NANYANG TECHNOLOGICAL UNIVERSITY
SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING
ACADEMIC YEAR 2022-2023
SEMESTER 1

EE3013 SEMINCONDUCTOR DEVICES AND PROCESSING

Ion-Implantation

Q1. Boron is implanted with an energy of 60 keV through a 0.25μm layer of silicon dioxide. The implanted dose is 1×10^{14} cm^{-2}. Find the boron concentration at the silicon-silicon dioxide interface if the straggle range ΔR_p is 0.09μm and the projected range R_p is 0.19μm.

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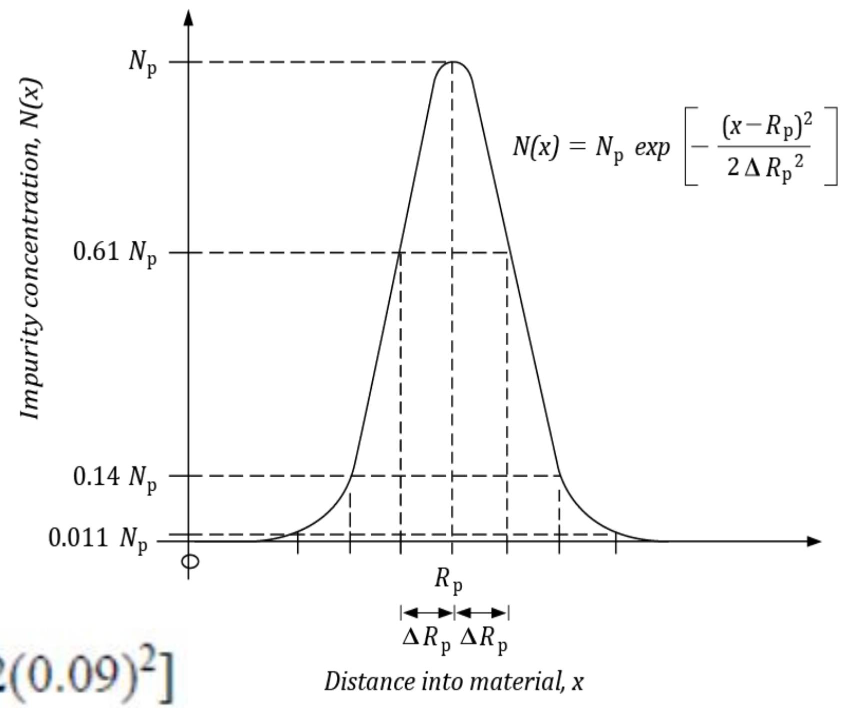
Solution:

Given R_p = 0.19 μm and ΔR_p = 0.09 μm. For the Gaussian implant,

$$N(x) = N_p \exp[-(x-R_p)^2/2\Delta R_p^2]$$



$$N_p = Q/[\Delta Rp \sqrt{(2\pi)}]$$
$$=(1\times10^{14})/[(0.09\times10^{-4})\sqrt{(2\pi)}]$$
$$= 4.43\times10^{18}\ cm^{-3}$$

$$N(0.25\ \mu m) = 4.43 \times 10^{18} \exp[-(0.25-0.19)^2/2(0.09)^2]$$
$$= 3.5 \times 10^{18}/cm^3$$

Q2. A 200 mm-silicon wafer is implanted with P^+ ions at 100 KeV for 5 seconds. If the average current measured is 10 µA, find

(a) the dose

(b) the maximum dopant concentration, and

(c) the depth at which the maximum dopant concentration occurs

(d) If a p-n junction is located at 0.3 µm, what is the background dopant concentration of the wafer? Sketch the dopant profile, and verify if there is one more p-n junction!

Use the charts (*Lecture Notes)* to determine the approximate values of R_p and ΔR_p.

Solution:

