Ion Implantation

Two-step diffusion

$$Q = \frac{2N_S\sqrt{Dt}}{\sqrt{\pi}}$$

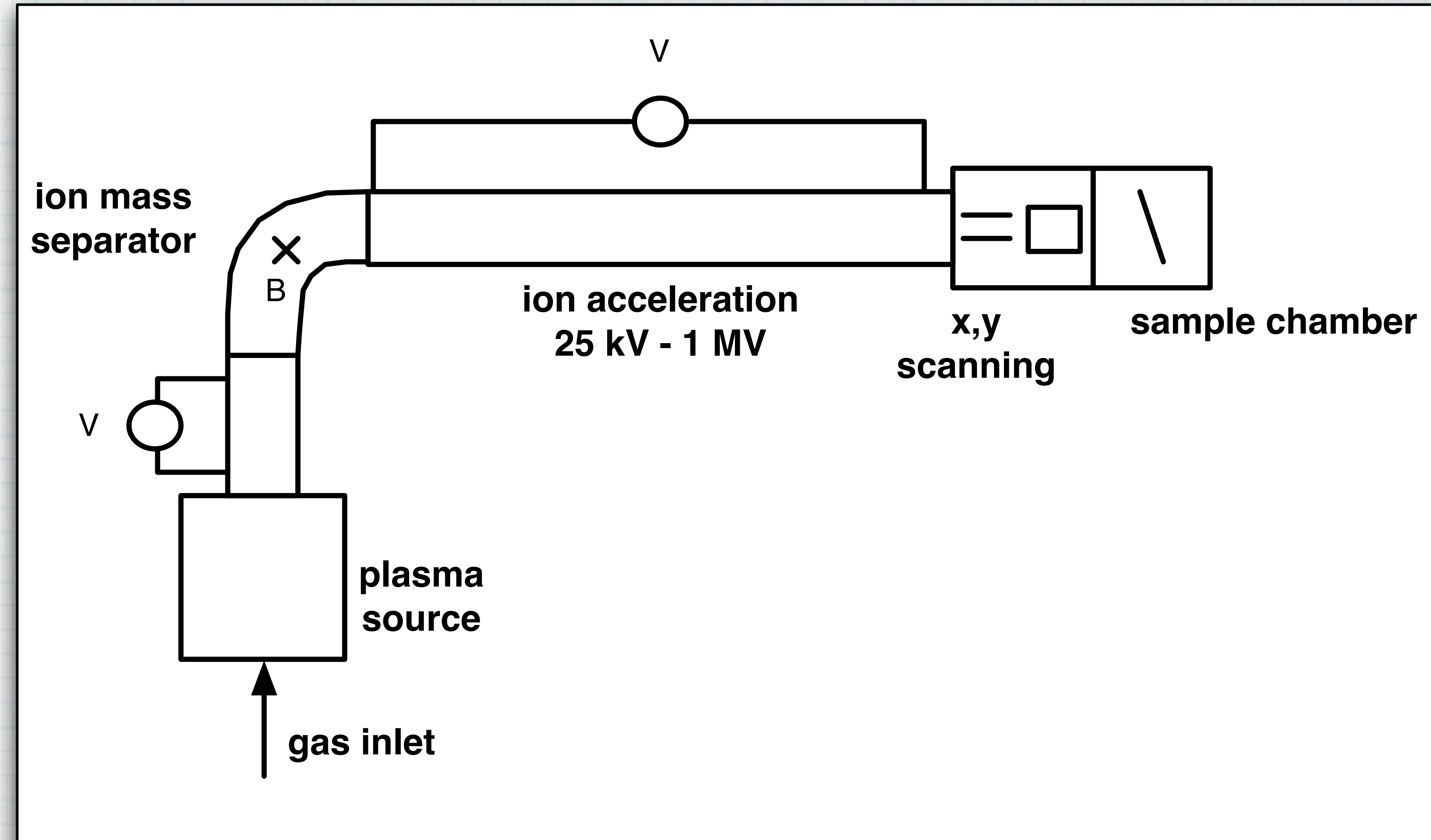
N_s → solid solubility limit → huge.

To get a low dose requires small Dt, which is difficult to control.

Ion implantation

- small, controllable doses
- profiles can be tailored, not restricted to error function or gaussian profiles
- much faster → one wafer completed in seconds
- low-temperature (sort of), so more flexibility in processing

Expensive !!



