EE415/515 Fundamentals of Semiconductor Devices Fall 2012

Lecture 9:
MS & Hetero-Junctions
(Chapter 9)

Schottky Barrier

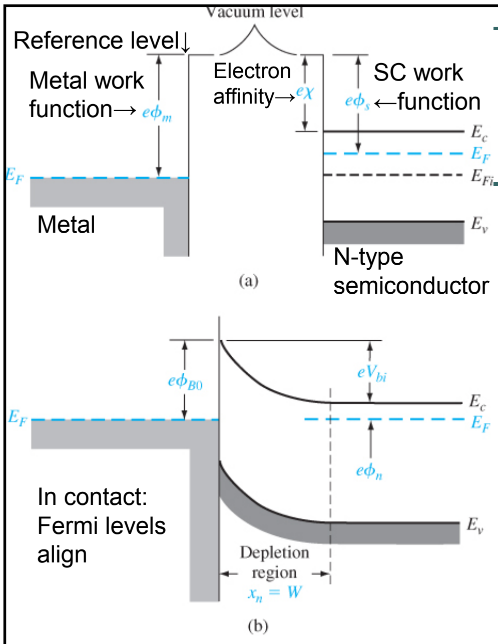


Figure 9.1 | (a) Energy-band diagram of a metal and semiconductor before contact; (b) ideal energy-band diagram of a metal–n-semiconductor junction for $\phi_m > \phi_s$.

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

Table 9.2 | Electron affinity of some semiconductors

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

Schottky barrier : $\varphi_{B0} = \varphi_m - \chi$

Built-in potential barrier: $V_{bi} = \varphi_{B0} - \varphi_n$

Schottky barrier bias

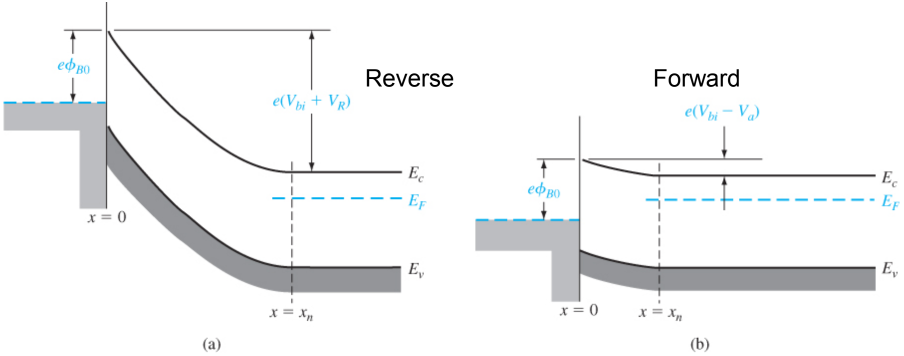


Figure 9.2 | Ideal energy-band diagram of a metal–semiconductor junction (a) under reverse bias and (b) under forward bias.

Ideal Schottky junction

In space charge region $\dfrac{dE}{dx}=\dfrac{\rho(x)}{\varepsilon}$

$$E=\int\frac{eN_d}{\varepsilon_s}dx \text{ for uniform doping}$$

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

$$=0 \text{ at } \mathrm{x}=\mathrm{x_n} \text{ so } \mathrm{C_1}=-\frac{eN_d x_n}{\varepsilon_s}$$

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

$$\text{Max } E(0)=-\frac{eN_d}{\varepsilon_s}x_n$$

$\mathrm{E}(0^-)$ is zero in metal, so (Gauss' Law) → negative interface surface charge in metal

Ideal Schottky junction

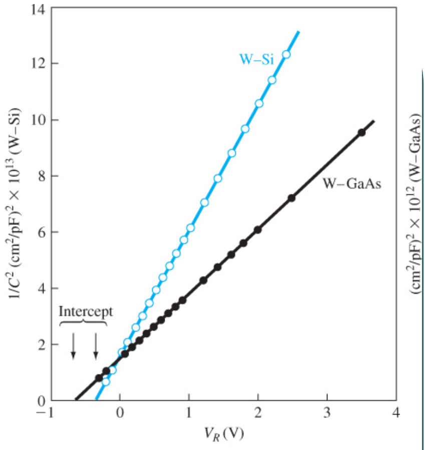


Figure 9.3 | $1/C^2$ versus V_R for W–Si and W–GaAs Schottky barrier diodes.
(From Sze and Ng [15].)

