PECULIARITIES OF SPACE-TIME PERTURBATION WAVE PROPAGATION IN SEMICONDUCTOR UNDER THE PHOTO GUNN EFFECT

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In the framework of a one-dimensional field model, we have carried out the theoretical investigation of the space-time perturbation wave propagation in a semiconductor with n-GaAs parameters under the simultaneous action of a carrier-warming electric field and a laser light (with the space-time constant intensity) in dependence on the control parameters: the incident light wave intensity, dopant compensation degree, and external electric field intensity. It is shown that it is possible to find a specific combination of the material parameters, external influence, and wave numbers, under which the spontaneous contact of equal-frequency surfaces can be observed in the crystal under study.

1. Introduction

The photo Gunn effect described in [1] attracts a significant attention of reaserchers from both the fundamental and applied points of view (e.g., [2–4]). At the same time, the physics of electron processes running in an illuminated semiconductor under the drift instability conditions still requires the further clarification. The majority of the existing studies on the photo Gunn effect deal with the computer modeling of the physical processes in a semiconductor subjected to the simultaneous action of the carrier-warming electric field and the incident laser light. In particular, in our previous papers [2, 3], we have investigated the conditions required for the observation of self-organizing phenomena in a semiconductor under the photo Gunn effect. In [4] in the framework of a linear model, it was shown that the high-field domains can be generated by coherent interference bands. At the same time, to our knowledge, there are no papers concerning such an important scientific and applied problem as the determination of the peculiarities of the external influence (the incident light intensity, dopant impurity concentration, etc.) on the propagation of the waves formed by space-time perturbations of the carrier stationary states in a crystal. The existence of such peculiarities can lead, in particular, to the appearance of the phenomena atypical for the classical Gunn effect. The investigation of these phenomena will enrich our knowledge of non-equilibrium physics and will also propose new control possibilities for the processes taking place under the photo Gunn effect. It could be made by a variation of the type and concentration of a doping impurity, the intensity and spectrum of the incident light, etc. This paper is dedicated to the partial solution of this problem.

2. Theoretical Model

Let us consider a bulk semiconductor with the n-GaAs structure which contains deep donor and acceptor levels (with the corresponding concentrations N_D and N_A) and is illuminated by a laser beam with the intensity I_0 and the frequency satisfying the impurity absorption requirement. A one-dimensional model describing the dynamics of carriers in the semiconductor under these conditions can be written in dimensionless variables as [2]

$$\frac{\partial y_1}{\partial \tau} = a(b - y_1) - y_1 y_2,$$

$$\frac{\partial y_2}{\partial \tau} = \frac{\partial y_1}{\partial \tau} + \alpha \frac{\partial}{\partial x}\left[y_2 v(y_3) + \beta \frac{\partial y_2}{\partial x}\right],$$

$$\frac{\partial y_3}{\partial x} = -\frac{1}{\alpha\beta}(y_2 - y_1 + 1), \tag{1}$$

with $\tau = \gamma N_A t$, $x = \epsilon\epsilon_0 E_s \gamma z/eD$, $y_1 = N_D^i/N_A$, $y_2 = n/N_A$, $y_3 = E/E_s$, $a = sI_0/\gamma N_A$, $b = N_D/N_A$, $\alpha = \epsilon\epsilon_0 E_s v_s/eDN_A$, $\beta = \epsilon\epsilon_0 E_s \gamma/ev_s$, $k = eD\kappa/\epsilon\epsilon_0 E_s \gamma$, the dimensionless drift velocity [1] $v \equiv v(y_3)/v_s = y_3(1 + Ay_3^3)/(1 + Ay_3^4)$, photo-ionization cross-section s, coefficients of recombination and diffusion γ and D, elementary charge e, dielectric constants of vacuum ϵ_0 and the semiconductor ϵ, saturation electron velocity v_s, saturation field E_s, and a coefficient A depending on the material parameters. It is assumed that the values of D, s, and γ are independent of both the electric field and coordinates.

