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Solid State Electronic Devices

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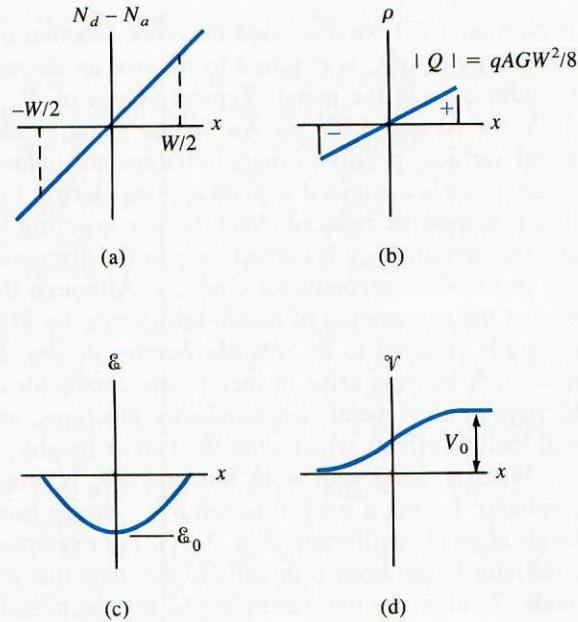
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**Figure 5-30**

Properties of the graded junction transition region: (a) net impurity profile; (b) net charge distribution; (c) electric field; (d) electrostatic potential.

In a graded junction the usual depletion approximation is often inaccurate. If the grade constant G is small, the carrier concentrations ($p - n$) can be important in Eq. (5-75). Similarly, the usual assumption of negligible space charge outside the transition region is questionable for small G . It would be more accurate to refer to the regions just outside the transition region as quasi-neutral rather than neutral. Thus the edges of the transition region are not sharp as Fig. 5-30 implies but are spread out in x . These effects complicate calculations of junction properties, and a computer must be used in solving the problem accurately.

Most of the conclusions we have made regarding carrier injection, recombination and generation currents, and other properties are qualitatively applicable to graded junctions, with some alterations in the functional form of the resulting equations. Therefore, we can apply most of our basic concepts of junction theory to reasonably graded junctions as long as we remember that certain modifications should be made in accurate computations.

Many of the useful properties of a p-n junction can be achieved by simply forming an appropriate metal–semiconductor contact. This approach is obviously attractive because of its simplicity of fabrication; also, as we shall see in this section, metal–semiconductor junctions are particularly useful when high-speed rectification is required. On the other hand, we also must be able to form nonrectifying (ohmic) contacts to semiconductors. Therefore, this section deals with both rectifying and ohmic contacts.