As for one-sided p^+n junction

$$W = x_n = \sqrt{\frac{2\varepsilon_s(V_{bi}+V_R)}{eN_d}}$$

$$C' = eN_d\frac{dx_n}{dV_R} = \sqrt{\frac{e\varepsilon_s N_d}{2(V_{bi}+V_R)}}$$

Plot $\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi}+V_R)}{e\varepsilon_s N_d}$ vs V_R gives V_{bi} (intercept) and N_d (slope)

Then $\phi_{B0} = V_{bi} - \phi_n$ where ϕ_n calculated as $E_C - E_F$

Ex 9.1 Ideal W to n-type GaAs M-S junction; N_d=5x10^{15}/cm^3. Find theoretical barrier height, built-in potential barrier, and maximum electric field for zero applied bias.

$$\phi_{B0} = \phi_m - \chi = 4.55 - 4.07 = 0.48\ \text{V}$$

$$\phi_n = V_t \ln\left(\frac{N_c}{N_d}\right) = (0.0259)\ln\left(\frac{4.7\times10^{17}}{5\times10^{15}}\right)$$

$$= 0.1177\ \text{V}$$

$$V_{bi} = \phi_{B0} - \phi_n = 0.48 - 0.1177 = 0.3623\ \text{V}$$

$$x_n = \left\{\frac{2\in_s V_{bi}}{eN_d}\right\}^{1/2}$$

$$= \left\{\frac{2(13.1)(8.85\times10^{-14})(0.3623)}{(1.6\times10^{-19})(5\times10^{15})}\right\}^{1/2}$$

$$= 3.24\times10^{-5}\ \text{cm}$$

$$|\mathrm{E}_{\max}| = \frac{eN_d x_n}{\in_s}$$

$$= \frac{(1.6\times10^{-19})(5\times10^{15})(3.24\times10^{-5})}{(13.1)(8.85\times10^{-14})}$$

$$= 2.24\times10^4\ \text{V/cm}$$

Ex 9.2 Find the GaAs doping concentration and Schottky barrier height for the W-GaAs diode in Fig 9.3 (slide 5).

From Figure 9.3,

$V_{bi} \cong 0.64\ \text{V}$

$$\frac{\Delta\left(\frac{1}{C'}\right)^2}{\Delta V_R} \cong \frac{8.5\times10^{12}}{3+0.64} = 2.335\times10^{12}$$

$$\text{Then}\quad N_d = \frac{2}{e\in_s}\cdot\frac{1}{\dfrac{\Delta\left(\frac{1}{C'}\right)^2}{\Delta V_R}}$$

$$= \frac{2}{(1.6\times10^{-19})(13.1)(8.85\times10^{-14})(2.335\times10^{12})}$$

$$\text{or}\quad N_d = 4.62\times10^{18}\ \text{cm}^{-3}$$

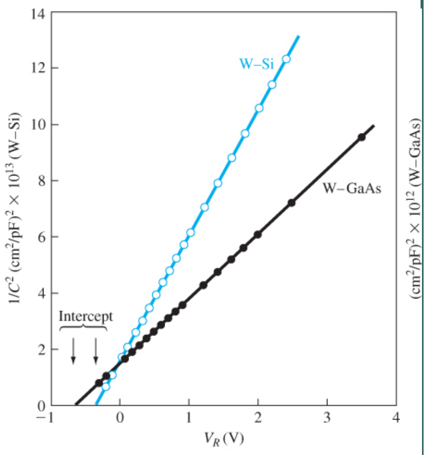


Figure 9.3 | $1/C^2$ versus V_R for W–Si and W–GaAs Schottky barrier diodes.
(From Sze and Ng [15].)

Schottky Effect (barrier lowering)

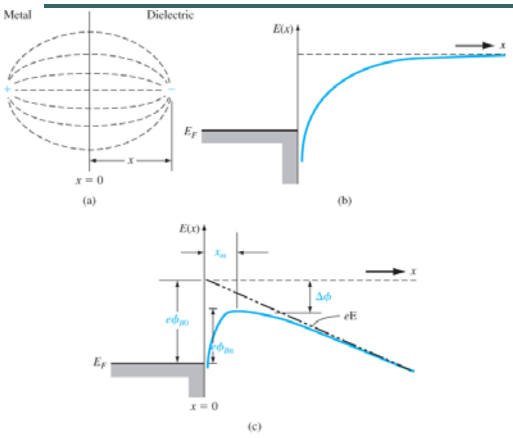


Figure 9.4 | (a) Image charge and electric field lines at a metal–dielectric interface. (b) Distortion of the potential barrier due to image forces with zero electric field and (c) with a constant electric field.

As electron leaves metal surface, image charge exerts restoring force

$$F = -eE = \frac{-e^2}{4\pi\varepsilon_s(2x)^2}$$

$$\text{Potential}: -\phi(x) = +\int_x^\infty \frac{e}{16\pi\varepsilon_s(x')^2}dx'$$

$$= \frac{-e}{16\pi\varepsilon_s x}\quad \text{for } \phi(\infty) = 0$$

With applied field E:

$$-\phi(x) = \frac{-e}{16\pi\varepsilon_s x} - Ex$$

$$\text{Maximum barrier when } \frac{d(e\phi(x))}{dx} = 0$$

$$\text{at } x_m = \sqrt{\frac{e}{16\pi\varepsilon_s E}}\quad \text{where } \Delta\phi = \sqrt{\frac{eE}{4\pi\varepsilon_s}}$$

