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The Radical Impact of Spatially Nonuniform Illumination on Giant Splash in the Photoelectric Gain of a Photoconductor

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ABSTRACT

We evaluated the impact of spatially nonuniform illumination on giant splash in the photoelectric gain of a photoconductor (PC) occurring with an increase in the concentration of recombination centers (traps) in semiconductors. Nonuniformity was considered along electric field in the PC. This study was performed beyond the quasi-neutrality (QN) approximation. It showed that the splash in the photoelectric gain at uniform and nonuniform illuminations can differ from each other by orders of magnitude due to the photoinduced space charge. In case of nonuniform illumination, the amplitude of the photoelectric gain splash strongly depends on the polarity of the applied bias voltage and the mutual directions of the gradient of incident radiation flux intensity and external electric field. A simple approach using QN approximation and uniform profile of photogenerated charge carriers does not allow to reveal the described features.

Keywords: Semiconductor, trap, intrinsic photoconductivity, photoinduced space-charge, photoelectric gain

Introduction

We used the following model and symbols: a) semiconductor was nondegenerate; b) photogeneration of charge carriers is band-to-band; c) density of photogeneration rate g(x)≠const along external electric field $\vec{E}$ with intensity $|\vec{E}_0|=E_0$, when $g = 0$; d) electric current contact electrodes are located at $x = 0$ and $x = W$; e) semiconductor is doped with shallow fully ionized donors and deep acceptors with concentrations N_d and $N = N_0 + N_-$, where N_0 and N_- are concentrations of neutral and singly negatively-charged acceptors; f) recombination occurs through acceptor energy states (traps); g) deviations in the concentrations of holes $\Delta p = p - p_e$, electrons $\Delta n = n - n_e$, neutral and singly negatively-charged acceptors $\Delta N_0 = N_0 - N_0^e = -\Delta N_- = -N_-^e - N_-$ from equilibrium values n_e, p_e, N_0^e, and N_-^e are small. This modeling approximation is often realized when low-intensity optical radiation is detected with PC [1, 2]. Trapping probabilities of electrons and holes are w_n and w_p. The absolute value of electron charge is q. Intrinsic concentration of charge carriers is n_i; n_{tr} is the value of n_e, when Fermi level E_F coincides with the energy level of the acceptor (trap) E_{tr}. Electron and hole mobility, diffusion constant and lifetime are denoted by μ_n, D_n, τ_n and μ_p, D_p, τ_p, respectively. Hole diffusion length is $L_p = \sqrt{D_p \tau_p}$. Density of photocurrent is I_{ph}.

Modeling of Photoconductor Performance

For simplicity, assume that the thickness of PC in the direction of the incident irradiation flux (see insert in Fig. 1a) is less than the absorption length. This means a uniform photogeneration of excess charge carriers in this direction. Linear approximation in g is used. Phenomenon of giant splash in the photoelectric gain G (Eq. (1)) of PC with an increase in the concentration N of the recombination centers (Fig. 1a) has been predicted [3] for $g(x) = \overline{g} = const$ and then described in detail [4-6] and reported [7].

$$G = I_{ph}/(q\bar{g}W) \tag{1}$$

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The effect of giant splash is due to a possible increase by several orders of electron τ_n and hole τ_p lifetimes with an increase in N (Fig. 1b), as was first shown in [9, 10]. Additionally, previously obtained results [3, 6] show that with increase in E_0, value $G(N)$ begins to depend strongly on the photoinduced space charge (PSC) density, even when the charge carriers were preheated by the electric field. I.e., with growth of E_0, the local QN of photoexcited plasma is disturbed. We studied the case when illumination was spatially nonuniform along $\vec{E}_0$. To determine the strongest effect of nonuniform illumination and PSC on $G(N)$, we analyzed the case $N = \hat{N}$, when $G(N)$ reached the maximum value $\hat{G} = G(\hat{N})$. Following the method given in [4-6, 9, 10], we can find analytical dependencies [9, 10] for τ_n, τ_p, and derive the relationship between Δp and Δn:

