EXCITATION OF UNSTABLE THERMOMAGNETIC WAVES IN IMPURITY SEMICONDUCTORS WITH TWO TYPES OF CHARGE CARRIERS

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In impurity semiconductors of GeAu type, thermomagnetic wave with a certain frequency appears under the influence of excited magnetic fields. The speed of hydrodynamic motions is directed perpendicular to the wave vector $\vec{k}$. The frequency of electron capture (at recombination) and the frequency of hole emission vary with certain ratios. The external electric field E_0 is directed perpendicular to the temperature gradient. For other directions of the temperature gradient and the external electric field, the excited thermomagnetic wave occurs with a different frequency. The conditions for instability of thermomagnetic waves depend on the value of the constant temperature gradient and on the temperature of the sample. The numerical values of impurities in a GeAu sample are very important for the excitation of thermomagnetic waves. The stated problem is solved without an external magnetic field.

Keywords: impurity semiconductors, unstable thermomagnetic waves, electron, hole, magnetic field.
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1. INTRODUCTION

Hydrodynamic motions of charge carriers in conductive media create an alternating magnetic field, which, in the presence of a constant temperature gradient, excites thermomagnetic waves [1] with a frequency $\omega_T = -c\Lambda'\vec{k}\vec{\nabla}T$ ($\vec{k}$ is wave vector, Λ' is Nerst-Ettinghausen effect coefficient). In isotropic and anisotropic conductive media, thermomagnetic waves can propagate in the longitudinal $\vec{k} \parallel \vec{\nabla}T$ and transverse directions $\vec{k} \perp \vec{\nabla}T$ [2]. In doped semiconductors, charge carriers change with time by generation and recombination, and the semiconductor passes into an uneven and equilibrium state.

For example, in the semiconductor GeAu, the gold (Au) atoms in the lattice are packed in five charge states, neutral, singly negative charge states, and doubly negative charge states, triply negative charge states, and positive charge states. Depending on the external conditions (presence of an electric field, magnetic field, temperature value, and so on), these impurity levels are more or less active. At room temperature, singly and twice negative gold impurities in Ge are more active [2]. Unstable states in the GeAu compound were theoretically studied in more detail in [3–5]. Of course, the excitation of thermomagnetic waves in semiconductors of the GeAu type is of scientific interest.

In this theoretical work, we will study the conditions for the excitation of thermomagnetic waves in semiconductors with two types of charge carriers (electronic and holes) in the presence of a constant temperature gradient. Taking into account the generation and recombination of charge carriers, we find the interval of change of the external electric field and the relationship between the generation and recombination frequencies during the excitation of unstable thermomagnetic waves in semiconductors of the GeAu type.

2. BASIC EQUATIONS OF THE PROBLEM

In the presence of hydrodynamic movements inside the sample, an electric field of the following form is created-

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

$\vec{E}$ is external electric field, $\vec{\vartheta}$ is speed of hydrodynamic movements, $\vec{H}$ is magnetic field, which is created in hydrodynamic movements, $\frac{T}{e}\frac{\nabla n_+}{n_+^0}$ and $\frac{T}{e}\frac{\nabla n_-}{n_-^0}$ eare electric fields excited inside the sample when the concentration of holes and electrons changes. The current density of electrons and holes has the form:

$$\begin{aligned} \vec{j}_- &= -\sigma_-\vec{E}^* - \sigma'_-\left[\vec{E}^*\vec{H}\right] - \alpha_-\vec{\nabla}T - \alpha'_-\left[\vec{\nabla}T\vec{H}\right] \\ \vec{j}_+ &= \sigma_+\vec{E}^* + \sigma'_+\left[\vec{E}^*\vec{H}\right] + \alpha_+\vec{\nabla}T + \alpha'_+\left[\vec{\nabla}T\vec{H}\right] \end{aligned} \tag{2}$$

$$\vec{j} = \vec{j}_+ - \vec{j}_- \tag{3}$$

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$$\vec{j} = \frac{c}{4\pi} rot\vec{H} \tag{4}$$

