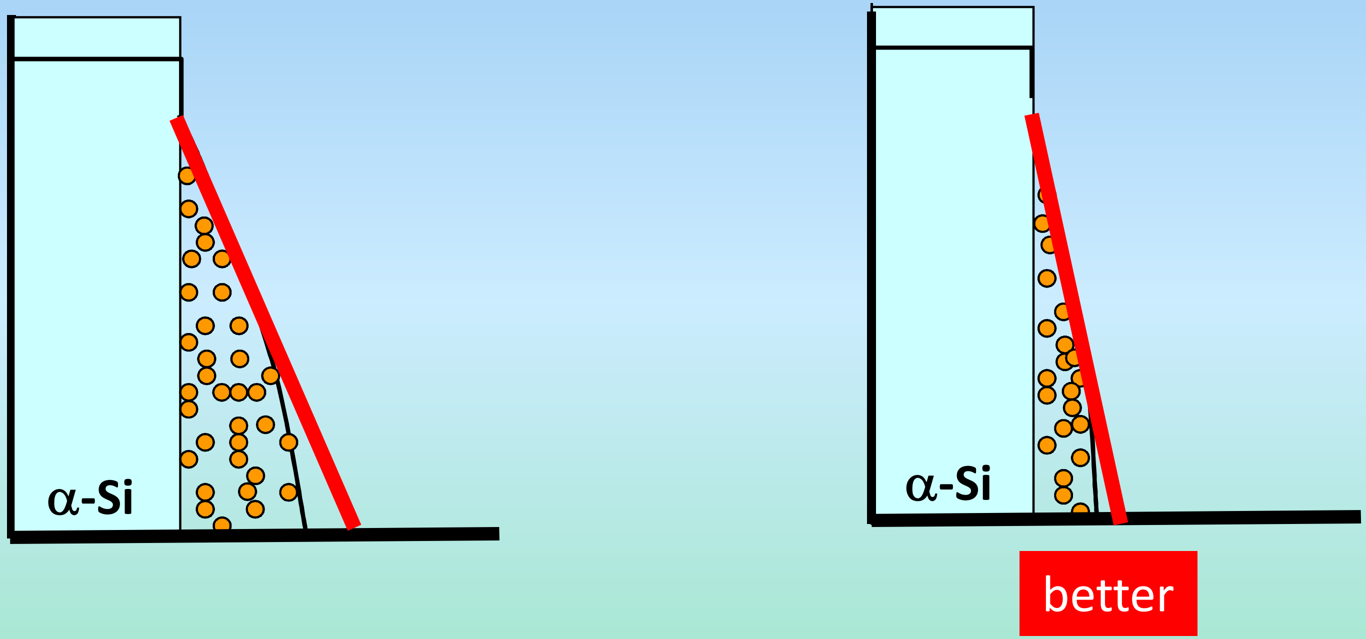



**Bigger cluster size makes better a/c interface abruptness**

# Cluster ion size effect

$C^+ < C_2^+ < C_3^+ < \cdots < C_{12}^+ < C_{13}^+ < C_{14}^+$




a/c interface abruptness

To form steep damage profile, Cluster C is preferable than monomer C.

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# Lighter cluster ion effect: simulation model

| Energy 6 keV | | Mass |
|---|---|---|
| $Ge^+$ | $\equiv$ | 72 |
| $Ar_2^+$ | $\equiv$ | 40 x 2 = 80 |
| $Si_3^+$ | $\equiv$ | 27 x 3 = 81 |
| $Ne_4^+$ | $\equiv$ | 20 x 4 = 80 |
| $O_5^+$ | $\equiv$ | 16 x 5 = 80 |
| $C_6^+$ | $\equiv$ | 12 x 6 = 72 |


