Self-organization in semiconductors with drift instability under influence of modulated light. II. Light response to external field variations

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The spectral dependence of photo-response for a finite size semiconductor under Gunn effect has been theoretically studied. A correlation has been established between the voltage variations across a sample and current and illumination time-harmonic variations. The problem of the light response frequency dispersion, in particular, in the voltage and current generation modes has been considered. The light response spectral dependences have been shown to be substantially different in voltage and current generation modes. For a semiconductor with *n*–GaAs parameters show that the above dependences for long and short samples are different in character. This fact is supposed to be caused by an area of spatially inhomogeneous distribution of volume charge appearing under illumination, that area contributing to different extent to the integral characteristic, depending on the sample length.

Теоретически исследована спектральная зависимость фотоотклика полупроводника конечных размеров в условиях существования Ганн-эффекта. Обнаружена связь между изменениями напряжения на образце и вариациями тока и освещенности, изменяющихся во времени по гармоническому закону. Рассмотрен вопрос о частотной дисперсии фотоотклика, в частности, в режимах генератора напряжения и тока. Показано, что спектральные зависимости фотоотклика в режимах генератора напряжения и тока существенно отличаются друг от друга. Для полупроводника с параметрами *n*–GaAs показывают, что характер указанных зависимостей для длинных и коротких образцов различен. Высказано предположение, что последнее, вероятно, обусловлено возникновением при освещении области пространственно-неоднородного распределения объемного заряда, которая дает различный вклад в интегральную характеристику в зависимости от длины образца.

A new non-linear optical effect in semiconductors, namely, the photo-refractive analog of Gunn effect, was predicted in [1]. The model described in that work supposes the sample illumination with two modulated waves of slightly different frequencies, in addition to the conditions necessary for the ordinary Gunn effect in alloyed semiconductor. The resulting moving interference patterns excite a series of Gunn domains, moving phase-locked with interference bands. A principal advantage of this effect is the possibility to control domain propagation speed by means of laser illumination intensity, modulation depth, frequency and phase shift of incident light waves. In [2], described is a numerical solution of a set of non-linear differential equations describing the photo-refractive Gunn effect. It has been confirmed that high-field domains can be triggered with moving interference pattern, as it was predicted by the model authors. Considering the system within the frame of linear stability theory, it is possible only to estimate the order of critical parameter values necessary to excite the photo-refractive Gunn effect. The feedback in the system studied is more complicated, including multiple wave generation from injecting contacts, wave damping, and chaos.

In our previous papers [3, 4], we used the self-organization methodology developed for dynamical systems to investigate the influence of three main control parameters (external electric field, illumination intensity, and dopant concentration) on stationary distributions of carrier concentrations and internal electric field for the model semiconductor under photo-induced Gunn effect. It was shown that spatially homogeneous stationary states are unstable under drift instability conditions, when two waves of space-time perturbations propagate along the sample with two different phase velocities. One of these waves is damping with time, while the other can lead to neutral perturbation mode of constant amplitude. The latter corresponds to the extreme point of current-voltage curve. Numerical calculations have shown that the concentration of acceptors has practically no influence on generation process in the system, while illumination intensity determines main characteristics of the process, resulting in switching between different stationary states. Basing on investigation results obtained, we have concluded that the predicted wave propagation phenomenon can be controlled with external electric field and laser illumination intensity, thus opening new prospects for experimental observation of photo-Gunn effect.

This work is focused on investigation of current-illumination, spectral, concentration, and field dependence of light response for a finite size semiconductor. The authors have determined the functions describing voltage variation for sinusoidal time-dependent changes of current and illumination. The analysis was carried out in low signal approximation, when all the variations considered were small and linearly dependent on each other. The influence of frequency modulation and incident light intensity on the system light response was studied separately in voltage and current generator operating modes.

