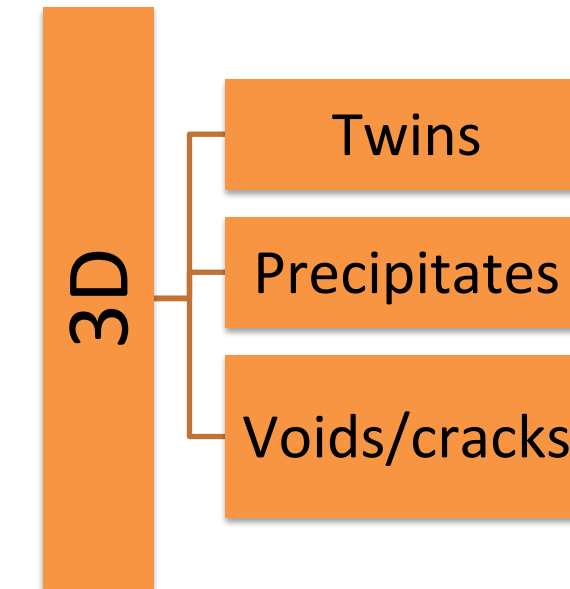
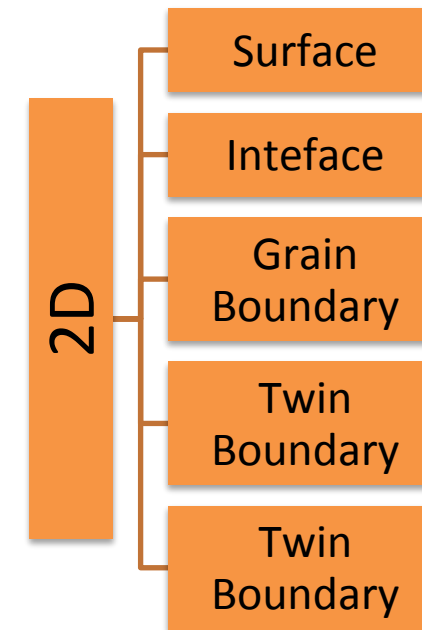
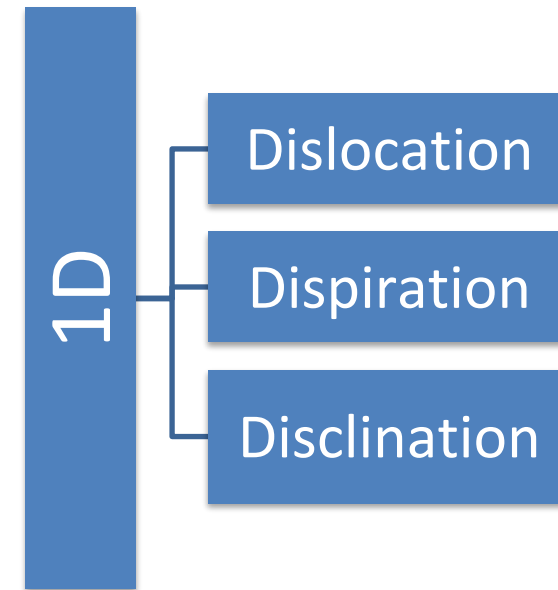
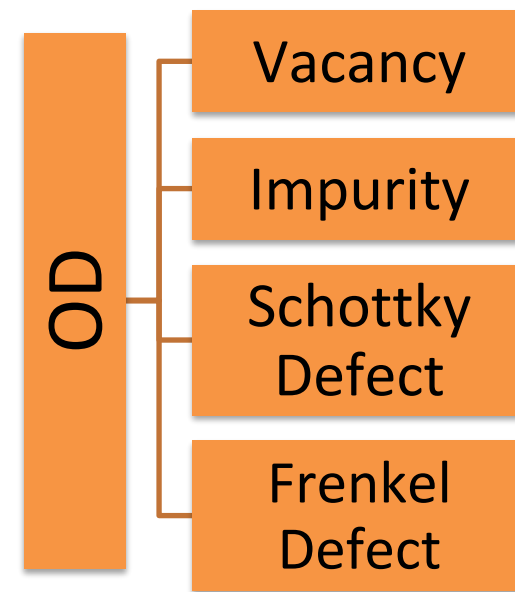


# Ion Implantation

# KEY CONCLUSIONS



# Defects



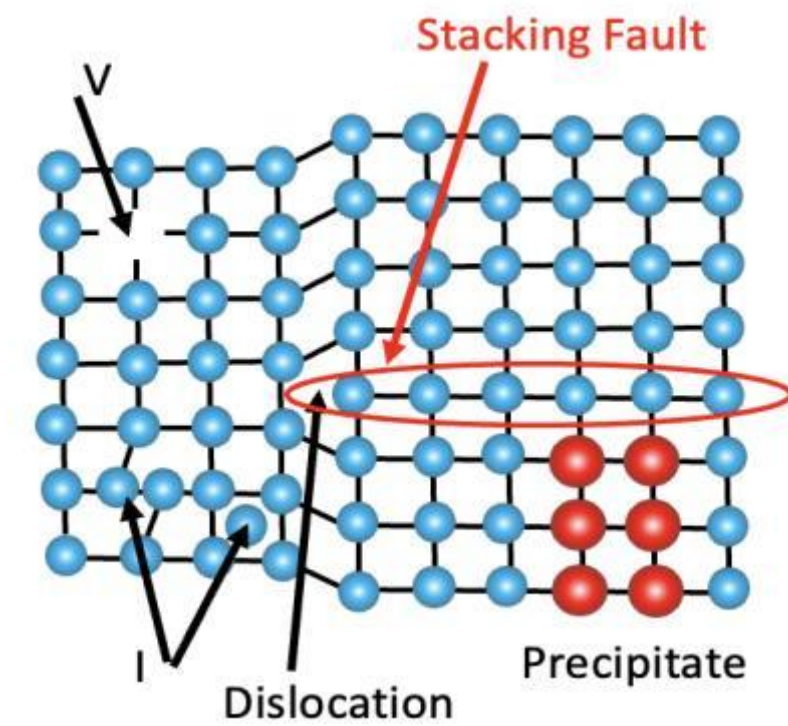
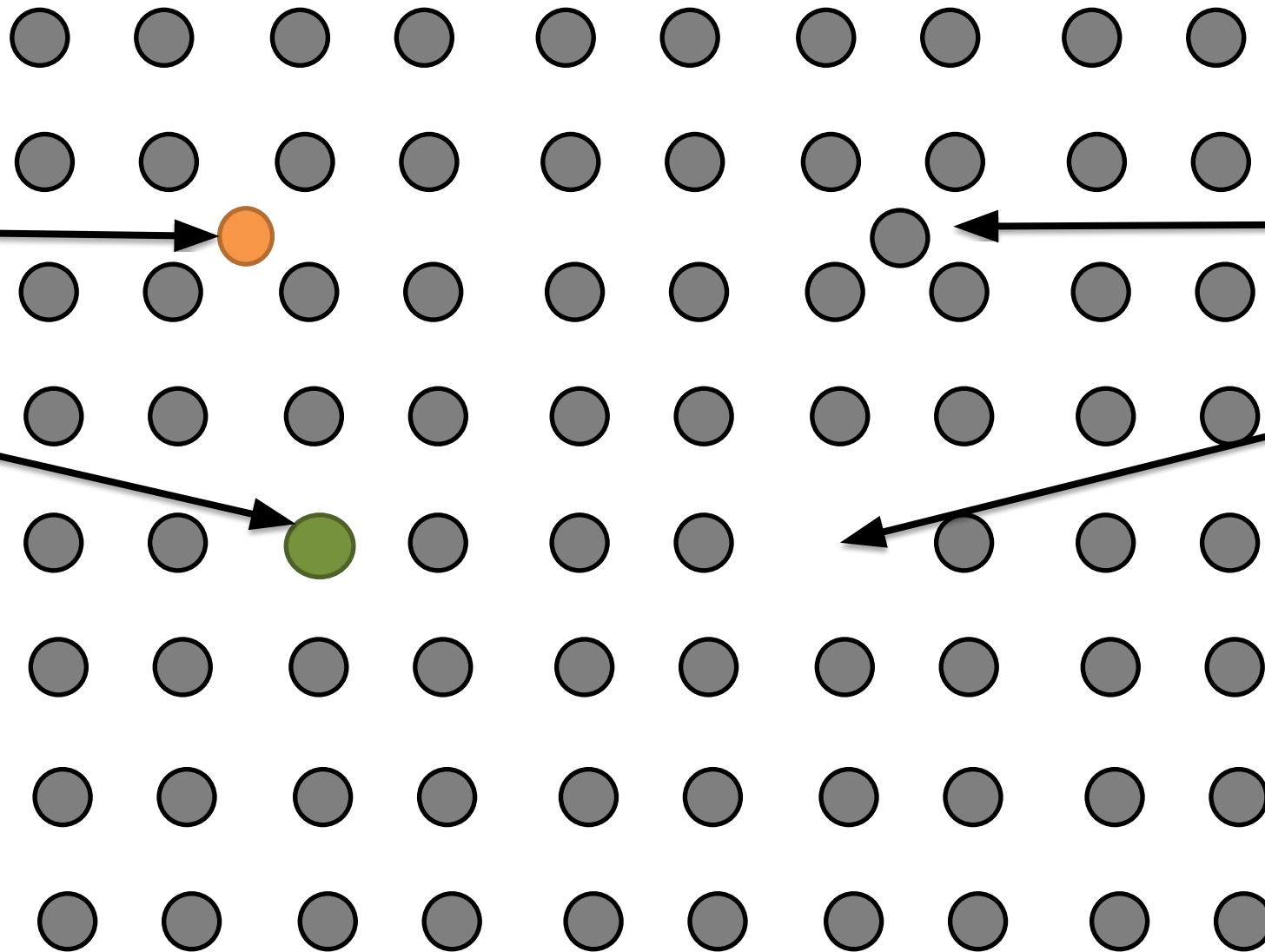
# Vacancy

