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OSCILLATIONS OF CURRENT IN IMPURITY SEMICONDUCTORS IN THE PRESENCE OF A TEMPERATURE GRADIENT IN EXTERNAL ELECTRIC AND WEAK MAGNETIC FIELDS

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Abstract- In semiconductors to happen to particular deep traps and both signs of charge carrier's energy radiations. Perhaps at different values of frequency of radiation of energy. For an electric field at a magnetic field is $\mu_{\pm}H >> C$. The sign a constant of scattering of charge carriers is defined. For parameters of a recombination and generation of charge carriers β_{+}^{γ} analytical expressions are found. The theory of fluctuation of current is constructed in the linear approximation. Frequency estimates (w_1, w_2, w_3) and an electric field. The (E_1, E_2, E_3) will quitely be coordinated with the existing experimental data. From above the specified semiconductors it is possible to use at preparation of superhigh-frequency generators and amplifiers.

Keywords: Semiconductor, Impedance, Ohmic Resistance, Frequencies, Coulomb Barrier.

1. INTRODUCTION

In impurity semiconductors, the theory of current oscillations in external electric and weak magnetic fields has been constructed in many works [1-5]. In these works, the theory of internal and external instability was constructed in various ratios of the concentrations of charge carriers (electrons and holes). The obtained analytical expressions for the critical electric field and for the oscillation frequency in specific impurity semiconductors are consistent with existing experiments. In this theoretical work, we prove that, in the presence of a constant temperature gradient in the semiconductors indicated below, the critical values of the electric field and the frequency of the current oscillation (the critical value corresponds to the occurrence of current oscillation in the semiconductors) with a weak external magnetic field ($\mu_{\pm}H_0 << c$, where $\mu_{\pm}$ is mobility of charge carriers, c is speed of light, H_0 is magnetic field strength) depend on the linear size of the semiconductor and the radiation of energy from the semiconductor amplifies with a decrease in the linear size of the semiconductor.

In this theoretical work, we consider the case when the semiconductor contacts are injecting and the carrier concentration ratios are determined as follows

$$\nu_{+}n_{-}^{0} = \nu_{-}n_{+}^{0} \tag{1}$$

where, ν_{+} is hole capture frequency, ν_{-} is electron capture frequency, n_{-}^{0} is equilibrium electron concentration values, n_{+}^{0} is equilibrium hole concentration values.

In [6], it was proved that in the presence of a temperature gradient in a solid-state plasma, hydrodynamic motions of charge carriers arise, and this process substantially changes the values of the electric field inside the medium. In the presence of hydrodynamic movements and a temperature gradient, the values of the electric field with two types of charge carriers have the form:

$$\vec{E}^{*} = \vec{E} + \frac{[\vec{v}\vec{H}]}{c} + \frac{T}{e}\left(\frac{\nabla n_{-}}{n_{-}^{0}} - \frac{\nabla n_{+}}{n_{+}^{0}}\right) \tag{2}$$

where, $\vec{v}$ is speed of hydrodynamic movements, e is positive elementary charge, T is temperature (in Ergs) of the medium.

2. NONLINEAR MOTOR DYNAMICS

In [1-5], we considered semiconductors with a concentration of doubly negatively charged centers and with concentrations of singly negatively charged centers

$$N_0 = N_{+}N_{-} \tag{3}$$

Under conditions (3), the kinetics equations of electrons and holes have the form:

$$\frac{\partial n_{-}}{\partial t} + div\vec{j}_{-} = \gamma_{-}(0)n_{1-}N_{-} - \gamma_{-}(E)n_{-}N = \left(\frac{\partial n_{-}}{\partial t}\right)_{rek} \tag{4}$$

$$\frac{\partial n_{+}}{\partial t} + div\vec{j}_{+} = \gamma_{+}(0)n_{1+}N - \gamma_{+}(0)n_{+}N_{-} = \left(\frac{\partial n_{+}}{\partial t}\right)_{rek} \tag{5}$$

The justifications of Equations (4-5) are described in detail in [1-5].

