Metal-Insulator-Semiconductor and Metal-Insulator-Metal Structures. Part III. Metal-Semiconductor Contacts

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Lecture 10

Metal-semiconductor contacts. Schottky contact

This chapter analyzes the electrical characteristics of a metal-semiconductor contact. Two different types of contacts can be produced: a contact with non-linear, rectifying current voltage characteristics called a Schottky contact, and a linear, non-rectifying contact called an ohmic contact.

5.1. Schottky diode

A Schottky contact or Schottky diode is formed when a rectifying contact is formed between a metal and a semiconductor. The rectifying properties of the contact are similar to those of a PN junction diode. The first semiconductor devices, dating back to the end of the nineteenth century were rectifying, metal-semiconductor, "point-contact" diodes. The rectifying effect in metal-semiconductor contact diodes was discovered in 1874 by F. Braun and was explained by Schottky and Mott in 1938. A typical semiconductor material used at that time was galena, a naturally occurring lead sulfide crystalline mineral.

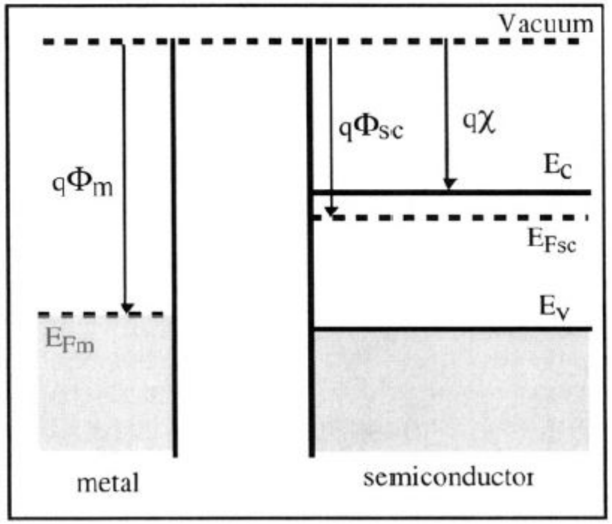

Figure 5.1: Energy bands in a metal and a semiconductor.

Metal-semiconductor contacts. Schottky contact

5.1.1. Energy band diagram

Consider an N-type semiconductor crystal and a metal. The energy band diagrams of these two materials are shown in Figure 5.1. We know because of the photoelectric effect (A. Einstein Nobel Prize, 1921), that electrons can be extracted from a metal in a vacuum, when light with a proper wavelength is shone onto the metal. In order to observe this effect the wavelength of the incident light must have a higher energy than a given critical value. In other words, the photons must carry enough energy to extract electrons from the metal and eject them into the vacuum. This energy $E = h\nu$ must be at least equal to the "work function" of the metal, noted $q\Phi_m$. The work function is, therefore, defined as the energy that must be supplied to an electron with an energy E_{Fm} (the metal Fermi level) in order for the electron to be ejected from the metal. Similarly, the work function of the semiconductor is the energy required to extract an electron located at its Fermi level, E_{Fsc}.

We know that in a semiconductor some electrons have an energy higher than E_{Fsc}. These can be found in the conduction band, and their energy is approximately equal to E_C. The energy needed to extract an electron from the conduction band into a vacuum is called the "electron affinity", and noted $q\chi$. In this Section we will consider an N-type semiconductor and a metal such that $E_{Fm} < E_{Fsc}$.

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When the metal is contacted with the semiconductor the Fermi levels align and thermodynamic equilibrium is established through the transfer of electrons from the semiconductor conduction band into the metal, since $E_C > E_{Fm}$. These electrons "leave behind" positively charged donor impurity atoms in the semiconductor. A space-charge region corresponding to the zone depleted of electrons, is, therefore, formed in the semiconductor near the interface with the metal. The width of this depletion region is noted W_o. The metal is considered as a perfect conductor. An electron charge, equal in magnitude to the depletion charge, appears in the metal at the metal-semiconductor interface. For all practical purposes this charge can be considered infinitely thin. Such a charge distribution is often called a "charge sheet". Because of the alignment of the Fermi levels and the presence of a depletion region the band curvature in the semiconductor is equal to:

$$qV_i = q(\Phi_m - \Phi_{sc}) \tag{5.1.1}$$

This curvature corresponds to a potential barrier, V_i, which prevents further electrons from migrating into the metal. Electrons in the metal, on the other hand, see a potential barrier, Φ_b, having an amplitude equal to (Figure 5.2):

