VE320 – Summer 2021

Introduction to Semiconductor Devices

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Chapter 9 Metal-Semiconductor Schottky Junction

Outline

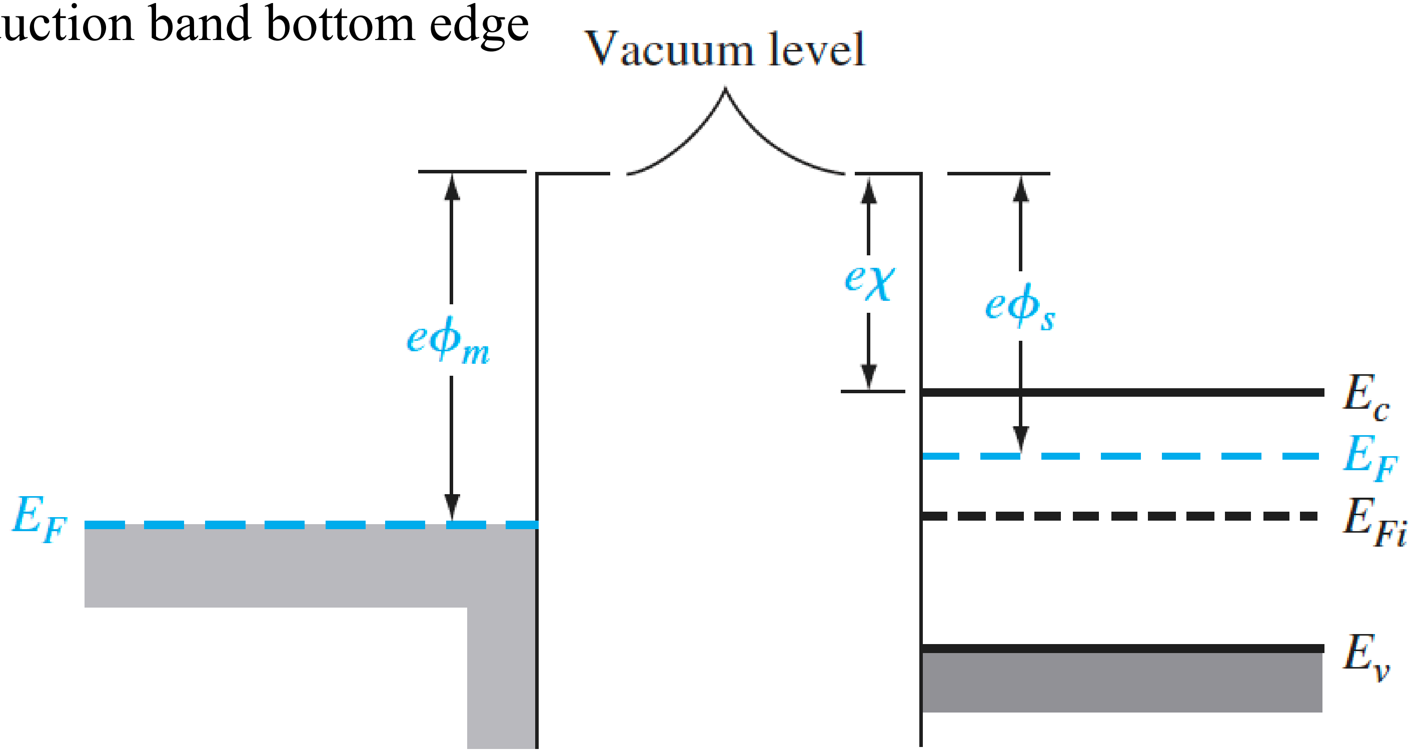
9.1 The Schottky barrier diode

9.2 Metal-semiconductor Ohmic contacts

9.1 The Schottky barrier diode

Qualitative characteristics

- Work function: energy difference between the vacuum energy level and the Fermi level
- Electron affinity: energy different between the vacuum energy level and conduction band bottom edge



9.1 The Schottky barrier diode

Qualitative characteristics

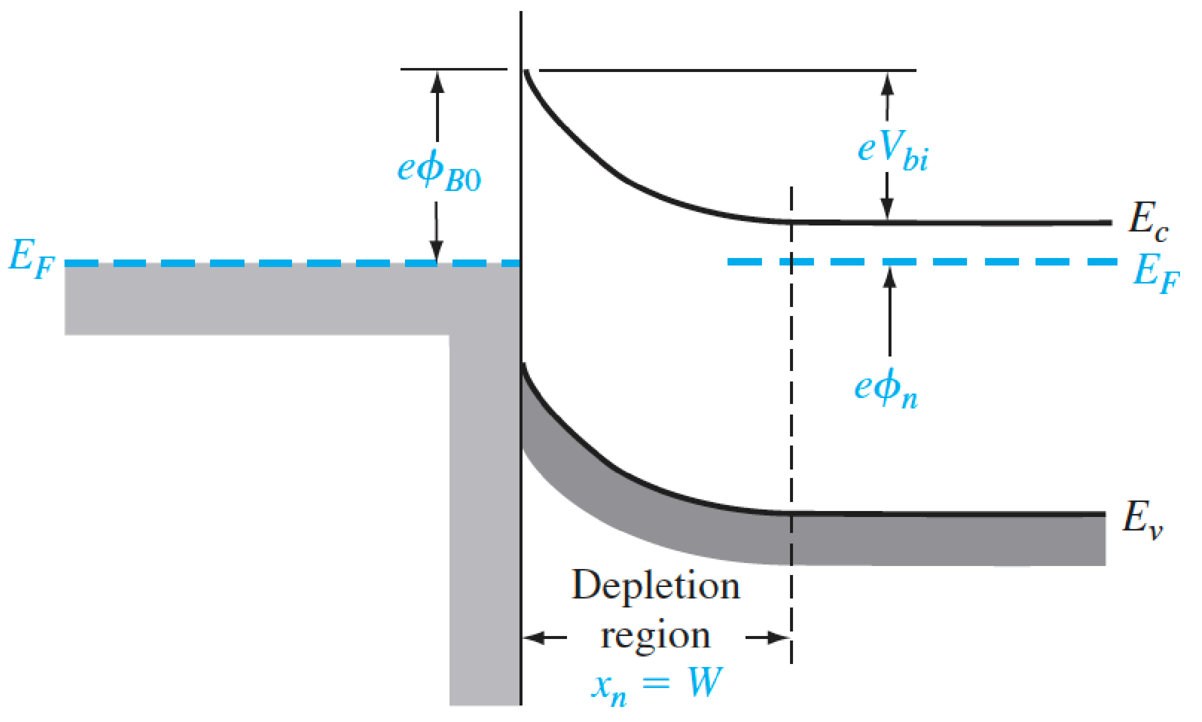
Element	Work function, ϕ_m
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

Element	Electron affinity, χ
Ge, germanium	4.13
Si, silicon	4.01
GaAs, gallium arsenide	4.07
AlAs, aluminum arsenide	3.5

