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

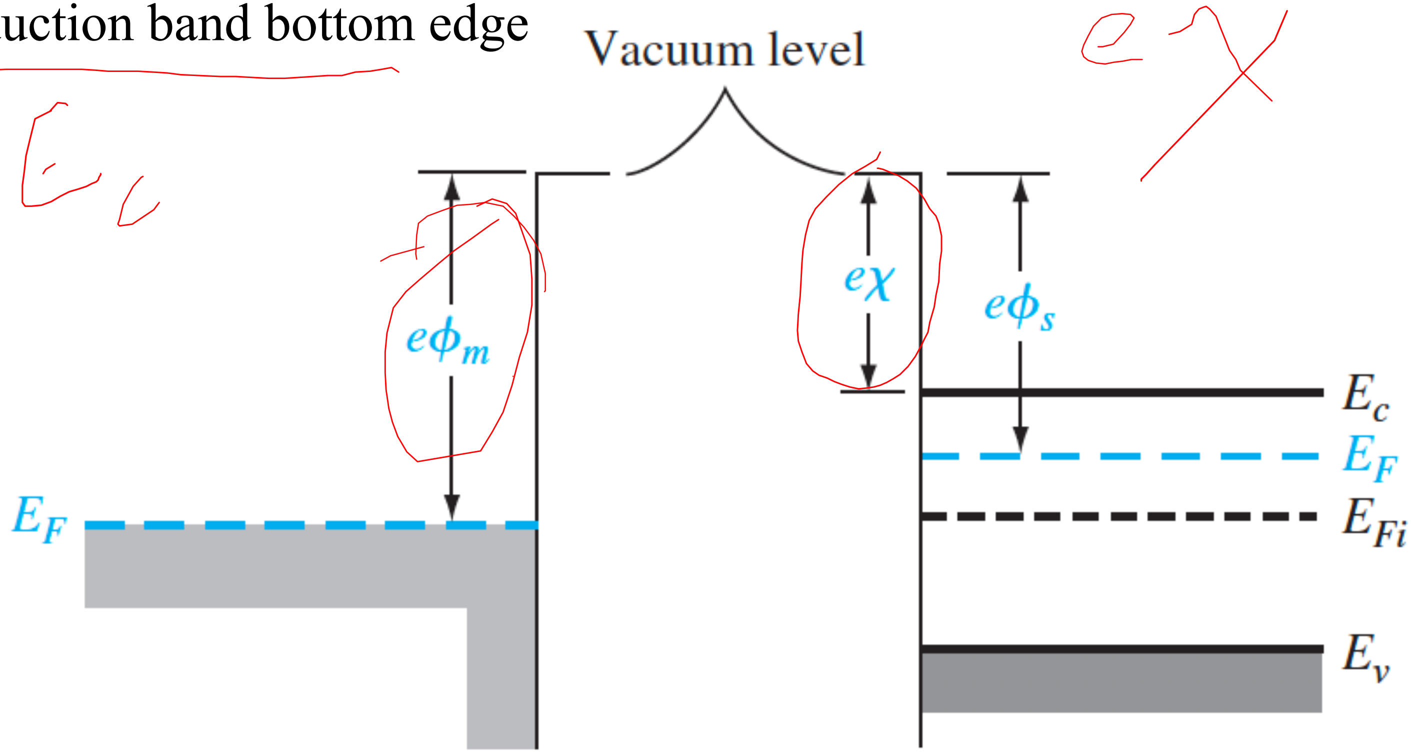
9.1 The Schottky barrier diode

<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

E_c

$e\chi$



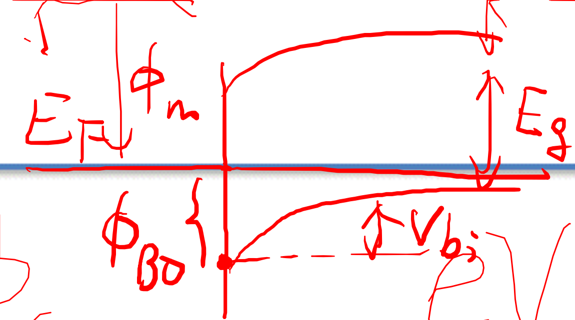
9.1 The Schottky barrier diode

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: $V_{bi} = \phi_{B0} - \phi_n$

ϕ_s

eV

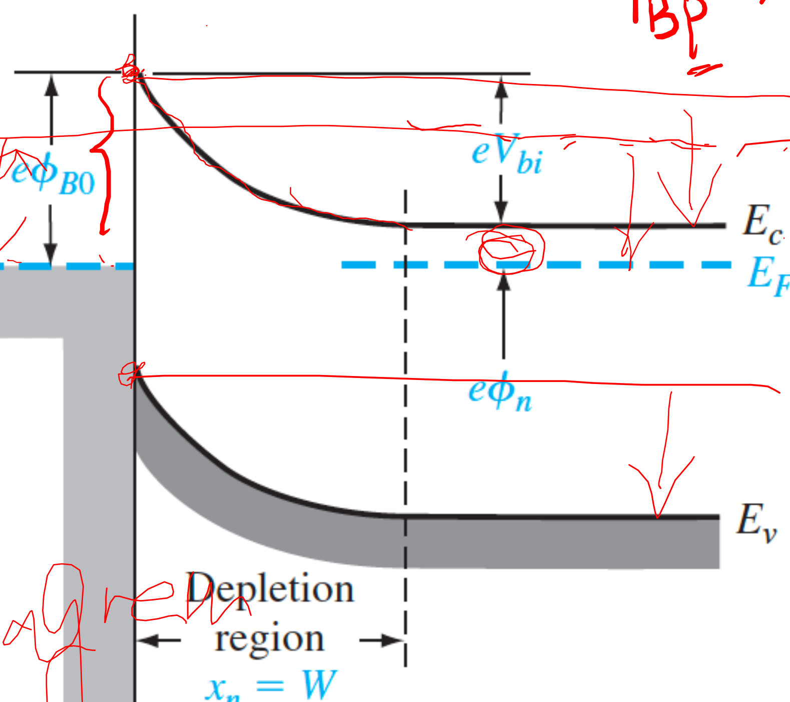
$E_F - E_v(\text{inter})$

eV

$\phi_{Bp} = \chi + E_g - \phi_m$

$qV_{bi} = q\phi_s - q\phi_m$

③ plot energy band diagram



9.1 The Schottky barrier diode

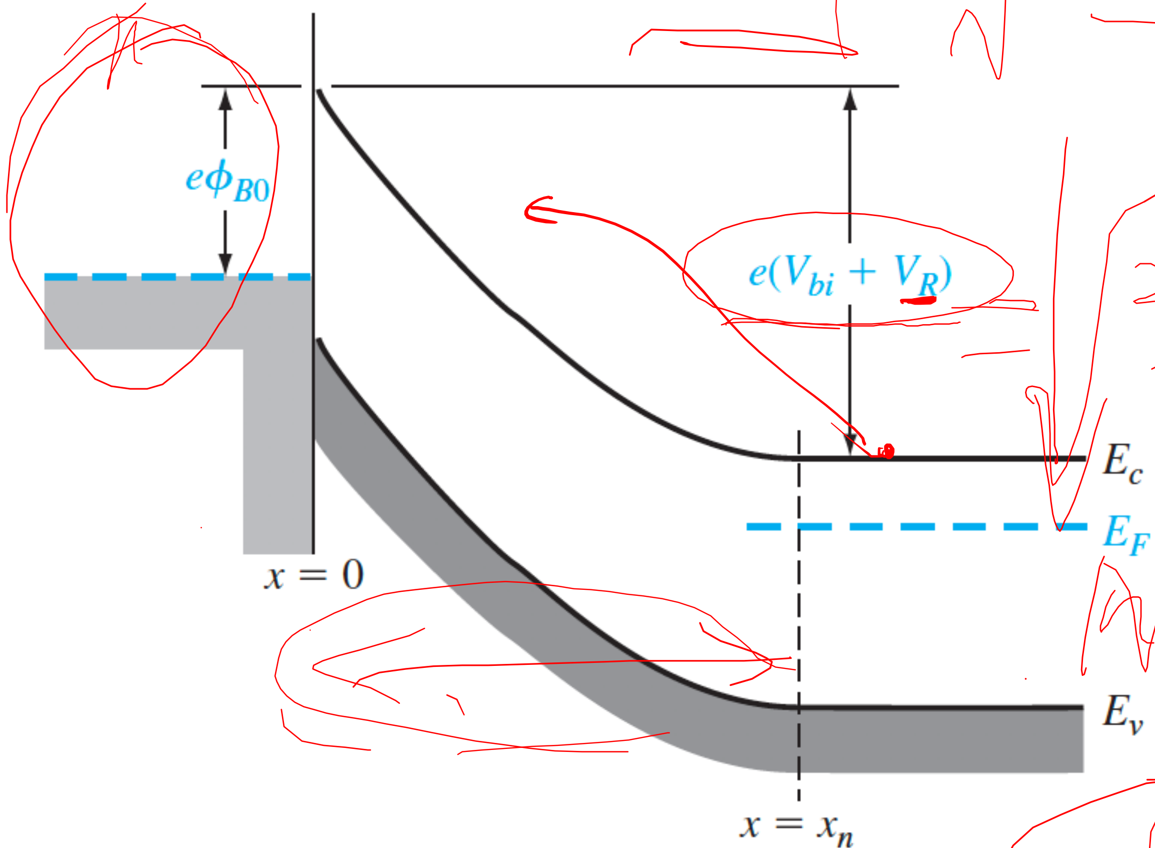
Qualitative characteristics

$W_{dep} = \sqrt{\frac{2\varepsilon(V_{bi}+V_R)}{e}\left(\frac{N_a+N_d}{N_aN_d}\right)}$

