MOBILITY OF CURRENT CARRIERS IN SEMICONDUCTORS WITH LARGE-SCALE STRUCTURAL DEFECTS

S.I. SHAKHOVTSOVA, L.I. SHPINAR, I.I. YASKOVETS

Institute of Physics, Nat. Acad. Sci. of Ukraine
(46, Nauky Prosp., Kyiv 03022, Ukraine, e-mail: yaskovets@svitonline.com)

UDC 621.315.592
©2006

In the diffusive approximation, the effect of the crystal structure imperfections, for which the characteristic space dimensions exceed the free length of current carriers, on a current carrier mobility is studied. Within the approximation considered, a change in the relative mobility $\Delta\mu$ is expressed through the root-mean-square (rms) fluctuation of the current carrier concentration ε_2 which is determined by the nature of inhomogeneities. It is shown that the Ohmic and Hall mobilities in the semiconductors with statistical inhomogeneities are different functions of ε_2. For the samples which are homogeneous on the average, with the use of specific models for inhomogeneities of different origins, the temperature dependences of $\Delta\mu$ are explained and the parameters of the regions with imperfections are estimated. A model describing the interaction of point defects with gadolinium clusters in p-Si is built.

1. Introduction

Large-scale inhomogeneities, hereinafter referred to as imperfection regions (IRs), belong to a widespread kind of complicated defects of different nature, which are statistically distributed within a crystal matrix. A peculiar feature of IRs is the considerable space extent (L) of the electrical fields associated with them and, as a result, their strong influence on the processes of electron transfer. A number of discrepancies characteristic of the semiconductors containing IRs, to which belong (i) a deviation of both the mobility $\mu(T)$ and other kinetic coefficients from empirical dependences, and (ii) the absence of a correlation between μ and weak-field-magnetoresistance, with these quantities being calculated in the approximation traditional for homogeneous materials either by means of introducing the corresponding scattering cross-section [1, 2] or in terms of the effective medium method [3], stimulated the search for another approach which could adequately describe the transport processes in inhomogeneous materials.

Herring [4] and Pekar [5] proposed the approach, for which the validity of the following relation is of decisive importance:

$$L >> \lambda, \qquad (1)$$

where L and λ are the characteristic size of inhomogeneities and the charge carrier free length, respectively. If condition (1) is fulfilled, a carrier moves diffusively in the IR field which can be taken into account in the transport equations in the same way as the external applied field is accounted for. The total electric field $\vec{E}(\vec{r})$ that acts on the current carriers consists of two components. The first one, $\langle\vec{E}\rangle$, is the field averaged over the volume, and the second one is the fluctuating component $\vec{E}_1(\vec{r}) = f(\vec{r})\langle\vec{E}\rangle$. The main problem consists in the calculation of the $f(\vec{r})$ function which depends on IR. In the general case, this task is solvable when a degree of inhomogeneity is small, namely in the case of point defects and dislocations [5, 6], for which $\frac{|n(\mathrm{r}\ )-\langle n\rangle|}{\langle n\rangle} << 1$, where $n(\vec{r})$ is a local value of the current carrier concentration. If the effect originating from remote regions of the IR potential is sufficiently strong, a relative change in the mobility $\Delta\mu = (\mu_0 - \mu)/\mu_0$ becomes proportional to $T^{-3/2}$ (here, μ_0 is the mobility in a homogeneous material, and μ in a material containing IRs). Such a kind of the dependence is actually observed in the case of weak inhomogeneities, but it is far from being typical of materials with a high degree of inhomogeneities, namely those containing disorder areas [7, 8], metallic clusters [9,10], and others. It is these arguments that stress the necessity to extend the theory beyond the limits of the Debye approximation.

The utilization of both the diffusive approach and the statistical method of averaging out enabled the authors of [11] to quantitatively describe the transport of current carriers in the semiconductors containing three-dimensional IRs of any scale with the simultaneous account of the realistic IR potentials. The theoretical calculations were confirmed experimentally by the example of materials with IRs of various origins.

Within the frames of this approach, the explanation can be given for some peculiar properties which are unusual from the point of view of the ordinary theory of kinetic phenomena in semiconductors. To these belongs the change in a sign of the isothermal Nernst—Ettingshausen effect that occurs as a degree of inhomogeneity grows, whereas the scattering mechanism for current carriers keeps invariable [12], as was observed in [13].

This paper presents a generalization of the theoretical and experimental results obtained by the authors.

