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The effect of photoinduced local space charge on the effective rate of photogeneration of carriers in a longitudinal photoresistor

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It is theoretically shown that the effective carrier photogeneration rate in a longitudinal photoresistor, which directly initiates the conversion of radiation into electric current, can be positive, zero, or negative, and significantly exceeds in absolute value the true carrier photogeneration rate. The effects are due to photoinduced local space charge.

Keywords: photoinduced charge, absorption coefficient.

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In a transverse photoresistor irradiated perpendicularly to dark electric field $\mathbf{E}_0$ (axis x, Fig. 1, a), special profiling of density of the incident photon flux $F(x)$ results in profiling also the density of carrier photogeneration rate (CPR) $g(x)$ and, hence, gives rise to unexpected photoelectric effects: $g(x)$ self–amplification and self–quenching, as well as its sign self–inversion [1–3]. These effects are caused by the photo–induced space charge (PSC) initiating effective CPR [2,3] (see below). Similarly to [1–3], this paper considers a longitudinal photoresistor (i.e., the radiation is directed along with or opposite to $\mathbf{E}_0$, Fig. 1, a) beyond of the quasi–neutral approximation (QNA). In this case, profile $g(x)$ cannot be deliberately varied. It is governed by the radiation absorption coefficient γ. However, results of [1–3] show that it will be physically and practically interesting to investigate the PSC influence on the total effective CPR in the sample (see below). This work is devoted to theoretical analysis of just this issue.

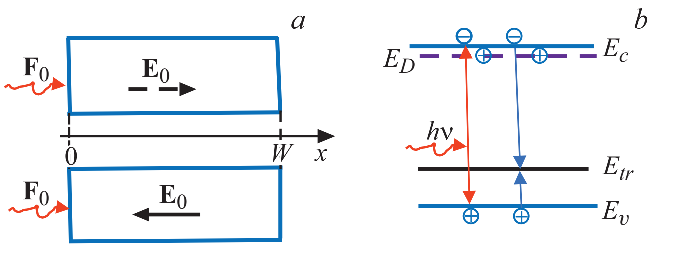

Figure 1. a — directions of the incident photon flux with density $\mathbf{F}_0$ and of dark electric field $\mathbf{E}_0$. The dashed and solid arrows correspond to the cases when the field is directed along $\mathbf{F}_0$ and opposite to it, respectively. b — schematic diagram of carrier photogeneration and recombination in a semiconductor. $h\nu$ is the photon energy, E_c, E_v, E_D and E_{tr} are the energies of the conductivity band bottom, valence band top, and levels of shallow donor and recombination impurities, respectively.

The problem definition is similar to that in papers [1–3]. In this study, a nondegenerate semiconductor with interband photogeneration and impurity recombination of carriers is considered. The semiconductor is doped with fully ionized shallow donors with concentration N_D; carrier recombination proceeds through acceptors with concentration N, which may be in the neutral or singly charged negative state, i.e., acceptors create a single recombination level with energy E_{tr} [4,5 (Part 1, p. 26)] (Fig. 1, b). Concentrations of the charged and neutral acceptors are N_- and N_0, their equilibrium values are $N_- = N_-^e$ and $N_0 = N_0^e$, respectively. The photoelectric effect is assumed to be intended for detecting weak radiation [6–10]. This allowed us to restrict ourselves to the approximation linear with respect to g. The value of $|\mathbf{E}_0|$ is small, hence, $\mathbf{E}_0$ does not affect the electron mobility μ_n and hole mobility μ_p. What is important is that we do not assume local quasi–neutrality of the irradiated sample. The presence of diffusion–drift processes and nonuniformity of $g(x)$ cause nonuniformity of photoelectron concentration distribution $n_{ph}(x)$ and photohole concentration distribution $p_{ph}(x)$. For instance, the photoelectron concentration distribution is defined by the following equation [11,12]:

$$Q(\partial^4 n_{ph}/\partial x^4) - D(\partial^2 n_{ph}/\partial x^2)$$
$$+ \mu E_0(\partial n_{ph}/\partial x) + n_{ph}/\tau_n = g_{efn}(x). \quad (1)$$

