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EXCITATION OF THERMOMAGNETIC AND RECOMBINATION WAVES IN IMPURITY WITH TWO TYPES OF CURRENT CARRIERS

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Abstract- It has been theoretically shown that, in the presence of a temperature gradient with a weak magnetic field, an impurity semiconductor emits energy with a certain frequency and leads to excitation of growing waves, the ratio of electron and hole concentrations in the case of growing waves is determined. The concentration of electrons and holes is determined from the obtained expression in theory in this paper. And for the appearance of current oscillations in the circuit, the main role is played by the injection of contacts in the mixed impurities. In this paper, we determine the frequency and increment of the rising waves, as well as the expressions for the external electric and magnetic fields upon excitation of the rising waves. And growth occurs in samples with a certain size.

Keywords: Electric Field, Magnetic Field, Impedance, Temperature Gradient, Frequency, Thermomagnetic Waves, Recombination Waves.

1. INTRODUCTION

In [1-6], we obtained some analytical formulas for the external electric field and for the frequency of the current oscillations, and we also constructed the theory of quasi-neutral current oscillations in semiconductors with two types of charge carriers. In these works, the internal and external instabilities of the semiconductor are analyzed and the values of the vibration frequency are determined.

It is known that during the motion of charge carriers an electric field also arises inside the medium due to the presence of a magnetic field and a gradient of charge carrier concentrations [1-10]. Since the influence of the motion of charge carriers on the corresponding instabilities is not shown in these works, we consider this problem. In the presence of a temperature gradient and an external magnetic field, thermomagnetic waves arise in the medium, which propagate in the medium at a certain speed. We indicate the formulas for the dependence of the velocity of these waves on the temperature gradient.

We also consider external instability in semiconductors with single and double negative impurity centers in the presence of weak magnetic fields (i.e., $\mu_{\pm} H_0 << c$, $\mu_{\pm}$ is the mobility of holes and electrons, c is the speed of light). In a semiconductor, the temperature gradient is constant $\nabla T = \text{const}$.

2. BASIC EQUATIONS OF THE PROBLEM

The equations of motion of electrons and holes in impurity semiconductors have the form [1-7]:

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

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

$$\beta_{\pm} = 2\frac{d\ln\mu_{\pm}}{d\ln\left(E_0^2\right)} \\ \vec{\vartheta}_{\pm} = \mu_{\pm}\vec{E}_0 \\ \beta_{\pm}^{\gamma} = 2\frac{d\ln\gamma_{\pm}}{d\ln\left(E_0^2\right)} \quad (3) \\ n'_{\pm} << n_+^0 \\ E' << E_0 \\ T << eE_0 l$$

Equilibrium values are marked by (0), where, $\nu_+ = \gamma_+(E_0)N_0$ is the electron capture frequency; $\nu_+ = \gamma_+(0)N_-^0$ is frequency of hole capture; $\nu_+^{\varepsilon} = \gamma_+\left(E_0\right)N_0$ is frequency of emission of holes; $\nu = \nu'_+ + \nu'_-$ is combined frequencies of capture and emission of electrons and holes.

$T = k_0 T$ is the lattice temperature, l is the mean free path, $N_{1-} = \frac{N_-^0 L_0}{N_-^0}$, $N_{1+} = \frac{N_+^0 L_-^0}{N_0}$, $L_0 = L_+ L_-$ is the total concentration of impurities, L is the singly negatively charged centers, L_- is the doubly negatively charged centers,

$N >> L_-$

$\Omega = \Omega_+ + \Omega_- = e(N_+\mu_+ + N_-\mu_-)$

$\Omega_1 = e(N_+\mu_+\beta_+ + N_-\mu_-\beta_-)$

$\nu = \nu'_+ + \nu'_-$ is the combined frequency of capture and emission of electrons and holes by nonequilibrium traps $\left(L_0, L_-^0\right) >> \left(N_\pm^0\right)$.

The centers in impurity semiconductors are in several charged states. Semiconductors with single and double negative impurities were considered in [1-8]. Under experimental conditions [11], these levels are more active.

$$\left(L_0, L_-^0\right) >> \left(N_+^0, N_-^0\right)$$

$$\Omega = e\left(N_+^0\mu_+^0 + N_-^0\mu_-^0\right) = \Omega_+ + \Omega_- \quad (4)$$

$$\Omega_1 = e\left(N_+^0\mu_+^0\beta_+ + N_-^0\mu_-^0\beta_-\right)$$

Replace E_0 with E_0^*, E' with $E^{*\prime}$ (3) from the equation of the effective value of the electric field inside the medium

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

where, $\vec{E}$ is the external electric field, $\vec{\vartheta}$ 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.

