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CURRENT OSCILLATIONS IN IMPURITY SEMICONDUCTORS WITH BOTH SIGNS OF CURRENT CARRIERS IN THE PRESENCE OF AN EXTERNAL ELECTRIC FIELD, A TEMPERATURE GRADIENT AND A WEAK MAGNETIC FIELD (μ_± H<<C)

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Abstract. It is theoretically shown for the first time that in an external electric and weak magnetic fields, when there is a temperature gradient, an impurity semiconductor radiates energy from itself with a certain frequency. The values of the frequency of current oscillations and the limit of change of the external electric field are found. It is shown that the resistance in the medium has only ohmic character. It is stated that in the above semiconductor, when the concentration of electrons and holes are determined from the obtained expression in theory, the injection of contacts plays a major role for the appearance of the indicated current oscillation in the circuit.

Keywords: *Theoretical, electric and weak magnetic fields, temperature gradient, semiconductor energy.*

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1. Introduction

In conducting media under the influence of an external electric field, charge carriers receive additional energy of the order of eEl from the electric field (e is the elementary charge, E is the electric field strength, l is the mean free path of charge carriers). In this case, charge carriers have an energy of the order of $\frac{3}{2}k_0T + eEl$ (k_{0-} is the Boltzmann constant, T is the lattice temperature) and the redistribution of charge carriers over the medium occurs in an uneven manner. This redistribution of charge propagates as a wave inside the medium. These waves can be unstable and therefore energy radiation begins from the crystal. The mechanism and cause of the appearance of unstable waves in different conducting media are different. Therefore, the theoretical study of unstable states requires different mathematical approaches. If the excited wave inside the medium does not go outside (ie, there is no current oscillation in the external medium), then the frequency of this wave is a complex value and the wave vector is a real value. In the opposite case (ie, frequency $\omega=\omega_0$, wave vector $k = k_0 + ik'$), current fluctuations occur in the external circuit and the medium radiates energy with frequency ω_0.

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In Hasanov et al. (2011, 2013), Hasanov and Hasanova (2018), Demirel et al. (2012), Guseynov (2024), Aliev and Hasanov (2018), Ibragimov et al. (2024), we theoretically studied various instabilities in semiconductor media and obtained some analytical formulas for an external electric field and for the current oscillation frequency. However, in impurity semiconductors, the excitation of unstable waves depends on many factors due to the presence of various impurity centers in the medium. Impurity centers, depending on the charge states, are capable of capturing (recombination) or emitting (generation) charge carriers. These recombination and generation processes can excite unstable waves inside the medium.

Gold atoms in germanium, in addition to the neutral state, can be singly, doubly and triply negatively charged centers. These impurity levels are located at different distances from the conduction band of the semiconductor. Depending on the temperature of the semiconductor, these energy levels are more or less active levels. In the experimental work (Iglitsyn, 1966), singly and doubly negative levels were active. In what follows, we will use the experimental model (Iglitsyn, 1966). It is clear that there is a Coulomb barrier around the negative charge. Electrons that have received energy from an external electric field can overcome this Coulomb barrier and be captured. As a result of thermal transfer, electrons can escape from the impurity center into the conduction bands. Due to the capture of electrons by impurity centers from the valence band, the number of holes increases. As a result of recombination and generation of electrons and holes, the electrical conductivity of the semiconductor changes. In Hasanov et al. (2011, 2013), Hasanov and Khalilova (2013), Hasanov and Hasanova (2018), Jabarov (2023), Demirel et al. (2012), Aliyev and Hasanov (2018) analyzes of kinetic equations in a semiconductor with singly and doubly negatively charged centers are presented in detail. These papers present the results of a theoretical study of internal and external instability. However, the equilibrium values of the electron and hole concentrations were arbitrary.

