Review: Analytical Solutions to Diffusion Equations
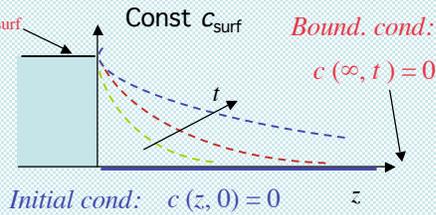
Solution for a **limitless source** of dopant (constant surface concentration):

Boundary cond:
$$c(0, t) = c_{surf}$$

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial z^2}$$

Const c_{surf}

Bound. cond:
$$c(\infty, t) = 0$$

$$c(z,t) = c_{surf}\,\text{erfc}\left[\frac{z}{2\sqrt{Dt}}\right], \quad t > 0$$

Initial cond: $c(z, 0) = 0$

where $\text{erfc}(x) = 1-\text{erf}(x)$ and t = diffusion time

$$\text{Dose } Q = (2/\sqrt{\pi})\ c_{surf}\ (Dt)^{1/2}$$

Dose in sample increases as $t^{1/2}$

Diffusion of a thin, **finite dose** predeposited surface layer into a solid

When a thin surface layer diffuses into a solid, what is $c(z,t)$?

Q = initial amount of dopant ('dose'), assumed to be a delta-function

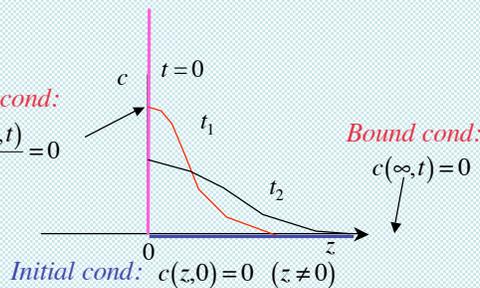$$\int_{-\infty}^{\infty} c(z,t)dz = Q = \text{const. (\# /area)}$$

c $t = 0$

Bound cond:
$$\frac{dc(0,t)}{dz} = 0$$

t_1

Bound cond:
$$c(\infty,t) = 0$$

Solution is a Gaussian.

$$c(z,t) = \frac{Q}{\sqrt{\pi Dt}}\exp\left[-\frac{z^2}{4Dt}\right]$$

t_2

Initial cond: $c(z,0) = 0 \quad (z \neq 0)$

diffusion length $a = 2\sqrt{Dt}$

Dose in sample constant in time

Example:

wafer originally has a uniform
dopant level, e.g. donor.

Predep plus drive-in
introduces a second dopant
an acceptor.

At a certain depth,
a *p-n* junction is formed.

A third pre-dep of donor
can then be done to make
an *n-p-n* transistor.

Problem:
can only make profiles
consisting of superposed
Gaussians centered at the
substrate surface.

Figure removed for copyright reasons.

Please see: Figure 4.14 in Ghandi, S. *VLSI Fabrication Principles: Silicon and Gallium Arsenide*. 2nd ed. New York, NY: Wiley-Interscience, 1994. ISBN: 0471580058.

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Maximum amount of dopant in Si
           is limited by solid solubility

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Please see: Figure 2-4 in Campbell, S. *The Science and Engineering of Microelectronic Fabrication* 1st ed. New York, NY: Oxford University Press, 1996. ISBN: 0195105087.

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Dopants introduced by diffusion:

'pre-deposition' and 'drive-in'(Gaussian), or inexhaustible source (erfc).

This process is limited:

-cannot exceed solid solubility of dopant

-difficult to achieve light or shallow doping

ION IMPLANTATION

Ion implantation often preferred to diffusion because:

-controlled, *low or high dose* can be introduced (10^{11} - 10^{18} cm^{-2})

-*depth* of implant can be controlled.

Used since 1970, despite substrate damage;

low throughput, and high cost.

Plummer Ch. 8, Campbell Ch. 5

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Ion Implantation

Beam of energetic dopant ions is directed into surface of wafer.
Ion energies typically 5 - 200 keV.