**Same energy and almost same momentum cluster ions**

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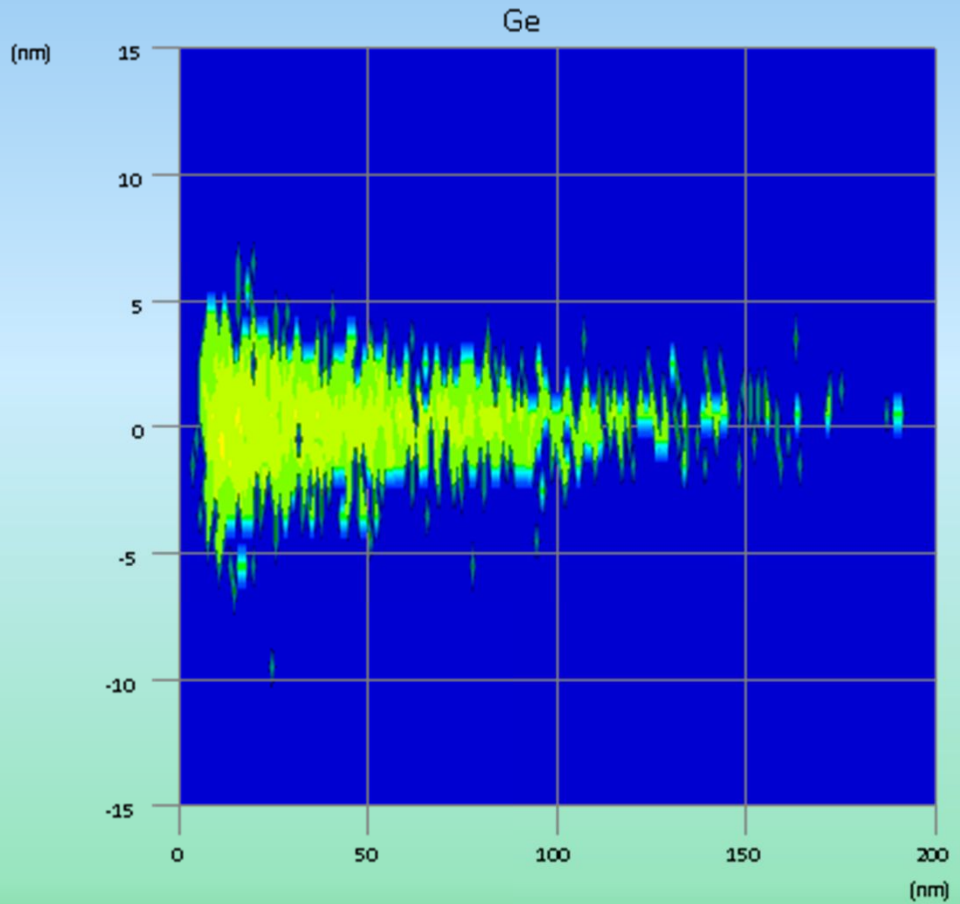
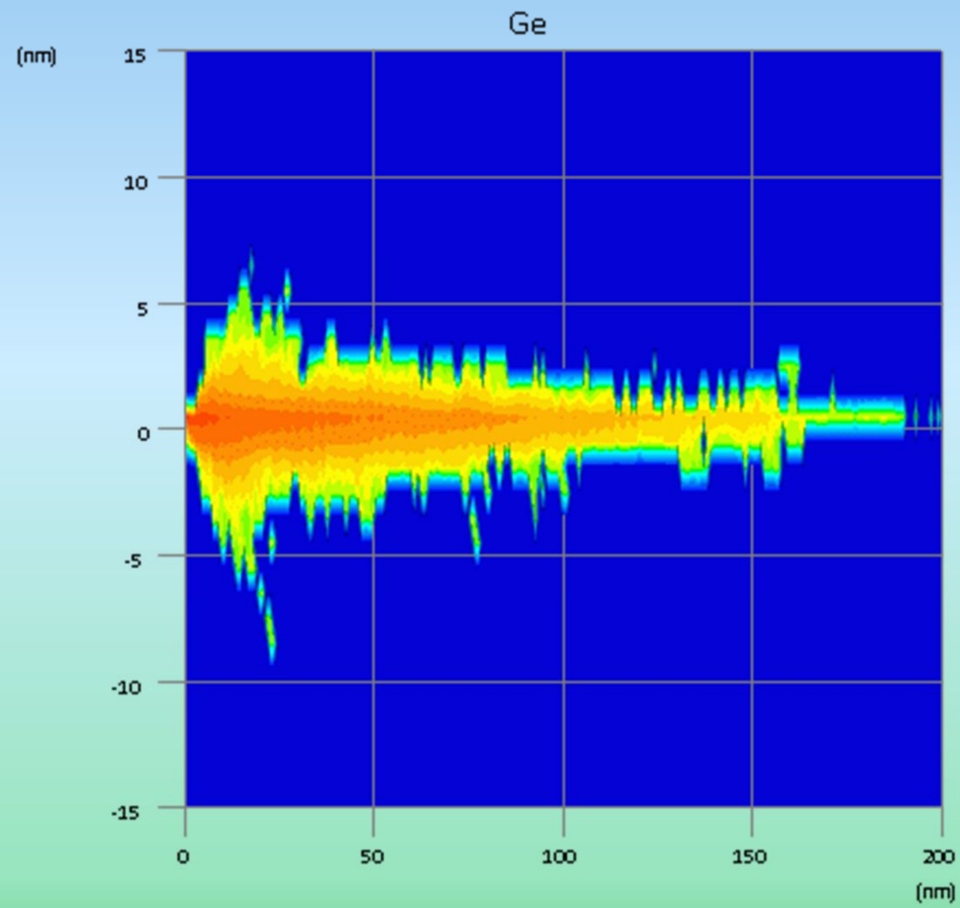
# a/c interface abruptness as a function of ion

## ☐ 2 dimension depth profile and damage profile

6 keV $1 \times 10^{15}$ cm$^{-2}$ tilt 0 twist 0




Depth profile




Damage profile

Lighter cluster ions make tighter and abrupt damage distribution.

