Chapter 14

Contacts and Schottky Dio

I IDEAL MS CONTACTS

An ideal MS contact has the following properties: (1) The metal and semiconductor are assumed to be in intimate contact on an atomic scale, with no layers of any type (such as an oxide) between the components. (2) There is no interdiffusion or intermixing of the metal and semiconductor. (3) There are no absorbed impurities or surface charges at the MS interface.

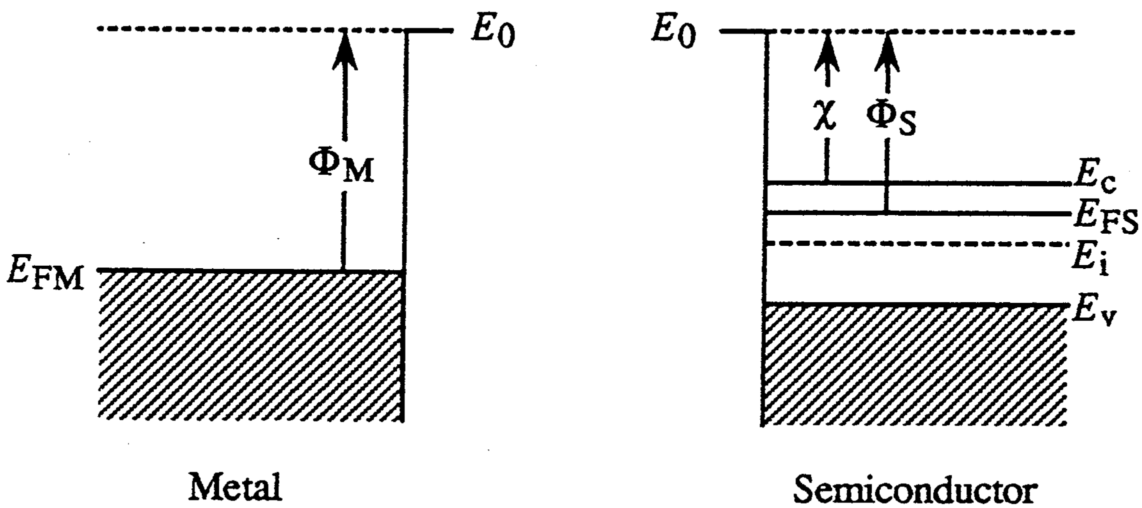


Fig. 14.1 Surface-included energy band diagrams for a metal (left) and *n*-type semiconductor (right).

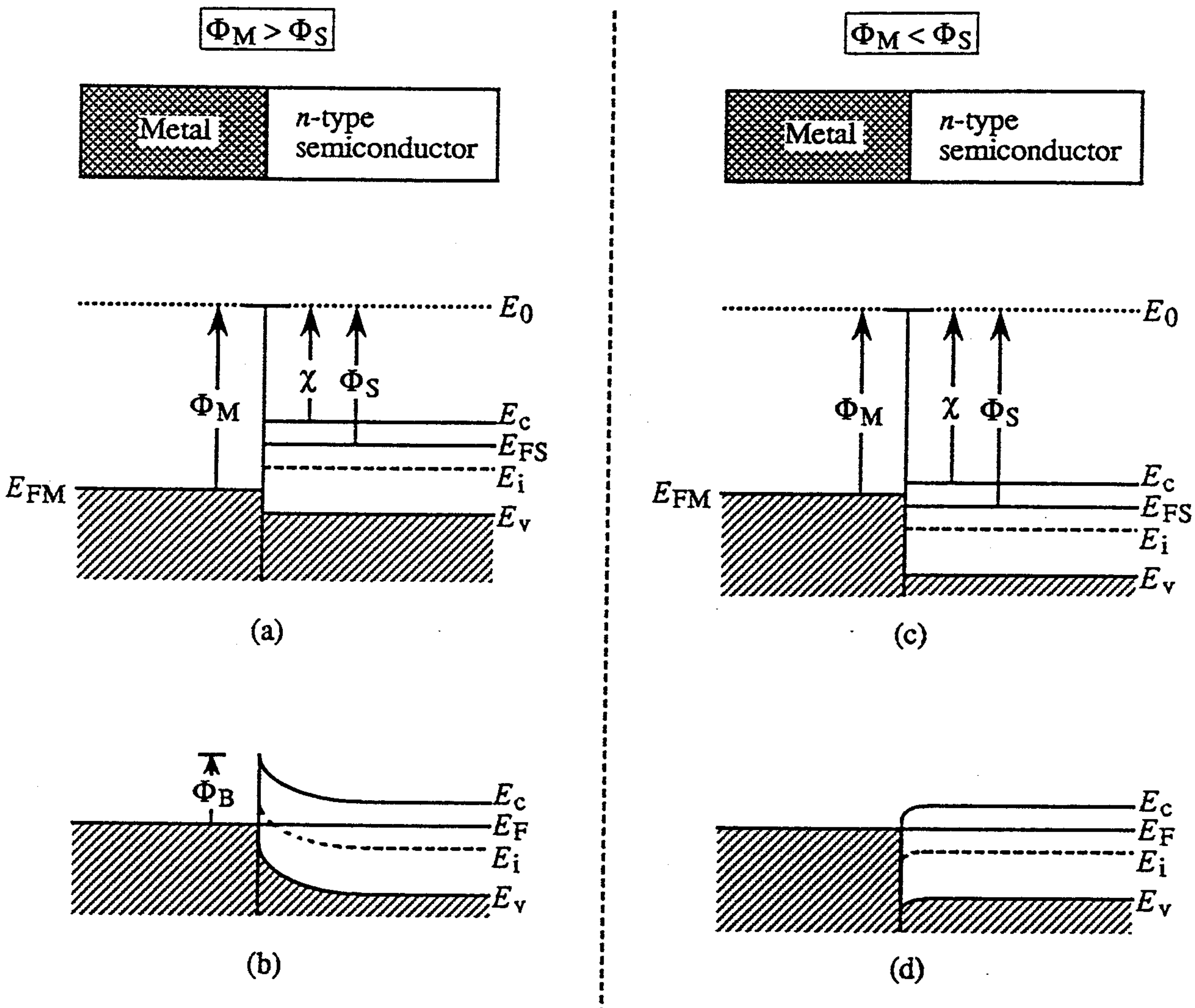


Fig. 14.2 Energy band diagrams for ideal MS contacts between a metal and an *n*-type semiconductor: $\Phi_M > \Phi_S$ system (a) an instant after contact formation and (b) under equilibrium conditions; $\Phi_M < \Phi_S$ system (c) an instant after contact formation and (d) under equilibrium conditions.

