THERMORECOMBINATION WAVES EXTRINSIC SEMICONDUCTORS WITH TWO TYPES OF CHARGE CARRIES

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It is theoretically shown that a non-stable thermorecombination wave propagates in semiconductors with the singly and doubly negatively charged impurity centers in the presence of constant electric field and constant temperature gradient. The frequency and increment of the thermorecombination wave are calculated. An analytic formula for the constant external electric field at which the wave instability begins is found.

Key words: frequency, increment, electric field, temperature gradients, impurity centers.
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INTRODUCTION

In paper [1], it is shown that hydrodynamic motion in non-equilibrium plasma, in which there is a temperature gradient $\vec{\nabla}\mathrm{T}$, results in the magnetic field excitation. In that paper, it is found that the plasma with a temperature gradient $\vec{\nabla}\mathrm{T}$ has oscillatory characteristics noticeably different from normal plasma. In the absence of external magnetic field and hydrodynamic motion in the plasma, transverse "thermo-magnetic" waves are possible, in which oscillations of the magnetic field alone take place. If there is a constant external magnetic field $\vec{\mathrm{H}}_0$, then the wave vector of the thermo-magnetic wave must be perpendicular to it and lie in the ($\vec{\mathrm{H}}_0, \vec{\nabla}\mathrm{T}$) plane.

In paper [2], conditions for the occurrence of thermo-magnetic wave instability in solid plasma with a single type of charge carriers (electrons) have been analyzed theoretically.

In paper [3-5], the instability conditions in the isotropic and anisotropic solid-state media with charge carriers of a single type have been theoretically derived. However, conditions for the occurrence and instability of thermo-magnetic waves in extrinsic semiconductors with two types of charge carriers remain indeterminate.

It is clear that the determination of instability condition in specific impurity semiconductors is of great scientific interest. In this theoretical paper we investigate conditions for the occurrence of non-stable thermorecombination waves in extrinsic semiconductors with two types of charge carriers.

BASIC EQUATIONS

In the presence of electric field $\vec{\mathrm{E}}$, of gradients of the electron n_- and hole n_+ concentrations, and temperature gradient $\vec{\nabla}\mathrm{T}$, the current density for electrons and holes is of the form [1]:

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

$$\vec{j}_+ = -\frac{\sigma_+\vec{\mathrm{E}}^*}{e} + \frac{\sigma_{1+}}{e}\left[\vec{\mathrm{E}}^*\vec{\mathrm{H}}\right] - \alpha_+\vec{\nabla}\mathrm{T} - \alpha'_+\left[\vec{\nabla}\mathrm{T}\vec{\mathrm{H}}\right] \quad (2)$$

$$\mathrm{E}^* = \vec{\mathrm{E}} + \frac{\mathrm{T}}{e}\left(\frac{\vec{\nabla}n_-}{n_-} - \frac{\vec{\nabla}n_+}{n_+}\right) \quad (3)$$

$$\vec{j} = \vec{j}_- + \vec{j}_+, \quad \sigma_\pm = en_\pm\mu_\pm, \quad \sigma_{1-} = en_\pm\mu_{1\pm} \quad (4)$$

Substituting equations (1), (2) and (3) in the equation (4), and using Maxwell equation $rot\vec{\mathrm{H}} = \frac{4\pi}{c}\vec{j}$, we obtain the following expression for electric field:

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

Here

$$\Lambda = \frac{\alpha_- - \alpha_+}{\sigma}; \quad \Lambda' = \frac{\alpha'\sigma - \alpha\sigma'}{\sigma^2}$$

$$\sigma = \sigma_+ + \sigma_-; \; \sigma'_1 = \sigma_{1+} - \sigma_{1-};$$

$$\alpha = \alpha_- - \alpha_+; \quad \alpha' = \alpha'_- - \alpha'_+$$

A detailed description of mathematical method, which enable (5) to be obtained from vector equation (1-4) is given in paper [1]. In (5), the quadratic terms in magnetic field and the diffusion terms are neglected because in semiconductors $k_0\mathrm{T} << e\mathrm{E}_0\ell_\pm$ where k_0 is the Boltzmann constant, $\ell_\pm -$ mean free path for holes and electrons, and E_0 is external constant electric field.