Ion implantation system

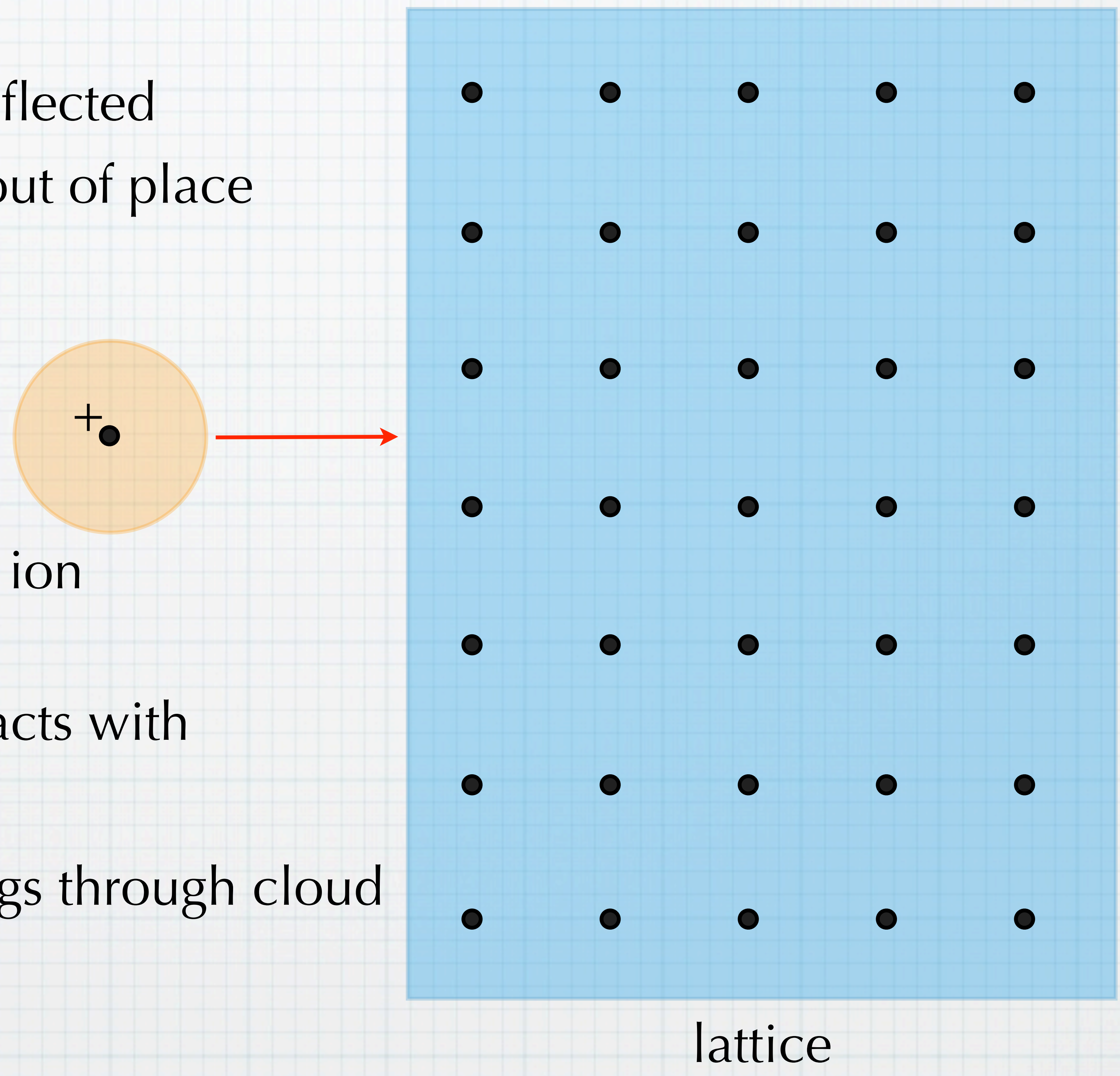
- Ions (B^+, P^+, As^+) are created in a plasma. (We'll study it later.)
- Desired ions are filtered out using *mass separation*.
- Dopant ions are accelerated to high energies (25 keV – 1 MeV).
- Ion beam is deflected and rastered across the wafer surface.

Example of a “smallish” ion implanter.

ion stopping

nuclear – ion cores interact

- incoming ion is strongly deflected
- lattice atoms are knocked out of place



electronic – ion interacts interacts with electron cloud of the lattice.

- energy is lost as the ion drags through cloud
- similar to viscous friction

- In stopping the ions, most of the energy is lost through electronic interactions.
- Nuclear interactions still have a strong effect – randomized motion and crystal damage.
- Detailed theories for nuclear stopping in solids have existed for several decades. Linhardt, Scharff, and Schiott (c. 1963) provided the first unified treatment that could be applied to semiconductors. Known as LSS theory. The treatment is beyond our purposes here, but you are welcome to read further on your own.

