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Direct current in non-steady-state photovoltaic effect

I.N. Volovichev[1*]

[1] *A.Usikov Institute for Radiophysics and Electronics, National Academy of Sciences of Ukraine, 12 Ac. Proscura St., Kharkov 61085, Ukraine*

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Abstract

A new non-steady-state photovoltaic effect in a uniform bipolar semiconductor doped with impurities changing their charge state under illumination is predicted. Direct electric current is shown to arise in the ring-shaped uniform bipolar semiconductor sample illuminated by a moving light pattern. The physical basis of the effect is the simultaneous change of the charge carriers density and mobility, as well as the difference in lifetimes of the ionized impurities, charge carriers and the light pattern traveling time along the semiconductor sample.

The expression for the short-circuit photocurrent in the semiconductor ring is obtained under the quasineutrality assumption, its dependence on the light pattern parameters, as well as on the semiconductor properties and on the sample size is analyzed. It is shown that there are the optimum light pattern velocity and the optimum semiconductor length providing the largest magnitude of the photovoltaic effect. It is found that the short circuit photocurrent is proportional to the squared amplitude of the light intensity modulation at its arbitrarily small value. The photocurrent is also sensitive to the mean intensity of light pattern and may change its sign with increasing the mean intensity of the incident light. Under a sufficiently strong illumination the photovoltaic effect vanishes.

Keywords: dynamic photovoltaic effect; photoelectricity; nonequilibrium current carriers; electromotive force; mobility

1 Introduction

Considerable recent attention has been focused on non-steady-state photovoltaic effects that are not related to the presence of potential barriers in semiconductor samples [1–3]. Likely the interest in such mechanisms as the Dember effect is due to the fact that they can be responsible for the emission

**Corresponding author: E-mail: vin@ire.kharkov.com*

of terahertz radiation by ultrashort laser pulses [4–6]. In the view of the pure semiconductor physics the non-steady-state photovoltaic phenomena are of interest because they manifest themselves in situations where the formation of the static photo-electromotive force (photo-emf) is impossible [7–9]. Also non-steady-state photovoltaic effect seems promising from a practical viewpoint as the physical basis for new adaptive photodetectors [7, 10].

Recently, a growing number of papers devoted to the study of known photoelectric effects in new materials and conditions, as well as of the photoconverters based on new principles, have been published. Many of them deal with organic semiconductors. Details on the study and principles of the operation of organic photovoltaic cells can be found in the review [11]. The progress in their computer simulation is presented in [12]. Recently, new models for computer simulation of solar cells based on polymer/fullerene bulk heterojunction have been proposed [13].

Nevertheless, there are still a number of problems in the theory of photoelectric effects in bipolar semiconductors [14]. Among the insufficiently studied photoelectric effects, one can include phenomena associated with the appearance of photo-emf in directions normal to the direction of the photocarrier diffusion under nonstationary conditions. Thus, a large transient lateral photovoltaic effect at UV wavelengths in synthetic single crystal diamond has been reported [15].

Not long ago an experimental technique for determining the mobility and lifetime of nonequilibrium carriers in a semiconductor — the moving-photocarrier-grating technique [16–18], as well as the underlying theory of the dynamic photoelectric effect was developed [19–21]. Recently, it has been proposed to make use of this experimental technique for automatic measurement of thin film semiconductor transport parameters [22].

Unlike static photovoltaic phenomena in the semiconductor sample with no potential barrier (e.g., the Dember effect [9, 23, 24] and the bulk photovoltaic effect [9, 25]), where the current carrier mobility difference or the spatial inhomogeneity of the current carrier density give rise to the photo-emf, non-steady-state photovoltaic effect is essentially a transient process, all the time supported by an external perturbation (e.g. by the time-dependant spatial inhomogeneity of the illumination due to the space-time modulation of the incident light, such as a vibrating light pattern). If the illumination of a uniform semiconductor were static the transient process would end with formation of the nonequilibrium distribution of excess current carriers in such a way that the arising built-in electric field is compensated by the diffusion current, and the photo-emf vanishes. In other words, in terms of the imrefs (the quasi-Fermi levels), the static illumination would give rise to the spatially constant electron and hole imrefs. From these considerations, it is commonly assumed that the non-steady-state photo-emf (or the short-circuit photocurrent in the closed circuit) is an alternating electric signal, in which the harmonic corresponding to the frequency of the light intensity spatial modulation (e.g., the vibration frequency of the light pattern) is dominated. Naturally, due to the semiconductor nonlinearity high order harmonics are also possible. No direct current is believed to flow in the closed circuit under conditions of the non-steady-state photovoltaic effect, unless the semiconductor medium itself possesses rectifying properties.