$$q\Phi_b = q(\Phi_m - \chi) = qV_i + (E_c - E_F) \tag{5.1.2}$$

Metal-semiconductor contacts. Schottky contact

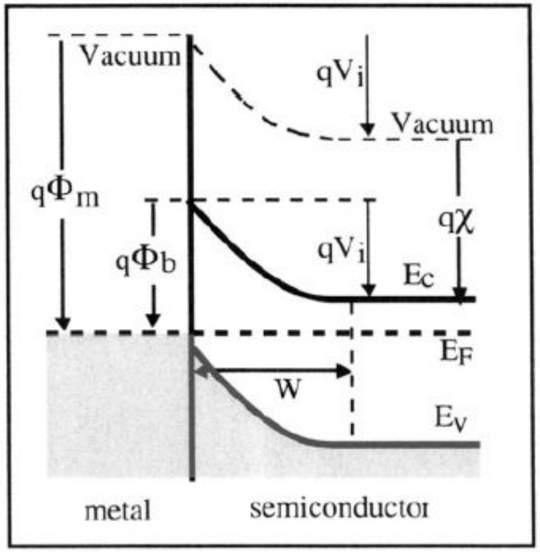

Figure 5.2: Energy band diagram of the Schottky contact.

At room temperature these potential barriers are significantly larger than *kT/q* and only a few electrons possess sufficient energy to overcome them. The current resulting from electrons from the semiconductor overcoming the barrier and migrating into the metal is noted $I_{m\rightarrow s}$. This notation is due to the fact that electrons carry a negative charge. Therefore, electrons migrating from the semiconductor into the metal corresponds to a "positive" current flow from the metal into the semiconductor.

At thermodynamic equilibrium and in the absence of any external bias the current $I_{m\rightarrow s}$ is exactly balanced by a current of electrons flowing from the metal into the semiconductor, noted $I_{s\rightarrow m}$. Thus, at equilibrium, we have: $I_{s\rightarrow m} = -I_{m\rightarrow s}$.

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If a forward bias $V_a > 0$ is applied to the structure (+ on the metal side, and - on the semiconductor side) the potential barrier on the semiconductor side is decreased from V_i to V_i-V_a (Figure 5.3A). A greater number of electrons can, therefore, flow from the semiconductor into the metal. On the other hand, the flow of electrons from the metal into the semiconductor, $I_{s \to m}$, remains constant because the potential barrier seen

from the metal side, Φ_b, is unchanged. As a result, a net electron current flow from the semiconductor into the metal is observed.

If a reverse bias, $V_a<0$, is applied to the structure (+ on the semiconductor side, and - on the metal side) the potential barrier in the semiconductor is increased from V_i to V_i-V_a (Figure 5.3B). As a result the electron flow from the semiconductor into the metal, $I_{m \to s}$, is reduced while $I_{s \to m}$ remains unchanged. As a result a small reverse current of electrons flowing from the metal into the semiconductor, $I_{s \to m}$ - $I_{m \to s}$, is measured. The asymmetry between the forward and reverse current flow mechanisms create non-linear current-voltage characteristics similar to the PN junction.