2. Theory

Within the frames of the diffusive approximation [5], the current density can be written as

$$\vec{J}(\vec{r}) = e\hat{\mu}_0 n(r)\bar{f}(\langle\vec{E}\rangle - \nabla W), \quad (2)$$

where $\widehat{\mu}_0$ is tensor of the current carrier mobility in a corresponding homogeneous semiconductor, and f is some function of electric and magnetic fields. The nonequilibrium correction term to the electrochemical potential $W(\vec{r}) = \Phi(\vec{r}) + \frac{kT}{e}\ln n(\vec{r})$, where $\Phi(\vec{r}) = e\varphi(\vec{r})/kT$, depends on the mean field $\langle\vec{E}\rangle$ acting on carriers and is determined from the equation $\mathrm{div}\vec{J}(\vec{r}) = 0$. In the approximation of paired correlations [11], the average current density can be expressed as

$$\langle\vec{J}\rangle = e\hat{\mu}_0\left\{\langle\vec{E}\rangle + \frac{1}{(2\pi)^3}\int \vec{p}(\hat{\mu}_0\langle\vec{E}\rangle\vec{p})g(\vec{p})K(\vec{p})dp\right\}\langle n\rangle, \quad (3)$$

where

$$g(\vec{p}) = \frac{1}{\vec{p}\hat{\mu}_0\vec{p} - m(\vec{p})},$$

$m(\vec{p})$ — mass operator. These equations are general and are suitable for the consideration of the case where inhomogeneities are of arbitrary shape, including also anisotropic ones with an arbitrary axial orientation relative to the vector of the average current $\langle J(\vec{r})\rangle$. The expression (3) is a partial sum of terms of the infinite series which is usually obtained upon the utilization of the ordinary perturbation theory for the determination of a current in an inhomogeneous medium [4, 5]. The complete analysis of expression (3) as well as the cases of its application to the description of the influence of inhomogeneities on the kinetic effects are presented in [13, 14]. All information about IRs is contained in the Fourier component $K(\vec{p})$ of the two-point correlation function, which is determined by the type of inhomogeneities:

$$K(\vec{r},\vec{r}\,') = \langle\kappa(\vec{r})\kappa(\vec{r}\,')\rangle \equiv \varepsilon_2 F(\vec{r},\vec{r}\,'),$$

$$\varepsilon_2 = \langle\kappa(\vec{r})^2\rangle, \quad \kappa(\vec{r}) = \frac{n(\vec{r}) - \langle n\rangle}{\langle n\rangle}.$$

The forms of correlation functions corresponding to different geometries of inhomogeneities are described in [14].

In the case of spherical inhomogeneities, it is pertinent to use $K(\vec{p})$ in the form $K(\vec{p}) = \pi^{3/2}\varepsilon_2 a^3\exp(-\frac{a^2p^2}{4})$, where the correlation length a coincides in order with the characteristic space dimensions of fluctuations in $n(\vec{r})$. In the case where magnetic fields are weak and inhomogeneities are three-dimensional, the Ohmic and Hall effective mobilities equal

$$\mu_c = \mu_c^0\frac{1-\frac{2}{3}\varepsilon_2}{1-\frac{1}{3}\varepsilon_2},\ \mu_{\mathrm{H}} = \mu_{\mathrm{H}}^0\frac{1-\varepsilon_2}{1-\frac{2}{3}\varepsilon_2}, \quad (4)$$

respectively. Here, μ_c^0 and μ_{H}^0 are the corresponding mobilities in a homogeneous semiconductor, and ε_2 is the rms fluctuation of the concentration of free current carriers. Expressions (4) are the sums of terms of the series obtained upon the utilization of the Pekar approach [5] under the additional condition $e\varphi(\vec{r}) << kT$ or the Herring one [4], provided that μ_c^0 and μ_{H}^0 are independent of the coordinate and the correlations of the order higher than two can be neglected in the mass operator $m(\vec{p})$. When $\varepsilon_2 \to 0$, the approximate results read as $\mu_c/\mu_c^0 = \mu_{\mathrm{H}}/\mu_{\mathrm{H}}^0 = 1 - \frac{1}{3}\varepsilon_2$ [4, 5]. It is only in this approximation that the Hall factor is independent of a degree of inhomogeneity and the determination of the current carrier concentration averaged over the volume from the measurements of the Hall effect is justified [11].

In the case where magnetic fields are strong, in the approximation of pair correlations, the Hall constant is determined by the current carrier concentration averaged over the volume, and the Hall factor equals the unity, as is observed in the case of homogeneous specimens. This result coincides with that following from the analysis of the transport phenomena in the case where strong inhomogeneities are present [15].