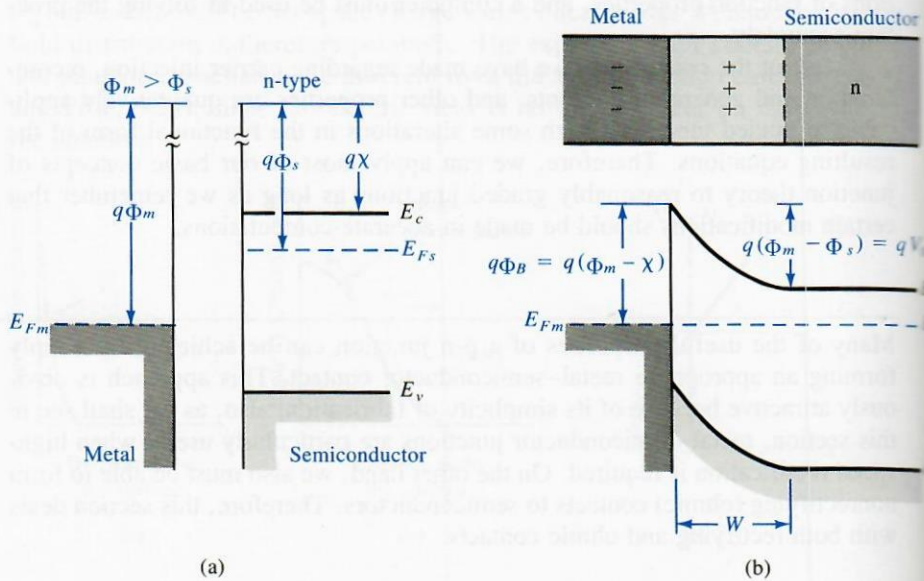
5.7 METAL- SEMICONDUCTOR JUNCTIONS

5.7.1 Schottky Barriers

In Section 2.2.1 we discussed the work function $q\Phi_m$ of a metal in a vacuum. An energy of $q\Phi_m$ is required to remove an electron at the Fermi level to the vacuum outside the metal. Typical values of Φ_m for very clean surfaces are 4.3V for Al and 4.8V for Au. When negative charges are brought near the metal surface, positive (image) charges are induced in the metal. When this image force is combined with an applied electric field, the effective work function is somewhat reduced. Such barrier lowering is called the *Schottky effect*, and this terminology is carried over to the discussion of potential barriers arising in metal–semiconductor contacts. Although the Schottky effect is only a part of the explanation of metal–semiconductor effects, rectifying contacts are generally referred to as *Schottky barrier diodes*. In this section we shall see how such barriers arise in metal–semiconductor contacts. First we consider barriers in ideal metal–semiconductor junctions, and then in Section 5.7.4 we will include effects which alter the barrier height.

When a metal with work function $q\Phi_m$ is brought in contact with a semiconductor having a work function $q\Phi_s$, charge transfer occurs until the Fermi levels align at equilibrium (Fig. 5-31). For example, when $\Phi_m > \Phi_s$, the semiconductor Fermi level is initially higher than that of the metal before contact is made. To align the two Fermi levels, the electrostatic potential of the semiconductor must be raised (i.e., the electron energies must be lowered) relative to that of the metal. In the n-type semiconductor of Fig. 5-31 a depletion region W is formed near the junction. The positive charge due to uncompensated donor ions within W matches the negative charge on the metal. The electric field and the bending of the bands within W are similar to effects already discussed for p-n junctions. For example, the depletion width W in the semiconductor can be calculated from Eq. (5-21) by using the p^+ -n approximation

Figure 5-31
A Schottky barrier formed by contacting an n-type semiconductor with a metal having a larger work function: (a) band diagrams for the metal and the semiconductor before joining; (b) equilibrium band diagram for the junction.



(i.e., by assuming the negative charge in the dipole is a thin sheet of charge to the left of the junction). Similarly, the junction capacitance is $A\epsilon_s/W$, as in the p^+-n junction.[†]

The equilibrium contact potential V_0 , which prevents further net electron diffusion from the semiconductor conduction band into the metal, is the difference in work function potentials $\Phi_m - \Phi_s$. The potential barrier height Φ_B for electron injection from the metal into the semiconductor conduction band is $\Phi_m - \chi$, where $q\chi$ (called the *electron affinity*) is measured from the vacuum level to the semiconductor conduction band edge. The equilibrium potential difference V_0 can be decreased or increased by the application of either forward- or reverse-bias voltage, as in the p-n junction.

Figure 5-32 illustrates a Schottky barrier on a p-type semiconductor, with $\Phi_m < \Phi_s$. In this case aligning the Fermi levels at equilibrium requires a positive charge on the metal side and a negative charge on the semiconductor side of the junction. The negative charge is accommodated by a depletion region W in which ionized acceptors (N_a^-) are left uncompensated by holes. The potential barrier V_0 retarding hole diffusion from the semiconductor to the metal is $\Phi_s - \Phi_m$, and as before this barrier can be raised or lowered by the application of voltage across the junction. In visualizing the barrier for holes, we recall from Fig. 5-7 that the electrostatic potential barrier for positive charge is opposite to the barrier on the electron energy diagram.