$\sigma_{\pm}$ is hole and electronic conductivities, $\sigma'_{\pm}$ is hole and electronic Hall conductivities, $\alpha_{\pm}$ is hole and electronic thermopower, $\alpha'_{\pm}$ is hole and electronic Hall thermopower, $\vec{H}$ is magnetic field excited by hydrodynamic motion. We consider the problem without an external magnetic field and therefore $\vec{H} = \vec{H}'$, $H_0 = 0$. Putting (1-3) into (4) we get:

$$\vec{E} = -\frac{\left[\vec{\vartheta}\vec{H}\right]}{c} + \Lambda'[\nabla TH] + \frac{c}{4\pi\sigma} rot\vec{H} + \\ + \frac{T}{e}\left(\frac{\nabla n_{+}}{n_{+}^{0}} - \frac{\nabla n_{-}}{n_{-}^{0}}\right) - \Lambda\nabla T \tag{5}$$

Here $\sigma = \sigma_{+} + \sigma_{-}$, $\Lambda = \frac{\alpha}{\sigma}$ is the differential thermopower, $\Lambda' = \frac{\alpha'\sigma - \alpha\sigma'}{\sigma^{2}}$ is coefficient of the Nernst-Ettinieshausen effect

$$\begin{gathered} (E', H') \sim e^{i\left(\vec{k}\vec{x} - wt\right)} \\ \frac{\partial H}{\partial t} = -crotE \\ H' = \frac{c}{\omega}\left[\vec{k}\vec{E}'\right] \end{gathered} \tag{6}$$

In the presence of recombination and generation of charge carriers, the continuity equation for electrons and holes has the form

$$\frac{\partial n_{-}}{\partial t} + div\vec{j}_{-} = \left(\frac{\partial n_{-}}{\partial t}\right)_{r}, \quad \frac{\partial n_{+}}{\partial t} + div\vec{j}_{+} = \left(\frac{\partial n_{-}}{\partial t}\right)_{r} \tag{7}$$

$$\frac{\partial n_{-}}{\partial t} = \gamma_{-}(0) n_{1-} N_{-} - \gamma_{-}(E) n_{-} N, \quad \frac{\partial n_{+}}{\partial t} = \gamma_{+}(E) n_{1+} N - \gamma_{+}(0) n_{-} N_{-} \tag{8}$$

Here N is once negative center, N_{-} is twice negative center, $n_{1+} = \frac{\gamma_{+}(0) N_{-}^{0}}{\gamma_{+}(E_0) N^{0}} n_{+}^{0}$ and $n_{1-} = \frac{\gamma_{-}(E_0) N^{0}}{\gamma_{-}(0) N_{-}^{0}} n_{-}^{0}$ are concentrations in the equilibrium state.

3. THEORY

To obtain the dispersion equation, we must solve together the equation (5-6-7-8) and

$$\frac{\partial N_{-}}{\partial t} = \left(\frac{\partial n_{+}}{\partial t}\right)_{r} - \left(\frac{\partial n_{-}}{\partial t}\right)_{r} \tag{9}$$

$$N = N + N_{-} = const \tag{10}$$

We introduce the following characteristic frequencies

$$\nu_{-} = \gamma_{-}(E_0) N^{0}, \ \nu_{+} = \gamma_{+}(0) N_{-}^{0}, \ \nu_{+}^{E} = \gamma_{+}(E_0) N^{0}, \ \nu_{-}(0) = \gamma_{-}(0) n_{1}, \nu_{+}(0) = \gamma_{+}(0) n_{+}^{0}$$

Considering, that $(E', H', n'_{\pm}) \sim e^{i\left(\vec{k}\vec{x} - wt\right)}$, we obtain from equation (5-10) the below two equations for E' and $n'_{\pm}$

$$
\begin{aligned}
&-i\omega n'_{+}+div\left\{\vec{\vartheta}_{+}n'_{+}+n_{+}^{0}\mu_{+}^{0}\vec{E}'+\frac{n_{+}^{0}\mu_{+}^{0}}{c}\left[\vec{\vartheta}_{0}\vec{H}'\right]+\right.\\
&+\frac{n_{+}^{0}\mu_{+}^{0}}{e}T\vec{k}\left(\frac{n'_{+}}{n_{+}^{0}}-\frac{n'_{-}}{n_{-}^{0}}\right)+\\
&\left.++i+n_{+}^{0}\mu_{1+}^{0}\left[\vec{E}_{0}\vec{H}'\right]+i\vec{k}\alpha_{+}n'_{+}\right\}=\\
&=-\nu_{+}^{E}\,\frac{\nu_{+}(0)n'_{+}-\nu_{-}n'_{-}}{i\omega-\Omega}-\nu_{+}(0)n'_{+}
\end{aligned}
\tag{11}
$$

