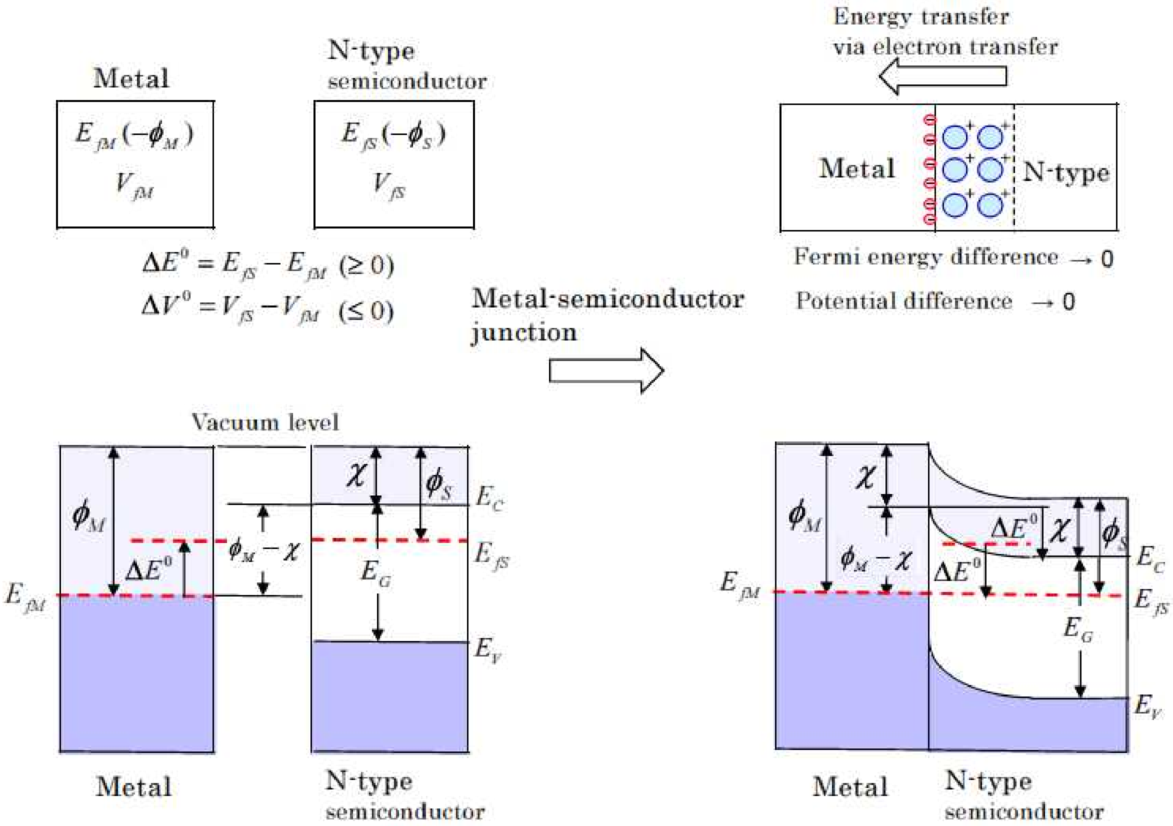
# 4 Metal-Semiconductor Junction and Devices

## 4.1 Metal-Semiconductor Junction

The idea of potential energy for electrons based on work function is also applied in metal-semiconductor junctions (historically, the phenomenon of metal-semiconductor junctions was discovered before that of PN junctions). In the case of a junction between a metal and a semiconductor, the properties of the junction differ greatly depending on the work function $\phi_M(=-E_{fM})$ of the metal and the work function $\phi_S(=-E_{fS})$ of the semiconductor for electrons. Where $E_{fM}$ is the Fermi energy level of the metal and $E_{fS}$ is the Fermi energy level of the semiconductor. Here, N-type semiconductors are used as semiconductors, and the cases (1) where $\phi_M \geq \phi_S(E_{fM} \leq E_{fS})$ (Schottky junction) and (2) where $\phi_M \leq \phi_S(E_{fM} \geq E_{fS})$ (ohmic junction) are described below.

(1) When $\phi_M \geq \phi_S(E_{fM} \leq E_{fS})$ (Schottky junction)

Figure 4.1 shows the energy band structure of the metal and N-type semiconductor for the case $\phi_M \geq \phi_S(E_{fM} \leq E_{fS})$ (a) before and (b) after the junction. In this case, the original energy of the semiconductor for electrons is $\Delta E^0$ higher than that of the metal. Therefore, during the junction, energy is transferred from the semiconductor to the metal via the transfer of electrons. A depletion layer is formed by ionized donors (positive charge) in the semiconductor junction due to electron transfer, and negative charge appears on the metal junction surface due to electrons that have migrated there. The positive charge due to donor ions in the semiconductor depletion layer and the negative charge due to electrons on the metal surface are of equal magnitude (the total charge sum is zero). This creates a potential difference $\Delta V_0$ between the semiconductor and the metal (the semiconductor is higher relative to the metal), which cancels out the potential difference $\Delta V^0$ (the semiconductor is lower relative to the metal) that existed originally, and the potentials become equal. This also creates an energy difference $\Delta E_0$ ( the semiconductor is lower than the metal), which cancels out the originally existing energy difference $\Delta E^0$ (the semiconductor is higher than the metal), making the energies (Fermi energy levels) equal and achieving a state of thermal equilibrium. When the Fermi energy level changes, the energy band structure changes (curves) accordingly, as in the case of other junctions.