This leads to implantation (burial) of the ions in the substrate.

What happens at the substrate?

Ions can: *bounce off*
              adsorb
              sputter (knock off) atoms (10 eV - 10 keV)
              implant into surface (5 keV - 200 keV)…
              and do tremendous damage

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Comparison of Diffusion and Ion implantation

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Please see: Figure 7.1 in May, G. S., and S. Sze. *Fundamentals of Semiconductor Fabrication* New York, NY: John Wiley & Sons, Inc., 2004. ISBN: 0471232793.

From May and Sze, Fig. 7.1

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Ion Implantation Equipment

- Ions generated in a source (from feed gas, e.g. BF_3, AsH_3, PH_3 ...
  or heated solid source, then ionized in arc chamber by electrons from hot filament)
- Accelerate for mass spectroscopy
- Select desired species by q/m, using a magnet (mass spectrometer),
- Accelerate by an E-field and focus using electrostatic lenses

(a bend removes neutrals)   impact substrate in raster pattern.

Figure removed for copyright reasons.

Please see: Figure 8.14 in Campbell, S. *The Science and Engineering of Microelectronic Fabrication* 2nd ed. New York, NY: Oxford University Press, 2001. ISBN: 0195136055.

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What happens to ions inside the material?

Implanted ion energy changes with depth, *dE/dx*,
by two types of interaction:
***elastic* with nuclei   and   inelastic with electrons**

N is number of incident ions

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

S_i(E) is Stopping power (eVcm²)

Ion *range* in target:

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

What can we say about nuclear and electronic stopping...

Nuclear stopping power: Coulomb scattering (assumed *elastic*)

Incident ion (E_1, M_1) interacts with nucleus of stationary ion (M_2); b = impact parameter

E_1, M_1

b

θ

M_2

ϕ

M_2/M_1
0 2 4 6 8 10

Energy transferred by incoming ion:

$$\Delta E = E_1\left\{1 - \frac{\sin^2\phi}{\cos\theta\sin\phi + \cos\phi\sin\theta}\right\}$$
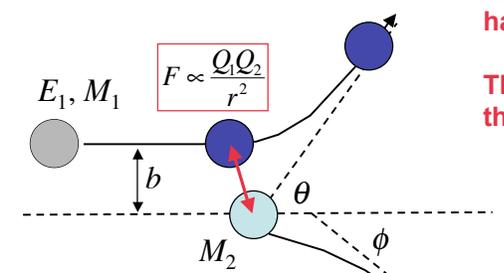
The angles depend on masses and on *b*.

Max. energy transfer when *b* = 0, ϕ = 0 (head-on collision):

$$\Delta E = E_1 \frac{4M_1M_2}{(M_1 + M_2)^2}$$

Nuclear stopping power: Coulomb scattering (assumed *elastic*)

$$F \propto \frac{Q_1 Q_2}{r^2}$$

E_1, M_1

b

θ

ϕ

M_2

At 100 keV an ion of 15 amu has velocity , $v_{ion} \approx 10^6$ m/s!

This is 1000 times faster than speed of sound in solids…
(explain phonons)

So fast ion is far past nucleus before nucleus can displace in response to Coulomb force

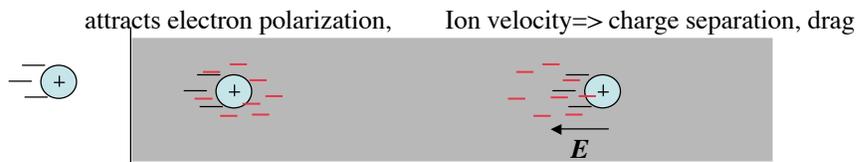**So nuclear scattering is not strong at high ion velocity; only significant when ion slows down.**

$$\text{Impulse} = \int_0^t F(t)dt = \Delta p$$

Short interaction time reduces impulse to M_2

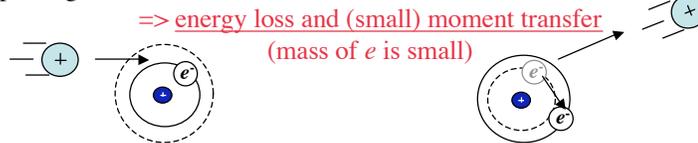There are also *inelastic* collisions that transfer energy…

