VE320 – Summer 2024

Introduction to Semiconductor Devices

Instructor: Yaping Dan （但亚平）
yaping.dan@sjtu.edu.cn

Chapter 9 Metal-Semiconductor Schottky Junction

Outline

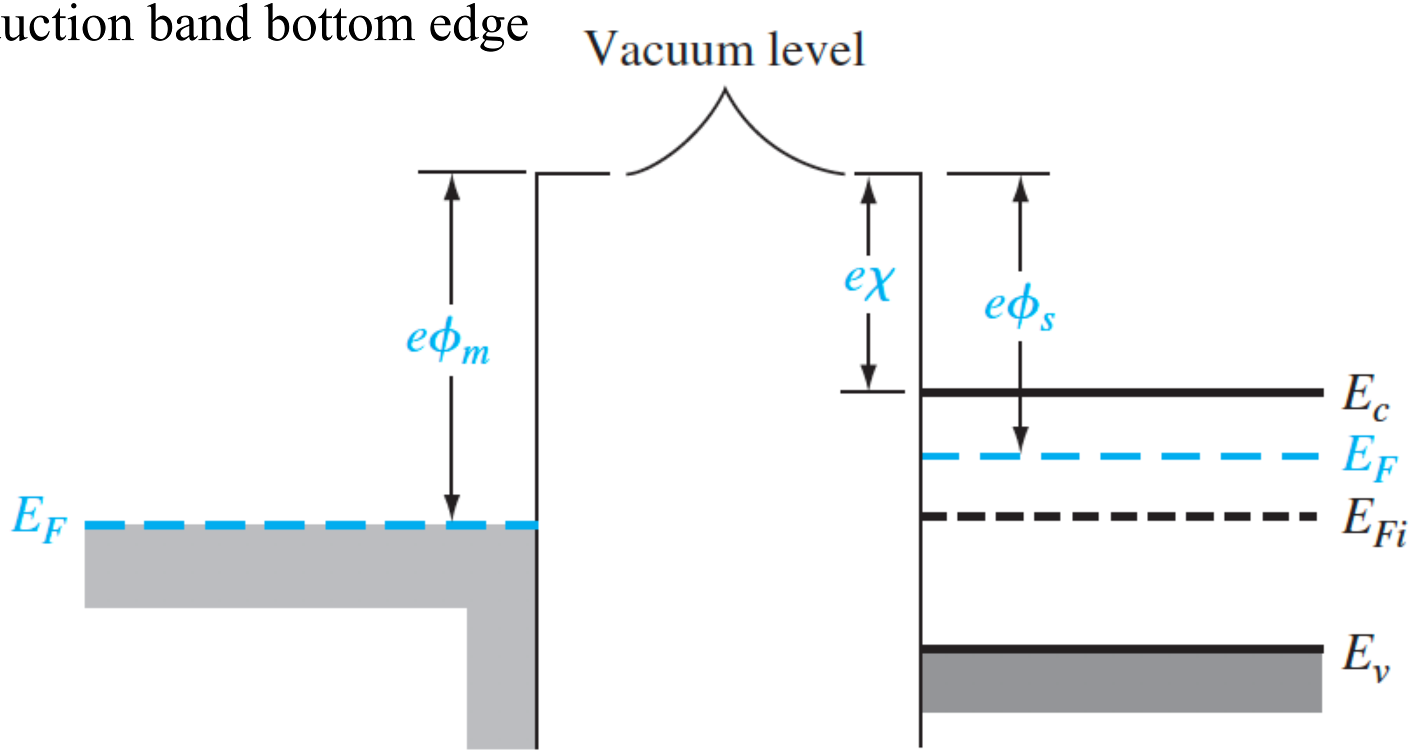
9.1 The Schottky barrier diode

9.2 Metal-semiconductor Ohmic contacts

9.1 The Schottky barrier diode

<u>Qualitative characteristics</u>

- 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

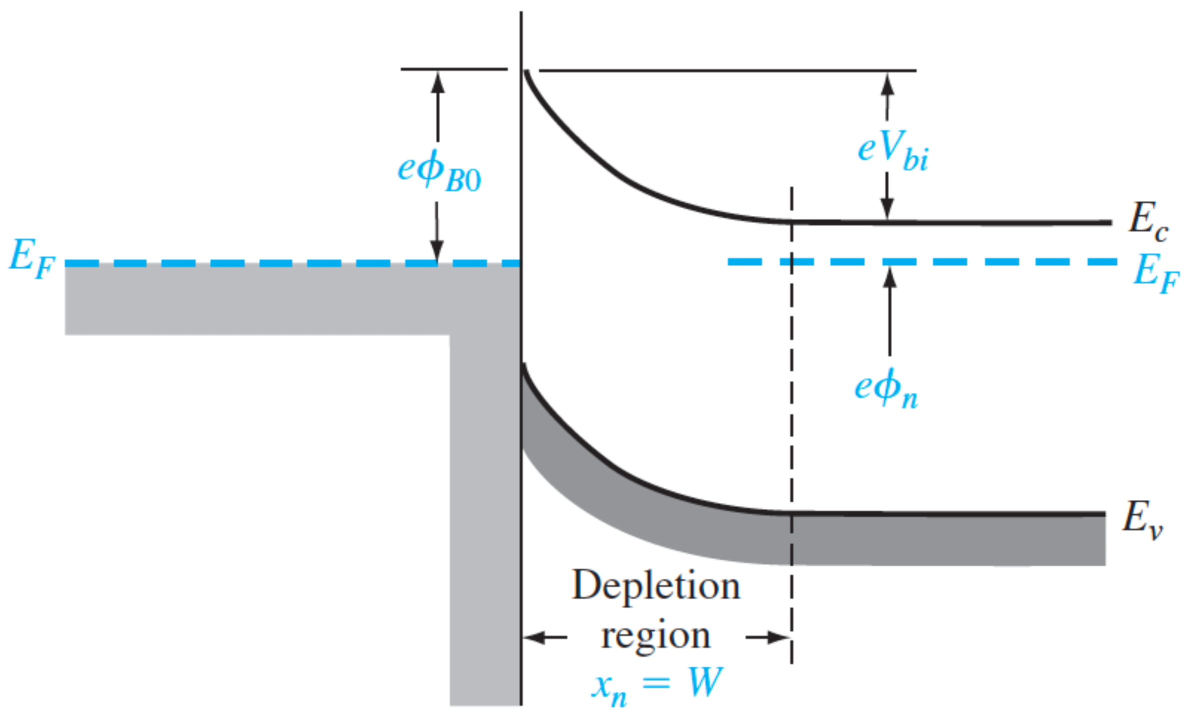
Element	Work function, ϕ_m
Ag, silver	4.26
Al, aluminum	4.28
Au, gold	5.1
Cr, chromium	4.5
Mo, molybdenum	4.6
Ni, nickel	5.15
Pd, palladium	5.12
Pt, platinum	5.65
Ti, titanium	4.33
W, tungsten	4.55