Wafer diameter =200 mm=20 cm,

$$A = \pi r^2 = 3.1416 \times 10^2 = 314.16\,\mathrm{cm}^2$$

$$\mathrm{P}^+ \text{ ion implanted at } V = 100\mathrm{KV}$$

$$\mathrm{E{=}100\,KeV,}\quad \mathrm{t\,{=}5\,Sec,\ I{=}10}\mu\mathrm{A}$$

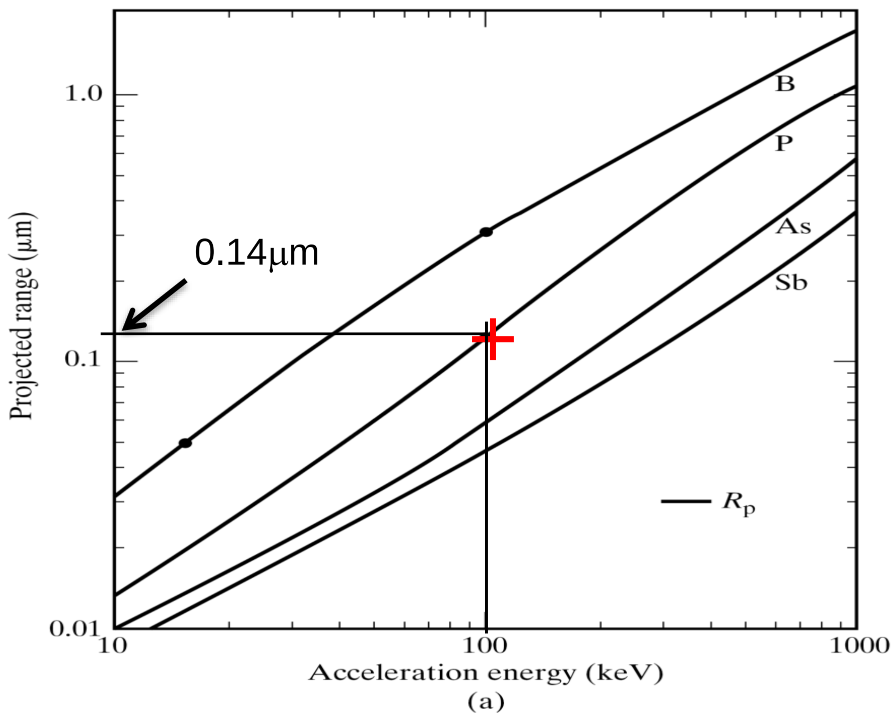
a) **Dose**

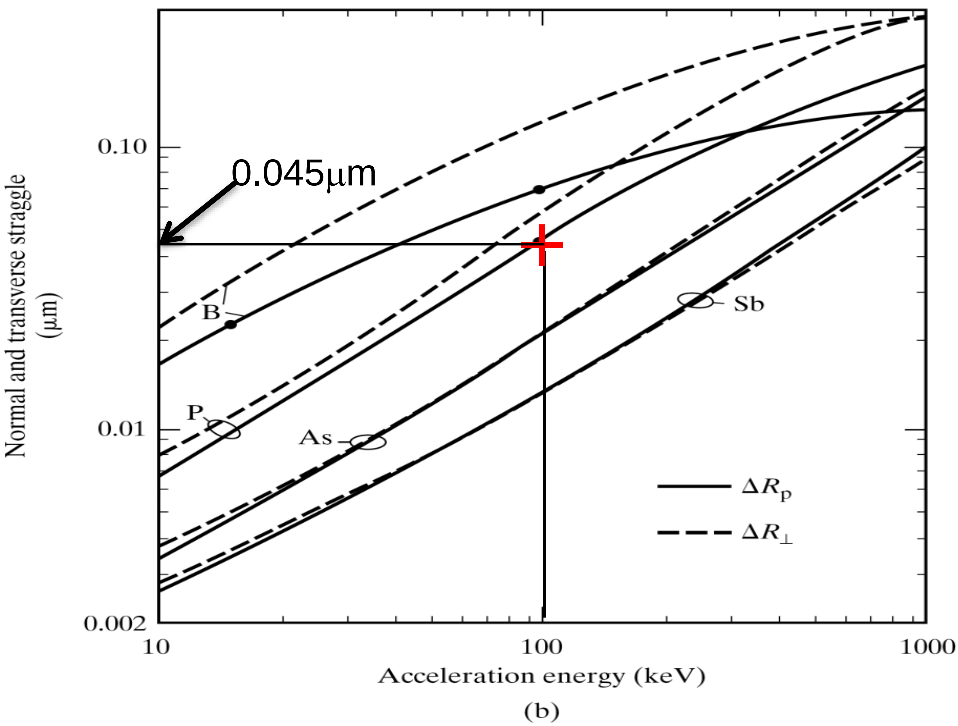
$$\mathrm{Q{=}}\frac{\mathrm{It}}{\mathrm{qA}} = 0.995\times10^{12}\,\mathrm{cm}^{-2} \approx 1\times10^{12}\,\mathrm{cm}^{-2}$$

$$\mathrm{Q{=}}\frac{\mathrm{It}}{\mathrm{qA}} = \frac{\mathrm{(C/s)(s)}}{\mathrm{C.\ cm}^2} = \mathrm{cm}^{-2}$$

From the charts, for P+ at 100 KeV, we have

$$R_p = 0.14\mu m; \quad \Delta R_p = 0.045\mu m$$





b) & c), Maximum dopant concentration occurs at a depth $x = \mathrm{R}_\mathrm{p}$

Maximum dopant concentration is obtained from

$$N(x) = \frac{Q}{\sqrt{2\pi}\Delta\mathrm{R}_\mathrm{p}} \cdot \exp\left(-\frac{(x-\mathrm{R}_\mathrm{p})^2}{2\Delta\mathrm{R}_\mathrm{p}^2}\right)$$

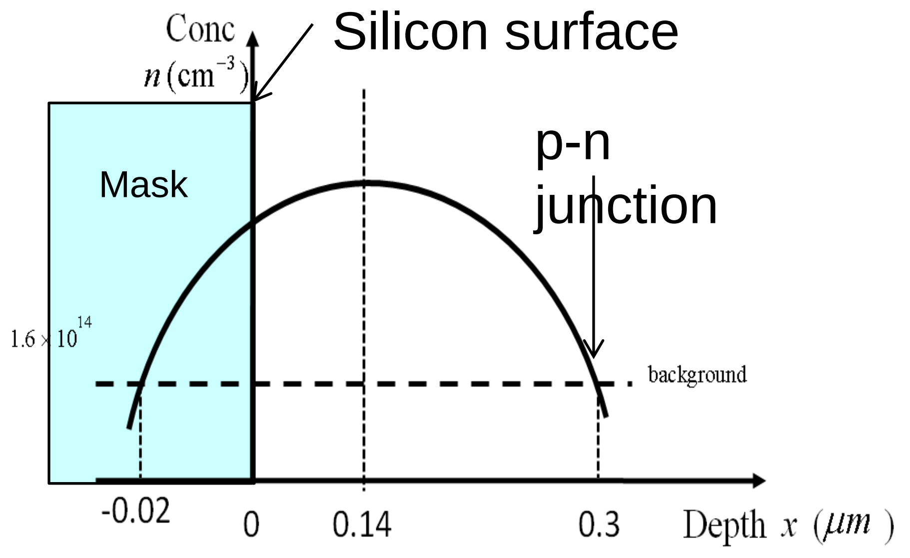
$$\therefore \quad N_{\max} = \frac{Q}{\sqrt{2\pi}\Delta\mathrm{R}_\mathrm{p}} \approx 8.87\times10^{16}\,\mathrm{cm}^{-3}$$

