ECE 416/516
IC Technologies
Lecture 5:
Ion Implantation

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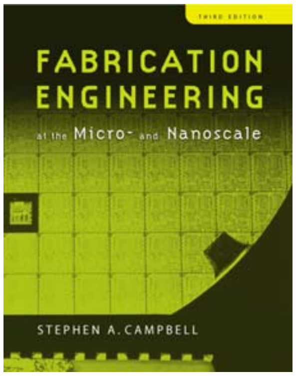
Chapter 5

Ion Implantation



Ion Implantation

- Introduction
- Implantation Systems
- Profiles
- Channeling and Tailing
- Damage and Annealing
- Practical Process Applications
- Stopping Range Theory

- Objectives
- Can describe implantation system & process
- Can calculate implant range & distribution
  - (including 3D and masking effects)
- Can calculate MOS gate voltage threshold shift
- Can follow theoretical concepts of energy loss and stopping theory

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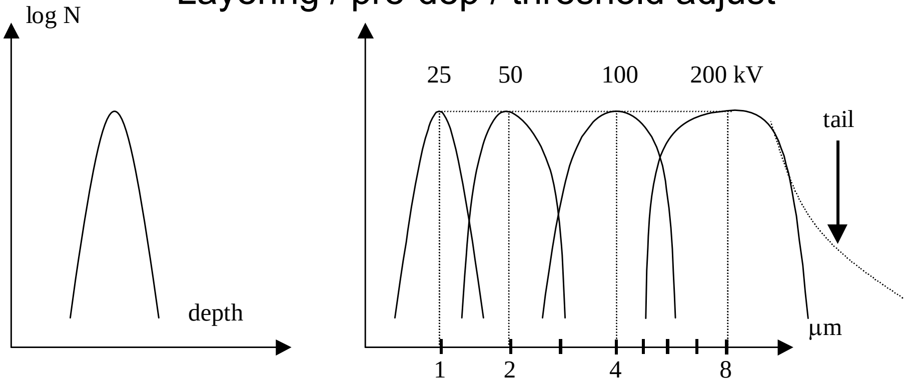
Introduction #1

- Low level dose below surface

- Layering / pre-dep / threshold adjust



Multiple Implants

Introduction #2

Multiple Implants

- Range α E, straggle
- Uniform profiles
- Complex profiles

  Hyperabrupt junctions
- Doses typ. 10^{11}-10^{17}/cm^2 ± 1%
  - Diffusion ±5-10%
- Diffusion surface sensitive,

  ..... ion implant not
- Doping more uniform across device
- Ion implant at low T
- Increasing flexibility in masking techniques
- Non-equilibrium process
  - not subject to thermodynamic limit
  - i.e. dope above solid solubility limit
- MOS threshold control
- Anneal lattice damage
  - possible during later processing
  - $(Dt)^{1/2} << R_p$ for negligible ion movement during anneal

Implantation Systems

Impure ion sources --> mass separation

Energy spread --> velocity filtering

Reproducibility --> measure beam current

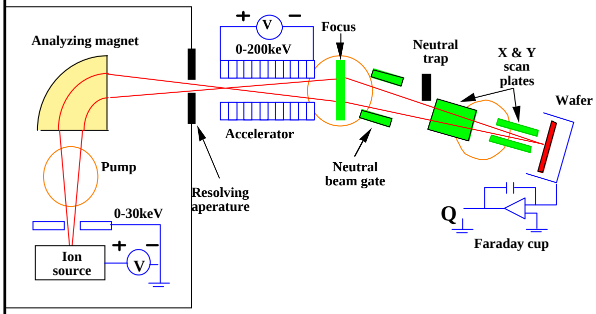
UHV techniques --> load-lock, etc.

Equipment more expensive than diffusion

ION IMPLANTATION
Basic Concepts

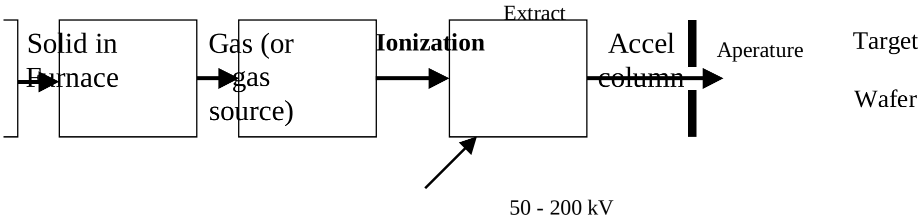
- Ion implantation is the dominant method of doping used today. In spite of creating enormous lattice damage it is favored because:
  - Large range of doses - 10^{11} to 10^{16} /cm^2
  - Extremely accurate dose control
  - Essential for MOS V_T control
  - Buried (retrograde) profiles are possible
  - Low temperature process
  - Wide choice of masking materials

MOS threshold voltage shift $\Delta V_T = q\ Q/C_{ox}$



- There are also some significant disadvantages:
- Damage to crystal.
- Anomalous transiently enhanced diffusion (TED). upon annealing this damage.
- Charging of insulating layers.

Ion Sources



- Plasma ionization: magnetic field forces ions into spiral to increase ionization efficiency

-For beam current IμA, wafer area A cm^2, time t sec

- ions/cm^2 = I x 10^{-6} t / 1.6×10^{-19} A → 5×10^{16}/cm^2 for 100 μA, 1000 sec (≈20 min), 4cm wafer ($A=\pi 2^2$)

-Typical P implant: 500 μA → 10^{16}/cm^2 in 1 min

- Metals (eg Cu) typically 1-10 μA → 10^{16}/cm^2 in 3-30hrs

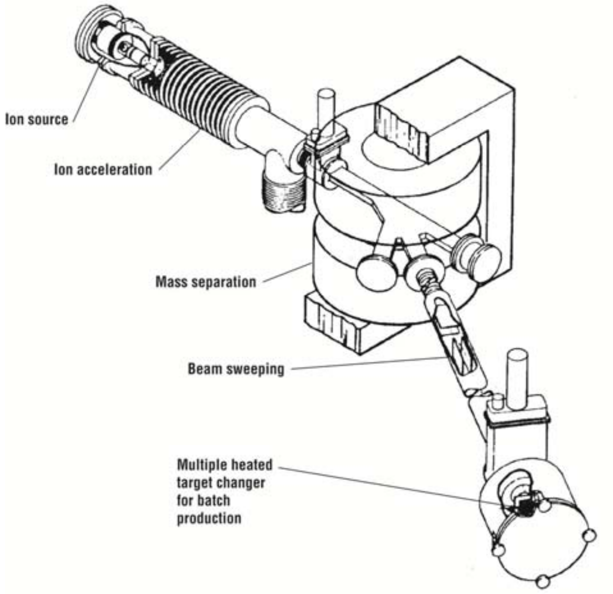


Figure 5.1 Schematic of an ion implanter *(after Mayer et al., reprinted by permission, Academic Press).*

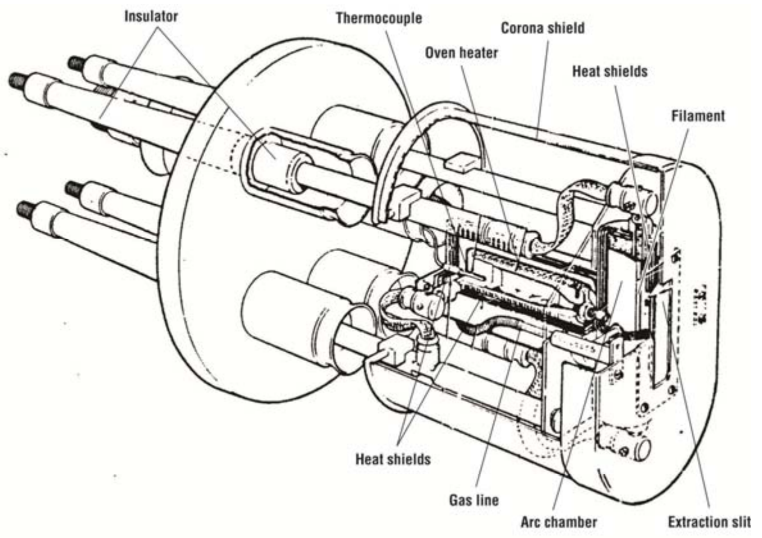
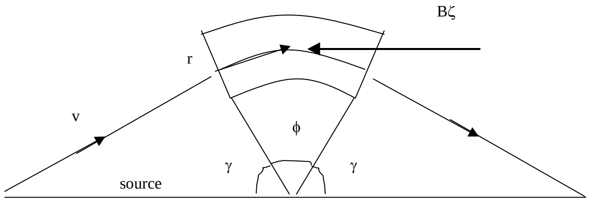


Figure 5.2 Schematic for a Freeman ion source. Solids can be vaporized in the oven heater, while gaseous sources may be injected directly into the arc chamber, newer system's use a Bernas ion source *(reprinted by permission, Elsevier Science, after Freeman in Mayer et al.).*

Mass Separation

- eg B from BF_3 / B_2H_6/BCl_3 → multiple ions, multiply charged
- Assume homogeneous magnetic field B



- F = q v x B --> circular path F=mv^2/r
- and ½ mv^2 = qV acceleration potential
- $\therefore$ r = $(2mV/q)^{1/2}$/B depends on m, V
- Select ion mass/energy by position of exit slit, i.e. r

$v=\sqrt{\frac{2E}{M}}\approx\sqrt{\frac{2qV_{ext}}{M}}$ since initial energy from source ~ 10eV << qV_{ext} extraction energy

and $\frac{Mv^2}{R}=qvB,\ \therefore\ R=\frac{Mv^2}{qvB}=\frac{M}{qB}\sqrt{\frac{2qV_{ext}}{M}}=\frac{1}{B}\sqrt{\frac{2MV_{ext}}{q}}$

For ion $M+dM$, $R+dR=\frac{1}{B}\sqrt{\frac{2(M+dM)V_{ext}}{q}}$, so $\left(1+\frac{dR}{R}\right)=\left(1+\frac{dM}{M}\right)^{\frac{1}{2}}\approx 1+\frac{1}{2}\frac{dM}{M}$,

so $\Delta R=R\left(\frac{dM}{2M}\right)$ and $D=R\frac{dM}{2M}\left(1-\cos\phi+\frac{L}{R}\sin\phi\right)$

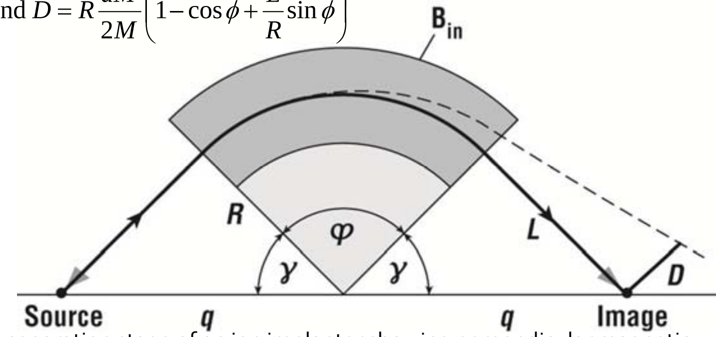


Figure 5.3 Mass separation stage of an ion implanter showing perpendicular magnetic field and ion trajectory: *D* corresponds to the displacement for an ion of $M+\delta M$.