9.1 The Schottky barrier diode

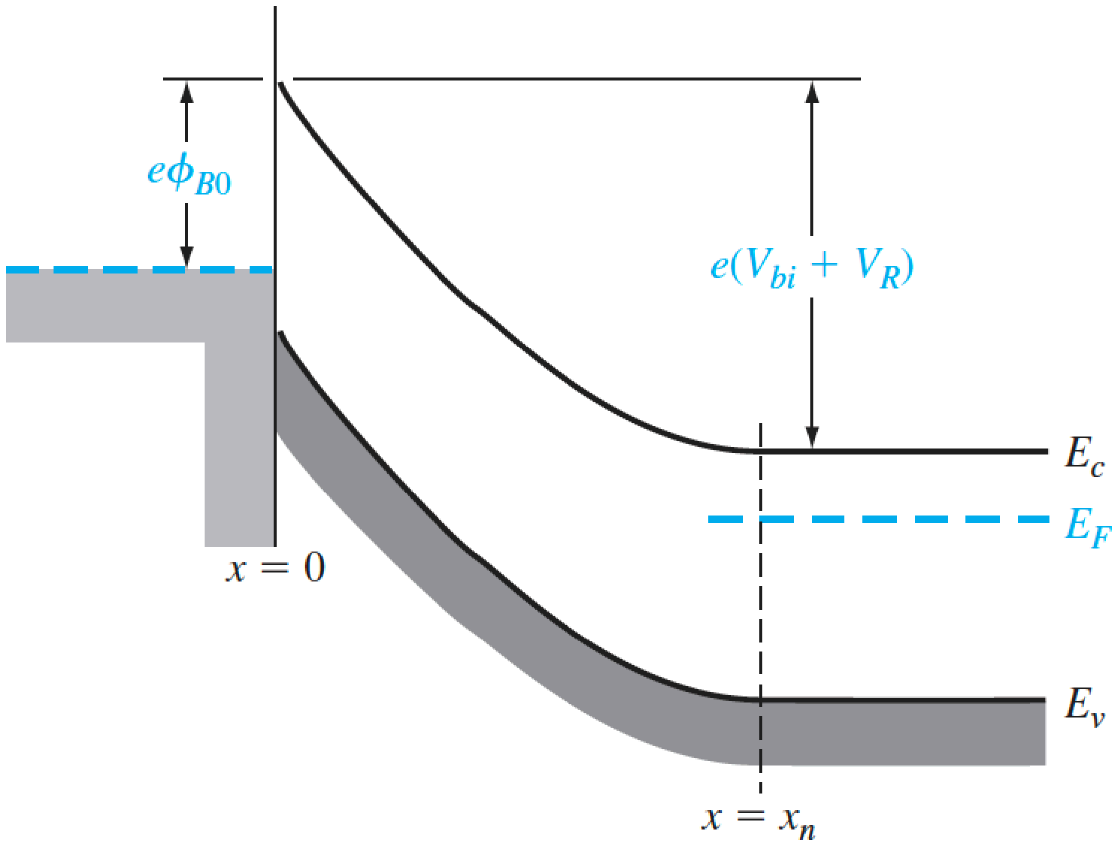
<u>Qualitative characteristics</u>

- Schottky barrier: $\phi_{B0} = (\phi_m - \chi)$
- Built-in potential barrier: $V_{\mathrm{bi}} = \phi_{B0} - \phi_n$



9.1 The Schottky barrier diode

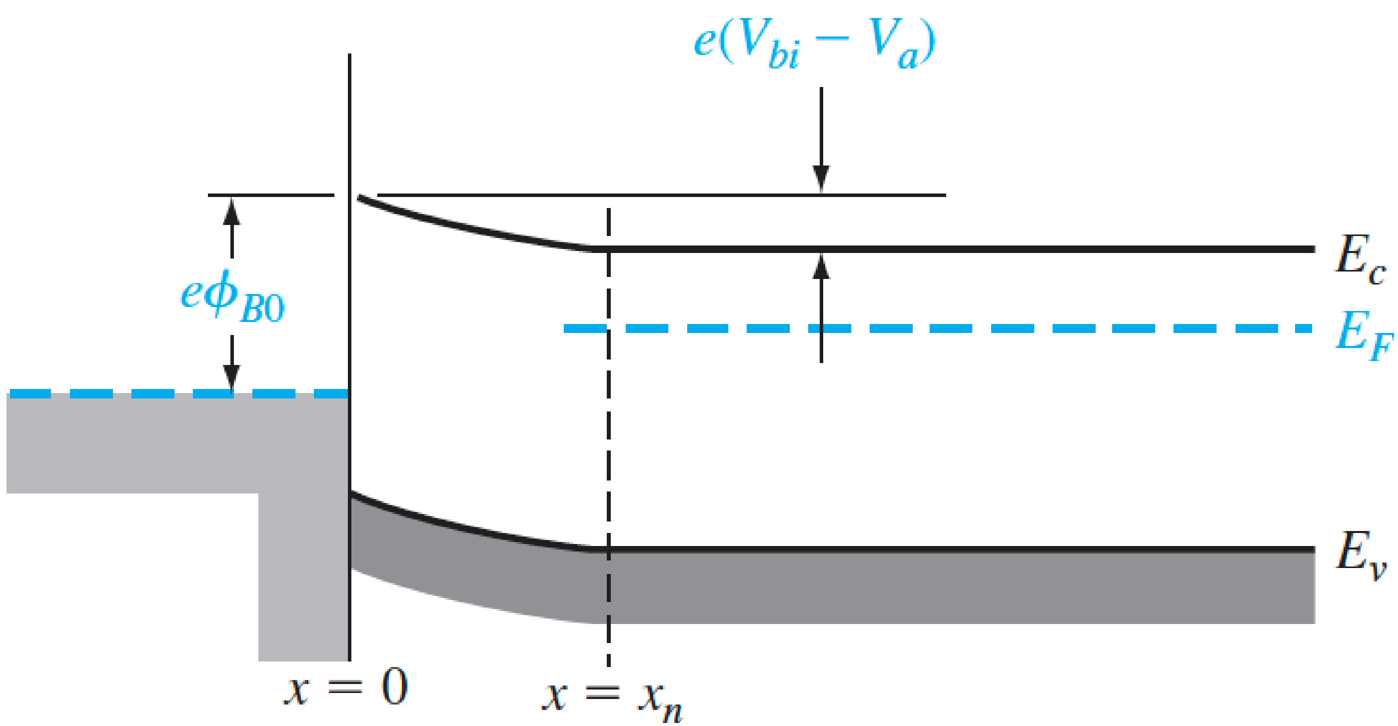
Qualitative characteristics



Reverse bias

9.1 The Schottky barrier diode

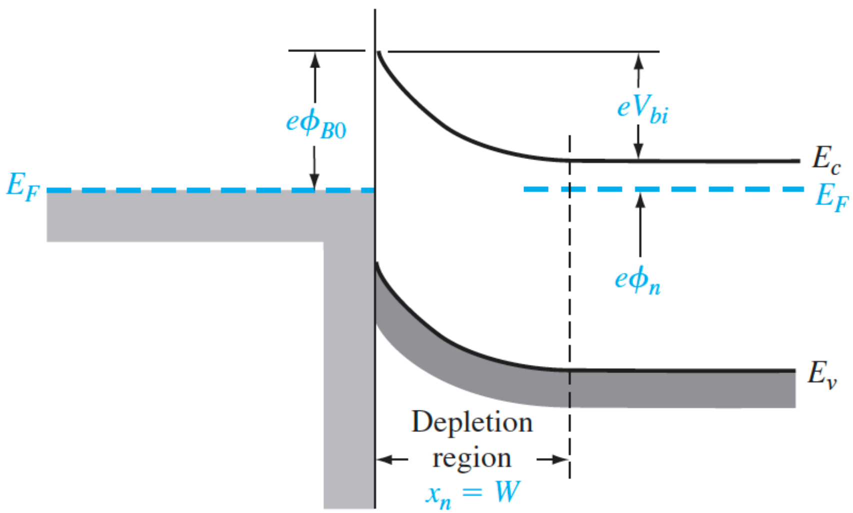
Qualitative characteristics



Forward bias

9.1 The Schottky barrier diode

Ideal junction properties



$$\frac{d\mathrm{E}}{dx} = \frac{\rho(x)}{\epsilon_s}$$

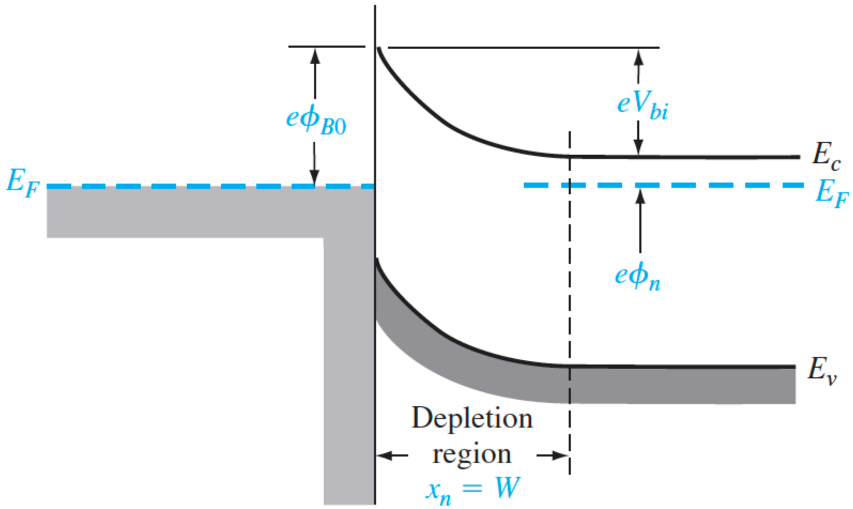
$$\mathrm{E} = \int \frac{eN_d}{\epsilon_s}dx = \frac{eN_d x}{\epsilon_s} + C_1$$

