7. Contact Phenomena in Metals and Semiconductors

7.1. The Work of Exit

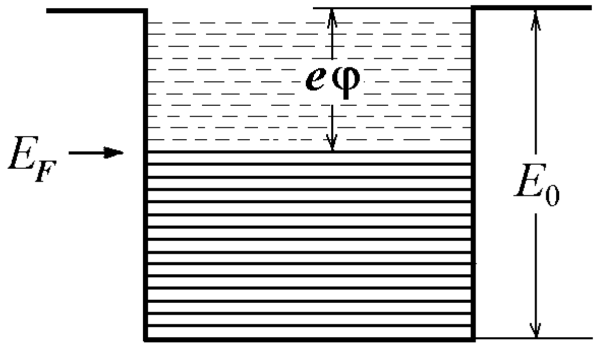

Fig.7.1. Potential well of a metal. The dashed lines show unoccupied energy levels.

In metal, the maximal electron total energy is less then that one of an electron at rest outside the metal. We should have in mind that the potential energy of an electron in metal is negative. The potential well is shown in Fig.7.1.

In order to leave the metal electrons are to pass the potential barrier. The minimum energy needed to leave a metal is called the **work of exit** (of the order of eV)**:**

$$\Phi = e\varphi = E_0 - E_F \tag{7.1}$$

The heat motion (thermionic emission) or absorption of a light quantum (photoelectric emission) can make an electron to leave a metal. Work of exit depends on the surface covering and cleanness.

7.2 Thermionic Emission

To undergo the emission from solid, the kinetic energy of an electron must be not less then $\Phi + E_F$ (see Fig.71). Those high-energy states are weakly populated and the Bolzmann approximation is true:

$$f(E_F) \to \exp\left(\frac{E_F - E}{k_0 T}\right), E >> E_F \qquad (7.2.)$$

The formula (4.68) for the electron density in velocity space is also true.

$$f_0 d\upsilon_x d\upsilon_y d\upsilon_z = \frac{1}{4}\left(\frac{m}{\pi\hbar}\right)^3 \exp\left(\frac{E_F}{k_0 T}\right)\exp\left(\frac{-m\left(\upsilon_x^2 + \upsilon_y^2 + \upsilon_z^2\right)}{2k_0 T}\right)\times \qquad (7.3.)$$
$$\times d\upsilon_x d\upsilon_y d\upsilon_z$$

To penetrate the barrier, the velocity component normal to the interface should be:

$$\upsilon_x \geq [2(\Phi + E_F)/m]^{1/2} \qquad (7.4.)$$

Outside the metal, the electron velocity becomes:

$$u_x = \left[\upsilon_x^2 - 2(\Phi + E_F)/m\right]^{1/2} \qquad (7.5.)$$

In accordance with (7.3):

$$n(\upsilon_x)d\upsilon_x = \frac{1}{4}\left(\frac{m}{\pi\hbar}\right)^3 \exp\left(\frac{E_F}{k_0T}\right)\exp\left(\frac{-m\upsilon_x^2}{2k_0T}\right)Y^2 d\upsilon_x, \qquad (7.6.)$$

The symbol Y substitutes the integral:

$$Y = \int_{-\infty}^{\infty} \exp\left(\frac{-m\upsilon_y^2}{2k_0T}\right)d\upsilon_y = (2\pi k_0T/m)^{1/2} \qquad (7.7.)$$

Introducing (7.7) into (7.6):

$$n(\upsilon_x)d\upsilon_x = \left(\frac{m^2k_0T}{2\pi^2\hbar^3}\right)\exp\left(\frac{E_F}{k_0T}\right)\exp\left(\frac{-m\upsilon_x^2}{2k_0T}\right)d\upsilon_x, \qquad (7.8.)$$

The density current at the interface:

$$\mathbf{J} = \int_{[2(\Phi+E_F)/m]^{1/2}}^{\infty} e\upsilon_x[1-r(\upsilon_x)]n(\upsilon_x)d\upsilon_x. \qquad (7.9.)$$

The quantity $r(\upsilon_x)$ is the reflection coefficient. We remind our readers that electrons are reflected by the barrier even when their energy is higher then that of the barrier. The coefficient depends on the barrier form.

