Devices always involve interfaces:

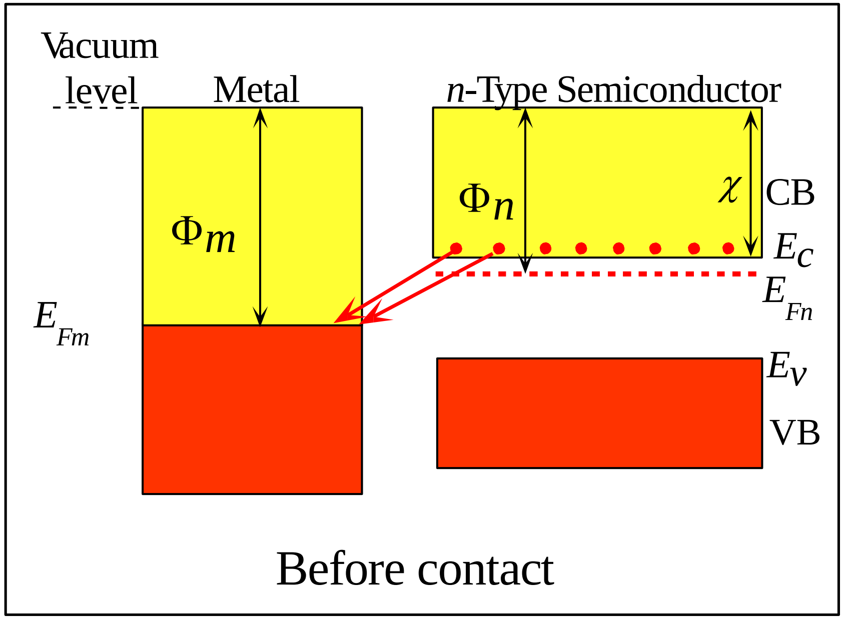
1. *metal-semiconductor*
   - *Schottky Junction*
   - *Ohmic Contact*

2. *semiconductor-semiconductor*
   - *PN Junction*

Before I came here I was confused about this subject. Having listened to your lecture I am still confused. But on a higher level.

Enrico Fermi (1901-1954; Nobel Laureate, 1938)

Metal-Semiconductor Interface: Schottky Junction （肖特基结）



Before contact

Work function (逸出功):

$\Phi = E_{vacuum} - E_F$

Formation of a Schottky junction:

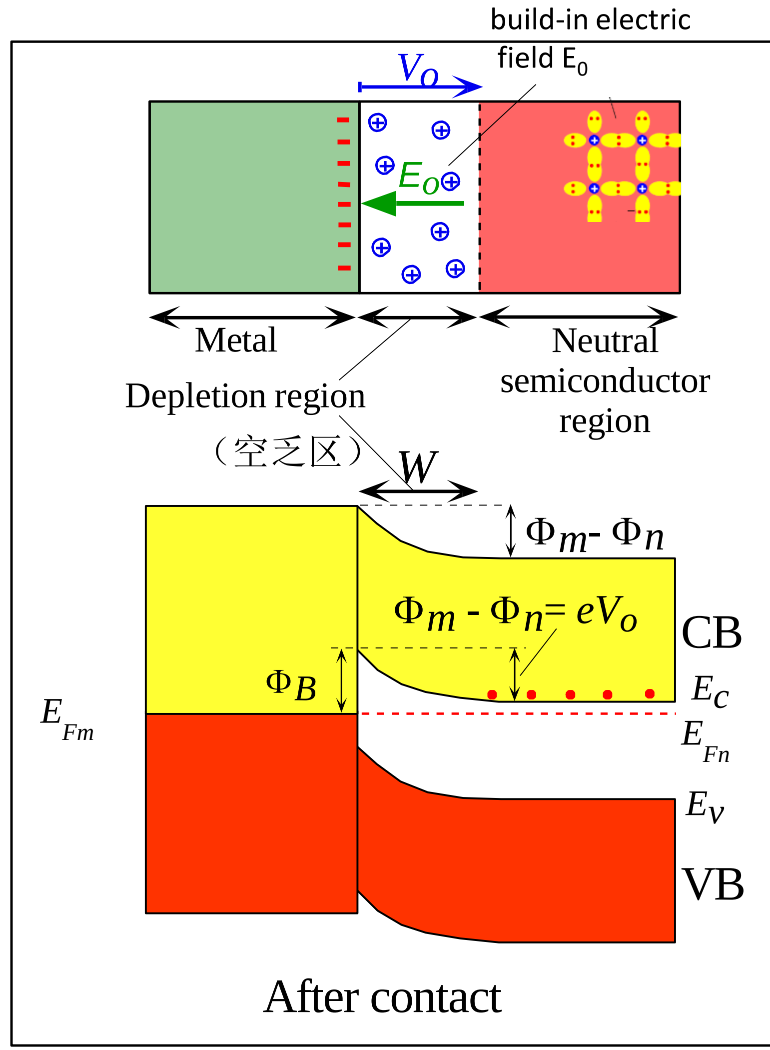
$\Phi_m > \Phi_n$

The build-in potential V_o（内置电位）：

$$V_0 = (\Phi_m - \Phi_n)/e$$

Schottky barrier height (势垒) Φ_B:

$$\Phi_B = \Phi_m - \chi = eV_0 + (E_c - E_{Fn})$$



After contact

When two materials are in contact, the **Fermi energy levels line up** at equilibrium