In the presence of an electric field (2) and a temperature gradient in the electric and magnetic fields, the current flux densities are as follows:

$$\vec{j}_- = -n_-\mu_- E^* - n_-\mu_{1-}[\vec{E}^*\vec{H}] - \alpha_-\vec{\nabla}T - \alpha'_-[\vec{\nabla}T\vec{H}] \qquad (6)$$

$$\vec{j}_+ = n_+\mu_+ E^* + n_+\mu_{1+}[\vec{E}^*\vec{H}] + \alpha_+\vec{\nabla}T + \alpha'_+[\vec{\nabla}T\vec{H}] \qquad (7)$$

$$\vec{J} = e(\vec{j}_+ - \vec{j}_-) \qquad (8)$$

Substituting (6-7) into (8) we obtain the following equations for determining $\vec{E}^*$ the electric field

$$\vec{E}^* = \frac{J}{\sigma} - \frac{\sigma_1}{\sigma}[\vec{E}^*\vec{H}] - \frac{\alpha}{\sigma}\nabla T + \frac{\alpha_1}{\sigma}[\nabla TH] \qquad (9)$$

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

The definition $\vec{E}^*$ from (9) reduces to solving the vector equation

$$\vec{E}^* = \vec{a} + \frac{\sigma_1}{\sigma}[\vec{H}\vec{E}^*] \qquad (10)$$

We denote and with multiplying (10) scalar on b we get $(\vec{b}\vec{E}^*) = (\vec{b}\vec{a})$, then we get easily

$$\vec{E}^* = \vec{a} + [\vec{b}\vec{a}] + [\vec{b}[\vec{b}E^*]] \qquad (11)$$

From (11) at $\mu_\pm H_0 << c$, we get

$$\vec{E} = -\frac{[vH]}{c} - \frac{\Lambda'}{\sigma}[\vec{\nabla}\vec{T}\vec{H}] + \frac{\vec{J}}{\sigma} - \frac{\sigma_1}{\sigma^2}[\vec{J}\vec{H}] + \\ + \Lambda\nabla T + \frac{T}{e}\left(\frac{\nabla n_-}{n_-^0} - \frac{\nabla n_+}{n_+^0}\right) \qquad (12)$$

where, $\Lambda = \frac{\alpha}{\sigma}$, $\Lambda' = \frac{\alpha_1\sigma - \alpha\sigma_1}{\sigma^2}$, Λ' is Nerst-Ettinghausen coefficient, and Λ is differential thermo electromotive force.

3. THEORY

Oscillations of current $J' \neq 0$ current occurs at the beginning of the emission of energy from the medium. The quasineutrality equation $\operatorname{div} J' = 0$ means that the total current does not depend on coordinates, but depends on time. At the beginning of radiation, the impedance of the sample decreases, i.e. becomes negative. To calculate the frequency of the current oscillation and the critical value of the electric field, gently calculate the impedance of the sample, i.e.

$$Z = \frac{1}{J'}\int_0^{L_x} E'_x dx \qquad (13)$$

Assuming $E = E_0 + E'$, $n_\pm = n_\pm^0 + n'_\pm$, $(E' << E_0,\ n'_\pm << n_\pm^0)$, we find E'_x from (12). At $v'_y = \frac{c}{H_0}E'_x$ (14) from (12) we get easily

$$E'_x = \frac{J'_x}{2\sigma_0\varphi} + \frac{E_1}{2\varphi}ikL_x\left(\frac{n'_-}{n_-^0} - \frac{n'_+}{n_+^0}\right) \qquad (14)$$

where, L_x is sample length, $E_1 = \frac{T}{eL_x}$; $\varphi = 1 - \frac{\Lambda\nabla T\gamma}{2E_0\sigma_0}$; $\gamma = 2d\ln\Lambda / d\ln(E_0^2)$; $\vec{E} = \vec{E}_{0x} = \vec{i}E_0$.

The contacts of the sample are injecting and, therefore, $n'_\pm$ must be located from the boundary conditions, i.e.

$$n'_\pm = \delta_\pm J' \qquad (15)$$

where, $n'_\pm$ in (15) can be represented as follows

$$n'_+ = c_1^+ e^{ik_1x} + c_2^+ e^{ik_2x},\ n'_- = c_1^- e^{ik_1x} + c_2^- e^{ik_2x} \qquad (16)$$

We writ e (16) at $x = 0$ and $x = L_x$

$$\begin{aligned} c_1^+ + c_2^+ &= \delta_+^0 J'_x \\ c_1^- + c_2^- &= \delta_-^0 J'_x \end{aligned} \qquad (17)$$

$$\begin{aligned} c_1^+ e^{ik_1L_x} + c_2^+ e^{ik_2L_x} &= \delta_+^L J'_x \\ c_1^- e^{ik_1L_x} + c_2^- e^{ik_2L_x} &= \delta_-^L J'_x \end{aligned} \qquad (18)$$