The model considered describes a bulk compensated n-type semiconductor of GaAs structure, featuring deep donor and acceptor levels, subjected to two quasi-monochromatic plane waves of slightly different frequencies ω_0 and $\omega_0 + \Omega$ ($\Omega \ll \omega_0$), forming moving interference patterns at intensity

$$I(z,t) = I_0[1 + m\cos(kz + \Omega t)], \tag{1}$$

where $k = 2\pi/\Lambda$ is the interference wave number; Λ, the distance between $I(z,t)$ peaks; the parameter m describes the interference pattern modulation depth and I_0 is time-averaged illumination intensity (calculated as the sum of squared amplitudes of incident wave components, averaged over the time intervals greater than $2\pi/\omega_0$ but smaller than $2\pi/\Omega$).

In the case considered, the electrons excited from deep donor levels become trapped by either acceptors or ionized donors without self-excitation. To investigate the changes of electron concentration n, ionized donors $N_D{}^i$ and electric field E with time t and coordinate z, the equation describing variation of donor concentration can be used:

$$\frac{\partial N_D^i}{\partial t} = sI(N_D - N_D^i) - \gamma n N_D^i, \tag{2}$$

as well as the continuity equation for electrons

$$\frac{\partial n}{\partial t} = \frac{\partial N_D^i}{\partial t} + \frac{\partial}{\partial z}\left(n\nu(E) + D\frac{\partial n}{\partial z}\right), \tag{3}$$

and Poisson equation

$$\frac{\partial E}{\partial z} = -\frac{e}{\varepsilon\varepsilon_0}(n - N_D^i + N_A). \tag{4}$$

Here, N_D is the total donor concentration; N_A, the concentration of negatively charged acceptors; s describes the photo-ionization cross-section; γ and D are recombination and diffusion coefficients, respectively; e is the magnitude of elementary charge; parameters ε_0 and ε are dielectric constants of vacuum and semiconductor. The carrier drift velocity $\nu(E)$ appearing in the formula (3) can be approximated [1] as

$$\nu(E) = \nu_s\left[1 + \frac{E/E_s - 1}{1 + A(E/E_s)^4}\right] \tag{5}$$

with saturation velocity of electrons v_s, saturation field E_s and material-dependent parameter A. The coefficients D, s and γ were considered to be independent of field and coordinate. Combining equations (2–4), it is easy to show that the expression for full current, including drift, diffusion and displacement current components, can be written as:

$$j(t) = e(n\nu(E) + D\frac{\partial n}{\partial z}) + \varepsilon\varepsilon_0\frac{\partial E}{\partial t}. \tag{6}$$

Introducing dimensionless units

$$\tau = \gamma N_A t, \quad x = \varepsilon\varepsilon_0 E_s \gamma z/eD, \quad y_1 = N_D^i/N_A, \quad y_2 = n/N_A, \quad y_3 = E/E_s, \tag{7}$$
$$a = sI_0/\gamma N_A, \quad b = N_D/N_A, \quad \alpha = \varepsilon\varepsilon_0 E_s v_s/eDN_A, \quad \beta = \varepsilon\varepsilon_0 E_s\gamma/ev_s,$$
$$k = eDk/\varepsilon\varepsilon_0 E_s\gamma, \quad \omega_0 = \Omega/\gamma N_A, \quad J = j/eN_A v_s$$

equations (2–4) can be rewritten as

$$\frac{\partial y_1}{\partial \tau} = af(x,\tau)(b - y_1) - y_1 y_2, \quad \frac{\partial y_2}{\partial \tau} = \frac{\partial y_1}{\partial \tau} + \alpha\frac{\partial}{\partial x}\left[y_2\nu(y_3) + \beta\frac{\partial y_2}{\partial x}\right], \quad \frac{\partial y_3}{\partial x} = -\frac{1}{\alpha\beta}(y_2 - y_1 + 1) \tag{8}$$

with dimensionless drift velocity

$$\nu = \nu(y_3)/\ v_s = y_3(1 + Ay_3^3)/(1 + Ay_3^4), \tag{9}$$

and

$$f(x,t) = 1 + m\cos(kx + \omega_0\tau). \tag{10}$$

In the adopted notation, the expression for full current (6) takes the form

$$J(\tau) = y_2\nu + \beta\left(\frac{\partial y_2}{\partial x} + \frac{\partial y_3}{\partial \tau}\right). \tag{11}$$