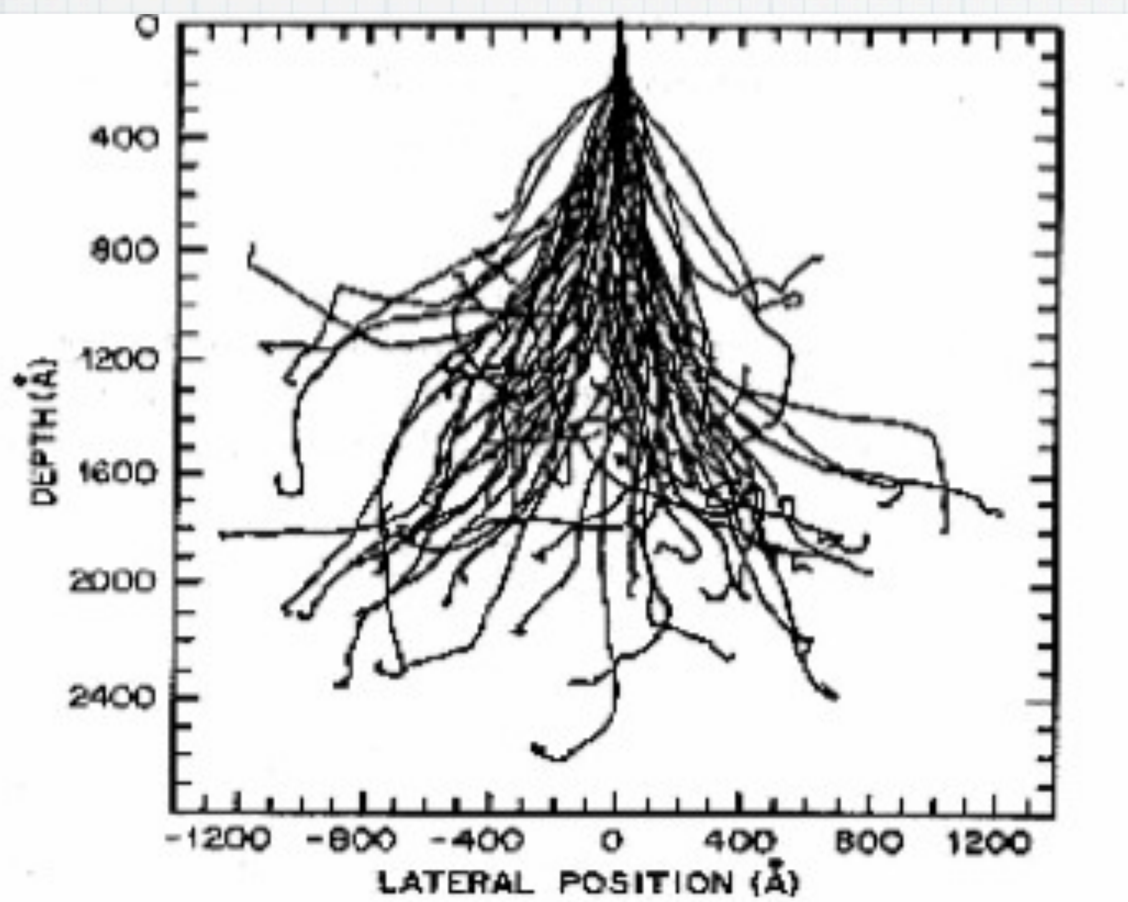


FIGURE 1
Monte Carlo calculation of 128 ion tracks for 50 keV boron implanted into silicon.

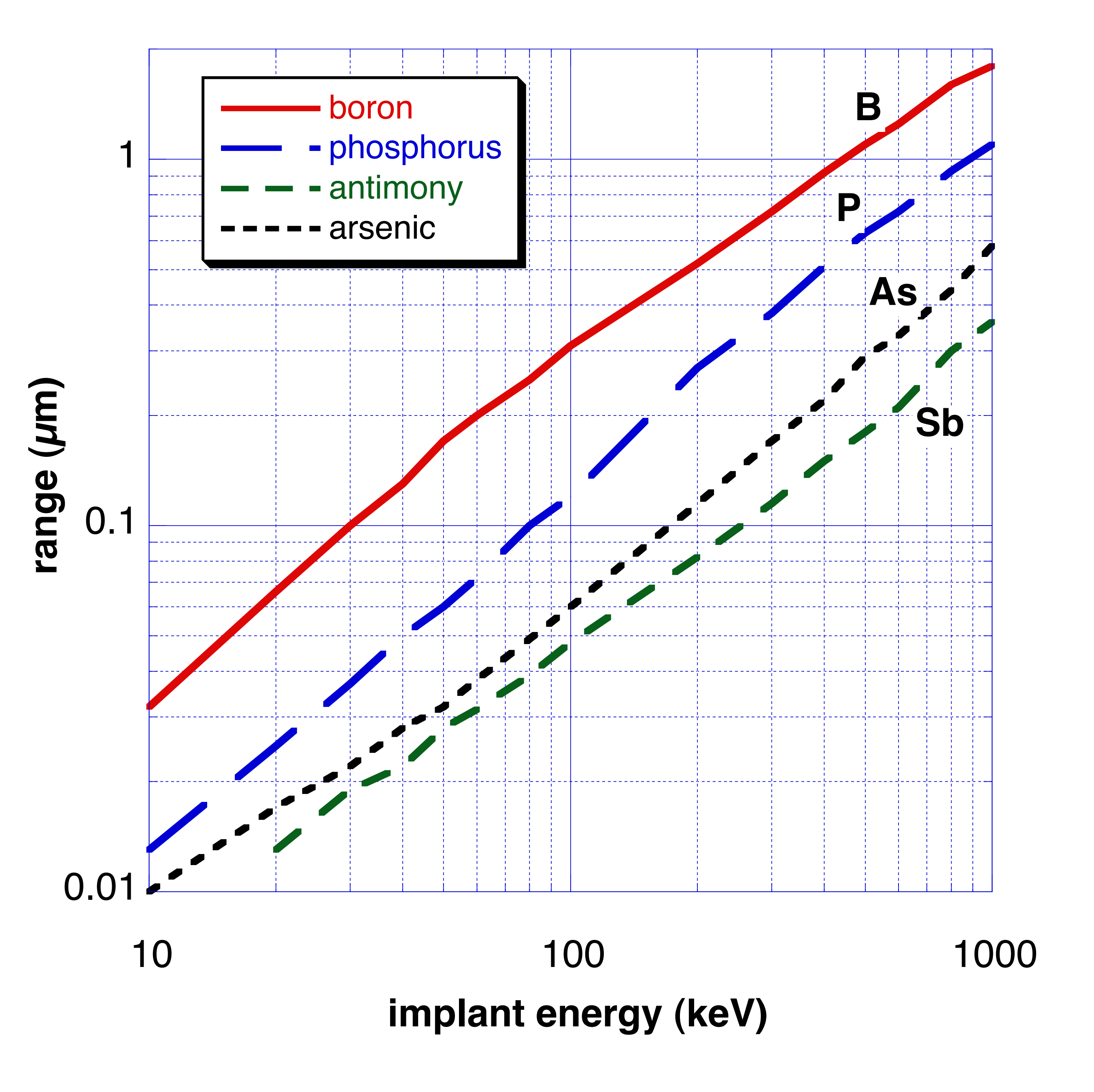
The theory provides a statistical description of the dopant profile.