However, from the physical point of view it is of interest to find out whether the appearance of the DC electric photocurrent as a result of non-steady-state illumination is in principle possible under conditions that fully rule out a static photo-emf? Or even more paradoxical formulation: may the only direct current (without alternating components) arise from the non-steady-state photovoltaic effect in the closed semiconductor circuit with no rectifying properties? For example, in the unbounded uniform bipolar semiconductor (the ring-shaped bipolar semiconductor sample)?

When studying the non-steady-state photovoltaic phenomena it is widely assumed that the effect of the light is limited to the generation of excess current carriers, i.e. it affects the only electron and hole density. However, in semiconductors doped with neutral or compensated impurities the illumination can also affect the current carrier mobility. The reason is that the impurity atom changes its charge state under illumination, so the cross section of the electron scattering by the impurity and hence the electron mobility also change. The simultaneous influence of the illumination on the excess current carriers density and their mobility gives rise to new photovoltaic effects, such as nonlin-

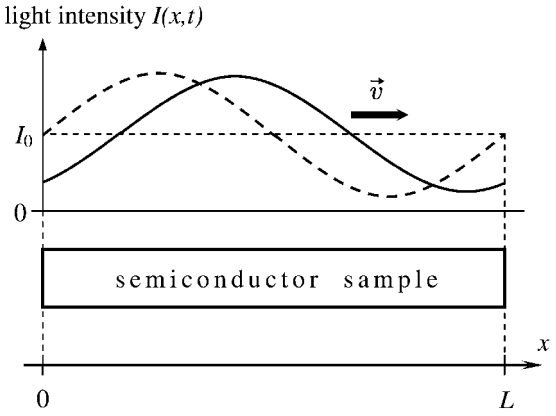

Figure 1: Semiconductor sample of length L, illuminated by moving light pattern.

ear photo-response in a uniform semiconductor ring illuminated by nonuniform incident light [26, 27]. As it will be shown below, the inclusion of the light-induced electron mobility change allows predicting the appearance of the direct photocurrent in the uniform semiconductor ring illuminated by the symmetric light pattern moving along the semiconductor. In this paper, in the framework of the quasi-neutrality assumption we develop the theory of the non-steady-state photovoltaic effect in a uniform bipolar semiconductor with neutral impurities that manifests itself in the appearance of the only direct photocurrent in the closed circuit.

2 Mathematical model of the photovoltaic effect

Let us consider a uniform bipolar semiconductor slab of the length L (see figure 1) illuminated by incident light with the intensity modulated as $I(x,t) = I_0 + I_a \cos[2\pi(x+vt)/L]$. Here I_0 is the mean intensity of the incident light; I_a represents the modulation depth of the light intensity in the "traveling wave"-type light pattern, moving along the semiconductor slab with its velocity v.

In order to simplify the calculations and to obtain a qualitative picture of the effect, we confine ourselves to the one-dimensional model, considering all the physical quantities in the transverse directions uniform.

