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Current oscillations in semiconductors with deep traps in strong electric and magnetic fields

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Abstract: *In semiconductors to happen to particular deep traps and both signs of charge carriers energy radiations. Perhaps at different values of frequency of radiation of energy. In each case defined values of an electric field at a magnetic field $\mu_{\pm}H \gg C$. The sign a constant of scattering of charge carriers is defined. For parameters of a recombination and generation of charge carriers $\beta_{\pm}^{\gamma}$analytical expressions are found. The theory of fluctuation of current is constructed in the linear approximation. Frequency estimates $(\omega_1, \omega_2, \omega_3)$ and an electric field (E_1, E_2, E_2) will quite be coordinated with the existing experimental datas. From above the specified semiconductors it is possible to use at preparation of superhigh-frequency generators and amplifiers.*
Keywords: *semiconductor, impedance, ohmic resistance, frequencie, Coulomb barrier.*

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I. Introduction

In [1–5], a theory of current oscillations in semiconductors with deep traps, and with two types of charge carriers, was constructed.
In these works constants $\beta_{\pm}^{\gamma} = 2\frac{d\ln\gamma_{\pm}}{d\ln(E_0^2)}, \beta_{\pm}^{\mu} = 2\frac{d\ln\mu_{\pm}}{d\ln(E_0^2)}$ were taken as positive constants.
However, we will show below that $\beta_{\pm}^{\mu}$ depending on the nature of scattering charge carriers can be negative value and $\beta_{\pm}^{\gamma}$remain positive. In this theoretical work, we construct a theory of current oscillations in semiconductors with specific deep traps and with two types of charge carriers in strong electric $v_d > S$ and magnetic $\mu_{\pm}H_0 \gg C$ fields at $\beta_{\pm}^{\mu} < 0$.

$$v_d = \mu_{\pm}E_0,$$

v_d is the drift velocity of charge carriers, $\mu_{\pm}$ are the mobilities of holes and electrons, E_0 is the intensity of a constant external electric field, H_0- is the intensity of an external magnetic field, and S is sound velocity in the crystal.
For $\beta_{\pm}^{\gamma}$ we have obtained analytical expansions as a function of the electric field, magnetic field, the current frequency oscillations.

II. Semiconductor model and basic equations of the problem.

At availability of an electric field electronic (and also holes) receive from electric field energy of the order eE_0l. (an e - positive elementary charge, l -length of free run of electron). Therefore at availability of an electric field electrons can overcome Coulomb barrier of unitary infected center and to be grasped (i.e. to recombine with this center). In addition, due to thermal junction, electrons can be generated from impurity centers (from deep traps) in the conduction band. The capture process decreases, and the transfer process increases the number of electrons in the conduction band. As for the holes, their number increases due to the capture of electrons by deep traps from the valence band and decreases due to the capture of electrons from deep traps by holes. Above the probability of generation and recombination lead to a change in carrier concentrations in the crystal. We will further mean a semiconductor with carriers of both signs, i.e. electrons and holes with concentrations n_- and n_+ respectively. In addition, in the semiconductor there are negatively charged deep traps with a concentration of N_0.
Of these, part N is the concentration of once negatively charged traps, and N _-- the concentration of double negatively charged traps,

$$N_0 = N_+N_- \quad (1)$$

The continuity equation for electrons in a semiconductor with higher trap types will be:

$$\frac{\partial n_-}{\partial t} + divj_- = \gamma_-(0)n_{1\_}N_- - \gamma_-(E)n_-N = \left(\frac{\partial n_-}{\partial t}\right)_{rek} \qquad (2)$$

Herein and further, $j_\pm$ is flux densities of electrons and holes, $j_{-(0)}$ is electron emission coefficient of doubly charged traps in the absence of an electric field. It can be called the thermal generation coefficient. $\gamma_-(E)$ electron capture coefficient of negatively charged traps once for the presence of an electric field. At E=0, $\gamma_-(E) = \gamma_-(0)$. In (2) the unknown constant $n_{1\_}$ having the dimensionality of concentration is defined as follows. In the absence of an electric field and stationary and equilibrium conditions. i.e. at $(\frac{\partial n_-}{\partial t})_{rek} = 0$ и $\gamma_-(E) = \gamma_-(0)$ from (2) we will get:

$$n_{1\_} = \frac{n_-^0 N_0}{N_-^0}$$

The electron flux density in the presence of electric and magnetic fields is determined by the expression

$$\overrightarrow{j_-} = -n\mu(E,H)\vec{E} + n\mu_{1\_}(E,H)\left[\vec{E}\vec{h}\right] - n\mu_2(E,H)\vec{h}(\overrightarrow{\vec{E}\vec{h}}) - D_-\vec{\nabla}n + D_{1\_}\left[\vec{\nabla}n\vec{h}\right] - D_2\vec{h}(\overrightarrow{\nabla n\_h}) \qquad (3)$$

