CURRENT OSCILLATIONS IN SEMICONDUCTORS WITH DEEP TRAPS IN STRONG ELECTRIC AND MAGNETIC FIELDS

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The external instability theory in definite impurity semiconductors at $E_0 \sim \mathrm{H}^4$ is constructed. It is shown that longitudinal current oscillations at $E_0 \sim \mathrm{H}_0$ take place in two extreme cases 1) current oscillation frequency is bigger than all character frequencies; 2) current frequency oscillations is less than all character frequencies.

The values of electric fields and current oscillation frequency are found in both cases. In all calculations is accepted that R active resistance and positive reactive resistance have the values $R = R_1 = Z_0$. The dependences $E_0(H), \omega(H)$ in all limited cases are constructed.

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The many works [1-5] are dedicated to experimental and theoretical investigations of current instability in semiconductors and appearing oscillating phenomena in them. The appearance of such quantity of works is connected with possibility of practical use of current instability phenomena in semiconductors for formation of high-frequency generators, amplifiers and also the tendency to develop the theory models for explanation of various reasons of instability appearance in semiconductors. The negative differential conductivity appears in strong electric field in the result of the dependence of current carrier trapping in semiconductor. The presence of negative conduction leads to appearance of current oscillations. The capture rate of charge carriers by impurity center in semiconductor strongly depends on charge carrier energy. The electric field presence increases the charge carrier energy; moreover, charge carrier capture rate depends on electric field. Consequently, the steady-state concentration of charge carriers in conduction band changes. At constant value of lattice temperature the recombination rate and generation rate changes only by electric field. The electron capture (recombination) increases when the negative impurity center is in semiconductor with increase of electron velocity at electric field. The current instability appears, i.e. current oscillations in chain takes place in processes of recombination and generation of charge carriers. The ohmic resistance introduced by semiconductor in chain, is negative one in frequency some region. The oscillations of charge carrier and electric field in wave form appear when the processes of recombination and charge carrier generation in semiconductor begin. These waves are absent if they propagate only inside the current oscillation in chain. Such oscillations lead to instable state inside semiconductor and they are called external instability. At definite values of electric field the inner space waves amplify and current oscillations in external chain take place, i.e. (external instability).

The inner and external instabilities in different semiconductors with different impurity centers take place at different values of electric field. Some impurities in semiconductors form the centers which are able to be in several charged states (one-, double- and etc. positive or negative charged ones). Thus, for example, Au atoms in germanium can be one-, double- and triply-charged centers besides neutral one and Cu atoms can be one-, double- and triply-charged centers besides neutral one and etc.

The several energy levels in forbidden band correspond to such impurity centers. These energy levels are situated in different distances from conduction band in forbidden semiconductor region. These deep levels (traps) are able to capture the charge carriers in the dependence on their charge states. The electrical conduction changes in the result of these captures.

In this theoretical work we will investigate the influence of external constant magnetic field on appearance conditions of external instability in definite impurity semiconductors. Let's confirm the values of external electric field and current oscillation frequency at which the external instability appears.

SEMICONDUCTOR MODEL AND MAIN EQUATIONS

We will consider the semiconductor with charge carriers of both signs, i.e. electrons and holes with n_- and n_+ concentrations correspondingly. The negatively charged traps with concentration N_0 are in semiconductor. From them N is concentration of one negatively-charged traps, N_- is concentration of double negatively charged traps [2]

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i.e. $$N_0 = N + N_- \qquad (1)$$

We will consider the current oscillation theory at presence of strong external magnetic field

$$H >> H_\pm = \frac{c}{\mu_\pm} \qquad (2)$$

The concentration of one- and double-charged traps N, N_- и $n_\pm$ satisfy to conduction

$$N_- << N\,,\; n_\pm << N, N_- \qquad (3)$$

The one charged centers capture electrons through Coulomb barrier and emit them through hole barrier, double-charged centers can emit the electrons and capture the holes at thermal excitations.

