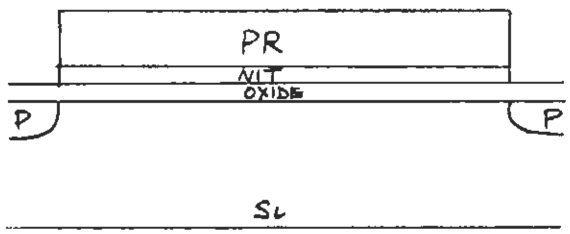
3.155J / 6.152J

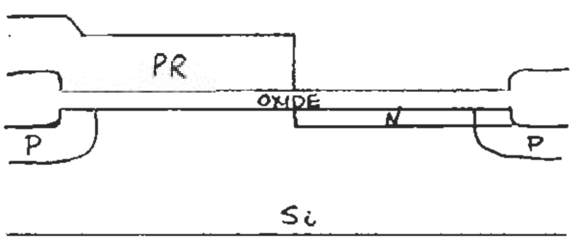
Fall 2005

HW #8 - Solutions

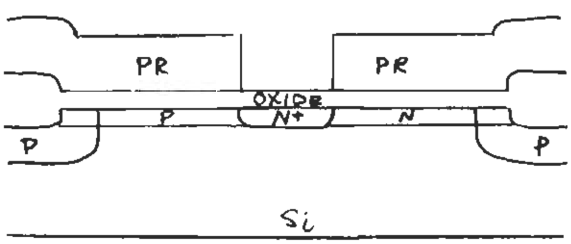
① Process Flow for E/D NMOS (there are many correct solutions)



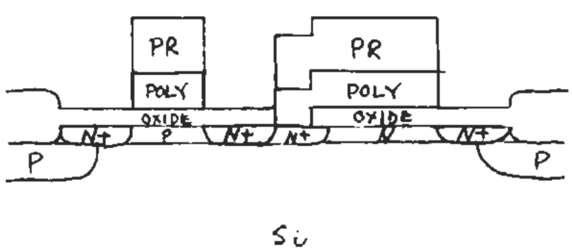
- Clean wafer, grow thin oxide, followed by low stress nitride deposition.
- Spin resist, pattern regions for the field adjustment implants and for LOCOS
- Implant with Boron to form the field adjustment implants shown



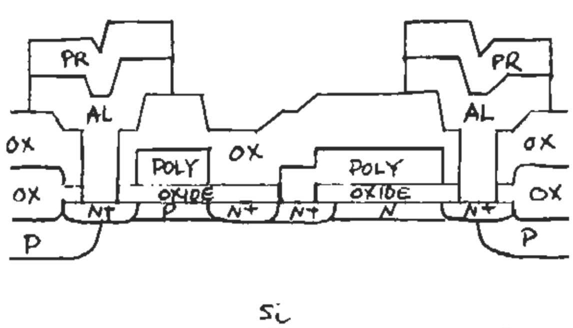
- Strip photoresist with Piranha or O_2 plasma
- Wet oxidation to create thick oxide for LOCOS isolation and field implant drive-in.
- Strip nitride using a Dry Etch or a wet, hot phosphoric acid strip.
- Spin resist, pattern region for threshold implant
- Implant Phosphorus first due to slower diffusivity.



- Strip photoresist, anneal to repair oxide and to drive in N-region (inert atmosphere)
- Spin resist, pattern other threshold implant.
- Implant Boron to form p-region, strip the resist, anneal to repair oxide and drive-in dopant.
- Spin and pattern resist for the depletion drain
- Implant Phosphorus to form depletion drain.



- Strip photo resist, spin new resist and pattern poly-drain contact hole.
- Dry etch or wet etch oxide for contact.
- Strip resist and use LPCVD to grow POLY.
- Spin resist and pattern the gate regions
- Dry etch the POLY to form gates as shown.
- Implant Phosphorus to form self-aligned source/drains.



- Strip photo resist and deposit thick oxide utilizing PECVD @ 400°C.
- Anneal thick oxide and drive in source/drains.
- Spin photo and pattern metal contact holes.
- Dry etch or wet etch away oxide for contact
- Strip photo resist and sputter/evaporate Al.
- Spin photo and pattern the electrical contacts
- Dry etch or wet etch away unwanted Al.

- Final step is to strip photoresist.

