# EE143 Microfabrication Technology
Spring 2011
Prof. J. Bokor

## Midterm Exam 2

**Name:** Solutions

**Signature:** ______________________________

**SID:** ____________________

CLOSED BOOK. TWO 8 1/2" X 11" SHEET OF NOTES, AND SCIENTIFIC POCKET CALCULATOR PERMITTED. MAKE SURE THE EXAM PAPER HAS 10 PAGES. DO ALL WORK ON THE EXAM PAGES. USE THE BACK OF PAGES IF NECESSARY.

*TIME ALLOTTED: 80 MINUTES*

Fundamental constants you might need:

Boltzmann's constant, $k = 1.38 \times 10^{-23}$ J/K

Permittivity of free space, $\varepsilon_o = 8.85 \times 10^{-12}$ F/m

Permeability of free space, $\mu_o = 1.26 \times 10^{-6}$ H/m

Speed of light in vacuum, $c = 2.998 \times 10^{8}$ m/s

Electron charge, $e = 1.6 \times 10^{-19}$ C

Free electron mass, $m_o = 9.1 \times 10^{-31}$ kg

Electron volt, 1 eV = $1.6 \times 10^{-19}$ J

Thermal voltage, $kT/q = 0.0258$ V (at 300K)

Relative dielectric constant of silicon, $K_s = 11.8$

Relative dielectric constant of silicon dioxide, $K_o = 3.9$

Effective masses in silicon at 300K. Electrons: $m_n^* = 1.18\ m_o$ ; Holes: $m_p^* = 0.81\ m_o$

Silicon band gap at 300K, $E_g = 1.12$ eV

1. Thin Film Deposition (25 points)
   a. In the EE143 lab, we use a thermal evaporator to deposit the aluminum thin film. Before the evaporation, a mechanical pump and turbo pump are used to lower the pressure of the chamber. (12 points)
      i) What is the purpose of this pumping step? (3 points)

We evacuate the chamber to ensure that the Al atoms follow straight trajectories from the source to the wafer without any collisions with backgroundgas molecules. We also want to preserve the purity of the deposited film.

      ii) If the pressure of chamber P = $10^{-2}$ Torr, will the evaporation work well? How about P = $10^{-4}$ torr? Explain. [Hint: Calculate the mean free path for molecular collisions. Use a diameter of 0.25nm for the Al atoms.] (6 points)

mean free path for collisions          chamber size ~ 15cm

$$\lambda(mm) = \frac{0.05}{P(torr)}$$

$$P = 10^{-2}\ torr \rightarrow \lambda \cong \frac{0.05}{10^{-2}} = 5\ mm << 15cm$$

So this doesnt work well

$$\text{for } P = 10^{-4}\ Torr \rightarrow \lambda = \frac{0.05}{10^{-4}} = 50cm > 15cm$$

So this works ok. Lower pressure would be even better

      iii) After our thermal evaporation step, the metal layer will not be conformal. Why? What methods can be used to make it more conformal? (List at least three) (3 points)

→ directional deposition is subject to shadowing which is not conformal.

1. Rotate and tilt the substrate
2. raise the substrate temperature
3. use a larger area source

b. For our EE143 chips, we use CVD to deposit phosphorus-doped polysilicon onto the wafer. (13 points)

i) What is the principle chemical reaction happening during this step? (1 point)

$SiH_4 \rightarrow Si + 2H_2$

also $2PH_3 \rightarrow 2P + 3H_2$ (not required)

ii) Why do we choose CVD instead of PVD in this case? (List at least 2 advantages of CVD) (2 points)

1. CVD has better uniformity than PVD

2 It is easy to dope phosporous into polysilicon by in-situ doping in CVD

3 CVD has good conformal coverage, better than CVD.

iii) A CVD process deposition is done at 600 °C with activation energy of 2 eV. The deposition time at 600 °C was found to be 30 min. Assuming the deposition is surface-reaction limited, calculate the deposition time needed for the same thin film thickness at 650 °C. (5 points)

