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THEORETICAL ANALYSIS OF A THIN P-N JUNCTION: CHARGE CARRIER DYNAMICS AND VOLTAGE-CURRENT CHARACTERISTICS

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ABSTRACT

When a thin p-n junction is observed, the junction region is considered to be very thin (surface active) so that the charge carriers can pass through the main charge flow mobility layer without recombination. This is the case $\mathcal{L}_0 \ll L_D$ *is represented by the inequality, where* $\mathcal{L}_0$ *- the thickness of the barrier layer and* L_D*- diffusion length. The contacts between the semiconductor and the metal electrodes are anti-disruptive and are located away from the junction. This ensures that any unbalanced charge carriers are fully recombined before reaching the contacts. So we can say that the voltage drop in the circuit is also ignored and all external potentials are applied across the p-n junction. This article discusses this in detail.*

Key words: *Theory of thin p-n junction, physical properties of charge carrier, short junction, main charge surface layer, recombination, barrier layer thickness, diffusion length, external potential, surface recombination, excess charge carrier concentration, linear recombination.*

INTRODUCTION

Let's calculate the VAX of the p-n junction according to the thin p-n junction theory. In order to simplify the solution of the problem, we assume the following points.

1. The transition is so short that charge carriers pass through the volume charge layer without recombination. This means that the thickness of the barrier layer is much smaller than the diffusion length:

$$\mathcal{L}_0 \ll L_D. \qquad (1)$$

Both regions of the semiconductor are heavily doped, i.e. $p_p \gg n_i$- and $n_n \gg n_i$. Therefore, the voltage drop in the sample can be neglected.

The contacts of the semiconductor with the metal to which the external potential difference is applied are designed to resist closure and are located so far from the junction that unbalanced charge carriers recombine completely before reaching them. The voltage drop in this circuit can also be neglected and all external potentials can be assumed to be applied to the *p*-*n* input of the difference.

There is no surface recombination, and the decrease in the excess concentration of charge carriers occurs only as a result of their recombination in the bulk of the semiconductor, which we consider linearly.

To calculate the voltage characteristics of the p-n junction, it is important to find the law of variation of the concentration of free charge carriers in the *p*- and *n*-fields. To do this, it is necessary to solve the continuity equations for holes and electrons, which have the following form:

$$\frac{\partial \mathrm{p}}{\partial \mathrm{t}} = -\frac{1}{\mathrm{e}}\frac{\partial \mathcal{J}_{\mathrm{p}}}{\partial \mathrm{x}} - \frac{\Delta \mathrm{p}}{\tau_{\mathrm{p}}}; \tag{2}$$

$$\frac{\partial \mathrm{n}}{\partial \mathrm{t}} = \frac{1}{\mathrm{e}}\frac{\partial \mathcal{J}_{\mathrm{n}}}{\partial \mathrm{x}} - \frac{\Delta \mathrm{n}}{\tau_{\mathrm{n}}} \tag{3}$$

We assume that the values of the coefficients, the mobilities of holes and electrons are the same in the *p*- and *n*-spheres (in fact, this is not true).

METHODS

The total current density of holes and electrons determined by the drift and diffusion components is equal to:

$$\left.\begin{aligned} \mathcal{J}_p &= ep\mu_p\mathcal{E} - eD_p\frac{dp}{dx} \\ \mathcal{J}_n &= ep\mu_n\mathcal{E} + eD_p\frac{dn}{dx}, \end{aligned}\right\} \tag{4}$$