Interstitial Impurity

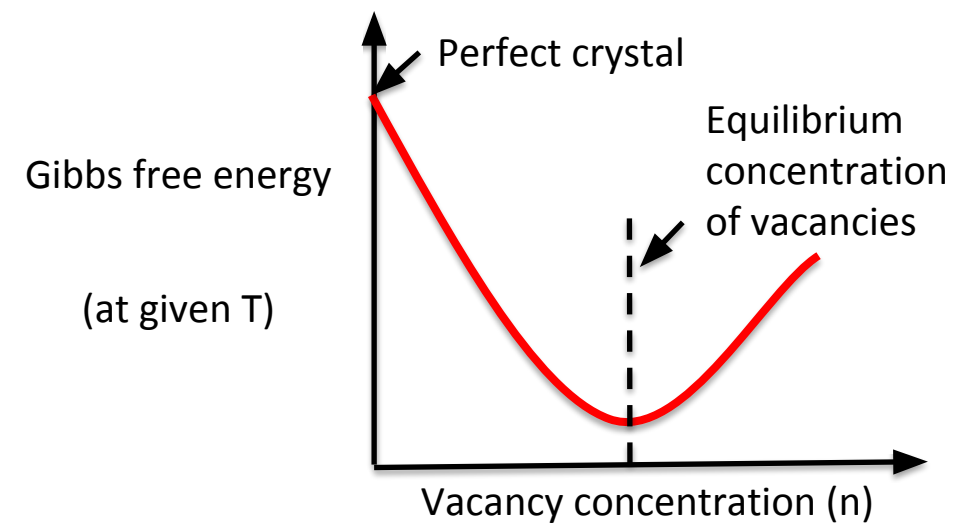
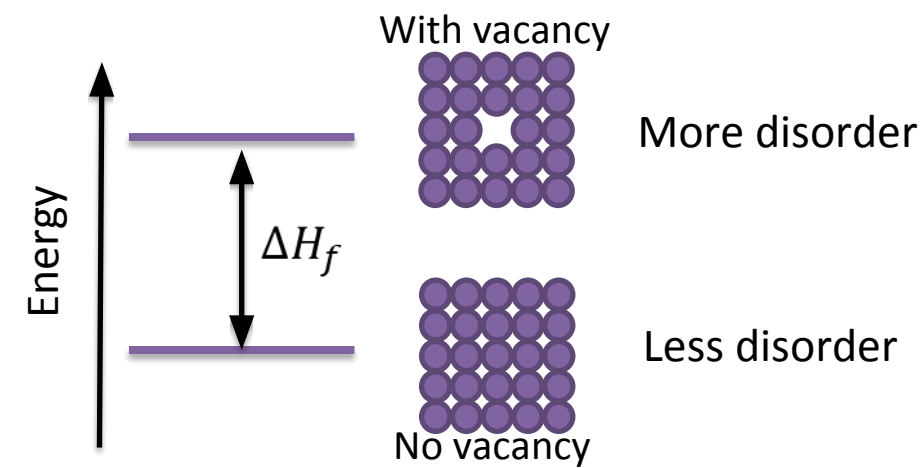
Substitutional Impurity

Self Interstitial

Vacancy



# Point Defects



Q: Then why do vacancy & interstitials form at all?



A: Because conformational entropy increases.

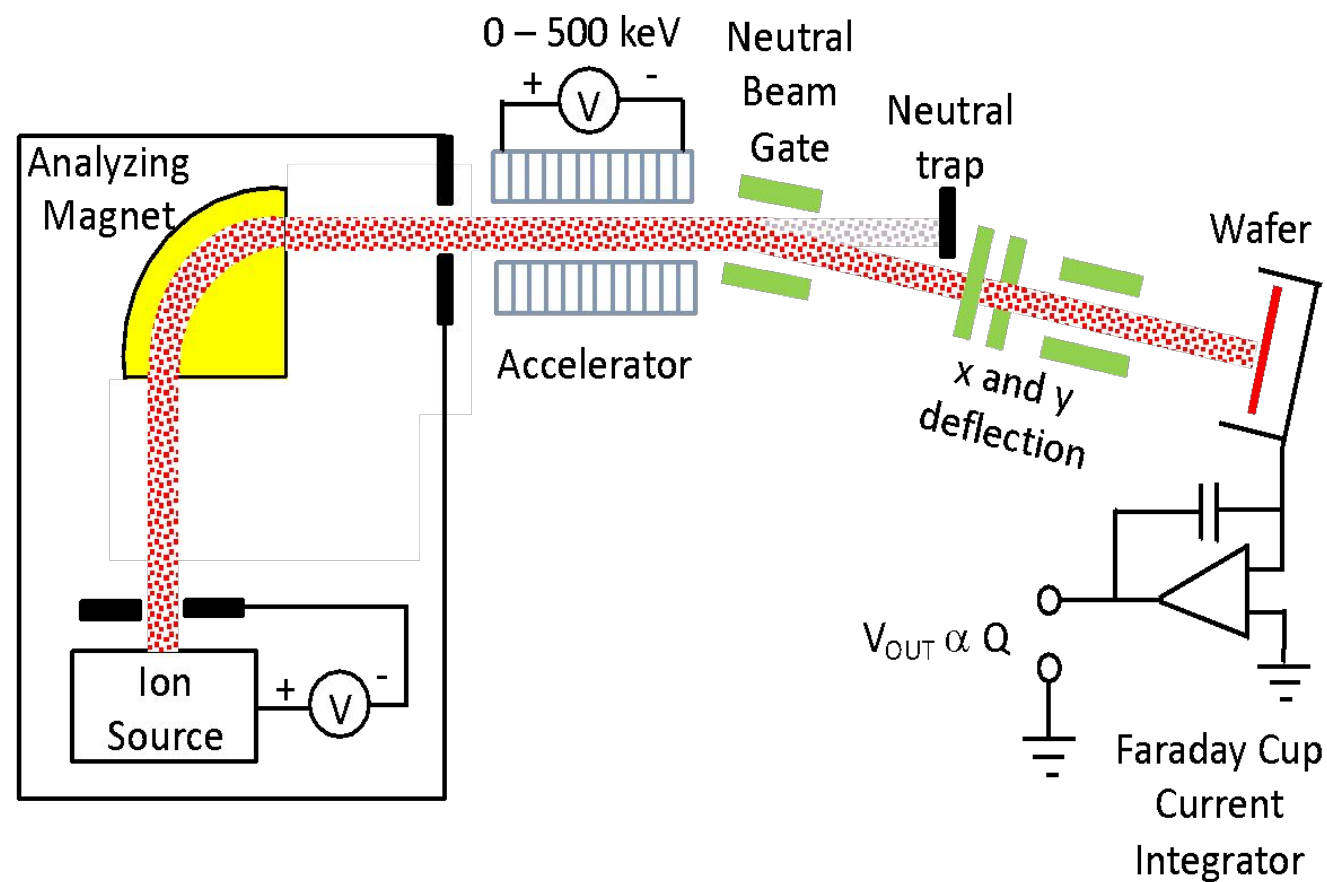
$$n \sim \exp\left(-\frac{\Delta H_f}{kT}\right)$$

In a perfect crystal, vacancy and self-interstitials are in equilibrium

n **exponentially** increases with T

- Point defects cannot be avoided
- Substitutional impurities are active sites for doping
- Interstitial sites are not active sites for doping
- IV pair also known as Frenkel pair contribute to doping
- Interstitialcy
- Point Defects are important!!!
- IV Pair can generate and recombine

