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Interface recombination influence on carrier transport

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Abstract
A theory of interface recombination in the semiconductor–semiconductor junction is developed. The interface recombination rate dependence on the nonequilibrium carrier densities is derived on the basis of a model in which the interface recombination occurs through the mechanism of trapping. The general relation between the interface recombination parameters at small carrier density deviation from the equilibrium ones is obtained. The validity of this relation is proved considering the generation of the Hall electric field in the extrinsic semiconductor sample. The anomalous Hall electromotive force in a weak magnetic field was investigated and interpreted by means of a new interface recombination model. The experimental data corroborate the developed theory.

1. Introduction

In connection with a broad interest of transport phenomena in semiconductors and semiconductor structures, researchers often have to deal with the nonequilibrium (NE) carriers. The recombination of the NE carriers in the bulk and in the surfaces/interfaces of the semiconductor structure plays an important role in the above problem. There are two types of recombination in semiconductor theory: the bulk recombination and the surface one. The bulk recombination model [1, 2], developed in the quasi-neutrality (QN) approximation, well describes the physical effects in a semiconductor, the Debye screening length r_D of which is significantly less than the diffusion length λ. The expression of bulk recombination rate at the small diffusion length ($\lambda \leqslant (5 \div 7)r_D$) is obtained in [3] on the basis of irreversible thermodynamics and is valid in the QN region as in the space charge region near a sample surface/interface. The interface recombination model is developed less than the bulk one in spite of many effects (photoconductivity, photoluminescence [4], magnetoconcentration effect [5], magnetogradient effect [6]), the values of which considerably depend on the interface recombination. The surface recombination velocity (SRV) was introduced into theory in the form of boundary conditions (BC) [2, 4]:

$$e^{-1} j_{ns} = -S_n^* \delta n_s, \; e^{-1} j_{ps} = S_p^* \delta p_s,$$

where $j_{ns}(j_{ps})$ is the electrons' (holes') current density in the surface, $S_n^*(S_p^*)$ is the SRV of electrons (holes) and δn_s, δp_s are the carrier density deviations from the equilibrium ones in the semiconductor surface. Later, for simplicity we will call the deviation of any physical quantity from the equilibrium one as the NE quantity. Since in the stationary state the current does not flow through the free semiconductor surface ($j_{ns} + j_{ps} = 0$) the additional condition $S_n^* \delta n_s = S_p^* \delta p_s$ arises; the latter condition does not follow from any physical concept and is difficult to interpret. Sometimes this condition is considered as an expression relating to the electron and hole surface recombination velocities [4], which is completely wrong. It is obvious that the SRV S_n^* and S_p^* are constant at small carrier concentrations deviation from the equilibrium ones, i.e. they cannot depend on the NE concentrations. The foregoing SRV definition is not applicable to the metal–semiconductor junction (MSJ) in which $\delta n_s = 0$ [8, 9] owing to constancy of metal chemical potential and continuity of the electrical potential in the MSJ. The definition of the surface recombination rates [2, 4] leads to contradiction of the classical Hall electric field generation model. It is known [7] that the Hall electric field arises in a semiconductor sample as a result of the NE surface charge generation, which occurs due to the effect of the Lorentz force. On the one hand, this NE surface charge depends only on the magnitude of the Hall electric field; on the other hand, this charge is bound to depend on the SRV.

Thus, the foregoing electron and hole surface recombination rate definition is invalid and must be changed.

It should be noted that in majority of works the SRV is used in the QN approximation. In the QN approximation BCs are formulated at virtual surfaces spaced from real semiconductor surfaces by several Debye lengths [2, 4]. Measurements of the interface recombination velocity [10–13] are also based on the QN model. Since the expression of interface recombination rate needs modification, it is necessary to prove the applicability of new interface recombination velocity conception in the QN approach.

This paper is aimed at the development of the interface recombination theory.

