Semiconductor Devices
Spring 2019

ROYAL INSTITUTE
OF TECHNOLOGY

Lecture 7

This Lecture

- Reading
  - Chapter 4, part III
- Concepts:
  - Metal-semiconductor contacts

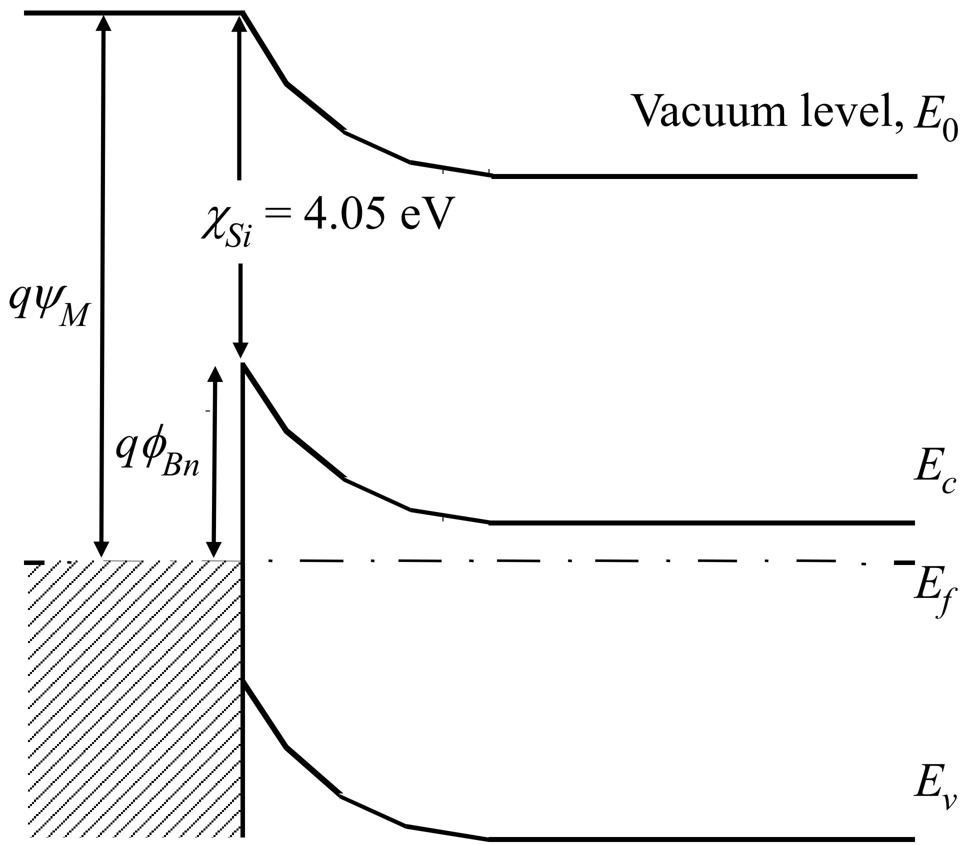
Part III: Metal-Semiconductor Junction

Two kinds of metal-semiconductor contacts:

- *Rectifying* ***Schottky diodes****: metal on lightly doped silicon*

- *Low-resistance* ***ohmic contacts****: metal on heavily doped silicon*

ϕ_{Bn} *Increases with Increasing Metal Work Function*



ψ_M : Work Function of metal

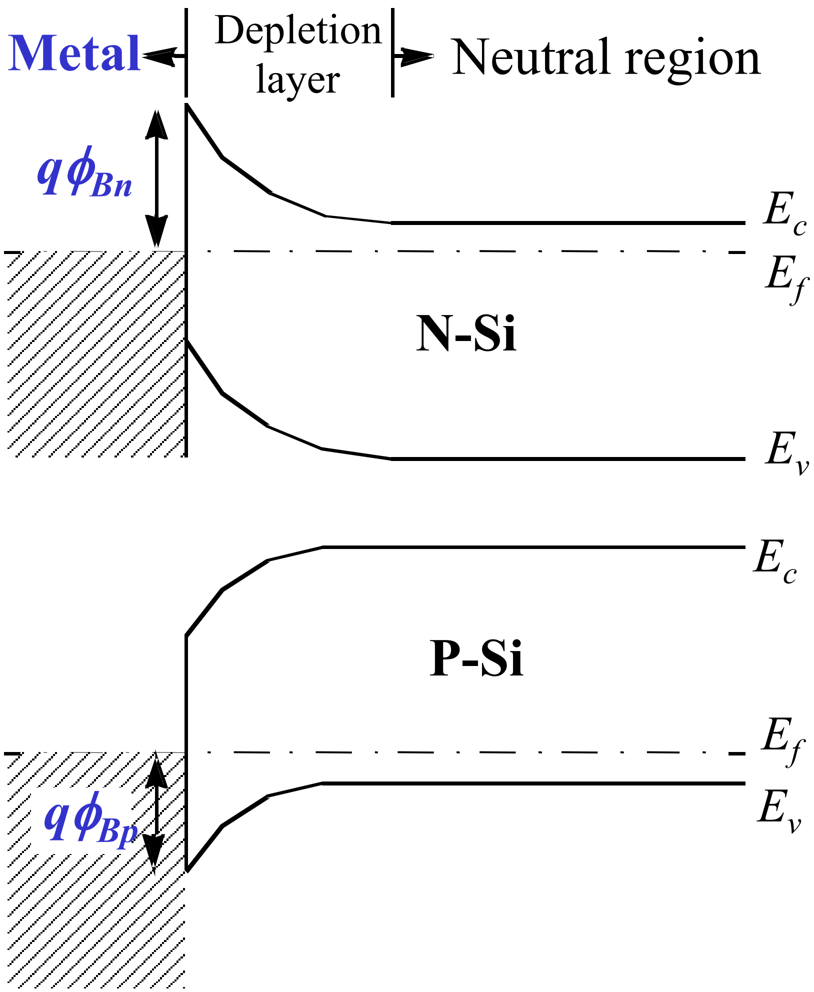
χ_{Si} : Electron Affinity of Si

Theoretically,

$$\phi_{Bn} = \psi_M - \chi_{Si}$$

4.16 Schottky Barriers

Energy Band Diagram of Schottky Contact



- Schottky barrier height, ϕ_B, is a function of the metal material.