$$C_1 = -\frac{eN_d x_n}{\epsilon_s}$$

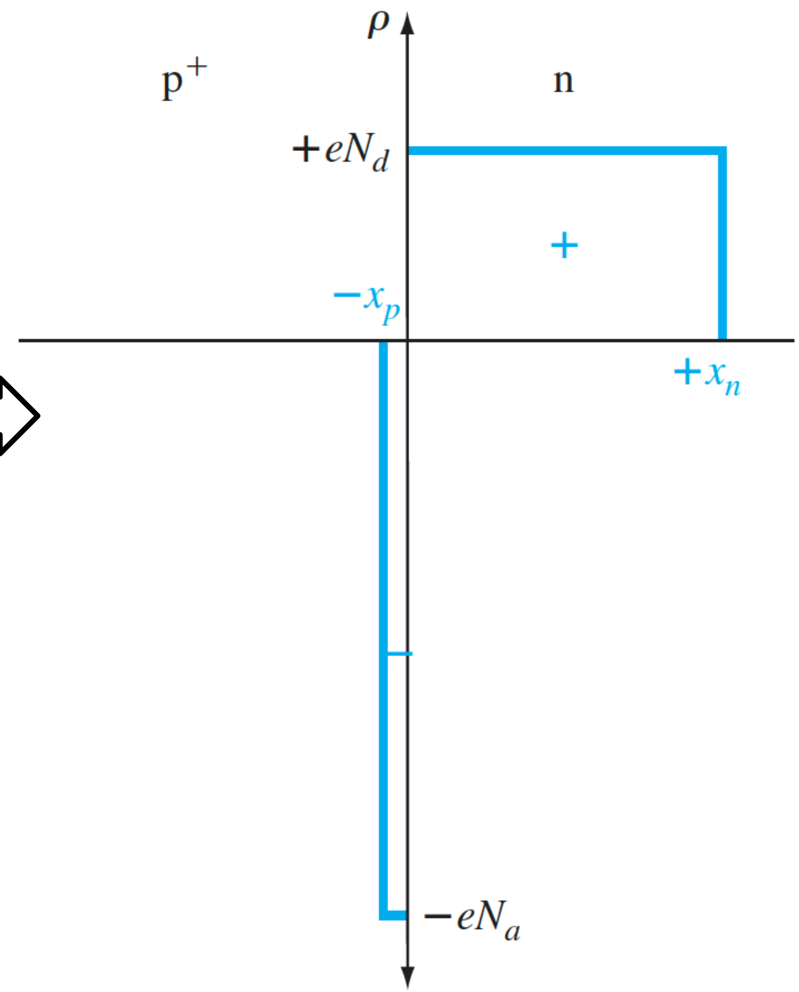
$$\mathrm{E} = -\frac{eN_d}{\epsilon_s}(x_n - x)$$

9.1 The Schottky barrier diode

Ideal junction properties



$\Leftrightarrow$



$$\boxed{W = \sqrt{\frac{2\varepsilon(V_{bi} + V_R)}{q} \frac{1}{N_d}} \approx x_n}$$

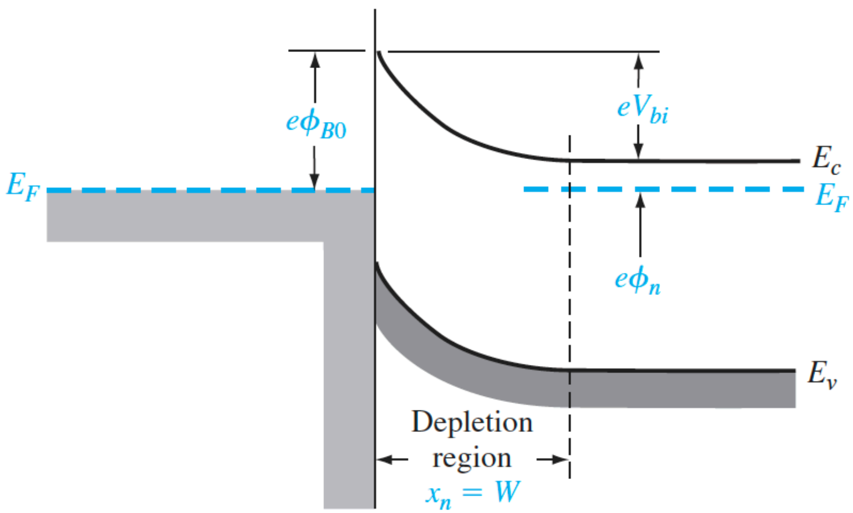
9.1 The Schottky barrier diode

Problem Example #1

Consider a contact between tungsten and n-type silicon doped to $N_d = 10^{16}$ cm^{-3} at T=300K. Determine the theoretical barrier height, built-in potential barrier and maximum electric field in the Schottky diode for zero applied bias. The work function of tungsten ϕ_m =4.55eV and electron affinity χ = 4.01eV.

9.1 The Schottky barrier diode

Ideal junction properties



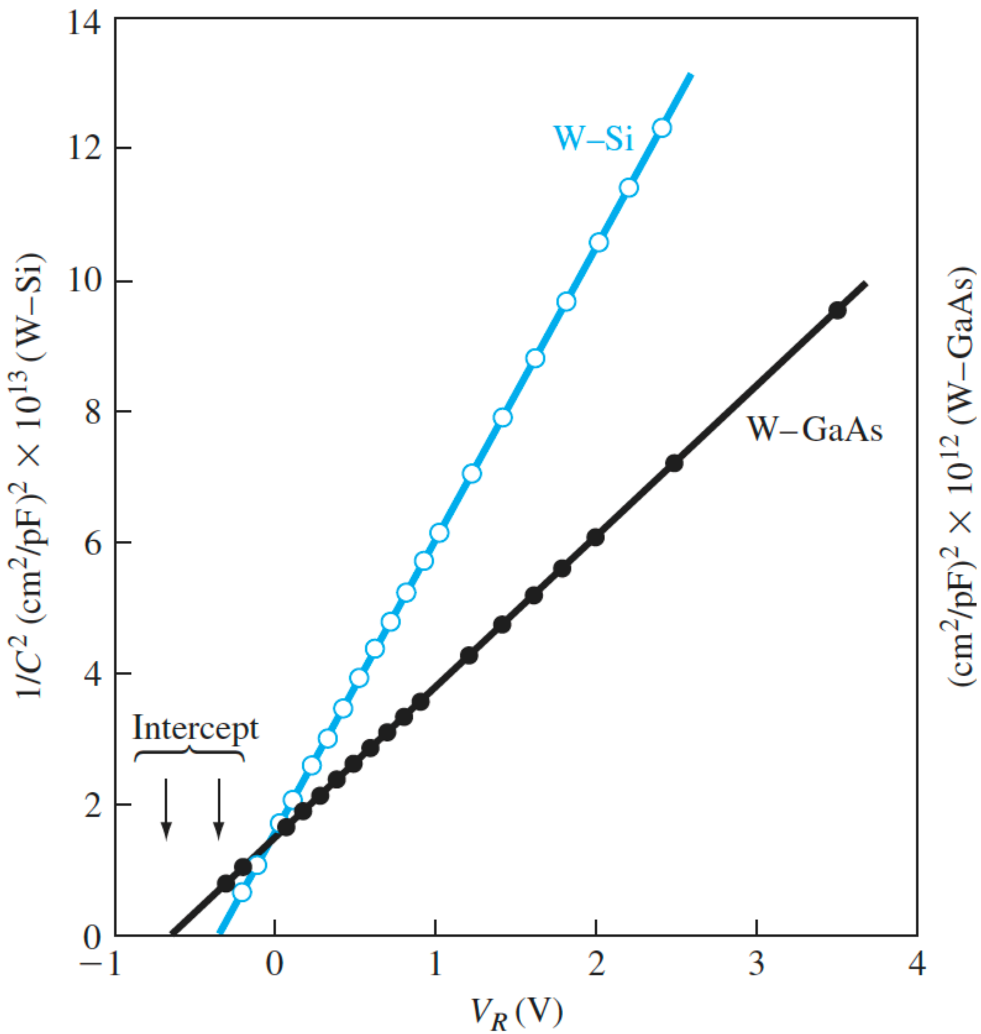
$$C' = C' = \frac{dQ}{dV_b}\Big|_{V_b=V_0} = \frac{\varepsilon}{W} = \sqrt{\frac{q\varepsilon N_D}{2\,(V_{bi}+V_R)}}$$