② Substrate doping is 10^{15} cm^{-3}. Source and drain have surface concentration of 10^{20} cm^{-3} and junction depth of 0.5 µm. Threshold adjustment implants should have surface concentration of 10^{17} cm^{-3} and junction depth of 0.5 µm.

(i) Gate oxide grown first: 25 nm, utilize dry oxidation

⇒ Dry O_2 atmosphere @ 1000°C (assume no initial oxide)

Deal-Grove: $(0.025)^2 + 0.165(0.025) = 0.0117(t + 0.37)$

$t = 0.036$ hours → 2.16 minutes.

⇒ note that this time is a little too close for comfort. We would opt to use a lower temperature but the parameters given in Campbell for 800°C and 920°C would give negative values. This is because A, B, and τ are approximate, empirical values. Looking at Lecture 3, the dry oxidation chart, we see that @ 900°C, 25 nm will take ~ 1.5 hours to grow.

LOCOS oxide growth: 0.75 µm, relatively thick, use wet oxidation

⇒ Wet O_2 atmosphere @ 640 torr, 1100°C (initial oxide of 25 nm)

Deal-Grove: $(0.75)^2 + 0.11(0.75) = 0.510(t + \tau)$

$t = 1.265$ hours

$\tau = \frac{0.025^2 + 0.11(.025)}{0.510} = .0066$ (negligible)

(ii) To calculate the implant doses, we need to make a few simplifying assumptions about the profiles. There are computer simulators which can assist with the exact calculation but for the purpose of this HW, we will just apply what has been learned in class.

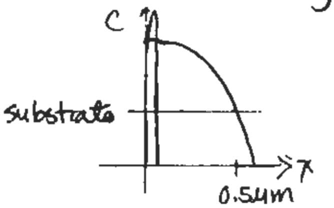
⇒ the following solutions will neglect electric field modified diffusivities as well as doping concentration modifications. (keeps life a tad simpler)

⇒ We can have two assumptions for the doping profile; one assumes that the implant is a delta function and the oxide-silicon interface is perfectly reflecting, the other assumes that we always have a perfect gaussian distribution and that the oxide-silicon interface is NOT perfectly reflecting.

(iii) The choice in assumptions will determine the anneal times and temperatures needed to drive in the implants. Calculations making both assumptions will be shown below. You need to keep in mind the thermal history of the process. A later drive-in will also drive in previous implants further.

(iv) The anneal steps have been included in the process flow of Problem 1. Modifications might include whether to implant the N or P threshold implant first. Also, some of the drive-ins mentioned on the flow might not be necessary.

(ii + iii) Assuming δ-function implant and perfectly reflecting boundaries.



⇒ making such an assumption, we will need very low energy implants and a high dosage

$$C(x,t) = \frac{[2Q]}{\sqrt{2\pi L(t)^2}} \exp\left(\frac{-(x-R_p)^2}{2L(t)^2}\right)$$

where $L(t)^2 = \Delta R_p^2 + 2Dt$ where Dt includes all diffusion times experienced.

* note the 2Q due to the assumption of a perfectly reflecting boundary.

- For the threshold adjustment implants, we want:

$$10^{17}\,\text{cm}^{-2} = \frac{2Q}{\sqrt{2\pi L(t)^2}} \exp\left(\frac{-R_p^2}{2L(t)^2}\right) \quad \text{and} \quad 10^{15}\,\text{cm}^{-3} = \frac{2Q}{\sqrt{2\pi L(t)^2}} \exp\left(\frac{-(0.5-R_p)^2}{2L(t)^2}\right)$$

⇒ we can choose the implant energy so that $R_p \ll 0.5\,\mu m$ and ΔR_p will be accordingly small to meet the δ-function approximation.

Dividing both equations: $10^2 = \exp\left(\frac{-R_p^2}{2L(t)^2} + \frac{(0.5-R_p)^2}{2L(t)^2}\right) = \exp\left(\frac{0.5^2 - R_p}{2L(t)^2}\right)$

- Applying the same arguements for the source/drain implants, we have:

$10^5 = \exp\left(\frac{0.5^2 - R_p}{2L(t)^2}\right)$ ⇒ note that R_p and $L(t)^2$ vary depending on the implant specie and the implant conditions

⇒ we need to start in reverse order to keep track of thermal history.

