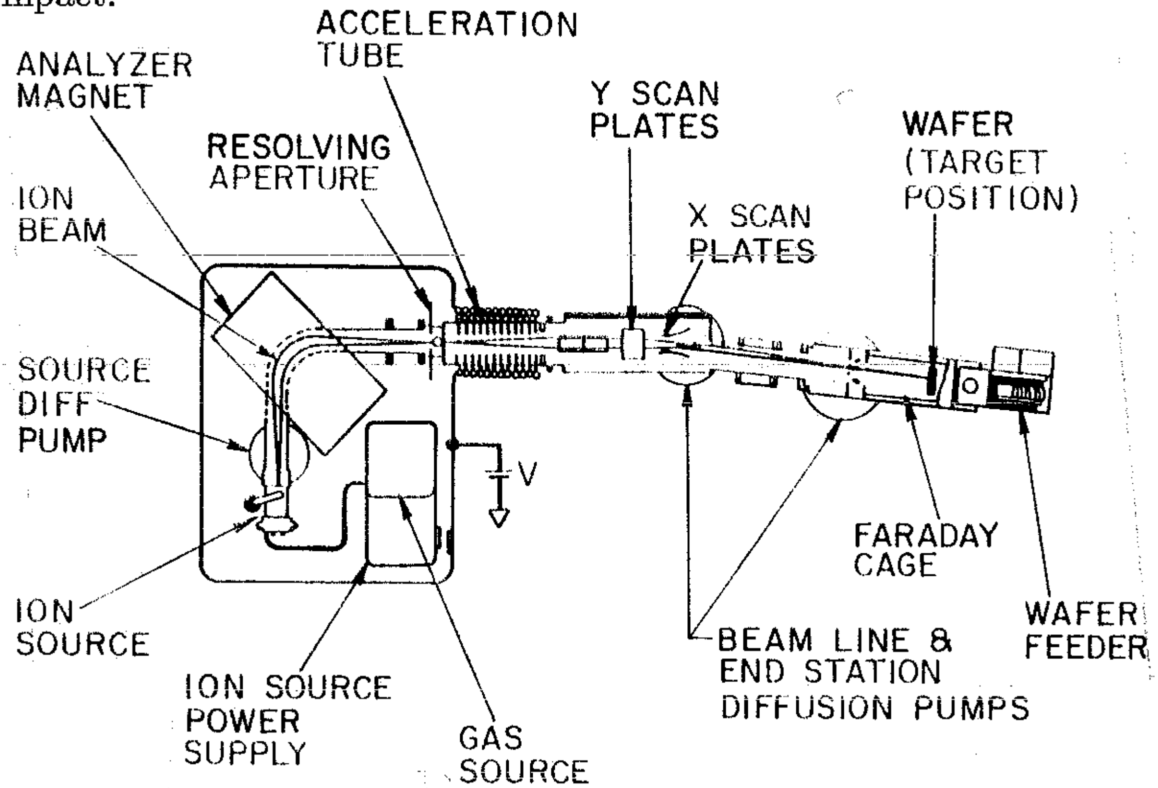
Ion Implantation

Ion implantation is a doping technique whereby impurities are ionized and accelerated to high energies such that they penetrate into the silicon substrate upon impact.



Gas Source: Provides desired impurities to be ionized. Extremely high purity is not essential since mass separation is usually done anyway.

Ion Source: Heated filament or other plasma source ionizes gas. High vaccuum required to prevent scattering due to collisions. Extraction voltage ($\sim$ 20kV) to move ions into analyzer and provide initial velocity.

Mass Separation: Magnetic field of analyzer chosen so that only ions of correct mass pass through aperture.

$$R = \frac{mv}{ZqB} = \frac{1}{B}\sqrt{\frac{mV}{Zq}} \tag{1}$$

Trade-off between resolution and maximum current.

Acceleration: A series of plates accelerates ions. Double charge ($Z = 2$) results in double energy.

Deflection: Beam scanned using two pairs of plates to deflect ions. Shift target off-center slightly to avoid the dopants that lose their charge. Deflection can distort beam/implant angle.

End Station: Wafer handling and support. Sometimes we may want to heat or cool the target.

Ion type determined by gas, magnetic field and extracting voltage.

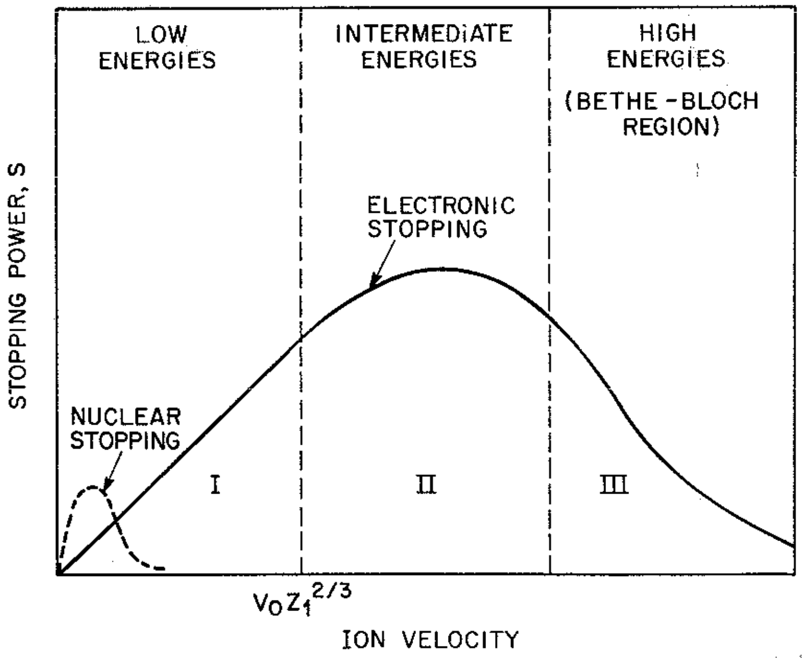
Ion energy determined by accelerating voltage.