Factors Q, D and μ in this equation depend on dimensionless parameter

$$\xi = (a_n + a_p)2\delta/(\delta^2\mu_n n_{tr} + 4\mu_p p_{tr}), \quad (2)$$

$$a_n = \frac{\varepsilon\varepsilon_0}{q}\frac{(1+\delta)w_p N n_e}{\delta\theta N + (1+\delta)(1+\delta^{-1})(n_e + \delta\theta p_e)}, \quad (3)$$

$$a_p = \frac{\varepsilon\varepsilon_0}{q}\frac{(1+\delta)w_p N p_e}{N + (1+\delta)(1+\delta^{-1})(n_e + \delta\theta p_e)}, \quad (4)$$

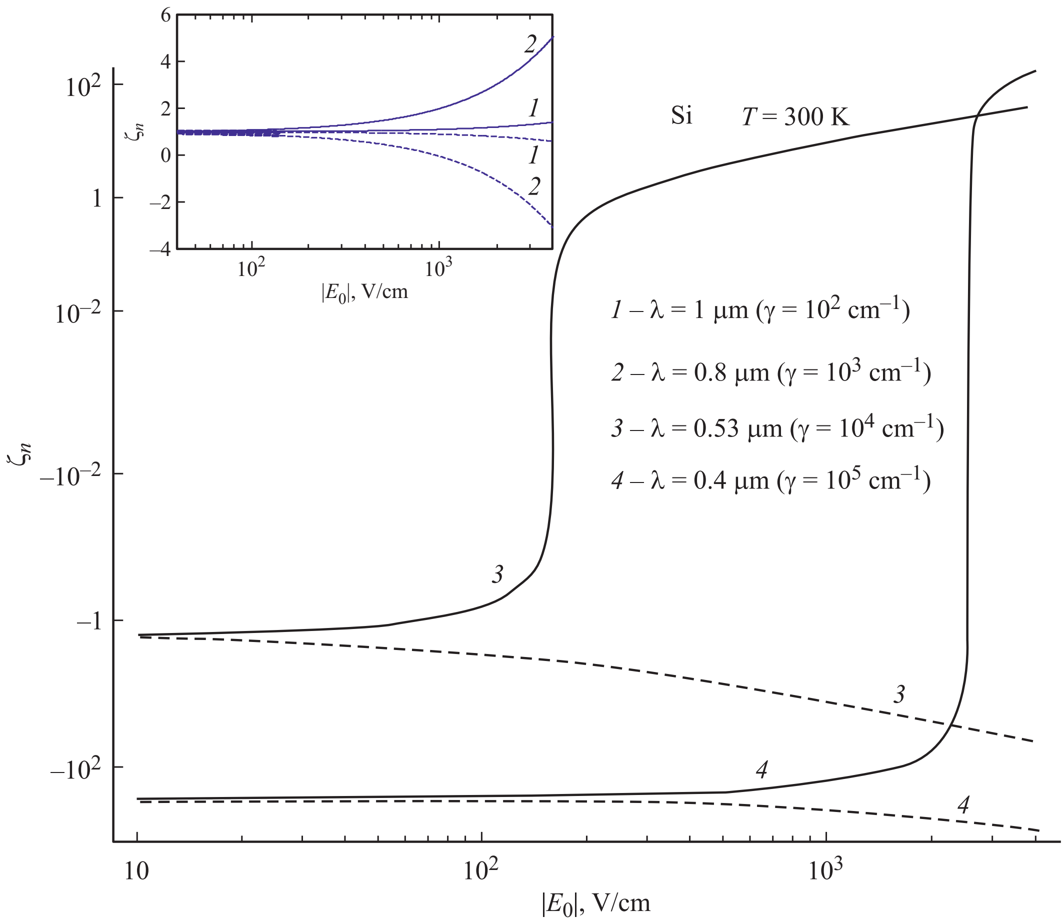

Figure 2. Ratio $\xi_n = g^{tot}_{efn}/g^{tot}$ between total ($g^{tot}_{efn} = \int_0^W g_{efn}(x)dx$) and true ($g^{tot} = \int_0^W g(x)dx$) carrier photogeneration rates in a longitudinal photoresistor versus the absolute intensity of dark electric field $|E_0|$ at different radiation wavelengths λ (radiation absorption coefficients γ). Dashed and solid lines are for radiation directions parallel and antiparallel to the electric field, respectively. The following values are accepted: $n_i/n_{tr} = 10^4$, $\theta \equiv w_p/w_n = 10^2$, $w_n = 10^{-8}\,\mathrm{cm^3/s}$ [4,5 (Part 1, p. 26), 11,12]; $\mu_n = 1500\,\mathrm{cm^2\cdot V^{-1}\cdot s^{-1}}$, $\mu_p = 400\,\mathrm{cm^2\cdot V^{-1}\cdot s^{-1}}$, $\varepsilon = 11.9$ [4,5 (Part 2, p. 447), 11,12]; $N = N_D = 10^{15}\,\mathrm{cm^{-3}}$ (n_i — is the intrinsic carrier concentration).

