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THEORY OF THE CURRENT-VOLTAGE CHARACTERISTIC OF A THREE-LAYER SEMICONDUCTOR DIODE UNDER THE ACTION OF AN ELECTRIC FIELD

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ANNOTATION

The current-voltage characteristic of a long three-layer semiconductor diode of the type: p+−n−n+, p+−n−p+, n+−n−n+, etc. has been calculated. Expressions are obtained for the current-voltage characteristic of a three-layer semiconductor structure, the base of which is made of a compensated semiconductor, taking into account the strength of the external electric field. It is shown that due to the presence of zero, minus and plus charged impurities in a compensated semiconductor, the dependence of the concentration of electrons and holes is non-linear.

KEY WORDS: ***current-voltage characteristic, semiconductor structure, electrons and holes.***

One of the main trends in the development of modern semiconductor electronics is the search and study of new modes of operation of bipolar multilayer semiconductor structures. This trend can be traced both in the analysis of the development of new semiconductor devices: high-power silicon energy converters [1–3], ultrafast switching transistors [4], drift diodes [5], and in the analysis of the operation of traditional devices, including diodes.

At first glance, this approach seems to be quite justified, since, in stationary and dynamic modes, the magnitudes of the external electric field strength are, as a rule, small. However, as the current density increases, the characteristic values increase, and it can be expected that taking into account the dependence of the current carrier mobility on may be necessary for the correct analysis of transient processes in ultrafast switching of specific cases, for example, on the types of semiconductor structures [6-7]. This assumption is confirmed for the description of the quasineutral approximation (see, for example, [8] and the list of literature cited there), where the traditional equations for current carrier flows are used. The results obtained in the framework of this approach describe well the experimental data at not too high current densities. However, the very first attempts to study the problem of static characteristics showed that, taking into account the dependence of the current carrier mobility on the electric field strength, even the dependence μ(E) that is weak in the quasi-neutral approximation leads to a significant change in the form of the equations that determine the distributions of the current carrier concentration and the electron and hole densities components of the current through the thickness of the base, as well as voltage drops in the structure [9-12].

In this regard, the question of the features of static transient processes in semiconductor three-layer structures, in which the base is made of a compensated semiconductor, at high current densities seems to be very relevant.

The purpose of this article is to derive equations that describe the distributions of the concentration and current densities of electrons and holes along the length of the base of injected charge carriers, and to analyze the solutions of these equations.

BASIC EQUATIONS

Let us first consider three-layer structures of the $p^+{-}n{-}n^+$, $p^+{-}n{-}p^+$, $n^+{-}n{-}n^+$, $p^+{-}p{-}n^+$, $p^+{-}p{-}p^+$, $n^+{-}p{-}n^+$ types, through which a current flows with a given density $J = J_n + J_p$, where J, J_n, J_p are densitiyes of total current, electron and hole currents. We

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assume that the right, for example, $p^+{-}n$ and left, for example, $n{-}n^+$-transitions of the structure are located at the points $x=0$ and $x=d$, respectively.

In the simplest case, the charge carrier transport equations have the form:

$$J_n = \left[ep\mu_n(n+n_0)E - eD_n\frac{dn}{dx}\right]\left(1+\frac{E}{E_0}\right), \quad (1)$$

$$J_p = \left[ep\mu_p(p+p_0)E - eD_p\frac{dp}{dx}\right]\left(1+\frac{E}{E_0}\right), \quad (2)$$

where $p(p_0)$ and $n(n_0)$ are non-equilibrium (equilibrium) concentrations of electrons and holes. Here, we took into account that the dependences of the mobility $\mu_i(E)$ and diffusion coefficient $D_i(E)$ on the strength of a weak external electric field $(\vec{E})$ are described as $\mu_i(E)=\mu_{io}\left(1+\frac{E}{E_0}\right)$, $D_i(E)=D_{io}\left(1+\frac{E}{E_0}\right)$ [9], where, E_0 is a negative value that has units of measurement of the electric field strength. Then from (1, 2) it is easy to obtain expressions for the electric field strength as

