7.6. An Electron-Hole Transition

We remind our readers that a *p-n* transition can be used as the current rectifier. When the voltage is applied through the transition, its potential barrier and charge carrier concentration can be controlled.

If a negative voltage is applied through the *n* –region, we can inject the non-basic carriers into a semiconductor. That property of a *p - n* transition is widely used in semiconductor electronics. The transition is usually produced by diffusion the impurities of one type into a semiconductor of the other type. It is done in order to have surplus of positive charge in one region, and of negative charge in the other.

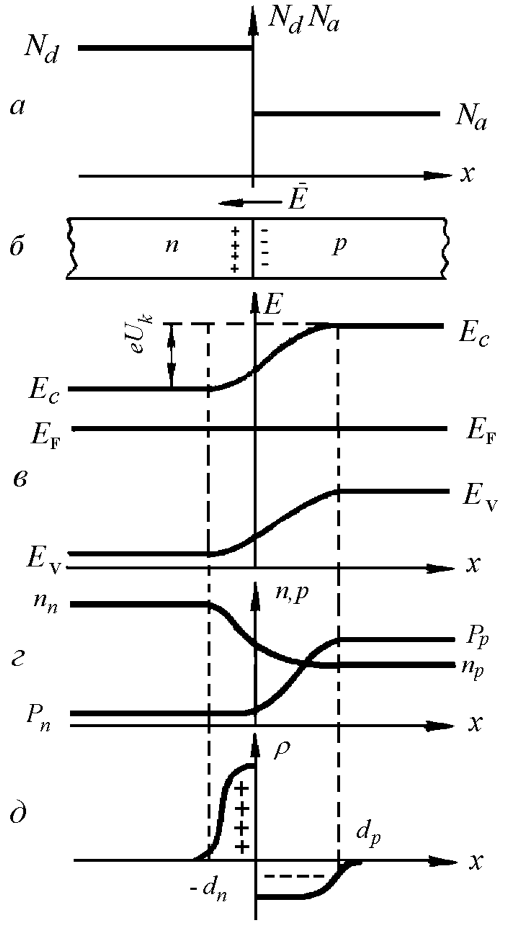

Fig.7.8. Generation of p-n transition when the donor impurity is injected into a p-type semiconductor: a- the impurity distribution; b-separation of charges at the contact between n- and p-regions; c-bending of zones; d-the distribution of carriers; e-the volume charge distribution

Let us study the *p - n* transition produced in a uniform semiconductor by diffusion of donor and acceptor impurities (Fig.7.8).

Assume that the semiconductor is of acceptor type with an uniformly distributed acceptor impurity. A donor impurity is injected thus that in a certain part of the semiconductor its concentration were greater $N_d > N_a$ (Fig.7.8a). The electric conductivity of that region would be of an electron type. The other region where the donor concentration is small would be of the hole type (Fig.7.8b).

The mutual diffusion of basic carriers would be produced at the interface between the regions with different types of conductivity. The hole would transist from *p*-region into *n* –region and vise versa. That process leads to separation of charges in the contact region of the transition.

In *p* region, the negative volume charge of acceptor ions is generated because the holes leave the region. In *n* region, the positive volume charge of donor ions is generated because the electrons leave that region.

Thus an electric field is generated in the contact region. That field initiates the drift of non-basic charge carriers. The holes drift from *n* –region into *p*-region. The electrons drift *p*-region into *n*-region.

The currents will run till the contact field equilibrium the both currents and the drift current of non-basic carriers will be equal to the diffuse current of basic carriers.

At normal condition in n-region, the basic carrier concentration n_n is gteater then the electron concentration (auxiliary carriers) n_p in p-region. In p-region, the concentration of the basic carries p_p is greater then the hole concentration p_n (auxiliary carriers) in n-region (Fig.7.8c). Having in mind that $N_d > N_a$:

$$n_n > p_p. \tag{7.73}$$

The generated contact field handicaps the electrons to leave the n-region and the holes to leave the p-region. The concentration of electrons n_n and holes p_p decrease rapidly with depth of the contact zone (Fig.7.8d).