If the photon energy is high enough, both the interband generation of electrons in the conduction band and holes in the valence band and the excitation of impurities simultaneously take place in the semiconductor. The impurity excitation also occurs with an increase of the charge carrier density (e.g., the ionization of an impurity energy level is accompanied by the electron transition from the impurity energy level to the conduction band). However, we assume that the impurity density is low enough to neglect their influence on the excess charge carrier density in the conduction and valence bands. In other words, we believe that the generation rate of the conduction electrons from the neutral impurity energy level substantially less than the rate of the interband photogeneration. At the same time the semiconductor temperature is taken to be low enough, so the impurity density is sufficient to ensure that the scattering of the charge carriers by the ionized impurities dominates. In other words, the model under consideration assumes that the excess charge carrier density is solely controlled by the interband transitions, while the carrier mobility is controlled exclusively by the impurity excitation.

We believe that the most favorable materials for such a situation are semiconductors with stoichiometric vacancies of $\mathrm{In_2Te_3}$-type[28]. In these semiconductors (which are remarkable by their radiation stability), in equilibrium, the impurities are always in the neutral state, while illumination or

ionizing radiation leads to the appearance of charged impurity levels, thus substantially changing their scattering cross-section, and hence the mobility of the current carriers.

Considering the process of the impurity photoexcitation in the Shockley-Read-Hall model [29], one can write the following expression for the density of the neutral impurities N_t:

$$\frac{\partial N_t}{\partial t} = R_t - G_t, \tag{2.1}$$

where $G_t = \alpha_g N_t I$ is the photogeneration rate of the conduction electrons from the impurity energy level, α_g is the scattering cross section of the impurity photoexcitation. The inverse process of the conduction electron capture by the impurity energy levels can be written as $R_t = \alpha_r n(N_{t0} - N_t)$, where N_{t0} is the dark density of neutral impurities, n is the electron density in the conduction band, α_r is the phenomenological parameter characterizing the probability of the conduction electron capture by the impurity energy level. Here we neglect the thermal excitation of the impurity, assuming a sufficiently low temperature. Recall that this condition is also necessary to ensure that the carrier scattering by impurities rather than by phonons prevails.

To obtain analytical solutions we restrict ourselves by the first order of the perturbation theory (i.e. by the linear approximation), considering the modulation depth of the incident light intensity to be low enough: $I_a \ll I_0$, $I_a \ll 2\pi v/(\alpha_g L)$. Physically the latter condition means that in a time the light pattern travels along the sample, only a small fraction of impurities (compared to their dark value) is ionized.

Then from Eq. (2.1) one obtains the following stationary distribution for the neutral impurities density in the semiconductor:

$$N_t = \overline{N}_t \left[1 - \zeta \cos \Omega(x,t)\right], \tag{2.2}$$

where

$$\Omega(x,t) = \frac{2\pi}{L}(x - x_0 + vt), \tag{2.3}$$

$$\overline{N}_t = \alpha_r n(I_0) \tau_g N_{t0}, \tag{2.4}$$

$$\zeta = \frac{\alpha_g \tau_g \tau_v}{\sqrt{\tau_g^2 + \tau_v^2}} I_a, \tag{2.5}$$

$$\sin \frac{2\pi x_0}{L} = \frac{\tau_g}{\sqrt{\tau_g^2 + \tau_v^2}}, \tag{2.6}$$

$$\tau_g = \left(\alpha_g I_0 + \alpha_r n(I_0)\right)^{-1}, \quad \tau_v = \frac{L}{2\pi v}. \tag{2.7}$$

In Eqs. (2.4)-(2.6) $n(I_0)$ is the conduction electron density in the semiconductor sample, uniformly illuminated by the incident light of the intensity I_0.

Physically the introduced above parameter τ_g represents the time scale for the photoexcitation of the impurity by the uniform illumination with the intensity I_0, and the parameter τ_v is the time the light pattern travels along the sample.

Eq. (2.2) shows that in darkness ($I_0 = I_a = 0$) one gets $N_t = N_{t0}$, as it might be expected, while for a sufficiently strong light $N_t \to 0$. Also, it turns out that the ionized impurity density is modulated by the same traveling wave law as the incident light intensity is modulated, but with some phase shift with respect to the latter. The space-time modulation depth of the unexcited impurity density ζ is the maximum for a still light pattern, with increase of the light pattern velocity v the modulation depth decreases, tending to zero for sufficiently large v. The phase shift represented by the parameter x_0 grows with the increase in the velocity v, tending to the limit $L/4$ at $v \to \infty$. Again, the increase of the mean incident light intensity I_0 reduces the phase shift which disappears in the limit of the infinitely strong illumination. As this takes place, the space-time modulation depth ζ of the unexcited impurity density also vanishes, indicating the complete ionization of impurities by a sufficiently strong light.

