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Photoconductivity and the photo-Hall effect in inhomogeneous semiconductor alloys

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Abstract. The classical effective-medium theory for the calculation of the conductivity and Hall coefficient of inhomogeneous semiconductor alloys with the presence of photogenerated nonequilibrium charge carriers is developed. Using the composite spherical inclusions model it is shown that the Hall mobility is always less than the initial one, while the Hall concentration of free charge carriers is defined mainly by the concentration of charge carriers in the connected region and does not coincide with the sample mean concentration. The Lux–Ampère characteristic of inhomogeneous semiconductor alloys is shown to be a linear function for weak and logarithmic function for high illumination intensities.

1. Introduction

The real semiconductor alloys (SA) are often characterized by the presence in them of large-scale composition inhomogeneities [1–3]. The characteristic space scale of these inhomogeneities L, as a rule, significantly exceeds such microscopic parameters as the free path length and the de Broglie wavelength of free charge carriers. This circumstance allows one to introduce the notion of local characteristics of the inhomogeneous medium (mobility, density of states, concentration etc) and also to use the classical representations for the description of the motion of free charge carriers in the internal potential relief, which is due to the inhomogeneities of the composition and which leads, as a rule, to the antiparallel modulation of the band edges [1]. If one averages the electric field and the current density over volumes with dimensions exceeding the inhomogeneity scale, then with respect to these quantities the inhomogeneous SA will look like a homogeneous and isotropic medium and can be characterized by effective ('integral') parameters, such as the effective conductivity σ^* and the effective Hall constant R^*, which are usually measured in experiments. In the same way one can characterize inhomogeneous SA in the nonequilibrium state—in the presence of nonequilibrium charge carriers (NCC), created, for example, by illumination (i.e. when investigating the photoconductivity (PC) and photo-Hall effects). In that case the character of the NCC distribution in the internal random potential relief plays an important role. It is known that the NCC distribution in SA can significantly differ from the quasiequilibrium one and that it cannot be described by introduction of a single Fermi quasilevel for the whole band [4]. Hence the knowledge of the percolation level for the given potential relief is already insufficient for the calculation of PC of the medium and one has to use new models.

The goal of this paper is the calculation of the effective conductivity and Hall constant in the presence of photogenerated NCC, when the inhomogeneous SA can be identified with

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the model medium, filled with spherical inclusions of different sizes, the latter in their turn comprising the low-resistance inhomogeneous cores, surrounded by homogeneous spherical layers.

2. Description of the model

Consider n-type SA homogeneously doped with shallow donors and comprising large-scale random inhomogeneities of the composition, which lead to fluctuations of the band edges and band-gap width E_g. We will consider the case of sufficiently high doping, when the Debye screening length $r_s \ll L$ and the compositional fluctuations of the majority-carrier band edges are completely screened [1], i.e. for the electrons the potential barrier is absent, while for minority carriers—holes—the potential relief has a rather big amplitude $\Delta \gg kT$ (k is the Boltzmann constant, T is the absolute temperature). If the parameters of the potential relief (Δ, L), and the diffusion (L_D) and drift (L_E) lengths of the holes satisfy the condition

$$\sqrt{\frac{\Delta}{kT}}\exp\left(-\frac{\Delta}{kT}\right) \ll \frac{L}{L_E} \ll 1 \qquad (L_D < L < L_E) \tag{1}$$

then, as was shown in [4], the distribution of the NCC in the sample follows the so-called B regime, when NCC generated over the whole volume of the sample are concentrated in the vicinity of the local minima of the band-gap , where they are distributed in a quasiequilibrium way. However quasiequilibrium among the different minima (and hence over all of the valence zone) does not exist.

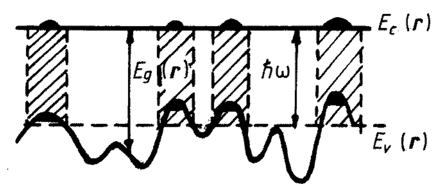

Figure 1. The band picture of inhomogeneous SA with $l \gg r_s$. The regions of localization of NCC are black; the generation regions are shaded.

