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A Semiconductor Is an Energy Source In The Presence Of a Temperature Gradient in an External Electric and Magnetic Field

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Abstract: *In the presence of a temperature gradient $\nabla_x T = const$, an external electric constant field E_0, an external magnetic constant field H_0, an increasing wave is excited in semiconductors with two types of charge carriers and certain deep traps. The frequency values and the increment of the rising wave are determined. It is proved that this unstable wave is excited at a classically strong $(\mu_{\pm} H_0 > c)$ magnetic field. The electric field with increasing wave has a certain value. Analytical formulas are obtained for the oscillation frequency and for the growth increment of the excited wave.*

***Keywords*:** *frequency, energy source , temperature gradient , impurity semiconductors, an external magnetic field, an external electric field.*

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I. Introduction

In [1], it was shown that hydrodynamic motions in a nonequilibrium plasma in which the temperature gradient is $\nabla T = const$ leads to the appearance of magnetic fields. In the same work, it was found that plasma with a temperature gradient has vibrational properties that are noticeably different from the properties of ordinary plasmas. In the absence of an external field and hydrodynamic motions, "Thermomagnetic" waves are excited in the plasma, in which only the magnetic field oscillates. In the presence of an external permanent magnetic field, the wave vector of thermomagnetic waves should be perpendicular to it and lie in the plane $(\vec{H}, \vec{\nabla}T)$.

In the presence of an external electric field, a temperature gradient $\nabla T = const$, and hydrodynamic motions $\vec{V}(\vec{r}, t)$, the electric current density has the form

$$\vec{J} = \sigma \overrightarrow{E^*} + \sigma' \left[\overrightarrow{E^*} \vec{H} \right] - \alpha \overrightarrow{\nabla T} - \alpha' \left[\overrightarrow{\nabla T} \vec{H} \right] \quad (1)$$

The electric field E^* consists of three parts [1]

$$E^* = \vec{E} + \frac{\left[\vec{V} \vec{H} \right]}{c} + \frac{T}{e} \frac{\Delta \rho}{\rho}, \; e > 0 \quad (2)$$

In a solid-state plasma, the conditions for the appearance of thermomagnetic waves were obtained in [2–3]. In impurity semiconductors in the presence of an external constant electric and magnetic field, the conditions for the appearance of unstably recombination waves were studied in detail in [4–6].

In [7], the conditions of internal and external instability in impurity semiconductors were studied theoretically when the ratios of the concentrations of charge carriers are determined as follows

$$\frac{n_-}{n_+} = \frac{v_-}{v_+} \quad (3)$$

n_+^- is the consensus of electron and hole carriers, v_- is the electron capture frequency and v_+ is the hole capture frequency.

In this theoretical work, we will study the conditions for the appearance of unstable waves inside a semiconductor in the presence of an external electric field, a temperature gradient, an external magnetic field, taking into account hydrodynamic movements, when condition (3) is satisfied.

II. Basic equations of the problem

Let us consider a semiconductor with two types of charge carriers with singly charged impurity centers with a concentration of N and two multiply negatively charged impurity centers N_-

$$N_0 = N + N_- = const \tag{4}$$

The continuity equation for electrons and holes in this semiconductor has the form [8]:

$$\frac{\partial n_-}{\partial t} + divj_- = \gamma_-(0)n_{1-}N_- - \gamma_-(E)n_-N_- = \left(\frac{\partial n_-}{\partial t}\right)_{rek} \tag{5}$$

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

$$\frac{\alpha\partial N_-}{\partial t} = \left(\frac{\partial n_+}{\partial t}\right)_{rek} - \left(\frac{\partial n_-}{\partial t}\right)_{rek} \tag{7}$$

$$\Im = e\left(j_+ + j_-\right) \tag{8}$$

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

The sign (0) shows the equilibrium value of the corresponding physical quantities. The electric field (2) in the aforementioned semiconductor has the form

$$\vec{E}^* = \vec{E} + \frac{\left[\vec{V}\vec{H}\right]}{c} + \frac{T}{e}\left(\frac{\nabla n_-}{n^0} - \frac{\nabla n_+}{n_+^0}\right) \tag{9}$$

(T-temperature in ergs).