Surface reaction limited: $R \propto e^{-E_A/kT}$

$$\frac{R(650)}{R(600)} = \frac{\exp\left(-\frac{2eV}{k}\frac{1}{923}\right)}{\exp\left(-\frac{2eV}{k}\frac{1}{873}\right)}$$

$$= \exp\left[\left(-\frac{3.2\times10^{-19}J}{1.38\times10^{-23}J/k}\right)\left(\frac{1}{923}-\frac{1}{873}\right)\right]$$

$$\simeq 4.22 \rightarrow t = \frac{30\,min}{4.22} \simeq \underline{7.12\,min}$$

iv) Redo (iii) assuming the deposition is mass-transport limited. (5 points)

Mass transport limit

$$R \propto T^{3/2}$$

$$\left(\frac{923}{873}\right)^{3/2} = 1.087$$

$$t = \frac{30 \text{ min}}{1.087} = \underline{27.6 \text{ min}}$$

**2.** Predeposition and Drive-in Design (30 points)

Design a two-step predeposition and drive-in diffusion for a pn junction made by diffusing phosphorous into a p-type wafer (background concentration $N_B$). Target junction depth is $x_j$ and the surface concentration is $N_S$. The predeposition is to be done at 900°C and the drive-in at 1150°C. (Use diffusion coefficient parameters prefactor $D_0$, and activation energy $E_A$.)

a. Show exactly how to calculate the drive-in time required. Assume the predeposition creates a delta function dopant distribution at the surface. You must show what equations you would use and any assumptions that you need to make. The final equation you show should be in the form of t = [ ], but you do not need to combine all expressions into one single equation. In other words, you can show how to calculate one or more parameters first, then use them in your equation for t. (10 points)

First calculate diffusion coefficient, $D_{di}$, for drive-in

$$D_{di} = D_0 e^{-E_A/kT_{di}}$$

use $T_{di} = 1150C$, or $1423 K$

The drive-in step is limited source diffusion!

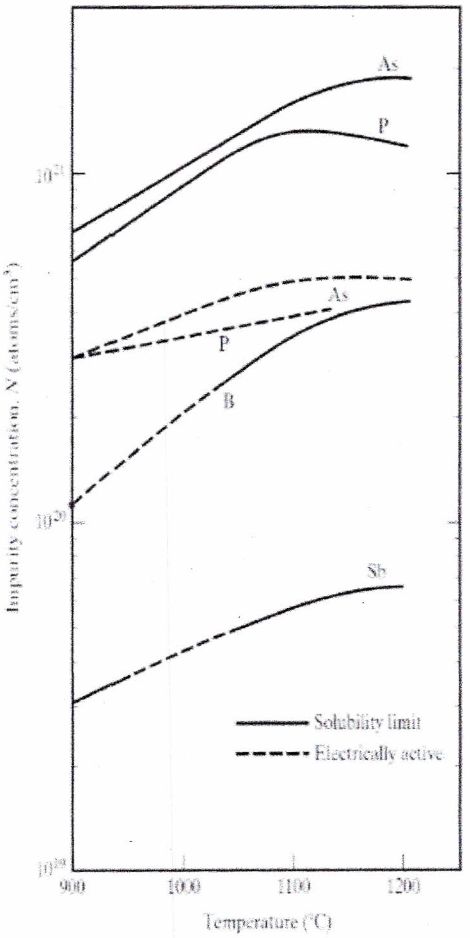
$$N(x,t) = N_s \exp\left[-\left(\frac{x}{2\sqrt{D_{di}t}}\right)^2\right]$$

at the junction, $x = x_j$, $N = N_B$

solve for $t$,

$$\boxed{t = \frac{x^2}{4D_{di}\ln(N_S/N_B)}}$$

b. In a similar fashion, show how to calculate the deposited dose and the predeposition time required. You need to show an expression for dose, Q = [ ], and predep time t = [ ]. (Use the solid-solubility curve given below.) (10 points)



The deposited dose is calculated from the integrated diffused-in profile.

$$N_S = \frac{Q}{\sqrt{\pi D_{di} t}}$$

so,

$$\boxed{Q = N_S \sqrt{\pi D_{di}}}$$

Now calculate predep time to get this dose.