2. Theory

To introduce the conception of interface recombination we must derive the BCs in the semiconductor–semiconductor junction. Let us consider a semiconductor–semiconductor junction which is spatially located at $x = 0$. Let us denote the semiconductor at $x < 0$ by subscript '$-$' and the one at $x > 0$ by subscript $+$. Let us assume that the transitional layer between two media is located in the region $-\Delta \leqslant x \leqslant \Delta$, where $\Delta \ll r_D$ and r_D is the Debye screening length. The basic equations for BCs' formulation are the continuity equations for a stationary state [2] and the Poisson equation:

$$\frac{\mathrm{d}j_n}{\mathrm{d}x} = \mathrm{e}(R - G), \tag{1}$$

$$\frac{\mathrm{d}j_p}{\mathrm{d}x} = -\mathrm{e}(R - G), \tag{2}$$

$$\frac{\mathrm{d}}{\mathrm{d}x}\left(\varepsilon\frac{\mathrm{d}\delta\varphi}{dx}\right) = -\frac{\delta\rho}{\varepsilon_0}, \tag{3}$$

where $-\mathrm{e}$ is the electron charge, $R(G)$ is the NE carrier recombination (generation) rate, $\delta\rho$ is the NE charge density, $\delta\varphi$ is the NE electric potential, ε is the semiconductor electrical permittivity and ε_0 is the vacuum permittivity. We assume below that the NE carrier generation occurs in the volume of the semiconductor and the temperatures of electrons, holes and phonons coincide.

The expressions of partial current densities take the form

$$\begin{aligned} j_n &= -\sigma_n\left(\frac{\mathrm{d}\delta\tilde{\varphi}_n}{\mathrm{d}x} + \alpha_n\frac{\mathrm{d}T}{\mathrm{d}x}\right) + j_n(B), \\ j_p &= -\sigma_p\left(\frac{\mathrm{d}\delta\tilde{\varphi}_p}{\mathrm{d}x} + \alpha_p\frac{\mathrm{d}T}{\mathrm{d}x}\right) + j_p(B) \end{aligned} \tag{4}$$

where $\sigma_{n,p}$ is the electron (hole) conductivity, $\delta\tilde{\varphi}_{n,p} = \delta\varphi \mp \delta F_{n,p}/e$ is the NE electrochemical potential of electrons (holes), $\delta F_{n,p}$ is the NE chemical potential of electrons (holes), T is the lattice temperature, $\alpha_{n,p}$ are the Seebeck coefficients and $j_{n,p}(B)$ is the x-component of electron (hole) current density caused by magnetic field B.

The NE chemical potentials of electrons and holes in nondegenerate semiconductor are equal to

$$\delta F_n = kT\ln\left(1 + \frac{\delta n}{n_e}\right), \quad \delta F_p = kT\ln\left(1 + \frac{\delta p}{p_e}\right),$$

where k is the Boltzmann constant, $n_e(p_e)$ is the equilibrium electron (hole) concentration and $\delta n(\delta p)$ is the NE electron (hole) concentration.

Let us integrate the Poisson equation (3) with x from $-\Delta$ to Δ. We obtain

$$\varepsilon_-\frac{\mathrm{d}\delta\varphi}{\mathrm{d}x}(-\Delta) = \varepsilon_+\frac{\mathrm{d}\delta\varphi}{\mathrm{d}x}(\Delta) + \frac{\delta\rho_s}{\varepsilon_0}, \tag{5}$$

where $\delta\rho_s = \int_{-\Delta}^{\Delta}\delta\rho\,\mathrm{d}x$ is the NE interface charge density.

Integrating the Poisson equation with x from $-\Delta$ to v and with v from $-\Delta$ to Δ we derive

$$\delta\varphi(\Delta) = \delta\varphi(-\Delta) + 2\Delta\frac{\varepsilon_-}{\langle\varepsilon\rangle}\frac{\mathrm{d}\delta\varphi}{\mathrm{d}x}(-\Delta) - \Delta\frac{\delta\rho_s}{\langle\varepsilon\rangle\,\varepsilon_0},$$

where $\langle\varepsilon\rangle = \frac{1}{2\Delta}\int_{-\Delta}^{\Delta}\varepsilon\mathrm{d}x$. Accounting for the finite value of $\delta\rho_s$ and negligible value of the Δ we obtain with a great accuracy

$$\delta\varphi(-\Delta) = \delta\varphi(\Delta). \tag{6}$$

Let us consider the interface recombination rate, by analogy with the volume one [3, 14], in the form [9]

$$\begin{aligned} R = {} & (S_n^+\delta n + S_p^+\delta p)\delta(x - \Delta + 0) \\ & + (S_n^-\delta n + S_p^-\delta p)\delta(x + \Delta - 0), \end{aligned} \tag{7}$$

where $\delta(x)$ is the Dirac delta function, $S_n^{\pm}$, $S_p^{\pm}$ are the parameters characterizing interface recombination of electrons and holes.