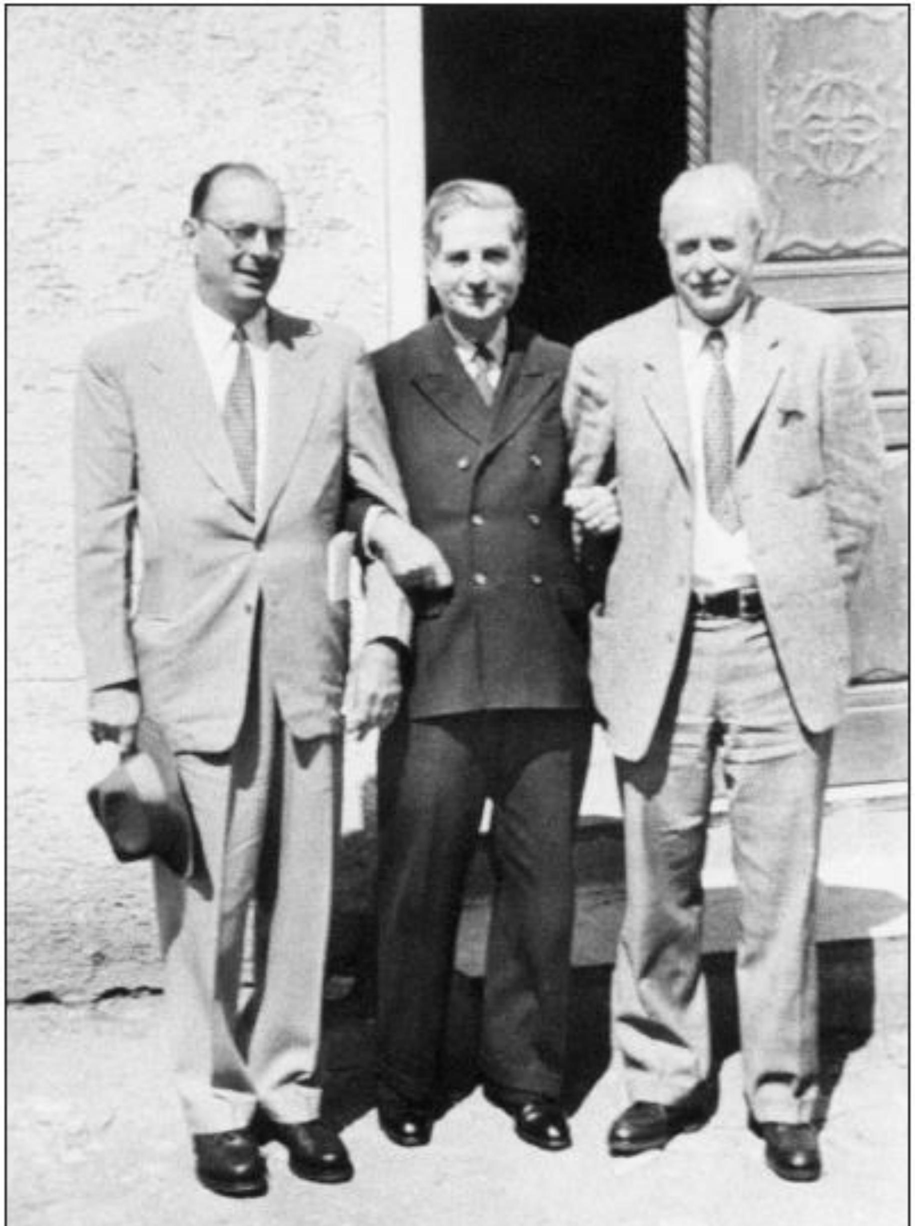
Metal-Semiconductor Interface: Schottky Junction

Assume $\Phi_m > \Phi_n$, when the metal and the semiconductor come into contact, the more energetic electrons in the CB of the semiconductor can readily tunnel into the metal in search of lower empty energy level (just above E_{Fm}) and accumulate near the metal surface.

There is an electron-depleted region of a width W in which there are exposed positively charged donors, in other words, net positive space charge. This region constitutes a space charge layer (SCL).

The contact potential, called build-in potential V_0 develops between the metal and the semiconductor.

The build-in electric field E_0 from the positive charges eventually prevents further accumulation of electrons.



John Bardeen, Walter Schottky, and Walter Brattain. Walter H. Schottky (1886–1976) obtained his PhD from the University of Berlin in 1912. He made many distinct contributions to physical electronics. He invented the screen grid vacuum tube in 1915, and the tetrode vacuum tube in 1919 while at Siemens. The Schottky junction theory was formulated in 1938. He also made distinct contributions to thermal and shot noise in devices. His book Thermodynamik was published in 1929 and included an explanation of the Schottky defect (Chapter 1).

Open circuit

Under open circuit condition, there is no net current flowing through the metal-semiconductor junction.