$\sqrt{\frac{2\varepsilon(V_{bi}+V_R)}{eN_d}}$

N_d

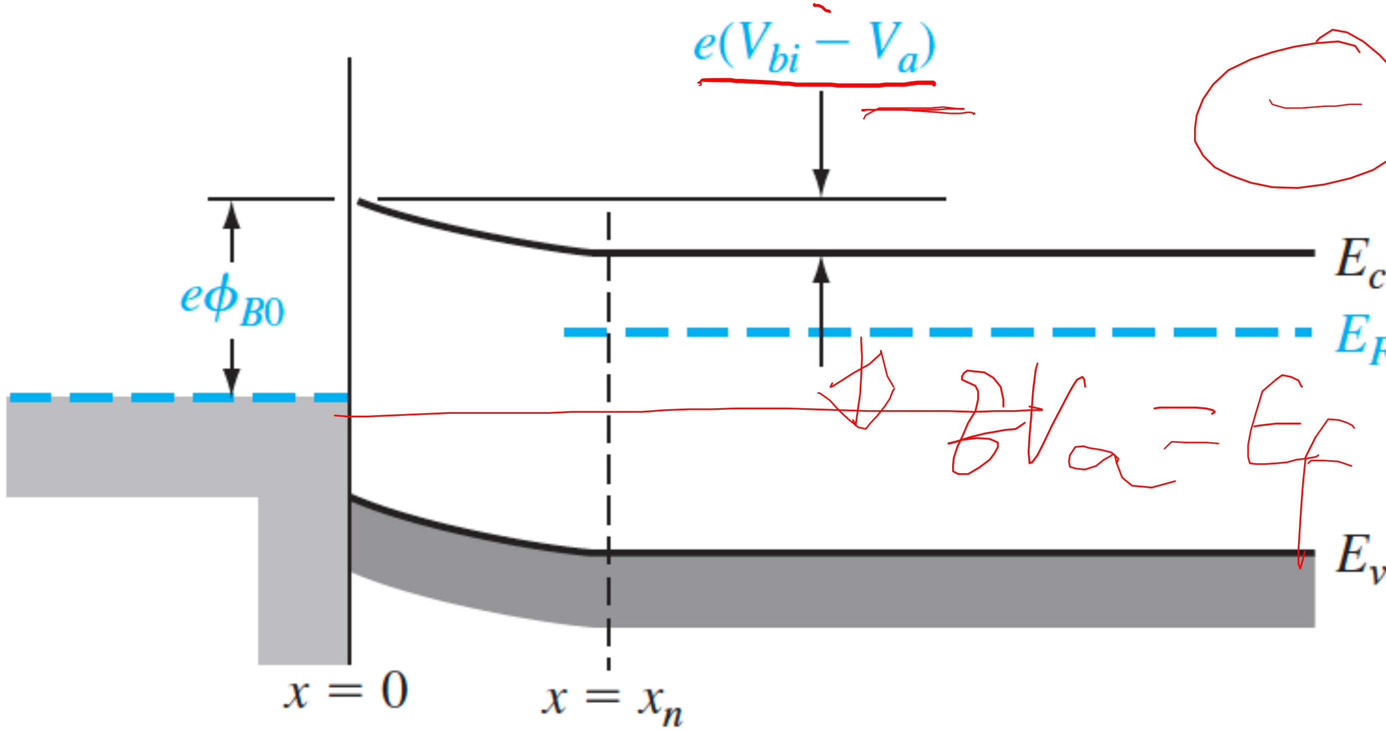
$+V$



Reverse bias

9.1 The Schottky barrier diode

Qualitative characteristics



$eV_a = E_F - e\phi_m$

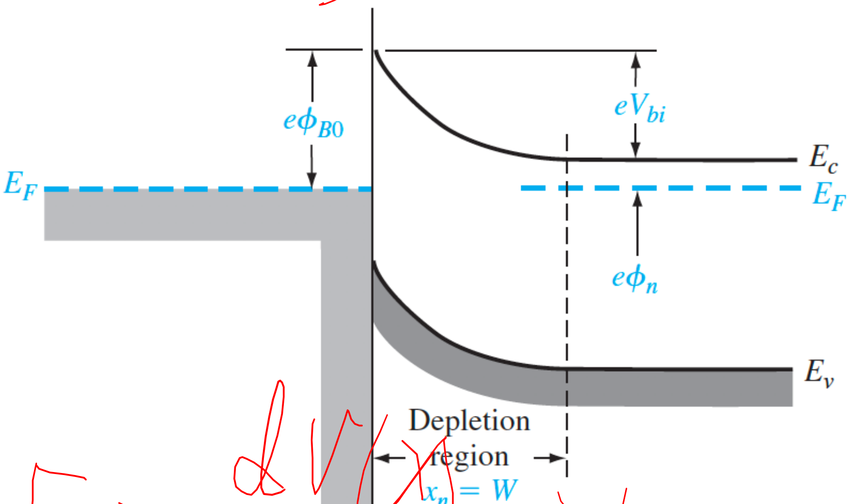
Forward bias

9.1 The Schottky barrier diode

Ideal junction properties (electric field)