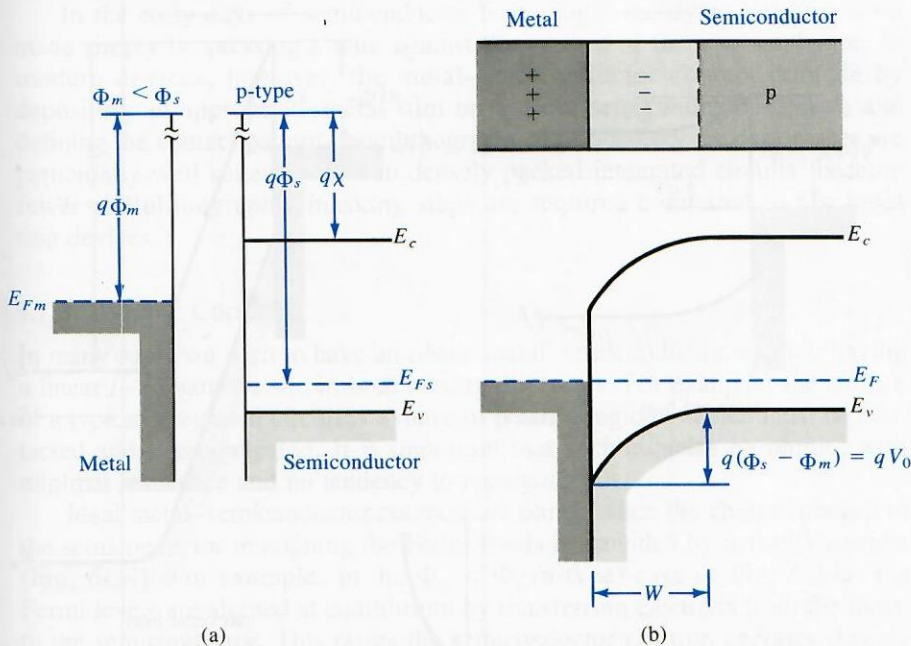


Figure 5-32

Schottky barrier between a p-type semiconductor and a metal having a smaller work function: (a) band diagrams before joining; (b) band diagram for the junction at equilibrium.

[†]While the properties of the Schottky barrier depletion region are similar to the p^+-n , it is clear that the analogy does not include forward-bias hole injection, which is dominant for the p^+-n but not for the contact of Fig. 5-31.

The two other cases of ideal metal-semiconductor contacts ($\Phi_m < \Phi_s$ for n-type semiconductors, and $\Phi_m > \Phi_s$ for p-type) result in nonrectifying contacts. We will save treatment of these cases for Section 5.7.3, where ohmic contacts are discussed.

