$$R = \frac{1}{2kN} E_0^{1/2} \simeq 20\sqrt{E_0} \ \text{Å}$$

We have used $k_{Si} = 2 \times 10^{-16} \ eV^{1/2} cm^2$

And again $R_p = \dfrac{R_{ES}}{1 + \dfrac{M_2}{3M_1}}$

Some Data :

		Z	M
1.	Phosphorous	15	30.973
2.	Arsenic	33	74.92
3.	Aluminium	13	26.98
4.	Boron	5	10.82
5.	Indium	49	114.82
6.	Silicon	14	28

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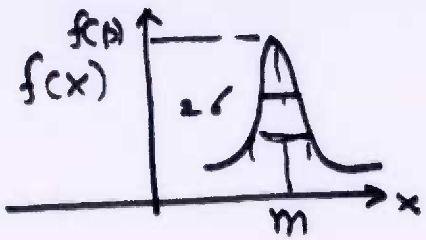
Probability :



i $f(x)$ is Gaussian with mean m is $= \int_{-\infty}^{+\infty} x f(x)\, dx$

ii Standard deviation $\sqrt{\sigma^2}$ is given

$$\sigma^2 = \text{expt. value}\left[(x-m)^2\right]$$

$$= \int_{-\infty}^{+\infty} (x-m)^2 f(x)\, dx$$

$$= E(x^2) - 2m^2 + m^2$$

$$= E(x^2) - m^2$$

$f(\sigma) = 0.606\,P$

$f(2\sigma) = 0.135\,P$

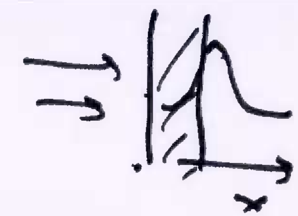
$f(4\sigma) = 1.81\,P$

P is Peak value of $f(p) = \dfrac{1}{\sqrt{2\pi\sigma^2}}$ at $x = m$

& $f(x) = \dfrac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-(x-m)^2 / 2\sigma^2\right]$

The Implantation process puts ions (atoms) below the surface and these ions come to rest at points which leads to Gaussian distribution. The Gaussian Profile is given by

$$N(x) = \frac{N_S}{\sqrt{2\pi}\,\Delta R_p} \exp\left[-\frac{1}{2}\frac{(x-R_p)^2}{\Delta R_p^2}\right]$$



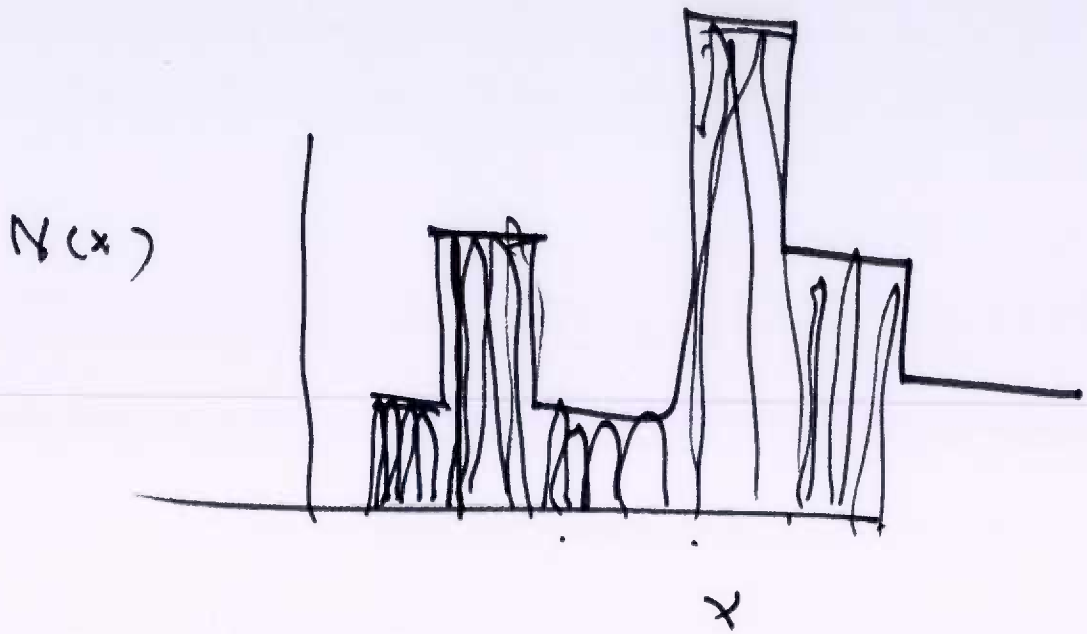
Here i ΔR_p is standard deviation called Straggle.