To perform a quantitative analysis of the influence of large-scale inhomogeneities on the current carrier mobility, it is necessary to calculate the rms fluctuations of the current carrier concentration which are defined by the fluctuations of the potential caused by all IRs:

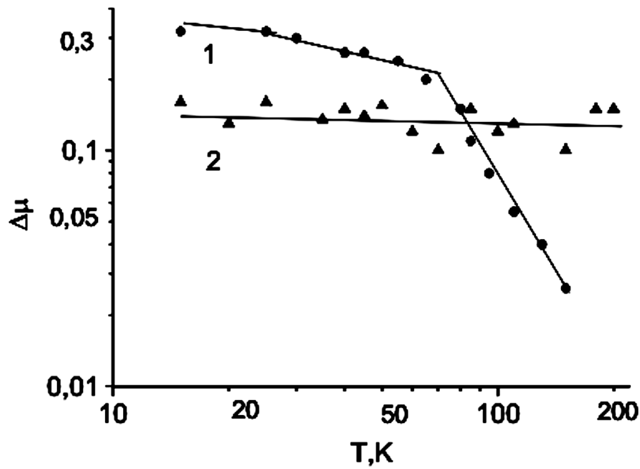

Fig. 1. Temperature dependences of the relative Hall mobility of electrons in n-Ge for the specimens of type I ($N_{\rm Sb} = 3\times10^{14}$ cm^{-3}, curve *1*) and II ($N_{\rm Sb} = 9.5 \times 10^{14}$ cm^{-3}, curve *2*) irradiated with neutrons at the dose 4.3×10^{13} neutron/cm^2. Scattered symbols and lines denote the experimental and theoretical data, respectively

$\varphi(\vec{r}) = \sum\limits_{i=1}^{N} \varphi_{\rm IR}(\vec{r} - \vec{r}_i)$. In this case, the problem is reduced to the determination of the averages of such a kind:

$$\left\langle \exp\left(-\frac{e\varphi(\vec{r})}{kT}\right)\right\rangle =$$

$$= \exp\left\{N_{\rm IR}\left\langle\int(\exp\left(-\frac{e\varphi_{\rm IR}(\vec{r})}{kT}\right) - 1)dr\right\rangle_f\right\},$$

where $\langle \ldots \rangle_f$ denotes the averaging over the distribution of the parameters of IRs. The approximate calculation of the integral within the limits $0 < r < r_2$ and $r_2 < r < \infty$, for which $e\varphi(\vec{r})/kT > 1$ and $e\varphi(\vec{r})/kT < 1$, respectively, leads to the result

$$\ln\left(1 + \frac{3\Delta\mu}{1 + 2\Delta\mu}\right) = \frac{4\pi}{3} N_{\rm IR}\left[r_2^3 + \frac{3}{2}L_{\rm D}r_2^2\right]. \quad (5)$$

Here, $N_{\rm IR}$ is the concentration of IRs, $L_{\rm D}$ the Debye length, r_2 the distance from the center of an IR, for which $e\varphi_{\rm IR}(\vec{r}_2) = kT$. A value of r_2 is determined by both the nature and structure of IRs.

For the further analysis of the temperature dependence of the current carrier mobility, it is necessary to specify the ideas of the structure of inhomogeneities.

3. Typical Kinds of Inhomogeneities in Semiconductors

3.1. Inhomogeneities induced by nuclear irradiation

Upon the irradiation of semiconductors with high-energy nuclear particles, one observes the formation of disorder regions (DRs) which are of the spherical shape, as generally accepted [16]. The inner area of a DR with geometric size r_1 is characterized by a high density of primary defects [17, 18], whereas the boundary with the matrix is a spherical p—n-junction.

For the first time, the analysis of the influence of DRs on the current carrier mobility in n-Ge irradiated with neutrons was performed in the diffusive approximation in [7]. According to this work, the relative change in the mobility can be expressed as

$$\Delta\mu = \frac{4\pi}{3} N_{\rm IR} a \frac{r_1^6}{L_{\rm D}^3}, \quad \text{when} \quad r_2 << L_{\rm D}, \quad (6a)$$

$$\Delta\mu = \frac{8\pi}{3} N_{\rm IR} a r_1^3, \quad \text{when} \quad r_2 >> L_{\rm D}, \quad (6b)$$

where a is a function of a degree of the filling of electron energy levels in a DR, which is temperature-independent at sufficiently low temperatures. Respectively, there are two types of the temperature dependences of $\Delta\mu$: $\Delta\mu \sim T^{-3/2}$ and $\Delta\mu \sim T^0$, which correspond to Eqs. (6a) and (6b), respectively.

If the potential gradually decreases with increase in the distance to a DR, then, for $L_{\rm D} >> r_2$, the remote potential region renders the main influence on the movement of carriers. In this case, the DRs exert the same influence as point defects with the effective charge $eN_1r_1^3$, where N_1 is the concentration of charged defects in a DR [5]. If $r_2 >> L_{\rm D}$, the electric potential is a quickly changeable function of the space coordinate. In this case, the change in the mobility is only determined by the geometric factor $f_\nu \approx N_{\rm DR}r_1^3$, i.e. by a fraction of the volume occupied by DRs, and $\Delta\mu$ is independent of temperature.

