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Current Oscillations In Impurity Semiconductors With Both Signs Of Current Carriers In The Presence Of An External Electric Field, Temperature Gradient, And Weak Magnetic Field ($\mu_\pm H_0 << c$)

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Abstract: *For the first time, it has been theoretically shown that in an external electric and weak magnetic field, when there is a temperature gradient, an impurity semiconductor emits energy from itself with a certain frequency. The values of the current oscillation frequency and the limit of variation of the external electric field are found. It is shown that in a medium the resistance has only an ohmic character. It is stated that in the aforementioned semiconductor, when the concentration of electrons and holes is determined from the obtained expression in theory, the injection of contacts play the main role for the appearance of the indicated current oscillation in the circuit.*

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I. Introduction

In conducting media, under the influence of an external electric field, charge carriers receive additional order energy eEl from the electric field (e is elementary charge, $\vec{E}$ is electric field strength, l is mean free path of charge carriers). In this case, the charge carriers have an energy of the order $\frac{3}{2}k_0T + eEl$ (k_0 is the Boltzmann constant, T isthe lattice temperature) and the charge carriers are redistributed over the medium in an uneven way). This redistribution of charge carriers propagates in the form of a wave inside the medium. These waves can be unstable, and energy radiation starts from the crystal. The mechanism and cause of the occurrence of unstable waves in different conductive media are different. Therefore, for the theoretical study of unstable states, different mathematical approaches are required. If the excited wave inside the medium does not go outside (i.e. there is no current oscillation in the external environment), then the frequency of this wave is a complex quantity, and the wave vector is a real quantity. In the opposite case (i.e. $w = w_0$ is the frequency, $k = k_0 + ik'$ is the wave vector), current oscillations occur in the external circuit, and the medium radiates energy with frequency.

In [1-6], we theoretically investigated various instabilities in semiconductor media and obtained some analytical formulas for an external electric field and for the frequency of current oscillations. However, in impurity semiconductors, the excitation of unstable waves depends on many factors due to the presence of different impurity centers in the medium. Impurity centers, depending on charge states, are capable of capturing the recombination of charge carriers. These recombination and generation processes can excite unstable waves inside the medium. Gold atoms in Germany, in addition to the neutral state, can be once, twice and triple 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 [7], once and twice negative levels were active. We will continue to use the experimental model [7]. It is clear that around the negative charge there is a Coulomb barrier. Electrons that receive energy from an external electric field can cross this Coulomb barrier and be captured. Electrons as a result of thermal transfer can exit the impurity center into conduction bands. Due to the capture of electrons by impurity centers from the valence band, the number of holes increases. As a result of the recombination and generation of electrons and holes, the electrical conductivity of the semiconductor changes.

In [1-6], an analysis of kinetic equations in a semiconductor with single and double negatively charged centers is described in detail. In these works, the results of a theoretical study of internal and external instability are presented. However, the equilibrium concentrations of electrons and holes were arbitrary. In this theoretical work, we will study current oscillations (i.e. external instability) in semiconductors with single and double negative impurity centers in an external and electric E_0 field in the presence of weak magnetic fields (i.e. $\mu_\pm H_0 << c$, $\mu_\pm$ is the mobility of holes and electrons, c is the speed of light). Taking into account injection at the semiconductor contacts, when the concentration of electrons n_- and holes n_+ is determined from $n_+\mu_- = n_-\mu_+$. In addition to the above conditions, the semiconductor has a constant temperature gradient $\nabla T = const$.

II. Basic equations of the problem

The kinetics equations for electrons and holes in semiconductors by the above impurity centers have the form [1-7]:

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

$$\frac{\partial n'_+}{\partial t} + divj'_+ = -\nu_+ n'_+ + \frac{\nu'_+}{\nu - i\omega}\left[\nu_+ n'_+ + \nu_- n'_- + \left(\nu_+^E n_{1+}\beta_+^\gamma + \nu_- n_- \beta_-^\gamma\right)\frac{e\left(\mu_+ n'_+ + \mu_- n'_-\right)}{\sigma + \sigma_1}\right] - \\ - \nu_+^E n_{1+}\beta_+^\gamma \frac{e\left(\mu_+ n'_+ + \mu_- n'_-\right)}{\sigma + \sigma_1} \tag{2}$$

$$\beta_\pm = 2\frac{d\ln\mu_\pm}{d\ln\left(E_0^2\right)};\ \vec{\vartheta}_\pm = \mu_\pm \vec{E}_0;\ \beta_\pm^\gamma = 2\frac{d\ln\gamma_\pm}{d\ln\left(E_0^2\right)};\ n'_\pm << n_+^0;\ E' << E_0;\ T << eE_0 l;$$

$T = k_0 T;\ T_0$ is the lattice temperature, l is the mean free path, $\nu_- = \gamma_-(E_0)N_0$ is the electron capture frequency, $\nu_+ = \gamma_+(E_0)N_-^0$ is the hole capture frequency, $\nu_+^E = \gamma_+(E_0)N_0$ is the hole emission frequency, $n_{1-} = \frac{n_-^0 N_0}{N_-^0}$, $n_{1+} = \frac{n_+^0 N_-^0}{N_0}$, $N_0 = N_+ N_-$ is -the total concentration of impurities, N is the singly negatively charged centers, and N_- is the doubly negative charged centers, $N >> N_-$, $\sigma = \sigma_+ + \sigma_- = e(n_+\mu_+ + n_-\mu_-),\ \sigma_1 = e(n_+\mu_+\beta_+ + n_-\mu_-\beta_-),\ \nu = \nu'_+ + \nu'_-$ is the combined electron and hole capture and emission frequencies of nonequilibrium traps $\left(N_0, N_-^0\right) >> \left(n_\pm^0\right)$.

