EE143 HW#4 Solutions

Problem 1

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

$3.5\times10^{20}\operatorname{erfc}\left[\frac{x_j}{2\sqrt{Dt}}\right] = 10^{16} \Rightarrow \frac{x_j}{2\sqrt{Dt}} = \operatorname{erfc}^{-1}(2.9\times10^{-5}) = 2.9$

Since $2\sqrt{Dt} = 0.73\times10^{-5}$ cm , $\mathbf{x_j} = 0.73\times10^{-5}\times2.9 = \mathbf{0.21\ \mu m}$

(b) $\mathbf{Q} = \frac{2C_S\sqrt{Dt}}{\sqrt{\pi}} = \frac{0.73\times10^{-5}\times3.5\times10^{20}}{1.77} = \mathbf{1.45\times10^{15}/cm^2}$

Problem 2

$R_s x_j = 50\ \Omega/\text{square}\times1\ \mu m = 50\ \Omega\text{-}\mu m$

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

$\Rightarrow$ surface concentration $C_o = 5\times10^{19}/cm^3$

Since $C_o e^{\left[\frac{-x_j^2}{4D_2t_2}\right]} = N_B$ at $x_j = 1\ \mu m$

$\therefore$ Drive-in Dt product $D_2t_2 = 4\times10^{-10}cm^2$

Using D_o=10.5 cm^2 /sec and E_a=3.69 eV for Boron diffusion,

D (Boron at 1100°C) =10.5 exp $\left[\frac{-3.69}{(8.614\times10^{-5}\times1373)}\right]$ $cm^2/sec = 2.96\times10^{-13}cm^2/sec$

$\therefore t_2 = 1351$ seconds **= 0.375 hours = drive-in time**

$Q_{predep} = Q_{drive\text{-}in} = C_o\sqrt{\pi D_2t_2} = 1.772\times10^{15}/cm^2$

Since solid solubility limit of boron at 1000°C (predep temp) $\approx 2\times10^{20}/cm^3 = C_s$

$\therefore Q_{predep} = \frac{C_s\ 2\sqrt{D_1t_1}}{\sqrt{\pi}} = 1.772\times10^{15}/cm^2 \Rightarrow D_1t_1 = 6.17\times10^{-11}cm^2$

D_1(boron at 1000 °C) = $2.55\times10^{-14}cm^2/sec$

$\therefore t_1 = 2420$ sec = **0.672 hours = predep time**

Problem 3

$R_sx_j = 264\ \Omega\text{–}\mu m \Rightarrow N_o = 10^{19}/cm^3$ from Irvins curve (p gaussian into n, $N_B = 10^{15}/cm^3$)

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

After additional drive-in:

$(Dt)_{total} = 1\ \mu m^2 + 7.2\times10^{-13}\times6.5\times3600\ cm^2$

$= 1\ \mu m^2 + 1.68\ \mu m^2 = 2.68\ \mu m^2$

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

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

$Q = C_s\sqrt{\pi Dt} = 1.1\times10^{15}/cm^3$

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

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

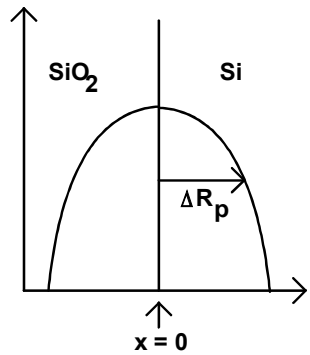
Problem 4

a) To position the Gaussian peak exactly at the Si/SiO2 interface will split the dose evenly into Si and SiO2.

For boron ions,

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

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



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

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

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

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).

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

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

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

e) Half the implant dose is inside Si and half is inside SiO2.

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

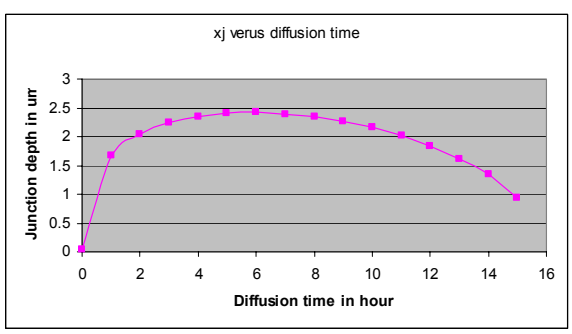
$\therefore \dfrac{Q}{\sqrt{\pi Dt}} \exp\left[\dfrac{-x_j^2}{4Dt}\right] = 10^{16}$ at $x_j = 2\ \mu m$ where Dt = total effective Dt.