$$E = \frac{jE_0}{e\mu_p\left[(p+p_0)+b(n+n_0)\right]E_0 - j} - \frac{eD_p\left(b\frac{\partial n}{\partial p}-1\right)E_0}{e\mu_p\left[(p+p_0)+b(n+n_0)\right]E_0 - j}\frac{dp}{dx}$$

or

$$E = \frac{j}{e\mu_p\left[p+p_0+b(n+n_0)+N_k\right]} - \frac{D_\rho}{\mu_p}\frac{b-\frac{\partial p}{\partial n}}{\left[p+p_0+b(n+n_0)+N_k\right]}\frac{dn}{dx}, \quad (3)$$

where $N_k = \frac{j}{e\mu_p E_0}$, b is the ratio of the mobility of electrons and holes.

Substituting (3) into (1) gives expressions for the electron current density, i.e.

$$j_n = \frac{e\mu_n(n+n_0)E_0\cdot j}{e\mu_p\left[p+p_0+b(n+n_0)\right]E_0+j} + \frac{e^2D_n\mu_p\left[p+p_0+\frac{\partial p}{\partial n}(n+n_0)\right]E_0 + e^2D_n\mu_p j}{e\mu_p\left[p+p_0+b(n+n_0)\right]E_0+j}\frac{dn}{dx}$$

or

$$j_n^{(x)} = \frac{b(n+n_0)j}{p+p_0+b(n+n_0)+N_k} + eD_n\frac{p+p_0+(n+n_0)\frac{\partial p}{\partial n}+N_k}{p+p_0+b(n+n_0)+N_k}\frac{dn}{dx}, \quad (4)$$

If we take into account the following expression for $\frac{1}{e}\cdot\frac{\partial j_n}{\partial x} = -\frac{n-n_0}{\tau_n}$ (τ_n is electron lifetime), then we have an equation for the electron concentration in the form

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$$\gamma_n \cdot \frac{d^2 n}{dx^2} + \tilde{D}_n \cdot \left(\frac{dn}{dx}\right)^2 + \alpha_n \frac{dn}{dx} = \frac{n - n_0}{\tau_n}, \tag{5}$$

and for the distribution of the electron current density:

$$L_n^2 \frac{p + p_0 + b(n + n_0)\frac{\partial p}{\partial x} + N_k}{p + p_0 + b(n + n_0) + N_k} \frac{d^2 j_n}{dx^2} - j_n + \frac{bnj}{p + p_0 + b(n + n_0) + N_k} = 0, \tag{6}$$

where $$\alpha_n = \frac{b}{e} \cdot j \frac{\left[p + p_0 + b(n + n_0) + N_k\right] - (n + n_0)\left(b + \frac{\partial p}{\partial x}\right)}{\left[p + p_0 + b(n + n_0) + N_k\right]^2},$$

$$\tilde{D}_n = D_n \frac{p + p_0}{p + p_0 + b(n + n_0) + N_k},$$

$$\gamma_n = D_n \frac{\left[p + p_0 + b(n + n_0) + N_k\right]\left[(n + n_0)\frac{\partial^2 p}{\partial n^2} + \frac{\partial p}{\partial n}\right] - (n + n_0)\left(\frac{\partial p}{\partial n}\right)^2 - b(p + p_0) + bN_k}{\left[p + p_0 + b(n + n_0) + N_k\right]^2}.$$

It can be seen from the last relations that equations (5) and (6) cannot be solved analytically. If we consider that there is a linear relationship between the concentrations of electrons and holes, for example, as $n = \theta\delta p$ (see, for example, [10] and the list of literature cited there), then it is easy to obtain an equation for the electron current density in the form

$$\frac{2n + bn_0 + \delta\theta(p_0 + N_k)L_n^2}{(1 + b\delta\theta)n + \delta\theta(p_0 + N_k) + b\delta\theta n_0} \cdot \frac{d^2 j_n}{dx^2} - j_n + \frac{b\delta\theta(n + n_0)j}{(1 + b\delta\theta)n + b\delta\theta n_0 + \delta\theta(p_0 + N_k)} = 0$$