It is worth noting that PC is realized in this case only through the majority nonequilibrium carriers (electrons) since, unlike holes, they do not have to be activated on the percolation level. However, in spite of the absence of the barriers in the conduction band the nonequilibrium electrons, because of the local quasineutrality, are distributed as inhomogeneously as the holes (figure 1). As a result it turns out that under the illumination of SA with light of frequency ω the concentration sharply rises near the local minima of the band-gap ($E_{g\min} < h\omega$) remaining practically unchanged in other parts of the sample. Since in the vicinity of $E_{g\min}$ the distribution of NCC is quasiequilibrium, their concentration is a maximum at the centre of the wells and decreases with the increase of the distance from the centre, gradually transforming into an equilibrium concentration (the illumination is supposed to be weak, so that the electron and hole gases in the wells can be considered nondegenerate). Hence from the point of view of electroconductivity and galvanomagnetic properties, the inhomogeneous SA under consideration is an inhomogeneous matrix of conductivity σ_0, in which, when it is illuminated, low-resistance spherical inclusions (LSI) appear, the conductivity of the latter being

$$\sigma(r) = \begin{cases} \sigma_1 \exp\left(-\dfrac{\beta r^2}{kT}\right) & r \leqslant a \\ \sigma_0 & r > a. \end{cases} \tag{2}$$

Here β characterizes the curvature of the potential relief in the vicinity of $E_{g\min}$, and σ_1 is the conductivity in the centre of the well, which depends on the intensity and the frequency of the light, as well as on the parameters of the potential relief. The radius a is obtained from the condition $\sigma(a) = \sigma_0$, i.e.

$$a = \sqrt{\frac{kT}{\beta}}\sqrt{\ln\frac{\sigma_1}{\sigma_0}} \equiv r_0\sqrt{\ln\frac{\sigma_1}{\sigma_0}}. \tag{3}$$

One must bear in mind that the LSI, appearing in inhomogeneous SA under illumination, are randomly distributed in the volume and differ from each other as regards the values of σ_1 and β (and hence of a). This circumstance and the necessity of knowing the distribution functions and correlation characteristics of the random potential relief significantly complicate the problem of direct calculations of the parameters of the inhomogeneous SA. To carry out these calculations in the presence of NCC we shall consider the following model of inhomogeneous SA.

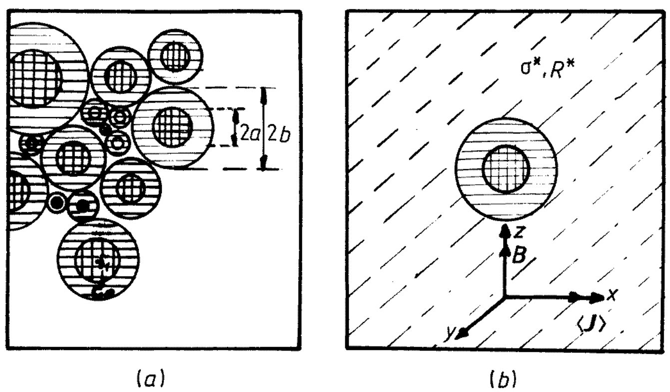

Figure 2. (a) The model of the medium filled by spherical inclusions with a/b = constant. (b) A spherical inclusion in the effective medium.

We fill the whole volume with large-scale spheres of different diameters (see figure 2), these spheres having a complex structure and each consisting of a core of radius a (the variation of the conductivity of the core is given by (2)) and of the surrounding spherical shell $a \leqslant r \leqslant b$, which has a constant conductivity σ_0. It is important that all of the spheres are chosen to have the same ratio of inner and outer radii a and b. Hence filling the volume of the sample with these spheres (big or small) we will keep unchanged the volume fraction of LSI:

$$\nu = a^3/b^3 = \text{constant}. \tag{4}$$

Such a model for inhomogeneous media was proposed originally in [5], where, however, only the case of homogeneous cores was investigated.