Taking into account equations (6) and (7) and integrating the continuity equations over the transitional layer [8, 9] we obtain

$$\begin{aligned} j_{ns}^+ &= \sigma_{ns}(\delta F_{ns}^+ - \delta F_{ns}^-)/\mathrm{e} + \mathrm{e}(S_n^+\delta n_s^+ + S_p^+\delta p_s^+), \\ j_{ps}^+ &= \sigma_{ps}(\delta F_{ps}^- - \delta F_{ps}^+)/\mathrm{e} - \mathrm{e}(S_n^+\delta n_s^+ + S_p^+\delta p_s^+) \end{aligned} \tag{8}$$

where $\sigma_{ns}^{-1} = \int_{-\Delta}^{\Delta}\sigma_n^{-1}\mathrm{d}x$, $\sigma_{ps}^{-1} = \int_{-\Delta}^{\Delta}\sigma_p^{-1}\mathrm{d}x$, σ_{ns} (σ_{ps}) is the interface conductivity of electrons (holes), $\delta F_{ns}^{\pm} = \delta F_n(\pm\Delta)$, $\delta F_{ps}^{\pm} = \delta F_p(\pm\Delta)$, $\delta n_s^+ = \delta n(\Delta)$ and $\delta p_s^+ = \delta p(\Delta)$.

In the same way we derive for j_{ns}^- and j_{ps}^-

$$\begin{aligned} j_{ns}^- &= \sigma_{ns}(\delta F_{ns}^+ - \delta F_{ns}^-)/\mathrm{e} - \mathrm{e}(S_n^-\delta n_s^- + S_p^-\delta p_s^-) \\ j_{ps}^- &= \sigma_{ps}(\delta F_{ps}^- - \delta F_{ps}^+)/\mathrm{e} + \mathrm{e}(S_n^-\delta n_s^- + S_p^-\delta p_s^-). \end{aligned} \tag{9}$$

From equations (8) and (9) we derive

$$j_{ns}^+ - j_{ns}^- = j_{ps}^- - j_{ps}^+ = eR_s, \tag{10}$$

where $R_s = S_n^+\delta n_s^+ + S_p^+\delta p_s^+ + S_n^-\delta n_s^- + S_p^-\delta p_s^-$ is the interface recombination rate.

The total current is continuous in the interface:

$$j_{ns}^+ + j_{ps}^+ = j_{ns}^- + j_{ps}^- = j. \tag{11}$$

As follows from equations (8) and (9) the parameters $S_{n,p}^{\pm}$ are not the interface recombination velocities.

Let us derive expressions of the parameters $S_{n,p}^{\pm}$ using for the interface recombination the Shockley–Read model [1]. The total rate of the electrons capture by interface trapping level E_{ts} is equal to

$$R_{ns} = \beta_{ns}[n_s(N_{ts} - n_{ts}) - n_{1s}n_{ts}], \tag{12}$$

where β_{ns} is the capture coefficient of electrons, N_{ts} is the total density of interface impurity states, n_{ts} is the density of interface impurity states filled by electrons, $n_{1s} = (N_{cs}/g_n)\exp[(E_{ts} - E_{cs})/kT_s)]$, N_{cs} is the effective density of states in conduction band at the interface, $(E_{cs} - E_{ts})$ is the

ionization energy of the interface level and g_n is the electron degeneracy coefficient of this level. The total rate of the holes capture by interface trapping level is equal to

$$R_{ps} = \beta_{ps}[p_s n_{ts} - p_{1s}(N_{ts} - n_{ts})], \tag{13}$$

where β_{ps} is the capture coefficient of holes, $p_{1s} = (N_{vs}/g_p)\exp[(E_{vs} - E_{ts})/kT_s)]$, N_{vs0} is the effective density of states in valence band at the interface, $(E_{ts} - E_{vs})$ is the splitting energy of holes from the levels E_{ts} and g_p is the hole degeneracy coefficient of the interface level.