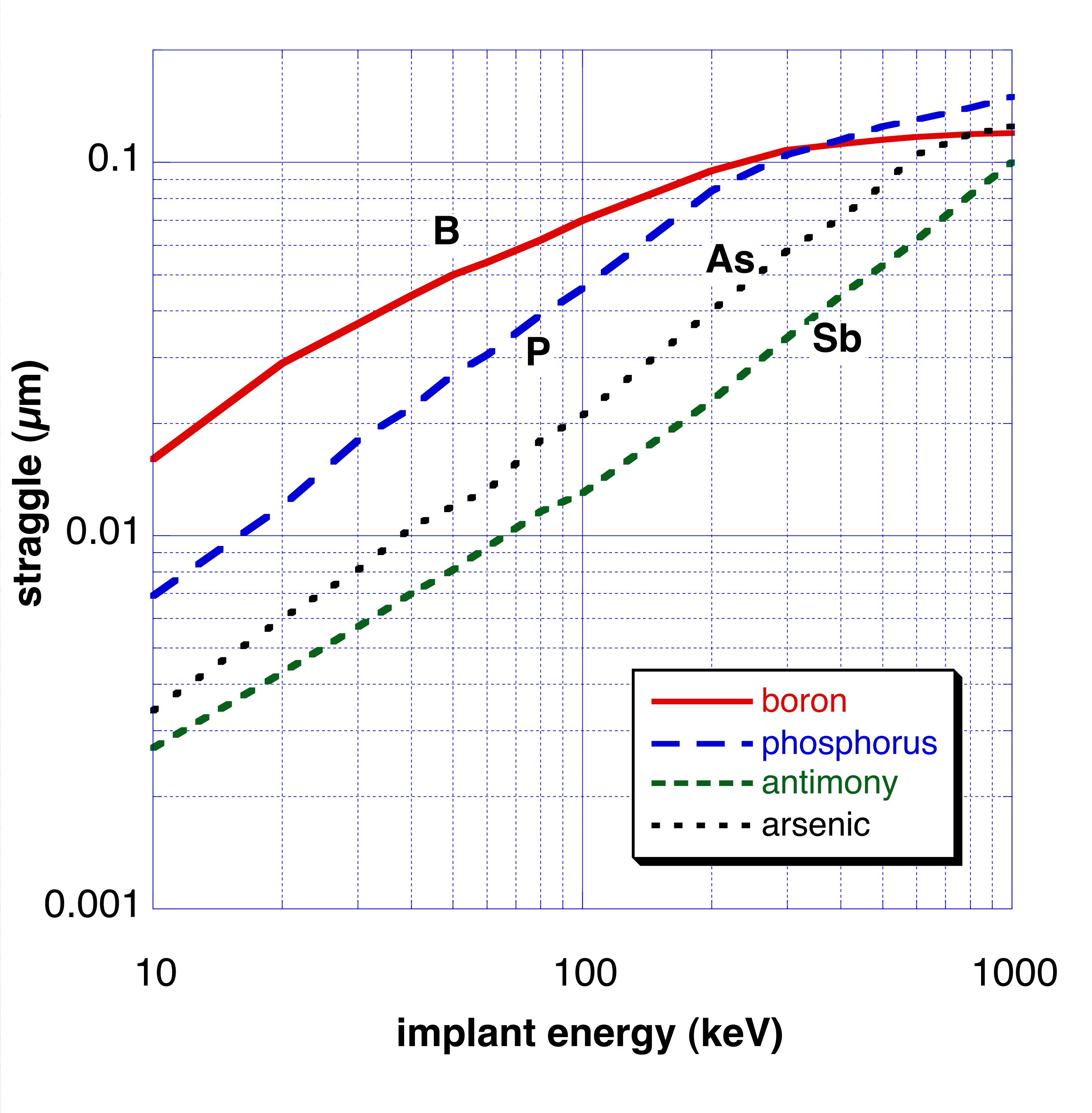
Range → average depth

straggle → deviation or variance

- Higher energies → deeper range and more straggle.
- Lighter ions → deeper range and more straggle.

Range and straggle for implants into silicon





R_p and ΔR_p are determined by ion energy.

