

Exam 1 Solutions

EE/MSE 486
Spring 2016

Problem 1.

For $0 < x < 20 \text{ nm}$, total doping is 10^{19} cm^{-3}

We can get $\mu_n \sim 1000 \text{ cm}^2/\text{V}\cdot\text{s}$, from the plot

$$\sigma_1 = 1.6 \times 10^{-19} \text{ C} \cdot 10^{19} \text{ cm}^{-3} \cdot 1000 \text{ cm}^2/\text{V}\cdot\text{s} = 160 \text{ cm}^{-1} \Omega^{-1}$$

For $20 \text{ nm} < x < 200 \text{ nm}$, total doping is $C_p + C_B = 6 \times 10^{17} \text{ cm}^{-3}$

We can get $\mu_n \sim 400 \text{ cm}^2/\text{V}\cdot\text{s}$

$$\begin{aligned} \sigma_2 &= 1.6 \times 10^{-19} \text{ C} \left[5 \times 10^{17} \text{ cm}^{-3} - 1 \times 10^{17} \text{ cm}^{-3} \right] \times 400 \text{ cm}^2/\text{V}\cdot\text{s} \\ &= 25.6 \text{ cm}^{-1} \Omega^{-1} \end{aligned}$$

$$\begin{aligned} R_s &= \frac{1}{\sigma_1 t_1 + \sigma_2 t_2} = \frac{1}{160 \text{ cm}^{-1} \Omega^{-1} \cdot 20 \text{ nm} + 25.6 \text{ cm}^{-1} \Omega^{-1} \cdot 180 \text{ nm}} \\ &= 1.28 \times 10^3 \Omega/\square \end{aligned}$$

$$\text{Mean} = 51.3$$

$$\text{Median} = 49$$

$$\text{Std. Dev} = 16.9$$

$$\text{Max} = 92$$

$$\text{Min} = 24$$

Problem 2.

(a) at $T = 1000^\circ\text{C}$ (1273K), $n_i \approx 10^{24.5} \text{ m}^{-3} = 10^{18.5} \text{ cm}^{-3} = 3.2 \times 10^{18} \text{ cm}^{-3}$ [From P]

$$\frac{P}{n_i} = \frac{N_A}{2n_i} + \sqrt{\frac{N_A^2}{4n_i^2} + 1} \sim 6.4 \quad [\text{here, } N_A = 2 \times 10^{19} \text{ cm}^{-3}]$$

$$h = 1 + \frac{N_A}{\sqrt{N_A^2 + 4n_i^2}} = 1.95$$

$$D_{B,1}^* = \left[0.05 \exp\left(\frac{-3.5}{kT}\right) + 0.95 \exp\left(\frac{-3.5}{kT}\right) \frac{P}{n_i} \right] \times h$$

$$= \left(7.05 \times 10^{-16} \text{ cm}^2/\text{s} + 1.34 \times 10^{-14} \text{ cm}^2/\text{s} \frac{P}{n_i} \right) \times 1.95 = 1.7 \times 10^{-13} \text{ cm}^2/\text{s}$$

$$Q = \frac{2C_s}{\sqrt{\pi}} \sqrt{D_{B,1}^* t} = \frac{2 \times 5 \times 10^{19} \text{ cm}^{-3}}{\sqrt{\pi}} \sqrt{1.7 \times 10^{-13} \text{ cm}^2/\text{s} \times 10\text{s}} = 7.4 \times 10^{13} \text{ cm}^{-2}$$