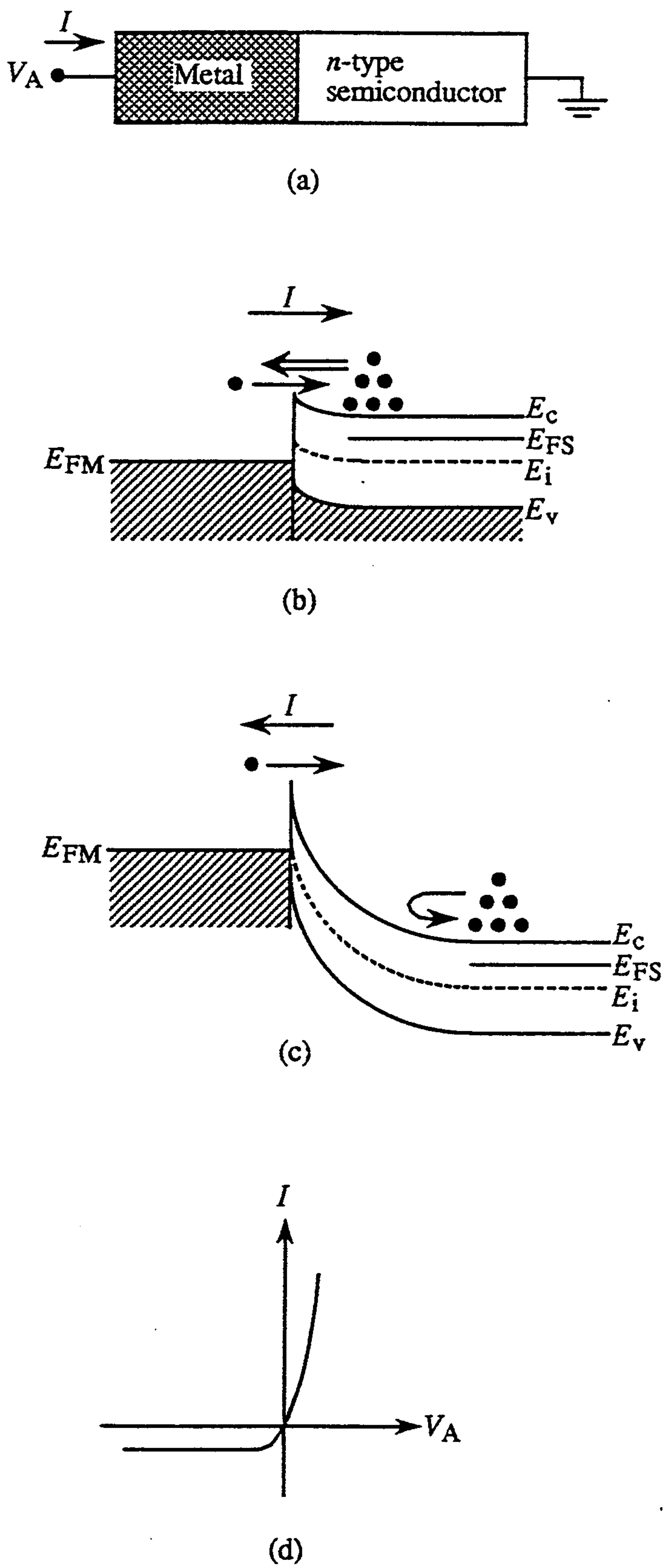
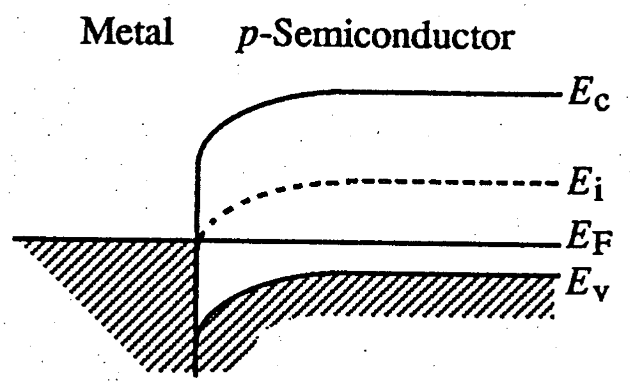
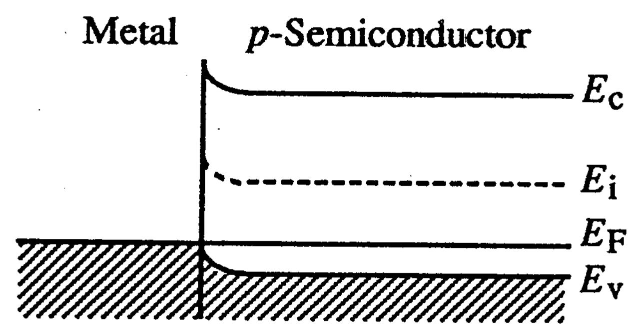


Fig. 14.3 Response of the $\Phi_M > \Phi_S$ (n-type) MS contact to an applied d.c. bias. (a) Definition of current and voltage polarities. (b) Energy band diagram and carrier activity when $V_A > 0$. (c) Energy band diagram and carrier activity when $V_A < 0$. (d) Deduced general form of the I–V characteristics.



(a) $\Phi_M < \Phi_S$



(b) $\Phi_M > \Phi_S$

$$\Phi_B = E_{FM} - E_v|_{interface} = (E_c - E_v) - (E_c|_{interface} - E_{FM})$$

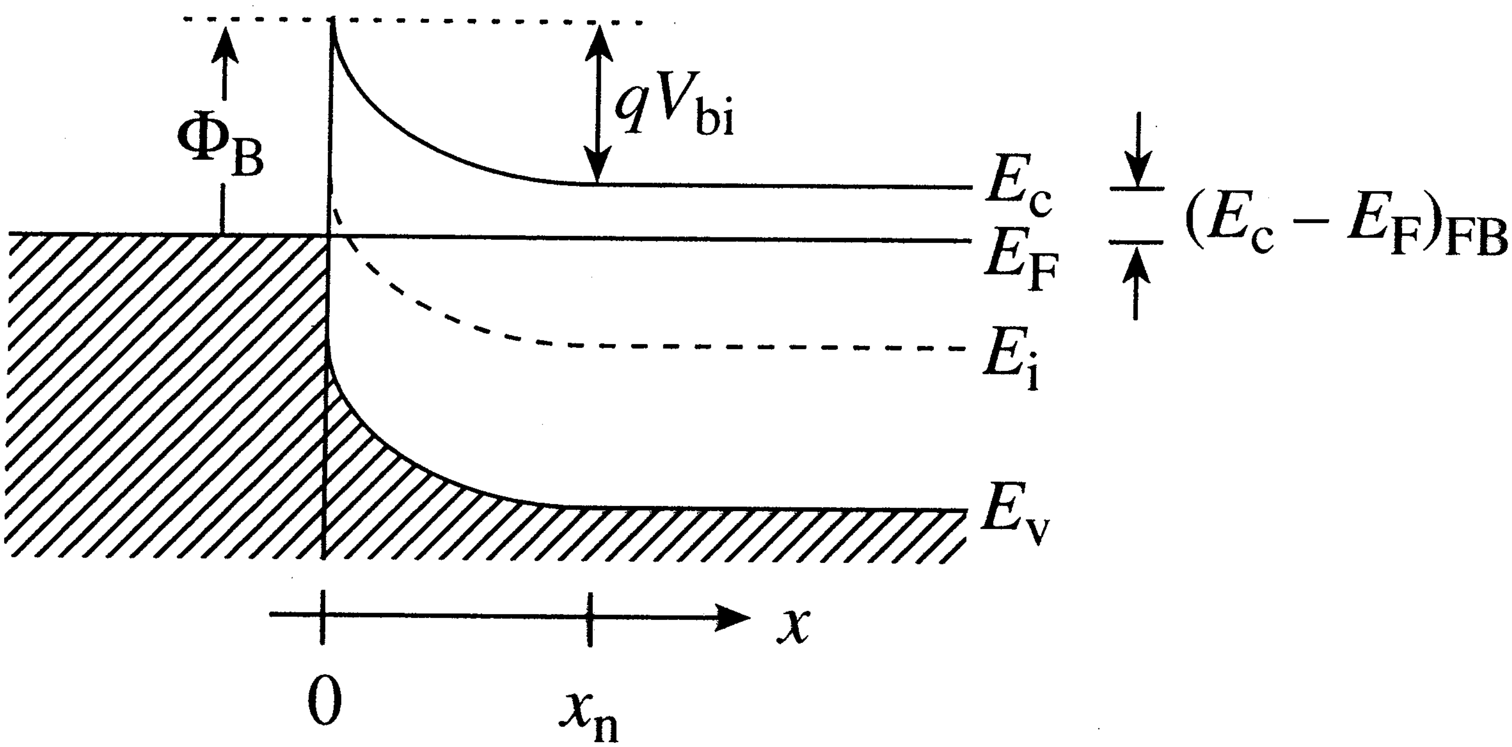
$$\Phi_B = E_G + \chi - \Phi_M \qquad \text{...ideal MS(}p\text{-type) contact}$$

Table 14.1 Electrical nature of ideal MS contacts.

	n-type semiconductor	*p*-type semiconductor
$\Phi_M > \Phi_S$	Rectifying	Ohmic
$\Phi_M < \Phi_S$	Ohmic	Rectifying