$$\frac{1}{C'^2} = \frac{2\,(V_{bi}+V_R)}{q\varepsilon N_D}$$

$$W = \sqrt{\frac{2\varepsilon(V_{bi}+V_R)}{q}\frac{1}{N_d}} \approx x_n$$

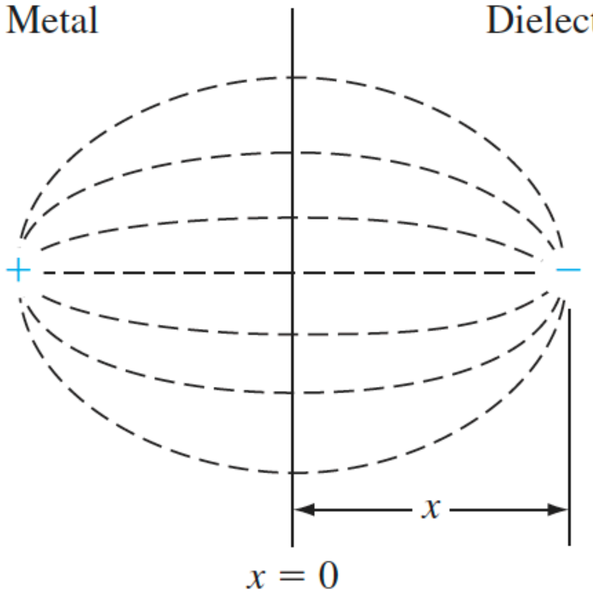
9.1 The Schottky barrier diode

<u>Ideal junction properties</u>



9.1 The Schottky barrier diode

Non-ideal effects on barrier height: charge imaging



(a)

$$F = \frac{-e^2}{4\pi\epsilon_s(2x)^2} = -e\mathrm{E}$$

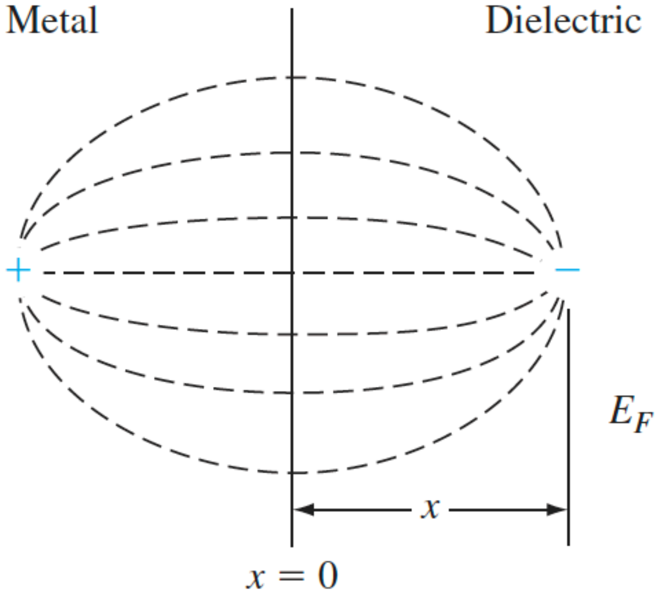
When the charge is moving from the infinity to x

$$-\phi(x) = +\int_x^{\infty} \mathrm{E}\,dx' = +\int_x^{\infty} \frac{e}{4\pi\epsilon_s \cdot 4(x')^2}\,dx' = \frac{-e}{16\pi\epsilon_s x}$$

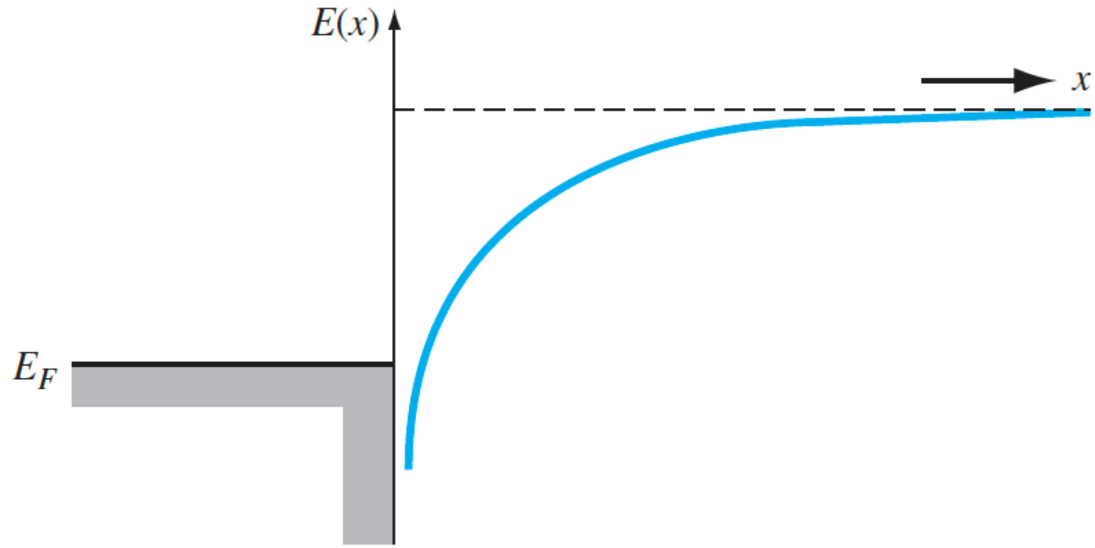
Imaging charges

9.1 The Schottky barrier diode

Non-ideal effects on barrier height: charge imaging



(a)



(b)

$$-\phi(x) = +\int_x^{\infty} \mathrm{E}\,dx' = +\int_x^{\infty} \frac{e}{4\pi\epsilon_s \cdot 4(x')^2}\,dx' = \frac{-e}{16\pi\epsilon_s x}$$

