Two kinds of metal-semiconductor contacts:

• metal on lightly doped silicon –
• rectifying Schottky diodes
• metal on heavily doped silicon –
• low-resistance ohmic contacts
9.1 Schottky Barriers

Energy Band Diagram of Schottky Contact

- Schottky barrier height, $\phi_B$, is a function of the metal material.

- $\phi_B$ is the single most important parameter. The sum of $q\phi_{Bn}$ and $q\phi_{Bp}$ is equal to $E_g$. 

**Schottky barrier heights for electrons and holes**

<table>
<thead>
<tr>
<th>Metal</th>
<th>Mg</th>
<th>Ti</th>
<th>Cr</th>
<th>W</th>
<th>Mo</th>
<th>Pd</th>
<th>Au</th>
<th>Pt</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{Bn}$ (V)</td>
<td>0.4</td>
<td>0.5</td>
<td>0.61</td>
<td>0.67</td>
<td>0.68</td>
<td>0.77</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>$\phi_{BP}$ (V)</td>
<td>0.61</td>
<td>0.5</td>
<td>0.42</td>
<td>0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Work Function</td>
<td>3.7</td>
<td>4.3</td>
<td>4.5</td>
<td>4.6</td>
<td>4.6</td>
<td>5.1</td>
<td>5.1</td>
<td>5.7</td>
</tr>
</tbody>
</table>

\[
\phi_{Bn} + \phi_{BP} \approx 1.1 \text{ V}
\]

$\phi_{Bn}$ increases with increasing metal work function
$\phi_{Bn}$ Increases with Increasing Metal Work Function

Ideally,

$$q\phi_{Bn} = q\psi_M - \chi_{Si}$$
$\phi_{Bn}$ is typically 0.4 to 0.9 V

• A high density of energy states in the bandgap at the metal-semiconductor interface pins $E_f$ to a range of 0.4 eV to 0.9 eV below $E_c$

**Question:** What is the typical range of $\phi_{Bp}$?
Schottky barrier heights of metal silicide on Si

<table>
<thead>
<tr>
<th>Silicide</th>
<th>ErSi$_{1.7}$</th>
<th>HfSi</th>
<th>MoSi$_2$</th>
<th>ZrSi$_2$</th>
<th>TiSi$_2$</th>
<th>CoSi$_2$</th>
<th>WSi$_2$</th>
<th>NiSi$_2$</th>
<th>Pd$_2$Si</th>
<th>PtSi</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{Bn}$ (V)</td>
<td>0.28</td>
<td>0.45</td>
<td>0.55</td>
<td>0.55</td>
<td>0.61</td>
<td>0.65</td>
<td>0.67</td>
<td>0.67</td>
<td>0.75</td>
<td>0.87</td>
</tr>
<tr>
<td>$\phi_{Bp}$ (V)</td>
<td>0.55</td>
<td>0.49</td>
<td>0.45</td>
<td>0.45</td>
<td>0.43</td>
<td>0.43</td>
<td>0.35</td>
<td>0.23</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Silicide-Si interfaces are more stable than metal-silicon interfaces. After metal is deposited on Si, an annealing step is applied to form a silicide-Si contact. The term *metal-silicon contact* includes silicide-Si contacts.
Using CV Data to Determine $\phi_B$

$$q\phi_{bi} = q\phi_{Bn} - (E_c - E_f)$$

$$= q\phi_{Bn} - kT \ln \frac{N_c}{N_d}$$

$$W_{dep} = \sqrt{\frac{2\varepsilon_s (\phi_{bi} + V)}{qN_d}}$$

$$C = \frac{\varepsilon_s}{W_{dep}} A$$

Question:
How should we plot the CV data to extract $\phi_{bi}$?
Using CV Data to Determine $\phi_B$

Once $\phi_{bi}$ is known, $\phi_B$ can be determined using

$$ \frac{1}{C^2} = \frac{2(\phi_{bi} + V)}{qN_d \varepsilon_s A^2} $$

$$ q\phi_{bi} = q\phi_{Bn} - (E_c - E_f) = q\phi_{Bn} - kT \ln \frac{N_c}{N_d} $$
9.2 Thermionic Emission Theory

\[ n = N_c e^{-q(\phi_B-V)/kT} = 2 \left[ \frac{2\pi m_n kT}{\hbar^2} \right]^{3/2} e^{-q(\phi_B-V)/kT} \]

\[ v_{th} = \sqrt{3kT/m_n} \quad \text{and} \quad v_{thx} = -\sqrt{2kT/\pi m_n} \]

\[ J_{S\rightarrow M} = -\frac{1}{2} qnv_{thx} = \frac{4\pi qm_n k^2}{\hbar^3} T^2 e^{-q\phi_B/kT} e^{qV/kT} \]

\[ = J_0 e^{qV/kT}, \text{where} \quad J_0 \approx 100 e^{-q\phi_B/kT} \text{ A/cm}^2 \]
9.3 **Schottky Diode**

