

## EE143 HW#5 Solutions

## Problem 1

$$(a) C(x,t) = C_S \operatorname{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)$$

$$3.5 \times 10^{20} \operatorname{erfc}\left[\frac{x_j}{2\sqrt{Dt}}\right] = 10^{16} \Rightarrow \frac{x_j}{2\sqrt{Dt}} = \operatorname{erfc}^{-1}(2.9 \times 10^{-5}) = 2.9$$

$$\text{Since } 2\sqrt{Dt} = 0.73 \times 10^{-5} \text{ cm, } x_j = 0.73 \times 10^{-5} \times 2.9 = \mathbf{0.21 \mu m}$$

$$(b) Q = \frac{2C_S\sqrt{Dt}}{\sqrt{\pi}} = \frac{0.73 \times 10^{-5} \times 3.5 \times 10^{20}}{1.77} = \mathbf{1.45 \times 10^{15}/cm^2}$$

## Problem 2

$$R_s x_j = 50 \Omega/\text{square} \times 1 \mu\text{m} = 50 \Omega\text{-}\mu\text{m}$$

Using Irvin curve with half-gaussian profile (p into n curve) and  $N_B = 10^{17}/\text{cm}^3$

$\Rightarrow$  surface concentration  $C_o = 5 \times 10^{19}/\text{cm}^3$

$$\text{Since } C_o e^{-\frac{x_j^2}{4D_2t_2}} = N_B \quad \text{at } x_j = 1 \mu\text{m}$$

$$\therefore \text{Drive-in Dt product } D_2t_2 = 4 \times 10^{-10} \text{ cm}^2$$

Using  $D_o = 10.5 \text{ cm}^2/\text{sec}$  and  $E_a = 3.69 \text{ eV}$  for Boron diffusion,

$$D(\text{Boron at } 1100^\circ\text{C}) = 10.5 \exp\left[\frac{-3.69}{(8.614 \times 10^{-5} \times 1373)}\right] \text{ cm}^2/\text{sec} = 2.96 \times 10^{-13} \text{ cm}^2/\text{sec}$$

$$\therefore t_2 = 1351 \text{ seconds} = \mathbf{0.375 \text{ hours} = \text{drive-in time}}$$

$$Q_{\text{predep}} = Q_{\text{drive-in}} = C_o \sqrt{\pi D_2 t_2} = 1.772 \times 10^{15}/\text{cm}^2$$

Since solid solubility limit of boron at  $1000^\circ\text{C}$  (predep temp)  $\approx 2 \times 10^{20}/\text{cm}^3 = C_s$

$$\therefore Q_{\text{predep}} = \frac{C_s \sqrt{D_1 t_1}}{\sqrt{\pi}} = 1.772 \times 10^{15}/\text{cm}^2 \Rightarrow D_1 t_1 = 6.17 \times 10^{-11} \text{ cm}^2$$

$$D_1(\text{boron at } 1000^\circ\text{C}) = 2.55 \times 10^{-14} \text{ cm}^2/\text{sec}$$

$$\therefore t_1 = 2420 \text{ sec} = \mathbf{0.672 \text{ hours} = \text{predep time}}$$

## Problem 3

$$R_s x_j = 264 \Omega\text{-}\mu\text{m} \Rightarrow N_o = 10^{19}/\text{cm}^3 \text{ from Irvin's curve (p gaussian into n, } N_B = 10^{15}/\text{cm}^3)$$

$$\therefore 10^{15} = 10^{19} \exp\left[\frac{-x_j^2}{4Dt}\right] \Rightarrow Dt = 1 \mu\text{m}^2$$

After additional drive-in:

$$\begin{aligned} (Dt)_{\text{total}} &= 1 \mu\text{m}^2 + 7.2 \times 10^{-13} \times 6.5 \times 3600 \text{ cm}^2 \\ &= 1 \mu\text{m}^2 + 1.68 \mu\text{m}^2 = 2.68 \mu\text{m}^2 \end{aligned}$$

$$\therefore 10^{15} = \frac{Q}{\sqrt{\pi(Dt)_{\text{total}}}} \exp\left[\frac{-x_j^2}{4(Dt)_{\text{total}}}\right]$$

However, Q can be found from original half-gaussian:

$$Q = C_s \sqrt{\pi Dt} = 1.1 \times 10^{15}/\text{cm}^2$$

$$\therefore 10^{15} = \frac{10^{19} \sqrt{\pi} \sqrt{1}}{\sqrt{\pi} \sqrt{2.68}} \exp \left[ \frac{-x_j^2}{4(Dt)_{\text{total}}} \right] \Rightarrow \frac{x_j}{\sqrt{4 \times 2.68}} = 3.0$$

$$\therefore x_j = 9.8 \mu\text{m}$$

**Problem 4**

a) To position the Gaussian peak exactly at the Si/SiO<sub>2</sub> interface will split the dose evenly into Si and SiO<sub>2</sub>.

