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Excitation Of Growing Waves In Impurity Semiconductors With Two Types Of Charge Carriers In The Presence Of A Temperature Gradient In An External Electric And Magnetic Field

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Abstract: *It is shown that in semiconductors with two types of charge carriers, in the presence of a temperature gradient, taking hydrodynamic motions into account leads to the excitation of growing waves. The frequency and increment of this wave are determined. Expressions are found for the external electric and magnetic fields upon excitation of growing waves. It has been proven that growth occurs in samples with a certain size. It was found that the speed of the rising waves is the same in all directions of the coordinate axes and is proportional to the speed of thermomagnetic waves. The concentration ratio of electrons and holes is found upon the appearance of growing waves.*

Keywords: *semiconductor, electric field, magnetic field, electrons, holes, frequency*

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I. Introduction

The theory of quasineutral current oscillations in semiconductors with two types of charge carriers, in the presence of once negatively and twice negatively charged impurities in external electric and magnetic fields, was constructed in [1–8]. In these works, the appearance of oscillations inside the semiconductor (i.e., internal instability) is mainly theoretically analyzed and the values of the oscillation frequency are determined. It also analyzes the conditions for the appearance of oscillations in the external circuit (i.e., external instability). However, in all these works, the influence of hydrodynamic motions of charge carriers on the corresponding instabilities is not taken into account. It is known that during hydrodynamic movements of charge carriers, in addition to an external electric field, an electric field arises inside the medium due to the presence of a magnetic field and due to the redistribution of charges in the sample (i.e., due to the presence of a gradient of concentration of charge carriers). Of course, when these fields are taken into account, the conditions for the appearance of oscillations will change significantly. In addition to taking into account the effective value of the electric field, in the presence of a temperature gradient and an external magnetic field, thermomagnetic waves arise in the medium. These waves propagate in the medium at a certain speed. The speed of thermomagnetic waves linearly depends on the value of the temperature gradient (below we indicate formulas for the frequency and speed of propagation of thermomagnetic waves).

In this theoretical work, we will theoretically analyze the appearance of fluctuations in physical quantities (electric field, charge carrier concentrations) inside a semiconductor with two types of charge carriers and with certain impurities in the presence of a temperature gradient and constant external electric and constant magnetic fields that are directed perpendicular to each other , and the temperature gradient is directed along the external electric field.

In the theoretical calculation, we will take into account the effective value of the electric field inside the medium

$$\vec{E}_{eff} = \vec{E} + \frac{\left[\vec{\upsilon}\vec{H}\right]}{c} + \frac{T}{e}\left(\frac{\nabla n_+}{n_+^0} - \frac{\nabla n_-}{n_-^0}\right) \tag{1}$$

Here: $\vec{E}$ is the external electric field, $\vec{\upsilon}$ is the speed of hydrodynamic movements, $\vec{H}$ is the external magnetic field, c is the speed of light, T is the temperature of the medium in ergs, e is the elementary positive charge, $\nabla n_\pm$ is the corresponding concentration gradients of holes and electrons, and $n_\pm^0$ is their equilibrium values.

II. Basic equations of the problem

Impurity centers in semiconductors are capable of being in several charged states. Semiconductors with single and double negative impurities were considered in [1–8]. Under experimental conditions [9], these levels are more active. The presence of impurity centers as a result of recombination and generation of charge carriers excite growing waves of a recombination nature in the medium.

The kinetic equations in the aforementioned semiconductor are described in detail in [1–7] for small fluctuations of the electric field and charge carrier concentrations.

$$\frac{\partial n'_-}{\partial t}+divj'_-=\nu_-n'_- -\frac{\nu'_-}{\nu_-i\omega}\left[\nu_+n'_+ +\nu_-n'_- +\left(\nu_+^{\varepsilon}n_{1+}\beta_+^{\gamma}+\nu_-n_-\beta_-^{\gamma}\right)\frac{e\left(\mu_+n'_+ +\mu_-n'_-\right)}{\sigma+\sigma_1}\right]+\nu_-n_-\beta_-^{\gamma}\frac{e\left(\mu_+n'_+ +\mu_-n'_-\right)}{\sigma+\sigma_1} \quad (2)$$