electrostatic

$x = 0$



$$E = -\frac{dV}{dx}$$

$x_n = ?$

$(0, W)$

$$\boxed{E = -\frac{eN_d}{\varepsilon_s}(x_n - x)}$$

$$E = \int \frac{eN_d}{\varepsilon_s}\,dx$$

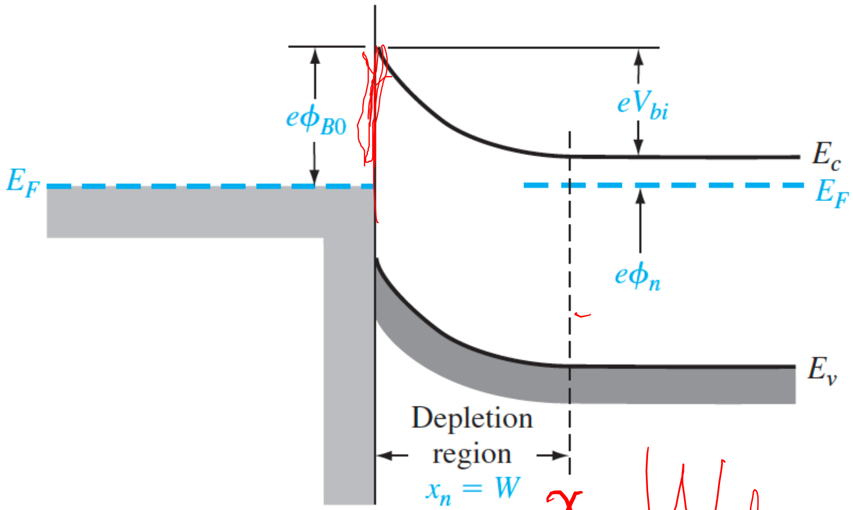
$$= \frac{eN_d}{\varepsilon_s}x + C_1$$

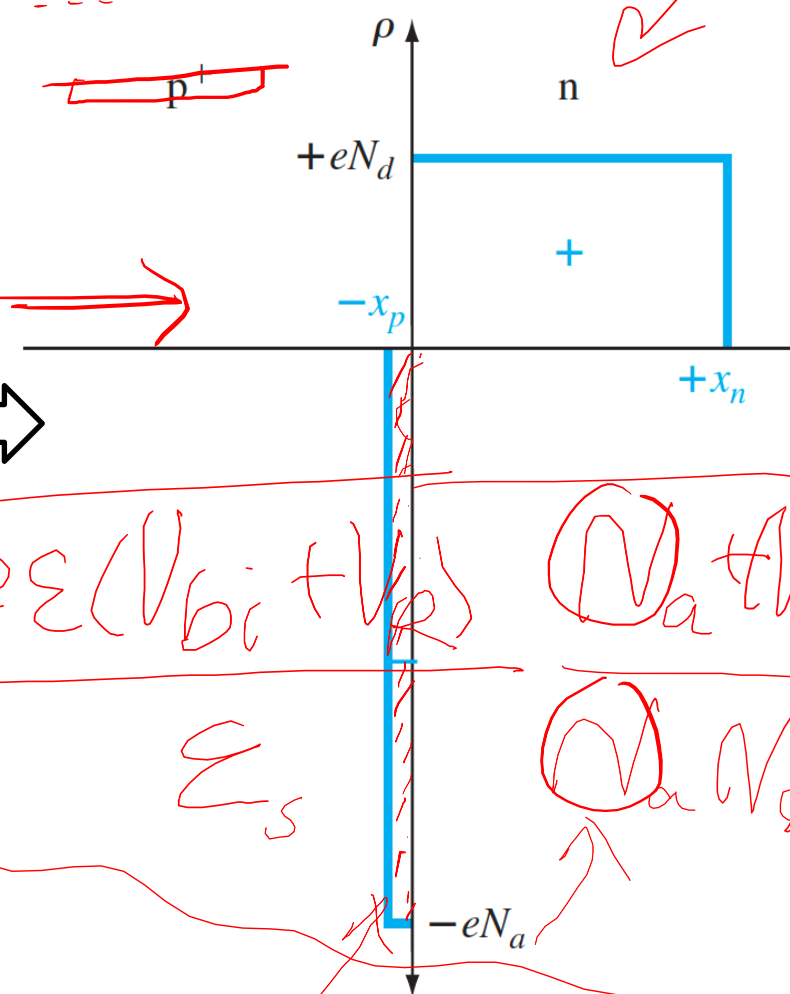
$$E(x_n) = 0$$

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

9.1 The Schottky barrier diode

Ideal junction properties





A_n

$\frac{1}{C'^2}$

x_n $W_{dep} = \sqrt{\frac{2\varepsilon(V_{bi}+V_R)}{\varepsilon_s}\frac{N_a+N_d}{N_a N_d}}$

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

Check your understanding

Problem example #1

$p_0 = N_v \exp\left(-\frac{E_F - E_v}{kT}\right)$

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.

5.12
4.3
0.82

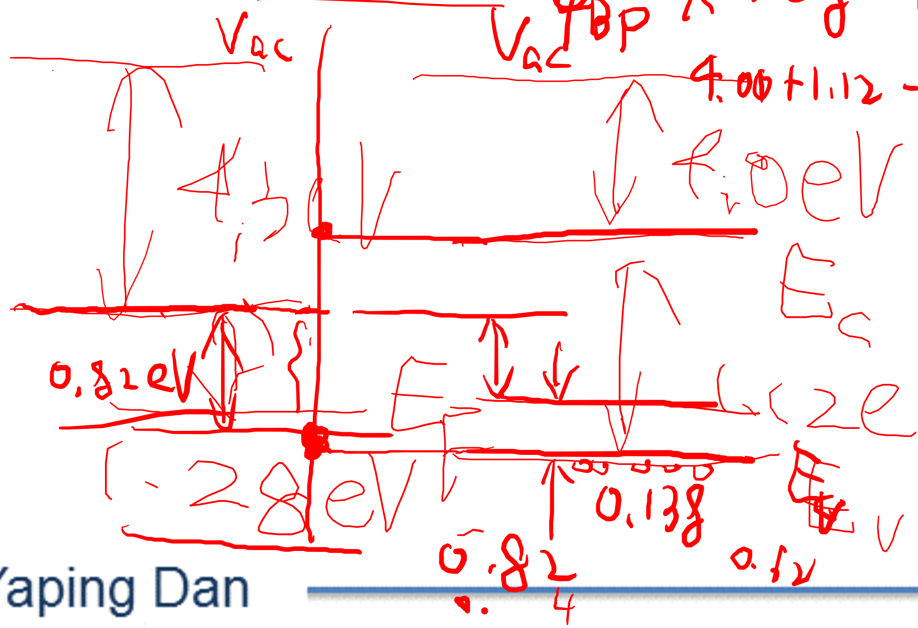
$\phi_{Bp} = \chi + E_g - \phi_m$

4.00 + 1.12 − 4.3

$E_F = E_v + kT \ln\frac{N_v}{N_a}$

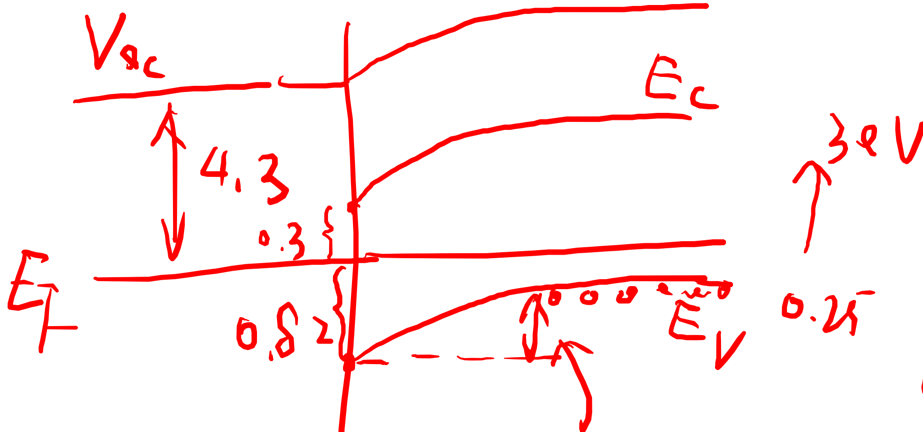
$= E_v + 0.138$

(a)