Ion dose determined by beam current (ionization yield)

Once the ions enter the substrate, they lose energy via two interactions:

- Electronic stopping (Coulombic).
- Nuclear stopping (Screened Coulombic potential and not nuclear).

Both of these energy loss processes depend on ion energy, with electronic stopping dominant at high energies and nuclear stopping dominant at low energies.

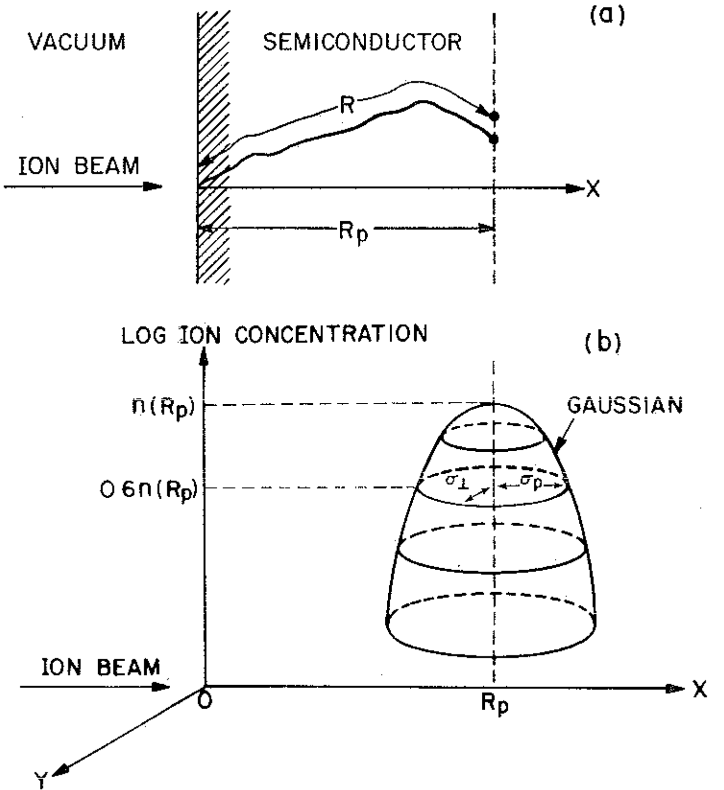


Stopping Power (S) is Energy Loss/Distance

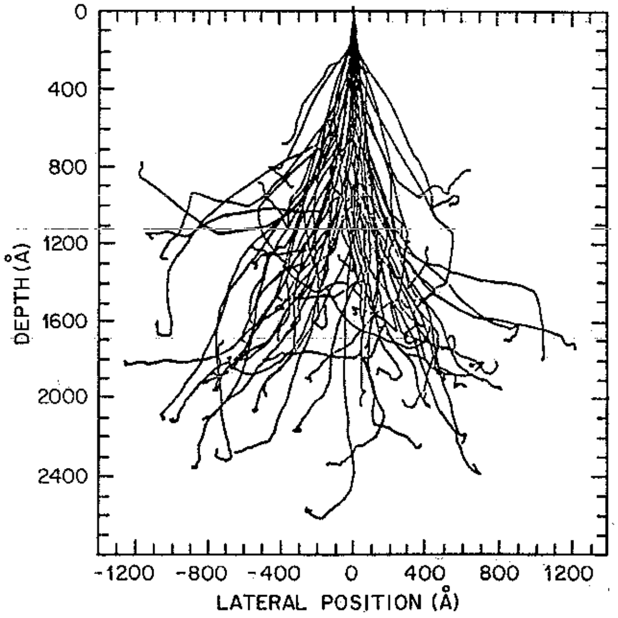
$$S = \left(\frac{\partial E}{\partial x}\right)_{\text{nuclear}} + \left(\frac{\partial E}{\partial x}\right)_{\text{electronic}} \tag{2}$$

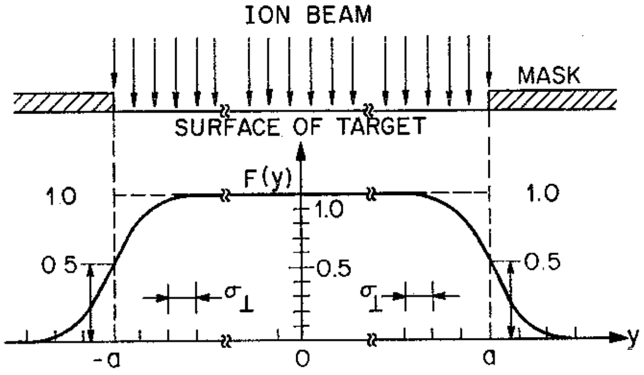
$$\text{Expected Range} = \int_0^{E_0} \frac{dE}{S_n(E) + S_e(E)} \tag{3}$$