Electronic stopping power: also Coulomb interactions, but *inelastic*

<u>**Non-local:**</u> ion experiences drag due to "free" or polarizable electrons:

incident ion

attracts electron polarization,   Ion velocity=> charge separation, drag

$+$

$+$

$+$

E

No change in direction; only viscous damping

<u>**Local:**</u> passing ion causes internal electronic transitions or ionization

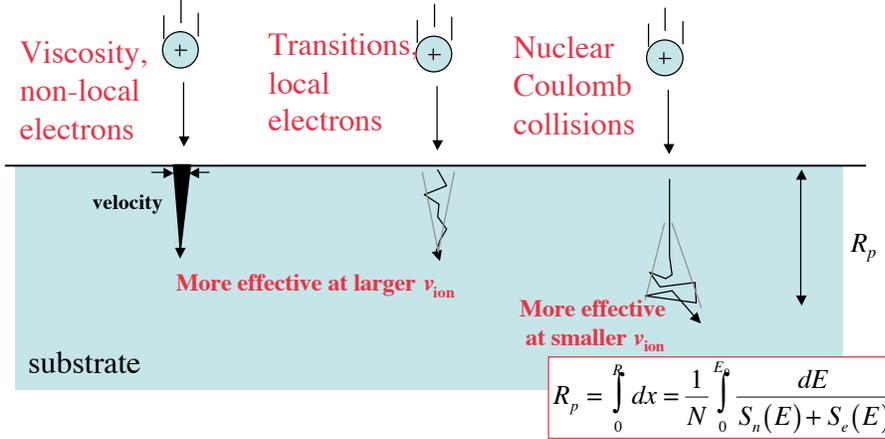=> energy loss and (small) moment transfer
(mass of e is small)

$+$

e

$+$

$+$

e

$+$

e

Because electrons can respond to fields up to optical frequencies, (their velocities are much faster than phonons) <u>electronic losses are more significant at higher ion velocities.</u>

$$S_e(E) \propto v_{ion} \propto E^{1/2}$$

Stopping power in Ion Implantation

With each interaction, ion loses some energy. It travels through a vertical projected range R_p before stopping. It transfers energy to target via both <u>electronic</u> and <u>nuclear</u> interactions
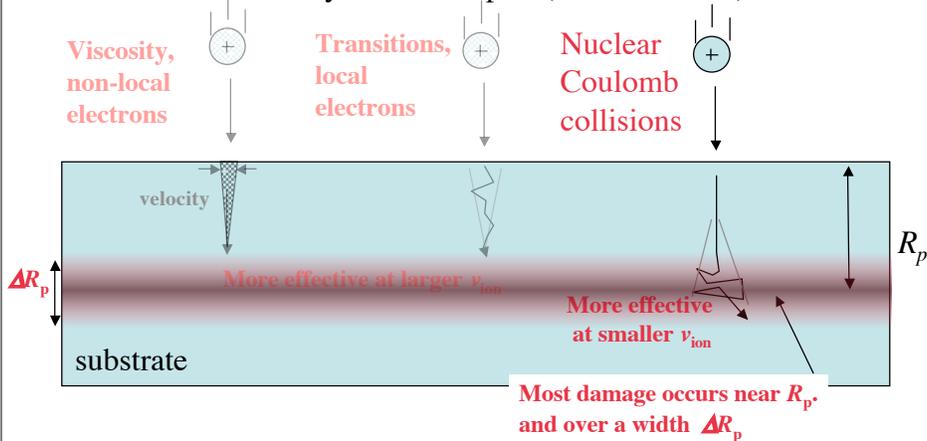
Viscosity, non-local electrons