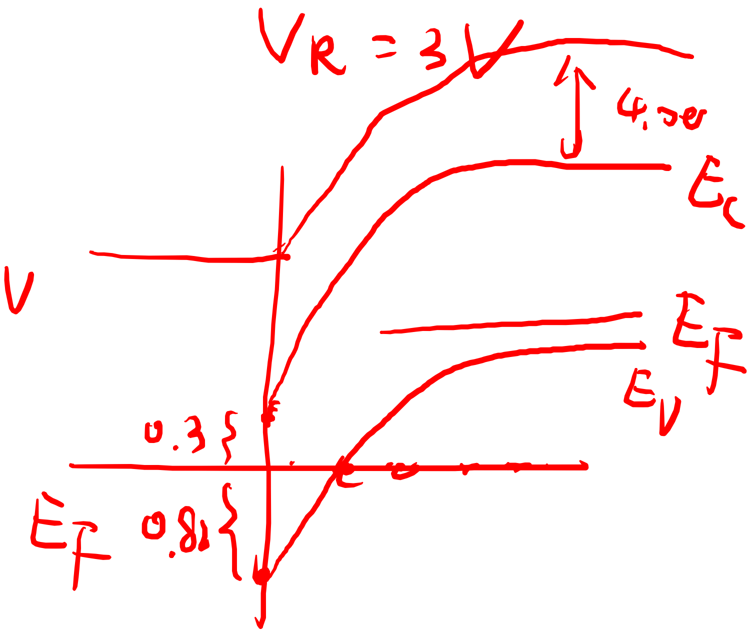
Check your understanding

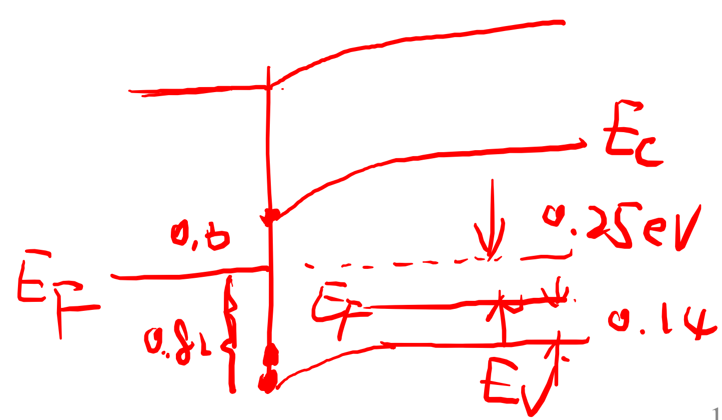
Problem example #1



$0.82 - 0.14$

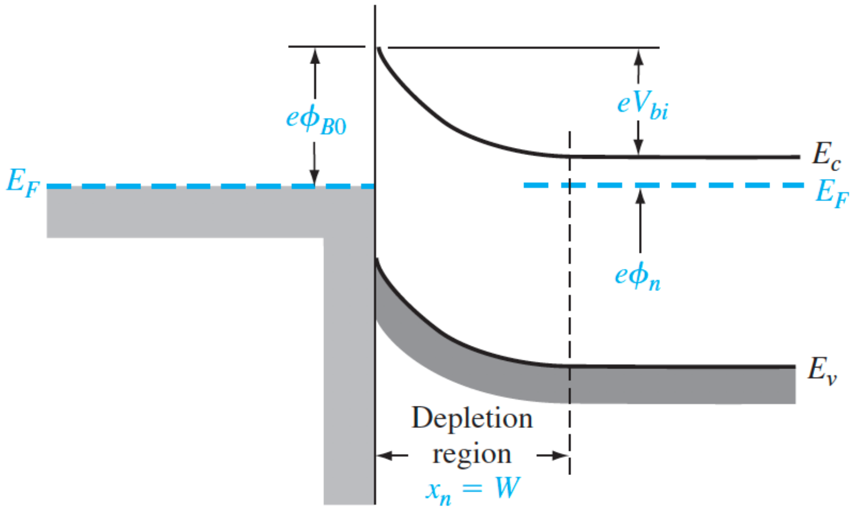
$= 0.68\ eV$





9.1 The Schottky barrier diode

Ideal junction properties (capacitance)



$$C = \left.\frac{dQ}{dV_b}\right|_{V_b = V_R} = \frac{\varepsilon}{W_{dep}}$$

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

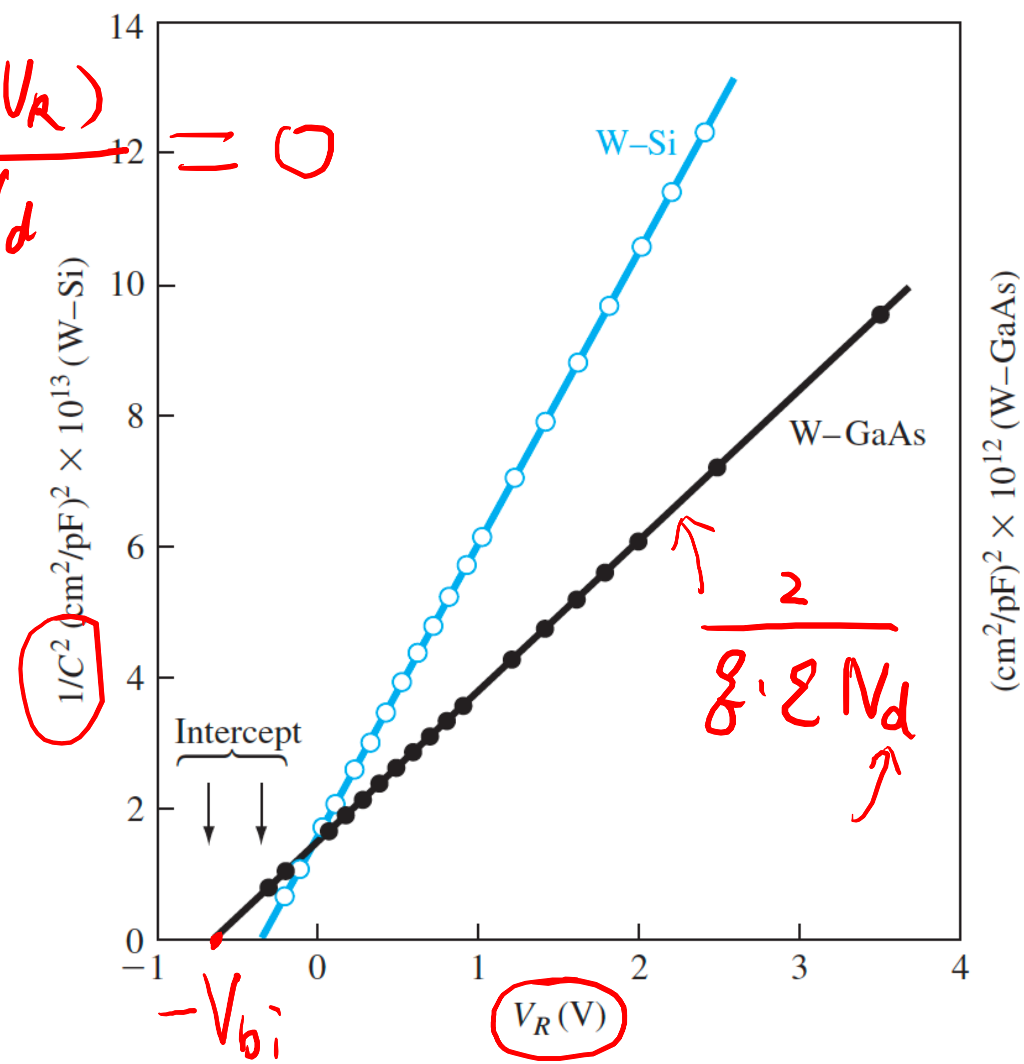
$$W_{dep} = \sqrt{\frac{2\varepsilon(V_{bi}+V_R)}{q} \frac{1}{N_d}}$$

