Ion Implantation

Ion Implantation is a Process wherein one can incorporate Dopant Impurities in a Substrate (In our case it is Silicon).

Dopant Impurities are created in their Ionic Form, and these charged Ions are accelerated using Electric Field. This causes increase in Energy of Ions. These Ions are focussed into a Beam and they Impinge on the Substrate (Normal incidense). Due to High Energy Ions enter Substrate and come to rest at a distant called "Range". The energy loss mechanism is interaction of Ions with nuclei of atoms of the Substrate, as well as with Free electrons available. Thus Energy-Range relation Is Created. Time for which Ions imping on the Substrate, decides the total amount of Impurities which resides in the substrate.

Amount of Impurities is measured as 'Dose' which Is no./area.

As impurities rest inside the Substrate after random interactions, the Impurity Profiles are Gaussian or Normal Distribution of Impurities is observed.

Dopant Incorporation in Semiconductors

a) Solid State Diffusion

b) Doping during Crystal Growth

c) Doping during Epi-Growth

d) Doping using At. Pressure CVD for Doped Glasses.

→ e) Ion Implantation

Advantages of Ion Implantation :

(i) Precise Control on Impurity Dose and at Depth
(ii) Impurities directly below Surface – Burried Profile
(iii) Relatively Low Temperature Process (wrt Diffusion)
(iv) Choice of Mask-Material

(v) Self Aligned structures are possible

(vi) Order of Impurity incorporation is not an Issue.

(vii) Arbitary Impurity Profile is Possible.

Disadvatages :-

(i) Low Throughput Rate

(ii) Self Passivation (Like SiO_2 creation in Drive-In Cycle) is not Possible

(iii) Crystal Damage

(iv) Anomolous Transient Enhanced Diffusion

(v) charging of Insulators

(vi) Very Costly Equipment

What Implantion Machine must provide for VLSI Fabrication Process? :

(i) Uniform Doping

(ii) Dose control from 10^{10} to 10^{16} /cm2

(iii) Energy of Ions required between 10 KeV to 300 KeV.

(iv) Different impurity Incorporation

(v) Automated Dose Control

(vi) Angular Implantation

(vii) Moderate to High Throughput

In MOS Technologies (CMOS, FINFET & others)

One needs :

(a) P-Well (b) N-well

(c) Channel Stopper

(d) Depletion Implant for Depletion Transistor

(e) Source & Drain Impurity Implant with Higher Doses

(f) Threshold Correction

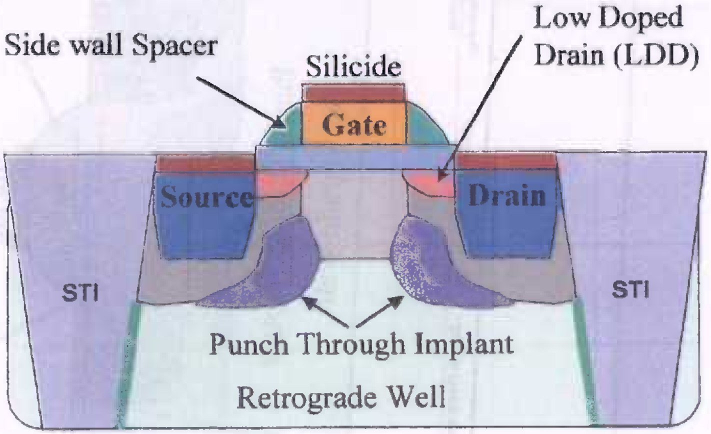
Few Terms of Interest in Implantation

(i)- DOSE $= \text{Ions/cm}^2 \simeq \frac{1}{qA}\int_0^{t'} I(t)\,dt$

(ii) Range and Projected Range

Lec-19
Note-8

Advanced CMOS Technology



Side wall Spacer

Silicide

Low Doped
Drain (LDD)