(a) before junction (b) after junction

Figure 4.1 Energy band structure of metal and N-type semiconductor ( for $\phi_M \geq \phi_S$ )

In the following, we will quantitatively analyze the changes in potential and energy caused by the transfer of electrons in a metal-semiconductor junction. Figure 4.2 shows (a) the analytical model of a metal-semiconductor junction and (b) the electric field $\mathsf{E}(x)$, potential $\boldsymbol{V}(\boldsymbol{x})$, and potential energy $\boldsymbol{E_P}(\boldsymbol{x})$.

Let the coordinates be as shown in (a) of the figure, and let $\mathsf{E}(x)$ and $\boldsymbol{V}(\boldsymbol{x})$ be the electric field and potential at x, respectively (where $\mathsf{E}(x)$ and $\boldsymbol{V}(\boldsymbol{x})$

are one-dimensional functions that vary only in the $x$ direction), then $\mathrm{E}(x)$ must satisfy the following equation.

$$\left.\begin{aligned} \frac{d\mathrm{E}(x)}{dx} &= \frac{eN_D}{\varepsilon_S} \qquad (0 \le x \le x_N) \\ \frac{d\mathrm{E}(x)}{dx} &= 0 \qquad (x \le 0),(x_N \le x) \end{aligned}\right\} \tag{4.1}$$

$\varepsilon_S$ is the permittivity of the semiconductor
$N_D$ is the ionized donor density, a constant value within the depletion layer

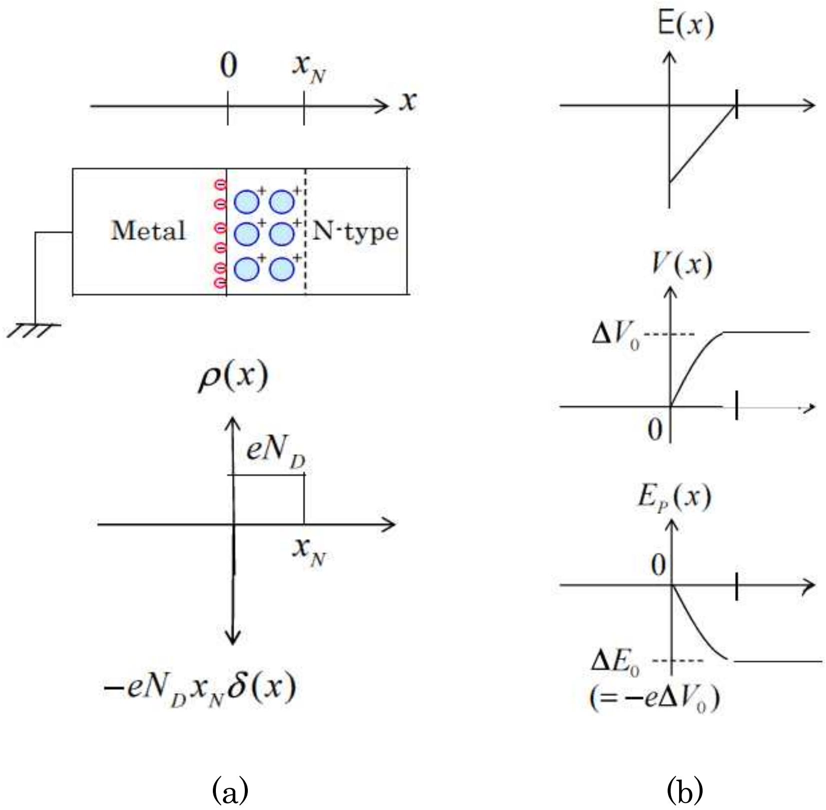



Figure 4.2 (a) analytical model and (b) electric field $\mathrm{E}(x)$ , potential $V(x)$, and potential energy $E_P(x)$ of a metal-semiconductor junction (for N-type semiconductor, $\phi_M \ge \phi_S$)

From the boundary conditions on the electric field $\mathrm{E}(x) = -dV(x)/dx$ ($\mathrm{E}(0) = \mathrm{E}(x_N) = 0$), $\mathrm{E}(x)$ can be obtained as follows where the direction of $\mathrm{E}(x)$

is expressed in the x-axis direction (right direction) as positive.