Metal-semiconductor contacts. Schottky contact

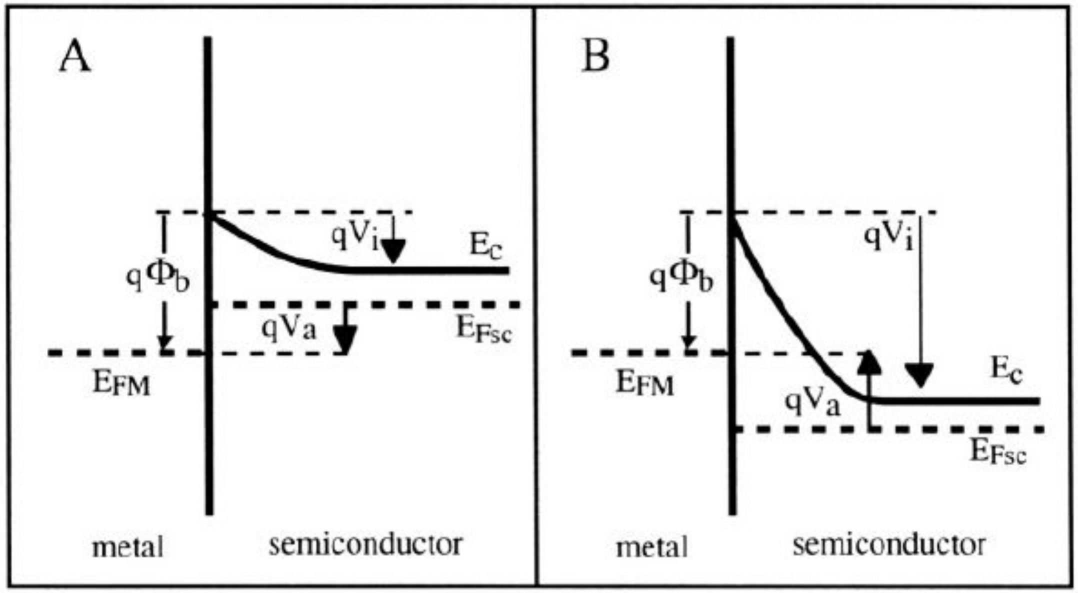

Figure 5.3: Energy band diagram under A: forward bias and B: reverse bias.

5.1.2. Extension of the depletion region

The width of the depletion zone in a Schottky diode can be calculated using the Poisson equation and the depletion approximation:

$$\frac{d^2\Phi(x)}{dx^2} = -\frac{\rho}{\varepsilon_{sc}} = -\frac{qN_d}{\varepsilon_{sc}} \qquad (5.1.3)$$

$$\Downarrow$$

$$\frac{d\Phi(x)}{dx} = \frac{qN_d}{\varepsilon_{sc}}(W-x) \qquad (5.1.4)$$

where W is the depth of the depletion region under an applied voltage V_a.

Metal-semiconductor contacts. Schottky contact

Note that the boundary conditions at $x=W$ are $\Phi(W) = 0$ and $\frac{d\Phi(W)}{dx} = 0$ since the potential, Φ, and the electric field ,$\mathcal{E}$, are equal to zero in the quasi-neutral part of the semiconductor. Integrating Expression 5.1.4 and applying the aforementioned boundary conditions we obtain:

$$\Phi(x) = -\frac{qN_d}{2\varepsilon_{sc}}(W-x)^2 \qquad (5.1.5)$$

The potential at $x=0$ is equal to the potential barrier on the semiconductor side, *i.e.* V_i-V_a where V_a is the applied voltage taken as positive when the diode is forward biased. Substituting V_i-V_a for $\Phi(x=0)$ in 5.1.5 gives the width of the depletion region:

Width of the depletion region

$$W(V_a) = \sqrt{\frac{2\varepsilon_{sc}}{qN_d}(V_i - V_a)} \qquad (5.1.6a)$$

The electric field at $x=0$ is $\mathcal{E}(0) = -qN_dW/\varepsilon_{sc}$, or, using Expression 5.1.4a:

$$\mathcal{E}(0) = -\sqrt{\frac{2qN_d}{\varepsilon_{sc}}(V_i - V_a)} \qquad (5.1.6b)$$

Metal-semiconductor contacts. Schottky contact

5.1.3. Schottky effect

The height of the potential barrier on the metal side, Φ_b, is not exactly constant and is slightly affected by the applied voltage. An actual lowering of Φ_b is observed. It is due to a mirror charge produced in the metal by electrons in the semiconductor. Electrostatics tells us that when a charge is near a "perfect" conductor (metal) a mirror charge of same magnitude but opposite sign is created inside the conductor, at a depth equal to the distance between the initial charge and the conductor surface (Figure 5.4). As a consequence, the charge is attracted by the metal, and in the case of the metal-semiconductor contact, the potential barrier is lowered.

The attraction exerted by the metal on an electron can be calculated as follows. Assuming the distance between the electron and the metal surface is x, the mirror charge bearing a charge $+q$ is located at a distance $-x$ inside the metal. Therefore, the Coulomb attraction force between the two charges is equal to $\dfrac{-q^2}{16\pi\varepsilon_{sc}x^2}$.