Such temperature dependences (Fig. 1) were observed by us in n-Ge irradiated with fast neutrons [7, 8]. Two types of the specimens doped with antimony were studied. For types I an II, the dopant concentrations were 3×10^{14} and 9.5×10^{15} cm^{-3}, and the compensation levels were 0.05 and 0.15, respectively. The conditions $f_\nu < 1$ and $\Delta\mu << 1$ are satisfied when the integral flows equal 4.3×10^{12} and 4.3×10^{13} neutron/cm^2, and, thus $N_{\rm DR} \approx 7.7 \times 10^{11}$ and 7.7×10^{12} cm^{-3} for the former and latter types, respectively. According to the electron microscopy studies [17],

$r_1 < 150$ Å in n-Ge. At these values of r_1 and the concentration of acceptors in DRs $N_1 \approx 10^{19}$ cm^{-3}, the values of r_2 equal $(2\div3)\times10^{-5}$ and $(5\div6)\times10^{-5}$ cm, for the specimens of types I and II, respectively.

For the specimens of type I, the criterion for the applicability of the diffusive approach is fulfilled within the range 70—250 K, where case (6a) is realized, according to which $\Delta\mu \sim T^{-3/2}$. The experimental dependence (Fig. 1, curve *1*) corresponds to the law $\Delta\mu \sim T^{-\nu}$ ($\nu = 1.5 \div 2$) and is almost insensitive to a radiation dose. For the specimens of type II, the criterion for the applicability of the diffusive approach is fulfilled within the range 10—250 K, where case (6b) is realized, according to which $\Delta\mu$ is practically independent of temperature (Fig. 1, curve *2*).

3.2. Inhomogeneities of a technological origin

Consider some kinds of technological inhomogeneities by the example of germanium and silicon. According to Section 2, r_2 in Eq. (5) can be represented in the form

$$r_2 = L_{\rm D}\left[\left(1 + \frac{3r_{\;1}}{L_{\rm D}}\frac{A}{kT}\right)^{\frac{1}{3}} - 1\right], \qquad (7)$$

where A is the difference of the work functions.

3.2.1. Mobility of current carriers in Ge doped with tin

The temperature dependence of the electron mobility was studied within the temperature range 80—300 K for n-Ge doped with both antimony and tin. The respective dopant concentrations were $N_{\rm Sb} = (2.5 \div 4.6) \times 10^{14}$ cm^{-3} and $N_{\rm Sn} = 5 \times 10^{19} \div 1.2 \times 10^{20}$ cm^{-3}; the compensation level was equal to 0.6 [10]. According to the phase diagram, the content of tin doesn't exceed 5×10^{20} cm^{-3}, and the strong segregation upon the crystallization hampers a homogeneous space distribution of tin [19]. As a rule, the space scale L of the electric fields of tin clusters exceeds the current carrier free length λ conditioned by the scattering by phonons ($\sim 10^2$ Å).

The corresponding work functions equal 4.46 and 4.38 eV for the matrix and the inclusion, respectively. Due to the transfer of electrons from tin to germanium, the nearest environment of the tin inclusions will be charged negatively. The clusters themselves can be considered as the metallic inclusions that bear a positive charge. A value of the potential within the inner cluster region is not significant, since the main influence on electrons is exerted by the external potential.

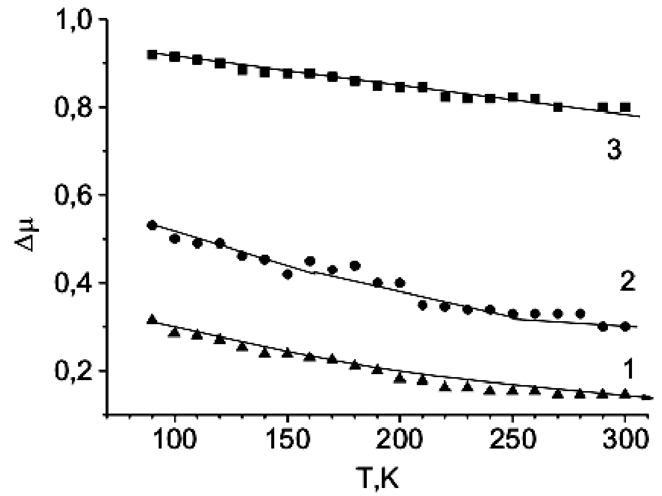

Fig. 2. The relative change in the mobility for the specimens of n-Ge doped with tin: $N_{\rm Sn}$ equal 1.5×10^{19} (*1*), 1×10^{20} (*2*), and 1.2×10^{20} (*3*). Scattered symbols and lines denote the experimental and theoretical data, respectively