Assuming that the mobility of electrons is proportional to the excited impurity density $\mu_n \propto (N_{t0} - N_t)$, let us represent the electron mobility in the following form:

$$\mu_n(x,t) = \mu_{n0} + \delta\mu_{n0} + \delta\mu_{nd} \cos \Omega(x,t), \tag{2.8}$$

where μ_{n0} is the electron mobility in the semiconductor sample in darkness, $\delta\mu_{n0}$ describes the static change in the electron mobility by the action of light, and the term with $\delta\mu_{nd}$ is the dynamic part of the electron mobility change induced by the moving light pattern. These values are, respectively:

$$\delta\mu_{n0} = -\left.\frac{\partial\mu_n}{\partial N_t}\right|_{N_t=N_{t0}} \alpha_g\tau_g N_{t0} I_0, \tag{2.9}$$

$$\delta\mu_{nd} = -\left.\frac{\partial\mu_n}{\partial N_t}\right|_{N_t=N_{t0}} \frac{\alpha_g\alpha_r n(I_0)\tau_g^2\tau_v}{\sqrt{\tau_g^2+\tau_v^2}} N_{t0} I_a. \tag{2.10}$$

Within the framework of the successive approximation we use, the charge carrier mobility change caused by the illumination is assumed small enough: $|\delta\mu_{n0}| \ll \mu_{n0}$, $|\delta\mu_{nd}| \ll \mu_{n0}$.

The ionization of impurities also affects the hole mobility, but for the sake of simplicity we neglect this influence, considering that the hole mobility is completely controlled by another scatterers (e.g., by phonons) and it is a constant μ_{p0}.

Note that the considerations above are equally valid for the excitation of the neutral impurity (gaining a positive charge due to the photoionization), as well as for initially negatively charged acceptor impurity (which turns into its neutral state under the action of the light). In both cases the light causes a significant change in the scattering cross section of the impurity for the conduction electrons, and therefore affects their mobility. The distinction between these two cases lies in the value and sign of $\partial\mu_n/\partial N_t$.

Let us find the photo-emf arising in the semiconductor under aforesaid conditions within the formalism of the current continuity equations that in the 1-D model are written as follows [8, 24, 30]:

$$\frac{\partial n}{\partial t} = \frac{1}{e}\frac{\partial j_n}{\partial x} - R_n + G_n, \tag{2.11}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{e}\frac{\partial j_p}{\partial x} - R_p + G_p \tag{2.12}$$

where e is the electron charge, $G_{n,p}$ and $R_{n,p}$ are the photogeneration and recombination rates of electrons and holes, respectively, and $j_{n,p}$ are the current densities for electrons and holes:

$$j_n = e\mu_n nE + k_B T\mu_n\frac{\partial n}{\partial x}, \tag{2.13}$$

$$j_p = e\mu_{p0} pE - k_B T\mu_{p0}\frac{\partial p}{\partial x}, \tag{2.14}$$

where n and p are the densities of electrons and holes, respectively; k_B is the Boltzmann constant, T is the temperature of the semiconductor, E is the electric field in the semiconductor.

To determine the electric field Eqs. (2.11)-(2.14) must be supplemented with the Poisson equation:

$$\frac{\partial E}{\partial x} = \frac{4\pi\rho}{\epsilon}, \tag{2.15}$$

where ρ is the space charge, ϵ is the semiconductor permittivity.