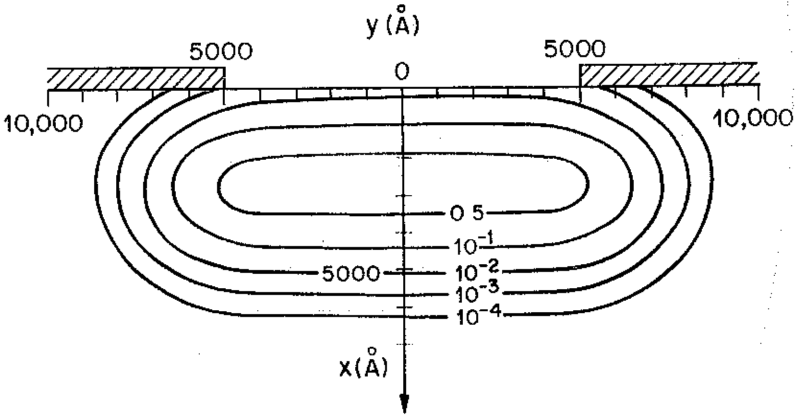
The energy losses are, of course, probabilistic. Resulting impurity distribution is centered around expected range (R_p).



For an implant over the entire wafer uniformly, we get convolution of impulse response with mask.







Nuclear Scattering

Screened Coulombic Potential (includes nucleus, core electrons and valence electrons):

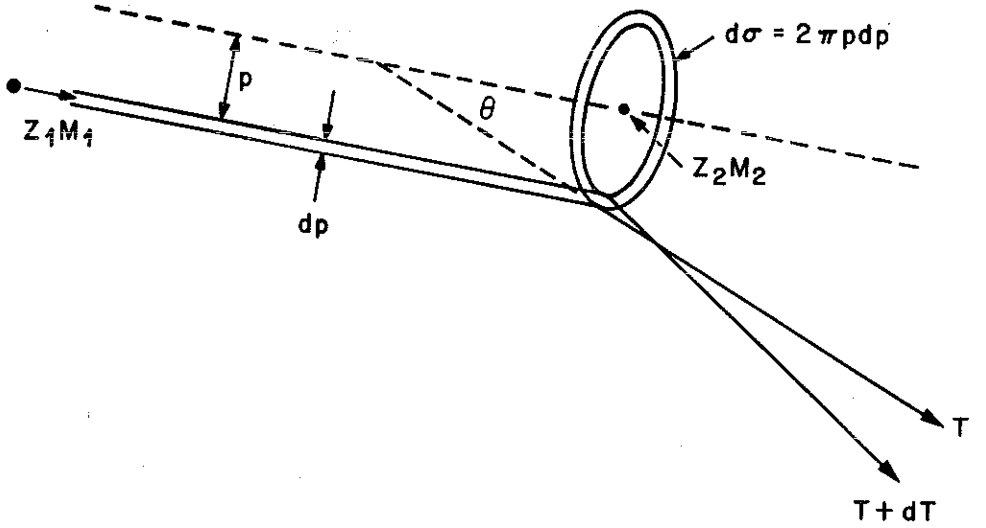
$$V(r) \cong \left(\frac{q^2 z_1 z_2}{4\pi\epsilon_0 r}\right) f_s(r) \qquad (4)$$

Assume elastic collisions which implies conservation of energy and momentum.

The ion energy loss T depends on angle of scattering θ which depends on impact parameter p

$$T(p) = \Delta E_{\text{ion}} = \frac{4m_1 m_2}{(m_1 + m_2)^2} E \sin^2\left(\frac{\theta(p)}{2}\right) \qquad (5)$$

where $\theta(p)$ is the angle of scattering in center of mass coordinates.



Scattering probabilities increase as $d\sigma$ increases. $d\sigma$ increases with increasing p, but the magnitude or strength of the interaction decreases.

Note that the fractional energy loss increases as the angle increases, while the angle decreases as the incoming velocity increases (less time for interaction to operate). Thus larger fraction of energy is lost at low energies.

The scattering angle (and energy loss) is also larger for heavier atoms since they are moving slower at the same energy.

Example: 100 keV boron into silicon. Estimate maximum energy loss ($T_{\max}$) and closest approach due to head-on collision. Use unscreened potential.

Momentum:

$$v_{imp} = v_1' - v_2'$$

$$|m_1 v_1'| = |m_2 v_2'|$$

$$\text{B: } m_1 \cong 11 m_H$$

$$\text{Si: } m_2 \cong 28 m_H$$

$$v_1' = 0.72 v_{imp}, \quad -v_2' = v_{CM} = 0.28 v_{imp}$$

Since $\theta = 180°$ (direct hit)

$$T_{\max} \frac{4 m_1 m_2}{(m_1 + m_2)^2} E \sin^2\left(\frac{\pi}{2}\right) = 81\,\text{keV}$$

Energies ($mv^2/2$):

$$E_1' = 52\,\text{keV}, \quad E_2' = 20\,\text{keV}, \quad E_{CM} = 28\,\text{keV}$$

At closest approach, kinetic energy all transformed to potential energy ($V(r) = 72\,\text{keV}$)

$$r = \frac{q^2 Z_1 Z_2}{4\pi\epsilon_0 V(r)} = 0.014\,\text{Å}$$

After collision,

$$v_1' = -0.72 v_{imp}, \quad v_2' = v_{CM} = 0.28 v_{imp}$$

$$v_1 = 0.44 v_{imp}$$

$$E = (0.44)^2 E_{imp} = 0.19 E_{imp}$$

The total nuclear stopping is

$$S_n = N \int_0^\infty T(p, E)\, d\sigma(p) = N \int_0^\infty T(p, E) 2\pi p\, dp \tag{6}$$

where N is the density of target atoms per volume.