It is easy to show that stationary space-homogeneous solutions ($x \to \infty$, $\tau \to \infty$, $m = 0$) of the equations (8), (11) for variables y_{10} and y_{20} are described with the following formulas [3, 4]

$$y_{10} = 0.5(\sqrt{(a-1)^2 + 4ab} - (a - 1)), \tag{12}$$
$$y_{20} = 0.5(\sqrt{(a-1)^2 + 4ab} - (a + 1)),$$

while the stationary field value for the specified current j_0 flowing through the sample can be obtained solving algebraic equation of fourth degree

$$J_0 = y_{20}\nu(y_{30}) \tag{13}$$

and selecting the solutions with positive y_{30} as physically correct ones.

Assuming that both current and illumination bring insignificant temporal variations to the system regarding its stationary states, it is possible to introduce small perturbations δa and δj, depending on coordinate but time-stable:

$$a(\tau) = a + \delta a \cdot \exp(-i\omega\tau), \quad j(\tau) = j_0 + \delta j \cdot \exp(-i\omega\tau), \tag{14}$$

where ω is a certain real frequency. In this case, the carrier concentration and electric field in the sample will also feel small variations

$$y_n = y_{n0} + \delta y_n \cdot \exp(-i\omega\tau), (n = 1 \ldots 3) \tag{15}$$

with time-independent $\delta y_n = f_n(x)$.

Let us assume that dynamical changes of the current and illumination have no effect on stationary concentration distribution (12) and internal electric field (13). Substituting (14) and (15) in equation set (8), (11) and solving the latter for perturbations δy_n, we obtain

$$\delta y_1 = -D^{-1} y_{10}(a + y_{20} + i\omega)(B_1 e^{\lambda_1 x} + B_2 e^{\lambda_2 x}) + D_2^{-1}(b - y_{10})(a + y_{10} + y_{20} + i\omega) \cdot \delta a, \quad (16)$$

$$\delta y_2 = B_1 e^{\lambda_1 x} + B_2 e^{\lambda_2 x} + D_2^{-1}(b - y_{10})(a + y_{10} + y_{20} + i\omega) \cdot \delta a,$$

$$\delta y_3 = D^{-1}\left(\frac{y_{20}}{\beta}\frac{\partial \nu}{\partial y_{30}} + i\omega\right) \times$$

$$\times \left[\frac{\delta j}{\beta} - (\lambda_1 + a_1) B_1 e^{\lambda_1 x} - (\lambda_2 + a_1) B_1 e^{\lambda_2 x} - D_2^{-1} a_1 (b - y_{10})(a + y_{10} + y_{20} + i\omega) \cdot \delta a\right],$$

where

$$D = (a + y_{20})^2 + \omega^2, \quad D_2 = (a + y_{10} + y_{20})^2 + \omega^2, \quad a_1 = \nu(y_{30})/\beta. \quad (17)$$

The values $\lambda_{1,2}$ are complex solutions of quadratic equation $\lambda^2 + a_1\lambda - (b_1 + ic_1) = 0$ with the coefficients

$$b_1 = \left\{\frac{y_{20}}{\beta}\frac{\partial \nu}{\partial y_{30}}\left[y_{10}(a + y_{20}) + D\right] + y_{10}\omega^2\right\}/(\alpha\beta D),$$
$$c_1 = \omega\left\{y_{10}\left[\frac{y_{20}}{\beta}\cdot\frac{\partial \nu}{\partial y_{30}} - (a + y_{20})\right] - D\right\}/(\alpha\beta D). \quad (18)$$