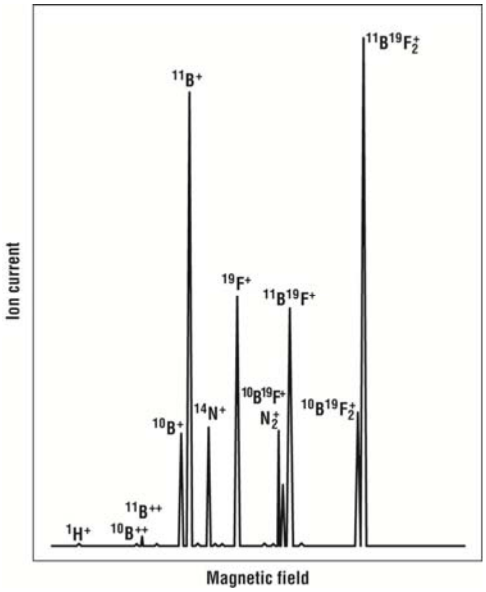
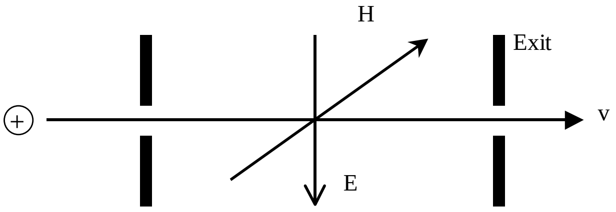


Figure 5.4 Typical mass spectrum for a BF_3 source gas *(after Ryssel and Ruge, reprinted by permission Wiley).*

Velocity/Energy Filtering



- Particle travels straight ONLY if:

$F_B = F_H$ --> $qE = qvB$ ie. $v = E/B$

- (orthogonal set /"Wien filter")
- Precise control

Beam Scanning

A. X-Y scanning:

(1) both electrostatic (more uniform)

(2) x electrostatic, y mechanical

B. Whole wafer - no scan

- usually for implant profile

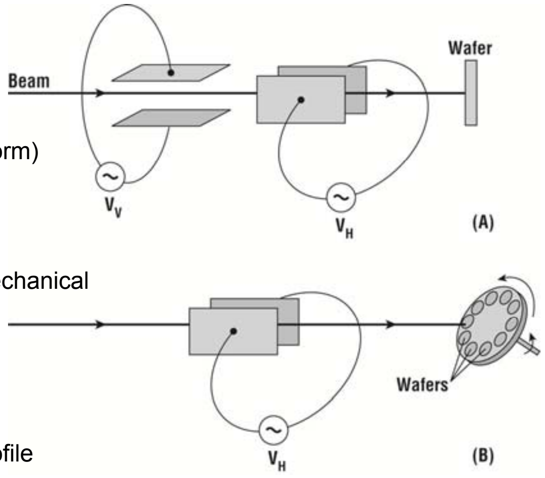
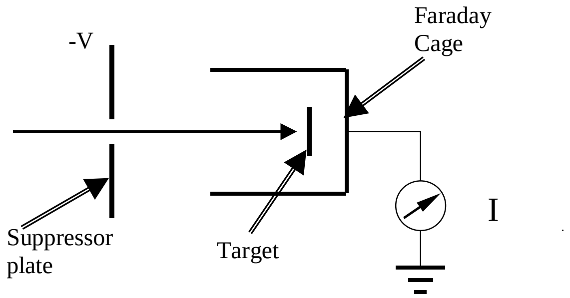


Figure 5.5 Typical scanning systems for ion implanters. (A) Electrostatic rastering commonly used in medium current machines. (B) Semielectrostatic scanning used on some high current machines.

Total energy transfer to wafer = $\int IV.dt = VQ$, heats photoresist
Bakes, so removal difficult; outgas, so carbonizes

Beam Current Measurement



- Electron suppression
- Neutrals (ion + e^-) -> electrostatic bend
- Suppress secondary electron emission
  - return electrons to wafer
  - small magnetic field or wafer voltage

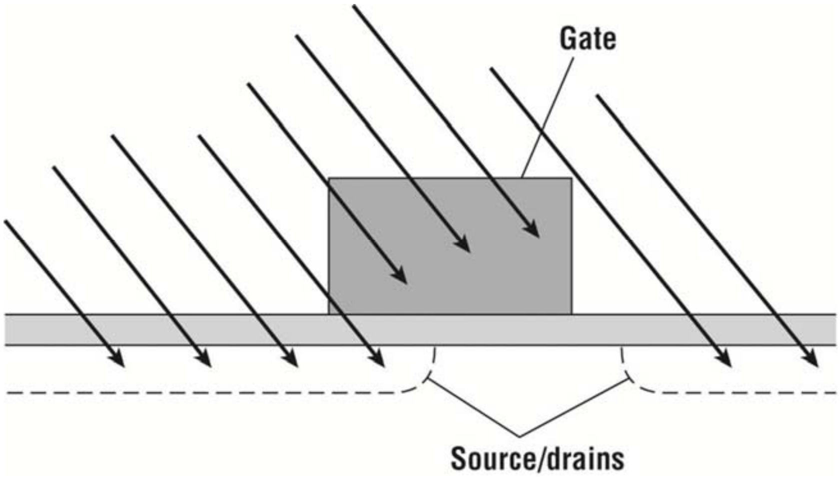
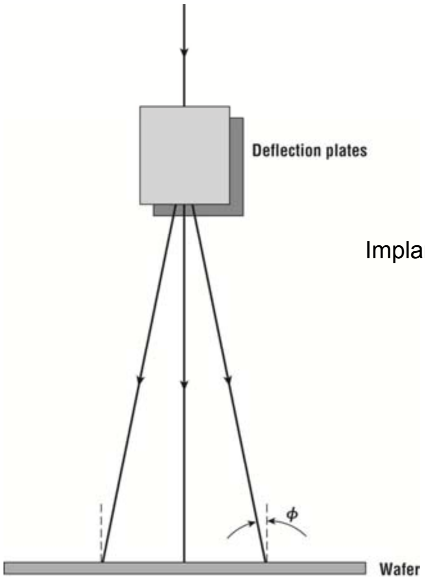


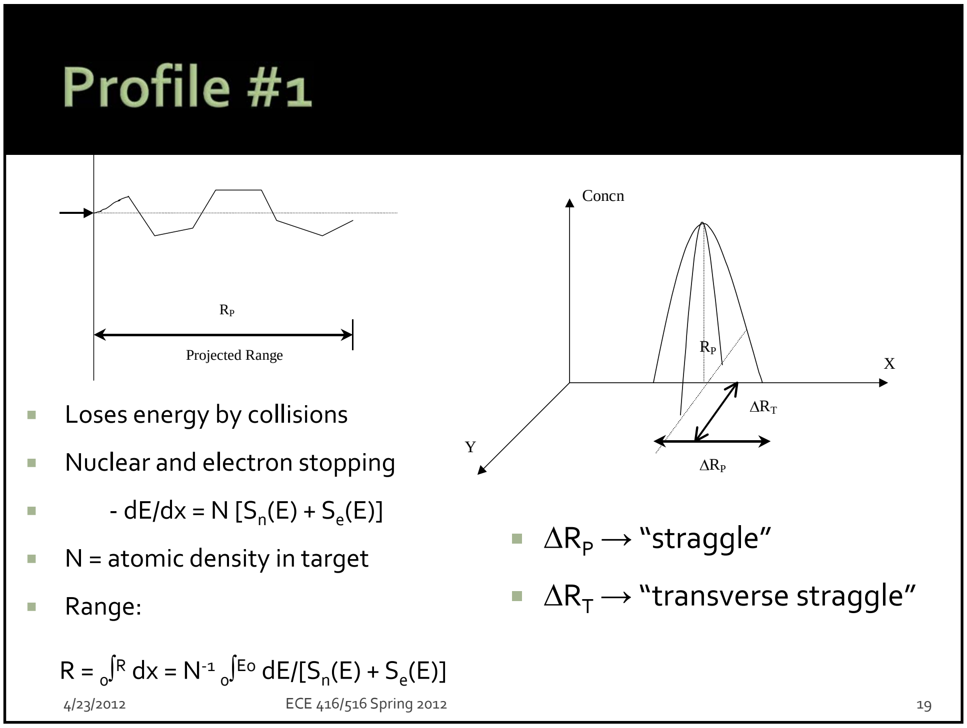
Figure 5.20 Simple shadowing example for deeply scaled MOSFET. As a result of the tilt angle one of the source/drain diffusions does not extend to the channel leading to poor *I–V* characteristics.

Control/vary angles during implant



Implant angle varies 5-9°

Figure 5.21 Variability of the angle between the incident beam and the surface normal in simple electrostatically scanned systems.

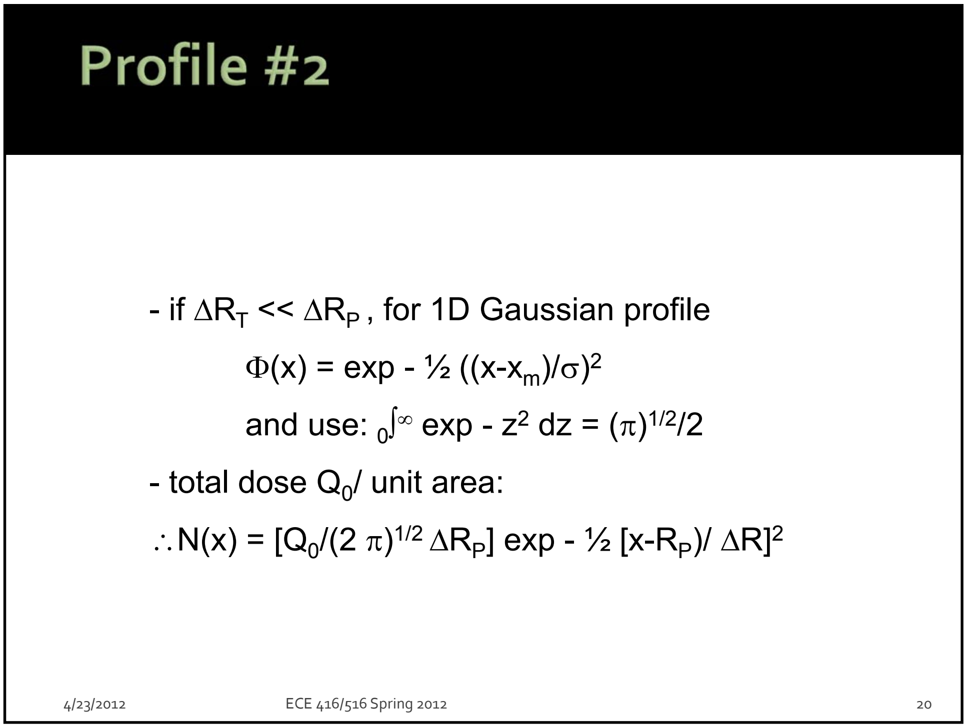


Profile #1

- Loses energy by collisions
- Nuclear and electron stopping
- $-\,dE/dx = N\,[S_n(E) + S_e(E)]$
- N = atomic density in target
- Range:

$$R = {}_0\!\int^{R} dx = N^{-1}\,{}_0\!\int^{E_0} dE/[S_n(E) + S_e(E)]$$

- $\Delta R_P \rightarrow$ "straggle"
- $\Delta R_T \rightarrow$ "transverse straggle"



Profile #2

- if $\Delta R_T << \Delta R_P$, for 1D Gaussian profile

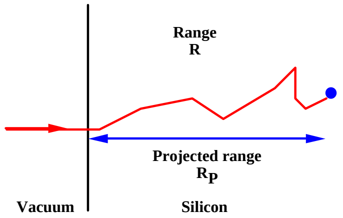
$$\Phi(x) = \exp - \tfrac{1}{2}\,((x-x_m)/\sigma)^2$$

and use: ${}_0\!\int^{\infty} \exp - z^2\,dz = (\pi)^{1/2}/2$

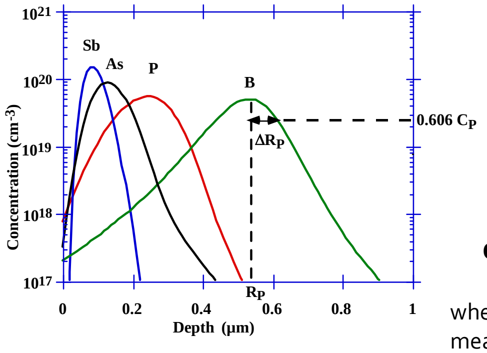
- total dose Q_0/ unit area:

$$\therefore N(x) = [Q_0/(2\,\pi)^{1/2}\,\Delta R_P]\,\exp - \tfrac{1}{2}\,[x-R_P)/\,\Delta R]^2$$

A. Implant Profiles



- At its heart ion implantation is a random process.
- High energy ions (1-1000keV) bombard the substrate and lose energy through nuclear collisions and electronic drag forces.

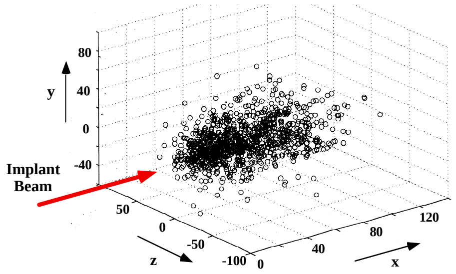


- Profiles can often be described by a Gaussian distribution, with a projected range and standard deviation. (200keV implants shown.)

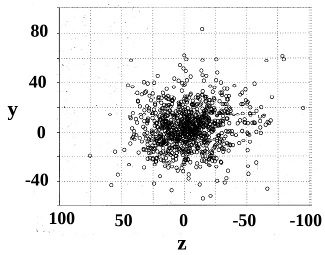
$$C(x) = C_P \exp\left(-\frac{(x-R_P)^2}{2\Delta R_P^2}\right) \qquad (1)$$

$$Q = \int_{-\infty}^{\infty} C(x)\,dx \quad \text{or} \quad Q = \sqrt{2\pi}\,\Delta R_P\, C_P \qquad (2)$$

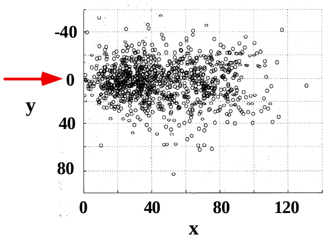
where Q is the dose in ions cm^{-2} and is measured by the integrated beam current.