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

then

$$\frac{\partial n'_+}{\partial t} + div\wp'_- = \nu_- n'_-\ ,\ \frac{\partial n'_-}{\partial t} + div\wp'_- = \nu_+ n'_+ \quad (6)$$

Combine the equations in (6)

$$\mathrm{div}J = e\mathrm{div}\left(\wp'_+ - \wp'_-\right) = 0 \quad (7)$$

The current flux densities in the presence of a temperature gradient are as follows:

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

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

We solve Equations (6), (7), (8) and (9) together.

3. THEORY

The current densities for electrons and holes are of the form:

$$\vec{\wp}_- = -n_-\mu_- E^* - n_-\mu_{1-}\left[E^* H\right] - \alpha_-\vec{\nabla}T - \alpha'_-\left[\vec{\nabla}T\vec{H}\right]$$
$$\vec{\wp}_+ = n_+\mu_+ E^* + n_+\mu_{1+}\left[E^* H\right] + \alpha_+\vec{\nabla}T + \alpha'_+\left[\vec{\nabla}T\vec{H}\right] \quad (10)$$

$$\vec{\Im} = e\left(\vec{\wp}_+ - \vec{\wp}_-\right) \quad (11)$$

Substituting (10) into (11) we find

$$E^* = \frac{\vec{\Im}}{\sigma} - \frac{\sigma_1}{\sigma}\left[\vec{E}^*\vec{H}\right] - \frac{\alpha}{\sigma}\vec{\nabla}T + \frac{\alpha_1}{\sigma}\left[\vec{\nabla}T\vec{H}\right] \quad (12)$$

where, $\sigma = \sigma_+ + \sigma_-$, $\alpha = \alpha_+ + \alpha_-$, $\alpha_1 = \alpha'_+ + \alpha'_-$.

The electric field inside the medium has the form:

$$E^* = \vec{E} + \frac{\left[\vec{V}\vec{H}\right]}{e} + \frac{T}{e}\left(\frac{\nabla n'_-}{n_-^0} - \frac{\nabla n'_+}{n_+^0}\right) \quad (13)$$

To find $\vec{E}^*$ from equation (12), we first write the equation as follows

$$\vec{E}^* = \vec{A} + \frac{\sigma_1}{\sigma}\left[\vec{H}\vec{E}^*\right] \quad (14)$$

Denote $\vec{B} = \frac{\sigma_1}{\sigma}\vec{H}$. Then

$$\vec{E}^* = \vec{A} + \left[B\vec{E}^*\right] \quad (15)$$

We obtain:

$$\vec{E}^* = \vec{A} + \left[\vec{B}\vec{A}\right] + \left[\vec{B}\left[\vec{B}\vec{E}^*\right]\right] \quad (16)$$

Opening the product in equation (16) at $\mu_\pm H_0 << c$ and substituting the expressions $\vec{E}^*$ in (13) we obtain the expressions for the electric field

$$\vec{E} = -\frac{\left[\vec{V}\vec{H}\right]}{c} - \frac{\Lambda'}{\sigma}\left[\vec{\nabla}T\vec{H}\right] + \frac{\vec{\Im}}{\sigma} - \frac{\sigma_1}{\sigma^2}\left[\vec{J}\vec{H}\right] +$$
$$+\Lambda\vec{\nabla}T + \frac{T}{e}\left(\frac{\nabla n'_-}{n_-^0} - \frac{\nabla n'_+}{n_+^0}\right) \quad (17)$$

The solution of Equation (11) in a general form is very complicated. Therefore, we will consider oscillations in a medium with frequencies $W = \pm\left(\nu_-\nu_+\right)^{1/2}$. In view of (12), from (11) we obtain $x_1 = u^{1/2} - i\frac{\delta_1}{2u^{3/2}}$, $x_2 = -u^{1/2} - i\frac{\delta_1}{2u^{3/2}}$.

The impedance of the medium can be calculated as follows

$$E = \frac{I}{I'}\int E'(x,t)dx \qquad (18)$$

We find $E'(x,t)$ from (17)

$$E'_x = \frac{I'_x}{\sigma_0 \Phi} + \frac{iT}{e\Phi}(k_1 + k_2)\left(\frac{n'_-}{n_-^0} - \frac{n'_+}{n_+^0}\right) \qquad (19)$$

$\Phi = 1 - \frac{E_1}{E_0}$, $E_1 = \Lambda_0 \gamma \nabla T$, $\gamma = 2\frac{d\ln\Lambda}{d\ln(E^2)}$, n'_- and n'_+ can be determined from $n'_- = c_1^- e^{ik_1 x} + c_2^- e^{ik_2 x}$, given that at $x = 0$, $n'_\pm = \delta_\pm^0 \Im'_x$ and at $x = L$.

