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Transverse Current Oscillations in Semiconductors with Define Deep Traps and Two Types of Charge Carriers

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Abstract: A theory of spontaneous oscillations of the current in the transverse direction of the electric field □ $\overrightarrow{E_0} \perp \vec{j}$ has been constructed. A theory of spontaneous current oscillations in the transverse direction of the electric field has been constructed. Analytical formulas for the external electric field and magnetic field are found. The frequency of current oscillations in the specified direction is less than the increment of the rise of the emerging waves inside the sample. Based on the experimental data, the frequency ω_0, the electric field E_0, and the magnetic field $H_0$are estimated. The characteristic frequencies included in the theory are determined by analytical expressions. The crystal size in the direction of the electric field L is of the order of 1 cm.

Keywords: electric field, magnetic field, impedance, current oscillation frequency, ohmic coefficient.
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I. INTRODUCTION

The theory of spontaneous current oscillations in semiconductors with deep traps located in an external electric and magnetic fields in the longitudinal direction of the current, i.e. when the external electric field $\overrightarrow{E_0} \,||\vec{j}$, ($\overrightarrow{E_0}$ is the electric field strength, $\vec{j}$, is the current flux density). In these works, the following conditions were used: $eE_0 l \gg T$, $H_0 > H_{\pm} = \frac{c}{\mu_{\pm}}$. Here e is the positive elementary charge, l is the mean free path of charge carriers, T is the lattice temperature in ergs, c is the speed of light, $\mu_{\pm}$is the mobility of holes and electrons. It should be noted that current oscillations occur not only in the longitudinal direction of the current, current oscillations are excited in all directions, i.e. $j'_{x,y,z} \neq 0$. Therefore, radiation from a semiconductor occurs with different frequencies in all directions.

In this theoretical work, we will study current oscillations in semiconductors with certain deep traps and with two types of charge carriers located in an external electric and magnetic fields. The electric and magnetic fields are determined by the following inequalities

$$H_0 \gg H_{\pm} = \frac{c}{\mu_{\pm}},\, eE_0 l \gg T(1)$$

1.1Basic equations of the problem

In [1–7], the kinetics equations for electron and hole carriers are described in detail, and therefore we will write the corresponding equations without explaining

$$\frac{\partial n_-}{\partial t} + div\overrightarrow{j_-} = \gamma_-(0)n_{1-}N_- - \gamma_-(E)n_-N = \left(\frac{\partial n_-}{\partial t}\right)_{rek} \qquad (2)$$

$$\frac{\partial n_+}{\partial t} + div\overrightarrow{j_+} = \gamma_+(E)n_{1+}N \quad - \gamma_+(0)n_+N_- = \left(\frac{\partial n_+}{\partial t}\right)_{rek} \qquad (3)$$

$$N_0 = N + N_- \qquad (4)$$

$$div\vec{j} = ediv(\overrightarrow{j_+} - \overrightarrow{j_-}) = 0 \qquad (5)$$

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

$$\overrightarrow{j_+} = n_+\mu_+(E,H)\vec{E} + n_+\mu_{1+}(E,H)\left[\vec{E}\vec{h}\right] + n_+\mu_{2+}(E,H)\vec{h}\left(\vec{E}\vec{h}\right) - D_+\vec{\nabla}n_+ - D_{1+}\left[\vec{\nabla}n_+\vec{h}\right] - D_{2+}\vec{h}\left[\vec{\nabla}n_+\vec{h}\right] \qquad (6)$$

$$\overrightarrow{j_-} = -n_-\mu_-(E,H)\vec{E} + n_-\mu_{1-}(E,H)\left[\vec{E}\vec{h}\right] - n_-\mu_{2-}(E,H)\vec{h}\left(\vec{E}\vec{h}\right) - D_-\vec{\nabla}n_- + D_{1-}\left[\vec{\nabla}n_-\vec{h}\right] - D_{2-}\vec{h}\left[\vec{\nabla}n_-\vec{h}\right] \qquad (7)$$

Here $\vec{h}$ is the unit vector in the magnetic field, $\mu_{\pm}(E,H)$is the ohmic, $\mu_{1\pm}(E,H)$is Hall$\mu_{2\pm}(E,H)$is the focusing mobility of holes and electrons, $D_{\pm}$, $D_{1\pm}$, $D_{2\pm}$are the ohmic, Hall, and focusing diffusion coefficients of holes and electrons, respectively. To simplify cumbersome calculations, we consider the case when the carriers have an effective temperature, and inequalities (1) are satisfied.