- Monte Carlo simulations of the random trajectories of a group of ions implanted at a spot on the wafer show the 3-D spatial distribution of the ions. (1000 phosphorus ions at 35 keV.)
- Side view (below) shows Rp and ΔRp while the beam direction view shows the lateral straggle.



Beam direction

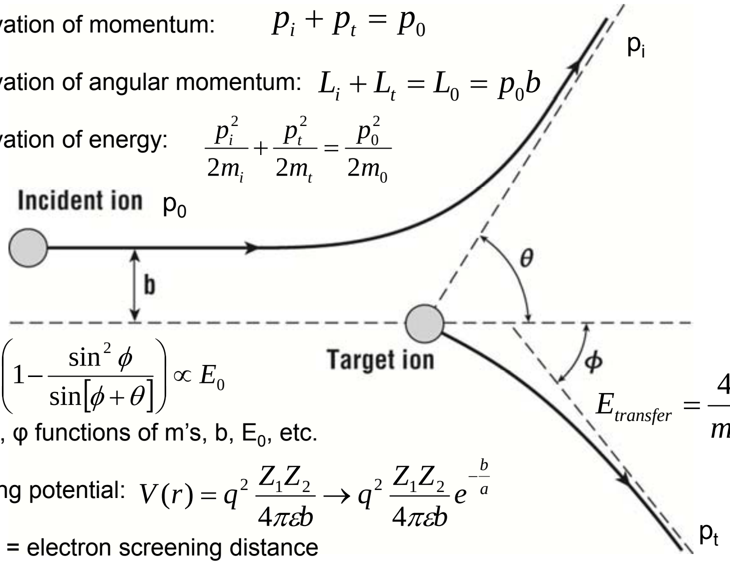


Side view

Conservation of momentum: $\overline{p_i} + \overline{p_t} = \overline{p_0}$

Conservation of angular momentum: $L_i + L_t = L_0 = p_0 b$

Conservation of energy: $\frac{p_i^2}{2m_i} + \frac{p_t^2}{2m_t} = \frac{p_0^2}{2m_0}$



$$\Delta E = E_0\left(1 - \frac{\sin^2\phi}{\sin[\phi+\theta]}\right) \propto E_0$$

where θ, φ functions of m's, b, E_0, etc.

$$E_{transfer} = \frac{4m_i m_t}{m_i + m_t} E_0$$

Scattering potential: $V(r) = q^2 \frac{Z_1 Z_2}{4\pi\varepsilon b} \rightarrow q^2 \frac{Z_1 Z_2}{4\pi\varepsilon b} e^{-\frac{b}{a}}$

where *a* = electron screening distance

Figure 5.6 Typical scattering problem. Figure inset shows electrostatic potential as a function of distance between the nuclei. The impact parameter is labeled *b*.

$$\text{"Viscous" drag} \propto v \propto \sqrt{E}$$

so electronic stopping $S_e = \frac{dE}{dx}|_e = k_e\sqrt{E}$

where $k_e \propto \sqrt{\frac{Z_i Z_t}{m_i^3 m_t}} \frac{(m_i + m_t)^{3/2}}{Z_i^{2/3} + Z_t^{2/3}}$

At high E, "viscous" model breaks down, & S_e peaks

(Z's are charge numbers)

Neutron stopping :

$$S_n^0 = 2.8\text{x}10^{-15} eV.cm^2 \frac{Z_i Z_t}{\left(Z_i^{2/3} + Z_t^{2/3}\right)^{1/2}}$$

(In fact, $S_n(E)$ is energy dependent)

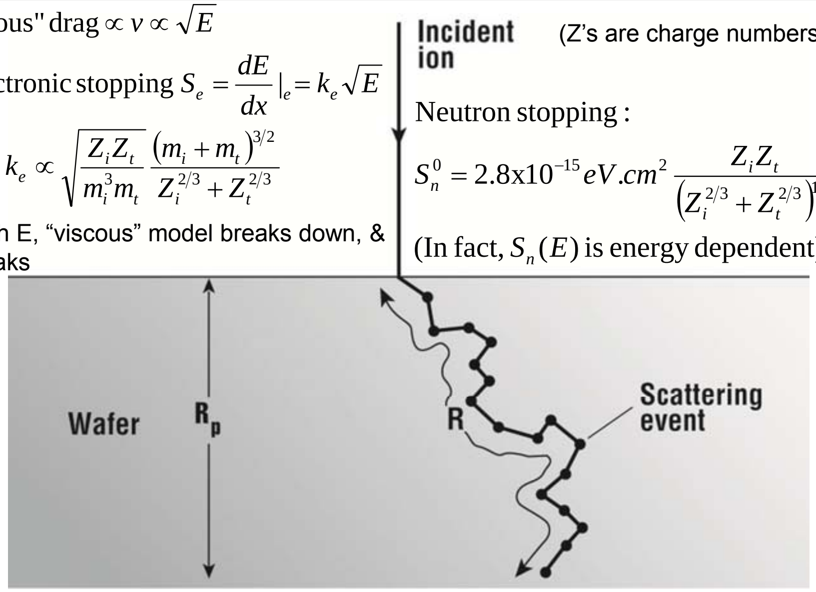


Figure 5.7 The total distance that an ion travels in the solid is the range. The projection of this distance along the depth axis is the projected range, R_p.

Range and Straggle

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

$$\& \; R_P = \int_0^{R_P} dx = \frac{1}{N_t}\int_0^{E_0} \frac{dE}{S_n(E) + S_e(E)}$$

$$\Delta R_P = \frac{2}{3} R_P \frac{\sqrt{m_i m_t}}{m_i + m_t}$$

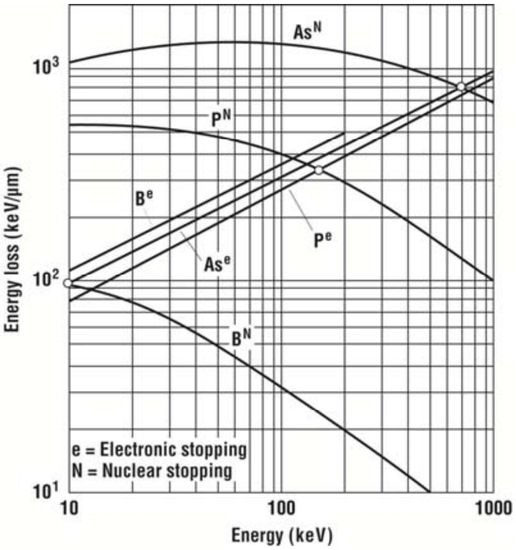
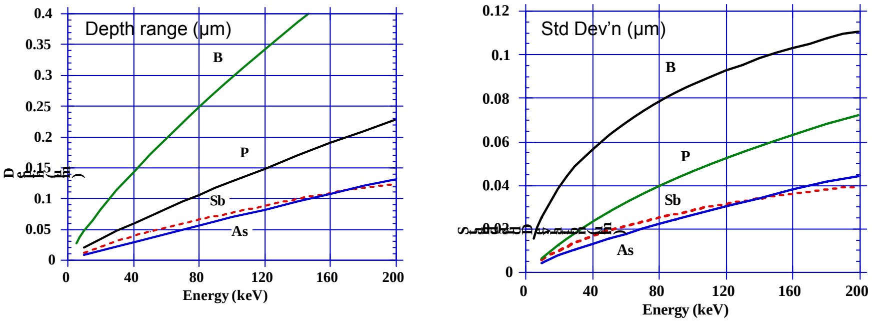


Figure 5.8 Nuclear and electronic components of *S*(*E*) for several common silicon dopants as a function of energy *(after Smith as redrawn by Seidel, "Ion Implantation," reproduced by permission, McGraw-Hill, 1983)*.



	Phos		As		Sb		Boron	
Energy (keV)	Range (µm)	Std Dev (µm)	Range (µm)	Std Dev (µm)	Range (µm)	Std Dev (µm)	Range (µm)	Std Dev (µm)
10	0.0199	0.0064	0.0084	0.0043	0.0121	0.0058	0.0473	0.0249
20	0.0342	0.0125	0.0156	0.0075	0.0219	0.0100	0.0826	0.0384
30	0.0473	0.0179	0.0226	0.0102	0.0306	0.0133	0.114	0.0483
40	0.0598	0.0229	0.0294	0.0128	0.0385	0.0162	0.143	0.0562
50	0.0717	0.0275	0.0362	0.0152	0.0459	0.0187	0.171	0.0628
60	0.0833	0.0317	0.0429	0.0176	0.0528	0.0209	0.198	0.0685
70	0.0947	0.0356	0.0495	0.0198	0.0594	0.0229	0.223	0.0736
80	0.105	0.0393	0.0561	0.0220	0.0656	0.0248	0.248	0.0780
90	0.116	0.0428	0.0626	0.0241	0.0716	0.0265	0.272	0.0821
100	0.127	0.0461	0.0692	0.0261	0.0773	0.0280	0.296	0.0857
120	0.148	0.0522	0.0821	0.0301	0.0883	0.0309	0.341	0.0922
140	0.169	0.0579	0.0950	0.0339	0.0985	0.0334	0.385	0.0978
160	0.189	0.0630	0.107	0.0375	0.108	0.0357	0.428	0.102
180	0.210	0.0678	0.120	0.0411	0.117	0.0378	0.469	0.107
200	0.229	0.0723	0.133	0.0446	0.126	0.0397	0.509	0.110

Ranges and standard deviation ΔRp of dopants in randomly oriented silicon.

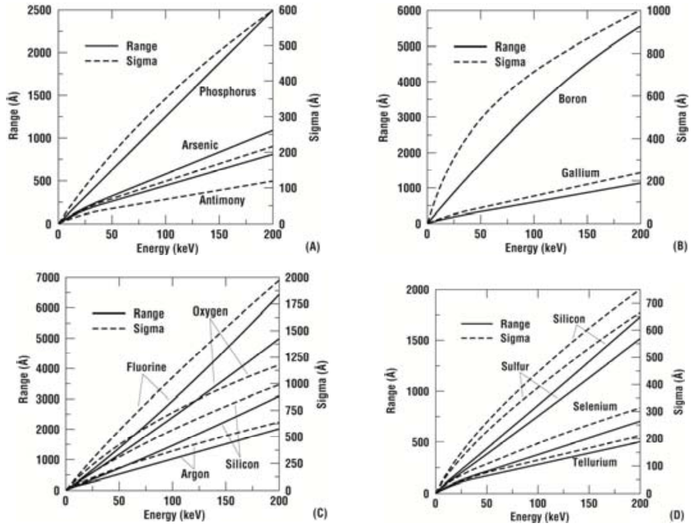


Figure 5.9 Projected range (solid lines and left axis) and standard deviation (dashed lines and right axis) for (A) n-type, (B) p-type, and (C) other species into a silicon substrate, and (D) n-type and (E) p-type dopants into a GaAs substrate, and several implants into (F) SiO_2 and (G) AZ111 photoresist *(data from Gibbons et al.).*

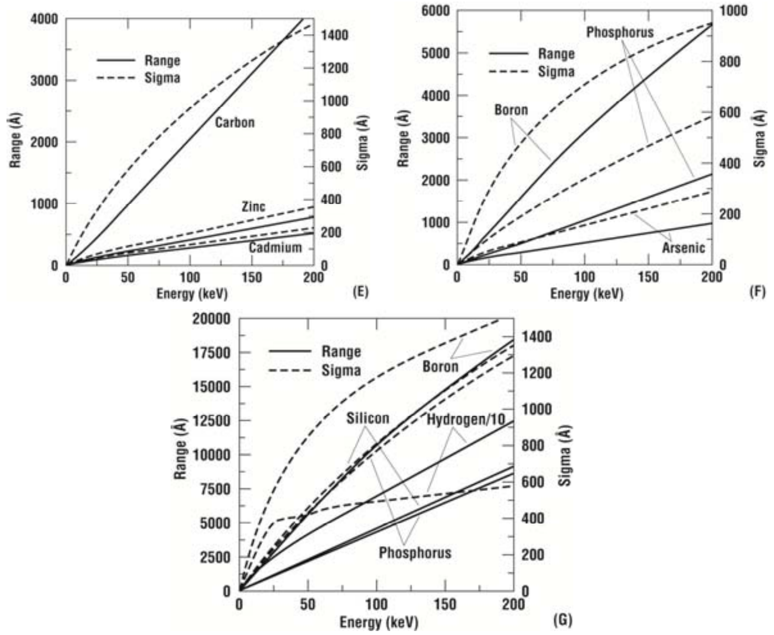


Figure 5.9 cont'd. For legend see previous page.