$n_e = (\delta/2)n_{tr}$ and $p_e = (2/\delta)p_{tr}$ are the equilibrium concentrations of electrons and holes, respectively; n_{tr} and p_{tr} are the equilibrium concentrations of electrons and holes in the case when the Fermi level energy is $E_F = E_{tr}$; w_n and w_p are the probabilities of the electron and hole capture by acceptors; $\theta = w_p/w_n$; ε is the dielectric permeability; ε_0 is the dielectric constant; q is the absolute electron charge. Electron lifetime in QNA is

$$\tau_n = \frac{1+\delta^{-1}}{w_p N}\frac{\delta\theta N + (1+\delta)(1+\delta^{-1})(n_e+\delta\theta p_e)}{N + (1+\delta)(1+\delta^{-1})(n_e+p_e)}. \quad (5)$$

The equation (1) right−hand part is defined as [11,12]

$$g_{efn}(x) = g(x) + \xi\tau_p[D_p(\partial g/\partial x) - \mu_p E_0(\partial^2 g/\partial x^2)], \quad (6)$$

D_p is the hole diffusion coefficient, their lifetime in QNA is

$$\tau_p = \frac{1+\delta^{-1}}{w_p N}\frac{\delta N + (1+\delta^2)(n_e+\delta\theta p_e)}{\delta N + (1+\delta)^2(n_e+p_e)}. \quad (7)$$

The parameter ξ value characterizes the PSC density. In QNA, $\xi = 0$, and equation (1) takes the habitual form [4–10]:

$$-D^n_a(\partial^2 n_{ph}/\partial x^2) + \mu^n_a E_0(\partial n_{ph}/\partial x) + n_{ph}/\tau_n = g(x), \quad (8)$$

where D^n_a and μ^n_a are ambipolar diffusion coefficient and ambipolar electron mobility [11,12]. Equation (6) shows that, as distinct from the case of QNA (8), functions $g_{efn}(x)$ and $g(x)$ do not coincide with each other at $g(x) \neq \mathrm{const}$. Therefore, $g_{efn}(x)$ may be called as effective density of the electron photogeneration rate; it directly initiates the radiation conversion into the electron component $I^{(n)}_{ph}$ of the photocurrent density I_{ph} (by definition of the difference between current densities under irradiation and without it).

Parameter $\delta = N^e_-/N^e_0$ has been introduced to ensure a convenient parametric method for solving the problem of the semiconductor photoelectric characteristics dependence on E_{tr} and

$$N = n_{tr}\frac{1+\delta}{2\delta^2}\left(4\frac{p_{tr}}{n_{tr}} + 2\delta\frac{N_D}{n_{tr}} - \delta^2\right). \quad (9)$$

This method, which once has revealed a possibility of a huge burst of $\tau_n(N)$, $\tau_p(N)$ and photocurrent with increasing N [12–15], was applied in this work.

The equation (1) left−hand part allows for the electron component of the photoelectric conversion (PEC) $G_0^{(n)} = I_{ph}^{(n)}/(qg_{efn}^{tot})$ [10–12], where

$$g_{efn}^{tot} = \int_0^W g_{efn}(x)dx, \quad (10)$$

W is the distance between the current contacts. Hence, the true coefficient of the PEC electron component is $G_n = I_{ph}^{(n)}/(qg^{tot}) = \xi_n G_0^{(n)}$, where total CPR g^{tot} is defined by the expression similar to (10) (see the Fig. 2 caption), $\xi_n = g_{efn}^{tot}/g^{tot}$, i.e. the photo−induced space charge can affect G_n. Let us analyze some of situations.