III. Theory

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

$$\vec{j}_- = -n_-\mu_- E^* - n_-\mu_{1-}\left[E^* H\right] - \alpha_- \vec{\nabla} T - \alpha'_-\left[\vec{\nabla} T\vec{H}\right]$$
$$\vec{j}_+ = n_+\mu_+ E^* + n_+\mu_{1+}\left[E^* H\right] + \alpha_+ \vec{\nabla} T + \alpha'_+\left[\vec{\nabla} T\vec{H}\right] \tag{3}$$

$$\vec{J} = e\left(\vec{j}_+ - \vec{j}_-\right) \tag{4}$$

Substituting (3) into (4) we find

$$E^* = \frac{\vec{J}}{\sigma} - \frac{\sigma_1}{\sigma}\left[\vec{E}^*\vec{H}\right] - \frac{\alpha}{\sigma}\vec{\nabla} T + \frac{\alpha_1}{\sigma}\left[\vec{\nabla} T\vec{H}\right] \tag{5}$$

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

In [8], it was proved that in the presence of a magnetic field and a temperature gradient, hydrodynamic motion of charge carriers occurs, and the electric field inside the medium has the form:

$$E^{*}=\vec{E}+\frac{\left[\vec{V}\vec{H}\right]}{e}+\frac{T}{e}\left(\frac{\nabla n'_{-}}{n_{-}^{0}}-\frac{\nabla n'_{+}}{n_{+}^{0}}\right) \qquad (6)$$

First, we find from the vector equation (5) as follows. We write (5) in the following form

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

Denote by $\vec{B}=\frac{\sigma_1}{\sigma}\vec{H}$. Then

$$\vec{E}^{*}=\vec{A}+\left[\vec{B}\vec{E}^{*}\right] \quad (8)$$

And the vector equation (8) can easily be obtained:

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

By revealing the vector product in (9) with $\mu_{\pm}H_0 << c$ and substituting the resulting expression for $\vec{E}^{*}$ in (6), we easily obtain the expressions for the electric field

$$\vec{E}=-\frac{\left[\vec{V}\vec{H}\right]}{c}-\frac{\Lambda'}{\sigma}\left[\vec{\nabla}T\vec{H}\right]+\frac{\vec{J}}{\sigma}-\frac{\sigma_1}{\sigma^2}\left[\vec{J}\vec{H}\right]+\Lambda\vec{\nabla}T+\frac{T}{e}\left(\frac{\nabla n'_{-}}{n_{-}^{0}}-\frac{\nabla n'_{+}}{n_{+}^{0}}\right) \quad (10)$$

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

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

Here

$$u=\frac{1}{\varphi_{-}\varphi_{+}\alpha^2},\ \varphi_{\mp}=\frac{\mu_{\mp}H_0}{c},\ \alpha^2=\frac{1}{8\varphi_{-}\varphi_{+}}\frac{\omega}{\nu_{+}},\ f=\frac{L_x\vartheta_{-}\omega}{\mu_{-}\mu_{+}E_2^2\alpha^2},\ \delta_0=\frac{L_x\left(\nu_{-}\nu_{+}-\omega^2\right)}{\mu_{-}\mu_{+}E_2^2\alpha^2\varphi_{-}\varphi_{+}},$$
$$\delta_1=\frac{L_x^2\omega\nu_{-}}{\mu_{-}\mu_{+}E_2^2\alpha^2\varphi_{-}\varphi_{+}},\ E_2=\frac{T}{eL_x}$$

The solution of equation (11) in a general form is very complicated. Therefore, we will study the oscillations of the medium under consideration with frequencies

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

In view of (12), from (11) it is easy to 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

$$Z = \frac{1}{J'} \int_0^1 E'(x,t) dx \qquad (14)$$

We find $E'(x,t)$ from (10)

$$E'_x = \frac{J'_x}{\sigma_0 \varphi} + \frac{iT}{e\varphi}(k_1 + k_2)\left(\frac{n'_-}{n_-^0} - \frac{n'_+}{n_+^0}\right) \qquad (15)$$

