VE320 Intro to Semiconductor Devices
Summer 2022 — Problem Set 7

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Exercise 7.1

(a) A Schottky barrier diode formed on n-type silicon has a doping concentration of $N_d = 5 \times 10^{15}$ cm^{-3} and a barrier height of $\phi_{B0} = 0.65$ V. Determine the builtin potential barrier V_{bi}.

(b) If the doping concentration changes to $N_d = 10^{16}$ cm^{-3}, determine the values of ϕ_{B0} and V_{bi}. Do these values increase, decrease, or remain the same?

(c) Repeat part (b) if the doping concentration is $N_d = 10^{15}$ cm^{-3}.

Answer:

(a)

$$
\begin{aligned}
V_{bi} &= \phi_{B0} - \phi_n \\
\phi_n &= V_t \ln\left(\frac{N_c}{N_d}\right) \\
&= (0.0259)\ln\left(\frac{2.8 \times 10^{19}}{5 \times 10^{15}}\right) \\
&= 0.2235 \text{ V} \\
V_{bi} &= 0.65 - 0.2235 = 0.4265 \text{ V}
\end{aligned}
$$

(b)

$$
\begin{aligned}
\phi_n &= (0.0259)\ln\left(\frac{2.8 \times 10^{19}}{10^{16}}\right) \\
&= 0.2056 \text{ V} \\
V_{bi} &= 0.65 - 0.2056 = 0.4444 \text{ V}
\end{aligned}
$$

V_{bi} increases, ϕ_{B0} remains constant

(c)

$$
\begin{aligned}
\phi_n &= (0.0259)\ln\left(\frac{2.8 \times 10^{19}}{10^{15}}\right) \\
&= 0.2652 \text{ V} \\
V_{bi} &= 0.65 - 0.2652 = 0.3848 \text{ V}
\end{aligned}
$$

V_{bi} decreases, ϕ_{B0} remains constant

Exercise 7.2

For a p type semiconductor in contact with a metal, when does it form a Schottky contact, and when does it form an Ohmic contact? Please draw the energy band diagram for each case, and explain using your own words

Answer:

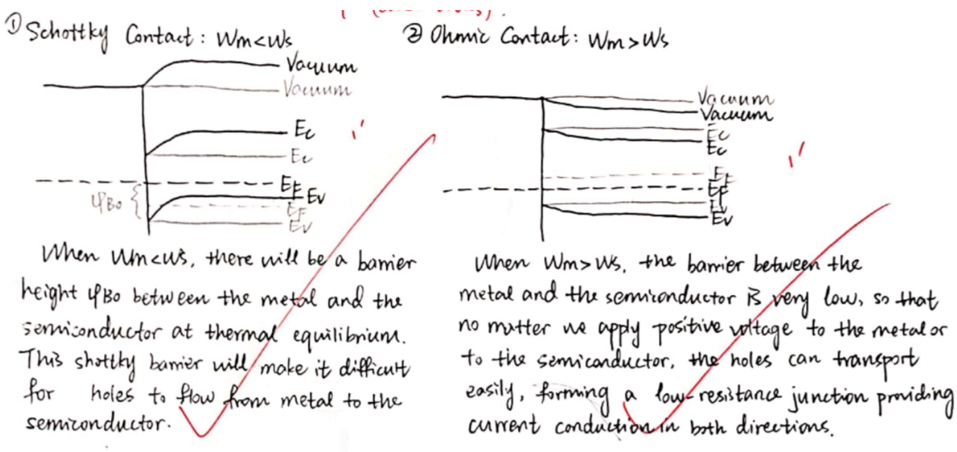

Figure 1: Figure for Problem 7.2

Exercise 7.3

A pn junction diode and a Schottky diode each have cross-sectional areas of $A = 8 \times 10^{-4}$ cm^2. The reverse saturation current densities at $T = 300$ K for the pn junction diode and Schottky diode are 8×10^{-13} A/cm^2 and 6×10^{-9} A/cm^2, respectively. Determine the required forward-bias voltage in each diode to yields currents of

(a) 150μA

(b) 700μA

(c) 1.2 mA

Answer:

For the pn junction,

$$I_s = \left(8 \times 10^{-4}\right)\left(8 \times 10^{-13}\right) = 6.4 \times 10^{-16} \text{ A}$$

(a)

$$\begin{aligned} V_a &= (0.0259) \ln\left(\frac{150 \times 10^{-6}}{6.4 \times 10^{-16}}\right) \\ &= 0.678 \text{ V} \end{aligned}$$

(b)

$$\begin{aligned} V_a &= (0.0259) \ln\left(\frac{700 \times 10^{-6}}{6.4 \times 10^{-16}}\right) \\ &= 0.718 \text{ V} \end{aligned}$$

(c)

$$\begin{aligned} V_a &= (0.0259) \ln\left(\frac{1.2 \times 10^{-3}}{6.4 \times 10^{-16}}\right) \\ &= 0.732 \text{ V} \end{aligned}$$

For the Schottky junction,

$$I_{sT} = \left(8 \times 10^{-4}\right)\left(6 \times 10^{-9}\right) = 4.8 \times 10^{-12} \text{ A}$$

(a) $V_a = (0.0259) \ln\left(\frac{150\times10^{-6}}{4.8\times10^{-12}}\right) = 0.447$ V

(b) $V_a = (0.0259) \ln\left(\frac{700\times10^{-6}}{4.8\times10^{-12}}\right) = 0.487$ V

(c) $V_a = (0.0259) \ln\left(\frac{1.2\times10^{-3}}{4.8\times10^{-12}}\right) = 0.501$ V

Exercise 7.4

A metal, with a work function $\phi_m = 4.2$ V, is deposited on an n-type silicon semiconductor with $\chi_s = 4.0$ V and $E_g = 1.12$eV. Assume no interface states exist at the junction. Let $T = 300$ K.