Having solved the Poisson's equation and assuming that a fraction of the volume occupied by damaged areas together with the accompanying volume charge is less than the unity, the relative mobility change can be expressed in the form [8]

$$\Delta\mu = \frac{4\pi}{9}N_{\rm OH}\left[r_2^3 + \frac{3}{2}r_2^2 L_{\rm D}\right]. \qquad (8)$$

The temperature dependence of a relative change of the current carrier mobility is determined by a relationship between r_1 and $L_{\rm D}$ [see Eqs. (6a) and (6b)]. The value of r_2 can be calculated from Eq. (7). The fitting parameters r_1 and $N_{\rm DR}$ (the concentration of tin clusters) can be determined from the data obtained at 300 K. Fig. 2 shows the experimental and calculated temperature dependences of the relative mobility for the specimens with various tin contents. The relative mobility change in the temperature range $80 \div 300$ K can be satisfactorily described within the frames of the approach utilized.

It is parameters $N_{\rm DR}$ and r_1 that are the characteristics of fluctuations of the specimen composition, and they are determined by the thermodynamic conditions of the crystal growth, provided that the tin concentration is given. The geometric dimensions of tin inclusions are the decreasing functions of the tin concentration and are changed from 4×10^{-5} to 1.5×10^{-5} cm for the range of the $N_{\rm Sn}$ values studied. Correspondingly, the cluster concentration $N_{\rm DR}$

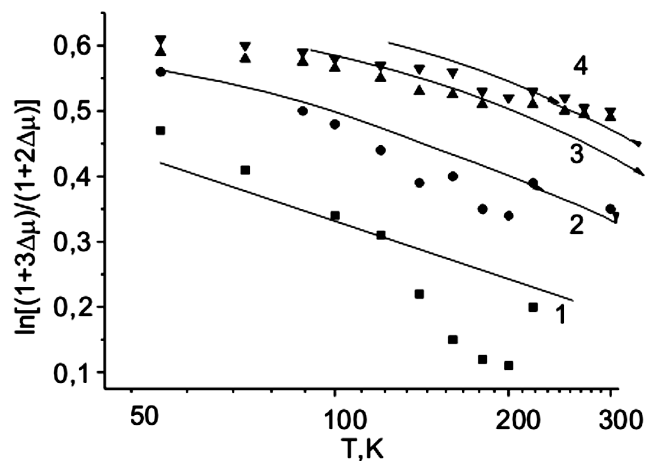

Fig. 3. Temperature dependences of the relative mobility $\Delta\mu$ for the $Ge_{1-x}Si_x$ solid solutions with $x = 0.0001$ (*1*), 0.01 (*2*), 0.02 (*3*), and 0.04 (*4*). Scattered symbols and lines denote the experimental and theoretical data, respectively

is changed from 1.5×10^9 to 2.3×10^{11} cm^{-3}. The behavior of the obtained parameters of fluctuations of the composition for the Ge-Sn system is indicative of a sufficient contribution of the entropic term to the free energy minimum, which leads, with increase in the tin concentration, not to an increase of the space dimensions of inclusions, but to a growth of their number.

3.2.2. Mobility of current carriers in Ge $_{1-x}Si_x$

Single crystals of germanium-like solid solutions $Ge_{1-x}Si_x$ ($0 < x < 0.14$) of the n-type of conductivity, which were doped with antimony, were the objects of our next investigation [20]. The strong segregation at crystallization, which is a result of the liquating character of the distribution of silicon in germanium, hampers the formation of homogeneous $Ge_{1-x}Si_x$ alloys. The scale of the composition fluctuations, determined from various experiments, allows one to make a conclusion that the IR geometric dimensions lie within the range $50 < r_1 < 100$ Å for IRs containing from 30 to 150 silicon atoms [21].

It was assumed that the location of the Fermi level inside an IR coincides with that characteristic of pure Si with the intrinsic conductivity. Such an assumption is justified in the case where IRs occupy a small volume fraction ($f_\nu \approx 10^{-2}$) and the concentration of impurities is sufficiently low ($N_{\rm Sb} \approx 10^{15}$ cm^{-3}). Then the maximal value of $\Phi(r)$ reads

$$\Phi_0 = \frac{0,6}{kT} + \left[\frac{3}{4}\ln\left(\frac{m_h}{m_e}\right)_{\rm Si} - \ln\left(\frac{N_c}{N_d}\right)_{\rm Ge}\right], \qquad (9)$$

where $m_h (m_e)$ is the effective mass of holes (electrons) in Si, N_c — the density of states in the germanium conductivity band, and N_d — the concentration of the antimony impurity. The values of the electron affinity were assumed to be 4.05 eV for Si and 4 eV for Ge. It was also made an assumption that the Si concentration in all IRs equal the concentration of silicon introduced in the alloy, and that IRs are uniformly distributed over the volume. The temperature dependence of the mobility was determined from Eq. (5).