In this theoretical work, we will investigate current oscillations (i.e., external instability) in semiconductors with singly and doubly negative impurity centers in an external electric field E_0 - in the presence of weak magnetic fields (i.e., $\mu_{\pm}H_0 << c$, $\mu_{\pm}$- are the mobility of holes and electrons, c is the speed of light). Taking into account the injection at the contacts of the semiconductor, when the concentrations of electrons η_-- and holes η_+ -are determined from the relation $\eta_+\mu_- = \eta_-\mu_+$. In addition to the above conditions, the semiconductor has a constant temperature gradient ΔT=const.

2. Basic equations of the problem

The kinetic equations for electrons and holes in semiconductors by the above impurity centers have the form (Hasanov *et al.*, 2011; 2013; Demirel *et al.*, 2012; Hasanov & Hasanova, 2018; Aliyev, 2018; Hasanov & Khalilova, 2013; Iglitsyn, 1966).

$$\frac{\partial\eta'_-}{\partial t} + divj'_- = \nu_-\eta'_- - \frac{\nu'_-}{\nu - i\omega}\left[\nu_+\eta'_+ + \nu_-\eta'_- + \left(\nu_+^E\eta_+\beta_+^\gamma + \nu_-\eta_-\beta_-^\gamma\right)\frac{e(\mu_+\eta'_+ + \mu\eta'_-)}{\sigma+\sigma_1}\right] + $$
$$+ \nu_-\eta_-\beta_-^\gamma\frac{e(\mu_+\eta'_+ + \mu\eta'_-)}{\sigma+\sigma_1}, \quad (1)$$

$$\frac{\partial\eta'_+}{\partial t} + divj'_+ = -\nu_+\eta'_+ + \frac{\nu'_+}{\nu - i\omega}\left[\nu_+\eta'_+ + \nu_-\eta'_- + \left(\nu_+^E\eta_+\beta_+^\gamma + \nu_-\eta_-\beta_-^\gamma\right)\frac{e(\mu_+\eta'_+ + \mu\eta'_-)}{\sigma+\sigma_1}\right] - $$
$$-\nu_+^E\eta_+\beta_+^\gamma\frac{e(\mu_+\eta'_+ + \mu\eta'_-)}{\sigma+\sigma_1}, \quad (2)$$

$$\beta_{\pm} = 2\frac{d\ln\mu_{\pm}}{d\ln(E_0^2)},\ \vec{v}_{\pm} = \mu_{\pm}\vec{E}_0,\ \beta_{\pm}^{\gamma} = 2\frac{d\ln\gamma_{\pm}}{d\ln(E_0^2)};\ \eta'_{\pm} \ll \eta_{\pm}^0,\ E' \ll E_0,\ T \ll eE_0 l.$$

$T = k_0 T_0$, T_0- grating temperature, l - mean free path. $\nu_- = \gamma_-(E_0)N_0$- electron capture frequency, $\nu_+ = \gamma_+(E_0)N_0$- hole capture frequency, $\nu_+^E = \gamma_+(E_0)N_0$- hole emission frequency, $\eta_- = \frac{\eta_-{}^0 N_0}{N_-{}^0}$, $\eta_+ = \frac{\eta_+{}^0 N_-{}^0}{N_0}$, $N_0 = N_+ N_-$ total concentration of impurities, N- singly negatively charged centers, N_- - doubly negatively charged centers, $N >> N_-$, $\sigma = \sigma_+ + \sigma_- = e(\eta_+\mu_+ + \eta_-\mu_-)$, $\sigma_1 = e\,(\eta_+\mu_+\beta_+ + \eta_-\mu_-\beta_-)$, $\nu = \nu'_+ + \nu'_-$- combined frequencies of capture and emission of electrons and holes by no uniform traps $(N_0, N_-^0) >> (\eta_{\pm}^0)$.