$$\left.\begin{array}{ll} \mathrm{E}(x)=\dfrac{eN_D(x-x_N)}{\varepsilon_S} & (0\le x\le x_N) \\ \mathrm{E}(x)=0 & (x\le 0),(x_N\le x) \end{array}\right\} \tag{4.2}$$

Furthermore, from the boundary condition on the potential $V(x)$ ($V(0)=0$), $V(x)$ can be obtained as follows

$$\left.\begin{array}{ll} V(x)=0 & (x\le 0) \\ V(x)=\dfrac{eN_D}{2\varepsilon_S}(-x^2+2x_N x) & (0\le x\le x_N) \\ V(x)=\dfrac{eN_D}{2\varepsilon_S}x_N^2 & (x_N\le x) \end{array}\right\} \tag{4.3}$$

From this, the potential difference $\Delta V_0$ at the junction is given by

$$\Delta V_0=V(x_N)-V(0)=\frac{eN_D}{2\varepsilon_S}x_N^2 \qquad (\ge 0) \tag{4.4}$$

Furthermore, using the relationship between potential energy and potential, the following energy difference $\Delta E_0$ occurs between metal and semiconductor

$$\Delta E_0=-e\Delta V_0 \qquad (\le 0) \tag{4.5}$$

The change in energy $\Delta E_0$ on the semiconductor side cancels the energy difference $\Delta E^0$ that originally existed between the metal and semiconductor, and the energies (Fermi energy levels) become equal, thus realizing a state of thermal equilibrium.

As the Fermi levels change, the energy band structure of the semiconductor also changes (curves). The value of the energy gap $E_G$ is conserved during the change. Figure 4.1(b) shows this situation. Note that according to the energy band structure in Fig. 4.1(b), a $\phi_M - \chi$ energy barrier for conduction electrons is formed at the metal-semiconductor junction. This energy barrier is called the Schottky barrier, and the junction is called a Schottky junction. From equation (4.4), the depletion layer thickness $x_N$ is given by

$$x_N = \sqrt{\frac{2\varepsilon_S \Delta V_0}{eN_D}} \tag{4.6}$$

From this, the charge $Q_N$ per unit area accumulated in the depletion layer at thermal equilibrium is

$$Q_N = ex_N N_D = eN_D \sqrt{\frac{2\varepsilon_S \Delta V_0}{eN_D}} = \sqrt{2\varepsilon_S eN_D \Delta V_0} = Q_0 \tag{4.7}$$

The capacitance $C_0$ per unit area at thermal equilibrium with a Schottky junction is given below, considering the voltage direction as shown in Figure 4.3.

$$C_0 = \frac{dQ_0}{d\Delta V_0} = \sqrt{2\varepsilon_S eN_D} \frac{1}{2\sqrt{\Delta V_0}} = \sqrt{\frac{\varepsilon_S eN_D}{2\Delta V_0}} \tag{4.8}$$

Furthermore, eliminating $\Delta V_0$ using equation (4.4), $C_0$ becomes

$$C_0 = \frac{\varepsilon_S}{x_N} \tag{4.9}$$

From this, in a Schottky junction, the (per unit area) capacitance $C_0$ (called the Schottky junction capacitance) due to a depletion layer of thickness $x_N$ is equivalent to that due to a parallel plate capacitor of thickness $x_N$. Figure 4.3 illustrates this.