Transitions, local electrons

Nuclear Coulomb collisions

velocity

More effective at larger v_{ion}

More effective at smaller v_{ion}

R_p

substrate

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

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Wafer damage in Ion Implantation

Most damage is done by nuclear interactions

About 15 eV needed to displace Si from lattice site,

create vacancy/interstitial pair (Frankel defect)

Viscosity, non-local electrons

Transitions, local electrons

Nuclear Coulomb collisions

velocity

More effective at larger v_{ion}

More effective at smaller v_{ion}

R_p

ΔR_p

substrate

**Most damage occurs near R_p.
and over a width ΔR_p**

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S_{nuc} is maximum at some small energy E.
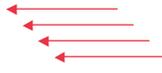S_{nuc} can be larger or smaller than S_e.

Ion flux

Figure removed for copyright reasons.

Please see: Figure 5.8 in Campbell, 2001.

Electronic loss
goes as E

small E:
bonds are
not broken
so less
energy is
transferred
(purely
elastic
collisions)

Smaller mass of
B means higher
velocity,

$(2E/m)^{1/2}$, less
nuclear stopping

large E: too
little time for
nuclear
energy
transfer

$\Sigma(S_{nuc}+S_{elec})$ **is almost constant,**
$\therefore$**range,** $R \propto \int dE/ (S_{nuc}+S_{elec})$ **is almost linear in** $E\ldots$

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From S_e and S_n, R_p and ΔR_p can be calculated:

Smaller mass of B
means higher
velocity,

$/m)^{1/2}$, less
nuclear stopping

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Please see: Figure 5.9, Parts A-D, in Campbell, 2001.

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Composition profile for ion implantation

If the depth is x, the impurity concentration $c(x)$ is approximated by a gaussian

$$c(x) = c_p \exp\left(-\frac{(x - R_p)^2}{2\Delta R_p^2}\right)$$

where c_p is the peak concentration, R_p the *projected range* and ΔR_p the standard deviation of the projected range (vertical straggle or spread).

The implanted dose is given by Q (Number/area)

$$Q = \int_{-\infty}^{\infty} c(x)dx \qquad\qquad Q = \sqrt{2\pi}\Delta R_P c_P$$

So a given dose will determine the peak concentration.

Greater velocity longer R_p;

less loss/collision => larger ΔR_p

Figure removed for copyright reasons.

Please see: Figure 8-2 in Plummer, J., M. Deal, and P. *Griffin. Silicon VLSI Technology: Fundamentals, Practice, and Modeling*. Upper Saddle River, NJ: Prentice Hall, 2000. ISBN: 0130850373.

Why do light atoms have greater projected *range R_p*

and *standard deviation ΔR_p* ?

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Please see: Figure 8-8 in Plummer et al., 2000.

Note: composition profiles are not always perfect Gaussians: there can be a skew or distortion (*kurtosis*) making the profile asymmetric.

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Creating unique profiles via Ion implantation

Clearly need different doses with each implant

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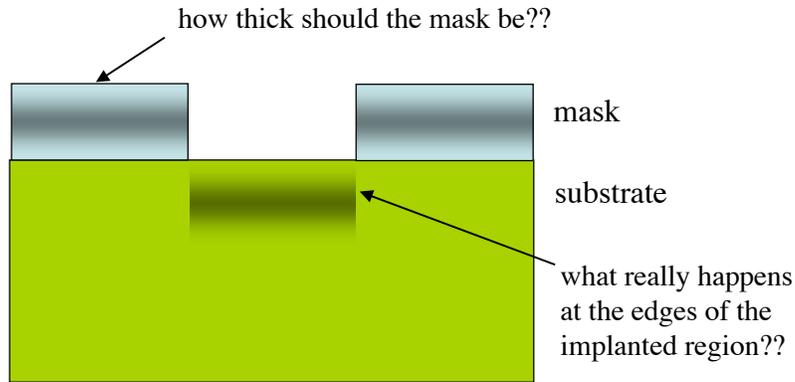
Please see: Figure 7.13 in May and Sze, 2004.

