Fall 2000

UNIVERSITY OF CALIFORNIA
College of Engineering
Department of Electrical Engineering and Computer Sciences

EE143 Midterm Exam #1

Family Name ________________________ **First name**____________________________

Signature____

Make sure the exam paper has 8 pages plus an appendix page at the end.

Instructions: DO ALL WORK ON EXAM PAGES
This is a 90-minute exam (3 sheets of notes allowed)

Grading: To obtain full credit, show correct units and algebraic sign in answers.
Numerical answers which are orders of magnitude off will receive no partial credit.

Problem 1 (20 points)________________

Problem 2 (25 points)_______________

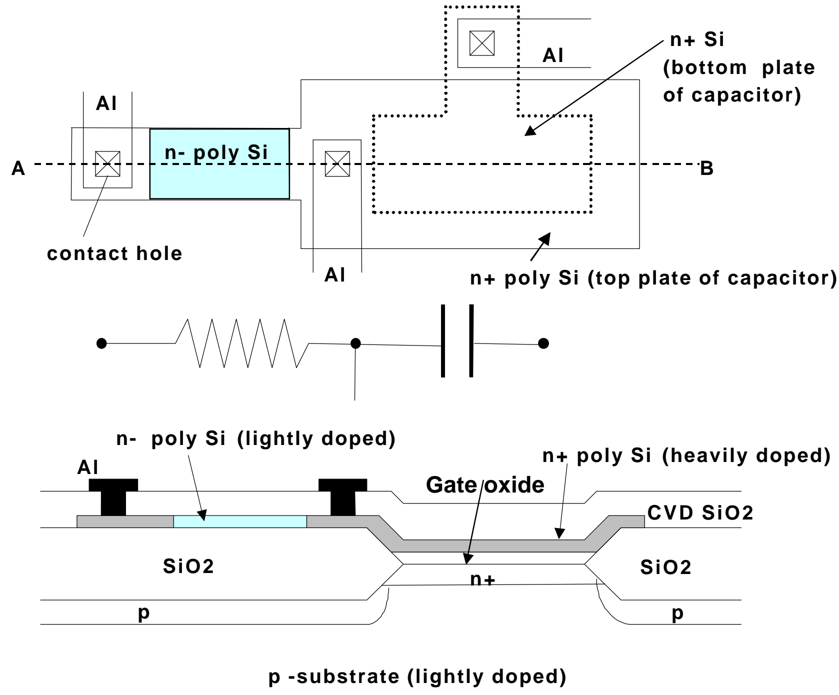
Problem 3 (30 points) ________________

Problem 4 (25 points) ________________

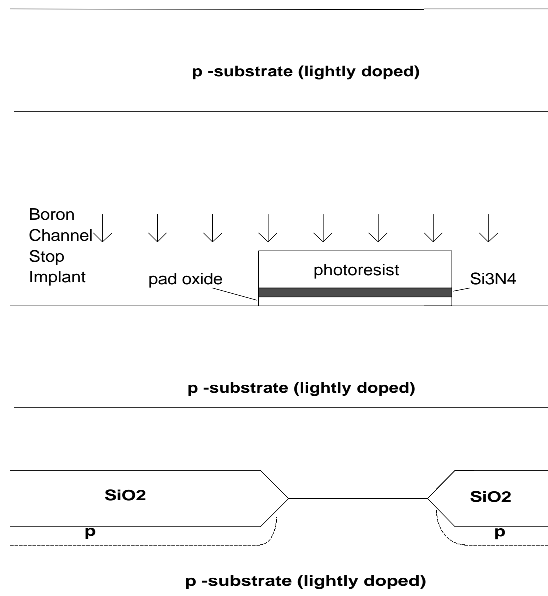
TOTAL (100 points) __________________

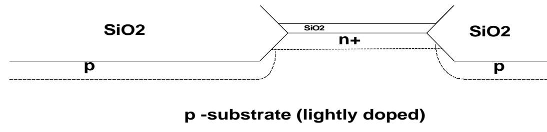
Problem 1 Process Sequence Description (20 points total)

