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On Analysis of Influence of Transport of Charge Carriers on Value of Their Velocity

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Abstract

In this paper we analyzed changing of velocity of transport of charge carriers with changing of it's conditions. We formulate recommendations for changing of conditions of the transport to obtain required value of the considered velocity.

Keywords: Transport of charge carriers, Controlling of velocity of charge carriers.

1 | Introduction

Manufacturing of new types of micro- and nanoelectronic devices and optimization of existing one is the basis to manufacturing of new integral circuits. Both during manufacturing of new types micro and nanoelectronic devices and during optimization of existing one it is necessary to analyze processes, which are existing during manufacturing of the considered devices and during their functioning [1–9]. One of actual points during functioning of the considered devices is analysis of velocity of movement of charge carriers. In this paper we consider of the considered velocity under influence of changing of conditions of their transport.

2 | Method of Solution

Let us describe spatiotemporal distributions of concentrations of charge carriers in the p-n-junction by the following system of equations

$$\begin{cases} \dfrac{\partial n(x,t)}{\partial t} = G + \dfrac{\partial}{\partial x}\left[D_n \dfrac{\partial n(x,t)}{\partial x}\right] - \dfrac{\partial}{\partial x}\left\{\mu_n n(x,t) \dfrac{\partial\left[\partial(x,t)+\partial_h(x,t)\right]}{\partial x}\right\} - k_{np}\left[n(x,t)p(x,t)-n_0p_0\right], \\ \dfrac{\partial p(x,t)}{\partial t} = G + \dfrac{\partial}{\partial x}\left[D_p \dfrac{\partial p(x,t)}{\partial x}\right] + \dfrac{\partial}{\partial x}\left\{\mu_p p(x,t) \dfrac{\partial\left[\partial(x,t)+\partial_h(x,t)\right]}{\partial x}\right\} - k_{np}\left[n(x,t)p(x,t)-n_0p_0\right]. \end{cases} \quad (1)$$

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Here ρ (x,t) (ρ = n, p) are the spatiotemporal (x is the coordinate, t is the time) distributions of concentrations of electrons (for ρ = n) and holes (for ρ = p); ρ_0 are the equilibrium distributions of charge carriers; D_ρ are the diffusion coefficients of charge carriers; μ_ρ are the mobilities of charge carriers; φ (x,t) is the distribution of potential in area of space charge; $\varphi_h(x,t)$ is the potential barrier of heterojunction (now we consider, that we can neglect by quantum effects); G is the velocity of generation of electron-hole pairs; k_{np} is the parameter of recombination. Boundary and initial conditions for the system of *Eq. (1)* could be written as

$$n(L_n,t) = n_n(t),\ n(-L_p,t) = n_p(t),\ p(L_n,t) = p_n(t),\ p(-L_p,t) = p_p(t),\ n(x,0) = n_0(x),\ p(x,0) = p_0(x). \quad (2)$$

Let us determine distribution of potential in area of space charge as solution of the following Poisson equation [4]

$$\frac{\partial^2 \varphi(x,t)}{\partial x^2} = e\frac{N_a(x,t) - N_d(x,t)}{\varepsilon\varepsilon_0} \quad (3)$$

where N_a (x,t) and N_d (x,t) are the spatiotemporal distributions of acceptor and donor dopants, respectively; e is the elementary charge; ε is the electric inductivity of materials; $\varepsilon_0 \approx 8{,}85\cdot 10^{-12}$ F/m is the dielectric constant. Boundary conditions for the Poisson equation could be written as

$$\varphi(L_n,t) = \varphi_k + U(t),\ \varphi(-L_p,t) = U(t), \quad (4)$$

where U(t) is the applied difference of potentials.

Farther let us consider single-carrier ionization, when $N_a(x,t) = p(x,t)$ and $N_d(x,t) = n(x,t)$. In this situation

$$\frac{\partial^2 \varphi(x,t)}{\partial x^2} = e\frac{p(x,t) - n(x,t)}{\varepsilon\varepsilon_0}$$

One can obtain solution of the above equation with boundary *Conditions (4)* in the following form

$$\varphi(x,t) = \varphi_k + U(t) + \frac{x - L_n}{L_p + L_n}\left\{\varphi_k + U(t) - \frac{e}{\varepsilon\varepsilon_0}\int_{-L_p}^{L_n}(L_n - v)\left[p(v,t) - n(v,t)\right]dv\right\} - \frac{e}{\varepsilon\varepsilon_0}\int_{x}^{L_n}(L_n - v)\left[p(v,t) - n(v,t)\right]dv \quad (5)$$

To determine spatiotemporal distributions of concentrations of carriers let us transform the *Eq. (1)* to integral form. The integral form of *Eqs. (1)* Is presented in Appendix. Integral form of the *Eq. (6)* after accounting the *Relation (5)* take the form

$$n(x,t) = n(x,t) + \frac{1}{L^2}\left(\int_0^t\int_0^x (x - v)\,G\,dv\,d\tau + \frac{e}{\varepsilon\varepsilon_0}\int_0^t\int_x^{L_n}(L_n - v)n(v,\tau)\left[p(v,\tau) - n(v,\tau)\right]\right.$$
$$\times\mu_n\,dv\,d\tau - \int_0^x (x - v)n(v,t)dv - \frac{1}{L_p + L_n}\left\{\varphi_k - \frac{e}{\varepsilon\varepsilon_0}\int_{-L_p}^{L_n}(L_n - v)\left[p(v,t) - n(v,t)\right]dv\right. \quad (6)$$

$$+U(t)\Big\}\int_0^t\int_{L_n}^x \mu_n n(v,\tau)\,dv\,d\tau+\int_0^x (x-v)n_0(v)dv-\int_0^t\int_{L_n}^x (x-v)\left[n(v,\tau)p(v,\tau)-n_0p_0\right]$$

$$\times k_{np}dv\,d\tau-\int_0^t\int_{L_n}^x \mu_n n(v,\tau)\frac{\partial\varphi_h(v,\tau)}{\partial v}dv\,d\tau+\int_0^t D_n\,n(x,\tau)\,d\tau-\int_0^t\int_{L_n}^x n(v,\tau)\frac{\partial D_n}{\partial v}dv\,d\tau$$

$$-\int_0^t D_n(L_n)\,n_n(\tau)d\tau+\int_0^{L_n}(L_n-v)\left[n(v,t)-n_0(v)\right]dv-\int_0^t\int_0^{L_n}(L_n-v)G\,dv\,d\tau+\frac{x-L_n}{L_p+L_n}$$

$$\times\left\{\frac{1}{L_p+L_n}\left\{\varphi_k+U(t)-\frac{e}{\varepsilon\varepsilon_0}\int_{-L_p}^{L_n}(L_n-v)\left[p(v,t)-n(v,t)\right]dv\right\}\int_0^t\int_{-L_p}^{L_n}\mu_n n(v,\tau)dv\,d\tau\right.$$

$$-\int_0^t n_n(\tau)D_n(L_n)d\tau+\frac{e}{\varepsilon\varepsilon_0}\int_0^t\int_{-L_p}^{L_n}\mu_n(L_n-v)n(v,\tau)\left[p(v,\tau)-n(v,\tau)\right]dv\,d\tau+\int_0^t\int_{-L_p}^{0}(L_p+v)$$

$$\times G\,dv\,d\tau-\int_0^t\int_{-L_p}^{L_n}(L_p+v)k_{np}\left[n(v,\tau)p(v,\tau)-n_0p_0\right]dv\,d\tau-\int_{-L_p}^{0}(L_p+v)\left[n(v,t)-n_0(v)\right]dv$$

$$+\int_0^t\int_{-L_p}^{L_n}\mu_n n(v,\tau)\frac{\partial\varphi_h(v,\tau)}{\partial v}dv\,d\tau+\int_0^t\int_{-L_p}^{L_n}n(v,\tau)\frac{\partial D_n}{\partial v}dv\,d\tau+\int_0^t D_n(-L_p)n_p(\tau)d\tau-\int_0^t\int_0^{L_n}G$$

$$\left.\times(L_n-v)dv\,d\tau+\int_0^{L_n}(L_n-v)\left[n(v,t)-n_0(v)\right]dv\right\},$$

$$p(x,t)=p(x,t)+\frac{1}{L^2}\left(\int_0^t\int_0^x(x-v)G\,dv\,d\tau-\int_0^x(x-v)p(v,t)dv+\frac{e}{\varepsilon\varepsilon_0}\int_0^t\int_{L_n}^x\mu_p(L_n-v)\left[p(v,\tau)\right.\right.$$

$$\left.-n(v,\tau)\right]p(v,\tau)dv\,d\tau+\int_0^t\int_{L_n}^x\mu_p p(v,\tau)\frac{\partial\varphi_h(v,\tau)}{\partial v}dv\,d\tau+\frac{1}{L_p+L_n}\left\{U(t)-\frac{e}{\varepsilon\varepsilon_0}\int_{-L_p}^{L_n}(L_n-v)\right.$$