3. Calculation of the effective parameters of the medium

Let the inhomogeneous SA be characterized by the local conductivity $\sigma(\boldsymbol{r})$ and local Hall constant $R(\boldsymbol{r})$. In the presence of the external magnetic field $\boldsymbol{B}$ at each point the Hall current is added to the ohmic current and thus in general the relation between the electric field $\boldsymbol{E}(\boldsymbol{r})$ and the current density $\boldsymbol{J}(\boldsymbol{r})$ is given by the expression

$$\boldsymbol{E}(\boldsymbol{r}) = \frac{1}{\sigma(\boldsymbol{r})}\boldsymbol{J}(\boldsymbol{r}) + R(\boldsymbol{r})\,[\boldsymbol{B}\cdot\boldsymbol{J}]\,. \tag{5}$$

By definition, a similar relation must hold also for the average quantities $\langle\boldsymbol{E}\rangle$ and $\langle\boldsymbol{J}\rangle$:

$$\langle\boldsymbol{E}\rangle = \frac{1}{\sigma^*}\langle\boldsymbol{J}\rangle + R^*\,[\boldsymbol{B}\cdot\langle\boldsymbol{J}\rangle] \tag{6}$$

where the brackets $\langle\cdots\rangle$ denote volume averaging over the entire volume of the sample. When solving (6) for $\langle\boldsymbol{J}\rangle$ and in the calculations below we will restrict ourselves to the region of weak magnetic fields ($\sigma^* R^* B \ll 1$). Thus keeping only terms linear in B we find

$$\langle\boldsymbol{J}\rangle = \sigma^*(\langle\boldsymbol{E}\rangle - \sigma^* R^*\,[\boldsymbol{B}\cdot\langle\boldsymbol{E}\rangle]). \tag{7}$$

Now consider the homogeneous medium with parameters σ^* and R^* (figure 2(*b*)). Let the current $\langle\boldsymbol{J}\rangle$ flow along the x-axis, and the magnetic field be directed along the z-axis. Remove from this medium a sphere of radius b and replace it with a complex sphere, which comprises a core of radius a and conductivity (2) and a spherical shell $a \leqslant r \leqslant b$ of conductivity σ_0 (figure 2(*b*)). Evidently the effective parameters of such a medium, σ^* and R^*, do not change if after the insertion of that inclusion the values of $\langle\boldsymbol{E}\rangle$ and $\langle\boldsymbol{J}\rangle$ do not change. From this it follows that if the parameters σ^* and R^* are chosen in such a way that after the insertion of the spherical inclusion the potential distribution outside of it does not change, then these values of σ^* and R^* are the searched-for effective parameters of the inhomogeneous medium [5].

To find σ^* and R^* in the model under consideration one must know the distribution of the electric potential $\phi(\boldsymbol{r})$ in the homogeneous medium which is in the external magnetic field and contains a single composite spherical inclusion. For this purpose one has to solve the continuity equation

$$\operatorname{div}\{\sigma(\boldsymbol{r})(\boldsymbol{E} - \sigma(r)R(\boldsymbol{r})\,[\boldsymbol{B}\cdot\boldsymbol{E}])\} = 0. \tag{8}$$

Here the conductivity and the Hall coefficient vary with the coordinate only within the core. We will assume that $R(\boldsymbol{r}) \sim 1/\sigma(\boldsymbol{r})$ and will write for the inner sphere $R(\boldsymbol{r})\sigma(\boldsymbol{r}) = \mu_1 = \text{constant}$. Expressing $\boldsymbol{E}$ through the potential of the electrostatic field: $\boldsymbol{E} = -\boldsymbol{\nabla}\phi$, we finally obtain from (8) the equation

$$\nabla^2\phi + \frac{\boldsymbol{\nabla}\sigma}{\sigma}\left(\boldsymbol{\nabla}\phi - \mu_1\,[\boldsymbol{B}\cdot\boldsymbol{\nabla}\phi]\right) = 0. \tag{9}$$

This equation must be solved separately in each of the following three regions: $0 \leqslant r \leqslant a$, $a \leqslant r \leqslant b$ and $r > b$.