The force is equivalent to that exerted on an electron by an electric field $\mathcal{E}_m(x)$ obeying the relationship:

$$-q\mathcal{E}_m(x) = \frac{-q^2}{16\pi\varepsilon_{sc}x^2}$$

Metal-semiconductor contacts. Schottky contact

The resulting potential energy of the electron is equal to:

$$P(x) = -qV(x) = \int_x^{\infty} -\frac{q^2}{16\pi\varepsilon_{sc}x^2}\,dx = \frac{-q^2}{16\pi\varepsilon_{sc}x}$$

the reference potential being $P(x=\infty) = 0$.

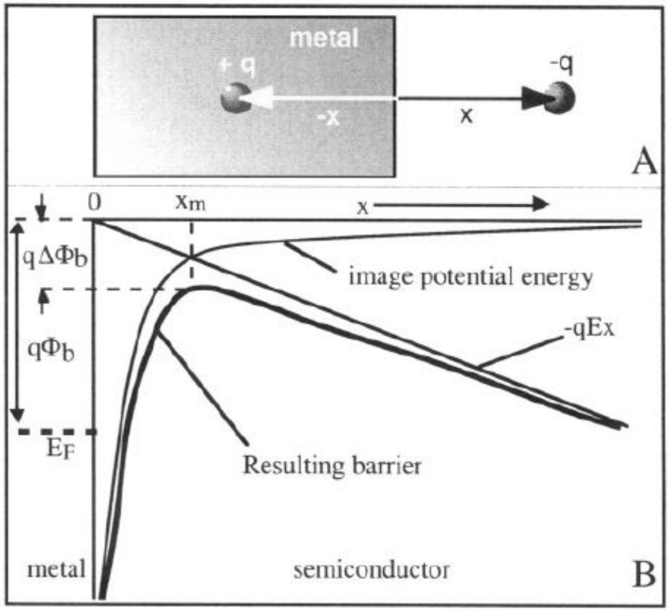

Figure 5.4: A: Mirror charge in a metal; B: the resulting lowering of the potential barrier. [1]

Note, that here the spatial dispersion of the semiconductor dielectric permittivity is not taken into account!

Metal-semiconductor contacts. Schottky contact

To find the total energy of the electron this potential energy must be added to the potential energy of the electron inside the semiconductor. In the depletion region the electric field is equal to $\frac{-qN_d}{\varepsilon_{sc}}(W-x)$. This field gives the electron in the conduction band a potential energy which is equal to $-\frac{q^2N_d}{2\varepsilon_{sc}}(W-x)^2 + E_c$. To simplify the problem we will assume that the electric field in the depletion region is constant . That field is noted $\mathcal{E}$ and gives the electron a potential energy $-q\mathcal{E}x$. The sum of the two potential energies (from the mirror charge and from the depletion region) yields the total potential energy $PE(x)$ of the electron:

$$PE(x) = -\frac{q^2}{16\pi\varepsilon_{sc}x} - q\,\mathcal{E}\,x + E_c \qquad (5.1.7)$$

Metal-semiconductor contacts. Schottky contact

The maximum potential energy can be found by writing $dPE(x)/dx=0$, which yields the maximum at $x = x_m = \sqrt{\frac{q}{16\pi\varepsilon_{sc}\mathcal{E}}}$. The potential energy at $x=x_m$ is equal to $PE(x_m) = -q\sqrt{\frac{q\mathcal{E}}{4\pi\varepsilon_{sc}}} < 0$, which corresponds to an effective lowering of the potential barrier $\Delta\Phi_b$ equal to:

$$\Delta\Phi_b = \sqrt{\frac{q\mathcal{E}}{4\pi\varepsilon_{sc}}} \qquad (5.1.8)$$

Using the value of the electric field at the semiconductor surface, given by equation 5.1.6b:

$$\mathcal{E}(0) = -\sqrt{\frac{2qN_d}{\varepsilon_{sc}}(V_i - V_a)} \qquad (5.1.9)$$

we find the magnitude of the potential barrier lowering, which constitutes the Schottky effect:

$$\Delta\Phi_b = \sqrt[4]{\frac{q^3N_d}{8\pi^2\varepsilon_{sc}{}^3}(V_i - V_a)} \qquad (5.1.10)$$