Here $\mathcal{E}$ – is the strength of the external electric field. Let's look at n fields. $\mathrm{p}-\mathrm{n}$ *of electrons that are not in equilibrium with the forward bias of the entrance* $n = n_n + \Delta n$ is the concentration. Because n- the field is heavily alloyed $n_n \gg \Delta n$ because $n_n \approx n$ the drift organizer of the flow in the favor $\mathrm{J}^{(\mathrm{n})}_{\mathrm{n\,dreyf}}$ diffusion organizer $\mathrm{J}^{(\mathrm{n})}_{\mathrm{n\,dif}}$ increases significantly, ie $\mathrm{J}^{(\mathrm{n})}_{\mathrm{n\,dreyf}} \gg \mathrm{J}^{(\mathrm{n})}_{\mathrm{n\,dif}}$ will be. Therefore, ***n*** is the electron current density in the field $\mathrm{J}^{(\mathrm{n})}_{\mathrm{n}}$ is approximately equal to the displacement component of the electron current:

$$\mathrm{J}^{(\mathrm{n})}_{\mathrm{n}} = \mathrm{J}^{(\mathrm{n})}_{\mathrm{n\,dreyf}} = \mathrm{en}\mu_{\mathrm{n}}\mathcal{E} \tag{5}$$

In the new n field $n_n \gg p_n$ *and* $\Delta p \gg p_n$ of value equal to the concentration of non-equilibrium holes near the p-n junction region $p = p_n + \Delta p,$ and the number of excess holes injected mainly from area $p\ \Delta p$ is determined by Therefore, the diffusion component of the hole exceeds the current displacement, i.e.

$$J_{n\,dreyf}^{(n)} \ll J_{n\,dif}^{(n)} \quad \textit{and} \quad J_p^{(n)} = J_{p\,dif}^{(n)} = -eD_p\frac{dp}{dx}. \qquad (6)$$

(5) taking into account the continuity equation for holes in the n -section for the steady state $\left(\frac{dp}{dx} = 0\right)$ can be written in the form.

$$D_p\frac{d^2p}{dx^2} - \frac{p-p_n}{\tau_p} = 0 \qquad (7)$$

$L_p^2 = D_{p\tau p}$ using the relation, we get the following equation:

$$\frac{d^2\Delta p}{dx^2} - \frac{\Delta p}{L_p^2} = 0 \qquad (8)$$

The general solution of such an equation has the following form:

$$\Delta p = Ae^{-x/L_p} + Be^{x/L_p} \qquad (9)$$

$(x \to \infty)$ when their concentration drops to zero, and the constant *B* must be zero. Then

$$p = p_n + \Delta p = p_n + Ae^{-x/L_p}. \qquad (10)$$

$x = \mathcal{L}_n$ The concentration of unbalanced holes at the boundary of the barrier layer is equal to:

$$p(\mathcal{L}_n) = p_n e^{\frac{eU}{kT}} \qquad (11)$$

$x = \mathcal{L}_n$ (11) considering the from we find:

$$A = p_n\left(e^{\frac{eU}{kT}} - 1\right) e^{\mathcal{L}_n/L_p} \qquad (12)$$

$x > \mathcal{L}_a$ The law of variation of the concentration of unbalanced holes in the field takes the following form:

$$p(x) = p_n + p_n\left(e^{\frac{eU}{kT}} - 1\right) e^{-(x-\mathcal{L}_n)L_p} \qquad (13)$$

and according to (12) for the hole current we get:

$$J_p^{(n)} = \frac{eD_p p_n}{L_p}\left(e^{\frac{eU}{kT}} - 1\right) e^{-(x-\mathcal{L}_n)L_p} \qquad (14)$$

After performing similar calculations, we find that the change in the concentration of non-equilibrium electrons in the p- field $x < -\mathcal{L}_p$ we determine that it is found in connection with.

$$n(x) = n_p + n_p\left(e^{\frac{eU}{kT}} - 1\right) e^{(x+\mathcal{L}_p)L_n} \qquad (15)$$

and the electronic component of the current has the following form:

$$J_n^{(p)} = \frac{eD_n n_p}{L_n}\left(e^{\frac{eU}{kT}} - 1\right) e^{(x+\mathcal{L}_p)L_n} \qquad (16)$$

The sum of the electron and hole current densities in any section of the semiconductor is constant and is expressed by the following equation:

$$J = J_p^{(p)} + J_n^{(p)} = J_n^{(n)} + J_p^{(n)} = \text{const.} \tag{17}$$

Since the volume charge layer is quite narrow and there is no recombination of charge carriers inside it, the hole currents at the boundary of the *p* barrier layer and in the n- regions are the same

$$J_p^{(p)}\Big|_{x=-\mathcal{L}_p} = J_p^{(n)}\Big|_{x=\mathcal{L}_n} \tag{18}$$