$$\frac{1}{C^2} = \frac{2(V_{bi}+V_R)}{q \cdot \varepsilon N_d}$$

9.1 The Schottky barrier diode

Ideal junction properties

$$\frac{1}{C^2} = \frac{2(V_{bi}+V_R)}{q\varepsilon N_d} = 0$$



9.1 The Schottky barrier diode

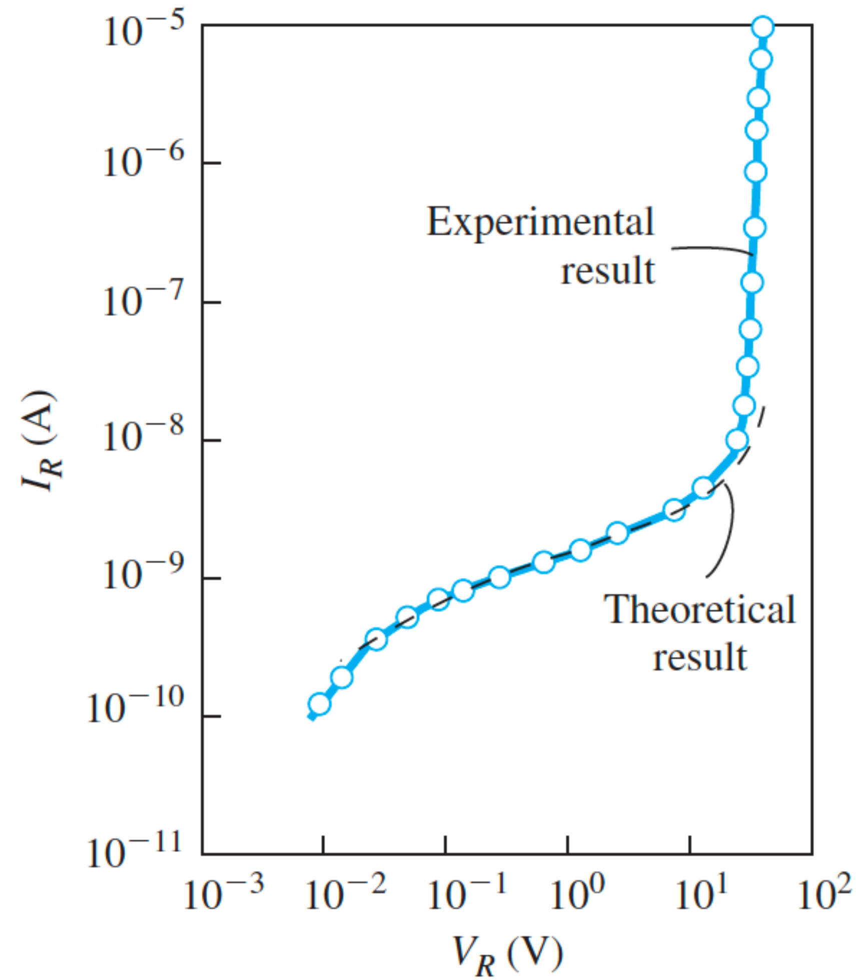
Current-voltage relationship

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

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

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

Richardson constant



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

9.1 The Schottky barrier diode

Compare Schottky diode and PN junction

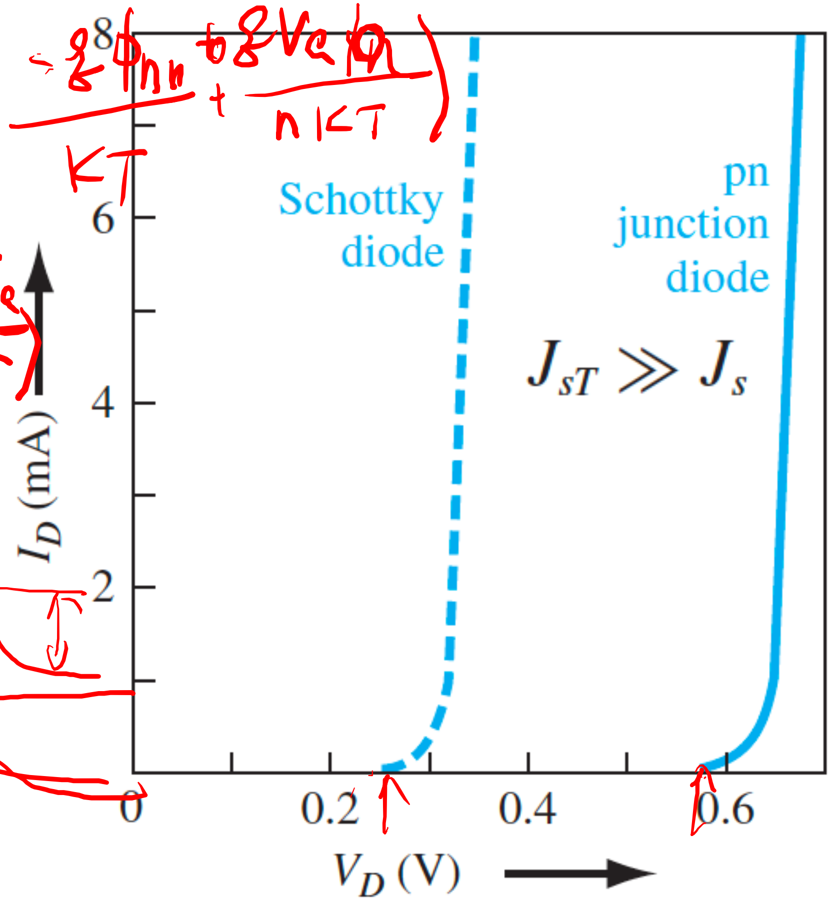
$>>1$

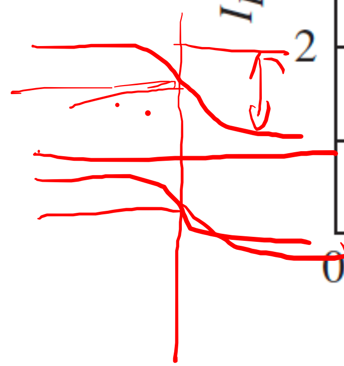
$$J = J_{sT}\left[\exp\left(\frac{eV_a}{kT}\right) - 1\right]$$

$$\exp\left(\frac{-q\phi_{Bn}}{kT} + \frac{qV_a}{nkT}\right)$$

$$I = A_c A^* \cdot T^2 \exp\left(\frac{-q\phi_{Bn}}{kT}\right)\exp\left(\frac{qV_a}{kT}\right)$$

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





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

Richardson constant

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

Check your understanding

Problem example #2

n-type

Consider a tungsten barrier on silicon with a measured barrier height of ϕ_{Bn} = 0.67eV. The effective Richardson constant is A* = 114 A/K²cm². T = 300K.

$V_a = 0.1\,V$

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

$$J_{ST} = 114 \times (300)^2 \cdot \exp\left(-\frac{0.67}{0.0259}\right)$$

$$= 5.98 \times 10^{-5}\ A/cm^2$$

$$J = J_{ST}\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right] = 5.98 \times 10^{-5}\left(e^{\frac{0.1}{0.0259}} - 1\right)$$

Check your understanding

$$J = J_{ST}\left[e^{\frac{qV_a}{kT}} - 1\right]$$

$$= 5.98\times10^{5}\left[e^{\frac{0.1}{0.0259}} - 1\right]$$

$$= 5.98\times10^{5}\,(46.5 - 1)$$

$$= 2.72\times10^{7}\ A/cm^{2}$$

Check your understanding

Problem example #3

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

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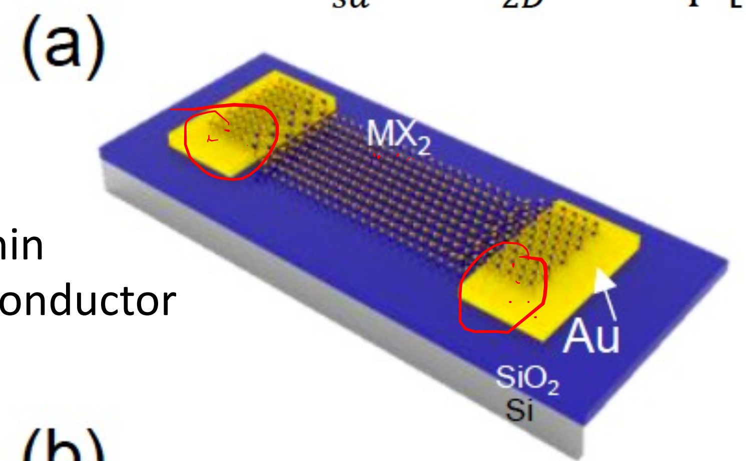
Under review in AIP Advances

Check your understanding

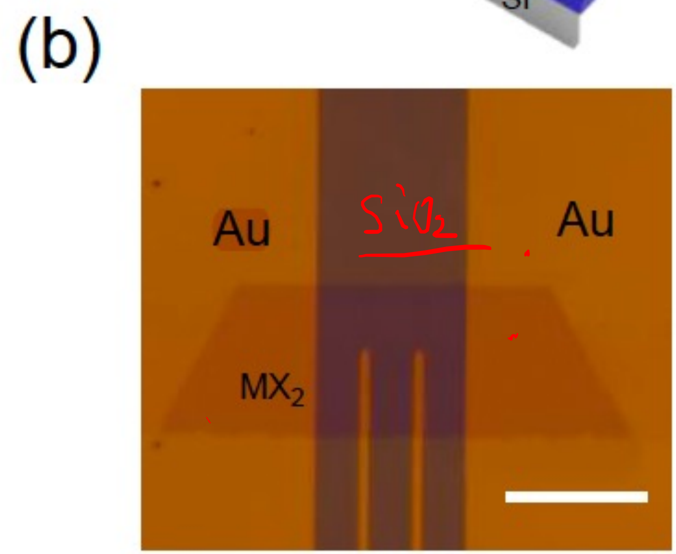
Problem example #3

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

ideality



WS$_2$ atomically thin monolayer semiconductor

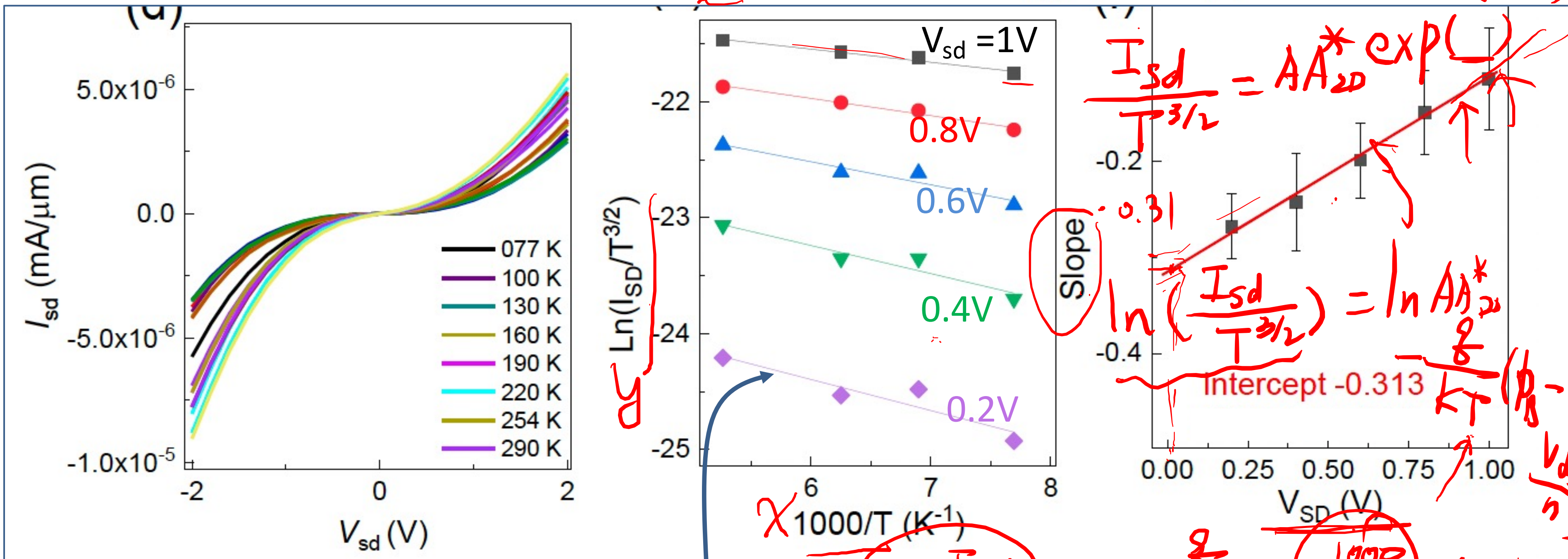


Check your understanding

$$\frac{I_{sd}}{AA^*_{2D}\, T^{3/2}} \qquad T^{(-3/2)}$$

Problem example #3

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



Line 1

$$y \quad \ln\frac{I_{sd}}{T^{3/2}} = -\frac{q}{k_B\times 1000}\times\frac{1000}{T}\left(\Phi_B - \frac{V_{ds}}{n}\right)$$

1) Write the analytical expression of Line 1 if we take 1000/T as x and ln($I_{SD}/T^{2/3}$) as y?