Ex 9.3 Calculate the Schottky barrier lowering for a GaAs M-S contact for which the electric field in the GaAs is E=6.8x10^{4}V/cm, for reverse biases of (a) V$_R$=1V & (b) V$_R$=5V.

$$x_n = \left\{\frac{2\in_s(V_{bi}+V_R)}{eN_d}\right\}^{1/2}$$

$$= \left\{\frac{2(11.7)(8.85\times10^{-14})(V_{bi}+V_R)}{(1.6\times10^{-19})(10^{16})}\right\}^{1/2}$$

$$= \left\{(1.294\times10^{-9})(V_{bi}+V_R)\right\}^{1/2}$$

(a) $V_R = 1\,\text{V},\ V_{bi} = 0.334\,\text{V}$

$$\Rightarrow x_n = 4.155\times10^{-5}\,\text{cm}$$

$$|\text{E}_{\max}| = \frac{eN_d x_n}{\in_s}$$

$$= \frac{(1.6\times10^{-19})(10^{16})(4.155\times10^{-5})}{(11.7)(8.85\times10^{-14})}$$

$$= 6.42\times10^4\,\text{V/cm}$$

$$\text{Then } \Delta\phi = \sqrt{\frac{e\text{E}}{4\pi\in_s}}$$

$$= \left\{\frac{(1.6\times10^{-19})(6.42\times10^4)}{4\pi(11.7)(8.85\times10^{-14})}\right\}^{1/2}$$

$$\Delta\phi = 0.0281\,\text{V}$$

(a) $V_R = 5\,\text{V},$

$$x_n = 8.309\times10^{-5}\,\text{cm}$$

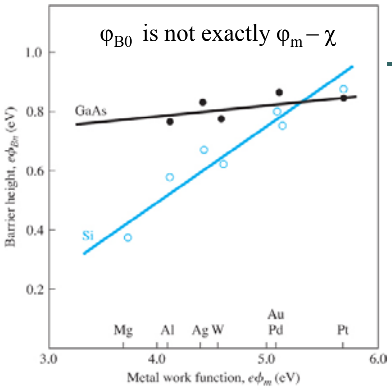
$$|\text{E}_{\max}| = \frac{(1.6\times10^{-19})(10^{16})(8.309\times10^{-5})}{(11.7)(8.85\times10^{-14})}$$

$$= 1.284\times10^5\,\text{V/cm}$$

$$\Delta\phi = \left\{\frac{(1.6\times10^{-19})(1.284\times10^5)}{4\pi(11.7)(8.85\times10^{-14})}\right\}^{1/2}$$

$$\Delta\phi = 0.0397\,\text{V}$$

Interface States



φ_{B0} is not exactly $\varphi_m - \chi$

Figure 9.5 | Experimental barrier heights as a function of metal work functions for GaAs and Si.
(From Crowley and Sze [2].)

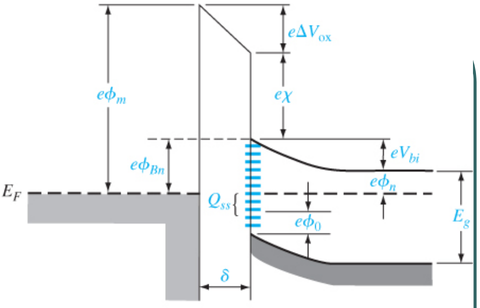


Figure 9.6 | Energy-band diagram of a metal–semiconductor junction with an interfacial layer and interface states.

More complete model:
- Thin oxide (electron transparent)
- D$_{it}$/cm^2.eV surface states in semiconductor
  - Donor states below eφ
  - Acceptor states above eφ

$$(E_g - e\phi_0 - e\phi_{Bn}) = \frac{1}{eD_{it}}\sqrt{2e\varepsilon_s N_d(\phi_{Bn}-\phi_n)} - \frac{\varepsilon_i}{eD_{it}\delta}[\phi_m - (\chi+\phi_{Bn})]$$

If $D_{it} \to \infty \ \phi_{Bn} = (E_g - e\phi_0)/\text{e}$ If $D_{it}\delta \to 0 \ \phi_{Bn} = \phi_m - \chi$

I-V characteristics

As before $dn = \dfrac{4\pi\left(2m_n^*\right)^{\frac{3}{2}}}{h^3}\sqrt{E-E_C}\,\exp-\left[\dfrac{E-E_F}{kT}\right]dE$

$$J = J_{s\to m} - J_{m\to s} = \left[A^*T^2\exp-\frac{e\phi_{Bn}}{kT}\right].\left[\exp\left(\frac{eV_a}{kT}\right)-1\right]$$

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

where $\mathrm{J}_{\mathrm{sT}} = A^*T^2\exp-\dfrac{e\phi_{Bn}}{kT}$ and $A^* = \dfrac{4\pi e m_n^* k^2}{h^3}$

and with barrier lowering $\mathrm{J}_{\mathrm{sT}} = A^*T^2\exp-\dfrac{e\phi_{Bn}}{kT}\exp\dfrac{\mathrm{e}\Delta\phi}{\mathrm{kT}}$

