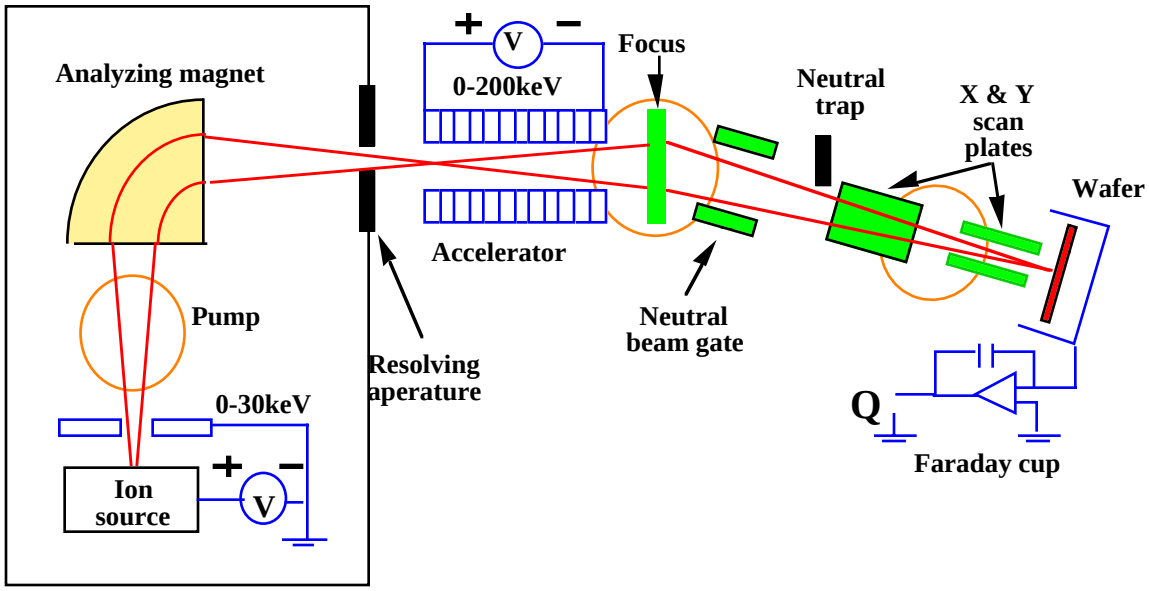
EE 212 FALL 1999-00

ION IMPLANTATION - Chapter 8

Basic Concepts

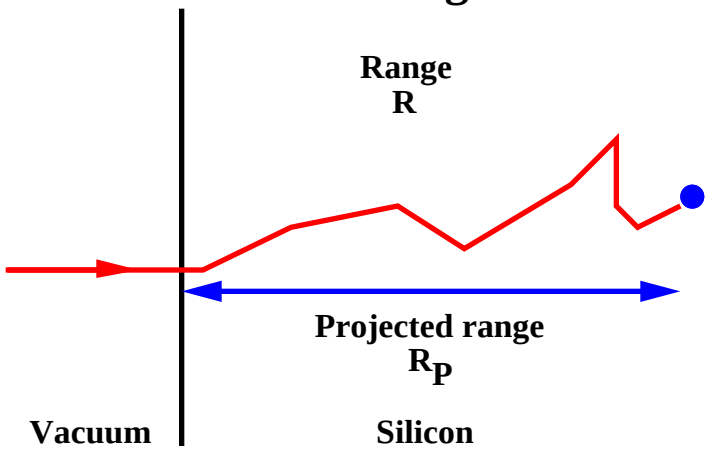
- **Ion implantation is the dominant method of doping used today. In spite of creating enormous lattice damage it is favored because:**
  - **Large range of doses - 10^{11} to 10^{16} /cm^2**
  - **Extremely accurate dose control**
  - **Essential for MOS V_T control**
  - **Buried (retrograde) profiles are possible**
  - **Low temperature process**
  - **Wide choice of masking materials**

- **There are also some significant disadvantages:**
  - **Damage to crystal**
  - **Anomalous transiently enhanced diffusion (TED) upon annealing this damage**
  - **Charging of insulating layers**

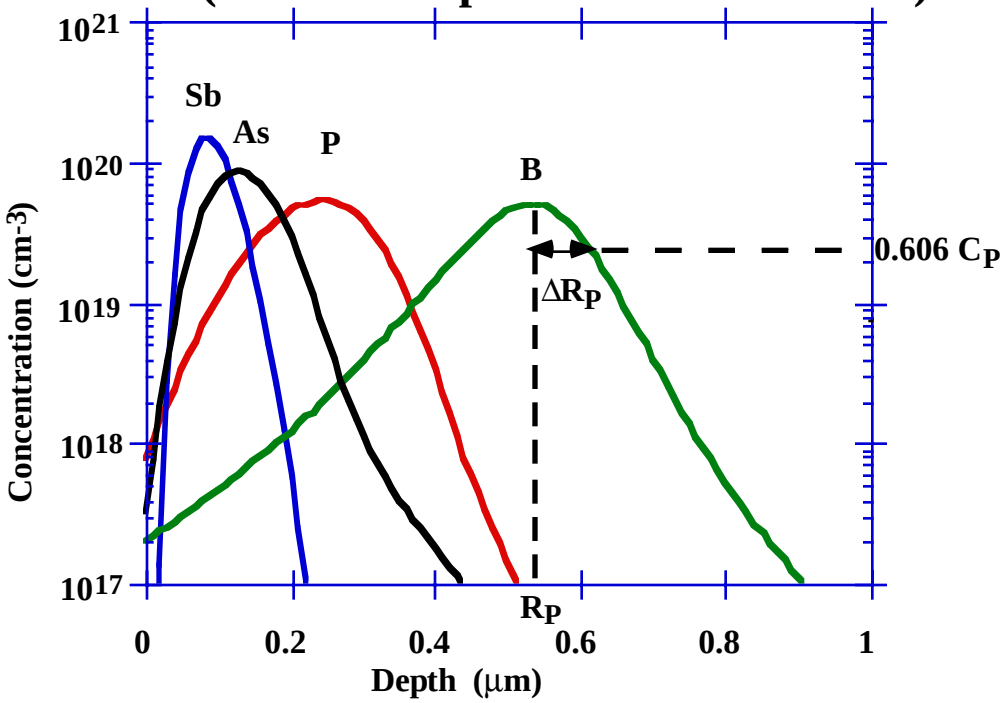


A. Implant Profiles

- At its heart ion implantation is a random process.
- High energy ions (1-1000keV) bombard the substrate and lose energy through nuclear collisions and electronic drag forces.



- Profiles can often be described by a Gaussian distribution, with a projected range and standard deviation. (200keV implants shown below.)