2) Write the expression of Slope in the right figure.

3) Find Schottky barrier height Φ_B

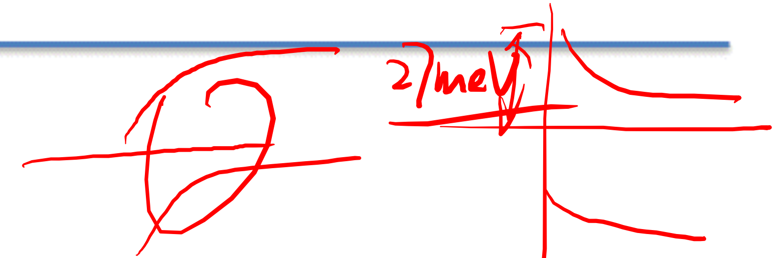
$$y' = -\frac{q}{1000k_B}\left(\Phi_B - \frac{x}{n}\right) \Rightarrow y' = -\frac{q}{1000k_B}\left(\Phi_B - \frac{V_{ds}}{n}\right)$$

$$\boxed{y = -\frac{q}{1000k_B}\left(\Phi_B - \frac{V_{ds}}{n}\right)\cdot x}$$

y'

Check your understanding

Problem example #3



$$\ln\left(\frac{I_{sd}}{T^{3/2}}\right) = \ln(A\cdot A^*_{2D}) - \frac{q}{1000k_B}\left(\phi - \frac{V_{ds}}{n}\right)\cdot\frac{1000}{T}$$

$$y = \ln(A A^*_{2D}) - \frac{q}{1000k_B}\left(\phi - \frac{V_{ds}}{n}\right)x$$

$$y: \text{slope} = -\frac{q}{1000k_B}\left(\phi_{Bn} - \frac{V_{ds}}{n}\right)$$

$$y' = -\frac{q}{1000k_B}\left(\phi_{Bn} - \frac{x'}{n}\right)$$

$$-0.31 = y_0 = -\frac{q}{1000k_B}\phi_{Bn}$$

$$\phi_{Bn} = 27\,\text{meV}$$

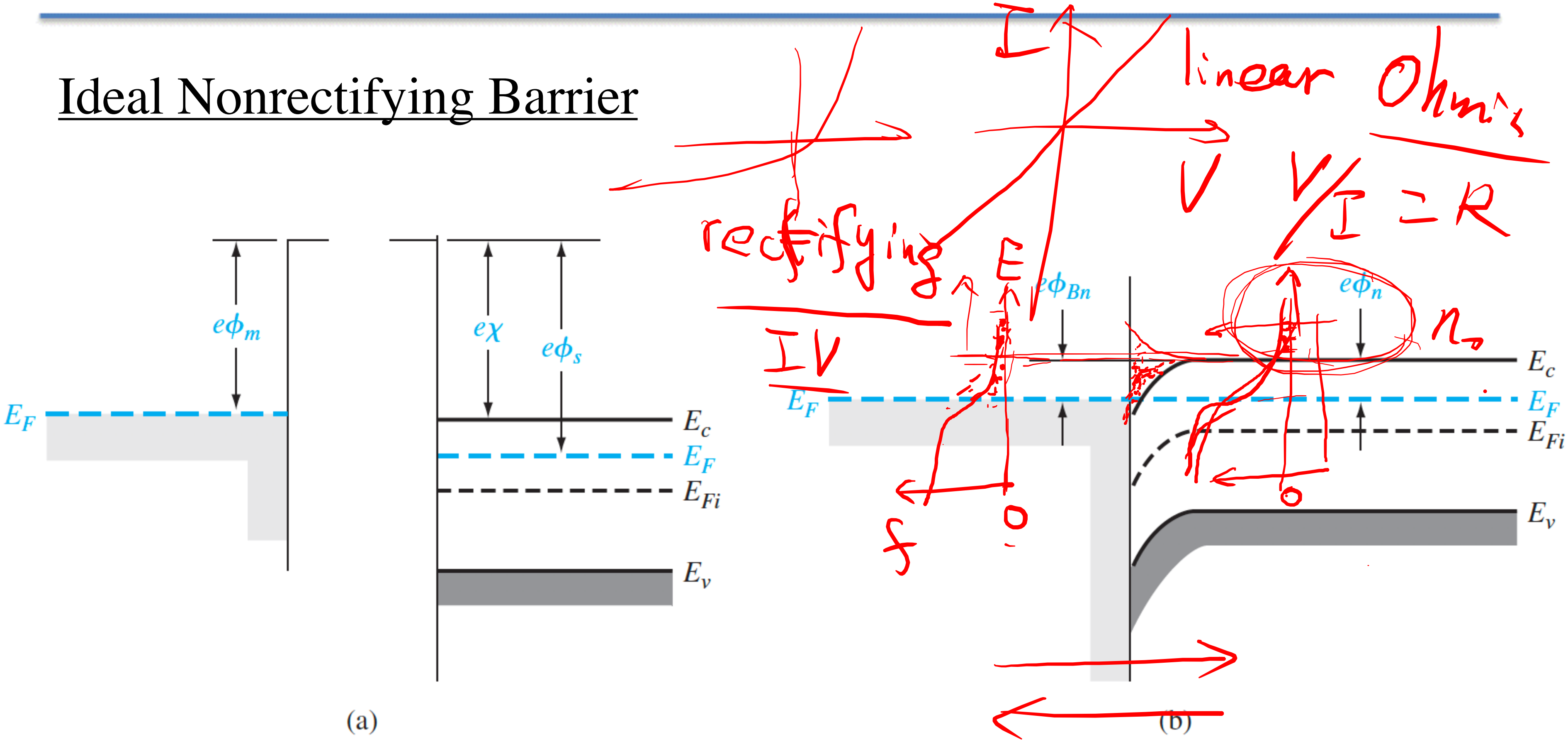
Outline

9.1 The Schottky barrier diode

9.2 Metal-semiconductor Ohmic contacts

9.2 Metal-semiconductor Ohmic contacts

Ideal Nonrectifying Barrier

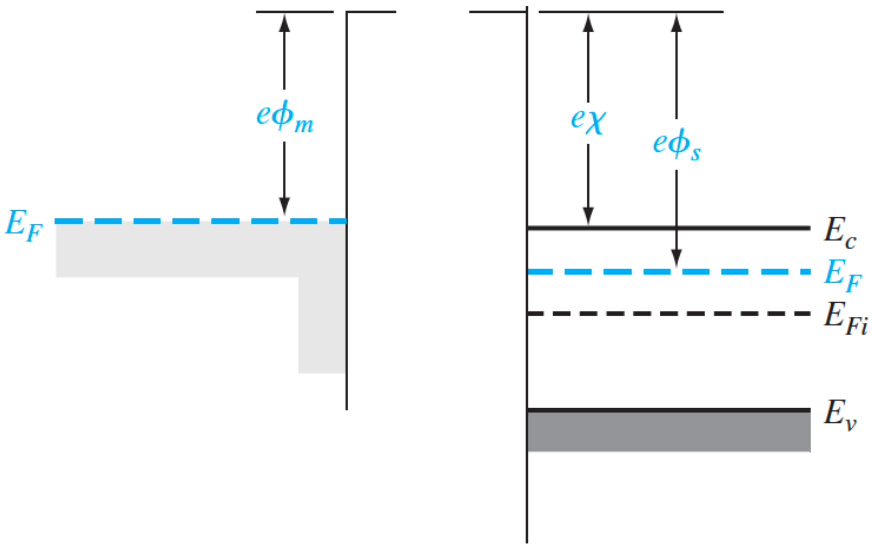


(a) (b)