Here $\vec{h}$ is a unitary vector by the magnetic field, μ (E, H) is the ohmic, $\mu_{1\_}(E,H)$ is Hall's, $\mu_2(E,H)$ is the focusing mobility of electrons, $D_-, D_{1\_}, D_{2\_}$ ohmic, Hall, focusing diffusion coefficients of electrons, respectively. To simplify cumbersome calculations, we consider the case where the carriers have an effective temperature. Then the diffusion coefficient

$$D_\pm = \frac{T_{eff}}{e}\mu_\pm, \quad T_{eff} = \frac{T}{3}\left(\frac{CE_0}{SH_0}\right)^2 \quad [6]$$

C - is light speed in a crystal; T - is the temperature in Erg. In addition, we will consider crystals, which dimensions satisfy the ratios.

$$L_y \ll L_x, \qquad L_z \ll L_x$$

The continuity equation for holes will be

$$\frac{\partial n_+}{\partial t} + divj_+ = \gamma_+(E)n_{1_+}N_+ - \gamma_+(0)n_+N_- = \left(\frac{\partial n_-}{\partial t}\right)_{rek} \qquad (4)$$

$$\overrightarrow{j_+} = n_+\mu_+(E,H)\overrightarrow{E+}n_+\mu_{1_+}(E,H)\left[\vec{E}\vec{h}\right] - n_+\mu_2(E,H)\vec{h}(\overrightarrow{\vec{E}\vec{h}}) - D_+\vec{\nabla}n_+ + D_{1_+}\left[\vec{\nabla}n\vec{h}\right] - D_{2_+}\vec{h}(\overrightarrow{\nabla n\_h}),$$

at $E = 0,\ \gamma_+ = \gamma_+(0),\ n_{1_+}\frac{n_+^0}{N_0}$

Owing to a recombination and oscillation in non-stationary conditions the number twice and single-passly negatively charged traps changes (of course, at the same time there is invariable the general concentration of traps). Change of twice negatively charged traps defines over time change of single-passly negatively charged traps. The equation defining of change of traps has an appearance over time:

$$\frac{\partial N_-}{\partial t} = \left(\frac{\partial n_+}{\partial t}\right)_{rek} - \left(\frac{\partial n_-}{\partial t}\right)_{rek} \qquad (5)$$

The external electric field is directed on an axis x, and a magnetic field on axis Z.

Put

$$n_\pm(\overrightarrow{r_1}\,t) = n_\pm^0 + \Delta n_\pm(\overrightarrow{r_1}\,t),\ N_-(\overrightarrow{r_1}\,t) = N_+^0 + \Delta N_-(\vec{r}\,t),\ \vec{E}(\vec{r},t) = \overrightarrow{E_0} + \Delta\vec{E}(\vec{r},t) \quad (6)$$

The deviation of a magnetic field from an equilibrium value is equal to zero as we considers longitudinal vibrations. We will ignore the badge (0) meaning an equilibrium value of the corresponding values further. We linearize the equations (2,4) taking into account (6) and we enter the following characteristic frequencies

$$v_- = \gamma_-(E_0)N_0,\ \ v_+ = \gamma_+(0)N_-^0,\ \ v_+^E = \gamma_+(E_0)N_0,\ \ \acute{v}_- = \gamma_-(E_0)n + \gamma_-(v)n_{1\_}$$

$\acute{v}_+ = \gamma_+(0)n_+ + \gamma_+(E_0)n_{1_+}$, we will designate numerical constants defined by dependences on an electric field

$$\beta_{\pm}^{\gamma} = 2\frac{dln\,\gamma_{\pm}(E_0)}{dln\,(E_0^2)};\quad \beta_{\pm}^{\mu} = 2\frac{dln\,\mu_{\pm}(E_0)}{dln\,(E_0^2)} \quad (7)$$

$\beta_{\pm}^{\gamma}$ is dimensionless parameter, depending on scattering of charge carriers $\beta_{\pm}^{\gamma}$ can have the negative sign, i.e. $\beta_{\pm}^{\gamma} < 0$. In work [7] it is shown that when scattering on optical and acoustic (the mixed scattering) photons $\beta_{\pm}^{\gamma} = -0{,}8$. In further we will consider $\beta_{\pm}^{\gamma} < 0$ in theoretical calculations.