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

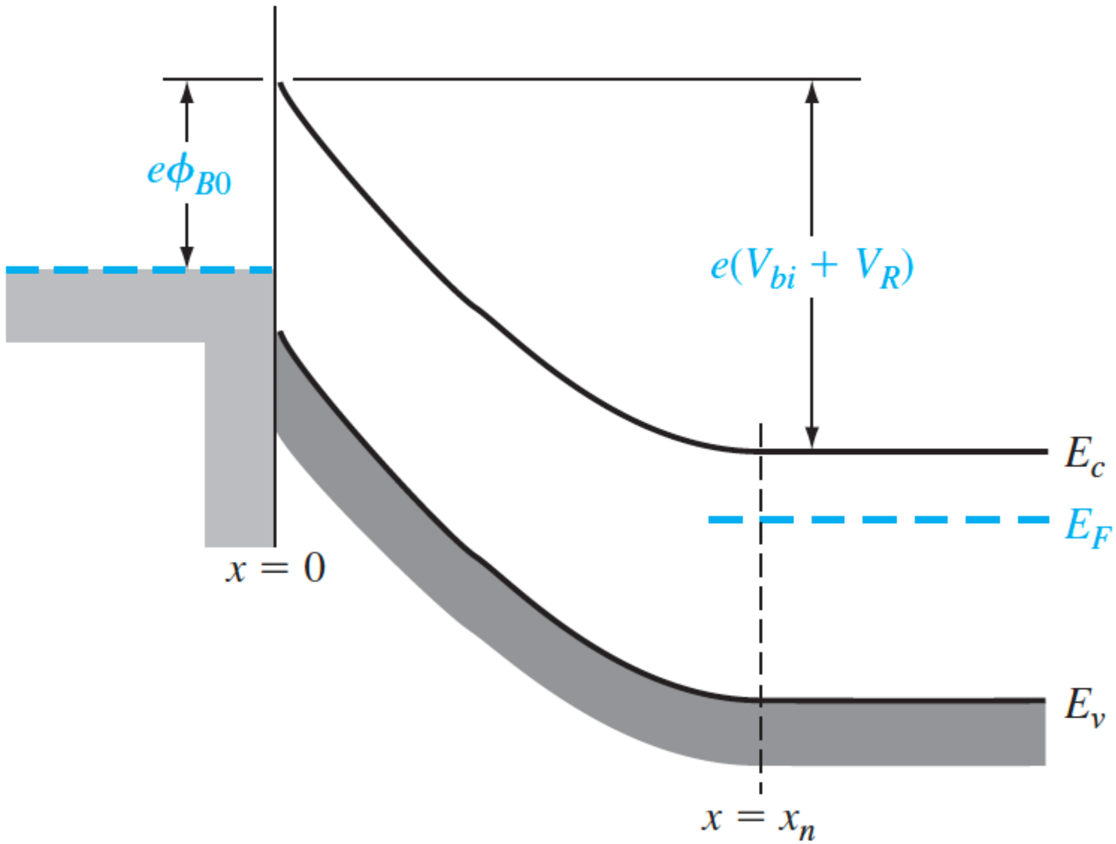
Qualitative characteristics

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



9.1 The Schottky barrier diode

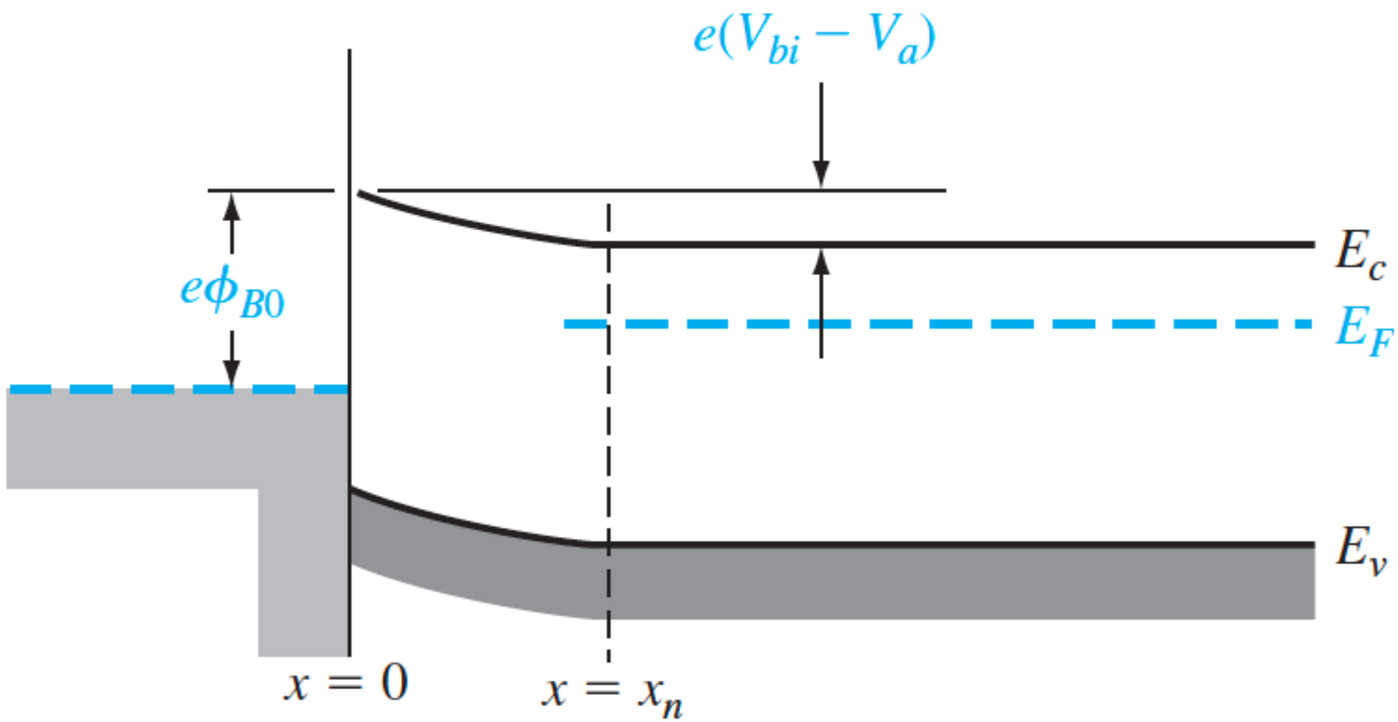
Qualitative characteristics



Reverse bias

9.1 The Schottky barrier diode

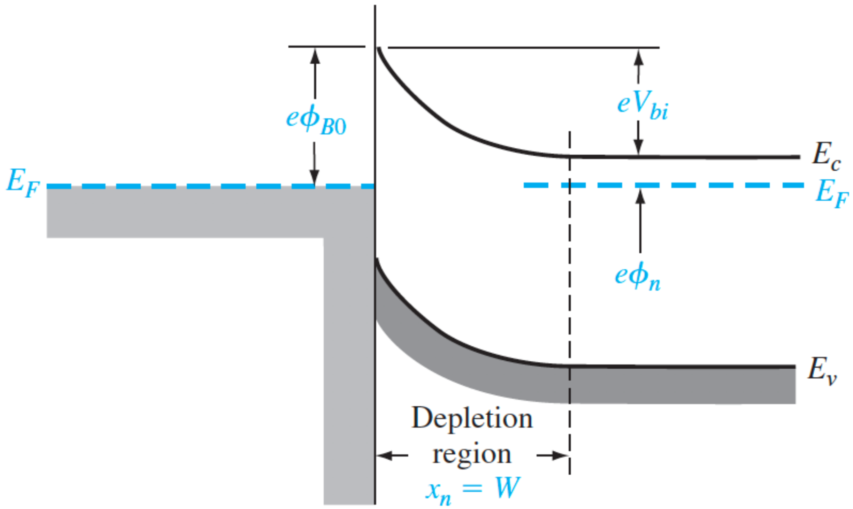
Qualitative characteristics



Forward bias

9.1 The Schottky barrier diode

Ideal junction properties



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

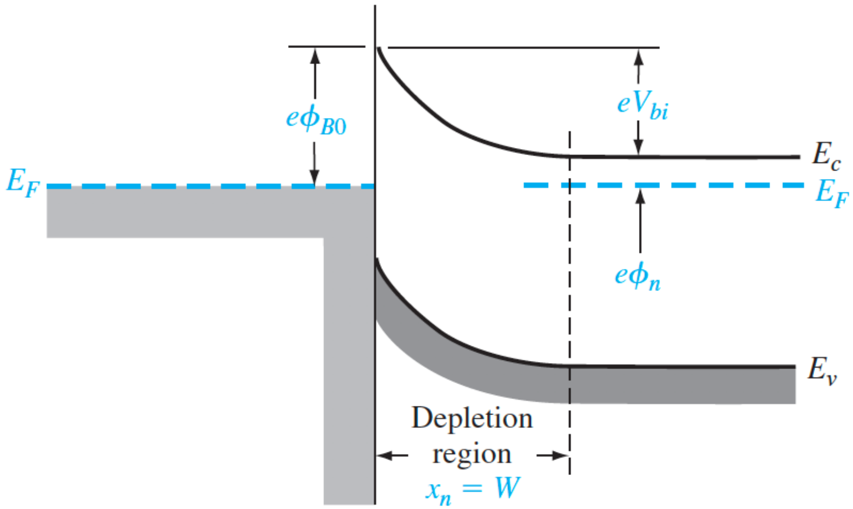
$$\mathrm{E} = \int \frac{eN_d}{\epsilon_s}\,dx = \frac{eN_d x}{\epsilon_s} + C_1$$

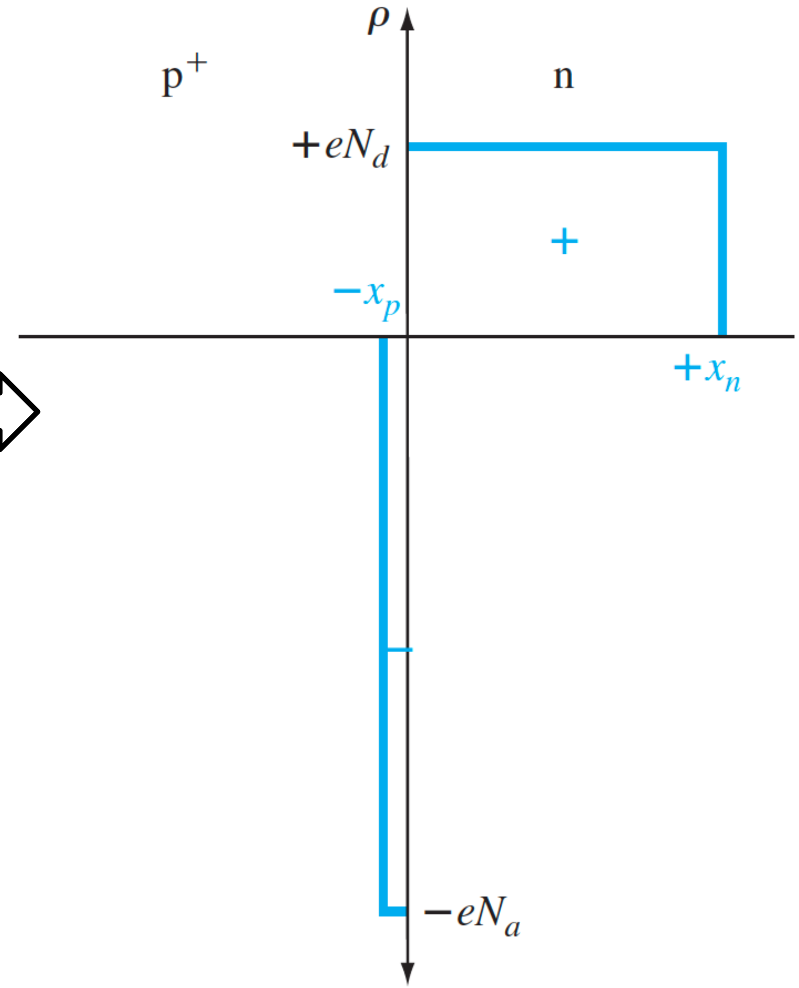