The diffusion coefficient at the predeposition temperature:

$$D_{pd} = D_o e^{-E_A/kT_{pd}}$$ use $T_{pd} = 900C = 1173K$

The predep step is for constant source diffusion

$$Q = 2N_o\sqrt{\frac{D_{pd}t}{\pi}}$$

solve for t

$$\boxed{t = \frac{\pi}{D_{pd}}\left(\frac{Q}{2N_o}\right)^2}$$ use Q from above

$N_o$ is the solid solubility of P at 900C

From the plot, $N_o \cong 5 \times 10^{20}\ cm^{-3}$

c. Assuming a constant solid-solubility limit for temperatures below 900°C, show how to calculate what predeposition temperature would be required in order for a predeposition time of 10min. (10 points)

Use equation from part b, solve for $D_{pd}$:

$$D_{pd} = \frac{\pi}{t}\left(\frac{Q}{2N_o}\right)^2$$

Use the new $D_{pd}$ to calculate T from

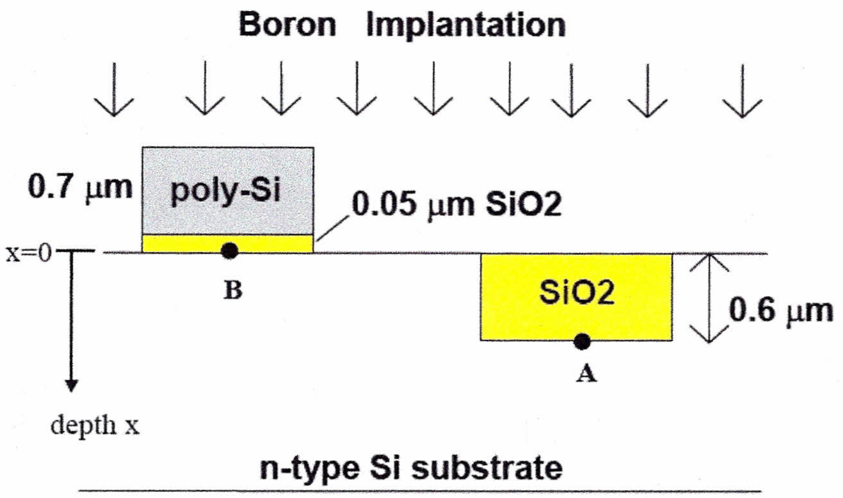
$$D_{pd} = D_o e^{-E_A/kT}$$

solve for T:

$$\boxed{T = \frac{E_A}{k \ln(D_o/D_{pd})}}$$

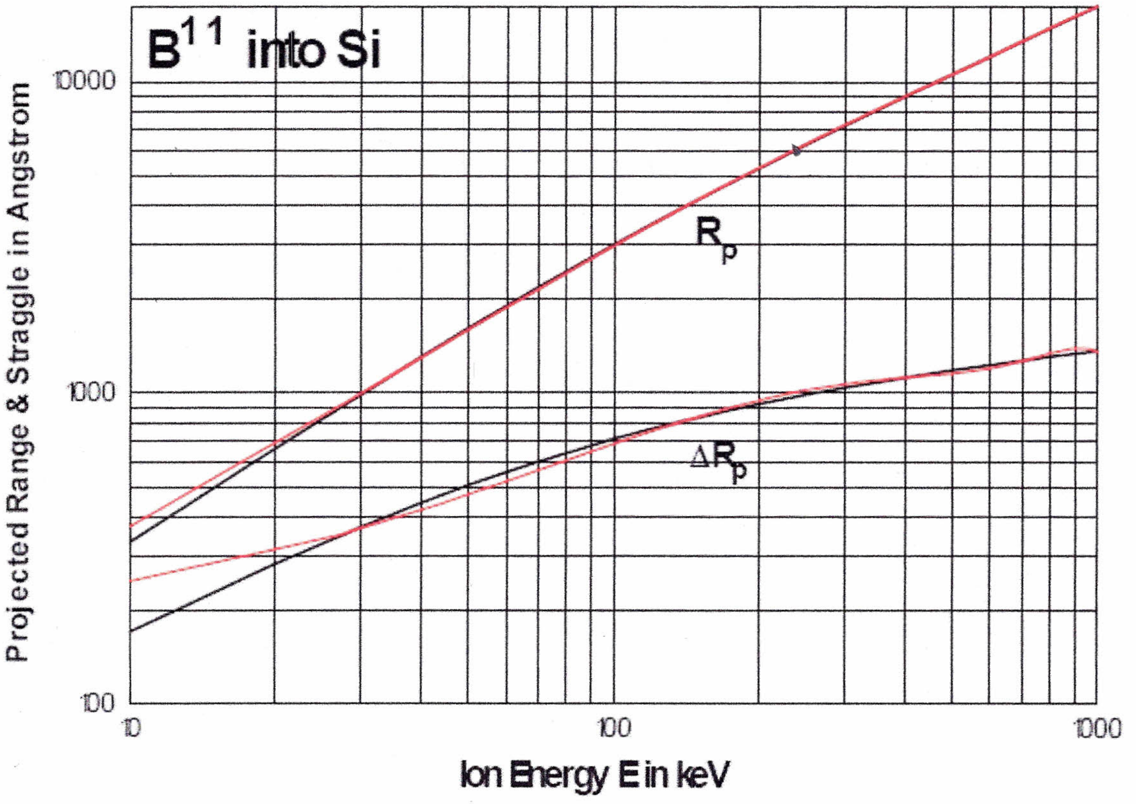
3. Ion Implantation (20 points)