Integration constants $B_{1,2}$ could be determined applying the volume electro-neutrality condition $\int_0^l (y_2 - y_1 + 1)dx = 0$, considering electron concentration at the anode to be constant $y_2(l) = y_{20}$ [5]:

$$B_1 = -\delta a \cdot \lambda_1 (e^{\lambda_2 l} - 1)(b - y_{10})(a + y_{10} + y_{20} + i\omega) D_2^{-1}\Delta^{-1}, \quad (19)$$
$$B_2 = -\delta a \cdot \lambda_2 (e^{\lambda_1 l} - 1)(b - y_{10})(a + y_{10} + y_{20} + i\omega) D_2^{-1}\Delta^{-1},$$
$$\Delta = \lambda_1 e^{\lambda_1 l}(e^{\lambda_2 l} - 1) - \lambda_2 e^{\lambda_2 l}(e^{\lambda_1 l} - 1).$$

Substituting (19) into the expression for δy_3 (16) and performing integration over the sample length l, we find the relation between voltage variations δV and δj, δa:

$$\delta V = D_1^{-1}\beta^{-1} l\left(\frac{y_{20}}{\beta}\cdot\frac{\partial \nu}{\partial y_{30}} + i\omega\right) \cdot \delta j - D_1^{-1} D_2^{-1} l a_1 (b - y_{10}) \times \quad (20)$$
$$\times (a + y_{10} + y_{20} + i\omega)\left(\frac{y_{20}}{\beta}\cdot\frac{\partial \nu}{\partial y_{30}} + i\omega\right) \cdot (1 + a_1^{-1} l^{-1}\Delta^{-1}(\lambda_2 - \lambda_1)(e^{\lambda_1 l} - 1)(e^{\lambda_2 l} - 1)) \cdot \delta a,$$

where $D_1 = \left(\frac{y_{20}}{\beta}\cdot\frac{\partial \nu}{\partial y_{30}}\right)^2 + \omega^2$. It is important that the coefficient appearing at δj corresponds to complex impedance of the sample

$$Z(\omega) = \frac{l}{\beta}\cdot\left(\frac{y_{20}}{\beta}\cdot\frac{\partial \nu}{\partial y_{30}} - i\omega\right)^{-1} = Z_R + iZ_I \quad (21)$$

with the components $Z_R = y_{20}\frac{l}{\beta^2}\frac{\partial \nu}{\partial y_{30}}\left[\omega^2 + \left(\frac{y_{20}}{\beta}\cdot\frac{\partial \nu}{\partial y_{30}}\right)^2\right]^{-1}$, $Z_I = \frac{l\omega}{\beta}\left[\omega^2 + \left(\frac{y_{20}}{\beta}\frac{\partial \nu}{\partial y_{30}}\right)^2\right]^{-1}$.

As it follows from (21), at negative differential conductivity $\frac{\partial \nu}{\partial y_{30}} < 0$, the impedance Z_R is also negative. In these conditions, the sample could be operated as an active element, i.e. an amplifier. It is worth noting that the curve $Z_I(\omega)$ has a peak at $\omega_m = \left|\frac{y_{20}}{\beta}\cdot\frac{\partial \nu}{\partial y_{30}}\right|$.

The coefficient at the item δa in (20) characterizes the value and frequency dispersion of the sample light response. To define the behavior of light response depending on modulation frequency ω a circuit including an external loading resistance of impedance Z_L and a constant voltage battery can be considered. In this case, applying the Kirchhoff law, the current variations can be found as:

$$Z_L \delta j + \delta V = 0. \tag{22}$$

Substituting (20) into (22) and introducing variation of total light quanta absorbed in semiconductor per time interval $\delta t = 1$ as $\delta\Phi = l\delta a$, causing excitement of the electrons from the extrinsic level to the conduction band, we will obtain the following expression describing the light response of the sample:

$$\frac{\delta j}{\delta\Phi} = a_1(b - y_{10})\left\{\left(Z_L + Z_R\right)\cdot\left(\frac{y_{20}}{\beta}\cdot\frac{\partial\nu}{\partial y_{30}} - i\omega\right)\cdot(a + y_{10} + y_{20} - i\omega)\right\}^{-1} \times$$
$$\times\left\{1 - \left[a_1 l(1 + (\lambda_1 - \lambda_2)^{-1}\left(\lambda_1(e^{\lambda_1 l} - 1)^{-1} - \lambda_2(e^{\lambda_2 l} - 1)^{-1}\right)\right]^{-1}\right\}. \tag{23}$$

As it is seen from (23), in general case, the light response of the system studied depends on the values of control parameters, such as illumination intensity a, sample compensation degree b, current density j_0, sample length l, and modulation frequency ω in a complex manner. In the first place, we will consider the limit case of long samples ($l >> 1$), when it is possible to neglect the expression written in square brackets in (23). This will yield a well-known formula [6]

$$\frac{\delta j}{\delta\Phi} = a_1(b - y_{10})\frac{\beta}{l}\tau_0\left\{(1 + \frac{Z_L}{R_0}(1 - i\omega\tau_1))\cdot(1 - i\omega\tau_0)\right\}^{-1},$$

with

$$\tau_0^{-1} = a + y_{10} + y_{20}, \quad \tau_1^{-1} = \frac{y_{20}}{\beta}\cdot\frac{\partial\nu}{\partial y_{30}}; \; R_0 = \frac{\tau_1}{C_0}, \quad \text{and } C_0 = \frac{\beta}{l}. \tag{24}$$

This kind of light response is characteristic for a circuit composed of parallel active resistivity R_0 and capacity C_0, connected in series to load resistivity with impedance Z_L. It is worth noting that formula (24) contains the factor $(b - y_{10})$, reflecting the sample compensation degree able to increase the light response significantly. As it follows from (24), the light response becomes lower when modulation frequency overcomes the carrier trapping one τ_0^{-1} characteristic for extrinsic centers or transition process frequency τ_1^{-1}.

Analysis of the expression (23) for all the impedance values possible makes a rather complicated task. In general, two limit cases are usually considered, when the sample is operated in voltage ($|Z_R >> Z_L|$) or current ($|Z_R << Z_L|$) generator modes. In the voltage generation mode, the item Z_L in denominator of (23) can be neglected. Substituting into the last formula expressions for complex coefficients $\lambda_{1,2}$ and taking into account (18), we will obtain solutions for real and imaginary parts of light response as:

$$\mathrm{Re}\frac{\delta j}{\delta\Phi} = (b - y_{10})\frac{\nu(y_{30})\tau_0}{l}\mathrm{K}\frac{1 - \Lambda\omega\tau_0}{1 + \omega^2\tau_0^2},$$

$$\mathrm{Im}\frac{\delta j}{\delta\Phi} = (b - y_{10})\frac{\nu(y_{30})\tau_0}{l}\mathrm{K}\frac{\Lambda + \omega\tau_0}{1 + \omega^2\tau_0^2}, \tag{25}$$

where K and Λ are complex functions of characteristic relaxation times, material parameters, sample length and external influence. As it follows from (25), one can expect to see two peaks at frequency curves of light response depending on Λ values. There could be also no peaks at all, when the real and imaginary light response components appear decreasing with ω. In the current generator mode, voltage variation at the load is considered, neglecting Z_R in denominator (23). It is possible to show that in this case, the frequency dependence of light response components can be written as:

$$\mathrm{Re}\frac{\delta V}{\delta\Phi} = (b - y_{10})\frac{\nu(y_{30})\tau_0}{l}\tau_1 K\frac{1 - \omega^2\tau_0\tau_1 - \Lambda\omega(\tau_0 + \tau_1)}{(1 + \omega^2\tau_0^2)(1 + \omega^2\tau_1^2)} \tag{26}$$

$$\mathrm{Im}\frac{\delta V}{\delta\Phi} = (b - y_{10})\frac{\nu(y_{30})\tau_0}{l}\tau_1 K\frac{\Lambda(1 - \omega^2\tau_0\tau_1) + \omega(\tau_0 + \tau_1)}{(1 + \omega^2\tau_0^2)(1 + \omega^2\tau_1^2)}.$$