$$C_1 = -\frac{eN_d x_n}{\epsilon_s}$$

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

9.1 The Schottky barrier diode

Ideal junction properties





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

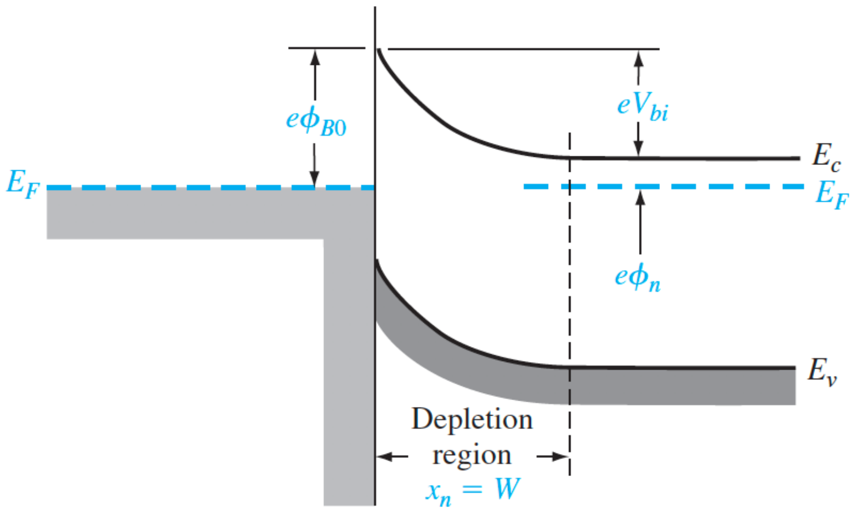
9.1 The Schottky barrier diode

Problem Example #1

A metal-semiconductor junction is formed between a metal with a work function of 4.3 eV and p-type silicon with an electron affinity of 4.0 eV. The acceptor doping concentration in the silicon is $N_a = 5 \times 10^{16}$ cm^{-3}. Assume T = 300K. (a) Sketch the 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 = 3V. (d) Sketch the energy-band diagram with applied forward-bias voltage of V_a = 0.25V. (15 points).