More detailed (Pearson) distributions:

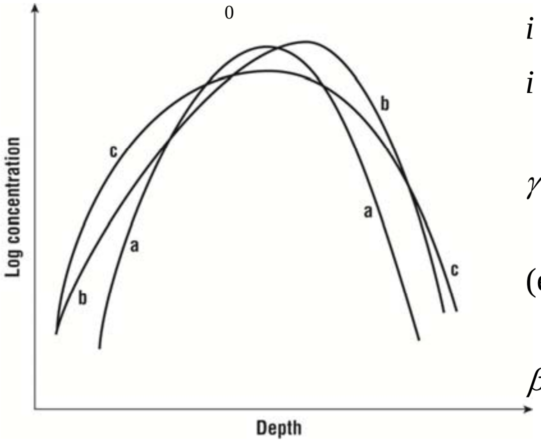
ith "moment" $m_i = \int_0^\infty (x - R_P)^i N(x)dx \rightarrow$

$i = 1 \rightarrow$ normalized dose m_1

$i = 2 \rightarrow m_1 \Delta R_P^2$

$i = 3 \rightarrow$ skewness $\gamma = m_3 / \Delta R_P^3$

$i = 4 \rightarrow$ kurtosis $\beta = m_4 / \Delta R_P^4$



$\gamma < 1$ increases concentration towards surface (e.g. Boron : $M_B << M_{Si}$, hence backscatter)

β flattens top of Gaussian

Figure 5.10 Curve (a) shows a standard Gaussian. (b) A negative skewness, which moves the peak slightly deeper and adds a tail extending toward the surface. (c) A large kurtosis flattens the peak of the distribution.

For Boron in Silicon:

$$n(x) = n(R_P)\exp\frac{\ln\left[b_0 + b_1(x-R_P) + b_2(x-R_P)^2\right]}{2b_2} - \frac{b_1(1+b_2)}{b_2\sqrt{4b_0b_2 - b_1^2}}\tan^{-1}\left[\frac{2b_2(x-R_P)+b_1}{\sqrt{4b_0b_2-b_1^2}}\right]$$

where

$$b_0 = -\frac{\Delta R_P^2(4\beta - 3\gamma^2)}{10\beta - 12\gamma^2 - 18}$$

$$b_1 = -\gamma\Delta R_P\frac{\beta + 3}{10\beta - 12\gamma^2 - 18}$$

$$b_2 = -\frac{2\beta - 3\gamma^2 - 6}{10\beta - 12\gamma^2 - 18}$$

- The two-dimensional distribution is often assumed to be composed of just the product of the vertical and lateral distributions.

$$\mathbf{C}(\mathbf{x},\mathbf{y}) = \mathbf{C}_{\mathbf{vert}}(\mathbf{x})\mathbf{exp}\left(-\frac{\mathbf{y}^2}{2\Delta\mathbf{R}_\perp^2}\right) \qquad (3)$$

- Now consider what happens at a mask edge - if the mask is thick enough to block the implant, the lateral profile under the mask is determined by the lateral straggle. (35keV and 120keV As implants at the edge of a poly gate from Alvis et al.)

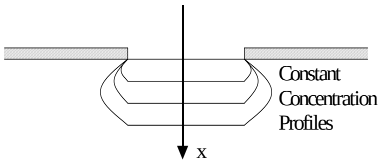
- The description of the profile at the mask edge is given by a sum of point response Gaussian functions, which leads to an error function distribution under the mask. (See notes on diffusion for a similar analysis.)

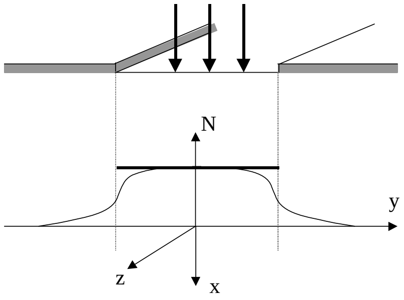
3D Profiles

3D profile for infinitely thin beam:

$$N(x)/\text{unit vol} = [N_0(\text{atoms}) / (2\pi)^{3/2}\Delta R_p\,\Delta y\,\Delta z]\ \exp -\tfrac{1}{2}\{[(x-R_p)^2/\Delta R_p{}^2]+[y^2/\Delta y^2]+[z^2/\Delta z^2]\}$$

where $\Delta y = \Delta z = \Delta R_t$

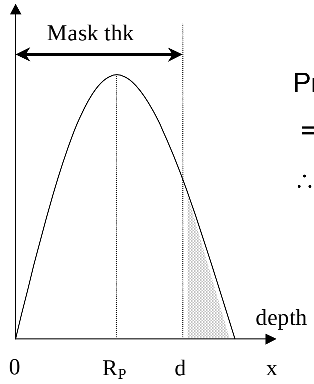




3D profile for practical beam:

$$N(x,y,z) = \{Q_0 / [(2\pi)^{1/2}\Delta R_p]\}\ \exp - \tfrac{1}{2}\{([(x-R_p)/\Delta R_p]^2 /\sqrt{\pi})\ \text{erfc}[\sqrt{\tfrac{1}{2}}(y-a)/\Delta R]\}$$

Masking

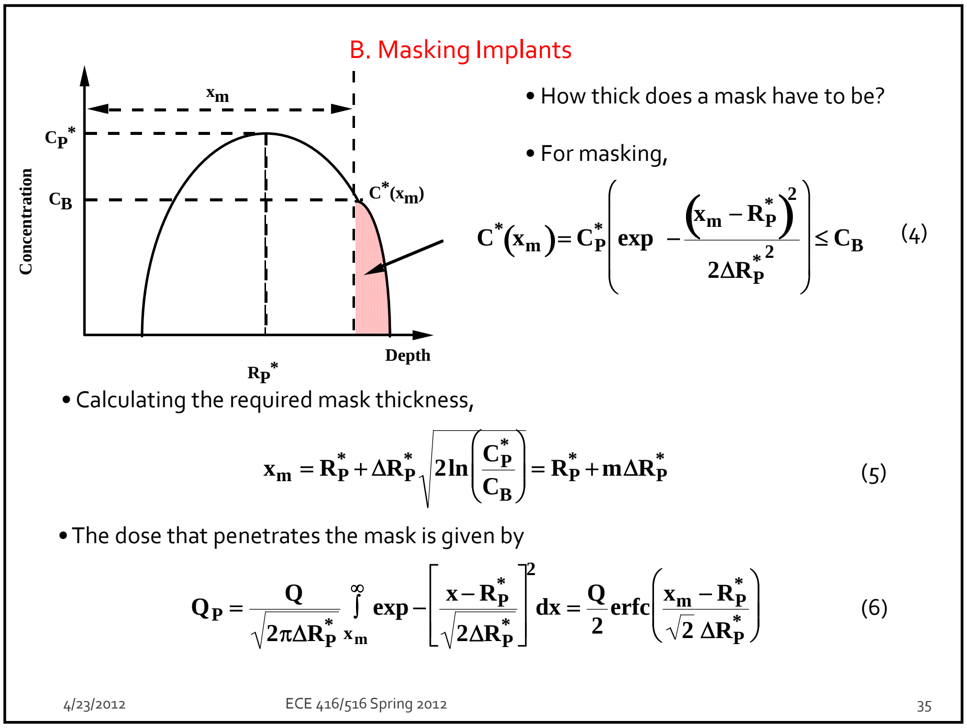


Proportion penetrating through mask (d)

$$= Q = [Q_0/(2\pi)^{1/2}\Delta R_p]\ {}_d\!\int^{\infty} \exp - \tfrac{1}{2}[(x-R_p)/\ \Delta R_p]\ dx$$

$$\therefore Q/Q_0 = \tfrac{1}{2}\ \text{erfc}\ [\ (d-R_p) / \sqrt{2}\ \Delta R_p\ ]$$

- $\therefore$ can find d necessary for 99.99% effective mask, for 99.999%, etc.
- use mask to control surface implants THROUGH mask



B. Masking Implants

- How does a mask have to be?

- For masking,

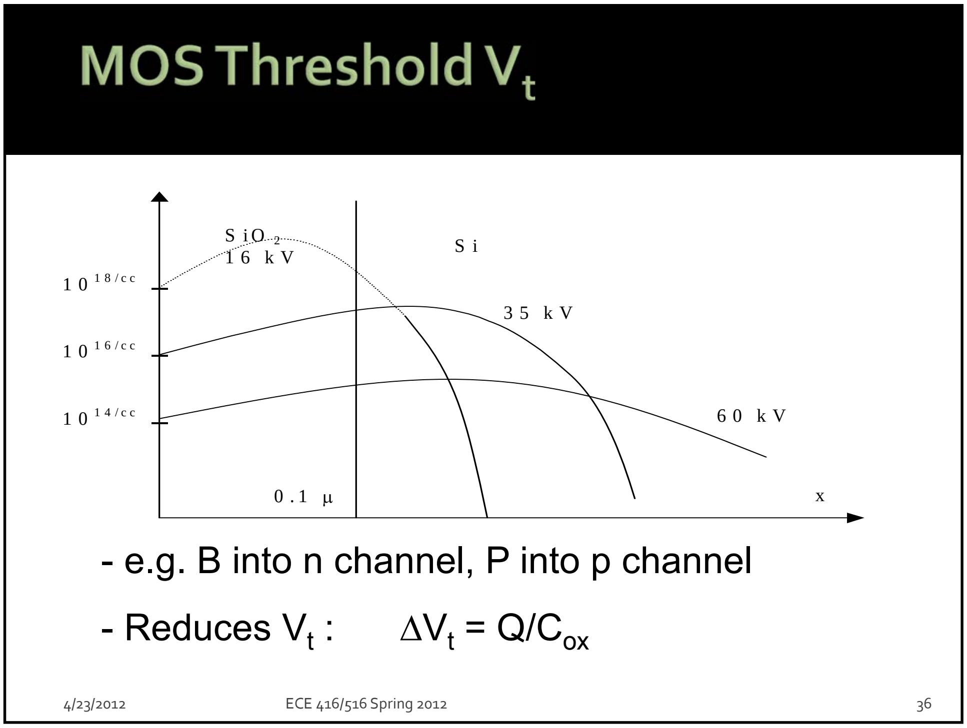
$$C^*(x_m) = C_P^* \left(\exp -\frac{(x_m - R_P^*)^2}{2\Delta R_P^{*2}} \right) \le C_B \qquad (4)$$

- Calculating the required mask thickness,

$$x_m = R_P^* + \Delta R_P^* \sqrt{2\ln\left(\frac{C_P^*}{C_B}\right)} = R_P^* + m\Delta R_P^* \qquad (5)$$

- The dose that penetrates the mask is given by

$$Q_P = \frac{Q}{\sqrt{2\pi}\Delta R_P^*} \int_{x_m}^{\infty} \exp -\left[\frac{x - R_P^*}{\sqrt{2}\Delta R_P^*}\right]^2 dx = \frac{Q}{2}\,\mathrm{erfc}\left(\frac{x_m - R_P^*}{\sqrt{2}\,\Delta R_P^*}\right) \qquad (6)$$

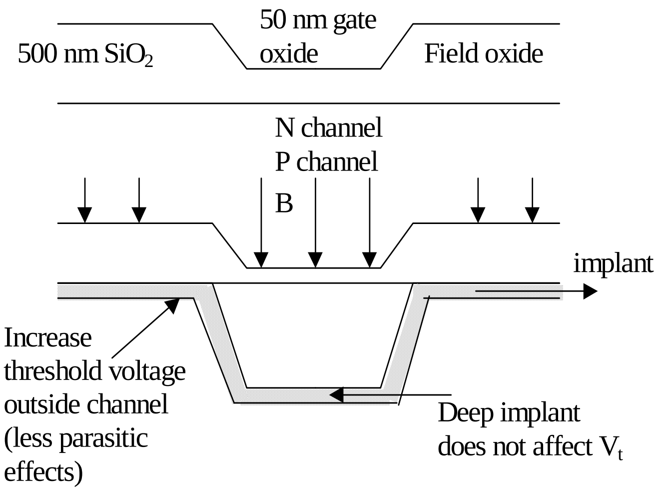


MOS Threshold V_t

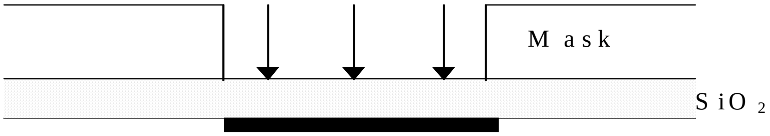
- e.g. B into n channel, P into p channel