d) If a p-n junction is located at 0.3μm, the background p-type concentration must equal to the implanted n-type profile at

$$x = x_j = 0.3\times10^{-4}\,\mathrm{cm}$$

$$\therefore \quad N(x_j) = 8.87\times10^{16} \cdot \exp\left(-\frac{(0.3-0.14)^2}{2\times0.045^2}\right) = 1.6\times10^{14}\,\mathrm{cm}^{-3}$$

To sketch the dopant profile:



Since the Gaussian curve is symmetrical about R_p, two junction depths will be obtained such that $\left(x_{j2} - \mathrm{R_p}\right) = \left(\mathrm{R_p} - x_{j1}\right)$

Where $x_{j2} > x_{j1}$ In this case,

$$x_{j2} - \mathrm{R_p} = 0.3 - 0.14 = 0.16\ \mu m \text{ and } x_{j1} = -0.02\ \mu m\ (\textit{outside Si})$$

One p-n junction only!

Q3. We wish to implant double-ionized boron into 0.25 μm oxide-covered n-type <100> silicon wafer with a background concentration of 1×10^{15} atoms/cm^3. The dose is 2×10^{13}cm^{-2}, and the acceleration voltage used is 150KV.

(a) Locate the p-n junctions and sketch the doping profile, if any.

(b) Determine the amount of boron atoms that ended up inside the silicon wafer.

You may assume that, for boron: R_p in Si = R_p in SiO_2, and ΔR_p in Si = ΔR_p in SiO_2. Values of R_p and ΔR_p can be taken from the graphs provided in the *Lecture Notes*.

Solution:

V=150 KV; doubly ionized B (B^{2+}); E = 300 KeV (2e×150KV), and Q = 2×10^{13} cm^{-2}.

From R_p and ΔR_p charts for B, R_p =0.7 μm and ΔR_p =0.1 μm.

$$N_p = \frac{Q}{\sqrt{2\pi}\cdot\Delta R_p} = 7.98\times10^{17}\ \mathrm{cm}^{-3}$$

Backgroud n-type conc. =1×10^{15} cm^{-3}.

(a) To solve for junction depth:

Refer to next slide to find Q

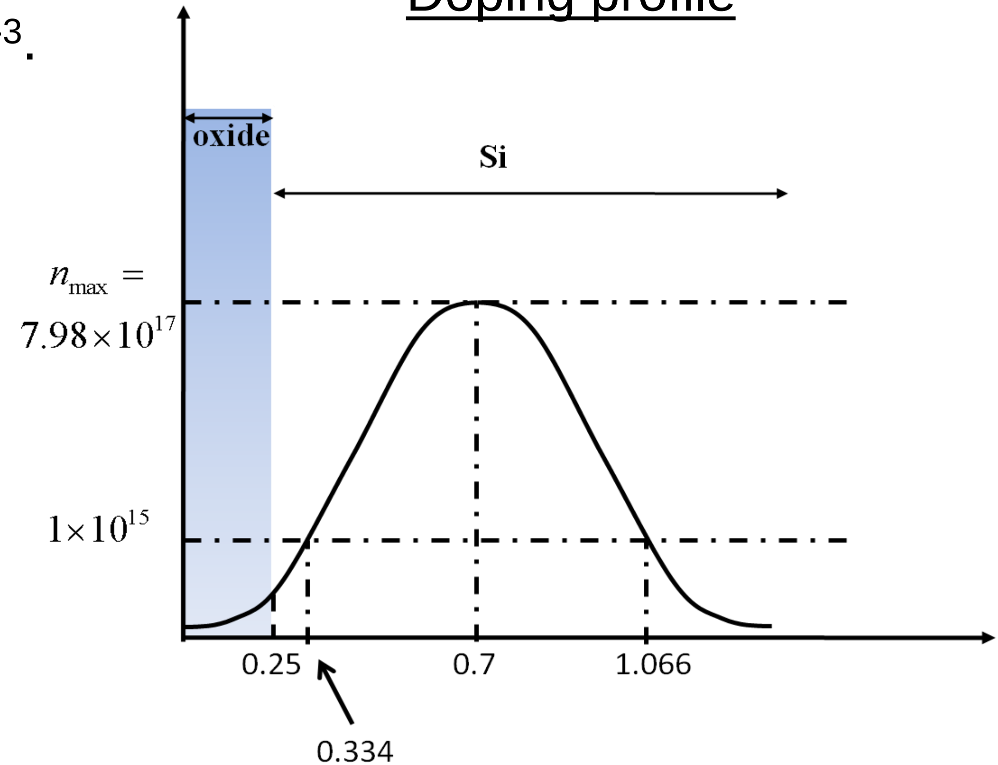
$$N_B = \frac{Q}{\sqrt{2\pi}\Delta R_p}\cdot\exp\left(-\frac{(x_j - R_p)^2}{2\Delta R_p^2}\right)$$