$$\left.\times\left[p(v,t)-n(v,t)\right]dv+\varphi_k\right\}\int_0^t\int_{L_n}^x\mu_p p(v,\tau)dv\,d\tau+\int_0^t D_p p(x,\tau)\,d\tau-\int_0^t\int_{L_n}^x k_{np}\left[n(v,\tau)p(v,\tau)\right.$$

$$\left.-n_0p_0\right](x-v)dv\,d\tau-\int_0^t\int_{L_n}^x p(v,\tau)\frac{\partial D_p}{\partial v}dv\,d\tau-\int_0^t D_p(L_n)p_n(\tau)d\tau+\int_0^{L_n}(L_n-v)p(v,t)dv$$

$$-\int_0^t\int_0^{L_n}(L_n-v)G\,dv\,d\tau+\frac{x-L_n}{L_p+L_n}\left(\frac{1}{L_p+L_n}\left\{U(t)-\frac{e}{\varepsilon\varepsilon_0}\int_{-L_p}^{L_n}(L_n-v)\left[p(v,t)-n(v,t)\right]dv\right.\right.$$

$$\left.+\varphi_k\right\}\int_0^t\int_{-L_p}^{L_n}\mu_p p(v,\tau)dv\,d\tau+\int_0^t\int_{-L_p}^{L_n}\mu_p p(v,\tau)\frac{\partial\varphi_h(v,\tau)}{\partial v}dv\,d\tau+\int_0^{L_n}(L_n-v)p(v,t)dv+\frac{e}{\varepsilon\varepsilon_0}$$

$$\times\int_0^t\int_{-L_p}^{L_n}\mu_p(L_n-v)p(v,\tau)\left[p(v,\tau)-n(v,\tau)\right]dv\,d\tau+\int_0^t\int_{-L_p}^{L_n}(L_p+v)\left[n(v,\tau)p(v,\tau)-n_0p_0\right]$$

$$\times k_{np}dv\,d\tau+\int_0^t\int_{-L_p}^{0}(L_p+v)G\,dv\,d\tau+\int_0^t\int_{-L_p}^{L_n}p(v,\tau)\frac{\partial D_p}{\partial v}dv\,d\tau-\int_0^t\int_0^{L_n}(L_n-v)G\,dv\,d\tau$$

$$\left.\left.-\int_{-L_p}^{0}(L_p+v)p(v,t)dv-\int_0^t D_p(L_n)p_n(\tau)d\tau+\int_0^t D_p(-L_p)p_p(\tau)d\tau\right\}\right).$$

Let us solve the system of *Eq. (6)* by method of averaging of functional correction [10]. Framework this method we replace concentrations of charge carriers n (x,t) and p (x,t) on their average values α_{n1} and α_{p1}, which not yet known now. The replacement gives us possibility to obtain first-order approximations of the concentrations in the following form

$$n_1(x,t)=\frac{1}{L^2}\Bigg(\int_0^t\int_0^x(x-v)\,G\,dv\,d\tau+(\alpha_{p1}-\alpha_{n1})\frac{e\alpha_{n1}}{\varepsilon\varepsilon_0}\int_0^t\int_x^{L_n}\mu_n(L_n-v)\,dv\,d\tau-\int_0^t\int_{L_n}^x\mu_n dv\,d\tau$$

$$\times\alpha_{n1}\left[\frac{\partial_k+U(t)}{L_p+L_n}-e(\alpha_{p1}-\alpha_{n1})\frac{L_n+L_p}{2\varepsilon\varepsilon_0}\right]-\int_0^t\int_{L_n}^x(x-v)k_{np}(\alpha_{n1}\alpha_{p1}-n_0p_0)\,dv\,d\tau-\alpha_{n1}$$

$$\times\int_0^t\int_{L_n}^x\mu_n\frac{\partial\varphi_h(v,\tau)}{\partial v}dv\,d\tau+\int_0^t D_n\,n(x,\tau)d\tau-\int_0^t D_n(L_n)n_n(\tau)d\tau+\int_0^{L_n}[\alpha_{n1}-n_0(v)](L_n$$

$$-v)dv+\alpha_{n1}\int_0^t D_n(L_n)d\tau-\int_0^t\int_0^{L_n}(L_n-v)G\,dv\,d\tau-\alpha_{n1}\int_0^t D_n d\tau+\int_0^x(x-v)n_0(v)\,dv-\alpha_{n1}\frac{x^2}{2}$$

$$+\frac{x-L_n}{L_p+L_n}\Bigg\{\left[\frac{\varphi_k}{L_p+L_n}-(\alpha_{p1}-\alpha_{n1})(L_n+L_p)\frac{e\alpha_{n1}}{2\varepsilon\varepsilon_0}\right]\int_0^t\int_{-L_p}^{L_n}\mu_n dv\,d\tau+\int_0^t\int_{-L_p}^{L_n}(L_n-v)\mu_n dv\,d\tau$$

$$\times\frac{e\alpha_{n1}}{\varepsilon_0\varepsilon_0}(\alpha_{p1}-\alpha_{n1})+\alpha_{n1}\int_0^t\int_{-L_p}^{L_n}\mu_n\frac{\partial\,\varphi_h(v,\tau)}{\partial\,v}dv\,d\tau-\int_0^t\int_{-L_p}^{L_n}(\alpha_{n1}\alpha_{p1}-n_0p_0)k_{np}(L_p+v)dv\,d\tau$$

$$-\int_{-L_p}^0(L_p+v)[\alpha_{n1}-n_0(v)]dv-\int_0^t D_n(L_n)n_n(\tau)d\tau+\int_0^t D_n(-L_p)n_p(\tau)d\tau+\alpha_{n1}\int_0^t D_n(L_n)d\tau+$$

$$\int_0^t\int_{-L_p}^0(L_p+v)G\,dv\,d\tau$$

$$+\int_0^{L_n}(L_n-v)[\alpha_{n1}-n_0(v)]dv-\alpha_{n1}\int_0^t D_n(-L_p)\,d\tau-\int_0^t\int_0^{L_n}G\,(L_n-v)\,dv\,d\tau\Bigg\}\Bigg)+\alpha_{n1} \qquad (7)$$

$$+\int_0^{L_n}(L_n-v)[\alpha_{n1}-n_0(v)]dv-\alpha_{n1}\int_0^t D_n(-L_p)\,d\tau-\int_0^t\int_0^{L_n}G\,(L_n-v)\,dv\,d\tau\Bigg\}\Bigg)+\alpha_{n1},$$

$$p_1(x,t)=\alpha_{p1}+\frac{1}{L^2}\Bigg(\int_0^t\int_0^x(x-v)\,G\,dv\,d\tau-\alpha_{p1}\int_0^x(x-v)dv+\frac{e\alpha_{p1}}{\varepsilon\varepsilon_0}\int_0^t\int_{L_n}^x(L_n-v)\mu_p\,dv\,d\tau$$

$$\times(\alpha_{p1}-\alpha_{n1})+\alpha_{p1}\left[\frac{\Delta\varphi_k+U(t)}{L_p+L_n}-e(\alpha_{p1}-\alpha_{n1})\frac{L_p+L_n}{2\varepsilon\varepsilon_0}\right]\int_0^t\int_{L_n}^x\mu_p dv\,d\tau-\int_0^t\int_{L_n}^x k_{np}[\alpha_{n1}\alpha_{p1}$$

$$-n_0p_0](x-v)dv\,d\tau+\alpha_{p1}\int_0^t D_p\,d\tau+\alpha_{p1}\int_0^t\int_{L_n}^x\mu_p\frac{\partial\varphi_h(v,\tau)}{\partial\,v}dv\,d\tau-\int_0^t D_p(L_n)p_n(\tau)d\tau$$

$$+\alpha_{p1}\frac{L_n^2}{2}-\int_0^t\int_0^{L_n}(L_n-v)G\,dv\,d\tau-\alpha_{p1}\int_0^t[D_p-D_p(L_n)]\,d\tau+\frac{x-L_n}{L_p+L_n}\Bigg\{\int_0^t\int_{-L_p}^{L_n}\mu_p(L_n-v)dv\,d\tau$$

$$\times(\alpha_{p1}-\alpha_{n1})\frac{\alpha_{p1}e}{\varepsilon\varepsilon_0}+\alpha_{p1}\int_0^t\int_{-L_p}^{L_n}\mu_p dv\,d\tau\left[\frac{\partial_k+U(t)}{L_p+L_n}-e(\alpha_{p1}-\alpha_{n1})\frac{L_p+L_n}{\varepsilon\varepsilon_0}\right]+\int_0^t\int_{-L_p}^0(L_p+v)$$

$$\times G\,dv\,d\tau+\alpha_{p1}\int_0^t\int_{-L_p}^{L_n}\mu_p\frac{\partial\varphi_h(v,\tau)}{\partial\,v}dv\,d\tau+\int_0^t\int_{-L_p}^{L_n}(L_p+v)(\alpha_{n1}\alpha_{p1}-n_0p_0)k_{np}dv\,d\tau+\alpha_{p1}\frac{L_n^2}{2}-$$

$$-\int_0^t D_p(L_n)p_n(\tau)d\tau+\int_0^t D_p(-L_p)p_p(\tau)d\tau-\int_0^t\int_0^{L_n}(L_n-v)G\,dv\,d\tau+\alpha_{p1}\int_0^t\int_{-L_p}^{L_n}\frac{\partial D_p}{\partial\,v}dv\,d\tau-\alpha_{p1}\frac{L_p^2}{2}\Bigg\}\Bigg)$$