As was shown in [2], the stationary space-homogeneous ($x \to \infty$, $\tau \to \infty$) solutions of system (1) regarding the phase variables y_{10} and y_{20} are as follows:

$$y_{10} = \frac{1}{2}\left[\sqrt{(a-1)^2+4ab}-(a-1)\right],$$

$$y_{20} = \frac{1}{2}\left[\sqrt{(a-1)^2+4ab}-(a+1)\right]. \qquad (2)$$

Stationary values of the electric field y_{30} inside the sample calculated for the given current density j_0 can be found solving the equation $j_0 = y_{20}v(y_{30})$.

Let us assume that the space-time perturbations (2) can be written in the form of a plane harmonic wave with frequency ω and the wave number k:

$$y_j = y_{j0} + \delta y_j e^{\omega\tau + ikx}, \quad j = 1,2,3. \qquad (3)$$

Substituting (3) into (1), we obtain a homogeneous system of algebraic equations for the perturbations obeying the corresponding dispersion relation:

$$\omega^2 + [\chi + \zeta - \xi]\,\omega + [\chi\zeta - \xi(y_{20}+a)] = 0,$$

$$\zeta \equiv a + y_{10} + y_{20}, \;\; \xi \equiv ik\alpha v - \alpha\beta k^2, \;\; \chi \equiv \frac{y_{20}}{\beta}\frac{\partial v}{\partial y_{30}}. \qquad (4)$$

As follows from (4), under the photo Gunn effect in a semiconductor illuminated with the homogeneous laser light, there exist two waves of space-time perturbations with the frequencies depending in a complicated way on their wave numbers.

Presenting the oscillation frequency $\omega(k)$ as a sum of real (ω_r) and imaginary (ω_i) components ($\omega = \omega_r + i\omega_i$), substituting this sum into (4), and separating the real and imaginary parts, we get a system of two fourth-order algebraic equations for ω_r and phase velocity $v_{\rm ph} = -\omega_i/k$ with the solutions

$$\omega_{r1,2} = \frac{1}{2}(\pm\sqrt{X} - A - B),$$

$$v_{\rm ph1,2} = -\frac{1}{2}\alpha v\left(1 \mp \frac{B-A}{\sqrt{X}}\right). \qquad (5)$$

In Eq. (5), the variable

$$X = \frac{1}{2}\left[-C + \sqrt{C^2 + 4\alpha^2k^2v^2(B-A)^2}\right] \geq 0 \qquad (6)$$

represents a positive solution of the corresponding quadratic equation with the coefficients

$$A = a + y_{20}, \qquad B = \alpha\beta k^2 + y_{10} + \frac{y_{20}}{\beta}\frac{\partial v}{\partial y_{30}},$$

$$C = -(B - A - 2y_{10})^2 + \alpha\beta k^2(\alpha v^2/\beta - 4y_{10}). \qquad (7)$$

3. Results of Numerical Calculations and Discussion

The obtained analytical solutions (5)—(7) for the frequencies ω_r and phase velocities $v_{\rm ph}$ allow us to investigate their dependence on the dimensionless control parameters, namely (a) the incident light intensity I_0 and (b) the dopant compensation degree N_D/N_A and the external electric field represented in y_{30}. For the calculations, we have used the following parameters of n-GaAs [1]: $\mu = 0.5$ m^{2}V^{-1}s^{-1}, $v_s = 8.5\times10^5$ m/s, $E_s = 1.7\times10^4$ V/m, $T = 300$ K, $\epsilon = 13.2$, $\alpha = 8.154$, $\beta = 0.146$, $\gamma = 10^{10}$s^{-1}, $D = 0.0129$ m^2/s, $N_A = 10^{16}$ cm^{-3}, and $A = 0.04$.