In extrinsic semiconductors the kinetic equations, which take the recombination and generation of charge carriers into account, must be added to equation (5) for electric field.

Certain impurities in semiconductors create centers which can be in several charged states. For example, Au

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atoms in Ge can be singly positively charged as well as singly, doubly and triply negatively charged centers, and besides that they can be in neutral state.

Several energy levels in the band gap correspond to such centers. Depending on their charged states, these energy levels (impurity centers) can capture electrons or holes. As a result of such capture, concentrations of electrons (in the conduction band) and holes (in the valence band) change, therefore the electrical conduction in semiconductor also changes.

In various experimental conditions, these impurity centers are more or less active, so the recombination and generation proceed generally via a certain number of impurity centers. For example, in experiment [6] (we will use its results), singly and doubly negatively charged Au centers in Ge were active centers.

In the presence of an electric field, electrons and holes gain energy on the order of $eE_0\ell_{\pm}$ (where e is the positive elementary charge) due to the electric field. Therefore, in the presence of the electric field, electrons can overcome the Coulomb barrier of the singly charged center and be captured. Electrons can also be generated owing to thermal transitions from impurity centers to the conduction band. The number of holes increases due to the capture of electrons from the valence band by impurity centers, and decreases due to the capture of electrons from impurity centers by holes. The probability of charge carrier generation and the probability of charge carrier recombination are different, and it leads to the change in concentrations of electrons and holes in semiconductors. A detailed description of kinetic equations for electrons and holes in the above-mentioned semiconductor was given in paper [7]. These equations are of the following form:

$$\frac{\partial n_-}{\partial t} + div\vec{j}_- = \gamma_-(0)n_{1-}N_- - \gamma_-(E)n_-N = \left(\frac{\partial n_-}{\partial t}\right)_{rec} \tag{6}$$

$$N_0 = N_- + N_+ = const \quad n_{1-} = \frac{n_-^0 N_0}{N_-^0} \tag{7}$$

Here N_0 is a total concentration of the singly negatively charged centers N and the doubly negatively charged centers N_-, and n_{1-} is a characteristic concentration found on condition that

$$E_0 = 0\,, \left(\frac{\partial n_-}{\partial t}\right)_{rec} = 0 \tag{8}$$

$$\frac{\partial n_+}{\partial t} + div\vec{j}_+ = \gamma_+(E)n_{1+}N - \gamma_+(0)n_+N_- = \left(\frac{\partial n_+}{\partial t}\right)_{rec} \tag{9}$$

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

In equations (6-10), $\gamma_-(0)$ is the coefficient of electron emission by the doubly negatively charged centers in the absence of electric field, $\gamma_-(E)$ is the coefficient of electron capture by the singly negatively charged centers, and $\gamma_+(0)$ is the coefficient of hole capture by the doubly negatively charged centers. The variation in the doubly negatively charged traps with time determines the variation in the singly negatively charged centers. Therefore, the equation determining the variation in charged centers with time is of the form:

$$\frac{\partial N_-}{\partial t} = \left(\frac{\partial n_+}{\partial t}\right)_{rec} - \left(\frac{\partial n_-}{\partial t}\right)_{rec} \tag{10}$$

In order to obtain the $\omega(k)$ dispersion relation, the set of equations (5), (6), (7), (9) and (10) must be solved simultaneously, taking into account the Maxwell equation

$$\frac{\partial \vec{H}}{\partial t} = -crot\vec{E} \tag{11}$$

where c is the velocity of light.