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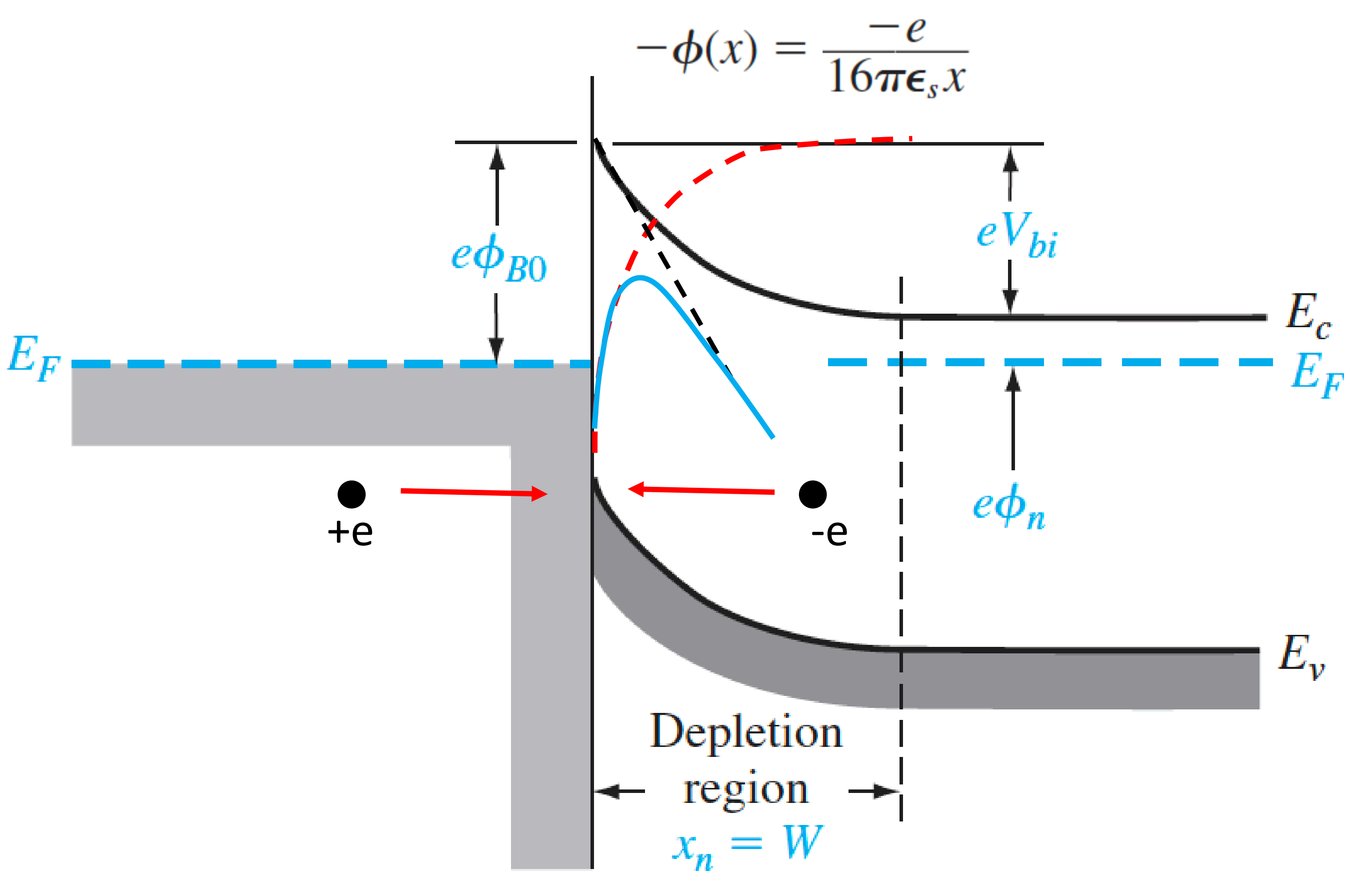
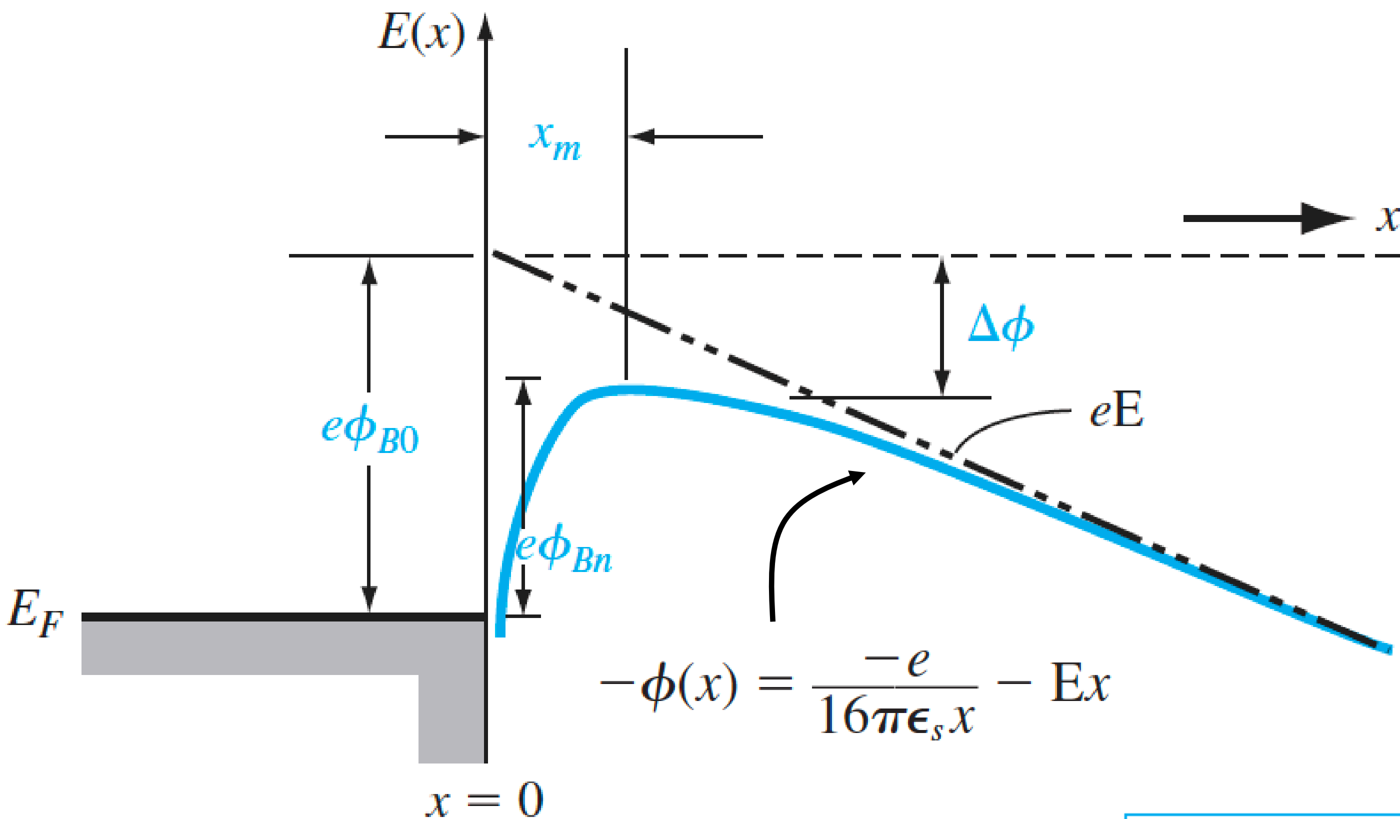
Non-ideal effects on barrier height: charge imaging



9.1 The Schottky barrier diode

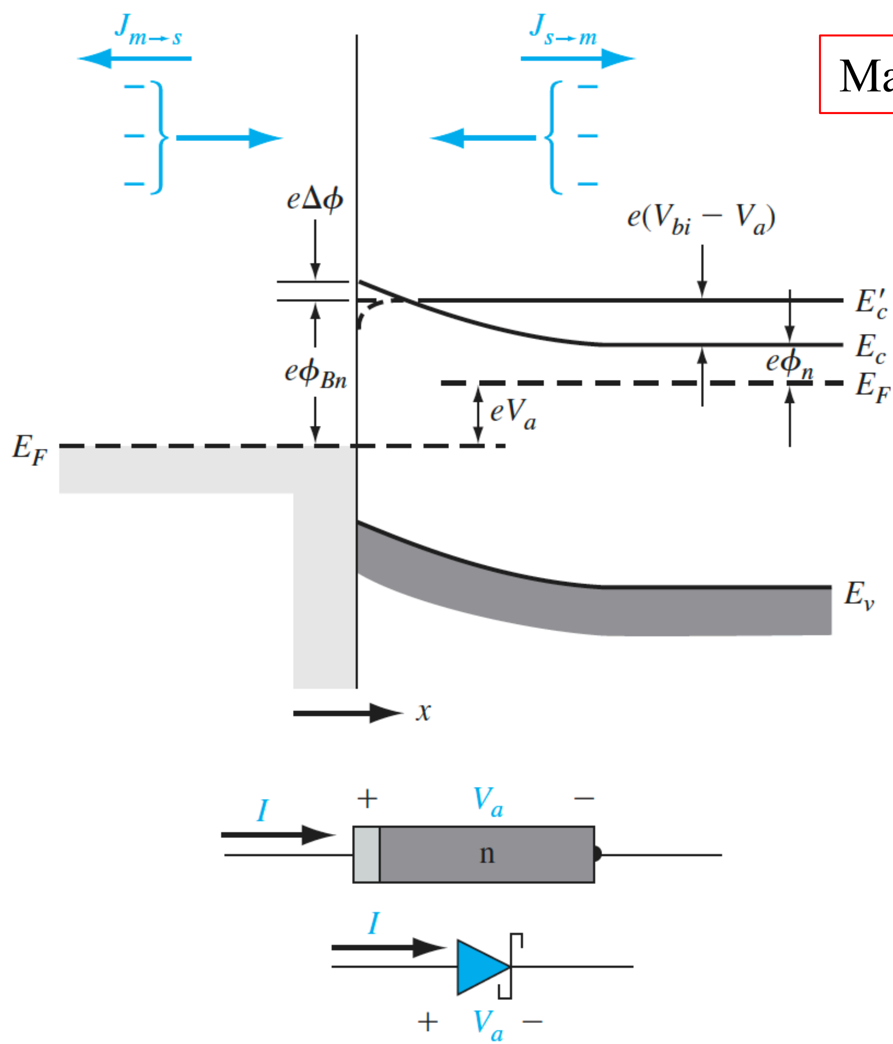
Non-ideal effects on barrier height: charge imaging



$$\frac{d[e\phi(x)]}{dx} = 0 \Longrightarrow \boxed{\Delta\phi = \sqrt{\frac{e\mathrm{E}}{4\pi\epsilon_s}}}$$