Let us consider the peculiarities of the ω_r and $v_{\rm ph}$ plots versus the wave vector k at the fixed parameters $a = 5\times10^{-3}$ and $y_{30} = 2.8$ and the variable b (Figs. 1 and 2). As follows from the figures, both ω_r and $v_{\rm ph}$ are even functions of k in accordance to formulas (5)—(7). Moreover, there exist the particular values of $k = k_0$ satisfying simultaneously the equations $v_{\rm ph1} = v_{\rm ph2}$ and $\omega_{r1} = \omega_{r2}$, which takes place for the specific relation between the parameters of the system and the values of external control factors. According to the terminology developed in [5], we are dealing with the spontaneous contact of equal-frequency surfaces (SCES) which does not follow from the symmetry of the crystal properties. Using Eqs. (5)—(7), it is possible to show that the expressions describing the contact point can be reduced to

$$k_0^2 = [a + y_{20} - y_{10} - \chi]\,(\alpha\beta)^{-1}, \qquad (8)$$

$$[a + y_{20} - y_{10} - \chi]\left[\frac{\alpha}{\beta}v^2 - 4y_{10}\right] - 4y_{10}^2 > 0. \qquad (9)$$

Values of the frequencies and the phase velocities at the k_0 point are equal to

$$\omega_{r1} = \omega_{r2} \equiv \omega_{k0} = a + y_{20},$$

$$|v_{\rm ph1}| = v_{\rm ph2} \equiv v_{\rm phk0} = \infty. \qquad (10)$$

As follows from (10), the waves of space-time perturbations gain the infinite velocity at the contact point. Their magnitudes testify to a loosing of the oscillatory movement character in the system under study, as the amplitude of the waves either increases (for $v_{\rm ph1}$) or decreases in time (for $v_{\rm ph2}$).

Curves *1* and *2* in Figs. 1 and 2 correspond to the case where conditions (8), (9) are not fulfilled, while curves *3*

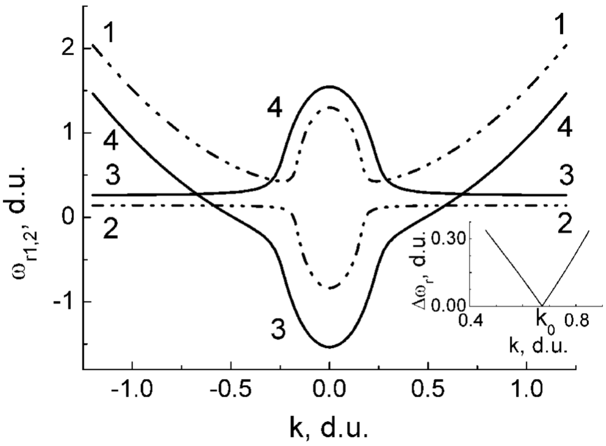

Fig. 1. Real frequencies ω_{r1} (curves *1, 3*) and ω_{r2} (curves *3, 4*) versus the wave vector k, calculated for $a = 5 \times 10^{-3}$, $y_{30} = 2.8$ at $b = 35$ (*1, 2*); 70 (*3, 4*). Inset: the deviation of the oscillatory branches $\Delta\omega_r$ in the vicinity of the contact point