Gate

Source

Drain

STI

STI

Punch Through Implant

Retrograde Well

(iii) Impurity Profile

(iv) Standard deviation — Straggle

(v) Energy

(vi) Nuclear Stopping

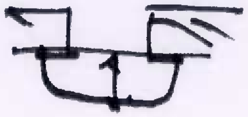
(vii) Electronic Stopping

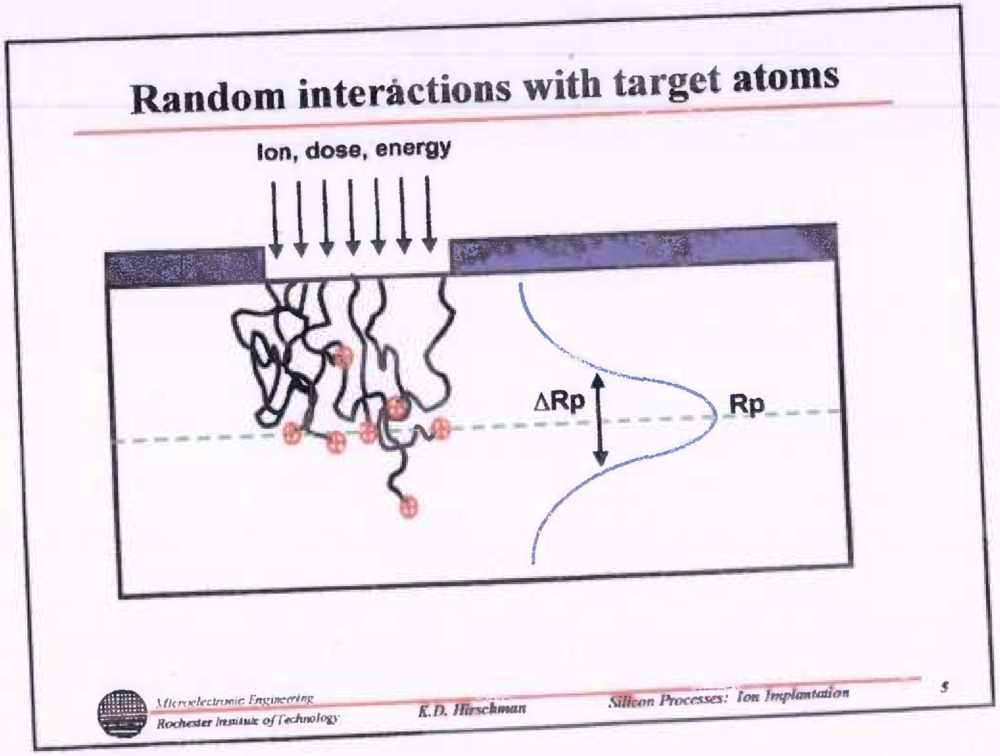
(viii) Transverse Straggle

(ix) Annealing & Drive-In

(x) Channeling

(xi) Masking

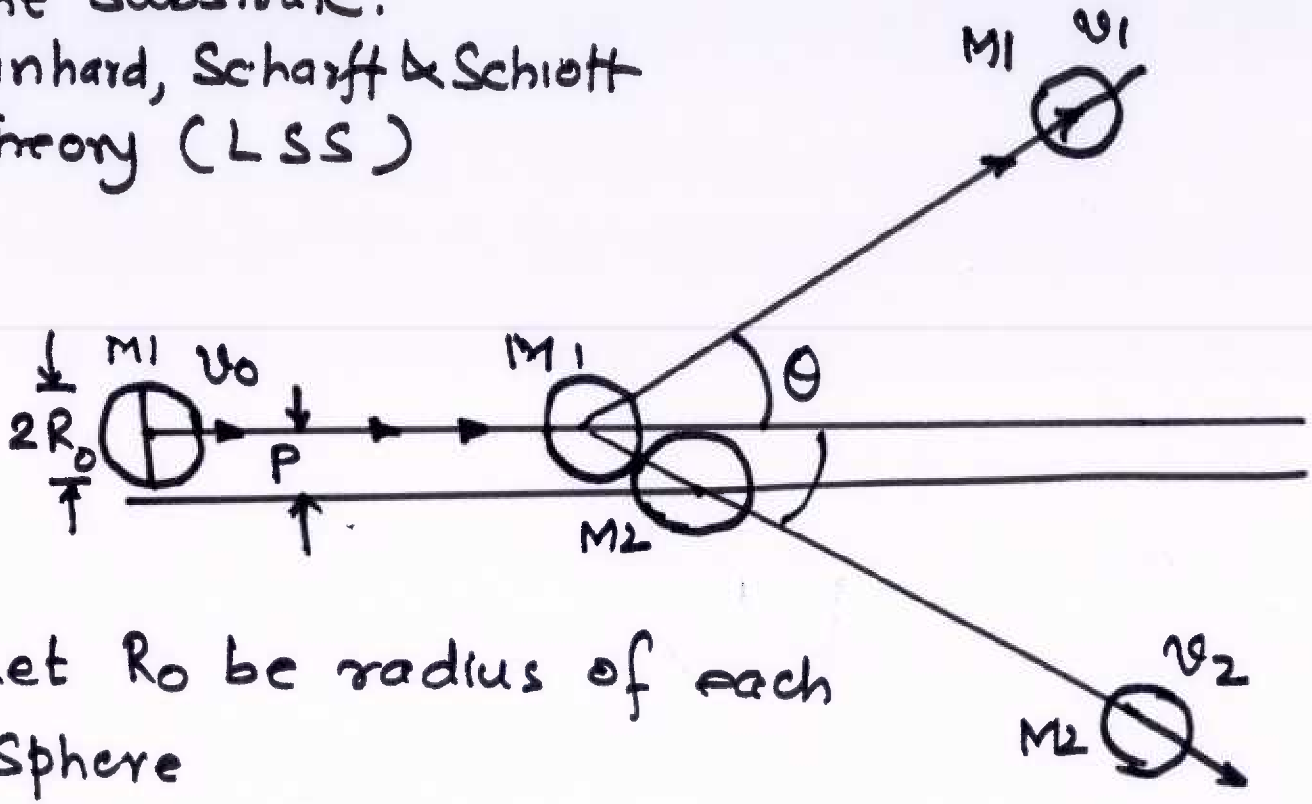




Random interactions with target atoms

Energy Loss Mechanism for Ions inside the Substrate.

Linhard, Scharff & Schiott Theory (LSS)



Let R_0 be radius of each sphere

Let v_0 and E_0 be velocity and Energy (KE) of the moving sphere (M_1 here). Let M_1 is the mass of the sphere. This sphere impinges on Stationary (atom) sphere which has Mass M_2 but KE = 0.0.

Further Let v_1 be velocity of sphere M1 after it's collision with M2. Let the M1 moves along the projectile with angle θ with movement direction of M_1 before Impiging.

The KE of M1 is then E_1.

The Stationary (atom) sphere M2 acquires energy due to collision and moves along $-\theta$ direction with KE = E_2

'p' is defined as separation between two spheres.

For Impact of M1 with M2 to occure, we must have