The concentrations $n_\pm$, N_- and current flow density satisfy to equations (1-3) at presence of electric and magnetic fields [2,3,4]:

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

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

$$\frac{\partial N_-}{\partial t} = \left(\frac{\partial n_+}{\partial t}\right)_{rek} - \left(\frac{\partial n_-}{\partial t}\right)_{rek} \quad ;\; divJ = ediv\left(\vec{j}_+ - \vec{j}_-\right) = 0$$

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

$$\vec{j}_- = -n_-\mu_-(E,H)\vec{E} + n_-\mu_{1-}(E,H)\left[\vec{E}\vec{h}\right] - n_-\mu_{2-}(E,H)\vec{h}(E,H) - D_-\nabla n_- + D_{1-}\left[\vec{\nabla}n_-\vec{h}\right] - D_{2-}\vec{h}\left(\vec{\nabla}n_-\vec{h}\right) \qquad (4)$$

Here $\vec{h}$ is unit vector in $\vec{H} = H\vec{h}$ magnetic field, $\mu_\pm(E,H)$ is ohmic mobility, $\mu_{1\pm}(E,H)$ is $\mu_{2\pm}(E,H)$ Hall mobility, $\mu_{2\pm}(E,H)$ is focusing mobility of holes and electrons, $D_\pm, D_{1\pm}, D_{2\pm}$ is corresponding ohmic, Hall and focused diffusion coefficients of charge carriers. We consider the case when carriers have the effective temperature for illumination of lengthy algebraic calculations. Then diffusion coefficients are:

$$D_\pm = \frac{T_{ÝÔÔ}}{e}\mu_\pm\,, \qquad T_{ÝÔÔ} = \frac{T}{3}\left(\frac{cE_0}{v_3 H}\right)^2 \qquad (5)$$

where v_3 is speed of sound, T is lattice temperature in erg.

Besides, we will consider the crystal the sizes of which satisfy to ratio:

$$L_y << L_x\,,\quad L_z << L_x \qquad (6)$$

$$n_{1-} = \frac{n_-^0 N_0}{N_-^0}\,; \qquad n_{1+} = \frac{n_+^0 N_-^0}{N_0}$$

The external electric field is directed along x axis and magnetic field is directed along z axis.

Let's suppose that $n_\pm(\vec{r},t) = n_\pm^0 + \Delta n_\pm(r,t)$,

$$N_- = N_-^0 + \Delta N_-(r,t)$$

$$\vec{E}(r,t) = \vec{E}_0 + \vec{\Delta}E(r,t) \qquad (7)$$

The inclination of magnetic field from equilibrium value is equal to zero as we consider the longitudinal current oscillations. The sign (0) means the equilibrium value of corresponding values, further it will be omitted.

Let's introduce the following frequencies of capture and emission by equilibrium centers:

$$\nu_- = \gamma_-(E_0)N_0\,, \qquad \nu_+ = \gamma_+(0)N_-^0\,,$$

$$\nu_+^E = \gamma_+(E_0)N_0$$

And also the combined frequencies:

$$\nu'_- = \gamma\,(E_0)n_-^0 + \gamma_-(0)n_{1-}\,,$$

$$\nu'_+ = \gamma_+(0)n_+^0 + \gamma_+(E_0)n_{1+} \qquad (8)$$

Let's designate the numerical factors:

$$\beta_\pm^\gamma = 2\frac{d\ln\gamma_\pm(E_0)}{d\ln\left(E_0^2\right)}\,; \qquad \beta_\pm^\mu = 1 + \frac{d\ln\mu_\pm(E_0)}{d\ln\left(E_0^2\right)}$$

$$\nu_- >> \nu'_-, \quad \nu_+ >> \nu'_+$$

Linearizing (4) and taking into consideration (5-7,8) we obtain the vector equation for $\vec{\Delta}E$,

$$\vec{\Delta}E = A\Delta\vec{J} + \vec{B}_1\Delta n_- + \vec{B}_2\Delta n_+ \qquad (9)$$

$\vec{B}_1$ and $\vec{B}_2$ are constants of current, character frequencies (8) from equilibrium values $n_\pm, E, H$ from numerical values $\beta_\pm^\gamma, \beta_\pm^\mu$. We won't write $A, \vec{B}_1, \vec{B}_2$ coefficients because they are so cumbersome ones. Let's divide the fluctuations $\Delta n_\pm(r,t), \Delta N_-(r,t), \Delta E(r,t)$ in parts which are proportional ones to oscillating current $\Delta J(t)$ in external chain.