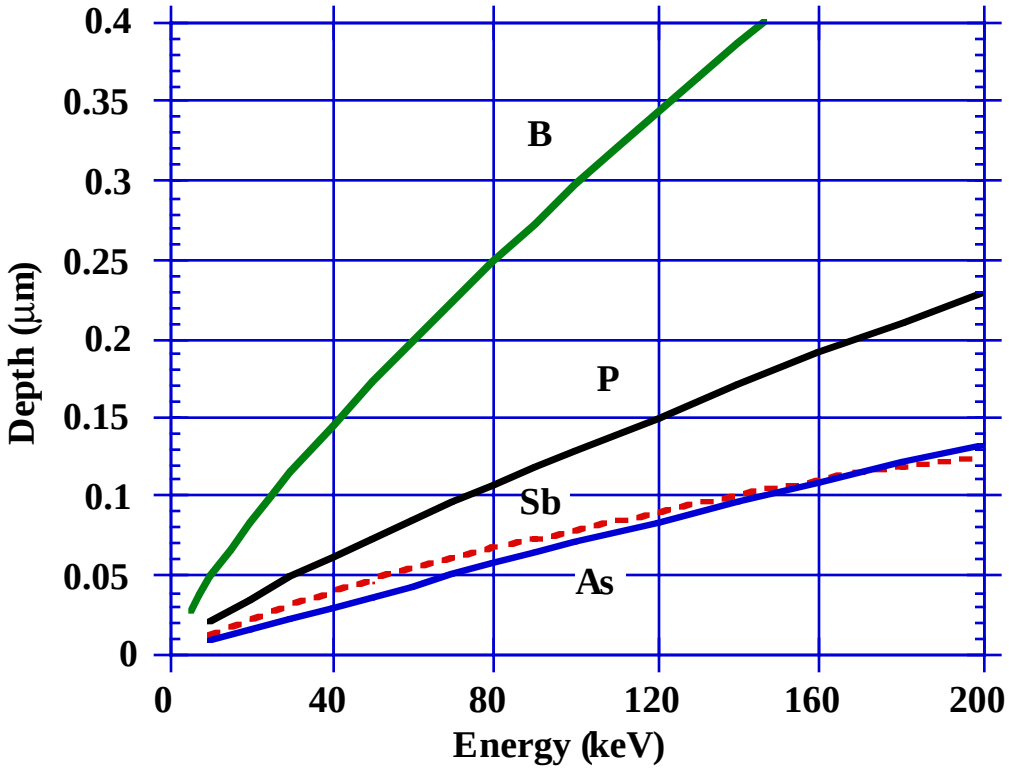


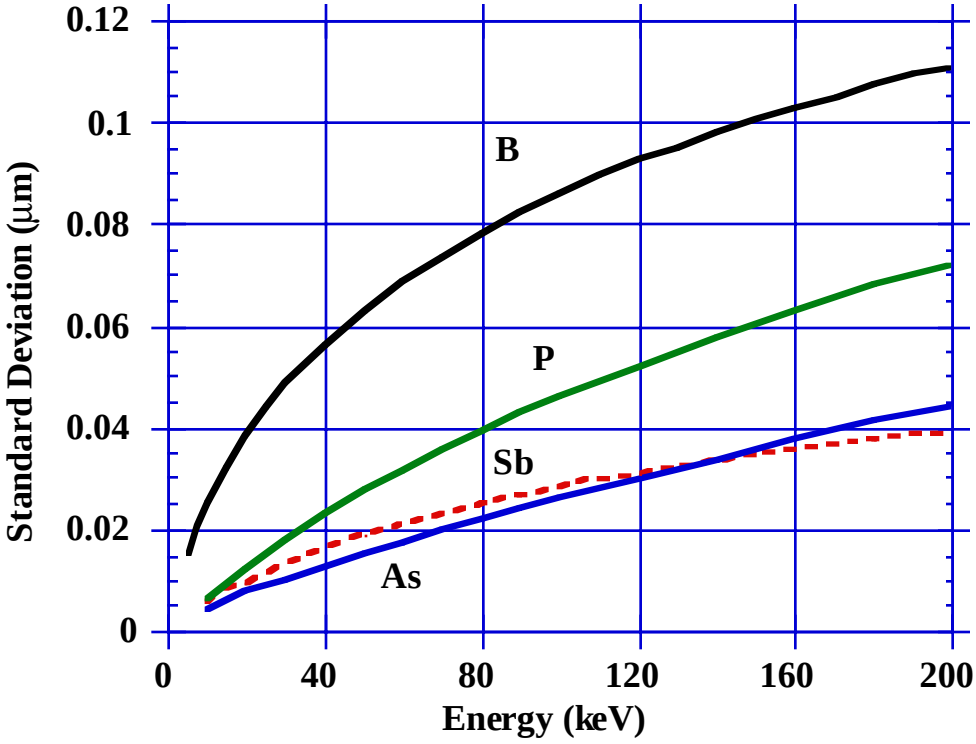
$$C(x) = C_P \exp\left(-\frac{(x - R_P)^2}{2\Delta R_P^2} \right) \qquad (1)$$

$$Q = \int_{-\infty}^{\infty} C(x)dx \text{ or } Q = \sqrt{2\pi}\, \Delta R_P\, C_P \qquad (2)$$

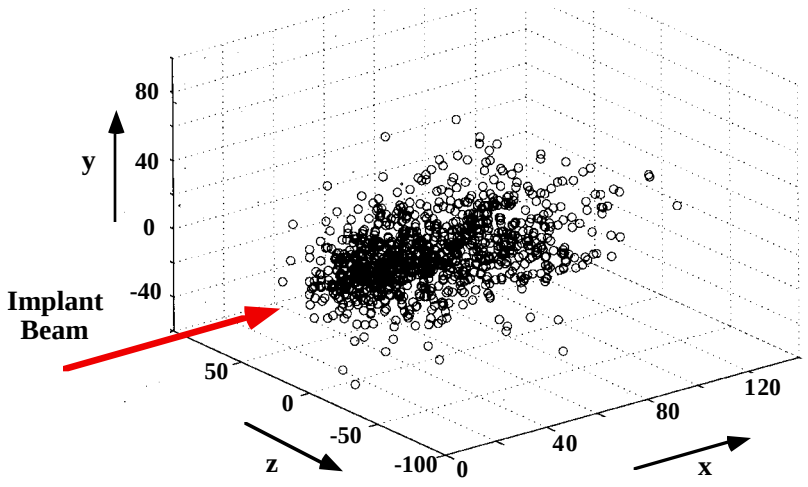
where Q is the dose in ions cm^{-2} and is measured by the integrated beam current.

- **The ranges and standard deviation ΔRp of the common dopants in randomly oriented silicon are shown below.**



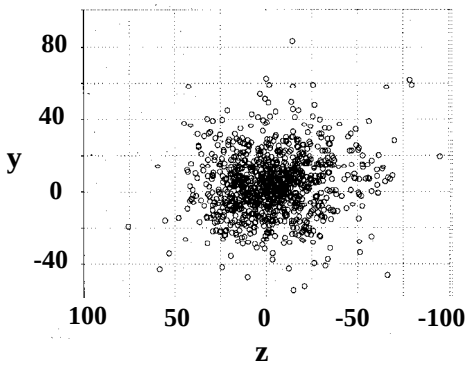


- **Monte Carlo simulations of the random trajectories of a group of ions implanted at a spot on the wafer show the 3-D spatial distribution of the ions. (1000 phosphorus ions at 35 keV.)**

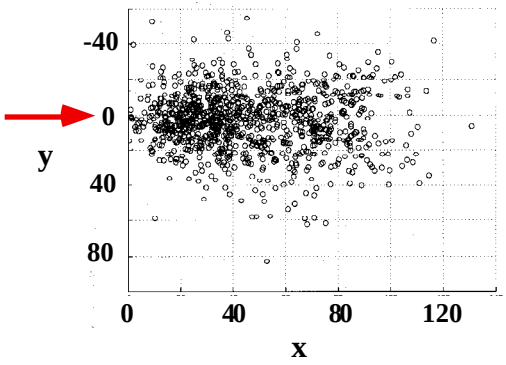


- **This appears as an elongated ellipse because most of the high energy ions undergo only small angle collisions.**

- **Side view shows Rp and ΔRp while the beam direction view shows the lateral straggle.**



Beam direction

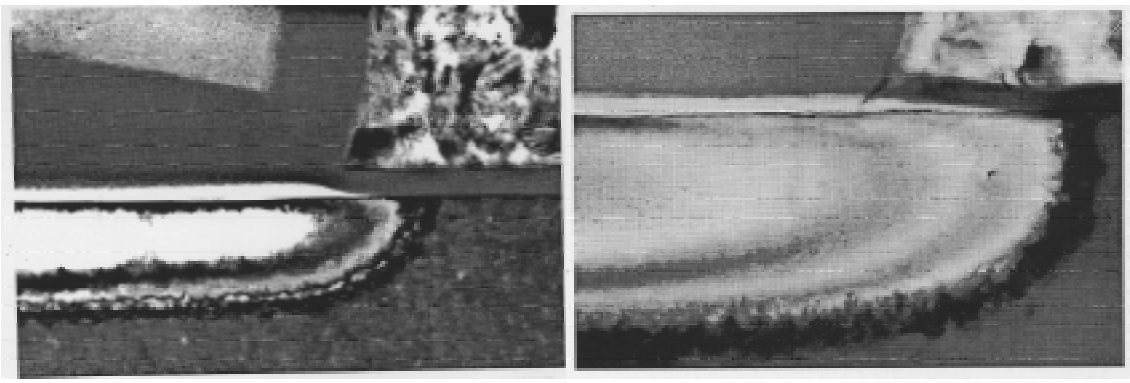


Side view

- **The two-dimensional distribution is often assumed to be composed of just the product of the vertical and lateral distributions.**

$$C(x,y) = C_{vert}(x)\exp\left(-\frac{y^2}{2\Delta R_{\perp}^2}\right) \qquad (3)$$

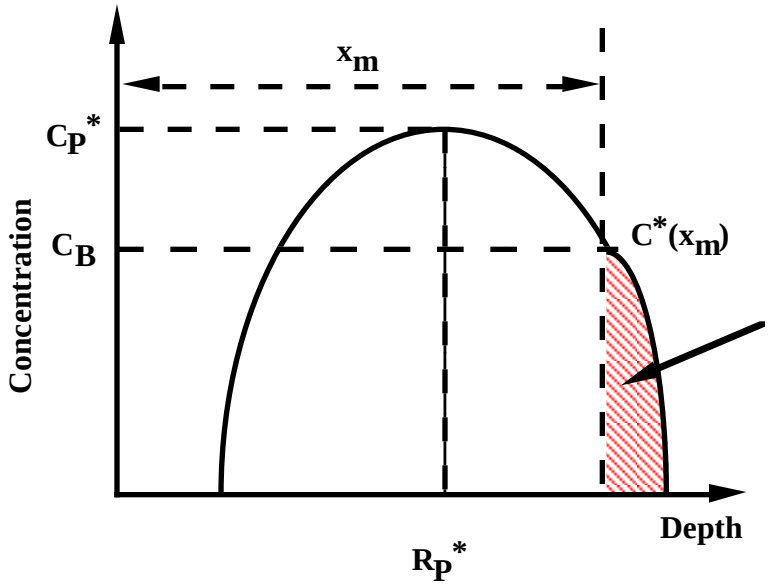
- **Now consider what happens at a mask edge - if the mask is thick enough to block the implant, the lateral profile under the mask is determined by the lateral straggle. (35keV and 120keV As implants at the edge of a poly gate from Alvis et al.)**



- **The description of the profile at the mask edge is given by a sum of point response Gaussian functions, which leads to an error function distribution under the mask.**

B. Masking Implants

How thick does a mask have to be?