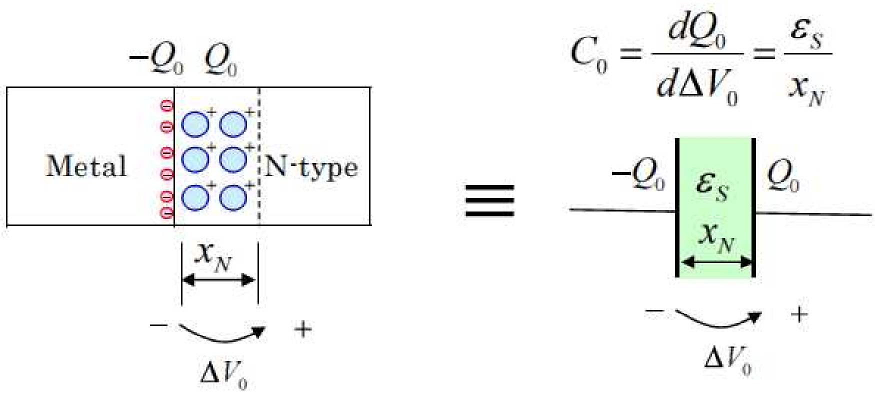



Figure 4.3 Schottky junction capacitance

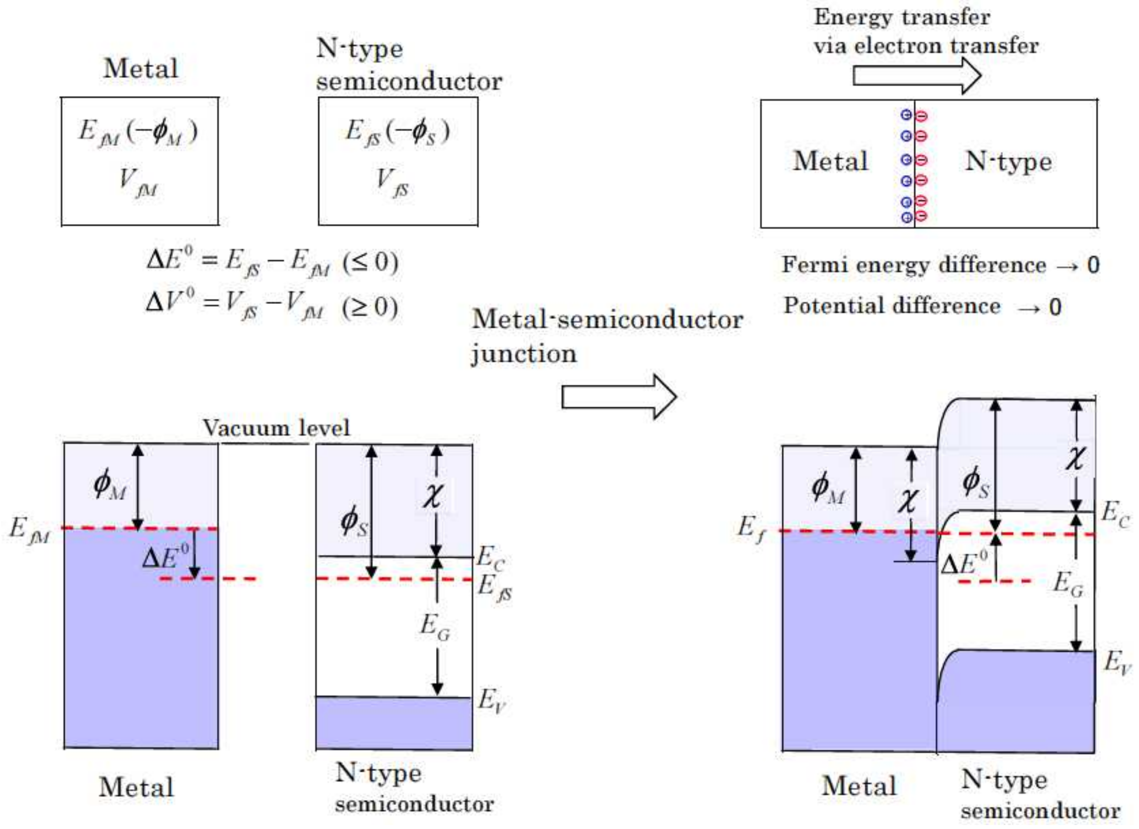
Incidentally, $x_N$, $Q_N$, and $C_0$ given for the Schottky junction in equations (4.6)-(4.8) above are equal to those given for the PN junction in Chapter 3, equations (3.13)-(3.16) with $N_A >> N_D$ for acceptor concentration. That is, the following relationship holds.

| PN junction | $N_A >> N_D$ | Schottky junction |
|---|---|---|
| $x_N = \sqrt{\frac{2\varepsilon_S N_A \Delta V_0}{eN_D(N_D + N_A)}}$ | ⇨ | $x_N = \sqrt{\frac{2\varepsilon_S \Delta V_0}{eN_D}}$ |
| $Q_N = eN_D x_N = \sqrt{\frac{2\varepsilon_S e N_A N_D \Delta V_0}{(N_A + N_D)}}$ | ⇨ | $Q_N = \sqrt{2\varepsilon_S e N_D \Delta V_0}$ |
| $C_0 = \frac{dQ_0}{d\Delta V_0} = \sqrt{\frac{\varepsilon_S e N_A N_D}{2(N_A + N_D)\Delta V_0}}$ | ⇨ | $C_0 = \sqrt{\frac{\varepsilon_S e N_D}{2\Delta V_0}}$ |

This suggests that the analysis of FETs with metal-semiconductor junctions (MESFETs), discussed below, can be performed using the same method as for PN-junction FETs (JFETs).

(2) When $\phi_M \leq \phi_S (E_{fM} \geq E_{fS})$ (ohmic junction)

Next, we discuss the case of $\phi_M \leq \phi_S$ in the metal-N-type semiconductor junction. Figure 4.4 shows the energy band structure of the metal-N-type semiconductor (a) before and (b) after the junction in the case of $\phi_M \leq \phi_S$.

