IOSR Journal of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 11, Issue 1 Ser. II (Jan. – Feb. 2019), PP 08-12
www.iosrjournals.org

Internal and External Instability in Low-Dimensional Conducting Medias

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Abstract: *A theory of current oscillations in low-dimensional electronic structures has been constructed. The frequencies of increasing waves are determined. The values of electric and magnetic fields are found at which energy is emitted. It is shown that the injection significantly affects to this effect. The frequency of the current oscillation and the value of the external electric current at which these oscillations arise, significantly depend on the sample size. The increment of the excited waves is determined. At current oscillations in the circuit, an inductive resistance takes places, and the real part of the impedance oscillates with a certain period.*

Keyword: *low-dimensional electronic structures, oscillation, increment.*

Date of Submission: 25-01-2019 Date of acceptance: 07-02-2019

I. Introduction

The theory of quasi-neutral current oscillations in semiconductors with deep traps in the presence of external electric and strong magnetic fields was constructed in [1-4]. Current oscillations in semiconductors with two types of charge carriers, taking into account the relaxation of charge carriers, were considered in [5, 6]. Many works are devoted to the theory of instability in conducting media (see the review [7]). However, in most of these studies, the effect of the size sample on unstable current oscillations has not been investigated. This paper is devoted to the theory of current oscillations in low-dimensional conducting media in external electric and magnetic fields. It is shown that with a change of the size sample , the frequency of the occurring current oscillations significantly changes, and the value of the external electric field, at which current oscillations appear, depends on the size sample.

II. Internal instability in low-dimensional conducting media

The current density in conducting media with one type of charge carrier in the presence of external electric and magnetic fields equal to [5]:

$$\vec{j} = \rho\mu\vec{E} - \rho\mu_1[Eh] + \rho\mu_2\vec{E} + vD\nabla\rho - D_1[\nabla\rho h] + D_2\nabla\rho \tag{1}$$

where: $\vec{H} = \vec{h}H_0, \rho = en,$ n is the electron concentration; μ, μ_1, μ_2 are the ohmic mobilities, Hall mobilities, focusing mobility of charge carriers, D, D_1, D_2 are the corresponding diffusion coefficients. The equation (1) must be solved together with the Poisson equation:

$$divE = \frac{4\pi}{\varepsilon}\rho' \tag{2}$$

Taking into account that $j = \vec{j}_0 + \vec{j}'$; $\vec{E} = \vec{E}_0 + \vec{E}'$; $\rho = \rho_0 + \rho'$ and $\vec{E}' << \vec{E}_0$, $\rho' << \rho_0$, $\vec{j}' << \vec{j}_0$ from formula (1) and (2) we are obtained:

$$\begin{aligned}\vec{j}' = \vec{\upsilon}_0\rho' + \rho_0\mu_0\vec{E}' + \rho_0\mu_0\vec{E}_0'\beta\frac{\vec{E}_0\vec{E}'}{E_0^2} - \rho_0\mu_1[\vec{E}'\vec{h}] - \\ - \rho_0\mu_1[\vec{E}_0\vec{h}]\beta_1\frac{\vec{E}_0\vec{E}}{E_0^2} - \rho'\mu_1[\vec{E}_0\vec{h}] + \vec{\upsilon}_1\rho' + \rho_0\mu_2\vec{E}' + \\ + \rho_0\vec{E}_0\mu_2\beta_2\frac{\vec{E}_0\vec{E}'}{E_0^2} + D\nabla\rho' - D_1[\nabla\rho h] + D_2\nabla\rho\end{aligned} \tag{3}$$

$$\rho' = \frac{\varepsilon}{4\pi} divE'$$

here $\vec{\upsilon}_0 = \mu_0 \vec{E}_0$, $\vec{\upsilon}_1 = \mu_2 \vec{E}_0$, $\beta = 2\frac{\mu}{E_0^2}$, $\beta_1 = 2\frac{\mu_1}{E_0^2}$, $\beta_2 = 2\frac{\mu_2}{E_0^2}$.