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

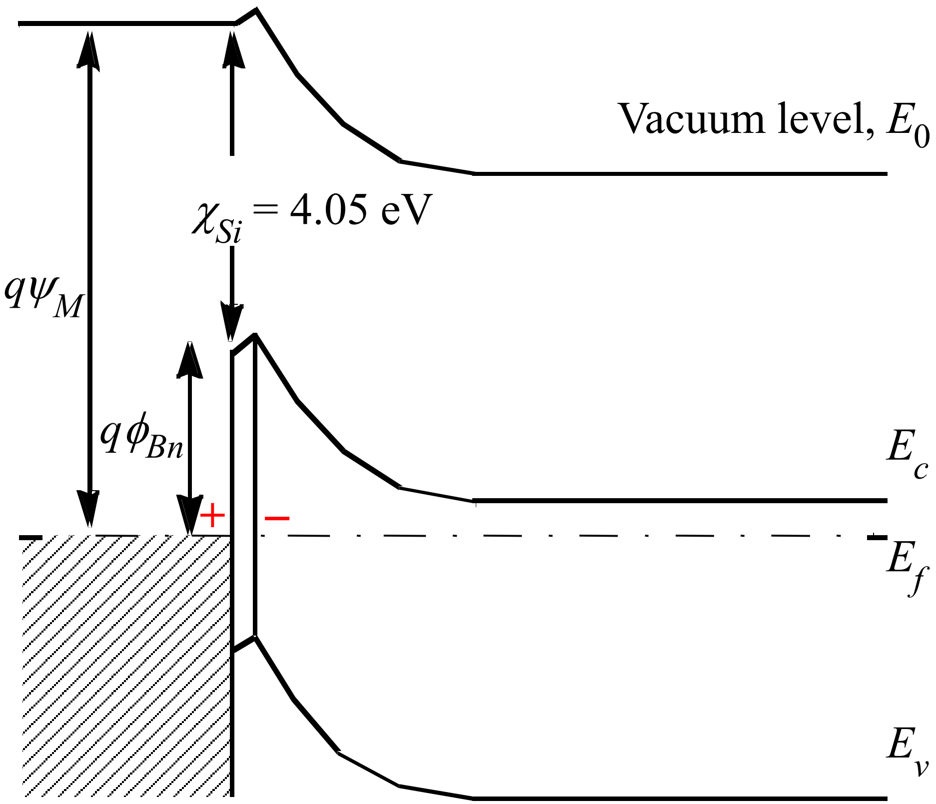
Schottky barrier heights for electrons and holes

Metal	Mg	Ti	Cr	W	Mo	Pd	Au	Pt
ϕ_{Bn} (V)	0.4	0.5	0.61	0.67	0.68	0.77	0.8	0.9
ϕ_{Bp} (V)		0.61	0.5		0.42		0.3	
Work Function ψ_m (V)	3.7	4.3	4.5	4.6	4.6	5.1	5.1	5.7

$$\phi_{Bn} + \phi_{Bp} \approx E_g$$

ϕ_{Bn} increases with increasing metal work function

Fermi Level Pinning



- A high density of energy states in the bandgap at the metal-semiconductor interface pins E_f to a narrow range and ***ϕ_{Bn} is typically 0.4 to 0.9 V***

- ***Question***: What is the typical range of ϕ_{Bp}?

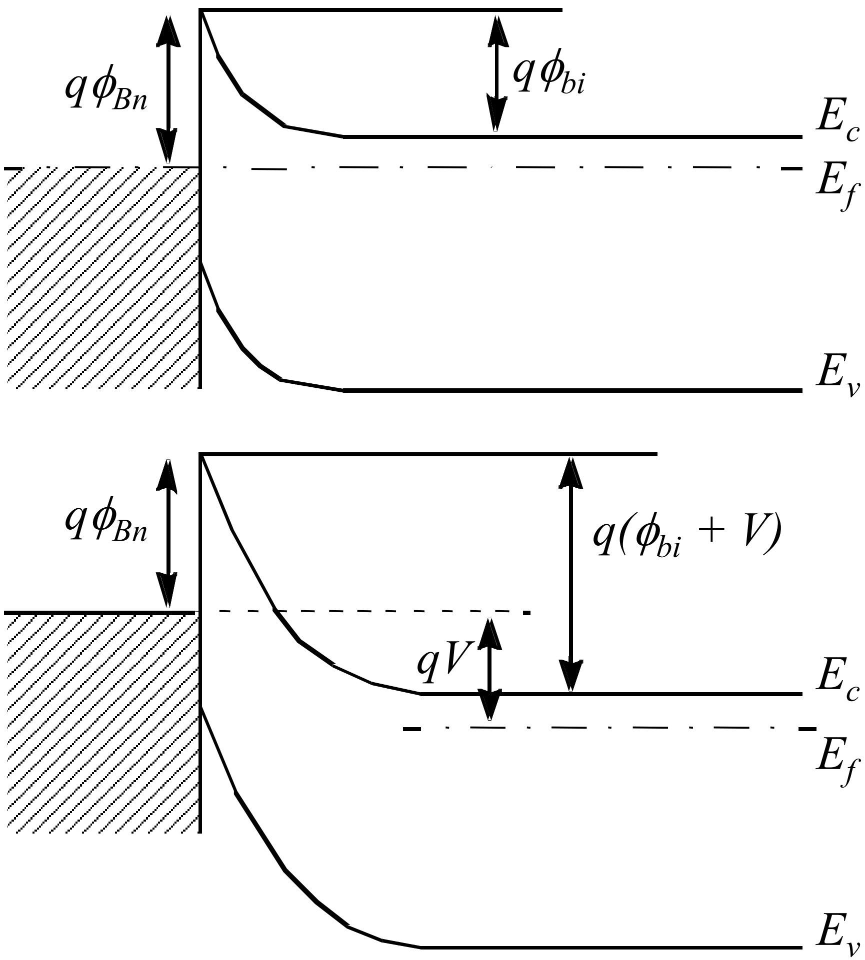
Schottky Contacts of Metal Silicide on Si