- For source/drain utilize Phosphorus. Assume 30keV ⇒ $R_p \sim 0.05\,\mu m$ and $\Delta R_p \sim 0.018\,\mu m$

$\therefore\ L(t)^2 = \Delta R_p^2 + 2Dt = [\ln(10^5)\cdot 2/(0.5^2 - 0.05)]^{-1} \Rightarrow .008685\,\mu m^2$ and $Dt = .0041805\ \mu m^2$

- For the P-region threshold, utilize Boron @ 10keV ⇒ $R_p \sim 0.05\,\mu m$ and $\Delta R_p \sim 0.03\,\mu m$

$\therefore\ L(t)^2 = \Delta R_p^2 + 2Dt = [\ln(10^2)\cdot 2/(0.5^2 - 0.03)]^{-1} \Rightarrow .021715\,\mu m^2$ and $Dt = .010408\ \mu m^2$

- For the N-region threshold, utilize Phosphorus @ 30keV ⇒ $R_p \sim 0.05\,\mu m$ and $\Delta R_p \sim 0.018\,\mu m$

$\therefore\ L(t)^2 = \Delta R_p^2 + 2Dt = [\ln(10^2)\cdot 2/(0.5^2 - 0.05)]^{-1} \Rightarrow .021715\,\mu m^2$ and $Dt = .010696\ \mu m^2$

⇒ Assuming all anneals/drive-in are conducted in N_2 @ 1000°C we can calculate the drive in times needed.

$D = D_0 \exp\left(\frac{-E_A}{k_B T}\right)$; @ 1000°C, $k_B T = .1098\,eV$ $\quad D_{Boron} = 1.0\exp\left(\frac{-3.5}{.1098}\right) = 1.4334 \times 10^{-14}\ cm^2/sec$

$D_{Phosphorus} = 4.70\exp\left(\frac{-3.68}{.1098}\right) = 1.3077 \times 10^{-14}\ cm^2/sec$

- Source/Drain Phosphorus needs a drive-in time of: $\frac{(.0041805)}{D_{phosphorus}}\left|\frac{cm}{10^4\,\mu m}\right|^2 = 3196.8$ sec ⇒ 53.28 minutes

- P-region threshold adjust needs a TOTAL drive-in time of:

$\frac{(.010408)}{D_{Boron}}\left|\frac{cm}{10^4\,\mu m}\right|^2 = 7261.0$ sec ⇒ 121.02 minute ⇒ 67.74 minutes needed

- N-region threshold adjust needs a TOTAL drive-in time of:

$\frac{(.010696)}{D_{phosphorus}}\left|\frac{cm}{10^4\,\mu m}\right|^2 = 8179.25$ sec ⇒ 136.32 minutes ⇒ 15.3 minutes needed

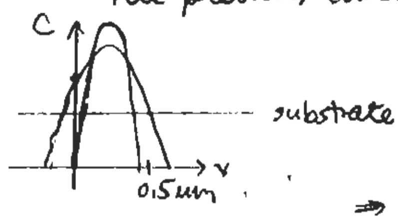
With our known values of $L(t)^2$, we can calculate the dosage Q for each implant using our assumed implant energies.

$$C_{surf} = \frac{2Q}{\sqrt{2\pi L(t)^2}} \exp\left(\frac{-R_p^2}{2L(t)^2}\right) \quad \text{and can check with} \quad C_{sub} = \frac{2Q}{\sqrt{2\pi L(t)^2}} \exp\left(-\frac{(0.5-R_p)^2}{2L(t)^2}\right)$$

- For the source/drain implant of Phosphorus @ 30keV, $R_p = 0.05$ um $Q = 1.35\times10^{15}$ cm^{-2}
- For P-region threshold with Boron @ 10keV, $R_p = 0.05$ um $Q = 1.96\times10^{12}$ cm^{-2}
- For N-region threshold with Phosphorus @ 30keV, $R_p = 0.05$ um $Q = 1.96\times10^{12}$ cm^{-2}

In Summary:	
⇒ Implant Phosphorus @ 30keV with $Q = 1.96\times10^{12}$ cm^{-2} Drive-in @ 1000°C for 15.3 minutes	} N-threshold
⇒ Implant Boron @ 10keV with $Q = 1.96\times10^{12}$ cm^{-2} Drive-in @ 1000°C for 67.74 minutes	} P-threshold
⇒ Implant Phosphorus @ 30keV with $Q = 1.35\times10^{15}$ cm^{-2} Drive-in @ 1000°C for 53.28 minute	} source/drains

(ii + iii) Assuming that the oxide will uptake diffused dopant as is it was an infinite piece of silicon (less accurate than the previous assumption of a δ-function)



⇒ we have $C(x,t) = \frac{Q}{\sqrt{2\pi L(t)^2}} \exp\left(\frac{-(x-R_p)^2}{2L(t)^2}\right)$

where $L(t) = \Delta R_p^2 + 2Dt$

⇒ we conduct similar calculations/arguement as before.