9.1 The Schottky barrier diode

Current-voltage relationship



Majority carrier device

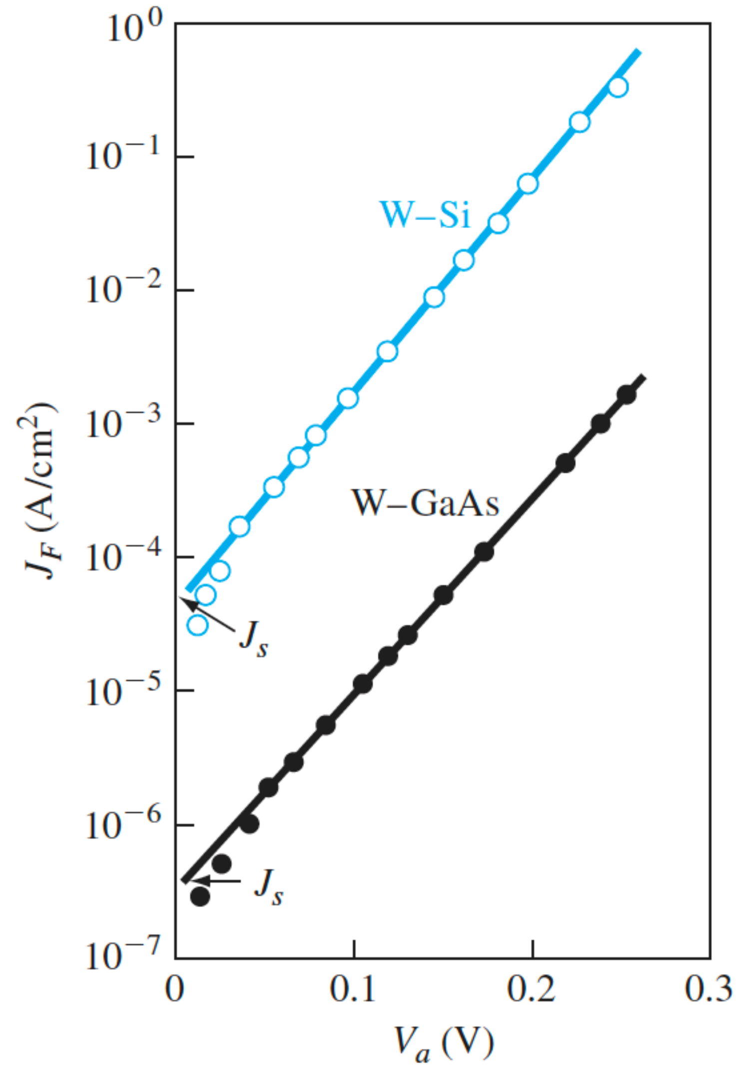
9.1 The Schottky barrier diode

Current-voltage relationship

$$J = J_{sT}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$$J_{sT} = A^* T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)$$

$$A^* \equiv \frac{4\pi e m_n^* k^2}{h^3}$$



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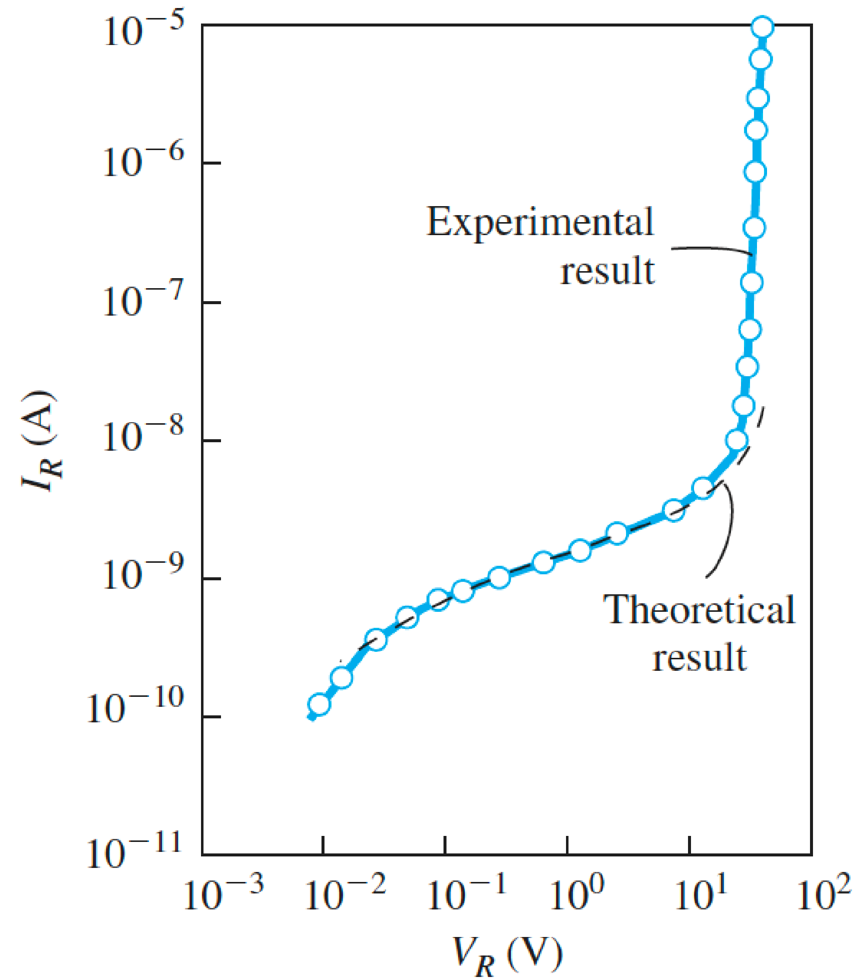
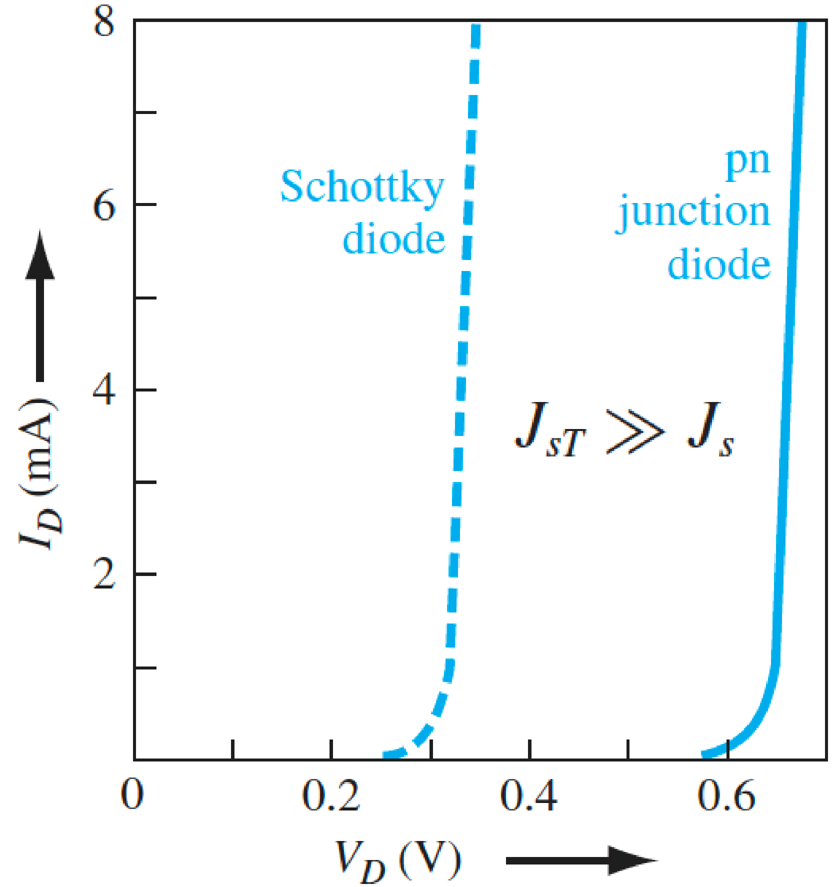


$$J_{sT} = A^*T^2 \exp\left(\frac{-e\phi_{B0}}{kT}\right)\exp\left(\frac{e\Delta\phi}{kT}\right)$$