For boron ions,

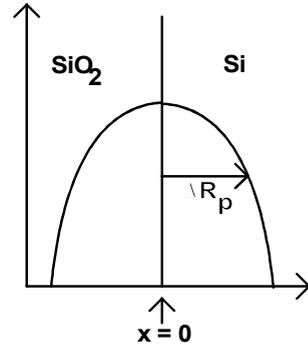
$$R_p(80 \text{ keV}) = 0.1 \mu\text{m}$$

$$\Delta R_p(80 \text{ keV}) = 0.04 \mu\text{m}$$

$$b) C_p = 1 \times 10^{18} = \frac{\phi}{\sqrt{2\pi} \Delta R_p}$$

$$\Rightarrow \text{dose } \phi = 1 \times 10^{18} \times 0.04 \times 10^{-4} \times \sqrt{2\pi}$$

$$= 1.0 \times 10^{13} / \text{cm}^2$$



c) The boron implant profile inside Si is a half-gaussian (characterized by ΔRp) is mathematically equivalent to a drive-in diffusion profile (characterized by Dt).

$$4Dt = 2(\Delta R_p)^2 \Rightarrow Dt = 8 \times 10^{-4} \mu\text{m}^2$$

$$d) 1 \times 10^{16} = C_p \exp \left[ \frac{-x_j^2}{2(\Delta R_p)^2} \right] \Rightarrow x_j = \left[ 2(\Delta R_p)^2 \cdot \ln \frac{C_p}{C_B} \right]^{1/2} = 0.121 \mu\text{m}$$

where  $C_p = \frac{\phi}{\sqrt{2\pi} \Delta R_p} = \frac{0.4\phi}{\Delta R_p}$  peak concentration of implant profile before annealing

e) Half the implant dose is inside Si and half is inside SiO<sub>2</sub>.

$$\text{Diffusion dose } Q \text{ in Si} = \frac{1}{2} \text{ implant dose} = 5 \times 10^{12} / \text{cm}^2$$

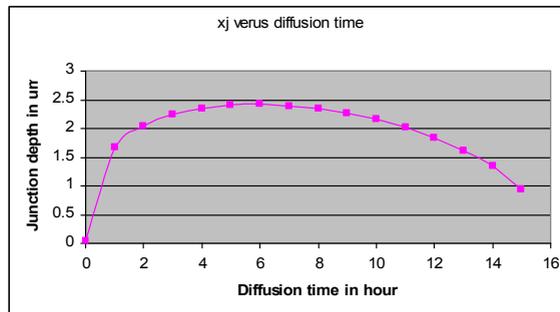
$$\therefore \frac{Q}{\sqrt{\pi Dt}} \exp \left[ \frac{-x_j^2}{4Dt} \right] = 10^{16} \text{ at } x_j = 2 \mu\text{m} \text{ where } Dt = \text{total effective } Dt.$$

$$\therefore 5 \times 10^{12} / 10^{16} = \sqrt{\pi Dt} \exp \left[ + 4 / (4Dt) \right] \times 10^{-4} \quad (10^{-4} \text{ because } Dt \text{ is expressed in } \mu\text{m}^2)$$

$$\text{Solving } Dt \text{ by trial and error } \Rightarrow Dt = 0.929 \mu\text{m}^2 = (Dt)_{\text{implant}} + (Dt)_{\text{drive-in}}$$

$$\therefore (Dt)_{\text{drive-in}} = (0.929 - 8 \times 10^{-4}) \approx 0.929 \mu\text{m}^2 \quad \therefore t_{\text{drive-in}} = 0.929 / 0.5 = 1.86 \text{ hr}$$

[Comments: The phosphorus implant inside SiO<sub>2</sub> does not affect the phosphorus diffusion in Si because Phosphorus diffusion in SiO<sub>2</sub> is negligible. Also the slope of concentration profile is zero at x=0 for all t. Starting at t=0, the junction depth will increase as the profile spreads out by diffusion. For very long diffusion time, the junction depth will reduce because the surface concentration is lowered as  $Q/\sqrt{\pi Dt}$ . You will also find another  $x_j = 2 \mu\text{m}$  solution at  $Dt = 5.5 \mu\text{m}^2$  !]



f.) We will first estimate the surface concentration of phosphorus at the Si/SiO<sub>2</sub> interface

$$N_0 = 5 \times 10^{12} / (\sqrt{\pi Dt}) = 1.6 \times 10^{16} / \text{cm}^3$$

$$\text{Irvin curve} \Rightarrow R_s \cdot x_j \approx 8 \text{ k}\Omega \cdot \mu\text{m} \quad \therefore R_s = 8 \text{ k}\Omega / 2 \approx 4 \text{ k}\Omega / \text{square}$$

g.) No high concentrations phosphorus diffusion effect because dopant concentration  $\ll n_i$

**Note:**  $n_i$  at 1200°C =  $10^{19} / \text{cm}^3$

$$\text{h.) Predep dose} = \frac{N_0 \cdot 2\sqrt{Dt}}{\sqrt{\pi}} = 5 \times 10^{12} / \text{cm}^2$$

$C_s$  (950°C) for phosphorus  $\approx 10^{21} / \text{cm}^3$  (from solid solubility chart)

