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EXCITATION OF UNSTABLE WAVES IN IMPURITY SEMICONDUCTORS WITH TWO TYPES OF CHARGE CARRIERS IN EXTERNAL ELECTRIC AND WEAK MAGNETIC FIELDS

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Abstract- In semiconductors with single and double impurity centers in an external electric and weak $(\mu_{\pm} H_0 << c)$ magnetic field, when the external electric field is directed along a constant temperature gradient, the conditions of internal and external instability are theoretically investigated. Analytical formulas are found for the oscillation frequency and electric field for internal and external instability. The role of injection on the contacts is revealed and their relationships are found. Analytical formulas are found for the equilibrium values of electrons and holes with external instability.

Keywords: Frequency, Injection, Instability, Impedance, Oscillations, Increment.

1. INTRODUCTION

Theoretical studies of unstable states of conductive media lead to the preparation of generators and amplifiers with high frequencies. Advantageous conductive media from a practical point of view are impurity semiconductors. In [1-3], the mechanism of the appearance of unstable waves in a germanium semiconductor with impurity centers of copper or gold is described in detail. The elements of copper and gold in germanium create various centers that are able to capture (recombine) or emit (generate) charge carriers. As a result of recombination and generation of charge carriers, the energy distribution function of charge carriers changes significantly and, as a result, charges and, of course, electric field are redistributed in the sample. The received carrier energy from an external electric field $eE_0 l$ along the mean free path of one carrier with a charge e (e elementary charge) if it is enough to pass the Coulomb barrier around a negative charge, then the charge propagates throughout the crystal in the form of a wave. Otherwise, the charge stops around the center and does not participate in conduction. Thus, the recombination and thermal generation of charge carriers changes the conductivity of the medium and, of course, the resistance of the sample changes. With decreasing resistance, unstable waves are excited inside the sample.

Such excited waves can attenuate inside the sample and in this case, in the external circuit, the total current remains constant. The frequency of the excited waves inside the sample is a complex quantity. The wave vector is determined from the condition of standing waves, i.e.

$$\varpi = \varpi_0 + ij \ , \ k = \frac{2\pi}{L} m \, , \ (m = 0, \pm 1, \pm 2, \dots) \tag{1}$$

where, L is linear size of the sample. If the excited wave inside the sample grows, and at the same time, current oscillations in the circuit begin, then the frequency is a real quantity and the wave vector is a complex quantity, i.e.

$$k = k_0 + ik_i \tag{2}$$

When condition (1) is satisfied, instability is called internal instability, and if condition (2) is fulfilled, instability is called external instability. We will investigate the instability of excited waves in a germanium semiconductor when condition (1) (i.e., internal instability) is satisfied and condition (2) (i.e., external instability) of a constant electric field E_0 and a weak magnetic field H_0 (i.e. $\mu_{\pm} H_0 << c$, $\mu_{\pm}$ is mobility of holes and electrons, c-speed of light), when germanium with specific impurity centers are influenced by a constant temperature gradient $\nabla T = \text{const}$.

2. BASIC EQUATIONS OF THE PROBLEM

In [4-5], it was proved that when there is hydrodynamic motion of charge carriers, in a semiconductor with two types of charge carriers, the total electric field has the form:

$$\vec{E}^* = \vec{E} + \frac{\left[\vec{V}\vec{H}\right]}{c} + \frac{T}{e}\left(\frac{\vec{\nabla} n_-}{n_-^0} - \frac{\vec{\nabla} n_+}{n_+^0}\right) \tag{3}$$

where, T is temperature in ergs, $\vec{\nabla} n_{\pm}$ is concentration gradient of holes and electrons, $n_{\pm}^0$ is their equilibrium values. The kinetics equations of electrons and holes under the condition $\nu_- n_+^0 = \nu_+ n_-^0$ have the form [5]:

$$\frac{\partial n'_+}{\partial t}+divj_+=-\nu_+ n'_+,\ \frac{\partial n'_-}{\partial t}+divj_-=-\nu_- n'_- \quad (4)$$

where, ν_- is electron capture frequency; ν_+ is hole capture frequency; $n'_\pm$ is nonequilibrium values of hole and electron concentrations. The semiconductor model is described in detail in [4-5] and therefore we restrict ourselves to a theoretical calculation. The density of the current flow $E,H,\nabla T$ in the presence of is:

$$\vec{j}_+=\frac{\sigma_+}{e}\vec{E}^*+\frac{\sigma_{1+}}{e}\left[\vec{E}^*\vec{H}\right]+\alpha_+\vec{\nabla}T+\alpha'_+\left[\vec{\nabla}T\vec{H}\right]$$
$$\vec{j}_-=-\frac{\sigma_-}{e}\vec{E}^*-\frac{\sigma_{1-}}{e}\left[\vec{E}^*\vec{H}\right]-\alpha_-\vec{\nabla}T-\alpha'_-\left[\vec{\nabla}T\vec{H}\right] \quad (5)$$

In (5), the corresponding diffusion terms do not take into consideration, i.e. $T<<eE_0 l$.