- Reduces V_t : $\Delta V_t = Q/C_{ox}$

Applications: Channel Stopper



Resistors



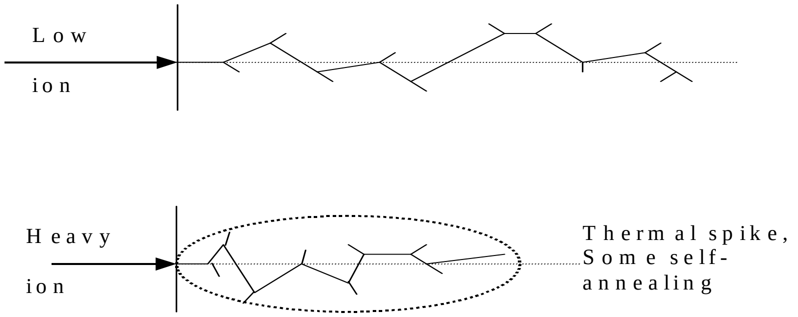
- High R layers just below surface

-Accurate to ≈ 1% & ≤ 4000 Ω/square

- Compare diffused resistors:

+/- 10% & < 125-180 Ω/square

Implantation Damage

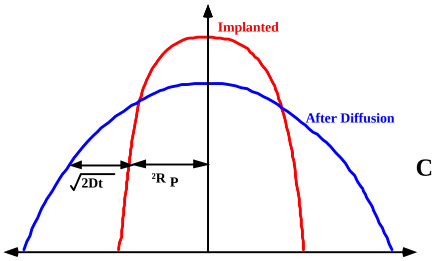


- to remove ALL damage requires melt and epitaxial re-growth,
∴damage anneal only partial

- Heavy damage -> effectively amorphous (obeys theory better -> no tail)
e.g. Pre-bombard with Si or Ar to damage before P implantation

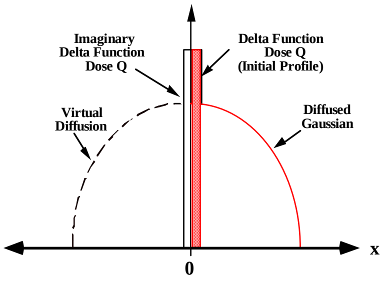
- Anneal progressively more difficult at higher doses

C. Profile Evolution During Annealing



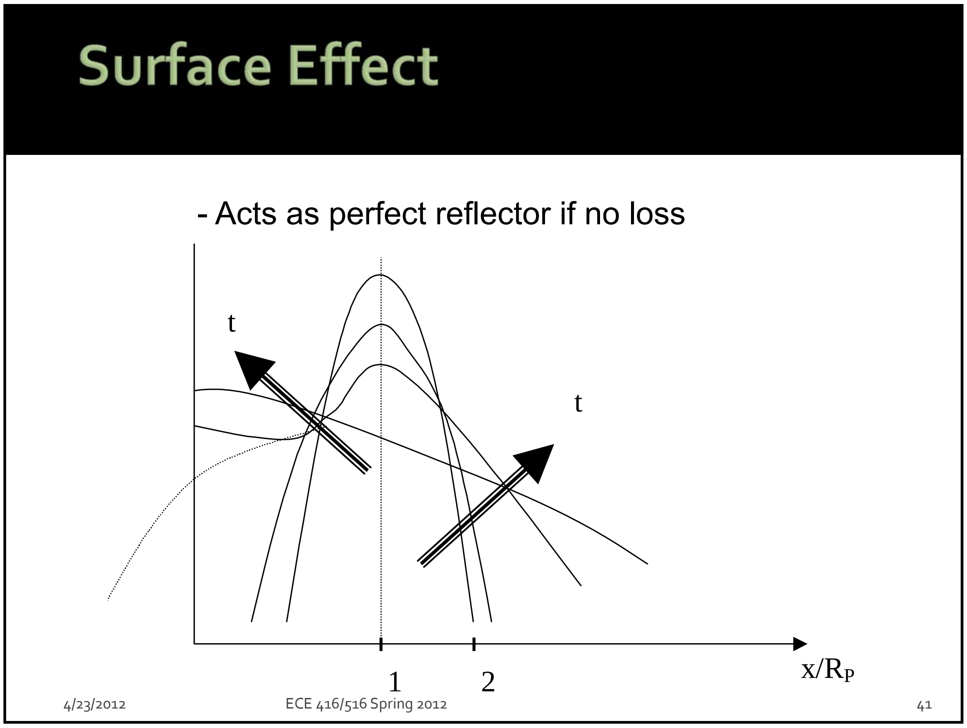
- Comparing Eqn. (1) with the Gaussian profile from the last set of notes, we see that ΔRp is equivalent to $\sqrt{2Dt}$ Thus

$$C(x,t)=\frac{Q}{\sqrt{2\pi\left(\Delta R_P^2+2Dt\right)}}\exp\left(-\frac{\left(x-R_P\right)^2}{2\left(\Delta R_P^2+2Dt\right)}\right) \qquad (7)$$



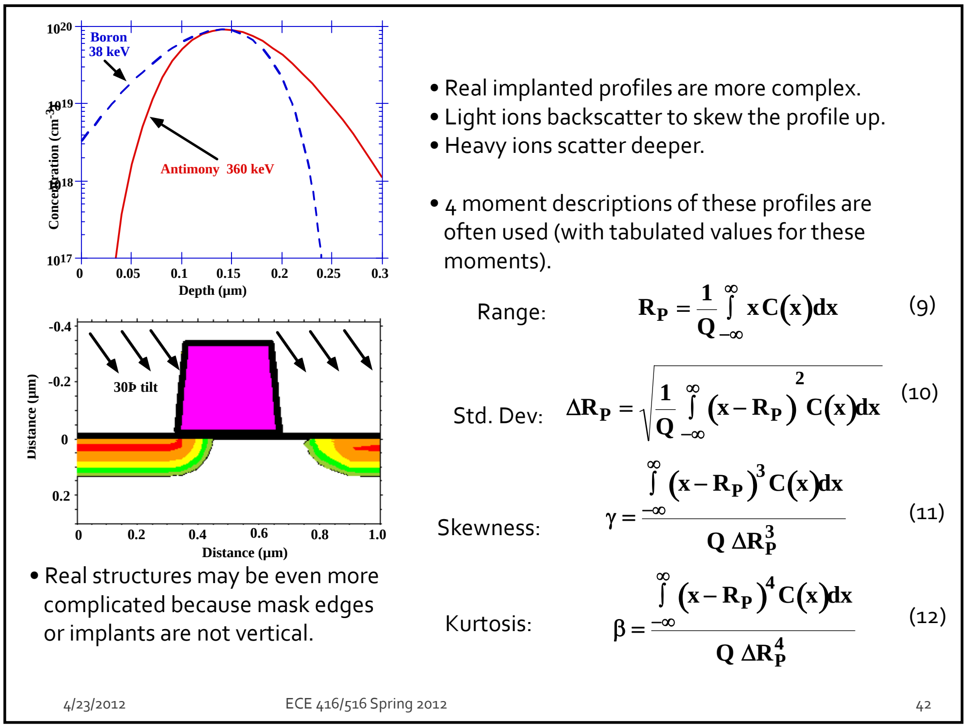
- The only other profile we can calculate analytically is when the implanted Gaussian is shallow enough that it can be treated as a delta function and the subsequent anneal can be treated as a one-sided Gaussian. (Recall example in Diffusion notes.)

$$C(x,t)=\frac{Q}{\sqrt{\pi Dt}}\exp\left(-\frac{x^2}{4Dt}\right) \qquad (8)$$



Surface Effect

- Acts as perfect reflector if no loss



- Real structures may be even more complicated because mask edges or implants are not vertical.

- Real implanted profiles are more complex.
- Light ions backscatter to skew the profile up.
- Heavy ions scatter deeper.

- 4 moment descriptions of these profiles are often used (with tabulated values for these moments).

Range: $$R_P = \frac{1}{Q}\int_{-\infty}^{\infty} x\,C(x)\,dx \qquad (9)$$

Std. Dev: $$\Delta R_P = \sqrt{\frac{1}{Q}\int_{-\infty}^{\infty} (x-R_P)^2\, C(x)\,dx} \qquad (10)$$

Skewness: $$\gamma = \frac{\int_{-\infty}^{\infty} (x-R_P)^3\, C(x)\,dx}{Q\,\Delta R_P^3} \qquad (11)$$

Kurtosis: $$\beta = \frac{\int_{-\infty}^{\infty} (x-R_P)^4\, C(x)\,dx}{Q\,\Delta R_P^4} \qquad (12)$$

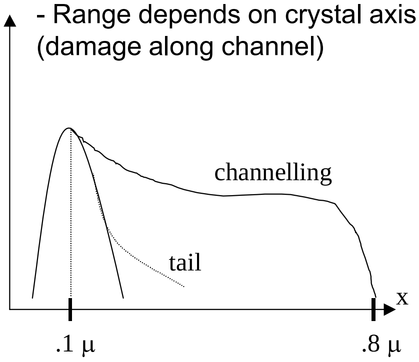
Channeling & Tailing

- Theory above OK for amorphous target

- if hit crystal orientation --> channel

- ion moves further through lattice

- Range depends on crystal axis, beam to crystal alignment, dose (damage along channel)



<u>Tail</u> due to:

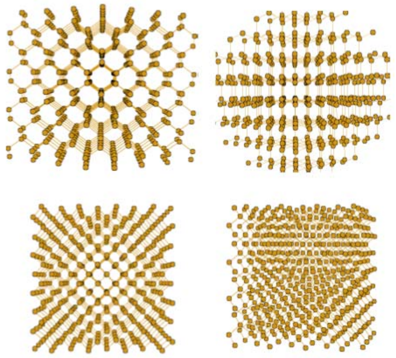
(1) Some ions in channels due to statistical distribution and diffusion after implantation

(2) Interstitial diffusion until find vacancy trap site

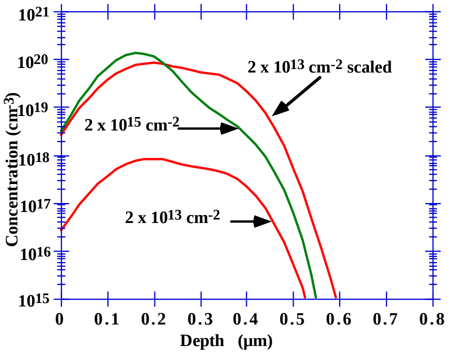
- Avoid channeling -> misalign 7-10°

$\therefore$ tail $n \sim n_0 \exp - x/(D\tau)^{1/2}$

D. Implants in Real Silicon - Channeling



- At least until it is damaged by the implant, Si is a crystalline material.
- Channeling can produce unexpectedly deep profiles.
- Screen oxides and tilting/rotating the wafer can minimize but not eliminate these effects. (7° tilt is common.)



- Sometimes a dual Pearson profile description is useful.
- Note that the channeling decreases in the high dose implant (green curve) because damage blocks the channels.

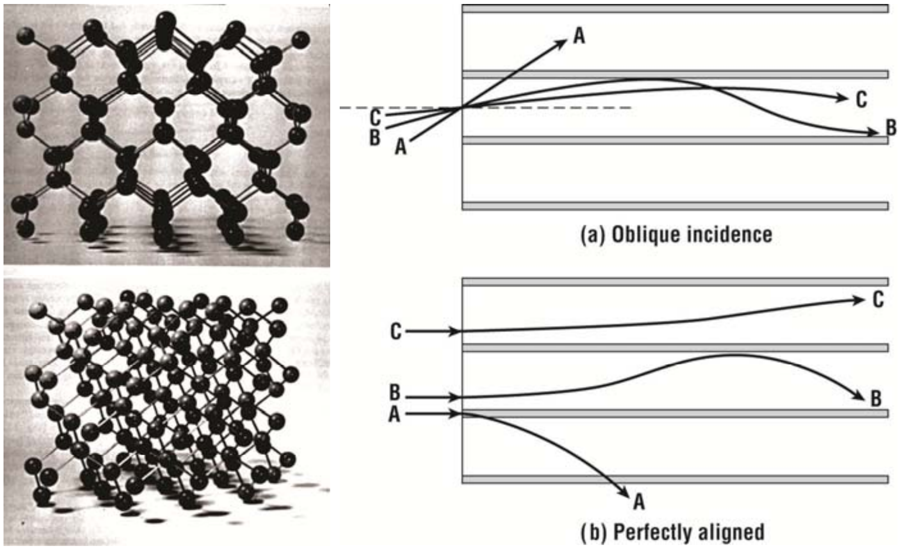
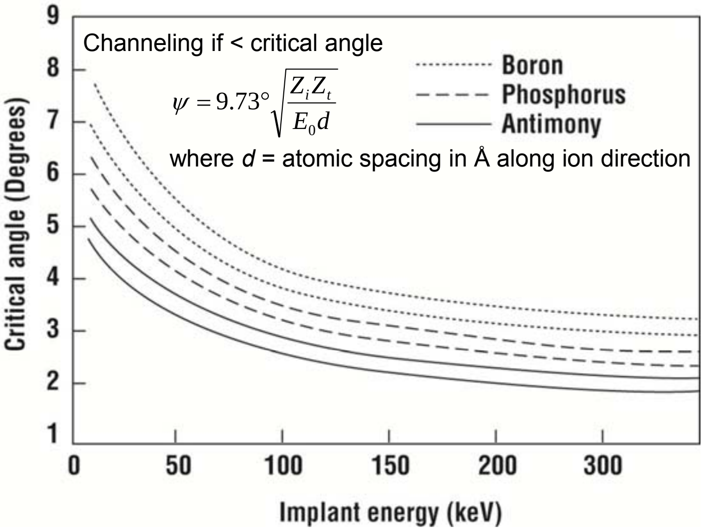


Figure 5.11 (A) Models of the diamond structure along a major crystal axis ⟨110⟩ and along a random direction. (B) Schematics of channeling *(reprinted by permission, Academic Press, after Mayer et al.)*.