$$p \leq 2R_0$$

For $p = 0$, it means 'Head-On' collision.

Assuming Elastic Collisions, we apply law of Conservation of Momentum and Energy

We have for Energy conservation:

$$\frac{1}{2} m_1 v_0^2 = \frac{1}{2} m_1 v_1^2 \cos^2\theta + \frac{1}{2} m_2 v_2^2 \cos^2\theta \quad \text{— [1]}$$

Clearly here $E_0 = \frac{1}{2} m_1 v_0^2$ or $v_0 = \sqrt{\frac{2}{m_1}}\, E_0^{1/2}$

& Similarly

$$\left.\begin{aligned} v_1 &= \sqrt{\frac{2}{m_1}}\, E_1^{1/2} \\ \&\quad v_2 &= \sqrt{\frac{2}{m_1}}\, E_2^{1/2} \end{aligned}\right] \longrightarrow [2]$$

From eq [1] $$\cos^2\theta = \frac{m_1 v_0^2}{m_1 v_1^2 + m_2 v_2^2}$$

or $$\cos\theta = \frac{\sqrt{m_1}\, v_0}{\sqrt{m_1 v_1^2 + m_2 v_2^2}} = \frac{E_0^{1/2}}{\sqrt{E_1^2 + E_2^2}} \quad \text{—[3]}$$

We also have Momentum Conservation, which means

$$m_1 v_0 = m_2 v_2 \cos\theta + m_1 v_1 \cos\theta \qquad \text{— [4]}$$

$$\text{or} \quad \cos\theta = \frac{m_1 v_0}{m_2 v_2 + m_1 v_1} \qquad \text{— [5]}$$

From [3] and [5]

$$\cos\theta = \frac{1}{2}\left[\left(1+\frac{m_2}{m_1}\right)\left(\frac{E_2}{E_0}\right)^{1/2} + \left(1-\frac{m_2}{m_1}\right)\left(\frac{E_0}{E_2}\right)^{1/2}\right] \qquad \text{— [6]}$$