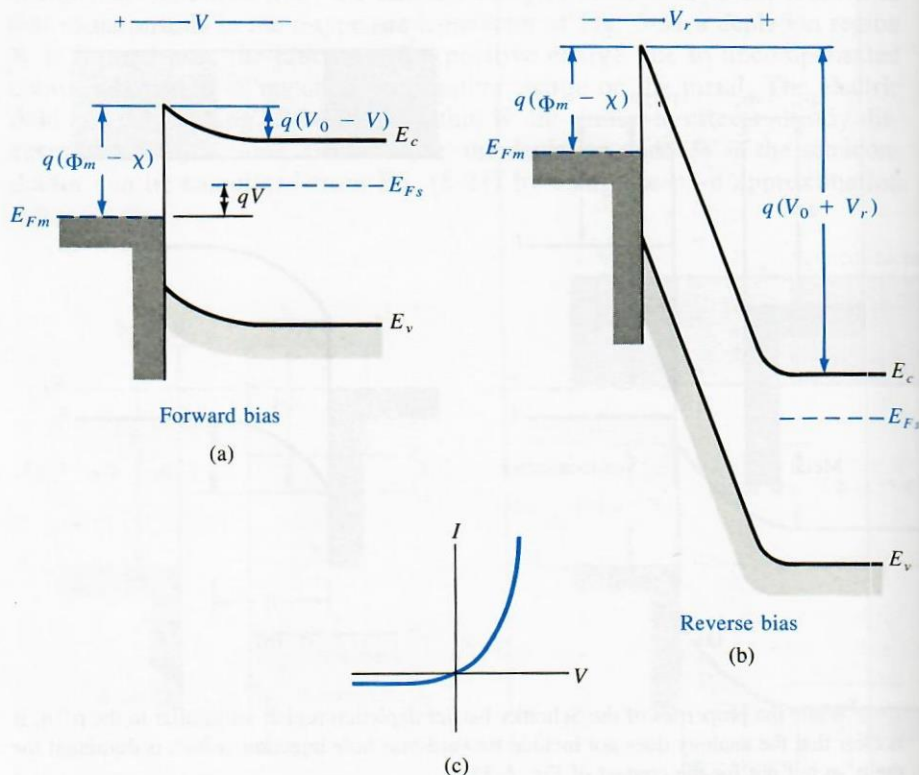
5.7.2 Rectifying Contacts

When a forward-bias voltage V is applied to the Schottky barrier of Fig. 5-31b, the contact potential is reduced from V_0 to $V_0 - V$ (Fig. 5-33a). As a result, electrons in the semiconductor conduction band can diffuse across the depletion region to the metal. This gives rise to a forward current (metal to semiconductor) through the junction. Conversely, a reverse bias increases the barrier to $V_0 + V_r$, and electron flow from semiconductor to metal becomes negligible. In either case flow of electrons from the metal to the semiconductor is retarded by the barrier $\Phi_m - \chi$. The resulting diode equation is similar in form to that of the p-n junction

$$I = I_0(e^{qV/kT} - 1) \quad (5-76)$$

as Fig. 5-33c suggests. In this case the reverse saturation current I_0 is not simply derived as it was for the p-n junction. One important feature we can predict intuitively, however, is that the saturation current should depend upon the size

Figure 5-33
Effects of forward and reverse bias on the junction of Fig. 5-31:
(a) forward bias;
(b) reverse bias;
(c) typical current-voltage characteristic.



of the barrier Φ_B for electron injection from the metal into the semiconductor. This barrier (which is $\Phi_m - \chi$ for the ideal case shown in Fig. 5-33) is unaffected by the bias voltage. We expect the probability of an electron in the metal surmounting this barrier to be given by a Boltzmann factor. Thus

$$I_0 \propto e^{-q\Phi_B/kT} \quad (5-77)$$

The diode equation (5-76) applies also to the metal–p-type semiconductor junction of Fig. 5-32. In this case forward voltage is defined with the semiconductor biased positively with respect to the metal. Forward current increases as this voltage lowers the potential barrier to $V_0 - V$ and holes flow from the semiconductor to the metal. Of course, a reverse voltage increases the barrier for hole flow and the current becomes negligible.

In both of these cases the Schottky barrier diode is rectifying, with easy current flow in the forward direction and little current in the reverse direction. We also note that the forward current in each case is due to the injection of *majority* carriers from the semiconductor into the metal. The absence of minority carrier injection and the associated storage delay time is an important feature of Schottky barrier diodes. Although some minority carrier injection occurs at high current levels, these are essentially majority carrier devices. Their high-frequency properties and switching speed are therefore generally better than typical p-n junctions.

In the early days of semiconductor technology, rectifying contacts were made simply by pressing a wire against the surface of the semiconductor. In modern devices, however, the metal–semiconductor contact is made by depositing an appropriate metal film on a clean semiconductor surface and defining the contact pattern photolithographically. Schottky barrier devices are particularly well suited for use in densely packed integrated circuits, because fewer photolithographic masking steps are required compared to p-n junction devices.