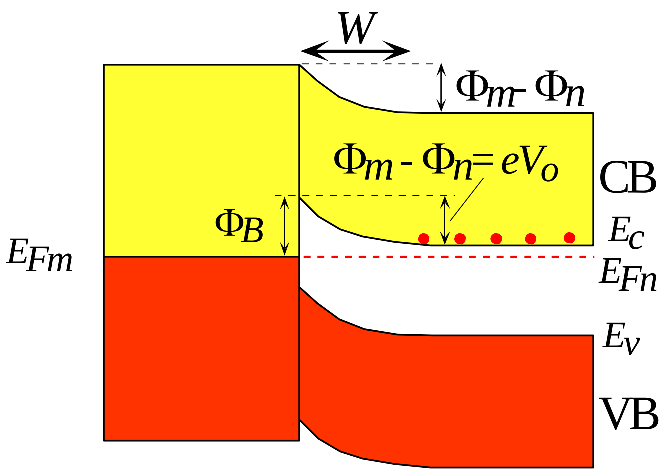
The current due to electrons being thermally emitted form the metal to the CB:

$$J_1 = C_1 \exp\left(-\frac{\Phi_B}{kT}\right)$$

C_1 is a constant.

The current due to electrons being thermally emitted from the CB of the semiconductor to the metal:

$$J_2 = C_2 \exp\left(-\frac{eV_0}{kT}\right)$$



After contact

In equilibrium:

$$J_{open-circuit} = J_2 - J_1 = 0$$

$$\Rightarrow \qquad J_2 = J_1 = J_0$$

Forward bias

Under forward bias condition, the negative terminal is connected to the semiconductor
The build-in voltage V_o is reduced to $\mathbf{V_0}$**-V.**

The current J_2^{for}, due to the electron emission from semiconductor to the metal:

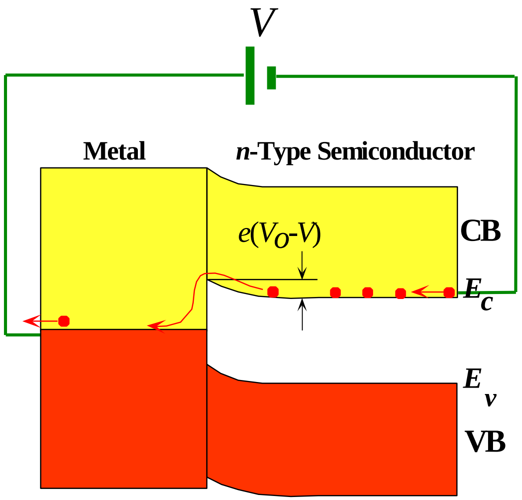
$$J_2^{for} = C_2 \exp\left(-\frac{e(V_0 - V)}{kT}\right)$$

Since Φ_B is the same, J_1 remains unchanged. The net current is then:

$$J = J_2^{for} - J_1 = C_2 \exp\left[-\frac{e(V_o - V)}{kT}\right] - C_2 \exp\left(-\frac{eV_o}{kT}\right)$$

$$\Rightarrow \qquad J = C_2 \exp\left(-\frac{eV_o}{kT}\right)\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$

$$\Rightarrow \qquad J = J_o\left[\exp\left(\frac{eV}{kT}\right) - 1\right]$$



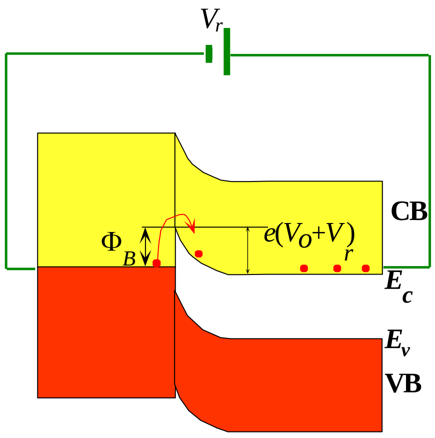
Note: $J_o = J_1$ or J_2 under the open circuit condition.

Reverse bias

When the Schottky junction is reverse biased, the positive terminal is connected to the semiconductor.
The build-in voltage V_o thus increases to **V_o+V**.

$$J_2^{rev} = C_2 \exp\left(-\frac{e(V_0+V)}{kT}\right)$$

$$\left|J_2^{rev}\right| << J_1$$



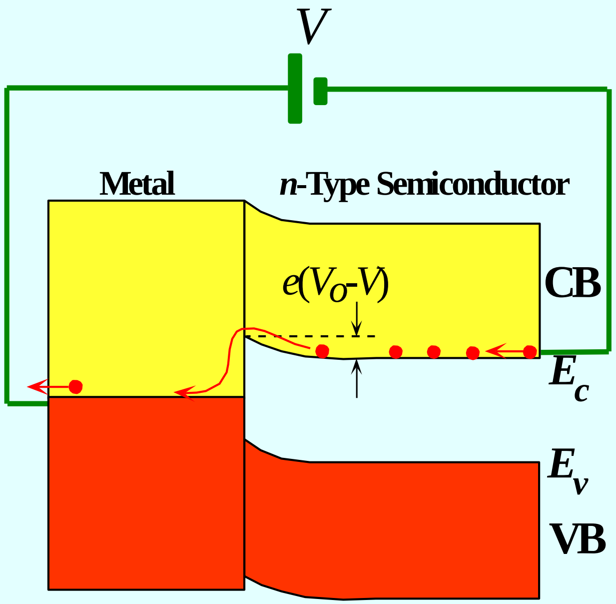
Assuming Φ_B is the same, J_1 remains unchanged. The net current is then:

$$J = J_2^{rev} - J_1 = C_2 \exp\left(-\frac{e(V_0+V)}{kT}\right) - C_2 \exp\left(-\frac{eV_0}{kT}\right)$$

