ECE 340 Homework XIV Spring 2003

Due: Friday, April 25, 2003

1. *Aluminum and polysilicon are commonly used as gate metals for the MOS structure in silicon. Assume that gold is used as the gate metal. Reconstruct a diagram similar to Figure 6-17 showing the variation of the metal-semiconductor work function potential difference F_{ms} with substrate doping concentration. The work function of Pt is 5.1 V and the electron affinity of silicon is 4.0 V. Show your work and draw to scale with accuracy.*

Solutions:

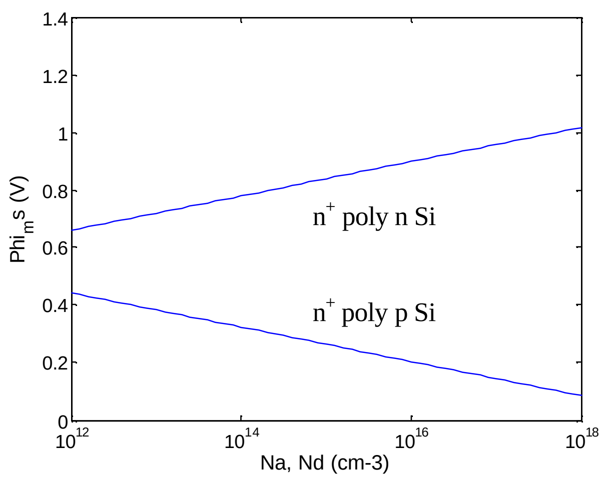
For n-type silicon:

$$\Phi_{ms} = \Phi_m - \Phi_s = \Phi_m - \left(c_{si} + \frac{E_g}{2} - \frac{kT}{q} \ln \frac{n}{n_i} \right) = 5.1 - \left(4.0 + 0.55 - 0.0259 \ln \frac{N_d}{n_i} \right) = 0.55 + 0.0259 \ln \frac{N_d}{n_i}$$

For p-type silicon:

$$\Phi_{ms} = \Phi_m - \Phi_s = \Phi_m - \left(c_{si} + \frac{E_g}{2} + \frac{kT}{q} \ln \frac{p}{n_i} \right) = 5.1 - \left(4.0 + 0.55 + 0.0259 \ln \frac{N_a}{n_i} \right) = 0.55 - 0.0259 \ln \frac{N_a}{n_i}$$

Plots based on these two equations:



2. (a) Find the voltage V_{FB} required to reduce to zero the negative charge induced at the semiconductor surface by a sheet of positive charge Q_{ox} located x' below the metal. (b) In the case of an arbitrary distribution of charge ρ(x') in the oxide, show that

$$V_{FB} = -\frac{1}{C_i} \int_0^d \frac{x'}{d}\, r(x')\,dx'$$

(a) There is a positive charge buried in the oxide that induces a negative charge in the metal and semiconductor. We need to apply a negative voltage so the charge in the semiconductor goes to zero.

Possible solution 1,

$$E_i = \frac{Q}{e_i},\ V_{FB} = -Ex' = \frac{-Q_{ox}x'}{e_i}$$

Possible solution 2:

$$C_x = \frac{e_i}{x'},\ V_{FB} = -\frac{Q_{ox}}{C_x} = -\frac{Q_{ox}x'}{e_i}$$

(b), A thin layer of thickness dx' has charge $r(x')dx'$. It is going to induce:

$$dV_{FB} = -\frac{r(x')x'dx'}{e_i},$$

Since $C_i = \frac{e_i}{d}$, $e_i = C_i d$, $dV_{FB} = -\frac{r(x')x'dx'}{C_i d}$

Integrate this over entire thickness to get total V_{FB}

$$V_{FB} = \int_0^d -\frac{r(x')x'dx'}{C_i d} = -\frac{1}{C_i}\int_0^d \frac{x'}{d} r(x')dx'$$

3. The flat band voltage is shifted to –3V for an n^+-polysilicon-SiO_2-Si capacitor. The SiO_2 thickness is 200Å and the substrate doping is $N_d = 10^{16}/cm^3$. Find the value of interface charge Q_i required to cause this shift in V_{FB}, with F_{ms} given by Fig. 6-17.