In equilibrium the interface recombination rates are equal to zero: $R_{ns} = R_{ps} = 0$. From this equation and equations (12)–(13) we obtain

$$n^e_{ts} = \frac{n_{es}N_{ts}}{(n_{es} + n_{1s})} = \frac{p_{1s}N_{ts}}{(p_{es} + p_{1s})};\ \frac{n_{es}}{n_{1s}} = \frac{p_{1s}}{p_{es}}. \tag{14}$$

In the stationary NE state the total current continuity equation takes the form

$$R_{ns} = R_{ps} = R_s. \tag{15}$$

Let us derive the value of n_{ts} from equation (15) and substitute it into equation (12). Accounting for equation (14) we derive finally

$$S^{\pm}_n = \frac{\beta^{\pm}_{ns}\beta^{\pm}_{ps}p^{\pm}_{es}N^{\pm}_{ts}[1 + \delta p^{\pm}_s/(p^{\pm}_{es} + p^{\pm}_{1s})]}{\beta^{\pm}_{ns}(n^{\pm}_{es} + n^{\pm}_{1s} + \delta n^{\pm}_s) + \beta^{\pm}_{ps}(p^{\pm}_{es} + p^{\pm}_{1s} + \delta p^{\pm}_s)}, \tag{16}$$

$$S^{\pm}_p = \frac{\beta^{\pm}_{ns}\beta^{\pm}_{ps}n^{\pm}_{es}N^{\pm}_{ts}[1 + \delta n^{\pm}_s/(n^{\pm}_{es} + n^{\pm}_{1s})]}{\beta^{\pm}_{ns}(n^{\pm}_{es} + n^{\pm}_{1s} + \delta n^{\pm}_s) + \beta^{\pm}_{ps}(p^{\pm}_{es} + p^{\pm}_{1s} + \delta p^{\pm}_s)}, \tag{17}$$

where $n^{\pm}_{es} = n^{\pm}_e(\pm\Delta)$ and $p^{\pm}_{es} = p^{\pm}_e(\pm\Delta)$. It follows from equations (16) and (17) that the parameters $S^{\pm}_{n,p}$ essentially depend on the NE carrier density at large injection level or at large photo-excitation one.

The parameters $S^{\pm}_{n,p}$ are constant under conditions $\delta n^{\pm}_s \ll n^{\pm}_{es} + n^{\pm}_1$, $\delta p^{\pm}_s \ll p^{\pm}_{es} + p^{\pm}_1$. In that case we have the general relation

$$S^{\pm}_n n^{\pm}_{es} = S^{\pm}_p p^{\pm}_{es}. \tag{18}$$

Let us prove the validity of the interface recombination model studying the generation of the Hall electric field in the semiconductor sample. Consider an n-type semiconductor plate which is spatially located at $-a \leqslant x \leqslant a$ and $a > 3\lambda_p$, where λ_p is the hole diffusion length. The surfaces $x = \pm a$ of the sample are in contact with dielectric. The external weak electric field E is applied along the y axis and the external weak magnetic field B is applied along the z axis.

The expressions for the x-component of partial currents take the form

$$\begin{aligned} j_n &= \sigma_n\left(-\frac{\mathrm{d}\varphi}{\mathrm{d}x} + \frac{kT}{en}\frac{\mathrm{d}n}{\mathrm{d}x} - \gamma\mu_n EB\right), \\ j_n &= \sigma_p\left(-\frac{\mathrm{d}\varphi}{\mathrm{d}x} - \frac{kT}{ep}\frac{\mathrm{d}p}{\mathrm{d}x} + \gamma\mu_p EB\right), \end{aligned} \tag{19}$$

where γ is the Hall factor and μ_n (μ_p) is the electron (hole) mobility.

Since there are no carriers in the air and the sample is electro-neutral we obtain from equations (5), (8) and (9) the BCs:

$$j_n(\pm a) = \mp e[S^{\pm}_n\delta n(\pm a) + S^{\pm}_p\delta p(\pm a)], \tag{20}$$

$$\frac{\mathrm{d}\delta\varphi}{\mathrm{d}x}(\pm a) = 0. \tag{21}$$

In most of the semiconductors the diffusion length significantly exceeds the Debye length. In that case the solution for equations (1)–(3) could be obtained in the way described in [15]. Let us consider the virtual surfaces $x = \pm a \mp l$, where $l = (5 \div 7)r_D$. The diffusion-recombination (DR) mode is the solution of equations (1)–(3) in the region $l - a \leqslant x \leqslant a - l$, and the quasi-surface (QS) mode is the solution of these equations in the regions $-a \leqslant x \leqslant l - a$ and $a - l \leqslant x \leqslant a$. The DR mode and the QS mode are denoted by the subscripts r and q accordingly. The NE carrier concentrations are continuous in the virtual surfaces. The NE electric potential is equal to the sum of the NE electric potentials of the DR and the QS modes.