(a) Sketch the energy-band diagram for zero bias for the case when no space charge region exists at the junction.

(b) Determine N_d so that the condition in part (a) is satisfied.

(c) What is the potential barrier height seen by electrons in the metal moving into the semiconductor?

Answer:

(a) Plot

(b) We need $\phi_n = \phi_m - \chi = 4.2 - 4.0 = 0.20$ V And

$$\phi_n = V_t \ln\left(\frac{N_c}{N_d}\right)$$

or

$$0.20 = (0.0259) \ln\left(\frac{2.8 \times 10^{19}}{N_d}\right)$$

which yields

$$N_d = 1.24 \times 10^{16} \text{ cm}^{-3}$$

(c)

Barrier height = 0.20 V

Exercise 7.5

A metal-semiconductor junction is formed between a metal with a work function of 4.3eV and p-type silicon with an electron affinity of 4.0eV. The acceptor doping concentration in the silicon is $N_a = 5 \times 10^{16}$ cm^{-3}. Assume $T = 300$ K.

(a) Sketch the thermal equilibrium energy-band diagram.

(b) Determine the height of the Schottky barrier.

(c) Sketch the energy-band diagram with an applied reverse-biased voltage of $V_R = 3$ V.

(d) Sketch the energy-band diagram with an applied forward-bias voltage of $V_a = 0.25$ V

Answer:

Plot

Exercise 7.6

The dc charge distributions of four ideal MOS capacitors are shown in Figure P10.1. For each case:

(a) Is the semiconductor n or p type?

(b) Is the device biased in the accumulation, depletion, or inversion mode?

(c) Draw the energyband diagram in the semiconductor region.

Answer:

(a) p-type; inversion

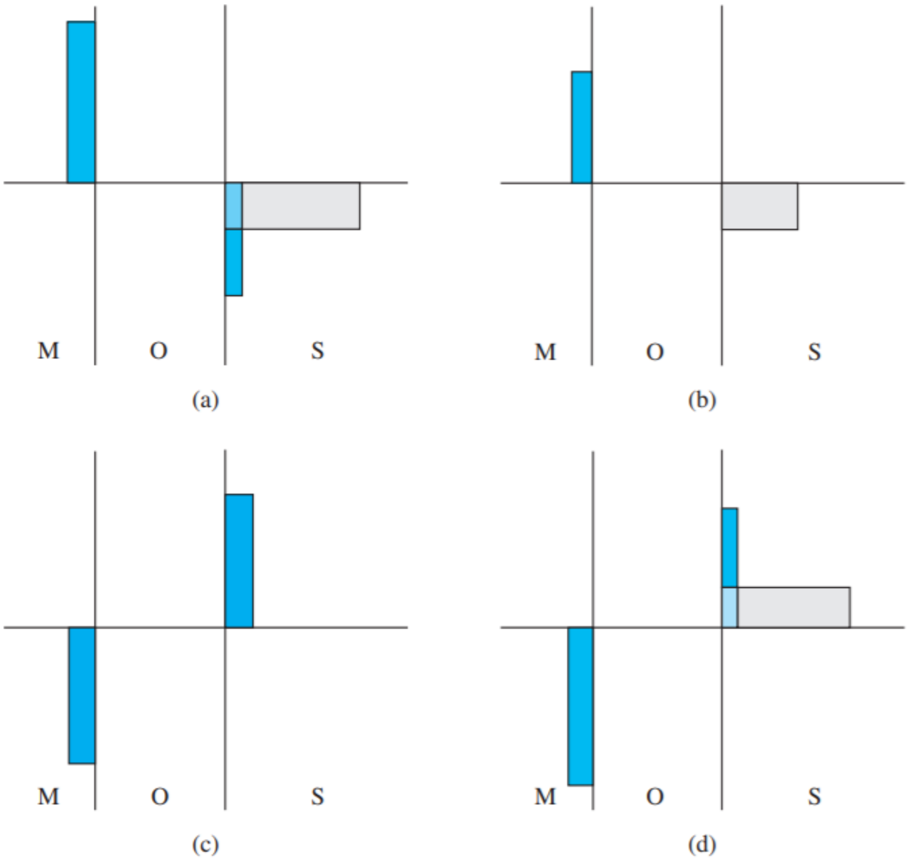

Figure 2: Figure for Problem 7.6

(b) p-type; depletion
(c) p-type; accumulation
(d) n-type; inversion

Exercise 7.7

(a) Consider an n^+polysilicon-silicon dioxide-n-type silicon MOS structure. Let $N_d = 4 \times 10^{15}$ cm^{-3}. Calculate the ideal flat-band voltage for $t_{ox} = 20$ nm $= 200\mathring{A}$

(b) Considering the results of part (a), determine the shift in flat-band voltage for (i) $Q'_{ss} = 4 \times 10^{10}$ cm^{-2} and (ii) $Q'_{ss} = 10^{11}$ cm^{-2}.