& ii R_p is mean range and is called Projected Range.

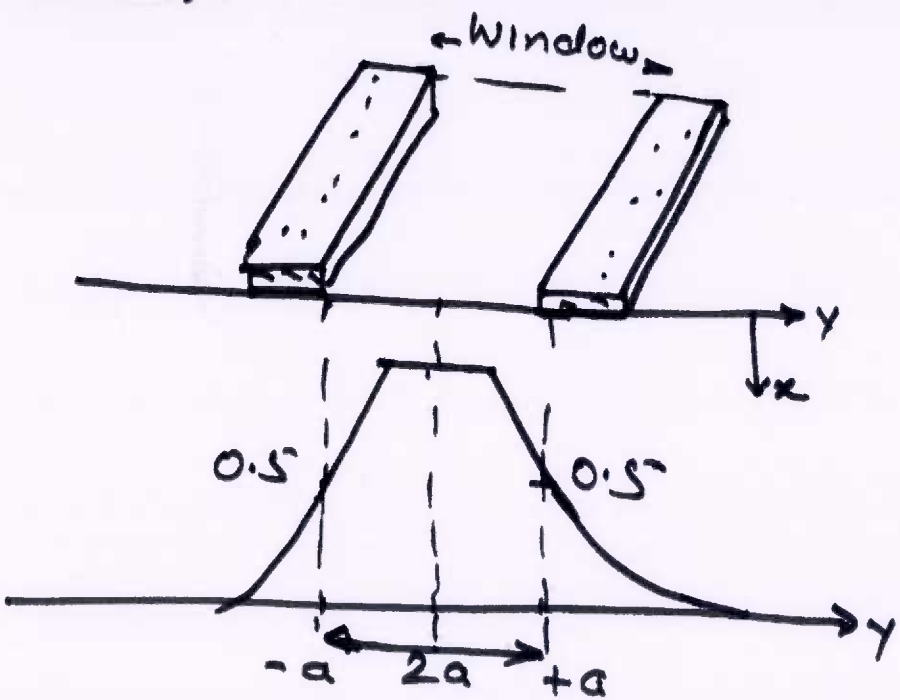
iii Peak concentration $N_p = N(R_p)$

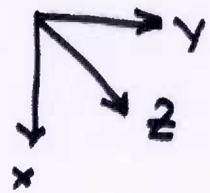
The total ions/atoms implanted per unit area is called

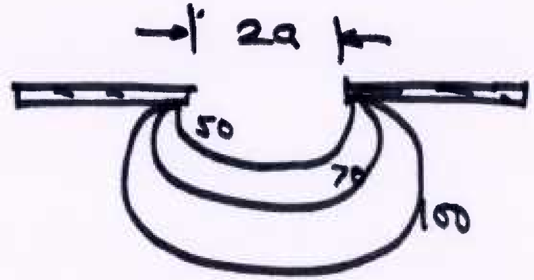
DOSE $N_S = \int_{-\infty}^{+\infty} N(x)\,dx$ & $N_p = \dfrac{0.4\,N_S}{\Delta R_p}$


N(x)
x

If Implantation is done through a Masked window, then there is Gaussian profile of ions even along lateral directions, and implanted species are mostly going vertically down.