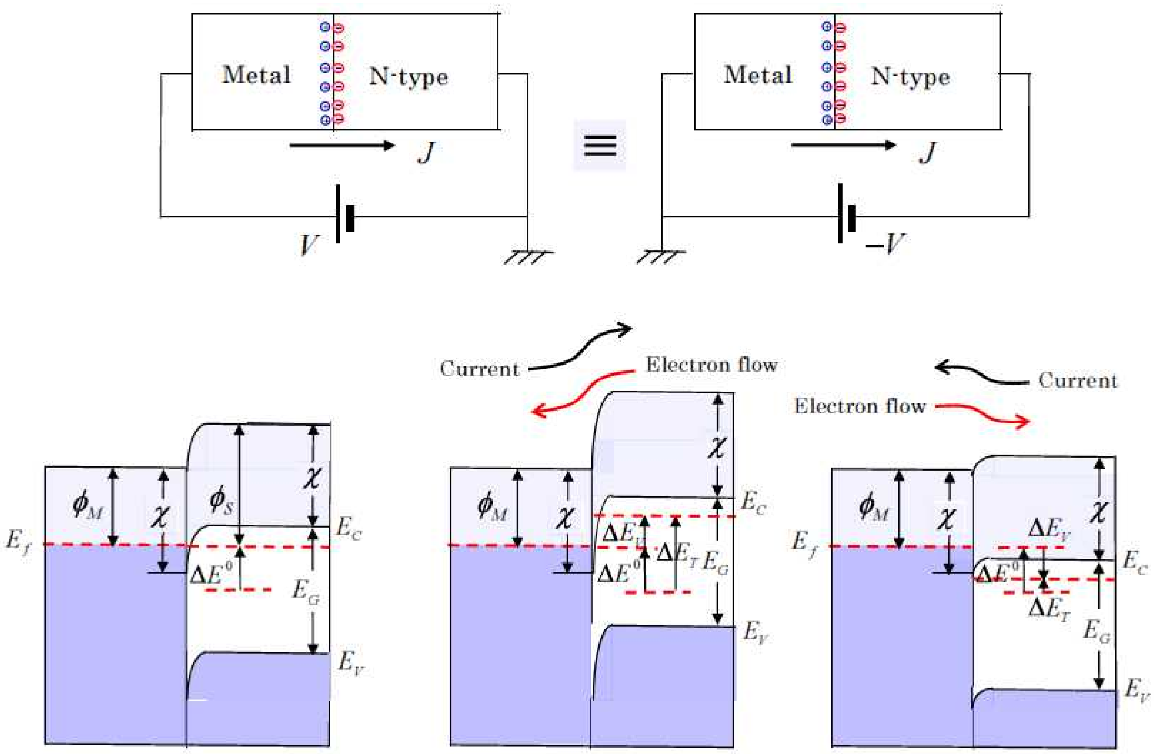



(a) before junction (b) after junction

Figure 4.4 Energy band structure of metal and N-type semiconductor (for $\phi_M \leq \phi_S$)

In this case, the original energy of the metal for electrons is $\Delta E^0$ higher than that of the semiconductor. Therefore, energy is transferred from the metal to the semiconductor via electron transfer during the junction. Due to the electron transfer, electron holes appear on the junction surface of the metal and conduction electrons appear on the junction surface of the semiconductor. This produces a potential difference $\Delta V_0 (= -\Delta V^0)$ between the metal and the semiconductor, and this potential difference causes an energy change $\Delta E_0 (= -\Delta E^0)$. As a result, the potential difference $\Delta V^0$ that originally existed between the metal and the semiconductor is canceled out and the potentials become equal, and the energy difference $\Delta E^0$ that originally existed is also canceled out and the energies (Fermi energy levels) become equal, thus realizing a thermal equilibrium state. When the Fermi energy level changes, the energy band structure changes (curves) correspondingly, as in the case of other junctions. Figure 4.4(b) shows such a situation.

Next, consider applying a bias to this junction. Figure 4.5 shows how the energy band structure changes when a bias voltage is applied to the metal-semiconductor junction. The two bias applying in the figure are equivalent. Here, for convenience of analysis, the metal side is set to ground (potential is 0) and the potential of the N- type semiconductor side is set to $-V$. The figures are shown for (a) $V \geq 0$ and (b) $V \leq 0$.




thermal equilibrium

($V = 0$) (a) $V \geq 0$ (b) $V \leq 0$

Figure 4.5 Change in energy band structure and current when bias voltage is applied to a metal-semiconductor junction (N-type semiconductor, $\phi_M \leq \phi_S$)

(a) When $V \geq 0$, the Fermi energy level $E_{fS}$ on the semiconductor side changes $\Delta E_V$ $(= -e(-V) = eV)$ $(\geq 0)$ (in the higher direction) compared to the thermal equilibrium state, and correspondingly the energy band structure also changes. At this time, conduction electrons flow from the semiconductor side to the metal side. This causes an electric current to flow from the metal side to the semiconductor side.