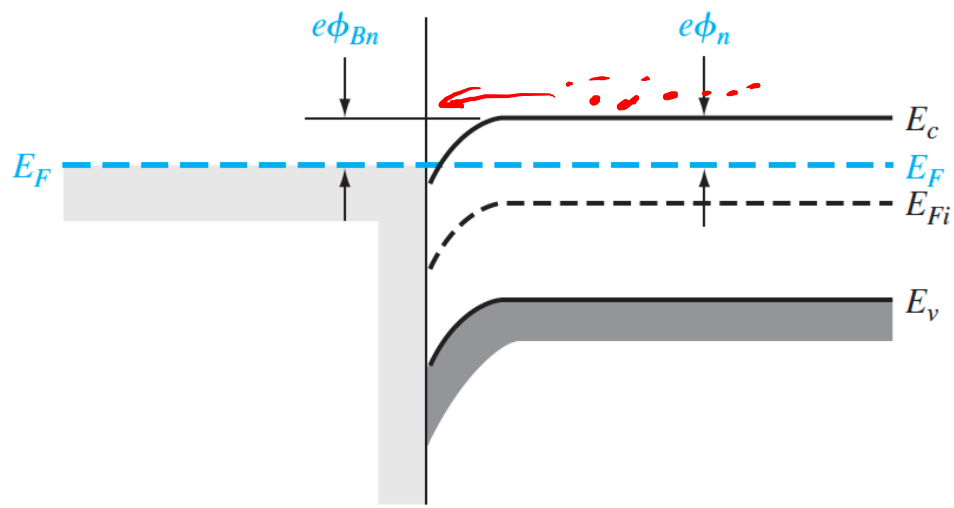
9.2 Metal-semiconductor Ohmic contacts

Ideal Nonrectifying Barrier

n-type $W_s > W_m \Rightarrow$ ohmic



(a)



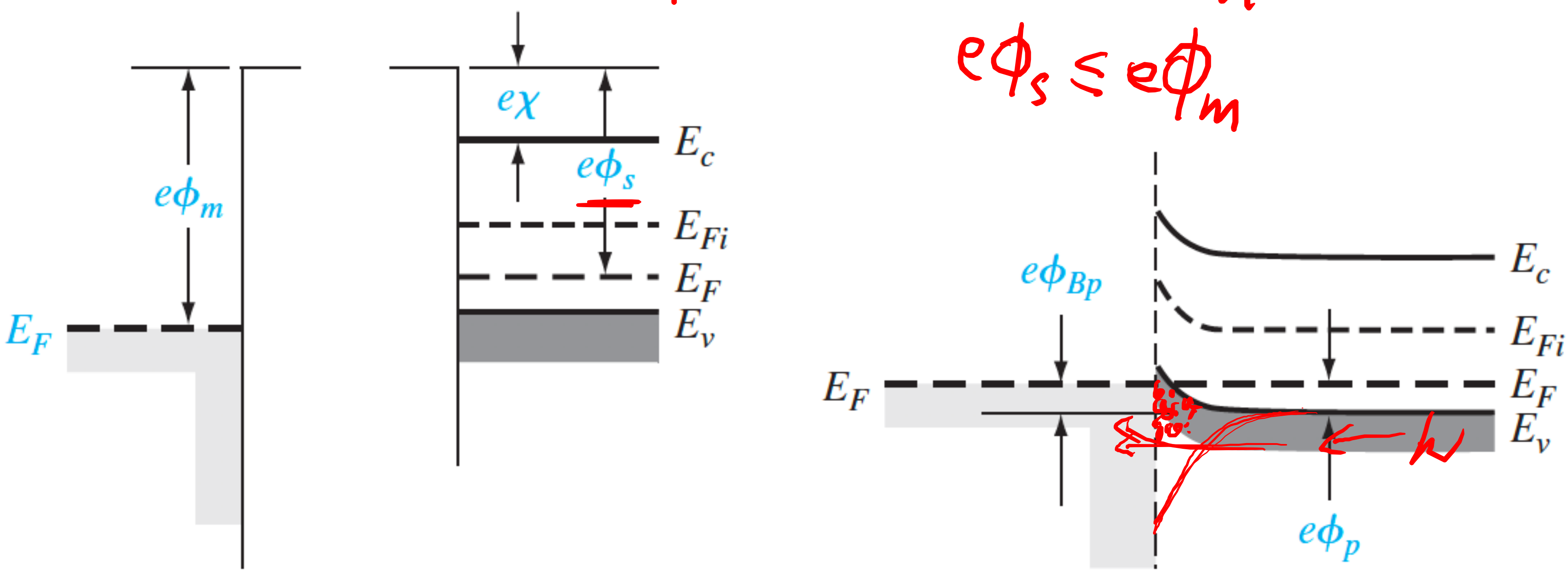
(b)

9.2 Metal-semiconductor Ohmic contacts

<u>Ideal Nonrectifying Barrier</u>

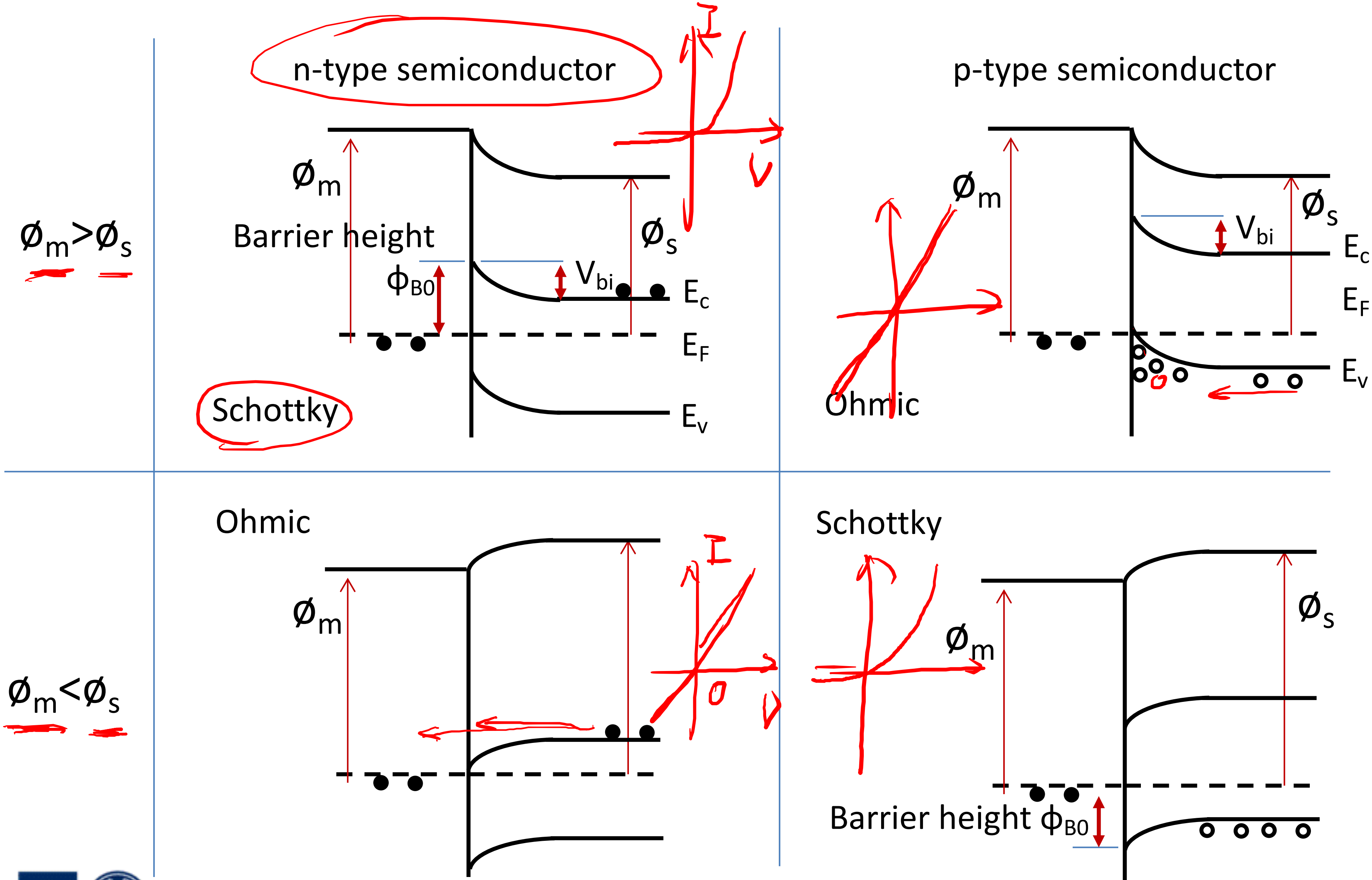
p-type $W_s \leq W_m$

$e\phi_s \leq e\phi_m$



(a) (b)