Channeling if < critical angle

$$\psi = 9.73^\circ \sqrt{\frac{Z_i Z_t}{E_0 d}}$$

where *d* = atomic spacing in Å along ion direction

Figure 5.12 Critical angle at which channeling begins for common impurities in silicon. For each impurity, the upper curve is implanting into ⟨111⟩ substrates. The lower curves correspond to ⟨100⟩ substrates.

Modeling of Range Statistics

- The total energy loss during an ion trajectory is given by the sum of nuclear and electronic losses (these can be treated independently).

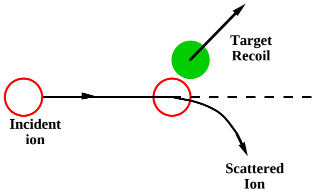
$$\frac{dE}{dx} = -N\left(S_n + S_e\right) \qquad (13)$$

$$R = \int_0^R dx = \frac{1}{N}\int_0^{E_0} \frac{dE}{S_n(E) + S_e(E)} \qquad (14)$$

A. Nuclear Stopping

- An incident ion scatters off the core charge on an atomic nucleus, modeled to first order by a screened Coulomb scattering potential.

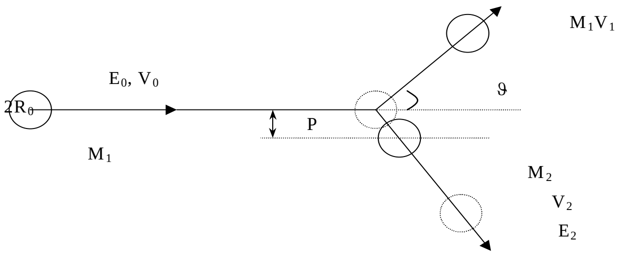
$$V(r) = \frac{q^2 Z_1 Z_2}{4\pi\varepsilon r}\exp\left(-\frac{r}{a}\right) \qquad (15)$$



- This potential is integrated along the path of the ion to calculate the scattering angle. (Look-up tables are often used in practice.)
- $S_n(E)$ in Eqn. (14) can be approximated as shown below where Z_1, m_1 = ion and Z_2, m_2 = substrate.

$$S_n(E) = 2.8x10^{-15} \frac{Z_1 Z_2}{\left(Z_1^{2/3} + Z_2^{2/3}\right)^{1/2}} \frac{m_1}{m_1 + m_2} \ \text{eV-cm}^2 \qquad (16)$$

Nuclear Stopping #1



- Momentum transfer along line of centers

- Conservation of KE

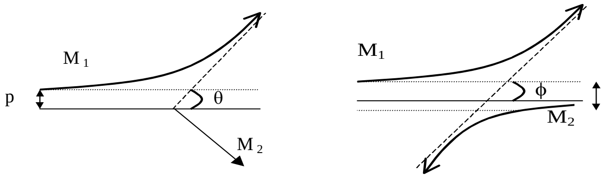
- gives $\cos\theta = \frac{1}{2}\{ (1 + (M_2/M_1))(E_2/E_0)^{1/2} + (1 - (M_2/M_1))(E_0/E_2)^{1/2} \}$

ie. Relates energy transfer to M_2 to scattering angle θ

- & $V_1^2 = V_0^2 [M_1\cos\theta + (M_2^2 - M_1^2\sin^2\theta)^{1/2}] / (M_1+M_2)$

Nuclear Stopping #2

- Electrostatic attraction/repulsion potential $V(r)$
  - $V(r) = q^2 z_1 z_2 / \pi\varepsilon r$



- $\Phi = \pi - Zp \int_{-\infty}^{R_m} r^{-2} [(1 - V(r)/E_r) - (p / r)^2]^{-1} dr$

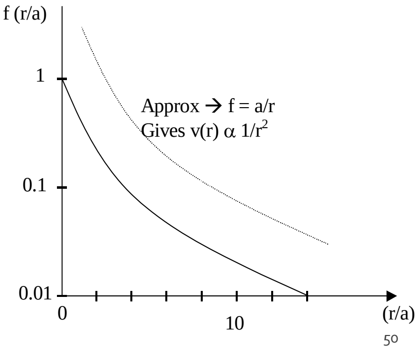
  where R_m is min distance of separation

  $E_r = ½ M_1 M_2 V_0^2 / (M_1 + M_2)$

  $\tan\theta = \sin\Phi / [\cos\Phi + M_1/M_2]$

Nuclear Stopping #3

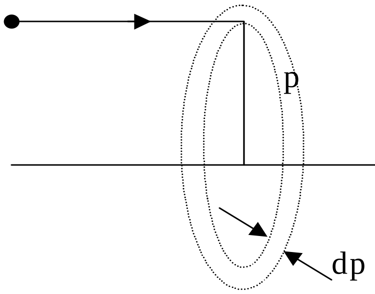
- include screening effects of electrons
  - $V(r) \dashrightarrow (q^2 z_1 z_2 / 4\pi\varepsilon r) f(r/a)$
  - where $f(r/a)$ is screening function
- a = screening parameter = $0.885 a_0 / (z_1^{2/3} + z_2^{2/3})^{1/2}$
- a_0 = Bohr radius = 0.053 nm



- Calculate Φ or θ for p from $f(r/a)$ to get energy loss in single collision $T_n(E,p)$

Nuclear Stopping #4

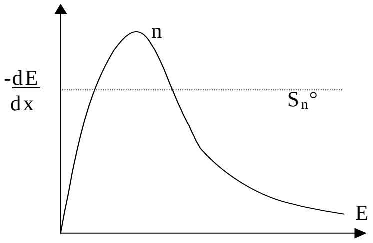
- Find total energy loss for target thickness Δx, N atoms/unit volume
- integrate over all p
- $\Delta E = -N \Delta x \, {}_0\int^{\infty} T_n (E,p) \, z\pi p \, dp = -N \Delta x \; S_n(E)$



Nuclear Stopping #5

- (Thomas Fermi result):

Rate of energy loss = $-dE/dx)_n = NS_n(E)$ as shown



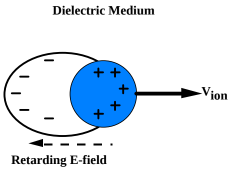
- As ion enters wafer with high E, energy loss rate low. Rate increases to max as slows down, then decreases to 0 at E=0.

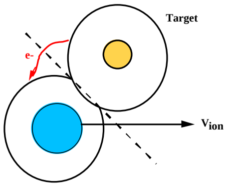
- Approx. $f(r/a) = a/r \dashrightarrow -dE/dx = S_n^o N = \text{const}$

$$= 2.8\times10^{-15} N \left((z_1 z_2)/(z_1^{2/3} + z_2^{2/3})^{1/2}\right) \left(M_1/(M_1+M_2)\right) \text{ eV/cm}$$

ie. 100 to 1000 eV/nm for most practical cases
Say 50kV --> 50 to 500nm

B. Non-Local and Local Electronic Stopping

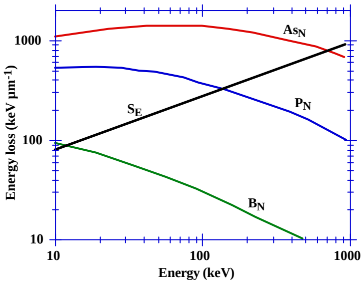




- Drag force caused by charged ion in "sea" of electrons (non-local electronic stopping).
- Collisions with electrons around atoms transfers momentum and results in local electronic stopping.
- To first order, $\mathbf{S_e(E) = cv_{ion} = kE^{1/2}}$ where $\mathbf{k \cong 0.2x10^{-15}\ ev^{1/2}\ cm^2}$ (17)

Typically (low energy): $S_e(E)$ ~ 10's of eV/nm

$S_e(E) << S_n(E)$



C. Total Stopping Power

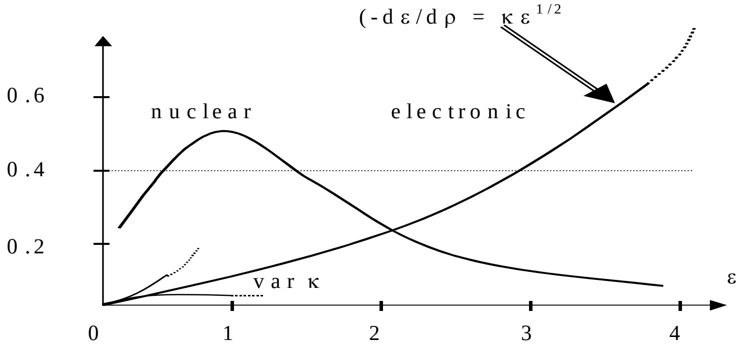
- The critical energy E_c when the nuclear and electronic stopping are equal is
  - B: ≈ 17keV
  - P: ≈ 150keV
  - As, Sb : > 500keV
- Thus at high energies, electronic stopping dominates; at low energy, nuclear stopping dominates.

Stopping Range #1

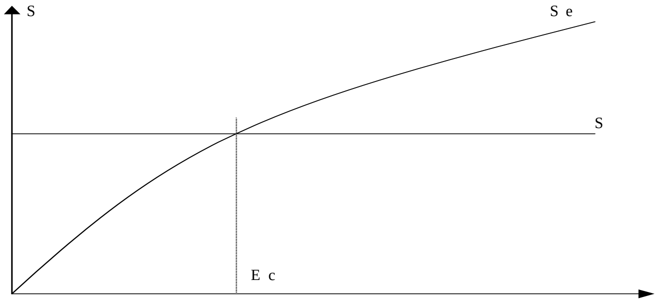
- From LSS theory for dimensionless parameters:

$$\rho = R\pi a^2N\, M_1M_2 / (M_1 + M_2)^2 \qquad \alpha\ R$$
$$\varepsilon = (Ea/q^2z_1z_2)M_2 / (M_1 + M_2) \qquad \alpha\ E$$

$$\mathbf{k = z_1^{1/6}\ 0.0793z_1^{1/2}z_2^{1/2}(M_1+M_2)^{3/2}\ (z_1^{2/3} + z_2^{2/3})^{-3/4}\ M_1^{-3/2}M_2^{-3/2}}$$



Stopping Range #2

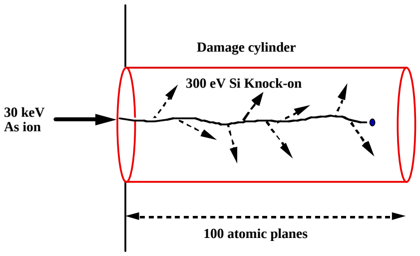


- if incident E

$>> E_C$, --> $S \approx S_e(E)$, $R \approx K_1 E_0^{1/2}$

$<< E_C$, --> $S \approx S_n(E)$, $R \approx K_2 E_0$

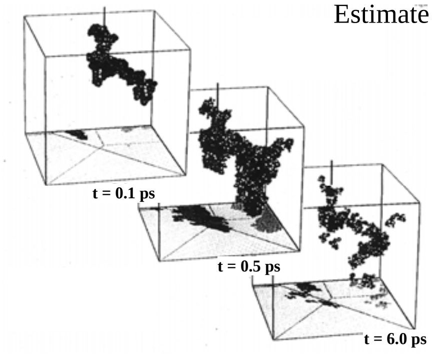
Damage Production



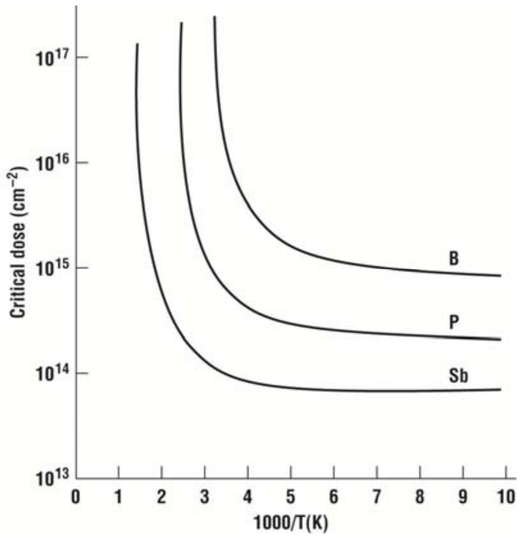
- Consider a 30keV arsenic ion, which has a range of 25 nm, traversing roughly 100 atomic planes.