Comparing (25) with (26), it is seen that voltage mode light response components exhibit a more complex behavior on wavelength frequency than that for current mode ones. It is worth noting that the value $\tau_0 > 0$ above describes true relaxation time, while τ_1 can be either positive or negative, depending on the sign of differential conductivity.

In long sample approximation ($l >> 1$), the formulas (25) and (26) for both operation modes can be transformed into

$$\frac{\mathrm{Re}\frac{\delta j(\delta V)}{\delta\Phi}}{\mathrm{Re}\frac{\delta j(\delta V)}{\delta\Phi}\Big|_{l>>1}} = 1 - \Lambda f(\omega), \quad \frac{\mathrm{Im}\frac{\delta j(\delta V)}{\delta\Phi}}{\mathrm{Im}\frac{\delta j(\delta V)}{\delta\Phi}\Big|_{l>>1}} = 1 - \frac{\Lambda}{f(\omega)}, \tag{27}$$

where $f(\omega) = \omega\tau_0$ for voltage generator mode and $f(\omega) = \dfrac{\omega(\tau_0 + \tau_1)}{1 - \omega^2\tau_0\tau_1}$ for current generator mode. As it follows from (27), the sample geometry influences significantly the frequency behavior of light response components in either operation mode.

More exact conclusions on the influence of control parameters on the light response of the system studied as well as on current and illumination variations in semiconductor under photo-Gunn effect could be made analyzing numerical calculation results. As our theoretical consideration was mainly focused on frequency dependence of the system light response, we