From total current continuity equation $j_n + j_p = 0$ we obtain for the DR mode

$$\delta\varphi_r = -\mu_n\gamma EBx + \left(1 - \frac{\mu_p}{\mu_n}\right)\frac{kT}{e}\frac{\delta n_r}{n_0}. \tag{22}$$

The electric potential of the plane $x = 0$ is assumed equal to zero. The QS mode satisfies the equations [8]

$$\frac{\mathrm{d}j_n}{\mathrm{d}x} = 0,\ \frac{\mathrm{d}j_p}{\mathrm{d}x} = 0 \tag{23}$$

because we can neglect the bulk recombination in the regions $-a \leqslant x \leqslant l - a$ and $a - l \leqslant x \leqslant a$ accounting for the inequality $r_D \ll \lambda$. Assume that $|\delta n_r| \ll p_0$ and evaluate the $\delta\varphi_q$ value. It follows from equations (21) and (22) that

$$|\delta\varphi_q(\pm a)| \approx |\delta\varphi_r(\pm a)|\, r_D/a \ll kT/e.$$

Under existing conditions the solution of equations (23) near the surfaces $x = \pm a$ has the form (see [15])

$$\begin{aligned} \delta n^{\pm}_q &= n_e\left(\frac{\delta n_r(\pm a)}{n_0} + \frac{e\delta\varphi^{\pm}_q}{kT}\right), \\ \delta p^{\pm}_q &= p_e\left(\frac{\delta n_r(\pm a)}{p_0} - \frac{e\delta\varphi^{\pm}_q}{kT}\right). \end{aligned} \tag{24}$$

Substituting equations (24) into BC (20) and taking into account the general relation (18) we derive

$$j_n(\pm a) = \mp eS^{\pm}\delta n_r(\pm a), \tag{25}$$

where $S^{\pm} = S^{\pm}_n\exp(\frac{e\varphi_{es}}{kT}) + S^{\pm}_p\exp(-\frac{e\varphi_{es}}{kT})$ is the SRV in the QN approximation and φ_{es} is the equilibrium surface potential (SP) [2]. The obtained SRV value coincides with that of [2]; it is as it should be.

The distributions of the NE carrier concentrations and the NE electric potential for the case of flat energy bands are:

$$\begin{aligned} \delta n = \frac{e\gamma EB}{kT}\Bigg[&\mu_n n_0 r_D\frac{\sinh(x/r_D)}{\cosh(a/r_D)} \\ &+ \frac{p_0\lambda_p(\mu_n + \mu_p)}{(1 + S\lambda_p/D_p)}\frac{\sinh(x/\lambda_p)}{\sinh(a/\lambda_p)}\Bigg], \end{aligned}$$

$$\begin{aligned} \delta p = \frac{e\gamma EB}{kT}\Bigg[&-\mu_n p_0 r_D\frac{\sinh(x/r_D)}{\cosh(a/r_D)} \\ &+ \frac{p_0\lambda_p(\mu_n + \mu_p)}{(1 + S\lambda_p/D_p)}\frac{\sinh(x/\lambda_p)}{\sinh(a/\lambda_p)}\Bigg], \end{aligned}$$

$$\delta\varphi = \gamma\mu_n EB\left[r_D\frac{\sinh(x/r_D)}{\cosh(a/r_D)} - x\right].$$

Thus, the QS mode does not depend on the interface recombination parameters and the Hall electric field, generated by the QS mode space charge, is equal to $E_H = \mu_n \gamma EB$ in the bulk of the sample, which was to be proved.

Let us investigate the influence of interface recombination on the Hall electromotive force (EMF) in p-type semiconductors. The sample has the parallelepiped form ($-a \leqslant x \leqslant a$, $-b \leqslant y \leqslant b$, $-d \leqslant z \leqslant d$) and $b \gg a$, $d \gg a$. The surface recombination is negligible on the surfaces $z = \pm d$ of the sample. The BCs in the MSJ are obtained in [8, 9]:

$$\begin{aligned} j_n(\pm a) &= \mp e S_p \delta p(\pm a), \\ \delta n(\pm a) &= 0, \\ \delta\varphi_m(\pm a) &= \delta\varphi(\pm a), \end{aligned} \tag{26}$$

where $\delta\varphi_m(\pm a)$ is the NE electric potential of metallic contacts. For simplicity we assume that the value of the interface recombination parameters coincide $S_p^{\pm} = S_p$.