Solutions:

Looking up Fig. 6-17, at $N_d = 10^{16}/cm^3$, $\Phi_{ms} = -0.25V$.

$$C_i = \frac{e_i}{d} = \frac{3.9\times 8.85\times 10^{-14}}{200\times 10^{-8}} = 1.726\times 10^{-7}\,F/cm^2$$

$V_{FB} = \Phi_{ms} - \frac{Q_i}{C_i} \rightarrow Q_i = (\Phi_{ms} - V_{FB})C_i = (-0.25+3)\times 1.726\times 10^{-7} = 4.746\times 10^{-7}\,C/cm^2$, which can also be written as $2.966\times 10^{12}\,q(C/cm^2)$

4. An n^+-polysilicon-gate n-channel MOS structure is made on a p-type Si substrate with $N_a = 5x10^{15}/cm^3$. The SiO_2 thickness is 150Å in the gate region, and the effective interface charge Q_i is $5x10^{10}$ qC/cm^2. Find W_m, V_{FB}, V_T. Also, sketch the C-V curve for this device and give important numbers for the scale.

Solutions:

Looking at Fig. 6-16, the important numbers for the curve includes C_i, V_T, C_{min}, and V_{FB}. Here I also give the solution to C_{FB}, but it's not required for grading purpose.

$$C_i = \frac{e}{d} = \frac{3.9\times 8.85\times 10^{-14}}{150\times 10^{-8}} = 2.301\times 10^{-7}\,F/cm^2$$

$$f_F = 0.0259\ln\frac{N_a}{n_i} = 0.0259\times\ln\frac{5\times 10^{15}}{1.5\times 10^{10}} = 0.329V$$

The Φ_{ms} can be obtained by looking up Fig 6-17, Φ_{ms} = -0.95V.

Or by assuming E_F of n+ gate lies at the conduction band:

$\Phi_{ms} = -\frac{E_g}{2} - f_F = -0.879V$ (we take both answers, below we use Φ_{ms} = -0.95V)

$$V_{FB} = \Phi_{ms} - \frac{Q_i}{C_i} = -0.95 - \frac{1\times10^{11}q}{2.301\times10^{-7}} = -1.020V$$

$$W_m = 2\sqrt{\frac{e_s f_F}{qN_d}} = 2\sqrt{\frac{11.8\times8.85\times10^{-14}\times0.329}{1.6\times10^{-19}\times5\times10^{15}}} = 4.145\times10^{-5}cm$$

$$Q_d = -qN_a W_m = -1.6\times10^{-19}\times5\times10^{15}\times4.145\times10^{-5} = -3.316\times10^{-8}C/cm^2$$

$$V_T = V_{FB} - \frac{Q_d}{C_i} + 2f_F = -1.020 - \frac{3.316\times10^{-8}}{2.301\times10^{-7}} + 2\times0.329 = -0.218V$$

At maximum depletion, we have minimal capacitance:

$$C_d = \frac{e_s}{W_m} = 2.52\times10^{-8}F/cm^2$$

$$C_{\min} = \frac{C_i C_d}{C_i + C_d} = 2.27\times10^{-8}F/cm^2$$

At flat-band condition, according to Eqn. 6-40, $C_{debye} = \frac{\sqrt{2}e_s}{L_D}\frac{e\sqrt{2q^2 p_0}}{\sqrt{e_s kT}}$,

Also, equation 6-25, $L_D = \sqrt{\frac{e_s kT}{q^2 p_0}}$, we have

$$C_{debye} = \sqrt{\frac{2e_s q^2 p_0}{kT}} = \sqrt{\frac{2\times11.8\times8.85\times10^{-14}\times1.6\times10^{-19}\times5\times10^{15}}{0.0259}} = 2.54\times10^{-7}F/cm^2$$

$$C_{FB} = \frac{C_{debye}C_i}{C_{debye} + C_i} = 1.21\times10^{-7}F/cm^2$$

The Figure is drawn similar to Fig 6-16 in the book. Please notice that there is difference between high-frequency measurement and low-frequency measurements.