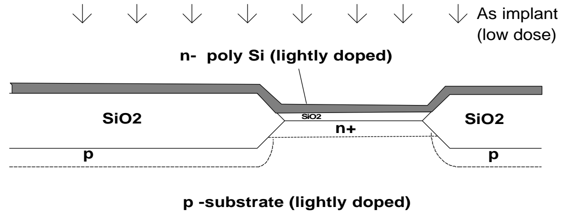
We would like to implement a simple RC low-pass filter in integrated form. The top view, the equivalent circuit, and the cross-section along line AB are shown below. The resistor body is lightly doped (n^-) poly-Si and the top capacitor plate of is heavily doped (n^+) poly-Si . Cross-sections along AB after major processing steps are sketched in the right column of the table shown below. **Fill in the sequence of process steps used in the left column.**

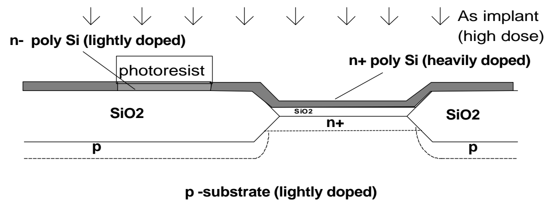


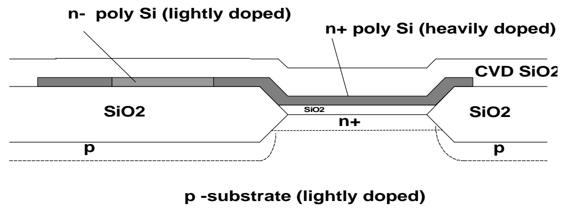
Process Description	Cross Section along AB
1) Starting wafer, p- Si	

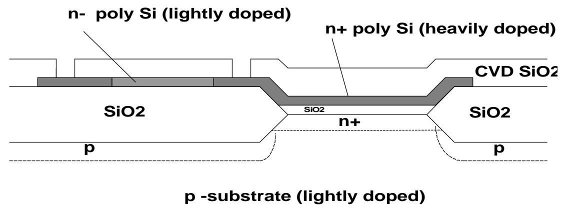


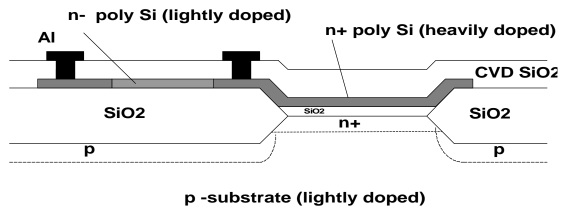

SiO2
SiO2
n+
SiO2
p
p
p -substrate (lightly doped)


As implant
(low dose)
n- poly Si (lightly doped)
SiO2
SiO2
SiO2
n+
p
p
p -substrate (lightly doped)


As implant
(high dose)
n- poly Si (lightly doped)
photoresist
n+ poly Si (heavily doped)
SiO2
SiO2
SiO2
n+
p
p
p -substrate (lightly doped)


n- poly Si (lightly doped)
n+ poly Si (heavily doped)
CVD SiO2
SiO2
SiO2
SiO2
n+
p
p
p -substrate (lightly doped)


n- poly Si (lightly doped)
n+ poly Si (heavily doped)
CVD SiO2
SiO2
SiO2
SiO2
n+
p
p
p -substrate (lightly doped)


n- poly Si (lightly doped)
Al
n+ poly Si (heavily doped)
CVD SiO2
SiO2
SiO2
SiO2
n+
p
p
p -substrate (lightly doped)

Problem 2 Thermal oxidation (25 points total)

(a) (10 points) For a particular oxidation process, it is known that the oxidation rate (dx_{ox}/dt) is 0.48µm /hour when the oxide thickness is 0.5 µm and it slows down to 0.266 µm /hour when the oxide thickness is 1 µm. Find the linear oxidation constant (B/A) and the parabolic oxidation constant B. Give answers in proper units.