In the region $0 \leqslant r \leqslant a$, equation (9) in spherical coordinates with (2) taken into account has the form

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\phi}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2\phi}{\partial\theta^2} + \frac{\operatorname{cotan}\theta}{r^2}\frac{\partial\phi}{\partial\theta} + \frac{2\mu_1 B}{r_0^2}\frac{\partial\phi}{\partial\varphi} + \frac{1}{r^2\sin^2\theta}\frac{\partial^2\phi}{\partial\varphi^2} - 2\frac{r}{r_0^2}\frac{\partial\phi}{\partial r} = 0. \tag{10}$$

We will look for the solution of this equation in the form

$$\phi(r,\theta,\varphi) = R(r)\sin\theta\cos\varphi + Y(r)\sin\theta\sin\varphi. \tag{11}$$

Substituting (11) into (10) we arrive at a system of two equations for the unknown functions $R(r)$ and $Y(r)$:

$$\begin{aligned}\frac{\mathrm{d}^2 R}{\mathrm{d}r^2}+\left(\frac{2}{r}-\frac{2r}{r_0^2}\right)\frac{\mathrm{d}R}{\mathrm{d}r}-\frac{2}{r^2}R+\frac{2\mu_1 B}{r_0^2}Y=0\\ \frac{\mathrm{d}^2 Y}{\mathrm{d}r^2}+\left(\frac{2}{r}-\frac{2r}{r_0^2}\right)\frac{\mathrm{d}Y}{\mathrm{d}r}-\frac{2}{r^2}Y+\frac{2\mu_1 B}{r_0^2}R=0.\end{aligned} \tag{12}$$

If now we exclude from these equations, for example, the function $Y(r)$, then for the definition of $R(r)$ we obtain an equation in which the corrections with respect to the magnetic field are proportional to B^2. Hence in the linear approximation over the B (we consider the case of such weak magnetic fields) we have that $R(r)\sim Y(r)$ and these radial functions are defined from the equation

$$\frac{\mathrm{d}^2 R}{\mathrm{d}r^2}+\left(\frac{2}{r}-\frac{2r}{r_0^2}\right)\frac{\mathrm{d}R}{\mathrm{d}r}-\frac{2}{r^2}R=0. \tag{13}$$

Introduce now a dimensionless radius $\rho=r/r_0$. Then the solution of (13) which is finite when $\rho\to 0$ can be represented in the form

$$R(\rho)=\frac{1}{\rho}\mathrm{e}^{\rho^2}-\left(2+\frac{1}{\rho^2}\right)\int_0^\rho \mathrm{e}^{\eta^2}\,\mathrm{d}\eta. \tag{14}$$

Thus the distribution of the potential (11) within the inner sphere $0\leqslant r\leqslant a$ has the form

$$\phi(\rho,\theta,\varphi)=R(\rho)(\alpha_1\cos\varphi\sin\theta+\beta_1\sin\theta\sin\varphi) \tag{15}$$

where $\alpha_1,\ \beta_1$ are unknown coefficients.

Outside the inner sphere $\boldsymbol{\nabla}\sigma=0$ and equation (9) for the potential reduces to Laplace's equation

$$\Delta\phi=0. \tag{16}$$

Before insertion of the composite sphere the solution of this equation over the entire homogeneous medium with parameters σ^* and R^* can be presented in the form

$$\phi(\rho,\theta,\varphi)=-\frac{|\langle \boldsymbol{J}\rangle|r_0}{\sigma^*}\rho\sin\theta\cos\varphi-R^*B|\langle \boldsymbol{J}\rangle|r_0\rho\sin\theta\sin\varphi \tag{17}$$

where the first term is the potential of the external electric field and the second term represents the potential of the Hall field.

After insertion of the inclusion the potential in the spherical layer $a\leqslant r\leqslant b$, where $\sigma(r)=\sigma_0$, is given by the formula

$$\phi(\rho,\theta,\varphi)=\left(\alpha_2\rho+\frac{\gamma_2}{\rho^2}\right)\sin\theta\cos\varphi+\left(\beta_2\rho+\frac{\delta_2}{\rho^2}\right)\sin\theta\sin\varphi \tag{18}$$

where the term with $\alpha_2\rho$ is the potential of the external field, and the term with $\beta_2\rho$ is the Hall field potential as before, while the terms proportional to $1/\rho^2$ describe the potential of the field, created by the sphere, which is polarized in one case along the x-axis, and in the other case along the direction of the Hall field.