or

$$\frac{d^2 j_n}{dx^2} - \frac{j_n - f_2 \cdot j}{f_1} = 0, \tag{7}$$

where $\delta = \frac{N_0^0}{N_-^0}$ is the ratio of the concentration of "zero" and "minus" charged impurities, $\theta = \frac{W_{-0}}{W_{0-}}$, W_{-0} ($\frac{W_{-0}}{W_{0-}}$) is probability of transition from the "zero" of the charged impurity to the "minus" of the charged impurity (conversely),

$$f_2 = \frac{b\delta\theta(n + n_0)}{(1 + b\delta\theta)n + b\delta\theta n_0 + \delta\theta(p_0 + N_k)}, \quad f_1 = \frac{2n + bn_0 + \delta\theta(p_0 + N_k)L_n^2}{(1 + b\delta\theta)n + \delta\theta(p_0 + N_k) + b\delta\theta n_0}. \tag{8}$$

Thus, (7) is analytically solved both for $n \gg n_0$ and for $n \ll n_0$, i.e., both at high and low injection levels, where the values of f_1 and f_2 become constant. Then the solution of Eq. (7) under the boundary condition of the form can be rewritten in the form

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$$j_n = j\frac{(\gamma_1 - f_{21})\cdot sh\frac{d-x}{\sqrt{f_1}} + (\gamma_2 - f_{21})\cdot sh\frac{x}{\sqrt{f_1}}}{sh\frac{d}{\sqrt{f_1}}} + f_{21}\cdot j \quad , \tag{9}$$

where $f_{21} = f_2 / f_1$, γ_1 is the fraction of the electron current density in the left (right) transition. Then the distribution of nonequilibrium electrons is determined by the relation

$$n(x) = \frac{jL_n^2}{eD_n\sqrt{f_1}}\cdot\frac{(\gamma_2 - f_2)\cdot ch\frac{x}{\sqrt{f_1}} + (f_1 - \gamma_1)\cdot sh\frac{d-x}{\sqrt{f_1}}}{sh\frac{d}{\sqrt{f_1}}} + f_{21}\cdot j\cdot \tag{10}$$

From the last relations, it is easy to obtain expressions that determine the electron density in transitions as

$$n(0) = \frac{j\cdot L_n^2}{eD_n\sqrt{f_1}}\cdot\frac{\gamma_2 - \gamma_1\cdot ch\frac{d}{\sqrt{f_1}} + f_2\left(ch\frac{d}{\sqrt{f_1}} - 1\right)\cdot sh\frac{d-x}{\sqrt{f_1}}}{sh\frac{d}{\sqrt{f_1}}}, \tag{11}$$

$$n(d) = \frac{j\cdot L_n^2}{eD_n\sqrt{f_1}}\cdot\frac{\gamma_2\cdot ch\frac{d}{\sqrt{f_1}} - \gamma_1 + f_2\left(1 - ch\frac{d}{\sqrt{f_1}}\right)}{sh\frac{d}{\sqrt{f_1}}}. \tag{10}$$

Similarly, it is not difficult to determine expressions for the electron current density in junctions.

CALCULATION OF THE CURRENT-VOLTAGE CHARACTERISTIC

The current-voltage characteristic for a given structure is determined by the relationship

$$V = \int_0^d E\cdot dx = V_1 + V_2, \tag{12}$$

where

$$V_1 = \frac{kT}{e}\cdot\frac{b\theta\delta - 1}{b\theta\delta + 1}\ln\frac{n(0)[1 + b\theta\delta] + bn_0 + p_0 + N_k}{n(d)[1 + b\theta\delta] + bn_0 + p_0 + N_k}, \tag{13}$$

$$V_2 = \frac{J\sqrt{f_1}}{e\mu_p(b\theta\delta + 1)}\cdot I, \tag{14}$$

$I=\int_0^d \frac{dx}{c_+ e^{\frac{x}{\sqrt{f_1}}}+c_- e^{-\frac{x}{\sqrt{f_1}}}+c'}$, $C'=\frac{p_0+bn_0-N_k}{b\aleph+1}$, $C_\pm=\frac{J\cdot L_n^2\left[\gamma_2-f_1+(\gamma_2-f_1)e^{\pm\frac{d}{\sqrt{f_1}}}\right]}{eD_n 2sh\frac{d}{\sqrt{f_1}}}$, γ_2 is the fraction of the electron current density in the right transition ($x=d$). The calculations took into account the dependence of the concentration of injected electrons in the base of the three-layer structure on the coefficient γ_2, i.e.