$$1\times10^{15} = 7.98\times10^{17}\exp\left(-\frac{(x_j - 0.7)^2}{2\times0.1^2}\right)$$

$$x_{j2} = 0.7 + 0.366 = 1.066\ \mu m$$

$$x_{j1} = 0.7 - 0.366 = 0.334\ \mu m$$

- Doping profile



Since oxide is 0.25 μm thick, both junctions are formed inside the semiconductor.

- <u>Boron inside Si</u>

$$Q(Si) = \frac{Q}{\sqrt{2\pi}\Delta R_p} \cdot \int_d^{\infty} \exp\left(-\frac{\left(x - R_p\right)^2}{2\Delta R_p^2}\right) dx$$

See lecture notes or Highlight slide

$$\frac{Q(Si)}{Q} = \frac{1}{2}\operatorname{erfc}\left(\frac{d - R_p}{\sqrt{2}\Delta R_p}\right) = \frac{1}{2}\operatorname{erfc}\left(\frac{0.25 - 0.7}{\sqrt{2}(0.1)}\right) = \frac{1}{2}\operatorname{erfc}(-3.182)$$

$$\operatorname{erfc}(-z) = 1 - \operatorname{erf}(-z) = 1 - \left[-\operatorname{erf}(z)\right] = 1 + \operatorname{erf}(z)$$

$$erf(-z) = -erf(z)$$

Erfc(-3.182) = 1+erf(3.182) = 1+0.999993

$$\therefore \quad \frac{Q(Si)}{Q} = \frac{1}{2}\left[1 + 0.999993\right] = 0.9999965$$

Thus $\quad Q(Si) \approx Q = 2 \times 10^{13}\ \mathrm{cm}^{-2}$

Supplementary

The complementary error function is defined as

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_z^{\alpha} \exp(-t^2)dt.$$

Hence,

$$Q(Si) = \frac{Q}{\sqrt{2\pi}\Delta \mathrm{R_p}} \cdot \int_d^{\infty} \exp(-\frac{\left(x - \mathrm{R_p}\right)^2}{2\Delta \mathrm{R_p^2}})\mathrm{d}x$$

$$\frac{Q(Si)}{Q} = \frac{1}{\sqrt{2\pi}\Delta \mathrm{R_p}} \cdot \int_d^{\infty} \exp\left(-\frac{x - R_p}{\sqrt{2}\Delta R_p}\right)^2 \mathrm{d}x$$

$$= \frac{1}{\sqrt{2\pi}\Delta \mathrm{R_p}} \cdot \int_d^{\infty} \exp\left(-\frac{x - R_p}{\sqrt{2}\Delta R_p}\right)^2 \mathrm{d}\left(\frac{x - R_p}{\sqrt{2}\Delta R_p}\right)(\sqrt{2}\Delta R_p)$$

$$= \frac{\sqrt{2}\Delta R_p}{\sqrt{2\pi}\Delta \mathrm{R_p}} \cdot \int_v^{\infty} \exp\left(-u^2\right)\mathrm{d}u \quad [\text{where } \ (\mathrm{u} = \frac{x - R_p}{\sqrt{2}\Delta R_p}) \text{ and } v = \frac{d - R_p}{\sqrt{2}\Delta R_p}]$$

$$= \frac{1}{\sqrt{\pi}} \cdot \frac{2}{2} \int_v^{\infty} \exp\left(-u^2\right)\mathrm{d}u = \frac{1}{2} \cdot \frac{2}{\sqrt{\pi}} \int_v^{\infty} \exp\left(-u^2\right)\mathrm{d}u$$

$$= \frac{1}{2}\mathrm{e}\,rfc(v) = \frac{1}{2} erfc(\frac{d - R_p}{\sqrt{2}\Delta R_p})$$

Q4. Boron was implanted into an n-type oxide-covered silicon wafer with a background concentration of $1x10^{15}cm^{-3}$. The oxide thickness was 0.6 μm and the ion dose used was $2x10^{13}$ atoms/cm^2. After implantation the wafer was annealed at 1050 ^oC for 30 minutes to activate the implanted ions. Assume that the values of projected range and straggle are same for B in Si and the oxide. Given R_p=700 nm and ΔR_p=100 nm, Diffusion Coefficient of B =$5x10^{-14}$ cm^2/s at 1050 ^oC.

(a) Calculate the peak concentration of the implanted profile and the junction depths from the wafer surface. Draw the schematic of the dopant profile.

(b) Calculate the peak concentration and the projected straggle after annealing. Does the peak location change after annealing?

(c) Find the required thickness of the oxide before and after annealing if the maximum concentration of B in Si is at most 10% of the background concentration.