(b) On the other hand, when $V \leq 0$, the Fermi energy level $E_{fS}$ of the semiconductor changes $\Delta E_V$ $(= -e(-V) = eV)$ $(\leq 0)$ (in the lower direction) compared to the thermal equilibrium state, and the energy band structure changes correspondingly. At this time, conduction electrons flow from the metal side to the semiconductor side. This causes an electric current to flow from the semiconductor side to the metal side. In this junction, there is no energy barrier at the junction as there is in a Schottky junction, and electrons flow smoothly from higher energy to lower energy even when the direction of the bias voltage is changed. This junction is called an ohmic junction.

## 4.2 Schottky Junction Diode

Consider applying a bias to the junction of the metal and N-type semiconductor ($\phi_M \geq \phi_S$) as shown in Figure 4.6. Bias applying in Figures (a) and (b) are equivalent.

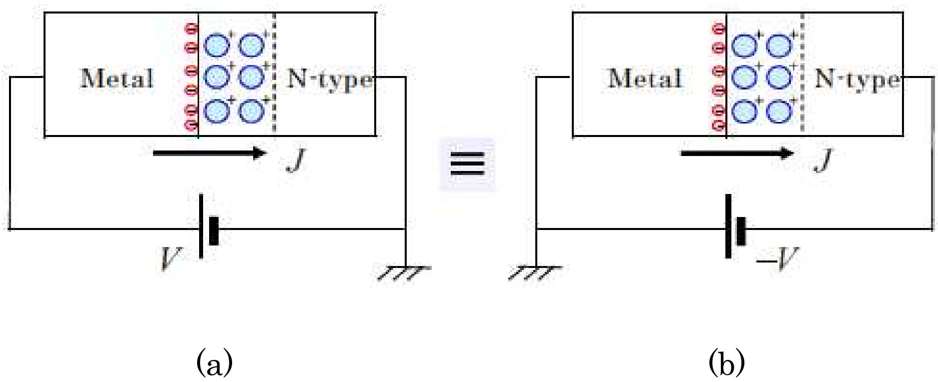
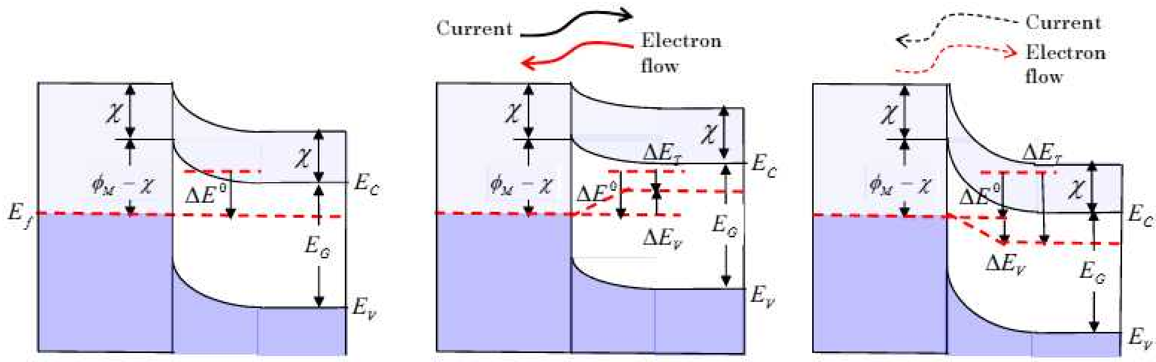



Figure 4.6 Applying a bias to a metal-semiconductor junction (N-type semiconductor, $\phi_M \geq \phi_S$)

Here, for convenience of analysis, we use Figure (b), i.e., the metal side is grounded (potential is 0) and the potential of the N- type semiconductor side is $-V$.

Figure 4.7 shows the change in energy band structure and current when a bias voltage is applied. The figures are shown for (a) $V \geq 0$ and (b) $V \leq 0$. In the following, the current characteristics for (1) the case $V \geq 0$ and (2) $V \leq 0$ are described for each case in turn. Note that the case $V = 0$ is for thermal equilibrium and has already been discussed in Section 4.1.




thermal equilibrium ($V = 0$) (a) $V \geq 0$ (b) $V \leq 0$

Figure 4.7 Change in energy band structure and current when bias voltage is applied to a metal-semiconductor junction (N-type semiconductor, $\phi_M \geq \phi_S$)

(1) Current characteristics for $V \geq 0$

At this time, the potential on the metal side is 0 and that on the semiconductor side is $-V$. From this, the Fermi energy level of the semiconductor is $\Delta E_V = -e(-V) = eV$ higher than at thermal equilibrium, and an excess of electrons flows from the semiconductor side to the metal side, resulting in current flow from the metal side to the semiconductor side.