$\sigma_+=en_+\mu_+$, $\sigma_-=en_-\mu_-$, $\sigma_{1+}=en_+\mu_{1+}$, $\sigma_{1-}=en_-\mu_{1-}$

In addition to (4-5), we must consider the quasineutrality condition

$$\vec{J}=e(\vec{j}_+-\vec{j}_-) \quad (6)$$

To determine the oscillation frequency of the corresponding quantities inside the specified semiconductor, we must solve nonlinear equations (3-5) together.

Assuming $n_\pm=n^0_\pm+n'_\pm$, $\vec{E}^*=\vec{E}^*_0+\vec{E}'$, $\vec{H}^*=\vec{H}^*_0+\vec{H}'$ from (5) we obtain:

$$\vec{E}^*=\vec{E}^*_0+\vec{E}'$$
$$j'_{+x}=\left(\frac{\sigma_{+0}}{e}+\frac{\sigma_{1+}\beta_{1+}}{e}+\frac{\alpha_+\nabla_x T\gamma_+}{E^*_{0x}}\right)E^{*\prime}_x+$$
$$+\frac{\sigma^0_{1+}}{e}\left(\frac{ck_x}{w}+1\right)E^{*\prime}_y+\frac{\sigma^0_{1+}}{e}E^*_{0y}\frac{n'_+}{n^0_+}$$
$$j'_{-x}=-\left(\frac{\sigma_{1-}}{e}+\frac{\sigma_{1-}\beta_{1-}}{e}+\frac{\alpha_-\nabla_x T\gamma_-}{E^*_{0x}}\right)E^{*\prime}_x-$$
$$-\frac{\sigma^0_{1-}}{e}\left(\frac{ck_x}{w}+1\right)E^{*\prime}_y-\frac{\sigma^0_{1-}}{e}E^*_{0y}\frac{n'_-}{n^0_-} \quad (7)$$

where, $\beta_{1\pm}=2\frac{d\ln\mu_\pm}{d\ln\left(E^{*\,2}_{0x}\right)}$, $\gamma_\pm=2\frac{d\ln\alpha_\pm}{d\ln\left(E^{*\,2}_{0x}\right)}$, $E^*_{0x}=\frac{J_{0x}}{\sigma_0}+\Lambda\nabla_x T$.

Putting (7) in (6) with allowance for $J'_y=J'_z=0$, we obtain for the electric field the expressions

$$\left[u(1+\beta)-\beta\right]E^*_x=u\frac{J'_x}{\sigma_0}+u\frac{J_{0x}\sigma'}{\sigma^2_o}+\frac{2T}{e}ik_x u\left(\frac{n'_-}{n^0_-}-\frac{n'_+}{n^0_+}\right) \quad (8)$$

$\sigma_0=en^0_+\mu^0_++en^0_-\mu^0_-$, $u=1+\frac{\Lambda_0\nabla_x T\sigma_0}{J_{0x}}$,

$\beta=2\frac{d\ln\Lambda}{d\ln\left(E^{*2}_0\right)}$.

where, $E_+=\frac{\sigma^0_+J_{0x}}{f\sigma^2_0}$, $E_-=\frac{\sigma^0_-J_{0x}}{f\sigma^2_0}$, $E_1=\frac{Tk_x}{fe}$,

$f=u(1+\beta)-\beta-\frac{\sigma_+\varphi_++\sigma_-\varphi_-}{\sigma_0}$, $\varphi_\pm=2\frac{d\ln\mu_\pm}{d\ln\left(E^{*2}_0\right)}$.