$$\frac{\partial n'_+}{\partial t}+divj'_+=\nu_+n'_+ +\frac{\nu'_+}{\nu_-i\omega}\left[\nu_+n'_+ +\nu_-n'_- +\left(\nu_+^{\varepsilon}n_{1+}\beta_+^{\gamma}+\nu_-n_-\beta_-^{\gamma}\right)\frac{e\left(\mu_+n'_+ +\mu_-n'_-\right)}{\sigma+\sigma_1}\right]-\nu_+^{\varepsilon}n_+\beta_+^{\gamma}\frac{e\left(\mu_+n'_+ +\mu_-n'_-\right)}{\sigma+\sigma_1} \quad (3)$$

$$\beta_\pm=2\frac{d\ln\mu_\pm}{d\ln\left(E_0^2\right)},\ \vec{\upsilon}_\pm=\mu_\pm\vec{E}_0,\ n_\pm=n_\pm^0+n'_\pm,\ \vec{E}=\vec{E}_0+\vec{E}',\ n'_\pm<<n_\pm^0,\ \vec{E}'<<\vec{E}_0,\ \beta_\pm^{\gamma}=2\frac{d\ln\gamma_\pm\left(E_0\right)}{d\ln\left(E_0^2\right)},$$

$$n_{1-}=\frac{n_-^0N_0}{N_-^0},\ n_{1+}=\frac{n_+^0N_-^0}{N_0}$$

The symbol (0) indicates the equilibrium values of the corresponding quantities:

$\nu_-=\gamma_-\left(E_0\right)N_0$ -frequency of electron capture;

$\nu_+=\gamma_+\left(0\right)N_-^0$ -frequency of hole capture;

$\nu_+^{\varepsilon}=\gamma_+\left(E_0\right)N_0$ - frequency of emission of holes;

$\nu=\nu'_+ +\nu'_-$ - combined frequencies of capture and emission of electrons and holes.

Upon receipt of equation (2-3), it is clear that N is the double negatively charged centers and N_- is double negatively charged centers are much larger than the equilibrium concentrations of electrons and holes

$$\left(N_0,N_-^0\right)>>\left(n_+^0,n_-^0\right) \quad (4)$$

$$\sigma=e\left(n_+^0\mu_+^0+n_-^0\mu_-^0\right)=\sigma_++\sigma_-,\ \sigma_1=e\left(n_+^0\mu_+^0\beta_++n_-^0\mu_-^0\beta_-\right)$$

To solve our problem, we must put E_0^* in (2,3) instead of E_0 and $E^{*'}$ instead E' from (1). In addition, we accept that the following equalities are satisfied

$$\nu_+n_+^0=\nu_-n_-^0, \quad (5)$$

Then from (2-3) we easily obtain:

$$\begin{aligned}&\frac{\partial n'_+}{\partial t}+divj'_-=\nu_-n'_-\\&\frac{\partial n'_-}{\partial t}+divj'_-=\nu_+n'_+\end{aligned} \quad (6)$$

In (6), one needs to add the quasineutrality equation

$divJ=ediv\left(j'_+-j'_-\right)=0$ (7)

In the presence of a temperature gradient, an external magnetic field, taking into account the hydrodynamic movements of the current flux density, they have the following form:

$$\vec{j}_+=n_+\mu_+\left[\vec{E}+\frac{\left[\vec{\upsilon}\vec{H}\right]}{c}+\frac{T}{e}\left(\frac{\nabla n_+}{n_+^0}-\frac{\nabla n_-}{n_-^0}\right)\right]+n_+\mu_{1+}\left\{\left[\vec{E}\vec{H}\right]-\frac{\left[\vec{H}\left[\vec{\upsilon}\vec{H}\right]\right]}{c}+\frac{T}{e}\frac{\left[\nabla n_+H\right]}{n_+^0}-\frac{T}{e}\frac{\left[\nabla n_-H\right]}{n_-^0}\right\}-\alpha_+\vec{\nabla}T-\alpha_{1+}\left[\vec{\nabla}T\vec{H}\right] \quad (8)$$

$$\vec{j}_-=-n_-\mu_-\left[\vec{E}+\frac{\left[\vec{\upsilon}\vec{H}\right]}{c}+\frac{T}{e}\left(\frac{\nabla n_+}{n_+}-\frac{\nabla n_-}{n_-}\right)\right]+n_-\mu_{1-}\left\{\left[\vec{E}\vec{H}\right]-\frac{\left[\vec{H}\left[\vec{\upsilon}\vec{H}\right]\right]}{c}+\frac{T}{e}\frac{\nabla n_+}{n_+^0}-\frac{T}{e}\frac{\nabla n_-}{n_-^0}\right\}+\alpha_-\vec{\nabla}T+\alpha_{1-}\left[\vec{\nabla}T\vec{H}\right] \quad (9)$$

To obtain the dispersion equation, we must solve the equations (6-7-8-9) together.