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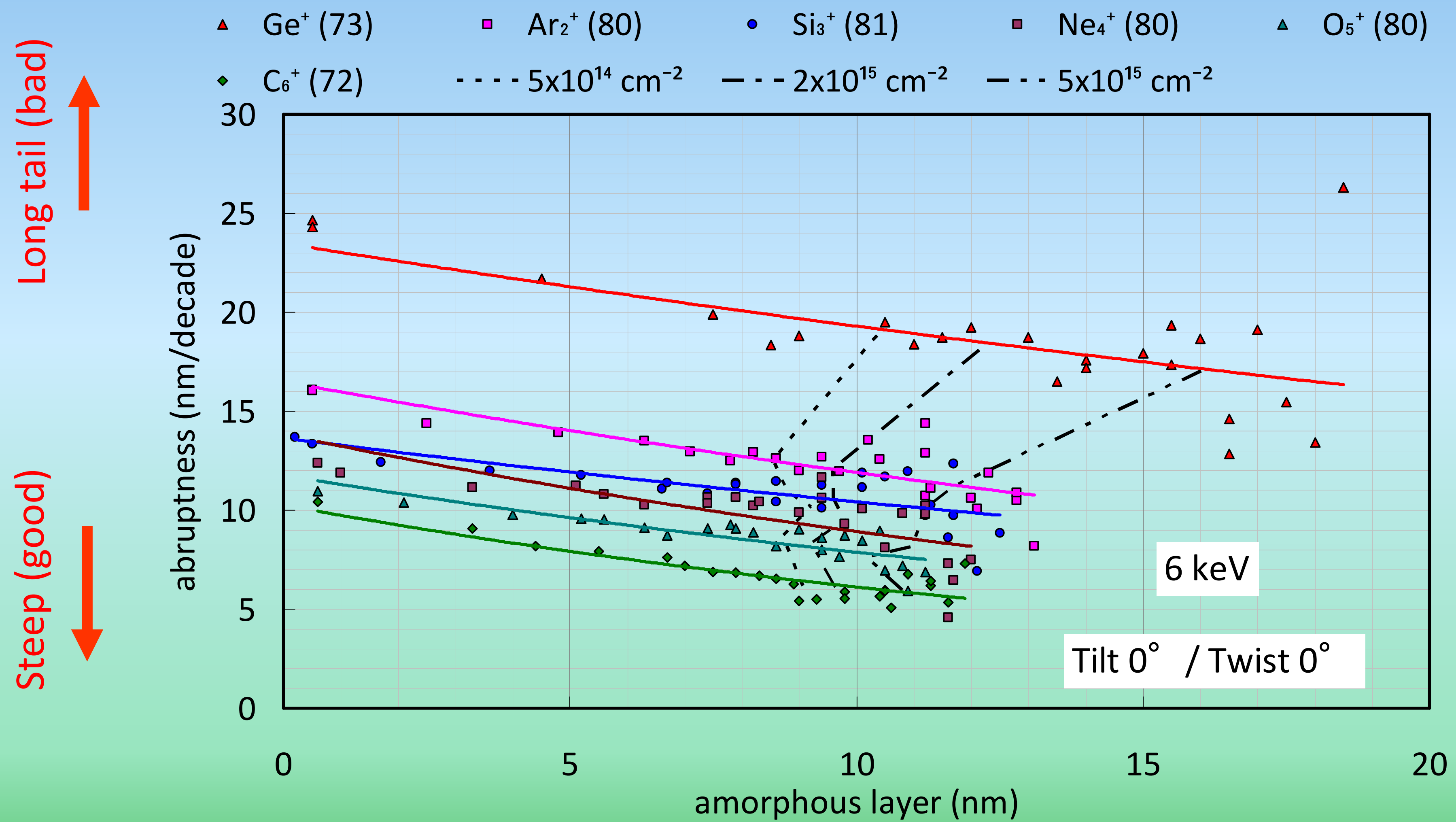
# Relationship between amorphous layer and a/c interface abruptness at same energy and almost same momentum




Lighter cluster ion makes better a/c interface abruptness at same amorphous layer.

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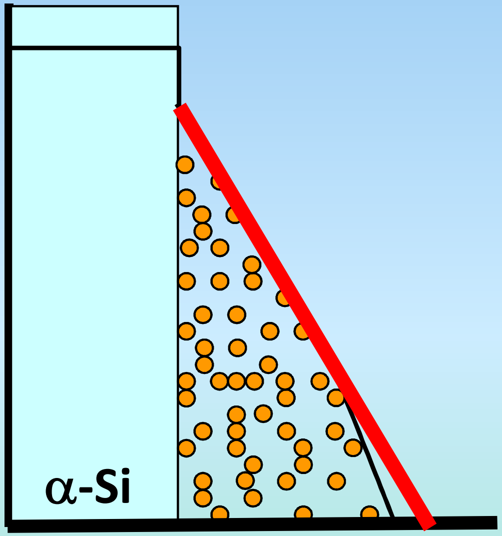
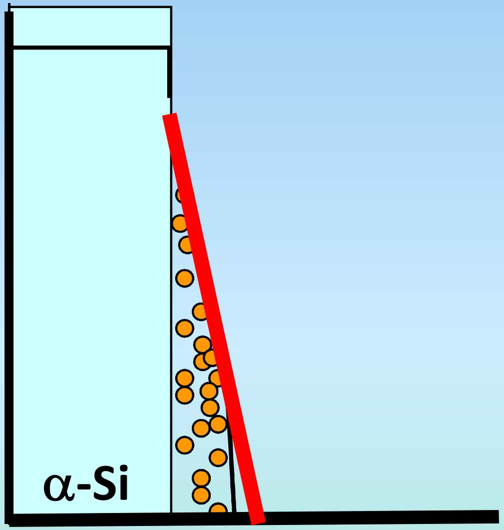
# Damage control mechanism of cluster ion mass

$Ge^{+} < Ar_{2}^{+} < Si_{3}^{+} < Ne_{4}^{+} < O_{5}^{+} < C_{6}^{+}$




bad




good

a/c interface abruptness

Comparing same energy and almost same momentum cluster ions, lighter ion cluster makes better a/c interface abruptness.