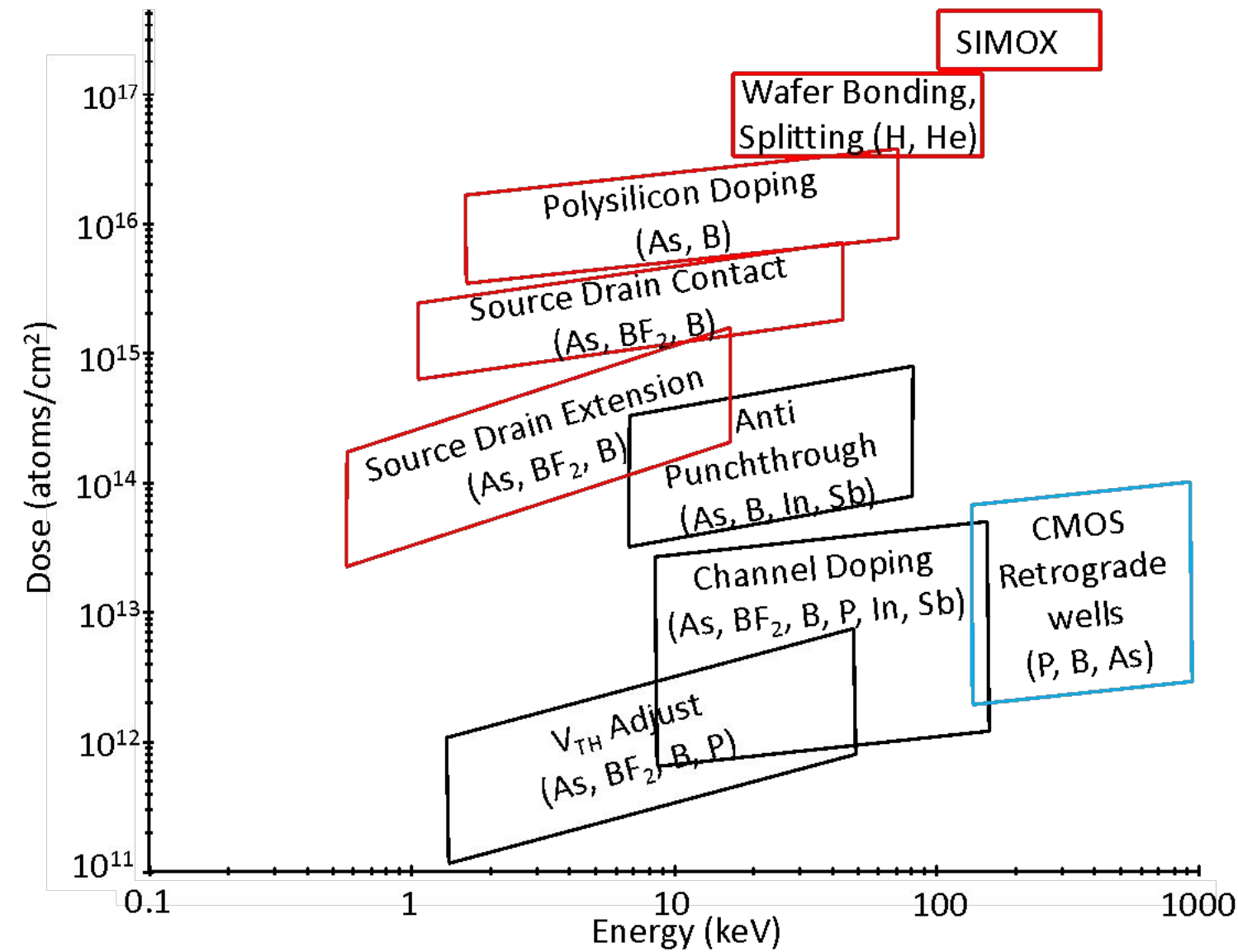
# Ion Implantation



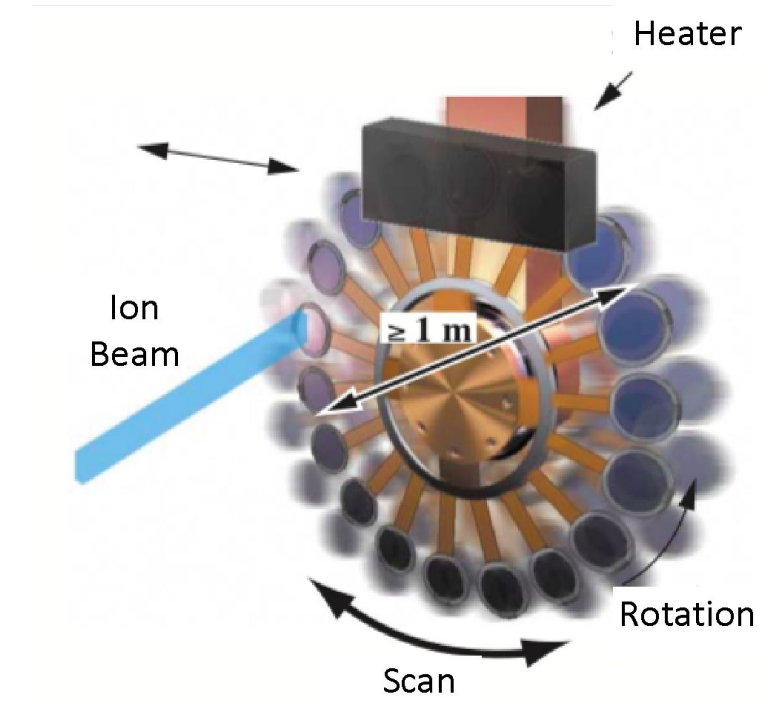
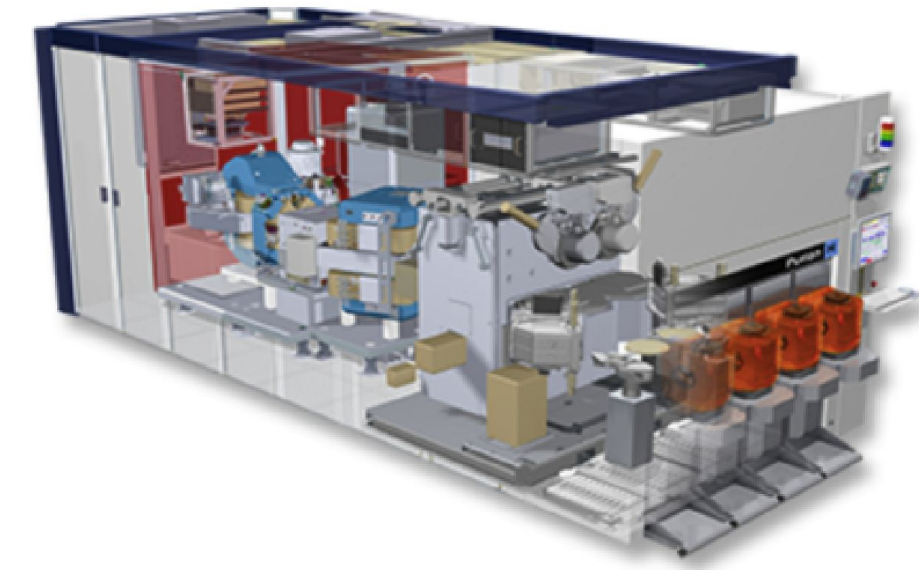
- Disadvantages
  - Damage to crystal.
  - Anomalous transiently enhanced diffusion (TED) when this damage is annealed.
  - Charging of insulating layers.

- Ion implantation is the dominant method of doping used today
- Advantages:
  - Large range of doses -  $10^{11}$  to  $10^{16}/\text{cm}^2$
  - Extremely accurate dose control
  - Essential for MOS  $V_T$  control
  - Buried (retrograde) profiles are possible
  - Low temperature process
  - Wide choice of masking materials

# Applications of Ion Implantation

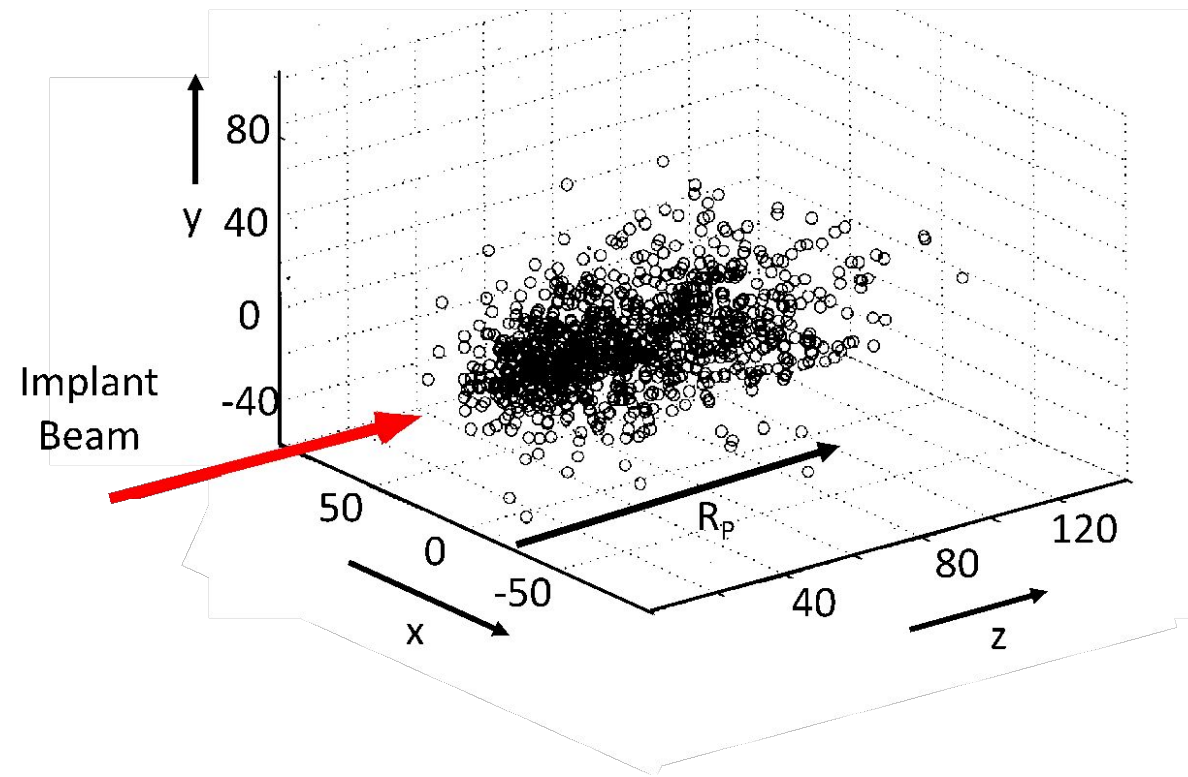


- Many applications of ion implantation in CMOS technology. High current (red), high voltage (blue).
- Beam currents up to 25 mA, voltages up to 1 MeV.





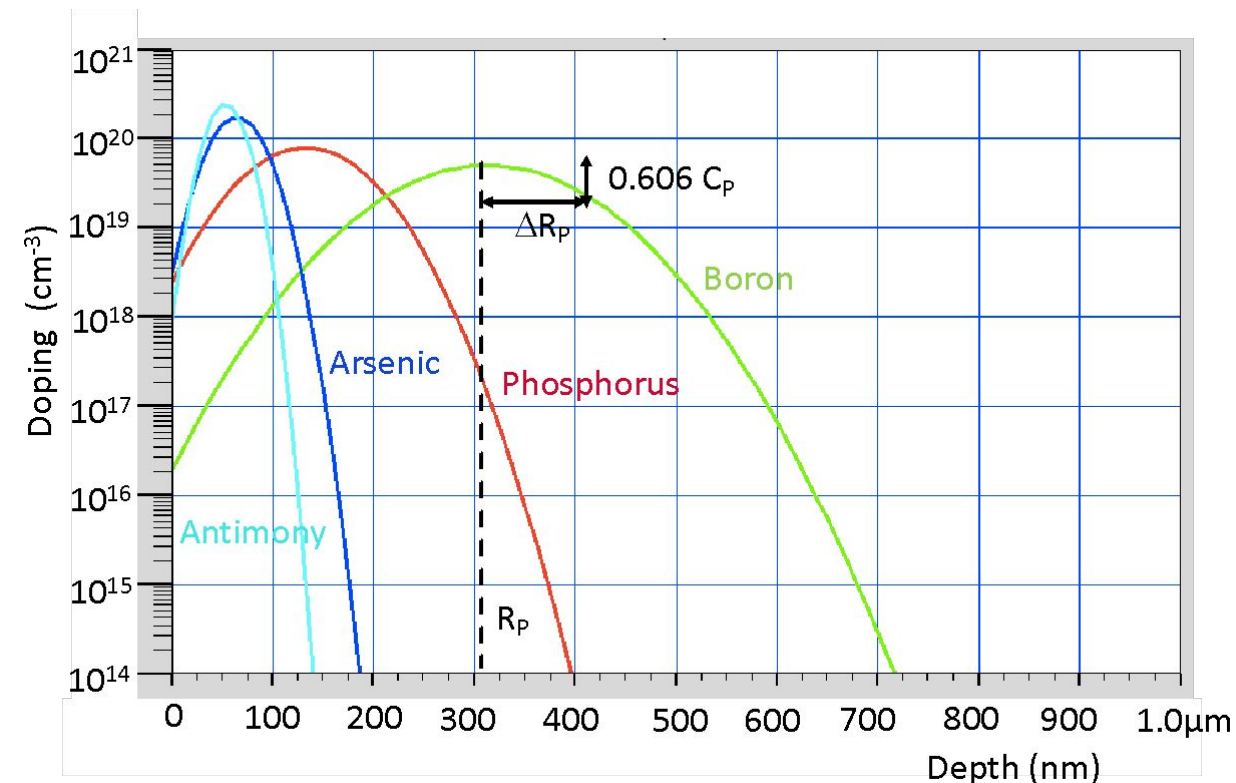
# Basics of Ion Implantation



- Ion implantation is a random process.
- High energy ions (1-1000keV) bombard the substrate
- and lose energy
- Nuclear Stopping
- Electronic stopping
- Gaussian Profile to the first order
- Dose can be accurately measured by integrating current