$\therefore 5\times 10^{12}/10^{16} = \sqrt{\pi Dt}\ \exp[+4/(4Dt)] \times 10^{-4}$ (10^{-4} beacuse Dt is expressed in μm^2)

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

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

[Comments: The phosphorus implant inside SiO_2 does not affect the phosphorus diffusion in Si because Phosphorus diffusion in SiO_2 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 μm solution at Dt=5.5 μm^2 !]



f.)We will first estimate the surface concentration of phosphorus at the Si/SiO2 interface

$N_o = 5\times10^{12}/(\sqrt{\pi Dt}) = 1.6\times10^{16}/cm^3$

Irvin curve $\Rightarrow$ $R_s \bullet x_j \approx 8k\,\Omega \bullet \mu m$ $\therefore$ $\mathbf{R_s} = 8k\Omega/2 \approx$ **4 kΩ/square**

g.) No high concentrations phosphorus diffusion effect because dopant concentration << n_i

Note: n_i at 1200°C = $10^{19}/cm^3$

h.) Predep dose = $\dfrac{N_o \bullet 2\sqrt{Dt}}{\sqrt{\pi}} = 5\times10^{12}/cm^2$

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

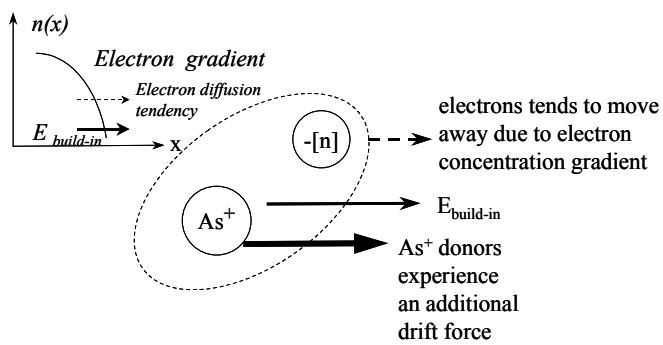
$\therefore (Dt)_{predep} \approx (5\times10^{12} / 10^{21})^2 = 2.5\times10^{-17}cm^2$

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

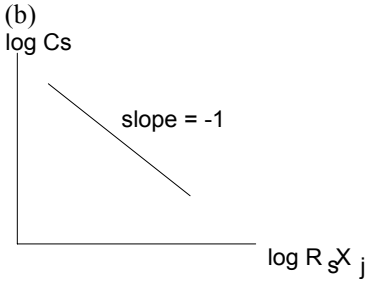
$\therefore$ **$(t)_{predep} \approx 0.025$ sec !** DIFFICULT TO CONTROL THE PREDEP DIFFUSION TIME USING A FURNACE !

Problem 5

(a)



(b)



With dose $Q_T = C_s\, x_j$ and the mobility constant, the sheet resistance $R_s = 1/(q\mu Q_T) = 1/(q\mu C_s\, x_j)$.

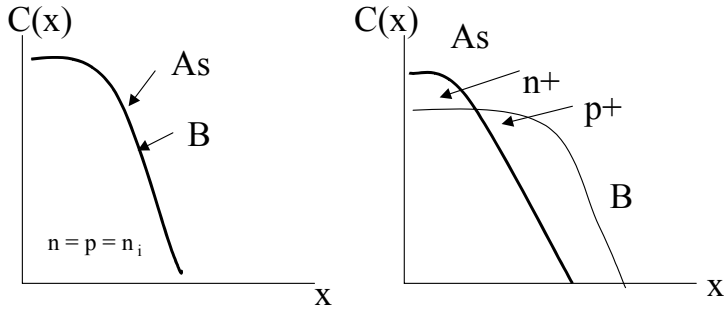
$\therefore C_s = 1/(q\mu R_s\, x_j)$.

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 ~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 observed high concentration diffusion effects in both regions.



Short Times
(negligible dopant movement)

Long Times
(B diffuses faster than As)

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 ($10^{20}/cm^3$or higher to ensure good ohmic contact and low sheet resistance). We will encountered 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 annilhilated 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 substituitional 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.