Using Maxwell's distribution function for conduction electrons, we will obtain detailed current characteristics. According to Maxwell, the probability that the conduction electron velocity is in the range $v \sim v + dv$ is given by

$$f(\mathbf{v})d\mathbf{v} = f(v_x, v_y, v_z)dv_x dv_y dv_z \tag{4.10}$$

where $f(v)$ is Maxwell's distribution function given by (for more information on Maxwell's distribution function, please refer to the literature [13], etc.)

$$f(\mathbf{v}) = \left(\frac{m_e^*}{2\pi k_B T}\right)^{\frac{3}{2}} \exp\left(-\frac{m_e^* v^2}{2k_B T}\right) = \left(\frac{m_e^*}{2\pi k_B T}\right)^{\frac{3}{2}} \exp\left(-\frac{m_e^*}{2k_B T}(v_x^2 + v_y^2 + v_z^2)\right) \tag{4.11}$$

From this, the number of conduction electrons $n_{S\to M}$ passing across the energy barrier (Schottky barrier) from the semiconductor to the metal side in unit time across the unit cross-section is given as follows. Note that the velocity $v_x$ is positive in the leftward direction (flow from the semiconductor side to the metal side).

$$n_{S\to M} = \int_{v_{x0}}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} v_x n f(\mathbf{v}) dv_x dv_y dv_z \tag{4.12}$$

where $n$ is the conduction electron density in the N-type semiconductor and is given by

$$n = N_C \exp\left(-\frac{E_C - E_f}{k_B T}\right) = 2\left(\frac{m_e^* k_B T}{2\pi\hbar^2}\right)^{\frac{3}{2}} \exp\left(-\frac{E_C - E_f}{k_B T}\right) \tag{4.13}$$

In addition, $v_{x0}$ (the velocity of the electrons at the junction plane $x = 0$) has an energy that exceeds the Schottky barrier and is given by

$$\begin{aligned}\frac{1}{2} m_e^* v_{x0}^2 &\geq \Delta E_T = \Delta E^0 + \Delta E_V \\ &= -\Delta E_0 + \Delta E_V = e(\Delta V_0 - V)\end{aligned} \longrightarrow v_{x0} = \sqrt{\frac{2e(\Delta V_0 - V)}{m_e^*}} \tag{4.14}$$

From this, the current (density) $J_{M\to S}$ flowing from the metal to the semiconductor is given by

$$J_{M\to S} = en_{S\to M} = \int_{v_{x0}}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} ev_x nf(\mathbf{v})dv_x dv_y dv_z$$
$$= en\left(\frac{m_e^*}{2\pi k_B T}\right)^{\frac{3}{2}}\int_{v_{x0}}^{\infty} v_x \exp\left(-\frac{m_e^* v_x{}^2}{2k_B T}\right)dv_x \int_{-\infty}^{\infty}\exp\left(-\frac{m_e^* v_y{}^2}{2k_B T}\right)dv_y \int_{-\infty}^{\infty}\exp\left(-\frac{m_e^* v_z{}^2}{2k_B T}\right)dv_z \quad (4.15)$$

Here, using the integral formula $\int_{-\infty}^{\infty}\exp\left(-\alpha x^2\right)dx = \sqrt{\frac{\pi}{\alpha}}$, $J_{M\to S}$ is obtained as follows

$$J_{M\to S} = en\left(\frac{m_e^*}{2\pi k_B T}\right)^{\frac{1}{2}}\int_{v_{x0}}^{\infty} v_x \exp\left(-\frac{m_e^* v_x{}^2}{2k_B T}\right)dv_x$$
$$= en\left(\frac{k_B T}{2\pi m_e^*}\right)^{\frac{1}{2}}\exp\left(-\frac{m_e^* v_{x0}{}^2}{2k_B T}\right) \quad (4.16)$$

Furthermore, using equations (4.13) for $n$ and (4.14) for $v_{x0}$

$$J_{M\to S} = 4\pi e\frac{m_e^* k_B^2 T^2}{h^3}\exp\left(-\frac{e\Delta V + E_C - E_f}{k_B T}\right)\exp\left(\frac{eV}{k_B T}\right)$$
$$= 4\pi e\frac{m_e^* k_B^2 T^2}{h^3}\exp\left(-\frac{\phi_M - \chi}{k_B T}\right)\exp\left(\frac{eV}{k_B T}\right) \quad (4.17)$$

where $\phi_M - \chi (= \Delta E^0 + E_C - E_f = e\Delta V_0 + E_C - E_f)$ is the height of the Schottky barrier seen from the metal side. On the other hand, the current $J_{S\to M}$ due to electron $n_{M\to S}$ flowing from the metal to the semiconductor side is constant because the barrier height is constant independent of the bias $V$. Since the net current through the junction is zero when the bias is $V = 0$

$$J_{S\to M} = -J_{M\to S}\big|_{V=0} = -4\pi e\frac{m_e^* k_B^2 T^2}{h^3}\exp\left(-\frac{\phi_M-\chi}{k_B T}\right) \tag{4.18}$$