Then

$$f(x,y,z) = \frac{1}{(2\pi)^{3/2}\Delta R_p \Delta x \Delta y} \times$$

$$\times \quad \operatorname{Exp}\left[-\frac{1}{2}\left\{\frac{(x-R_p)^2}{\Delta R_p^2} + \frac{y^2}{\Delta y^2} + \frac{z^2}{\Delta z^2}\right\}\right]$$

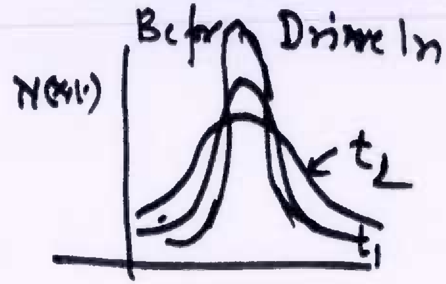
We assume $\Delta y = \Delta z = \Delta R_t$ – Transverse Straggle

$$N(x,y,z) = \frac{N_S}{\sqrt{2\pi}} \exp\left\{-\frac{1}{2}\frac{(x-R_p)^2}{\Delta R_p}\right\}\left\{\frac{1}{\sqrt{\pi}} \operatorname{erfc} \frac{(y-a)}{\sqrt{2}\,\Delta R_t}\right\}$$

For $y \gg a$ $\quad \operatorname{erfc}(\infty) = \sqrt{\pi}$

Drive-In of Implanted Impurities.

Thermal Cycle after implant, just flattens the Gaussian Profile, which essentially means that one will have lower Peak conc. and larger Standard Deviation σ or extra ΔR_p



We know that Diffusion distances $\propto \sqrt{Dt}$

Hence the new Profile is

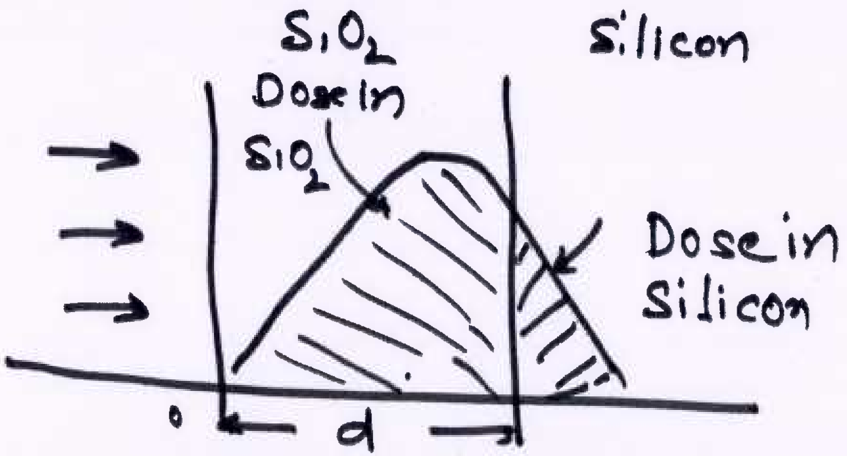
$$N(x,t) = \frac{N_s}{\sqrt{2\pi}\,(\Delta R_p^2 + 2Dt)^{1/2}} \exp\left\{-\frac{1}{2}\left[\frac{(x-R_p)^2}{\Delta R_p^2 + 2Dt}\right]\right\}$$

where Drive-In is performed at temp. T_1 where $D = D(T_1)$ and time of Drive-In is t.

Masks for Implantation:

1. Photoresist
2. Silicon dioxide
3. Silicon Nitride

4. Heavy Metals like Gold, Tungsten, Platinum & Vanadium.



We take 'd' as thickness of the Mask-layer (In Fig. it is SiO_2) Ions can be stopped in SiO_2 if d is large. However some 'tail' of Profile will allow a few impurity dose will enter Si.

Hence we can find 'd' for a given Stopping dose.

If Q is the residual dose of Ions in Silicon after being mostly in Mask material of thickness d, then

$$Q = \int_d^\infty \frac{N_s}{\sqrt{2\pi}\,\Delta R_p}\left[-\frac{1}{2}\frac{(x-R_p)^2}{\Delta R_p^2}\right] dx$$

We define $y = \frac{x-R_p}{\sqrt{2}\Delta R_p}$, then $dy = \frac{1}{\sqrt{2}\,\Delta R_p} dx$

Also $x = d \quad y(d) = \frac{(d-R_p)}{\sqrt{2}\,\Delta R_p} = y_0$ & $x = \infty \quad y < \infty$

$$\therefore Q = \int_{y_0}^\infty \frac{N_s}{\sqrt{2\pi}\,\Delta R_p} \cdot (\sqrt{2}\,\Delta R_p)\exp[-y^2]\,dy$$

$$= \frac{N_s}{\sqrt{\pi}} \int_{y_0}^\infty e^{-y^2} dy = \frac{N_s}{\sqrt{\pi}}\left[\int_0^\infty e^{-y^2} dy - \int_0^{y_0} e^{-y^2} dy\right]$$