In an equilibrium state, there is no current through the p-n transition and the Fermi levels of both regions are identical. But from the both sides of the transition there are the volume charges of the opposite sign relative to that of the basic carriers of each region. It leads to formation of potential barriers for the basic carriers. The energy zones bend (Fig.7.8c). In accordance with (7.57) the penetration depths of the contact layer into in p- and n-region are different (Fig.7.8e). Taking into account (7.73) we assume that:

$$|\zeta|_p = \zeta_n. \tag{7.74}$$

The penetration depths can be found by solution of the Poisson equation. Taking into account (7.51) i.e. that in n-region, the volume charge is produced by donor ionized atoms, and in p-region by ionized acceptor atoms we get:

$0 < x < \zeta_n$

$$d^2\varphi / dx^2 = en_n / \text{æ}_0 \tag{7.75}$$

$-\zeta_p < x < 0$

$$d^2\varphi / dx^2 = -ep_p / \text{æ}_0. \tag{7.76}$$

In section 7.5 we discussed the like equations. The boundary condition:

$$\varphi = 0 \quad and \quad d\varphi/dx = 0 \quad for \quad x = \zeta_n; \tag{7.77}$$

$$\varphi = U_K \quad and \quad d\varphi/dx = 0 \quad fou \quad x = -\zeta_p \tag{7.78}$$

The solution of (7.75) and (7.76) are [(see (7.56)]:

$$\varphi_p = U_K - ep_p/2\text{æ}_0(\zeta_p - x)^2 \quad for \quad -\zeta_p < x < 0.$$

$$\varphi_n = en_n/2\text{æ}_0(\zeta_n - x)^2 \quad for \quad 0 < x < \zeta_n; \tag{7.79}$$

(7.80)

At the boundary, the both solutions coincide:

$$\varphi_n\big|_{x=0} = \varphi_p\big|_{x=0}, \tag{7.81}$$

$$d\varphi_n/dx\big|_{x=0} = d\varphi_p/dx\big|_{x=0}. \tag{7.82}$$

Having in mind (7.81), (7.79), and (7.80) we get:

$$\zeta_n/\zeta_p = p_p/n_n. \tag{7.83}$$

$\zeta = \zeta_p + \zeta_n$: Using (7.81) and (7.83) we find the potential and thickness of volume charge layer

$$U_K = \frac{e}{2\text{æ}_0}\left(n_n\zeta_n^2 + p_p\zeta_p^2\right) = \frac{e}{2\text{æ}_0}\frac{n_n p_p}{n_n + p_p}\zeta^2, \tag{7.84}$$

$$\varsigma = \sqrt{\frac{2\text{æ}_0 U_K}{n_0 e}\frac{n_n + p_p}{n_n p_p}}. \tag{7.85}$$

A glance at formula (7.85) shows that the less is the carrier concentration the greater is the thickness. Thus the thickness decreases with the concentration of the alloy impurity. The contact field potential depends [likewise a metal-semiconductor contact (7.50)] on the difference of exit works:

$$eU_K = \Phi_n - \Phi_p. \tag{7.86}$$

Substituting Φ_n and Φ_p in accordance with (7.41) and (7.43) we get:

$$eU_K = \Delta E - k_B T \ln N_c N_v / N_a N_d. \tag{7.87}$$

Thus for a non-degenerated semiconductor, the quantity eU_K is less then ΔE . Using (6.50) we can transform (7.87):

$$eU_K = k_B T \ln p_p n_n / n_i^2 \tag{7.88}$$

7.7. The volt-ampere Characteristic of a P-N Transition

Mainly auxiliary charge carriers cause the rectification properties of a metal-semiconductor contact. Thus the generation and recombination of carriers in a p-n transition is of importance.