9.1 The Schottky barrier diode

Ideal junction properties



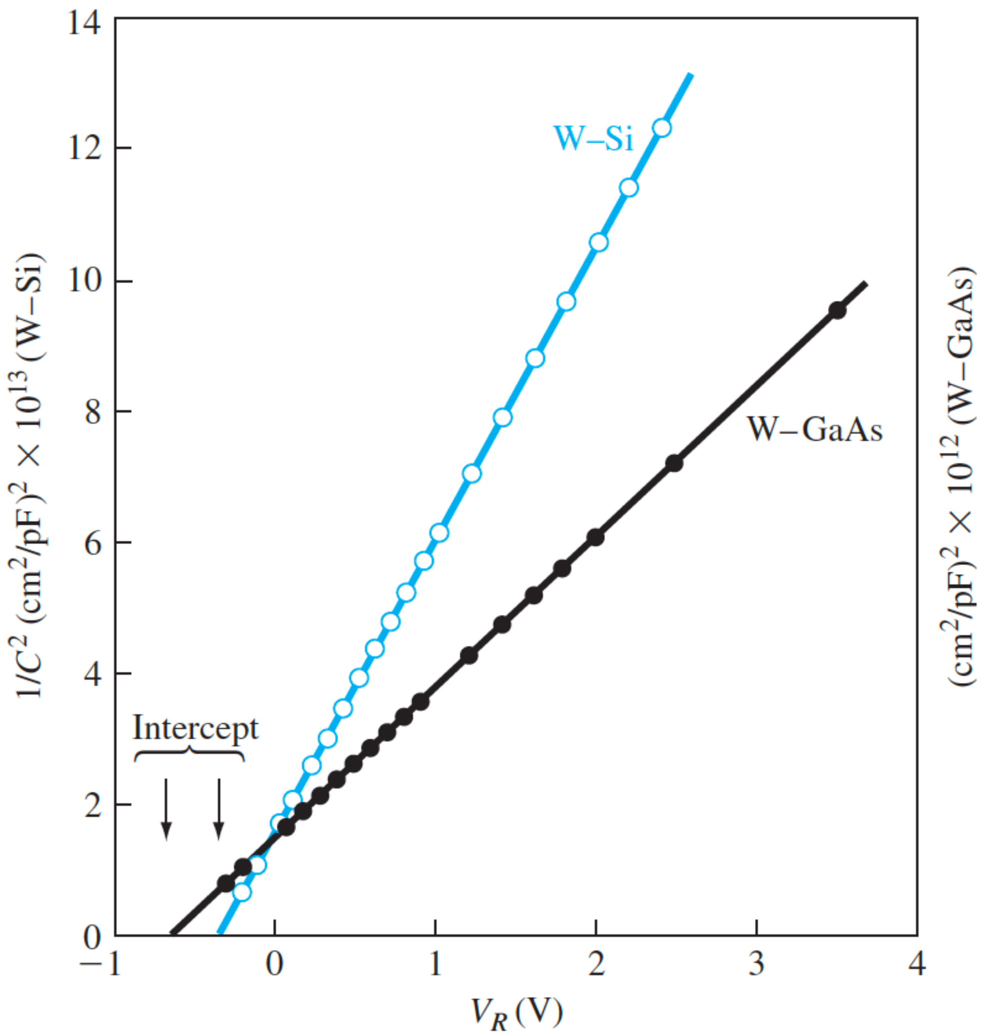
$$C' = C' = \frac{dQ}{dV_b}\Big|_{V_b=V_0} = \frac{\varepsilon}{W} = \sqrt{\frac{q\varepsilon N_D}{2\,(V_{bi}+V_R)}}$$