***Silicide*: A silicon and metal compound. It is conductive similar to a metal.**

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 and almost always means silicide-Si contacts.

Silicide	$ErSi_{1.7}$	HfSi	$MoSi_2$	$ZrSi_2$	$TiSi_2$	$CoSi_2$	WSi_2	$NiSi_2$	Pd_2Si	PtSi
ϕ_{Bn} (V)	0.28	0.45	0.55	0.55	0.61	0.65	0.67	0.67	0.75	0.87
ϕ_{Bp} (V)			0.55	0.49	0.45	0.45	0.43	0.43	0.35	0.23

Using C-V Data to Determine ϕ_B



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

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

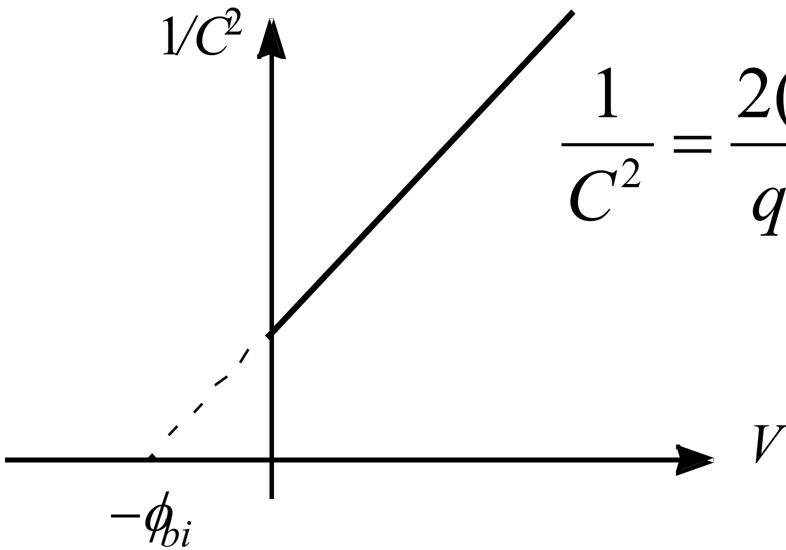
$$W_{dep} = \sqrt{\frac{2\varepsilon_s(\phi_{bi} + V)}{qN_d}}$$

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

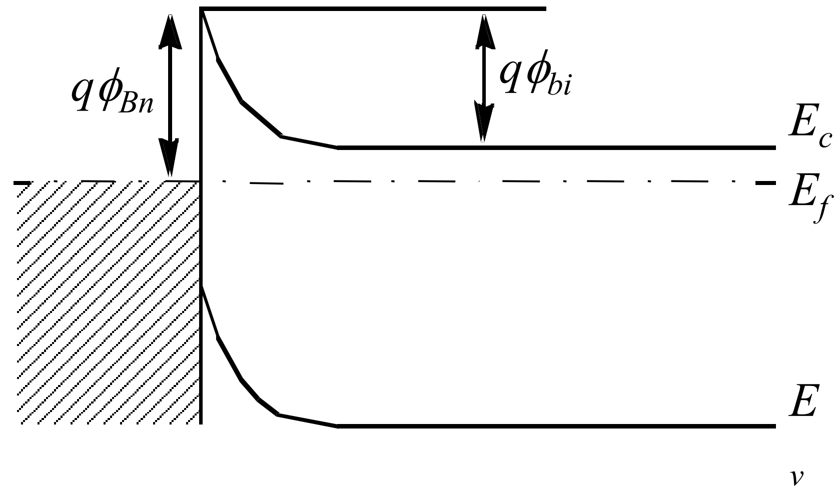
Question:

How should we plot the CV data to extract ϕ_{bi}?