From (17-18), we get easily

$$\begin{aligned} c_1^+ &= J'_x\frac{\delta_+^0 e^{i\alpha_2} - \delta_+^L}{e^{i\alpha_2} - e^{i\alpha_1}},\ c_2^+ = J'_x\frac{\delta_+^L - \delta_+^0 e^{i\alpha_1}}{e^{i\alpha_2} - e^{i\alpha_1}} \\ c_1^- &= J'_x\frac{\delta_-^0 e^{i\alpha_2} - \delta_-^L}{e^{i\alpha_2} - e^{i\alpha_1}},\ c_2^+ = J'_x\frac{\delta_+^L - \delta_+^0 e^{i\alpha_1}}{e^{i\alpha_2} - e^{i\alpha_1}} \\ c_1^- &= J'_x\frac{\delta_-^0 e^{i\alpha_2} - \delta_-^L}{e^{i\alpha_2} - e^{i\alpha_1}},\ c_2^- = J'_x\frac{\delta_-^L - \delta_-^0 e^{i\alpha_1}}{e^{i\alpha_2} - e^{i\alpha_1}} \\ \alpha_1 &= k_1L_x,\ \alpha_2 = k_2L_x \end{aligned} \qquad (19)$$

For a specific calculation $c_1^\pm$ and $c_2^\pm$ we must find the wave vectors k_1 and k_2 which are calculated from (4) and (5) taking into account (6) and (7) and (12). In [7], we have proved that under condition (1), equations (4) and (5) have the following form:

$$\frac{\partial n'_-}{\partial t} + \operatorname{div} j'_- = -\nu_- n'_-,\ \frac{\partial n'_+}{\partial t} + \operatorname{div} j'_+ = -\nu_+ n'_+ \qquad (20)$$

Substituting $\operatorname{div} j'_+$ from (6)-(7), taking into account (12) into (20), we easily obtain the following dispersion equations for determining the wave vectors k_1 and k_2.

$$x^4 - \frac{1}{\beta_-\beta_+\alpha^2}x^2 - iL_x[\vartheta_+(\nu_- - iw) - \\ -\vartheta_-(\nu_+ - iw)]\frac{1}{\mu_{1+}\mu_{1-}E_1^2\alpha^2}x - \\ -\frac{L_x^2(\nu_- - iw)(\nu_+ - iw)}{\mu_{1+}\mu_{1-}E_1^2\alpha^2} = 0 \qquad (21)$$

where, $\beta_- = \frac{\mu_- H_0}{c}$, $\beta_+ = \frac{\mu_+ H_0}{c}$, $\vartheta_- = \mu_- E_0$, $\vartheta_+ = \mu_+ E_0$, $\alpha = \frac{\vartheta_{0x} H_0}{cE_0}$ and $x = kL_x$.

The equation is simplified when

$$\frac{\nu_-}{\nu_+} = \frac{\mu_-}{\mu_+} = \frac{n_-^0}{n_+} \qquad (22)$$

$$x^4 - ux^2 + fx - \delta_0 + i\delta = 0 \qquad (23)$$

where, $\delta_0 = \frac{L_x^2(\nu_-\nu_+ - w^2)}{\mu_-\mu_+ E_1^2\alpha^2\beta_-\beta_+}$ and $\delta_1 = \frac{L_x^2 w\nu_-}{\mu_-\mu_+ E_1^2\alpha^2\beta_-\beta_+}$.

To find the wave vectors k_1 and k_2 we consider the following two cases: 1) x<<1; 2) x>>1 (it is clear that the case x=1 has no physical meaning).
1) x<<1:

From (23) we get easily:

$$x_1 = i\left(\frac{\beta}{2}\right)^{\frac{1}{2}},\ x_2 = \left(\frac{\beta}{2}\right)^{\frac{1}{2}}(2-i)$$
$$\beta = \frac{L_x}{\alpha}\left(\frac{w\nu_-}{2\mu_-\mu_+E_1^2\beta_-\beta_+}\right) \tag{24}$$