Implant profile

simplest description

$$N(x) = \frac{Q}{\sqrt{2\pi}\Delta R_p} \exp\left[-\frac{(x-R_p)^2}{2(\Delta R_p)^2}\right]$$

$Q \rightarrow$ dose

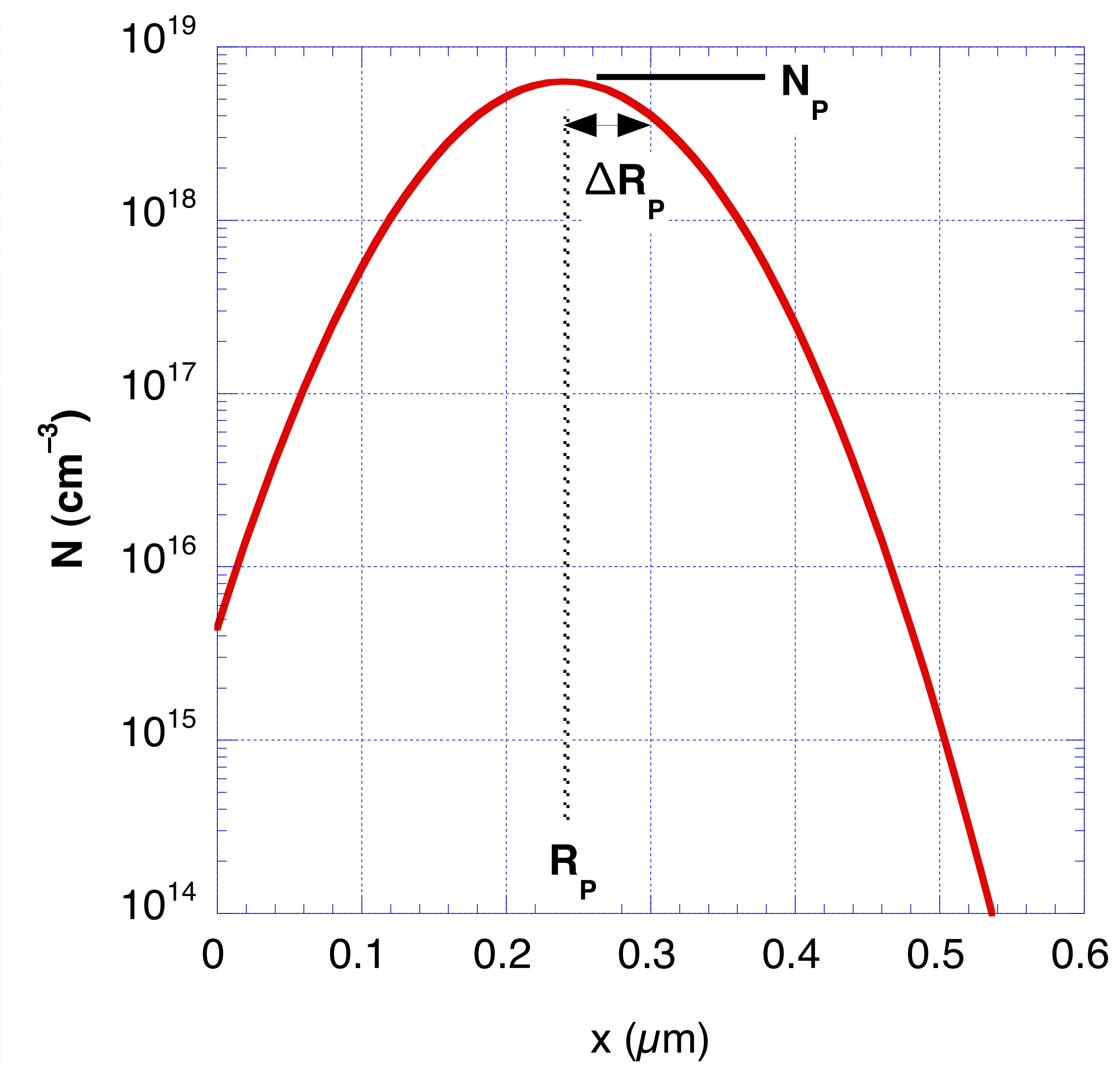
$R_p \rightarrow$ range (average depth of ion travel)

$\Delta R_p \rightarrow$ straggle (variance in ion depth)

Q is fixed by the implant time

$$Q = \frac{1}{q}\int_0^t I_{beam}(t')\,dt'$$

Measure the beam current. Stop after the required amount of charge (in the form of dopant atoms) has arrived.