For this purpose, we linearize the set (5-10) in the following way:

$$\vec{E} = \vec{E}_0 + \vec{E}\,;\; n_{\pm} = n_{\pm}^0 + n'_{\pm}\,;\; \vec{\nabla}T = const$$

$$\left(\vec{E}', n'_{\pm}\right) \sim e^{i(\vec{k}\vec{r} - \omega t)}$$

$$\vec{E}' \ll \vec{E}_0 \quad ; \quad n'_{\pm} \ll n_{\pm}^0 \tag{12}$$

Here $\vec{k}$ is a wave vector, and ω is the wave frequency. Substituting equation (11) into (5), we get:

$$\vec{E} = -\frac{c\Lambda'}{\omega}\left[\vec{\nabla}T\left[\vec{k}\vec{E}'\right]\right] + \frac{ic^2}{4\pi\omega\sigma}\left[\vec{k}\left[\vec{k}\vec{E}'\right]\right] + \frac{iE_1\vec{k}}{k}\left(\frac{n'_-}{n_-^0} - \frac{n'_+}{n_+^0}\right) + \Lambda\vec{\nabla}T \tag{13}$$

Linear zing equation (10), we get:

$$N'_- = \frac{N^0 \lambda \dfrac{\vec{E}'\vec{E}_0}{E_0^2} + \omega_-(E_0)n'_- - \omega_+(0)n'_+}{\nu - i\omega} \tag{14}$$

Here

$$\nu = \nu_+ + \nu_- = \gamma_+(E_{0)})n_{1+} + \gamma_+(0)n'_+ + \gamma_-(0)n_{1-} + \gamma_-(E_0)n_-^0$$

$$\lambda = \gamma_+(E_0)n_{1+}\varphi_+ + \gamma_-(E_0)n_-^0\varphi; \quad \omega_-(E_0) = \gamma_-(E_0)N^0, \quad \omega_+(0) = \gamma_+(0)N_-^0$$

$$\varphi_\pm = 2\frac{d\hbar\sigma_\pm}{d\hbar(E_0^2)};$$

$$div\vec{j}'_\pm = \left[\pm\frac{i\sigma_+^0\delta_+}{e} + \frac{ic\sigma_{1\pm}}{e}\left(\vec{k}\vec{E}_0\right)\right] - \frac{ic\sigma_{1\pm}}{e\omega}\left(\vec{E}_0\vec{E}'\right) + \frac{\sigma_\pm^0 E_1 k}{e}\left(\frac{n'_-}{n_-^0} - \frac{n'_+}{n_+^0}\right);$$

$$E_1 = \frac{Tk}{e}; \tag{15}$$

$$\theta_\pm = 2\frac{d\hbar\alpha_\pm}{d\left(E_0^2\right)}; \qquad \delta_\pm = 1 \pm \varphi_\pm$$

Expanding the vector products in (13), we get:

$$\left(1 + \frac{\omega_T}{\omega} + \frac{ic^2k^2}{4\pi\sigma_0\omega}\right)\vec{E}' = -\frac{c\Lambda'\vec{k}\left(\vec{\nabla}T\vec{E}'\right)}{\omega} + \frac{ic^2\vec{k}\left(\vec{k}\vec{E}'\right)}{4\pi\omega\sigma_0} + \frac{iE_1\vec{k}}{k}\left(\frac{n'_-}{n_-^0} - \frac{n'_+}{n_+^0}\right) + \vec{\nabla}T\Lambda U\frac{\vec{E}_0\vec{E}'}{E_0^2},$$

$$U = 2\frac{d\hbar\Lambda}{d\hbar E_0^2} \tag{16}$$

where $\omega_T = -c\Lambda'\vec{k}\vec{\nabla}T$ is the frequency of thermo-magnetic waves [1]. Multiplying (15) scalar wise at first by $\vec{E}_0$ and after that by $\vec{k}$, we can easily get:

$$\vec{E}_0\vec{E}' = iE_0E_1a\left(\frac{n'_-}{n_-^0} - \frac{n'_+}{n_+^0}\right); \; \vec{k}\vec{E}' = iE_1ka\left(\frac{n'_-}{n_-^0} - \frac{n'_+}{n_+^0}\right)$$

$$a = \frac{\Lambda'ck}{\omega_T\Lambda U\cos\alpha} \qquad \left(\vec{E}_0\vec{k}\right) = E_0k\cos\alpha \tag{17}$$