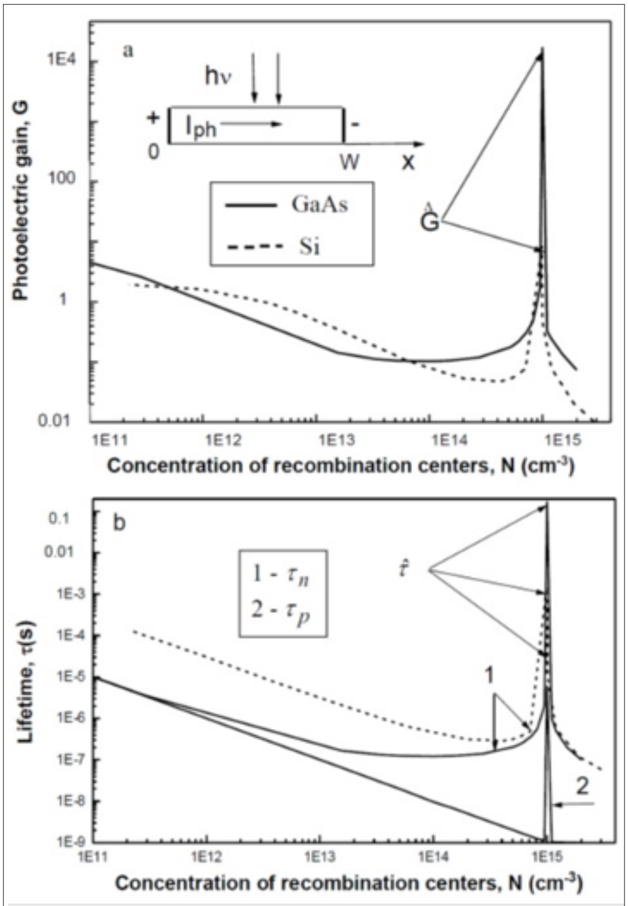

Figure 1. Dependencies of photoelectric gain at uniform illumination ($g(x) = const$) (a) and electron and hole lifetimes (b) on N; $\hat{\tau}$ - maximal values of τ_n, τ_p. It is assumed: T=300 K, W=0.1 cm, N_d=10^15 cm^-3, E_0=10 V/cm, n_{tr}/n_i=10^4, w_n=10^-8 cm^3/s, $\theta = w_n/w_p$=10^2. The values of semiconductor parameters are taken from [8]

$$\Delta p = (1+\chi)\frac{\tau_p}{\tau_n}\Delta n - \chi\tau_p\left[g + \mu_n E_0\frac{\partial \Delta n}{\partial x} + D_n\frac{\partial^2 \Delta n}{\partial x^2}\right]. \quad (2)$$

Equation for $\Delta n(x)$ at maximum point of function $G(N)$ can be written as:

$$Q\frac{\partial^4 \Delta n}{\partial x^4} - D\frac{\partial^2 \Delta n}{\partial x^2} + \frac{\Delta n}{\tau_n} = = g + \xi\tau_p\left(\mu_p E_0\frac{\partial g}{\partial x} - D_p\frac{\partial^2 g}{\partial x^2}\right)' \quad (3)$$

where $Q = \xi D_n L_p^2$; $D = D_a + D_E + D_\xi$ - effective diffusion coefficient consists of the ambipolar diffusion constant D_a and components due to PSC: D_E - electric field assisted and D_ξ - nonrelated to electric field:

$$D_a = \frac{n_e\tau_p + p_e\tau_n}{(D_n n_e + D_p p_e)\tau_n} D_n D_p; \quad (4.1)$$