Finally, outside the inclusion ($r>b$) the solution takes a form analogous to (18):

$$\phi(\rho,\theta,\varphi)=\left(-\frac{|\langle \boldsymbol{J}\rangle|r_0}{\sigma^*}\rho+\frac{\gamma_3}{\rho^2}\right)\sin\theta\cos\varphi+\left(-R^*B|\langle \boldsymbol{J}\rangle|r_0\rho+\frac{\delta_3}{\rho^2}\right)\sin\theta\sin\varphi. \tag{19}$$

The so far unknown coefficients α_1, β_1, α_2, β_2, γ_2, δ_2, γ_3, δ_3 are defined from the condition of the continuity of the potential and of the radial component of the current

$$J_r = -\sigma\left(\frac{\partial\phi}{\partial r} + \frac{\sigma RB}{r}\frac{\partial\phi}{\partial\varphi}\right) \tag{20}$$

on the spherical surfaces $r = a$ and $r = b$. Introducing new dimensionless radii $a' = a/r_0$ and $b' = b/r_0$ we finally arrive at the following system of equations:

$$\begin{aligned}
&\alpha_1 a'^2 R(a') - \alpha_2 a'^3 - \gamma_2 = 0\\
&\beta_1 a'^2 R(a') - \beta_2 a'^3 - \delta_2 = 0\\
&\alpha_1 a'^3 R'(a') + \beta_1 a'^2 \mu_1 B R(a') - \alpha_2 a'^3 - \beta_2\mu_0 B a'^3 + 2\gamma_2 - \mu_0 B\delta_2 = 0\\
&\beta_1 a'^3 R'(a') - \alpha_1 a'^2 \mu_1 B R(a') - \beta_2 a'^3 + \alpha_2 a'^3 \mu_0 B + 2\delta_2 + \mu_0 B\gamma_2 = 0\\
&\alpha_2 b'^3 + \gamma_2 + \frac{|\langle \boldsymbol{J}\rangle| r_0}{\sigma^*} b'^3 - \gamma_3 = 0\\
&\beta_2 b'^3 + \delta_2 + \frac{|\langle \boldsymbol{J}\rangle| r_0}{\sigma^*}\mu^* B b'^3 - \delta_3 = 0\\
&\alpha_2\sigma_0 b'^3 - 2\gamma_2\sigma_0 + \mu_0\sigma_0 B b'^3\beta_2 + \delta_2\sigma_0\mu_0 B = -|\langle \boldsymbol{J}\rangle| r_0 b'^3 - 2\gamma_3\sigma^* + \delta_3\sigma^*\mu^* B\\
&\beta_2\sigma_0 b'^3 - \alpha_2\sigma_0\mu_0 B b'^3 - \sigma_0\mu_0 B\gamma_2 - 2\sigma_0\delta_2 = -2\delta_3\sigma^* - \sigma^*\mu^* B\gamma_3.
\end{aligned} \tag{21}$$

Here $\mu_0 = \sigma_0 R_0$, $\mu^* = \sigma^* R^*$ are Hall mobilities. Solving these equations we find the coefficients γ_3 and σ_3, expressed through the effective σ^* and R^*. Again in calculations we keep only terms linear in the magnetic field. Since our aim is to find such σ^* and R^* that after the introduction of the inclusion the field outside of it does not change, one can see from (19) that it is necessary to put $\gamma_3 = \delta_3 = 0$. So we find two equations for the final deduction of σ^* and R^*. After these calculations we have

$$\sigma^* = \sigma_0\frac{1 + 2\nu(1+u)}{1 - \nu(1+u)} \tag{22}$$

$$R^* = R_0\frac{[1 - \nu(1+u)]^2 + \nu u^2(\mu_1/\mu_0 - 1)}{[1 + 2\nu(1+u)]^2} \tag{23}$$

where

$$u = \frac{3}{4}\frac{1}{\xi}\frac{1 - (2\xi + 1/\xi)D(\xi)}{D(\xi)} \qquad \xi = \sqrt{\ln\frac{\sigma_1}{\sigma_0}}$$

and $D(\xi)$ is the Doson integral [6]:

$$D(\xi) = \mathrm{e}^{\xi^2}\int_0^{\xi}\mathrm{e}^{\eta^2}\,\mathrm{d}\eta. \tag{24}$$

The formulae obtained are correct for all values of ν. For $\nu = 0$ we have a homogeneous material and naturally $\sigma^* = \sigma_0$ and $R^* = R_0$.