- **For masking,**

$$C^*(x_m) = C_P^* \left(\exp\ -\frac{\left(x_m - R_P^*\right)^2}{2\Delta R_P^{*2}} \right) \le C_B \qquad (4)$$

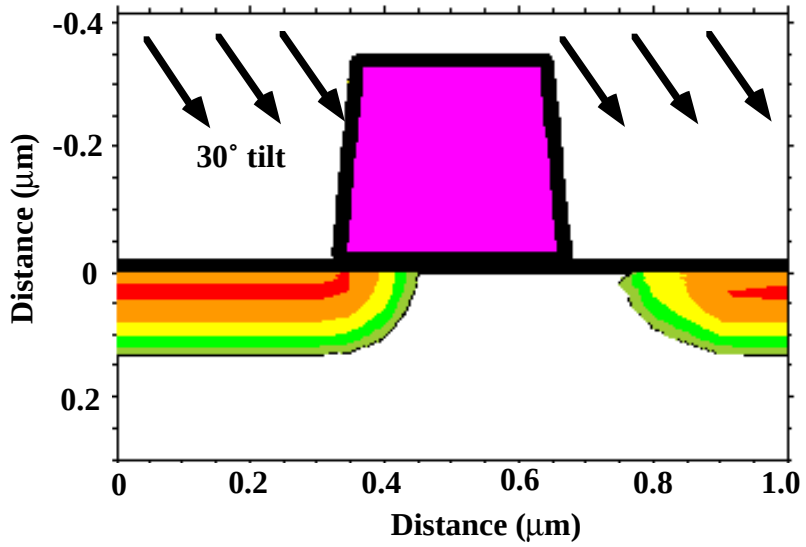
- **Calculating the required mask thickness,**

$$x_m = R_P^* + \Delta R_P^* \sqrt{2 \ln\left(\frac{C_P^*}{C_B}\right)} = R_P^* + m\Delta R_P^* \qquad (5)$$

• The dose that penetrates the mask is given by

$$Q_P = \frac{Q}{\sqrt{2\pi\Delta R_P^*}} \int_{x_m}^{\infty} \exp - \left[\frac{x - R_P^*}{\sqrt{2\Delta R_P^*}} \right]^2 dx = \frac{Q}{2} \operatorname{erfc}\left(\frac{x_m - R_P^*}{\sqrt{2}\,\Delta R_P^*} \right) \quad (6)$$

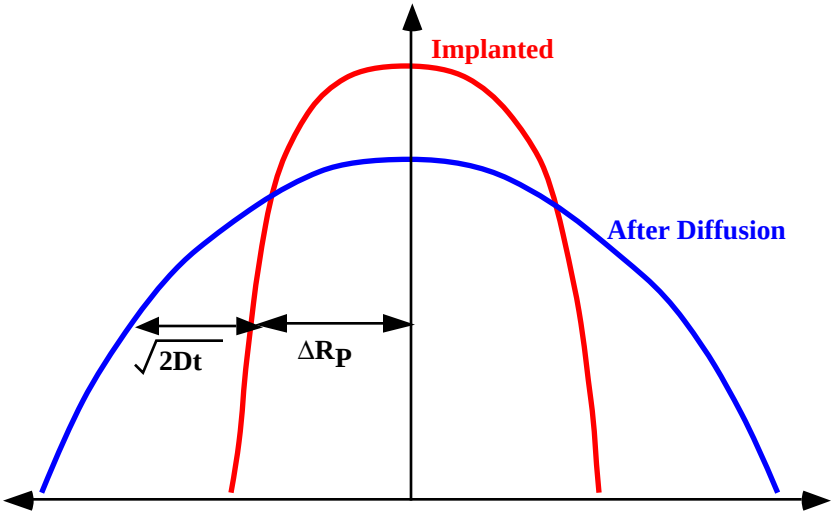
• Real structures may be more complicated because mask edges or implants are not vertical.



C. Profile Evolution During Annealing

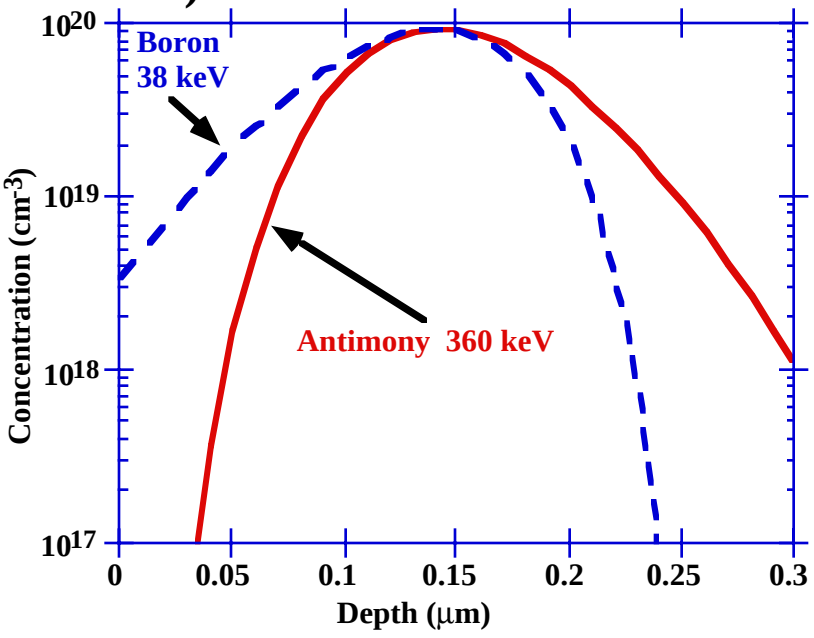
• Comparing Eqn. (1) with the Gaussian profile from the last set of notes, we see that ΔRp is equivalent to $2\sqrt{Dt}$. Thus

$$C(x,t) = \frac{Q}{\sqrt{2\pi\left(\Delta R_P^2 + 2Dt\right)}} \exp\left(- \frac{\left(x - R_P\right)^2}{2\left(\Delta R_P^2 + 2Dt\right)} \right) \quad (7)$$



- **Thus if the implanted profile is Gaussian, later thermal cycles produce a Gaussian profile as well (assuming the surface doesn't come into play).**

- **The only other profile we can calculate analytically is when the implanted Gaussian is shallow enough that it can be treated as a delta function and the subsequent anneal can be treated as a one-sided Gaussian. (Recall example in diffusion notes.)**



- Real implanted profiles are more complex.
  - Light ions backscatter to skew the profile upwards.
  - Heavy ions scatter deeper.

- 4 moment descriptions of these profiles are often used (with tabulated values for these moments).

Range:
$$R_P = \frac{1}{Q}\int_{-\infty}^{\infty} x\,C(x)\,dx \qquad (8)$$

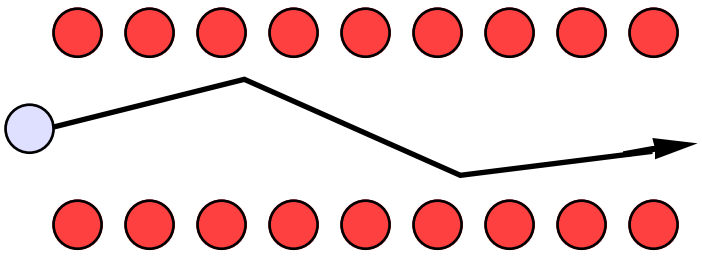
Std. Dev:
$$\Delta R_P = \sqrt{\frac{1}{Q}\int_{-\infty}^{\infty}\left(x - R_P\right)^2 C(x)\,dx} \qquad (9)$$

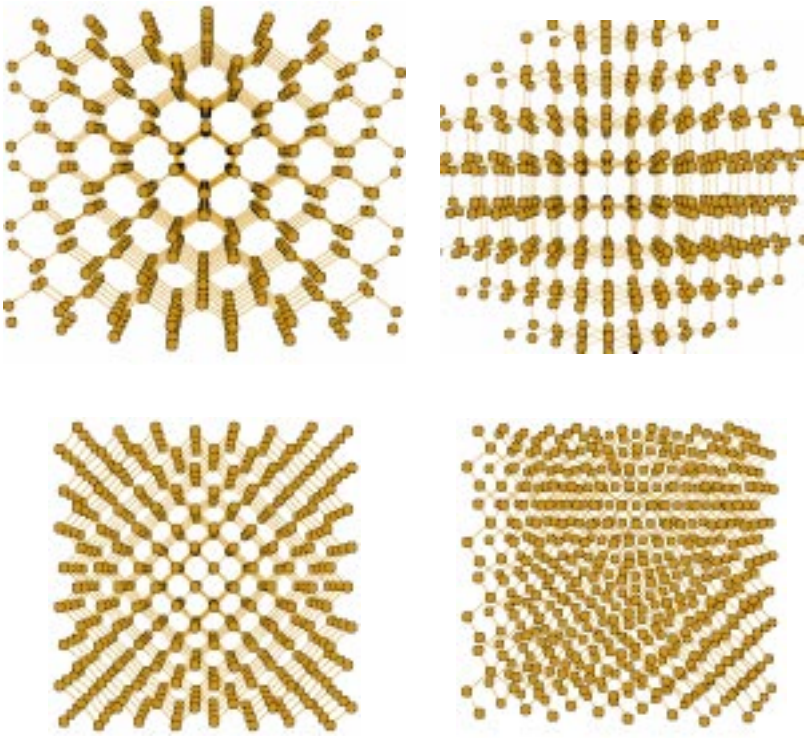
Skewness:
$$\gamma = \frac{\int_{-\infty}^{\infty}\left(x - R_P\right)^3 C(x)\,dx}{Q\,\Delta R_P^3} \qquad (10)$$