Generating of auxiliary charge carriers is due to the initial diffusion of basic carriers. That process depends on the basic carrier concentration, which can be accelerated by a external electric field.

The recombination depends mainly on the life time and diffusion length of auxiliary carriers. Thus the thickness of p-n transition is of importance. We assume that the p-n transition is thin, and the recombination is negligible. Hence the diode rectification theorem is true ($L >> \zeta$).

The diffuse rectification theorem is true when the recombination in a thick transition layer ($L << \zeta$) is under investigation. Besides opposite to metal-semiconductor situation, the current of holes and electrons must be taken in consideration.

Thus there are four current components: diffuse currents of the basic carriers electrons $\mathbf{j}_{nD}$ and holes $\mathbf{j}_{pD}$, and the drift currents of auxiliary charge carriers $\mathbf{j}_{nE}$ and $\mathbf{j}_{pE}$:

In the state of thermodynamic equilibrium:

$$\mathbf{j}_{nD} + \mathbf{j}_{pD} + \mathbf{j}_{nE} + \mathbf{j}_{pE} = 0 \tag{7.89}$$

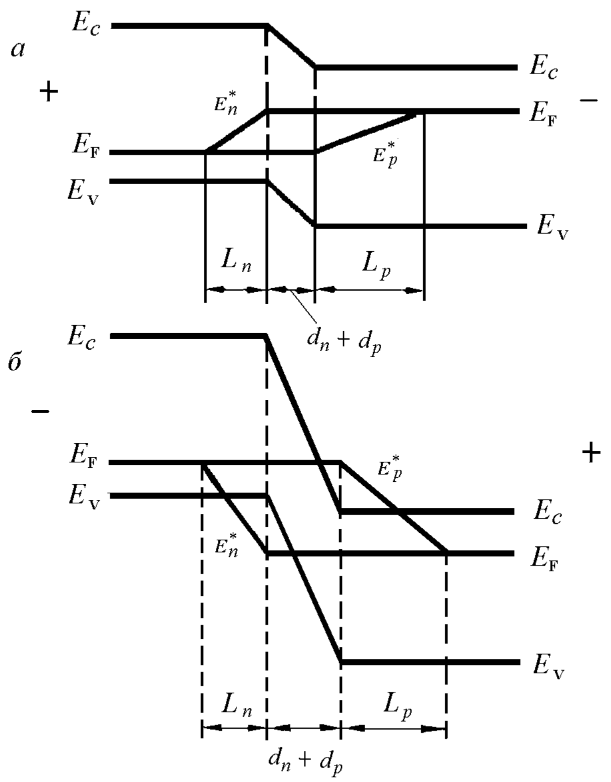

Fig.7.9. The energy diagram of a p-n transition: a-the direct voltage, b-the blackout voltage

If a positive voltage is applied through the p-region and a negative voltage is applied through the n-region of a p-n tramnsition, the potential barrier becomes less. It is a direct voltage $V < 0$. An electron flux from n-region into p-region increases and the hole flux from p-region into n-region becomes greater too. Thus the basic carrier flux increases. The external electric field can become greater then the contact one and the potential barrier can diminish at all.

The energy zones with inclination caused by a strong external field form a '**potential slope**' for electrons of p-region and holes of n-region (Fig.7.9a). The current through the transition depends on the applied voltage, and recombination of electrons in n-region and holes in p-region. If the polarity of an external voltage changes in contact region of the transition, the volume charge of donors and acceptors at rest would increase. It is due to the removal of mobile electrons and hole under action of the external field. The electric current through the transition almost vanishes (see Fig.7.10). It is a blackout voltage: $V > 0$. The thickness of p-n transition depends on applied voltage polarity:

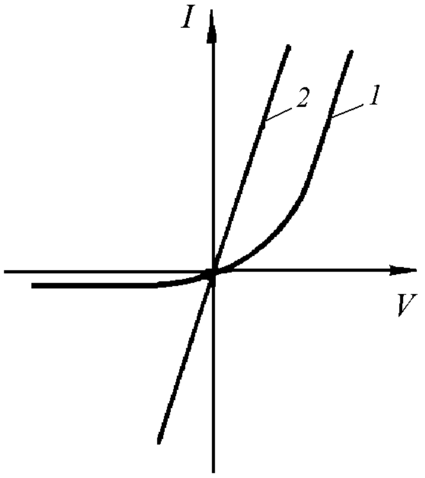

Fig.7.10. The volt-ampere dependence of a p-n transition (1); and ideal ohm contact (2)

$$\zeta = \sqrt{\frac{2\varepsilon\varepsilon_0 (U_K + V)}{e} \frac{n_n + p_p}{n_n p_p}}. \qquad (7.90)$$

When the voltage is direct ($V < 0$) the thickness becomes less; when the voltage is blacking ($V > 0$) the thickness increases. Thus the conductivity of a p-n transition is asymmetric and the current rectification is possible (Fig.7.10).

Excess concentration of auxiliary charge carriers in the contact region of a hole-electron transition (Δp for n–region and Δn for p–region):

$$\Delta p = p - p_n; \quad \Delta n = n - n_p, \tag{7.91}$$

$$\begin{aligned} p &= p_n e^{-eV/k_B T}; \\ n &= n_p e^{-eV/k_B T} \end{aligned} \tag{7.92}$$

Introducing (7.92) into (7.91) we get:

$$\Delta p = p_n\left(e^{-eV/k_B T} - 1\right); \quad \Delta n = n_p\left(e^{-eV/k_B T} - 1\right) \tag{7.93}$$

It follows that when applying the direct voltage $V < 0$ the additional concentration of non-equilibrium charge carriers increases and the direct current increases too. Thus a p-n transition **injects** non-equilibrium auxiliary charges.

Accordingly to (7.89) there are four current components. At certain condition some of them can be considered as negligible. In strong alloyed semiconductors, the concentration (n_n) of basic carriers is great. основных носителей велика. The contact region is electric neutral:

$$\Delta p = \Delta n, \tag{7.94}$$

The electron concentration in n-region:

$$n = n_n + \Delta n(x). \tag{7.95}$$

The electron current consists of diffuse and drifts component:

$$\mathbf{j}_{nD} + \mathbf{j}_{nE} = en\mu_n \mathbf{E} + eD_n\, dn/dx, \tag{7. 96}$$

When **E** is small the diffuse component is small too. Thus we assume that in n-region:

$$\mathbf{j}_{nE} = \mathbf{j}_n^n = en\mu_n \mathbf{E} \tag{7. 97}$$

The electron concentration in p-region:

$$n = n_p + \Delta n'(x). \tag{7.98}$$

$\Delta n'$ is the quantity of injected electrons. The quantity n_p is small and the diffuse component dominants the drift one.

$$\mathbf{j}_{nD} = \mathbf{j}_n^p = eD_n\, dn/dx. \tag{7. 99}$$

Соотношение (7.99) с учетом (7.93) может быть представлено в виде:

$$\mathbf{j}_n^p = \frac{eD_n n_p}{L_n}\left(e^{-eV/k_B T} - 1\right). \tag{7.100}$$

When the p-n transition is thin (there is no recombination) the electron currents at both sides of the transition are identical

$$\mathbf{j}_n^n\Big|_{x=\zeta_n} = \mathbf{j}_n^p\Big|_{x=\zeta_p}. \tag{7.101}$$

Thus the diffuse component dominates.