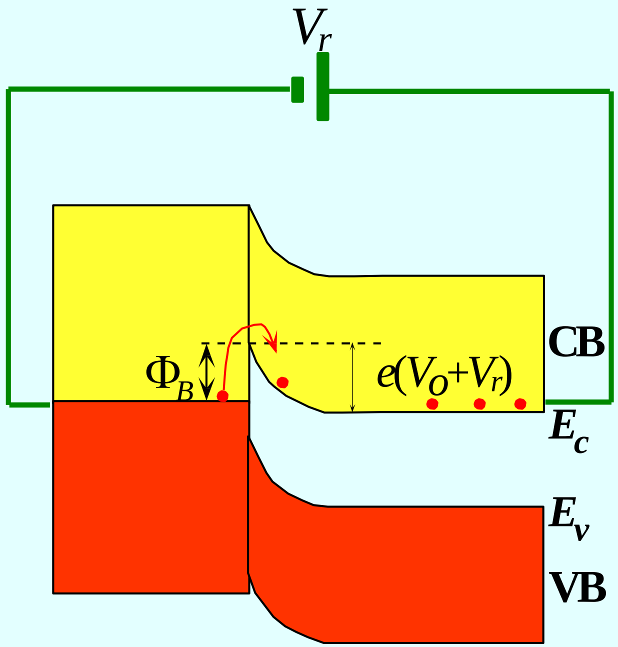
$$\Rightarrow \quad J = -C_2 \exp\left(-\frac{eV_0}{kT}\right)\left[1-\exp\left(-\frac{eV}{kT}\right)\right] = -J_0\left[1-\exp\left(-\frac{eV}{kT}\right)\right]$$

The reverse current J saturates quickly with increasing reverse bias and becomes **J_0**, which is also known as the **reverse saturation current**.

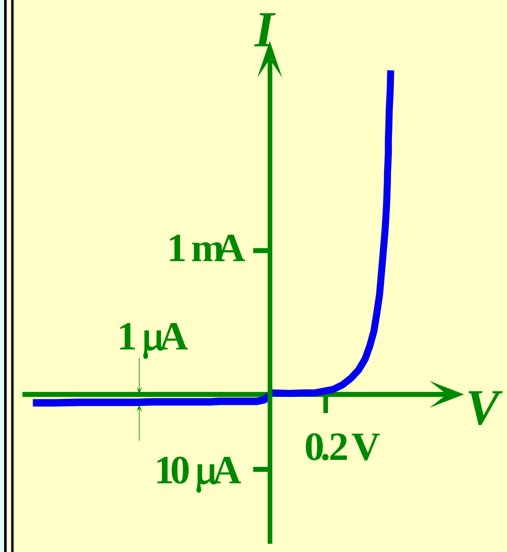
The Schottky junction



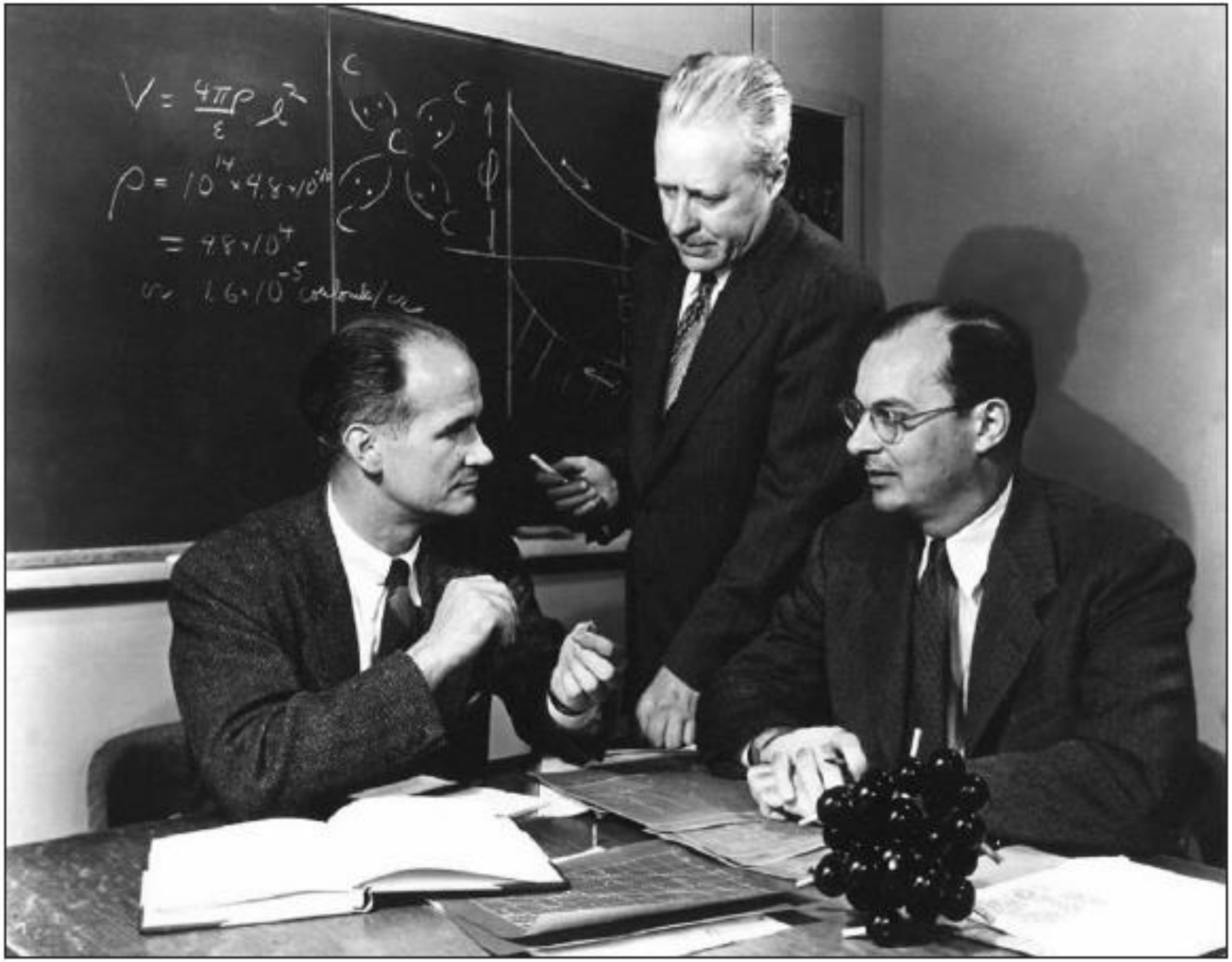
(a) Forward biased Schottky junction. Electrons in the CB of the semiconductor can readily overcome the small *PE* barrier to enter the metal.