Kurtosis:
$$\beta = \frac{\int_{-\infty}^{\infty}\left(x - R_P\right)^4 C(x)\,dx}{Q\,\Delta R_P^4} \qquad (11)$$

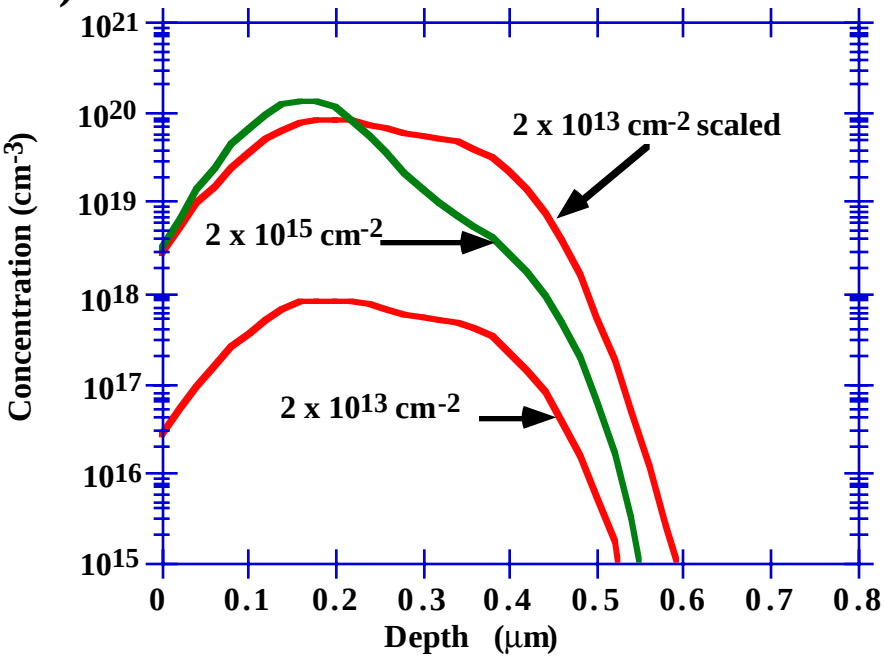
D. Implants in Real Silicon - Channeling

- At least until it is damaged by the implant, Si is a crystalline material.
- Channeling can produce unexpectedly deep profiles.





• **Screen oxides and tilting/rotating the wafer can minimize but not eliminate these effects. (7˚ tilt is common.)**



• **Sometimes a dual Pearson profile description is useful.**

Modeling of Range Statistics

- The total energy loss during an ion trajectory is given by the sum of nuclear and electronic losses (these can be treated independently).

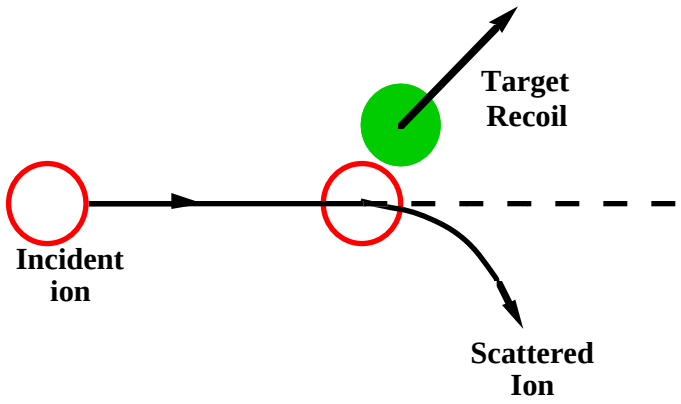
$$\frac{dE}{dx} = -N\left(S_n + S_e\right) \qquad (12)$$

$$R = \int_0^R dx = \frac{1}{N}\int_0^{E_0} \frac{dE}{S_n(E) + S_e(E)} \qquad (13)$$

A. Nuclear Stopping

- An incident ion scatters off the core charge on an atomic nucleus, modeled to first order by a screened Coulomb scattering potential.

$$V(r) = \frac{q^2 Z_1 Z_2}{4\pi\varepsilon r} \exp\left(-\frac{r}{a}\right) \qquad (14)$$



- This potential is integrated along the path of the ion to calculate the scattering angle. (Look-up tables are often used in practice.)

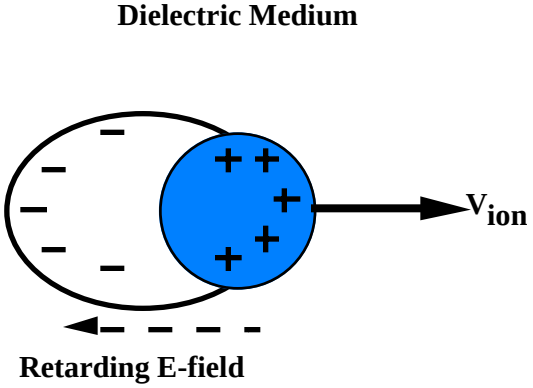
• $S_n(E)$ in Eqn. (13) can be approximated by

$$S_n(E) = 2.8x10^{-15} \frac{Z_1 Z_2}{\left(Z_1^{2/3} + Z_2^{2/3}\right)^{1/2}} \frac{m_1}{m_1 + m_2} \quad eV - cm^2 \tag{15}$$

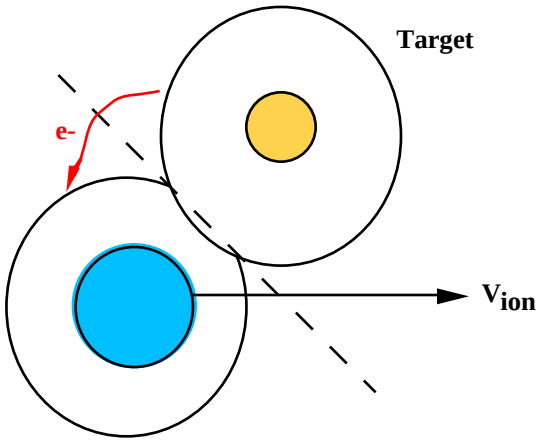
where Z_1, m_1 = ion and Z_2, m_2 = substrate.

B. Non-Local and Local Electronic Stopping

• Drag force caused by charged ion in "sea" of electrons (non-local electronic stopping).



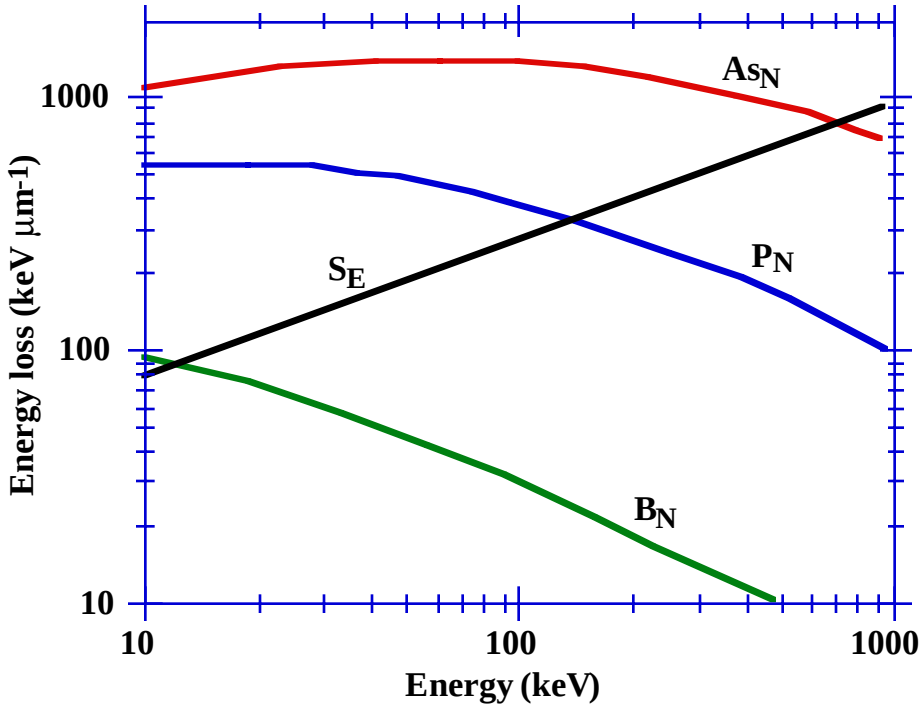
• Collisions with electrons around atoms transfers momentum and results in local electronic stopping.