III. Theory

Let us direct the external constant magnetic field and the electric field as follows

$\vec{H}_0 = \vec{h}H_{0z} = \vec{h}H_0$, $\vec{E}_0 = \vec{i}E_{0x} = \vec{i}E_0$ ($\vec{i}, \vec{h}$ are the unit vectors in x and z).

From (1) we easily obtain:

$$\vec{E}_0^{*\prime} = \vec{i}E_0 - \vec{j}\frac{\upsilon_{0x}H_0}{c} + \vec{i}\frac{\upsilon_{0y}H_0}{c}, \quad \vec{E}^{*\prime} = E' - \vec{j}\frac{H_0}{c}\upsilon'_y + \frac{T}{e}i\vec{k}\left(\frac{n'_+}{n_+} - \frac{n'_-}{n_-}\right) \qquad (10)$$

Here: $\vec{j}$ is the unit vectors in y, $\vec{k}$ is the wave vectors in, $\vec{\upsilon} = \vec{\upsilon}_0 + \vec{\upsilon}'$

From (10) we easily obtain:

$$\vec{E}_0^{*}E^{*\prime} = E_0E'_x - \frac{\upsilon_{0x}H_0}{c}E'_y + iE_1\left(\frac{n'_+}{n_+^0} - \frac{n'_-}{n_-^0}\right)E_0k_xL_x + \frac{H_0E_0}{c}\upsilon'_y + \frac{H_0^2\upsilon_{0x}}{c^2}\upsilon'_x$$

$$\left(E_0^*\right)^2 = E_0^2\left(1 + \frac{H_0\upsilon_{0y}}{cE_0}\right) \qquad (11)$$

We consider longitudinal oscillations and therefore from the Maxwell equation $\frac{\partial H'}{\partial t} = -rotE^*$ we find

$$\left[\vec{k}E^*\right] = 0 \qquad (12)$$

Substituting (1) in (12) we obtain:

$$k_yE'_z - k_zE'_y + \frac{k_zH_0}{c}\upsilon'_x = 0 \qquad (13)$$

$$k_zE'_x - k_xE'_z + \frac{k_zH_0}{c}\upsilon'_y = 0 \qquad (14)$$

$$k_xE'_y - k_yE'_x + \frac{k_zH_0}{c}\upsilon'_z - H_0\left(k_x\upsilon'_x + k_y\upsilon'_y + k_z\upsilon'_z\right) = 0 \qquad (15)$$

We consider a one-dimensional problem and therefore

$$J'_y = 0 \qquad (16)$$

$$J'_z = 0 \qquad (17)$$

$$\frac{\partial J'_x}{\partial x} = 0 \qquad (18)$$

From (13-18), after algebraic calculations, we obtain for the components of the variable electric field E'_x, E'_y, E'_z and for the components of the velocity of hydrodynamic movement υ'_x, υ'_y, υ'_z the following expressions

$$E'_x = \frac{L_x^2E_1}{L_yL_z}u, \quad E'_y = -E_0f, \quad \upsilon'_x = -c\frac{E_0}{H_0}\left(\frac{a'_1}{a} + \frac{iE_1\varphi'}{aE_0}\frac{c}{\mu_-H_0} + \frac{b}{a}\frac{E}{E_0}\frac{L_x}{L_z}u + \frac{L_x^2}{L_y^2}u\right)$$

$$E'_z = \frac{L_x}{L_z}u, \quad \varphi' = \frac{n'_+}{n_+^0} - \frac{n'_-}{n_-^0}, \quad E_1 = \frac{T}{e}k_x, \quad u = \frac{\mu_{1+}n'_+ - \mu_{1-}n'_-}{n_-\mu_1}\frac{H_0}{E_1}\frac{\upsilon_{0y}}{c} - i\varphi' - \frac{\mu_+n'_+ - \mu_-n'_-}{n_-\mu_{1-}}\frac{H_0\upsilon_{0y}}{cE_1}$$

$$\upsilon'_y = \frac{cE_1}{H_0}\left(1 - \frac{L_x^2}{L_yL_z}\right)u, \quad \upsilon'_z = \frac{c}{\mu_-H_0}c\frac{E_1}{E_0}\left(\frac{L_x}{L_z}u + i\varphi'\right) \qquad (19)$$