The DR mode satisfies the diffusion equation

$$\frac{\mathrm{d}^2 \delta n_r}{\mathrm{d}x^2} - \frac{2g}{\lambda}\frac{\mathrm{d}\delta n_r}{\mathrm{d}x} - \frac{\delta n_r}{\lambda^2} = 0, \tag{27}$$

where $g = \frac{e\lambda(\mu_n+\mu_p)}{2kT}\gamma EB$, $\lambda = \sqrt{D_n \tau_n}$ is the diffusion length, τ_n is the lifetime of the electron-hole pairs in the bulk of the sample and $D_n = kT\mu_n/\mathrm{e}$ is the electron diffusion coefficient. The QS mode satisfies equation (23). From the solution of equations (23), (26) and (27) after some mathematical manipulation we arrive at the general expression of the Hall EMF $U_H = \delta\varphi_m(a) - \delta\varphi_m(-a)$:

$$U_H = U_{H0} - \frac{kT}{\mathrm{e}} \ln\left(\frac{n_0 + \delta n_r^+}{n_0 + \delta n_r^-}\right), \tag{28}$$

where $U_{H0} = 2a\mu_p\gamma EB$ is the classical Hall EMF, $\delta n_r^{\pm} = \pm 2gn_0 \frac{u[\cosh\tilde{u} - \exp(\pm\tilde{g})] + (\tilde{s}_{ef} \pm g)\sinh\tilde{u}}{(1+\tilde{s}_{ef}^2)\sinh\tilde{u} + 2\tilde{s}_{ef} u\cosh\tilde{u}}$ is the NE electron (hole) concentration in the virtual surface $x = \pm a \mp l$, $\tilde{u} = 2ua/\lambda$, $u = \sqrt{g^2+1}$, $\tilde{g} = 2ga/\lambda$, $\tilde{s}_{ef} = \frac{S_{ef}\lambda}{D_n}$, $S_{ef} = S_p \frac{p_0}{n_0} \exp\left(-\frac{e\varphi_{es}}{kT}\right)$ is the effective interface recombination velocity (IRV).

3. Discussion of results

Introducing the SRV in the QN approach it was assumed that (1) the Debye length is significantly less than the diffusion length [2] and (2) the carrier concentration deviations from the equilibrium ones are small enough [2] ($|\delta n| \ll n_0, |\delta p| \ll p_0$). There are no such assumptions in the present work. Therefore BCs (6), (8), (9) and interface recombination parameters $S_{n,p}^{\pm}$ may be used for analysis of various effects at any value of external force/excitation in any semiconductor.

The BCs formulation is based on the continuity equations, the Poisson equation and the partial current density expressions. The continuity equations and the Poisson equation follow from the Maxwell equations and Boltzmann kinetic equation. In the stationary state the continuity equations express the law of conservation of charge in any semiconductor point. The equations of partial current density are the result of the Boltzmann kinetic equation solution [2, 7]. Therefore BCs (6) and (8) are valid in the framework of correctness of partial current expressions [2].

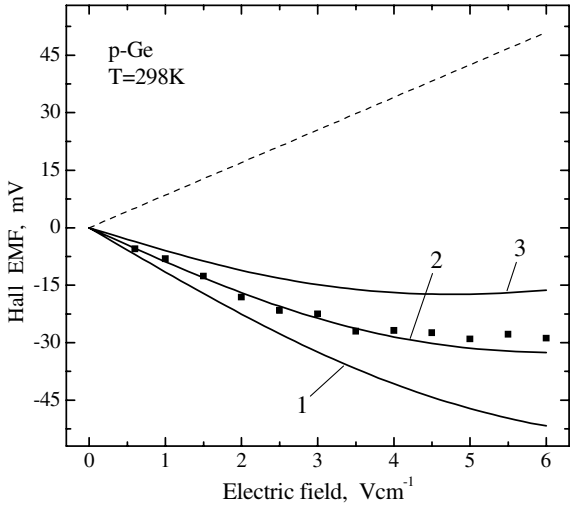

Figure 1. The Hall EMF dependence on the external electric field for some effective IRV values: 1 – $S_{ef} = 0$, 2 – $S_{ef} = 185$ cm s^{-1}, 3 – $S_{ef} = 490$ cm s^{-1}. The dashed line gives the classical Hall EMF. The solid squares represent experimental data.