$$D_E = \xi\tau_p\mu_p\mu_n E_0^2; \quad (4.2)$$

$$D_\xi = \xi_p\frac{\tau_p}{\tau_n}D_p + \xi_n D_n, \quad (4.3)$$

parameters χ, ξ, and $\xi_{n,p} < \xi$ characterize the deviation of the assemble of photogenerated charge carriers from local QN [4-6]. In QN approximation, $\chi = \xi = \xi_n = \xi_p = 0$. In deriving Eq. (3), it was taken into account that coefficient preceding $\frac{\partial \Delta n(x)}{\partial x}$ vanishes (within small corrections [4-6]) at the same value $N = \hat{N}$, where functions $\tau_n(N)$ and $\tau_p(N)$ reach maxima $\hat{\tau}_n$ and $\hat{\tau}_p$ (Fig. 1b). Photocurrent density:

$$I_{ph} = \Delta I_n(x) + \Delta I_p(x) \quad (5)$$

consists of electron and hole components:

$$\Delta I_n(x) = q\left[\mu_n[E_0\Delta n(x) + n_e\Delta E] + D_n\frac{d\Delta n(x)}{dx}\right], \quad (6)$$

$$\Delta I_p(x) = q\left[\mu_p[E_0\Delta p(x) + p_e\Delta E] - D_p\frac{d\Delta p(x)}{dx}\right], \quad (7)$$

where $\Delta E = E - E_0$ - photoinduced electric field intensity (difference between electric field intensity in the sample under illumination E and without illumination E_0). Considering the sample with sweep-out effect at contacts, i.e., with conditions at conta:

$$\Delta n(0) = \Delta p(0) = \Delta n(W) = \Delta p(W) \quad (8)$$

and nonuniform illumination along or against the direction of
and nonuniform illumination along or against the direction of
electric field $\vec{E}_0$. Due to the fact, that the illumination does not change the electrical voltage drop on the sample, we get from Eqs. (5)-(7):

$$I_{ph} = I_{ph}^{n} + I_{ph}^{p}, \tag{9}$$

where electron I_{ph}^{n} and hole I_{ph}^{p} photocurrents:

$$I_{ph}^{n} = q\mu_n \langle \Delta n \rangle E_0 \tag{10}$$

$$I_{ph}^{p} = q\mu_p \langle \Delta p \rangle E_0 \tag{11}$$

and $\langle \Delta n \rangle$ and $\langle \Delta p \rangle$ - arithmetic mean values of photoelectrons and photoholes concentra:

$$\langle \Delta n \rangle = \frac{1}{W}\int_0^W \Delta n(x)dx \ , \tag{12}$$

$$\langle \Delta p \rangle = \frac{1}{W}\int_0^W \Delta p(x)dx \ , \tag{13}$$

For definiteness, assume an exponential dependence of the illumination intensity along x axis of PC (see insert in Fig. 1a):

$$g(x) = g(0)\exp(-\beta x), \tag{14}$$

where $\beta > 0$ - decay index. When the density of irradiation flux is reversal, i.e., maximal at $x = W$, then $g(x)$ can be found from Eq. (14) by the replacement x on $W - x$. Eq. (3) has the exact solution under studied conditions. For simplicity, let's limit the consideration by I_{ph}^{n} (Eq. (10)) and accordingly, electronic photoelectric gai:

$$G_n = \frac{I_{ph}^{n}}{q g_{tot}} \ , \tag{15}$$

where

$$g_{tot} = \int_0^W g(x)dx = \frac{g(0)}{\beta}\left[1 - \exp(-\beta W)\right] \tag{16}$$

is the total density of the photogeneration rate of charge carriers in PC.

The required four boundary conditions are determined by Eqs. (2) and (8). Expressions for I_{ph}^{n} and G_n are of a very cluttered appearance. Therefore, Fig. 2 shows only the solution found for $\hat{G}_n(E_0)$.

Discussion and Conclusions

The results of the calculation beyond local quasi-neutrality (QN) approximation shows that nonuniformity of the photogeneration rate density along the external electric field can drastically affect the giant splash of the photoelectric gain (G) in the photoconductor (PC), with an increase in the concentration of the recombination centers N (Fig. 2). This influence grows with an increase in $|\nabla g(x)|$.