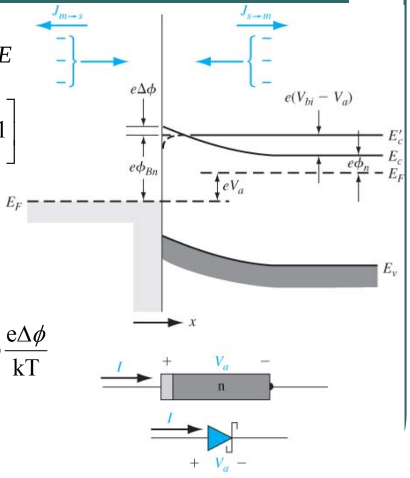


Figure 9.7 | Energy-band diagram of a forward-biased metal–semiconductor junction including the image lowering effect.

Device characteristics

Reverse current increases with V_R due to barrier lowering

Plot gives J_{sT} and hence (Si) $A^*=114\mathrm{A/K^2.cm^2}$ for $\varphi_{Bn}=0.67\mathrm{V}$

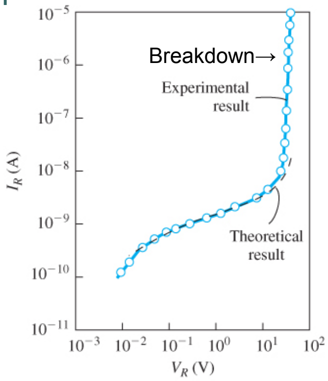


Figure 9.8 | Experimental and theoretical reverse-biased currents in a PtSi–Si diode. *(From Sze and Ng [15].)*

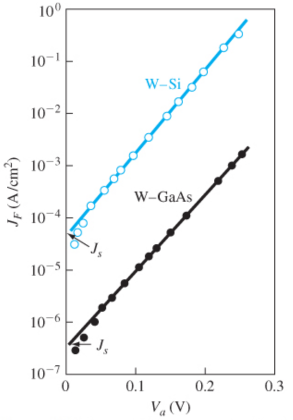


Figure 9.9 | Forward-bias current density J_F versus V_a for Wi–Si and W–GaAs diodes. *(From Sze and Ng [15].)*

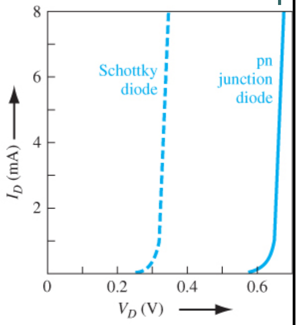


Figure 9.10 | Comparison of forward-bias I–V characteristics between a Schottky diode and a pn junction diode

Ex 9.4 Calculate the ideal Richardson constant for a free electron.

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

Assume $m_n^* = m_o$, then

$$A^* = \frac{4\pi\left(1.6\times10^{-19}\right)\left(9.11\times10^{-31}\right)\left(1.38\times10^{-23}\right)^2}{\left(6.625\times10^{-34}\right)^3}$$

$$= 1.20\times10^6 \text{ A/K}^2\text{-m}^2$$

$$\Rightarrow A^* = 120 \text{ A/K}^2\text{-cm}^2$$

Ex 9.5 Use the results of Example 9.5 to determine the forward bias voltages required to produce a current of 10μA in a W-Si diode of measured barrier height φ_{Bn}=0.67eV and a P-N junction of J_s=3.66x10^{-11}A/cm^2. Assume junction areas of 10^{-4}cm^2.

$$I \cong AJ_s \exp\left(\frac{V_a}{V_t}\right)$$

so that $V_a = V_t \ln\left(\frac{I}{AJ_s}\right)$

For the pn junction:

$$V_a = (0.0259)\ln\left(\frac{10\times10^{-6}}{\left(10^{-4}\right)\left(3.66\times10^{-11}\right)}\right)$$

$$= 0.5628 \text{ V}$$

For the Schottky junction:

$$V_a = (0.0259)\ln\left(\frac{10\times10^{-6}}{\left(10^{-4}\right)\left(5.98\times10^{-5}\right)}\right)$$

$$= 0.1922 \text{ V}$$

Ex 9.6 A PN diode and a Schottky diode have equal c/s areas and forward bias currents of 0.5mA. The Schottky reverse saturation current is 5x10-7A. The difference between the forward bias voltages is 0.30V. Find the reverse saturation current of the PN diode.

$$\frac{I_{ST}\exp\left(\frac{V_a-0.3}{V_t}\right)}{I_S\exp\left(\frac{V_a}{V_t}\right)}=1=\frac{I_{ST}}{I_S}\exp\left(\frac{-0.3}{V_t}\right)$$

Then

$$I_S=\left(5\times10^{-7}\right)\exp\left(\frac{-0.3}{0.0259}\right)$$

$$\Rightarrow I_S=4.66\times10^{-12}\text{ A}$$

M-S Ohmic Contacts:

Ideal non-rectifying barrier (N-type)

Previous case: $\varphi_m>\varphi_s$, (Schottky diode.) Consider now $\varphi_m<\varphi_s$ (below).
No barrier to electron flow semiconductor → metal
Effective barrier height for electron flow metal →semiconductor is $\varphi Bn=\varphi n$ (small)
Hence ohmic contact.