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or $Q = \frac{N_s}{\sqrt{\pi}} \left[\frac{\sqrt{\pi}}{2} - \frac{\sqrt{\pi}}{2} \operatorname{erf}(y_0) \right]$

$= \frac{N_s}{2} \left[1 - \operatorname{erf}(y_0) \right] = \frac{N_s}{2} \operatorname{erfc}(y_0)$

$= \frac{N_s}{2} \operatorname{erfc}\left(\frac{d - R_p}{\sqrt{2}\, \Delta R_p} \right)$

or $\frac{2Q}{N_s} = \operatorname{erfc}\left(\frac{d - R_p}{\sqrt{2}\, \Delta R_p} \right)$

or $d = R_p + \sqrt{2}\, \Delta R_p \operatorname{erfc}^{-1}\left(\frac{2Q}{N_s} \right)$

If we say, we need 6 nines Blocking (99.9999 %) in Mask, then Dose in Silicon $= \frac{Q}{N_s} = 0.000001$

or $\frac{2Q}{N_s} = 0.000002$

Then $d = R_p + \sqrt{2}\,\Delta R_p \,\mathrm{erfc}^{-1}(2\times 10^{-6})$

$= R_p + \sqrt{2}\,\Delta R_p \,\mathrm{erf}^{-1}(0.999998)$

$d \Rightarrow$ will be thus different for different energy of implantation (R_p & ΔR_p) as also Blocking needed.

We made an assumption here that $R_{p_{SiO_2}} = R_{p_{Si}}$ & so are Straggles. But in reality, this is not true.

Then $d_{actual} = \dfrac{R_p \text{ in Mask layer}}{R_p \text{ in Silicon}} \cdot d_{obtained}$. (as above)

Typically assumption of R_p in Mask layer = R_p in Si is good for SiO_2
Si_3N_4

Activation of Impurities:

After Implantation we need to anneal the wafers for recovering damged surface.

Typically this is done between 600°C to 1000°C temperature anneal. Hence activation is automatic during damage recovery

Damage Creation & Recovery

As ions are extremely energetic (30 keV to 300 keV), they even displace Silicon atoms during relaxation process. This results in Amorphisation of surface layers, of Silicon (in Si IC cases). This could be one of the major disadvantage of Ion Implantation. Others being Cost and Throughput.

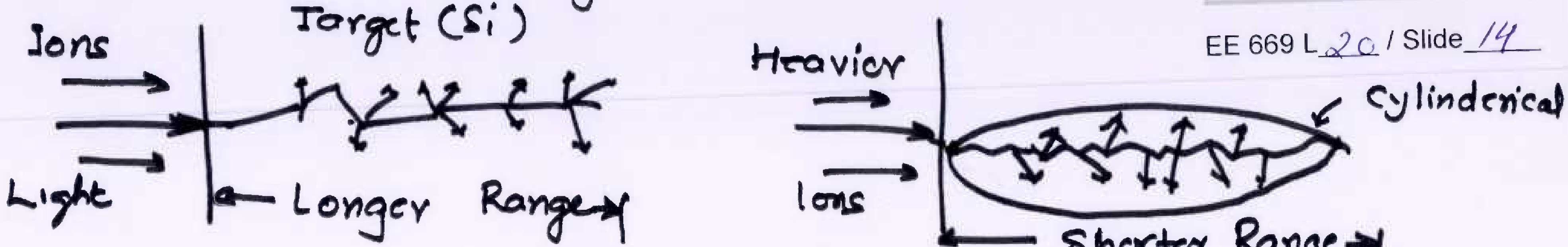
If E_d is the activation energy for creation of Frankle Pair (vacancy - Interstitial), we can say that during energy transfer from Ion to Silicon lattice, it is possible that Si-Si bond can break and Frankle - pair can be created.