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# Sub Summary

- Cold implantation is effective to the damage control. At cold temperature recombination of interstitials and vacancies are suppressed. Therefore cold implantation makes thicker amorphous layer.
- End of range defects (EORD) is related to not only amorphous layer thickness but also amorphous crystal (a/c) interface abruptness.
- Bigger cluster size ion makes better a/c interface abruptness.
  ($C^+ < C_2^+ < C_3^+ < \cdots < C_{12}^+ < C_{13}^+ < C_{14}^+$)
- Lighter cluster ion makes better a/c interface abruptness.
  ($Ge^+ < Ar_2^+ < Si_3^+ < Ne_4^+ < O_5^+ < C_6^+$)
- We can design not only amorphous layer thickness but also a/c interface abruptness using crystal-TRIM simulation.
- We can control damage using cluster ion implantation.

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# High Dose Dopant Implantation to Heated Si Substrate without Amorphous Layer Formation

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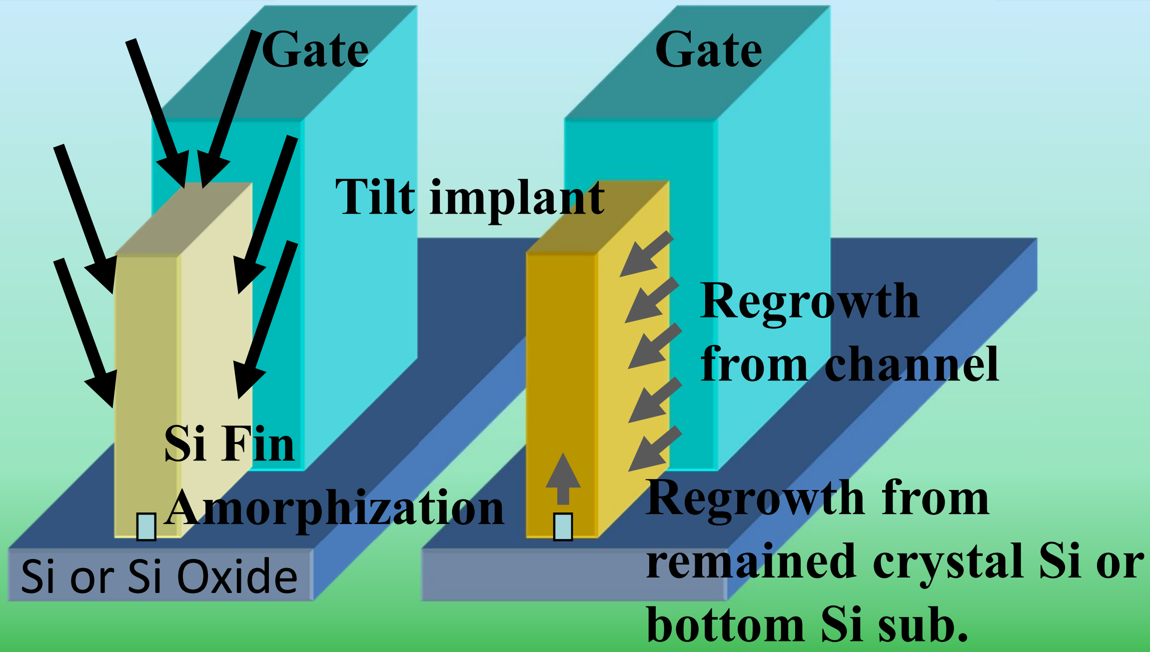
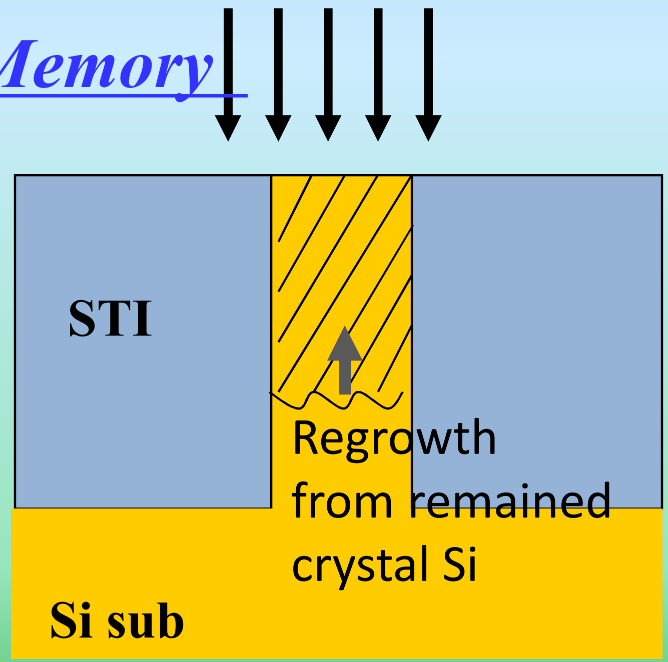
# Motivation

- In Fin-FET structures, SDE ion implantation amorphizes Si Fin. It would be very difficult to recover Si single crystal structure with anneal, especially when Fin width becomes small or amorphization reaches to the Si Fin bottom. Flash memory SDs are the same situation.
- Basic studies for high dose & high activation doping without amorphous formation for advanced device structures by using <u>heated implantation.</u>