If you don't have enough energy to move the atoms from lattice sites, they vibrate in their positions (heat)

Electronic Stopping

Electronic stopping is caused by interaction of ion with target electrons. Accurate analysis is very difficult, but the process can be considered analogous to a drag due to movement through a viscous medium.

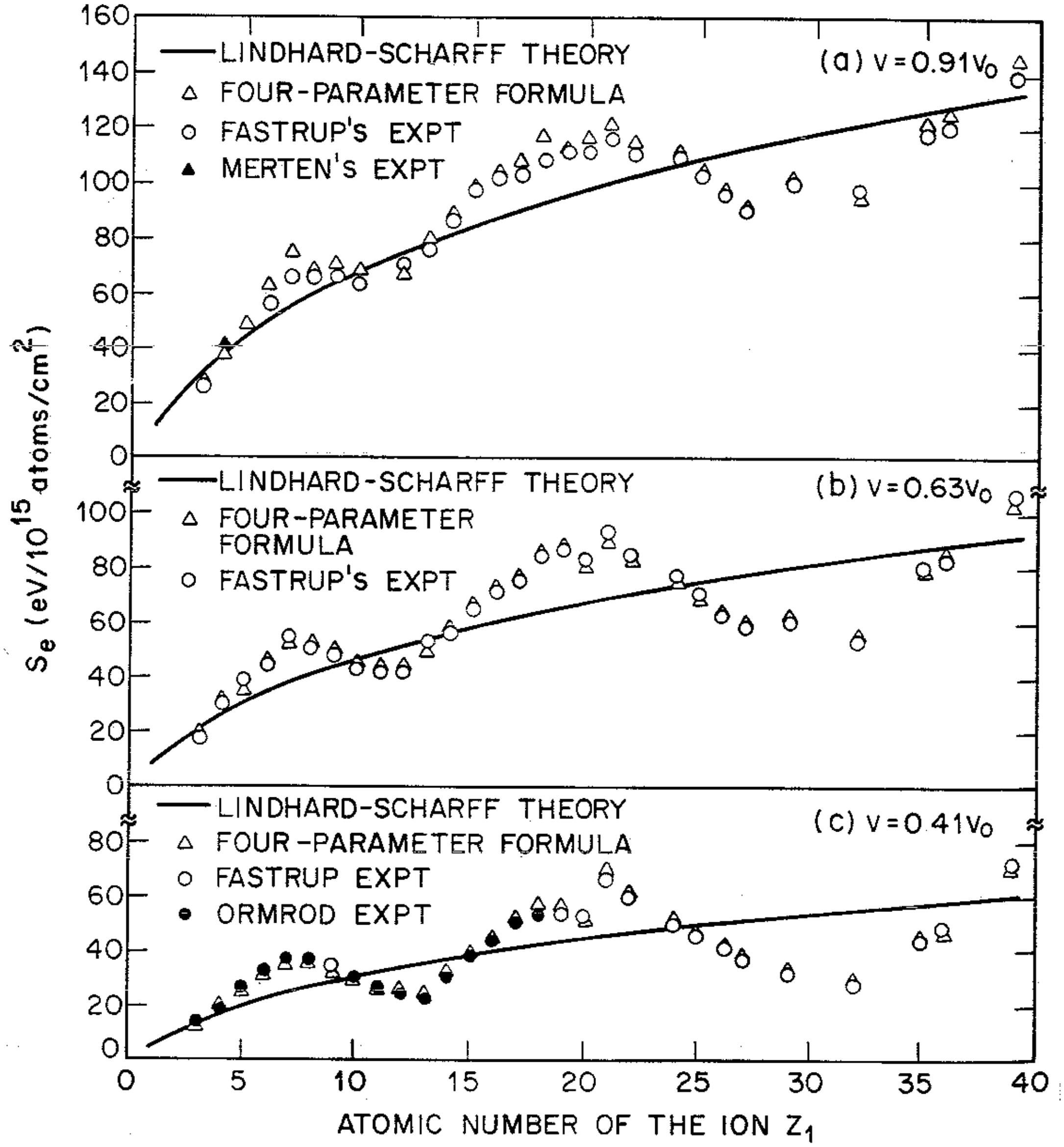
A commonly-used expression for lower energies (Lindhard and Scharff) is:

$$S_e = \left[\frac{2q^2 a_0 Z_1^{7/6} Z_2 N}{\epsilon_0 \left(Z_1^{2/3} + Z_2^{2/3} \right)^{3/2}} \right] \frac{v}{v_0} \tag{7}$$

where Z_1 and Z_2 are the atomic numbers of the ion and target, a_0 and v_0 are the Bohr radius and velocity.