3. Results and discussion

In the presence of an external magnetic field and a temperature gradient, the current densities for electrons and holes have the form:

$$\overrightarrow{j_-} = -\eta_-\mu_- E^* - \eta_-\mu_{l-}[E^* H] - \alpha_-\overrightarrow{\nabla T} - \alpha'_-[\overrightarrow{\nabla T}\,\vec{H}]$$
$$\overrightarrow{j_+} = \eta_+\mu_+ E^* + \eta_+\mu_{l+}[E^* H] + \alpha_+\overrightarrow{\nabla T} + \alpha'_+[\overrightarrow{\nabla T}\,\vec{H}] \quad (3)$$

$$\vec{J} = e(\overrightarrow{j_+} - \overrightarrow{j_-}). \quad (4)$$

Substituting (3) into (4) we find

$$E^* = \frac{\vec{J}}{\sigma} - \frac{\sigma_1}{\sigma}[\vec{E}^*\vec{H}] - \frac{\alpha}{\sigma}\overrightarrow{\nabla T} + \frac{\alpha_1}{\sigma}[\overrightarrow{\nabla T}\,\vec{H}], \quad (5)$$

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

It was proved in Gurevich (1963) that in the presence of a magnetic field and a temperature gradient, hydrodynamic motions of charge carriers arise and the electric field inside the medium has the form:

$$E^* = \vec{E} + \frac{[\vec{v}\,\vec{H}]}{e} + \frac{T}{e}\left(\frac{\nabla\eta'}{\eta^0} - \frac{\nabla\eta'_+}{\eta_+^0}\right). \quad (6)$$

First, we find $\overrightarrow{E^*}$ from the vector Equation (5) as follows. We write (5) in the following form

$$\overrightarrow{E^*} = \vec{A} + \frac{\sigma_1}{\sigma}[\vec{H}\,\overrightarrow{E^*}]. \quad (7)$$

Denote $\vec{B} = \frac{\sigma_1}{\sigma}\vec{H}$, them

$$\overrightarrow{E^*} = \vec{A} + [\vec{B}\,\overrightarrow{E^*}]. \quad (8)$$

From the vector Equation (8) we can easily obtain:

$$\overrightarrow{E^*} = \vec{A} + [\vec{B}\,\vec{A}] + \left[\vec{B}[\vec{B}\,E^*]\right]. \quad (9)$$

Expanding the vector product in (9) at $\mu_{\pm}H_0 \ll C$ and substituting the resulting expression for $\overrightarrow{E^*}$ in (6), we easily obtain the expressions for the electric field

$$\vec{E} = -\frac{[\vec{v}\,\vec{H}]}{e} - \frac{\Lambda'}{\sigma}[\overrightarrow{\nabla T}\,\vec{H}] + \frac{\vec{J}}{\sigma} - \frac{\sigma_1}{\sigma_2}[\vec{J}\,\vec{H}] + \Lambda\nabla T + \frac{T}{e}\left(\frac{\nabla\eta'_-}{\eta_-^0} - \frac{\nabla\eta'_+}{\eta_+^0}\right). \quad (10)$$

Substituting (3-4), taking into account (10) in (1-2), we obtain the following dispersion equations for determining the wave vectors k_1 and k_2

$$x^4 - ux^2 + fx - \delta_0 + i\delta_1 = 0, x = L_x k. \quad (11)$$

Here $u = \frac{1}{\varphi_- \varphi_+ \alpha^2}$; $\varphi_\pm = \frac{\mu_\pm H_0}{c}$; $\alpha^2 = \frac{1}{8\varphi_- \varphi_+} \cdot \frac{\omega}{\nu_+}$;

$f = \frac{L_x u \omega}{\mu_- \mu_+ E_2^2 \alpha^2}$; $\delta_0 = \frac{L_x^2(\nu_- \nu_+ - \omega^2)}{\mu_- \mu_+ E_2^2 \alpha^2 \varphi_- \varphi_+}$; $\delta_1 = \frac{L_x^2 \omega \nu_-}{\mu_- \mu_+ E_2^2 \alpha^2 \varphi_- \varphi_+}$; $E_2 = \frac{T}{eL_x}$