To simplify subsequent calculations we use the quasineutrality approximation $\rho \approx 0$ [30–33]. To meet the latter condition it is requisite that the sample size vastly larger than the Debye screening length $L \gg r_D$, $r_D = (\epsilon k_B T/2\pi e^2 n(I_0))^{1/2}$, and all the problem time scales far exceed the Maxwell time $\tau_g \gg \tau_M$, $\tau_v \gg \tau_M$, $\tau_M = \epsilon/(4\pi\sigma_0)$ [8, 34]. Here σ_0 denotes the dark conductivity of the semiconductor: $\sigma_0 = e(\mu_{n0}n_0 + \mu_{p0}p_0)$, where n_0, p_0 are the densities of electrons and holes in the unlit semiconductor, respectively. When the above requirements are met, the Poisson equation becomes redundant and can be used for subsequent verification of the excess charge carrier density obtained. Due to the small impurity density and therefore its negligible influence on the charge carrier density, the condition of the space charge absence takes the form: $\delta n = \delta p$, where $\delta n = n - n_0$, $\delta p = p - p_0$.

As mentioned above, we assume that direct interband transitions make the major contribution to the charge carrier photogeneration rate. Then $G_n = G_p = g_I I(x,t)$, where g_I is the phenomenological factor, describing the efficiency of generation of electron-hole pairs [29, 35]. In the present context the expression for the interband recombination can be written in the following form [35]: $R_n = R_p = \delta n/\tau_R$, where τ_R is the charge carrier lifetime.

The system of differential equations in Eqs. (2.11)-(2.15) must be supplied with the appropriate boundary conditions (BCs). It should be emphasized that the correct choice of the BCs is crucial to accurately determine the value of the photo-emf in bounded semiconductors [36–38]. For example, properties of the "metal-semiconductor" interface affect not only the magnitude but also the sign of the Dember emf [37]. To avoid painstaking study of the contact region impact on the value of the photovoltaic effect, as well as to significantly simplify the calculations, we will connect the ends of the semiconductor (points $x = 0$ and $x = L$), forming the semiconductor ring. The most important physical parameter of the photoelectric effect in such a configuration is the short-circuit photocurrent. For this problem definition the BCs are extremely simplified and consist in the continuity conditions at $x = 0$ and $x = L$. In the quasineutrality approximation the continuity of the charge carrier density ($n(0) = n(L)$, $p(0) = p(L)$) is ensured by the single equation:

$$\delta n(0) = \delta n(L). \tag{2.16}$$

In view of Eq. (2.16) and Eqs. (2.13)-(2.14) the continuity condition for the electric potential $\varphi(0) = \varphi(L)$ and the electric field $E(0) = E(L)$ allow us to rewrite the continuity condition for the electron and hole currents $j_{n,p}(0) = j_{n,p}(L)$ as the continuity condition for the first-order derivative of the excess charge carrier density with respect to the coordinate:

$$\frac{\partial \delta n}{\partial x}(0) = \frac{\partial \delta n}{\partial x}(L). \tag{2.17}$$

Let us express the electric field in the semiconductor from Eqs. (2.13)-(2.14) :

$$E = \sigma^{-1}\left[j_0 - ek_BT\left(\mu_n \frac{\partial n}{\partial x} - \mu_{p0}\frac{\partial p}{\partial x}\right)\right], \tag{2.18}$$

where j_0 is the total electric current in the circuit (which, in general, has the dc and the ac components, i.e. $j_0 = j_0(t)$), $\sigma = e(\mu_n n + \mu_{p0} p)$ is the conductivity of the semiconductor. From the electric potential continuity, which for the closed circuit can be written as $\int_0^L E\mathrm{d}x = 0$, one obtains an expression for the short-circuit current:

$$j_0 = k_BT \int_0^L \frac{\mu_n - \mu_{p0}}{\sigma}\frac{\partial \delta n}{\partial x}\mathrm{d}x \left(\int_0^L \frac{\mathrm{d}x}{\sigma}\right)^{-1}. \tag{2.19}$$