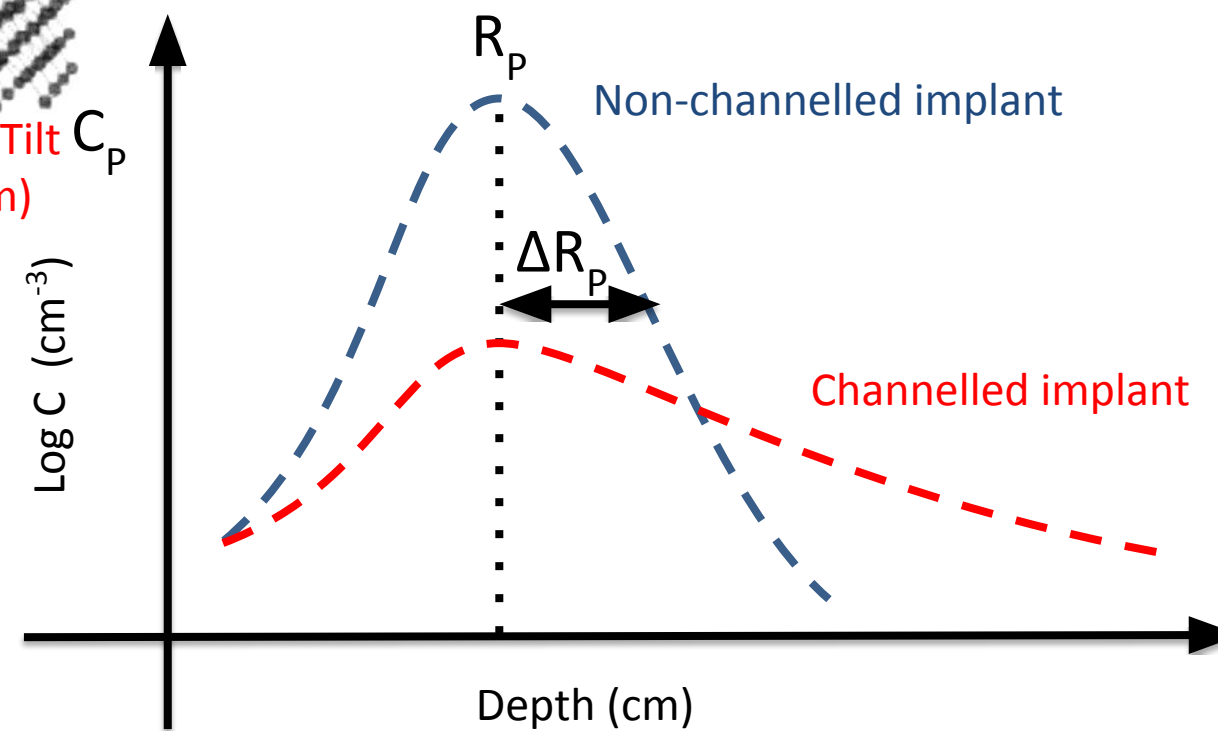
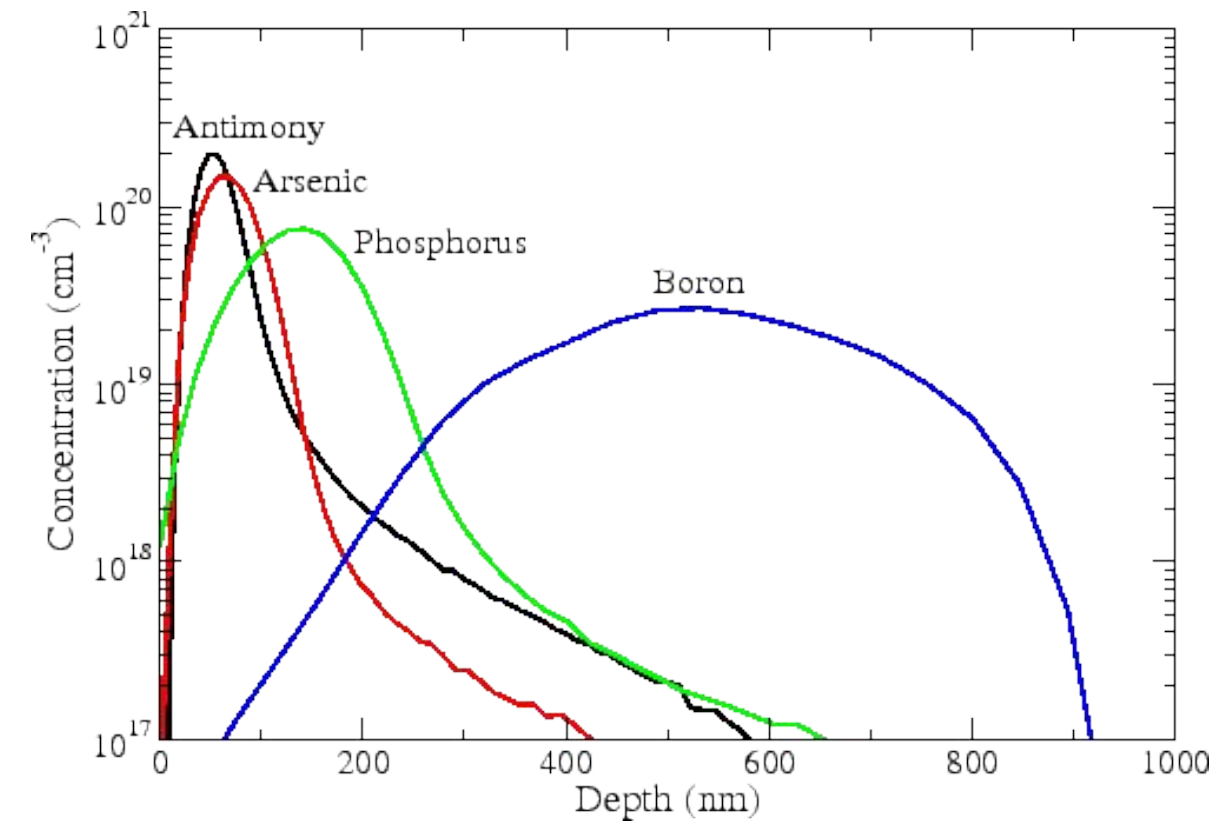
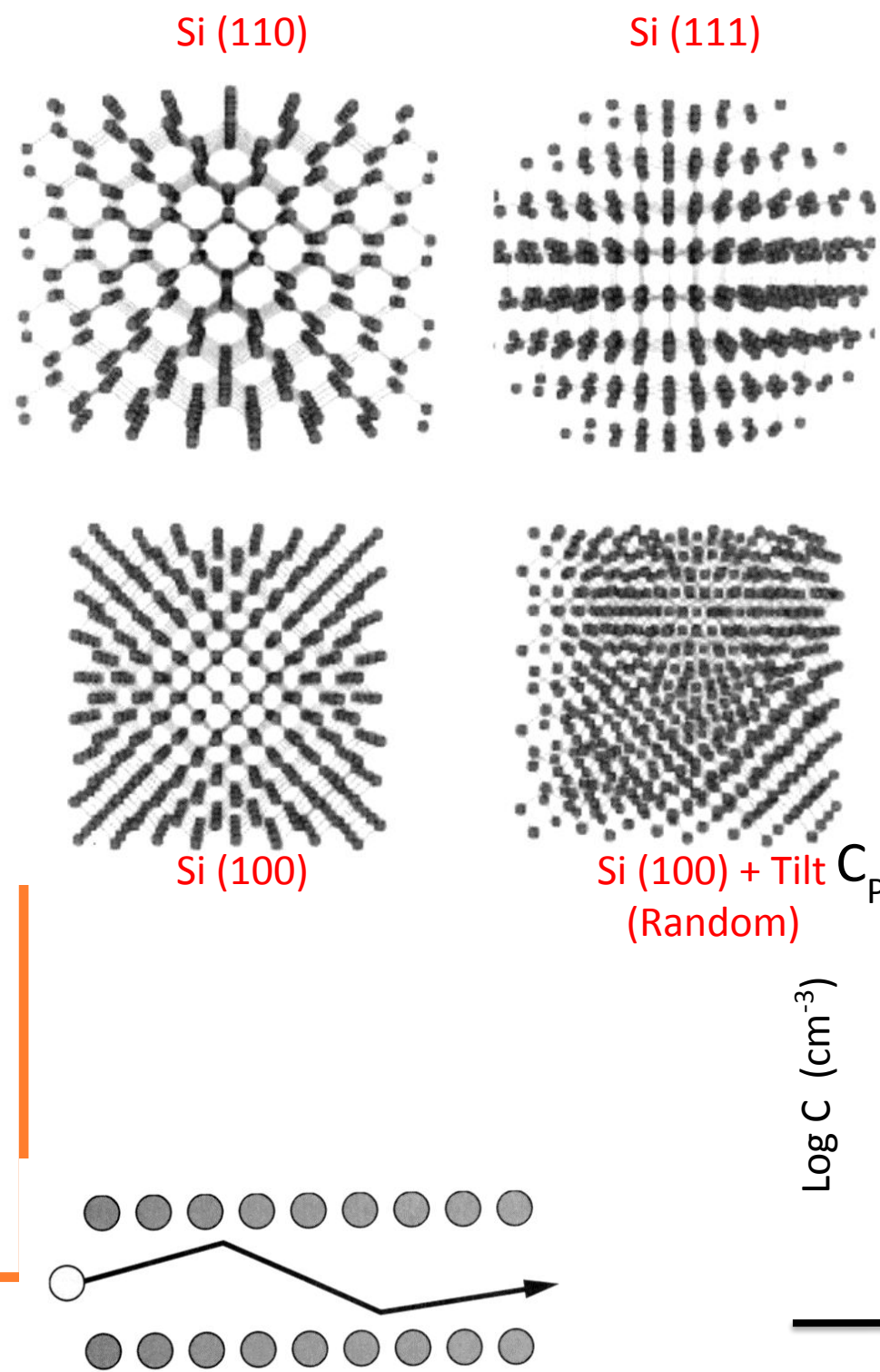
$$C(x) = C_p \exp \left( -\frac{(x - R_p)^2}{2\Delta R_p^2} \right)$$

$$Q = \int_{-\infty}^{\infty} C(x) dx = \sqrt{2\pi} \Delta R_p C_p$$





# Non-Ideal Effects – Channeling & Back Scattering



- Ions undergo many small angle deflections when traveling in a channel
- Channel enhances the depth to which ions reach
- Distribution shows a “tail”
- Backscattering – Light ions

# More accurate 1D model – Pearson model

- Range – Projected depth
- Straggle – Standard Deviation
- Skew – Symmetry of the distribution around the mean value
- Kurtosis – Distribution in the tail

Range:

$$R_p = \frac{1}{Q} \int_{-\infty}^{\infty} x C(x) dx$$

Std. Deviation:  
(Straggle)