Using CV Data to Determine ϕ_B



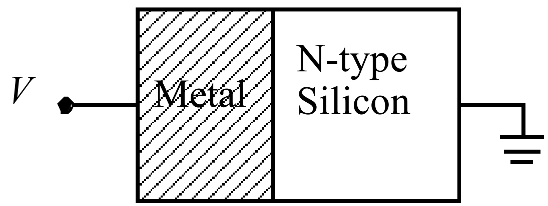
$$\frac{1}{C^2} = \frac{2(\phi_{bi} + V)}{qN_d \varepsilon_s A^2}$$

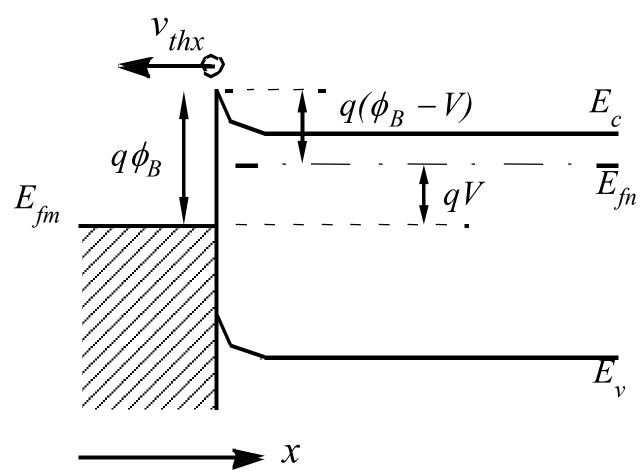


Once ϕ_{bi} is known, ϕ_B can be determined using

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

4.17 Thermionic Emission Theory





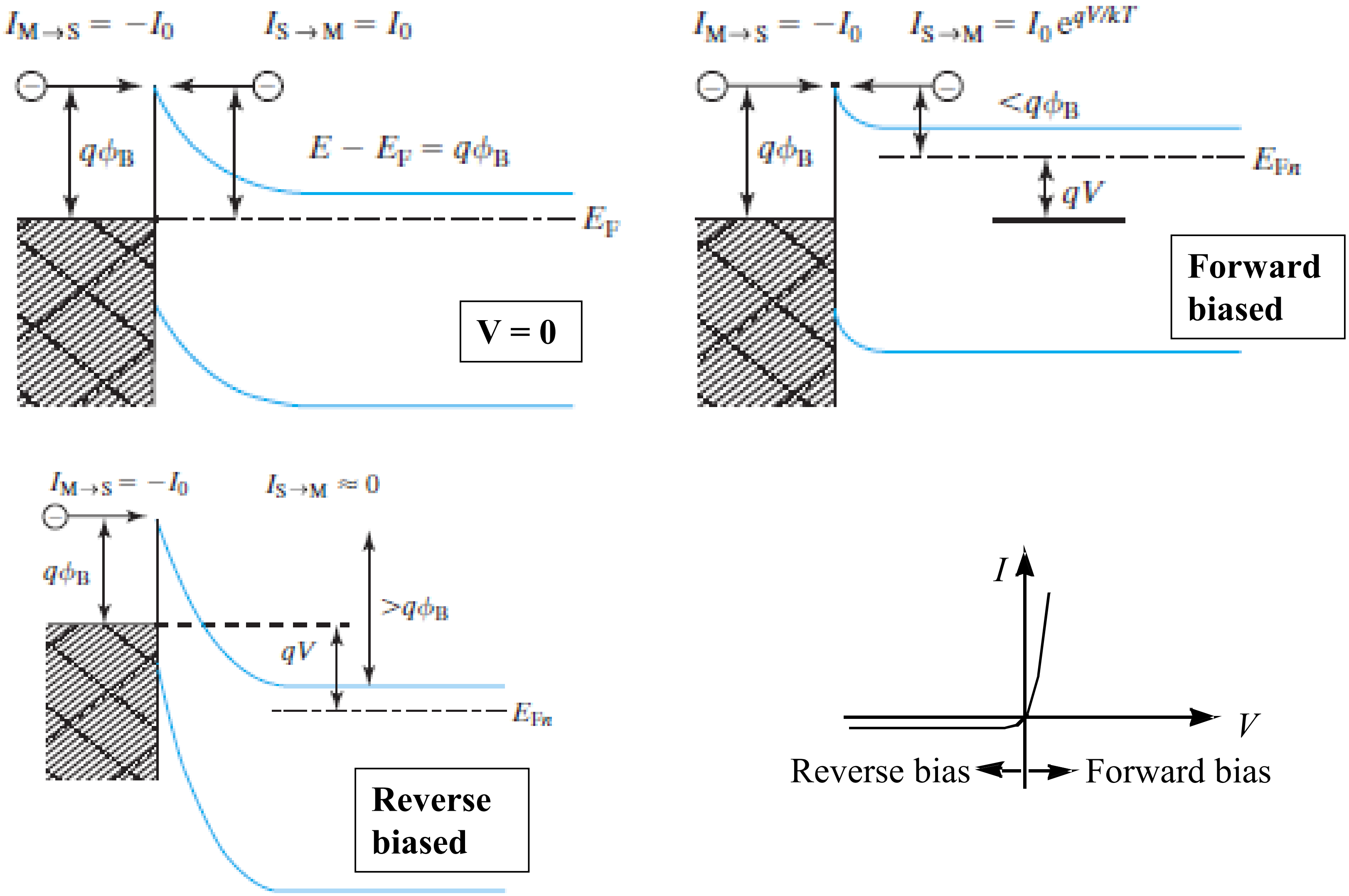
$$n = N_c e^{-q(\phi_B - V)/kT} = 2\left[\frac{2\pi m_n kT}{h^2}\right]^{3/2} e^{-q(\phi_B - V)/kT}$$