Current densities are of the form:

$$\overrightarrow{J_+} = \mu_+ n_+ \vec{E}^* + \mu_{1+}\left[\vec{E}^*\vec{H}\right] + \alpha_+\left[\vec{\nabla} T\vec{H}\right] \tag{10}$$

$$\overrightarrow{J_-} = -\mu_- n_- \vec{E}^* + \mu_{1-}\left[\vec{E}^*\vec{H}\right] - \alpha\nabla T - \alpha_+'\left[\vec{\nabla} T\vec{H}\right] \tag{11}$$

III. Theory

To obtain the dispersion equation for the current oscillations inside the crystal, it is necessary to solve equations (5,6,7,8) together with (9,10,11). First, we determine the electric field from (8). Substituting $\vec{\Im} = \frac{c}{4\pi} rot\vec{H}$ into (8) we obtain

$$\frac{c}{4\pi} rot\vec{H} = \left(\sigma_- + \sigma_+\right)\left[\vec{E}^*\vec{H}\right] + \left(\alpha_+ + \alpha_-\right)\vec{\nabla} T + \left(\alpha_+' + \alpha_-'\right)\left[\vec{\nabla} T\vec{H}\right], \tag{12}$$

The definition of $\vec{E}$ from (12) is reduced to solving the vector equation

$$\vec{x} = \vec{a} + \left[\vec{b}\vec{x}\right], \tag{13}$$

From (13)

$$\left[\vec{b}\vec{x}\right] = \vec{b}\vec{a} \tag{14}$$

Substitute instead of $\left[\vec{x}\vec{b}\right]$ the right side of his expression $\vec{a}+\left[\vec{b}\vec{x}\right]$ then

$$\vec{x}=\vec{a}+\left[\vec{b}\vec{a}\right]+\vec{b}\left[\vec{b}\vec{x}\right]=\vec{a}+\left[\vec{b}\vec{a}\right]+\vec{b}\left(\vec{b}\vec{a}\right)-b^2x$$

$$\vec{x}=\frac{\vec{a}+\left[\vec{b}\vec{a}\right]+\left(\vec{a}\vec{b}\right)\vec{b}}{1+b^2}, \qquad (15)$$

Substituting $\vec{a}$ and $\vec{b}$ from (12) in (13), we obtain the electric field of the expression:

$$\vec{E}=-\frac{\left[\vec{V}\vec{H}\right]}{c}-\lambda'\left[\vec{\nabla}T\vec{H}\right]+\frac{c}{4\pi\sigma}rot\vec{H}-\frac{c\sigma'}{4\pi\sigma^2}\left[rotH,\mathrm{H}\right]+\frac{T}{e}\left(\frac{\nabla n_+}{n_+^0}-\frac{\nabla n_-}{n_-^0}\right)+\lambda\nabla T \qquad (16)$$

Here $\sigma=\sigma_++\sigma_-$, $\lambda=\dfrac{\alpha_++\alpha_-}{\sigma}$, $\lambda'=\dfrac{\alpha'\sigma_--\alpha\sigma'}{\sigma^2}$;

$\alpha'=\alpha'_++\alpha'_-$; $\sigma'=\sigma_{1+}+\sigma_{1-}$.

The system of equations (5,6,7,8), taking into account (16), determines the dispersion equation for determining the frequency of current oscillations inside the sample. The total current does not depend on the coordinates, but depends on the times $\vec{\Im}=\vec{\Im}(t)$, and with internal instability, the current does not oscillate in the circuit. We will investigate the one-dimensional problem, i.e $\Im'_x=\Im'_x(t)\neq 0$.

$$\Im'_n=\Im'_x=0,$$

Considering all physical variables in the form of monochromatic waves

$E=E_0+E'$; $n_\pm=n_\pm^0+n'_\pm$, $\left(E',n'_\pm\right)\sim e^{i\left(\vec{k}\vec{x}-\omega t\right)}$, $E'<<E_0$, $n'_\pm<<n_\pm^0$.

(k is the wave vector, ω is the oscillation frequency). Determining the current components from (8) after not complicated calculations, we obtain:

$$\Im'_x=\sigma_0E'_x+E_{0x}+i\sigma_0k_xL_xE_1\left(\frac{n'_-}{n_-^0}-\frac{n'_+}{n_+^0}\right)+\sigma_{10}E'_y-2\frac{\sigma_{10}}{c}V_{0x}H_{0z}+\alpha_0\gamma\nabla_xT\frac{\vec{E}^*_{0x}\vec{E}^{*'}}{\left(E^*_{0x}\right)^2} \qquad (I)$$

$$\Im'_y=\sigma_0E'_y-\frac{\sigma_0k_xc}{\omega}E'_y+\frac{\sigma' V_{0x}}{c}H_{0z}-\sigma_{10}\frac{E_{0x}}{H_{0z}}H'_z-\sigma_{10}E'_x-\sigma'_1E_{0x}-\frac{2\sigma_{10}V_{0y}}{c}H'_z-\frac{\sigma_{10}V_{0z}}{c}H'_y-$$