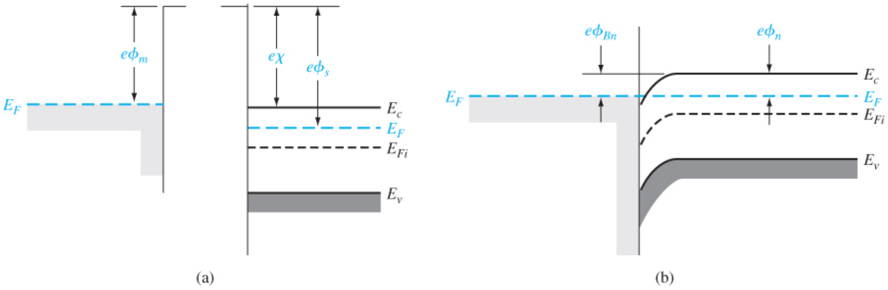
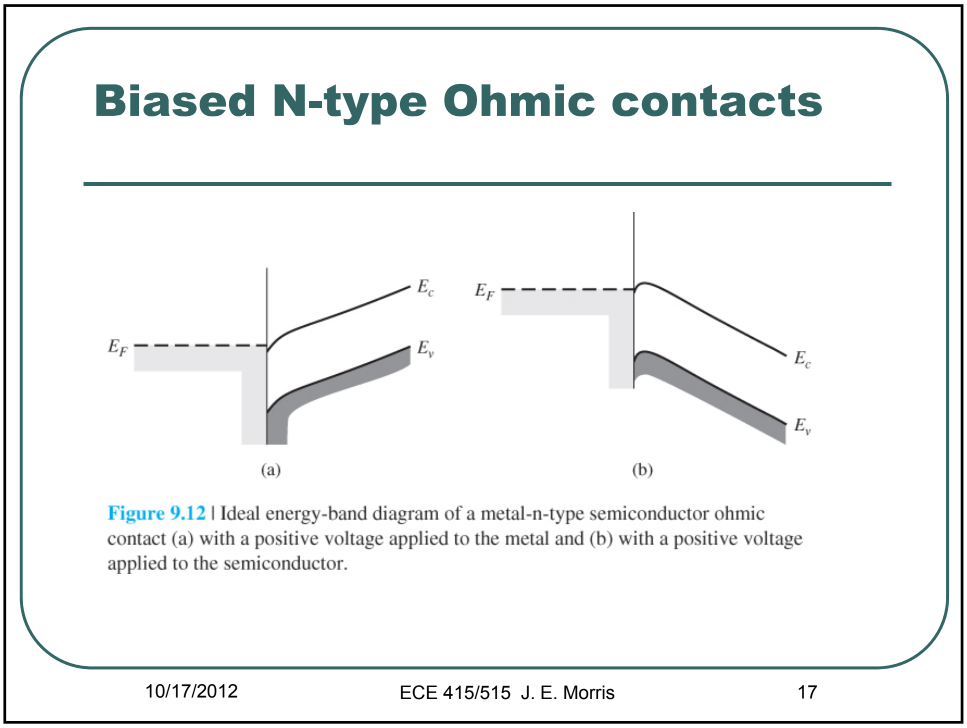
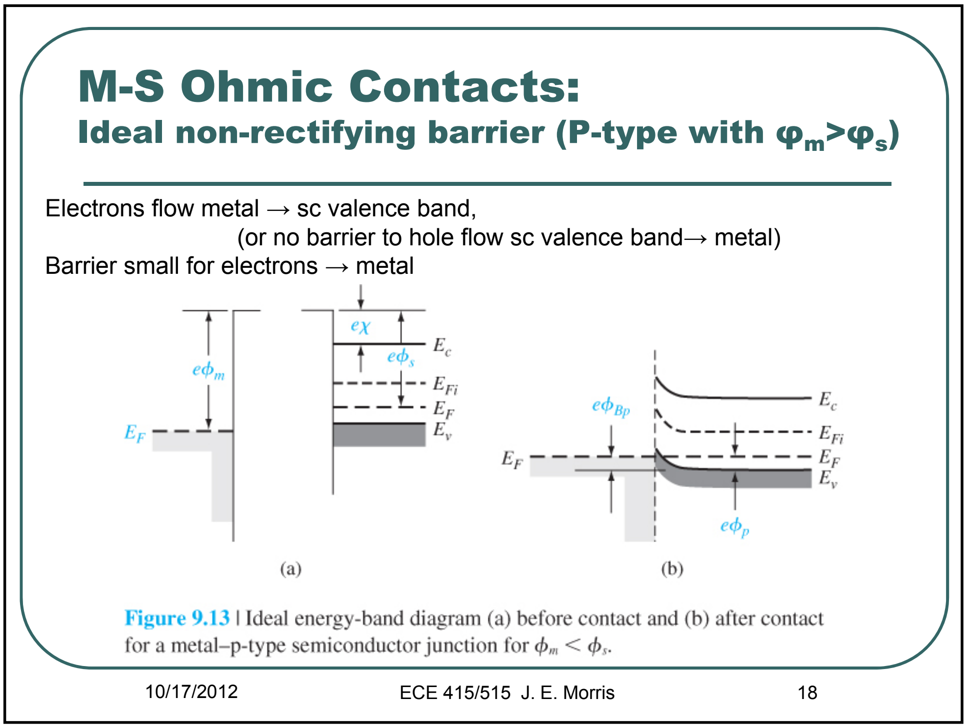


