1. Construct the equilibrium energy band diagram appropriate for an ideal p-type semiconductor in metal contact where $E_{cB} < E_{vF}$.

2. Repeat part (a) when $E_{cB} > E_{vF}$.

3. Verify that an ideal p-type hole flow from a metal and a p-type semiconductor will be rectifying if $E_{cB} < E_{vF}$ and ohmic-like if $E_{cB} > E_{vF}$.

4. Establish an expression for the barrier height, $\Phi_B = E_{cB} - E_{\text{vacuum}}$ of the rectifying p-type contact.

5. (a) The "p-rectification" for drawing the equilibrium energy band diagram established in the text can be summarized as follows: (i) Draw the surface-included energy band diagrams for the individual components. (ii) Vertically align the diagrams to the common $E_F$ reference level, and join the diagrams at the metal-semiconductor interface. (iii) Without changing the interfacial positioning of the semiconductor bands, move the field-free semiconductor bulk (the region far from the interface) up or down until $E_F$ is constant everywhere. (iv) Appropriately connect up the $E_c$, $E_v$, and $E_F$ at the interface with the field-free positioning of the bands in the semiconductor bulk. (v) Eliminate unnecessary lines. Following the cited prescription one obtains the equilibrium energy band diagrams shown above.

6. (c) Hole flow under bias must be examined to determine whether the given Si contacts are rectifying or ohmic. Empty electronic states in the metal, which decrease exponentially with energy below its Fermi level, can be thought of as holes for the purpose of the discussion. For the $E_{cB} < E_{vF}$ contact, there is clearly a barrier to hole flow in both directions under equilibrium conditions. Moving $E_{cB}$ upward (toward $E_{vF}$) reduces the barrier to hole flow from the semiconductor to the metal. The resulting $S > 0$ hole current in $E_{cB}$ is expected to increase exponentially with increased separation between $E_{cB}$ and $E_{vF}$. Reversing the bias blocks hole flow from the semiconductor to the metal, leaving only a saturating hole current from the metal to the semiconductor. The $E_{cB} < E_{vF}$ contact is obviously rectifying. For the $E_{cB} > E_{vF}$ contact, there is no barrier to hole flow from the semiconductor to the metal. Moreover, the small barrier to hole flow from the metal to the semiconductor vanishes if $E_{cB}$ is moved only slightly downward relative to $E_{vF}$. The $E_{cB} > E_{vF}$ contact is concluded to be ohmic-like, thereby completing the required verification.

7. (d) The (+) and (−) charge areas on the $p-x$ and $n-x$ plots must be equal, or $-\frac{q}{2}(\Phi_B - \Phi_a) = \frac{q}{2}(\Phi_a + \Phi_B - \Phi_a) = \frac{q}{2}(\Phi_B - \Phi_a)$. Alternatively, the $E_{vF}$-field must be continuous at $x = x_s$, giving $E_{vF}(x_s) = E_{vF}(x_s) = \frac{q}{2}(\Phi_a + \Phi_B - \Phi_a) = \frac{q}{2}(\Phi_B - \Phi_a)$.
Noting that

\[ (E_x - E_{2h})/E_x = E_x = (E_x - E_{2h})/E_x = E_x = E_{2h} + kT \ln(N_a/N_x) \]

and employing \( kT = 0.0259 \text{ eV}, E_x = 1.12 \text{ eV} \) and \( N_x = 10^{16} \text{ cm}^{-3} \), one calculates

\[ 0.08 \text{ eV} = (E_x - E_{2h}) = 0.32 \text{ eV} \quad \text{... if } 10^{16} \text{ cm}^{-3} < N_x < 10^{19} \text{ cm}^{-3} \]

\[ 0.80 \text{ eV} = (E_x - E_{2h}) = 1.04 \text{ eV} \quad \text{... if } 10^{19} \text{ cm}^{-3} < N_x < 10^{20} \text{ cm}^{-3} \]

