

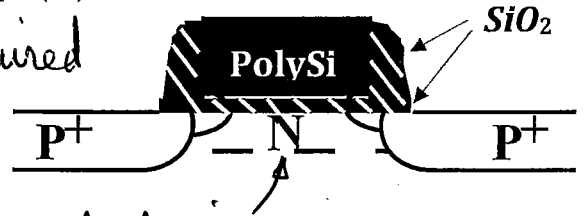
Midterm Exam - EE486

Spring 2017

There are 5 problems on 5 pages, plus a page of tables/plots. Show all your work. Use back of page if needed.

1. Describe a process to fabricate the structure shown below with a minimal number of photolithography steps. Be specific about the nature of the critical deposition and etching steps. (16)

Just one photolithography step is required



- 0) Start with n-type Si wafer
- 1) Predep with P or As to form channel doping
- 2) Drive in channel doping (after removing doping source)
Steps (1) and (2) could be replaced with implant and anneal
- 3) Grow thin thermal oxide for gate dielectric (usually in dry O_2)
- 4) Deposit polysilicon for gate.
- 5) Photolithography process to pattern poly-gate
(apply and expose photoresist, then develop PR and use as mask to etch poly). Note that also removing oxide in S/D regions will make spacer formation easier.
- 6) p-type (Boron) implant to form source and drain extensions. Use low energy to keep shallow. Could also use predep.
- 7) Deposit conformal oxide.
- 8) Etch oxide anisotropically (vertical only), removing oxide from source/drain regions and top of poly, but leaving oxide on sidewall of poly (spacers).
- 9) Implant (or predep) with boron to form p^+ source/drain contact regions.
- 10) Anneal/drive-in to activate boron S/D.

2. Silicon is doped with phosphorus via a predep followed by drive-in.

- (a) If the surface concentration during pre-dep is fixed at $2 \times 10^{20} \text{ cm}^{-3}$ at 1050°C , what would be the time required to get a dose of $2 \times 10^{14} \text{ cm}^{-2}$? Assume constant equilibrium diffusivity appropriate for average P doping of 10^{20} cm^{-3} . (12)

$$n_i = 3.1 \times 10^{16} T^{3/2} \exp\left(-\frac{0.603 \text{ eV}}{kT}\right) \text{ cm}^{-3} = 7.54 \times 10^{18} \text{ cm}^{-3}$$

$$\frac{n}{n_i} = \frac{N_D}{2n_i} + \sqrt{\frac{N_D^2}{4n_i^2} + 1} = 13.34, \text{ where } N_D = 10^{20} \text{ cm}^{-3}$$

$$h = 1 + \frac{N_D}{\sqrt{N_D^2 + 4n_i^2}} = 1.989$$

$$D_p = \left[D_0 + D \frac{n}{n_i} + D \left(\frac{n}{n_i} \right)^2 \right] \times h = 1.989 \times \left[3.85 \times \exp\left(-\frac{3.66}{kT}\right) + 4.44 \exp\left(-\frac{4.0}{kT}\right) \right] \times 13.34 + 44.2 \times \exp(-4.37/kT) \times 13.34^2$$

$$= 5.14 \times 10^{-13} \text{ cm}^2/\text{s}$$

$$Q = \frac{2C_s}{\sqrt{\pi}} \sqrt{D_p t} \Rightarrow D_p t_1 = \left(\frac{Q \sqrt{\pi}}{2C_s} \right)^2 = 7.85 \times 10^{-13} \text{ cm}^2 \Rightarrow t_1 = \frac{D_p t_1}{D_p} = 1.5278 \text{ s}$$

- (b) If the background acceptor doping is $5 \times 10^{18} \text{ cm}^{-3}$, what would be the junction depth for a drive-in of 120 s at 1050°C . Assume constant diffusivity for average P doping of $5 \times 10^{19} \text{ cm}^{-3}$ and assume erfc profile for a given Dt can be approximated by a 1-sided Gaussian with 0.8 Dt. (10)

$$N_D = 5 \times 10^{19} \text{ cm}^{-3} \Rightarrow \frac{n}{n_i} = \frac{N_D}{2n_i} + \sqrt{\frac{N_D^2}{4n_i^2} + 1} = 6.78$$

$$h = 1 + \frac{N_D}{\sqrt{N_D^2 + 4n_i^2}} = 1.957$$

$$D_p = \left[D_0 + D \frac{n}{n_i} + D \left(\frac{n}{n_i} \right)^2 \right] \times h = 1.957 \times \left[3.85 \times \exp\left(-\frac{3.66}{kT}\right) + 4.44 \exp\left(-\frac{4.0}{kT}\right) \right] \times 6.78 + 44.2 \times \exp(-4.37/kT) \times 6.78^2$$