1.2 Theory

Under external influences within the sample occurs fluctuations of physical quantities $n_{\pm}, E, H$

$$n_{\pm} = n_{\pm}^{0} + n_{\pm}^{'}, \vec{E} = \overrightarrow{E_0} + \overrightarrow{E^{'}}, \vec{H} = \overrightarrow{H_0} + \overrightarrow{H^{'}} \qquad (9)$$

The fluctuation values $n_{\pm}^{'}, \overrightarrow{E^{'}}, \overrightarrow{H^{'}}$ have different values within the sample and fluctuation waves arise. These waves can grow or die out under various conditions. The growth of fluctuation waves propagating, can go out, i.e. current oscillations in the circuit may occur. Oscillations of this type are called external instabilities. With external instability, the current-voltage characteristic of the sample becomes nonlinear. When a nonlinear characteristic appears in the circuit, energy is emitted from the sample. The radiation frequency is a real value, and the wave vector is a complex value. If the fluctuation rise waves propagate only inside the sample, the frequency is a complex value, and the wave vector is a real value and is determined from the condition of standing waves, i.e.

$$\omega = \omega_0 = i\omega_1 \text{и} K = \frac{2\pi}{L} n_1 (\text{ n=0,±1, ±2}) \qquad (10)$$

L is the sample size by wave propagation. Conditions (10) determine the presence of internal instability of the sample. It is clear that external instability (i.e., the onset of radiation of the sample) occurs after the onset of internal instability. If the external electric field $\overrightarrow{E_0} \perp j^{'}$, the vibrations are called longitudinal, with $\overrightarrow{E_0} \parallel j^{'}$, the vibrations are called transverse. In [1–7], we will develop the theory of longitudinal current oscillations in various semiconductors. In this theoretical work, we study the conditions for transverse current oscillations in impurity semiconductors with two types of charge carriers

$$\overrightarrow{E_0} \perp j^{'} \qquad (11)$$

Representing $\left(n_{\pm}^{'}, \overrightarrow{E^{'}}, \overrightarrow{H^{'}}\right) \sim e^{i(\vec{k}\vec{r}-\omega t)}$and substituting (9) into (6) we get the following expressions for the oscillatory values of the hole current

$$j_{x+}^{'} = n_+\mu_+E_x^{'} + \frac{n_+\mu_+E_0}{H_0}\frac{ck}{\omega}\left(E_x^{'} - E_y^{'}\right) + n_+\mu_+E_y^{'} + v_{1+}(1+\beta_{1+})n_+^{'}$$

$$j_{y+}^{'} = n_+\mu_+E_y^{'} - n_+\mu_{1+}E_x^{'} + [v_+(1+\beta_+) + v_{1+}(1+\beta_{1+})]n_+^{'}$$

$$j_{z+}^{'} = n_+\mu_+E_z^{'} - \frac{n_+\mu_{1+}E_0}{H_0}\frac{ck}{\omega}\left(E_y^{'} - E_z^{'}\right) + n_+\mu_{2+}E_z^{'} + \frac{n_+\mu_{2+}E_0}{H_0}\frac{ck}{\omega}(E_z^{'} - E_x^{'})$$

$$H_x^{'}\frac{ck}{\omega}\left(E_y^{'} - E_z^{'}\right),\ H_y^{'}\frac{ck}{\omega}(E_z^{'} - E_x^{'}),\ H_z^{'}\frac{ck}{\omega}\left(E_x^{'} - E_y^{'}\right)$$

$$\beta_{\pm} = 2\frac{dln\,\mu_{\pm}}{dln\,(E_0^2)}, \beta_{1\pm} = 2\frac{dln\,\mu_{1\pm}}{dln\,(E_0^2)}, E_0 = E_{0y}, v_{1\pm} = \mu_{1\pm}E_0, v_{\pm} = \mu_{\pm}E_0$$