Equation (3) is written by components, directing the electric field E along the x axis ($\vec{i}$ is the unit vector):

$$j'_x = [\rho_0\mu_0(1+\beta) + \rho_0\mu_1(1+\beta_1)\nu + \rho_0\mu_2(1+\beta_2)]E'_x + \frac{\varepsilon}{4\pi}(\upsilon_0+\upsilon_1)di\vartheta E' + \\ + \frac{ik\varepsilon}{4\pi}(\upsilon_0+\upsilon_2)(E'_y+E'_z) + \frac{\varepsilon}{4\pi}(\upsilon_0+\upsilon_1)\frac{\partial E'_x}{\partial x} + \frac{\varepsilon}{4\pi}D_2\frac{\partial^2 E_x}{\partial x^2} - \frac{\varepsilon D_2 k^2}{4\pi}(E'_y+E'_z) \quad (4)$$

$$j'_y = \rho_0\mu_1(1+\beta_1)E'_x + [\rho_0\mu_1(1+\beta) + \rho_0\mu_2]E'_y + \frac{\varepsilon D}{4\pi} + \frac{\varepsilon}{4\pi}(D_0+D_1)\left(\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_y}{\partial x \partial y} + \frac{\partial^2 E_z}{\partial x \partial z}\right) \quad (5)$$

Since we are investigating current oscillations along the x axis, then $j'_y = j'_z = 0$.

Representing the values of the electric field in the following form $E'_x = E_1(x)e^{i(\vec{k}\vec{r}-\omega t)}$, $E'_y = E_y(0)e^{i(\vec{k}\vec{r}-\omega t)}$, $E'_z = E_z(0)e^{i(\vec{k}\vec{r}-\omega t)}$, E'_y , E'_z and $k_y = k_z = \frac{2\pi}{L_z}$ we obtain the following equation to determine

$$\sigma_1 E'_x + \sigma_2 E'_y - \frac{\varepsilon D n_y^2}{4\pi}\left(E'_y + E'_z\right) + \frac{i\varepsilon n_y D}{4\pi}\frac{\partial E'_x}{\partial x} + \frac{\varepsilon D_2}{4\pi}\frac{\partial^2 E_x}{\partial x_2} - \frac{\varepsilon D_2}{4\pi}k_x n_y\left(E'_y + E'_z\right) = 0 \quad (6)$$

$$\sigma_2 E'_z + \frac{i n_y D_2}{4\pi}\frac{\partial E_x}{\partial x} - \frac{\varepsilon n_y^2 D_2}{4\pi}\left(E'_y + E'_z\right) = 0 \quad (7)$$

here $\sigma_1 = \rho_0\mu_1(1+\beta_1)$, $\sigma_2 = \rho_0\mu_0(1+\beta) + \rho_0\mu_2$. Solving together equations (6) and (7), one can determine E'_y and E'_z, which have form.

$$E'_y = \frac{\Omega_я}{\sigma_2^2}\cdot\frac{ik_y D_z}{4\pi}\cdot\frac{\partial E_x}{\partial x}; \quad E'_z = \frac{\Omega_y}{\sigma_2^2}\cdot\frac{ik_y D_z}{4\pi}\cdot\frac{\partial E_x}{\partial x} + \frac{\pi_0}{\sigma_2}E'_x + \frac{i\varepsilon n_y D}{4\pi\sigma_2}\cdot\frac{\partial E_x}{\partial x} + \frac{\varepsilon D_2}{\sigma_2}\cdot\frac{\partial^2 E'_x}{\partial x^2} \quad (8)$$

here $\Omega_z = \frac{\varepsilon D_z k_x n_y}{4\pi} - \frac{\varepsilon D k_y^2}{4\pi}$; $\Omega_y = \sigma_2 - \frac{\varepsilon D n_y^2}{4\pi} - \frac{\varepsilon D_z k_x k_y}{4\pi}$

To determine the x component of the electric field E'_x, it is necessary to solve the continuity equation for the current density, which has the form:

$$\frac{d\rho'}{dx} + divj'_x = 0 \quad (9)$$

together with Poisson's equation (2). From (9) and (2) we have an equation for determining E'_x

$$\sigma_1 E'_x + \frac{\varepsilon\upsilon_2}{4\pi}\frac{\partial E_x}{\partial x} + \frac{\varepsilon D_2}{\varepsilon}\frac{\partial E_x}{\partial x} + \frac{\varepsilon D_z}{\varepsilon}\frac{\partial^2 E_x}{\partial x^2} + \left(\frac{\varepsilon\upsilon_2}{2\pi}in_y - \frac{\varepsilon D_2 k_y{}^2}{4\pi} - \frac{i\omega\varepsilon}{4\pi}\right)\left(E'_y + E'_z\right) = 0 \quad (10)$$