(b) Reverse biased Schottky junction. Electrons in the metal can not easily overcome the *PE* barrier Φ_B to enter the semiconductor.

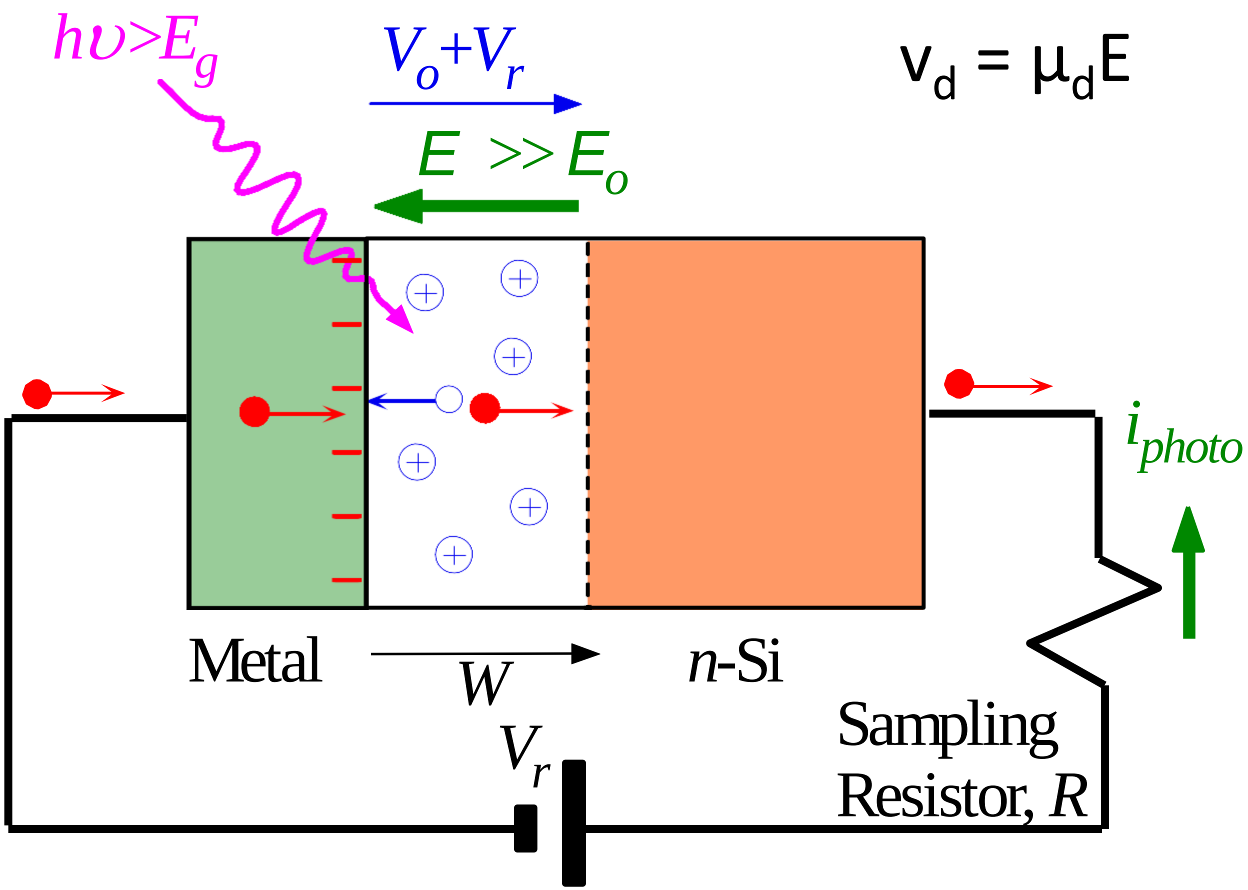


(c) *I-V* Characteristics of a Schottky junction exhibits rectifying properties (negative current axis is in microamps)



The three inventors of the transistor (晶体管): William Shockley, Walter Brattain, and John Bardeen . They shared the Nobel prize in 1956.