$$
\begin{aligned}
&-i\omega n'_{-}+div\left\{-\vec{\vartheta}_{-}n'_{-}-n_{-}^{0}\mu_{-}^{0}\vec{E}'-\frac{n_{-}^{0}\mu_{-}^{0}}{c}\left[\vec{\vartheta}_{0}\vec{H}'\right]-\right.\\
&--i\frac{n_{-}^{0}\mu_{-}^{0}T}{e}\vec{k}\left(\frac{n'_{+}}{n_{+}^{0}}-\frac{n'_{-}}{n_{-}^{0}}\right)+\\
&\left.++n_{-}^{0}\mu_{1-}^{0}\left[\vec{E}_{0}\vec{H}'\right]-i\vec{k}\alpha_{-}n'_{-}\right\}=\\
&=\nu_{-}(0)\frac{\nu_{+}(0)n'_{+}-\nu_{-}n'_{-}}{i\omega-\Omega}-\nu_{-}n'_{-}
\end{aligned}
\tag{12}
$$

$$
\begin{aligned}
&\left(1+\frac{2\omega_{T}}{\omega}-\frac{2\vec{k}\vec{\vartheta}_{0}}{a\omega}+i\frac{c^{2}k^{2}}{4\pi a\sigma\omega}\right)\vec{E}'=\\
&=\frac{iT}{e}\vec{k}\left(\frac{n'_{+}}{n_{+}^{0}}-\frac{n'_{-}}{n_{-}^{0}}\right)+\frac{2\Lambda\vec{\nabla}T\gamma}{E_{0}^{2}}\vec{E}_{0}\vec{E}'\\
&\Omega=\nu_{+}+\nu_{-}+\nu_{+}(0)+\nu_{-}(0)\\
&a=1+\frac{2\vec{k}\vec{\vartheta}_{0}}{\omega},\ \vec{\vartheta}_{\pm}=\mu_{\pm}\vec{E}_{0}
\end{aligned}
\tag{13}
$$

Substituting (13) into (11-12) we get

$$
\begin{aligned}
&\left[-i\omega+ik\vartheta_{+}-\frac{\mu_{+}Tk^{2}}{e}-k^{2}\alpha_{+}+\right.\\
&\left.+\nu_{+}(0)+\frac{\nu_{+}^{E}\nu_{+}(0)}{i\omega-\Omega}-\mu_{+}\varphi\vec{k}\vec{E}_{x}\right]n'_{+}+\\
&+\left[\frac{n_{+}^{0}}{n_{-}^{0}}\cdot\frac{Tk^{2}\mu_{+}}{e}+\frac{\nu_{+}^{E}\nu_{-}}{i\omega-\Omega}+\mu_{+}\frac{n_{+}^{0}}{n_{-}^{0}}\varphi\vec{k}\vec{E}_{x}\right]n'_{-}=0
\end{aligned}
\tag{14}
$$

$$
\begin{aligned}
&\left[\frac{n_{-}^{0}}{n_{+}^{0}}\cdot\frac{Tk^{2}\mu_{+}}{e}-\frac{\nu_{-}(0)\nu_{+}(0)}{i\omega-\Omega}+i\mu_{-}\frac{n_{-}^{0}}{n_{+}^{0}}\varphi_{1}\vec{k}\vec{E}_{x}\right]n'_{+}+\\
&+\left[-i\omega-i\vec{k}\vec{\vartheta}_{-}-\frac{\mu_{-}Tk^{2}}{e}+k^{2}\alpha_{-}+\right.\\
&\left.++\nu_{-}-\frac{\nu_{-}(0)\nu_{-}}{i\omega-\Omega}-\mu_{-}\varphi_{1}\vec{k}\vec{E}_{x}\right]n'_{-}=0
\end{aligned}
\tag{15}
$$

$$
\varphi=1+\frac{2i\vec{k}\vec{\vartheta}_{0}}{a\omega}+\frac{2i\mu_{1+}}{\mu_{+}}\frac{c^{2}k^{2}}{a^{2}\omega^{2}},\quad \varphi_{1}=1+\frac{2i\vec{k}\vec{\vartheta}_{0}}{a\omega}+\frac{2i\mu_{1-}}{\mu_{-}}\frac{c^{2}k^{2}}{a^{2}\omega^{2}},
\tag{16}
$$