Taking into account the multiple internal reflection, it is possible to define the density of carrier photogeneration rate by expression

$$g(x) = \gamma\left[a_-\exp(-\gamma x) + a_+\exp(\gamma x)\right], \quad (11)$$

in which

$$a_- = \frac{(1-R)F_0}{1-R^2\exp(-2\gamma W)}, \quad a_+ = a_- R\exp(-2\gamma W), \quad (12)$$

where F_0 is the density of the incident photon flux (Fig. 1, a), and the radiation reflection coefficient is

$$R = \left(\sqrt{\varepsilon}-1\right)^2/\left(\sqrt{\varepsilon}+1\right)^2. \quad (13)$$

Relations (6), (10)−(13) show that parameter ξ_n is defined as

$$\xi_n \equiv \frac{g_{efn}^{tot}}{g^{tot}} = 1 - \xi\tau_p\gamma\left[\gamma D_p + \mu_p E_0 f(\gamma W, R)\right], \quad (14)$$

where

$$f(\gamma W, R) = f_1(\gamma W, R)/f_2(\gamma W, R),$$

$$f_{1,2}(\gamma W, R) = 1 - (1 \pm R)\exp(-\gamma W) \pm R\exp(-2\gamma W).$$

One can see in Fig. 2 that the existence of photo−induced space charge makes ratio $\xi_n \equiv g_{efn}^{tot}/g^{tot}$ between effective g_{efn}^{tot} and true g^{tot} rates of electron photogeneration in the sample strongly different from unity and even negative. This fact is to affect the PEC coefficient G_n. The coefficient should be expected to appear either significantly higher or significantly lower than in QNA. Moreover, G_n may prove to be even negative and depending on the radiation and electric field mutual directions.

Beyond QNA, as well as in QNA, photohole concentration $p_{ph}(x)$ is connected with photoelectron concentration $n_{ph}(x)$ by an analytical (but another) relation [11,12]. This allows us to assume that PSC may also essentially and differently affect also total PEC coefficient $G = I_{ph}/(qg^{tot})$ of the longitudinal photoresistor.

Emphasize that it is impossible to obtain the above−mentioned effects in QNA. Jointly with previous results [1–3], the results obtained here dictate the necessity to fundamentally and comprehensively analyze the expected effects in order to clarify perspectives of their application in photoelectronics.

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Conflict of interests

The author declares that he has no conflicts of interest.

References

[1] V.A. Kholodnov, Global J. Astron. Appl. Phys. (USA), **2** (1), 1 (2020). DOI: 10.46940/gjaap.02.1002
[2] V.A. Kholodnov, J. Commun. Technol. Electron., **66** (9), 1103 (2021). DOI: 10.1134/S1064226921090059.
[3] V.A. Kholodnov, J. Commun. Technol. Electron., **67** (3), 340 (2022). DOI: 10.1134/S106422692203006.
[4] A.G. Milns, *Deep impurities in semiconductors* (John Wiley and Sons, N.Y.−London−Sydney−Toronto, 1973).
[5] S.M. Sze, *Physics of semiconductor devices* (John Wiley and Sons, N.Y.–Chichester–Brisbane–Toronto–Singapore, 1981).
[6] G. Lutz, *Semiconductor radiation detectors* (Springer-Verlag, Berlin−Heidelberg−N.Y., 2007).
[7] A. Rogalski, *Infrared detectors* (CRC Press, Taylor & Francis Group, Boca Raton−London−N.Y., 2011).
[8] V.P. Ponomarenko, A.M. Filachev, *Infrakrasnaya tekhnika i elektronnaya optika* (Fizmatkniga, M., 2016). (in Russian)
[9] V.P. Ponomarenko, *Kvantovaya fotosensorika* (Orion, M., 2018). (in Russian)
[10] A.M. Filachev, I.I. Taubkin, M.A. Trishenkov, *Tverdotel'naya fotoelektronika. Fotorezistory i fotopriemnye ustroystva* (Fizmatkniga, M., 2012). (in Russian)
[11] V.A. Kholodnov, J. Commun. Technol. Electron., **64** (9), 1038 (2019). DOI: 10.1134/S1064226919090110.
[12] V.A. Kholodnov, M.S. Nikitin, in *Optoelectronics — materials and devices*, ed. by S.L. Pyshkin, J. Ballato (InTech, 2015), ch. 12, p. 301−348. www.intechopen.com
[13] A.A. Drugova, V.A. Kholodnov, Solid-State Electron., **38** (6), 1247 (1995). DOI: 10.1016/0038-1101(94)00154-8
[14] V.A. Kholodnov, Semiconductors, **30** (6), 538 (1996).
[15] V.A. Kholodnov, JETP Lett., **67** (9), 685 (1998) DOI: 10.1134/1.567702.