9.1 The Schottky barrier diode

Current-voltage relationship



$$\boxed{J = J_{sT}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]}$$

$$\boxed{J_{sT} = A^*T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)}$$

$$J_s = \frac{eD_n n_{po}}{L_n} + \frac{eD_p p_{no}}{L_p}$$

Outline

9.1 The Schottky barrier diode

9.2 Metal-semiconductor Ohmic contacts

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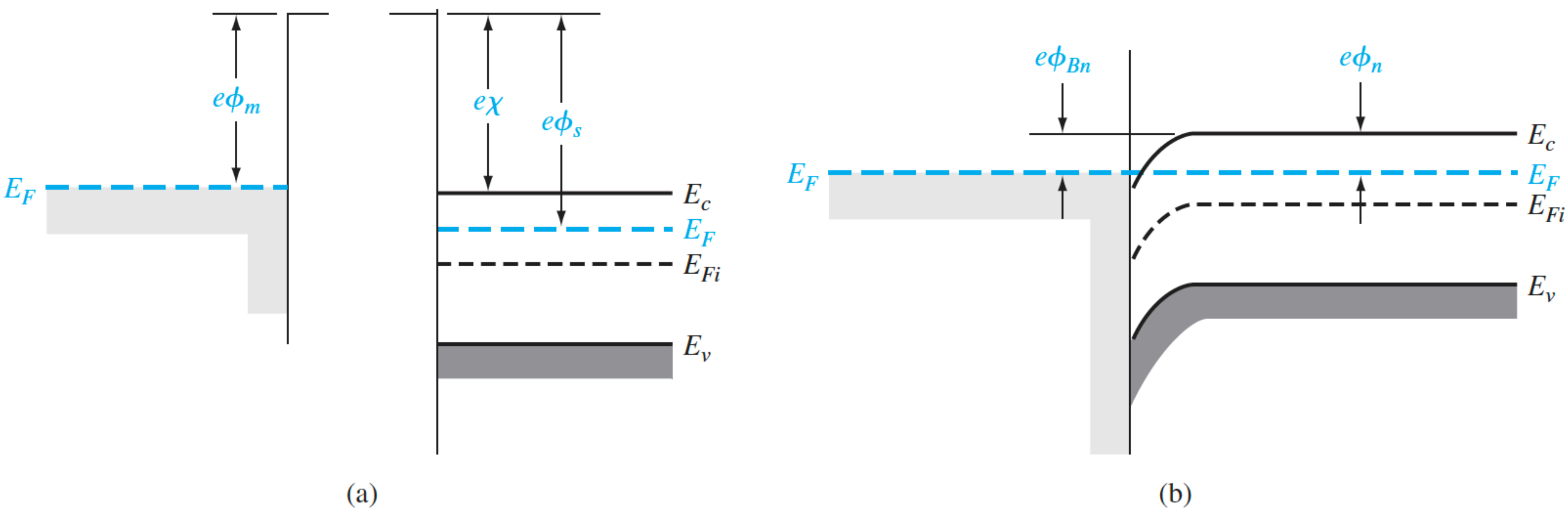
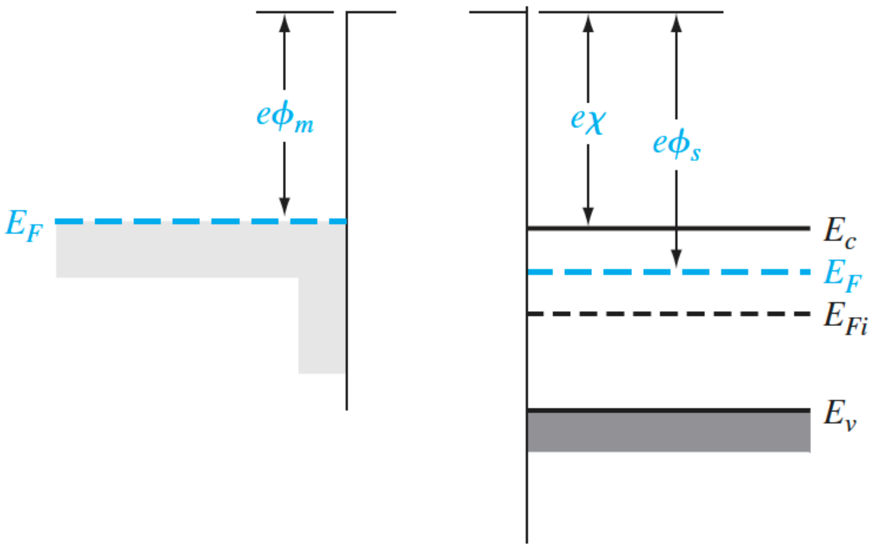
Ideal Nonrectifying Barrier

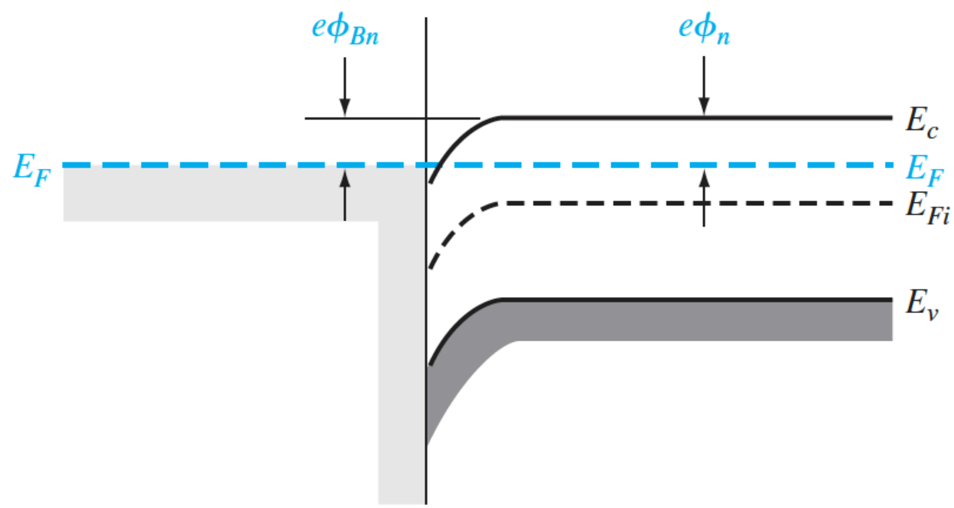


9.2 Metal-semiconductor Ohmic contacts

Ideal Nonrectifying Barrier



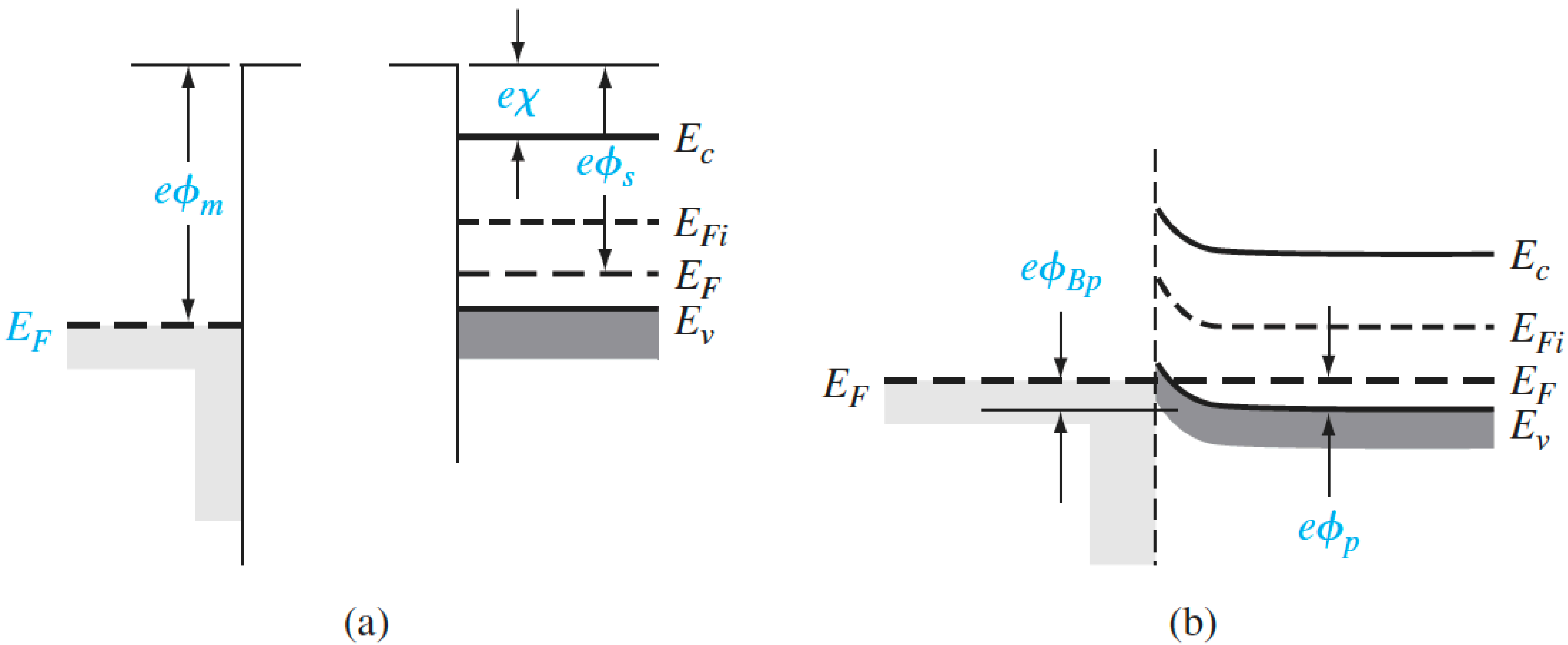
(a)