Solution:

(a) Peak concentration, junction depth and dopant profile **before annealing**:

$$N(x)=\frac{Q}{\sqrt{2\pi}\Delta \mathrm{R_p}}\cdot\exp\left(-\frac{\left(x-\mathrm{R_p}\right)^2}{2\Delta \mathrm{R_p^2}}\right),$$

$$\mathrm{R_p}=0.7\,\mu\mathrm{m},\ \Delta\mathrm{R_p}=0.1\,\mu\mathrm{m},\ Q=2\times10^{13}\ \mathrm{cm^{-2}}$$

- Peak concentration of implanted profile:

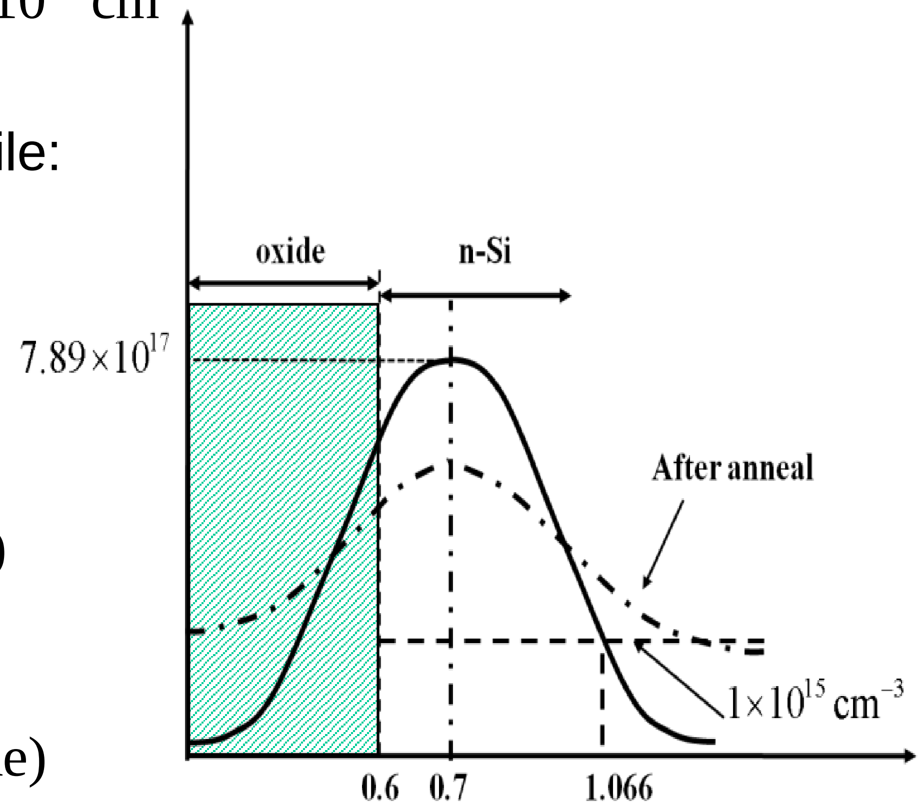
$$N_p=\frac{2\times10^{13}}{\sqrt{2\pi}\times0.1\times10^{-4}}\mathrm{cm^{-3}}=7.98\times10^{17}\mathrm{cm^{-3}}$$

  - Junction depth:

$$1\times10^{15}=7.98\times10^{17}\times\exp\left(-\frac{\left(x-0.7\right)^2}{2\times0.1^2}\right)$$

$$\Rightarrow\quad x_{j2}=1.066\,\mu\mathrm{m},$$

$$x_{j1}=0.334\,\mu\mathrm{m}\ \text{(Invalid as it is in oxide)}$$



(b) Peak concentration, straggle and peak location **after annealing**

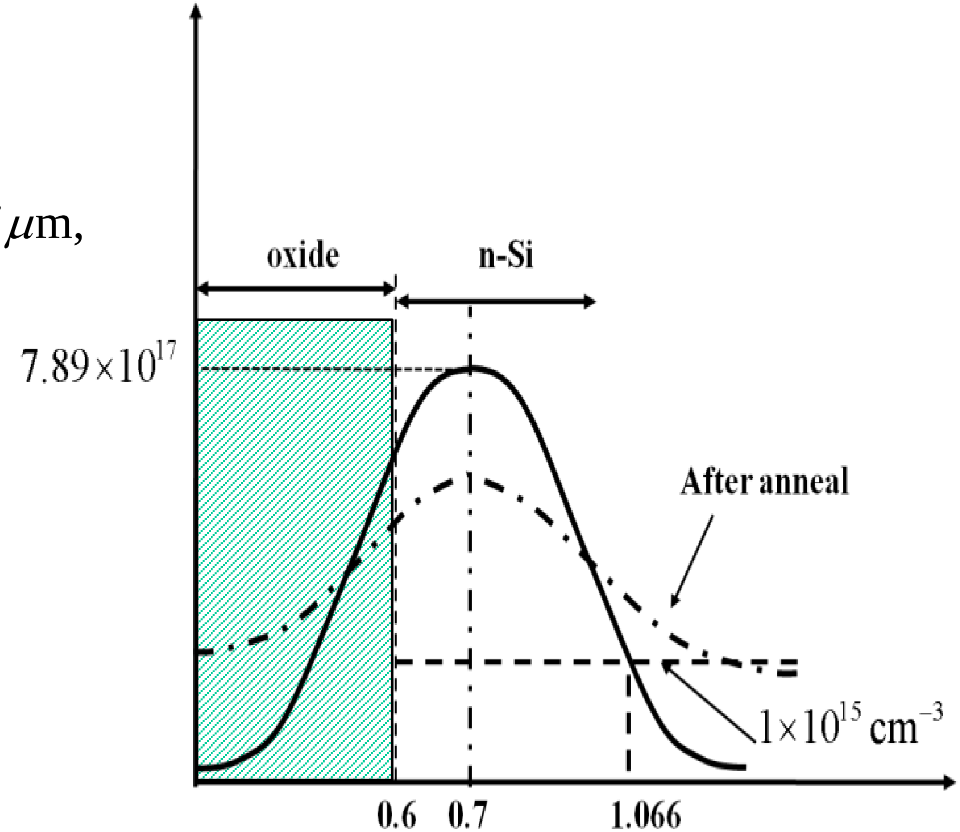
$$N'_{\max} = \frac{Q}{\sqrt{2\pi}\left(\Delta \mathrm{R}_\mathrm{p}^2 + 2Dt\right)^{1/2}}$$