Assume (practice show that it is true) that the coefficient $r(\upsilon_x)$ slowly changes in the basic region of the integral (7.9). Thus we can put the factor (1 - r) in front of the integral:

$$\mathbf{J} = \left(\frac{em^2k_0T}{2\pi^2\hbar^3}\right)(1-r)\exp\left(\frac{E_F}{k_0T}\right)\int_{[2(\Phi+E_F)/m]^{1/2}}^{\infty} \upsilon_x \exp\left(\frac{-m\upsilon_x^2}{2k_0T}\right)d\upsilon_x. \qquad (7.10.)$$

Substituting $y = \left(\frac{m\upsilon_x^2}{2k_0T}\right)$ we get:

$$\int_{[2(\Phi+E_F)/m]^{1/2}}^{\infty} \upsilon_x \exp\left(\frac{-m\upsilon_x^2}{2k_0T}\right)d\upsilon_x = \frac{k_0T}{m}\int_{[2(\Phi+E_F)/m]^{1/2}}^{\infty} e^{-y}dy = \frac{k_0T}{m}\exp\left[\frac{-(\Phi+E_\Phi)}{k_0T}\right]. \qquad (7.11.)$$

And finally the thermionic emission current density:

$$\mathbf{J} = \left(\frac{em^2 k_0^2 T^2}{2\pi^2 \hbar^3} \right) (1 - r) \exp\left(\frac{-\Phi}{k_0 T} \right), \qquad (7.12)$$

The formula (7.12) ca be written in the form (7.13), which is called the Richardson – Dashman law:

$$\mathbf{J} = AT^2 (1 - r) \exp(-\Phi / k_0 T), \qquad (7.13.)$$

$$A = \left(\frac{emk_0^2}{2\pi^2 \hbar^3} \right) = 1{,}2{*}10^6 \text{ A/(м}^2\text{ K}^2). \qquad (7.14)$$

The quantities $A(1 - r)$ and Φ can be found by intersection of the ordinate axis and the Richardson curve inclination (dependence of $\lg(J/T^2)$ on $1/T$) [see F.g.7.2].

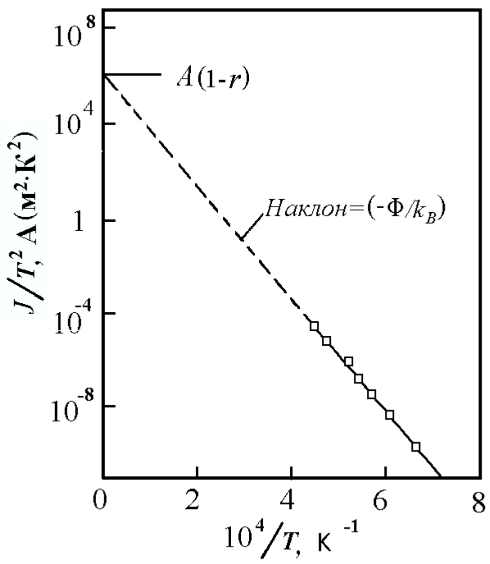

Fig.7.2. The Richardson law for tungsten. Determination of the exit work and inclination constant

The experimental quantities $A(1 - r)$ for uncovered samples coincide usually with the theoretical ones but the work of exit varies in wide range.

The measurement of the exit work is complicated by the temperature dependence, by anisotropy of crystals, and by the surface impurity. The anisotropy can be explained by the zone theory and can not be explained by the free electron approximation.

In a polycrystal-metal sample, the measured work of exit depends on many effects. The crystalline planes of the less surface work of exit are of main importance.

Sometime the surface impurities can be of use, sometime not. It depends The exit work of metals with the Fermi energy considerably lower then that in vacuum, is strongly violated by the surface absorbed gases, impurity and cover atoms, and the population of the surface energy states.

The small variation of the exit work produces great effects. The variation of 1% changes the emission current by 80% (at temperature 1000K).

The great increasing of the emission current is observed when the atoms of a substance with small exit work are distributed on the surface of a substance with a great work of exit.

Decreasing of the exit work by the surface covering is of a great engineering importance. It can be used when constructing electron tubes without high temperature cathode heating.

It should be noted that in spite of the wide application of transistors, the electron tubes with thermionic emitters are widely used, for example the high power and electron-beam tubes.

7.3 Emission in an External Field. Autoelectronic Emission

We assumed while discussing the thermionic emission that the potential energy makes a step at the metal interface (from zero inside the metal up to $\Phi + E_F$ near the external side (seeFig.71 and 7.3).