• To first order,

$$S_e(E) = cv_{ion} = kE^{1/2}, \quad k \cong 0.2x10^{-15} \ \ ev^{1/2}\ cm^2 \quad (16)$$

C. Total Stopping Power



• The critical energy E_c when the nuclear and electronic stopping are equal is

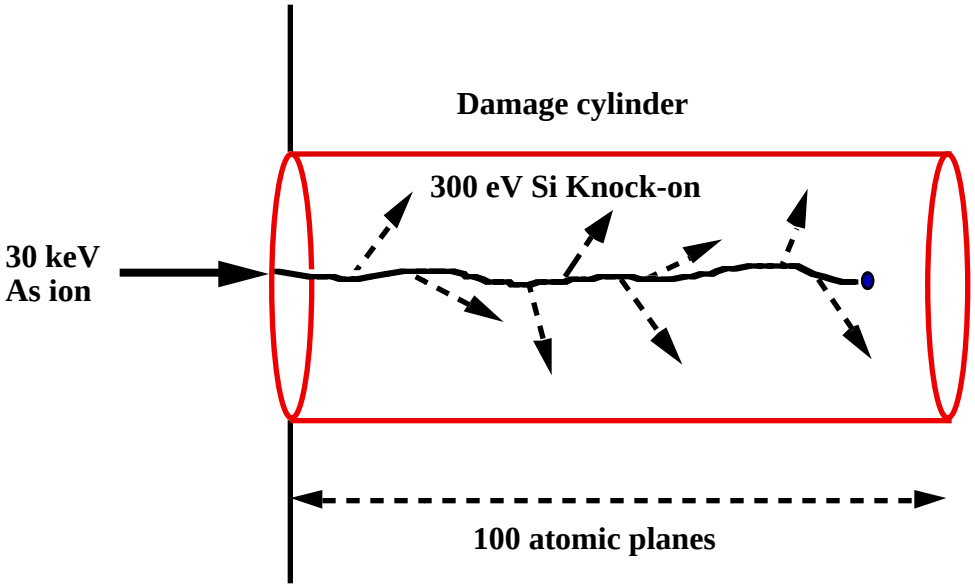
B: ≈ 17keV
P: ≈ 150keV
As, Sb : > 500keV

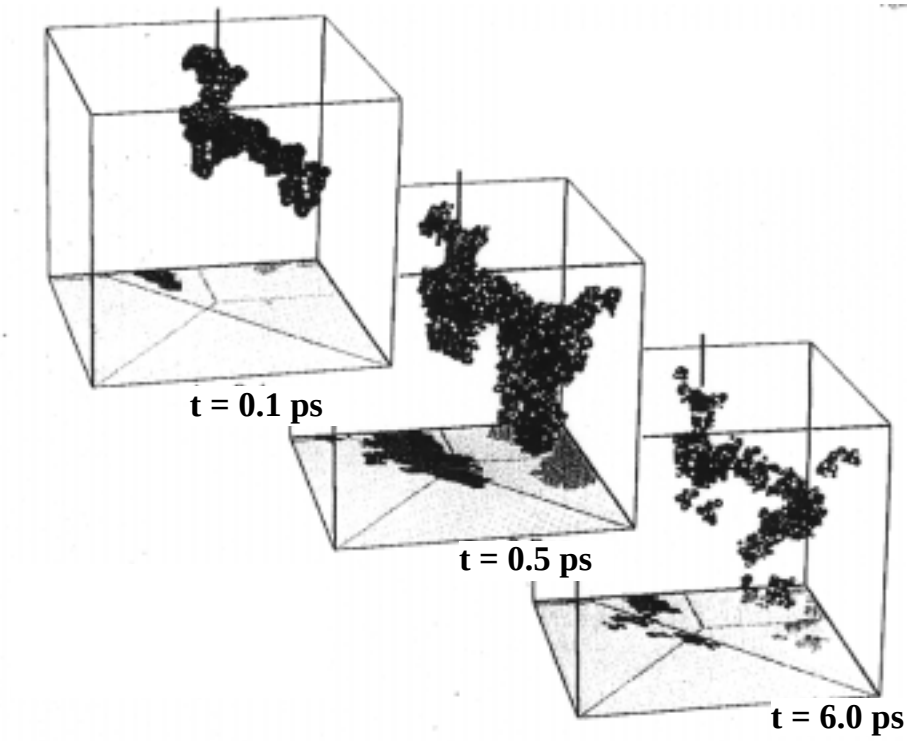
Damage Production

• Consider a 30keV arsenic ion, which has a range of 25 nm, traversing roughly 100 atomic planes.

- **The number of displaced particles created by an incoming ion is given by**

$$n = \frac{E_n}{2E_d} = \frac{30,000}{2 \times 15} = 1000 \quad \text{ions} \qquad (17)$$

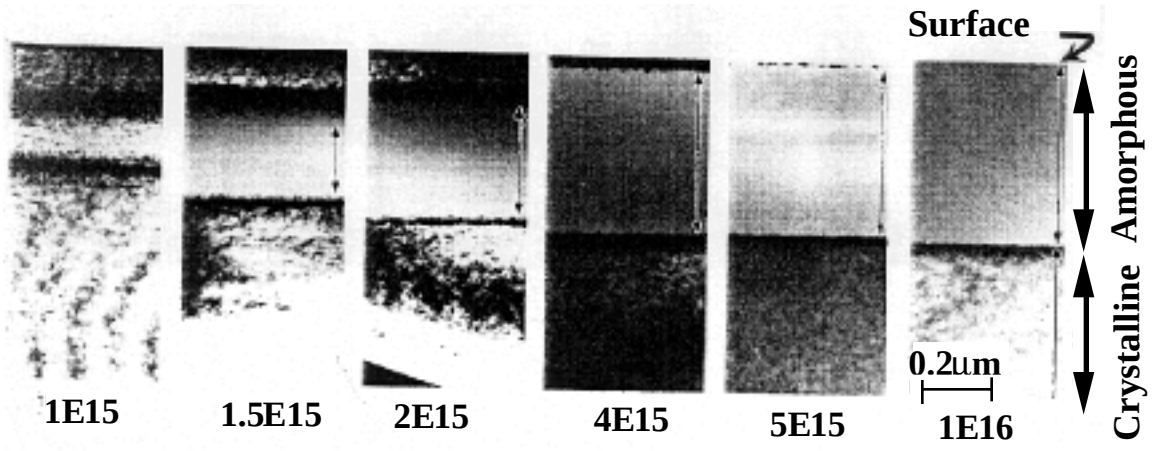




- **Molecular dynamics simulation of a 5keV Boron ion implanted into silicon [de la Rubia, LLNL]**

Amorphization

- For high enough doses, the crystal becomes amorphous and loses all long range order. At this point, the arrangement of lattice atoms is random and the damage accumulation has saturated.

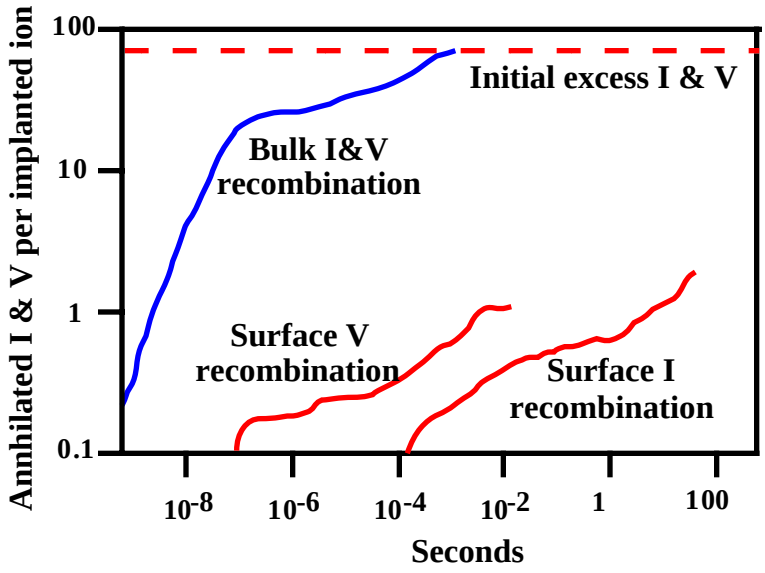


- Cross sectional TEM images of amorphous layer formation with increasing implant dose (300keV Si -> Si) [Rozgonyi]

Damage Annealing

Goals:

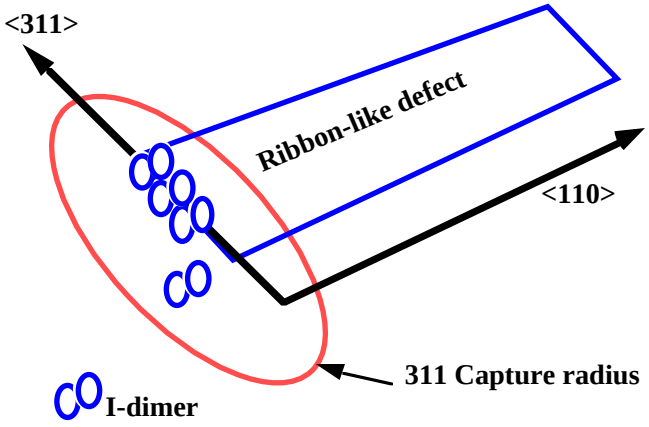
- Remove primary damage created by the implant and activate the dopants.
- Restore silicon lattice to its perfect crystalline state.
- Restore the electron and hole mobility.
- Do this without appreciable dopant redistribution.