$$= 2.12 \times 10^{-13} \text{ cm}^2/\text{s}$$

$$(Dt)_{\text{total}} = D_p t_1 \times 0.8 + D_p t_2 = 7.85 \times 10^{-13} \text{ cm}^2 \times 0.8 + 2.12 \times 10^{-13} \text{ cm}^2/\text{s} \times 120 \text{ s} = 2.61 \times 10^{-11} \text{ cm}^2$$

$$5 \times 10^{18} \text{ cm}^{-3} = \frac{Q}{\sqrt{\pi(Dt)_{\text{total}}}} \exp\left(-\frac{x^2}{4(Dt)_{\text{total}}}\right) \Rightarrow x = 1.25 \times 10^{-5} \text{ cm} = 0.125 \mu\text{m}$$

3. Arsenic is implanted at 20 keV to a dose of $2 \times 10^{15} \text{ cm}^{-2}$ through a 20nm polysilicon film (same range statistics as Si) on top of a thick Si_3N_4 layer.

(a) What is the peak doping and its location in the poly film? (8)

$$\theta \quad R_p = 15 \text{ nm}, \quad \Delta R_p = 7.5 \text{ nm}$$

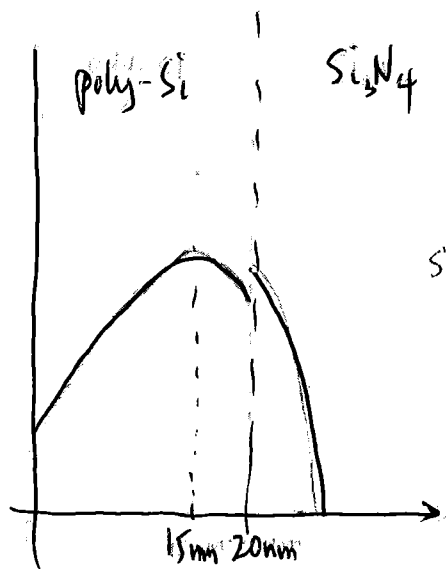
The Peak doping should be in poly silicon for $R_p < 20 \text{ nm}$.

$$C_p = \frac{Q}{\sqrt{2\pi} \Delta R_p} = \frac{2 \times 10^{15} \text{ cm}^{-2}}{\sqrt{2\pi} 7.5 \times 10^{-7} \text{ cm}} = 1.06 \times 10^{21} \text{ cm}^{-3}$$

(b) What dose will end up in the poly-Si film? Sketch the depth profile (10)

The Penetrated dose in the Si_3N_4 layer is $Q_p = \frac{Q}{2} \text{erfc}\left[\frac{20 \text{ nm} - 15 \text{ nm}}{\sqrt{2} 7.5 \text{ nm}}\right]$
 $= 5.05 \times 10^{14} \text{ cm}^{-2}$

The dose ~~is~~ remained in the poly-Si layer is $Q_{\text{poly}} = Q - Q_p = 2 \times 10^{15} \text{ cm}^{-2} - 5.05 \times 10^{14}$
 $= 1.495 \times 10^{15} \text{ cm}^{-2}$



Scaling method is used for the depth profile.
 Since Si_3N_4 is denser than Si, the range and straggle for the implantation are smaller.

More detail can be found in equation (13) and (14) in Supplementary Notes on Ion Implantation.

4. A 100 wafer with an initial 20 nm of oxide grown at the same temperature is oxidized in dry O₂ at 1000 °C.

(a) What would be the initial oxidation rate (include impact of thin oxide kinetics)? (8)

$$\frac{dx_0}{dt} = \frac{B}{2x_0 + A} + C_0 e^{-x_0/L}$$

At $x_0 = 20 \text{ nm} = 0.02 \mu\text{m}$

$$\frac{dx_0}{dx} = \frac{0.0105 \mu\text{m}^2/\text{h}}{2(0.02 \mu\text{m}) + 0.233 \mu\text{m}} + 0.18 e^{-\frac{20}{7 \mu\text{m}}} \left(\frac{B}{A} \right)_{100} = \left(\frac{B}{A} \right)_{111} / 1.68 = \frac{6.23 \times 10^6}{1.68} \exp\left(-\frac{2.0 \text{ eV}}{kT}\right) \frac{\mu\text{m}}{\text{h}}$$

$$= 0.049 \frac{\mu\text{m}}{\text{h}} = \underline{\underline{49 \text{ nm/h}}}$$