(b) (15 points) A lightly doped Si wafer has been processed by some unknown IC processing steps.

You then perform a thermal oxidation experiment [fixed temperature and fixed oxidizing ambient] with this wafer and observed the following oxide growth results:

Oxidation Time	SiO2 Thickness
0 hour	0
1 hour	2000 Å
4 hours	2500 Å

Are the following conjectures TRUE or FALSE ? You have to give brief explanations to justify your answers.

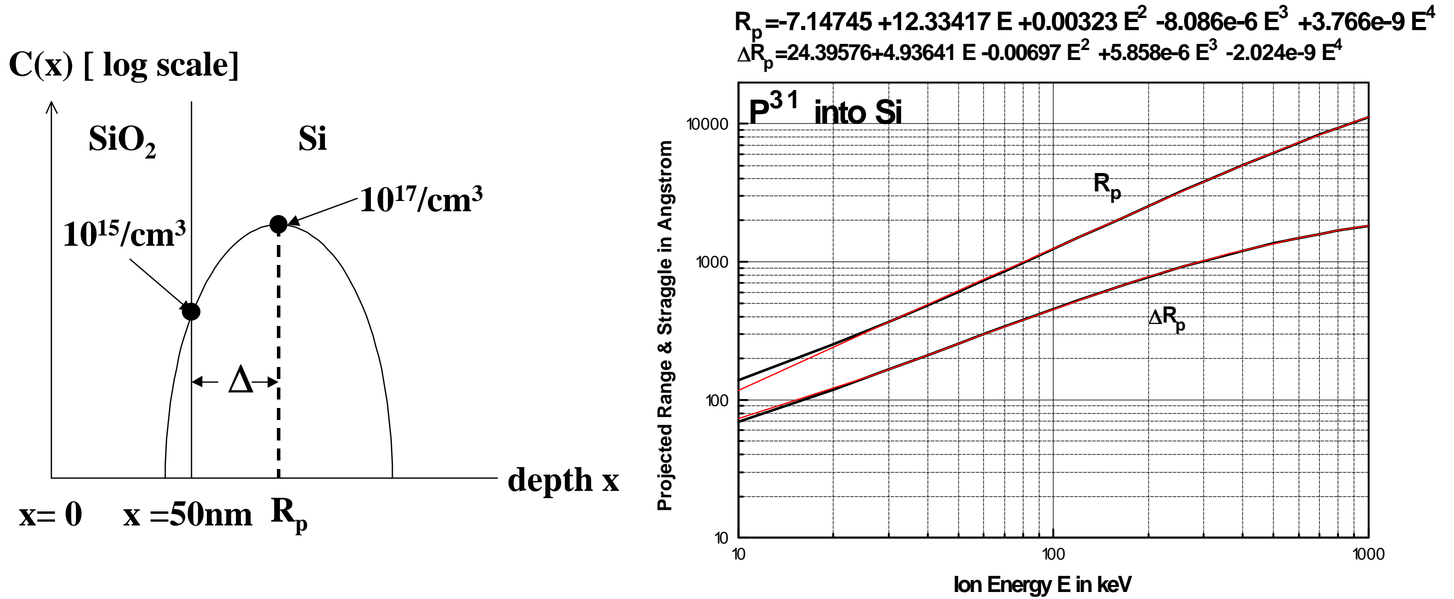
Conjecture 1 : The processed Si wafer was oxidized first to an oxide thicknes of 100 **Å** and then have the oxide dissolved in HF.

Conjecture 2 : The processed Si wafer has a highly doped surface layer (doping > $10^{19}/cm^3$) which is less than 1000 Å thick.