Figure 9.11 | Ideal energy-band diagram (a) before contact and (b) after contact for a metal-n-type semiconductor junction for $\phi_m < \phi_s$.



Biased N-type Ohmic contacts

Figure 9.12 | Ideal energy-band diagram of a metal-n-type semiconductor ohmic contact (a) with a positive voltage applied to the metal and (b) with a positive voltage applied to the semiconductor.



M-S Ohmic Contacts:

Ideal non-rectifying barrier (P-type with $\varphi_m > \varphi_s$)

Electrons flow metal → sc valence band,
(or no barrier to hole flow sc valence band→ metal)
Barrier small for electrons → metal

Figure 9.13 | Ideal energy-band diagram (a) before contact and (b) after contact for a metal–p-type semiconductor junction for $\phi_m < \phi_s$.

Tunneling barrier

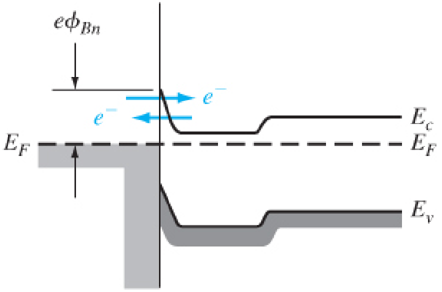


Figure 9.14 | Energy-band diagram of a heavily doped n-semiconductor-to-metal junction.

When a Schottky barrier would otherwise result, (n - type with $\phi_m > \phi_s$ or p - type with $\phi_m < \phi_s$) dope the semiconductor very heavily.

Space charge $\propto N_d^{-\frac{1}{2}}$ so barrier very thin, and electrons can tunnel through.

$$J_t \propto \exp - \frac{2e\phi_{Bn}}{e\hbar}\sqrt{\frac{\varepsilon_s m_n^*}{N_d}}$$

Ex 9.7 Calculate the space charge width of a rectifying metal-GaAs junction. Assume N_d=7x10^{18}/cm^3 in the GaAs and that the built-in potential barrier is V_{bi}=0.80V.

We have

$$x_n = \left\{\frac{2\in_s V_{bi}}{eN_d}\right\}^{1/2}$$

$$= \left\{\frac{2(13.1)(8.85\times10^{-14})(0.80)}{(1.6\times10^{-19})(7\times10^{18})}\right\}^{1/2}$$

$$= 1.287\times10^{-6}\,\text{cm}$$

or $x_n = 128.7\overset{o}{A}$

Contact resistance

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

For recifying contact, thermionic current dominates:

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

$$\text{so } R_c = \frac{1}{A^* T^2} . \frac{kT}{e} . \exp\frac{+e\phi_{Bn}}{\text{kT}}$$

For tunneling contact (large N_d)

$$\mathrm{R_c} \propto \exp\left(\frac{2\sqrt{\varepsilon_s m_m^*}}{\hbar} . \frac{\phi_{Bn}}{\sqrt{N_d}} \right)$$

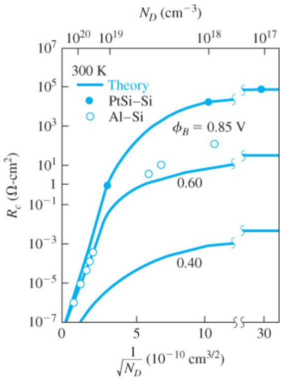


Figure 9.15 | Theoretical and experimental specific contact resistance as a function of doping.
(From Sze and Ng [15].)

Heterojunctions

Homojunctions → same semiconductor (e.g. GaAs) on both sides
Heterojunctions → different materials

e.g. GaAlAs system …. Vary composition to vary band-gap

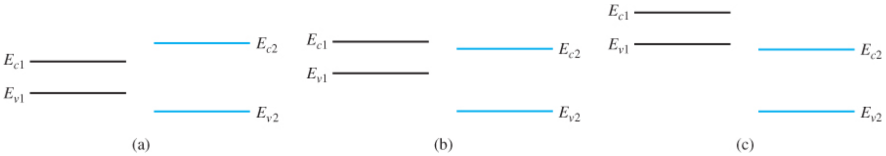


Figure 9.16 | Relation between narrow-bandgap and wide-bandgap energies: (a) straddling, (b) staggered, and (c) broken gap.