*Fin FET*




*Flash Memory*



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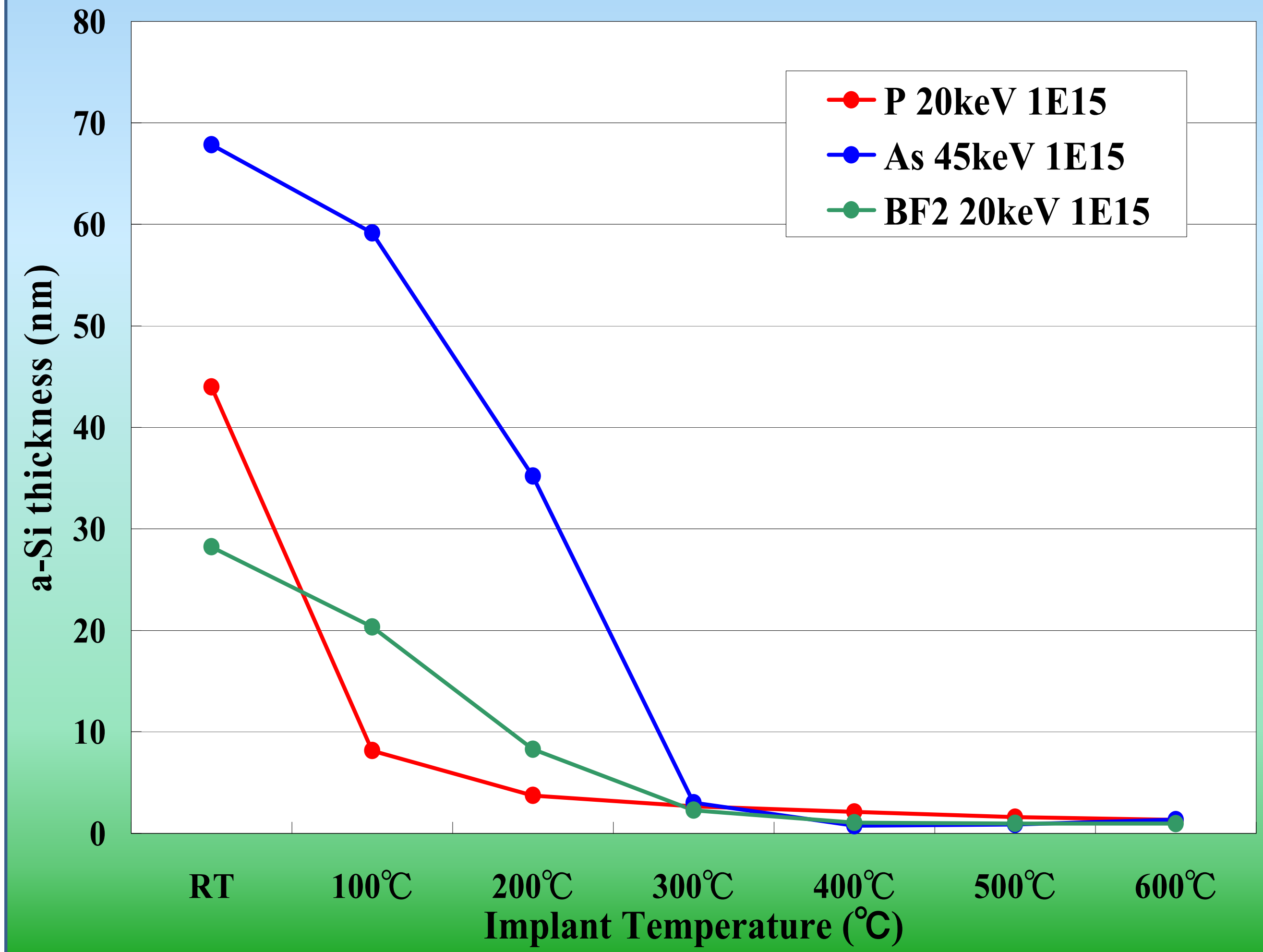
# a-Si thickness

- Amorphous Si thickness decreases with increasing implant temperature.
- Around 300°C is the key temperature for implant damage recovery.
  Si single crystal structure seems to be maintained at over 300°C.




**Critical Amorphization Dose**

$BF_2$ 20keV 7.0E14/cm²
P 20keV 1.2E14/cm²
As 45keV 1.2E14/cm²

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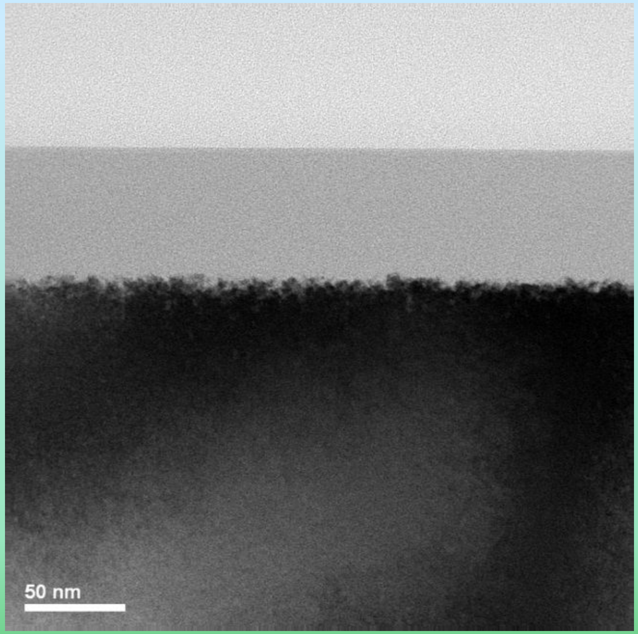
# XTEM for As implant