Analogously the hole current is dominated by the diffuse component:

$$\mathbf{j}_p^n\Big|_{x=\zeta_p} = \frac{eD_p p_n}{L_p}\left(e^{-eV/k_BT} - 1\right). \qquad (7.102)$$

The total current through the hole-electron transition:

$$j = j_p^n + j_n^p = e\left(\frac{D_p p_n}{L_p} + \frac{D_n n_p}{L_n}\right)\left(e^{-eV/k_BT} - 1\right) = j_S\left(e^{-eV/k_BT} - 1\right). \qquad (7.103)$$

Equation (7.103) is like equation (7.64). But the saturation current in the first case can be considerably smaller then that one through a metal-semiconductor contact. It leads to greater asymmetry of a p-n transition in comparison with metal-semiconductor contact. A glance at equation (7.103) shows that when the direct voltage (V<0) is applied the current increase exponentially, when the blackout voltage is applied the current tends to saturation. In accordance with (7.103) the saturation current density:

$$j = e\left(\frac{D_p p_n}{L_p} + \frac{D_n n_p}{L_n}\right) = en_i^2\left(\frac{D_p}{L_p n_n} + \frac{D_n}{L_n p_p}\right) = e\left(\frac{n_p L_n}{\tau_n} + \frac{p_n L_p}{\tau_p}\right) \qquad (7.104)$$

The saturation current decreases with concentration of basic carriers and lifetime of auxiliary carriers. The current increases with temperature because the concentration od basic carriers becomes greater.

At great direct voltage, the recombination must be taken into account. The equation would take form:

$$j = j_S\left(e^{-eV/k_BT} - 1\right). \qquad (7.105)$$

7.8. The Other Contacts. Heterotransitions

Metal-semiconductor contact with different exit work of its components is not linear and can rectify currents. The non-linearity is used signal transformation, generation, modulation, detection and others. The auxiliary carrier concentration control of p-n transition is widely used in electronics.

The linear contacts are also used in engineering (the volt-ampere characteristic is linear, see Fig.7.10). Those contacts do not distort the signal form and are called the **ohm contacts.** The ohm contact does not change the auxiliary carrier concentration. Applying the voltage across anti-blackout layers of n-type (Fig.7.5) or p-type (Fig.7.6) semiconductor can produce the conducting contacts.

The contact characteristics strongly depend on the contact surface. Upon the surfaces of real semiconductors there are defects, which distort the ideal conception.

The electron-hole transition discussed is a homogeneous one because it is build inside monocrystals.

The transitions through a contact of semiconductors with different width of forbidden zone are called the **heterotransitions**.

When those contacts are build, the charge carriers redistribute. The contact voltage is generated. The Fermi levels become identical (Fig.7.11). The widths of the energy zones are different and the zones can be disrupted.

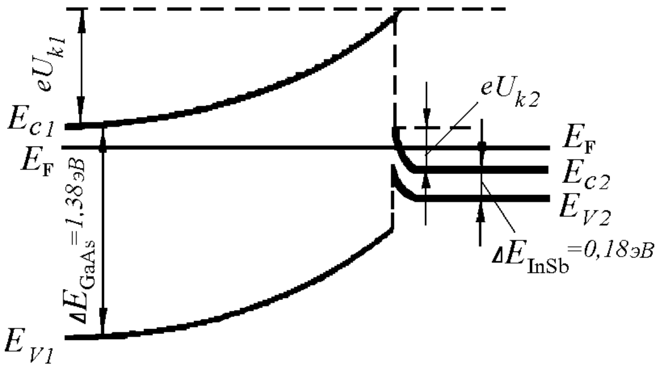

Fig.7.11. The energy diagram of a heterotransition

The properties of the contacts are of very wide range. For example, the structures of $n-n^+$ and $p-p^+$ - types can be formed. An external voltage can control the barrier height.

The technique of heterotransition producing is rather complicated. In order to build a good transistor, the crystalline lattice of one semiconductor must smoothly coincide with that one of the other. Nowadays a great number of heterotransitios is known in Ge, GaAs, Cu_2S – ZnS, GaAs – GaP and others.

If to form a p-n-transition, degenerated semiconductors are used and the thickness of of the volume charge is small a new mechanism (tunneling) is produced.