2 Schottky Diode Electrostatics

Built-In Voltage



$$V_{bi} = \frac{1}{q}\left[\Phi_B - (E_c - E_F)_{FB}\right]$$

$\Phi_B = \Phi_M - \chi$ ...ideal MS(n-type) contact

$\rho, \mathcal{E}, V$

$$\rho \cong \begin{cases} qN_D & \ldots 0 \le x \le W \\ 0 & \ldots x > W \end{cases}$$

$$\frac{d\mathcal{E}}{dx} = \frac{\rho}{K_S\varepsilon_0} \cong \frac{qN_D}{K_S\varepsilon_0} \qquad \ldots 0 \le x \le W$$

$$\int_{\mathcal{E}(x)}^{0} d\mathcal{E}' = \int_{x}^{W} \frac{qN_D}{K_S\varepsilon_0} dx'$$

$$\mathcal{E}(x) = -\frac{qN_D}{K_S\varepsilon_0}(W-x) \qquad \ldots 0 \le x \le W$$

$$\frac{dV}{dx} = -\mathcal{E} \cong \frac{qN_D}{K_S\varepsilon_0}(W-x) \qquad \ldots 0 \le x \le W$$

$$\int_{V(x)}^{0} dV' = \int_{x}^{W} \frac{qN_D}{K_S\varepsilon_0}(W-x')dx'$$

$$V(x) = -\frac{qN_D}{2K_S\varepsilon_0}(W-x)^2 \qquad \ldots 0 \le x \le W$$

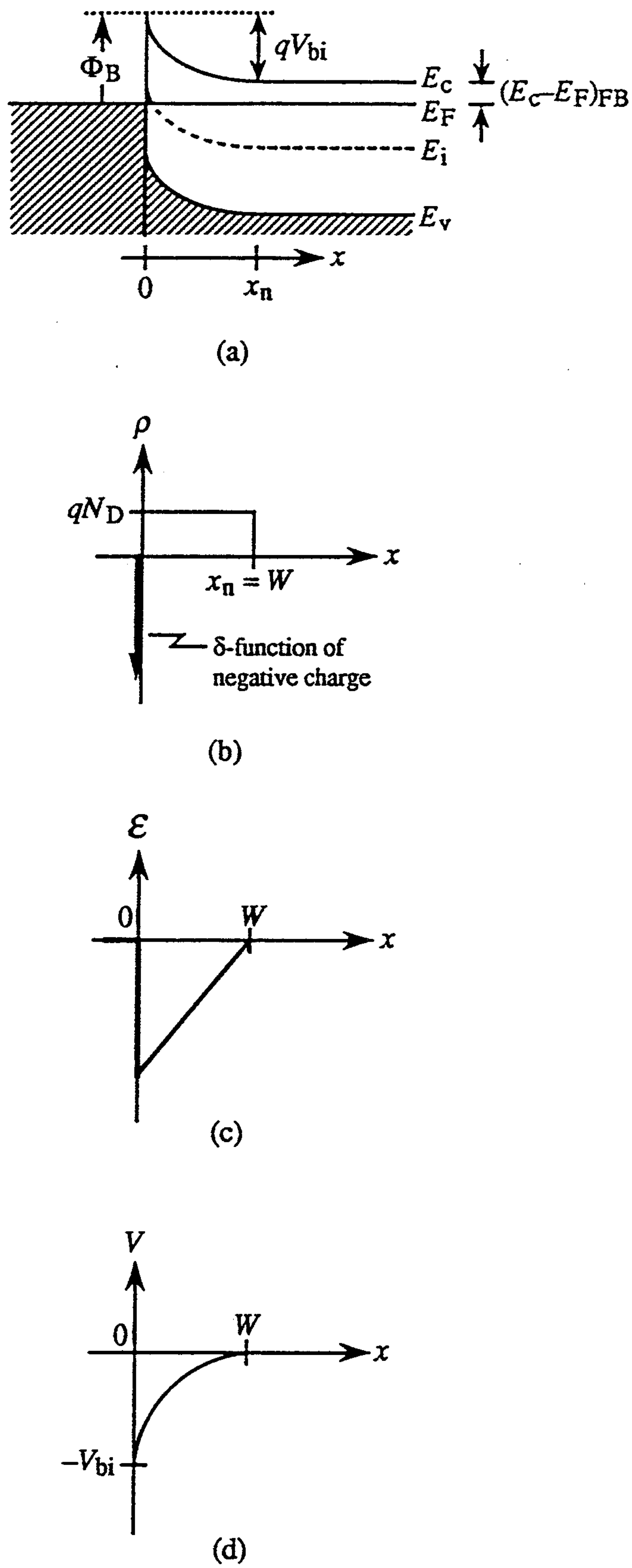


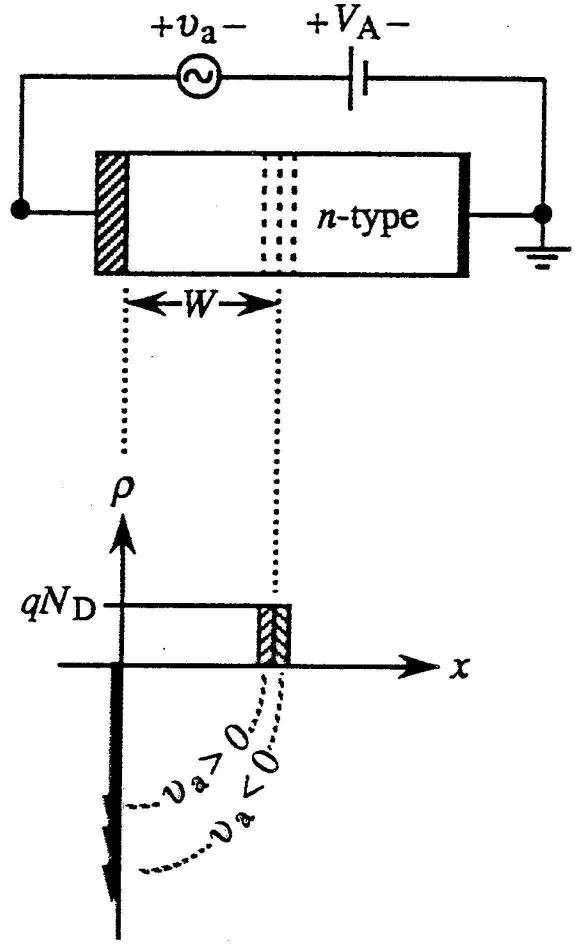
Fig. 14.4 Electrostatic variables in an MS (*n*-type) diode under equilibrium conditions. (a) Equilibrium energy band diagram. (b)–(d) Charge density, electric field, and electrostatic potential as a function of position.