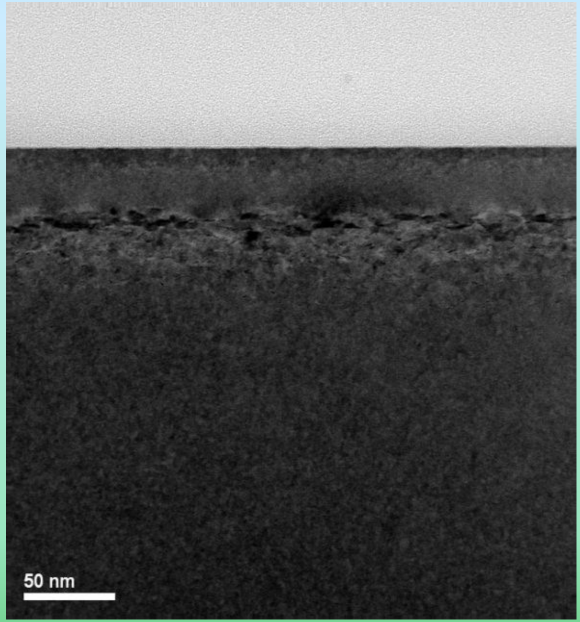
- Single crystal structure remains in As as-implanted at higher than 300ºC.
- However, many dislocations remain in the crystal structures.

**As 45keV 1E15**

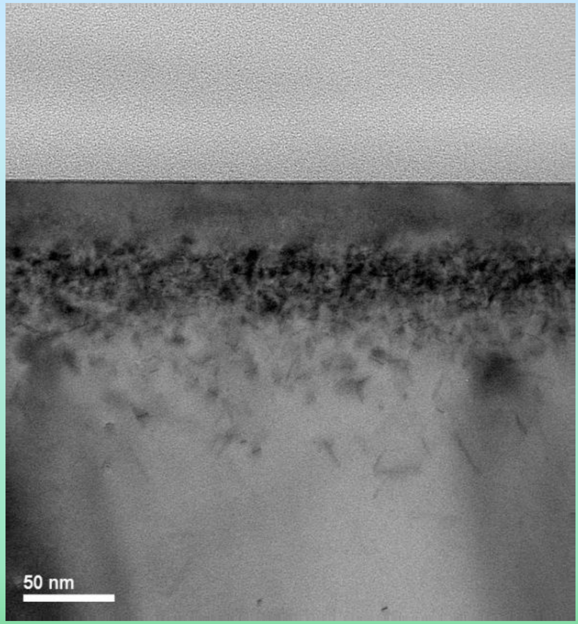
**RT**




**300ºC**




**600ºC**



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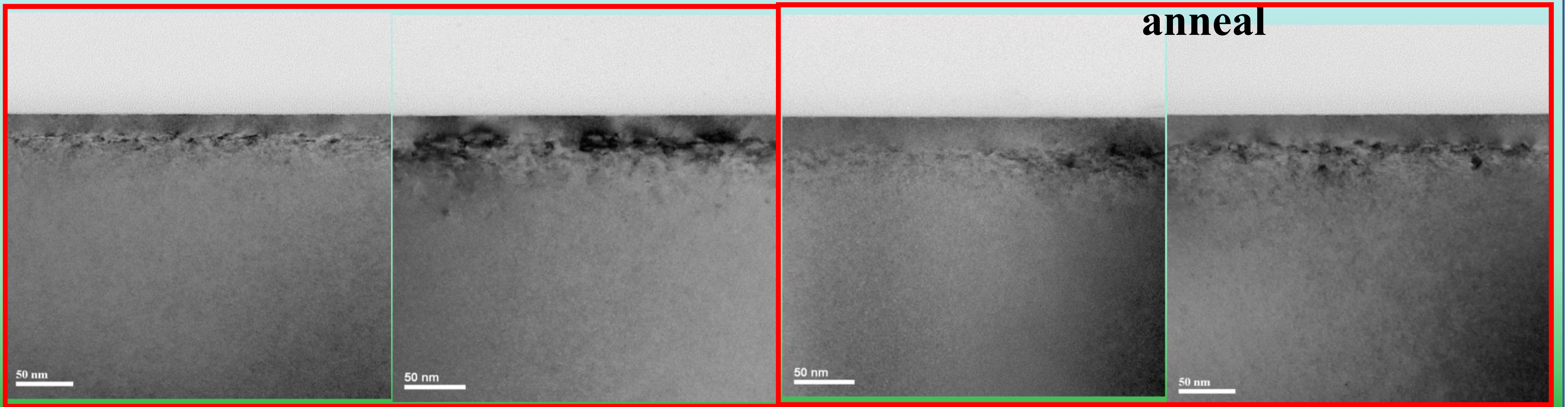
# XTEM after 600°C 1H anneal - $BF_2$ and P -

- Low temperature long time anneal cannot remove the defects.
- Only results in growth of the defect size and widens defect formed band width.
- $As^+$ implantation results in the similar defects remained.