(a) $V = 0$. $I_{S \rightarrow M} = I_0$

(b) Forward bias. Metal is positive wrt Si. $I_{M \rightarrow S} \gg |I_{M \rightarrow S}| = I_0$

(c) Reverse bias. Metal is negative wrt Si. $I_{S \rightarrow M} \ll |I_{M \rightarrow S}| = I_0$

(d) Schottky diode IV.

\[ E - E_f = q \phi_B \]
\[ E_f > q \phi_B \]
\[ qV \]
\[ E_{fn} \]
9.3 Schottky Diode

\[ I_{\text{M} \rightarrow \text{S}} = -I_0 \quad I_{\text{S} \rightarrow \text{M}} = I_0 e^{qV/kT} \]

\[ I_0 = AKT^2 e^{-q\phi_B/kT} \]

\[ K = \frac{4\pi q m_n k^2}{h^3} \approx 100 \text{A}/(\text{cm}^2 \cdot \text{K}^2) \]

\[ I = I_{\text{S} \rightarrow \text{M}} + I_{\text{M} \rightarrow \text{S}} = I_0 e^{qV/kT} - I_0 = I_0 (e^{qV/kT} - 1) \]
9.4 Applications of Schottky Diodes

- $I_0$ of a Schottky diode is $10^3$ to $10^8$ times larger than a PN junction diode, depending on $\phi_B$. A larger $I_0$ means a smaller forward drop $V$.

- A Schottky diode is the preferred rectifier in low voltage, high current applications.

$$I = I_0 (e^{qV/kT} - 1)$$
$$I_0 = AKT^2 e^{-q\phi_B / kT}$$

Diagram showing the current-voltage ($I-V$) characteristics of a Schottky diode and a PN junction diode.
**Question:** What sets the lower limit in a Schottky diode’s forward drop?

**Synchronous Rectifier:** For an even lower forward drop, replace the diode with a wide-W MOSFET which is not bound by the tradeoff between diode $V$ and $I_0$: $I = I_0 e^{qV/kT}$
There is no minority carrier injection at the Schottky junction. Thus, the CMOS latch-up problem can be eliminated by replacing the source/drain of the NFET with Schottky junctions.

In addition, the Schottky S/D MOSFET would have shallow junctions and low series resistance. So far, Schottky S/D MOSFETs have lower performance.

9.4 Applications of Schottky Diodes

No excess carrier storage. What application may benefit from that?
GaAs MESFET

The MESFET has similar IV characteristics as the MOSFET, but does not require a gate oxide.

Question: What is the advantage of GaAs over Si?
9.5 *Ohmic Contacts*

![Diagram of Ohmic Contacts](Image)
After the spacer is formed, a Ti or Mo film is deposited. Annealing causes the silicide to be formed over the source, drain, and gate. Unreacted metal (over the spacer) is removed by wet etching.

**Question:**
- What is the purpose of siliciding the source/drain/gate?
- What is self-aligned to what?
9.5 Ohmic Contacts

\[ W_{\text{dep}} = \sqrt{\frac{2\varepsilon_s \phi_{Bn}}{qN_d}} \]

Tunneling probability:
\[ P = e^{-H\phi_{Bn}/\sqrt{N_d}} \]

\[ H = 4\pi \sqrt{\varepsilon_s m_n / h} = 5.4 \times 10^9 \sqrt{m_n / m_o} \text{ cm}^{-3/2} \text{V}^{-1} \]

\[ J_{S \rightarrow M} \approx \frac{1}{2} qN_d \nu_{thx} P = qN_d \sqrt{kT / 2\pi m_n} e^{-H(\phi_{Bn}-V)/\sqrt{N_d}} \]
9.5 Ohmic Contacts

\[
R_c \equiv \left( \frac{dJ_{S \rightarrow M}}{dV} \right)^{-1} = \frac{e^{H\phi_{Bn}/\sqrt{N_d}}}{q\nu_{thx} H \sqrt{N_d}} \propto e^{H\phi_{Bn}/\sqrt{N_d}} \Omega \cdot \text{cm}^2
\]