It is clear that the final results (22), (23) are independent of the parameters a, b, r_0 and therefore their distribution functions. This is a specific consequence of our model, according to which the sample sizes are much larger than characteristic sizes of inclusions and all inclusions have spherical form and the same ratio of the inner to outer radii. Therefore for all samples, filled with inclusions of different radii but all with the same ν, the media are statistically homogeneous and isotropic and can be characterized by the same integral parameters σ^*, R^*, which are independent of the specified distribution of spherical inclusions.

4. Conclusions

Investigating the expressions obtained for σ^* and R^* one must remember that in our model the volume fraction of the inclusions ν and their conductivity σ_1 are interconnected:

$$\nu = \frac{a^3}{b^3} = \frac{r_0^3}{b^3}\left(\ln\frac{\sigma_1}{\sigma_0}\right)^{3/2} = \left(\frac{\xi}{\xi_m}\right)^3. \tag{25}$$

The case of $\xi = 0$ ($\sigma_1 \to \sigma_0$) corresponds to a homogeneous material with the conductivity σ_0. With the increase of σ_1 the core radius a also increases, approaching the external radius of the inclusions b. Hence for the parameter ξ there is a maximum variation limit $\xi \leqslant \xi_m = b^3/r_0^3$. For rather smooth macroscopic inhomogeneities and low temperatures one can assume that $\xi \gg 1$. It is also easy to see that the function $u(\xi)$ which enters (22), (23) is limited, $-1 \leqslant u(\xi) \leqslant 0$, and has the following asymptotic behaviour:

$$u(\xi) \approx= \begin{cases} -1 + 2.458\xi^2 & \xi \to 0 \\ -\dfrac{3}{4\xi^2} & \xi \gg 1. \end{cases} \tag{26}$$

In the linear approximation over the magnetic field the effective parameters of the medium σ^* and R^* do not depend on B. The effective conductivity σ^* does not depend on R_1 and R_0 either. For simplicity, in what follows we will assume that the mobility of the electrons in the inclusions and in the matrix do not differ from each other ($\mu_0 = \mu_1 = \mu$). As one can see from (22), σ^* is mainly determined by σ_0 and weakly depends on σ_1. This result is partially due to peculiarities of our model, where for any values of $\nu < 1$ the percolation through LSI is absent and σ^* is determined by the conductivity of the connected region σ_0. In experiments often the so-called Hall mobility is measured:

$$\mu_B = \sigma^* R^* = \mu\frac{1 - \nu(1+u)}{1 + 2\nu(1+u)} \tag{27}$$

which, as can be seen from (27), is always less than the initial one for all values of ν. The Hall concentration of the free charge carriers

$$n_B = \frac{1}{eR^*} = n_0\left[\frac{1 + 2\nu(1+u)}{1 - \nu(1+u)}\right]^2 \tag{28}$$

it is always greater than n_0 and for all values of ν is mainly determined by the concentration in the connected region. It must be noted that n_B does not coincide with the averaged free-charge-carrier concentration of the sample:

$$n_{av} = n_0\left(1 - \nu - \nu\frac{r_0^2}{2a^2}\right) + n_1\frac{\nu}{2}\frac{r_0^2}{a^3}\int_0^{a/2} \mathrm{e}^{\eta^2}\,\mathrm{d}\eta. \tag{29}$$

While n_B weakly depends on n_1, the average concentration strongly increases with the increase of the core conductivity (and hence simultaneously of the radius a) of the inclusion $\sigma_1 = en_1\mu$. For example, when $\nu \to 1$

$$\begin{aligned} n_B &\approx 16n_0\left(\ln\frac{n_1}{n_0}\right)^2 \\ n_{av} &\approx \frac{\sqrt{\pi}}{4}n_1\frac{1}{(\ln n_1/n_0)^{3/2}} \end{aligned} \tag{30}$$

and at large values of n_1 the average concentration always exceeds the Hall one, n_B. This result confirms the conclusion of [7] that in general when investigating inhomogeneous materials there is no basis for identification of the measured Hall concentration with the averaged concentration of the free charge carriers of the sample [8].