$$\mathbf{n} = \frac{\mathbf{E_n}}{\mathbf{2E_d}} = \frac{\mathbf{30,000}}{\mathbf{2 \times 15}} = \mathbf{1000 \quad ions} \qquad (18)$$

$$\text{Estimate time to rest} = \frac{Range}{Velocity} = \frac{R_P}{\sqrt{E/2m}} \approx 10^{-13}\ \text{sec}$$



- Molecular dynamics simulation of a 5keV Boron ion implanted into silicon [de la Rubia, LLNL].
- Note that some of the damage anneals out between 0.5 and 6 psec (point defects recombining), and by diffusion ~ns.



n(x) damage density generated
N(x) local defect density
N_α amorphous threshold

$$\Delta n(x) = n(x).\, f_{rec} \cdot \left(1 - \frac{N(x)}{N_\alpha} \right)$$

f_{rec}=recombination factor

(If $N=N_\alpha$, then $\Delta n(x)=0$
since already amorphous)

Figure 5.13 Critical implant dose required to amorphize a silicon substrate as a function of substrate temperature for several common silicon dopants *(after Morehead and Crowder).*

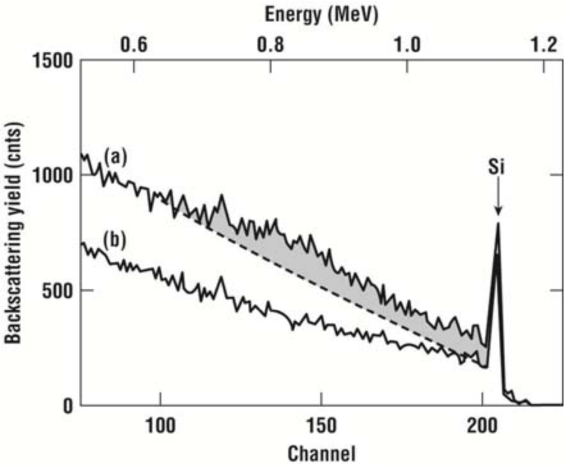


Figure 5.14 RBS spectra showing the backscattered He intensity as a function of energy. Curve (b) is an unimplanted wafer. The curve labeled (a) is a wafer after a 2 ´ 10^{15} B implant at 200 keV. The dashed line represents the component of the spectrum corresponding to the remaining crystalline silicon. The shaded area represents the contribution of displaced atoms *(reprinted by permission of Elsevier Science, after Schreutelkamp et al.).*

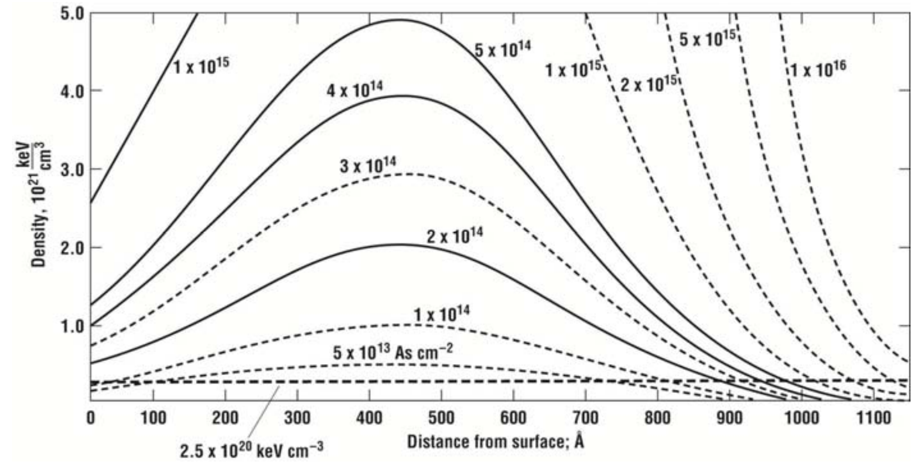
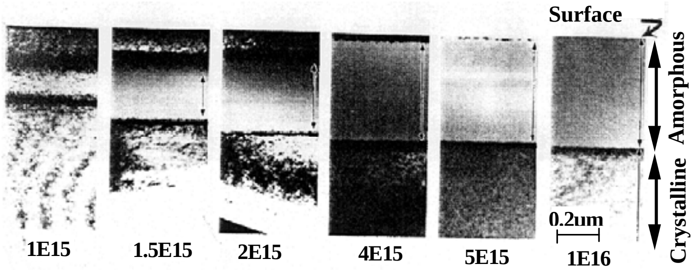


Figure 5.16 Damage density distribution for 100 keV arsenic implanted into silicon with dose as a parameter *(reprinted by permission, AIP).*

Amorphization

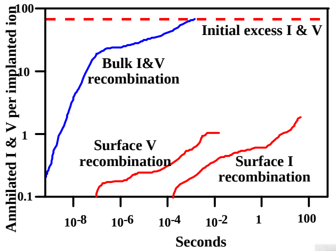
- For high enough doses, the crystal becomes amorphous and loses all long range order. At this point, the arrangement of lattice atoms is random and the damage accumulation has saturated.



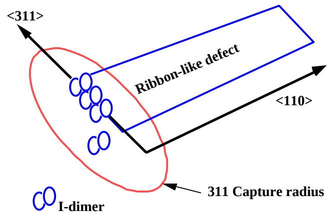
- Cross sectional TEM images of amorphous layer formation with increasing implant dose (300keV Si -> Si) [Rozgonyi]
- Note that a buried amorphous layer forms first and a substantially higher dose is needed before the amorphous layer extends all the way to the surface.
- These ideas suggest preamorphizing the substrate with a Si (or Ge) implant to prevent channeling when dopants are later implanted.

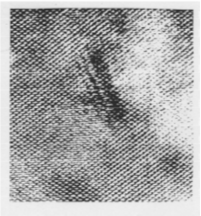
Damage Annealing - “+1” Model

Goals:
- Remove primary damage created by the implant and activate the dopants.
- Restore silicon lattice to its perfect crystalline state.
- Restore the electron and hole mobility.
- Do this without appreciable dopant redistribution.



- In regions where SPE does not take place (not amorphized), damage is removed by point defect recombination.
- Bulk and surface recombination take place on a short time scale.





- "+1" I excess remains. These I coalesce into {311} defects which are stable for longer periods.
- {311} defects anneal out in sec to min at moderate temperatures (800 - 1000˚C) but eject I ⇒ TED.

SPE = solid phase epitaxy; TED = transient enhanced diffusion

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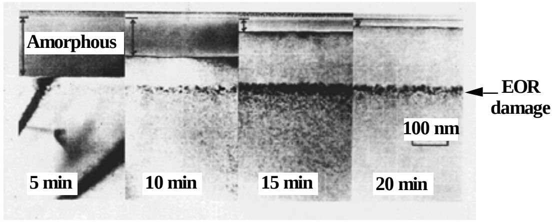
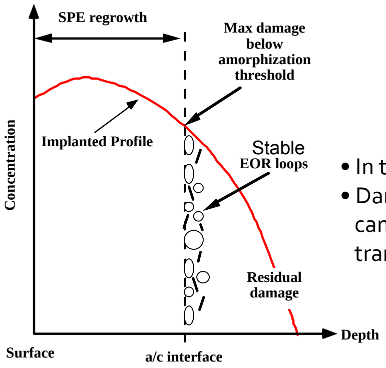
Damage Annealing - Solid Phase Epitaxy



- If the substrate is amorphous, it can regrow by SPE.
- In the SPE region, all damage is repaired and dopants are activated onto substitutional sites.
- Cross sectional TEM images of amorphous layer regrowth at 525˚C, from a 200keV, 6e15 cm^{-2} Sb implant.



- In the tail region, the material is not amorphized.
- Damage beyond the amorphous/crystalline interface can nucleate stable, secondary defects and cause transient enhanced diffusion (TED).

EOR = end of range; SPE = solid phase epitaxy; TED = transient enhanced diffusion

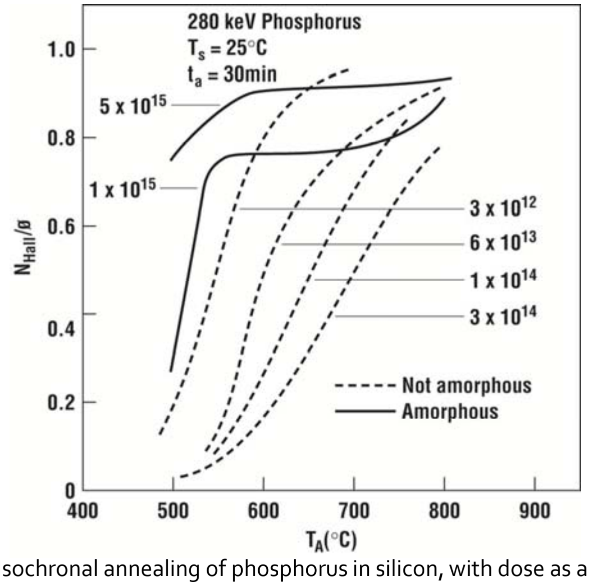


Figure 5.17 Isochronal annealing of phosphorus in silicon, with dose as a parameter. The solid lines correspond to implants that amorphized the substrate *(reprinted by permission, AIP, after Crowder and Morehead).*

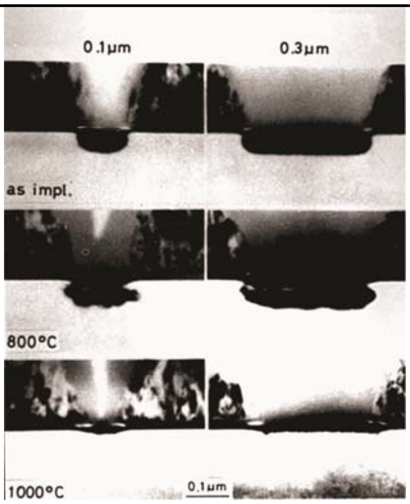
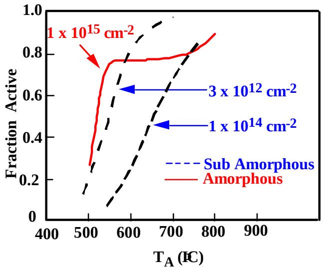
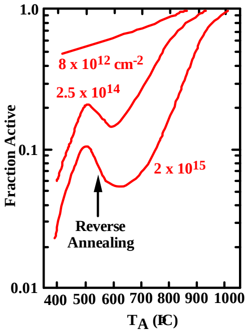


Figure 5.18 Cross-sectional TEMs image of implant damage in submicron areas for a high dose arsenic implant (5 × 10^{15} cm^{-2} at 25 keV) immediately after implant, after an 800°C anneal, and after a 1000°C anneal. Notice that even at the highest temperature residual damage remains at the edges of the implanted regions *(reprinted by permission of Elsevier Science, after Gyulai [26]).*

Dopant Activation

- When the substrate is amorphous, SPE provides an ideal way of repairing the damage and activating dopants (except that EOR damage may remain).
- At lower implant doses, activation is much more complex because stable defects form.





- Plot (above left) of fractional activation versus anneal temperature for boron.
- Reverse annealing (above right) is thought to occur because of a competition between the native interstitial point defects and the boron atoms for lattice sites.