Let us integrate *Eq. (6)* in limits from -L_p to L_n at coordinate and from 0 to Θ at time. After the integration we obtain system of equations for average values of charge carriers concentrations α_{n1} и α_{p1}. The system is bulky. Therefore is presented in *Appendix*. The second-order approximations of charge carrier's concentrations could be calculated by standard iterative procedure. Framework the iterative procedure the replacement n (x,t) →α_{n2}+n_1 (x,t) and p (x,t)→α_{p2}+p_1(x,t) should be done. After the replacement in the *Eq. (6)* we obtain the second-order approximations concentrations of charge carriers

$$n_2(x,t)=\alpha_{n2}+n_1(x,t)+\frac{1}{L^2}\Bigg[\int_0^t\int_0^x(x-v)\,G\,dv\,d\tau+\frac{e}{\varepsilon\varepsilon_0}\int_0^t\int_x^{L_n}\mu_n(L_n-v)\left[\alpha_{n2}+n_1(v,\tau)\right]$$

$$\times\left[\alpha_{p2}+p_1(v,\tau)-\alpha_{n2}-n_1(v,\tau)\right]dv\,d\tau-\int_0^t\int_{L_n}^x\mu_n\left[\alpha_{n2}+n_1(v,\tau)\right]dv\,d\tau-\int_0^x(x-v)\left[\alpha_{n2}\right.$$

$$\left.+n_1(v,t)\right]dv\left\{\partial_k+U(t)-\frac{e}{\varepsilon\varepsilon_0}\int_{-L_p}^{L_n}(L_n-v)\left[\alpha_{p2}+p_1(v,t)-\alpha_{n2}-n_1(v,t)\right]dv\right\}\frac{1}{L_p+L_n}$$

$$-\int_0^t\int_{L_n}^x(x-v)k_{np}\left\{\left[\alpha_{n2}+n_1(v,\tau)\right]\left[\alpha_{p2}+p_1(v,\tau)\right]-n_0p_0\right\}dv\,d\tau+\int_0^x(x-v)n_0(v)dv-\int_0^t\int_{L_n}^x\mu_n$$

$$\times\left[\alpha_{n2}+n_1(v,\tau)\right]\frac{\partial\varphi_h(v,\tau)}{\partial v}dv\,d\tau+\int_0^tD_n\left[\alpha_{n2}+n_1(x,\tau)\right]d\tau+\int_0^{L_n}\left[\alpha_{n2}+n_1(v,t)-n_0(v)\right](L_n$$

$$-v)\,dv-\int_0^tD_n(L_n)n_n(\tau)d\tau-\int_0^t\int_{L_n}^x\left[\alpha_{n2}+n_1(v,\tau)\right]\frac{\partial D_n}{\partial v}dv\,d\tau-\int_0^t\int_0^{L_n}(L_n-v)G\,dv\,d\tau$$

$$+\frac{x-L_n}{L_p+L_n}\Bigg(\frac{e}{\varepsilon\varepsilon_0}\int_0^t\int_{-L_p}^{L_n}\mu_n(L_n-v)\left[\alpha_{n2}+n_1(v,\tau)\right]\left[\alpha_{p2}+p_1(v,\tau)-\alpha_{n2}-n_1(v,\tau)\right]dv\,d\tau$$

$$+\int_0^t\int_{-L_p}^0(L_p+v)G\,dv\,d\tau+\frac{1}{L_p+L_n}\Bigg\{\varphi_k+U(t)-\frac{e}{\varepsilon\varepsilon_0}\int_{-L_p}^{L_n}(L_n-v)\left[\alpha_{p2}+p_1(v,\tau)-\alpha_{n2}\right.$$

$$\left.-n_1(v,\tau)\right]dv\Bigg\}\int_0^t\int_{-L_p}^{L_n}\mu_n\left[\alpha_{n2}+n_1(v,\tau)\right]dv\,d\tau-\int_0^tD_n(L_n)n_n(\tau)d\tau-\int_0^t\int_{-L_p}^{L_n}\left\{\left[\alpha_{n2}+n_1(v,\tau)\right]\right.$$

$$\left.\times\left[\alpha_{p2}+p_1(v,\tau)\right]-n_0p_0\right\}k_{np}(L_p+v)dv\,d\tau-\int_{-L_p}^0(L_p+v)\left[\alpha_{n2}+n_1(v,t)-n_0(v)\right]dv$$

$$+\int_0^tD_n(-L_p)n_p(\tau)d\tau-\int_0^t\int_0^{L_n}(L_n-v)G\,dv\,d\tau+\int_0^{L_n}(L_n-v)\left[\alpha_{n2}+n_1(v,t)-n_0(v)\right]dv$$

$$+\int_0^t\int_{-L_p}^{L_n}\mu_n\left[\alpha_{n2}+n_1(v,\tau)\right]\frac{\partial\varphi_h(v,\tau)}{\partial v}dv\,d\tau+\int_0^t\int_{-L_p}^{L_n}\frac{\partial D_n}{\partial v}\left[\alpha_{n2}+n_1(v,\tau)\right]dv\,d\tau\Bigg)\Bigg],$$

$$p_2(x,t)=\alpha_{p2}+p_1(x,t)+\frac{1}{L^2}\Bigg[\int_0^t\int_0^x(x-v)G\,dv\,d\tau-\int_0^x(x-v)\left[\alpha_{p2}+p_1(v,\tau)\right]dv+\frac{e}{\varepsilon\varepsilon_0}$$

$$\times\int_0^t\int_{L_n}^x\mu_p(L_n-v)\left[\alpha_{p2}+p_1(v,\tau)\right]\left[\alpha_{p2}+p_1(v,\tau)-\alpha_{n2}-n_1(v,\tau)\right]dv\,d\tau+\frac{1}{L_p+L_n}\int_0^t\int_{L_n}^x\mu_p$$

$$\times\left[\alpha_{p2}+p_1(v,\tau)\right]dv\,d\tau\left\{U(t)+\varphi_k-\frac{e}{\varepsilon\varepsilon_0}\int\limits_{-L_p}^{L_n}(L_n-v)\left[\alpha_{p2}+p_1(v,t)-\alpha_{n2}-n_1(v,t)\right]dv\right\}$$

$$+\int\limits_0^t\int\limits_{L_n}^x\mu_p\frac{\partial\varphi_h(v,\tau)}{\partial v}\left[\alpha_{p2}+p_1(v,\tau)\right]dv\,d\tau-\int\limits_0^t\int\limits_{L_n}^x k_{np}\left\{\left[\alpha_{n2}+n_1(v,\tau)\right]\left[\alpha_{p2}+p_1(v,\tau)\right]-n_0p_0\right\}$$

$$\times(x-v)dv\,d\tau-\int\limits_0^t\int\limits_0^{L_n}G(L_n-v)dv\,d\tau+\int\limits_0^{L_n}(L_n-v)\left[\alpha_{p2}+p_1(v,t)\right]dv-\int\limits_0^t D_p(L_n)p_n(\tau)d\tau$$

$$-\int\limits_0^t D_p(L_n)p_n(\tau)d\tau+\int\limits_0^t\int\limits_{-L_p}^0(L_p+v)G\,dv\,d\tau+\int\limits_0^t D_p(-L_p)p_p(\tau)d\tau-\int\limits_0^t\int\limits_0^{L_n}G(L_n-v)dv\,d\tau$$

$$+\int\limits_0^t\int\limits_{-L_p}^{L_n}\frac{\partial D_p}{\partial v}\left[\alpha_{p2}+p_1(v,\tau)\right]dv\,d\tau-\int\limits_{-L_p}^0(L_p+v)\left[\alpha_{p2}+p_1(v,t)\right]dv+\int\limits_0^t\left[\alpha_{p2}+p_1(x,\tau)\right]$$

$$\times D_p\,d\tau\Big)(x-L_n)/(L_p+L_n)\Big].$$

Parameters α_{n2} and α_{p2} have been determined framework standard procedure of method of averaging of function corrections, i.e.

$$\alpha_{\rho2}=\frac{1}{\Theta L}\int\limits_0^\Theta\int\limits_0^L\left[\rho_2(x,t)-\rho_1(x,t)\right]dx\,dt. \quad \textbf{(8)}$$

Here $\rho=n,p$; Θ is time of observation on dynamics of carriers. Substitution of the first- and the second-order approximations of carriers concentrations in the *Relation (7)* gives us possibility to obtain system of equations for parameters α_{n2} and α_{p2}. The system is presented in the Appendix. Solution α_{n2} and α_{p2} of the system is

$$\alpha_{p2}=\sqrt[3]{\sqrt{\frac{p^3}{27}+\frac{q^2}{4}}-\frac{q}{2}}-\sqrt[3]{\sqrt{\frac{p^3}{27}+\frac{q^2}{4}}+\frac{q}{2}}-\frac{b_2b_8+b_1b_9}{3(b_2b_6+b_1b_7)},\ \alpha_{n2}=\frac{b_1\alpha_{n2}^2-b_4\alpha_{p2}-b_5}{b_2\alpha_{p2}+b_3}.$$

where

$$q=\frac{2}{27}\left(\frac{b_2b_8+b_1b_9}{b_2b_6+b_1b_7}\right)^3-(b_2b_8+b_1b_9)\frac{(b_3b_8-b_7b_4-b_5b_7-b_4b_9+b_2b_{10})}{3(b_2b_6+b_1b_7)^2}+\frac{b_3b_{10}-b_5b_9}{b_2b_6+b_1b_7},$$

$$p=\frac{b_3b_8-b_7b_4-b_5b_7-b_4b_9+b_2b_{10}}{b_2b_6+b_1b_7}-\frac{1}{3}\left(\frac{b_2b_8+b_1b_9}{b_2b_6+b_1b_7}\right)^2.$$

Relations for the parameters b_i are presented in the *Appendix*. Analysis of spatiotemporal distributions of charge carriers has been done analytically by using their second-order approximation and has been amended numerically.