RESULTS

Taking into account the above, the following formula can be used for the total current density in the p-n junction:

$$J = J_p^{(p)}\Big|_{x=-\mathcal{L}_p} + J_n^{(p)}\Big|_{x=-\mathcal{L}_p} = J_p^{(n)}\Big|_{x=\mathcal{L}_n} + J_n^{(p)}\Big|_{x=-\mathcal{L}_p} \tag{19}$$

(18) and based on (16). the current density is correspondingly equal to:

$$J_p^{(n)}\Big|_{x=\mathcal{L}_n} = \frac{eD_p p_n}{L_p}\left(e^{\frac{eU}{kT}} - 1\right) \tag{20}$$

$$J_p^{(n)}\Big|_{x=-\mathcal{L}_p} = \frac{eD_n n_p}{L_n}\left(e^{\frac{eU}{kT}} - 1\right) \tag{21}$$

There fore, VAX is described by the equation of a short p-n transition

$$J = e\left(\frac{D_n n_p}{L_n} + \frac{D_p p_n}{L_p}\right)\left(e^{\frac{eU}{kT}} - 1\right) = J_s\left(e^{\frac{eU}{kT}} - 1\right) \tag{22}$$

Here J_s is the saturation current density, which is defined as follows

$$J_s = J_{sn} + J_{sp} = \frac{eD_n n_p}{L_n} + \frac{eD_p p_n}{L_p} = en_i^2\left(\frac{D_n}{L_n p_p} + \frac{D_p}{L_p n_n}\right) = e\left(\frac{n_p L_n}{\tau_n} + \frac{p_n L_p}{\tau_p}\right) \tag{23}$$

For direct and reverse biases, the balance and excess charge carriers through the p-n transition formed according to (22) - (23) are in the form of distribution curves of the concentration of currents.

For direct and reverse biases, the balance and excess charge carriers through the r-n transition formed according to (22) - (23) are in the form of distribution curves of the concentration of currents.

The following conclusion follows from the equation (23): the current passing through the input in the p-n direct current increases exponentially with the applied potential difference, while the reverse current increases uniformly and reaches the saturation current. Thus, the p-n junction has a strong rectifying effect, the better it is, the lower the saturation current. According to (21), the J_s-saturated current charge decreases with an increase in the concentration of n_n and p_p main charge carriers (that is, p_p and n decreases with an increase in the doping level of the n spheres), and τ_n and τ_p are the residence time of a small number of charge carriers. An increase in temperature leads to an increase in internal concentration $\boldsymbol{n_i}$ and saturation current density $\boldsymbol{J_s}$.

So, when the critical value of the negative voltage is reached, the saturation current increases rapidly. Such a significant increase in current is due to the fact that electrons and holes in a narrow layer have sufficient kinetic energy for impact ionization of valence electrons. Free charge carriers that appear in this case, in turn, are accelerated by the field and participate in the formation of electron-hole pairs. An avalanche increases in the concentration of free charge carriers, as a result of which this type of r-n transition is called an avalanche.

When an external p - n voltage is applied to the junction, the state of the semiconductor is characterized by the quasi-Fermi levels F_n and F_p, and they become unbalanced. If the external potential difference U is not very large, the excess concentration of charge carriers will exist on the right and left sides of the transition only at a distance of a few diffusion lengths L_n and L_p, and the Fermi quasi-levels in these areas also depend on the ***x*** coordinate.