W

$$-(V_{bi} - V_A) = -\frac{qN_D}{2K_S\varepsilon_0} W^2$$

$$W = \left[\frac{2K_S\varepsilon_0}{qN_D} (V_{bi} - V_A)\right]^{1/2}$$

3 SCHOTTKY DIODE a.c. RESPONSE

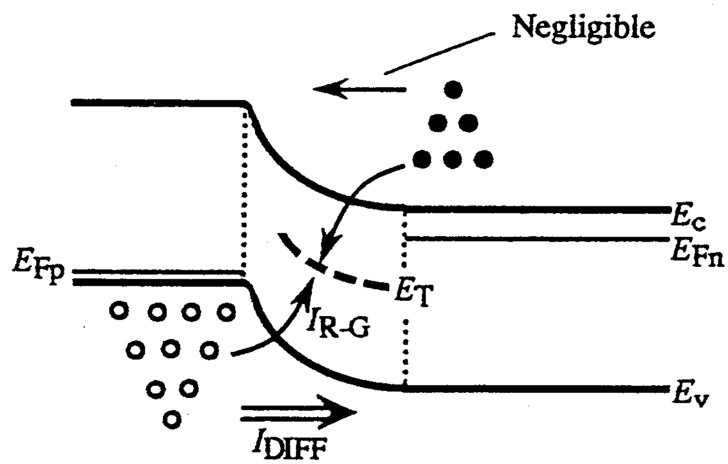


$$C = \frac{K_S \varepsilon_0 A}{W}$$

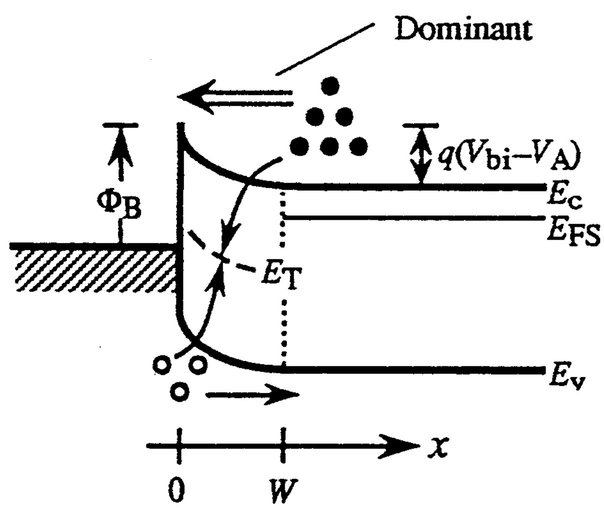
$$C = \frac{K_S \varepsilon_0 A}{\left[\frac{2K_S\varepsilon_0}{qN_D}(V_{bi}-V_A)\right]^{1/2}}$$

4 Schottky Diode I-V Characteristics

Dominant Current Component



(a) p^+-n junction diode



(b) MS Diode

Fig. 14.5 Negligible and dominant current components in a forward biased (a) p^+-n junction diode and (b) MS diode.

THERMIONIC EMISSION THEORY PRELIMINARIES

- APPLICABILITY... *Thermionic Emission theory is applicable for high-mobility semiconductors with moderate dopings.* (See SZE-II, p. 263)

- SINGLE-SIDE SIMPLIFICATION

$$J(V_A) = J_{S\to M}(V_A) + J_{M\to S}(V_A)$$

but $J_{M\to S}(V_A) = J_{M\to S}(0)$

so

$$J(V_A) = J_{S\to M}(V_A) + J_{M\to S}(0)$$

however $J(V_A) = 0$ when $V_A = 0$

giving $0 = J_{S\to M}(0) + J_{M\to S}(0)$

thus

$$J(V_A) = J_{S\to M}(V_A) - J_{S\to M}(0)$$

← ONLY NEED CONSIDER S→M

- BASIC CURRENT RELATIONSHIP

$$dJ = -q\, v_x\, n(v_x)\, dv_x \qquad (\vec{J}_{N|drift} = -q\vec{v}_d n)$$

I-V_A SOLUTION
[100] Si SCHOTTKY DIODE

d^3n DERIVATION

With the Si surface and current flow oriented in the [100] direction, it is convenient to set up an x-y-z coordinate system with the x-axis in [100] direction, the y-axis in the [010] direction, and the z-axis in the [001] direction. The E-k relationship for the various constant energy surface can then be expressed as

$$E - E_c = \begin{cases} \hbar^2 k_x^2/2m_\ell^* + \hbar^2(k_y^2+k_z^2)/2m_t^* & [100] \text{ and } [\bar{1}00] \\ \hbar^2(k_x^2+k_z^2)/2m_t^* + \hbar^2 k_y^2/2m_\ell^* & [010] \text{ and } [0\bar{1}0] \\ \hbar^2(k_x^2+k_y^2)/2m_t^* + \hbar^2 k_z^2/2m_\ell^* & [001] \text{ and } [00\bar{1}] \end{cases}$$

(ELLIPSOIDS)

We can write in general that

$$\left(\frac{\text{allowed energy state}}{\text{Unit volume of k-space}}\right) = \frac{abc}{4\pi^3}$$

and

$$\left(\begin{matrix}\text{Energy states with} \\ \text{k-values between } k_j \\ \text{and } k_j + dk_j \ldots j = x, y, z\end{matrix}\right) = \left(\frac{abc}{4\pi^3}\right) dk_x dk_y dk_z$$

Considering the [100] and [$\bar{1}$00] ellipsoids we note

$$v_x = \frac{1}{\hbar}\frac{\partial E}{\partial k_x} = \frac{\hbar k_x}{m_l^*} \; ; \; v_y = \frac{1}{\hbar}\frac{\partial E}{\partial k_y} = \frac{\hbar k_y}{m_t^*} \; ; \; v_z = \frac{1}{\hbar}\frac{\partial E}{\partial k_z} = \frac{\hbar k_z}{m_t^*}$$

and $$dv_x = \frac{\hbar}{m_l^*} dk_x \; ; \; dv_y = \frac{\hbar}{m_t^*} dk_y \; ; \; dv_z = \frac{\hbar}{m_t^*} dk_z$$

thus we conclude

$$\begin{pmatrix} \text{Energy states with} \\ v\text{-values between } v_j \\ \text{and } v_j + dv_j \ldots j = x, y, z \end{pmatrix} = \left(\frac{abc}{4\pi^3}\right)\left(\frac{m_l^* m_t^{*2}}{\hbar^3}\right) dv_x \, dv_y \, dv_z$$

also

$$E - E_c = \frac{1}{2}\left(m_l^* v_x^2 + m_t^* v_y^2 + m_t^* v_z^2\right)$$

The number of electrons per unit spacial volume (abc) with velocities between v_j and $v_j + dv_j$, $j = (x, y, z)$, which we give the symbol d^3n, is then

$$d^3n = \begin{pmatrix} \text{Energy states with} \\ v\text{-values between } v_j \\ \text{and } v_j + dv_j \ldots j = x, y, z \end{pmatrix} f(E)/(abc)$$

or

$$\left[d^3n = 2\left(\frac{m_l^* m_t^{*2}}{h^3}\right) f(E)\, dv_x\, dv_y\, dv_z \right]$$

where for an assumed non-degenerate semiconductor

$$\left[f(E) \simeq e^{(E_F - E)/kT} = e^{(E_F - E_C)/kT} e^{-\frac{1}{2kT}(m_l^* v_x^2 + m_t^* v_y^2 + m_t^* v_z^2)} \right]$$

└── [100] and [$\bar{1}$00] ellipsoids

If the development is repeated for the other four ellipsoids, one obtains the same d^3n expression with only the m_l^* effective mass being associated with the v_y^2 term or v_z^2 term in the $f(E)$ exponential.

$J_{S\to M}$ CALCULATION

By analogy with the isotropic effective mass calculation

$$J_{S\to M} = q \int_{v_{MIN}\,(v_x)}^{\infty}\int_{-\infty\,(v_y)}^{\infty}\int_{-\infty\,(v_z)}^{\infty} v_x \, d^3n \quad \text{... for all six ellipsoids}$$

or

$$J_{S\to M} = 2q\left(\frac{m_l^* m_t^{*2}}{h^3}\right) e^{\frac{E_F-E_C}{kT}} \Bigg[2\int_{v_{MIN}}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} v_x e^{-\frac{1}{2kT}(m_l^* v_x^2 + m_t^* v_y^2 + m_t^* v_z^2)} dv_z\, dv_y\, dv_x$$

$$+ 4\int_{v_{MIN}}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} v_x e^{-\frac{1}{2kT}(m_t^* v_x^2 + m_t^* v_y^2 + m_l^* v_z^2)} dv_z\, dv_y\, dv_x \Bigg]$$

where we have combined the [010]-[0$\bar{1}$0] and [001]-[00$\bar{1}$] integrals because the y and z integrals are interchangeable.