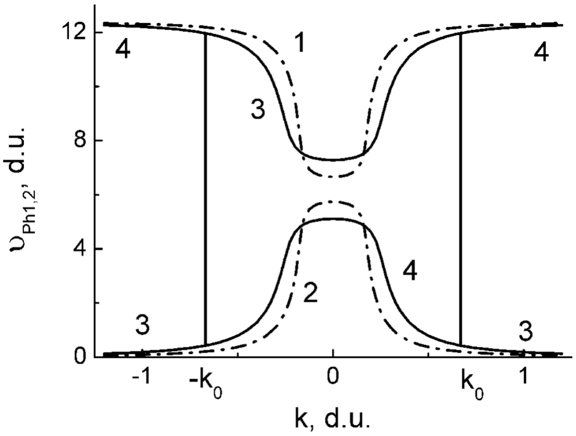

Fig. 2. The same as in Fig. 1, but for the phase velocities v_{ph1} and v_{ph2}

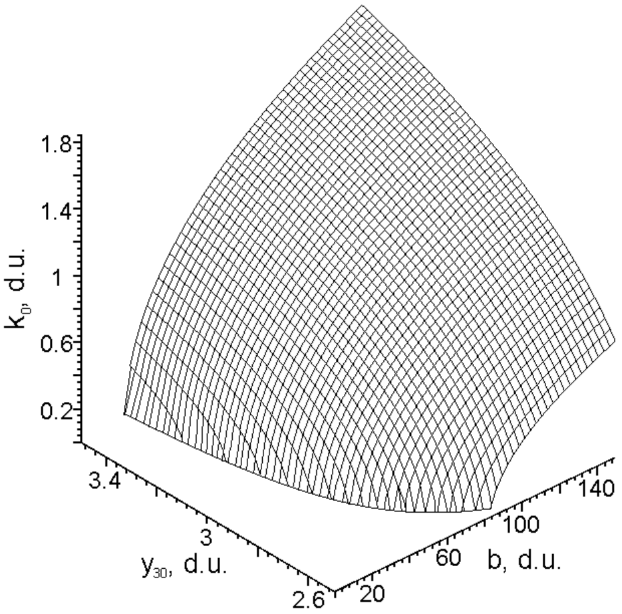

Fig. 3. Two-parameter surface of the contact point $k_0 = f(b, y_{30})$ calculated for $a = 5 \times 10^{-3}$

and *4* illustrate the opposite situation. The proof of the fact that we are dealing with the SCES is the k-linear divergence of oscillatory branches $\Delta\omega_r = \omega_{r1} - \omega_{r2}$ in the vicinity of the contact point [5] (inset to Fig. 1). It is important that, upon passing throught the k_0 point, both $\omega_{r1}(k)$ and $\omega_{r2}(k)$ branches gradually change their places (Fig. 1), whereas the jump-like transition is revealed for the velocities v_{ph1} and v_{ph2} (Fig. 2).

Conditions (8), (9) yield that the position of the spontaneous contact point k_0 can be controllably changed by varying the external control parameters (a, b and y_{30}). In Fig. 3, we have presented the surface $k_0 = f(b, y_{30})$ calculated for $a = 5 \times 10^{-3}$ which shows the significant non-linear dependence on the arguments b and y_{30}. The detailed investigations have shown that a similar dependence takes place for the negative differential conductivity ($2.5 < y_{30} < 3.5$), when the parameter a changes in the range $10^{-3} \div 10^{-2}$, and the parameter $b = 20 \div 82$ depending on the other coefficients of the system (1).

According to [5], the presence of the cone-shaped surfaces $\omega_{r1}(k)$ and $\omega_{r2}(k)$ in the vicinity of the point k_0 can cause the conical wave refraction [5]. It is important that the existence of the SCES leads to the variation of the imaginary component of the dielectric constant of a material, which is quadratic in both the temperature T and frequency ω for the crystals without the center of symmetry and proportional to ω^2 and T^4 for the center-symmetric crystals [5]. This fact allows us to predict the possible detectability of the SCES effect and the conical wave refraction in experiments carried out on a semiconductor sample with n-GaAs parameters under the conditions required to observe the photo Gunn effect in the high-frequency part of the spectrum under elevated temperatures.

4. Conclusions

Therefore, we have shown that two space-time perturbation waves may exist in the electron system under study which are propagating with different phase velocities. Upon the fulfillment of certain relations between the material parameters, external influence (the laser light intensity and the dopant compensation degree), and wave number, one can expect to observe the effect of the spontaneous contact of equal-frequency surfaces. We also assume that this SCES effect and the secondary phenomenon of conical wave refraction in n-GaAs can be observed experimentally.

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ОСОБЛИВОСТІ ПОШИРЕННЯ ХВИЛЬ ПРОСТОРОВО-ЧАСОВИХ ЗБУРЕНЬ У НАПІВПРОВІДНИКУ ЗА НАЯВНОСТІ ФОТОЕФЕКТУ ГАННА

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Резюме

У рамках одновимірної польової моделі проведено теоретичні дослідження закономірностей поширення хвиль просторово-часових збурень у напівпровіднику з параметрами n-GaAs під дією нагріваючого носії заряду електричного поля та лазерного опромінення (з постійною у просторі та часі інтенсивністю) в залежності від величин керуючих параметрів: інтенсивності зовнішньої світлової хвилі, ступеня компенсації легуючих домішок та напруженості зовнішнього електричного поля. Показано можливість існування таких співвідношень між параметрами матеріалу, величинами зовнішніх факторів та значеннями хвильового числа, за яких у кристалі виникає ефект випадкового контакту ізочастотних поверхонь.