From (8) we obtain:

$$E^{*\prime}_x=\frac{u}{\sigma_0 f}J'_x+\left(E_+-iE_1\right)u\frac{n'_+}{n^0_+}+\left(E_-+iE_1\right)u\frac{n'_-}{n^0_-} \quad (9)$$

Choosing the following coordinate system $\vec{H}_0=H_{oz}=H_0$, $E^*_0=E^*_{0x}=E_0$, substituting (9) into (4) taking into account (5), we obtain the following systems of equations for determining the frequency in the case of internal instability $J'_x=0$ (or wave vectors in the case of external $J'_x\neq0$ instability of excited waves)

$$\left(\nu_+-i\varpi\right)n'_++ik\frac{\sigma_+}{e}E^{*\prime}_x+ik\left[\frac{\sigma^2_{1+}J_{0x}}{\sigma^2 ea}\left(1+\frac{ck}{\varpi}\right)+\frac{\sigma_{1+}}{e}\right]\cdot$$
$$\cdot\frac{n'_+}{n^0_+}+ik\frac{\sigma_{1+}\sigma_{1-}}{e\sigma^2 a}J_{ox}\left(1+\frac{ck}{\varpi}\right)\frac{n'_-}{n^0_-}=0 \quad (10)$$

$$\left(\nu_--i\varpi\right)n'_--ik\frac{\sigma_-}{e}E^{*\prime}_x-ik\left[\frac{\sigma^2_{1-}J_{0x}}{\sigma^2 ea}\left(1+\frac{ck}{\varpi}\right)+\frac{\sigma_{1-}}{e}\right]\cdot$$
$$\cdot\frac{n'_-}{n^0_-}-ik\frac{\sigma_{1-}\sigma_{1+}}{e\sigma^2 a}\left(1+\frac{ck}{\varpi}\right)\frac{n'_+}{n^0_+}=0 \quad (11)$$

where,

$J_{0x}=\sigma_0E_0$, $\sigma_0=e\left(n^0_+\mu^0_++n^0_-\mu^0_-\right)$, $a=1-\frac{ck}{\varpi}$,

$\sigma_{1\pm}=en^0_\pm\mu^0_{1\pm}$.

To determine the frequency of oscillations of the excited waves inside the aforementioned semiconductor, we must solve (10-11) together under condition (1). From (10-11), considering (9), we easily obtain the following dispersion equation

$$\varpi^3+\left(k\vartheta_--2ck+i\nu_-\right)\varpi^2+$$
$$+\left(c^2k^2-2ckk\vartheta_--i22ck\nu_-\right)\varpi \quad (12)$$
$$+c^2k^2\left(k\vartheta_-+i\nu_-\right)=0$$

where, $\vartheta_\mp=\mu_\mp E_0$ ($\vartheta_\mp$ is drift velocities of electrons and holes). Upon receipt of the dispersion equation (12), $\nu_->>\nu_+$ was considered and

$$E_0=\frac{\mu_+H_0}{2c}\Lambda_0\nabla_x T+\left[\left(\frac{\mu_+H_0}{2c}\Lambda_0\nabla_x T\right)^2+E^2_{char}\right]^{1/2} \quad (13)$$

$$E^2_{char}=\frac{\nu_+\nu_-}{k^2\mu_-\mu_+}+\frac{\nu_+\vartheta_{1-}}{k\mu_-\mu_+}+\frac{\nu_-\vartheta_{1+}}{k\mu_-\mu_+}+\vartheta^-_T\vartheta^+_T\left(\frac{H_0}{c}\right)^2 \quad (14)$$

where, $\vartheta^+_T=\mu_+\Lambda_0\nabla_x T$, $\vartheta^-_T=\mu_-\Lambda_0\nabla_x T$, $\vartheta_{1-}=\mu_-E_1$, $\vartheta_{1+}=\mu_+E_1$, $E_1=\frac{T}{eL}$.

Equating the real and imaginary parts of (12) to zero, we can easily obtain the following values for the frequency and increment of oscillations inside the crystal:

$$\varpi = \varpi_0 + i\varpi_1 \,,\; \varpi_1 << \varpi_0 \,,\; \varpi_0 = -k\vartheta_- \,,\; \varpi_1 = \nu_- \tag{15}$$

When obtaining (15) from (12) for the frequency of thermomagnetic waves inside the sample, the following expressions were found

$$\varpi_T = \frac{\mu_-}{\mu_+}\left(\frac{c^2}{\mu_-\mu_+ H_0^2}\nu_+ - k\vartheta_-\right) \tag{16}$$

Thus, an unstable recombination wave with a frequency $\varpi_0 = -k\mu_- E_0$ and increment $\varpi_1 = \nu_-$ is excited inside the aforementioned semiconductor. In addition to this excited wave with a frequency ϖ_0 and increment ϖ_1, a thermomagnetic wave with a frequency is also excited (16). This thermomagnetic wave propagates with a frequency (16). The frequency of the thermomagnetic wave is greater than the frequency of the recombination wave.