Note that

$$v_{MIN} = \sqrt{\frac{2q}{m_l^*}(V_{bi}-V_A)} \quad \text{... first triple integral}$$

$$= \sqrt{\frac{2q}{m_t^*}(V_{bi}-V_A)} \quad \text{... second triple integral}$$

We conclude

$$J_{S\to M} = \underbrace{\left[\frac{4\pi q(2m_t^* + 4\sqrt{m_\ell^* m_t^*})k^2}{h^3}\right]}_{\mathcal{A}^*} T^2 e^{\frac{E_F - E_C - qV_{bi}}{kT}} e^{\frac{qV_A}{kT}}$$

I-V_A RELATIONSHIP

Noting
$$\frac{E_F - E_C - qV_{bi}}{kT} = \frac{E_F - E_C + E_C - E_F - \Phi_B}{kT} = -\frac{\Phi_B}{kT}$$

$$J = J_{S\to M} + J_{M\to S} = J_{S-M} - J_{S-M}(V_A=0)$$

$$I = JA \qquad \ldots A = \text{diode AREA}$$

$$\boxed{I = \underbrace{A\mathcal{A}^* T^2 e^{-\Phi_B/kT}}_{I_S}\left(e^{qV_A/kT} - 1\right)}$$

EXAMINATION OF a^*

$$a = \frac{4\pi q m_0 k^2}{h^3}$$ ... Richardson's Constant

$$\frac{a^*}{a} = 2\frac{m_t^*}{m_0} + 4\sqrt{\frac{m_\ell^*}{m_0}\frac{m_t^*}{m_0}}$$

Employing the 4K values for the m_ℓ^* and m_t^* of Si in Table 3.1 of Volume VI, we obtain

$$\frac{a^*}{a} = 2(0.1905) + 4\sqrt{(0.9163)(0.1905)} = 2.05$$

plane relative to the principal axes of the ellipsoid, and m_x^*, m_y^*, and m_z^* are the components of the effective mass tensor. For Ge the emission in the conduction band arises from minima at the edge of the Brillouin zone in the ⟨111⟩ direction. These minima are equivalent to four ellipsoids with longitudinal mass $m_l^* = 1.64m_0$ and transverse mass $m_t^* = 0.082m_0$. The sum of all the A_l^* values has a minimum in the ⟨111⟩ direction:

$$\left(\frac{A^*}{A}\right)_{n\text{-Ge}\langle 111\rangle} = m_t^*/m_0 + [(m_t^*)^2 + 8m_l^* m_t^*]^{1/2}/m_0 = 1.11. \tag{26}$$

The maximum A^* occurs for the ⟨100⟩ direction:

$$\left(\frac{A^*}{A}\right)_{n\text{-Ge}\langle 100\rangle} = \frac{4}{m_0}\left[\frac{(m_t^*)^2 + 2m_t^* m_l^*}{3}\right]^{1/2} = 1.19. \tag{27}$$

For Si the conduction band minima occur in the ⟨100⟩ directions and $m_l^* = 0.98m_0$, $m_t^* = 0.19m_0$. All minima contribute equally to the current in the ⟨111⟩ direction, yielding the maximum A^*:

$$\left(\frac{A^*}{A}\right)_{n\text{-Si}\langle 111\rangle} = \frac{6}{m_0}\left[\frac{(m_t^*)^2 + 2m_t^* m_l^*}{3}\right]^{1/2} = 2.2. \tag{28}$$

The minimum value of A^* occurs for the ⟨100⟩ direction:

$$\left(\frac{A^*}{A}\right)_{n\text{-Si}\langle 100\rangle} = 2m_t^*/m_0 + 4(m_l^* m_t^*)^{1/2}/m_0 = 2.1. \tag{29}$$

For holes in Ge, Si, and GaAs the two energy maxima at $\mathbf{k} = 0$ give rise to approximately isotropic current flow from both the light and heavy holes. Adding the currents due to these carriers, we obtain

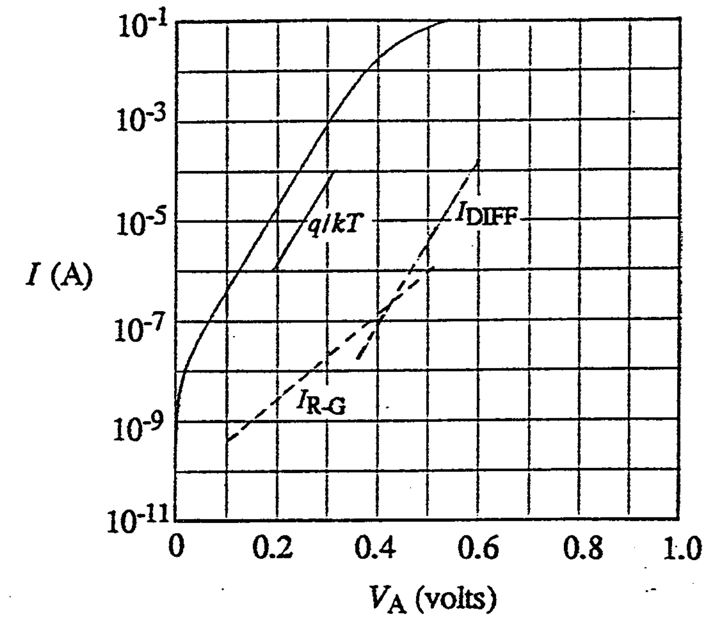
$$\left(\frac{A^*}{A}\right)_{p\text{-type}} = (m_{lh}^* + m_{hh}^*)/m_0. \tag{30}$$

Table 1 gives a summary of the values[13] of (A^*/A).

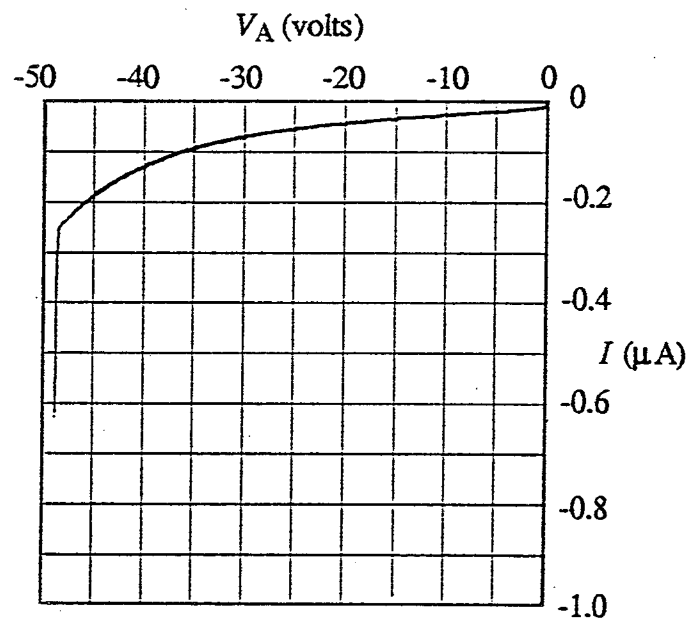
Since the barrier height for electrons moving from the metal into the semiconductor remains the same, the current flowing into the semiconductor is thus unaffected by the applied voltage. It must therefore be equal to the current flowing from the semiconductor into the metal when thermal equilibrium prevails (i.e., when $V = 0$). The corresponding current density

Table 1 Values of A^*/A

Semiconductor	Ge	Si	GaAs	
p-type	0.34	0.66	0.62	
n-type ⟨111⟩	1.11	2.2	0.068 (low field)	1.2 (high field)
n-type ⟨100⟩	1.19	2.1	0.068 (low field)	1.2 (high field)



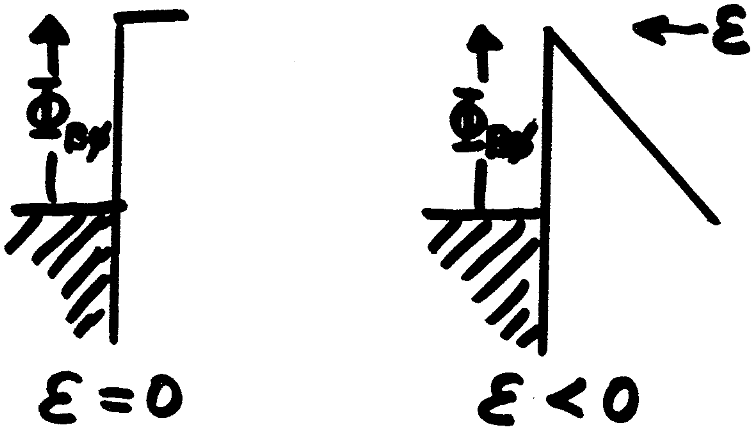
(a)