Using the formulae obtained one can also calculate the photoconductivity of the inhomogeneous SA:

$$\frac{\Delta\sigma}{\sigma_0} = 3\nu\frac{1+u}{1-\nu(1+u)}. \tag{31}$$

The effective conductivity of the medium σ^* depends on σ_1, which in its turn is determined by the illumination intensity. In the model of inhomogeneous inclusions under consideration, σ_1 in general is not proportional to the rate G of spatial generation of NCC. Their relationship can be found from the condition of conservation of the total number of NCC, which in stationary conditions has the form

$$G\tau = \left[\int_0^a (n_1 e^{-\beta r^2/kT} - n_0)4\pi r^2\, dr\right] \Big/ \frac{4}{3}\pi b^3 = 3n_0\frac{r_0^3}{b^3}\int_0^\xi (e^{\xi^2-\eta^2} - 1)\eta^2\, d\eta \tag{32}$$

where τ is the NCC lifetime. For the given generation rate G, determining from (32) the value of the parameter ξ (i.e. σ_1) and substituting it into (31) one can obtain the Lux–Ampère characteristics of the PC of inhomogeneous SA. It is easy to show that for low illumination intensities, when the inclusion conductivity σ_1 differs slightly from the conductivity of the matrix (i.e. $\xi \to 0$),

$$\begin{aligned} \frac{\Delta\sigma}{\sigma_0} &\approx 2.458\frac{r_0^3}{b^3}\xi^5 \\ G\tau &\approx \frac{2}{3}n_0\frac{r_0^3}{b^3}\xi^5 \end{aligned} \tag{33}$$

from which it follows that $\Delta\sigma/\sigma_0 \sim G$, i.e. the Lux–Ampère characteristic is linear. With the increase of the illumination intensity, the dependence $\Delta\sigma(G)$ becomes weaker, and when $\xi \gg 1$

$$\frac{\Delta\sigma}{\sigma_0} \approx \ln\frac{G}{G_0} \tag{34}$$

where

$$G_0 = \frac{3\sqrt{\pi}}{4}\frac{n_0}{\tau}\left(\frac{r_0}{b}\right)^3.$$

It should be noted that our calculation of Lux–Ampère characteristics is based on the approximation of linear recombination (or constant lifetime) when the average density of NCC (the left-hand side of equation (32)) is proportional to the generation rate G. At high generation rates ($\xi \gg 1$) the lifetime as a rule becomes dependent on the density of NCC, and therefore the characteristics of photoconductivity can be changed. However, this factor cannot noticeably change our conclusions about the character of Lux–Ampère characteristics, because in the case of quadratic recombination the left-hand side of equation (32), instead of a linear dependence, will contain a square-root dependence upon G, which can alter only the prelogarithmic multiplier in equation (34).

Similarly, knowing the dependence of σ_1 on G, and using of expression (23), one can find the dependence of the Hall coefficient of the inhomogeneous SA on the intensity of the illumination.

References

[1] Petrosyan S G and Shik A Y 1982 *JETP Lett.* **35** 357–9
[2] Petrosyan S G and Shik A Y 1988 *Sov. Phys.–Semicond.* **22** 2192–8
[3] Petrosyan S G, Chaldyshev V V and Shik A Y 1984 *Sov. Phys.–Semicond.* **18** 1565–72
[4] Asrian L V, Petrosyan S G and Shik A Y 1987 *Sov. Phys.–Semicond.* **21** 1765–70
[5] Mathew M G and Mendelson K S 1974 *J. Appl. Phys.* **45** 4370–2
[6] *Handbook of Mathematical Functions* 1964 ed M Abramowitz and I A Stegun (Washington, DC: National Bureau of Standards)
[7] Gergel V A and Suris R A 1978 *Sov. Phys.–Semicond.* **12** 2055–6
[8] Abessonova L I, Dobrovolskikh V I, Zharkikh Y S Frolov Y S and Shik A Y 1976 *Sov. Phys.–Semicond.* **10** 406–9