In deriving equation (10), we defined k_y,k_x, в следующем виде:

$$k_y^2 = \frac{4\pi\sigma_2}{D_2}, \quad k_x^2 = \frac{4\pi}{\varepsilon}\frac{D\sigma_2}{D_2^2} \quad \text{i.e} \quad L_x = \left(\frac{\varepsilon\pi D_{2^2}}{D\sigma_2}\right)^{\frac{1}{2}}; \quad L_y = \left(\frac{\varepsilon\pi D_2}{\sigma_2}\right)^{\frac{1}{2}} \quad (11)$$

Substituting E'_y *and* E'_z from (8) into equation (10) we get:

$$\frac{\varepsilon D_2}{4\pi}\left[1+\frac{i\varepsilon}{2\pi\sigma_2}\left(k_y\upsilon_2-\frac{\omega}{2}\right)\right]\frac{\partial^2 E_x}{\partial x^2}+\frac{\varepsilon\upsilon_2}{4\pi}\left[1+\frac{\omega\varepsilon}{4\pi\upsilon_2 n_y}-i\left(1+\frac{D_z k_y}{2\upsilon_2}\right)\right]\frac{\partial E_x}{\partial x}+$$
$$+\left[1-\sigma_1+\frac{i\omega\varepsilon}{4\pi}\left(\frac{n_y\upsilon_2\omega}{\sigma_2}-\frac{\omega\sigma_1}{\sigma_2}\right)\right]E'_x=0 \qquad (12)$$

Solving equation (12) determines the variable part of the electric field inside the medium with dimensions (11). When the oscillations of the electric field, charge density and current density occur only inside the medium, the wave vector is a real value, and the frequency of oscillation is a complex quantity, i.e.

$$k=k_0,\ \omega=\omega_0+i\omega_1 \qquad (13)$$

From the solution of equation (12), taking into account $j'_y=j'_z=0$ and (13), we easily obtain:

$$\omega_0=\frac{1}{2}\left[\rho_0\mu_1(1+\beta)+\rho_0\mu_2(1+\beta_2)-\frac{\varepsilon D_2 k_x k_y}{4\pi}\left(1+\frac{2\pi\sigma_1}{\varepsilon D_2 k_x k_y}\right)\right] \qquad (14)$$

$$\omega_1=\frac{1}{2}\left[\rho_0\mu_0(1+\beta)+\rho_0\mu_2(1+\beta_2)-\sigma_2\left(\frac{c}{\mu_0 H}\right)^2-\frac{\sigma_2 k_x}{n_y}+\frac{1}{2}\sigma_1\right] \qquad (15)$$

When formulas (14) and (15) are obtained, the electric field is given by expression:

$$E_0=\frac{2\pi}{\varepsilon}\frac{\sigma_2}{k_y\mu_2} \qquad (16)$$

From (15) it can be seen that for β,β_1 *and* β_2 equal to $\pm\frac{1}{2}$ when the electric field is determined by formula (16) the excited wave inside the medium with frequency ω_0 (14) , is growed. For the meanings β,β_1 *and* β_2 equal to $\pm\frac{3}{2}$ the wave with frequency ω_0 (14) is damped. It should be noted that if the values of the β,β_1, β_2 coefficients are determined by first value this is corresponded of the charge carriers scattering by acoustic phonons. If the $\beta,\beta_1 and \beta_2$ are determined by second values takes place the scattering by the optical phonons and on lattice defects. If the Einstein relation holds, then from (16) we obtain for the value of the magnetic field the formulas

$$H=\frac{c}{S'}\left(\frac{\pi nT}{3\varepsilon}\right)^{1/2} \qquad (17)$$

here n is the charge carriers concentration, S' is the sound velocity.
It is easy to verify that $\mu_0 H >> c$.

III. External instability in low-dimensional conducting medias

For external instability the following relation takes place

$$\omega=\omega_0,\ k_x=k_0+ik'_x \qquad (18)$$

The solution of equation (14) determines E'_x and therefore the sample impedance

$$Z=\frac{1}{I'_x}\int_0^{L_x}E'_x(x)dx \qquad (19)$$

To determine E'_x, we must take into account the injection of charge carriers at the sample contacts. The concentration of charge carriers varies in the sample due to the input and output of charge carriers at the contacts. Thus, the oscillatory part of the current changes due to the injection, i.e.