Since \( \phi_{\text{sh}} = (1/4)\phi_0 \epsilon_x' = x' = (E_x - E_{2h})/E_x \) to signify a \( \phi_{\text{sh}} = 0 \) clearly requires

\[ 0.08 \text{ eV} = 0.08 \times 0.32 \text{ eV} \quad \text{...} \]

\[ 0.80 \text{ eV} = 0.80 \times 1.04 \text{ eV} \]

Thus

\[ \epsilon_x' = E_{2h}/E_x = \epsilon_x = 0.82 \text{ eV} \]

or

\[ \epsilon_x' = E_{2h}/E_x = \epsilon_x = 0.26 \text{ eV} \]

and

\[ N_x = \epsilon_x'^{1/2} = 10^{20} \text{ cm}^{-3} = 2.29 \times 10^{16} \text{ cm}^{-3} \]

Thus

\[ \epsilon_x' \text{ part: } N_x = 2.29 \times 10^{16} \text{ cm}^{-3} = \text{MOS-C with } \phi_{\text{sh}} = 0 \]

(a) The electric field is uniformly proportional to the slope of the energy bands. The deduced \( \epsilon_x' \) dependence is sketched below.

\[ \text{SOI} \rightarrow \text{B} \]

(b) If \( \epsilon_x' = 0 \), \( \epsilon_x = \epsilon_x' \) and the inside energy bands are a linear function of position. \( \epsilon_x' = \epsilon_x'' \) if there is charge distributed throughout the oxide. \( \epsilon_x'' \) becomes a function of position and the inside energy bands will be two atomic curves. Since the inside energy bands are a linear function of position in Fig. 18.1 and \( \epsilon_x'' = \epsilon_x \) constant, we conclude \( \epsilon_x'' = \epsilon_x \).

(c) The normal component of the \( D \)-field, where \( D = \epsilon_x E_x \), must be continuous if there is no place of charge at an interface between two dissimilar materials.

When a place of charge does exist, there is a discontinuity in the \( D \)-field equal to the charges/cm² between the interface. Clearly, with \( D = \epsilon_x E_x \) and \( \epsilon_x = \epsilon_x'' \), there must be a place of charge at the Si-SiO₂ interface, the density characterized by Fig. 18.1. However, since \( \epsilon_x'' = \epsilon_x' = \epsilon_x \), the interface charge must be positive. The final charge closely approximates a place of positive charge at the Si-SiO₂ interface and we suppose \( \epsilon_x'' = \epsilon_x \).

(In present a \( D \)-field discontinuity at the Si-SiO₂ interface can arise from other sources of interface charge. These include the mobile ion charge drained to the O-S interface during \( +V \) stressing and the interface trap charge.)

Note: \( kT = 2.87 \times 10^{-19} \text{ J} \), \( \epsilon_x' = 0.15 \text{ eV} \), in these.

\[ V_b = \text{V}_{\text{me}} + \text{V}_g \]

(d) When \( V_b > 0 \), both semiconductor components are accounted. Then \( C \) approaches \( C_p \) at large positive gate bias. When \( V_b = 0 \), the two semiconductor components form in place and then invert. Inversion occurs at the same bias voltage for the two sides of the MOS-C because \( N_x(p-wide) = N_x(n-wide) \). The high-frequency capacitance is therefore expected to smoothly decrease to \( C_{\text{so}} \) at large negative bias. As sketched below, the deduced characteristic should look very similar to a standard n-wide high-frequency MOS-C C-V curve.

(e) Reflecting on the answers to previous parts of the problem, particularly part (c), we are led to model the MOS-C as three equations in series. In the equivalent circuit for the MOS-C shown above, \( C_{\text{so}} \) and \( C_p \) are respectively the p- and n-wide semiconductor capacitance.

\[ C_{\text{so}} = \epsilon_x' E_x / \epsilon_{\text{so}} \]

\[ C_p = \epsilon_x' E_x / \epsilon_{\text{so}} \]

\[ C_{\text{so}} = 1 + \epsilon_x' / \epsilon_{\text{so}} \]

\[ C_p = 1 + \epsilon_x' / \epsilon_{\text{so}} \]

\[ \text{the minimum capacitance occurs under the inversion biasing where } W = W_{\text{so}}. \]