Typically 15 eV energy is required for separated Frankle pair, i.e. $E_d = 15\,eV$

If energetic ions are heavy (As, or Phosphorous), then energy loss mechanism is due to Nuclear Stopping. While Boron ions (M=11) are light ions and they loose energy by Electronic Stopping.

Typically it takes 0.1 ps for creation of Damage

As Lighter ions loose energy by Electronic scattering, they go deeper in Lattice but show minor damage like trail & dislocation



However Heavy Ions loose energy by Nuclear Stopping.
Hence damage is localised (Smaller range) by heavier.
Many Frankle pairs can be formed as Heavier ion traverses no. of Planes in the lattice till it gets range values.
Typically 2.5 nm is spacing between Si-planes.
Hence no. of planes $= \frac{\text{Range}}{2.5\,\text{nm}} = n$ which will be traversed

Energy lost per plane then is

$$= \frac{\text{Initial Implantation energy}}{\text{no. of planes.}}$$

No. of atoms involved N

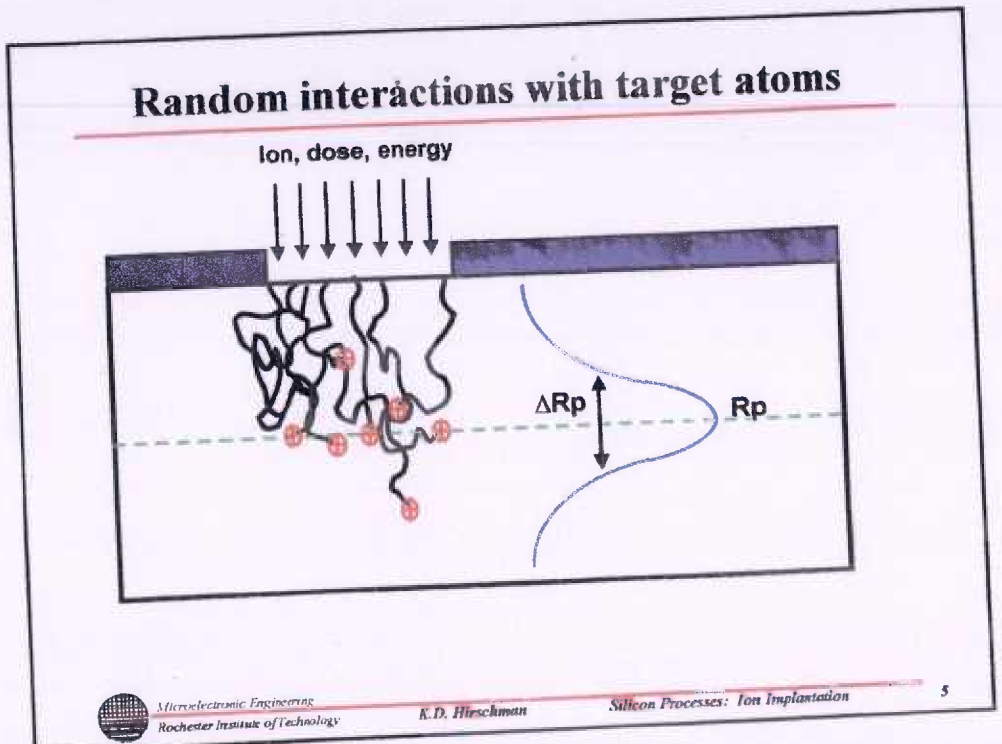
$$= \text{no. of planes} \cdot \frac{\text{Energy lost per Plane}}{2 \times E_d}$$

$$= \text{no. of Planes} \times \frac{1}{2E_d} \times \frac{\text{Initial Implantation Energy}}{\text{no. of Planes}}$$

$$= \frac{\text{Initial Implantation Energy}}{2 \times \text{Energy of displacement for FP.}}$$

An 50 keV, Implant of Heavy atoms, will displace Si- FPairs

$$= \frac{50 \times 10^3}{2 \times 15} = \frac{10}{6} \times 10^3 \simeq 1700 \text{ FP. (Si atoms displaced)}$$


Random interactions with target atoms
Ion, dose, energy
ΔRp
Rp
Microelectronic Engineering
Rochester Institute of Technology
K.D. Hirschman
Silicon Processes: Ion Implantation
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