$$B_{100}^{\text{dry}} = B_{111}^{\text{dry}} = 772 \exp\left(-\frac{1.23 \text{ eV}}{kT}\right) \frac{\mu\text{m}^2}{\text{h}}$$

$$= 772 \exp\left(\frac{-1.23}{8.62 \times 10^{-5} \frac{\text{eV}}{\text{K}} \times 1273 \text{ K}}\right)$$

$$= 0.0105 \mu\text{m}^2/\text{h}$$

$$C = 3.6 \times 10^8 \exp(-2.35/kT) \mu\text{m}/\text{h}$$

$$= 0.18 \mu\text{m}/\text{h}$$

$$A = B / (B/A) = \frac{0.0105 \mu\text{m}^2/\text{h}}{0.045 \mu\text{m}/\text{h}} = 0.233 \mu\text{m}$$

(b) Estimate the time required to grow an additional 30 nm of oxide. (8)

Growth rate changes as film grows, but oxidation rate with thin oxide kinetics hard to solve after integrating. Estimate by using final oxidation rate ($x_0 = 50 \text{ nm}$)

$$\frac{dx_0}{dt} = \frac{0.0105 \mu\text{m}^2/\text{h}}{2(0.05 \mu\text{m}) + 0.233 \mu\text{m}} + 0.18 e^{-20/7} \frac{\mu\text{m}}{\text{h}} = 0.032 \mu\text{m}/\text{h} = 32 \text{ nm/h}$$

$$\Delta t = \frac{\Delta x}{\frac{1}{2}(49 \frac{\text{nm}}{\text{h}} + 32 \frac{\text{nm}}{\text{h}})} = \frac{60}{81} \text{ h} = 0.74 \text{ h} = \underline{\underline{44.4 \text{ min}}}$$

(c) What would be the average interstitial super/undersaturation in the nearby Si during this oxidation step?

(6)

Average oxidation rate is $30 \text{ nm} / 0.74 \text{ h} = 40.5 \text{ nm/h} = 0.04 \mu\text{m}/\text{h}$

From plot, $\frac{\langle D_p \rangle}{D_p^*} \cong 3.2 = f_I^p \frac{C_I}{C_F} + (1 - f_I^p) \frac{C_I^*}{C_I} \Rightarrow \frac{C_I}{C_I^*} = 3.3$

Using $C_I C_V \cong C_F^* C_V^*$

5.

- (a) How would oxidation impact the electrical activation of arsenic in the underlying silicon (increase, decrease, no change)? Explain. (6)

Oxidation leads to $C_I > C_I^*$, $C_V < C_V^*$

Arsenic deactivates by clustering with vacancies.

Fewer vacancies $\Rightarrow$ fewer clusters $\Rightarrow$ more activation of As

- (b) A boron predep is done with surface concentration near solid solubility. If there was an As buried layer, would its broadening be more, less or the same compared to the same thermal cycle without the B doping source? Explain. (6)

B diffuses almost solely with interstitials. Boron gradient leads to BI gradient and flux of BI into silicon.

As they dissociate, an I excess results (and V undersaturation)

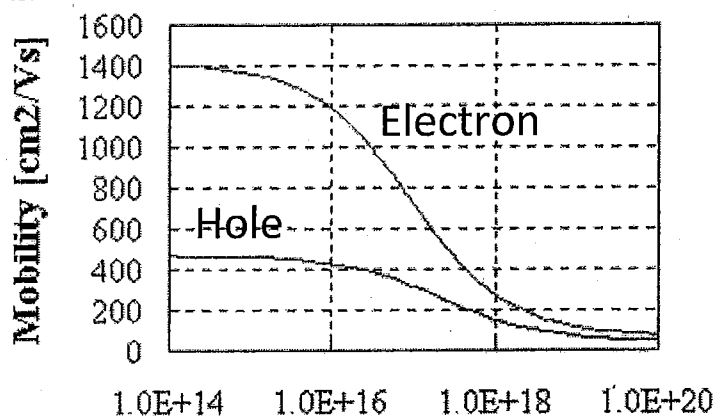
Arsenic diffuses nearly equally with both I and V ($f_I = 0.4$)

As long as $C_I/C_I^* > 1.5$ As diffusion would be enhanced for $C_I C_V = C_I^* C_V^*$, but if $C_I/C_I^* < 1.5$, As diffusion would be retarded (high T or low B concentration).