Conjecture 3: The processed Si wafer has a thin layer of poly-Si layer on top surface.

Problem 3 Ion Implantation (30 points total)

(a) Phosphorus ions are implanted through 50nm of SiO_2 into an underlying silicon substrate. Design an implantation step which will give the following phosphorus profile which has a peak concentration of $10^{17}/cm^3$ and a concentration of $10^{15}/cm^3$ at the Si/SiO_2 interface. Assume the stopping power of SiO_2 is the same as silicon.



(i) Express the distance Δ in terms of the straggle ΔR_p of the implant profile.

(ii) Choose the required approximate energy for the Phosphorus ions.

(iii) Calculate the dose required.

Problem 3 continued

(b) (15 points) To form the source/drain regions of a state-of-the-art MOSFET by in ion implantation followed by an annealing step, it is required to have (1) very shallow junction depths x_j ; **AND** (2) very low sheet resistance R_S.

(i) Discuss two major physical mechanisms which limit the formation of ultra-shallow junction depths.

(ii) Discuss one major physical mechanism which limits the formation of low sheet resistance source/drain layers.

(iii) Discuss the difficulty to satisfy both the shallow junction depths x_j AND low sheet resistance R_S requirements.

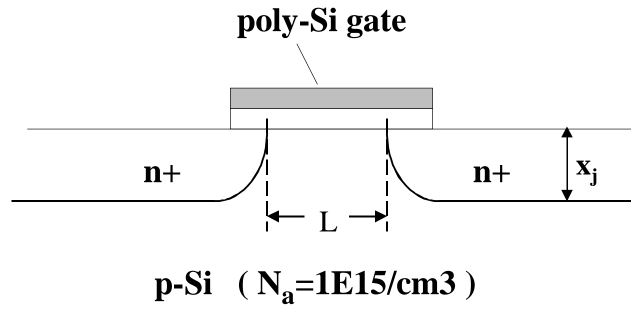
Problem 4 Diffusion (25 points total)

(a) (10 points)
A boron predeposition step is performed into an n-type Si substrate with a background concentration C_B of $1 \times 10^{15}/cm^3$. The predeposition thermal cycle is 975 °C for 60 minutes.
Given: Boron solid solubility at 975 °C = $3.5 \times 10^{20}/cm^3$
Boron diffusion constant at 975 °C = 1.5×10^{-14} cm^2/sec

(i) Calculate the junction depth x_j.

(ii) Calculate the incorporated boron dose Q.

(b) (10 points) You are faced with the following three choices for forming the source and drain of a NMOS transistor.



(Process i) Shallow diffusion predeposition dose of Q phosphorus atoms /unit area , followed by a drive-in at 1100°C for 60 minutes.
(Process ii) Shallow diffusion predeposition dose of Q phosphorus atoms /unit area , followed by a drive-in at 1150°C for 30 minutes.
(Process iii) Shallow implantation dose of Q phosphorus atoms / unit area , followed by an anneal at 950°C for 10 minutes
Use the following diffusivity values:

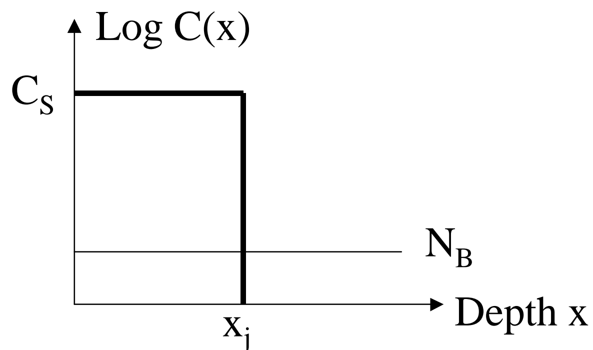
TEMPERATURE	D(Phosphorus)
950°C	5×10^{-5} μm^2 / min
1100°C	2×10^{-3} μm^2 / min
1150°C	5×10^{-3} μm^2 / min

Problem 4 continued

(i) Which process will give the shortest MOSFET channel length L ? Justify your answer.