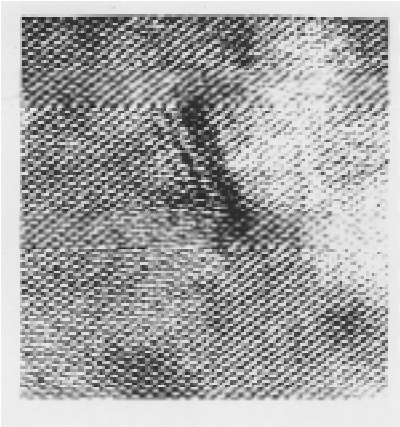


- **Bulk and surface recombination take place on a short time scale.**

- **"+1" I excess remains. These I coalesce into {311} defects which are stable for longer periods.**

- **{311} defects anneal out in sec - min at moderate temperatures (800 - 1000˚C) but eject I ⇒ TED.**

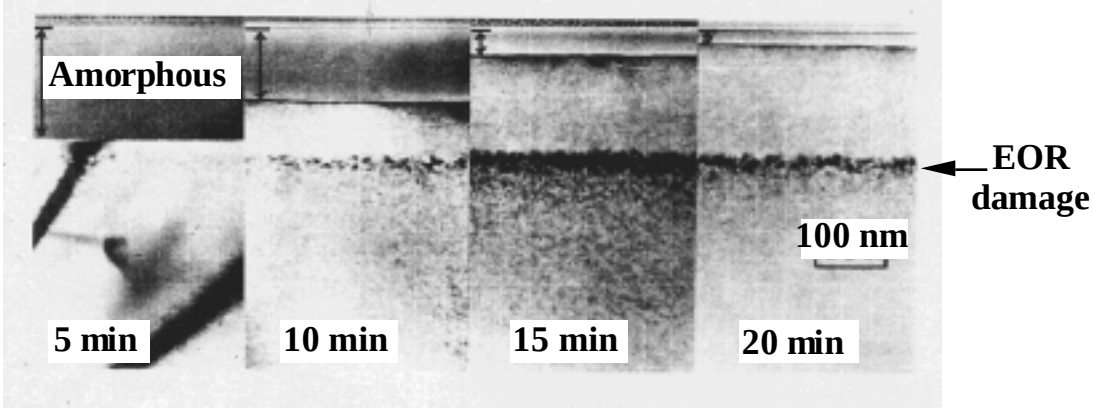




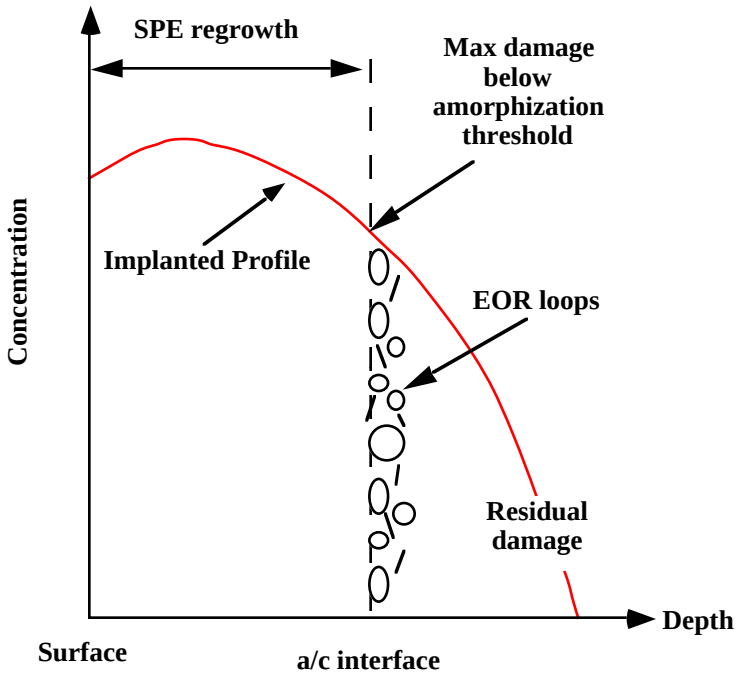
- **Stable dislocation loops can form when the damage is greater (amorphizing implant - see below).**

Solid Phase Epitaxy

- If the substrate is amorphous, it can regrow by SPE.



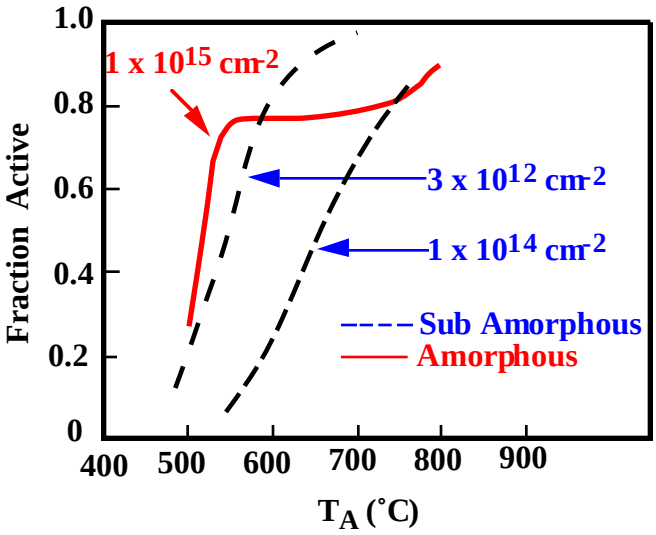
- Cross sectional TEM images of amorphous layer regrowth at 525˚C, from a 200keV, 6e15 cm^{-2} Sb implant [Fletcher].

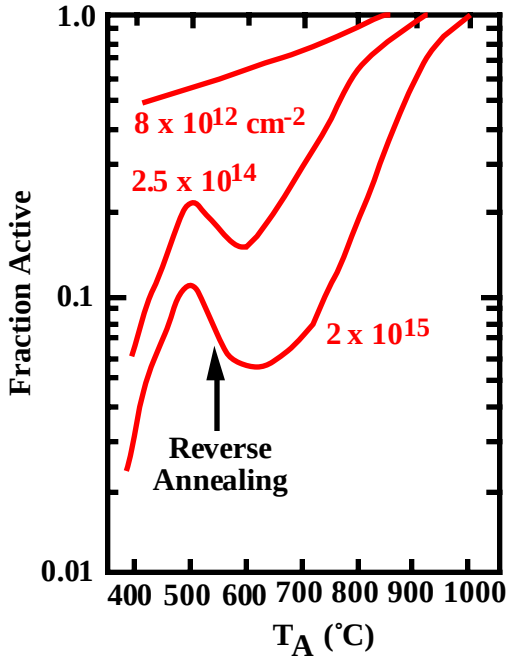


- BUT - the tail of damage beyond the a/c interface can nucleate stable, secondary defects and cause transient enhanced diffusion (TED).

Dopant Activation

- When the substrate is amorphous, SPE provides an ideal way of repairing the damage and activating dopants.
- At lower implant doses, activation is much more complex because stable defects form.

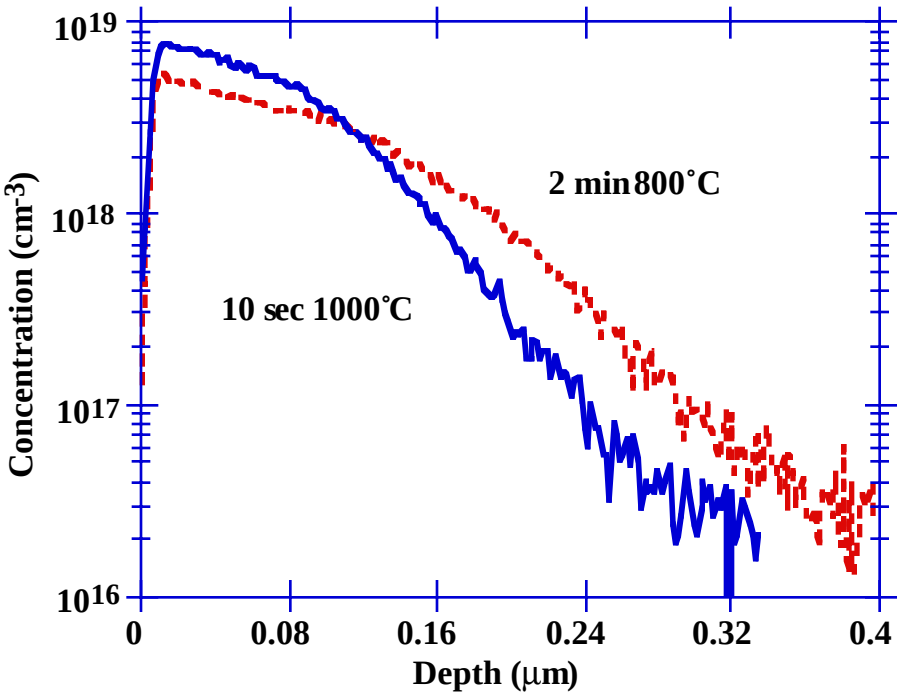




- Plot (above) of fractional activation versus anneal temperature for Boron. The intermediate temperature range represents reverse annealing.