$\varphi = 1 - \frac{E_1}{E_0}$, $E_1 = \Lambda_0 \gamma \nabla T$, $\gamma = 2\frac{d \ln \Lambda}{d \ln(E^2)}$

n'_- and n'_+ it is necessary to find, taking into account injection, at the contacts of the medium as follows

$$n'_- = c_1^- e^{ik_1 x} + c_2^- e^{ik_2 x}, \; n'_+ = c_1^+ e^{ik_1 x} + c_2^+ e^{ik_2 x} \qquad (16)$$

Given $x = 0,\; n'_\pm = \delta_\pm^0 J'_x$ and $x = L$

$n'_\pm = \delta_\pm^L J'_x$ (17) we find from (16), taking into account (17) for constants $c_{1,2}^-$ and $c_{1,2}^+$, the following expressions

$$c_1^- = J'_x \frac{\delta_-^0 e^{ik_2 L_x} - \delta_-^L}{e^{ik_2 L_x} - e^{ik_1 L_x}};\; c_2^- = J'_x \frac{\delta_-^L - \delta_-^0 e^{ik_1 L_x}}{e^{ik_2 L_x} - e^{ik_1 L_x}};\; c_1^+ = J'_x \frac{\delta_+^0 e^{ik_2 L_x} - \delta_+^L}{e^{ik_2 L_x} - e^{ik_1 L_x}};\; c_2^- = J'_x \frac{\delta_+^L - \delta_+^0 e^{ik_1 L_x}}{e^{ik_2 L_x} - e^{ik_1 L_x}} \qquad (18)$$

or

$$c_1^- = \delta_1^- J'_x,\; c_2^- = \delta_2^- J'_x,\; c_1^+ = \delta_1^+ J'_x,\; c_2^+ = \delta_2^+ J'_x \qquad (19)$$

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

$$Z = \frac{T}{e\varphi}\left(1 + \frac{k_2}{k_1}\right)\left(\frac{\delta_1^-}{n_-^0} - \frac{\delta_1^+}{n_+^0}\right)\left(e^{ik_1 L_x} - 1\right) + \frac{T}{e\varphi}\left(1 + \frac{k_1}{k_2}\right)\left(\frac{\delta_2^-}{n_-^0} - \frac{\delta_2^+}{n_+^0}\right)\left(e^{ik_2 L_x} - 1\right) + \frac{L_x}{\sigma_0} \qquad (20)$$

When obtaining (15), we took into account that $H' = 0$, i.e. $\vec{k} \parallel \vec{E}'$.

In obtaining the values of the wave vectors k_1 and k_2 we took into account the inequality

$$f_0 > \frac{\delta_1}{u^{1/2}}, \text{т.е. } E_0 > \frac{L_x \nu_-}{\mu} \frac{c}{\mu H_0} \frac{1}{2\sqrt{2}} \left(\frac{\mu_-}{\mu_+}\right)^{1/4} = E_{char} \qquad (21)$$

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

$$Z = \frac{T}{e\varphi}(u-1)\left[\frac{\delta_-^L}{n_-^0} - \frac{\delta_+^L}{n_+^0} + 2\left(\frac{\delta_+^0}{n_+^0} - \frac{\delta_-^0}{n_-^0}\right)\right] \qquad (22)$$

$$u = 4\left(\frac{\mu_-}{\mu_+}\right)^2 \left(\frac{\nu_-}{\nu_+}\right)^{1/2}, u >> 1$$

It follows from (22) that the impedance of the medium is purely real, i.e. $J_m Z = 0$. This means that when an oscillation with a frequency of (12) appears inside, resistance of capacitive and inductive nature does not arise, i.e. resistance is ohmic. To find the electric field with the appearance of current fluctuations in the circuit, we must solve the following equations

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

Thus, equation (23) has the form:

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

From (24) we easily obtain the following expressions for the electric field when a current oscillation with a frequency appears (12)

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

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

IV. Discussion of the results

For a positive value with frequency (12), the following limiting cases are shown

1. $\frac{\delta_-}{n_-} = \frac{\delta_+}{n_+}$, $2\delta_-^0 > \delta_-^L$ и $2\delta_+^0 > \delta_+^L$,

$\frac{n_-}{n_+} = \frac{\delta_-^0}{\delta_+^0}$ or $\frac{n_-^0}{n_+^0} = \frac{\delta_-^L}{\delta_+^L}$; $E_0 = E_1$; $\omega = \pm(\nu_- \nu_+)^{1/2}$;

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

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

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

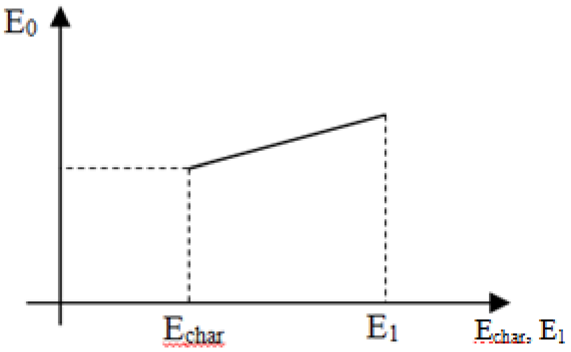

Figure Dependence of the electric field on characteristic fields

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