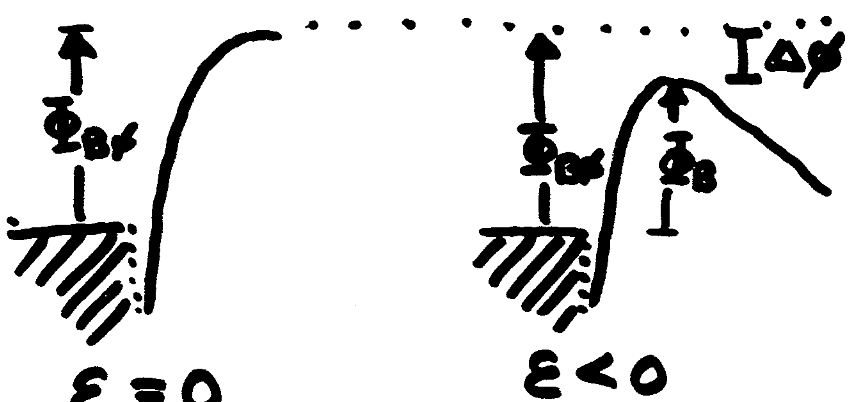
(b)

Fig. 14.6 Measured *I–V* characteristics derived from a MBR040 MS diode: (a) forward bias; (b) reverse bias. The dashed lines in (a) are theoretical estimates of the diffusion (I_{DIFF}) and recombination-generation ($I_{R\text{-}G}$) currents flowing in the diode. The experimental data was obtained employing an HP4145B Semiconductor Parameter Analyzer.

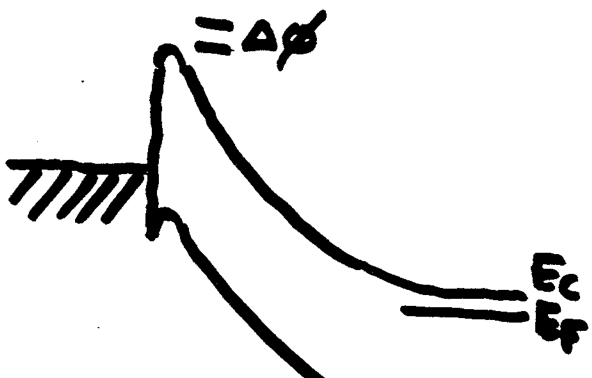
SCHOTTKY BARRIER LOWERING



⇐ FIRST ORDER MODEL



⇐ Model developed by Schottky. Properly models emission current from metal when $\varepsilon < 0$ applied.



⇐ SIMILAR SITUATION AT INTERFACE OF MS CONTACTS

$$\Phi_B = \Phi_{B0} - \Delta\phi$$

$$\Delta\phi = \left[\frac{q|\mathcal{E}_s|}{4\pi K_S \varepsilon_0}\right]^{\frac{1}{2}}$$

... use $\mathcal{E}_s$ computed ignoring Schottky effect

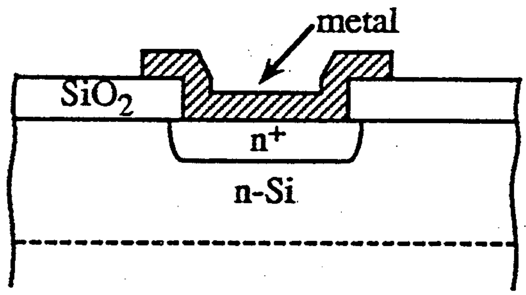
NOTE: ① $\Delta\phi \uparrow$ as $V_R \uparrow$

