ECE 541/ME 541
Microelectronic Fabrication Techniques

Lecture 03 Review of Metal-Semiconductor Contacts

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Metal-semiconductor (MS) junctions

Importance of metal-semiconductor contacts is due to

1) *Ohmic metal-semiconductor junctions* (e.g. for metal interconnects contacting a Si device in an integrated circuit)

2) *Rectifying metal-semiconductor junctions = Schottky diodes* (e.g. for high-speed rectifier diodes)

Metal-Semiconductor junctions are also used as *ohmic-contact* to carry current into and out of the semiconductor device.

Many of the properties of pn junctions can be realized by forming an appropriate *metal-semiconductor rectifying contact* (Schottky contact)

- Simple to fabricate
- Switching speed is much higher than that of p-n junction diodes
Ideal MS contacts

Assumptions for Ideal MS contacts
M and S are in intimate contact, on atomic scale
No oxides or charges at the interface
No intermixing at the interface

$$E = \frac{1240}{\lambda \text{ (nm)}} \quad \begin{array}{c} \text{400 nm } \rightarrow 3.1 \text{ eV} \\ \text{600 nm } \rightarrow -1.9 \text{ eV} \end{array}$$
**MS contacts**

Vacuum level, $E_0$ - corresponds to energy of free electrons.

The difference between vacuum level and Fermi-level is called workfunction, $\Phi$ of materials.

- **Workfunction**, $\Phi_M$ is an invariant property of metal. It is the minimum energy required to free up electrons from metal. (3.66 eV for Mg, 5.15 eV for Ni etc.)

The semiconductor **workfunction**, $\Phi_s$, depends on the doping.

$$\Phi_s = \chi + (E_C - E_F)_{FB}$$

where $\chi = (E_0 - E_C)_{SURFACE}$ is a fundamental property of the semiconductor. (Example: $\chi = 4.0$ eV, 4.03 eV and 4.07 eV for Ge, Si and GaAs respectively)

- $\min \Phi_s = \chi, \quad E_f = E_c$
- $\max \Phi_s = \chi + E_g, \quad E_f = E_v$
Energy band diagrams for ideal MS contacts

(a) and (c) An instant after contact formation

(b) and (d) under equilibrium conditions

$\Phi_M > \Phi_S$

$\Phi_M < \Phi_S$
Equilibrium energy band diagram for \( pn \)-homojunction

\[
n = n_i \exp\left(\frac{E_F - E_i}{kT}\right)
\]

\[
p = n_i \exp\left(\frac{E_i - E_F}{kT}\right)
\]

\( E_F = \text{same everywhere under equilibrium} \)

Join the two sides of the band by a smooth curve.
**MS (n-type) contact with $\Phi_M > \Phi_S$**

Soon after the contact formation, electrons will begin to flow from S to M near junction.

Creates surface depletion layer, and hence a built-in electric field (similar to p⁺-n junction).

Under equilibrium, net flow of carriers will be zero, and Fermi-level will be constant.

A barrier $\Phi_B$ forms for electron flow from M to S.

$\Phi_B = \Phi_M - \chi$ ... ideal MS (n-type) contact. $\Phi_B$ is called “barrier height”.

Electrons in semiconductor will encounter an energy barrier equal to $\Phi_M - \Phi_S$ while flowing from S to M.
Response to applied bias for n-type semiconductor

Note: An applied positive voltage lowers the band since energy bands are drawn with respect to electron energy.
MS (n-type) contact with $\Phi_M < \Phi_S$

No barrier for electron flow from S to M. So, even a small $V_A > 0$ results in large current.

As drawn, small barrier exists for electron flow from M to S, but vanishes when $V_A < 0$ is applied to the metal. Large current flows when $V_A < 0$.

The MS(n-type) contact when $\Phi_M < \Phi_S$ behaves like an **ohmic contact**.

![Graph](image-url)
## Electrical nature of ideal MS contacts

<table>
<thead>
<tr>
<th></th>
<th>n-type</th>
<th>p-type</th>
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<tr>
<td>$\Phi_M &gt; \Phi_S$</td>
<td>rectifying</td>
<td>ohmic</td>
</tr>
<tr>
<td>$\Phi_M &lt; \Phi_S$</td>
<td>ohmic</td>
<td>rectifying</td>
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Schottky diode

\[ V_{bi} = \frac{1}{q} \left( \Phi_B - (E_C - E_F)_{FB} \right) \]

\[ \rho \approx qN_D \quad \text{for} \quad 0 \leq x \leq W \]
\[ \approx 0 \quad \text{for} \quad x > W \]

\[ \frac{d\varepsilon}{dx} = \frac{\rho}{\varepsilon_{Si}} = \frac{qN_D}{\varepsilon_{Si}} \quad \text{for} \quad 0 \leq x \leq W \]

\[ \varepsilon(x = 0) = \frac{qN_D W}{\varepsilon_{Si}} \]

\[ W = \left[ \frac{2\varepsilon_{Si}}{qN_D} (V_{bi} - V_A) \right]^{1/2} \]
**Review**