- (c) If a high dose of Ge is implanted into Si prior to a low dose As implant, how would that effect the resulting implant depth. Explain. (6)

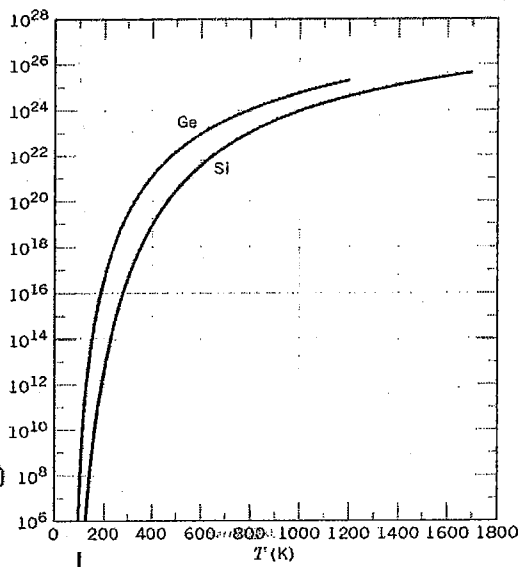
As a heavy ion, Ge is effective at damaging Si due to nuclear stopping. That pre-existing damage would reduce channeling and thus reduce implant depth.

	Si	B	In	As	Sb	P
D ⁰ .0	560	0.05	0.6	0.011	0.214	3.85
D ⁰ .E	4.76	3.5	3.5	3.44	3.65	3.66
D ⁺ .0		0.95	0.6			
D ⁺ .E		3.5	3.5			
D ⁻ .0				31.0	15.0	4.44
D ⁻ .E				4.15	4.08	4.0
D ⁼ .0						44.2
D ⁼ .E						4.37



Doping concentration [cm⁻³]

	f _i	f _v
Silicon	0.6	0.4
Boron	1.0	0
Phosphorus	0.95	0.05
Arsenic	0.4	0.6
Antimony	0.02	0.98



β	$\text{erf}(\beta)$	$\text{erfc}(\beta)$
0	0	1.0
0.05	0.056372	0.943628
0.1	0.112463	0.887537
0.15	0.167996	0.832004
0.2	0.222703	0.777297
0.25	0.276326	0.723674
0.3	0.328627	0.671373
0.35	0.379382	0.620618
0.4	0.428392	0.571608
0.45	0.475482	0.524518
0.5	0.520500	0.479500
0.55	0.563323	0.436677
0.6	0.603856	0.396144
0.65	0.642029	0.357971
0.7	0.677801	0.322199
0.75	0.711156	0.288844
0.8	0.742101	0.257899
0.85	0.770668	0.229332
0.9	0.796908	0.203092
0.95	0.820891	0.179109
1.0	0.842701	0.157299
1.1	0.880205	0.119795
1.2	0.910314	0.089686
1.3	0.934008	0.065992
1.4	0.952285	0.047715
1.5	0.966105	0.033895
1.6	0.976348	0.023652
1.7	0.983790	0.016210
1.8	0.989091	0.010909
1.9	0.992790	0.007210
2.0	0.995322	0.004678
2.1	0.997021	0.002979
2.2	0.998137	0.001863
2.3	0.998857	0.001143
2.4	0.999311	0.000689
2.5	0.999593	0.000407
2.6	0.999764	0.000236
2.7	0.999866	0.000134
2.8	0.999925	0.000075
2.9	0.999959	0.000041
3.0	0.999978	0.000022

Ambient	B (<111>)	B/A (<111>)
Dry O ₂	$C_1 = 7.72 \times 10^2 \mu^2 \text{ hr}^{-1}$ $E_1 = 1.23 \text{ eV}$	$C_2 = 6.23 \times 10^6 \mu \text{ hr}^{-1}$ $E_2 = 2.0 \text{ eV}$
Wet O ₂	$C_1 = 2.14 \times 10^2 \mu^2 \text{ hr}^{-1}$ $E_1 = 0.71 \text{ eV}$	$C_2 = 8.95 \times 10^7 \mu \text{ hr}^{-1}$ $E_2 = 2.05 \text{ eV}$
H ₂ O	$C_1 = 3.86 \times 10^2 \mu^2 \text{ hr}^{-1}$ $E_1 = 0.78 \text{ eV}$	$C_2 = 1.63 \times 10^8 \mu \text{ hr}^{-1}$ $E_2 = 2.05 \text{ eV}$

$$\frac{dx_0}{dt} = \frac{B}{2x_0 + A} + Ce^{-\frac{x_0}{L}}; C = C_0 e^{-\frac{E_A}{kT}};$$

$$C_0 = 3.6 \times 10^8 \frac{\mu\text{m}}{h}; E_A = 2.35 \text{ eV}; L = 7 \text{ nm}$$