$$-\sigma_1E_1ik_xL_x\left(\frac{n'_-}{n_-^0}-\frac{n'_+}{n_+^0}\right)-\left(\alpha'\right)_0\nabla_xT=0 \qquad (II)$$

$$\Im'_z=\sigma_0E'_z-\frac{\sigma_0k_xc}{\omega}E'_z+\frac{\sigma' V_{0x}}{c}H_{0z}+\sigma_{10}\frac{E_{0x}}{H_{0z}}H'_y-\frac{2\sigma_{10}V_{0z}}{c}H'_z+\frac{\sigma_{10}V_{0z}}{c}H'_z+$$

$$+\frac{\sigma_{10}}{c}\left(V_yH_y+V_{0z}H'_z\right)=0 \qquad (III)$$

Here:

$$\sigma_0=\sigma'_{0-}+\sigma'_{0+},\ \vec{E}_0=i\vec{E}_{0x},\ \vec{H}_0=\hbar H_{0z},\ \sigma'=\frac{d\sigma'^2}{dE_{0x}^2},$$

L_x islength of the sample H'_y, H'_z are the components of the variable magnetic field which are determined from the Maxwell equation

$$\frac{\partial\vec{H}'}{\partial t}=-c\,rot\vec{E}'$$

Defining (II), (III) E'_y and E'_z we put in (I), we easily obtain:

$$\Im'_x=\sigma_0uE'_x+e\upsilon+\left[1+\frac{V_{0y}}{c}-2\frac{V_{0y}}{c}\beta_{1+}\frac{\mu_{1+}}{\mu_+}\frac{E_1}{E_{0x}}ik_xL_x+\frac{\nabla_xT\left(\alpha_+\gamma_+-\alpha_-\gamma_-\right)}{E_{0x}n_+\left(n_+\mu_++n_-\mu_-\right)}\right]n'_++$$

$$+e\upsilon - \left[1 - \frac{V_{0y}}{c} + 2\frac{V_{0y}}{c}\frac{\mu_{1-}}{\mu_-}\frac{E_1}{E_{0x}} ik_x L_x + \frac{\nabla_x T(\alpha_+\gamma_+ - \alpha_-\gamma_-)}{E_{0x} n_+ (n_-\mu_- + n_-\mu_-)}\right] n'_- \quad (17)$$

Here:

$$u = 2\frac{\sigma_{1+}}{\sigma_0}\frac{V_{0y}}{c}\beta_{1+} + 2\frac{\sigma_{1-}}{\sigma_0}\beta_{1-} + \frac{e\nabla_x T(\alpha_+\gamma_+ + \alpha_-\gamma_-)}{E_{0x}\sigma_0}$$

$$\beta_{1\pm} = \frac{d \ln \mu_{1\pm}}{d \ln (E_{0x}{}^2)}$$

When obtaining (17) from (II),(III) we took into account that $\frac{V_{0y}}{c} H_{0z} << E_{0x}$, $\mu_\pm E_{0x} << E_{0x}$ $V_{0y} << c\frac{V_{0y}}{c}$

We write (17) in the following form

$$E'_x = \frac{\Im'_x}{\sigma_0 u} - \frac{e\vartheta_+\varphi_+}{\sigma_0 u} n'_+ - \frac{e\vartheta_-\varphi_-}{\sigma_0 u} n'_-$$

In [7], it was proved that in the presence of relation (3), equations (5,6,7) have the following form:

$$\frac{\partial n'_+}{\partial t} + div j'_+ = -\nu_+ n'_+$$

$$\frac{\partial n'_-}{\partial t} + div j'_- = -\nu_- n'_- \quad (18)$$

ν is the electron capture frequency, ν_+ is the hole capture frequency. Having determined from (10-11) $j'_\pm$ and substitutingin into (18), then we will obtain the following system of equations for determining the oscillation frequency inside the sample.

$$i(k_x\vartheta_+ A_+ - \omega)n'_+ + \left(A_+ - iA_+ + 2\frac{V_{0y}}{c}\frac{\mu_{1-}}{\mu_-}k_x L_x\right)k_x\vartheta_- n'_- = 0 \quad \text{(I)*}$$

$$i(k_x\vartheta_- A_- - \omega)_- n'_- = 0 \quad \text{(II)*}$$

$$A_+ = \frac{2\sigma_{1+}V_{0y}}{\sigma_0 uc} + \frac{\vartheta_+}{\sigma_0 u L_x};$$