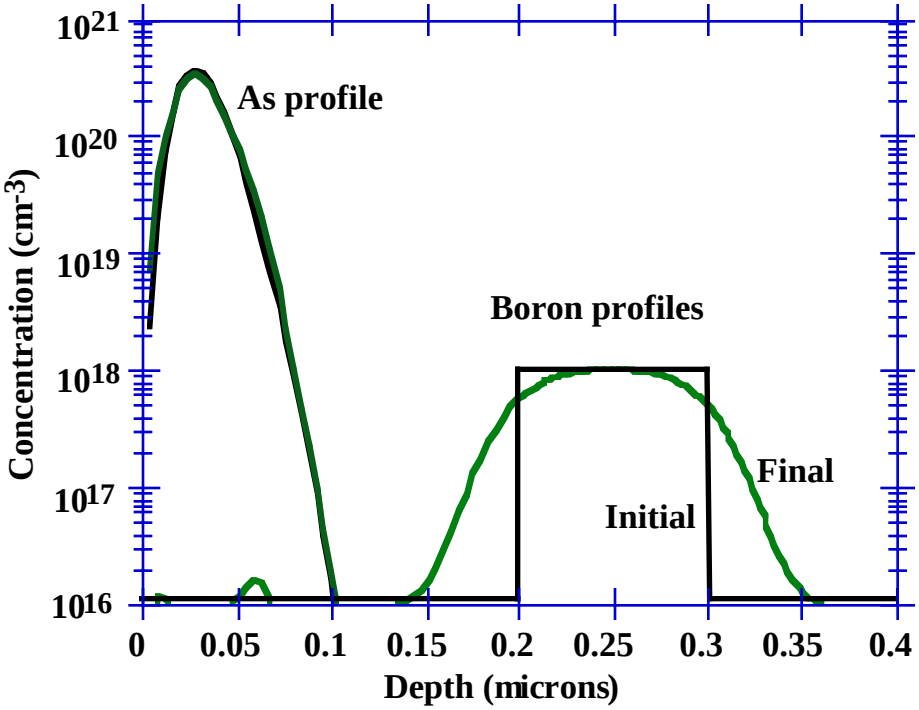
- Reverse annealing is though to occur because of a competition between the native interstitial point defects and the boron atoms for lattice sites.

Transient Enhanced Diffusion



- TED is the result of interstitial damage from the implant enhancing the dopant diffusion for a brief transient period.
- It is the dominant effect today that determines junction depths in shallow profiles.
- It is anomalous diffusion, because profiles can diffuse more at low temperatures than at high temperatures for the same Dt.

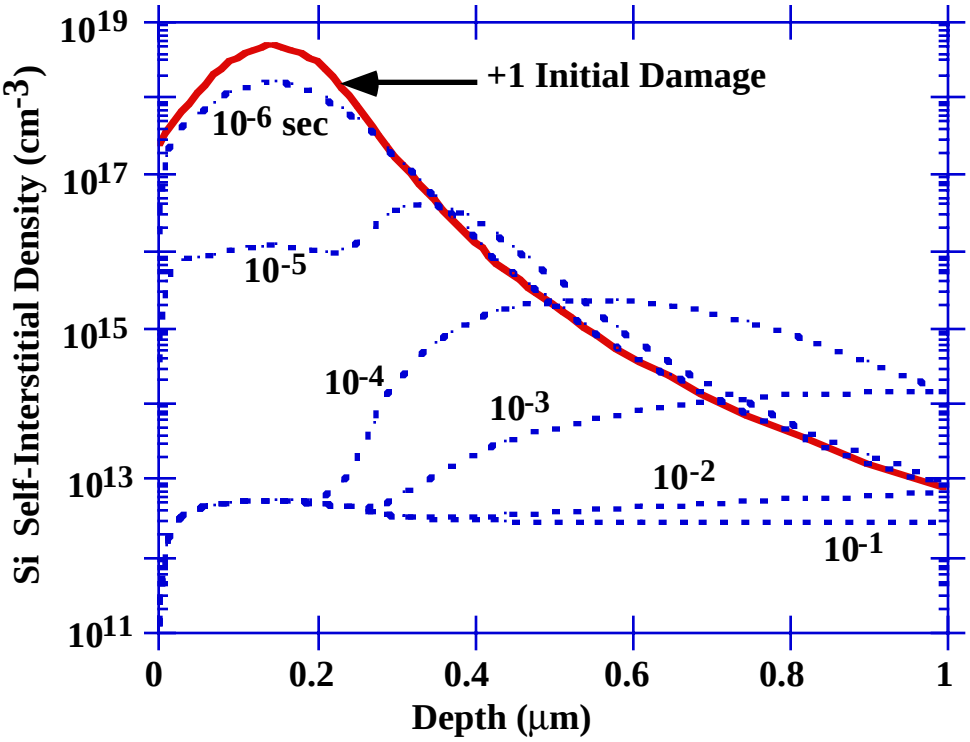
- **The basic model for TED assumes that all the implant damage recombines rapidly, leaving only 1 interstitial generated per dopant atom when the dopant atom occupies a substitutional site (the +1 model) [Giles].**



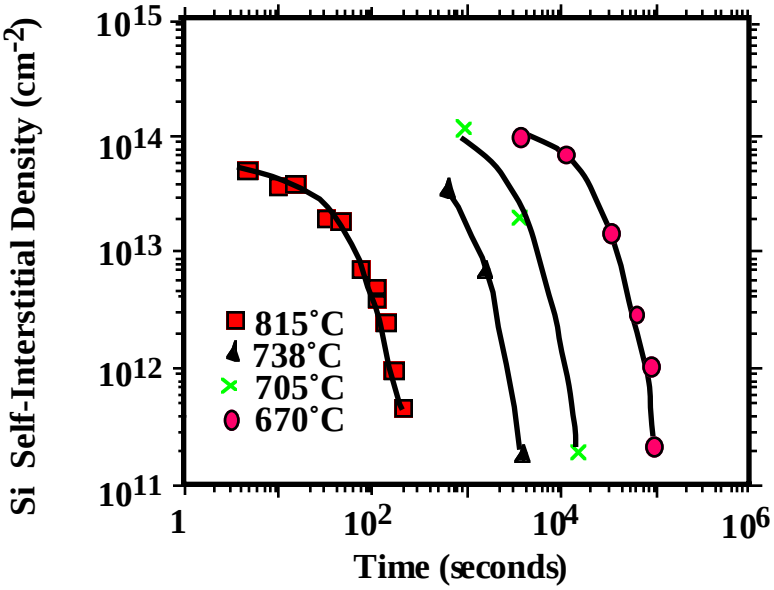
- **TED effects may be very non-local. Here the As profile recrystallizes by SPE without much TED. The buried boron layer is drastically affected by the +1 interstitials in the As tail region.**

Atomic Level Understanding Of TED

- **{311} clusters form rapidly and then are stable for extended periods (sec - min), driving TED by emitting I while they shrink.**



- **By 0.1 sec (750˚C), the {311} defects have formed and C_I is down to ≈ 10^{13} cm^{-3} (SUPREM).**
- **But C_I^* ≈ 10^8 cm^{-3} at 750˚C, so the enhancement is > 10^5!**



- This enhancement decays over a time period of sec - min as the {311} clusters break up.

- Given this picture, we can model the {311} behavior as follows:

$$I + Cl_n \Leftrightarrow Cl_{n+1} \qquad (18)$$

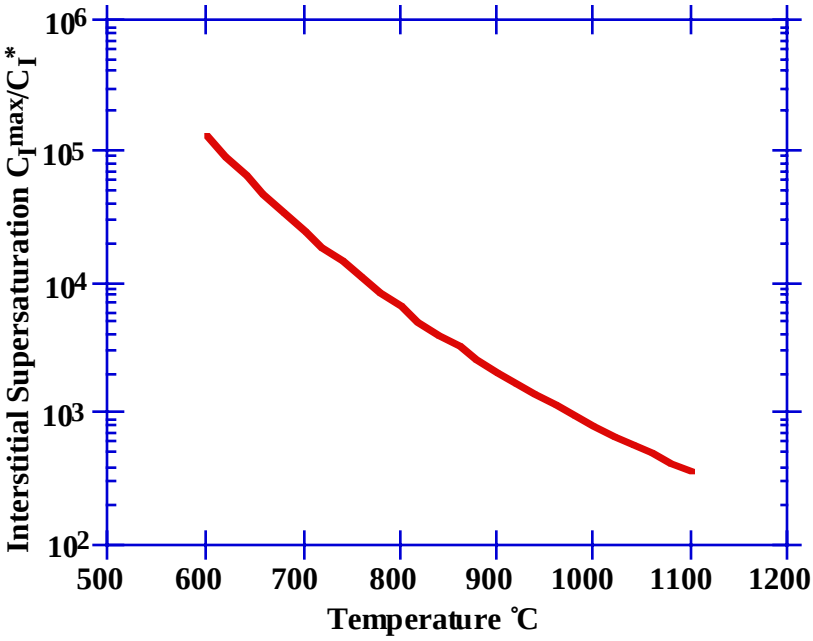
where Cl_n is a cluster with n interstitials.

$$-\frac{\partial C_I}{\partial t} = \frac{\partial Cl}{\partial t} = k_f C_I Cl - k_r Cl \qquad (19)$$
$$= \text{growth} - \text{shrinkage}$$

- The most important part of the transient is while the {311} clusters are evaporating I, maintaining a constant supersaturation of I.