Schottky junction fast photodetector （光电探测器）

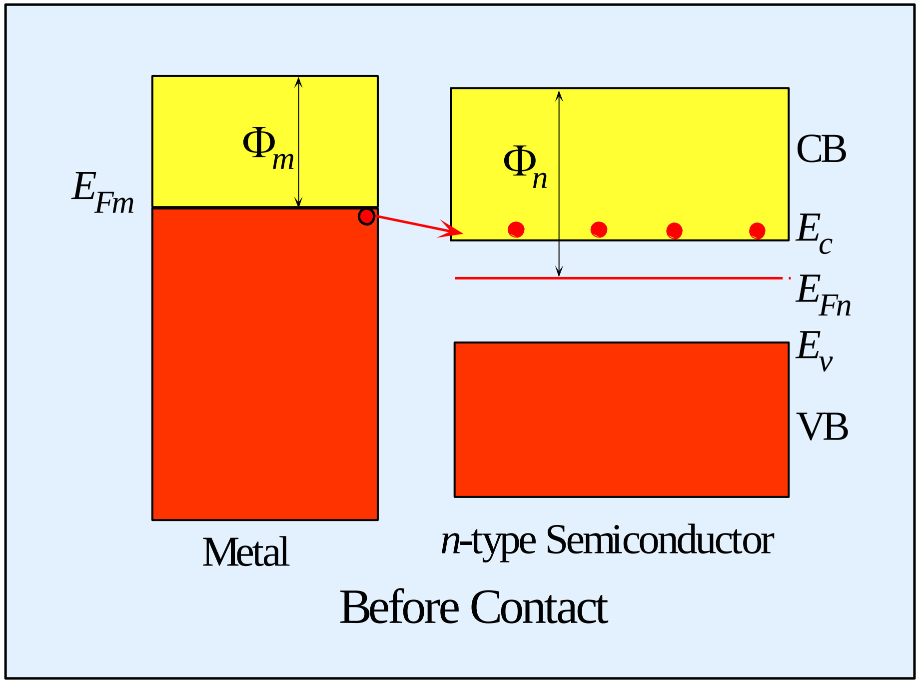


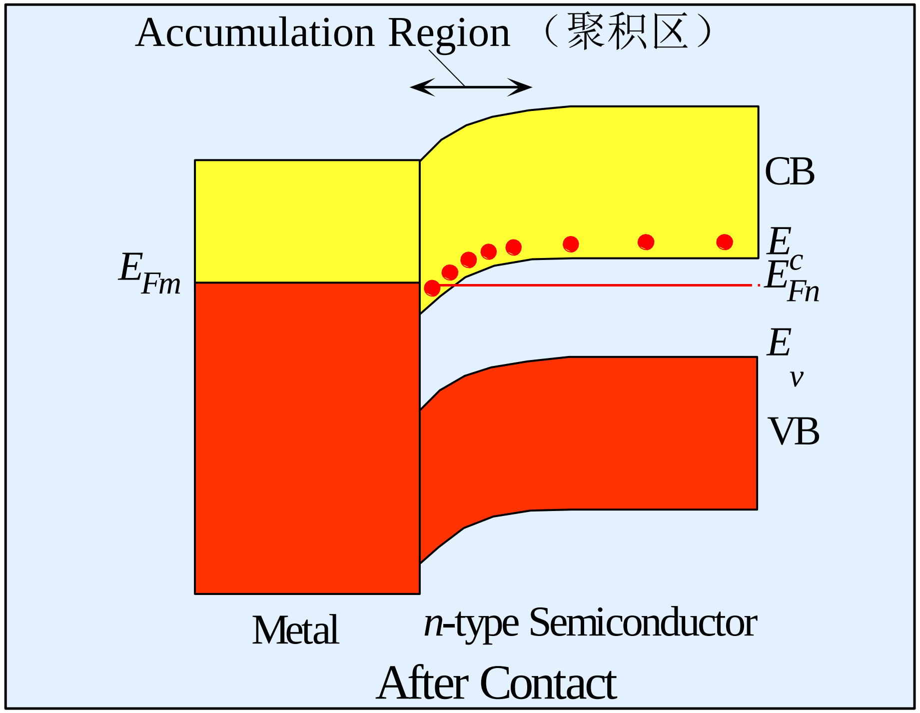
Reverse biased Schottky photodiodes are frequently used as fast photodetectors.

Ohmic contact（欧姆接触）

An ohmic contact is a junction between a metal and a semiconductor, that does not limit the current flow.