(iii) If the substrate doping is increased from 1×10^{15} to 1×10^{16} boron atoms /cm^3 , which of the three processes will exhibit the **greatest change in channel length** ? Explain your reasoning.

(c) (5 points) For *high-concentration* Arsenic drive-in diffusion, the diffusion depth profile is approximately rectangular with a peak concentration equals to the solid solubility C_S. Qualitatively plot the Irvin Curve [i.e., log C_S versus log (R_S x_j)] for low background concentrations N_B. What is the vlaue of the slope for this plot? Show your derivations.



APPENDIX for Midterm #1

$$\textbf{erf}(z) = \frac{2}{\sqrt{\pi}} \int_0^z e^{-y^2}\,dy \qquad \textbf{erfc}(z) \equiv 1 - \textbf{erf}(z)$$

$\text{erf}(0) = 0 \qquad \text{erf}(\infty) = 1 \qquad \text{erf}(-\infty) = -1$

$\text{erf}(z) \approx \frac{2}{\sqrt{\pi}} z$ for $z \ll 1$ $\qquad$ $\text{erfc}(z) \approx \frac{1}{\sqrt{\pi}} \frac{e^{-z^2}}{z}$ for $z \gg 1$

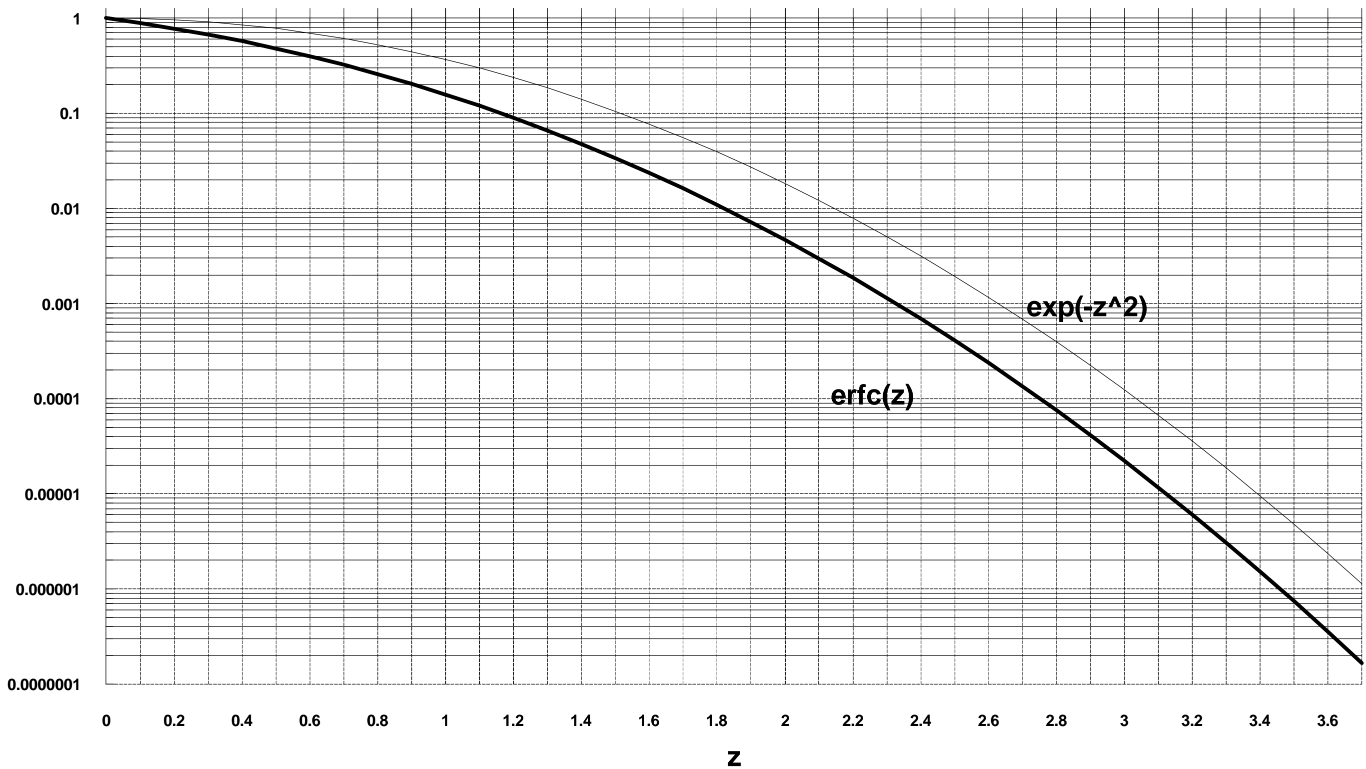
$$\frac{d\,\text{erf}(z)}{dz} = -\frac{d\,\text{erfc}(z)}{dz} = \frac{2}{\sqrt{\pi}} e^{-z^2}$$