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

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

9.1 The Schottky barrier diode

Ideal junction properties



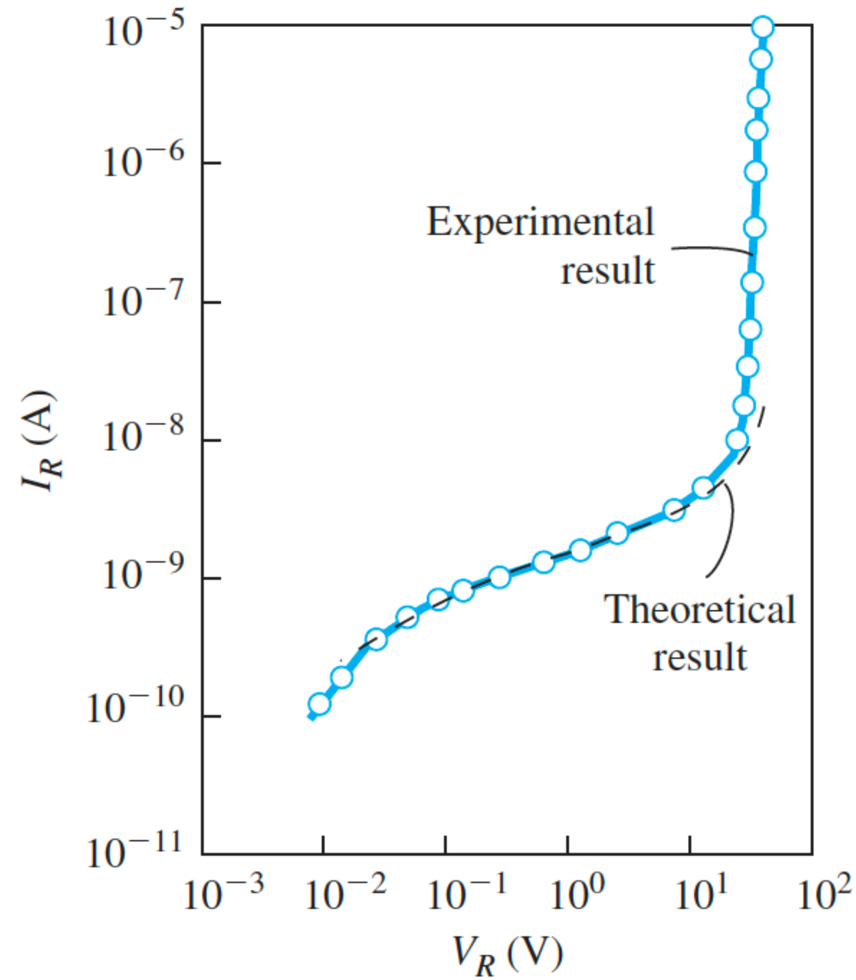
9.1 The Schottky barrier diode

Current-voltage relationship

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

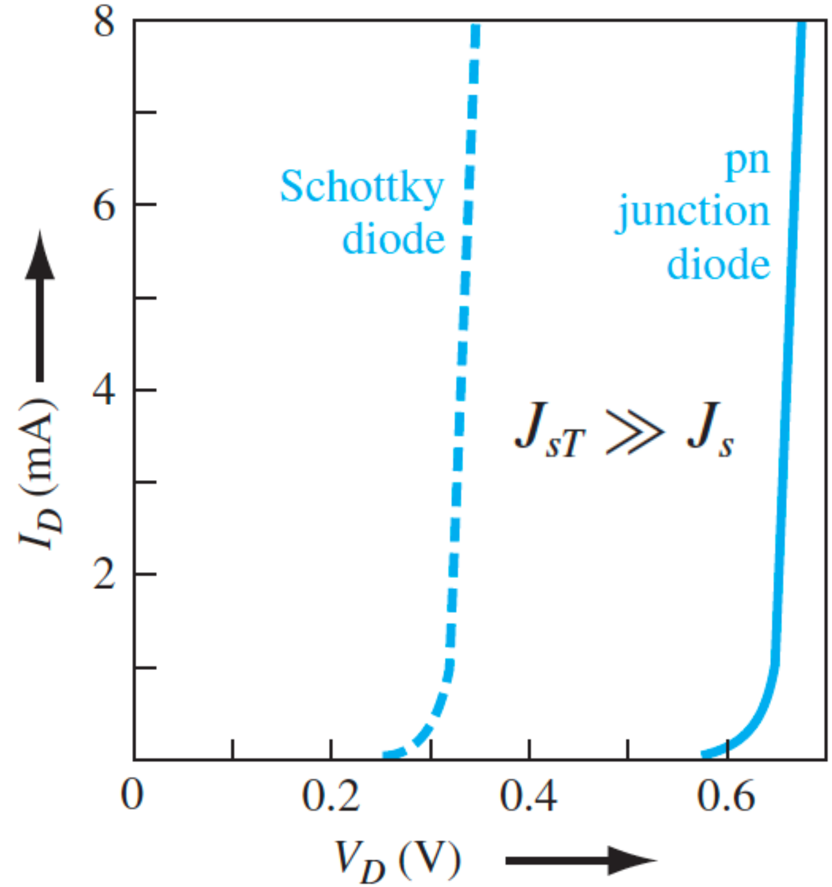
$$J_{sT} = A^*T^2 \exp\left(\frac{-e\phi_{Bn}}{kT}\right)$$

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



9.1 The Schottky barrier diode

Current-voltage relationship



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

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

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

Richardson constant

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

Check your understanding

Problem example #2

Consider a tungsten barrier on silicon with a measured barrier height of ϕ_{Bn} = 0.67eV. The effective Richardson constant is A^* = 114 A/K^2cm^2. T = 300K.

Check your understanding

Problem example #3

Control of the Schottky Barrier Height in Monolayer WS_2 FETs using Molecular Doping

*Siyuan Zhang, Hsun- Jen Chuang, Son T. Le, Curt A. Richter, Kathleen M. McCreary, Berend T. Jonker, Angela R. Hight Walker, Christina A. Hacker**

Dr. S. Zhang, Dr. S. T. Le
Theiss Research, La Jolla, CA 92037, USA

Dr. H.- J. Chuang,
Nova Research Inc
Washington DC 20375, USA

Dr. K. M. McCreary, Dr. B. T. Jonker
Material Science & Technology Division, Naval Research Laboratory
Washington, DC 20375, USA

Dr. S. Zhang, Dr. S. T. Le, Dr. C. A. Richter, Dr. A. R. Hight Walker, Dr. C. A. Hacker
Physical Measurement Laboratory, National Institute of Standards and Technology (NIST)
Gaithersburg, MD 20899, USA
E-mail: christina.hacker@nist.gov

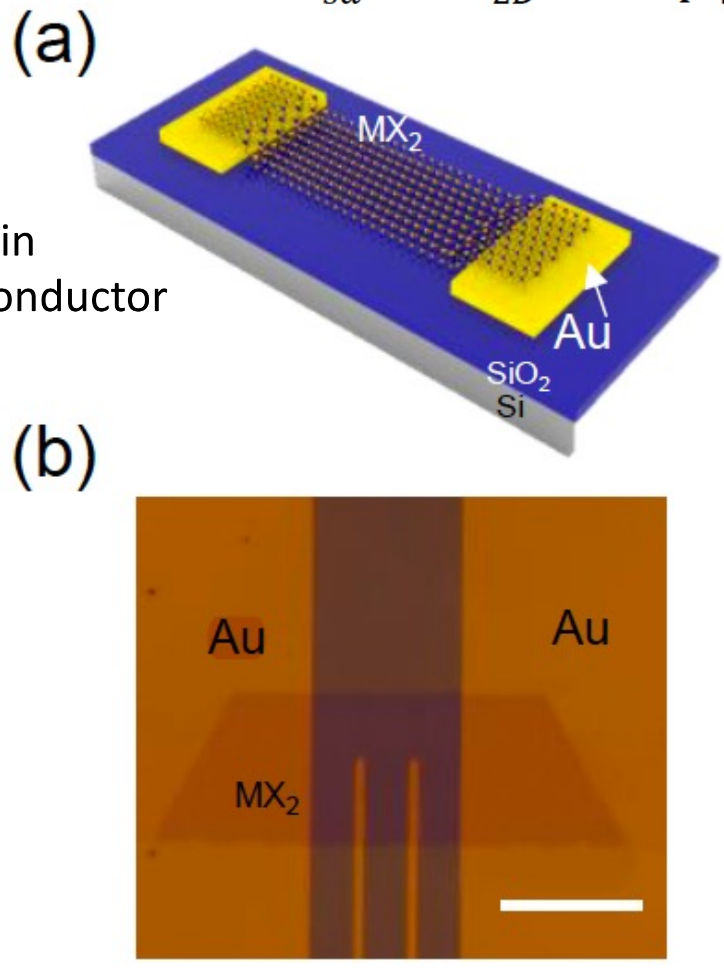
Under review in AIP Advances

Check your understanding

Problem example #3

$$I_{sd} = AA^*_{2D}T^{3/2}\exp\left[-\frac{q}{k_B T}\left(\Phi_B - \frac{V_{ds}}{n}\right)\right]$$