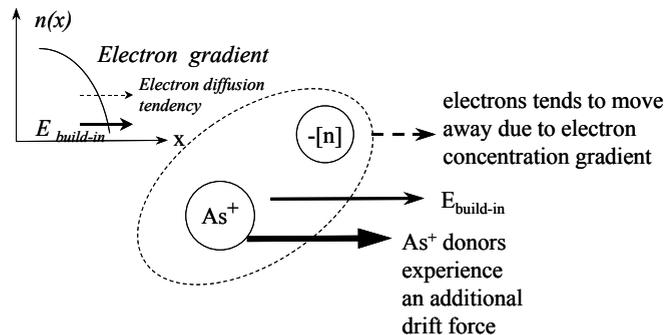
$$\therefore (Dt)_{\text{predep}} \approx (5 \times 10^{12} / 10^{21})^2 = 2.5 \times 10^{-17} \text{ cm}^2$$

$D$  (950°C) for phosphorus  $\approx 10^{-15} \text{ cm}^2$

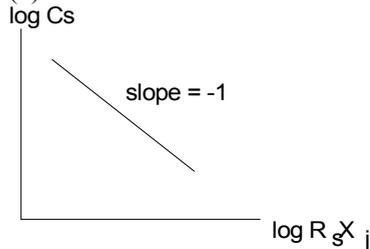
$\therefore (t)_{\text{predep}} \approx 0.025 \text{ sec!}$  DIFFICULT TO CONTROL THE PREDEP DIFFUSION TIME USING A FURNACE!

### Problem 5

(a)



(b)



With dose  $Q_T = C_s x_j$  and the mobility constant, the sheet resistance

$$R_s = 1 / (q\mu Q_T) = 1 / (q\mu C_s x_j).$$

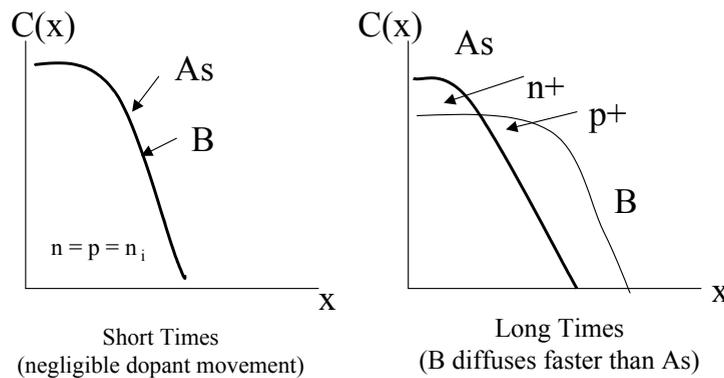
$$\therefore C_s = 1 / (q\mu R_s x_j).$$

The  $\log(C_s)$  versus  $\log(R_s x_j)$  plot will be a straight line with a **slope of -1**

[Comment : If you eyeball all the Irvin's curves shown in Jaeger with low background concentration, they do have slopes approximately equal to -1]

(c) During the **initial stage** of diffusion near time  $\sim 0$ , all doped regions are intrinsic ( $N_a(x) = N_d(x)$  for all  $x$  implies  $n(x) = p(x) = n_i$ ). We won't expect to see any high concentration diffusion effect.

For longer diffusion times, **Boron diffuses faster than As** and the near surface region becomes highly n-doped and the deeper region becomes p-doped. Since the net carrier concentration can still be higher than  $n_i$ . We will start to observe high concentration diffusion effects in both regions.



### Problem 6

(i)

#### (A) Ion channeling---

Although a tilt-and-rotate geometry can minimize the primary channeling effect, we can still have a small fraction of the scattered ions bouncing into various axis or planes, giving a “channeling tail” of the doping profile. The only way to eliminate this “lucky ion” channeling effect is to preamorphise the surface region with Si implantation. However, the risk is the formation of residual defects after annealing.

(B) For source/drain regions, the surface concentration is very high ( $10^{20}/\text{cm}^3$  or higher to ensure good ohmic contact and low sheet resistance). We will encounter enhanced diffusion due to **high concentration diffusion effects** such as E-field enhancement and charged point defects [vacancies and interstitials].

#### (C) Transient Enhanced Diffusion---

The excess point defects created by collision events of ion implantation will enhance dopant diffusion, creating deeper junction depths than desired. This transient enhancement is observed at the initial stage of annealing and will subside when the excess point defects are annihilated with longer time annealing. There is no established technology yet to bypass this mechanism. One possibility is to co-implant Ge or C into Si substrates to reduce the concentration of these excess point defects.

(ii) Key mechanism which will limit low sheet resistance :

Dopants have a **finite solid solubility** in Si. The excess concentration above solid solubility is not electrically active. This sets the lower limit for sheet resistance with a given junction depth.

(iii) A shallow junction depth requires a small  $Dt$  product (i.e., a lower diffusion temperature or a very short annealing time). However, too low a diffusion temperature may not place the dopants into the substitutional sites of Si crystal (i.e., dopants not electrical active).

Implanting a very high dose of dopant will increase the chemical concentration (i.e., height of the dopant profile) which can lower  $R_s$ . However,  $R_s$  is determined by the concentration of electrically active dopants (not chemical). It is still limited by the solid solubility of dopant in Si.