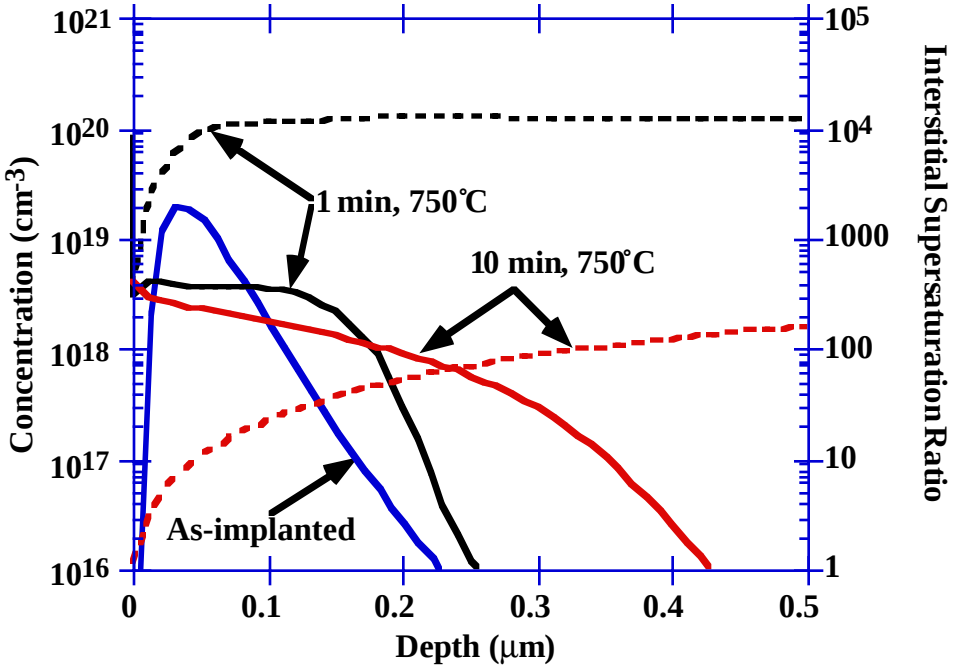
- During this period, dopant diffusivity enhancements are ≈ constant and given by (see text):

$$\frac{C_I^{max}}{C_I^*} = \frac{1}{4\pi a^3 C_I^0} \exp\left(-\frac{E_b - E_F}{kT}\right) \qquad (20)$$



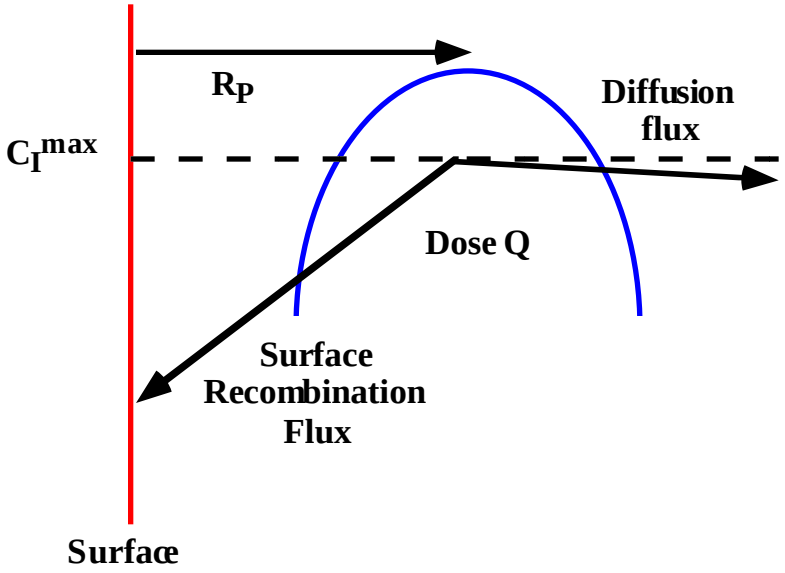
Estimating the Duration of TED

- **Over time the interstitial supersaturation decays to zero and TED ends.**



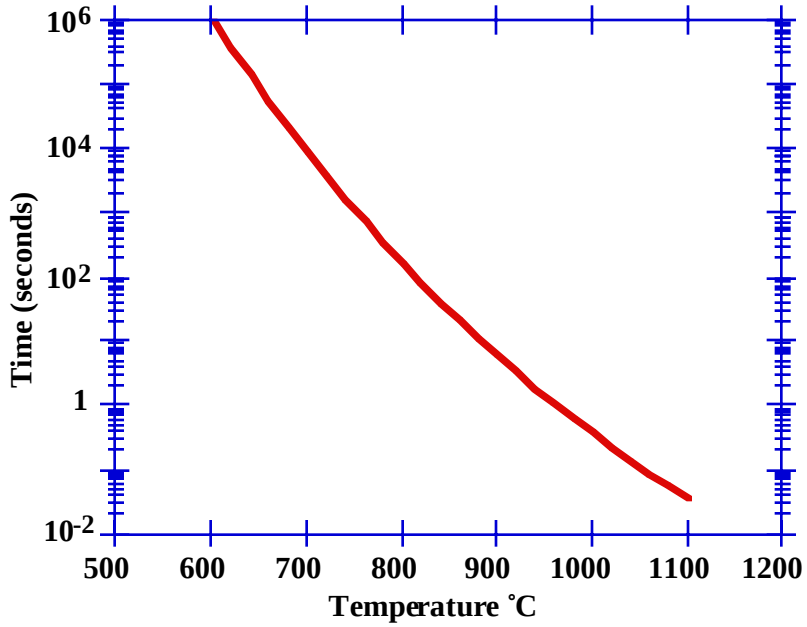
- **Example - Boron TED. Note that $C_I/\ C_I^*$ has dropped from 10^4 to 10^2 in 10 min at 750˚C.**

- The excess I diffuse into the bulk and recombine at the surface.

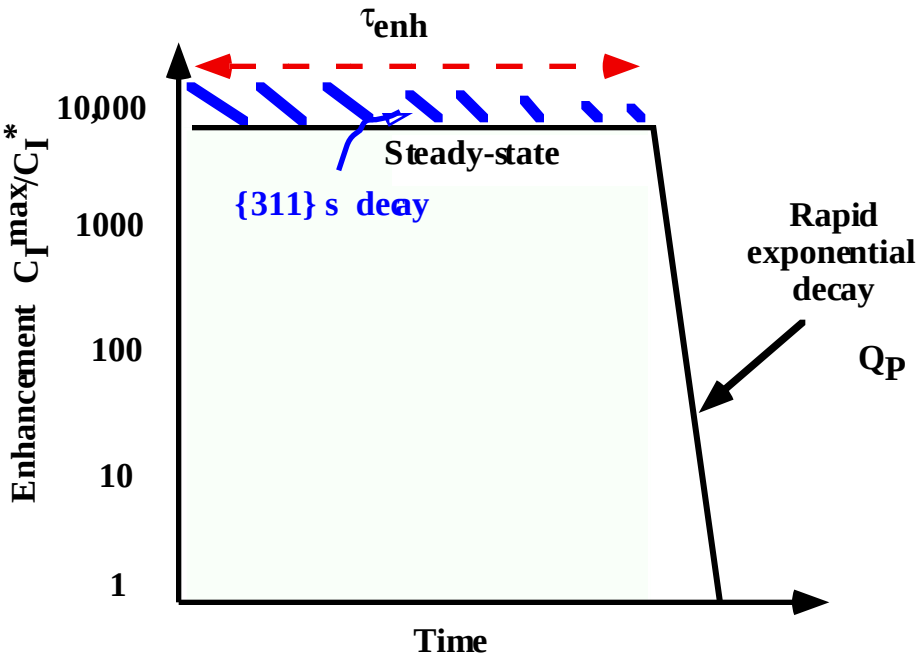


- The flux towards the surface is $d_I C_I^{max} / R_P$ where R_P is the range of the implant.
- The time to dissolve the clusters is given by the dose divided by the flux (see text):

$$\tau_{enh} = \frac{4\pi a^3 R_P Q}{d_I} \exp\left(\frac{E_b}{kT}\right) \qquad (21)$$



- **Thus the general picture of TED that emerges is:**



- **Because the {311} clusters exist for longer times at low T, there can actually be greater dopant motion during low T anneals.**