To find the change of state of the Fermi quasi-levels $x = —\mathcal{L}_p$. We determine the non-equilibrium electron concentration at the point. This is found as follows:

$$n\left(—L_p\right)=n_p e^{\frac{eU}{kT}} = N_c e^{-\left[E_c-F_n\left(-L_p\right)\right]/kT} \tag{24}$$

Here $F_n\left(—L_p\right)$ for electrons $x = —L_p$ quasi-Fermi level at the point. Three diffusion lengths from the contact $\left(3L_n\right)$ concentration of equilibrium electrons at distance n_p is equal to and it is determined by the following relation.

$$n\left(3L_n\right)=n_p = N_c e^{-\frac{E_c-E_p}{kT}} \tag{25}$$

Substituting the value in equation (25) n_p into equation (23), we write the following equation:

$$F_p = F_n\left(-L_p\right)-eU \tag{26}$$

So, that's right $p-n$ quasi-Fermi level p for electrons in the field to transition $F_n\left(x\right)$ located at a distance. $\left(2\div3\right)$ L_n raised by eU quantity E_v away from the top of the valence band (Fig. 1, a).

Therefore, it is true $p-n$ if a tooth is formed, p - the quasi-Fermi level of the hole in the field approaches the upper edge of the valence band and n -For electrons in the - field, the quasi-Fermi level rises to the lower part of the conduction band.

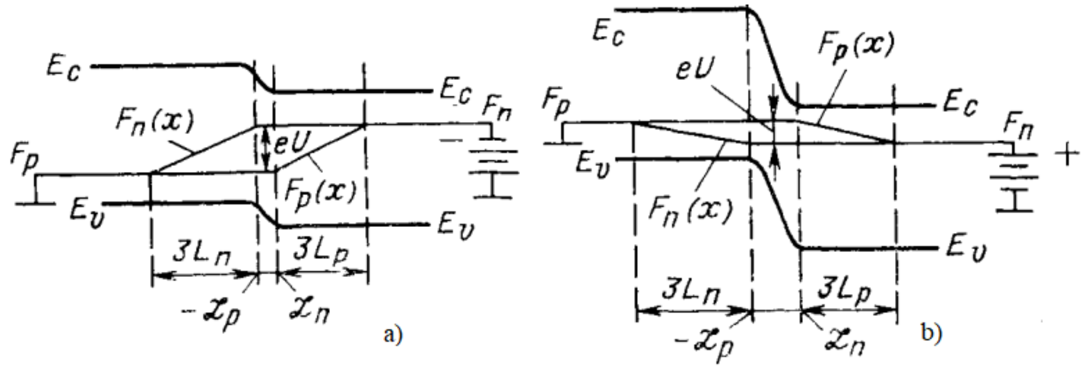

Figure 1. Quasi-Fermi level at the entrance. (a) right bend; (b) reverse bending.

Such a change in quasi-Fermi levels determines the increase in the concentration of few charge carriers near the contact. $p-n$ decrease in the number of non-main charge carriers near the contact with the opposite direction of transition and quasi-Fermi levels $F_n(x)$ and $F_p(x)$ moves away from the corresponding zones in the areas of close contact (Fig. 2, b).

DISCUSSION

Based on (24) and (25), $p-n$ we calculate the ratio of the electron and hole constituents of the current density through the input as follows.

$$\frac{J_n}{J_p}=\frac{J_{sn}}{J_{sp}}=\frac{D_n n_p L_p}{D_p p_n L_n}=\frac{\mu_n n_p L_p}{\mu_p p_p L_n}=\frac{\sigma_n L_p}{\sigma_p L_n} \tag{27}$$

$p-n$ mainly the ratio of electron and hole currents passing through the contact n and p determined by the ratio of the concentrations of the main charge carriers in their fields. If the doping level of both parts of the semiconductor is approximately the same $(\sigma_n \approx \sigma_p)$ such $p-n$ input injects electrons and holes equally, and the total current density is defined by the following expression:

$$J=(J_{sn}+J_{sp})(e^{eU/kT}-1) \tag{28}$$

If the p -field is much more heavily doped than the n-field $(\sigma_p \gg \sigma_n)$ in that case $J_{sp} \gg J_{sn}$ current also $p-n$ flows through the inlet. Vice versa, $\sigma_n \gg \sigma_p$ if the electronic component of the current gives the main share to the total current.

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