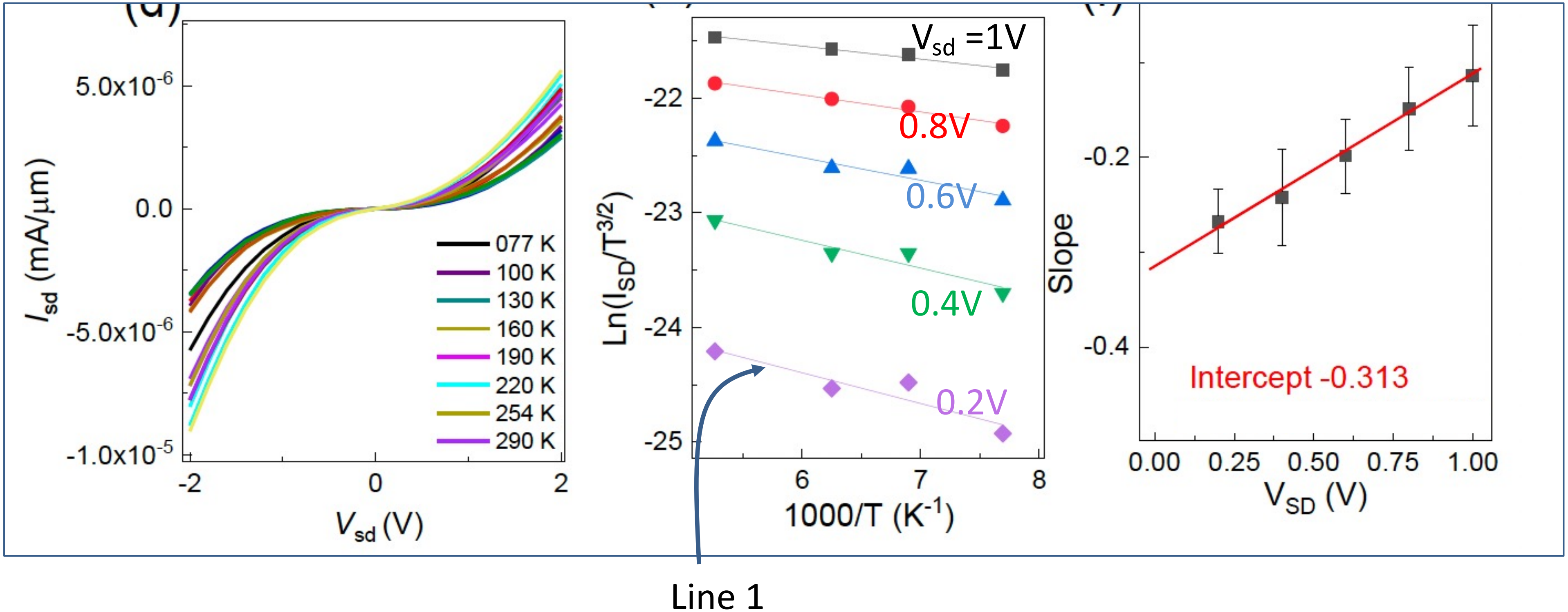
WS_2 atomically thin monolayer semiconductor



Check your understanding

Problem example #3

$$I_{sd} = AA_{2D}^{*}T^{3/2}\exp\left[-\frac{q}{k_BT}\left(\Phi_B - \frac{V_{ds}}{n}\right)\right]$$



1) Write the analytical expression of Line 1 if we take 1000/T as x and ln(ISD/T2/3) as y?
2) Write the expression of Slope in the right figure.
3) Find Schottky barrier height Φ_B