We assume that

$$\upsilon_{0x} = \upsilon_{0y} = \upsilon_{0z}, \quad E_0 >> H_0\frac{\upsilon_{0y}}{c} \quad (20)$$

Substituting (20) in (6) we obtain:

$$\begin{cases} \left(-\frac{L_x^2}{L_yL_z} + \frac{H_0}{E_1}\theta_1 + ik_xL_x\right)\frac{n'_+}{n_+^0} + \left(\alpha\frac{L_x^2}{L_yL_z} + \frac{H_0}{E_1}\theta_2 - ik_xL_x\right)\frac{n'_-}{n_-^0} = 0 \\ \left(-r + \frac{H_0}{E_0}R_1 + i\frac{E_1}{E_0}k_xL_x\right)\frac{n'_+}{n_+^0} + \left(-\delta + \frac{H_0}{E_0}R_2 - i\frac{E_1}{E_0}k_xL_x\right)\frac{n'_-}{n_-^0} = 0 \end{cases} \qquad (21)$$

Substituting (20) into (6), expressions for dimensionless constants $\theta_1, \theta_2, r, R_1, R_2$ are easily obtained. Due to the bulkiness of their expression, we do not write out. Equating the real and imaginary parts to zero the dispersion equation obtained from (21) we obtain for the external electric field E_0, for the magnetic field H_0 the following expressions

$$E_0 = H_0 \frac{\mu_- H_0}{c}\left(1 + \frac{2\mu_- H_0}{c}\right); \quad \frac{\mu_- H_0}{c} = \left(\frac{E_1}{E_0}\right)^{1/2} \qquad (22)$$

From (22) it is easily seen that $\mu_- H_0 << c$ and

$$E_0 = H_0 \left(\frac{E_1}{H_0}\right)^{1/2} \qquad (23)$$

In obtaining (23), we used expressions for the sample length

$$L_x = \frac{2\pi T}{eH_0}\left(\frac{c}{\mu_- H_0}\right)^2 \qquad (24)$$

If (23-24) is valid from the dispersion equation (21) for

$$L_y = 2\pi L_z = (2\pi)^4 \frac{T\mu_-}{ec} \qquad (25)$$

For frequency ω_0 and slew increment ω_1, the following values

$$\omega_0 = 2\nu_+, \ \omega_1 = \nu_+ \qquad (26)$$

(25) it is true if the magnetic field and the velocities of hydrodynamic motions have values

$$H_0 = \frac{c}{\mu_-}\frac{1}{2\pi} \qquad (27)$$

$$\upsilon_{0x} = \upsilon_{0y} = \upsilon_{0z} = \frac{\upsilon_T\left(\alpha_{1+} + \alpha_{1-}\right)\gamma}{\Lambda' \sigma_0 H_0} \qquad (28)$$

Where υ_T is the speed of propagation of thermomagnetic waves

$$\upsilon_T = c\Lambda' \nabla T \qquad (29)$$

The ratio of electron and hole concentrations is determined by the expression

$$\frac{n_-^0}{n_+^0} = \frac{\mu_+}{\mu_-} \frac{\left(1 + \frac{\alpha_-}{\alpha_+}\right)\left(1 + \frac{\gamma_-}{\gamma_+}\right)}{1 + \frac{\beta_-}{\beta_+}} \qquad (29)$$

IV. Discussion

Thus, taking into account the hydrodynamic motion of charge carriers substantially changes the excitations of growing waves in the aforementioned semiconductors. The values of the external electric field and magnetic field are quite measurable, and can be estimated by formulas (23), (26). Concrete expressions are obtained for the semiconductor size. Therefore, for the excitation of growing waves with a frequency and increment (26), impurity semiconductors with dimensions (24–25) are needed.

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