Boron implantation (using B+ ions) is performed on the following structure to a boron dose of $10^{13}/\text{cm}^2$. The B+ ion energy is chosen such that the **boron concentration at Location A is a maximum**. For simplicity, let us assume the ion stopping powers and ion scattering characteristics are identical for both silicon and silicon dioxide.



Answer the following questions using the graph below. Calculate your answers to 2 significant digits.

$$R_p = 51.051 + 32.60883\,E - 0.03837\,E^2 + 3.758\text{e-}5\,E^3 - 1.433\text{e-}8\,E^4$$
$$\Delta R_p = 185.34201 + 6.5308\,E - 0.01745\,E^2 + 2.098\text{e-}5\,E^3 - 8.884\text{e-}9\,E^4$$



a. What B+ ion energy should you should choose? (6 points)

We need $R_p = 0.6\,\mu m$ From the graph, $\boxed{E = 235\,keV}$

b. Calculate the maximum boron concentration at Location A? (8 points)

The distribution of implanted dopant is given by a Gaussian function.

The relation between dose and peak concentration is

$$Q = \sqrt{2\pi}\, N_p \Delta R_p$$

From the graph, $\Delta R_p = 100\,nm$. So

$$N_p = Q/\sqrt{2\pi}\,\Delta R_p = \frac{10^{13}\,cm^{2}}{2.5 \cdot 10^{-5}\,cm} = \boxed{4 \times 10^{17}\,cm^{-3}}$$

c. Now, let us consider ion channeling effect. Will you expect a longer channeling tail in the crystalline silicon substrate underneath Location A or Location B? Write down your reasoning. (6 points)

If the ion stopping power and scattering characteristics are the same for Silicon and silicon dioxide, then A has less scattering than B because the total thickness is less (0.6 μm vs 0.75 μm). So the channeling tail will be longer at location A.

**4.** Metallization (25 points)

a. List two benefits of using chemical mechanical polishing for multilevel metal process integration. (4 points)

1. Reduced depth of focus requirement
2. Reduced overetch time due to steps (no stringers)
3. Improved step coverage for film deposition.

b. Assume copper has an electromigration failure activation energy $E_A = 0.66$ eV. The activation energy for aluminum is $E_A = 0.5$ eV. If the same MTF was desired between Cu and Al lines, how much more current density can be passed through Cu lines over Al lines at 400K? (4 points)

$$MTF \propto J^{-2} \exp\left[E_A/kT\right]$$

at 400C, $kT = 0.0347\,eV$

$$\frac{J_{Cu}^{-2}\, e^{0.66/0.0347}}{J_{Al}^{-2}\, e^{0.5/0.0347}} = 1$$

$$\frac{J_{Cu}}{J_{Al}} = \sqrt{\frac{e^{0.66/.0347}}{e^{0.5/.0347}}} = \boxed{10}$$

c. Copper has lower resistivity and less susceptibility to electromigration failure. However, it is also a deep-level impurity that can destroy MOS devices. How do we prevent Cu contamination once the metal lines are formed? (2 points)

Use a diffusion barrier, such as TiN.

d. How does adding a small (1-4%) of Cu impurity improve the electromigration resistance of Al? (2 points)

The Cu segregates to the grain boundaries, forming $AlCu_3$ alloy precipitates. These block grain boundary diffusion, which is the cause of electromigration