The solution of Equation (11) in general form is very difficult. Therefore, we will investigate oscillations in the considered medium with frequencies

$$\omega = \pm(\nu_- \nu_+)^{1/2}. \quad (12)$$

Taking into account (12), from (11) we easily obtain:

$$x_1 = u^{1/2} - i\frac{\delta_1}{2u^{3/2}}; \; x_2 = -u^{1/2} - i\frac{\delta_1}{2u^{3/2}}. \quad (13)$$

After finding the dimensionless wave vectors x_1 and x_2, we can calculate the impedance of the medium as follows

$$Z = \frac{1}{J_1}\int_0^{L_x} E'(x,t)dx \,. \quad (14)$$

Find $E'(x,t)$ from (10)

$$E_x' = \frac{J_x'}{\sigma_0 \varphi} + \frac{iT}{e\varphi}(k_1 + k_2)\left(\frac{\eta_-'}{\eta_-^0} - \frac{\eta_+'}{\eta_+^0}\right) \quad (15)$$
$$\varphi = 1 - \frac{E_1}{E_0}; \; E_1 = \Lambda_0 \gamma \nabla T; \; \gamma = 2\frac{d \ln \Lambda}{d \ln(E_2)}.$$

η_-' and η_+' must be found, taking into account injection, on the contacts of the medium as follows

$$\eta_-' = c_1^- e^{ik_1 x} + c_2^- e^{ik_2 x}, \eta_+' = c_1^+ e^{ik_1 x} + c_2^+ e^{ik_2 x} \;. \quad (16)$$

Considering that at $x = 0$, $\eta_\pm' = \delta_\pm^0 J_x'$ and that $x = L$, $\eta_\pm' = \delta_\pm^L J_x'$ (17)
we find from (16) taking into account (17) for the constants $C_{1,2}^-$ and $C_{1,2}^+$ the following expressions

$$C_1^- = J_x' \frac{\delta_-^0 e^{ik_2 L_x} - \delta_-^L}{e^{ik_2 L_x} - e^{ik_1 L_x}}; \; C_2^- = J_x' \frac{\delta_-^L - \delta_-^0 e^{ik_1 L_x}}{e^{ik_2 L_x} - e^{ik_1 L_x}}; \; C_1^+ = J_x' \frac{\delta_+^0 e^{ik_2 L_x} - \delta_+^L}{e^{ik_2 L_x} - e^{ik_1 L_x}}; \; C_2^+ = J_x' \frac{\delta_+^L - \delta_+^0 e^{ik_1 L_x}}{e^{ik_2 L_x} - e^{ik_1 L_x}}; \quad (18)$$

or

$$C_1^- = \delta_1^- J_x'; \; C_2^- = \delta_2^- J_x'; \; C_1^+ = \delta_1^+ J_x'; \; C_2^+ = \delta_2^+ J_x'. \quad (19)$$

Substituting (15) taking into account (18-19) we obtain the following expressions for the impedance of the medium

$$Z = \frac{T}{e\varphi}\left(1 + \frac{k_2}{k_1}\right)\left(\frac{\delta_1^-}{\eta_-^0} - \frac{\delta_1^+}{\eta_+^0}\right)\left(e^{ik_1L_x} - 1\right) +$$
$$+ \frac{T}{e\varphi}\left(1 + \frac{k_1}{k_2}\right)\left(\frac{\delta_2^-}{\eta_-^0} - \frac{\delta_2^+}{\eta_+^0}\right)\left(e^{ik_2L_x} - 1\right) + \frac{L_x}{\delta_0}. \quad (20)$$

When deriving (15), we take into account that $H' = 0$, т.е. $\vec{k} \parallel \overrightarrow{E'}$.