3 | Discussion

Velocity of movement of charge carriers has two components: heat velocity v_T and drift velocity v_{dr} [10]. Modulus of these components could be written as

$$v_T=\sqrt{\frac{3kT}{m}},\ v_{dr}=\mu E, \quad \textbf{(9)}$$

where T is the temperature; k =1,38·10^{-23} J/K is the Boltzmann constant; m is the mass of charge carriers; μ is the charge carriers mobility; E is the modulus of electric field strength. Value of velocity of movement of charge carriers decreases inversely proportional to the square root of the mass of charge carriers and increases linearly with increasing electric field strength. The considered velocity also linearly depends on the mobility of charge carriers. At the same time the considered mobility changing with changing of temperature. Qualitatively the dependence can be described using the following relation [8]:

$$\mu = a\cdot T\cdot \exp(-b\cdot T), \tag{10}$$

where a and b are the temperature-independent parameters. At high temperatures, the charge carriers mobility is inversely proportional to the square root of the cube of temperature: $\mu = \mu_0 T^{-3/2}$ [11]. The considered dependence of the charge carrier velocity on temperature has a maximum value at the following temperature value

$$T = \sqrt{\mu_0 E}\sqrt[4]{3mk^{-1}}\,. \tag{11}$$

The dependences of the velocity of the charge carriers are shown in *Figs. 1-3*.

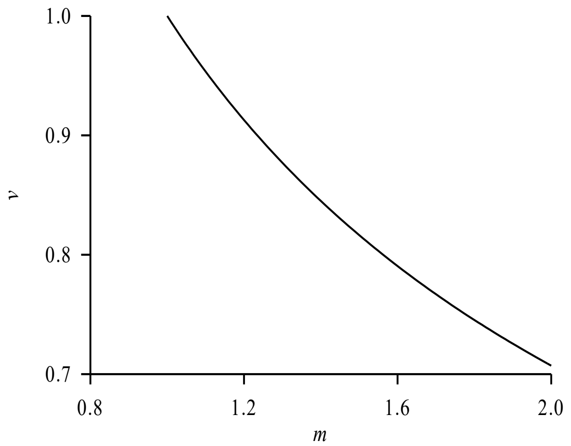

Fig. 1. Typical dependence of the velocity of charge carriers on their mass.

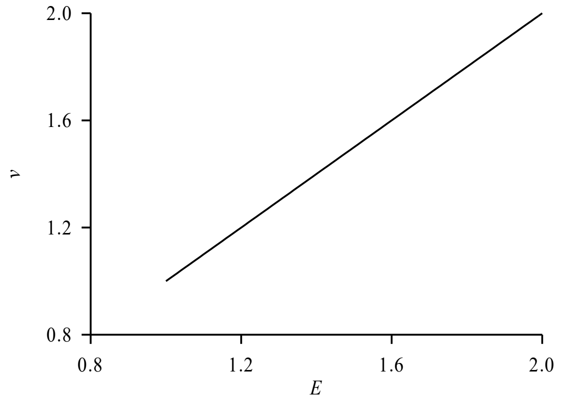

Fig. 2. The typical dependence of the velocity of charge carriers on the strength of electric field.

Similarly, the dependence of the velocity of the charge carriers on their mobility looks without taking into account its dependence on temperature.

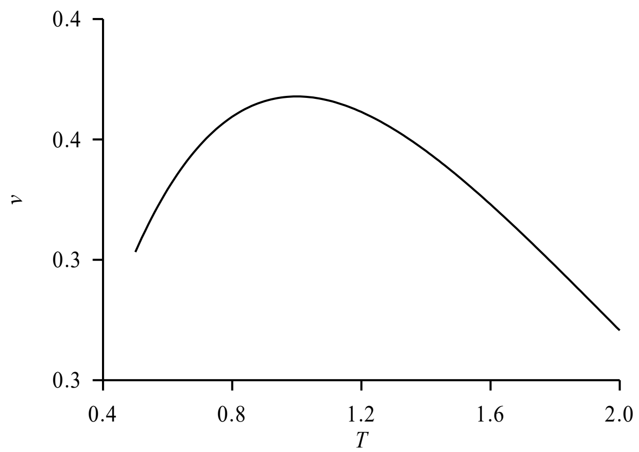

Fig. 3. Typical dependence of the velocity of charge carriers on temperature.

4 | Conclusion

In this paper, the analysis of changes in the speed of transport of charge carriers with changes in its conditions is carried out. Recommendations on acceleration and deceleration of the considered transport with changing parameters are formulated.

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Al results of this paper are own results of this author.

Conflicts of Interest

The authors declare no conflict of interest.

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Appendix

Integral form of *Eq. (6)*

$$n(x,t)=n(x,t)+\Bigg(\int_0^t\int_0^x (x-v)\,G\,dv\,d\tau-\int_0^x (x-v)\,n(v,t)\,dv-\int_0^t\int_{L_n}^x \mu_n n(v,\tau)\frac{\partial\varphi(v,\tau)}{\partial v}\,dv\,d\tau$$

$$-\int_0^t\int_{L_n}^x (x-v)k_{np}\left[n(v,\tau)p(v,\tau)-n_0p_0\right]dv\,d\tau+\int_0^x (x-v)\,n_0(v)\,dv+\int_0^t D_n n(x,\tau)\,d\tau-\int_0^t\int_{L_n}^x \mu_n$$

$$\times n(v,\tau)\frac{\partial\varphi_h(v,\tau)}{\partial v}\,dv\,d\tau-\int_0^t D_n(L_n)\,n_n(\tau)\,d\tau-\int_0^t\int_{L_n}^x n(v,\tau)\frac{\partial D_n}{\partial v}\,dv\,d\tau+\int_0^{L_n}(L_n-v)\big[n(v,t)$$

$$-n_0(v)\big]dv-\int_0^t\int_0^{L_n}(L_n-v)\,G\,dv\,d\tau+\frac{x-L_n}{L_p+L_n}\Bigg\{\int_0^t\int_{-L_p}^0 (L_p+v)\,G\,dv\,d\tau+\int_0^t\int_{-L_p}^{L_n} n(v,\tau)\frac{\partial\varphi(v,\tau)}{\partial v}$$

$$\times\mu_n\,dv\,d\tau-\int_0^t\int_{-L_p}^{L_n}(L_p+v)k_{np}\left[n(v,\tau)p(v,\tau)-n_0p_0\right]dv\,d\tau-\int_{-L_p}^0 (L_p+v)\left[n(v,t)-n_0(v)\right]dv$$

$$+\int_0^t\int_{-L_p}^{L_n}\mu_n n(v,\tau)\frac{\partial\varphi_h(v,\tau)}{\partial v}\,dv\,d\tau+\int_0^{L_n}(L_n-v)\left[n(v,t)-n_0\right]dv-\int_0^t D_n(L_n)\,n_n(\tau)\,d\tau+\int_0^t n_p(\tau)$$

$$\times D_n(-L_p)\,d\tau-\int_0^t\int_0^{L_n}(L_n-v)\,G\,dv\,d\tau+\int_0^t\int_{-L_p}^{L_n} n(v,\tau)\frac{\partial D_n}{\partial v}\,dv\,d\tau\Bigg\}\Bigg)\frac{1}{L^2},$$

$$p(x,t)=p(x,t)+\Bigg(\int_0^t\int_0^x (x-v)\,G\,dv\,d\tau-\int_0^t\int_{L_n}^x (x-v)k_{np}\left[n(v,\tau)p(v,\tau)-n_0p_0\right]dv\,d\tau$$

$$-\int_0^x (x-v)p(v,t)dv+\int_0^t\int_{L_n}^x \mu_p p(v,\tau)\frac{\partial\varphi(v,\tau)}{\partial v}dvd\tau+\int_0^t\int_{L_n}^x \mu_p p(v,\tau)\frac{\partial\varphi_h(v,\tau)}{\partial v}dvd\tau$$