$$n(x)=\frac{J\cdot L_n^2}{eD_n\sqrt{f_1}}\frac{(\gamma_2-f_2)\left(e^{\frac{x}{\sqrt{f_1}}}+e^{-\frac{x}{\sqrt{f_1}}}\right)+(\gamma_2-f_1)\left(e^{\frac{d-x}{\sqrt{f_1}}}+e^{-\frac{d-x}{\sqrt{f_1}}}\right)}{sh\frac{d}{\sqrt{f_1}}}. \quad (15)$$

ANALYSIS OF THE RESULTS

As indicated in paragraph 2, that the form of the current-voltage characteristic of the structure depends on the type of three-layer structures. This is because the values and are different for the structures $p^+–n–n^+$, $p^+–n–p^+$, $n^+–n–n^+$, $p^+–p–n^+$, $p^+–p–p^+$, $n^+–p–n^+$. Therefore, for various structures, below are expressions for $C_\pm$:

for $p^+-n-n^+ \;\; (\gamma_1=0,\; \gamma_2=1)$

$$C_+=p\frac{j\cdot L_n^2\left[1+f_2\left(e^{-\frac{d}{\sqrt{f_1}}}-1\right)\right]}{eD_n\sqrt{f_1}\cdot 2sh\frac{d}{\sqrt{f_1}}},\quad C_-=p\frac{j\cdot L_n^2\left[1+f_2\left(e^{\frac{d}{\sqrt{f_1}}}-1\right)\right]}{2eD_n\sqrt{f_1}\cdot sh\frac{d}{\sqrt{f_1}}}; \quad (16)$$

for $p^+-n-p^+(\gamma_1=0,\; \gamma_2=0)$

$$C_+=\frac{j\cdot L_n^2}{2eD_n\sqrt{f_1}}\cdot\frac{f_2\left(e^{-\frac{d}{\sqrt{f_1}}}-1\right)}{sh\frac{d}{\sqrt{f_1}}},\; C_-=\frac{j\cdot L_n^2}{2eD_n\sqrt{f_1}}\cdot\frac{f_2\left(e^{\frac{d}{\sqrt{f_1}}}-1\right)}{sh\frac{d}{\sqrt{f_1}}}; \quad (18)$$

for $n^+-n-n^+(\gamma_1=0,\; \gamma_2=0)$

$$C_+=\frac{(1-f_2)\left(1-e^{\frac{d}{\sqrt{f_1}}}\right)}{sh\frac{d}{\sqrt{f_1}}}\cdot\frac{j\cdot L_n^2}{2eD_n\sqrt{f_1}},\;\; C_-=\frac{(f_2-1)\left(e^{\frac{d}{\sqrt{f_1}}}-1\right)}{2sh\frac{d}{\sqrt{f_1}}}\cdot\frac{j\cdot L_n^2}{eD_n\sqrt{f_1}} \quad (19)$$

and etc.

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Now let's analyze the values $f_{1,2}$. It can be seen from relation (8) that a) $f_1 = L_n^2$ for $b\theta\delta = 1$ and $n \gg n_0,\ \theta\delta N_k$ b) $f_1 = \dfrac{2}{b\theta\delta + 1 + a\theta\delta} L_n^2$ for $n \gg n_0 b,\ b\theta\delta n_0,\ \theta\delta N_k,\ b\theta\delta n_0$, c) $f_1 = 0$ for $b\theta\delta = 2$ and $n \gg n_0,\ \theta\delta N_k$, d) if the condition is satisfied $n = a \cdot N_k$, then $f_1 \to \infty$ for $b\theta\delta + 1 = a\theta\delta$. The latter case requires the fulfillment of the condition $\dfrac{f_-^0}{f_0^0} \cdot \dfrac{W_{-0}}{W_{0-}} = \dfrac{N_0^0}{N_-^0} \cdot \dfrac{W_{-0}}{W_{0-}} \neq \dfrac{\mu_p}{\mu_n}$, which is realizable in experimental studies.