$BF_2$ and P 20keV 1E15/cm$^2$ at 300°C

(a)$BF_2$ as-impl. (b)$BF_2$ after 600°C 1H anneal (c)P as-impl. (d)P after 600°C 1H anneal



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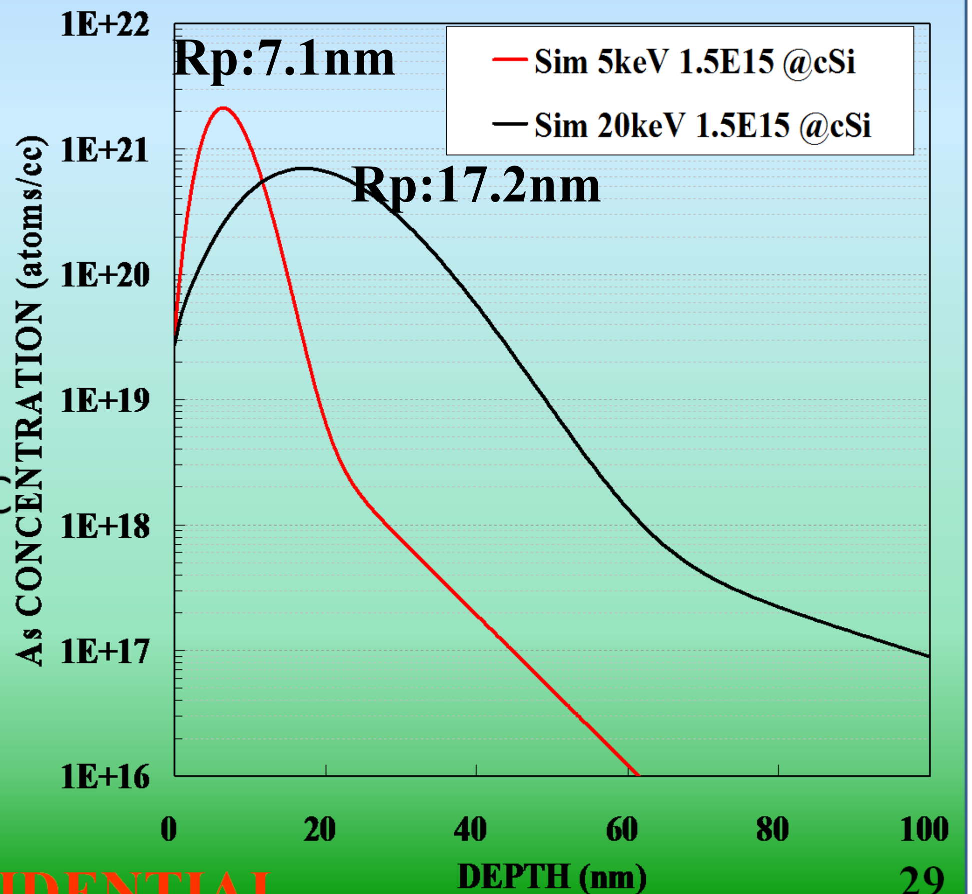
# Experimental

In order to obtain defects free crystal after annealing,

- Generally used annealing conditions in device manufacturing
- Shallower As profiles for reducing residual defects after anneal; location of defects are close to the surface, and defects could be removed through Si surface.




- As Ion Implantation
  - As 5keV 1.5E15/cm$^2$ RT - 550°C
  - As 20keV 1.5E15/cm$^2$ 300°C - 550°C
- Anneal
  - Spike RTA 1015°C

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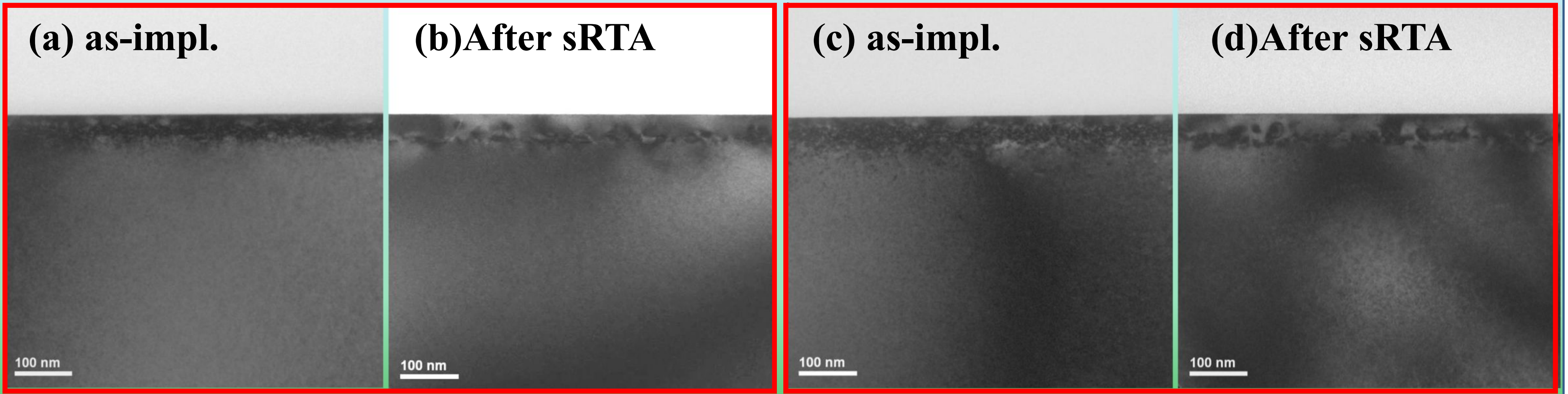
# XTEM after 1015°C spike RTA
# - As 20keV 1.5E15/cm$^2$ -

- There still remains thick density of defects. Size of the defects get larger and defects density become less.
- Spike RTA 1015°C also cannot remove the defects in As$^+$ 20keV implant.