Denote

$$
\begin{aligned}
&\Omega_{+}=i\vec{k}\vec{\vartheta}_{+}-i\vec{k}\vec{\vartheta}_{1+}-k^{2}\alpha_{+}+\nu_{+}(0)\\
&\Omega_{-}=-i\vec{k}\vec{\vartheta}_{-}-i\vec{k}\vec{\vartheta}_{1-}+k^{2}\alpha_{-}+\nu_{-}
\end{aligned}
\tag{17}
$$

When $\alpha_{+}=\frac{\nu_{+}(0)}{k^{2}},\ \alpha_{-}=-\frac{\nu_{-}(0)}{k^{2}}$, dispersion equations (15-16) have the form

$$\left[-i\omega(i\omega-\Omega)+\omega_+(i\omega-\Omega)+\nu_+(0)\nu_+^E+\vec{k}\vartheta_{+x}A_+(i\omega-\Omega)\right]n'_+ + \\ +\left[\frac{n_+^0}{n_-^0}\vec{k}\vartheta_{1+}(i\omega-\Omega)+i\vec{k}\vec{\vartheta}_{+x}\frac{n_+^0}{n_-^0}A_+(i\omega-\Omega)+\nu_+^E\nu_-\right]n'_-=0 \tag{18}$$

$$\left[\frac{n_-^0}{n_+^0}\vec{k}\vec{\vartheta}_{1-}(i\omega-\Omega)-\nu_-(0)\nu_+(0)+i\vec{k}\vec{\vartheta}_{-x}\frac{n_-^0}{n_+^0}A_-(i\omega-\Omega)+\nu_+^E\nu_-\right]n'_+ + \\ +\left[-i\omega(i\omega-\Omega)+\omega_-(i\omega-\Omega)-\nu_-(0)\nu_- -\vec{k}\vartheta_{-x}A_-(i\omega-\Omega)\right]n'_-=0 \tag{19}$$

Here $\vec{k}\vartheta_{\pm x}=\dfrac{\mu_\pm E_1 k^2}{\varphi_1}\left(1+\dfrac{2\Lambda_0\vec{\nabla}T\vec{E}_0}{E_0^2}\right)$, $\omega_\pm=\pm i\vec{k}\vec{\vartheta}_\pm-\vec{k}\vec{\vartheta}_{1\pm}$, $A_\pm=1+i\dfrac{2\vec{k}\vec{\vartheta}_0}{a\omega}+i\dfrac{2\mu_{1\pm}}{\mu_{1\pm}}\dfrac{c^2k^2}{a^2\omega^2}$

At $\vec{k}\perp\vec{v}_0$, $\mu_- >> \mu_+$, $\dfrac{\nu_-(0)}{\nu_+^E}=\left[\dfrac{\nu_+(0)}{\nu_-}\right]^{1/3}$, $E_0\perp\nabla T$, from (18-19) we get below dispersion equation .

$$x^6-(b+ib_1)x^5+(d+i\varphi)x^4-(\theta+i\theta_1)x^3+ \\ +(\gamma+i\gamma_1)x^2+(r+ir_1)x-u=0 \tag{20}$$

$$x=\frac{\omega}{ck},\ b=\frac{4\omega_T}{ck},\ b_1=\frac{ck}{2\pi\sigma}+\frac{\Omega}{ck}+\frac{\vartheta_{1-}k}{ck}$$

$$d=\frac{4\omega_T^2}{c^2k^2}+\frac{c^2k^2}{16\pi^2\sigma^2}-\frac{\Omega_-}{2\pi\sigma}-\frac{\vartheta_+\vartheta_-}{c^2}- \\ -\frac{\vartheta_{1-}k}{4\pi\sigma}-\frac{\Omega_+\vartheta_{1-}}{c^2k}-\frac{n_-^0}{n_+^0}\frac{\vartheta_{1-}\vartheta_{1+}}{c^2}$$