Fig. 3 presents the temperature dependence of the relative mobility $\Delta\mu$ for $Ge_{1-x}Si_x$ alloys with the contents of antimony $N_{\rm Sb} = 0.4 \div 1 \times 10^{15}$ cm^{-3} and silicon $10^{-4} < x < 4 \times 10^{-2}$ (curves *1*–*4*). The only fitting parameter was the cluster size r_1.

As is seen from Fig. 3, in the entire range of the compositions studied, there is a satisfactory agreement between the experimental and calculated curves within the range 100—300 K. At low concentrations of Si, the experimental and theoretical dependences coincide with one another with accuracy of a few per cents. The scatter of the experimental values observed in the alloys with $x > 0.01$ is associated with increase in the relative error in the experimental determination of $\Delta\mu$. The discrepancies between the experimental and calculated values of $\Delta\mu$, observed in the alloys with the higher Si content at low temperatures, are concerned with the model approximation that considers IRs as inclusions of silicon displaying the intrinsic conductivity. The variation of Φ_0 allows one to improve the fitting reliability at higher x values. In the concentration range $10^{-4} < x < 4 \times 10^{-2}$, the geometric IR dimensions are within the limits $50 < r_1 < 700$ Å. The higher x, the greater r_1 is. Taking a possible distribution of the IR geometric dimensions into account doesn't lead to any change in the $\Delta\mu(T)$ dependences [21]. The main contribution to $\Delta\mu$ results from the large-size regions, since the contribution from the dispersively distributed silicon atoms, as well as their small clusters, is negligible.

The diffusive approach, used for the analysis of the current carrier mobility in $Ge_{1-x}Si_x$ having the hole type of conduction [22] and in a $Si_{1-x}Ge_x$ solid solution, gives rise to the $\Delta\mu(T)$ dependence which is similar to that obtained by us. This fact is indicative of a similarity of the mechanisms responsible for the charge mobility in the alloys with fluctuations of the composition.

3.2.3. Mobility of current carriers in p-Si doped with gadolinium

For the single crystals of silicon doped with boron and gadolinium ($N_\mathrm{B} = 5 \times 10^{13}$ cm^{-3}, $N_\mathrm{Gd} = 1 \times 10^{16}$ cm^{-3}, the compensation level equaled 0.4), irradiated with the $\gamma-$quanta from a ^{60}Co source, the temperature dependence of the Hall mobility of holes was studied [9]. A growth in the Gd doping level gives rise to an increase in both the dimensions and concentration of IRs. Both the factors lead to the mobility decrease, comparing to the case of homogeneous p-Si. However, after the irradiation of the Gd-doped samples with doses up to $\Phi_\gamma = 5 \times 10^8$ rad, the sensitivity of the current carrier concentration to the irradiation is observed to decrease, whereas the Hall mobility of holes to increase (Fig. 4). And only the increase in the dose Φ_γ gives rise to a decrease in the mobility which is pronounced below some temperature T^* depending on both the Gd concentration and Φ_γ (see Fig. 4, curves *3* and *4*).

To explain the effect of the carrier mobility growth, we proposed the model with deep donor states of the radiation origin, which appear near the IR boundary and change the potential profile of the Gd$-p$-Si contact in the process of irradiation. Let us present the main results of calculations.

The relative mobility change is described by Eq. (9), where r_2 can be found by means of solving the Poisson equation for the Gd$-p$-Si contact. The work functions were assumed to equal 3.07 and 4.8 eV for Gd and Si, respectively. r_0 means the distance, at which the height of the potential barrier on the contact $e\varphi_0 = A$. The solution of the Poisson equation under the corresponding boundary conditions imposed on the potential of the Gd$-p$-Si contact leads to the determination of r_2^*: $r_2^* = L_\mathrm{D}^* \left[\left(1 + \frac{3r_1}{L_\mathrm{D}kT} A^*\right)^{1/3} - 1 \right]$, where

$$A^* = A - \frac{1}{2}kT(\gamma R)^2, \quad R = r_1 - r_0,$$

$$\gamma = \sqrt{\frac{4\pi e^2}{kT}(N_\mathrm{B} + N_a)}, \quad \frac{1}{L_\mathrm{D}} = \sqrt{\frac{4\pi e^2}{kT}(N_\mathrm{B} - N_d)}$$

(here and below, * denotes the quantities after the irradiation).