Note that if the illumination does not affects the charge carrier mobility (i.e., if $\mu_n = \mu_{n0} = \mathrm{const}$), there is no current in the circuit, because in this case the integrand in Eq. (2.19) is the total differential of the function dependant only on δn with $\delta n(0) = \delta n(L)$. Assuming that the light-induced change of the electron mobility is small $\mu_n = \mu_{n0} + \delta\mu_n$, $|\delta\mu_n| \ll \mu_{n0}$, we expand the integrand in Eq. (2.19) in terms of $\delta\mu_n$ holding only the linear term. After some rearrangements one obtains:

$$j_0 = \frac{eD}{\mu_{n0}L}\int_0^L \delta\mu_{nd}\frac{\partial \delta n}{\partial x}\cos\Omega(x,t)\mathrm{d}x, \tag{2.20}$$

where $D = k_BT\mu_{n0}\mu_{p0}(n_0 + p_0)/\sigma_0$ is the ambipolar diffusion coefficient; $\sigma_0 = e(\mu_{n0}n_0 + \mu_{p0}p_0)$ is the dark conductivity of the semiconductor.

To derive Eq. (2.20) the above remarks that terms in the integrand, that do not explicitly depend on the coordinate, do not contribute to the short-circuit current are taken into account, and terms of higher order of smallness are omitted.

We emphasize that only the spatially nonuniform variation of the electron mobility $\delta\mu_{nd}$ appears in Eq. (2.20), while the uniform variation of the electron mobility $\delta\mu_{n0}$ drops out of the solution.

To calculate the excess charge carrier density δn we note that the integrand already contains a small quantity $\delta\mu_{nd}$ as a factor. So, when using the method of successive approximations to get the solution of Eqs. (2.11)-(2.12), one may assign $\mu_n = \mu_{n0}$ and hold only the linear terms with respect to δn. Granting this, substituting Eq. (2.18) in Eq. (2.13) and then Eq. (2.13) in Eq. (2.11) we finally obtain the following linear differential equation for the excess electron density:

$$\frac{\partial \delta n}{\partial t} = D\frac{\partial^2 \delta n}{\partial x^2} - \frac{\delta n}{\tau_R} + g_I I(x,t). \tag{2.21}$$

3 Results and discussion

Since we are interested in the stationary (but not static!) distribution of the charge carrier density (that is set, when all the transients, originated on the illumination switching on, are over), we seek the solution of Eq. (2.21) as a "traveling wave" with some phase shift relative to the incident light intensity:

$$\delta n = \delta n_0 + \delta n_s \sin\Omega(x,t) + \delta n_c \cos\Omega(x,t). \tag{3.1}$$

Then one easily obtains the following excess charge carrier densities:

$$\delta n_0 = g_I \tau_R I_0, \tag{3.2}$$

$$\delta n_s = g_I \frac{\tau_v^2 \tau}{\tau_v^2 + \tau^2} I_a, \tag{3.3}$$

$$\delta n_c = g_I \frac{\tau_v \tau^2}{\tau_v^2 + \tau^2} I_a, \tag{3.4}$$

where

$$\tau = \tau_R \left(1 + 4\pi^2 \frac{L_D^2}{L^2}\right)^{-1}, \tag{3.5}$$

and $L_D^2 = D\tau_R$ is the ambipolar diffusion length.

Note that the parameter τ is an effective carrier lifetime in the semiconductor ring. In a long sample it coincides with the charge carrier lifetime τ_R and decreases with reduction in the semiconductor length. The latter physically means lesser impact of recombination in a short sample: in this case the excess charge carriers have enough time to repeatedly go through the semiconductor ring before recombining.

Substituting the excess carrier density distribution obtained Eq. (3.1) and the electron mobility Eq. (2.8) into Eq. (2.20) one obtains the following expression for the photocurrent in the semiconductor ring:

$$j_0 = \pi e g_I \alpha_r \alpha_g \frac{D n_0 N_{t0}}{\mu_{n0} L} \left.\frac{\partial \mu_n}{\partial N_t}\right|_{N_t = N_{t0}} \frac{\tau_g^2 \tau_v^3 \tau(\tau_g - \tau)}{(\tau_v^2 + \tau_g^2)(\tau_v^2 + \tau^2)} I_a^2. \tag{3.6}$$

As it can be seen from Eqs. (3.6), the moving light pattern induces the constant electric current in the uniform ring-shaped semiconductor doped with neutral impurities. Surprisingly, the current has no alternating component at all (at least in the first order of the perturbation theory). It is particularly remarkable that even the main harmonic of the electric current (at the frequency of the incident light intensity modulation in each point of the semiconductor $f_0 = v/L$) is also suppressed.