Note that the electronic stopping is proportional to v or $E^{1/2}$, so it is more important at higher energies.

From experiments, the actual relationship between energy and electronic stopping is more complicated and has been matched to empirical models.



Electronic Stopping is generally considered inelastic because electrons that gain energy lose it immediately in the form of heat.

Light ions, high energy $\Longrightarrow$ Electronic, inelastic

Heavy ions, low energy $\Longrightarrow$ Nuclear, elastic

Range Statistics

$$R_p \equiv \text{Expected range (depth)}$$

$$\sigma_p \equiv \text{Standard deviation of vertical profile (straggle)}$$

$$\sigma_\perp \equiv \text{Standard deviation of lateral spread}$$

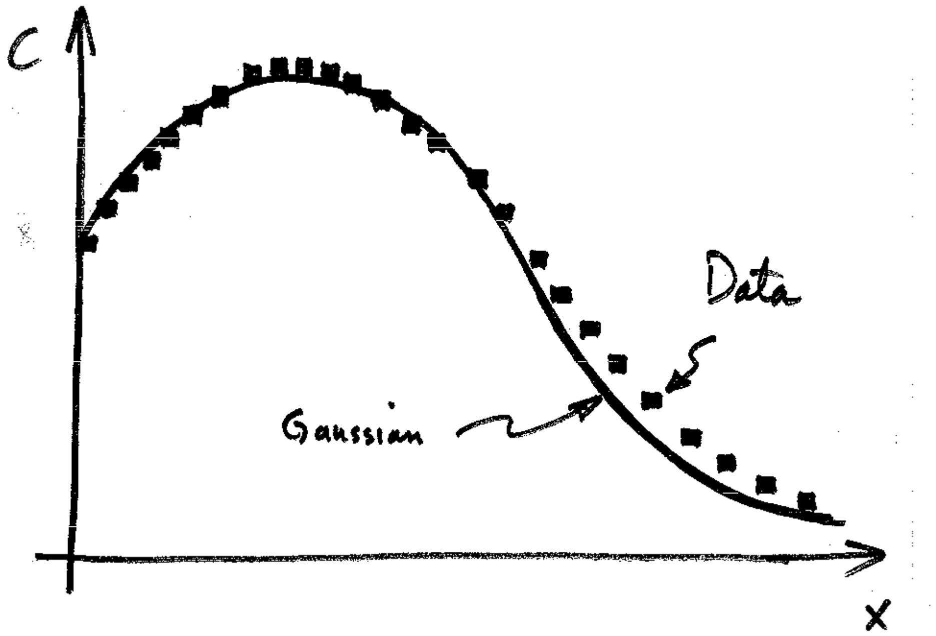
$$\Phi \equiv \text{Total dose } (\text{cm}^{-2})$$

Simple Gaussian profile,

$$n(x) = n_0 \exp\left(-\frac{(x-R_p)^2}{2\sigma_p^2}\right) \tag{1}$$

$$n_0 = \frac{\Phi}{\sqrt{2\pi}\sigma_p} \cong \frac{0.4\Phi}{\sigma_p} \tag{2}$$

Real profile are more complicated than simple Gaussians:



Can model in different ways:

- Dual-Gaussian (two Gaussians, meeting at peak)
- 4 moment model (Pearson)
- Dual Pearson (two Pearsons, meeting at peak)

1st moment — Mean

2nd moment — Standard Deviation

3rd moment — Assymetry of profile (skewness)

4th moment — Flatness of peak (kurtosis)

$$m_i = \frac{1}{\Phi}\int_{-\infty}^{\infty} (x - R_p)^i\, n(x)dx \tag{3}$$

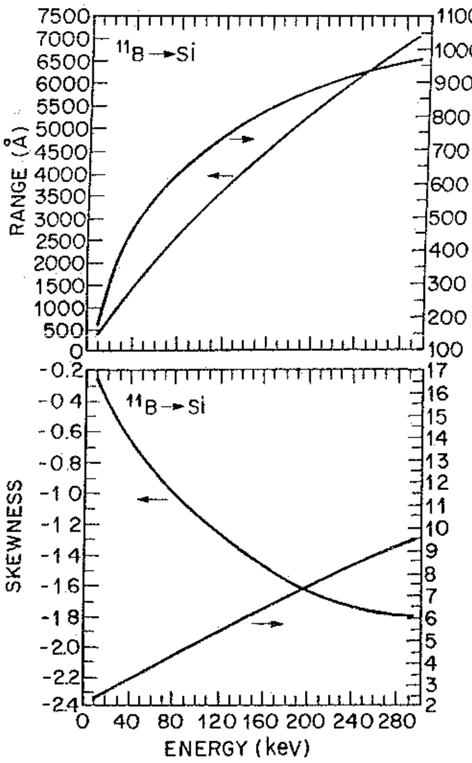
$$R_p = m_1, \qquad \sigma_p = \sqrt{m_2} \tag{4}$$