$$n'=\delta I' \qquad (20)$$

where δ is the injection coefficient, n' - is the variable part of charge carrier consentration, J' -is the variable current in the circuit.
The solution of the equation (14) in the following form shall be found

$$E'_x = C_1 e^{ik_1 x} + C_2 e^{ik_2 x} \tag{21}$$

The wave vectors k_1 and k_2 are determined from differential equation (14).
The constants C_1 and C_2 are need to be determined from the boundary conditions for an electric field. Representing the electric field in form $E'_x \sim e^{ik_x x}$ we define from (14) k_1 and k_2. After some algebraic calculations we get:

$$k_1 = \frac{\varepsilon k_0}{2\pi}\left(-1+ix\right) = -k_2;\; x = \frac{1}{2}\left[\sqrt{\upsilon^2+\upsilon'_1}+\upsilon\right]^{1/2}$$

$$k_0 = \frac{\pi\sigma_2}{\varepsilon\upsilon_2 k_y};\; \upsilon = \frac{\varepsilon\sigma_2}{4\pi\upsilon_2};\; \upsilon_1 = \frac{\sigma_2 U}{\upsilon_2 k_y \upsilon_2} \quad U = \frac{\beta_1 + \frac{\mu H}{c}\left(1+\beta_2\right)}{2+\beta} \tag{22}$$

At obtaining formula (22), we used the inequality

$$k_y \upsilon_2 > \sigma_2 \tag{23}$$

From the Poisson equation we get

$$di\vec{v}E' = \frac{4\pi e}{\varepsilon}n' = \frac{4\pi e}{\varepsilon}\delta I' \quad \frac{\partial E'}{\partial x} = \frac{4\pi e}{\varepsilon}\delta I' \tag{24}$$

The boundary conditions for the second equation in (24) have the form:

$$\begin{cases} \left.\dfrac{dE'}{dx}\right|_{x=0} = \dfrac{4\pi e\delta_0 I'}{\varepsilon} \\ \left.\dfrac{dE'}{dx}\right|_{x=L_ч} = \dfrac{\nu\pi e\delta_{L_ч} I'}{\varepsilon} \end{cases} \tag{25}$$

Using the expression for the electric field (21) in formulas (24) for constant $C_1 and C_2$ we obtain:

$$C_1 = \frac{4\pi e I'}{ik\varepsilon}\cdot\frac{\delta_0 e^{-ikL_x} - \delta L_x}{e^{-ikL_x} - e^{ikL_x}} \tag{26}$$

$$C_2 = \frac{4\pi e I'}{ik\varepsilon}\cdot\frac{\delta_0 e^{-ikL_x} - \delta L_x}{e^{-ikL_x} - e^{ikL_x}}$$

Substituting (26) into (21) and used obtained expressions in the formula (19) after integration we get:

$$\operatorname{Re} Z = f\,\frac{2\sin 2\alpha}{e^{2\alpha} - 2\cos^2\alpha};\quad I_m Z = f\,\frac{e^{2\alpha}}{e^{2\alpha} - 2\cos^{2\alpha}} \tag{27}$$

$$f = \frac{2\pi}{\varepsilon}\frac{e(\delta_{Lx} + \delta_0)}{k_0^2};\quad \alpha = k_0 L_x \tag{28}$$

From the expression (27) it is seen that when $k_0 L_x \geq 1$ the formula (27) have the following form:

$$\operatorname{Re} Z = 2fe^{-2\alpha}\sin 2\alpha;\;\; \operatorname{Im} Z = f > 0 \tag{29}$$

Then $f + R_1 = 0$ and $2fe^{-2\alpha}\sin 2\alpha + R = 0 \quad R_1 < 0,\, R > 0$. From equations (28) we get:

$$\sin 2\alpha = -\frac{R}{2|R_1|}e^{2\alpha} \tag{30}$$

At all negative values of $\sin 2\alpha$, the relation (30) is satisfied. From (27) it can be seen that $\operatorname{Re} Z$ oscillates with argument 2α, and $\operatorname{Im} Z$ is received the positive value therefore a capacitance resistance must be added to the circuit.
At receive the formula (27), we determined the frequencies the current oscillations which have the following form

$$\omega = k_y \upsilon_2 \qquad E_0 = \frac{2\pi}{\varepsilon} \frac{en}{k_y} \tag{31}$$

IV. Conclusion

In this paper are shown that in low-dimensional conducting media in external electric and perpendicular to it magnetic fields the high-frequency rising wave is excited. The transverse and longitudinal dimensions at which energy is emitted of are determined. The values of the electric and strong magnetic fields are found at which the radiation of energy takes place. The frequencies of the excited wave are calculated. When a current begins to oscillate in a circuit, inductive resistance arises, and the real part of the impedance oscillates with a certain period. The injection at the contacts of the medium enhances the rising of the wave. A conductive medium with the specified dimensions can be a source of radiation energy.

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