Remarkable that even the electric current harmonic at the frequency of the incident light intensity modulation in each point of the semiconductor is also suppressed.

Physical foundation of the photovoltaic effect under consideration is as follows. Firstly, it is the simultaneous influence of light on both the excess charge carrier density and their mobility due to the presence of the impurities with controllable by light charge state. Secondly, it is the difference in the excited impurity lifetime τ_g and the effective lifetime τ of excess charge carriers. With $\tau_g = \tau$

the electric current in the circuit vanishes. Finally, the motion of a symmetric light pattern breaks the spatial symmetry of the problem, enabling the appearance of the photo-emf and the electric current, with sign being determined by the direction of the light pattern movement.

The considered photovoltaic effect features the square-law dependence on the amplitude of the incident light intensity modulation I_a for an arbitrarily small its value. Recall that for the known mechanisms of the photoelectric phenomena the magnitude of the photo-emf depends linearly on the incident light intensity, at least for low intensity.

As to the dependence of the short circuit current j_0 on the mean incident light intensity I_0, appearing in the definition of the parameter τ_g in Eq. (2.7), note two things. Firstly, the presence of the factor $\tau_g - \tau$ in Eq. (3.6) implies that for an appropriate choice of the semiconductor parameters the photovoltaic effect strongly depends on the mean incident light intensity. As the latter increases, one may observe even the change in sign of the electric current in the circuit. Secondly, a sufficiently high mean intensity of the light pattern suppresses the photovoltaic effect. As discussed above, it is due to the complete ionization of impurities at high-intensity illumination. However, let us note that this conclusion, despite its physical evidence, is not sufficiently justified by Eq. (3.6). In fact, Eq. (3.6) itself is obtained with assumption of the small I_0. Thus, one can speak correctly only about the tendency of the dynamical suppression of the photovoltaic effect with increasing the mean intensity of the incident light due to the depletion of the un-ionized impurities density in the sample.

Note that the considered non-steady-state photovoltaic effect takes place with appearance of the quasi-neutral ambipolar packet of excess charge carriers, rather than the nonequilibrium space charge as it is usually the case for dynamic photovoltaic phenomena [1–3, 39]. Moreover, the time dependence of the charge carrier density in the left hand side of Eqs. (2.11)-(2.12) is not crucial for the phenomenon under investigation. It would be possible to solve the system of equations in Eqs. (2.11)-(2.15), neglecting terms of $\partial n/\partial t$ and $\partial p/\partial t$ at all (though, of course, this approximation is not physically valid), and get a nonzero photocurrent $j_0 \neq 0$. Fundamental point is the phase shift between the excess electron density and the electron mobility (i.e., the ionized impurity density). Thus, the effect under consideration can be called a quasistatic photovoltaic effect.

Let us analyze the dependence of the short-circuit photocurrent j_0 on the basic parameters appearing in Eq. (3.6). First of all, note that the value of j_0 depends on the velocity of the light pattern movement v. It is the velocity of light pattern along with the sample length that determines the value of the parameter t_v (see Eq. (2.7)). For a sufficiently high light pattern velocity ($v \to \infty$) the photovoltaic effect vanishes as $j_0 \sim v^{-3}$. At the same time, for a sufficiently small light pattern velocity $j_0 \sim v$. The latter means that the considered photovoltaic effect is nonexistent when the semiconductor is illuminated by a fixed symmetric light pattern. The pattern motion breaks the spatial symmetry of the problem, giving rise to the electric current. Moreover, sign of j_0 is determined by direction of the light pattern movement (i.e. by sign of the velocity v)

From the above it follows that there is an optimal value of the light pattern velocity v^*, where the photovoltaic effect is most pronounced. One can show that $|v^*| = L/2\pi\tau_v^*$, where $\tau_v^* = (\tau^2 + \tau_g^2 + \sqrt{\tau^4 + 14\tau^2\tau_g^2 + \tau_g^4})/2$.