(c) Repeat parts (a) and (b) for an oxide thickness of $t_{ox} = 12$ nm $= 120\mathring{A}$.

Answer:

(a) $\phi_{ms} \cong -0.42$ V $V_{FB} = \phi_{ms} = -0.42$ V

(b) $C_{ox} = \frac{(3.9)\left(8.85\times10^{-14}\right)}{200\times10^{-8}} = 1.726 \times 10^{-7}$ F/cm^2

(i) $\Delta V_{FB} = -\frac{Q'_{ss}}{C_{ox}} = -\frac{\left(4\times10^{10}\right)\left(1.6\times10^{-19}\right)}{1.726\times10^{-7}} = -0.0371$ V

(ii) $\Delta V_{FB} = -\frac{\left(10^{11}\right)\left(1.6\times10^{-19}\right)}{1.726\times10^{-7}} = -0.0927$ V

(c) $V_{FB} = \phi_{ms} = -0.42$ V $C_{ox} = \frac{(3.9)\left(8.85\times10^{-14}\right)}{120\times10^{-8}} = 2.876 \times 10^{-7}$ F/cm^2

(i) $\Delta V_{FB} = -\frac{\left(4\times10^{10}\right)\left(1.6\times10^{-19}\right)}{2.876\times10^{-7}} = -0.0223$ V

(ii) $\Delta V_{FB} = -\frac{\left(10^{11}\right)\left(1.6\times10^{-19}\right)}{2.876\times10^{-7}} = -0.0556$ V

Exercise 7.8

Consider an n^+polysilicon gate on silicon dioxide with a p-type silicon substrate doped to $N_{\mathrm{a}} = 3 \times 10^{16}$ cm^{-3}. Assume $Q_{\mathrm{ss}}{}' = 5 \times 10^{10}$ cm^{-2}. Determine the required oxide thickness such that the threshold voltage is $V_{\mathrm{TN}} = +0.65$ V. Please provide the process of derivation.

Answer:

$$\Phi_{tp} = V_t \ln\left(\frac{N_a}{n_i}\right) = (0.0259)\ln\left(\frac{3\times10^{16}}{1.5\times10^{10}}\right) = 0.376 \text{ V}$$

$$X_{d\tau} = \left\{\frac{4 \in s\phi_{fp}}{dV_a}\right\}^{\frac{1}{2}} = \left\{\frac{4\times11.7\times8.85\times10^{-14}\times0.376}{1.6\times10^{-19}\times3\times10^{16}}\right\}^{\frac{1}{2}} = 1.8\times10^{-5} \text{ cm}$$

$$\left|Q'_{sp}(\max)\right| = eN_a x_{dT} = 1.6\times10^{-19}\times3\times10^{6}\times1.8\times10^{-5} = 8.646\times10^{-8}\text{C/cm}^2$$

$$\text{We have } V_{TN} = (\mid Q'_{sd\,\max}) \mid -Q'_{ss})\left(\frac{t_{\mathrm{ox}}}{\in_{ox}}\right) + \phi_{\mathrm{ms}} + 2\phi_{fp} \Rightarrow t_{ox} = 4.5\times10^{-6} \text{ cm}$$

Exercise 7.9

Draw the C-V curves of a MOS capacitor with n-type Si as the substrate, at low frequency and high frequency, respectively. Explain why they are different.

Answer:

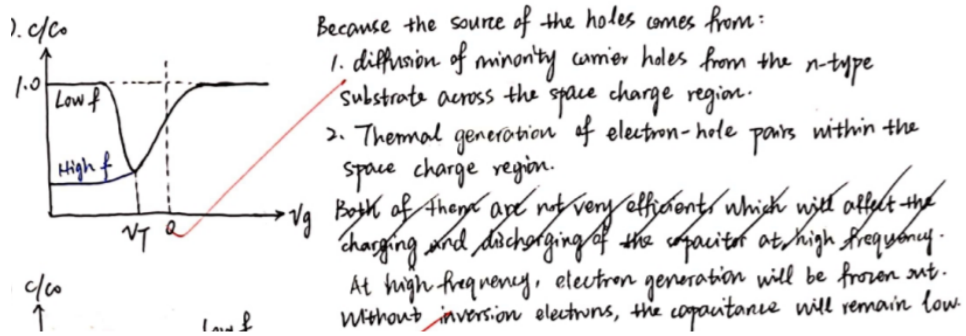

Figure 3: Figure for Problem 7.9

Reference

1. Neamen, Donald A. Semiconductor physics and devices: basic principles. McGraw-hill, 2003.