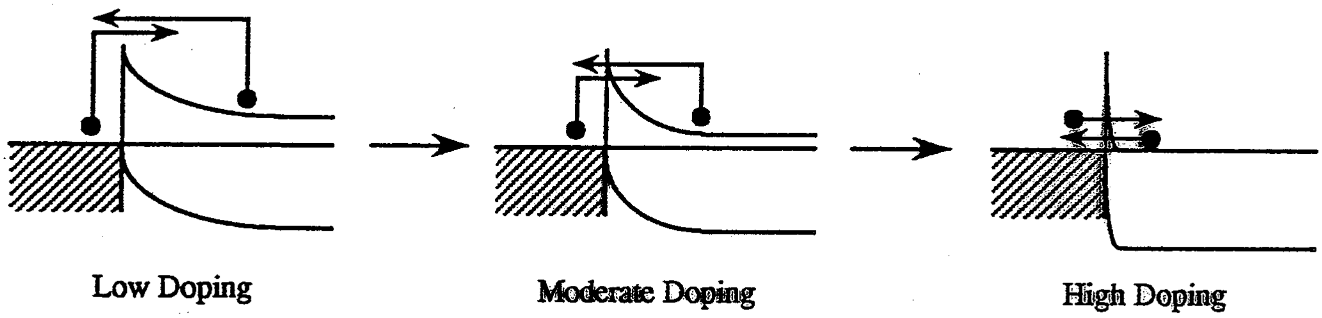
② $\Delta\phi$ small

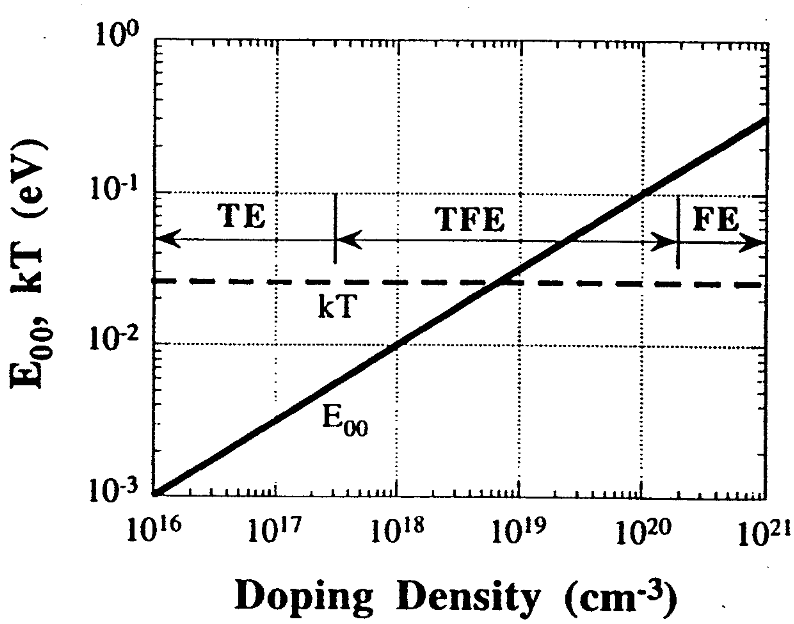
5 Practical MS Contact Considerations

Rectifying Contacts

Ohmic Contacts

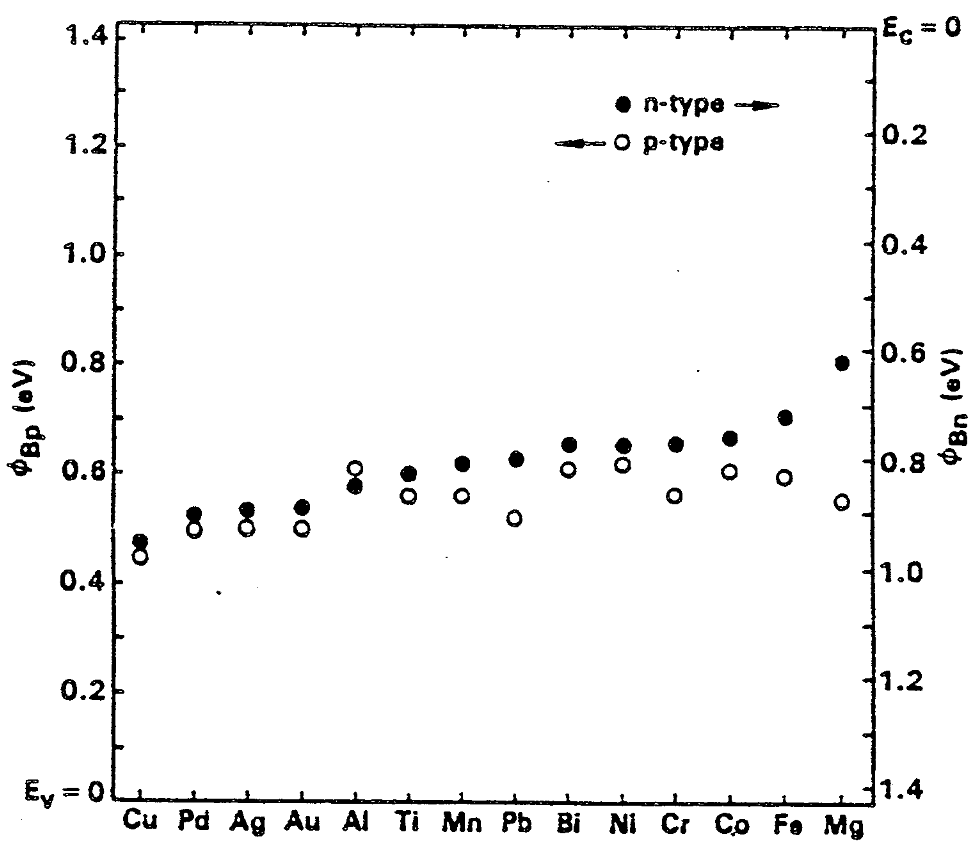






FROM: J. R. WALDROP, J. VAC. SCI. TECHNOL. B, 2, 445 (JULY-SEPT, 1984).

Metal	$\phi_{Bn}^{IV^a}$ (eV)	ϕ_{Bn}^{CV} (eV)	$\phi_{Bp}^{IV^b}$ (eV)	$(\phi_{Bn}^{IV} + \phi_{Bp}^{IV})$ (eV)	ϕ_m^c (eV)
Cu	0.96	0.96	0.45	1.41	4.65
Pd	0.91	0.93	0.50	1.41	5.12
Ag	0.90	0.89	0.50	1.40	4.26
Au	0.89	0.87	0.50	1.39	5.1
Al	0.85	0.84	0.61	1.46	4.28
Ti	0.83	0.83	0.56	1.39	4.33
Mn	0.81	0.89	0.56	1.37	4.1
Pb	0.80	0.91	0.52	1.32	4.25
Bi	0.77	0.79	0.61	1.38	4.22
Ni	0.77	0.91	0.62	1.39	5.15
Cr	0.77	0.81	0.56	1.33	4.5
Co	0.76	0.86	0.61	1.37	5.0
Fe	0.72	0.75	0.60	1.32	4.5
Mg	0.62	0.66	0.55	1.17	3.66



Φ_B MEASUREMENTS

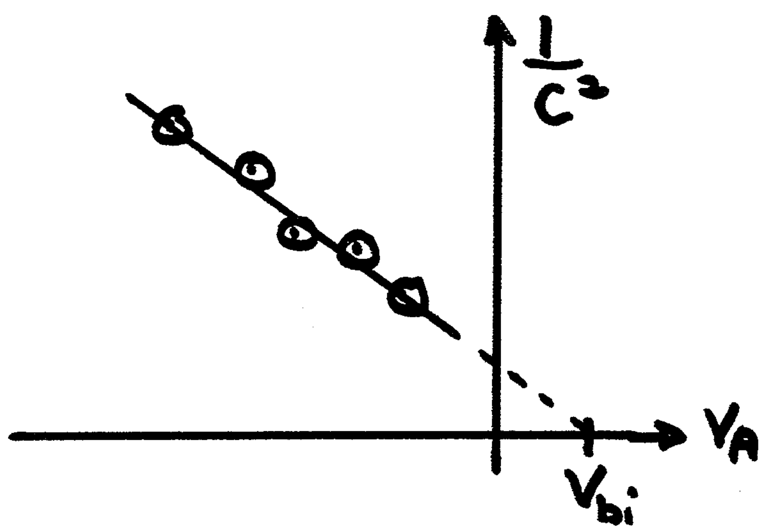
(1) C–V

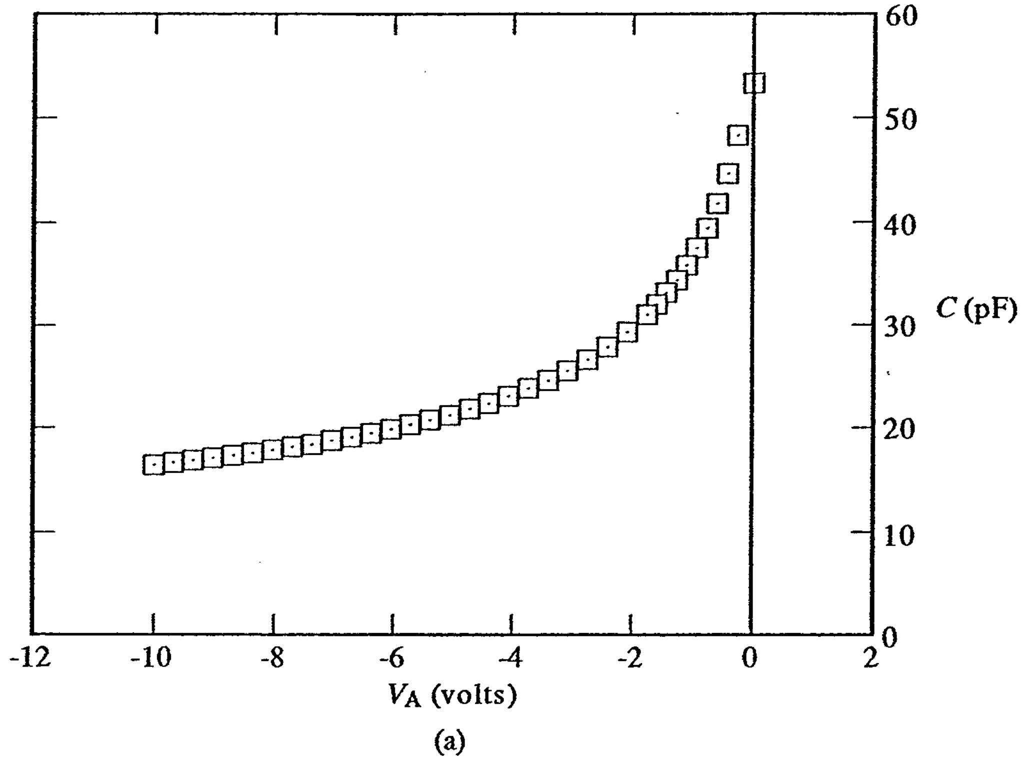
For a reverse-biased MS-diode that is uniformly doped n-type

$$C = \frac{K_S \epsilon_0 A}{W} = \frac{K_S \epsilon_0 A}{\left[\frac{2K_S\epsilon_0}{qN_D}(V_{bi}-V_A)\right]^{1/2}}$$