$$+\int_0^t D_p p(x,\tau)\,d\tau+\int_0^{L_n}(L_n-v)p(v,t)dv-\int_0^t D_p(L_n)p_n(\tau)d\tau-\int_0^t\int_{L_n}^x p(v,\tau)\frac{\partial D_p}{\partial v}dvd\tau$$

$$-\int_0^t\int_0^{L_n}(L_n-v)\,G\,dvd\tau+\frac{x-L_n}{L_p+L_n}\left\{\int_0^t\int_{-L_p}^{L_n}\mu_p p(v,\tau)\frac{\partial\varphi(v,\tau)}{\partial v}dvd\tau+\int_0^t\int_{-L_p}^{L_n}\mu_p\frac{\partial\,\varphi_h(v,\tau)}{\partial v}\right.$$

$$\times p(v,\tau)dvd\tau+\int_0^{L_n}(L_n-v)p(v,t)dv+\int_0^t\int_{-L_p}^{L_n}(L_p+v)\,k_{np}\left[n(v,\tau)p(v,\tau)-n_0p_0\right]dvd\tau$$

$$-\int_0^t D_p(L_n)p_n(\tau)d\tau+\int_0^t D_p(-L_p)p_p(\tau)d\tau+\int_0^t\int_{-L_p}^{L_n}\frac{\partial D_p}{\partial v}p(v,\tau)dvd\tau+\int_0^t\int_{-L_p}^{0}(L_p+v)$$

$$\left.\times\,G\,dvd\tau-\int_{-L_p}^{0}(L_p+v)p(v,t)dv-\int_0^t\int_0^{L_n}(L_n-v)G\,dvd\tau\right\}\frac{1}{L^2}.$$

System of equations for parameters α_{n1} and α_{p1}

$$\frac{1}{2}\int_0^\Theta(\Theta-t)\int_0^{L_n}(L_n-x)^2G\,dxdt-\frac{1}{2}\int_0^\Theta(\Theta-t)\int_{-L_p}^{0}(L_p+x)^2G\,dxdt-\alpha_{n1}\left(L_n^3+L_p^3\right)\frac{\Theta}{6}+\frac{e\alpha_{n1}}{\varepsilon\varepsilon_0}$$

$$\times\left(\alpha_{p1}-\alpha_{n1}\right)\int_0^\Theta(\Theta-t)\left[\left(L_n+L_p\right)\int_0^{L_n}\mu_n(L_n-x)dxd\tau-\int_0^{L_n}\mu_n(L_n-x)^2dxd\tau-\int_{-L_p}^{0}\mu_n(L_n-x)\right.$$

$$\left.\times\left(L_p+x\right)dxd\tau\right]-\frac{1}{2}\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}\left(L_p+x\right)^2k_{np}\left(\alpha_{n1}\alpha_{p1}-n_0p_0\right)dxdt-\left(L_p+L_n\right)^2\int_0^\Theta(\Theta-t)$$

$$\times\frac{\alpha_{n1}}{2}\left[\frac{\varphi_k+U(t)}{L_p+L_n}-e\left(\alpha_{p1}-\alpha_{n1}\right)\frac{L_n+L_p}{2\varepsilon\varepsilon_0}\right]dt+\alpha_{n1}\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}D_n\,dxd\tau-\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}\mu_n$$

$$\times\alpha_{n1}\left(L_p+x\right)\frac{\partial\varphi_h(x,t)}{\partial x}dxdt+\Theta\left(L_n+L_p\right)\int_0^{L_n}(L_n-x)\left[\alpha_{n1}-n_0(x)\right]dx-\left(L_n+L_p\right)\int_0^\Theta n_n(t)$$

$$\times(\Theta-t)D_n(L_n)dt-\alpha_{n1}\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}D_n dxdt+\frac{1}{2}\int_0^\Theta\int_0^{L_n}n_0(x)(L_n-x)^2dxdt+\alpha_{n1}\left(L_n+L_p\right)$$

$$\times\int_0^\Theta(\Theta-t)D_n(L_n)dt+\frac{1}{2}\int_0^\Theta\int_{-L_p}^{0}\left(L_p+x\right)^2n_0(x)dxdt-\left(L_n+L_p\right)\int_0^\Theta(\Theta-t)\int_0^{L_n}(L_n-x)G\,dxd\tau$$

$$-\frac{\left(L_n+L_p\right)^2}{2\left(L_p+L_n\right)}\left\{\int_0^\Theta(\Theta-t)\left[\frac{\varphi_k+U(t)}{L_p+L_n}-\left(\alpha_{p1}-\alpha_{n1}\right)\left(L_n+L_p\right)\frac{e\alpha_{n1}}{2\varepsilon\varepsilon_0}\right]\int_{-L_p}^{L_n}\mu_n dxdt-\int_0^\Theta(\Theta-t)\right.$$

$$\times\int_{-L_p}^{L_n}\left(L_p+x\right)k_{np}\left(\alpha_{n1}\alpha_{p1}-n_0p_0\right)dxdt+\int_0^\Theta(\Theta-t)\int_{-L_p}^{0}\left(L_p+x\right)G\,dxdt+\left(\alpha_{p1}-\alpha_{n1}\right)\frac{\alpha_{n1}e}{\varepsilon_0\varepsilon}$$

$$\times\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}\mu_n(L_n-x)dxdt+\alpha_{n1}\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}\mu_n\frac{\partial\varphi_h(x,t)}{\partial x}dxdt+\int_0^\Theta(\Theta-t)D_n(L_n)\,dt$$

$$\times\alpha_{n1}-\Theta\int\limits_{-L_p}^{0}\left(L_p+x\right)\left[\alpha_{n1}-n_0\left(x\right)\right]dx+\Theta\int\limits_0^{L_n}\left(L_n-x\right)\left[\alpha_{n1}-n_0\left(x\right)\right]dx+\Theta\int\limits_0^{L_n}\left[\alpha_{n1}-n_0\left(x\right)\right]\left(L_n\right.$$

$$\left.-x\right)dx-\int\limits_0^{\Theta}(\Theta-t)D_n\left(L_n\right)n_n\left(t\right)dt-\alpha_{n1}\int\limits_0^{\Theta}(\Theta-t)D_n\left(-L_p\right)dt+\int\limits_0^{\Theta}(\Theta-t)D_n\left(-L_p\right)n_p\left(t\right)dt$$

$$\left.-\int\limits_0^{\Theta}(\Theta-t)\int\limits_0^{L_n}\left(L_n-x\right)G\,dx\,dt\right\}=0,$$

$$\frac{1}{2}\int\limits_0^{\Theta}(\Theta-t)\int\limits_0^{L_n}\left(L_n-x\right)^2G\,dx\,dt+\frac{1}{2}\int\limits_0^{\Theta}(\Theta-t)\int\limits_{-L_p}^{0}\left(L_p+x\right)^2G\,dx\,dt-\alpha_{p1}L_n^3\frac{\Theta}{6}-\alpha_{p1}L_p^3\frac{\Theta}{6},$$

$$+\alpha_{p1}\int\limits_0^{\Theta}(\Theta-t)\left[\frac{\varphi_k+U(t)}{L_p+L_n}-e\left(\alpha_{p1}-\alpha_{n1}\right)\frac{L_p+L_n}{2\varepsilon\varepsilon_0}\right]\int\limits_0^{L_n}\left(L_n-x\right)\mu_p\,dx\,dt-\alpha_{p1}\int\limits_0^{\Theta}(\Theta-t),$$

$$\times\left[\frac{\varphi_k+U(t)}{L_p+L_n}-e\left(\alpha_{p1}-\alpha_{n1}\right)\frac{L_p+L_n}{2\varepsilon\varepsilon_0}\right]\int\limits_{-L_p}^{0}\left(L_p+x\right)\mu_p\,dx\,dt+\left(\alpha_{p1}-\alpha_{n1}\right)\frac{e\alpha_{p1}}{\varepsilon\varepsilon_0}\int\limits_0^{\Theta}(\Theta-t)$$

$$\times\int\limits_{-L_p}^{L_n}\left(L_n-x\right)\mu_p\,dx\,dt+\alpha_{p1}\int\limits_0^{\Theta}(\Theta-t)\int\limits_{-L_p}^{L_n}D_p\,dx\,dt-\frac{1}{2}\int\limits_0^{\Theta}\int\limits_0^{L_n}\left(L_n-x\right)^2k_{np}\left(\alpha_{n1}\alpha_{p1}-n_0p_0\right)dx$$

$$\times(\Theta-t)dt+\frac{1}{2}\int\limits_0^{\Theta}(\Theta-t)\int\limits_{-L_p}^{0}\left(L_n+x\right)^2k_{np}\left(\alpha_{n1}\alpha_{p1}-n_0p_0\right)dx\,dt+\left(L_n+L_p\right)\int\limits_0^{\Theta}(\Theta-t)D_p\left(L_n\right)$$

$$\times p_n\left(t\right)dt+\alpha_{p1}\int\limits_0^{\Theta}(\Theta-t)\int\limits_{-L_p}^{L_n}\mu_p\frac{\partial\varphi_h\left(x,t\right)}{\partial x}dx\,dt-\alpha_{p1}\int\limits_0^{\Theta}(\Theta-t)\int\limits_{-L_p}^{L_n}\left[D_p-D_p\left(L_n\right)\right]dx\,dt+\Theta$$