From this, the total current (density) $J$ flowing through the junction becomes

$$\begin{aligned} J &= J_{M\to S} + J_{S\to M} = 4\pi e\frac{m_e^* k_B^2 T^2}{h^3}\exp\left(-\frac{\phi_M-\chi}{k_B T}\right)\left(\exp\left(\frac{eV}{k_B T}\right)-1\right) \\ &= A^* T^2 \exp\left(-\frac{\phi_M-\chi}{k_B T}\right)\left(\exp\left(\frac{eV}{k_B T}\right)-1\right) \end{aligned} \tag{4.19}$$

$$A^* = 4\pi e\frac{m_e^* k_B^2}{h^3} \qquad \text{(Richardson's constant)}$$

(2) Current characteristics for $V \leq 0$

Next, consider the operation when a bias voltage $V \leq 0$ is applied. In this case, conduction electrons flowing from the semiconductor to the metal side almost disappear, but the electron flow from the metal to the semiconductor side remains unchanged because the barrier height is unchanged. As a result, the total current density $J$ through the junction is given as $V \leq 0$ in Eq. (4.19).

As described above, the Schottky junction exhibits rectification characteristics (diode characteristics) with current characteristics differing greatly depending on the direction of the bias voltage. This diode is called a Schottky junction diode. The current characteristic of equation (4.19) has the same form as Chapter 3, equation (3.31), obtained for a PN-junction diode. The major difference, however, is that the current in a PN junction is caused by the diffusion of minority carriers, while the current in a Schottky junction is generated by majority carriers.

## 4.3 Metal-Semiconductor Junction FET (MESFET)

Figure 4.8 shows a structure model of a metal-semiconductor junction FET

(GaAs MESFET) using a GaAs compound semiconductor as the semiconductor. As shown in the figure, the FET consists of a source (S), drain (D), and gate (G) terminals in an epitaxial layer on a semi-insulating GaAs substrate. The S and D terminals are connected to the N- type semiconductor ( $n$-GaAs ) by an ohmic junction (actually through $n^+$-GaAs to reduce resistance), and the G terminal is connected by a Schottky junction between the N- type semiconductor ($n$-GaAs) and the metal.

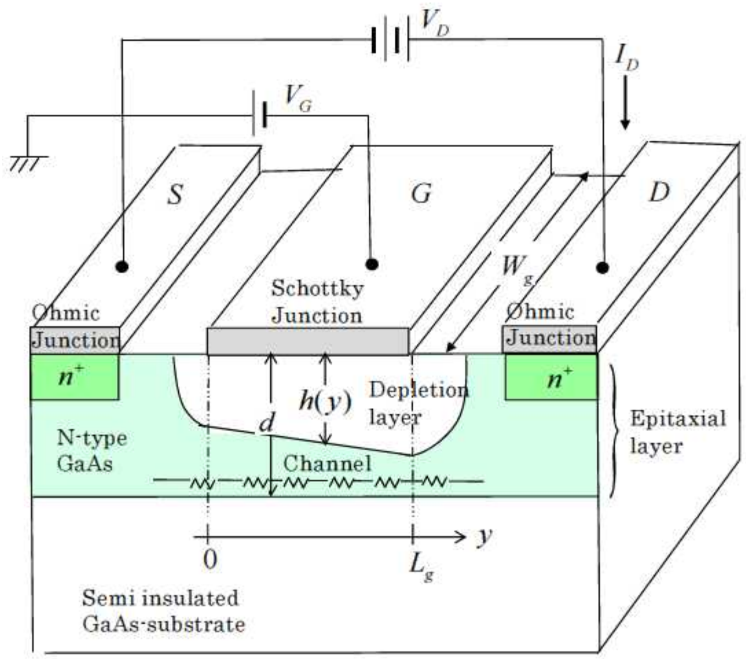



Figure 4.8 Structure model of a GaAs metal-semiconductor junction FET (GaAs MESFET)

When a voltage V is applied between D and S, a drift current due to conduction electrons flows. A depletion layer is formed at the Schottky junction, and conduction electrons flow through the channel portion where no depletion layer is formed. Controlling the voltage $V_G$ applied between G and S changes the depletion layer spread, which in turn changes the channel thickness. As a result, the current $I_D$ flowing between S and D is controlled. The behavior of the depletion layer, which plays a major role in channel control, is almost identical to that of a PN junction with $N_A >> N_D$, as described earlier (see Section 4.1). From this, the operating mechanism of the metal-semiconductor junction FET (MESFET) can be considered the same as that of the PN junction FET (JFET), and similar $I_D - V_D$ static and $g_m$ characteristics can be obtained.

The original motivation for adopting MESFETs made of GaAs semiconductors is to obtain high-speed operation characteristics due to the high electron mobility $\mu_e$ of GaAs semiconductors. High-speed operation provides high gain, high frequency, low noise, and high efficiency performance. In the case of GaAs semiconductors, a metal-semiconductor Schottky junction is used instead of a PN junction to construct a FET. On the other hand, it is difficult to form good-performing insulating films (oxide films) in GaAs semiconductors, as is the case with MOS junctions in Si (see below), and this is another reason why Schottky junctions are used.