In the process of irradiation, both donor (N_d) and acceptor (for simplification assume that N_a = const) defects, which can be in different charge states, are formed in the near-contact region ($r_0 - r_1$). Depending on a relationship between the specimen and irradiation parameters, one of the two cases can be realized:

$$\Delta\mu^* = \frac{4\pi}{3} N_\mathrm{IR} r_1 L_\mathrm{D}^{*2} \frac{A^*}{kT}, \quad \frac{3r_1 A^*}{L_\mathrm{D}^* kT} >> 1, \tag{10a}$$

$$\Delta\mu^* = \frac{2\pi}{3} N_\mathrm{IR} r_1 L_\mathrm{D}^{*2} \left(\frac{A^*}{kT}\right)^2, \quad \frac{3r_1 A^*}{L_\mathrm{D}^* kT} << 1. \tag{10b}$$

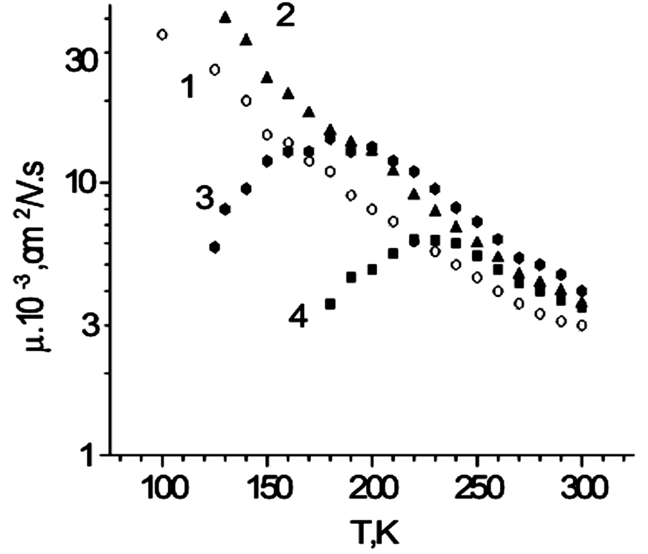

Fig. 4. Temperature dependences of the Hall mobility of electrons in the Gd-doped p-Si ($p = 5.8 \times 10^{13}$ cm^{-3}, $N_\mathrm{Gd} = 1 \times 10^{16}$ cm^{-3}) irradiated with $\gamma-$quanta from a ^{60}Co source. $\Phi_\gamma = 0$, 1.6×10^8, 3×10^8, and 5×10^8 rad for curves *1–4*, respectively

The value of A^* essentially depends on the distribution of the IR field. For low-Ohmic specimens (for example, with $p \approx 10^{15}$ cm^{-3}), $A^* \approx A$, and the situation described by relation (10a) is realized. In the case of high-resistance specimens irradiated with the same dose, both the value of r_0 and the quantity of negatively charged acceptors in the region ($r_0 - r_1$) are greater. The sharp drop in A^* leads to the fulfillment of the relations $\frac{A^*}{A} < \frac{p}{N_a}$ and $\Delta\mu^* < \Delta\mu$, i.e. to a decrease in the effective mobility μ^*.

Upon a further growth in the irradiation dose, the process of the formation of defect complexes within the semiconductor volume dominates, which is confirmed by the increase in the velocity of the current carrier removal. In this case, inequality (10b) is realized. At the doses where the inequality $\frac{A^*}{kTA} > 2\frac{L_\mathrm{D}^2}{L_\mathrm{D}^* r_1}$ is fulfilled, the effective carrier mobility in the irradiated material becomes lower than that in the non-irradiated one, i.e. $\Delta\mu^* > \Delta\mu$.

Thus, for the specimens of p-Si doped with Gd, the behavior of the mobility as a function of temperature and the irradiation dose is successfully described within the frames of the model of metallic clusters serving as a drain for primary defects.

4. Conclusions

1. The probability-theoretic method, which makes it possible to study a wide class of three-dimensional inhomogeneities and their influence on the transport properties of current carriers, is developed in this work.

2. Important features of the temperature dependence of the current carrier mobility in the semiconductors with imperfection regions of various nature are explained. The parameters of IRs, namely their concentration and dimensions, are estimated, basing on the comparison of the calculated dependences with the experimental ones.

3. For the specimens with p-Si containing Gd clusters, the formation of defects is specified. The so-called effect of "small doses", i.e. the increase in the current carrier mobility observed at the initial stages of the specimen irradiation with γ-quanta, is explained.