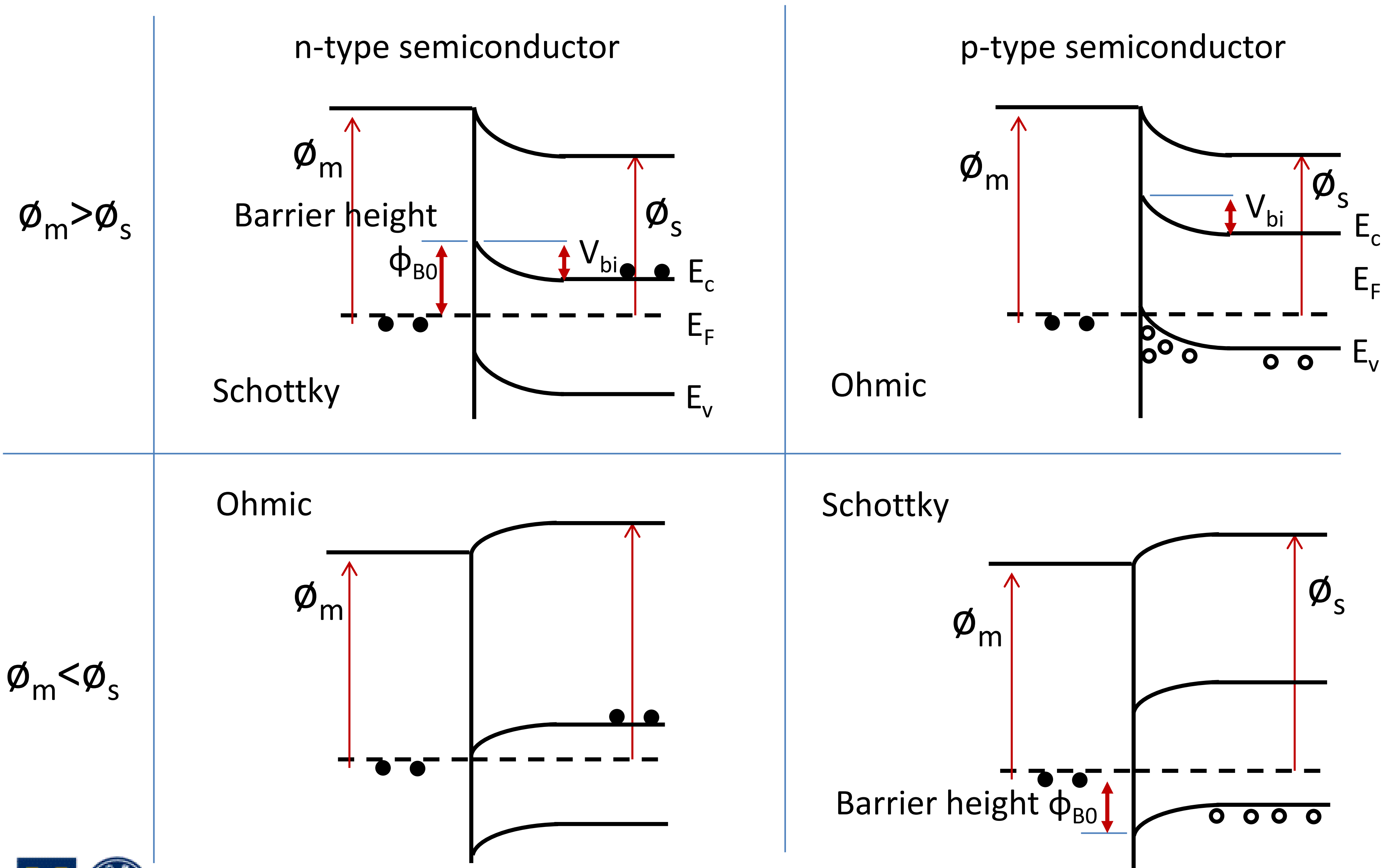
(b)

9.2 Metal-semiconductor Ohmic contacts

Ideal Nonrectifying Barrier

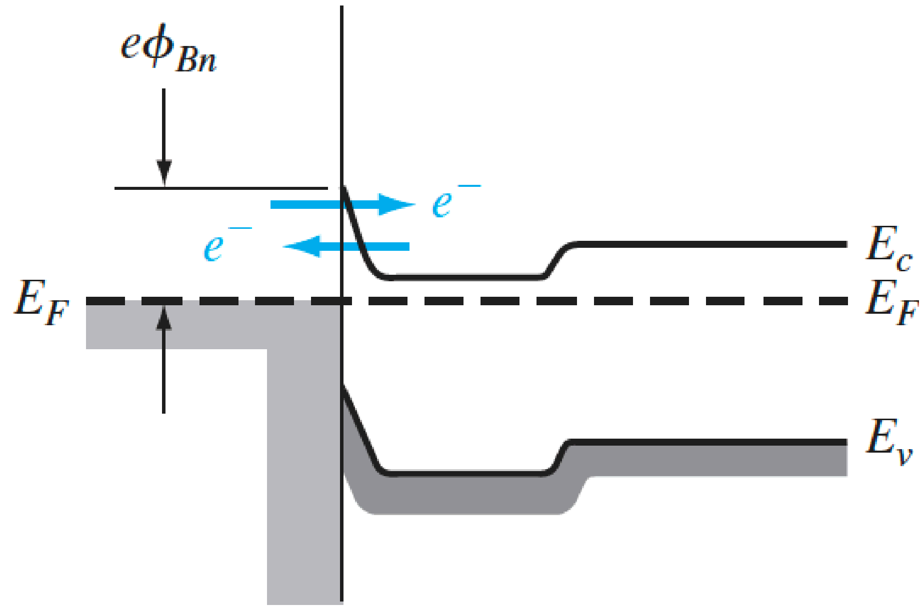


9.2 Metal-semiconductor Ohmic contacts



9.2 Metal-semiconductor Ohmic contacts

Tunneling Barrier



The tunneling current has the form

$$J_t \propto \exp\left(\frac{-e\phi_{Bn}}{E_{oo}}\right)$$

where

$$E_{oo} = \frac{e\hbar}{2}\sqrt{\frac{N_d}{\epsilon_s m_n^*}}$$

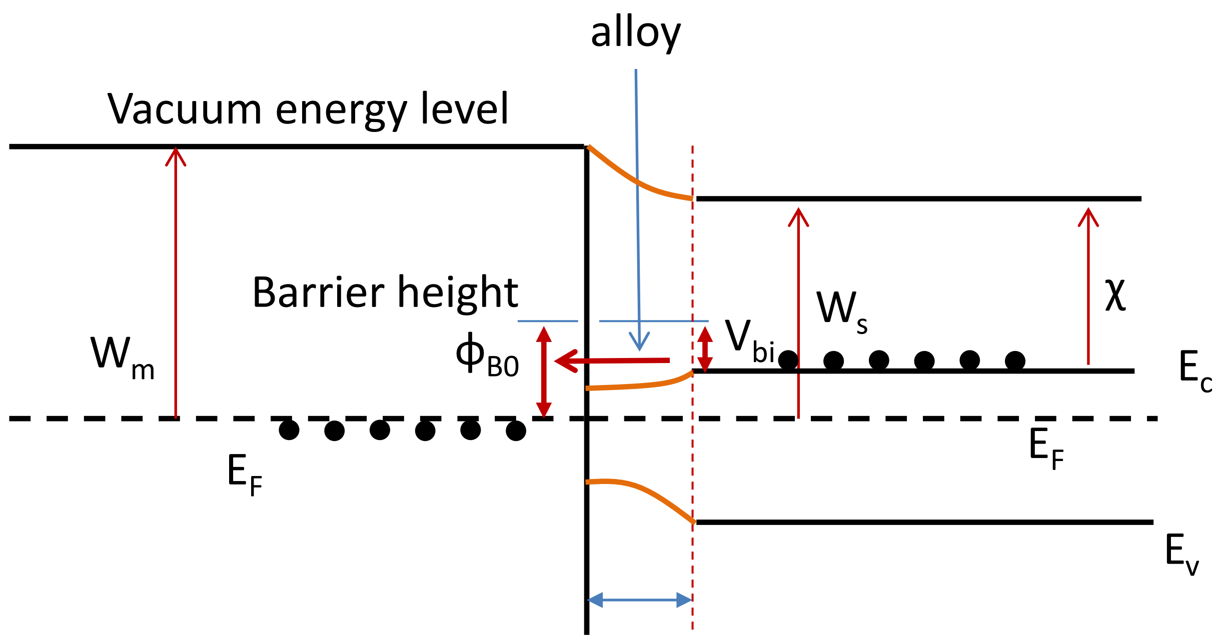
The tunneling current increases exponentially with doping concentration.

9.2 Metal-semiconductor Ohmic contacts

Silicide alloy

Nickel silicide, NiSi

Titanium silicide, $TiSi_2$



silicide

9.2 Metal-semiconductor Ohmic contacts

Specific contact resistance

$$R_c = \left(\frac{\partial J}{\partial V}\right)^{-1}\Bigg|_{V=0} \qquad \Omega\text{-cm}^2$$

$$J_n = A^*T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

$$R_c = \frac{\left(\frac{kT}{e}\right)\exp\left(\frac{+e\phi_{Bn}}{kT}\right)}{A^*T^2}$$