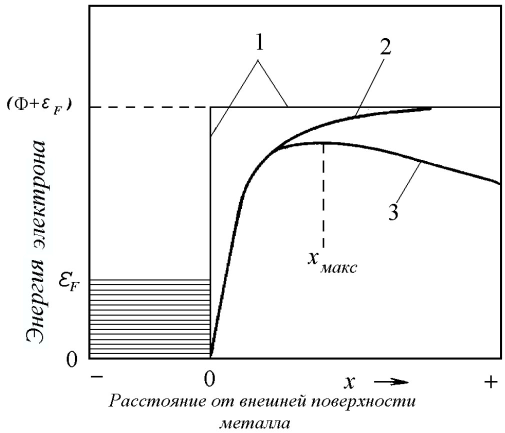

Fig.7.3.The electron energy inside and outside a metal The energy of an electron at rest inside the metal is chosen to be zero. 1-infinite potential barrier. 2-the barrier when the force between an electron and metallic wall is taken into account. 3-the change of the barrier form and lowering its height by an external electric field.

Shottki in 1914 assumed that the barrier is not such steep. We can expect that the quantity *V(x)* linearly increases with the distance. At a distance of several angstroms, between the electron and its image (- *e)* the interaction force appears. Thus the potential energy:

$$V(x) = (\Phi + E_F) - \left(e^2/16\pi\varepsilon_0 x\right) \text{ (great } x\text{).} \qquad (7.15)$$

The curve 2 (Fig.7.3) describes the potential rather well:

$$V(x) = 0, x < 0,$$

$$V(x) = \frac{(\Phi + E_F)^2}{(\Phi + E_F) + \left(e^2/16\pi\varepsilon_0 x\right)} \quad x>0 \qquad (7.16)$$

For an electron with kinetic energy a little higher then ($\Phi + E_\Phi$), the probability of reflection (see 7.16) is considerably less then that one while reflecting from the step barrier.
Assume that outside of a crystal, the electric field normal to interface is produced. The potential has the form (the curve 3 in Fig.7.3):

$$V(x) = (\Phi + E_F) - \left(e^2/16\pi\varepsilon_0 x\right) - exE_x. \qquad (7.16a)$$

Differentiating potential energy with respect to *x,* and using the standard procedure we get the barrier maximum position.

$$x_{макс} = \left(e/16\pi\varepsilon_0 x\right)^{1/2},$$

$$V_{макс} = (\Phi + E_F) - \left(e^3 E_x/4\pi\varepsilon_0\right)^{1/2}. \qquad (7.16b)$$

The external electric field decreases slightly the work of exit. The phenomenon is called the **emission in external field.** The electrons, which could not emit from metal when there was not the additional field, produce the electric current in the outer space when the external field is applied. Shotki described the phenomenon in 1914-1923.

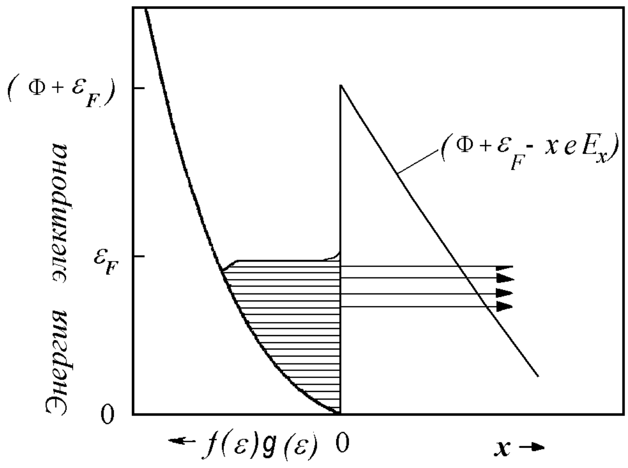

Fig.7.4. A potential barrier at the metal interface at very strong electric field. If the barrier width is several angstroms, the autoelectronic emission is appreciable.

At electric field strength ~10^8 V/m, the **autoelectronic** (or **cold**) emission is produced. The definition '*cold*' is used because the process is happening at any temperature.

The potential barrier (Fig.7.4) becomes thin, and the penetration probability appreciable. The quantity Φ/eE_x is about 10Å).

Fauler and Nordheim evaluated the penentration probabilyty througth the triangle barrier shown in Fig. 7.4. The current density is given by:

$$\mathbf{J} = \alpha E^2 \exp(-\beta\Phi / E). \tag{7.17}$$

A glance at (7.13) and (7.17) shows that instead of temperature, the electric field is the control factor.

The penetration probability is negligible till the barrier width is less then 10 angstroms. Taking into account that the work of exit is about 3eV, the electric field strength needed to start the emission is 3-10^9 V/m.

In reality, the initial electric field strength is 30 times less. It is possible to assune that the local non-uniformity causes the strong local electric field strength and emission at those points. In general the experimental data coincide with (7.17).