$$\int_0^z \text{erfc}(y)dy = z\,\text{erfc}(z) + \frac{1}{\sqrt{\pi}}(1 - e^{-z^2}) \qquad \int_0^\infty \text{erfc}(z)dz = \frac{1}{\sqrt{\pi}}$$

The value of erf(z) can be found in mathematical tables, as build-in functions in calculators and spread sheets. If you have a programmable calculator, you may find the following approximation useful (it is accurate to 1 part in 10^7): $\text{erf}(z) = 1 - (a_1 T + a_2 T^2 + a_3 T^3 + a_4 T^4 + a_5 T^5)\, e^{-z^2}$

where $T = \frac{1}{1 + P z}$ and $P = 0.3275911$

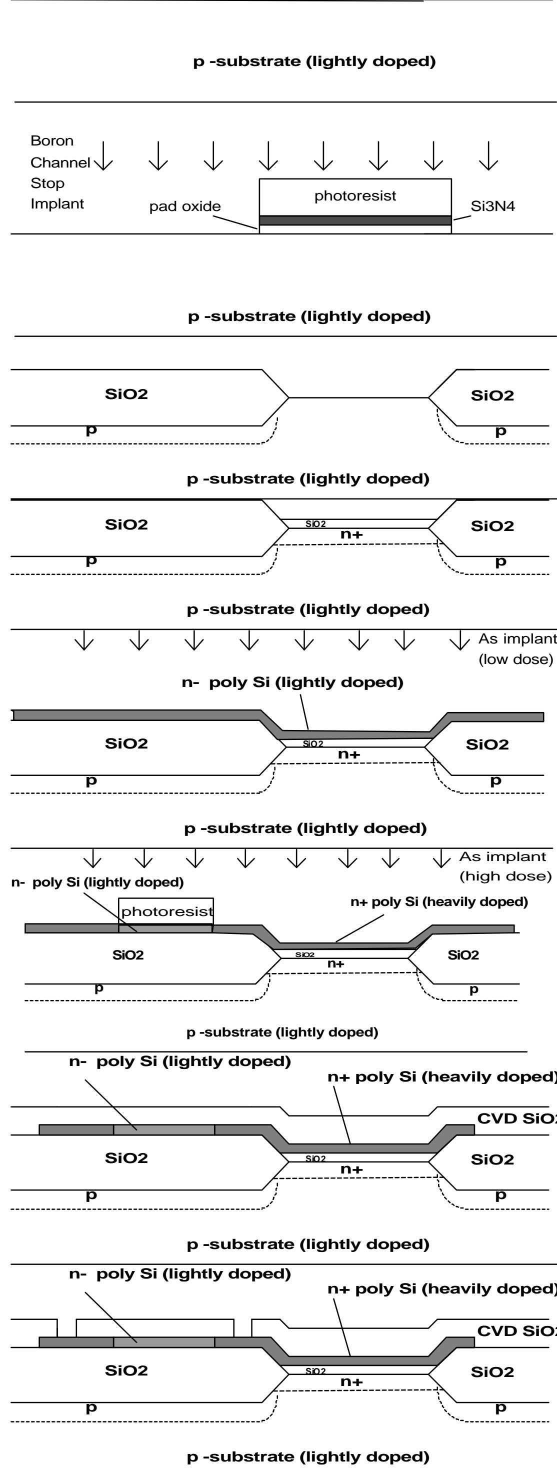
$a_1 = 0.254829592$ $\quad a_2 = -0.284496736$ $\quad a_3 = 1.421413741$ $\quad a_4 = -1.453152027$ $\quad a_5 = 1.061405429$