$$\times\alpha_{p1}\left(L_n+L_p\right)\frac{L_n^2}{2}-\left(L_n+L_p\right)\int\limits_0^{\Theta}(\Theta-t)\int\limits_0^{L_n}\left(L_n-x\right)G\,dx\,dt-\left(L_p+L_n\right)^2\frac{\alpha_{p1}}{2}\left\{\left[\frac{\varphi_k}{L_p+L_n}-\left(\alpha_{p1}\right.\right.\right.$$

$$\left.\left.-\alpha_{n1}\right)e\frac{L_p+L_n}{\varepsilon\varepsilon_0}\right]\int\limits_0^{\Theta}(\Theta-t)\int\limits_{-L_p}^{0}\mu_p\,dx\,dt+\left(\alpha_{p1}-\alpha_{n1}\right)\frac{\alpha_{p1}e}{\varepsilon\varepsilon_0}\int\limits_0^{\Theta}(\Theta-t)\int\limits_{-L_p}^{L_n}\mu_p\left(L_n-x\right)dx\,dt+\alpha_{p1}$$

$$\times\Theta\left(L_n+L_p\right)\frac{L_n^2}{2}+\alpha_{p1}\int\limits_0^{\Theta}(\Theta-t)\int\limits_{-L_p}^{L_n}\mu_p\frac{\partial\varphi_h\left(x,t\right)}{\partial v}dx\,dt+\int\limits_0^{\Theta}(\Theta-t)\int\limits_{-L_p}^{0}\left(L_p+x\right)G\,dx\,dt+\alpha_{p1}$$

$$\times\int\limits_0^{\Theta}(\Theta-t)\left[D_p\left(L_n\right)-D_p\left(-L_p\right)\right]dt+\int\limits_0^{\Theta}(\Theta-t)\int\limits_{-L_p}^{L_n}\left(L_p+x\right)\left(\alpha_{n1}\alpha_{p1}-n_0p_0\right)k_{np}\,dx\,dt-\int\limits_0^{\Theta}(\Theta$$

$$-t)\int\limits_0^{L_n}G\left(L_n-x\right)dx\,dt-\int\limits_0^{\Theta}(\Theta-t)p_n\left(t\right)D_p\left(L_n\right)dt+\int\limits_0^{\Theta}(\Theta-t)D_p\left(-L_p\right)p_p\left(t\right)dt-\frac{\alpha_{p1}\Theta}{2}$$

$$\times L_p^2=0.$$

System of equations for parameters α_{n2} and α_{p2} could be written as

$$\frac{1}{2}\int\limits_0^{\Theta}(\Theta-t)\int\limits_0^{L_n}\left(L_n-x\right)^2G\,dx\,dt+\frac{e}{\varepsilon\varepsilon_0}\int\limits_0^{\Theta}(\Theta-t)\int\limits_{-L_p}^{L_n}\left(L_p+x\right)\left[\alpha_{p2}+p_1\left(x,t\right)-\alpha_{n2}-n_1\left(x,t\right)\right]$$

$$\times\mu_n\left[\alpha_{n2}+n_1(x,t)\right](L_n-x)\,dx\,dt-\frac{1}{2}\int_0^\Theta\int_0^{L_n}(L_n-x)\left[\alpha_{n2}+n_1(x,t)\right]dx-\frac{1}{2}\int_0^\Theta\int_{-L_p}^0(L_p+x)\left[\alpha_{n2}\right.$$

$$\left.+n_1(x,t)\right]dx\,dt-\int_0^\Theta\left\{\varphi_k+U(t)-\frac{e}{\varepsilon\varepsilon_0}\int_{-L_p}^{L_n}(L_n-v)\left[\alpha_{p2}+p_1(v,t)-\alpha_{n2}-n_1(v,t)\right]dv\right\}$$

$$\times\frac{1}{L_p+L_n}\int_{-L_p}^{L_n}\mu_n(L_p+x)\left[\alpha_{n2}+n_1(x,\tau)\right]dx\,d\tau\,dt+\frac{1}{2}\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}(L_p+x)\Big\{\left[\alpha_{n2}+n_1(x,t)\right]$$

$$\times\left[\alpha_{p2}+p_1(x,t)\right]-n_0p_0\Big\}k_{np}\,dx\,dt+\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}(L_p+x)\left[\alpha_{n2}+n_1(x,t)\right]\frac{\partial\varphi_h(x,t)}{\partial x}dx\,dt$$

$$+\frac{1}{2}\int_0^\Theta\int_0^{L_n}n_0(x)(L_n-x)^2dx\,dt-\frac{1}{2}\int_0^\Theta\int_{-L_p}^0n_0(x)(L_p+x)^2dx\,dt-\int_0^\Theta(\Theta-t)D_n(L_n)n_n(t)\,dt\,\big(L_n$$

$$+L_p\big)+\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}D_n\left[\alpha_{n2}+n_1(x,t)\right]dx\,dt-(L_n+L_p)\int_0^\Theta(\Theta-t)\int_0^{L_n}(L_n-x)G\,dx\,dt+\int_0^\Theta\int_0^{L_n}\big(L_n$$

$$-x\big)\left[\alpha_{n2}+n_1(x,t)-n_0(x)\right]dx\,dt+\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}\left[\alpha_{n2}+n_1(x,t)\right]\frac{\partial D_n}{\partial x}dx\,dt+\frac{(L_n-L_p)^2}{2(L_p+L_n)}$$

$$\times\Big\{\frac{e}{\varepsilon\varepsilon_0}\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}\mu_n(L_n-x)\left[\alpha_{n2}+n_1(x,t)\right]\left[\alpha_{p2}+p_1(x,t)-\alpha_{n2}-n_1(x,t)\right]dx\,dt+\int_0^\Theta\big(\Theta$$

$$-t\big)\int_{-L_p}^{L_n}G\,dx\,dt+\frac{1}{L_p+L_n}\int_0^\Theta\left\{\partial_k+U(t)-\frac{e}{\varepsilon\varepsilon_0}\int_{-L_p}^{L_n}(L_n-x)\left[\alpha_{p2}+p_1(x,t)-\alpha_{n2}-n_1(x,t)\right]dx\right\}$$

$$\times\int_0^t\int_{-L_p}^{L_n}\mu_n\left[\alpha_{n2}+n_1(x,\tau)\right]dx\,d\tau\,dt-\int_0^\Theta(\Theta-t)D_n(L_n)n_n(t)\,dt+\int_0^\Theta(\Theta-t)D_n(-L_p)\,n_p(t)\,dt$$

$$-\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}k_{np}(L_p+x)\Big\{\left[\alpha_{n2}+n_1(x,t)\right]\left[\alpha_{p2}+p_1(x,t)\right]-n_0p_0\Big\}dx\,dt-\int_0^\Theta(\Theta-t)\int_0^{L_n}(L_n-x)$$

$$\times G\,dx\,dt+\int_0^\Theta\int_0^{L_n}(L_n-x)\left[\alpha_{n2}+n_1(x,t)-n_0(x)\right]dx\,dt+\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}\mu_n\left[\alpha_{n2}+n_1(x,t)\right]$$

$$\times\frac{\partial\varphi_h(x,t)}{\partial x}dx\,dt+\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}\frac{\partial D_n}{\partial v}\left[\alpha_{n2}+n_1(x,t)\right]dx\,dt-\int_0^\Theta\int_{-L_p}^0(L_p+x)\left[n_1(x,t)\right.$$

$$\left.+\alpha_{n2}-n_0(x)\right]dx\,dt\Big\}=0,$$

$$\frac{1}{2}\int_0^\Theta(\Theta-t)\int_0^{L_n}(L_n-x)^2G\,dx\,dt+\frac{e}{\varepsilon\varepsilon_0}\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}\mu_n\left[\alpha_{p2}+p_1(x,t)-\alpha_{n2}-n_1(x,t)\right]\left[\alpha_{n2}\right.$$

$$\left.+n_1(x,t)\right](L_p+x)(L_n-x)\,dx\,dt-\frac{1}{2}\int_0^\Theta\int_0^{L_n}(L_n-x)\left[\alpha_{n2}+n_1(x,t)\right]dx-\frac{1}{2}\int_0^\Theta\int_{-L_p}^0(L_p+x)\left[\alpha_{n2}\right.$$

$$+n_1(x,t)\Big]\,dx\,dt-\frac{1}{L_p+L_n}\int_0^{\Theta}\Big\{U(t)-\frac{e}{\varepsilon\varepsilon_0}\int_{-L_p}^{L_n}(L_n-v)\big[\alpha_{p2}+p_1(v,t)-\alpha_{n2}-n_1(v,t)\big]\,dv$$

$$+\varphi_k\Big\}\int_{-L_p}^{L_n}\mu_n(L_p+x)\big[\alpha_{n2}+n_1(x,\tau)\big]dx\,d\tau\,dt+\frac{1}{2}\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}k_{np}(L_p+x)\Big\{\big[\alpha_{n2}+n_1(x,t)\big]$$