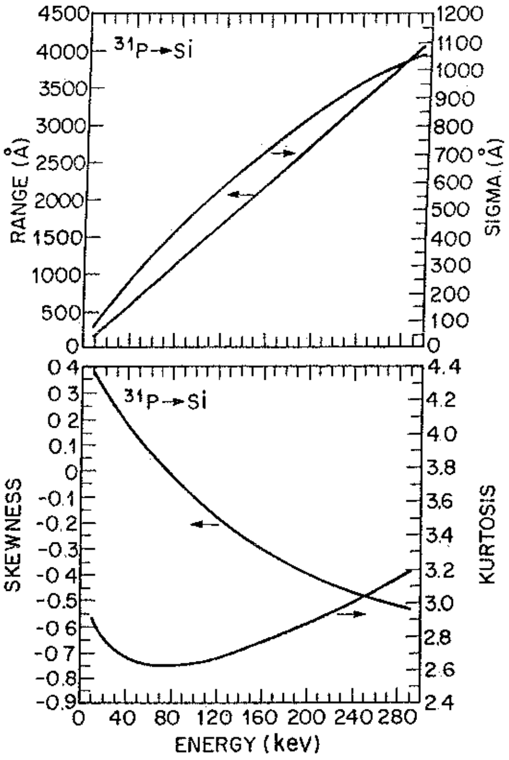
$$\gamma \text{ (skewness)} = \frac{m_3}{\sigma_p^3} \quad (\gamma > 0 \Rightarrow \text{peak near surface, 0 for Gaussian}) \tag{5}$$

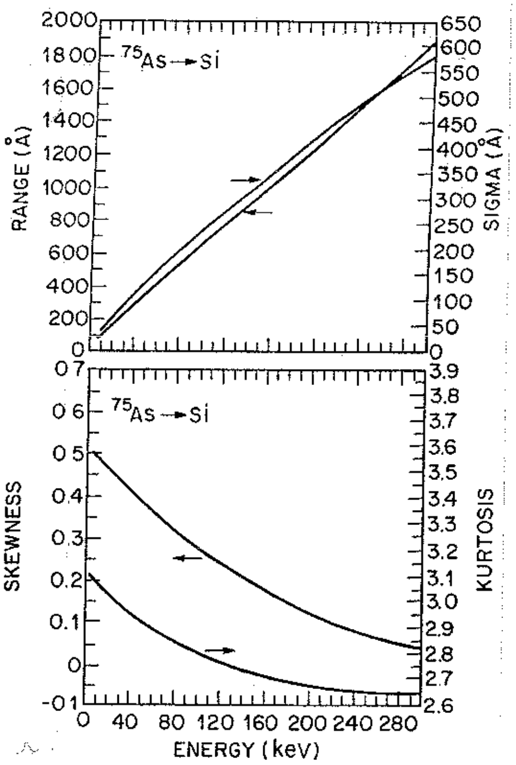
$$\beta \text{ (kurtosis)} = \frac{m_4}{\sigma_p^4} \quad (\text{Smaller } \beta \Rightarrow \text{flatter peak, 3 for Gaussian}) \tag{6}$$

In general, range and straggle increase with energy, while skewness becomes more negative and kurtosis typically obeys $\beta \cong 2.8 + 2.4\gamma^2$.

As ion mass increases for the same energy, range decreases more, straggle decreases more slowly and skewness becomes more positive.







The Pearson distributions are a commonly-used example of functions which can be described in terms of their moments.

$$\frac{df(s)}{ds} = \frac{(s-a)\,f(s)}{b_0 + b_1 s + b_2 s} \tag{7}$$

where $s = x - R_p$ and

$$a = b_1 = -\gamma\sigma_p(\beta+3)/A \tag{8}$$

$$b_0 = -\sigma_p^2(4\beta - 3\gamma^2)/A \tag{9}$$

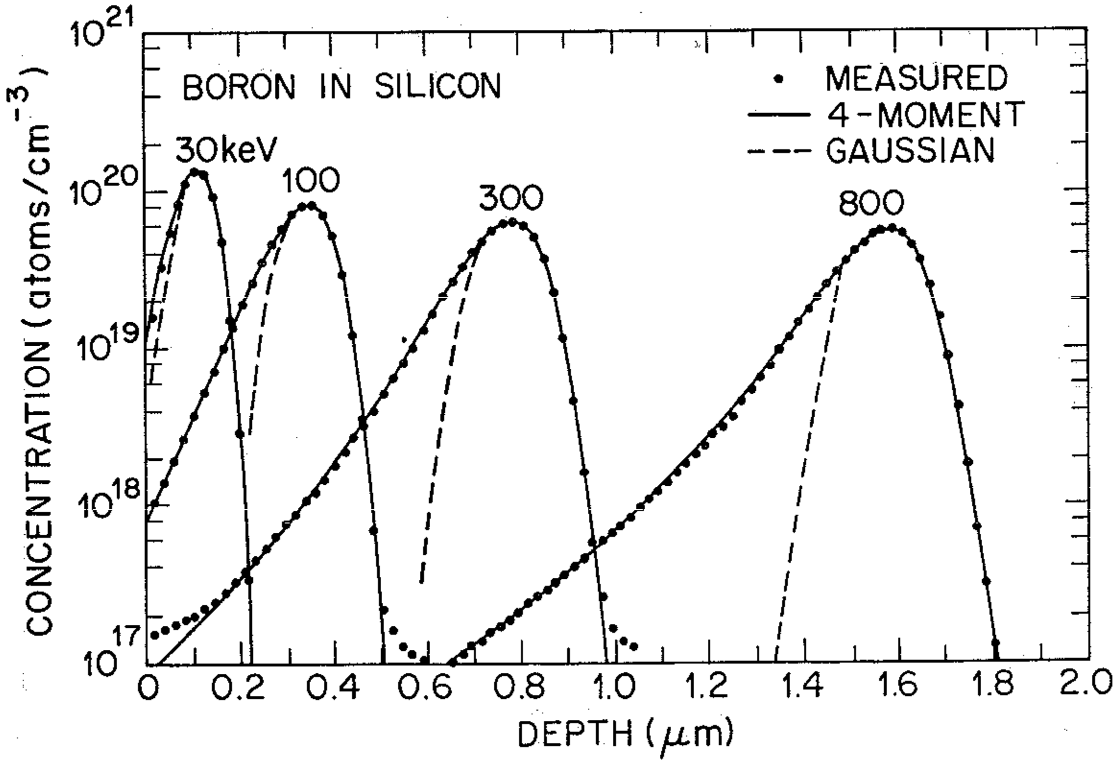
$$b_2 = -(2\beta - 3\gamma^2 - 6)/A \tag{10}$$