When obtaining the values of the wave vectors k_1 and k_2, we take into account the inequality

$$f_0 > \frac{\delta_1}{u^{\frac{1}{2}}} \qquad \text{i.e.} \qquad E_0 > \frac{L_x\nu}{\mu}\frac{c}{\mu H_0}\frac{1}{2\sqrt{2}}\left(\frac{\mu_-}{\mu_+}\right)^{\frac{1}{4}} = E_{xar}. \quad (21)$$

Substituting $C_{1,2}^{\pm}$ into (20), taking into account (21), we obtain:

$$Z = \frac{T}{e\varphi}(u-1)\left[\frac{\delta_-^L}{\eta_-^0} - \frac{\delta_+^L}{\eta_+^0} + 2\left(\frac{\delta_+^0}{\eta_+^0} - \frac{\delta_-^0}{\eta_-^0}\right)\right],\ u = 4\left(\frac{\mu_-}{\mu_+}\right)^2\left(\frac{\nu_-}{\nu_+}\right)^{\frac{1}{2}},\ u \gg 1. \quad (22)$$

It can be seen from (22) that the impedance of the medium is purely real, i.e. $J_m Z = 0$. This means that when oscillation (12) appears, there is no capacitive and inductive resistance inside, i.e. resistance is ohmic. To find the electric field when the current fluctuates in the circuit, we must solve the following equation

$$Z + R = 0\ . \quad (23)$$

Thus, Equation (23) ν has the form:

$$Z = \pm\frac{T}{e\varphi Z_0}4\left(\frac{\mu_-}{\mu_+}\right)^{\frac{3}{2}}\left(\frac{\delta_-^L - 2\delta_-^0}{\eta_-^0} - \frac{\delta_+^L - 2\delta_+^0}{\eta_+^0}\right) + 1 + \frac{R}{Z_0} = 0,\ \ Z_0 = \frac{L_x}{\sigma_0}. \quad (24)$$

From (24) we can easily obtain the following expression for the electric field at the appearance of current oscillations with frequency (12)

$$E_0 = \frac{E_1}{1 \pm \frac{4T}{eZ_0 r}\frac{\mu_-}{\mu_+}\left(\frac{\delta_-}{\eta_-^0} - \frac{\delta_+}{\eta_+^0}\right)}, \quad (25)$$

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

For a positive value of E_0 with frequency (12) shows the following limiting cases

1) $\frac{\delta_-}{\eta_-} = \frac{\delta_+}{\eta_+}$, $\quad 2\delta_-^0 > \delta_-^L$ и $2\delta_+^0 > \delta_+^L$, $\quad \frac{\eta_-}{\eta_+} = \frac{\delta_-^0}{\delta_+^0}$ or $\frac{\eta_-^0}{\eta_+^0} = \frac{\delta_-^L}{\delta_+^L}$; $\quad E_0 = E_1$, $\quad \omega = \pm(\nu_-\nu_+)^{\frac{1}{2}}$.

2) $\frac{\eta_-^0}{\eta_+^0} < \frac{\delta_-^L}{\delta_+^L}$ or $\frac{\eta_-^0}{\eta_+^0} < \frac{\delta_-^0}{\delta_+^0}$; $\quad E_0 < E_1$, $\quad \omega = +(\nu_-\nu_+)^{\frac{1}{2}}$.

3) $\frac{\eta_-^0}{\eta_+^0} > \frac{\delta_-^L}{\delta_+^L}$ or $\frac{\eta_-^0}{\eta_+^0} > \frac{\delta_-^0}{\delta_+^0}$; $\quad E_0 < E_1$, $\quad \omega = -(\nu_-\nu_+)^{\frac{1}{2}}$.

4) $\frac{\eta_-^0}{\eta_+^0} < \frac{\delta_-^L}{\delta_+^L}$ or $\frac{\eta_-^0}{\eta_+^0} < \frac{\delta_-^0}{\delta_+^0}$; $E_0 > E_1$, $\omega = -(\nu_- \nu_+)^{\frac{1}{2}}$.

4. Conclusion

Thus, the value of the external electric field in all listed cases exceeds the characteristic field E_{car}, but does not exceed the value of E_1. Then the radiation of the medium occurs when E_0 changes from E_{car} to E_1.

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