3. EXTERNAL INSTABILITY

To calculate the frequency of the current oscillations in the circuit, we must calculate the crystal impedance as follows

$$Z = \frac{1}{J'_x}\int_0^1 E'_*\left(x,t\right)dx \tag{17}$$

Substituting (8) into (17), we can calculate the impedance. However, we must first calculate the nonequilibrium concentration values $n'_\pm$ inside the sample. For this, it is necessary to use the boundary conditions for the concentrations of charge carriers. These boundary conditions are as follows:

$$\begin{aligned} n'_+ &= \delta_+^0 J'_x \text{ at } x=0 \\ n'_+ &= \delta_+^L J'_x \text{ at } x=L \\ n'_- &= \delta_-^0 J'_x \text{ at } x=0 \\ n'_- &= \delta_-^L J'_x \text{ at } x=L \end{aligned} \tag{18}$$

where, L is crystal's linear size.

Firstly, we determine the wave vectors of current oscillations from the solution of dispersion equation (12) with respect to k. Denoting $kL = x$ from (12), we obtain:

$$\begin{aligned} &\varpi^3 + \left(\frac{L\varpi}{\vartheta_-} + i\frac{L\nu_-}{\vartheta_-}\right)x^2 + \left(\frac{\varpi^3 L^2}{c^2} - i2\frac{L^2\nu_-\varpi}{c\vartheta_-}\right)x + \\ &+\frac{\left(L\varpi\right)^3}{c^2\vartheta_-} + i\frac{L^3\nu_-\varpi^2}{c^2\vartheta_-} = 0 \end{aligned} \tag{19}$$

Introducing,

$$x = x_0 + ix_1 \,,\; x_1 << x_0 \tag{20}$$

Equating the real and imaginary parts of (19), we obtain the following two values for x.

$$x_1 = \frac{2L\nu_-}{\sqrt{3}c} - i\frac{L\nu_-}{\vartheta_-} \,,\; x_1 = -\frac{2L\nu_-}{\sqrt{3}c} + i\frac{L\nu_-}{\vartheta_-} \tag{21}$$

We will try for $n'_\pm$ in the following form (22)

$$\begin{aligned} n'_+ &= c_1^+ e^{ik_1 x} + c_2^+ e^{ik_2 x} \\ n'_- &= c_1^- e^{ik_1 x} + c_2^- e^{ik_2 x} \end{aligned} \tag{22}$$

Considering the boundary conditions (18) from (22), we easily obtain the following values for the constants

$$\begin{aligned} c_1^+ &= J'_x \frac{\delta_+^0 e^{ix_{20}} - \delta_+^L}{e^{ix_{20}} - e^{ix_{10}}} \,,\; c_2^+ = J'_x \frac{\delta_+^L - \delta_+^0 e^{ix_{10}}}{e^{ix_{20}} - e^{ix_{10}}} \\ c_1^- &= J'_x \frac{\delta_-^0 e^{ix_{20}} - \delta_-^L}{e^{ix_{20}} - e^{ix_{10}}} \,,\; c_2^- = J'_x \frac{\delta_-^L - \delta_-^0 e^{ix_{10}}}{e^{ix_{20}} - e^{ix_{10}}} \end{aligned} \tag{23}$$

Substituting (22), considering (23) into (8), after calculating the integral (17), we obtain:

$$\frac{Z}{Z_0} = 1 + \frac{\delta_1}{\delta_0}(\cos\alpha - 1)\frac{1}{2\sin\alpha} + \frac{\delta_2}{\delta_0} \tag{24}$$

where,

$$\delta_1 = 2\delta_- - 2i\delta_-^0\sin\alpha + i\frac{\sqrt{3}\vartheta_+}{c}\delta_+^0\sin\alpha - \frac{\vartheta_+}{\sqrt{3}c}\delta_+ -$$

$$-i\delta_- - \delta_-^0\sin\alpha - \frac{2\vartheta_+}{\sqrt{3}c}\delta_-$$

$$\delta_2 = 1 + \frac{J_{0x}e\mu_-\vartheta_-}{\sigma_0\nu_- L}\left(\delta_1\frac{1}{2\sin\alpha}\left(\cos\alpha - 1\right)\right) + \frac{J_{0x}e\mu_-\vartheta_-}{\sigma_0\nu_- L}$$

$$\frac{J_{0x}e\mu_-\vartheta_-}{\sigma_0\nu_- L} = \frac{1}{\delta_0}$$

$$\alpha = \frac{2\nu_- L}{\sqrt{3}c},\quad Z_0 = \frac{L}{\sigma_0},\quad \vartheta_- > L\nu_-,\quad \delta_+^L - \delta_+^0\cos\alpha = \delta_+,$$

$$\delta_-^L - \delta_-^0\cos\alpha = \delta_-,\; J_{0x} = \sigma_0 E_0,\; \vartheta_- = \frac{8c^3}{\left(\varpi L\right)^2}$$