From May and Sze, Fig. 7.13

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Masking implants

Implant only certain parts of wafer: use a mask such that R_p lies within the mask material. Use to form self-aligned source and drain regions, for example, in a MOSFET.

how thick should the mask be??

mask

substrate

what really happens at the edges of the implanted region??

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Ion implantation through a mask*

Define range, R_p^* and std. deviation , ΔR_p^* for ions hitting mask

For an <u>efficient mask</u>:

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

Background concentration in substrate

Invert $\Rightarrow$ mask thickness:

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

x_m = range +
     some multiple, m, of std deviation

Dose penetrating mask:

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

Figure removed for copyright reasons.

$$Q_P = \frac{Q}{2}\mathrm{erfc}\left(\frac{x_m - R_P^*}{\sqrt{2}\Delta R_P^*}\right)$$

Please see: Figure 8-5 in Plummer et al., 2000.

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Note: SiO_2 is better
ion-implant mask
than is photoresist

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Please see: Figure 5.9, Parts F and G, in Campbell, 2001.

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Minimum mask thickness for Ion implantation in Si

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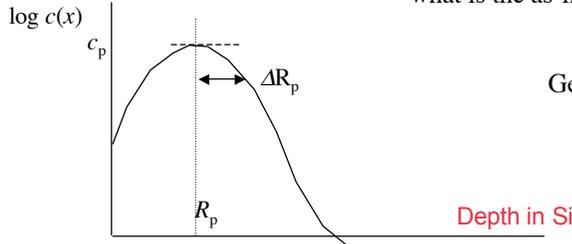Please see: Figure 7.14 in May and Sze, 2004.

From May and Sze, Fig. 7.14
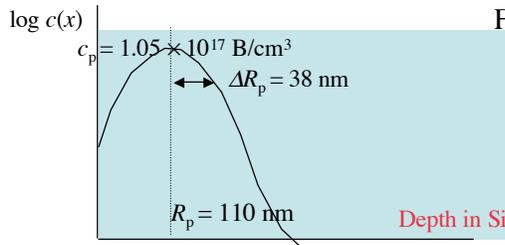
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Example:

30 keV B is implanted into **bare Si**. The dose is 10^{12} cm^{-2}.

-what is the as-implanted profile?

log $c(x)$

c_p

ΔR_p

R_p Depth in Si

Get R_p, ΔR_p from chart: B in Si

also $Q = c_p(2\pi)^{1/2}\Delta R_p$

get $c_p = Q/(2\pi)^{1/2}\Delta R_p$

Solution: 30 kV B into bare Si.
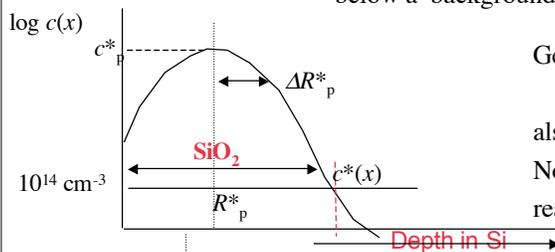
log $c(x)$

$c_p = 1.05 \times 10^{17}$ B/cm^3

$\Delta R_p = 38$ nm

$R_p = 110$ nm   Depth in Si

From slide 15:

$R_p = 110$ nm $= 1.1 \times 10^{-5}$ cm,

$\Delta R_p = 38$ nm $= 0.38 \times 10^{-5}$ cm

also from $Q = 10^{12}$ cm^{-2},

$c_p = Q/\{(2\pi)^{1/2}\Delta R_p\}$

$c_p = 1.05 \times 10^{17}$ B/cm^3.