$$v_{th} = \sqrt{3kT/m_n} \qquad v_{thx} = -\sqrt{2kT/\pi m_n}$$

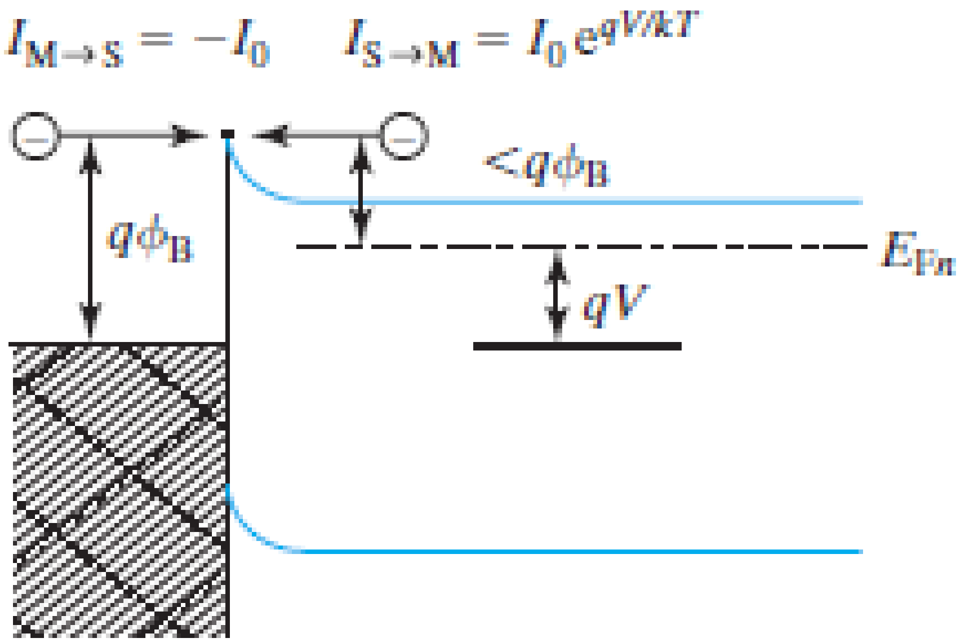
$$J_{S\rightarrow M} = -\frac{1}{2}qnv_{thx} = \frac{4\pi q m_n k^2}{h^3}T^2 e^{-q\phi_B/kT} e^{qV/kT}$$

$$= J_0 e^{qV/kT}, \text{where } J_o \approx 100 e^{-q\phi_B/kT} \text{ A/cm}^2$$

4.18 Schottky Diodes



4.18 Schottky Diodes

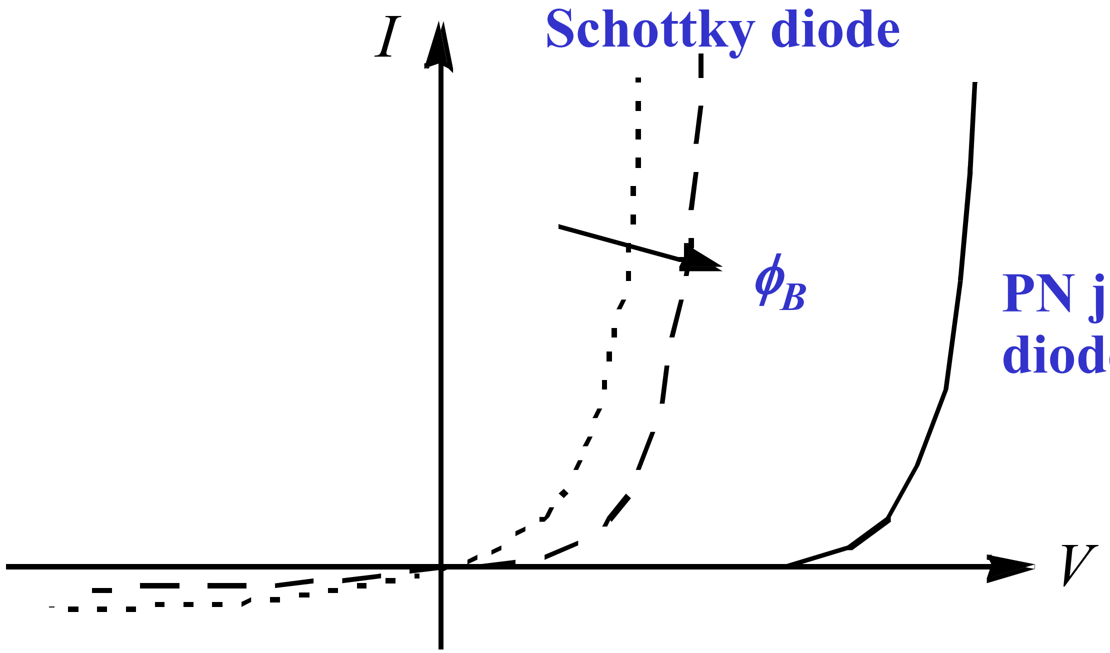


$$I_0 = AKT^2 e^{-q\phi_B/kT}$$

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

$$I = I_{S\rightarrow M} + I_{M\rightarrow S} = I_0 e^{qV/kT} - I_0 = I_0(e^{qV/kT} - 1)$$