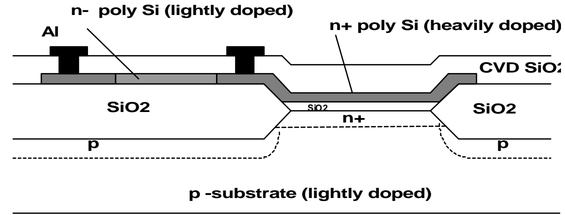
EE143 Midterm #1 Solutions **Fall 2000**

Problem 1

Process Description	**Cross Section along AB**
1) Starting wafer, p- Si	
2) Pad oxide growth Si_3N_4 deposition Active area patterning (Mask #1) Channel stop Boron implantation Remove photoresist	
3) Local oxidation to grow field oxide Strip Si_3N_4 Strip pad oxide (chemical dip)	
4) As implantation to form n^+ in active region Gate oxide oxidation	
5) Undoped poly-Si deposition Blanket As implant (low dose) to form n^- poly-Si	
6) Masking resistor region with photoresist (Mask #2) As implantation (high dose) to form n^+poly-Si	
7) Pattern poly-Si (Mask #3) Deposit CVD SiO_2 Diffuse and activate dopants in poly-Si with short time annealing (≈ 900°C)	
8) Metal contact opening (Mask #4)	



9) Al deposition
Al interconnect patterning (Mask #5)



Problem 2

(a) From the Grove model, we have : $x_{ox}^2 + Ax_{ox} = B(t+\tau)$

Therefore,

$$2x_{ox}\frac{dx_{ox}}{dt} + A\frac{dx_{ox}}{dt} = B$$

or $\frac{dx_{ox}}{dt} = \frac{B}{A+2x_{ox}}$

From $0.48 = \frac{B}{A+0.5\times 2}$ and $0.266 = \frac{B}{A+1\times 2}$, we get

A=0.243 μm , B= 0.597 μm^2/hour and B/A = 2.46 μm/hour

(b) The observed indicates the growth rate is slower than the Deal-Grove model after 2000 Å of oxide is grown. Even if we take the limit that growth rate is proportional $(time)^{1/2}$, the oxide will be thicker than 4000 **Å** after 4 hours of oxidation. The Si surface layer must have a faster oxide rate than the bulk of the wafer.

***Conjecture 1* :** The processed Si wafer was oxidized first to an oxide thickness of 100 Å and then have the oxide dissolved in HF. **FALSE**
Dopant segregation can enhance oxidation rate but the small oxide growth cannot change the surface layer dopant concentration due to dopant segregation.

Conjecture 2 : The processed Si wafer has a highly doped surface layer (doping > $10^{19}/cm^3$) which is less than 1000 Å thick. **TRUE**
The Si wafer has a highly doped surface layer ($N > 10^{19}/cm^3$) which is less than 1000 Å thick (i.e., 0.46 × 2000 Å ≈1000 Å). The underneath substrate is lightly doped. The Si wafer has a highly doped region underneath a lightly doped surface region. Oxidation rate is higher when the doping concentration is higher than $10^{19}/cm^3$, mainly through the linear term B/A. After this layer of highly doped Si is consumed, the growth rate slows down.