In case of Ion Implantation, the KE used as above is due to momentum gained by atoms of Mass M_1 and M_2

However due charged nature of Ions, they also experience Coloumbs force. This lead to Potential $V(r) = \frac{q^2 Z_1 Z_2}{r} \exp(-r/a)$

where Z_1 and Z_2 are atomic no. of atoms with mass m_1 and m_2. The parameter a is called Screening Parameter given by

$$a = \frac{0.885 a_0}{\left[Z_1^{2/3} + Z_2^{2/3}\right]^{1/2}}$$; Here a_0 is Bohr's radius

The Screening potential $V(r)$ is integrated along the path of Ions to get Scattering angle.

We have thus two mechanism for energy relaxation and are called Stopping Power. They are

1. Nuclear Stopping Power

ii Electronic Stopping power.

o.r $$\frac{dE}{dx} = -N\left[S_n(E)+S_e(E)\right]$$

where N is no. of atoms/cc

$S_n(E)$ = Nuclear Stopping Power

In first approx., $S_n(E)$ is constant (not function of E)

or $$S_n(E) = S_n^0 = \frac{2.8\times10^{-15} Z_1 Z_2}{\left[Z_1^{2/3}+Z_2^{2/3}\right]^{1/2}} \frac{M_1}{M_1+M_2} \text{ eV cm}^2$$

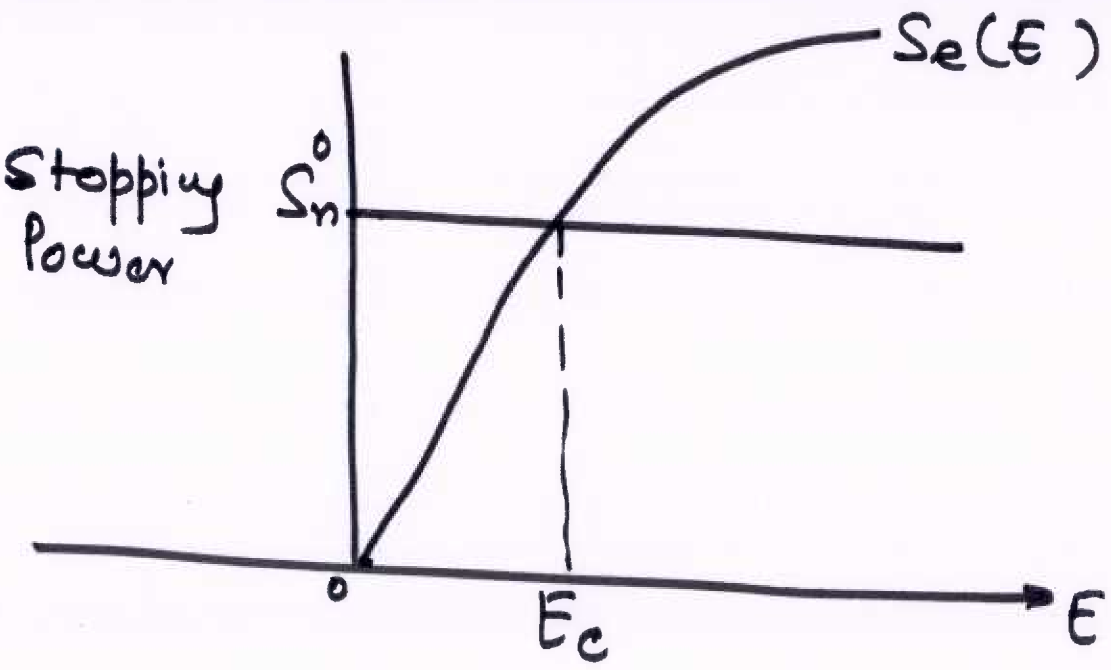
where M_1 and Z_1 are incident Ionic Mass & it's atomic no.

M_2 & Z_2 are Substrate atoms with Mass & At no. Z_2

To first order, Electronic stopping power

$S_e(E) = k\, E^{1/2}$, where $k = 0.2 \times 10^{-15}\ eV^{1/2}\ cm^2$
for Silicon.