The resulting potential barrier height is equal to:

$$\Phi'_b = \Phi_b - \Delta\Phi_b \qquad (5.1.11)$$

Metal-semiconductor contacts. Schottky contact. Current-voltage characteristics

Electrons overcome the potential barrier between the metal and the semiconductor through a quantum-mechanical process called "thermionic emission". This process is activated by the thermal energy of the electrons. Although the potential barrier is clearly larger than kT/q at room temperature there exists a non-zero probability that some electrons gather enough energy to overcome the barrier. When a forward bias V_a is applied to the device the potential barrier that the electrons have to overcome to transit from the semiconductor into the metal is equal to Φ_b' - Va. The resulting thermionic emission current is given by:

$$I_{m \to s} = A\,R^*\,T^2\,exp\left[-\frac{q(\Phi'_b - V_a)}{kT}\right] \qquad (5.1.12)$$

where R^* is called the "Richardson constant" and is equal to $\frac{4\pi\, m_e\, q\, k^2}{h^3}$ and A is the diode area.

Using the fact that $I_{m \to s} = -I_{s \to m}$ when $V_a=0$, and that $I_{s \to m}$ is constant and independent of the applied voltage one can write:

$$I_{s \to m} = -\,A\,R^*\,T^2\,exp\left[\frac{-q\Phi'_b}{kT}\right] \qquad (5.1.13)$$

Since the net current in the diode is equal $I_{m \to s} + I_{s \to m}$, the expression of the current as a function of the applied voltage is:

$$I = A\,R^*\,T^2\,exp\left[\frac{-q\Phi'_b}{kT}\right]\left[exp\left(\frac{qV_a}{kT}\right) - 1\right] \qquad (5.1.14)$$

This equation describes a current-voltage characteristics similar to that of a PN junction. In addition the current depends on both the temperature and the height of the potential barrier between the metal and the semiconductor.

Metal-semiconductor contacts. Comparison of the PN and Schottky junctions

Current-voltage characteristics (PN junction and Schottky diodes)

PN junction diode:

$$I = A\, q\, n_i^2 \left(\frac{D_p}{N_d L_p} + \frac{D_n}{N_a L_n}\right)\left(exp\left(\frac{qV_a}{nkT}\right) - 1\right) \tag{5.1.16}$$

or:

$$I = I_s\left(exp\left(\frac{qV_a}{nkT} - 1\right)\right) \tag{5.1.17}$$

Schottky diode:

$$I = A\, R^*\, T^2\, exp\left[\frac{-q\Phi'_b}{kT}\right]\left[exp\left(\frac{qV_a}{nkT}\right) - 1\right] \tag{5.1.18}$$

or:

$$I = I_s\left[exp\left(\frac{qV_a}{nkT}\right) - 1\right] \tag{5.1.19}$$

Introducing adequate numerical values into these equations one observes that the reverse saturation current of a Schottky diode is 100 to 1000 times larger than that of a PN junction which accounts for a larger leakage current. In the forward mode, the I-V characteristics of a silicon Schottky diode shows strong conduction at 0.2-0.3 V, compared to 0.7 V in a silicon PN junction diode (Figure 5.6).

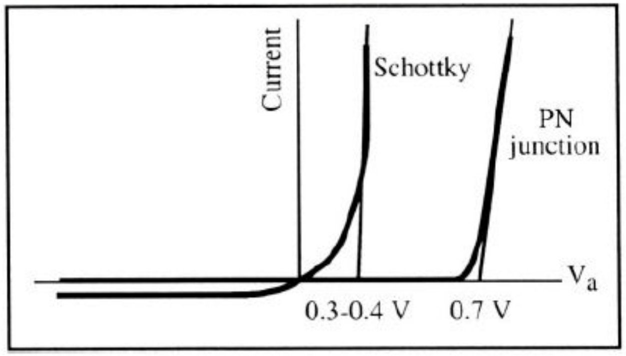

Figure 5.6: Current-voltage characteristics of a Schottky and a PN junction diode.