5.7.3 Ohmic Contacts

In many cases we wish to have an *ohmic* metal–semiconductor contact, having a linear I – V characteristic in both biasing directions. For example, the surface of a typical integrated circuit is a maze of p and n regions, which must be contacted and interconnected. It is important that such contacts be ohmic, with minimal resistance and no tendency to rectify signals.

Ideal metal–semiconductor contacts are ohmic when the charge induced in the semiconductor in aligning the Fermi levels is provided by majority carriers (Fig. 5-34). For example, in the $\Phi_m < \Phi_s$ (n-type) case of Fig. 5-34a, the Fermi levels are aligned at equilibrium by transferring electrons from the metal to the semiconductor. This raises the semiconductor electron energies (lowers the electrostatic potential) relative to the metal at equilibrium (Fig. 5-34b). In this case the barrier to electron flow between the metal and the semiconductor is small and easily overcome by a small voltage. Similarly, the case $\Phi_m > \Phi_s$ (p-type) results in easy hole flow across the junction (Fig. 5-34d). Unlike the

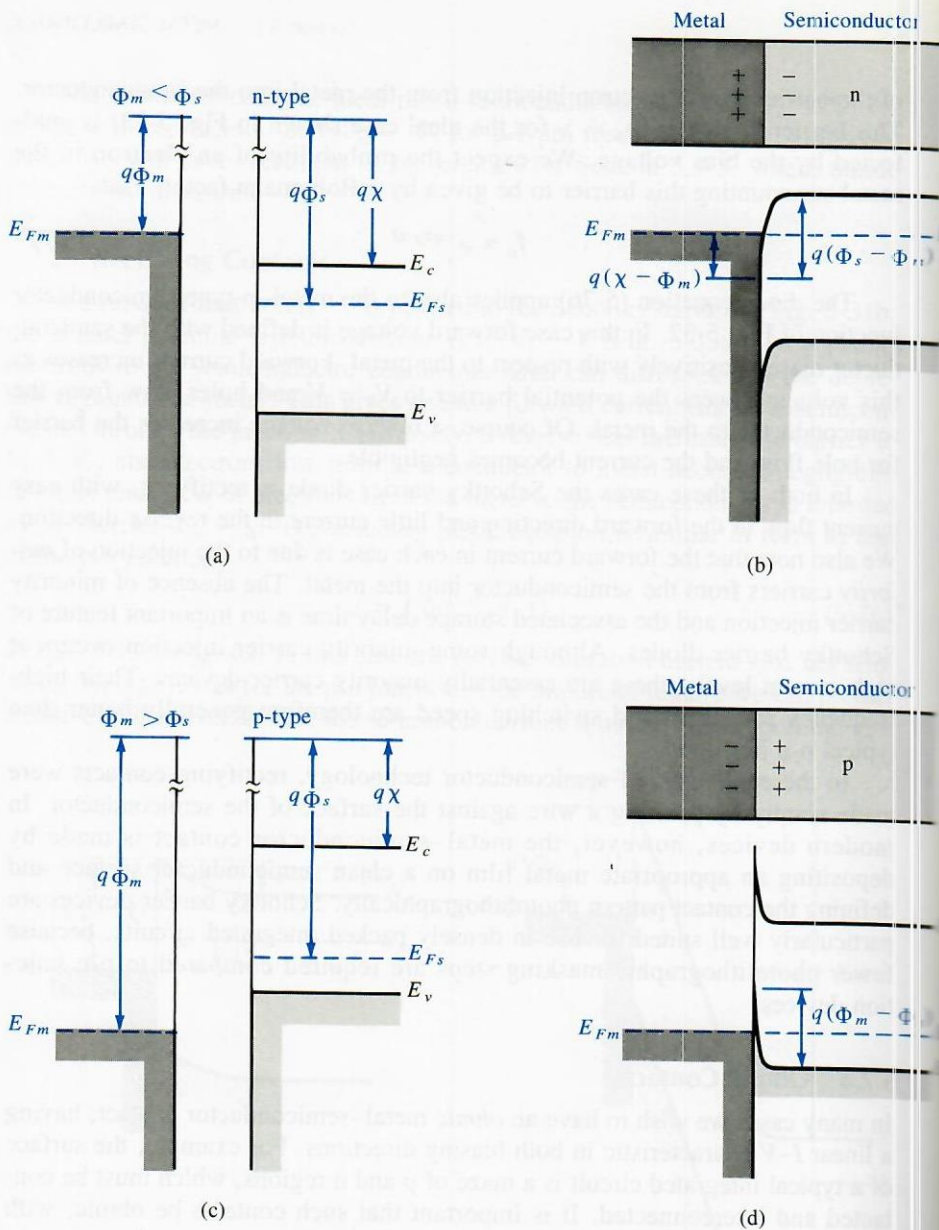


Figure 5-34

Ohmic metal-semiconductor contacts:

- (a) $\Phi_m < \Phi_s$ for an n-type semiconductor, and
- (b) the equilibrium band diagram for the junction;
- (c) $\Phi_m > \Phi_s$ for a p-type semiconductor, and
- (d) the junction at equilibrium.

rectifying contacts discussed above, no depletion region occurs in the semiconductor in these cases since the electrostatic potential difference required to align the Fermi levels at equilibrium calls for accumulation of majority carriers in the semiconductor.

A practical method for forming ohmic contacts is by doping the semiconductor heavily in the contact region. Thus if a barrier exists at the interface, the depletion width is small enough to allow carriers to tunnel through the barrier. For example, Au containing a small percentage of Sb can be alloyed to n-type