Performing the indicated computation gives

\[ \phi_{\text{sh}} = \phi_x' = 0.0259 \times 10^{-2} \text{ eV} = 0.298 \text{ V} \]

\[ W_{\text{so}} = \frac{2.87 \times 10^{-19} \text{ J}}{4 \epsilon_x'} \left( \frac{1}{100} \right) \left( \frac{1}{100} \right) = 0.0259 \times 10^{-2} \text{ eV} = 0.298 \text{ V} \]

\[ C_{\text{so}} = \epsilon_x' E_x / \epsilon_{\text{so}} = 1 + \epsilon_x' / \epsilon_{\text{so}} = 0.0259 \times 10^{-2} \text{ eV} = 0.298 \text{ V} \]

\[ C_p = \epsilon_x' E_x / \epsilon_{\text{so}} = 1 + \epsilon_x' / \epsilon_{\text{so}} = 0.0259 \times 10^{-2} \text{ eV} = 0.298 \text{ V} \]

\[ C_{\text{so}} = 1 + \epsilon_x' / \epsilon_{\text{so}} = 0.0259 \times 10^{-2} \text{ eV} = 0.298 \text{ V} \]

\[ C_p = 1 + \epsilon_x' / \epsilon_{\text{so}} = 0.0259 \times 10^{-2} \text{ eV} = 0.298 \text{ V} \]

\[ C_{\text{so}} = 1 + \epsilon_x' / \epsilon_{\text{so}} = 0.0259 \times 10^{-2} \text{ eV} = 0.298 \text{ V} \]

\[ C_p = 1 + \epsilon_x' / \epsilon_{\text{so}} = 0.0259 \times 10^{-2} \text{ eV} = 0.298 \text{ V} \]
Figure 6.1 is the energy-band diagram of the MOS system at thermal equilibrium for the materials shown in Figure 6.1. There is a voltage difference between the metal and the silicon brought about by the differing work functions equal to 0.7 eV which is (4.0 - 3.3) or 0.8 V. Since Figure 6.2 indicates that 0.4 V is dropped across the oxide, the voltage drop at the silicon surface is 0.4 V.

Because there is no charge in the SiO₂, the oxide field \( E_o \) is constant and the voltage across the oxide \( V_o \) is simply \( E_o \times x_o \), where \( x_o \) is the oxide thickness. Therefore, \( x_o \) can be found once \( E_o \) is known.

Because the oxide-silicon interface has been assumed to be charge-free, the electric displacement \( D \), perpendicular to the interface, is continuous and the field in the oxide is therefore related to the field at the surface of the silicon \( E_o \) by the equation

\[
E_o = \frac{1}{\varepsilon_o} \times E \]

There is a depletion layer at the surface of the silicon with a constant charge density \( qN_o \) that extends a distance \( x_d \) away from the Si-SiO₂ interface.

We can write expressions for the surface field \( E_s \) in the silicon and for the depletion-layer width \( x_d \):

\[
E_s = \frac{qN_o}{\varepsilon_o} \]

and

\[
x_d = \frac{2qN_o}{E_s} \]

The acceptor density \( N_a \) in the silicon can be obtained with \( p = N_a \) and \( (E_s - E_p) \) as given in Figure 6.1. From Figure 6.1, we have

\[
(E_s - E_p) = 0.4 - 0.35 = 0.05 \text{ eV} \]

and, from Equation 5.1:

\[
p = N_a = n\exp[(E_s - E_p)/kT] \]

which is \( 1.1 \times 10^{14} \text{ cm}^{-3} \).

Using the value \( n_i = 6.4 \text{ cm}^{-3} \), we calculate \( x_d = 887 \text{ nm} \), and

\[
E_s = 3.505 \times 10^4 \text{ V cm}^{-1} \]

Therefore,

\[
d = 3.505 \times 10^4 \text{ V cm}^{-1} \times \frac{1}{E_s} = 114 \text{ nm} \]