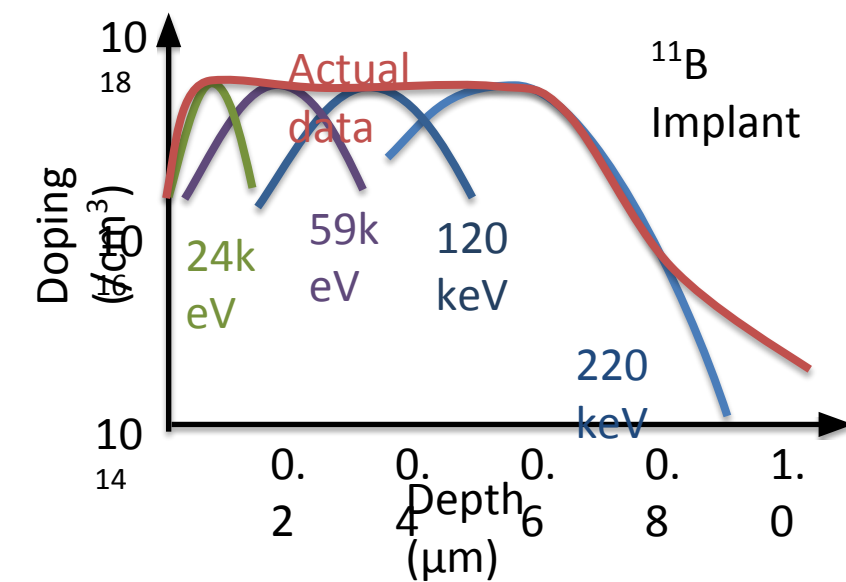
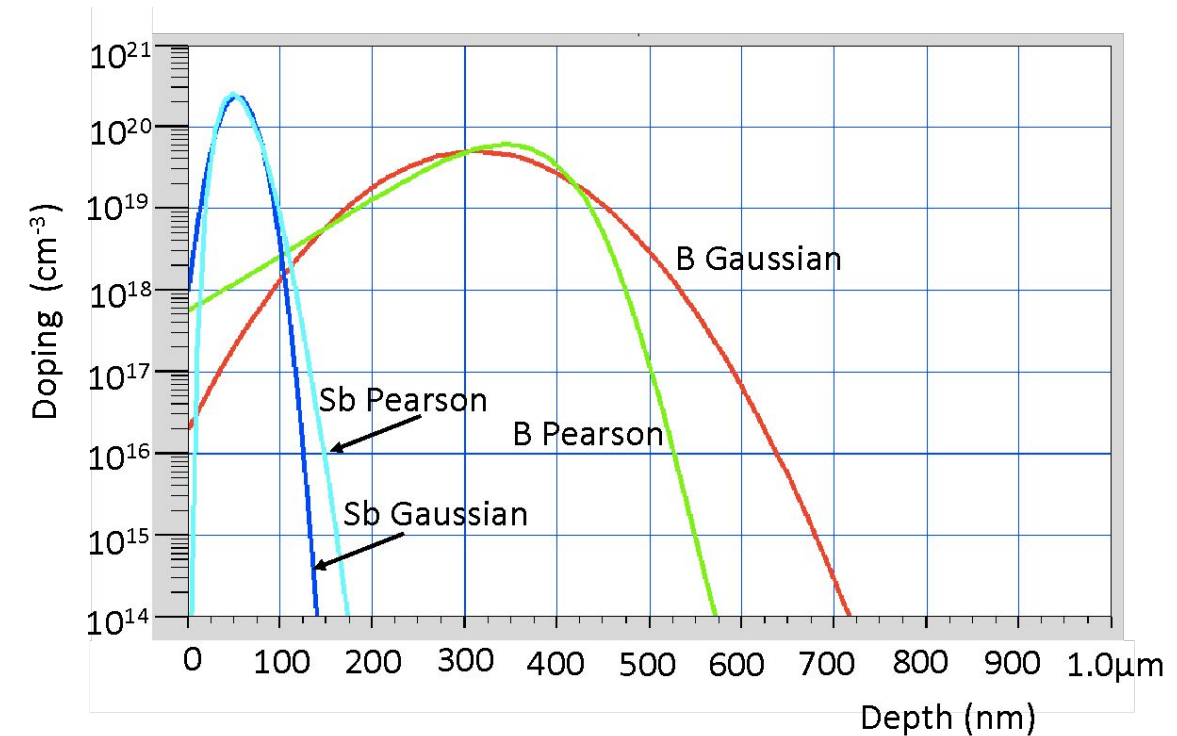
$$\Delta R_p = \sqrt{\frac{1}{Q} \int_{-\infty}^{\infty} (x - R_p)^2 C(x) dx}$$

Skewness:

$$\gamma = \frac{\int_{-\infty}^{\infty} (x - R_p)^3 C(x) dx}{Q \Delta R_p^3}$$

Kurtosis:

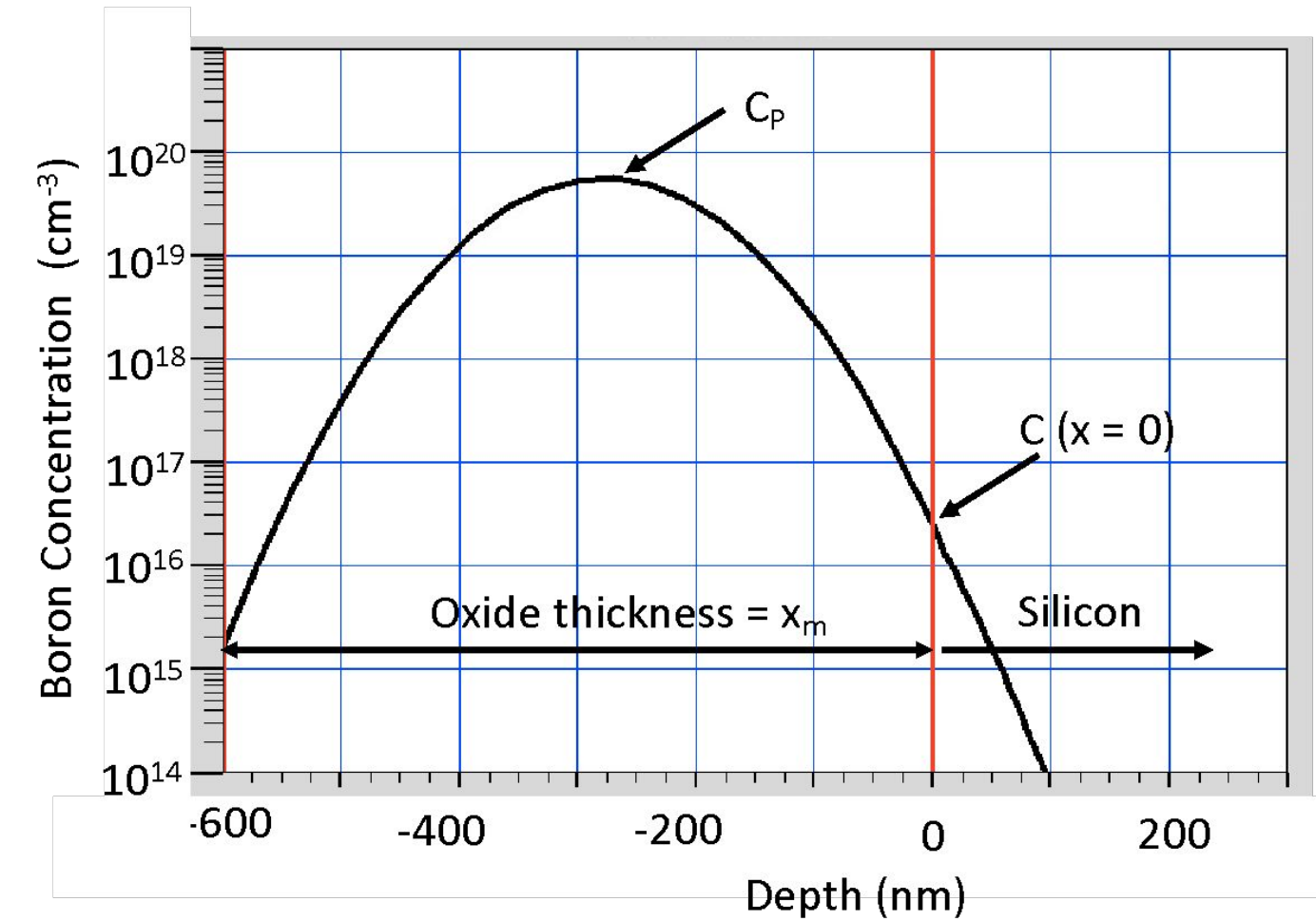
$$\beta = \frac{\int_{-\infty}^{\infty} (x - R_p)^4 C(x) dx}{Q \Delta R_p^4}$$



- Asymmetry
- Pearson model
- Look up tables

# Masking layer and thickness

- Photoresist
- Silicon Dioxide
- Silicon Nitride
- Tungsten, Platinum and Vanadium



$$Q_P = \frac{Q}{\sqrt{2\pi\Delta R_P}} \int_{x_m}^{\infty} \exp - \left[ \frac{x - R_P}{\sqrt{2\Delta R_P}} \right]^2 dx = \frac{Q}{2} \operatorname{erfc} \left( \frac{x_m - R_P}{\sqrt{2\Delta R_P}} \right)$$

$$x_m = R_P + \Delta R_P \sqrt{2 \ln \left( \frac{C_P}{C_B} \right)} = R_P + m \Delta R_P$$

# Total and Nuclear Stopping powers

Energy Loss

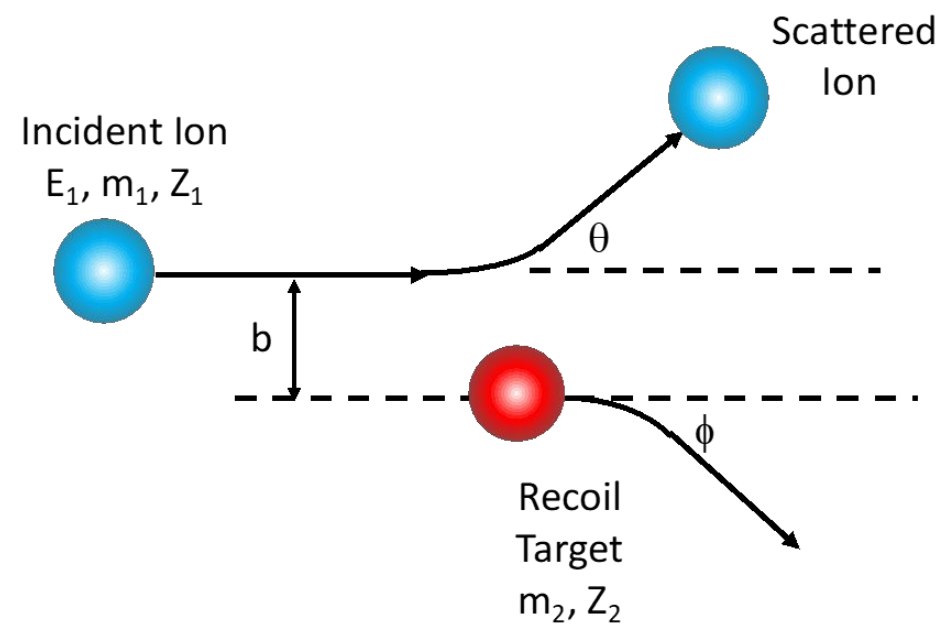
$$\frac{dE}{dx} = -N[S_n(E) + S_e(E)]$$

Range

$$R = \int_0^R dx = \frac{1}{N} \int_0^{E_0} \frac{dE}{[S_n(E) + S_e(E)]}$$

Projected Range

$$R_p = \frac{R}{[1 + m_2/3m_1]}$$



$$\Delta E = E_1 \frac{4m_1m_2}{(m_1 + m_2)^2} \cos^2 \phi$$

Energy Loss - Scattering

$$V(r) = \frac{q^2 Z_1 Z_2}{r} \exp(-r/a)$$

Screening Potential

$$a = \frac{0.885a_0}{[Z_1^{2/3} + Z_2^{2/3}]^{1/2}}$$

Screening Parameter

$$S_n(E) = S_n^o = \frac{2.8 \times 10^{-15} Z_1 Z_2}{[Z_1^{2/3} + Z_2^{2/3}]^{1/2}} \frac{m_1}{m_1 + m_2}$$