$$\Delta n_\pm(r,t) = \Delta n'_\pm e^{i\left(\vec{k}\vec{r}-\omega t\right)} + \Delta n''_\pm e^{-i\omega t}$$

$$\Delta N_-(r,t) = \Delta N'_- e^{i\left(\vec{k}\vec{r}-\omega t\right)} + \Delta N''_- e^{-i\omega t} \qquad (10)$$

$$\Delta E(r,t) = \Delta E' e^{i\left(\vec{k}\vec{r}-\omega t\right)} + \Delta E'' e^{-i\omega t}$$

Let's obtain system of heterogeneous equations:

$$\begin{cases} c''_-\Delta n''_- + c''_+\Delta n''_+ = c\Delta J \\ D''_-\Delta n''_- + D''_+\Delta n''_+ = D\Delta J \end{cases} \qquad (11)$$

and the system of linear homogeneous equations for $\Delta n'_\pm$:

$$\begin{cases} c'_-\Delta n'_- + c'_+\Delta n'_+ = 0 \\ D'_-\Delta n'_- + D'_+\Delta n'_+ = 0 \end{cases} \qquad (12)$$

It is necessary to take into consideration the charge carrier injections on contacts by following way:

$$\Delta n_\pm(0) = \delta_\pm^0 \Delta J,$$

$$\Delta n_\pm(L) = \delta_\pm^L \Delta J \qquad (13)$$

where $\delta_\pm^{0,L}$ are injection coefficients of holes and electrons

Substituting (14) into (12) we will definite $\Delta n'_\pm$. After it one can calculate the alternating potential difference on crystal ends and impedance:

$$Z = \frac{\Delta v}{\Delta J}\ ; \quad Z = \frac{1}{\Delta JS'} \int_0^L \Delta E(x,t)dx \qquad (14)$$

S is crystal cross-section.

$$Z = \mathrm{Re}\, z + iJmz$$

After cumbersome algebraic calculations from (14) we obtain:

$$\frac{\mathrm{Re}\, z}{Z_0} = \frac{y_2}{\alpha_+}\left\{1 - \frac{2n_-\nu_-\beta_-^\gamma\omega^3}{n_0\omega_1^4 y\theta}\left[\left(\alpha_- + \frac{\nu_+^2}{\omega^2}\right)(\cos\varphi - 1) + \frac{\nu_-}{\omega\alpha_+\beta_+^\mu}\sin\varphi\right] + \right.$$
$$\left. + \frac{2n_+\nu_+^E\omega^3\beta_+^\gamma\alpha_+}{n_0\omega_1^4\theta}\left[\frac{\mu_+}{\mu_-}\frac{\left(\nu_+\omega^2 + \nu_-^2\nu_+^2\right)\cos\varphi}{\nu_+^E\omega^2\alpha_-\phi_+^\beta} - \left(\alpha_- + \frac{\nu_-^2}{\omega^2}\right)\frac{\mu_+}{\mu_-}\left(\frac{1}{\beta_+^\mu} + \frac{\nu_+}{\omega\beta_+\mu}\sin\varphi\right) - \frac{evx\delta}{\theta\alpha_+}\frac{\mu_+}{\mu_-}\sin\varphi\right]\right.$$

$$\frac{Jmz}{z_0} = \frac{x}{\theta}\left\{\frac{3\omega^3\mu_+}{n_0\,\omega_1^4\alpha_+\beta_+^\mu\mu_-}\frac{E_0}{E(L_y)}\left(\frac{\mu_-\nu_3 H}{\mu_+ cE_0}\right)^2 * \right.$$
$$* \left[n_+\nu_+^E\beta_+^\gamma\left(\alpha_+ + \frac{\nu_-^2}{\omega^2}\right) - n_-\nu_-\mu_-\beta_-^\gamma\left(\alpha_- + \frac{\nu_+^2}{\omega^2}\right)\right] + \frac{ev\delta y}{2\alpha_+}\left(\frac{\mu_+}{\mu_-}\right)^2\cos\varphi \qquad (15)$$