4.19 Applications of Schottly Diodes

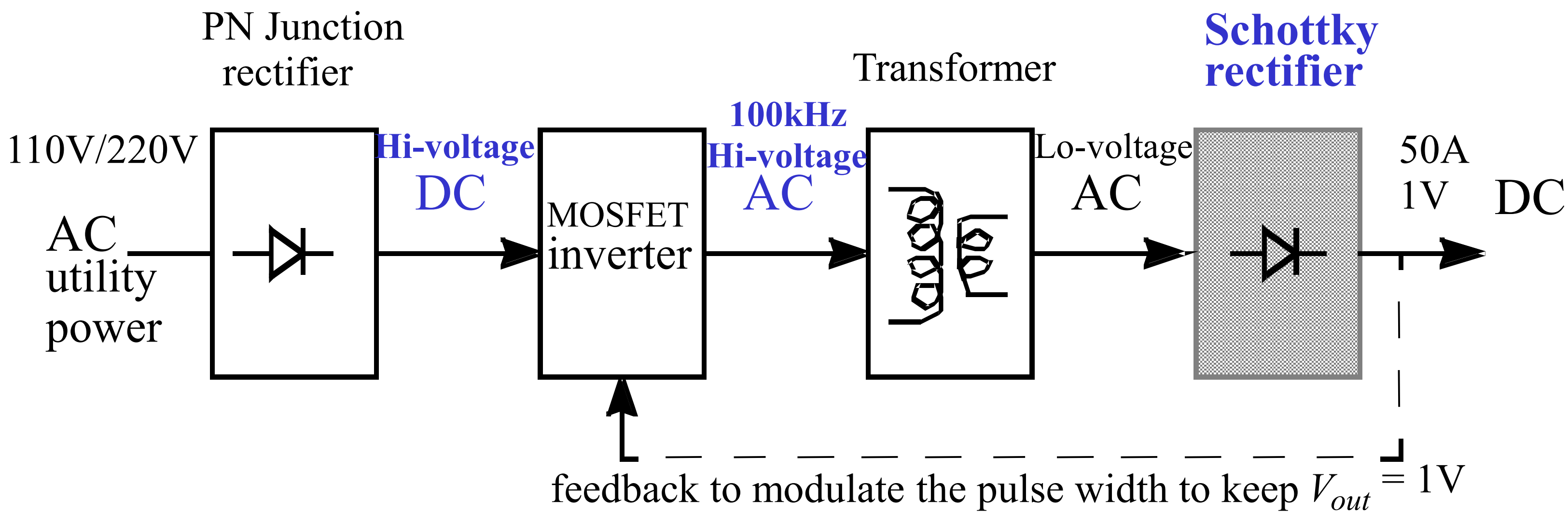


$$I = I_0(e^{qV/kT} - 1)$$

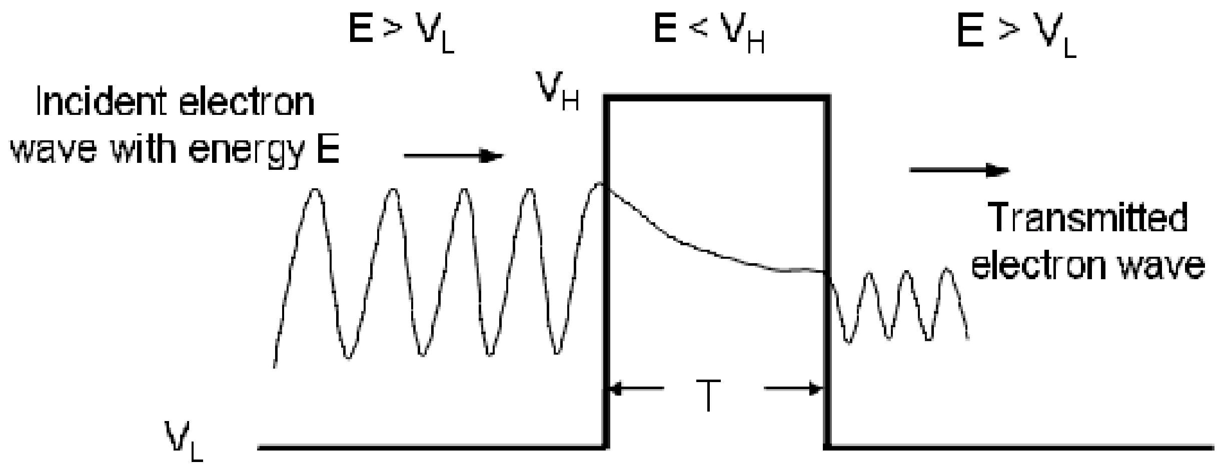
$$I_0 = AKT^2 e^{-q\phi_B/kT}$$

- I_0 of a Schottky diode is 10^3 to 10^8 times larger than a PN junction diode, depending on ϕ_B. A larger I_0 means a smaller forward drop V.
- A Schottky diode is the preferred rectifier in low voltage, high current applications.

Switching Power Supply



4.20 Quantum Mechanical Tunneling



***Tunneling probability*:**

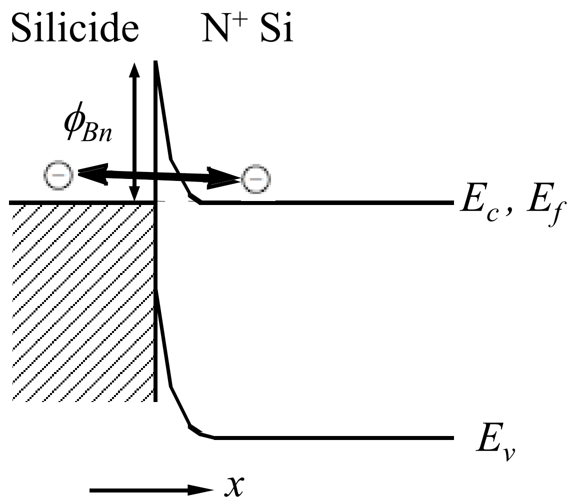
$$P \approx \exp\left(-2T\sqrt{\frac{8\pi^2 m}{h^2}(V_H - E)}\right)$$