$$\times\big[\alpha_{p2}+p_1(x,t)\big]-n_0p_0\Big\}dx\,dt+\frac{1}{2}\int_0^{\Theta}\int_0^{L_n}(L_n-x)^2 n_0(x)\,dx\,dt+\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}(L_p+x)\big[\alpha_{n2}$$

$$+n_1(x,t)\big]\mu_n\frac{\partial\varphi_h(x,t)}{\partial x}dx\,dt-\frac{1}{2}\int_0^{\Theta}\int_{-L_p}^{0}(L_p+x)^2 n_0(x)\,dx\,dt-\int_0^{\Theta}(\Theta-t)D_n(L_n)n_n(t)\,dt\,(L_n$$

$$+L_p)+\int_0^{\Theta}\int_0^{L_n}(L_n-x)\big[\alpha_{n2}+n_1(x,t)-n_0(x)\big]\,dx\,dt+\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}\big[\alpha_{n2}+n_1(x,t)\big]\frac{\partial D_n}{\partial x}dx\,dt$$

$$+\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}D_n\big[\alpha_{n2}+n_1(x,t)\big]dx\,dt-(L_n+L_p)\int_0^{\Theta}(\Theta-t)\int_0^{L_n}(L_n-x)G\,dx\,dt+\frac{(L_n-L_p)^2}{2(L_p+L_n)}$$

$$\times\frac{e}{\varepsilon\varepsilon_0}\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}(L_n-x)\mu_n\big[\alpha_{p2}+p_1(x,t)-\alpha_{n2}-n_1(x,t)\big]\big[\alpha_{n2}+n_1(x,t)\big]\,dx\,dt+\int_0^{\Theta}(\Theta$$

$$-t)\int_{-L_p}^{0}(L_p+x)G\,dx\,dt+\int_0^{\Theta}\Big\{U(t)-\frac{e}{\varepsilon\varepsilon_0}\int_{-L_p}^{L_n}(L_n-x)\big[\alpha_{p2}+p_1(x,t)-\alpha_{n2}-n_1(x,t)\big]\,dx$$

$$+\varphi_k\Big\}\frac{1}{L_p+L_n}\int_0^{t}\int_{-L_p}^{L_n}\mu_n\big[\alpha_{n2}+n_1(x,\tau)\big]dx\,d\tau\,dt-\int_0^{\Theta}(\Theta-t)D_n(L_n)n_n(t)\,dt+\int_0^{\Theta}(\Theta-t)n_p(t)$$

$$\times D_n(-L_p)\,dt-\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}k_{np}(L_p+x)\Big\{\big[\alpha_{n2}+n_1(x,t)\big]\big[\alpha_{p2}+p_1(x,t)\big]-n_0p_0\Big\}dx\,dt$$

$$+\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}\mu_n\big[\alpha_{n2}+n_1(x,t)\big]\frac{\partial\varphi_h(x,t)}{\partial x}dx\,dt\times-\int_0^{\Theta}(\Theta-t)\int_0^{L_n}(L_n-x)G\,dx\,dt-\int_0^{\Theta}\int_{-L_p}^{0}(L_p$$

$$+x)\big[\alpha_{n2}+n_1(x,t)-n_0(x)\big]dx\,dt+\int_0^{\Theta}\int_0^{L_n}(L_n-x)\big[\alpha_{n2}+n_1(x,t)-n_0(x)\big]\,dx\,dt+\int_0^{\Theta}(\Theta-t)$$

$$\times\int_{-L_p}^{L_n}\frac{\partial D_n}{\partial v}\big[\alpha_{n2}+n_1(x,t)\big]\,dx\,dt\Big\}=0$$

Parameters b_i are determined by the following relations

$$b_1=M_{n00np11}+M_{n00np11}+\frac{1}{2}(L_n-L_p)^2M_{n00np10}+M_{n00np00}(L_n-L_p)^4\big/4(L_p+L_n)^2,$$

where, $M_{\rho ij\rho\rho kl}=\frac{e}{\varepsilon\varepsilon_0}\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}\mu_\rho(L_p+x)^k(L_n-x)^l\rho_1^i(x,t)\rho_1^j(x,t)\,dx\,dt$,

$$b_2=M_{n00np01}\frac{(L_n-L_p)^2}{2(L_p+L_n)}-M_{n00np00}\frac{(L_n-L_p)^4}{4(L_p+L_n)^2}-\frac{2L_pL_nN_{1000}}{(L_p+L_n)^2}-M_{n00np10}\frac{(L_n-L_p)^2}{2(L_n+L_p)},$$

$+M_{n00np11}$

where, $N_{ijkl}=\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}k_{np}(L_p+x)^i(L_n-x)^j n_1^k(x,t)p_1^l(x,t)\,d\,x\,d\,t$,

$$b_3=M_{n01np11}-M_{n10np11}-M_{n10np11}+\frac{eP_{n1p11n0}}{\varepsilon\varepsilon_0(L_p+L_n)}-\frac{1}{L_p+L_n}\int_0^{\Theta}[\varphi_k+U(t)]\int_0^t\int_{L_n}^x\mu_n\,d\,v\,d\,\tau\,d\,t$$

$$+\frac{N_{1001}}{2}+\int_0^{\Theta}(\Theta-t)[D_n(L_n)-D_n(-L_p)]\,d\,t-M_{n10np10}\frac{(L_n-L_p)^2}{2(L_n+L_p)}+\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}(L_p+x)\mu_n$$

$$\times\frac{\partial\varphi_h(x,t)}{\partial x}d\,x\,d\,t+\frac{(L_n-L_p)^2}{2(L_p+L_n)^2}\int_0^{\Theta}[\varphi_k+U(t)]\int_0^t\int_{-L_p}^{L_n}\mu_n d\,x\,d\,\tau\,d\,t+(M_{n01np01}-M_{n10np01})$$

$$\times\frac{(L_n-L_p)^2}{2(L_p+L_n)}-M_{n10np01}\frac{(L_n-L_p)^2}{2(L_p+L_n)}+M_{n10np00}\frac{(L_n-L_p)^4}{4(L_p+L_n)^2}-(P_{n1p10}-P_{n1n10})\frac{(L_n-L_p)^2}{2(L_p+L_n)^2}$$

$$\times\frac{e}{\varepsilon\varepsilon_0}-N_{1001}\frac{(L_n-L_p)^2}{2(L_p+L_n)^2}+\Theta\frac{L_n^2}{4}+\frac{(L_n-L_p)^2}{2(L_p+L_n)^2}\int_0^{\Theta}(\Theta-t)[D_n(L_n)-D_n(-L_p)]\,d\,t-\Theta L_p^2$$

$$\times\frac{3(L_n-L_p)^2}{2(L_p+L_n)^2}+\frac{(L_n-L_p)^2}{(L_p+L_n)^2}\int_0^{\Theta}\frac{(\Theta-t)}{2}\int_{-L_p}^{L_n}\mu_n\frac{\partial\varphi_h(x,t)}{\partial x}d\,x\,d\,t+\Theta\frac{L_n^2(L_n-L_p)^2}{4(L_p+L_n)^2},$$

where $P_{\rho isjkvl}=\int_0^{\Theta}\int_{-L_p}^{L_n}(L_n-x)^i s_1^j(x,t)\,d\,x\int_0^t\int_{-L_p}^{L_n}\mu_\rho(L_p+x)^k v_1^l(x,\tau)\,d\,x\,d\,\tau\,d\,t$,

$$b_4=M_{n10np01}\frac{(L_n-L_p)^2}{2(L_p+L_n)}-M_{n10np10}\frac{(L_n-L_p)^2}{2(L_n+L_p)}-M_{n10np00}\frac{(L_n-L_p)^4}{2(L_p+L_n)^2}+\frac{2L_nL_pN_{1010}}{(L_p+L_n)^2}$$