We find following expressions for $c_{1,2}^-$ and $c_{1,2}^+$ from $n'_+ = c_1^+ e^{ik_1 x} + c_2^+ e^{ik_2 x}$, $n'_- = c_1^- e^{ik_1 x} + c_2^- e^{ik_2 x}$, $n'_+ = c_1^+ e^{ik_1 x} + c_2^+ e^{ik_2 x}$ with $n'_\pm = \delta_\pm^L \Im'_x$

$$c_1^- = \Im'_x \frac{\delta_-^0 e^{ik_2 L_x} - \delta_-^L}{e^{ik_2 L_x} - e^{ik_1 L_x}}$$

$$c_2^- = \Im'_x \frac{\delta_-^L - \delta_-^0 e^{ik_1 L_x}}{e^{ik_2 L_x} - e^{ik_1 L_x}}$$

$$c_1^+ = \Im'_x \frac{\delta_+^0 e^{ik_2 L_x} - \delta_+^L}{e^{ik_2 L_x} - e^{ik_1 L_x}} \qquad (**)$$

$$c_2^- = \Im'_x \frac{\delta_+^L - \delta_+^0 e^{ik_1 L_x}}{e^{ik_2 L_x} - e^{ik_1 L_x}}$$

or

$c_1^- = \delta_1^- \Im'_x$, $c_2^- = \delta_2^- \Im'_x$, $c_1^+ = \delta_1^+ \Im'_x$, $c_2^+ = \delta_2^+ \Im'_x$

Substituting $c_1^- = \delta_1^- \Im'_x$, $c_2^- = \delta_2^- \Im'_x$, $c_1^+ = \delta_1^+ \Im'_x$ and $c_2^+ = \delta_2^+ \Im'_x$ taking into account (**) we obtain expressions for the impedance

$$Z = \frac{T}{e\Phi}\left(1 + \frac{k_2}{k_1}\right)\left(\frac{\delta_1^-}{n_-^0} - \frac{\delta_1^+}{n_+^0}\right)\left(e^{ik_1 L_x} - 1\right) + \frac{T}{e\Phi}\left(1 + \frac{k_1}{k_2}\right)\left(\frac{\delta_2^-}{n_-^0} - \frac{\delta_2^+}{n_+^0}\right)\left(e^{ik_2 L_x} - 1\right) + \frac{L_x}{\sigma_0} \qquad (20)$$

$H' = 0$, i.e. $\vec{k} \parallel \vec{E}'$.

Substituting $c_{1,2}^\pm$ (20) taking into account $f_0 > \frac{\delta_1}{u^{1/2}}$, i.e. $E_0 > \frac{L_x \nu_-}{\mu}\frac{c}{\mu H_0}\frac{1}{2\sqrt{2}}\left(\frac{\mu_-}{\mu_+}\right)^{1/4} = E_{charak}$

We obtain:

$$Z = \frac{T}{e\Phi}\left(4\left(\frac{\mu_-}{\mu_+}\right)^2\left(\frac{\nu_-}{\nu_+}\right)^{1/2} - 1\right)\left[\frac{\delta_-^L}{n_-^0} - \frac{\delta_+^L}{n_+^0} + 2\left(\frac{\delta_+^0}{n_+^0} - \frac{\delta_-^0}{n_-^0}\right)\right] \qquad (21)$$

$u >> 1$

It is seen from (22) that $J_m Z = 0$, and this means that the impedance of the medium is real and, when oscillating with a frequency inside, the resistance is ohmic. To find the electric field with the appearance of current oscillations in the circuit, we must solve.

$$Z = \pm\frac{T}{e\varphi Z_0}4\left(\frac{\mu_-}{\mu_+}\right)^{3/2}\left(\frac{\delta_-^L - 2\delta_-^0}{n_-^0} - \frac{\delta_+^L - 2\delta_+^0}{n_+^0}\right) + 1 + \frac{R}{Z_0} = 0 \qquad (22)$$

$Z_0 = \frac{L_x}{\sigma_0}$. From here

$$E_0 = \frac{E_1}{1 \pm \frac{4T}{eZ_0 r}\frac{\mu_-}{\mu_+}\left(\frac{\delta_-}{n_-^0} - \frac{\delta_+}{n_+^0}\right)} \qquad (23)$$

where, $\chi = 1 + \frac{R}{Z_0}$, $\delta_- = \delta_-^L - 2\delta_-^0$, $\delta_+ = \delta_+^L - 2\delta_+^0$.