peak concentration

$$N_P = \frac{Q}{\sqrt{2\pi}\Delta R_P}$$

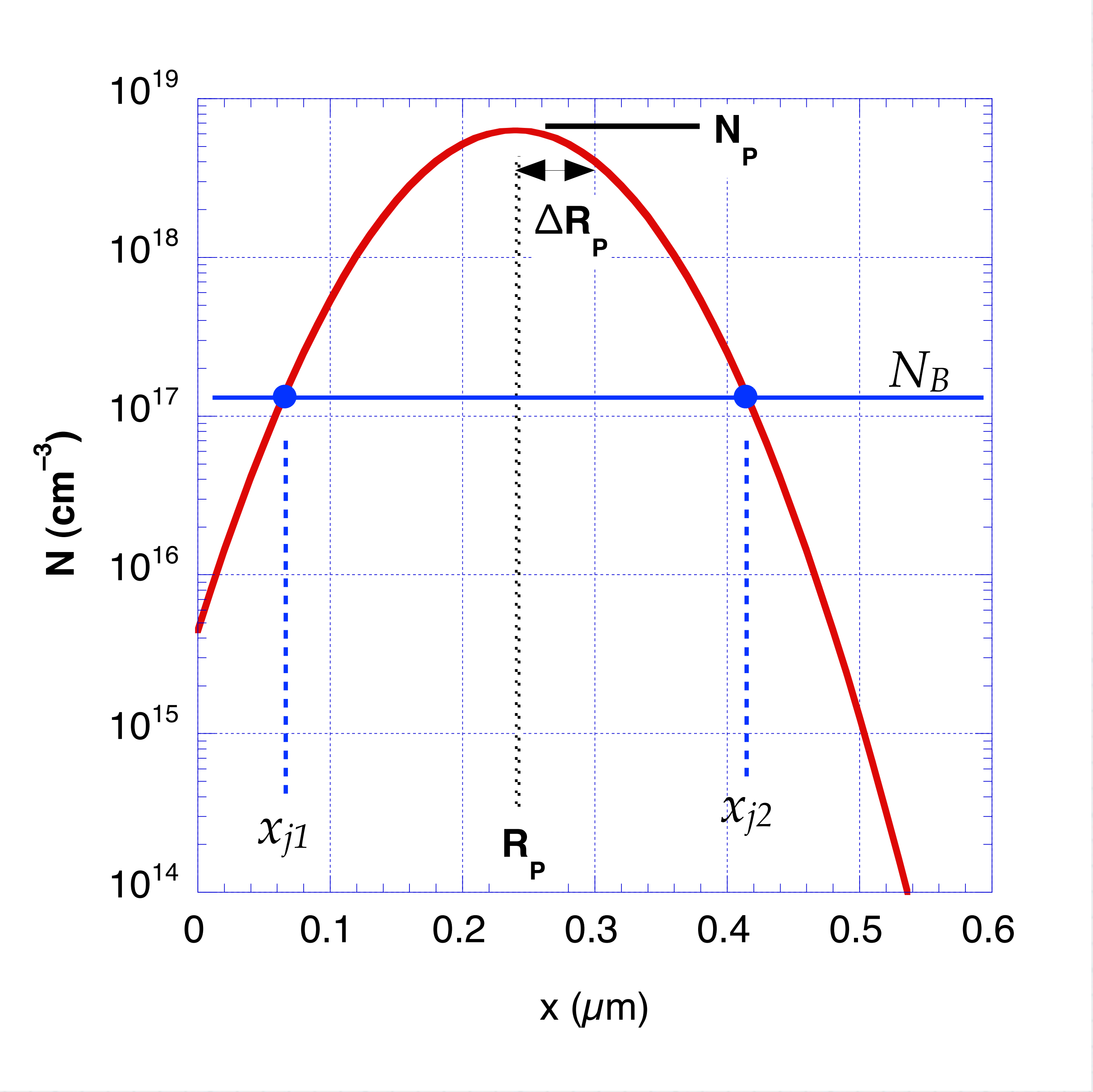
Junction depth

same as diffusion – look for where doping profiles cross

$$N(x_j) = N_B$$

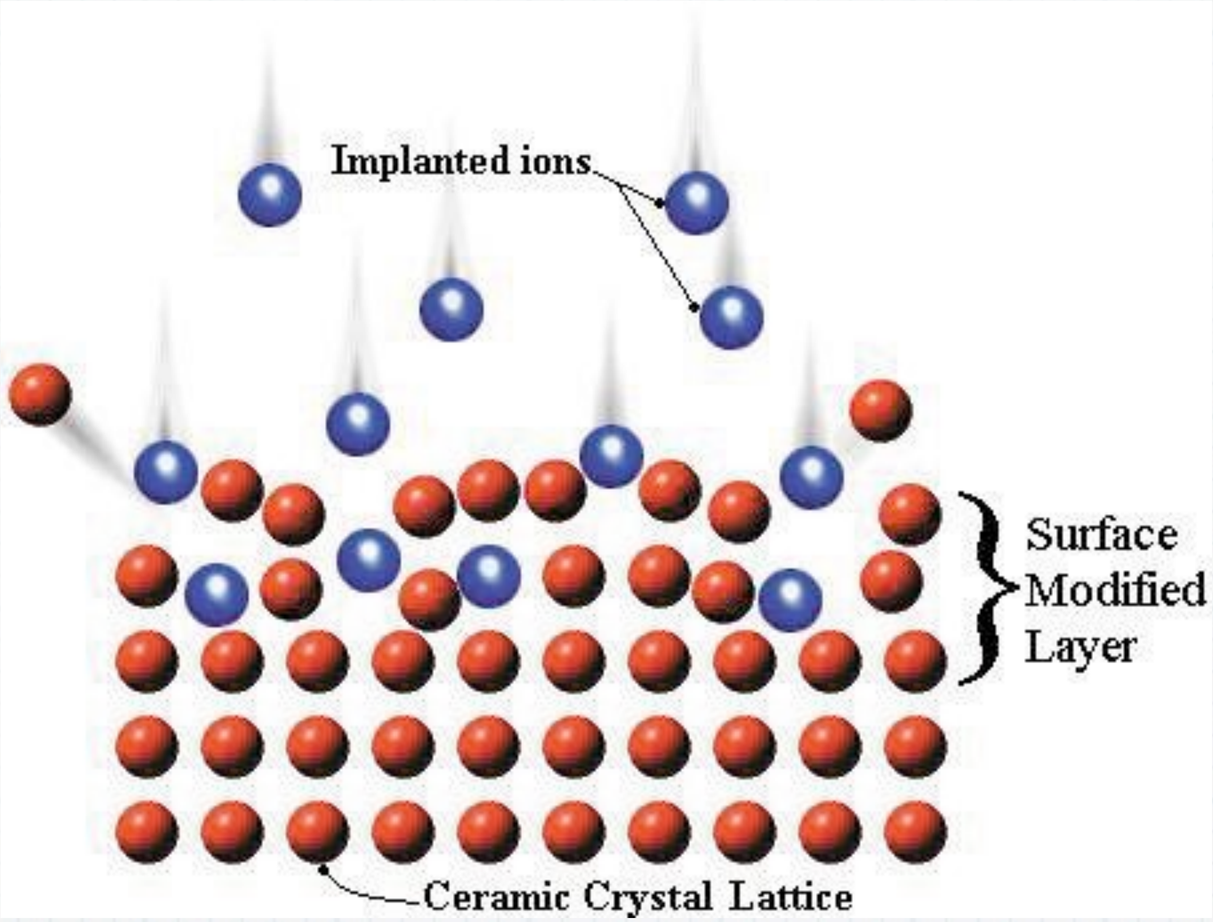
$$N_B = N_P \exp\left[-\frac{(x_j - R_p)^2}{2(\Delta R_p)^2}\right]$$