Now we will analyze in more detail the distribution of electrons over the thickness of the base, i.e.

$$n(x) = b \cdot chx + c \cdot shx\ , \tag{20}$$

where

which for structure $p^+\!-\!n\!-\!n^+$ equal to $b = \dfrac{\left[f_2 \left(ch \dfrac{d}{\sqrt{f_1}} - 1 \right) + 1 \right] j \cdot L_n^2}{eD_n \sqrt{f_1} \cdot sh \dfrac{d}{\sqrt{f_1}}}$. Then for case $d < \sqrt{f_1}$ we will take

$$c = \frac{-f_2 \cdot j \cdot L_n^2}{eD_n \sqrt{f_1}},\ \frac{b}{c} = \frac{\sqrt{f_1}}{eD_n f_2}.$$

For $p^+ - n - n^+$ with a short base, where the condition $b^2 < c^2 + a^2$ is satisfied, the integral I, with which the voltage drop V_2 is determined (see formula (14)) takes the form $I = \dfrac{1}{\sqrt{a^2 + c^2 - b^2}} \ln \left. \dfrac{(a-b) th \dfrac{x}{2} - c + \sqrt{a^2 + c^2 - b^2}}{(a-b) th \dfrac{x}{2} - c - \sqrt{a^2 + c^2 - b^2}} \right|_0^d$,

from which it can be seen that the condition $N_k \neq -\dfrac{(b\delta\theta + 1)\, jL_n^2}{eD_p d} + b\delta\theta n_0 + \delta\theta p_0$ must be satisfied, where $a = \dfrac{b\delta\theta n_0 + \delta\theta (p_0 - N_k)}{b\delta\theta + 1}$. Next, consider the following cases: a) if $b \gg a$ then $I_1 = \dfrac{1}{\sqrt{c^2 - b^2}} \ln \dfrac{c + b \cdot th \dfrac{x}{2} - \sqrt{c^2 - b^2}}{-c + b \cdot th \dfrac{x}{2} + \sqrt{c^2 - b^2}}$; b) if $b \gg c$ then $I_2 = \dfrac{1}{c} \ln \dfrac{b \cdot th \dfrac{x}{2}}{c + b \cdot th \dfrac{x}{2}}$. Condition *b*) should not be used, since $x = 0$ it has no physical meaning, apparently, it can be used only for $x > 0, c \gg b$.

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If $d \square \sqrt{f_1}$, then, for a structure of type $p^+ - n - n^+$ we have $b \frac{f_2 j \cdot L_n^2}{eD_n \sqrt{f_1}}$, $c = -\frac{f_2 j \cdot L_n^2}{eD_n \sqrt{f_1}}$, and inequality $b^2 < c^2 + a^2 4$ is satisfied and we get $I_1 = \frac{1}{a} \ln \frac{(a-b) \cdot th\frac{x}{2} + a - c}{(a-b) \cdot th\frac{x}{2} - a - c} \Bigg|_0^d$. Then at $a \square c$ the voltage V_2 is determined by the expression $I_1 = \frac{1}{a} \ln \frac{th\frac{x}{2} + 1}{th\frac{x}{2} - 1} \Bigg|_0^{d/\sqrt{f_1}}$, and at $a \square c$ - $I_2 = \frac{1}{a} \ln \frac{ath\frac{x}{2}}{ath\frac{x}{2} - 2c} \Bigg|_0^{d/\sqrt{f_1}}$.

Thus, the use of the results obtained in this article requires a specific approach (the relationship of characteristic quantities, for example, a, b, c) and from the model. In particular, in the last case, $a \square c$ is suitable for the structure $p^+ - n - n^+$, but for this structure the condition $a \square c$ is not satisfied.

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