Values of x_1 and x_2 are obtained in an electric field

$$E_0 = \frac{\Lambda\nabla T\gamma}{2\sigma_0} \tag{25}$$

$$\frac{\vartheta_{0x}}{c} = \frac{E_0 c}{2H_0^2}\left(\frac{w}{2\mu_+\nu_+}\right)^{\frac{1}{2}} \tag{26}$$

Substituting x_1 and x_2 in (19) and after integration (13), we obtain the following expressions for the sample impedance.

$$\frac{Z}{Z_0} = -\left\{1+\sigma_0 E_1\left[\frac{1}{n_+^0}\left(\delta_+^0-\delta_+^L\right)-\frac{1}{n_-^0}\left(\delta_-^0-\delta_-^L\right)\right]\right\} \tag{27}$$

It is seen from (27) that the impedance is purely real, i.e. $\operatorname{Im}Z = 0$. This means that, as the resistance of the sample changes, the injection of minority carriers is the main one for the occurrence of current oscillations.

It can be seen from (27) that for identical injections at the contacts, i.e. $\delta_+^0 = \delta_-^0 = \delta_+^{L_x} = \delta_-^{L_x}$ and $Z = -Z_0$ the equation $R = Z_0$ determines the radiation conditions. So, the sample's size has

$$L_x = R\sigma_0 = eR\left(n_-^0\mu_- + n_+^0\mu_+\right) \tag{28}$$

It is seen from (27) that with $\frac{\delta_-^0}{n_-^0} > \frac{\delta_+^0}{n_+^0}$ and $\frac{\delta_+^L}{n_+^0} > \frac{\delta_-^L}{n_-^0}$ radiation, the energy from the sample is amplified. This reinforcement continues if inequality persists.

$$\delta_+^L\delta_-^0 > \delta_-^L\delta_+^0 \tag{29}$$

Radiation continues if

$$\delta_+^{L_x} > \delta_+^0,\ \delta_-^{L_x} < \delta_-^0 \tag{30}$$

Under the opposite inequality, i.e. $\delta_+^{L_x} < \delta_+^0$ and $\delta_-^{L_x} > \delta_-^0$ radiation will cease, if $E_1\sigma_0\delta_\pm^L \ge 1$ this also requires a very large value of injection coefficients $\delta_\pm$.
2) x>>1:

From (23) we get easily:

$$x_1 = \frac{1}{\alpha}\left(\frac{1}{\beta_-\beta_+}\right)^{\frac{1}{2}},\ x_2 = -\frac{1}{\alpha}\left(\frac{1}{\beta_-\beta_+}\right)^{\frac{1}{2}} \tag{31}$$

Substituting (31) in (19) and after integration (13) we obtain:

$$\frac{Z}{Z_0} = \left[-1+\sigma_0E_1\left(\frac{\delta_-^0}{n_-^0}+\frac{\delta_+^{L_x}}{n_+}-\frac{\delta_-^{L_x}}{n_-}-\frac{\delta_+^0}{n_+}\right)\right],\ \sigma_0 = \sigma_+\left(\frac{\nu_-}{\nu_+}\right)^2 \tag{32}$$

It can be seen from (32) that $\operatorname{Im}Z = 0$ and $\delta_-^0 = \delta_+^0 = \delta_+^{L_x} = \delta_-^{L_x}$ at radiation also occurs in a sample with a linear size (27).
It is easily seen from (32) that at $\delta_-^0 > \delta_-^{L_x}$ and $\delta_+^{L_x} > \delta_+^0$ and if $e\vartheta_\pm\delta_-^0 < 1$ the radiation continues.

Radiation is amplified if $\delta_-^{L_x} > \delta_-^0$ and $\delta_+^0 > \delta_+^{L_x}$. The radiation ceases with strong injection, i.e. $e\vartheta_\pm\delta_\pm^{L_x,0} \ge 1$.