$$A = 10\beta - 12\gamma^2 - 18 \tag{11}$$

If it is assumed that $0 < b_1^2/4b_0b_2 < 1$ (Pearson-IV, SUPREM IV default),

$$\ln\left[\frac{f(s)}{f_0}\right] = \frac{1}{b_2}\ln\left(b_0 + b_1 s + b_2 s^2\right) - \frac{b_1/b_2 + 2b_1}{\sqrt{4b_0b_2 - b_1^2}}\tan^{-1}\left(\frac{2b_2 s + b_1}{\sqrt{4b_0b_2 - b_1^2}}\right) \tag{12}$$

Example: Boron exhibits large negative skewness at high energies due to backscattering (light atom).



Dose Matching and Scaling

Usually, ion implantation is done on a preprocessed wafer with some films on top.

Range, straggle, etc., vary for implants into different materials.

Boron ranges in various materials[13,14,15]

100 keV boron implantation				
~~Material~~	**~~Symbol~~**	**~~Density (g/cm^3)~~**	~~R_p(Å)~~	~~σ_p(Å)~~
Silicon	Si	2.33	2968	735
Silicon dioxide	SiO_2	2.23	3068	666
Silicon nitride	Si_3N_4	3.45	1883	408
Photoresist AZ111	$C_8H_{12}O$	1.37	10569	1202
Titanium	Ti	4.52	2546	951
Titanium silicide	$TiSi_2$	4.04	2154	563
Tungsten	W	19.3	824	618
Tungsten silicide	WSi_2	9.86	1440	555

The most important factor is the density of the material, which strongly affects the expected range and straggle.

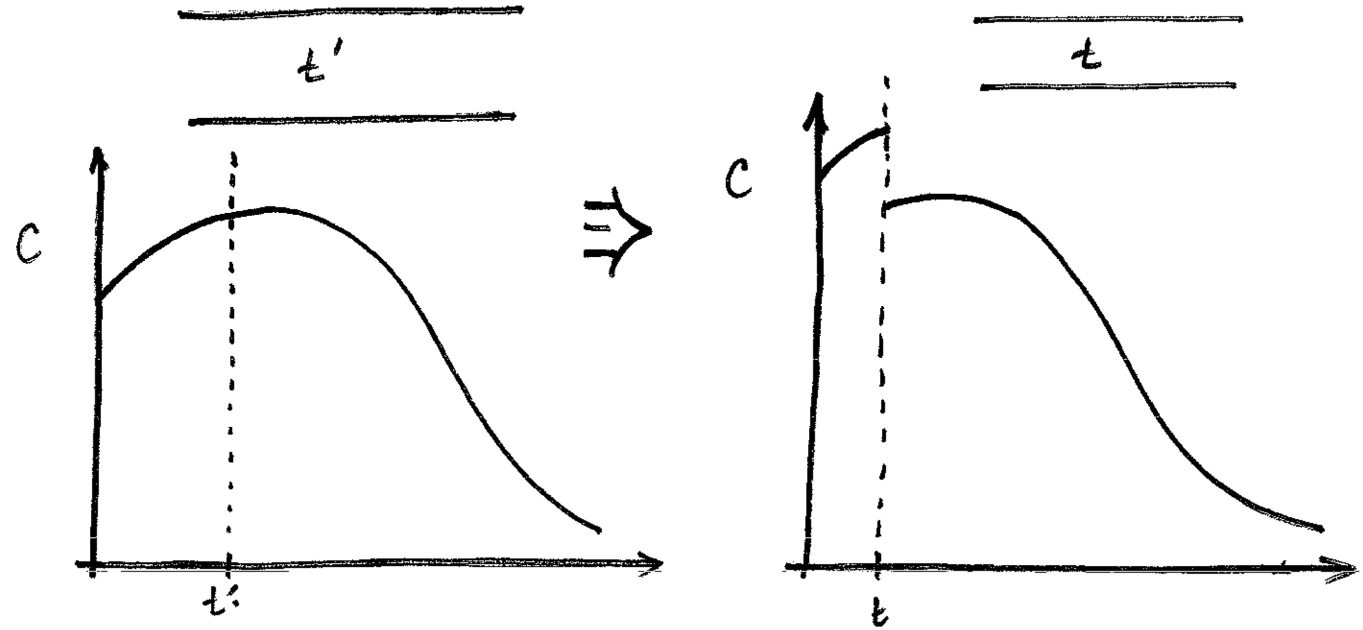
There are a couple of simple alternatives to dealing with this situation:

The simplest method, scaling is to replace a film by an equivalent thickness of the substrate material,

$$t \Rightarrow t' = \left(\frac{R_p^{\text{substrate}}}{R_p^{\text{film}}} \right) t \tag{13}$$

Following the implant, which results in a profile of $n'(x')$ into effective film/substrate combination,

$$n(x) = \begin{cases} \dfrac{t'}{t} n' \left(\dfrac{x t'}{t} \right) & 0 < x < t \\ \\ n' \left[x - (t - t') \right] & x > t \end{cases} \tag{14}$$



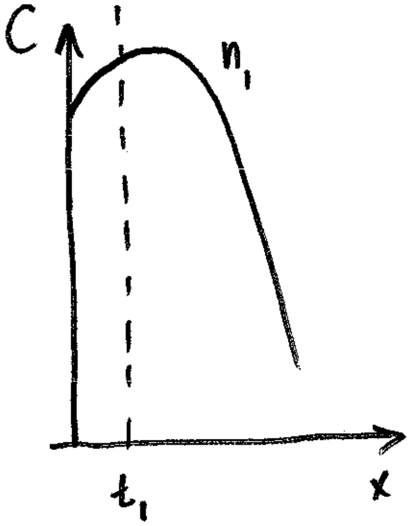
Although more complex to implement, the alternative, dose matching, does a better job of giving the correct distribution in the film. It takes advantage of the fact that the implant profile in the film is nearly independent of the underlying substrate (little difference in backscattering).

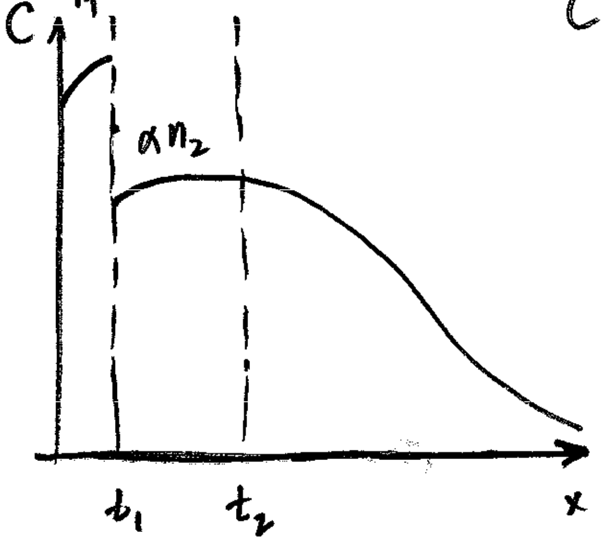
Thus

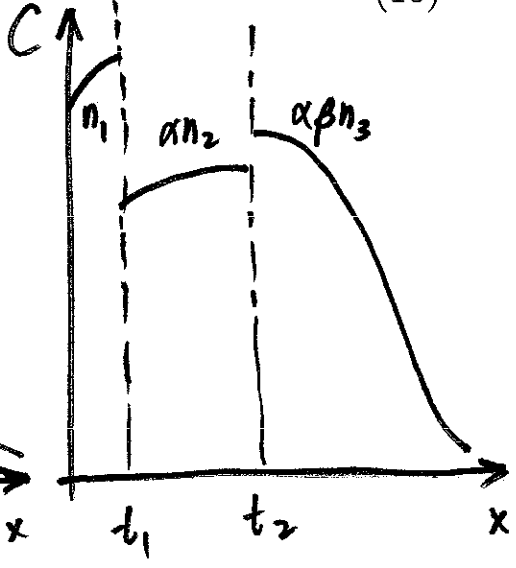
$$n(x) = \begin{cases} n_1(x) & 0 < x < t \\ \alpha n_2\left[x - (t - t')\right] & x > t \end{cases} \tag{15}$$

where α is chosen so that the total dose is correct:

$$\Phi = \int_0^\infty n(x)dx \tag{16}$$







This technique can be continued to deal with an arbitrary number of films.

Implants are generally made into patterned wafers.

There is limited experimental data to characterize the lateral distribution of implants, although Monte-Carlo simulations can be used to give estimates.

Thus, Gaussian lateral distributions are generally used. The point profile (distribution due to infinitesimally small opening) is:

$$n_\delta(x,y,z) = \frac{n(x)}{2\pi\sigma_\perp^2}\exp\left(-\frac{y^2+z^2}{2\sigma_\perp}\right) \qquad (17)$$

For an opening with $a_1 < y < a_2$ and $b_1 < z < b_2$,

$$n(x,y,z) = \int_{a_1}^{a_2}\int_{b_1}^{b_2} n_\delta(x, y-y', z-z')\,dy'dz' \qquad (18)$$

which is just the convolution of the point profile (impulse response) with the mask opening.

Mask edges are not ideally vertical (depends on etching process), so some dopant penetrates near edges.

This effect can be considered by noting that the masking function that should be used in the convolution is not a step function and can add a shift in the x-direction.

In addition, implants are generally done at an angle to reduce channeling, which displaces profiles laterally if wafer is not rotated (and slightly reduces vertical range).