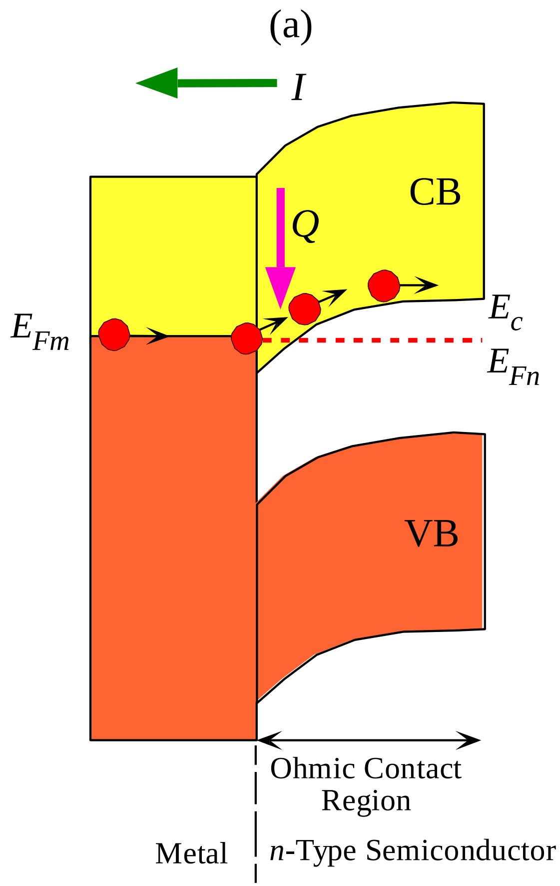
The work function of the metal Φ_m is **smaller** than the work function Φ_n of the semiconductor.





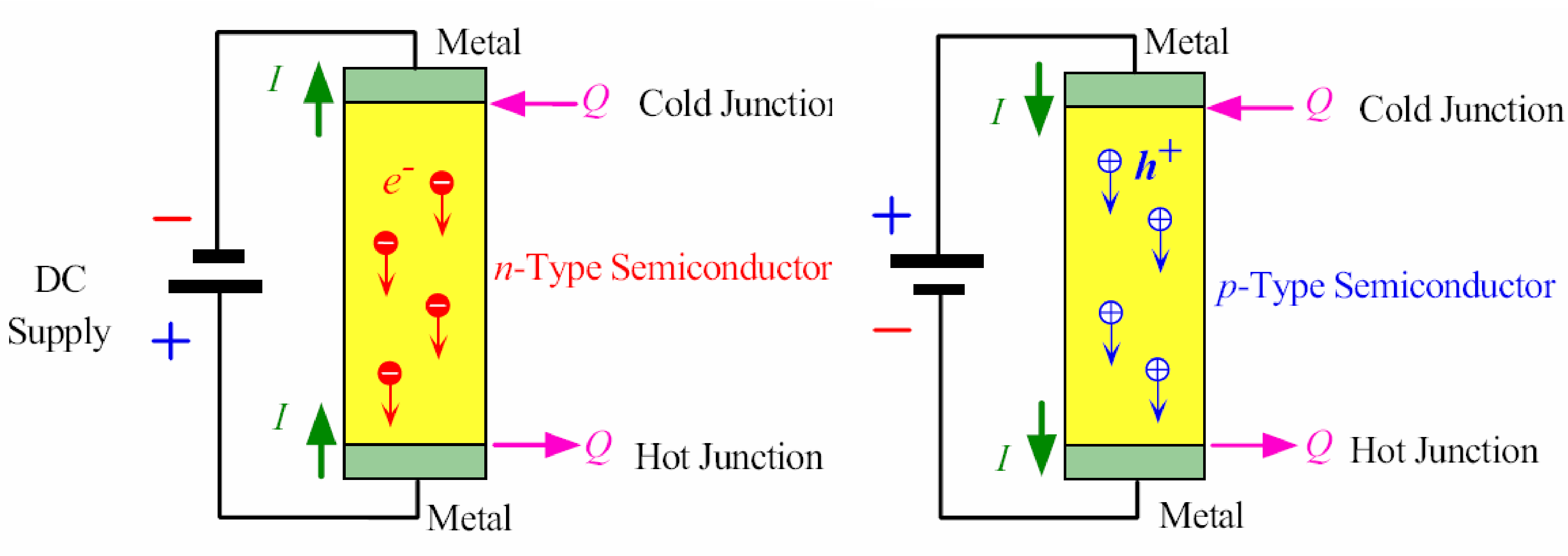
When a metal with a smaller work function than an n-type semiconductor are put into contact, the excess electrons in the accumulation region *increase* the conductivity of the semiconductor in this region, the resulting junction is an Ohmic contact in the sense that it does not limit the current flow.