Substituting (9) into (7), we obtain for the vibrational values of the electron current $j_{x\_}^{'}, j_{y\_}^{'}, j_{z-}^{'}$. From the condition $j_{x+}^{'} - j_{x_}^{'} = 0, j_{y+}^{'} - j_{y_}^{'} = 0$determine the components of the electric field $E_y^{'}\text{и}E_x^{'}$.

$$E_x^{'} = -\frac{e}{\sigma_1}[v_{1+}(1+\beta_{1+})n_+^{'} + v_1(1+\beta_{1-})n_-^{'}]; E_y^{'} = \frac{\alpha+1}{\alpha-1}E_x^{'}, \alpha = \frac{ckE_0}{\omega H_0}$$

and

$$j_{z+}^{'} - j_{z\_}^{'} = \alpha\sigma_2E_z^{'} + \frac{e\alpha}{\sigma_1}\sigma_2(v_{1+}\beta_+n_+^{'} + v_{1-}\beta_-n_-^{'}) \qquad (12)$$

$$\sigma_2 = n_+\mu_{2+} + n_-\mu_{2-}$$

Substituting (12) into (5) we get the following expressions:

$$E_z^{'} = -\frac{e}{\sigma_1}(v_{1+}\beta_+n_+^{'} + v_{1-}\beta_-n_-^{'}) \qquad (13)$$

Linearizing (2-3) will get the following dispersion equations.

$$\left[-i\omega + k_+v_{1+}\beta_+ + \nu_+\left(1 - \frac{\nu_+^{'}\varphi_+}{\nu_-i\omega} + \nu_{1+}\beta_+\right)\right]\left[-i\omega + k_-v_{1-}\beta_- + \nu_-\left(1 - \frac{\nu_-^{'}\varphi_-}{\nu_-i\omega} - \nu_{1-}\beta_-\right)\right] - \left[k_+v_{1-}\beta_- +\right.$$

ν−ν+'ν−iωβ+−v1+μ−μ+β−k−v1+β++ν+ν−'ν−iωβ−−v1−μ+μ−β+=0 (14)

Here

$$\nu_{1+} = \nu_+^{E}\frac{\sigma_{1+}}{\sigma_1}\beta_+^{\gamma}\frac{\alpha-1}{\alpha+1}, \qquad \nu_{1-} = \nu_-\frac{\sigma_1}{\sigma_1}\beta_-^{\gamma}\frac{\alpha-1}{\alpha+1},$$

$$k_+ = ik\frac{\sigma_{1+}}{\sigma_1}\frac{2\alpha}{\alpha-1} - ik\frac{\sigma_{2+}}{\sigma_1}, \quad k_- = ik\frac{\sigma_{2-}}{\sigma_1} + ik\frac{\sigma_{1-}}{\sigma_1}\frac{2\alpha}{\alpha-1},$$

$$\sigma_{1+} = en_+\mu_{1+}, \sigma_{1-} = en_-\mu_{1-}, \sigma_{2+} = en_+\mu_{2+}, \sigma_{2-} = en_-\mu_{2-}$$

$$\sigma_+ = en_+\mu_+, \sigma_- = en_-\mu_-, \varphi_+ = 1 + \frac{\nu_-}{\nu_+}\frac{\sigma_{1+}}{\sigma_1}\beta_+u\frac{\alpha+1}{\alpha-1}, \varphi_- = 1 - \frac{\nu_-}{\nu_+}\frac{\sigma_{1-}}{\sigma_1}\beta_-u\frac{\alpha+1}{\alpha-1}$$

$$u = \beta_-^{\gamma} + \frac{\nu_+^{E}n_{1+}\beta_+^{\gamma}}{\nu_-n_-}, \beta_-^{\gamma} = 2\frac{dln\,\gamma_-(E)}{dln\,E_0^2}, \beta_+^{\gamma} = 2\frac{dln\,\gamma_+(E)}{dln\,E_0^2}$$