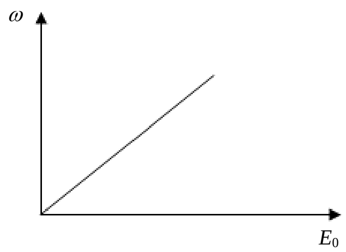

Figure 1. Frequency dependence of the electric field

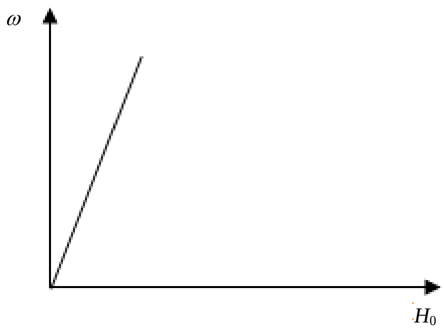

Figure 2. Frequency dependence of the magnetic field

With an increase in the external magnetic field, the frequency increases as a function of the magnetic field quadratically, and as a function of the speed of hydrodynamic movements in the environment. We considered oscillations occurring in one direction. In fact, in the presence of an external magnetic field, current oscillations occur in all three directions, and the interaction of oscillations in three directions leads to a corresponding oscillation.

To fully describe the further course of oscillations, it is necessary to construct a nonlinear theory. The approximation of small fluctuations (i.e. $n' << n_0$, $E' << E_0$, $H' << H_0$) is not enough. We can build a graph of the dependence of frequencies on the electric field and on the external constant magnetic field.

These dependences (Figures 1-2) were obtained for small fluctuations of the electric field, magnetic field, and carrier concentrations. In these vibrations, the size of the sample plays a major role. For the same values of the coefficients $\delta_\pm^{0,L}$ at the ends of the samples, the linear size of the medium has values (28).

For cases (29-30), a environment of a different size is required. Thus, these fluctuations occur in media with a certain size. We estimate the length of the sample from expression (27).

It is seen from (27) that if $\delta_-^L > \delta_-^0$ and $\delta_+^0 > \delta_+^L$ the impedance of sample is negative, then current oscillations continue. This oscillation occurs in a environment with a length determined from following equation

$$\frac{\sigma_0 T}{eL_x}\left(\frac{\delta_+^0}{n_+^0}+\frac{\delta_-^L}{n_-^0}\right)=1-\frac{R}{Z_0} \tag{33}$$

$$L_x=\frac{\sigma_0 T}{e}\left(\frac{\delta_+^0}{n_+^0}+\frac{\delta_-^L}{n_-^0}\right)\frac{1}{1-R/Z_0} \tag{34}$$

It can be seen from (34) that for $L_x > 0$, $R < Z_0$ and therefore we can write

$$L_x=\frac{\sigma_0 T}{e}\left(\frac{\delta_+^0}{n_+^0}+\frac{\delta_-^L}{n_-^0}\right) \tag{35}$$

Given that $e\mu\delta E_0 < 0$ and $\mu > \mu_+$, when $n_-^0 \sim n_+^0$ $\delta_+^0 \sim \delta_-^L$ from (35) we easily get:

$$L_x < T/eE_0,\ L_x < L_1 \tag{36}$$

At room temperature, the characteristic length $L_1 \sim 10^{-6}$ cm ($E_0 \sim 10^2$ V/cm). Then, in approximately the nano-sized semiconductors mentioned above, if the injection of minority carriers on the contacts has different values ($\delta_-^L > \delta_-^0$, $\delta_+^0 > \delta_+^L$), current oscillations with a certain frequency and with a certain value of an external electric current are excited.

4. DISCUSSION

In semiconductors with two types of charge carriers, taking into account the injection of minority charge carriers, current fluctuations occur in the external circuit when the electric field reaches a value $E_0=\frac{\Lambda\nabla T\gamma}{2\sigma_0}$. The frequency of these oscillations is determined from (26)

$$w=4\nu_+\frac{\mu_+ H_0^2}{E_0 c}\left(\frac{\vartheta_{0x}}{c}\right)^2$$

With an increase in the magnetic field, the oscillation frequency increases quadratically as a function of the external constant magnetic field. With an increase in the electric field, the oscillation frequency decreases, which means that when the electric field increases, the condition is violated, $e\vartheta_\pm\delta_\pm < 1$, i.e. this requires very strong injections at the contacts, and in this case the recombination and generation of the main charge carriers is disrupted. With strong injection, recombination of minority charge carriers begins, and this case is not taken into account in our theory. For the current to oscillate in the circuit, injection at the contacts must satisfy certain relations (29-30). The appearance of oscillations in the circuit does not cause resistance inductive and capacitive nature. Oscillations inside the sample occur if the linear size of the sample is important.

$$L_x=eR(n_-^0\mu_- + n_+^0\mu_+)$$

where, R is ohmic resistance in a chain. For some semiconductors $L_x \sim 10^{-3}$ cm.

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