It should be noted that $a \neq \infty$ and so in the expression for a one cannot assume $\alpha = 90^0$. Hereinafter we will omit superscript *0* of the equilibrium quantities $n_\pm^0, N^0, E_0$. Substituting (15-17) into the set (6-9), we get:

$$\left\{-i\omega - iku_+a + \lambda_+(0) + \omega_+(\mathrm{E}_0)\frac{n_{1+}}{n_+^0}\varphi_+\frac{ia\mathrm{E}_1}{\mathrm{E}} - \frac{\nu_+}{\nu_- i\omega}\left[i\lambda_+ + \omega_+(0)\right]\right\}n'_+ + \tag{18}$$
$$+\left\{iku_+a\frac{n_+}{n_-} + \frac{n_+}{n_-}ku_{1+} - \omega_+(\mathrm{E}_0)\frac{n_{1+}}{n^0}\varphi_+\frac{ia\mathrm{E}_1}{\mathrm{E}} + \frac{\nu_+}{\nu_- i\omega}\left[i\lambda_- + \omega_-(\mathrm{E}_0)\right]\right\}n'_- = 0$$

$$\left\{i\frac{n_-}{n_+}ku_-a - \frac{n_+}{n_-}ku_{1-} - \omega_-(\mathrm{E}_0)\frac{n_-}{n_+}\varphi_-\frac{ia\mathrm{E}'}{\mathrm{E}} + \frac{\nu_-}{\nu - i\omega}\left[i\lambda_+ + \omega_+(0)\right]\right\}n'_+ + \tag{19}$$
$$+\left\{-i\omega - iu_-ka + \lambda_-(\mathrm{E}) + \omega_-(\mathrm{E}_0)\varphi_-\frac{ia\mathrm{E}'}{\mathrm{E}} - \frac{\nu_-}{\nu - i\omega}\left[i\lambda_- + \omega_-(\mathrm{E}_0)\right]\right\}n' = 0$$

Here

$$\lambda\frac{a\mathrm{E}'}{\mathrm{E}}\frac{\mathrm{N}}{n_-} = \lambda_-; \quad \frac{\mathrm{N}}{n_+}\frac{a\mathrm{E}'}{\mathrm{E}} = \lambda_+ \quad \omega_+(0) - u_{1+}k = \lambda_+(0) \quad \omega_-(\mathrm{E}_0) + u_{1-}k = \lambda_-(\mathrm{E})$$

Let us write equations (18) and (19) in the following form:

$$\begin{cases}\lambda_1 n'_+ + \lambda_2 n' = 0\\ \lambda_3 n'_+ + \lambda_4 n'_- = 0\end{cases} \tag{20}$$

$$\lambda_1\lambda_4 - \lambda_2\lambda_3 = 0 \tag{21}$$

Substituting $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ from equations (18-19) into (21), we get an equation determining the frequency and increment of “thermorecombination” wave:

$$\omega^2 + i\left(A_- + A_+\right)\omega + B_+B_- - A_+A_- = 0 \tag{22}$$

$$\begin{aligned}
A_- &= -iku_-a + \lambda_-(\mathrm{E}_0) + \omega_-(\mathrm{E}_0)\varphi_-\frac{ia\mathrm{E}'}{\mathrm{E}}\\
A_+ &= iku_+a\frac{n_+}{n_-} + \frac{n_+}{n_-}ku_{1+} - \omega_+(\mathrm{E}_0)\varphi_+\frac{ia\mathrm{E}'}{\mathrm{E}}\\
B_- &= iku_-a\frac{n_-}{n_+} - \frac{n_-}{n_+}ku_{1-} - \omega_-(\mathrm{E}_0)\frac{n_-}{n_+}\varphi_-\frac{ia\mathrm{E}'}{\mathrm{E}}\\
B_+ &= iku_+a\frac{n_+}{n_-} + \frac{n_+}{n_-}ku_{1+} - \omega_+(\mathrm{E}_0)\frac{n_{1+}}{n_-}\varphi_+\frac{ia\mathrm{E}'}{\mathrm{E}}
\end{aligned} \tag{23}$$