$$\beta_{\pm} = 1 + 2\frac{dln\,\mu_{\pm}(E)}{dln\,E_0^2}, \nu_+ = \gamma_+(0)N_-^{0}, \nu_- = \gamma_-(E_0)N_0\ ,\ \nu_+^{E} = \gamma_+(E_0)N_0$$

$$n_{1+} = \frac{n_+^0 N_-^0}{N_0},\ n_{1-} = \frac{n_-^0 N_0}{N_-^0},\ \ \nu_+^{'} = \gamma_+(0)n_+^0 + \gamma_+(E_0)n_{1+},\ \nu_-^{'} = \gamma_-(0)n_-^0 + \gamma_-(0)n_{1-}$$

$$\nu = \nu_+^{'} + \nu_-^{'},\ \sigma_1 = en_+\mu_{1+} + en_-\mu_{1-}$$

From (14) we get the frequency of the current oscillation. However:

$$k_\pm = k_\pm^0 + ik_\pm^{'},\ \nu_{1\pm} = \nu_{1\pm}^0 + i\,\nu_{1\pm}^{'},\ \varphi_\pm = \varphi_\pm^0 + i\varphi_\pm^{'} \qquad (15)$$

Substituting (15) into (14)

$$k_+^0 \upsilon_{1+} = \nu_{1+}^0,\quad k_+^{'}\upsilon_{1+} = \nu_{1+}^{'},\quad k_-^0\upsilon_{1-} = \nu_{1-}^0,\quad k_-^{'}\upsilon_{1-} = \nu_{1-}^{'} \qquad (16)$$

anddispersion equation (14) will be:

$$[-\omega^2 + 2\nu_{1+}^0\beta_+\nu + \nu_+(\nu - i\omega) - i2\nu_{1+}^0\beta_+\omega + i2\nu_{1+}^{'}\beta_+\nu + 2\nu_{1+}^{'}\beta_+\omega - \nu_+\nu_+^{'}\varphi_+^0 - i\nu_+\nu_+^{'}\varphi_+^{'}][-\omega^2 + \nu_-\nu -$$

iων−−ν−ν−′φ−0−ν−ν−′φ−′−ν−ν+ν+′ν−′β+β− (17)

From (17) we get equation for define frequency ω

$$\omega^4 + \Omega_1\omega^3 + \Omega_2^2\omega^2 + \Omega_3^3\omega - \nu_-\nu_+\nu_+^{'}\nu_-^{'}\beta_+\beta_- = 0 \qquad (18)$$

Designating$\frac{\omega}{\nu_-} = x$form (18) we get:

$$\omega = \omega_0 + i\omega_1,\ \Omega = ck\frac{E_0}{H_0}$$

$$x^4 + \left(i + \frac{\nu_+^{'}}{\nu_-^{'}}\beta_+ u\frac{\sigma_{1+}}{\sigma_1}\frac{\omega_1}{2\Omega}\right)x^3 + \left(-\frac{\nu_-^{'}}{\nu_-} + i\frac{\nu_-^{'}}{2\nu_-}\frac{\sigma_{1+}}{\sigma_1}\beta_- u\frac{\omega_1}{\Omega} + i\frac{\nu_+}{\nu_-}\right)x^2 + \left(-\frac{\nu_+^{'}}{\nu_-}\beta_+ u\frac{\sigma_{1+}}{\sigma_1}\frac{\omega_1}{2\Omega} - i\frac{\nu_+\nu_+^{'}}{\nu_-^2}\frac{\sigma_{1-}}{\sigma_1}\beta_- u\frac{\omega_1}{2\Omega} -\right.$$

iν+ν−′ν−2−ν+ν−′ν−2σ1−σ1β−uω12Ω−iν+ν+′ν−2−ν+ν−′ν−2σ1−σ1β−uω12Ωx−ν+ν+′ν−′ν−3β +β−=0 (19)

Substituting$x = x_0 + ix_1$, at$x_1 \ll x_0$from (19)we get

$$x_0^4 + \varphi x_0^3 - 3x_0^2x_1 - \frac{\nu_-^{'}}{\nu_-}x_0^2 - 2x_0x_1\delta + \theta x_0 - \theta_1 x_1 - r = 0 \qquad \text{I}$$

$$x_0^3 + 3x_0^2x_1\varphi - \frac{\nu_-^{'}}{\nu_-}2x_0\ x_1 + \delta x_0^2 - \theta x_1 - \theta_1 x_0 - r = 0 \qquad \text{II}$$