$$d_1=\frac{\omega_T}{\sigma}+\frac{4\omega_T\Omega_-}{c^2k^2}+\frac{2\vartheta_{1-}\omega_T}{c^2k}-\frac{n_-}{n_+}\frac{\vartheta_{1-}\vartheta_{1+}}{c^2}$$

$$\theta=\frac{4\omega_T\vartheta_T\vartheta_-}{c^3k}+\frac{2\omega_T\Omega_+\vartheta_{1+}}{c^3k}+ \\ +\frac{2\omega_T\vartheta_{1-}\vartheta_{1+}}{c^3k}-\frac{n_-^0}{n_+^0}\frac{\vartheta_{1-}\vartheta_{1+}k}{4\pi\sigma c}$$

$$\theta=\frac{2\vartheta_+\vartheta_-}{4\pi\sigma ck}+\frac{\Omega_+\vartheta_{1+}k}{4\pi\sigma c}+\frac{\vartheta_{1-}\vartheta_{1+}k}{4\pi\sigma c}-\frac{n_-}{n_+}\frac{2\omega_T\vartheta_{1-}\vartheta_{1+}}{c^3k}$$

$$\gamma=\frac{4\omega_T^2\vartheta_-\vartheta_+}{c^2k^2}-\frac{\vartheta_{1-}\vartheta_{1+}}{16\pi^2\sigma^2}-\frac{2n_-}{n_+}\frac{\vartheta_{1-}\vartheta_{1+}}{c^2}$$

$$\gamma_1=\frac{\omega_T\vartheta_-\vartheta_+}{c^2\sigma}+\frac{2\vartheta_{1-}\vartheta_{1+}}{c^2}\left(2+\frac{n_-}{n_+}\right)+\frac{2\vartheta_{1-}\vartheta_{1+}\alpha_+}{c^2}$$

$$r=\frac{2\omega_T\vartheta_{1-}\vartheta_{1+}}{c^2ck}-\frac{\vartheta_{1-}\vartheta_{1+}k}{4\pi ck\sigma},\quad r_1=\frac{2\omega_T\vartheta_{1-}\vartheta_{1+}\alpha_+}{c^3k}-\frac{n_-}{n_+}\frac{\vartheta_{1-}\vartheta_{1+}k}{4\pi c\sigma}$$

$$u=\frac{4\vartheta_{1-}\vartheta_{1+}\alpha_+\alpha_-}{c^2}$$

Denoting $x=\dfrac{\omega}{ck}$ and $x=x_0+ix_1$, $x_1<<x_0$ from (20) we get

$$\omega=\omega_0+\omega_1,\ \omega_0=\frac{10}{3}\omega_T,\ x_1=\frac{\theta_1}{4}$$

and for instability

$$40\omega_T>3ck\theta_1 \tag{21}$$

$$\frac{n_-}{n_+}=\frac{2\pi\omega_T\sigma\alpha_+}{c^2k^2} \tag{22}$$

$$\alpha_T=\frac{\mu_+H_0}{c}<<1 \\ E_0>\frac{4\omega_T}{k\mu_-} \\ E_0>\frac{c[\Lambda'\nabla T]^{1/3}}{\left[2\sqrt{2}\mu_+\mu_-^2\right]^{1/3}} \\ E_0<E_1\left(\Lambda'\nabla T\frac{\sigma}{ck}\right)^{1/2} \tag{23}$$

$$\Lambda'\nabla T > \left(\frac{ck}{\sigma}\right)^6 \left[\frac{c}{E_1\left(2\sqrt{2}\mu_+\mu_-^2\right)^{1/3}}\right]^6$$

$$E_1 = \frac{Tk}{e}.$$

4. CONCLUSIONS

Thus, in the above impurity semiconductors of type of GeAu, at the presence of a constant temperature gradient due to hydrodynamic movements, an unstable thermomagnetic wave is excited. A thermomagnetic wave is excited if the external electric field changes within a certain interval.

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