We plot stopping powers as function of E



Clearly at $E = E_c$ $\quad S_n^0 = S_e(E_c)$

or $$\frac{2.8\times10^{-15}\, Z_1 Z_2}{\left[Z_1^{2/3} + Z_2^{2/3} \right]^{1/2}} \frac{M_1}{M_1+M_2} = k\sqrt{E_c}$$

or $$E_c = \frac{1}{k^2}\left[\frac{2.8\times10^{-15}\, Z_1 Z_2}{\left(Z_1^{2/3} + Z_2^{2/3} \right)^{1/2}} \frac{M_1}{M_1+M_2} \right]$$

Hence If $E < E_c$ Nuclear Stopping is Dominant

But if $E > E_c$ Electronic Stopping Dominates.

Example

Arsenic is Implanted in Silicon at $E_0 = 250$ keV

Data : $M_{1_{As}} = 1.2433\times10^{-22}$ gm/atom

$Z_{As} = 33$

$M_{2_{Si}} = 4.6628\times10^{-23}$ gm/atom

$Z_{2_{Si}} = 14$

At $E = E_c$ $\quad S_n(E_c) \doteq S_n^0 = S_e(E_c)$

or $\quad k\, E_c^{1/2} = S_n^0$

or $\quad E_c = \frac{1}{k^2}\left[S_n^0\right]^2$

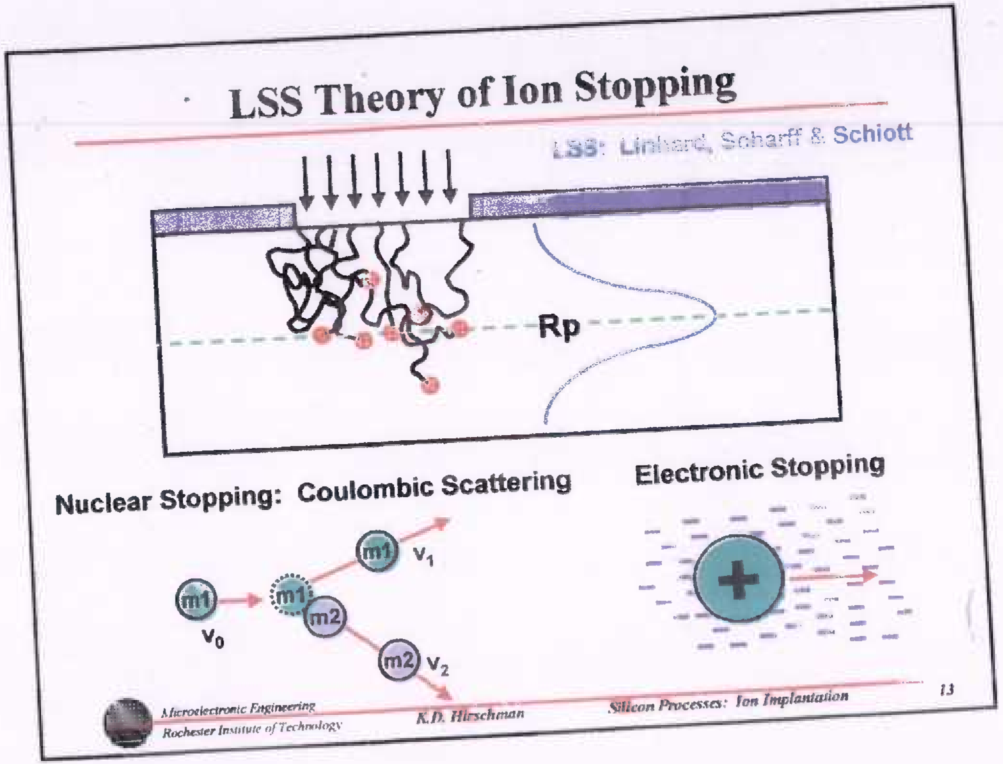
For As-Si combination with E = 250 keV implant

$$E_c = \frac{1}{(2\times10^{-16})^2}\cdot\left(2.34\times10^{-12}\right)^2$$

$$= 13750 \text{ KeV}$$

Clearly E given << E_c

Hence Nuclear Stopping dominates in our case.



LSS Theory of Ion Stopping

LSS: Linhard, Scharff & Schiott

Nuclear Stopping: Coulombic Scattering

Electronic Stopping