Metal-semiconductor contacts. Comparison of the PN and Schottky junctions

Schottky diodes are capable of very fast switching because their operation is based on majority carriers (unlike PN junction diodes where device operation is slowed down by storage and recombination of excess minority carriers). Majority carriers have a relaxation time on the order of ten picoseconds, which allows for operation at frequencies up to tens of gigahertz. The frequency performance of a Schottky diode can be appreciated by its cutoff frequency, which is given by $f_{co} = \dfrac{1}{2\pi RC}$ where

$$R = \left.\frac{dV_a}{dI}\right|_{V_a=0}$$

is the diode dynamic resistance, and where the depletion capacitance is equal to $C = A\,\varepsilon_{sc}/W(V_a)$. In a P^+N junction diode the cutoff frequency is given by $f_{co} = \dfrac{1}{2\pi R(C_D + C_T)}$ where C_D is the diffusion capacitance (Expression 4.5.9) and C_T is the transition capacitance (Expression 4.5.3b). The diffusion capacitance is proportional to the lifetime of minority carriers, ranging from 100 psec to several μs, which limits the frequency response of PN junction diodes.

Metal-semiconductor contacts. Ohmic contacts

An ohmic contact is a non-rectifying contact. The current-voltage characteristics of the contact should obey Ohm's law $V=IR$ and the resistance of the contact should be as low as possible. Consider the contact between the metal and the semiconductor shown in Figure 5.7. In this particular example $E_{FM} > E_F$ such that the energy bands of the N-type semiconductor are bent downwards near the contact. The magnitude of the band bending and its extension into the semiconductor are very small. As a result there is virtually no potential barrier between the metal and the semiconductor and electrons can flow freely through the contact. Such a contact is ohmic.

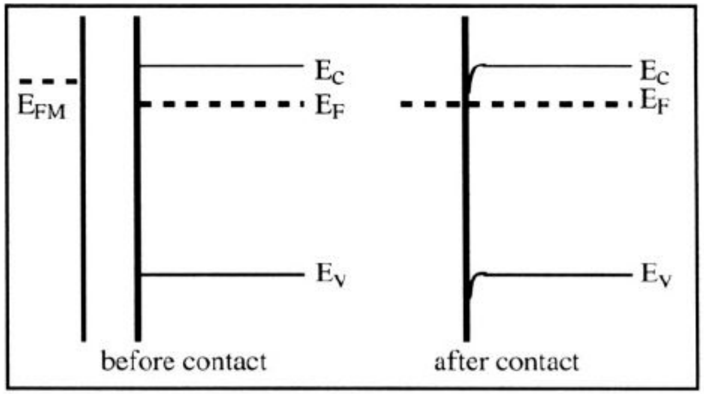

Figure 5.7: Energy bands of an ohmic contact.

It is also possible to obtain an ohmic contact between a metal and a semiconductor that would *a priori* form a Schottky diode, such as a metal where $E_{FM} < E_F$ in Figure 5.8. In practice a Schottky contact behaves as an ohmic contact if the impurity concentration in the semiconductor is high enough (e.g. $N_d = 10^{20}$ cm^{-3}). The width of the depletion region in the semiconductor is given by Expression 5.1.6a:

$$W(V_a) = \sqrt{\frac{2\varepsilon_{sc}}{qN_d}(V_i - V_a)}$$

Metal-semiconductor contacts. Ohmic contacts

where V_i is the built-in potential barrier height and V_a is the applied bias. If, for instance, $N_d=10^{20}$ cm^{-3}, $V_i=0.5$V and $V_a=0$ the thickness of the depletion zone is only 2.5 nm. Electrons can easily tunnel through such a thin potential barrier, which yields a low-resistance ohmic contact between the metal and the semiconductor. In metal-to-silicon contacts, current flow by tunnel effect becomes larger than current flow by thermionic emission when the doping concentration is larger than 10^{17} cm^{-3}. In practice, ohmic contacts between a metal and the terminals of semiconductor devices are always made on heavily doped areas.

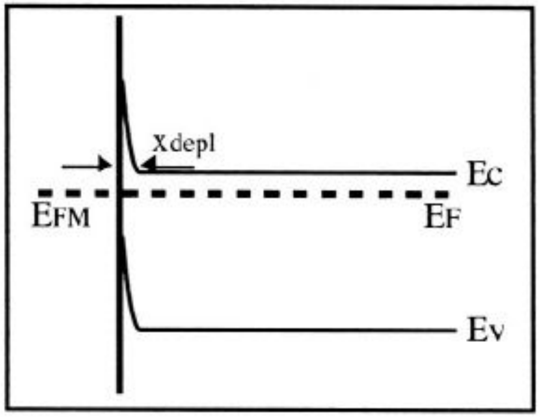

Figure 5.8: Energy bands in a contact between a metal and heavily doped silicon of an ohmic contact.