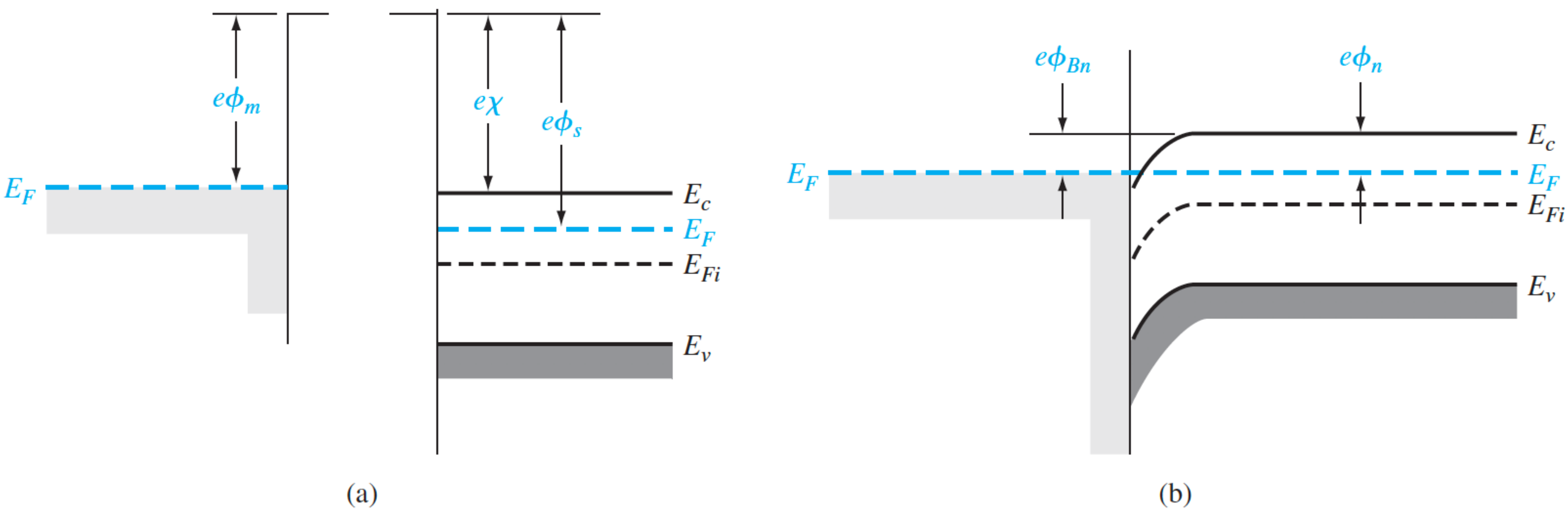
Outline

9.1 The Schottky barrier diode

9.2 Metal-semiconductor Ohmic contacts

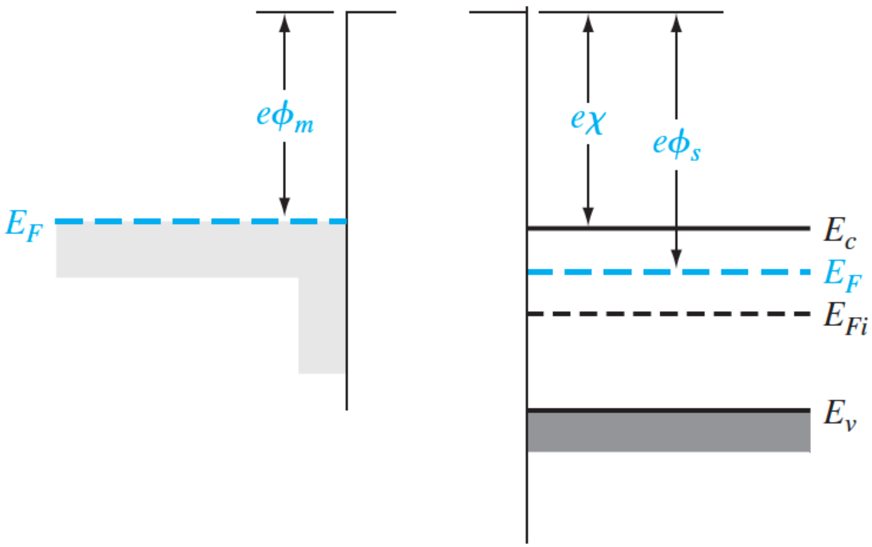
9.2 Metal-semiconductor Ohmic contacts

Ideal Nonrectifying Barrier

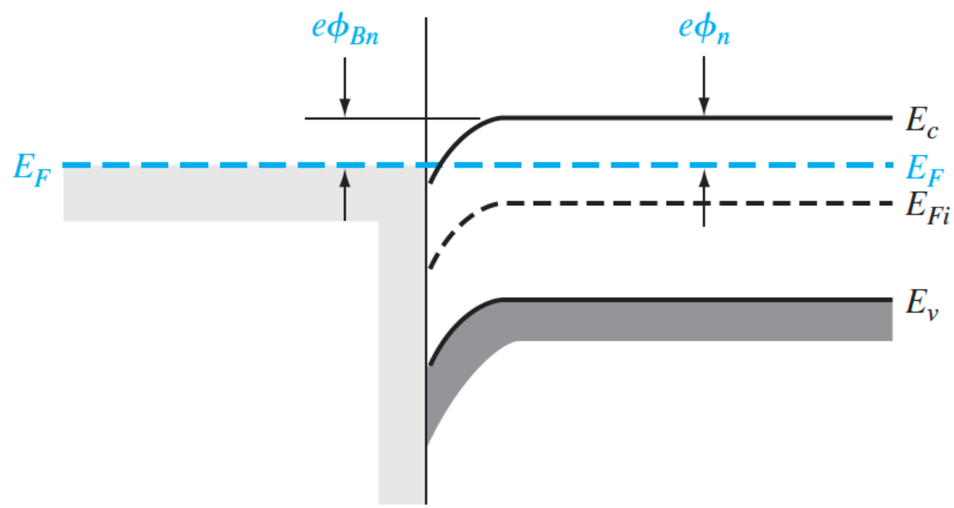


9.2 Metal-semiconductor Ohmic contacts

Ideal Nonrectifying Barrier



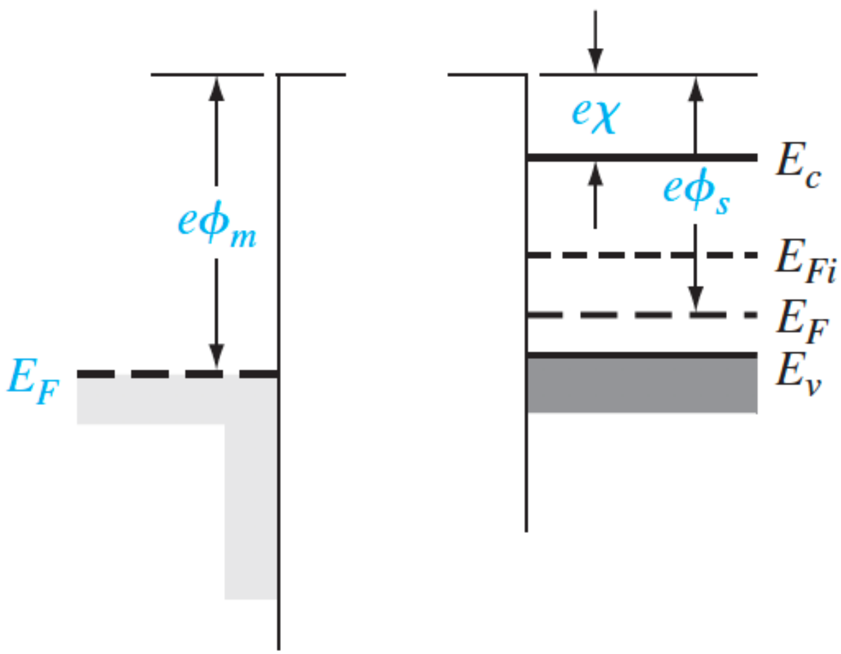
(a)



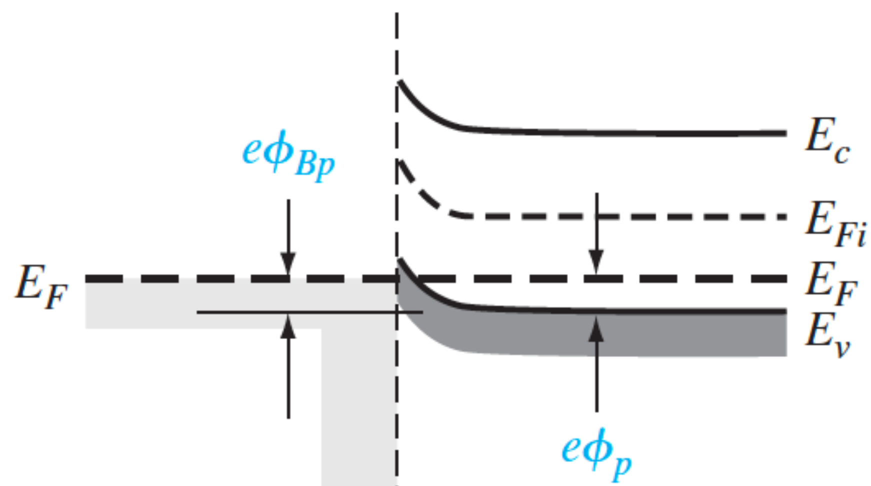
(b)