$$x_j = R_p \pm \sqrt{2}(\Delta R_P)\left[\ln\left(\frac{N_P}{N_B}\right)\right]^{\frac{1}{2}}$$



Note that there might be two junctions. Usually not desirable, but a possibility.

Damage and annealing



The top surface of the semiconductor crystal (R_P plus few ΔR_P) will be heavily damaged. Probably becomes completely amorphous.

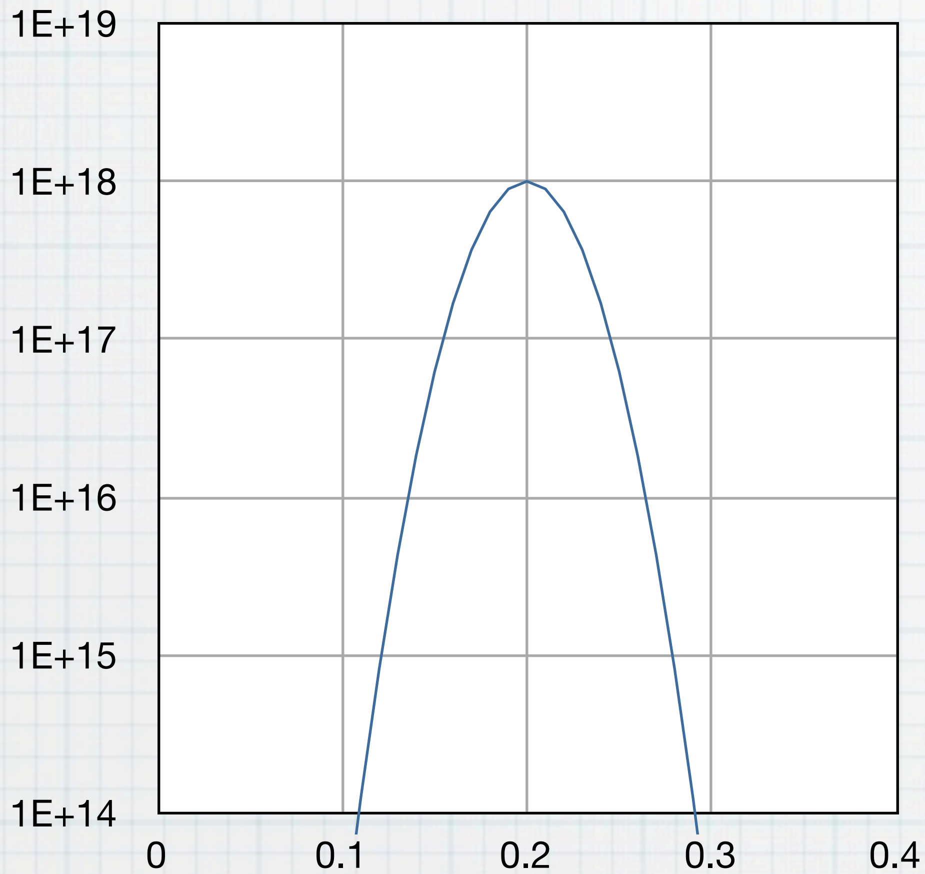
Damage can be healed by annealing. At high temperatures, the dislodged atoms can “diffuse” back into the correct lattice positions.

Annealing at 1000°C for 30 minutes is typically enough to restore crystallinity.