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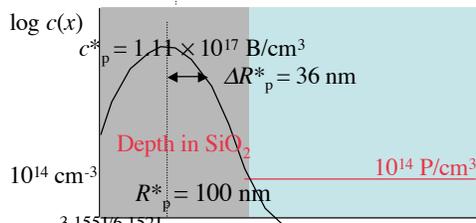## Example (cont):

-what thickness of silica mask would you need to keep the B content in Si

below a background P doping level of 10^{14} cm^{-3}?

log $c(x)$

c^*_p

ΔR^*_p

SiO$_2$

10^{14} cm^{-3} $c^*(x)$

R^*_p

Depth in Si

Get R_p^*, ΔR_p^* in SiO$_2$ from chart:

(B in SiO$_2$)

also from Q you can get c^*_p

Now find the depth at which $c^*(x)$

reaches the background depth.

Solution: thickness of silica mask so $c_B(x)$ content in Si < $c_P = 10^{14}$ P/cm^3

log $c(x)$

$c^*_p = 1.11 \times 10^{17}$ B/cm^3

$\Delta R^*_p = 36$ nm

Depth in SiO$_2$

10^{14} cm^{-3} 10^{14} P/cm^3

$R^*_p = 100$ nm

From slide 23:

$R_p^* = 100$ nm $= 1.0 \times 10^{-5}$ cm,

$\Delta R_p^* = 36$ nm $= 0.36 \times 10^{-5}$ cm

same $Q => c_p = 1.11 \times 10^{17}$/cm^3.

$$c(x_m) = c_p \exp\left\{-\frac{(x_m - R_p^*)^2}{2\Delta R_p^{*2}}\right\} \leq 10^{14} \; P/cm^3$$

$$\boxed{x_m \geq R_p^* + \Delta R_p^*\sqrt{2\ln\left(\frac{c_p}{10^{14}}\right)} = 474 \;\; nm}$$

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60 keV As implant at different angles to normal

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Please see: Figure 7.15 in May and Sze, 2004.

Oblique implant can give very shallow doped layer

From May and Sze, Fig. 7.15

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Channeling

If the ions are incident parallel to a major crystal direction, they can pass through the structure with less scattering, so the range is much larger than expected.

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Please see: Figure 8-10 in Plummer et al., 2000.

Si lattice seen from different directions

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Nuclear Stopping

3-D Monte Carlo simulation of

35 keV phosphorus

Nuclear stopping, S_n, can be modeled by Coulomb scattering (so it depends on impact parameter, relative masses, and E)

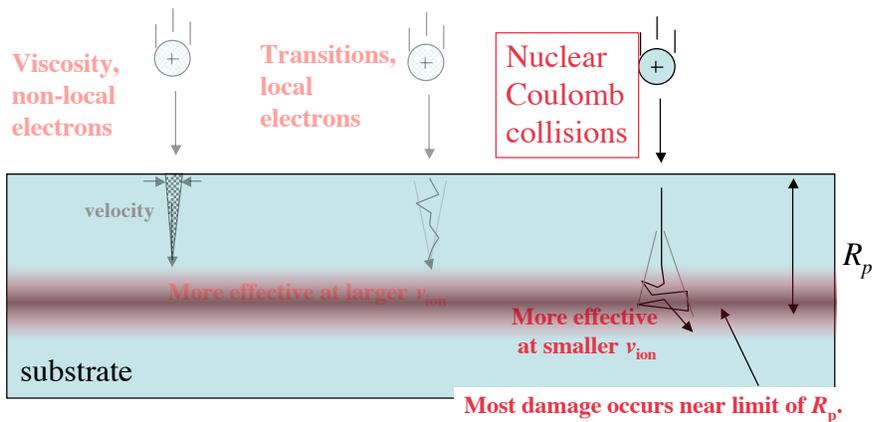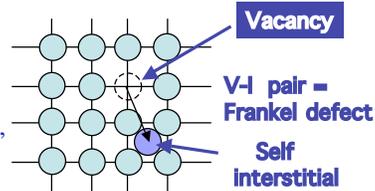$$c(x,y) = c_{\text{vert}}(x)\exp[-\frac{y^2}{2\Delta R_\perp^2}]$$

Figure removed for copyright reasons.