FromIwe get for$x_1$we get following expressions

$$x_1 = \frac{r - x_0^4 - \varphi x_0^3 + \frac{\nu_-^{'}}{\nu_-}x_0^2 + |\theta|x_0}{3x_0^2 + 2x_0\delta + |\theta_1|} \qquad (20)$$

$$\varphi = \frac{\nu_+^{'}}{\nu_-^{'}}\beta_+ u\frac{\sigma_{1+}}{\sigma_1}\frac{\omega_1}{2\Omega},\ \delta = \frac{\nu_+}{\nu_-} + \frac{\nu_-^{'}}{\nu_-^{'}}\frac{\sigma_{1+}}{\sigma_1}\beta_+ u\frac{\omega_1}{2\Omega}$$

$$\theta = -\frac{\nu_+^{'}}{\nu_-^{'}}\beta_+ u\frac{\sigma_{1+}}{\sigma_1}\frac{\omega_1}{2\Omega} - \frac{\nu_+\nu_-^{'}}{\nu_-^2}\frac{\sigma_{1-}}{\sigma_1}\beta_- u\frac{\omega_1}{\Omega}$$

$$\theta_1 = -\frac{\nu_+\nu_+^{'}}{\nu_-^2}\frac{\sigma_{1-}}{\sigma_1}\beta_- u\frac{\omega_1}{2\Omega} - \frac{\nu_+\nu_-^{'}}{\nu_-^2},\ r = \frac{\nu_+\nu_+^{'}\nu_-^{'}}{\nu_-^3}\beta_+\beta_- \ll 1$$

To increase the excited waves inside the sample $x_1$the dolten has a positive sign. From (20) we get

$$x_1 = \frac{\nu_-^{'2}}{4\nu_-\nu_+^{'}}\frac{1}{x_0} \qquad (21)$$

From II we get

$$x_0 = \frac{\nu_+^{'}}{\nu_-^{'}} \qquad (22)$$

and $x_0 \gg x_1$. Thus,from (16-20-21) we define$\omega_0 = \nu_-\frac{\nu_+^{'}}{\nu_-^{'}},\ \omega_1 = \frac{\nu_-^{'3}}{4\nu_+^{'2}}$

$$H_0 = \frac{2C}{\mu_+}\frac{\nu_+^E\nu_+^{'2}}{\nu_-^{'3}}\beta_+ \qquad (23)$$

$$E_0 = \frac{\nu_+^E}{\sqrt{2}k\mu_+}\beta_+ \qquad (24)$$

II. CONCLUSIONS

In semiconductors with two types of charge carriers, singly negatively charged N and doubly negatively charged N_deep traps, growing waves with frequency $\omega_0$and increment ω_1 are spontaneously excited. These waves are increasing at a certain value of the external electric field (23).

The magnetic field has certain values (22) ($\mu_+H_0 \gg c$). The characteristic frequencies (ν_- is the electron capture frequency, ν_+^E is the hole emission frequency, the combined frequencies $\nu_-^{'}$and $\nu_+^{'}$) determine the values of the wave growth increment, the electric field and the magnetic field. It is easy to estimate the frequencies $\omega_0 \sim 10^7$ Hertz, the electric field $E_0 \sim 2 * 10^3$V/sm, $\frac{\mu_+H_0}{c} \sim 7$.

Thus, a semiconductor with the above deep traps can be a source of radiation energy. To find the radiation frequency, you need to calculate the sample impedance. It is clear that the growth of waves inside the sample is limited to non-linear oscillations. In the linear approximation, small fluctuations

$$\left(n_\pm^{'}, E^{'}, H^{'}\right) \ll \left(n_\pm^0, E_0, H_0\right) \qquad (25)$$

In the nonlinear approximation, inequality (25) does not use and

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

To find the amplitude $A(t)$, we need to construct a nonlinear theory.

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