Nuclear Stopping power

□ Elastic collisions

□ Presence of electric field alters the path

□ To the first order independent of energy



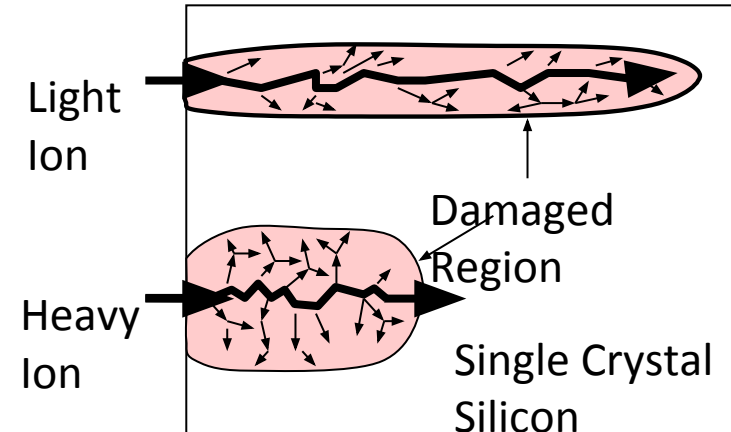
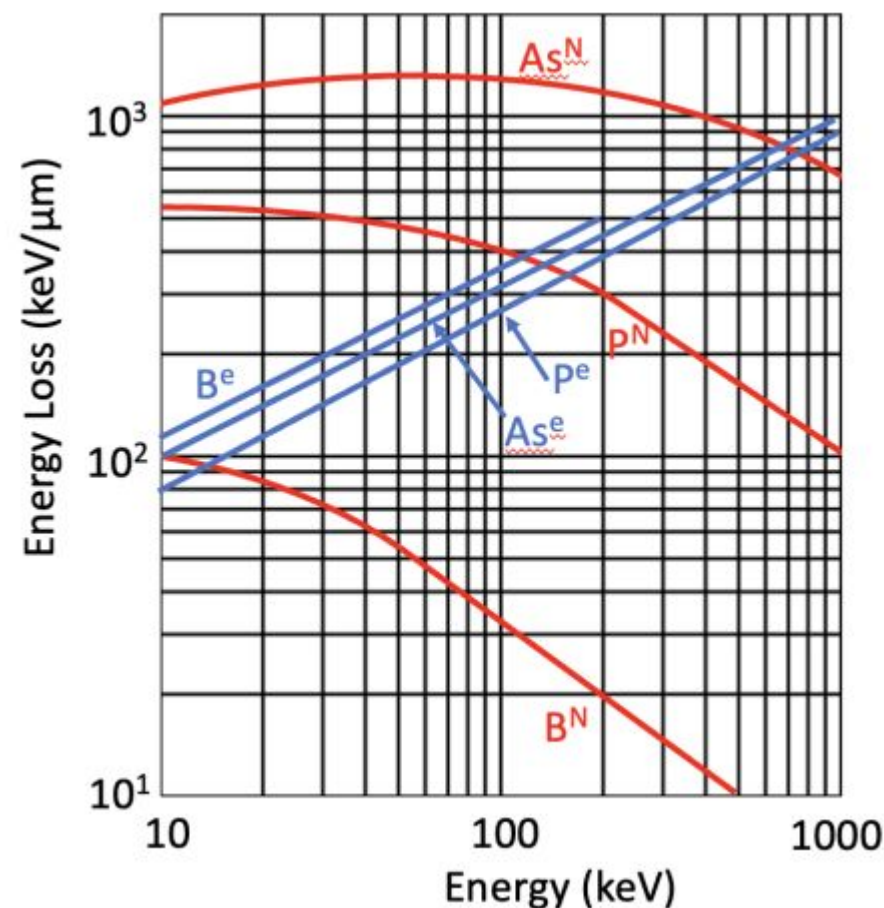
# Total and Electronic Stopping powers

## Electronic Stopping Power

$$S_e(E) = kE^{1/2}$$

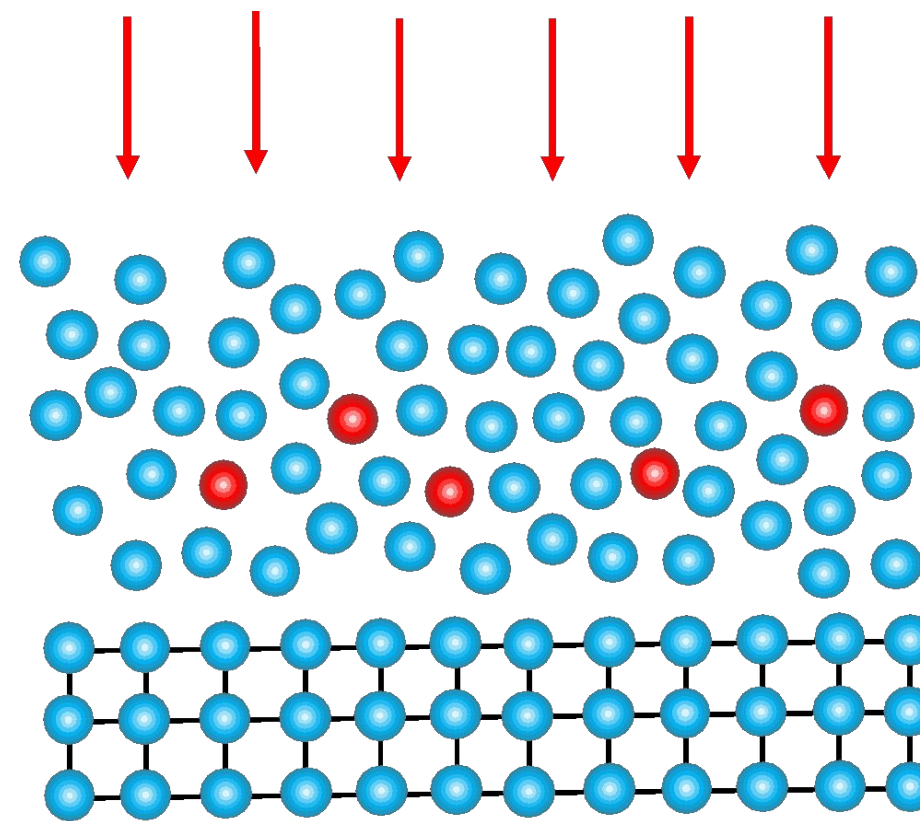
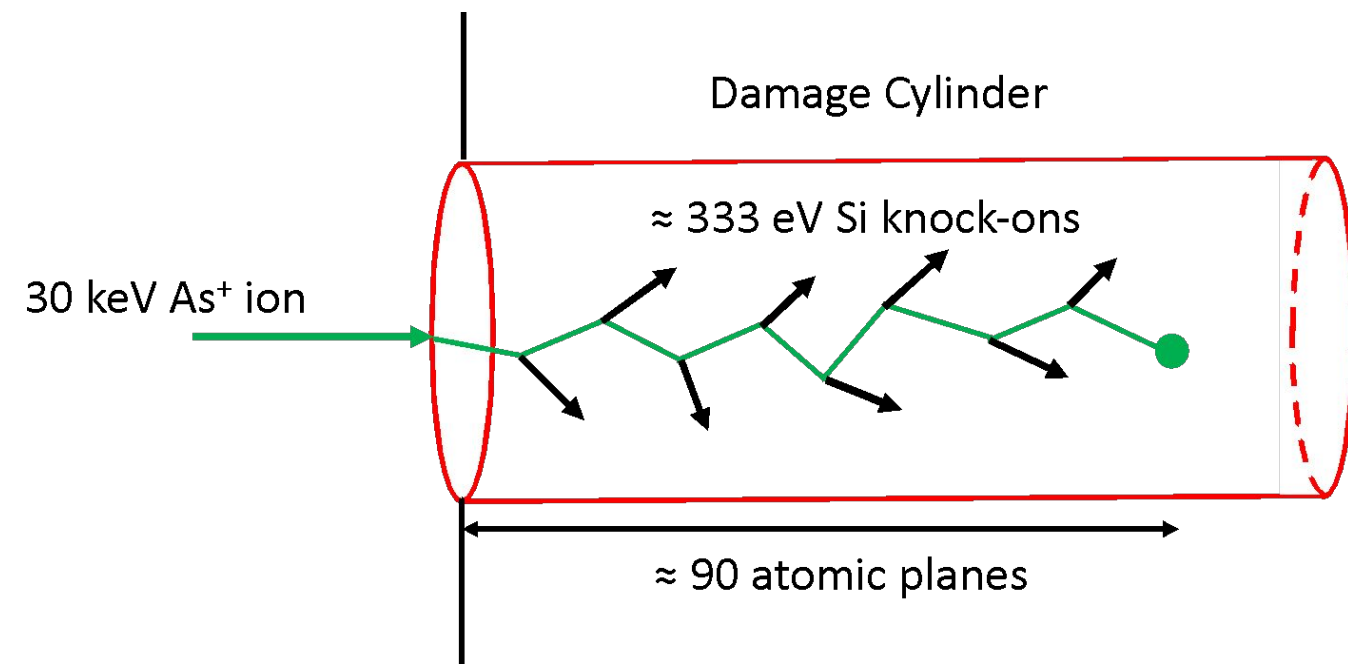
$$k = 0.2 \times 10^{-15} \text{eV}^{1/2} \text{cm}^2 \text{ for silicon}$$