In obtaining expression (24) for the equilibrium values of the concentrations of charge carriers, the following values are taken into account

$$\begin{aligned} n_+^0 &= \frac{2T\sigma_0^2}{e^2 J_{0x}^l \mu_+} \\ n_-^0 &= \frac{\nu_-}{\nu_+}\cdot\frac{2T\sigma_0^2}{e^2 J_{0x}^l \mu_+} \\ n_-^0 &>> n_+^0 \end{aligned} \tag{25}$$

Analysis (24) shows that, when the following expressions for the injection coefficients are satisfied,

$$\begin{aligned} \delta_-^0 &= \delta_+^0\frac{2\vartheta_-}{3c} \\ \delta_+ &= \frac{2c}{\vartheta_+}\delta_- \end{aligned} \tag{26}$$

The electric field has the following form:

$$\begin{aligned} E_0^2 &= E_{char}^2\left(1 + \frac{R}{Z_0}\right)\frac{\sin\alpha}{\cos\alpha - 1} \\ E_{char} &= \frac{\nu_- L}{\mu_-} \end{aligned} \tag{27}$$

where, R is ohmic resistance.

From (26) it is clear that for a positive value E_0 the trigonometric functions $\sin\alpha$ and $\cos\alpha$ must have negative values. The frequency of the current oscillation is determined by the formula

$$\varpi = 2\sqrt{2}\,\frac{c^{3/2}}{L\vartheta_{-}^{1/2}} \tag{28}$$

Thus, the frequency and electric field are determined for internal and external instability in the above impurity semiconductor.

4. DISCUSSION OF THE RESULTS

Thus, in a semiconductor with single and double impurity centers and two types (electrons and holes) of charge carriers in an external electric field E_0, in the presence of a constant external (weak $\mu_{\pm}H_0 << c$) magnetic field and temperature gradient $\nabla_x T = \text{const}$, recombination and thermomagnetic waves are excited. The frequency of thermomagnetic waves is greater than the frequency of recombination waves. The directions of the electric field, magnetic field and temperature gradient are as follows $\vec{H}_0 \perp \vec{E}_0$, $\vec{E}_0 \parallel \vec{\nabla}_0 T$. When fluctuations of physical quantities (E, H, n_+, n_-) occur only inside the sample (i.e., internal instability), the recombination wave is increasing. The growth increment is determined by the electron capture frequency, i.e. $\varpi_1 = \nu_-$, and the wave propagation frequency is determined by the value of the electric field, i.e.

$$\varpi_0 = -k\mu_- E_0$$

$$E_0 = E_1 + \sqrt{E_1^2 + E_2^2}$$

$$E_1 = \vartheta_T^- \frac{H_0^2}{c^2}\mu_+ \frac{\nu_+}{\nu_-} + \frac{H_0}{c}\frac{\mu_+}{\mu_-}\vartheta_T^- + \frac{H_0}{c}\vartheta_T^+ + \frac{H_0^2}{c^2}\mu_+\vartheta_T^-$$

$$E_2^2 = \frac{\nu_+\nu_-}{k^2\mu_-\mu_+} + \frac{k\nu_+\nu_1^-}{\mu_-\mu_+} + \frac{k\nu_+\nu_1^+}{\mu_-\mu_+} + \frac{H_0^2}{c^2}\vartheta_T^+\vartheta_T^-$$

With external instability, the frequency of current oscillation (26) is much larger than the frequency with internal instability, i.e.

$$\frac{\varpi_{exterior}}{\varpi_{internal}} \approx \left(\frac{c}{\vartheta_-}\right)^{3/2} >> 1$$

Electric field relations

$$\frac{E_{exterior}}{E_{internal}} \sim \frac{c}{\mu_- H_0}\frac{\nu_- L}{\vartheta_T^{\sim}} \sim \frac{c}{\mu_- H_0}\frac{\nu_- L}{\mu_-\Lambda_0\nabla_x T} >> 1$$

Thus, with an increase in the electric field, the frequency of the excited waves inside the sample increases and the current oscillates in the circuit, i.e. begins to emit energy from the sample.

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