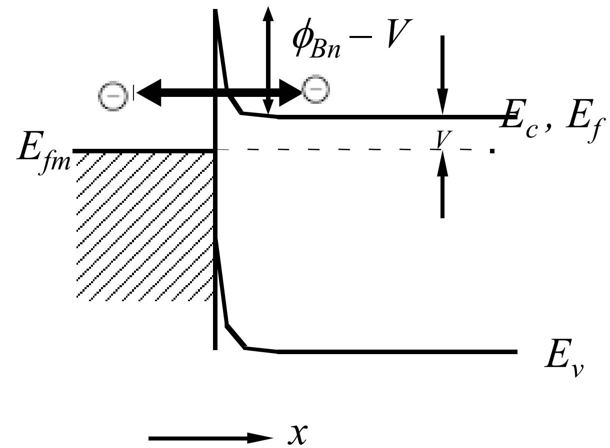
4.21 Ohmic Contacts

$$W_{dep} = \sqrt{\frac{2\varepsilon_s \phi_{Bn}}{qN_d}}$$

Tunneling probability:

$$P \approx e^{-H\phi_{Bn}/\sqrt{N_d}}$$



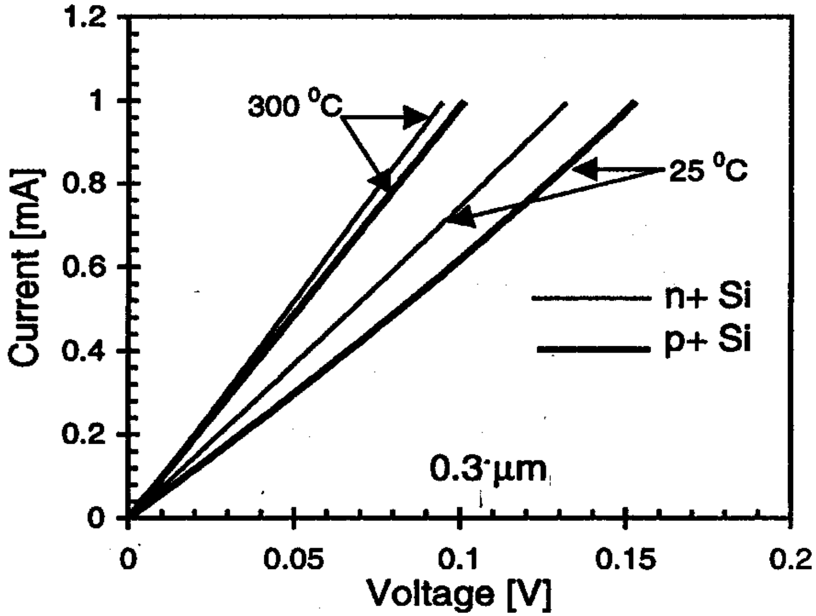


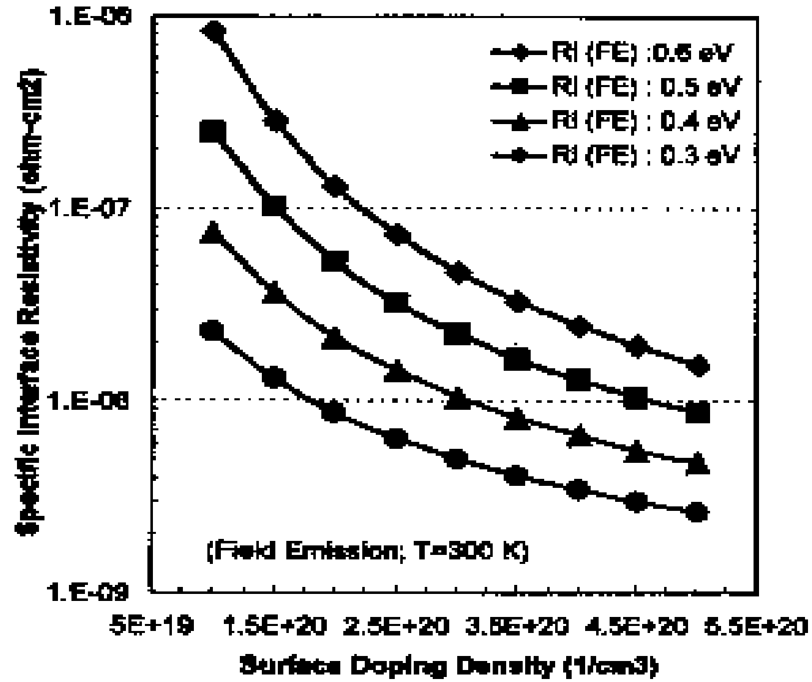
$$T \approx W_{dep}/2 = \sqrt{\varepsilon_s \phi_{Bn}/2qN_d}$$

$$H = \frac{4\pi}{h}\sqrt{\varepsilon_s m_n/q}$$

$$J_{S\to M} \approx \frac{1}{2} qN_d v_{thx} P = qN_d \sqrt{kT/2\pi m_n}\, e^{-H(\phi_{Bn}-V)/\sqrt{N_d}}$$

4.21 Ohmic Contacts





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

4.22 Chapter Summary

Part I: PN Junction

$$\phi_{bi} = \frac{kT}{q}\ln\frac{N_d N_a}{n_i^{\,2}}$$

The potential barrier increases by 1 V if a 1 V reverse bias is applied

depletion width

$$W_{dep} = \sqrt{\frac{2\varepsilon_s \cdot potential\ barrier}{qN}}$$

junction capacitance

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

4.22 Chapter Summary

- Under forward bias, minority carriers are injected across the jucntion.

- The quasi-equilibrium boundary condition of minority carrier densities is:

$$n(x_p) = n_{P0}e^{qV/kT}$$
$$p(x_N) = p_{N0}e^{qV/kT}$$

- Most of the minority carriers are injected into the more lightly doped side.