It is too complicated to solve the equation (22) taking into account (23), so we will solve the equation (22) for certain analytical expressions of the external electric field. It is easy to verify that if $A_- = A_+$ then

$$\mathrm{E} = \frac{\omega_+(0)\varphi_-\left[1 - \frac{\mu_-k\mathrm{E}'}{\omega_+(0)} - \frac{\omega_+(\mathrm{E})}{\omega_+(0)}\frac{n_{1+}}{n_+}\frac{\varphi_+}{\varphi_-}\right]}{k\mu_-\left(\delta_- + \frac{\omega_\mathrm{T}}{ck}r_- + \frac{\omega_\mathrm{T}}{ck}\frac{\mu_+}{\mu_-}r_+\right)} \tag{24}$$

$$r_- = \frac{\alpha_-\theta_-\vec{\mathrm{E}}_0\vec{\nabla}\mathrm{T}}{\mathrm{E}^2 n_-\mu_-}; \quad r_+ = \frac{\alpha_+\theta_+\vec{\mathrm{E}}\vec{\nabla}\mathrm{T}}{\mathrm{E}^2 n_+\mu_+}; \quad \frac{B_-}{B_+} = \left(\frac{\nu_-}{\nu_+}\right)^2 \tag{25}$$

Taking into account (24-25), from (22) we get:

$$\omega_{1,2} = -iA_{-} \pm iB_{+}\frac{\nu_{-}}{\nu_{+}} \tag{26}$$

Substituting A_{-} and B_{+}, we get the following expressions for the frequency and increment of thermorecombination wave:

$$\omega_1 = -ku_{-}a + \omega_{-}(\mathrm{E}_0)\varphi_{-}\frac{a\mathrm{E}'}{\mathrm{E}} - \frac{\nu_{-}}{\nu_{+}}ku_{+}a\frac{n_{+}}{n_{-}} + \frac{\nu_{-}}{\nu_{+}}\omega_{+}(\mathrm{E})\frac{n_{+}}{n_{-}}\varphi_{+}\frac{a\mathrm{E}'}{\mathrm{E}} + i\left[\frac{\nu_{-}}{\nu_{+}}\frac{n_{+}}{n_{-}}ku_{1+} - \lambda(\mathrm{E})\right] \tag{27}$$

$$\omega_2 = -ku_{-}a + \omega_{-}(\mathrm{E}_0)\varphi_{-}\frac{a\mathrm{E}'}{\mathrm{E}} + \frac{\nu_{-}}{\nu_{+}}ku_{+}a\frac{n_{+}}{n_{-}} - \frac{\nu_{-}}{\nu_{+}}\omega_{+}(\mathrm{E})\frac{n_{+}}{n_{-}}\varphi_{+}\frac{a\mathrm{E}'}{\mathrm{E}} - i\left[\frac{\nu_{-}}{\nu_{+}}\frac{n_{+}}{n_{-}}ku_{1+} + \lambda(\mathrm{E})\right] \tag{28}$$

ANALYSIS OF THE OBTAINED RESULTS

As follows from (26-27), the wave with frequency ω_2 (28) is a damped wave, and there is no energy emission from the above-mentioned semiconductor at the frequency ω_2. Emission from the above-mentioned semiconductor occurs if the wave increment

$$\omega_1 = \frac{\nu_{-}}{\nu_{+}}\frac{n_{+}}{n_{-}}ku_{1+} - \lambda_{-}(\mathrm{E}) \tag{29}$$

is positive, and a high hole concentration and a low electron concentration are required for that. One can see from (27) $\omega = \omega_0 + i\omega_1$ that $a \sim \frac{1}{\omega_{\mathrm{T}}}$. The thermo-magnetic waves decrease frequencies of thermorecombination wave, and the frequency of electron capture and the frequency of hole emission increase frequencies of thermorecombination wave.

Probably, there are values of $\omega_{\pm}(\mathrm{E}_0)$ and ω_{T} at which semiconductors with the above-mentioned model emit energy nearly stable. Such a situation can occur at certain values of the external electric field and the constant temperature gradient.

The presence of constant and alternating magnetic field can change conditions of the thermorecombination wave generation. When energy is emitted from a medium, a resistance of the medium decreases and the current variations in external circuit occur. For investigation of external instability (i.e. when the real part of impedance is negative $\mathrm{Re}\, z < 0$), the impedance of semiconductor has to be calculated. This problem requires taking into account the boundary conditions across electric field at ends of the medium and of course the injection at ends of the medium.

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