As 20keV 1.5E15/cm$^2$ at 300°C

As 20keV 1.5E15/cm$^2$ at 550°C



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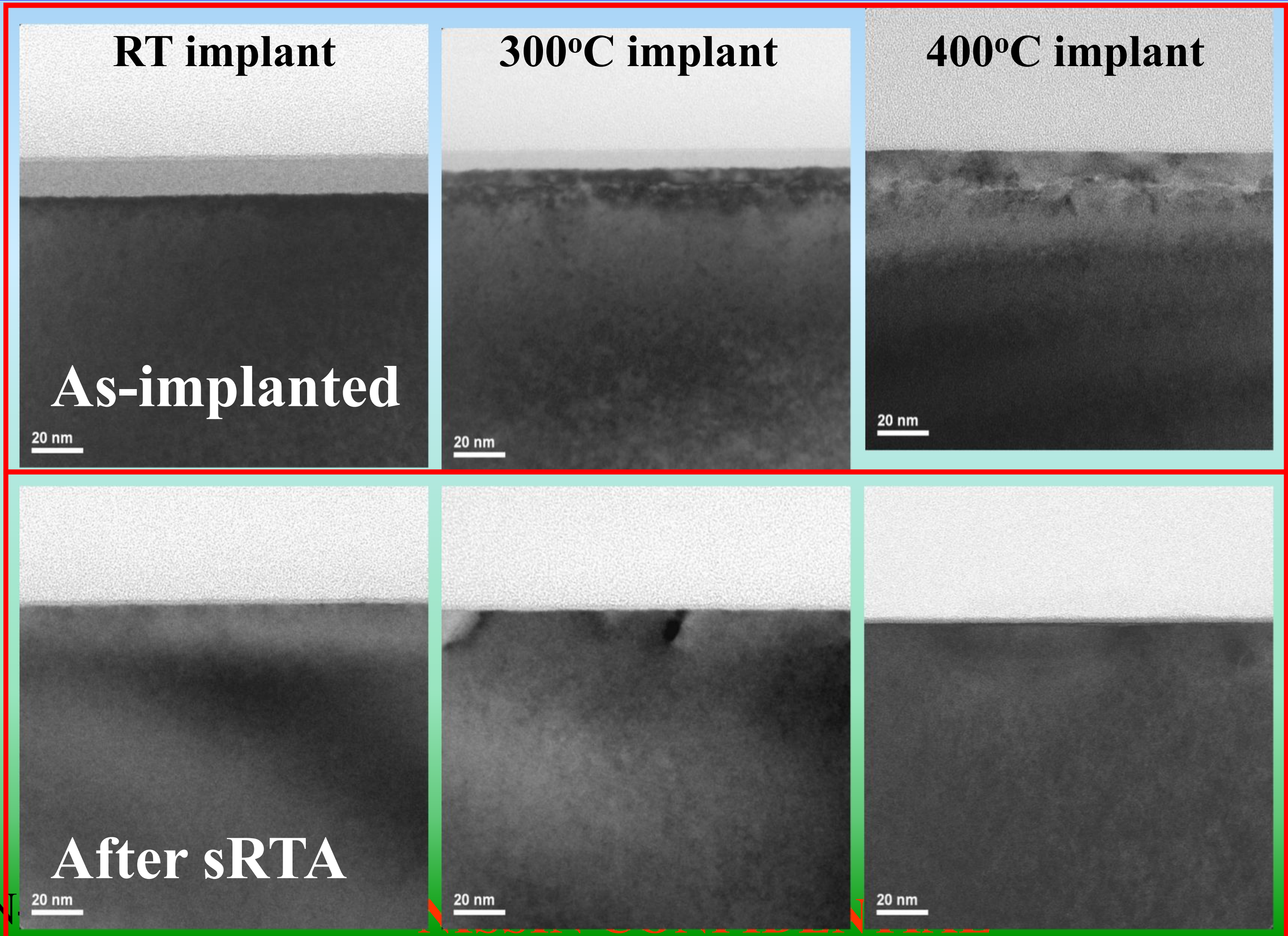
# XTEM after 1015°C spike RTA
## - As 5keV 1.5E15/cm$^2$ -

- Crystal structure remains during implant at implant temperature more than somewhere between 300°C-400°C. Many defects, however, remain in crystal Si.
- The residual defects are removed after 1015°C spike RTA.



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# Sub Summary

High Dose doping without amorphous formation for advanced device structures by using heated implantation has been studied.

1. High dose implantation with keeping single crystal structure has been embodied at implant substrate temperature higher than somewhere between 300$^{o}$C and 400$^{o}$C by heated implantation.
2. Many defects remain in as-implanted Si and were eliminated after spike RTA. Lower energy implant realizes defect free doping after anneal.

It has been shown that high dose doping without amorphization and also without defect can be successfully embodied. This technology can be applied to FinFET and memory processes, which prefer doping without a-Si formation.

# Thank you for your attention!

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