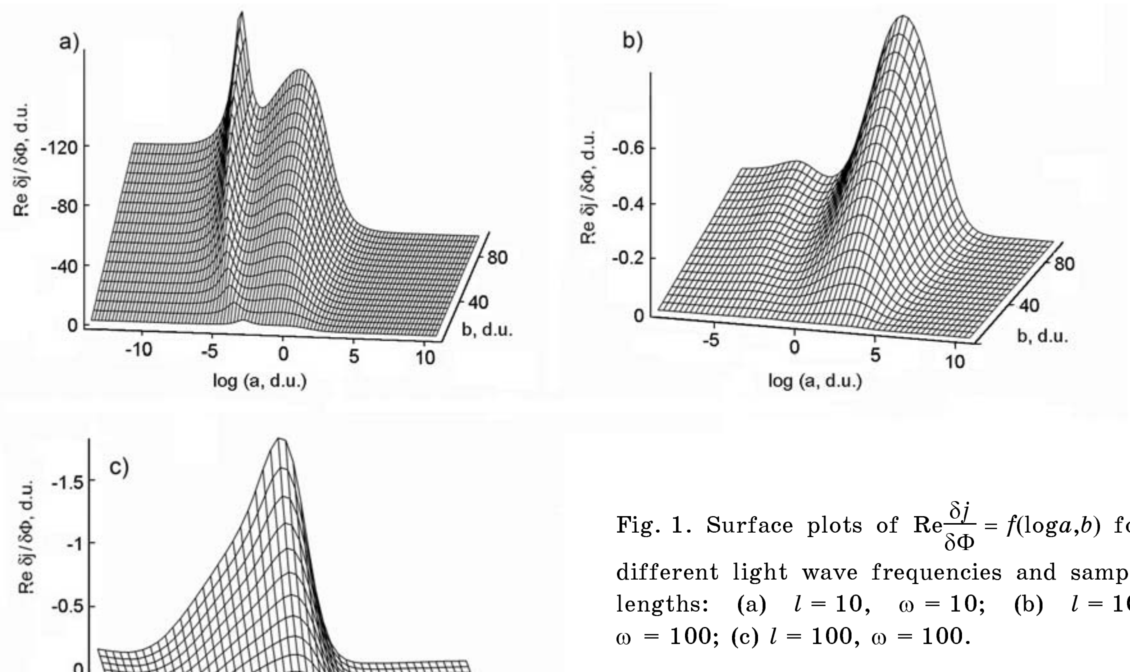

Fig. 1. Surface plots of $\mathrm{Re}\frac{\delta j}{\delta\Phi} = f(\log a, b)$ for different light wave frequencies and sample lengths: (a) $l = 10$, $\omega = 10$; (b) $l = 10$, $\omega = 100$; (c) $l = 100$, $\omega = 100$.

will carry further investigations regarding illumination intensity (parameter a) and compensation degree (parameter b) for voltage generator sample operation mode. A model semiconductor material was chosen to have the parameters of n–GaAs at $T = 300$ K [1], i.e. $v_s = 8.5 \cdot 10^3$ m/s, $E_s = 1.7 \cdot 10^5$ V/m, $\varepsilon = 13.2$, $\gamma = 10^{10}$ s^{-1}, $D = 0.02$ m^2/s, $N_a = 10^{22}$ m^3. Fig. 1 shows surface plots of $\mathrm{Re}\frac{\delta j}{\delta\Phi} = f(\log a, b)$ for two different light wave frequencies and sample lengths, calculated for the fixed $y_{30} = 3$. As is seen according to the formula (25), the system light response increases in its absolute value with parameter b and is characterized by selective behavior with respect to illumination intensity and modulation. For the case of short samples (Fig. 1a,b), the surface $\mathrm{Re}\,\frac{\delta j}{\delta\Phi}$ shows two peaks appearing at low (parameter $a \approx 10^{-2}$) and medium ($a \approx 1$) light intensity. The distance between the peaks, their absolute value and shape (sharp or smooth) depend on the frequency ω. Increase of l under the long sample approach results in fisuon of the peaks (Fig. 1c).

Thus, the processes taking place in the semiconductors with monopolar conductivity for non-stationary photo-generation of the carriers excited from extrinsic centers under Gunn effect, are characterized with complex frequency behavior of the system light response. The different character thereof for short and long samples can be explained by different contribution of inhomogeneous space-charge layer thickness $l_{sc} \approx \frac{\tau_0\tau_1}{\tau_0 + \tau_1} v_s$. Indeed, for long samples, l_{sc} is small in comparison with sample length, making little influence on integral characteristics $\mathrm{Re}\frac{\delta j}{\delta\Phi}$. For short samples with $l \le l_{sc}$, the influence of space charge region may become dominating. The obtained analytical and numerical data on light response peculiarities can be used for further investigations, in particular, for experimental observation of photo-induced Gunn effect.

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Самоорганізація у напівпровідниках з дрейфовою нестабільністю під впливом модульованого світла. II. Фотовідгук на варіації зовнішнього поля

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Теоретично досліджено спектральну залежність фотовідгуку напівпровідника кінцевих розмірів в умовах існування Ганн-ефекту. Знайдено зв'язок між варіаціями напруги на зразку та варіаціями струму та освітлення, які змінюються з часом за гармонійним законом. Розглянуто питання про частотну дисперсію фотовідгуку і, зокрема, у режимах генератора напруги та струму. Показано, що спектральні залежності фотовідгуку у режимах генератора напруги та струму суттєво відрізняються одна від іншої. Для напівпровідника з параметрами n–GaAs характер зазначених залежностей для довгих і коротких зразків є різним. Висловлено припущення, що останнє, напевно, обумовлено виникненням при освітленні області просторово-неоднорідного розподілу об'ємного заряду, яка дає різний вклад в інтегральну характеристику в залежності від довжини зразка.