In linear approximation ($|\delta n| \ll n_0, |\delta p| \ll p_0$) it follows from equations (10), (18) and (24) that

$$j_{ns}^+ - j_{ns}^- = S^+ \delta n_r^+ + S^- \delta n_r^-, \tag{29}$$

where $S^{\pm} = S_n^{\pm} n_{es}^{\pm}/n_0^{\pm} + S_p^{\pm} p_{es}^{\pm}/p_0^{\pm}$ and $\delta n_r^{\pm}$ is the NE concentration of electron-hole pairs in virtual surfaces $x = \pm l$. Since the inequality $\delta n_r^+ \neq \delta n_r^-$ is valid in the p–n junction [2] and heterojunction, so we cannot introduce the definition of the IRV in the semiconductor–semiconductor junction. It follows from equation (29) that the definition of the IRV is possible in the free semiconductor surface and in the MSJ because there is no surface recombination in metal and dielectric ($S^- = 0$). Note that in wideband semiconductors (Ge, Si, GaAs) the condition of linear approximation limits external excitation considerably stronger than the condition of constancy of the interface recombination parameters $S_{n,p}$ (see above) and therefore the linear approximation does not fulfill in many experiments.

It follows from equations (25) and (28) that the effective IRV in the MSJ essentially differs from the SRV in the free semiconductor surface. Furthermore, the effective IRV expression is valid at any value of the NE carrier concentration unlike of the SRV in the free semiconductor surface.

It follows from equation (28) that the Hall EMF nonlinearly depends on the external electric/magnetic field in the nonmassive sample ($a \leqslant \lambda$) at a small enough effective IRV magnitude ($S_{ef} \ll D_n/\lambda$). The U_H sign is opposite to the sign of the classical Hall EMF. This effect is caused by significant electron concentration deviation from the equilibrium one in the virtual surfaces, which arises due to the influence of the Lorentz force.

The Hall EMF dependence on the electric field E in p–Ge ($p_0 = 2 \times 10^{14}$ cm^{-3}, $\lambda = 0.1$cm, $\mu_n = 3800$ cm^2 V^{-1} s^{-1}, $\mu_p = 1800$ cm^2 V^{-1} s^{-1}) at $T = 298$ K and $B = 0.2$ T is shown in figure 1. The dimensions of the sample are $2a = 0.2$ cm, $2b = 2$ cm, $2d = 0.3$ cm. Solid squares represents the experimental data. The sample was supplied

by antiphased voltage pulses, so that the electric potential of the Hall contacts is zero in the absence of the magnetic field. The pulse duration is equal to 5×10^{-4} s and the repetition frequency is 20 Hz, so the sample heating by external voltage is negligible. Accounting for the typical value of the equilibrium SP $\varphi_{es} \cong (0.2 \div 0.22)$V from the S_{ef} definition and figure 1 we obtain $S_p \approx (4 \div 9) \times 10^3$cm s^{-1}, which is quite realistic in germanium [10].

Thus general relation (18) makes it possible to build the consistent theory of the Hall electric field generation in the semiconductor sample. The continuity of the electric potential was used in [16] for computer modeling of the semiconductor structure and good coincidence of calculations with observed data was obtained.

The represented theory may be applied to the analysis of any effect the value of which depends on the interface recombination. In the new interface recombination theory the range of the external excitation value is significantly larger than that in the linear approximation [2]. The measurement of two independent effects and general relation (18) are necessary for determination of the interface recombination parameters in the semiconductor–semiconductor junction.

4. Conclusions

The theory of interface recombination in abrupt semiconductor–semiconductor junctions was developed. The interface recombination rate dependence on the NE electron and hole concentrations was obtained. The validity of the new interface recombination model was proved considering the Hall electric field formation in the extrinsic semiconductor sample with any energy band bending. The anomalous nonlinear Hall EMF in a weak magnetic field was investigated. The experimental data corroborate the developed interface recombination theory. Obtained boundary conditions and expressions of interface recombination parameters may be successfully used for the study of transport process in semiconductor structures.

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