Opposite to local QN approximation, the case beyond local Opposite to local QN approximation, the case beyond local QN assumes occurring PSC; therefore, the value $G = \hat{G}$ at a maximum of $G(N)$ depends strongly on the mutual directions of ∇g and $\vec{E}_0$. I.e., value $\hat{G}$ depends on the polarity of the applied bias voltage (curves 1 and 2 in Fig. 2). Note that in QN approximation (curve 4 in Fig. 2), there is no such dependence, because ξ=0 in this approximation. Therefore, the external electric field does not affect the distribution of photoelectrons in the sam.

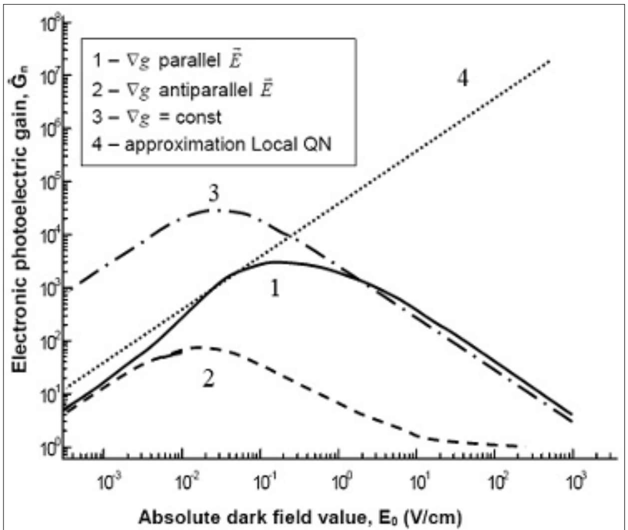

Figure 2. Dependencies of the maximal value $G_n(N) = \hat{G}_n$ on E_0 in GaAs photoconductor with a sweep-out effect at contacts. Assumed values: $E_{tr} = \frac{E_g}{2} - 0.24$ eV, β=10^4 cm^{-1}, bandgap E_g=1.42 eV [8]. Other parameters are the same as in Fig. 1

In PCs with a sweep-out effect at current contacts, the increase in $|\nabla g(x)|$ leads usually to decreases in $\hat{G}$. Here, as in the case $\nabla g(x) = 0$, function $\hat{G}(E_0)$ has a maximum. This is caused by an increase in the term D_E Eq. (4.2) of effective diffusion coefficient D (a coefficient preceding $\frac{\partial^2 \Delta n}{\partial x^2}$ Eq. (3)) with growth of E_0. The latter provides increase in the loss of photogenerated charge carriers due to the diffusion to contacts and subsequent recombination there. With parallel ∇g and $\vec{E}_0$, the maximum value $\hat{G}(E_0)$ is larger and is achieved at higher E_0 than in the antiparallel case. Due to PSC, effective density of photogeneration rate (right side of Eq. (3)) depends on the mutual directions of ∇g and $\vec{E}_0$. QN approximation is not feasible for the calculation of $\hat{G}(E_0)$ dependency.

Used calculation method is described in detail in [11-13].

Similarly, it was reported for the first time in [14] (see also [15]) about the availability of a minimum and a region of weak growth (by 24%) in the experimental dependence of the lifetime of the nonequilibrium charge carriers on the concentration of the recombination centers. Moreover, lifetime increased under irradiation of the sample with a high-energy electron flux. Much later, an increase in lifetime was observed experimentally [16], possibly due to an increase in N at least several times. However, any physical explanation or theoretical justification was not given.

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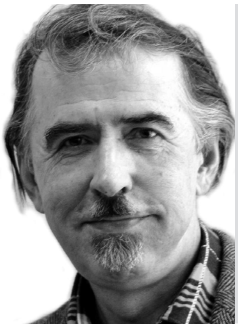

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