9.2 Metal-semiconductor Ohmic contacts



Check your understanding

Problem example #4

n-type

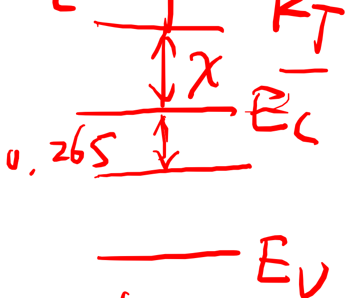
For Si, if it is doped with phosphorus at a concentration of 10^{15} cm^{-3}, what metal you can choose from the list for Ohmic contact. Ag Au

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. (Au, Ni, Pd, Pt)

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

$$n_0 = N_c \exp\left(\frac{E_F - E_c}{kT}\right) \Rightarrow E_F - E_c = kT \ln\frac{n_0}{N_c} = 0.0259 \times \ln\frac{10^{15}}{2.8\times10^{19}} = -0.265\ \text{eV}$$



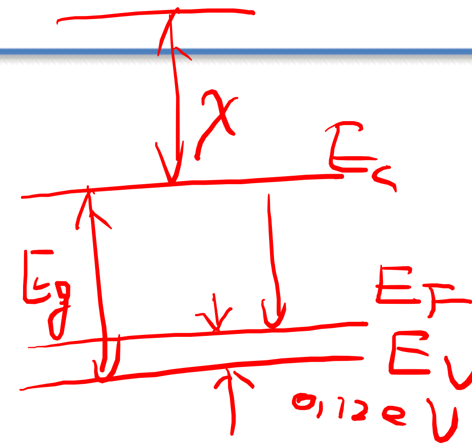
$$E_F = E_c - 0.265\ \text{eV} = -4.01\ \text{eV} - 0.265\ \text{eV} = -4.275\ \text{eV}$$

$$\phi_s = 4.275\ \text{eV}$$

$$\phi_s > \phi_m$$

Check your understanding

<u>Problem example #4</u>



$$p_0 = N_c \exp\left(\frac{E_v - E_F}{kT}\right)$$

$$\frac{p_0}{N_c} = \exp\left(\frac{E_v - E_F}{kT}\right)$$

$$\ln\frac{p_0}{N_c} = \frac{E_v - E_F}{kT}$$

$$kT\ln\frac{p_0}{N_c} = E_v - E_F$$

$$E_F = E_v - kT\ln\frac{p_0}{N_c} = E_v + 0.12\,\text{eV}$$

$$E_F = -5.13 + 0.12\,\text{eV}$$
$$= -5.01\,\text{eV}$$

$$E_v = -\chi - E_g$$
$$= -4.01 - 1.12$$
$$= -5.13\,\text{eV}$$

$$\phi_s = 5.01\,\text{eV}$$

$\boxed{\phi_s \le \phi_m}$ for ohmic

9.2 Metal-semiconductor Ohmic contacts

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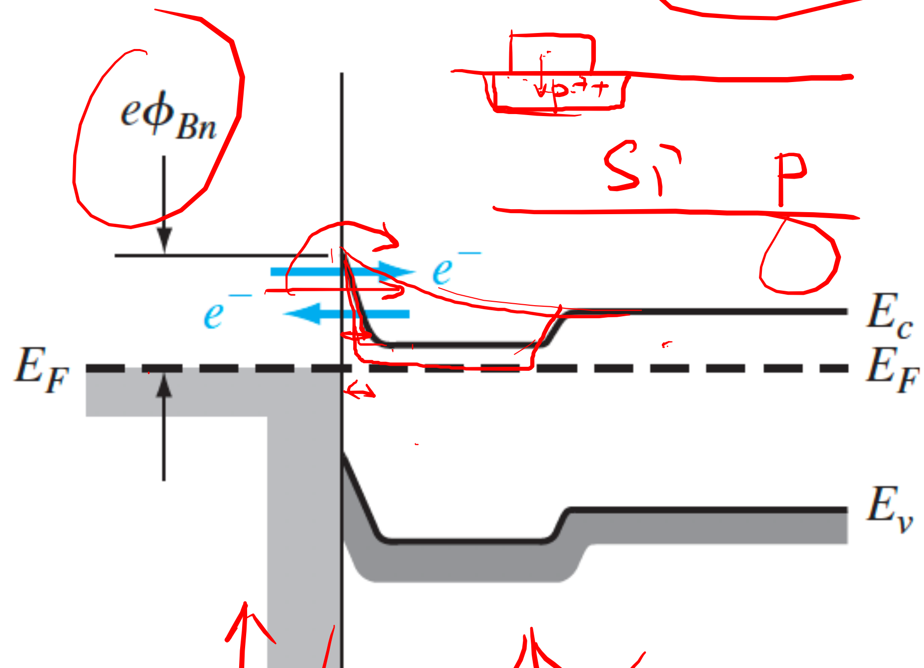
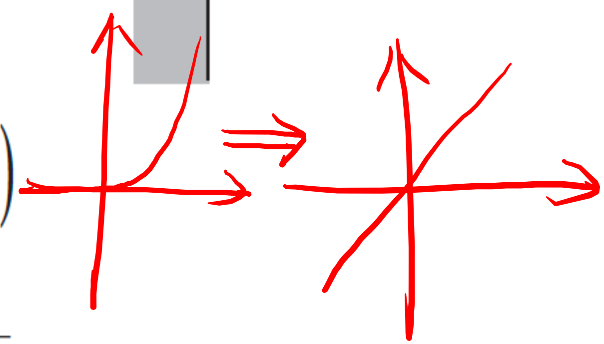
1.Tunneling Barrier



The tunneling current has the form

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



where

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

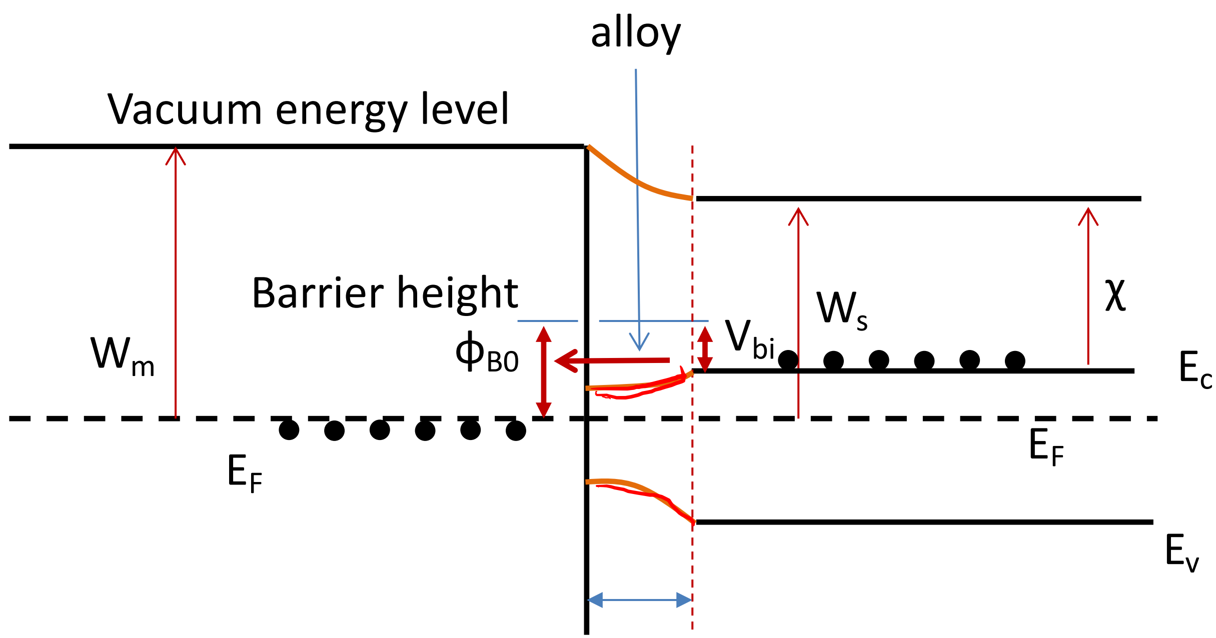
The tunneling current increases exponentially with doping concentration.

9.2 Metal-semiconductor Ohmic contacts

2.Silicide alloy

Nickel silicide, NiSi

Titanium silicide, $TiSi_2$



silicide