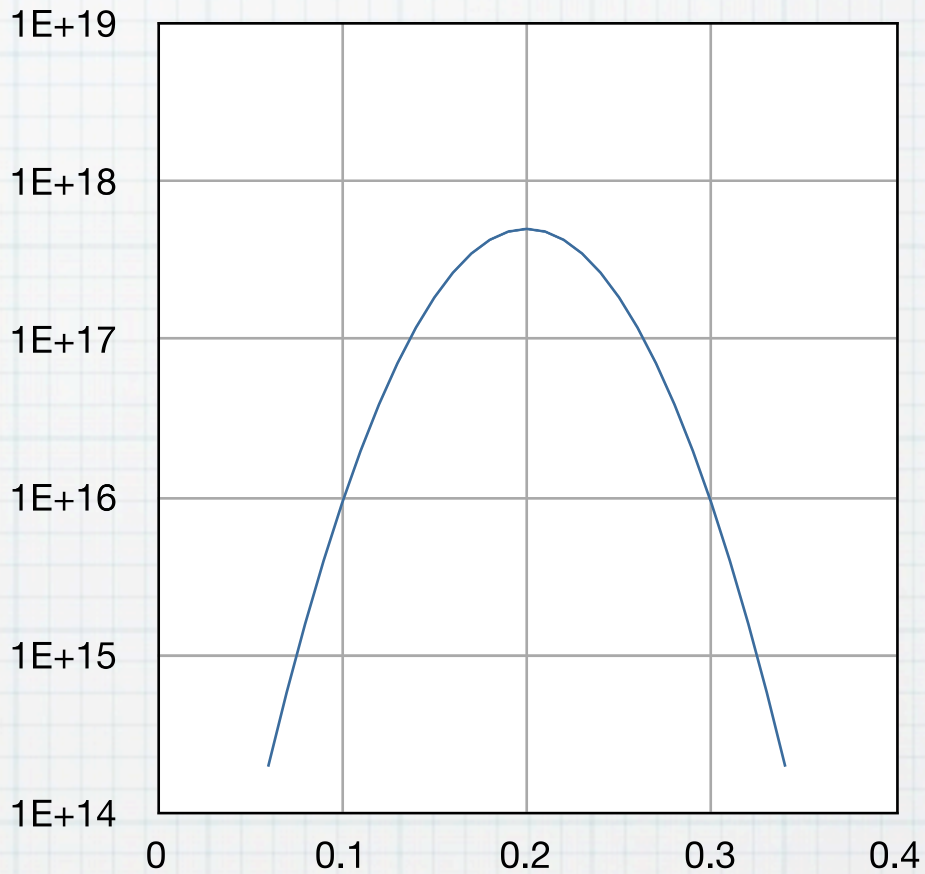
Dopant diffusion during annealing

Of course, during the anneal, dopant will diffuse.

Before anneal

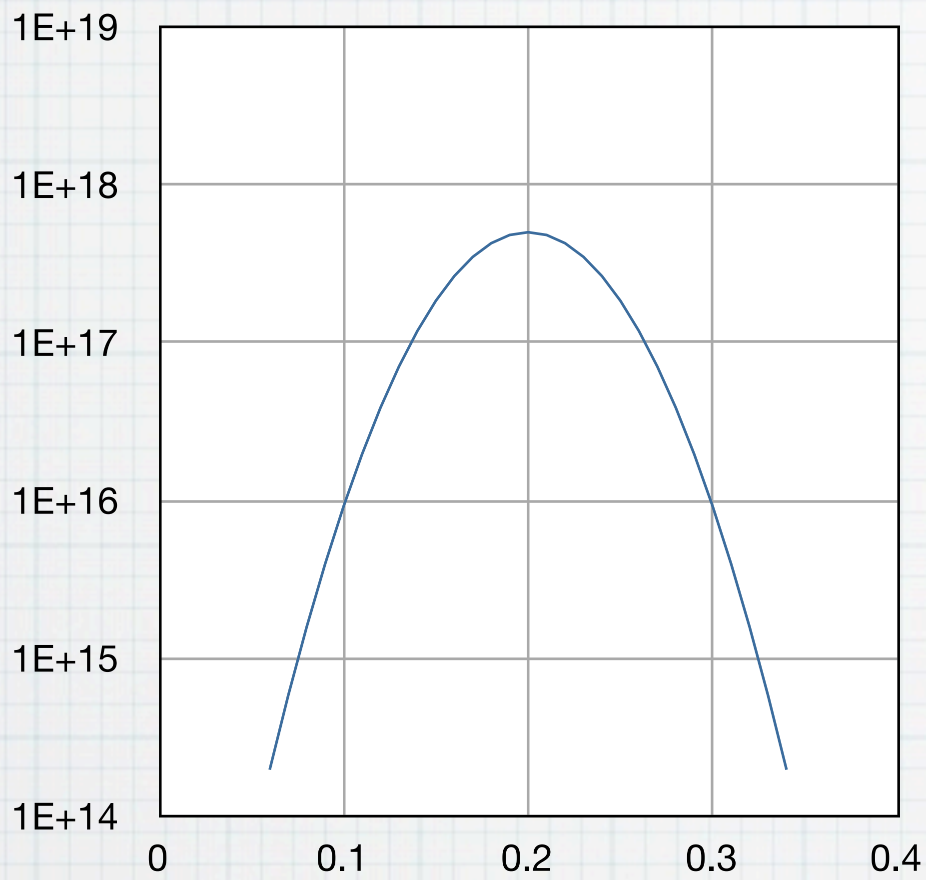


After anneal



We lose some of the advantages of the ion implant.

Accounting for diffusion



implant

$$N(x) = \frac{Q}{\sqrt{2\pi}\Delta R_P} \exp\left[-\frac{(x - R_P)^2}{2(\Delta R_P)^2}\right]$$

diffusion

$$N(x) = \frac{Q}{2\sqrt{\pi D t}} \exp\left[-\frac{(x - R_P)^2}{4Dt}\right]$$

Treat the implant like it was a diffusion with $(Dt)_{imp} = \frac{(\Delta R_P)^2}{2}$

Add the *Dt*'s, as we've discussed with diffusions

$$N(x) = \frac{Q}{2\sqrt{\pi\left[\frac{(\Delta R_P)^2}{2} + Dt\right]}} \exp\left(-\frac{(x - R_P)^2}{4\left[\frac{(\Delta R_P)^2}{2} + Dt\right]}\right)$$