For threshold implants: $10^2 = \exp\left(\frac{0.5^2 - R_p}{2L(t)^2}\right)$
For source/drain implants: $10^5 = \exp\left(\frac{0.5^2 - R_p}{2L(t)^2}\right)$
} But now we choose higher implant energies.

- For source/drain, implant Phosphorus @ 120 keV $R_p = 0.15$ um, $\Delta R_p = \sim 0.052$ um
  $L(t)^2 = \Delta R_p^2 + 2Dt = [\ln(10^5)\cdot 2/(0.5^2 - .15)]^{-1} = .004343$ um^2 and $Dt = 8.195\times10^{-4}$ um^2
- For P-threshold, implant Boron @ 40 keV, $R_p = 0.14$ um, $\Delta R_p = \sim 0.058$ um
  $L(t)^2 = \Delta R_p^2 + 2Dt = [\ln(10^2)\cdot 2/(0.5^2 - 0.14)]^{-1} = .011943$ um^2 and $Dt = 42.895\times10^{-4}$ um^2
- For N-threshold, implant Phosphorus @ 120keV as well.
  $L(t)^2 = \Delta R_p^2 + 2Dt = [\ln(10^2)\cdot 2/(0.5^2 - .15)]^{-1} = .010857$ um^2 and $Dt = 40.765\times10^{-4}$ um^2

Assuming all anneals are conducted in N_2 @ 1000°C

$D_{PHOSPHORUS} = 1.3077\times10^{-14}$ cm^2/sec ; $D_{BORON} = 1.4334\times10^{-14}$ cm^2/sec

- Source/Drain time needed is: 626.67 sec ⇒ 10.44 minutes
- Total P-threshold time needed: 2992.54 sec ⇒ 49.87 minutes.
- Total N-threshold time needed: 3117.30 sec ⇒ 51.96 minutes

∴ P-threshold needs an additional 39.43 minutes and the N-threshold needs an additional 2.09 minutes

Calculate Q by: $C_{surf} = \frac{Q}{\sqrt{2\pi L(t)^2}} \exp\left(\frac{-R_p^2}{2L(t)^2}\right)$; check against $C_{sub} = \frac{Q}{\sqrt{2\pi L(t)^2}} \exp\left(\frac{-(x-R_p)^2}{2L(t)^2}\right)$

- For source/drain Boron, $Q = 2.2028 \times 10^{16}\ cm^{-2}$
- For P-threshold, $Q = 6.2232 \times 10^{12}\ cm^{-2}$
- For N-threshold, $Q = 7.3614 \times 10^{12}\ cm^{-2}$

In Summary:

⇒ Implant Phosphorus @ 120keV with $Q = 7.3614 \times 10^{12}\ cm^{-2}$ } N-threshold
Drive-In @ 1000°C for 2.09 minutes

⇒ Implant Boron @ 40keV with $Q = 6.2232 \times 10^{12}\ cm^{-2}$ } P-threshold
Drive In @ 1000°C for 39.43 minutes

→ Implant Phosphorus @ 120keV with $Q = 2.2028 \times 10^{16}\ cm^{-2}$ } source/drains.
Drive In @ 1000°C for 10.44 minutes

⇒ Keep in mind that second order effects on the diffusivity were neglected and that many assumptions were made regarding the dopant time evolution profile.

⇒ There are many possible solutions with various drive-in temperatures, choice of dopant, and implant energies. One drive-in temperature was used to simplify calculations but it is possible to use various temperatures. One just needs to keep track of the changes in diffusivity.

(ie. $[Dt]_{effective} = D_A t_A + D_B t_B + \ldots$) where D_A is diffusivity at temperature T_A and the drive in was conducted for time t_A