Here,

$$A_- = \frac{2\sigma_{1-}V_{0y}}{\sigma_0 uc} + \frac{\vartheta_-}{\sigma_0 u L_x} \quad (19)$$

$$\vartheta_{1\pm} = \mu_{1\pm}E_1\beta_{1\pm}\,;\; u = 2\beta\frac{\vartheta_-}{\sigma_0 L_x} + \frac{\alpha\gamma - \nabla_x T}{\sigma_0 E_0}$$

If the scattering of charge carriers comes from one factor (i.e., scattering only from the optical phonon, etc.) then $\beta_{1+} = \beta_{1-} = \beta$. From (I-II) we obtain the following dispersion equations for detect current fluctuations inside the sample

$$\omega^2 - k_x\vartheta\left(A_- + \frac{\mu_+}{\mu_-}A_+\right)\omega + k_x^2\vartheta_-\vartheta_+ A_- A_+ - (k_x\vartheta_-)^2\frac{\vartheta_-}{\sigma_0 L_x u}\left(A_+ + \frac{k_x}{\sigma_{1-}}\vartheta_{1-} - iA_+\right) = 0 \quad (20)$$

Denoting $\frac{\omega}{k_x \vartheta_-} = Z$ from solution (20) we easily obtain

$$Z_{1,2} = \frac{\vartheta_-}{\sigma_0 L_x u}\left[1 \pm \sqrt{\frac{\sigma_0}{n_-^0} - i\frac{2\mu_{1+}}{\mu_-}}\right] \tag{21}$$

$$\sqrt{\frac{\sigma_0}{\sigma_-} - i\frac{2\mu_{1+}}{\mu_-}} = xIy = \frac{1}{\sqrt{2}}\left[\sqrt{1+\frac{4\mu_+^2}{\mu_-^2}} + 1\right]^{\frac{1}{2}} + i\left[\sqrt{1+\frac{4\mu_+^2}{\mu_-^2}} - 1\right]^{\frac{1}{2}} = 3/2$$

From (21) it can be seen that a wave with a frequency

$$Z_1 = \frac{\vartheta_-}{\sigma_0 L_x u}(1 + x + iy)$$

$$Z_2 = \frac{\vartheta_-}{\sigma_0 L_x u}(1 - x - iy)$$

is growing, and the wave

$\omega_0 = \frac{2k_x \vartheta_-^2}{\sigma_0 L_x u}$, and the growth increment

$$\omega_1 = \frac{3k_x \vartheta_-^2}{2\sqrt{2}\sigma_0 L_x u}, \tag{23}$$

$$\frac{V_{0y}}{c} = \frac{\vartheta_-}{\sigma_1 - L_x}, \tag{24}$$

From (22-23) $\frac{\omega_0}{\omega_1} > 1$.

When obtaining (22-23) from (20), it was taken into account that

$$\frac{\mu_+ H_{0z}}{c} = \frac{L_x \sigma_{1-}}{\mu_- E_1} >> 1 \tag{25}$$

$$E_1 = \frac{2\pi T}{eL_x}$$

(T is the temperature in ergs).

$$L_x >> L_{xar} = \frac{\mu_- E_1}{\sigma_{1-}} \tag{26}$$

From (24-26) we obtain

$$\frac{\mu_+ H_{0z}}{c} >> \left(\frac{E_1}{eL_x}\right)^2 \tag{27}$$

IV. Discussion

Thus, in semiconductors with two types of charge carriers, once negatively charged by deep traps and two times negatively charged by deep traps, a wave is excited, which leads to a current oscillation inside the sample. This growing wave is excited when the values of the external magnetic field satisfy condition (27). The electric field in the presence of growing waves, with n_-frequency (22) and increments (23) are determined by expression (24), i.e.

$$E_0 = \frac{2V_{0y}L_x}{c} en_- \frac{\mu_- H_0}{c}$$

In a crystal of length L_x ~1см, E_0 ~10^3см $\frac{\hat{a}}{\tilde{n}\grave{i}}$.

The frequency is ω_0 ~$3\cdot10^8$(сек)$^{-1}$, the increment is ω_1 ~$3/2\sqrt{2}\cdot10^8$(сек)$^{-1}$. The estimated value of the oscillation frequency inside the crystal is high. When you go outside (that is, the current oscillates in the circuit), you can receive energy radiation from the specified semiconductor. To study the radiation of energy from the above semiconductor, you need to calculate the impedance of the sample.

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