Conjecture 3 : The processed Si wafer has a thin layer of poly-Si layer on top surface. **TRUE**
Initial oxidation of poly-Si is very fast. After poly-Si is all consumed, the oxidation rates slows down.

Problem 3

(a)

(i) $N_p \exp[\frac{-(\Delta)^2}{2(\Delta R_p)^2}] = N_B$

Let $z = \frac{\Delta}{\sqrt{2}\,\Delta R_p}$, $\exp[-z^2] = 10^{-2}$ implies z = 2.15 from gaussian chart.

Therefore , $\Delta = 2.15 \times\sqrt{2}\times\Delta R_p = 3.04\ \Delta R_p$

(ii) The required phosphorus energy has to satisfy R_p= 500 Å+ 3.04 ΔR_p
From the R_p and ΔR_p curves, an energy of ~300keV will satisfy this condition with
Rp = 3600 Å and ΔR_p= 1000 Å

(iii) $N_p = \frac{0.4 \times \phi}{\Delta R_p}$

Dose $\phi = \frac{10^{17} \times 10^{-5}}{0.4} = 2.5 \times 10^{12}/cm^2$.

(b)

(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) Transient Enhanced Diffusion---
The excess point defects created by ion implantation will enhance dopant diffusion , creating deeper junction depths than desired. There is no established technology yet to eliminate these effect. One possibility is to co-implant Ge or C into the S/D regions which sink the excess point defects.

(ii) 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 for a given junction depth.

(iii) The sheet resistance is inversely proportional to the area under the concentration profile curve. 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 activate all the implanted dopants or completely restore the crystal damage. Implanting a very high dose of dopant will increase the height of the dopant profile (i.e., lowers R_S) but we are limited by the solid solubility.

Problem 4

(a)

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

$3.5 \times 10^{20} \operatorname{erfc}\left[\frac{x_j}{2\sqrt{Dt}}\right] = 10^{15} \Rightarrow \frac{x_j}{2\sqrt{Dt}} = \operatorname{erfc}^{-1}(2.9 \times 10^{-6}) = 3.3$

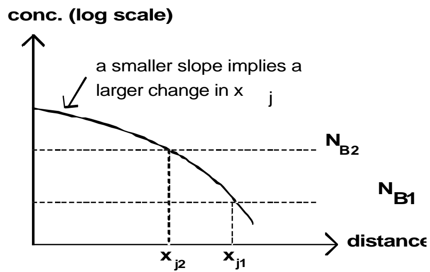
Since $2\sqrt{Dt} = 1.47 \times 10^{-5}$ cm , $x_j = 1.47 \times 10^{-5} \times 3.3 = 0.49\ \mu m$

(ii) $Q = \frac{2C_S\sqrt{Dt}}{\sqrt{\pi}} = \frac{1.47 \times 10^{-5} \times 3.5 \times 10^{20}}{1.77} = 2.9 \times 10^{15}/cm^2$

(b) The lateral junction depth is proportional to the vertical junction depends on Dt product.
(i) $\sqrt{Dt}$ of (ii) $>$ $\sqrt{Dt}$ of (i) $>$ $\sqrt{Dt}$ (iii)

$\therefore$ Process (ii) has the largest lateral diffusion
$\therefore$ Process(ii) gives shortest MOSFET channel.

(ii)

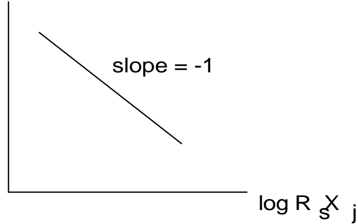


Since the dose Q is the same, a lager $\sqrt{Dt}$ implies a smaller slope (i.e., more dopant spread-out)

$\therefore$ Process (ii) gives the greatest change in channel length

(c)

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