4.22 Chapter Summary

• Steady-state continuity equation:

$$\frac{d^2 p'}{dx^2} = \frac{p'}{D_p \tau_p} = \frac{p'}{L_p{}^2}$$

$$L_p \equiv \sqrt{D_p \tau_p}$$

• Minority carriers diffuse outward $\propto e^{-|x|/L_p}$ and $e^{-|x|/L_n}$

• L_p and L_n are the diffusion lengths

$$I = I_0 (e^{qV/kT} - 1)$$

$$I_0 = Aqn_i{}^2 \left(\frac{D_p}{L_p N_d} + \frac{D_n}{L_n N_a} \right)$$

4.22 Chapter Summary

Part II: Optoelectronic Applications

$$\text{Solar cell power} = I_{sc} \times V_{oc} \times FF$$

•~100um Si or <1um direct–gap semiconductor can absorb most of solar photons with energy larger than E_g.

•Carriers generated within diffusion length from the junction can be collected and contribute to the Short Circuit Current I_{sc}.

•Theoretically, the highest efficiency (~24%) can be obtained with 1.9eV $>E_g>$1.2eV. Larger E_g lead to too low I_{sc} (low light absorption); smaller E_g leads to too low Open Circuit VoltageVoc.

4.22 Chapter Summary

LED and Solid-State Lighting

•Electron-hole recombination in direct-gap semiconductors such as GaAs produce light.

•Tenary semiconductors such as GaAsP provide tunable E_g and LED color.

•Quatenary semiconductors such as AlInGaP provide tunable E_g and lattice constants for high quality epitaxial growth on inexpensive substrates.

•White light can be obtained with UV LED and wavelength conversion

•Organic semiconductor is an important low-cost LED material class. Used in OLED displays both for iPhones and other brands

4.22 Chapter Summary

Part III: Metal-Semiconductor Junction

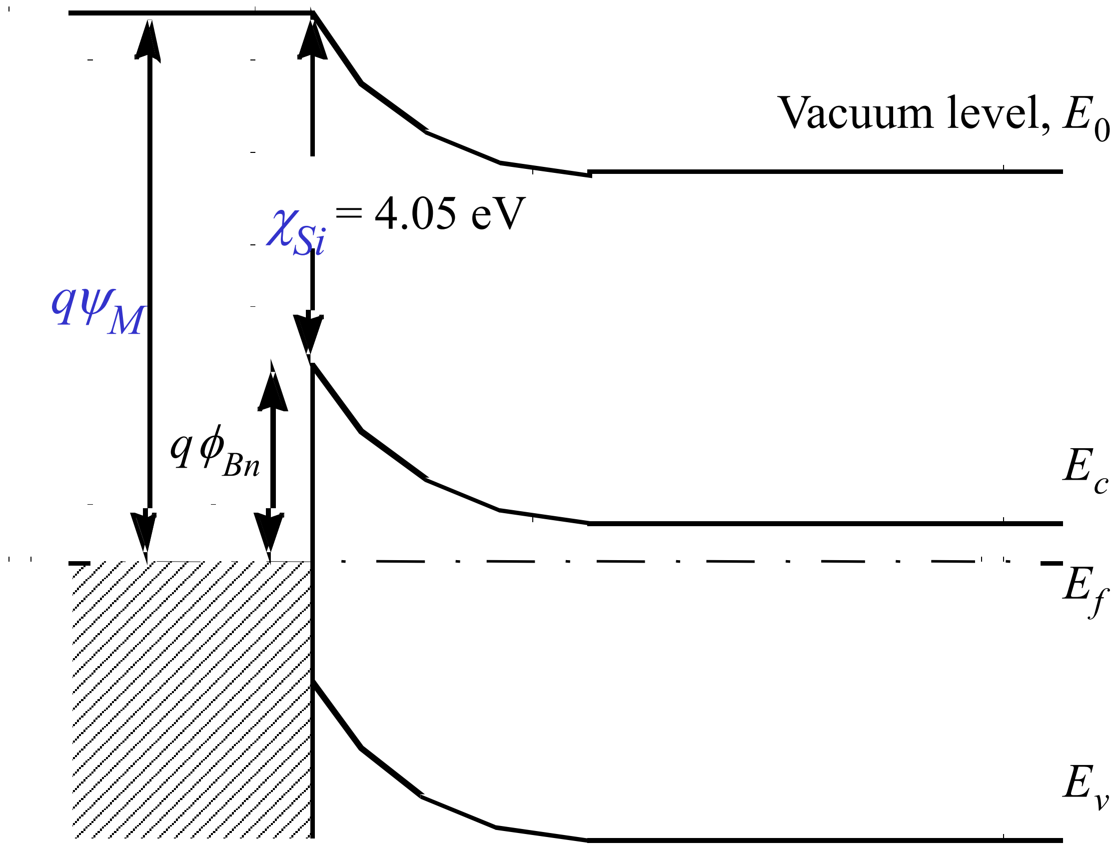
$$I_0 = AKT^2 e^{-q\phi_B / kT}$$

•Schottky diodes have large reverse saturation current, determined by the Schottky barrier height ϕ_B, and therefore lower forward voltage at a given current density.

•Ohmic contacts relies on tunneling. Low resistance contact requires low ϕ_B and higher doping concentration.

$$R_c \propto e^{-(\frac{4\pi}{h}\phi_B \sqrt{\varepsilon_s m_n / qN_d})} \Omega \cdot \text{cm}^2$$

ϕ_{Bn} Increases with Increasing Metal Work Function



Ideally,

$\phi_{Bn} = \psi_M - \chi_{Si}$