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INFLUENCE OF A STRONG ELECTRIC FIELD ON THE CURRENT-VOLTAGE CHARACTERISTIC OF THREE-LAYER SEMICONDUCTOR STRUCTURES IN A DIODE CONNECTION

Abstract. The effect of an external electric field on the current-voltage characteristics of a three-layer semiconductor structure in a diode connection is calculated. It is assumed that the base of this structure is made of a compensated semiconductor, where there are three: zero, minus and charged impurities. It is taken into account that, in this case, the dependence of the electron and hole concentrations is nonlinear.

Expressions are obtained for the current-voltage characteristic of a long three-layer semiconductor for structures of the following types: *p+–n–n+, p+–n–p+, n+–n–n+* etc.

Keywords: external electric field, current-voltage characteristic, three-layer semiconductor structure, compensated semiconductor, impurities.

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], and drift diodes [5], and in the analysis of the operation of traditional devices, including diodes.

The dynamics of transient processes in diode structures have been studied in many works. In the vast majority of these works, the description of the dynamics of processes was carried out in the framework of either a quasi-neutral diffusion approximation or a quasi-neutral drift approximation [6]. At the same time, when studying dynamic transient processes in the quasi-neutral approximation, the dependence of the mobility of charge carriers and the coefficient on the electric field strength in three-layer semiconductor structures, in which the base is made of a compensated semiconductor, was not taken into account.

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 may be necessary for the correct analysis of transient processes in ultrafast switching of specific cases, for example, on the types of semiconductor structures [7]. This assumption is confirmed in the description of the quasineutral approximation (, 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 $\mu(E)$ 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.

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 $(\rho = 7.5\Omega\, cm, N_D \approx 6\cdot 10^{14}\ cm^{-3})$, where $\Delta\nu_x(cm^{-1}) = \left(\frac{1}{\lambda_0(nm)} - \frac{1}{\lambda_x(nm)}\right)\times\frac{10^7}{cm}$ are densities of total current, electron and hole currents. We 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:

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

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

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

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

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

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

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

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

and for the distribution of the electron current density:

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

where

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

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

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

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

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

or

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

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

$$f_2=\frac{b\delta\theta(n+n_0)}{(1+b\delta\theta)n+b\delta\theta n_0+\delta\theta(p_0+N_k)},$$

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

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

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

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

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

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

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

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

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

$$V=\int_0^d E\cdot dx=V_1+V_2, \quad (12)$$

where

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

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

$$I=\int_0^d\frac{dx}{c_+e^{\frac{x}{\sqrt{f_1}}}+c\_e^{-\frac{x}{\sqrt{f_1}}}+c'},\ C'=\frac{p_0+bn_0-N_k}{b\aleph+1},$$

$$C_\pm=\frac{J\cdot L_n^2\left[\gamma_2-f_1+\left(\gamma_2-f_1\right)e^{\pm\frac{d}{\sqrt{f_1}}}\right]}{eD_n 2sh\frac{d}{\sqrt{f_1}}},$$

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.

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

In conclusion, we note that the discussion of our theoretical results on specific three-layer semiconductor structures in a diode inclusion requires separate consideration.

References:

1. Taylor J. D. (Ed.). Ultra-wideband radar technology. CRC press. 2000.
2. Rodin P., Ebert U., Hundsdorfer W., & Grekhov I. Tunnelling-assisted impact ionization fronts in semiconductors. Journal of applied physics,– 92(2). 2002.– P. 958–964.
3. Omar M. A., & Reggiani L. Drift and diffusion of charge carriers in silicon and their empirical relation to the electric field. Solid-state electronics, – 30(7). 1987. – P. 693–697.
4. Vainshtein S. N., Yuferev V. S., & Kostamovaara J. T. Ultrahigh field multiple Gunn domains as the physical reason for superfast (picosecond range) switching of a bipolar GaAs transistor. Journal of applied physics,– 97(2). 2005.– 024502.
5. Rasulov R. Ya., Madgaziyev A. A., Rayimjonova U., Mamatova M. A., & Muminov I. A. Agency of surface recombination on volt-ampere characteristic of the diode with double injection. European science review,– 11–12. 2019.– P. 70–73.
6. Rasulov R. Ya., Rayimjonova U., Mamatova M. A., Nosirov M. X., & Muminov I. A. To the theory of current-voltage characteristics of the three-layer structure of semiconductors in diode switching. European science review,– 11–12. 2019.– P. 74–76.
7. Mamatova M. A., Rasulov R. Ya. Volt-ampere characteristic of multilayer semiconductor structures.– Fergana. Poligraf Super Servis. 2021.– 178 p. (in Uzbek).