Si, forming an n^+ layer at the semiconductor surface and an excellent ohmic contact. Similarly, p-type material requires a p^+ surface layer in contact with the metal. In the case of Al on p-type Si, the metal contact also provides the acceptor dopant. Thus the required p^+ surface layer is formed during a brief heat treatment of the contact after the Al is deposited. As we shall see in the discussion of integrated circuits in Chapter 9, Al makes good ohmic contact to p-type Si, but n-type material requires an n^+ diffusion or implantation before contacting by Al.

5.7.4 Typical Schottky Barriers

The discussion of ideal metal–semiconductor contacts does not include certain effects of the junction between the two dissimilar materials. Unlike a p–n junction, which occurs within a single crystal, a Schottky barrier junction includes a termination of the semiconductor crystal. The semiconductor surface contains *surface states* due to incomplete covalent bonds and other effects, which can lead to charges at the metal–semiconductor interface. Furthermore, the contact is seldom an atomically sharp discontinuity between the semiconductor crystal and the metal. There is typically a thin interfacial layer, which is neither semiconductor nor metal. For example, silicon crystals are covered by a thin (10–20 Å) oxide layer even after etching or cleaving in atmospheric conditions. Therefore, deposition of a metal on such a Si surface leaves a glassy interfacial layer at the junction. Although electrons can tunnel through this thin layer, it does affect the barrier to current transport through the junction.

Because of surface states, the interfacial layer, microscopic clusters of metal–semiconductor phases, and other effects, it is difficult to fabricate junctions with barriers near the ideal values predicted from the work functions of the two isolated materials. Therefore, measured barrier heights are used in device design. In compound semiconductors the interfacial layer introduces states in the semiconductor band gap that pin the Fermi level at a fixed position, regardless of the metal used (Fig. 5-35). For example, a collection of interface