"Straddling" most common, and considered below

"Anisotype" → different doping
→ Np or Pn (where "N" or "P" indicates the larger bandgap material
"Isotype" → Nn or Pp

e.g. nP (Ge/GaAs)

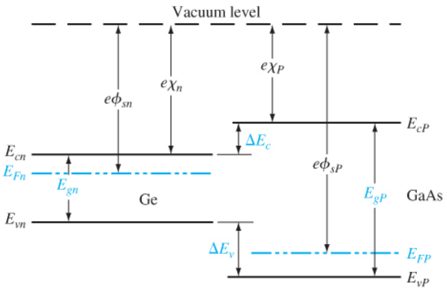


Figure 9.17 | Energy-band diagrams of a narrow-bandgap and a wide-bandgap material before contact.

$$\Delta E_c = e(\chi_n - \chi_P)$$
$$\Delta E_c + \Delta E_v = E_{gP} - E_{gn} = \Delta E$$

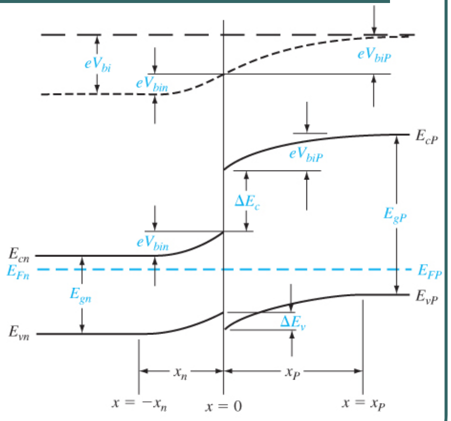


Figure 9.18 | Ideal energy-band diagram of an nP heterojunction in thermal equilibrium.

Np heterojunction

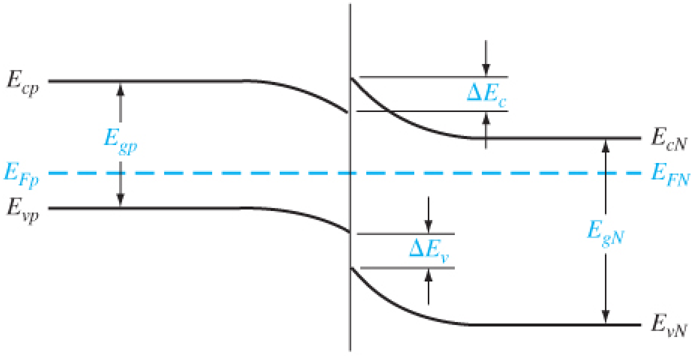


Figure 9.23 | Ideal energy-band diagram of an Np heterojunction in thermal equilibrium.

pP heterojunction

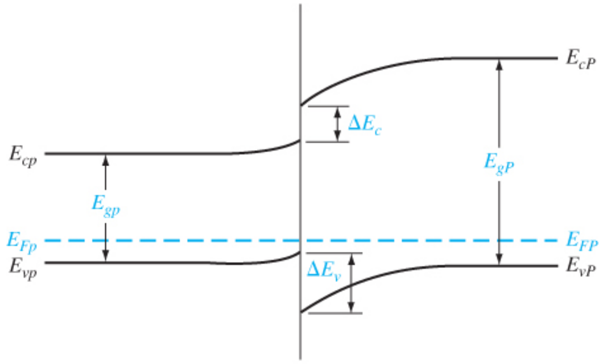


Figure 9.24 | Ideal energy-band diagram of a pP heterojunction in thermal equilibrium.

nN GaAs-AlGaAs heterojunction

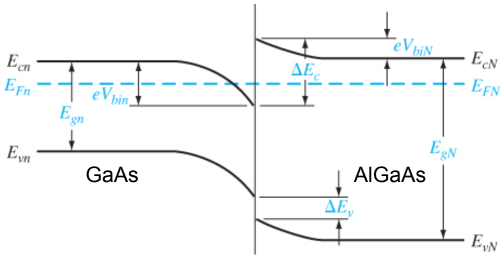


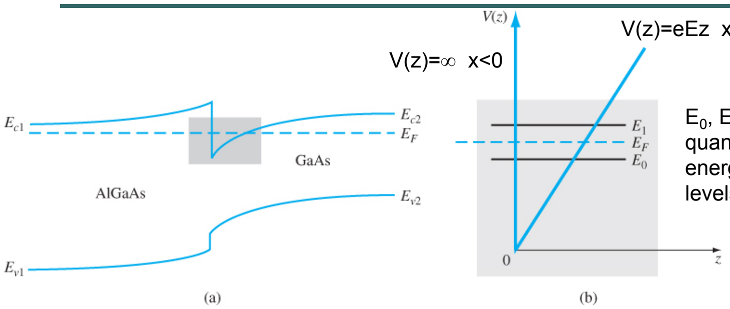
Figure 9.19 | Ideal energy-band diagram of an nN heterojunction in thermal equilibrium.