$+M_{n10np10}$;

$$b_5=M_{n11np11}-M_{n20np11}-\frac{1}{2}\int_0^{\Theta}\int_0^{L_n}(L_n-x)n_1(x,t)\,d\,x-\frac{1}{2}\int_0^{\Theta}\int_{-L_p}^{0}(L_p+x)\,n_1(x,t)\,d\,x-\frac{1}{L_p+L_n}$$

$$\times\int_0^{\Theta}[\varphi_k+U(t)]\int_0^t\int_{-L_p}^{L_n}\mu_n(L_p+x)n_1(x,\tau)\,d\,x\,d\,\tau\,d\,t+\frac{1}{2}\int_0^{\Theta}(\Theta-t)\int_0^{L_n}(L_n-x)^2G\,d\,v\,d\,t-\frac{1}{L_p+L_n}$$

$$\times\frac{eP_{n1n11}}{\varepsilon\varepsilon_0}+\frac{eP_{n11p11n1}}{(L_p+L_n)\varepsilon\varepsilon_0}+\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}\mu_n(L_p+x)n_1(x,t)\frac{\partial\varphi_h(x,t)}{\partial x}d\,x\,d\,t-\frac{n_0p_0N_{1000}}{2}$$

$$-(L_n+L_p)\int_0^{\Theta}(\Theta-t)D_n(L_n)\,n_n(\tau)\,d\,\tau+\frac{N_{1011}}{2}+\frac{1}{2}\int_0^{\Theta}\int_0^{L_n}(L_n-x)^2n_0(x)\,d\,x\,d\,t-\frac{1}{2}\int_0^{\Theta}\int_{-L_p}^{0}n_0(x)$$

$$\times(L_p+x)^2\,d\,x\,d\,t+\int_0^{\Theta}\int_0^{L_n}(L_n-x)[n_1(x,t)-n_0(x)]\,d\,x\,d\,t+\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}D_n\,n_1(x,t)\,d\,x\,d\,t$$

$$+\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{L_n}n_1(x,t)\frac{\partial D_n}{\partial x}d\,x\,d\,t+\frac{(L_n-L_p)^2}{2(L_p+L_n)}\int_0^{\Theta}(\Theta-t)\int_{-L_p}^{0}(L_p+v)G\,d\,v\,d\,\tau-(L_n+L_p)$$

$$\times\int_0^\Theta(\Theta-t)\int_0^{L_n}(L_n-x)G\,d\,x\,d\,t+M_{n11np01}-\frac{\left(L_n-L_p\right)^2}{2\left(L_p+L_n\right)}\int_0^\Theta(\Theta-t)\,D_n\left(L_n\right)n_n\left(t\right)d\,t,$$

$$b_6=\frac{2eP_{p1n01p0}+2\varepsilon\varepsilon_0\left(L_p+L_n\right)M_{p00np11}-\varepsilon\varepsilon_0M_{p00np00}L_n^2+\varepsilon\varepsilon_0\left(L_n-L_p\right)^2M_{p00p01}}{2\varepsilon\varepsilon_0\left(L_p+L_n\right)}$$

$$b_7=\left(N_{1000}-M_{p00np01}\right)\frac{\left(L_n-L_p\right)^2}{2\left(L_n+L_p\right)}-\frac{eP_{p1n0n1p1}}{\varepsilon\varepsilon_0\left(L_p+L_n\right)}-L_n^2\frac{M_{p00np00}}{2\left(L_p+L_n\right)}-N_{1100}-M_{p00np11},$$

$$b_8=M_{p01np11}-M_{p10np11}+M_{p01np11}-\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}\mu_p\left(L_p+x\right)\frac{\partial\varphi_h\left(x,t\right)}{\partial x}d\,x\,d\,t+L_n^2L_p\frac{\Theta}{2}$$

$$-\frac{5}{6}\Theta L_p^3+\frac{eL_n^2M_{p01np10}}{4\varepsilon\varepsilon_0\left(L_p+L_n\right)}-\frac{1}{L_p+L_n}\int_0^\Theta(\Theta-t)\left[\varphi_k+U(t)\right]\int_0^t\int_{-L_p}^{L_n}\left(L_p+x\right)\mu_p\,d\,x\,d\tau\,d\,t$$

$$+\frac{1}{L_p+L_n}\frac{e}{\varepsilon\varepsilon_0}\int_0^\Theta(\Theta-t)\int_0^t\int_{-L_p}^{L_n}(L_n-x)\left[p_1\left(x,\tau\right)-n_1\left(x,\tau\right)\right]d\,x\int_{-L_p}^{L_n}\left(L_p+x\right)\mu_p\,d\,x\,d\tau\,d\,t$$

$$+2\int_0^\Theta(\Theta-t)\left[D_p\left(L_n\right)-D_p\left(-L_p\right)\right]d\,t-\frac{e}{\varepsilon\varepsilon_0}\frac{1}{L_p+L_n}\int_0^\Theta\int_{-L_p}^{L_n}(L_n-x)\left[p_1\left(x,t\right)-n_1\left(x,t\right)\right]d\,x$$

$$\times\int_0^t\int_{-L_p}^{L_n}\mu_p d\,v\,d\tau\,d\,t+2\int_0^\Theta(\Theta-t)\left[D_p\left(L_n\right)-D_p\left(-L_p\right)\right]d\,t+\Theta\frac{L_n^3}{3}+\frac{1}{L_p+L_n}\int_0^\Theta\left[\varphi_k+U\left(t\right)\right]$$

$$\times\int_0^t\int_{-L_p}^{L_n}\mu_p\,d\,x\,d\tau\,d\,t-N_{1110}+\frac{\left(L_n-L_p\right)^2}{2\left(L_n+L_p\right)}\left\{\int_0^\Theta(\Theta-t)\left[D_p\left(L_n\right)-D_p\left(-L_p\right)\right]d\,t+\int_0^\Theta(\Theta-t)\right.$$

$$\times\int_{-L_p}^{L_n}\mu_p\frac{\partial\varphi_h\left(x,t\right)}{\partial x}d\,x\,d\,t+2M_{p01np01}-2M_{p10np01}+\frac{\Theta}{2}\left(L_n^2-L_p^2\right)\left(M_{p01np01}-M_{p10np01}\right)$$

$$\left.+N_{1010}\right\},$$

$$b_9=\frac{2\left(L_n-L_p\right)^2N_{1001}-4\left(N_{1101}+M_{p01np11}\right)\left(L_n+L_p\right)-L_n^2M_{p01np10}-2\left(L_n-L_p\right)^2M_{p01np01}}{4\left(L_n+L_p\right)};$$

$$b_{10}=\frac{1}{2}\int_0^\Theta(\Theta-t)\int_0^{L_n}(L_n-x)^2G\,d\,x\,d\,t+\frac{1}{2}\int_0^\Theta(\Theta-t)\int_{-L_p}^0\left(L_p+x\right)^2G\,d\,x\,d\,t-\frac{1}{2}\int_0^\Theta\int_0^{L_n}(L_n-x)^2$$

$$\times p_1\left(x,t\right)d\,x\,d\,t-\frac{1}{L_p+L_n}\int_0^\Theta(\Theta-t)\left[\varphi_k+U\left(t\right)\right]\int_0^t\int_{-L_p}^{L_n}\left(L_p+x\right)\mu_p\,p_1\left(x,\tau\right)d\,x\,d\tau\,d\,t+\frac{e}{\varepsilon}$$

$$\times\frac{\left(P_{p1p11p1}-P_{p1p11n1}\right)}{\varepsilon_0\left(L_p+L_n\right)}+M_{p02np11}-N_{1111}-\int_0^\Theta(\Theta-t)\int_{-L_p}^{L_n}\left(L_p+x\right)\mu_p p_1\left(x,t\right)\frac{\partial\varphi_h\left(x,t\right)}{\partial x}d\,x\,d\,t$$

$$+\frac{1}{2}\int_0^\Theta\int_{-L_p}^0\left(L_p-x\right)^2p_1\left(x,t\right)d\,x\,d\,t-M_{p11np11}+\left(L_p+L_n\right)\int_0^\Theta\int_0^{L_n}(L_n-x)p_1\left(x,t\right)d\,x\,d\,t+N_{1100}$$

$$\times p_0 n_0 - \int_0^{\Theta}(\Theta - t)\int_0^{L_n}(L_n - x) G\, d x\, d t + \int_0^{\Theta}(\Theta - t)\int_{-L_p}^{L_n} p_1(x,t)\frac{\partial D_p}{\partial x} d x\, d t - \int_0^{\Theta}(\Theta - t) D_p(L_n)$$

$$\times p_n(t) d t + \frac{1}{L_p + L_n}\int_0^{\Theta}\left[\varphi_k + U(t)\right]\int_0^{t}\int_{-L_p}^{L_n}\mu_p p_1(v,\tau) d v\, d\tau\, d t + \int_0^{\Theta}(\Theta - t)\int_{-L_p}^{L_n} p_1(x,t)\frac{\partial \varphi_h(x,t)}{\partial x}$$

$$\times \mu_p d x\, d t \frac{(L_n - L_p)^2}{2(L_n + L_p)} - \frac{(L_n - L_p)^2}{2(L_n + L_p)}\int_0^{\Theta}(\Theta - t) D_p(L_n) p_n(t) d t + \frac{(L_n - L_p)^2}{2(L_n + L_p)}\int_0^{\Theta}(\Theta - t)\int_{-L_p}^{0}(L_p$$

$$+ x) G\, d x\, d t + \frac{(L_n - L_p)^2}{2(L_n + L_p)}\int_0^{\Theta}(\Theta - t)\int_{-L_p}^{L_n} p_1(x,t)\frac{\partial D_p}{\partial x} d x\, d t - \frac{(L_n - L_p)^2}{2(L_n + L_p)}\int_0^{\Theta}(\Theta - t)\int_0^{L_n}(L_n - x)$$

$$\times G\, d x\, d t + \frac{(L_n - L_p)^2}{2(L_n + L_p)}\Bigg[\int_0^{\Theta}(\Theta - t) D_p(-L_p) p_p(t) d t - \int_0^{\Theta}\int_{-L_p}^{0}(L_p + x) p_1(x,t) d x\, d t + (N_{1011}$$

$$- n_0 p_0 N_{1000})\Bigg].$$