1. *Weisberg L.R.* // J. Appl. Phys. — 1962. — **33**, N5. — P.1817—1821.
2. *Dzhandiyeri M.Sh., Tsertsvadze A.A.* // Fiz. Tekhn. Polupr. — 1971. — **5**, N7. — P.1445—1453.
3. *Kirkpatrick S.* // Rev. Mod. Phys. — 1973. — **45,** N4. — P.574—588.
4. *Herring C.* // J. Appl. Phys. — 1960. — **31,** N11. — P.1939—1953.
5. *Pekar S.I.* // Fiz. Tekhn. Polupr. — 1966. — **8**, N5. — P.1115—1122.
6. *Kornyushin Yu.V., Pekar S.I.* // Ibid. — **8**, N4. — P.1122—1128.
7. *Shakhovtsov V.I., Shakhovtsova S.I., Shpinar L.I., Yaskovets I.I.* // Fiz. Tverd. Tela.— 1975. — **9**, N11. — P.2200—2202.
8. *Shakhovtsov V.I., Shakhovtsova S.I., Shpinar L.I., Yaskovets I.I.* // Ibid.— 1977. — **11**, N10. — P.1967—1971.
9. *Antonenko R.S., Karpov Yu.A., Shakhovtsov V.I. et al.* // Ibid.— 1978. — **12**, N9. — P.1707—1713.
10. *Shakhovtsova S.I., Shpinar L.I., Yaskovets I.I.* // Abstract Book of Intern. School-Conference "Modern Problems of Semiconductor Physics". — Drogobych, Ukraine. — 2003. — P. 1901.
11. *Shpinar L.I., Yaskovets I.I.* // Fiz. Tverd. Tela..— 1984. — **26**, N6. — P.1725—1730.
12. *Shpinar L.I., Yaskovets I.I.* // Fiz. Tekhn. Polupr. — 1983. — **17**, N9. — P.1691—1694.
13. *Safaraliev G.I., Vagabova L.K.* // Ibid. — 1981. — **15**, N5. — P.839—845.
14. *Shpinar L.I.*Electron Properties of Semiconductors with the Regions Including Distortions: Author's Abstract of the Candidate Thesis (Phys. and Math.). — Kyiv: Inst. Phys. of Acad. Sci. UkrSSR, 1984 (in Russian).
15. *Shik A.Ya., Shklovskii V.I., Efros A.L.* // Uspekhi Fiz. Nauk. — 1975. — **117**, N3. — P.401—435.
16. *Gossick B.R.* // J. Appl. Phys. — 1959. — **36**, N8. — P.1214—1221.
17. *Konopleva R.F., Litvinov V.L., Ukhin N.A.* Features of the Radiation Damage of Semiconductors by High-Energy Particles. — Moscow: Atomizdat, 1971 (in Russian).
18. *Vinetskii V.L., Kholodar' G.A.* Radiation Physics of Semiconductors. — Kyiv: Naukova Dumka, 1979 (in Russian).
19. *Shimizu H.* // Sci. Light. — 1972. — **21,** N1. — P.53—88.
20. *Shakhovtsov V.I., Shakhovtsova S.I., Shvarts M.M. et al.* // Fiz. Tekhn. Polupr.— 1989. — **23**, N1. — P.48—51.
21. *Shakhovtsova S.I., Shakhovtsov K.V., Shpinar L.I., Yaskovets I.I.* // Ibid.— 1993. — **27**, N6. — P.1035—1039.
22. *Shlimak I.S., Efros A.L., Yanchev I.Ya.* // Ibid.— 1977. — **11**, N2. — P.257—261.

Received 18.03.05.
Translated from Ukrainian by A.I. Tovstolytkin

РУХЛИВІСТЬ НОСІЇВ СТРУМУ В НАПІВПРОВІДНИКАХ З КРУПНОМАСШТАБНИМИ ДЕФЕКТАМИ СТРУКТУРИ

С.І.Шаховцова, Л.І.Шпінар, І.І.Ясковець

Р е з ю м е

У дифузійному наближені розглянуто вплив на рухливість носіїв струму недосконалостей структури кристалів, характерні просторові розміри яких перевищують довжину вільного пробігу носіїв λ. Зміну відносної рухливості $\Delta\mu$ в розглянутих наближеннях виражено через середньоквадратичну флуктуацію концентрації носіїв струму ε_2, яка визначається природою недосконалостей. Показано, що омічна та холлівська рухливості у напівпровідниках із статистичними неоднорідностями є різними функціями величини ε_2. Використовуючи конкретні моделі неоднорідностей різного походження у зразках, однорідних у середньому, пояснено температурні залежності $\Delta\mu$ і оцінено параметри ділянок недосконалості. Побудована модель взаємодії точкових дефектів з кластерами гадолінію в p-Si.