- Inelastic Collisions
- To the first order is independent of ion

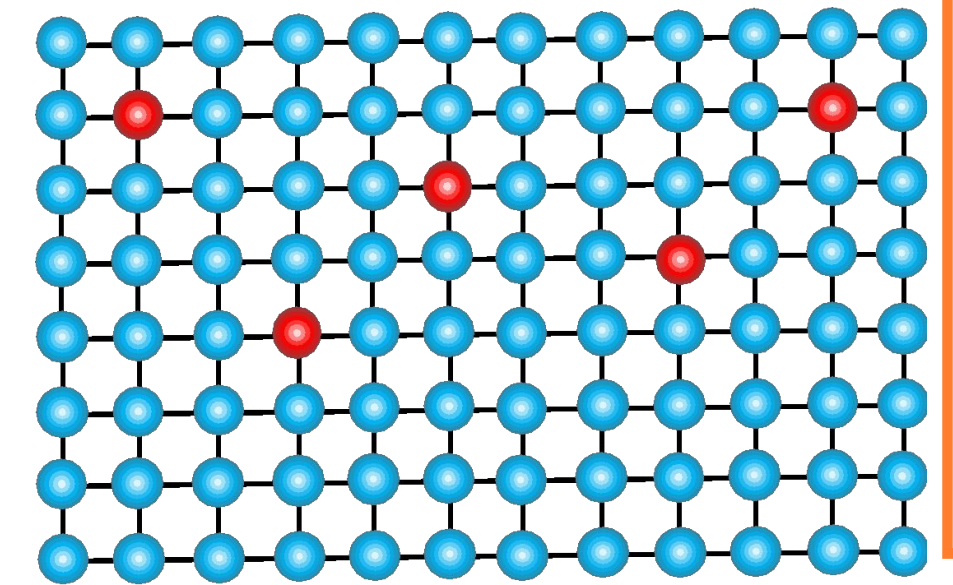


1. For heavy ions like As, Nuclear stopping power dominates
2. For lighter ions like B, Electronic stopping power dominates
3. For phosphorous, electronic stopping power dominates at high acceleration voltages and nuclear stopping power dominates at low voltages
4. Assumption of electronic stopping power is independent of ion is mostly valid
5. Heavy ions will produce damage along their entire path.
6. Light ions mostly introduce damage near the end of their path (near  $R_p$ ).

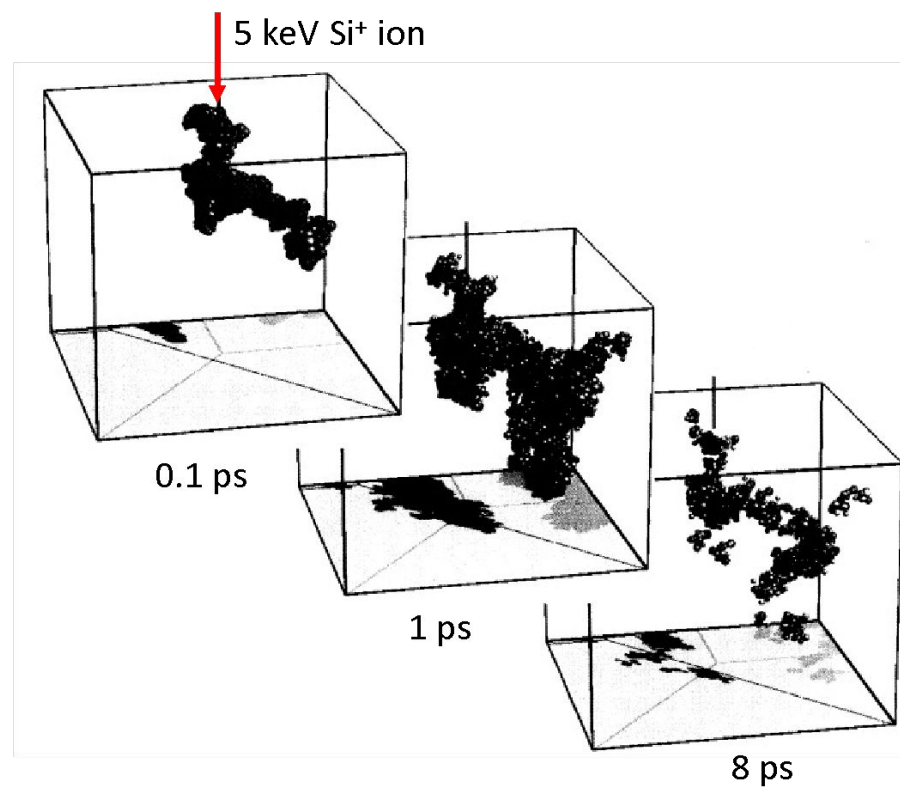
# Annealing



After Implant



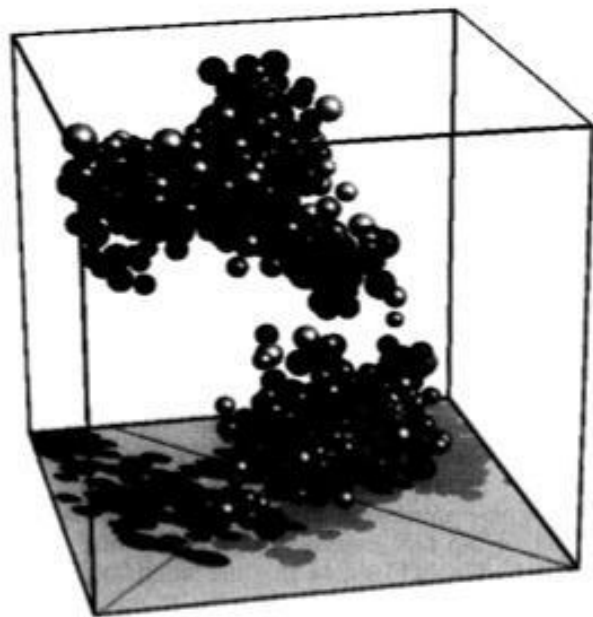
After Anneal and  
Dopant Activation



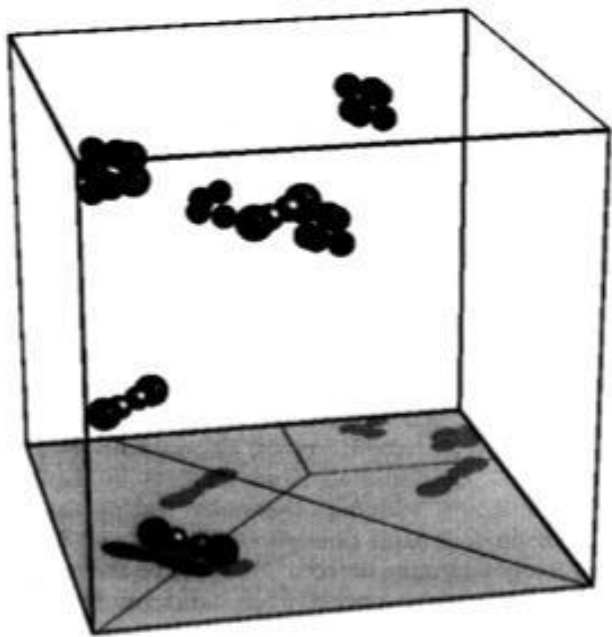
- One ion displaces 1000 atoms
- Vacancy interstitials are created
- Within 8 ps, a significant fraction gets back to the origin location