Note that the above results are obtained under the assumption of constant velocity of the light pattern $v = \mathrm{const}$. For a variable velocity of the light pattern an additional study is required, but it is clear that in this case the non-steady-state photovoltaic effect also takes place. However, due to the essential nonlinearity of the dependence $j_0(\tau_v)$ the spectrum of the short-circuit photocurrent most likely contains the ac components at the frequency of the light pattern velocity alternation as well as its harmonics.

From the analysis of Eq. (3.6) one can see that the value of j_0 depends essentially on the length of the semiconductor L just as explicitly (since the denominator of Eq. (3.6) includes L), so via dependencies of the times τ_v and τ on L. It can be shown that the electric current in the circuit vanishes as L^2 with decrease in the sample length. At the same time, in long samples the short-circuit photocurrent decreases by the law L^{-2} with increase in the sample length. This suggests that there is some optimal length of the sample for which the photovoltaic effect is expressed in its fullest extent.

Let us analyze the dependence of the short-circuit photocurrent j_0 on the charge carrier lifetime τ_R. In the case of extremely strong recombination $\tau_R \to 0$, hence $\tau \to 0$ (see Eq. (2.7)), so the current in the circuit vanishes as $j_0 \sim \tau_R \to 0$. The physical reason for this result is clear: very high recombination rate at the quasi-neutrality means there are no excess charge carriers [30, 35]. All the electron-hole pairs generated by light recombine at the place of their generation, not having a chance to contribute to the photo-emf. In the opposite limiting case, in the absence of recombination ($\tau_R \to \infty$), the effective charge carrier lifetime τ is finite $\tau = L^2/4\pi^2 D$. Accordingly, the electric current in the circuit remains a finite value as well. It is interesting to note that in the limiting case of the absence of recombination for closely-related mechanisms of the photovoltaic phenomena (e.g., the Dember effect and the bulk photovoltaic effect) the photo-emf continuously increases with increase of the charge carrier lifetimes [8, 9, 23–25].

4 CONCLUSIONS

The above analysis demonstrates that a light pattern moving along the uniform ring-shaped semiconductor doped with impurities, changing their charge when exposed to light, gives rise to the direct electric current. This effect is resulted from the simultaneous action of the light on the charge carrier mobility and density, the existence of the characteristic time hierarchy (the charge carrier lifetime, the ionized impurity lifetime and the light pattern travel time), as well as the spatial symmetry violation by the movement of the light pattern.

The considered non-steady-state effect is a quasi-static phenomenon by its physical nature since it is not related to the nonequilibrium space charge in the semiconductor. The excess charge carrier transport is ambipolar.

The magnitude of the photovoltaic effect nonlinearly depends on the light pattern velocity, while sign of the electric current is determined by direction of the light pattern movement. There is an optimum velocity of the light pattern, whereby the electric current in the circuit reaches its maximum value. For immobile or moving too fast light patterns the photovoltaic effect vanishes.

The dependence of the short-circuit photocurrent in the closed semiconductor circuit is a bulky strongly nonlinear function of the semiconductor parameters and the sample length. There is an optimal length of the semiconductor, for which the photovoltaic effect is most pronounced.

The photovoltaic effect in question exhibits the nonlinear (square-law) dependence on the amplitude of the light intensity modulation. The effect is also sensitive to the mean intensity of the incident light. If the mean incident light intensity is high enough, the photovoltaic effect is suppressed. Furthermore, for an appropriate choice of parameters the photo-emf and the electric current in the circuit may change in sign with increasing the mean intensity of the light pattern.

Now it is difficult to consider a practical implementation of the predicted effect, more likely it is of a pure theoretical interest. However, it may be relevant as a source of noise in photoresistors and photoconverters.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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