(b) Using drive in, $N_A = 1 \times 10^{19} \text{ cm}^{-3}$

$$\frac{P}{n_i} = \frac{N_A}{2n_i} + \sqrt{\frac{N_A^2}{4n_i^2} + 1} \sim 3.4, \quad h = 1 + \frac{N_A}{\sqrt{N_A^2 + 4n_i^2}} = 1.84$$

$$D_{B,2} = (7.05 \times 10^{-16} \text{ cm}^2/\text{s} + 1.34 \times 10^{-14} \text{ cm}^2/\text{s} \times 3.4) \times 1.84 = 8.6 \times 10^{-14} \text{ cm}^2/\text{s}$$

$$(Dt)_{\text{eff}} = (Dt)_{\text{predep}} + (Dt)_{\text{drive in}} = 0.8 \times 10\text{s} \times D_{B,1} + 90\text{s} \times D_{B,2}$$

$$= 8\text{s} \times 1.7 \times 10^{-13} \text{ cm}^2/\text{s} + 90\text{s} \times 8.6 \times 10^{-14} \text{ cm}^2/\text{s}$$

$$= 9.1 \times 10^{-12} \text{ cm}^2$$

$$C = \frac{a}{\sqrt{\pi Dt}} \exp\left(-\frac{x^2}{4Dt}\right) = 10^8 \text{ cm}^{-3}$$

$$\Rightarrow \exp\left(-\frac{x^2}{4Dt}\right) = \frac{Q/\sqrt{\pi Dt}}{10^8 \text{ cm}^{-3}} = \frac{7.4 \times 10^{13} \text{ cm}^{-2}}{\sqrt{\pi \times 9.1 \times 10^{-12} \text{ cm}^2}} \times \frac{1.38 \times 10^{19}}{10^8} = 13.8$$

$$\Rightarrow \exp\left(-\frac{x^2}{4Dt}\right) = 13.8 \Rightarrow \frac{x^2}{4Dt} = \ln(13.8) \Rightarrow x^2 = 4 \times 9.1 \times 10^{-12} \text{ cm}^2 \times 2.625$$

$$\Rightarrow x \approx 98 \text{ nm}$$

3. Arsenic is implanted at 40 keV to a dose of $1.5 \times 10^{15} \text{ cm}^{-2}$ through a 20nm polycrystalline Si film (same range statistics as Si).

(a) What is the peak doping and its location in the poly-Si film? (10)

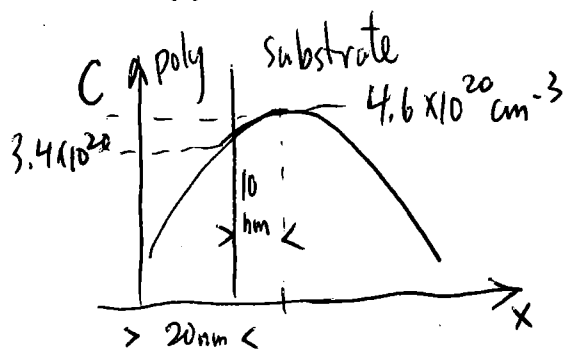
From attached plots, for As at 40 keV, $R_p \approx 30 \text{ nm}$ and $\Delta R_p \approx 13 \text{ nm}$.

For poly/Si, peak of doping would be at 30nm, which is 10nm deep into Si crystalline substrate. Actual peak in poly is at poly/Si interface.

$$\text{Concentration at } R_p \text{ is } C_p = \frac{Q}{\sqrt{2\pi} \Delta R_p} = \frac{1.5 \times 10^{15} \text{ cm}^{-2}}{\sqrt{2\pi} (13 \times 10^{-7} \text{ cm})} = 4.6 \times 10^{20} \text{ cm}^{-3}$$

$$\text{Concentration at interface } C(20) = C_p \exp\left(-\frac{(20-30)^2}{2(13)^2}\right) = 3.4 \times 10^{20} \text{ cm}^{-3}$$

(b) What dose will penetrate through the poly-Si film into the crystalline substrate? (10)



$R_p >$ film thickness, so most of dose penetrates through to substrate

$$\text{Dose} = Q_{\text{sub}} = \int_{20 \text{ nm}}^{\infty} C_p \exp\left(-\frac{(x-30 \text{ nm})^2}{2(13 \text{ nm})^2}\right) dx$$