# Annealing

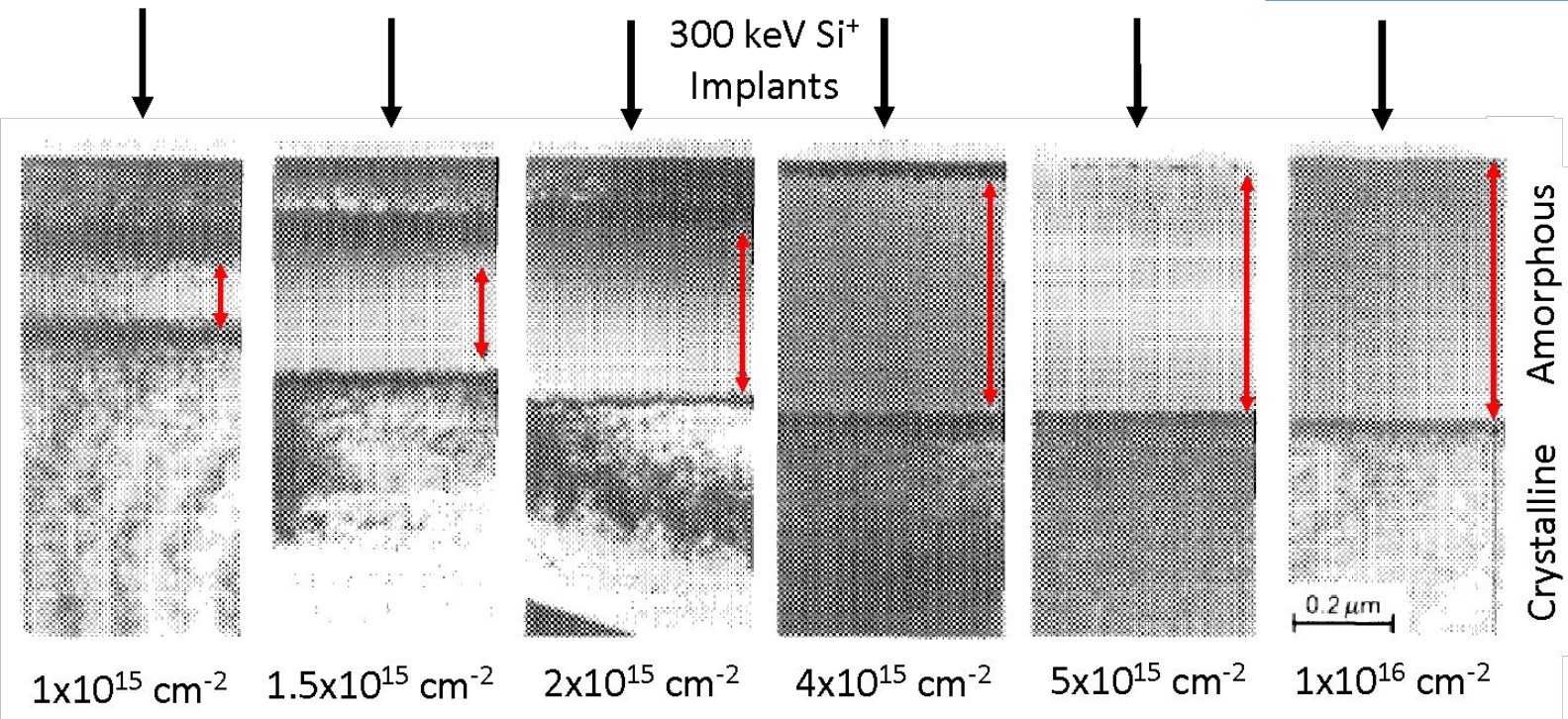


Before anneal

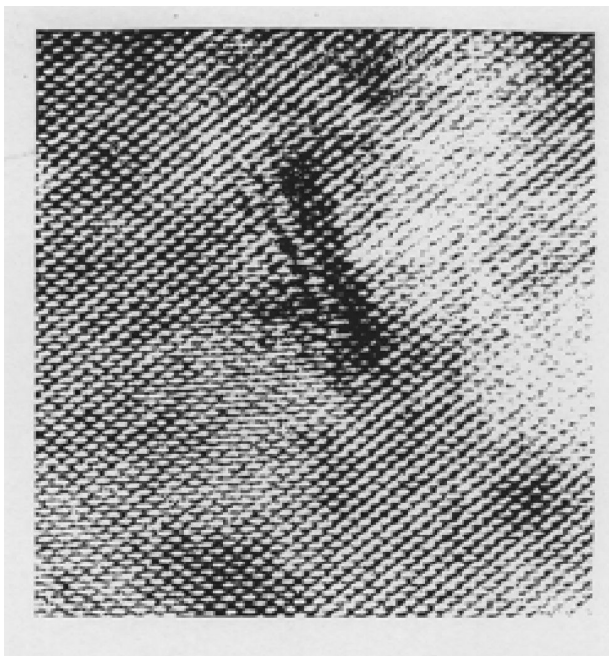
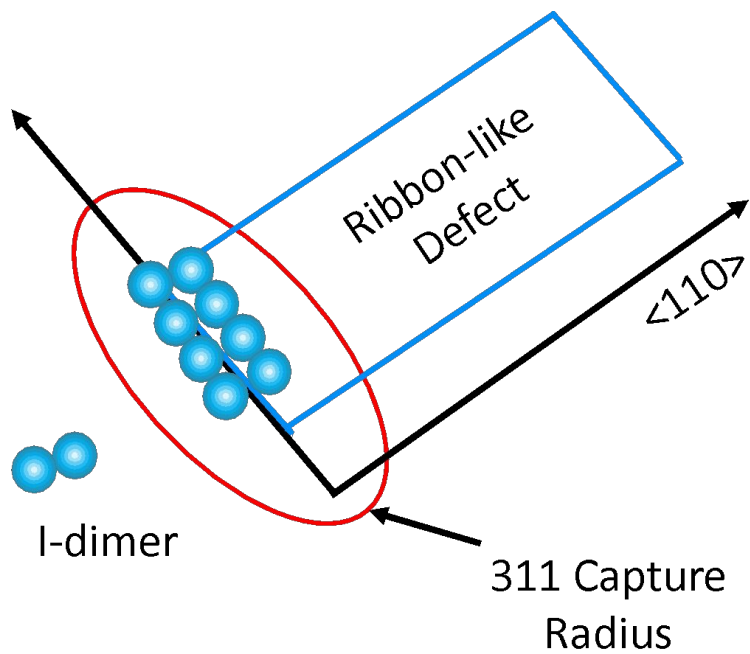


After anneal

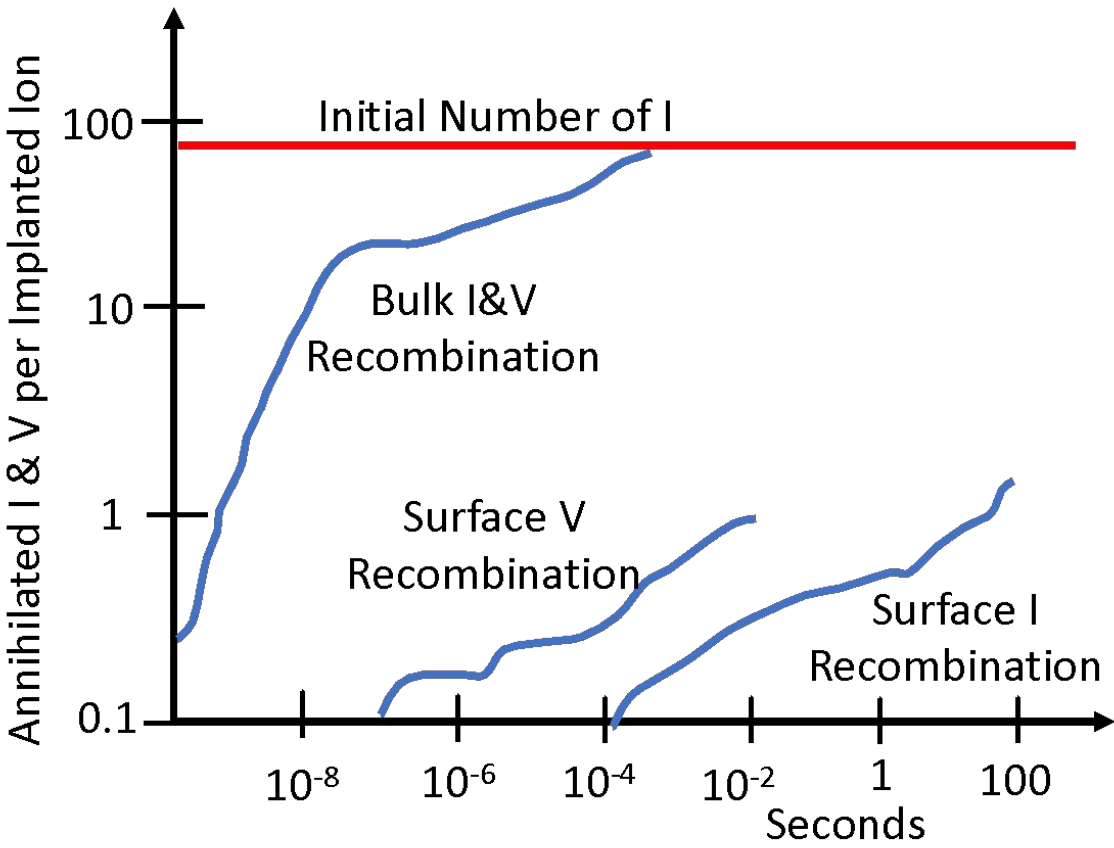
1025 °C 1 ns



Amorphization

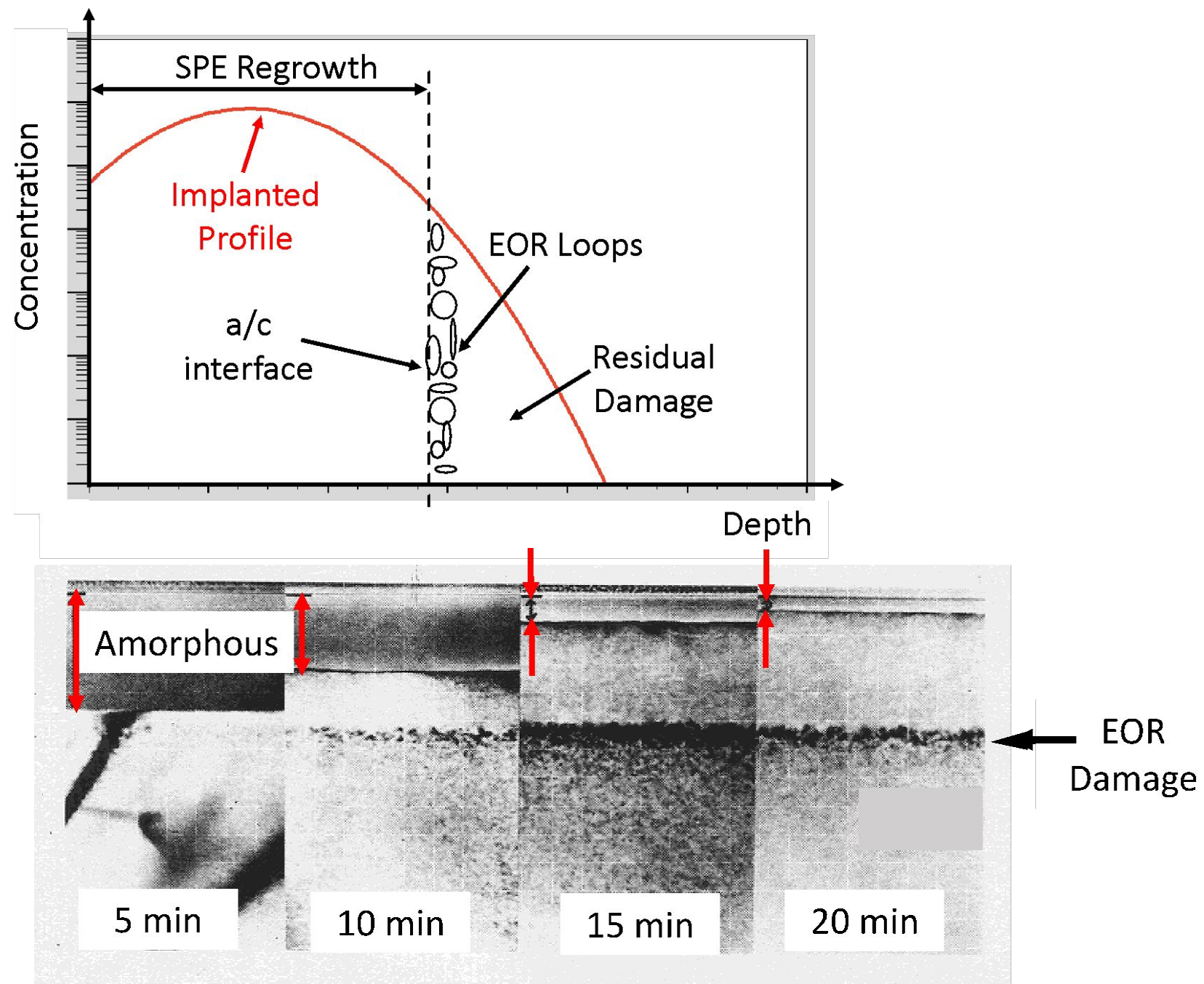


+1 Defects  
{311} plane





# Solid Phase Epitaxy



1. Amorphization is desirable
2. Regrowth is by Solid Phase Epitaxy
3. Crystal grows perfectly till the amorphous crystalline interface
4.  $\{311\}$  defects – Dislocation loops – Hard to remove
5. +1 should ideally form an epi layer
6. Transient Enhanced Diffusion
7. Release of Interstitials during the anneal step or subsequent thermal steps enhance dopant diffusion and the profile changes
8. Rapid thermal annealing

THANK YOU