In the absence of a recombination and oscillation of carriers, the condition of quasi neutrality means that the number of changes of electrons is equal number of changes of holes i.e. $\Delta n = \Delta n_{+}$. In the presence of a recombination and oscillation of charge carriers the condition of quasi-neutrality means that the total current doesn't depend on coordinates, but depends on time.

$$div \underset{I}{\rightarrow} = ediv\left(\underset{j}{\rightarrow} \mp \underset{j}{\rightarrow}_{-}\right) = 0 \quad (8)$$

After a mineralization of the equations (2,4,8) we will receive the equation for an electric field of the following look:

$$\overrightarrow{\Delta E} = a_1\overrightarrow{\Delta J} + \overrightarrow{a_2}\Delta n_{-} + \overrightarrow{a_3}\Delta n_{+} \quad (9)$$

Where, a_1, a_2, a_3 are the stationary values depending on an oscillation frequency, the characteristic frequencies from equilibrium values of concentration of charge carriers, electric and magnetic fields, numerical multipliers $\beta_{\pm}^{\gamma}$, $\beta_{\pm}^{\mu}$. Owing to bulkiness of coefficients a_1, a_2, a_3 we will be limited to the indication of the scheme of the decision

Divide functional $\Delta n_{\pm}(\vec{r}, t), \Delta N_{-}(\vec{r}, t), \Delta E(\vec{r}, t)$ on the parts proportional to oscillatory current ΔJ in an external circuit.

$$\Delta n_{\pm}(\vec{r}, t) = \Delta n_{\pm}^{'} e^{i(\vec{k}\vec{r} - \omega t)} + \Delta n_{+}^{''} e^{-i\omega t} \quad (10)$$

We will do similar divisions for $\Delta N_{-}, \Delta E$. After simple algebraic calculations from (2, 4, 7, 8) and taking (9) we will receive two sets of equations

$$\begin{cases} d_{-}^{''}\Delta n_{-}^{''} + d_{+}^{''}\Delta n_{+}^{''} = d\Delta J \\ b_{-}^{''}\Delta n^{''} + b_{+}^{''}\Delta n_{+}^{''} = b\Delta J \end{cases} \quad (11) \qquad \begin{cases} d_{-}^{'}\Delta n^{'} + d_{+}^{'}\Delta n_{+}^{'} = 0 \\ b_{-}^{'}\Delta n^{'} + b_{+}^{'}\Delta n_{+}^{'} = 0 \end{cases} \quad (12)$$

From the decision (10) we define $\Delta n_{-}^{''}$и $\Delta n_{+}^{''}$.

To we find wave vectors from the dispersive equation

$$d_{-}^{'}b_{+}^{'} + b_{-}^{'}d_{+}^{'} = 0 \quad (13)$$

Write (10) in the following form

$$\Delta n_{\pm}(\vec{r}, t) = \sum_{j-1}^{4} \lambda_{\pm}^{j} e^{i(k_j - r_i)} + \Delta n_{\pm}^{''} e^{-i\omega t} \quad (14)$$

(where k_j are roots of the dispersive equation (13)).

Constants $\lambda_{\pm}^{j}$ are defined from the following boundary conditions.

$$\Delta n_{\pm}(0) = \delta_{\pm}^{0}\Delta I, \quad \Delta n_{\pm}(L_x) = \delta_{\pm}^{L_x}\Delta I \quad (15) \quad [8]$$

Then it is possible to calculate a variable - a potential difference on the ends of a crystal and impedance

$$Z = \frac{\Delta V}{\Delta I} = \frac{1}{\Delta I}\int_0^{L_x} E(x, t)dx = ReZ + ImZ \quad (16)$$

$$\frac{ReZ}{Z_0} = x_{+}^{2}\{1 + \varphi\left[(cos\alpha - 1) + \frac{\upsilon_{-}}{\omega\beta_{+}^{\mu}}sin\alpha\right] + \varphi_{+}(cos\alpha) -$$

$$- \frac{e\upsilon\delta x}{\theta}\beta_{+}^{\mu}\left(\frac{\mu_{+}}{\mu_{-}}\right)sin\alpha - (1 + \frac{\upsilon_{-}^{2}}{\omega^{2}})[\frac{\mu_{+}}{\beta_{+}^{\mu}\beta_{-}^{\mu}\mu_{-}} + \frac{\upsilon_{+}}{\beta_{+}^{\mu}\omega\mu}sin\alpha]\varphi_{+}\} \quad (17)$$

$$\frac{ImZ}{Z_0} = \frac{x_+}{\Theta}\left[Bn_+v_+^E\mu_+\beta_+^\gamma\left(1+\frac{v_-^2}{\omega^2}\right) - Bn_-v_-\mu_-\beta_-^\gamma\left(1+\frac{v_+^2}{\omega^2}\right) + \frac{ev\delta x_+}{2}\left(\frac{\mu_+}{\mu_-}\right)^2 cos\alpha\ \right] \quad (18)$$