$$= \frac{2\times10^{13}}{\sqrt{2\pi}\left(0.1^2 + 2\times5\times10^{-14}\times30\times60\right)^{1/2}}$$

$$= 4.77\times10^{17}\,\mathrm{cm}^{-3}$$

$$\mathrm{R}'_\mathrm{p} = 0.7\,\mu\mathrm{m}, \quad \Delta\mathrm{R}'_\mathrm{p} = \left(\Delta\mathrm{R}_\mathrm{p}^2 + 2Dt\right)^{1/2} = 0.167\,\mu\mathrm{m},$$

- Peak position remains unchanged although junction goes deeper after annealing,



(c) Required thickness of oxide with implanted B of 10% of background ($1\text{x}10^{15}\text{cm}^{-3}$) at the surface of Si.

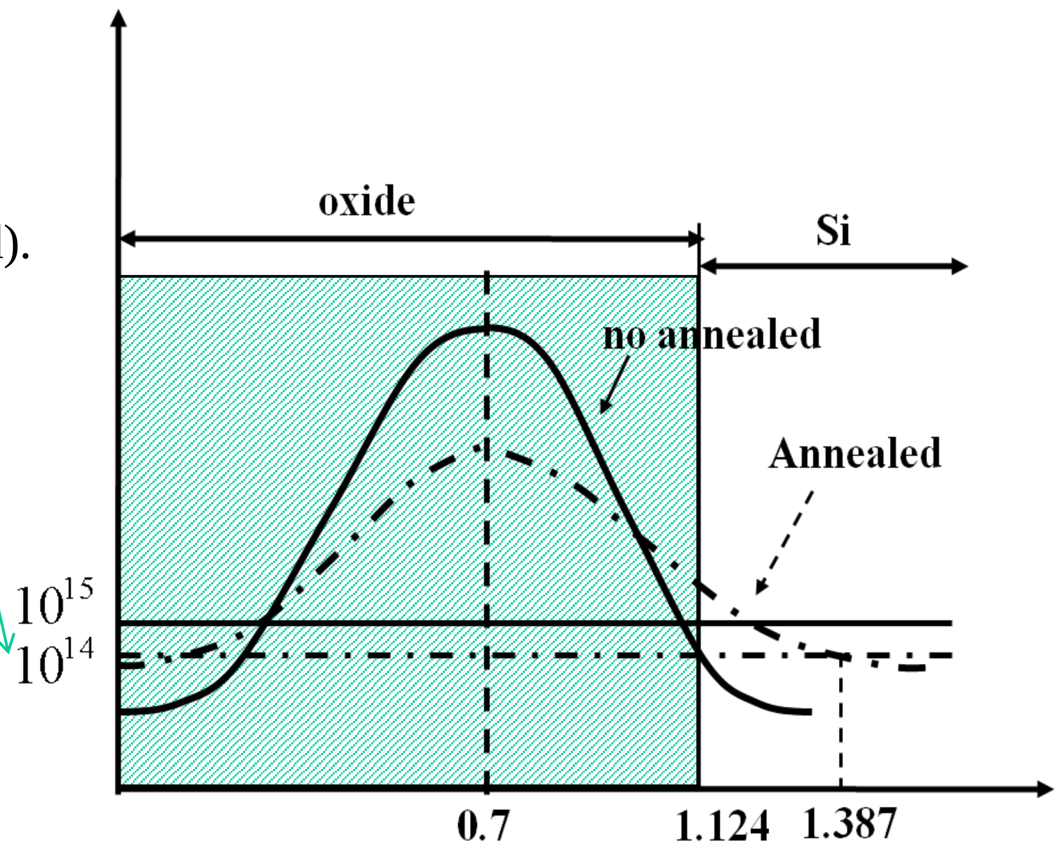
- **Before annealing**, $N(x) = 7.98\times10^{17}\cdot\exp(-\frac{(x-\mathrm{R_p})^2}{2\Delta\mathrm{R_p^2}})$

When x=d, $N(d) = N_B/10 = 10^{14}\,\text{cm}^{-3}$

$$10^{14} = 7.98\times10^{17}\cdot\exp(-\frac{(d-0.7)^2}{2\times0.1^2})$$

$\therefore \quad d_2 = 1.124\,\mu\text{m},\ d_1 = 0.276\,\mu\text{m}$ (invalid).