9.2 Metal-semiconductor Ohmic contacts

Ideal Nonrectifying Barrier

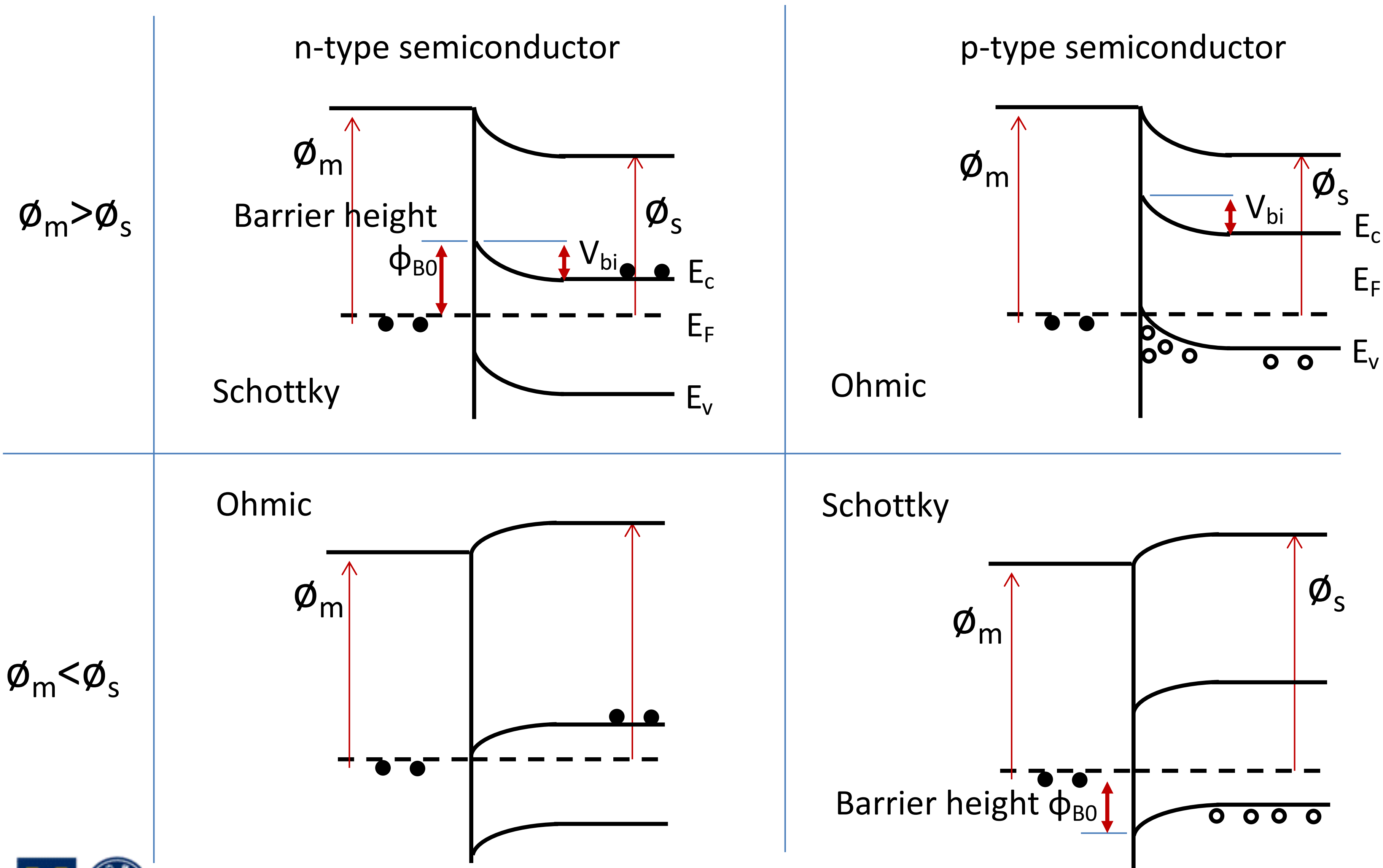


(a)



(b)

9.2 Metal-semiconductor Ohmic contacts



Check your understanding

Problem example #4

For Si, if it is doped with phosphorus at a concentration of 10^{15} cm^{-3}, what metal you can choose from the list for Ohmic contact.

Repeat the question above for p-type Si doping at the concentration of 10^{17} cm^{-3}.

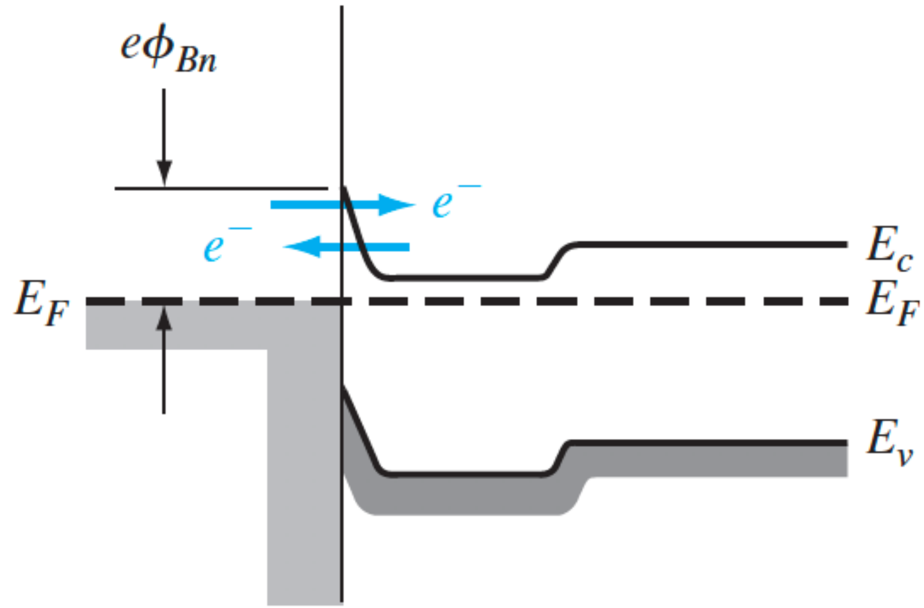
Si has an electron affinity of 4.01 eV and a bandgap of 1.12eV.

Table 9.1 | Work functions of some elements

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

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

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

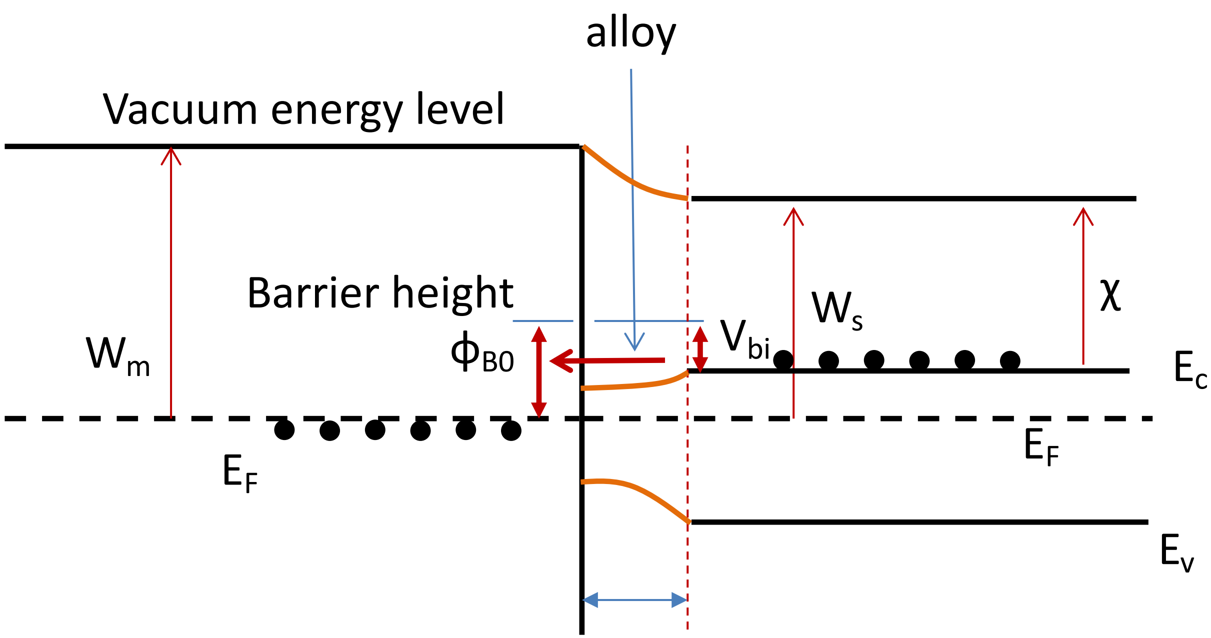
The tunneling current increases exponentially with doping concentration.

9.2 Metal-semiconductor Ohmic contacts

<u>Silicide alloy</u>

Nickel silicide, NiSi

Titanium silicide, $TiSi_2$



silicide

9.2 Metal-semiconductor Ohmic contacts

Specific contact resistance

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

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

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