Property of an Ohmic Contact: Peltier effect （珀耳帖效应）

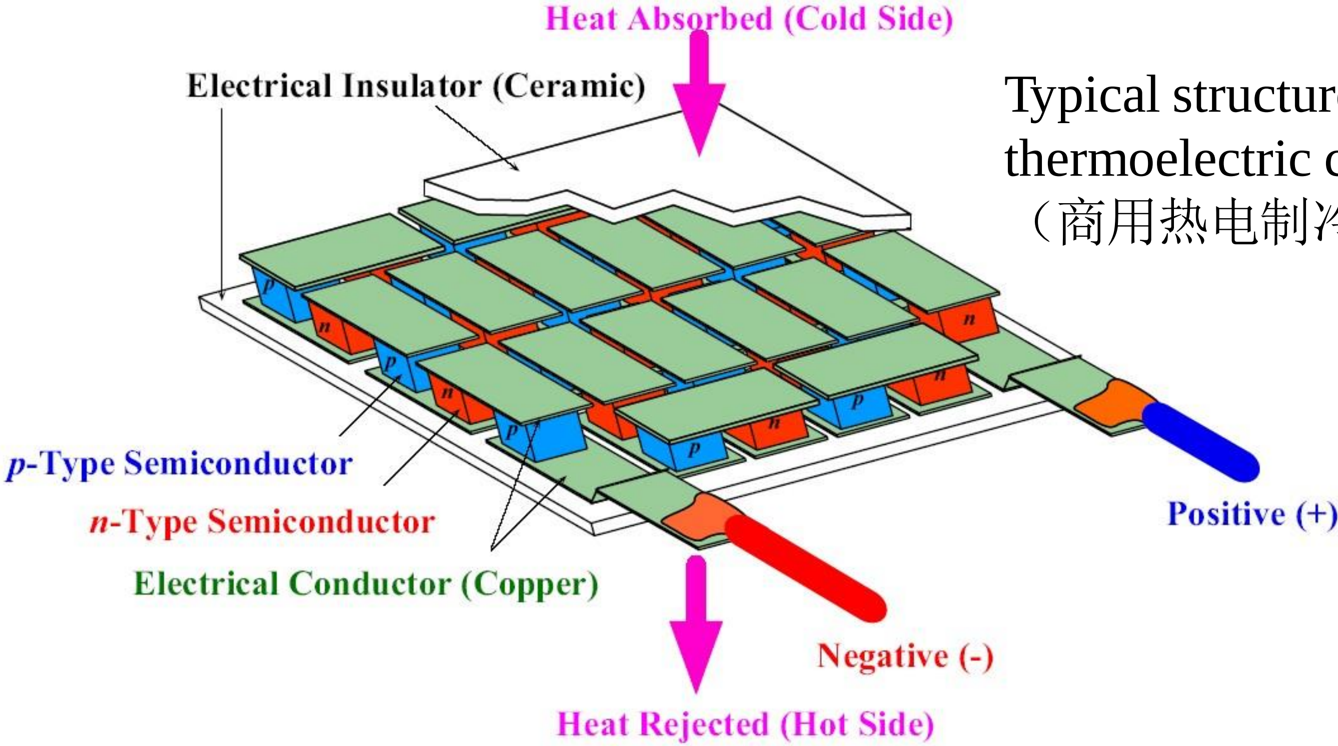


(a) Current from an n-type semiconductor to the metal results in heat absorption at the junction. (b) Current from the metal to an n-type semiconductor results in heat release at the junction.

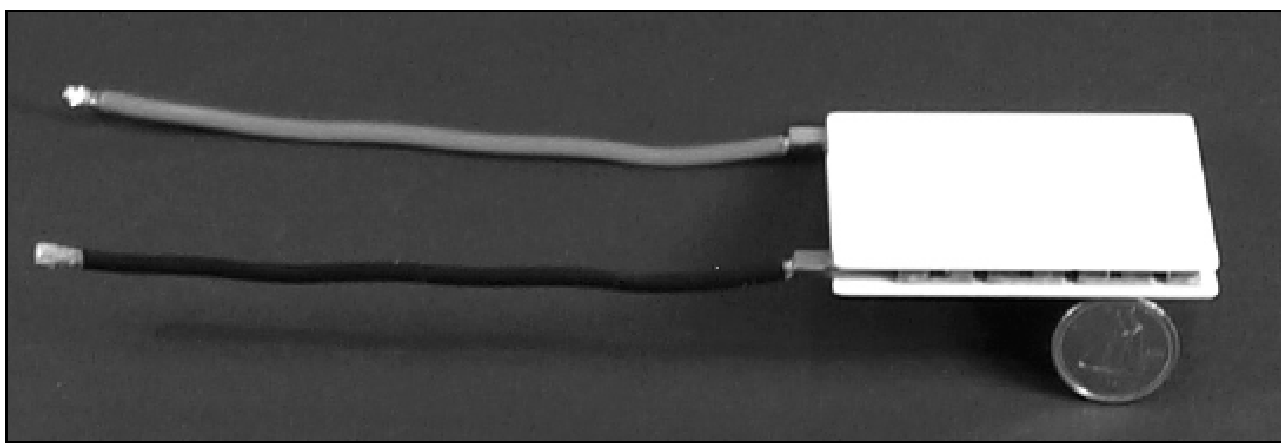
Cooler



When a dc current is passed through a semiconductor to which metal contacts have been made, one junction absorbs heat and cools (the cold junction) and the other releases heat and warms (the hot junction).



Typical structure of a commercial thermoelectric cooler
（商用热电制冷器）



A commercial thermoelectric cooler (by Melcor); an example of the Peltier effect. The device area is 5.5 cm × 5.5 cm (approximately 2.2 inches × 2.2 inches). Its maximum current is 14 A; maximum heat pump ability is 67 W; maximum temperature difference between the hot and cold surfaces is 67 °C.