- If we have an oxide of 1.124 µm, the max conc. of the implanted dopant in the Si surface will be 10% of background concentration. The oxide should be > 1.124 µm for mask purpose.



- **After annealing**,

$$\Delta R_p' = \left(\Delta R_p^2 + 2Dt\right)^{1/2} = 0.167\,\mu\text{m},$$

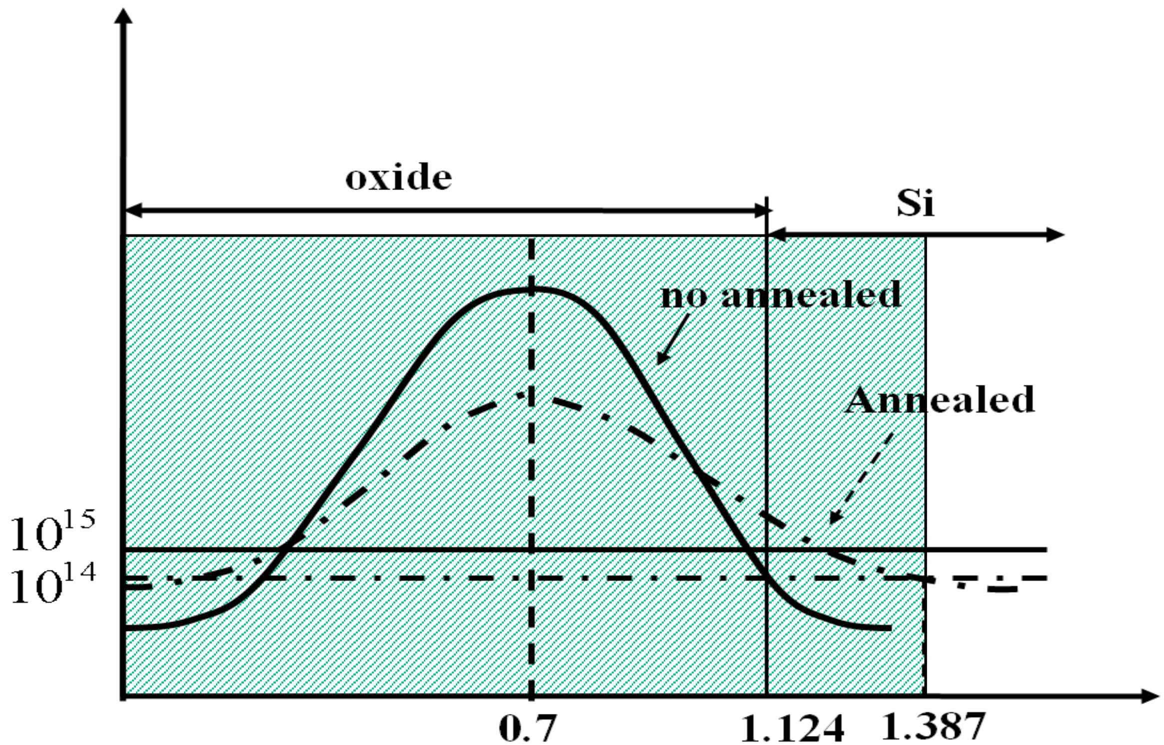
$$N'_{max} = \frac{Q}{\sqrt{2\pi}\cdot\Delta R_p'} = 4.77\times10^{17}\,\text{cm}^{-3};$$

$$\therefore 10^{14} = 4.77\times10^{17}\cdot\exp\!\left(-\frac{\left(d-0.7\right)^2}{2\times0.167^2}\right)$$

$$\Rightarrow\quad d_2 = 1.387\,\mu\text{m},$$

$$d_1 = 0.013\,\mu\text{m (invalid))}$$

- Oxide thickness required in this case is at least 1.387 μm.



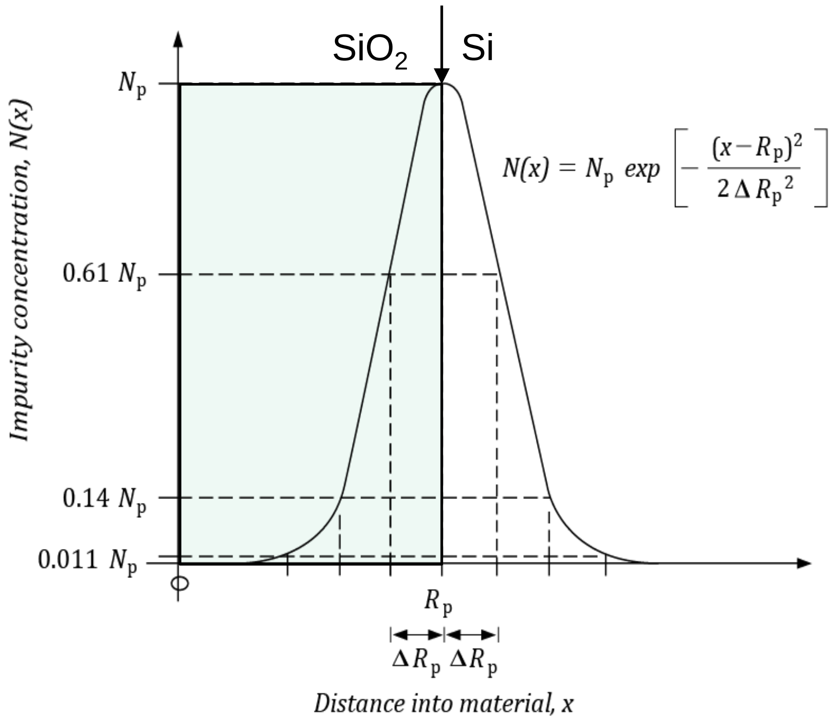
Q5. An arsenic dose of $1x10^{12}$ cm^{-3} is implanted through a 50 nm layer of silicon dioxide with the peak of the distribution at the Si-SiO_2 interface. The straggle range ΔR_p is 0.017μm. A silicon nitride film on top of the silicon oxide is to be used as a barrier material in the regions where arsenic is not desired. How thick should the nitride layer be if the background concentration is $1x10^{15}$ cm^{-3}? Assume silicon oxide is only 85% effective in stopping ions as compared to silicon nitride.