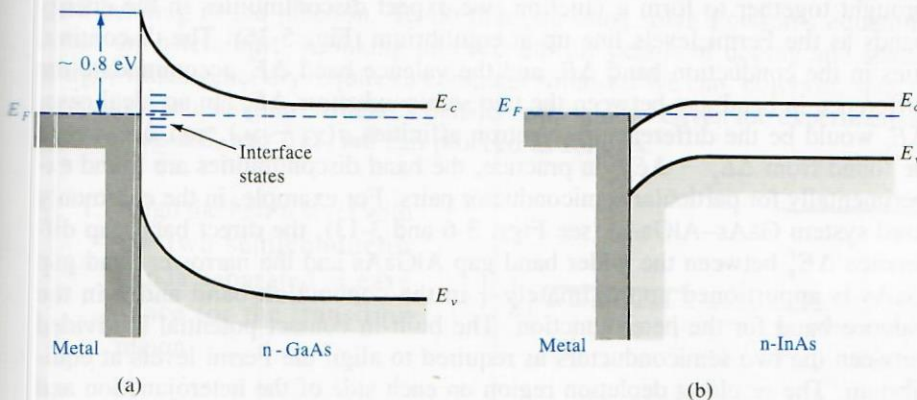


Figure 5-35 Fermi level pinning by interface states in compound semiconductors: (a) E_F is pinned near $E_C - 0.8$ eV in n-type GaAs, regardless of the choice of metal; (b) E_F is pinned above E_C in n-type InAs, providing an excellent ohmic contact.

states located $0.7 \sim 0.9$ eV below the conduction band pins E_F at the surface of n-type GaAs, and the Schottky barrier height is determined from this pinning effect rather than by the work function of the metal. An interesting case is n-type InAs (Fig. 5-35b), in which E_F at the interface is pinned *above* the conduction band edge. As a result, ohmic contact to n-type InAs can be made by depositing virtually any metal on the surface. For Si, good Schottky barriers are formed by various metals, such as Au or Pt. In the case of Pt, heat treatment results in a platinum silicide layer, which provides a reliable Schottky barrier with $\Phi_B \approx 0.85$ V on n-type Si.

A full treatment of Schottky barrier diodes results in a forward current equation of the form

$$I = ABT^2 e^{-q\Phi_B/kT} e^{qV/nkT} \quad (5-78)$$

where B is a constant containing parameters of the junction properties and n is a number between 1 and 2, similar to the ideality factor in Eq. (5-71) but arising from different reasons. The mathematics of this derivation is similar to that of *thermionic emission*, and the factor B corresponds to an effective Richardson constant in the thermionic problem.

5.8 HETEROJUNCTIONS

Thus far we have discussed p-n junctions formed within a single semiconductor (*homojunctions*) and junctions between a metal and a semiconductor. The third important class of junctions consists of those between two lattice-matched semiconductors with different band gaps (*heterojunctions*). We discussed lattice-matching in Section 1.4.1. The interface between two such semiconductors may be virtually free of defects, and continuous crystals containing single or multiple heterojunctions can be formed. The availability of heterojunctions and multilayer structures in compound semiconductors opens a broad range of possibilities for device development. We will discuss many of these applications in later chapters, including heterojunction bipolar transistors, field-effect transistors, and semiconductor lasers.

When semiconductors of different band gaps and electron affinities are brought together to form a junction, we expect discontinuities in the energy bands as the Fermi levels line up at equilibrium (Fig. 5-36). The discontinuities in the conduction band ΔE_c and the valence band ΔE_v accommodate the difference in band gap between the two semiconductors ΔE_g . In an ideal case, ΔE_c would be the difference in electron affinities $q(\chi_2 - \chi_1)$, and ΔE_v would be found from $\Delta E_g - \Delta E_c$. In practice, the band discontinuities are found experimentally for particular semiconductor pairs. For example, in the commonly used system GaAs–AlGaAs (see Figs. 3-6 and 3-13), the direct band gap difference ΔE_g^Γ between the wider band gap AlGaAs and the narrower band gap GaAs is apportioned approximately $\frac{2}{3}$ in the conduction band and $\frac{1}{3}$ in the valence band for the heterojunction. The built-in contact potential is divided between the two semiconductors as required to align the Fermi levels at equilibrium. The resulting depletion region on each side of the heterojunction and the amount of built-in potential on each side (making up the contact potential V_0) are found by solving Poisson's equation with the boundary condition of