EOR = end of range; SPE = solid phase epitaxy; TED = transient enhanced diffusion

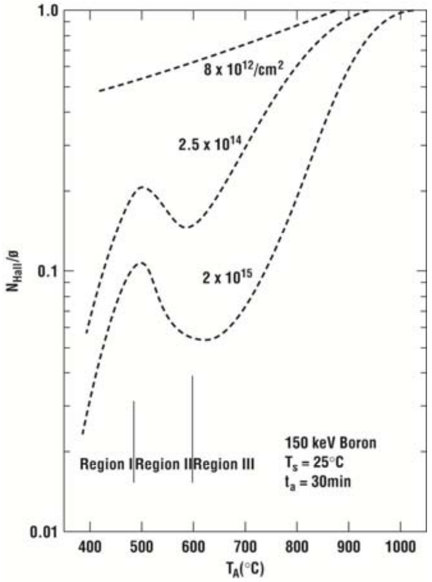
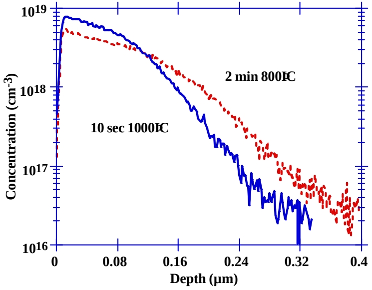
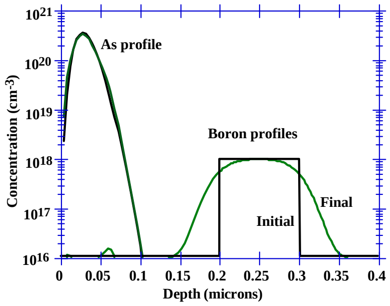


Figure 5.15 Fraction of implanted boron activated in silicon for several isochronal anneals *(after Seidel and MacRae, reprinted by permission, Elsevier Science).*

Transient Enhanced Diffusion

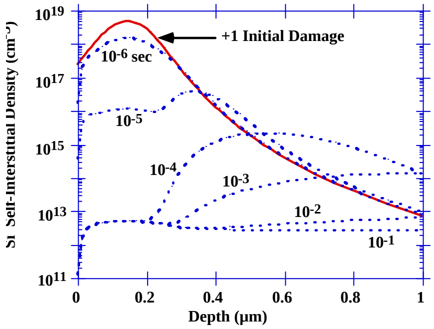




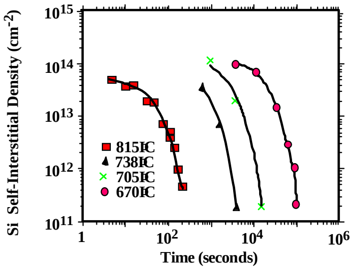
- TED is the result of interstitial damage from the implant enhancing the dopant diffusion for a brief transient period.
- It is the dominant effect today that determines junction depths in shallow profiles.
- It is anomalous diffusion, because profiles can diffuse more at low temperatures than at high temperatures for the same Dt.
- The basic model for TED assumes that all the implant damage recombines rapidly, leaving only 1 interstitial generated per dopant atom when the dopant atom occupies a substitutional site (the +1 model) [Giles].

- TED effects may be very non-local.
- After 900˚C, 1 sec anneal, the amorphous As surface profile recrystalizes by SPE without much TED.
- The buried boron layer is drastically affected by the +1 interstitials in the As tail region.

Atomic Level Understanding of TED



- {311} clusters form rapidly and then are stable for extended periods (sec - min), driving TED by emitting I while they shrink.
- By 0.1 sec (750˚C), the {311} defects have formed and C_I is down to ≈ 10^{13} cm^{-3} (SUPREM).
- But $\mathbf{C_I^*}$ ≈ 10^8 cm^{-3} at 750˚C, so the enhancement is > 10^5!



- On a much larger time scale, the {311} clusters decay.
- These act as an ongoing source of excess interstitials which drives TED.
- TED lasts hours at very low T, minutes at intermediate T and msec at very high T.

Time to dissolve clusters :

$$\tau_{\text{enh}} = \frac{4\pi a^3 R_P Q}{d_I} \exp\frac{E_b}{kT} = \frac{4\pi a^3 R_P Q}{d_I^0} \exp\frac{E_b + E_m}{kT}$$

- Given this picture, we can model the {311} behavior as follows: (where Cl_n is a cluster with n interstitials)

$$\mathbf{I + Cl_n \Leftrightarrow Cl_{n+1}} \qquad (19)$$

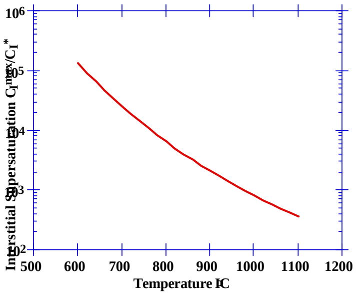
$$\therefore \quad -\frac{\partial C_I}{\partial t} = \frac{\partial Cl}{\partial t} = k_f C_I Cl - k_r Cl \qquad (20)$$

$$= \mathbf{growth} - \mathbf{shrinkage}$$

$$k_f = 4\pi a d_I \;\&\; k_r = (d_I / a^2)\exp - E_b / kT$$

a = nearest neighbor distance; d_I interstitial diffusion constant

- The most important part of the transient is while the {311} clusters are evaporating I, maintaining a constant supersaturation of I.
- During this period, dopant diffusivity enhancements are ≈ constant and given by:



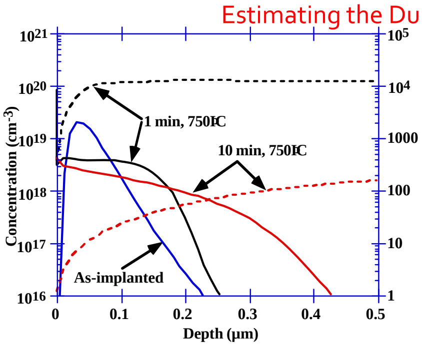
$$\frac{C_I^{max}}{C_I^*} = \frac{1}{4\pi a^3 C_I^0}\exp\left(-\frac{E_b - E_F}{kT}\right) \qquad (21)$$

- Note that the diffusivity enhancement is as large as 10,000 at low T and falls off to 100 - 1000 at RTA temperatures.
- These calculated values agree with experimental measurements.

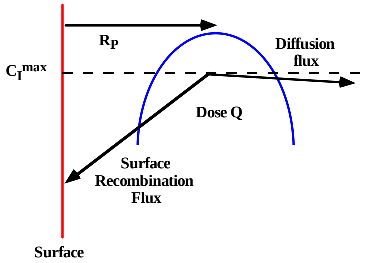
$$\frac{\partial Cl}{\partial t} = 0 \text{ at equilibrium} \rightarrow \text{steady state}$$

$$C_I^{max} = \frac{k_r}{k_f} = \frac{1}{4\pi a^3}\exp - \frac{E_b}{kT} \;\&\; \frac{C_I^{max}}{C_I^*} = \frac{1}{4\pi a^3 C_I^0}\exp - \frac{E_b - E_F}{kT}$$

Estimating the Duration of TED

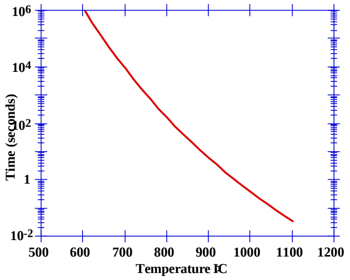


- Over time the interstitial supersaturation decays to zero and TED ends.
- Example - Boron TED (TSUPREM IV). Note that C_I/C_I^* has dropped from 10^4 to 10^2 in 10 min at 750˚C.
- The excess I diffuse into the bulk and recombine at the surface.
- Note the relatively flat interstitial profiles (dashed) except at the surface where recombination is occurring.

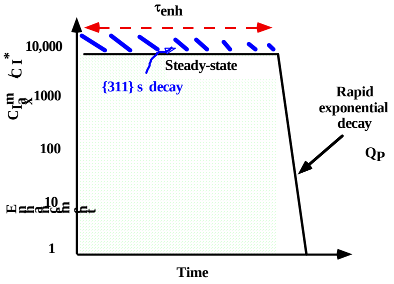


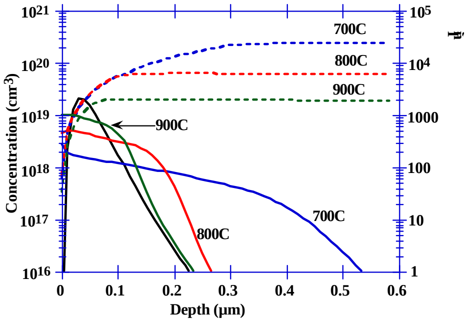
- The flux towards the surface is $\mathbf{d_I C_I^{max} / R_P}$ where R_P is the range of the implant.
- The time to dissolve the clusters is given by the dose divided by the flux (see text):

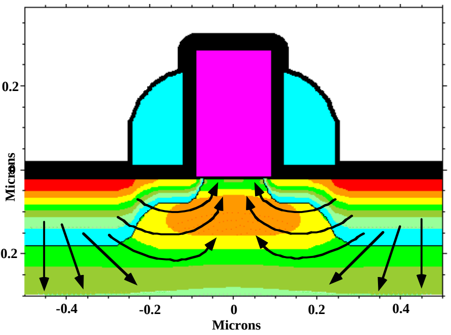
$$\tau_{enh} = \frac{4\pi a^3 R_P Q}{d_I}\exp\left(\frac{E_b}{kT}\right) \qquad (22)$$

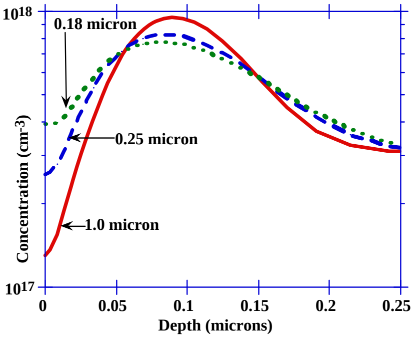


- Plot of Eqn. 22. This matches the experimental data on slide 41.
- Note that TED persists for hours at low T and disappears in msec at very high T.
- Thus the general picture of TED that emerges is as shown on the lower left.
- Because the {311} clusters exist for much longer times at low T, there can actually be greater dopant motion during low T anneals (below).









- 2D SUPREM simulation of small MOS transistor.
- Ion implantation in the S/D regions generates excess I. These diffuse into the channel region pushing boron (channel dopant) up towards the surface.
- Effect is more pronounced in smaller devices.

- Result is that V_{TH} depends on channel length (the "reverse short channel effect" only recently understood).

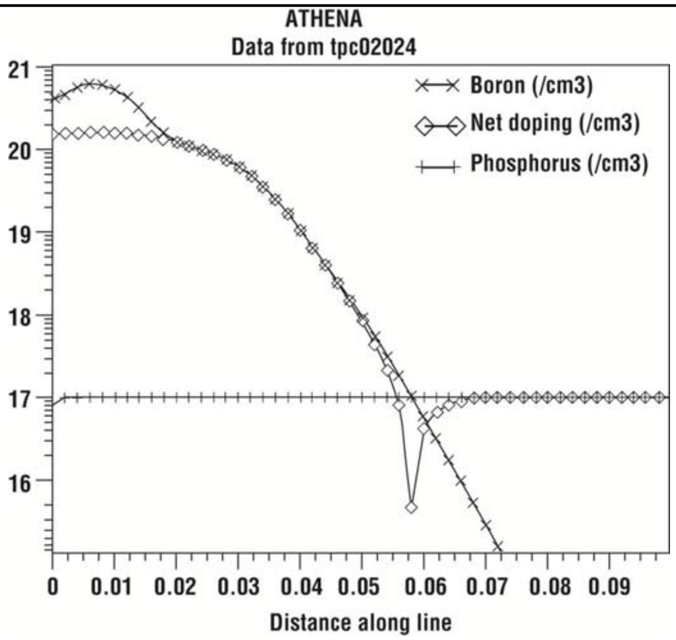


Figure 5.22

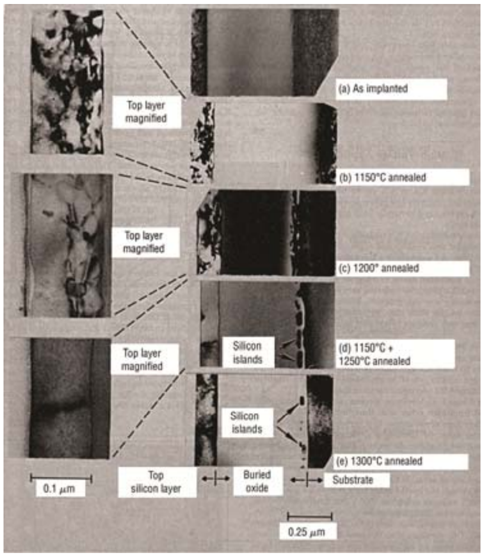


Figure 5.19 Cross-sectional TEMs of SIMOX layers for different anneal conditions. Samples were implanted at 150 keV with an oxygen dose of 2.25 ´ 10^{18} cm^{-2} *(after Lam, reprinted by permission, © 1987 IEEE).*

Summary

- Ion doping, damage, annealing
- Implantation equipment & development
- Implant profiles
- Masking effects
-Threshold adjustment
-Channeling
-Nuclear/electron stopping & Range
-Dopant activation
-Transient enhanced diffusion (TED)
-Simulation

Summary of Key Ideas

- Ion implantation provides great flexibility and excellent control of implanted dopants.
- Since implanted ion energies are >> Si-Si binding energy (≈ 15 eV), many Si lattice atoms are displaced from lattice positions by incoming ions.
- This damage accumulates with implanted dose and can completely amorphize the substrate at high doses.
- The open structure of the silicon lattice leads to ion channeling and complex as-implanted profiles.
- TED is the biggest single problem with ion implantation because it leads to huge enhancements in dopant diffusivity.
- Understanding of TED has led to methods to control it (RTA annealing).
- Nevertheless, achieving the shallow junctions required by the NTRS will be a challenge in the future since ion implantation appears to be the technology choice.

Assignment #2

- Campbell: Problems
  (Use text data rather than lecture slides)

4.3
4.4
4.6
4.8

5.2
5.3
5.7
5.10