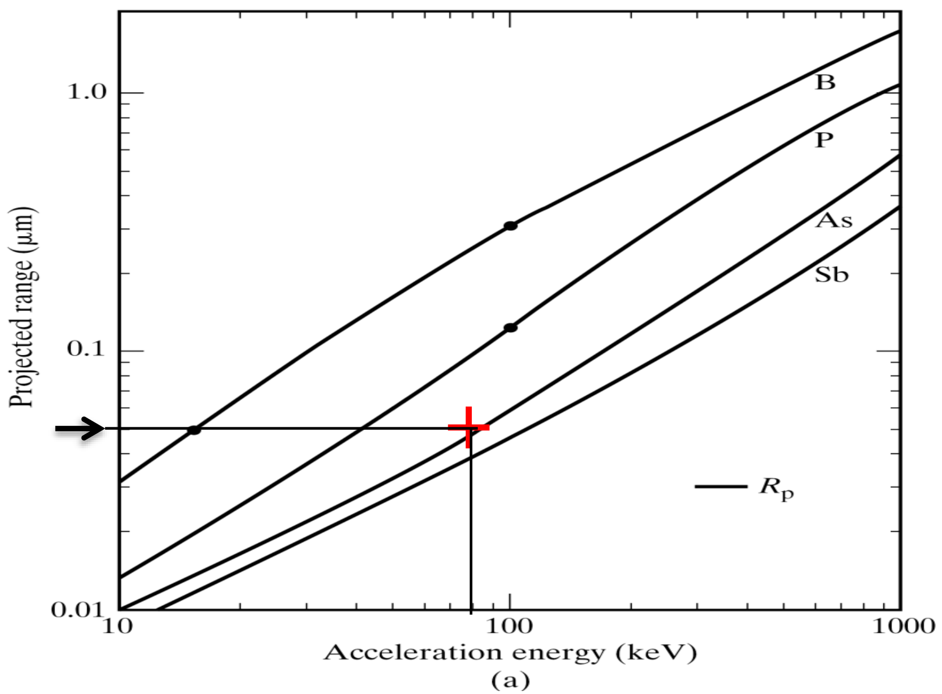
Solution:

- First, calculate the total oxide thickness needed to ensure that the implanted impurity concentration is less than $10^{15}/10 = 10^{14}/cm^3$ at the Si-SiO_2 interface.
- We know that $R_P = 0.05$ µm which is the thickness of the oxide. For arsenic, this requires E = 80 keV from the R_p vs Acceleration energy chart, and $\Delta R_p = 0.017$ µm.

$$N_P = Q/\Delta R_P\sqrt{2\pi} = 2.35 \times 10^{17}/cm^3.$$

Given that the peak of the distribution at the Si-SiO_2 interface





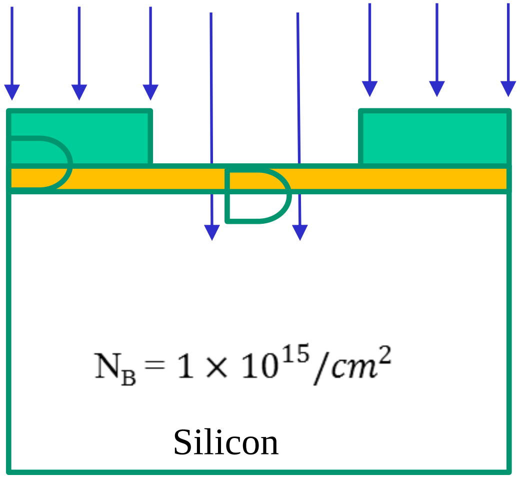
Solution:

- Recall from lecture that:

$$N\left(t_{ox}\right)=N_p \exp\left[-\frac{\left(t_{ox}-R_p\right)^2}{2\Delta R_p^2}\right]<\frac{N_B}{10}$$

and the required oxide thickness for the mask is:

$$t_{ox}\geq R_p+\Delta R_p\sqrt{2\ln\left(\frac{10N_p}{N_B}\right)}$$



See lecture notes or Highlight slide

- Here, $N_P/N_B = 235$, $t_{ox} = R_P + 3.94\Delta R_P$

➔ $t_{ox} = R_P + 3.94\Delta R_P = 0.05 + 3.94(0.017) = 0.117$ µm of oxide

- The additional oxide required is 3.94(0.017) = 0.067 µm

- However, $t_{SiN} = 0.85\ t_{ox}$ so only 0.057 µm of silicon nitride is required.