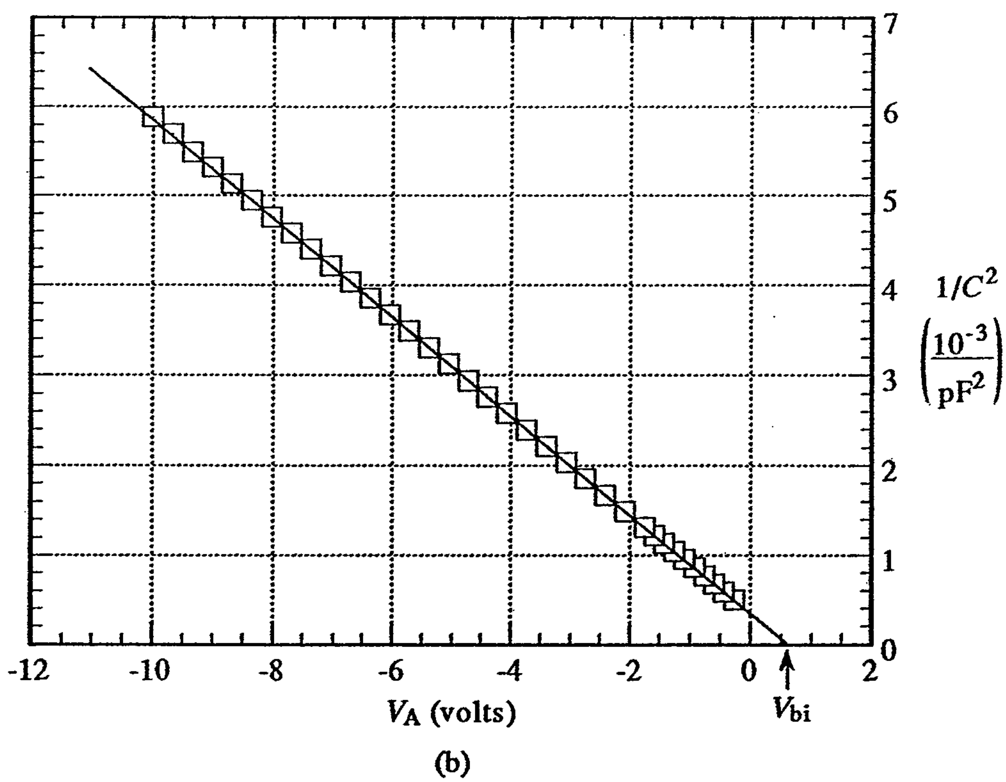
where $V_{bi} = \frac{1}{q}\left[\Phi_B - (E_c - E_F)|_{bulk}\right]$

Thus $$\frac{1}{C^2} = \left(\frac{2}{qK_S\epsilon_0 A^2 N_D}\right)(V_{bi}-V_A)$$





(a)

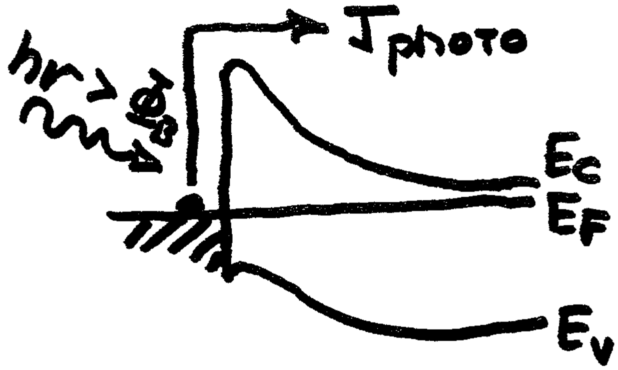


(b)

Figure 14.8 (a) Sample C–V data derived from a MBR040 MS diode. (b) $1/C^2$ versus V_A plot constructed from the experimental C–V data. [*Note:* To correct for the encapsulation-related stray capacitance shunting the MS diode, 3.4 pF was subtracted from all measured capacitance values before constructing the part (b) plot.]

(2) PHOTOCURRENT

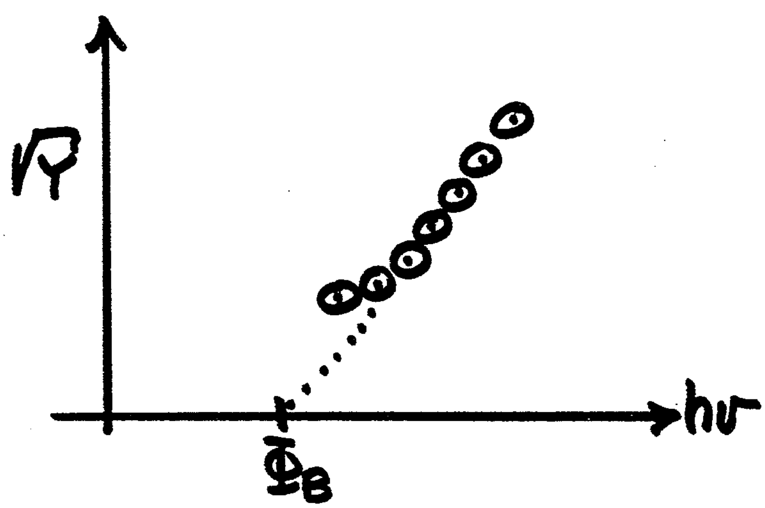
Basic idea...



$$Y = \frac{J_{photo}}{\text{\# photons absorbed}} \propto (h\nu - h\nu_0)^2 \quad \ldots h\nu_0 = \Phi_B$$

VALID $(h\nu - h\nu_0) \gtrsim 3kT$

PLOT $\sqrt{Y}$ vs. $h\nu$ ⇒ should be straight line with extrapolated $\sqrt{Y} = 0$ intercept of Φ_B



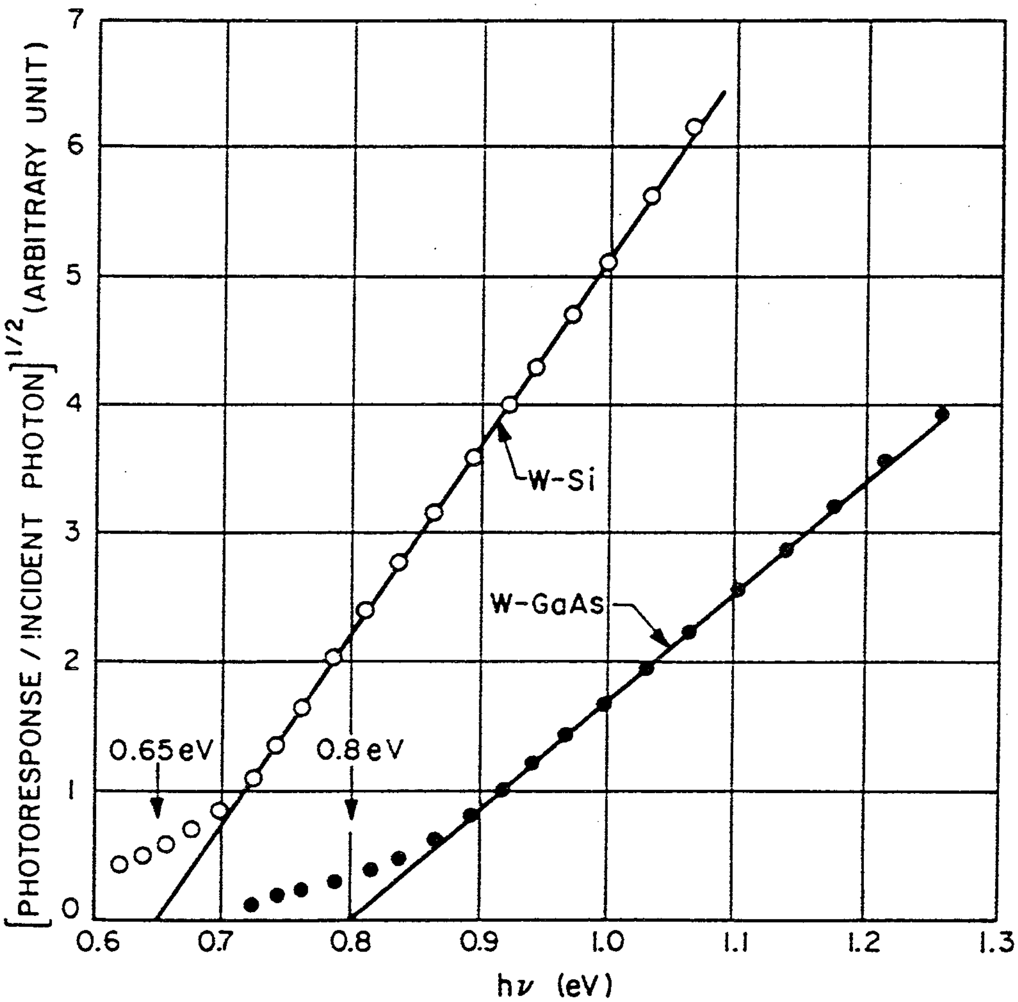


Fig. 32, p. 290 of Sze, 2nd edition.