Electrons flow to align E_F’s
n-type GaAs ← N-type AlGaAs

Electrons in interface potential well

“2-D electron gas”
Quantized energy levels _|_ j’n
Free to move in 2D ∥ junction

Approximate by triangular potential well



V(z)=eEz x>0

V(z)=∞ x<0

E_0, E_1
quantized
energy
levels

Figure 9.20 | (a) Conduction-band edge at N-AlGaAs, n-GaAs heterojunction; (b) triangular well approximation with discrete electron energies.

2D electron gas

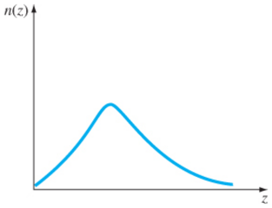


Figure 9.21 | Electron density in triangular potential well.

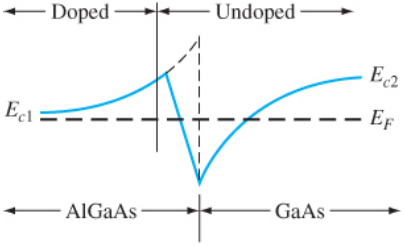
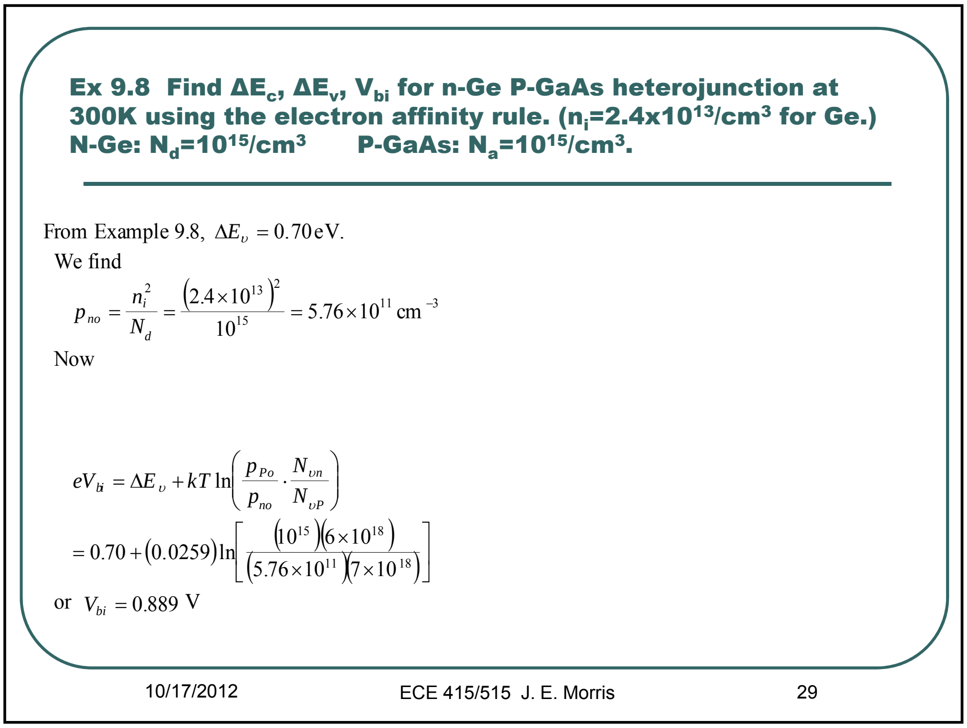


Figure 9.22 | Conduction-band edge at a graded heterojunction.

2D currents ‖junction high mobility
since doping light

See also 9.3.4 junction electrostatics



Ex 9.8 Find ΔE_c, ΔE_v, V_{bi} for n-Ge P-GaAs heterojunction at 300K using the electron affinity rule. ($n_i=2.4\text{x}10^{13}/\text{cm}^3$ for Ge.) N-Ge: $N_d=10^{15}/\text{cm}^3$ P-GaAs: $N_a=10^{15}/\text{cm}^3$.

From Example 9.8, $\Delta E_\upsilon = 0.70\,\text{eV}$.

We find

$$p_{no} = \frac{n_i^2}{N_d} = \frac{\left(2.4\times10^{13}\right)^2}{10^{15}} = 5.76\times10^{11}\ \text{cm}^{-3}$$

Now

$$eV_{bi} = \Delta E_\upsilon + kT\ln\left(\frac{p_{Po}}{p_{no}}\cdot\frac{N_{\upsilon n}}{N_{\upsilon P}}\right)$$

$$= 0.70 + (0.0259)\ln\left[\frac{\left(10^{15}\right)\left(6\times10^{18}\right)}{\left(5.76\times10^{11}\right)\left(7\times10^{18}\right)}\right]$$

or $V_{bi} = 0.889$ V