Please see: Figure 8-4 in Plummer et al., 2000.

2-D projections

Damage in Ion Implantation

Most damage is done by nuclear interactions

About 15 eV needed to displace Si from lattice site,

create vacancy/interstitial pair

Vacancy

V-I pair = Frankel defect

Self interstitial

Viscosity, non-local electrons

Transitions, local electrons

Nuclear Coulomb collisions

velocity

R_p

More effective at larger v_{ion}

More effective at smaller v_{ion}

substrate

Most damage occurs near limit of R_p.

Implantation damage

The ions damage the crystal structure, and might cause amorphization.

Dose needed to amorphize a silicon substrate

Need solid-phase epitaxy to recrystallize the amorphous regions

Figure removed for copyright reasons.

Please see: Figure 5.13 in Campbell, 2001.

How many Si atoms does an implant displace?

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Implantation damage

A post-implant anneal (e.g. >850˚C) must be done to restore atoms to lattice sites and 'activate' the dopant. This causes diffusion of the dopant profile, and formation of defect clusters. Transient effect on diffusion are very important!

Effective transient diffusion distance for B in Si after implantation with Si ions.

Figure removed for copyright reasons.

Please see: Figure 8-40 in Plummer et al., 2000.

As the damage anneals out, diffusion const, D, decreases

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Annealing temperature vs. dose
for 90% activation of B and P dopants

Onset
Solid-phase
Epitaxy

(amorphized layer
near R_p
has higher diffusion
rate)

Figure removed for copyright reasons.
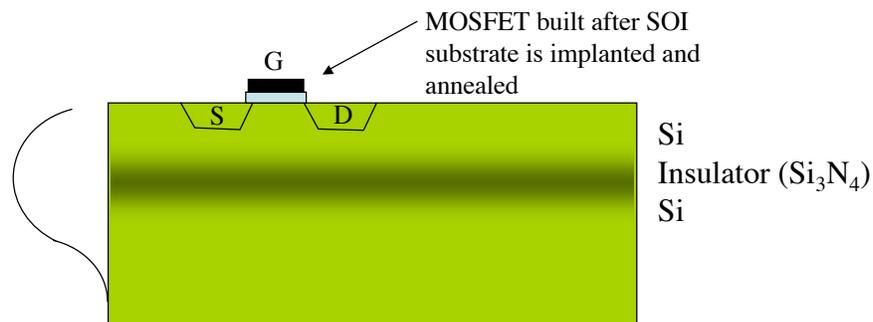
Please see: Figure 7.11 in May and Sze, 2004.

From May and Sze, Fig. 7.11

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Buried dielectrics, e.g. SOI (Silicon on insulator)
Form Si_3N_4 using N^+ implant, or SiO_2 using O^+ implant

Useful to isolate devices: why is this important?

MOSFET built after SOI
substrate is implanted and
annealed

G

S   D

Si
Insulator (Si_3N_4)
Si

Reduced capacitance of devices increases their speed.
Mac G5 attributes its speed to SOI technology.

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IBM Silicon-on-Insulator: different from normal bulk CMOS production.
   IBM puts silicon junction on electrical insulator.
   Normal CMOS is slower (capacitance between the layers and Si)

With silicon oxide layer over silicon substrate, circuits capacitance reduced

Diagram removed for copyright reasons.

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Diagram removed for copyright reasons.

How IBM Silicon-on-Insulator made: "Separation by Implantation of Oxygen"
Oxygen implanted, very heavy dose;
          wafer is annealed at a high T so thin layer of SiO formed.
Once SiO film made, transistor fab follows same process as bulk CMOS production,
                                                                same lithography,

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