Multiple approaches possible:

$$\text{A) Dose in poly} = \text{Dose below } R_p + 10 \text{ nm} = \frac{Q}{2} \operatorname{erfc}\left(\frac{10 \text{ nm}}{\sqrt{2} 13 \text{ nm}}\right)$$

$$\begin{aligned} \text{Thus dose in substrate} &= Q \left(1 - \frac{1}{2} \operatorname{erfc}(0.544)\right) = Q \left[\frac{1}{2} (1 - \operatorname{erf}(0.544))\right] \\ &= \frac{Q}{2} (1 + \operatorname{erf}(0.544)) = \frac{1.5 \times 10^{15} \text{ cm}^{-2}}{2} (1 + 0.56) \\ &= \underline{\underline{1.17 \times 10^{15} \text{ cm}^{-2}}} \end{aligned}$$

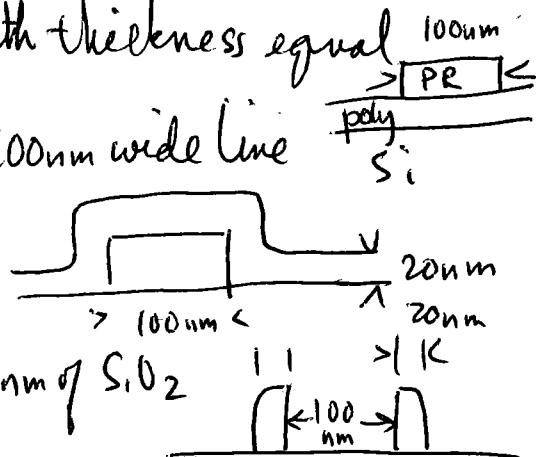
B) Alternatively, can look at definition of erf and see that $\operatorname{erf}(-z) = -\operatorname{erf}(z)$

$$\text{Thus the regular formula can be used, } Q_{\text{sub}} = \frac{Q}{2} (1 - \operatorname{erf}(-0.544)) = \frac{Q}{2} [1 + \operatorname{erf}(0.544)]$$

4.

- (a) Describe how you would make a pair of 20 nm wide SiO_2 lines with 100 nm gap between them using the sidewall spacer method (as in self-aligned source/drain extensions). (8)

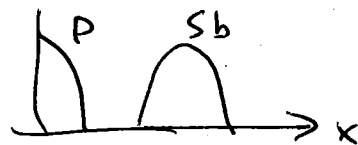
- 1) Deposit robust sacrificial layer such as poly, with thickness equal to desired line height.
- 2) Pattern photoresist (deposit, expose, develop) to make 100 nm wide line
- 3) Anisotropic etch to replicate pattern in poly
- 4) Conformal deposition of 20 nm of SiO_2
- 5) Anisotropic (vertical) etch of a little more than 20 nm of SiO_2
- 6) Etch away poly using selective etch



- (b) A phosphorus predep is done with surface concentration near solid solubility. If there was an Sb buried layer, would its broadening be more, less or the same compared to the same thermal cycle without the P doping source? Explain. (6)

If (as I intended), buried layer was below predep, then I excess from coupled diffusion would cause V undersaturation and reduce diffusion of Sb, with $f_I = 0.02$

If Sb was within predep region, then more diffusion due to $(n/n_i) > 1$ and $D_{\text{Sb}} = D_{\text{Sb}}^0 + D_{\text{Sb}}^- (n/n_i)$ and electric field effects.



- (c) Compare B and P implants at 20 keV. Which would have stronger electronic stopping and which would generate more lattice damage? Explain why. (8)

electronic stopping proportional to velocity. With lower mass, B would have higher velocity for same kinetic energy and thus more stronger electronic stopping.

Energy lost to either electronic or nuclear stopping. With less electronic stopping P would have more energy lost to nuclear collisions and thus more lattice damage. P also shallower, so damage more concentrated.

- (d) Why are the chemical (maximum impurity concentration before precipitates form) and electrical (maximum active doping concentration) different? (6)

At high concentration, dopants can form small clusters with point defects (e.g. P_4V , As_4V , B_3I) that are inactive so that "electrical solubility" or active doping concentration is less than "chemical solubility" or total doping concentration in solid solution.