**Homo-pn-junction Diode**

\[
V_{bi} = \frac{kT}{q} \ln \left( \frac{p^n n^i}{n^2} \right) = \frac{kT}{q} \ln \left( \frac{N_A N_D}{n^2} \right)
\]

\[
V(x) = \frac{qN_A}{2\varepsilon} (x_p + x)^2 \quad -x_p \leq x \leq 0
\]

\[
= V_{bi} - \frac{qN_D}{2\varepsilon} (x_n - x)^2 \quad 0 \leq x \leq x_n
\]

\[
\varepsilon(x) = \frac{qN_A}{\varepsilon} (x_p + x) \quad -x_p \leq x \leq 0
\]

\[
= -\frac{qN_D}{\varepsilon} (x_n - x) \quad 0 \leq x \leq x_n
\]

\[
= 0 \quad x < -x_p; \quad x > x_n
\]

\[
\varepsilon_{\text{max}} = -qN_A x_p / \varepsilon = -qN_D x_n / \varepsilon
\]

\[
W = \left[ \frac{2\varepsilon}{q} \left( \frac{N_A + N_D}{N_A N_D} \right) V_{bi} \right]^{1/2}
\]
Example

Find barrier height, built-in voltage, maximum E-field, and the depletion layer width at equilibrium for W-Si (n-type) contact.

Given: \( \Phi_M = 4.55 \text{eV} \) for W; \( \chi(\text{Si}) = 4.01 \text{eV} \); Si doping = \( 10^{16} \text{ cm}^{-3} \)

Draw the band diagram at equilibrium.

**Solution:**

Find \( E_F - E_i \), \( E_F - E_i = 0.357 \text{eV} \)

Find \( E_C - E_F \), \( E_C - E_F = 0.193 \text{eV} \)

\[ \Phi_B = \Phi_M - \chi = 0.54 \text{eV} \]

\[ \Phi_S = \chi + (E_C - E_F)_{FB} = 4.203 \text{ eV} \]

\[ V_{bi} = 0.347 \text{ V} \]

\[ W = 0.21 \mu\text{m} \]

\[ E(x = 0) = E_{max} = 3.4 \times 10^4 \text{ V/cm} \]
Schottky diode I-V characteristics

Schottky diode is a metal-semiconductor (MS) diode
Historically, Schottky diodes are the oldest diodes
MS diode electrostatics and the general shape of the MS diode I-V characteristics are similar to p⁺n diodes, but the details of current flow are different.
Dominant currents in a p⁺n diode
- arise from recombination in the depletion layer under small forward bias.
- arise from hole injection from p⁺ side under larger forward bias.
Dominant currents in a MS Schottky diodes
- Electron injection from the semiconductor to the metal.
Current components in a $p^+n$ and MS Schottky diodes
**I-V characteristics of Schottky diode**

\[
I = I_s \left( \frac{qV_A}{e^{kT}} - 1 \right) \quad \text{where} \quad I_s = A^* A T^2 e^{\frac{\Phi_B}{kT}}
\]

where $\Phi_B$ is Schottky barrier height, $V_A$ is applied voltage, $A$ is area, and $A^*$ is Richardson’s constant.

The reverse leakage current for a Schottky diode is generally much larger than that for a p+n diode.

Since MS Schottky diode is a majority carrier devices, the frequency response of the device is much higher than that of equivalent p+n diode.
**Review**

**I-V characteristics of pn-homojunction diode**

**Shockley equation**

\[ J = J_0 \left( e^{\frac{qV_A}{kT}} - 1 \right) \]

with \[ J_0 = \left( \frac{qD_p}{L_p} p_{n0} + \frac{qD_n}{L_n} n_{p0} \right) \]

Large forward bias \((V_A >> kT/q)\): \[ J = J_0 e^{\frac{qV_A}{kT}} \]

Large reverse bias \((V_A << -kT/q)\): \[ J = -J_0 \]
“Tunneling” Ohmic contact

The MS(n-type) contact when $\Phi_M < \Phi_S$ behaves like an ohmic contact.