Here $\quad n_0 = n_+ + n_-\ , \quad v = (\mu_- + \mu_+)E_0\,, \ E(L_y) = \dfrac{Tk_y}{e}; \quad z_0 = \dfrac{L_x}{\sigma_0 s}$

$$\omega_1^4 = \omega^4 + \nu_-^2\nu_+^2 + \omega^2\left(\nu_-^2 + \nu_+^2\right); \ \varphi = \frac{\mu_- H}{c\theta}\ ; \ \sigma_0 = e(n_+\mu_+ + n_-\mu_-)$$

$$\theta = \frac{L_y L_x \nu_- \left(n_+ \nu_+^E \beta_+^\gamma \beta_-^\mu + n_- \nu_- \beta_-^\gamma \beta_+^\mu \dfrac{\mu_+}{\mu_-} \right)}{2\pi n_0 \nu_-^2 \left(\beta_-^\mu + \beta_+^\mu \right)} = \left(\frac{E_1}{E_0} \right)^2 ;$$

$$\delta = \delta_+^0 + \delta_-^0 + \delta_+^L + \delta_-^L , \qquad x = \frac{\mu_+ H}{c} ; y = \frac{\mu_- H}{c}$$

From (15) it is seen that the definition of E_0 electric field and ω current oscillation frequency is too complex and that's why we will definite E_0 and ω in two limit cases.

HIGH-FREQUENCY CURRENT OSCILLATIONS

i.e. $\omega >> \nu_+^E , \nu_- , \nu_+$ (16)

The oscillations in external chain appear at $\operatorname{Re} z < 0$ condition.
Substituting the positive resistance in (14) one can define the current oscillation frequencies in chain. The equation

$$\frac{\operatorname{Re} z}{z_0} + \frac{R}{z_0} = 0 \qquad (17)$$

defines the current oscillation frequencies.

At negative value $\operatorname{Re} z < 0$ JmZ can have the positive or negative sign, i.e. the reactance of capacitive or inductive character. Then the equation

$$\frac{Jmz}{z_0} + \frac{R_1}{z_0} = 0 \qquad (18)$$

will define the electric field value at which the current oscillations in chain.

From (18) we easy obtain the following taking into consideration (15):

$$\frac{\omega}{\nu_-} \left(\frac{E_0^3}{E_3 E_1^2} \cos\varphi - \frac{R_1}{y z_0} \right) = \frac{a E_0}{E(L_y)} (\varphi_+ - \varphi_-) \qquad (19)$$

$$a = \left(\frac{Y \mu_- \nu_3}{\mu_+} \right)^2 \frac{3}{E_1^2} ; \ \varphi_+ = \frac{\nu_+^E n_+}{\nu_- n_0} \alpha + \frac{\mu_+}{\mu_-} \beta_+^\gamma ;$$

$$\varphi_- = \frac{n_- \beta_-^\gamma \alpha_-}{n_0 \alpha_+}$$

From equation (17) we easily obtain:

$$E_0^2 = E_1^2 \frac{1 + \dfrac{R\alpha_+}{z_0 y^2}}{\dfrac{2 n_+ \nu_+^E \beta_+^\gamma \alpha_+ \alpha_- \mu_+}{n_0 \omega \ y \mu_- \beta_+ \mu} - \dfrac{2 n_- \nu_- \beta_-^\gamma \alpha_- \alpha_+^2}{\omega y n_0 \beta_+ \mu}} \qquad (20)$$

$$\cos\varphi = \frac{\nu_+^E n_+ \beta_+^\gamma \mu_+}{\nu_- n_- \mu_-} \frac{\alpha_+^2}{\alpha_-} \frac{1}{y} \frac{E_3 E_1^2}{E_0^3} , E_3 = \frac{1}{e\delta\mu_-} \qquad (21)$$

For E_0 positiveness

$$\frac{\nu_+ n_+ \beta_+^\gamma \mu_+}{\mu_-} > \nu_- n_- \beta_-^\gamma \alpha_- \alpha_+ \qquad (22)$$

is required .
Taking into (20-22) from (17) we obtain:

$$\cos\varphi = \frac{1}{\left[1 + \left(\dfrac{\nu_+^E}{\omega} \right)^2 U^2 (1 - r)^2 \right]^{1/2}} \qquad (23)$$

$$U = \frac{E_\delta E_1^2}{E_0^3 Y^2} \frac{2 n_+ \beta_+^\gamma \alpha_+}{n_0} \left(\frac{\mu_+}{\mu_-} \right)^2 ; r = \frac{\nu_- n_- \beta_-^\gamma \alpha_- \alpha_+ \mu}{\nu_+^E n_0 \beta_+^\gamma \mu_+} << 1$$