If we direct the external constant magnetic field $\vec{H}_0 = \vec{h}H_{0z} = \vec{h}H_0$ and the electric field $\vec{E}_0 = \vec{i}E_{0x} = \vec{i}E_0$ ($\vec{i}, \vec{h}$ are unit vectors in x and z) the equation of the effective value (*) of the electric field inside the medium can be written as follows:

$$\vec{E}^{*\prime} = E' - \vec{\gamma}\frac{H_0}{c}\vartheta'_y + \frac{T}{e}i\vec{k}\left(\frac{n'_+}{n_+} - \frac{n'_-}{n_-}\right)$$

$$\vec{E}_0^{*\prime} = \vec{i}E_0 - \vec{\gamma}\frac{\vartheta_{0x}H_0}{c} + \vec{i}\frac{\vartheta_{0y}H_0}{c} \qquad (24)$$

where, $\vec{\gamma}$ is unit vector in y and $\vec{k}$ is wave vector in, $\vec{\vartheta} = \vec{\vartheta}_0 + \vec{\vartheta}'$

From (24) we obtain:

$$\vec{E}_0^* E^{*\prime} = E_0 E'_x - \frac{\vartheta_{0x}H_0}{c}E'_y + iE_1\left(\frac{n'_+}{n_+^0} - \frac{n'_-}{n_-^0}\right)E_0 k_x L_x + \frac{H_0 E_0}{c}\vartheta'_y + \frac{H_0^2 \vartheta_{0x}}{c^2}\upsilon'_x \qquad (25)$$

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

Due to the cumbersomeness of solving the equation, we will write the final expressions for the external electric field E_0 and magnetic field H_0.

$$E_0 = H_0\frac{\mu_- H_0}{c}\left(1 + \frac{2\mu_- H_0}{c}\right), \quad \frac{\mu_- H_0}{c} = \left(\frac{E_1}{E_0}\right)^{1/2} \qquad (26)$$

$$\mu_- H_0 << c, \quad E_0 = H_0\left(\frac{E_1}{H_0}\right)^{1/2} \qquad (27)$$

Length of sample is determined from

$$l_x = \frac{2\pi T}{eH_0}\left(\frac{c}{\mu_- H_0}\right)^2, \quad l_y = 2\pi L_z = (2\pi)^4\frac{T\mu_-}{ec} \qquad (28)$$

$\varpi_0 = 2\nu_+$ is frequency and $\varpi_1 = \nu_+$ is increment.

Speed hydrodynamic movements:

$$\vartheta_{0x} = \vartheta_{0y} = \vartheta_{0z} = \frac{\vartheta_T(\alpha_{1+} + \alpha_{1-})\gamma}{\Lambda'\sigma_0 H_0} \qquad (29)$$

where, $\vartheta_T = c\Lambda'\nabla T$ is propagation speed of thermomagnetic waves.

The ratio of the concentrations of electrons and holes

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

4. CONCLUSIONS

Thus, the values of the external electric exceed the characteristic field E_{charak}, and the radiation of the medium occurs when the value E_0 varies from E_{charak} to E_1 field in the cases listed below

1. $\frac{\delta_-}{n_-} = \frac{\delta_+}{n_+}$, $2\delta_-^0 > \delta_-^L$ and $2\delta_+^0 > \delta_+^L$, $\frac{n_-}{n_+} = \frac{\delta_-^0}{\delta_+^0}$ or $\frac{n_-^0}{n_+^0} = \frac{\delta_-^L}{\delta_+^L}$; $E_0 = E_1$; $\varpi = \pm(v_- v_+)^{1/2}$
2. $\frac{n_-^0}{n_+^0} < \frac{\delta_-^L}{\delta_+^L}$ or $\frac{n_-^0}{n_+^0} < \frac{\delta_-^0}{\delta_+^0}$; $E_0 < E_1$; $\varpi = (v_- v_+)^{1/2}$
3. $\frac{n_-^0}{n_+^0} > \frac{\delta_-^L}{\delta_+^L}$ or $\frac{n_-^0}{n_+^0} > \frac{\delta_-^0}{\delta_+^0}$; $E_0 < E_1$; $\varpi = -(v_- v_+)^{1/2}$
4. $\frac{n_-^0}{n_+^0} < \frac{\delta_-^L}{\delta_+^L}$ or $\frac{n_-^0}{n_+^0} < \frac{\delta_-^0}{\delta_+^0}$; $E_0 > E_1$; $\varpi = -(v_- v_+)^{1/2}$

The motion of charge carriers significantly affects the excitation of growing waves in impurity semiconductors. For excitation of growing waves with frequency $\varpi_0 = 2v_+$ and increment $\varpi_1 = v_+$, impurity semiconductors with dimensions of $l_x = \frac{2\pi T}{eH_0}\left(\frac{c}{\mu_- H_0}\right)^2$, $l_y = 2\pi l_z = (2\pi)^4 \frac{T\mu_-}{ec}$ are needed.

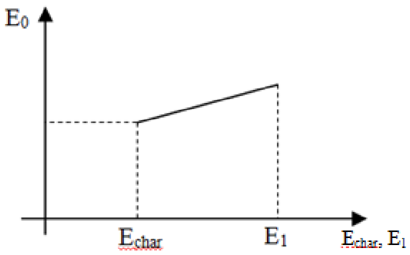

Figure 1. Dependence of electric field on characteristic fields

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