Finding $\cos\varphi$ from (19) and equate it with (23) we obtain:

$$\omega = \nu_+^E \frac{n_0}{(n_+ n_-)^{1/2}} \left(\frac{\mu_- \nu_+^E}{\mu_+ \nu_- \beta_+^\gamma \alpha_-} \right)^{1/2} \cdot \frac{1}{y^{1/2}} \sim y^{-1/2} \qquad (24)$$

$$E_0 = E_1 \left(\frac{n_+ \beta_+^\gamma}{n_-} \frac{\nu_+^E}{\nu_-} \frac{\mu_+}{\mu_-} \right)^{1/3} \cdot \frac{1}{y^{1/3}} \sim y^{-1/3} \qquad (25)$$

From (24-25) it is seen, that the electric field and current oscillation frequency decrease with increase of external constant magnetic field (at which the external instability appears). However, $\omega >> \nu_+^E$ equality should be satisfied at increase of magnetic field. In all conclusions we accept that $R = Z_0 = \dfrac{L_x}{\sigma_0 S}$ and we use equality $\mu_- >> \mu_+$.

LOW-FREQUENCY CURRENT

$$\omega << \nu_+^E, \nu_-, \nu_+ \tag{26}$$

Taking into consideration (26) we obtain

$$E_0 = \frac{E_\delta}{E_1 E(L_y)} \left(\frac{\nu_3 \mu_-}{\mu_+^2}\right)^2 \left(\frac{\nu_-}{\nu_+}\right)^3 \frac{3n_0}{n_- \beta_-^\gamma} y^4 \sim y^4 \tag{27}$$

$$\omega = \frac{\nu_+^2}{\nu_-} \left[\frac{E(L_y)}{2E_\delta} \frac{n_- \nu_+ \beta_-^\gamma \mu_-}{6n_+ \nu_+^E \beta_+^\gamma \mu_+}\right]^{2/3} \left(\frac{E_1 \mu_+^2}{\nu_3 \mu_-}\right)^{4/3} y^{-2/3} \sim \mathrm{y}^{-2/3} \tag{28}$$

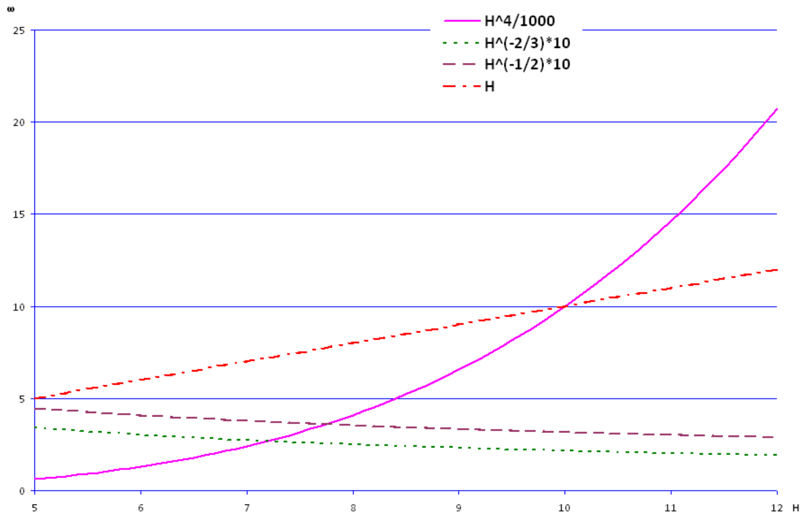
in low-frequency case at $R_1 > 0$ and $R_1 = Z_0$ from (14,15).

From (27-28) it is seen, that electric field increases as $E_0 \sim \mathrm{H}^4$ function and frequency decreases as function $\omega \sim \mathrm{H}^{-2/3}$ with increase of constant magnetic field.

CONCLUSION

The oscillations with definite frequencies take place in semiconductors with above mentioned impurity centers with two types (electrons and holes) of charge carriers at presence of electric and magnetic fields $E_0 \perp H_0$. At $\omega >> \nu_+^E, \nu_-, \nu_+$ the electric field $E_0 \sim \frac{1}{\sqrt{\mathrm{H}}}$ and frequency $\omega \sim \frac{1}{\sqrt[3]{H}}$ depend on magnetic field correspondingly. At $\omega << \nu_+^E, \nu_-, \nu_+$ electric field is as function $E_0 \sim \mathrm{H}^4$ and frequency is as $\omega \sim \mathrm{H}^{-2/3}$.

Thus, the current oscillation takes place.



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