Here, $\delta = \delta_+^0 + \delta_-^0 + \delta_+^{L_x} + \delta_-^{L_x}$, $v = (\mu_- + \mu_+)E_0$, $Z_0 = \frac{L_x}{\sigma_0 S}$, $\sigma_0 = e(n_-\mu_- + n_+\mu_+)$, S - transverse section of sample.

$$\theta = \frac{2L_x v_-}{n_0 k_y v^2\left(1+\frac{\beta_+^\mu}{\mu_+^\mu}\right)}\left(n_+v_+^E\beta_+^\gamma + n_-v_-\frac{\beta_+^\mu}{\beta_-^\mu}\beta_-^\gamma\right); n_0 = n_+ + n_-\ ,\ \varphi_- = \frac{2n_-v_-\omega^3}{n_0\omega_1^4 x_+\theta}\beta_-^\gamma\ ,$$

$$\varphi_- = \frac{2n_+v_+\omega^3}{n_0\omega_1^4 x_+\theta}\beta_+^\gamma\ ,\ \omega_1^4 = \omega^2(v_-^2 + v_+^2) + \omega^4 + v_-^2v_+^2\ ,\ x_+ = \frac{\mu_+ H}{c} \gg 1\ ,\ k_y = \frac{2\pi}{L_y}$$

We used the following known expressions of mobility in the stronger magnetic field

$$\mu_\pm(H) = \left(\frac{c}{H}\right)^2 \cdot \frac{1}{\mu_\pm^0}\ ;\ \mu_{1\pm} \approx \sqrt{2}\frac{c}{H}\ ;\ \mu_{2\pm} \approx \mu_\pm^0 \qquad [9]$$

When fluctuations of current in an external circuit begin, the current voltage characteristic of sample becomes non-linear. Real part of an impedance of Rez has negative sign. The imaginary part of ImZ of an impedance can have any sign. Adding on an ohmic resistance of R from the solution of the equation

$$-\frac{ReZ}{Z_0} + R = 0 \qquad (19)$$

$$\frac{ImZ}{Z_0} + \frac{R_1}{Z_0} = 0 \qquad (20)$$

We find an electric field where are happened fluctuations of current in a chain.
From (18) we will express β_+^γ via β_-^γ.

$$\beta_+^\gamma = \frac{n_-v_-\mu}{n_+v_+^E\mu_1}\cdot\frac{\omega^2+v_+^2}{\omega^2+v_-^2}\beta_-^\gamma \qquad (21);$$

then $\frac{ImZ}{Z_0} = \frac{ev\delta\beta_-^\mu}{2}\left(\frac{\mu_+x_+}{\mu}\right)^2 cos\alpha$ (22)

Write (17) in the following form

$$\frac{ReZ}{Z_0} = \Phi_0 + \Phi_1 sin\alpha + \Phi_2 cos\alpha \qquad (23)$$

Define from (23) β_+^γ and β_-^γ as following form:

$\Phi_0 = 0, \Phi_1 = 0$, then we will get:

$$\beta_+^\gamma = \frac{X_+^2}{A_+\left[1+\frac{v_+}{\omega}\left(\frac{\omega}{v_-}+\frac{v_-}{\omega}\right)\right]},\qquad \beta_-^\gamma = \frac{X_+^2\left(1+\frac{v_-^2}{\omega^2}\right)}{A_-\left(\frac{v_-v_+}{\omega 2}+\frac{v_-^2}{\omega^2}+1\right)}$$

$$A_+ = \frac{2n_0v_+^E a x_+}{n_0\omega\theta\beta_+\mu}\frac{\mu_+}{\mu_-};\quad A_- = \frac{2nv_-ax_+}{n_0\omega\theta\beta_+\mu}\ ;a = \frac{\omega^4}{\omega^4} \qquad (24)$$

$$\omega_1^4 = \omega^4 + \omega^2(v_-^2 + v_+^2) + v_-^2v_+^2$$

Equating the relations $\frac{\beta_+^\gamma}{\beta_-^\gamma}$ from (21) and (24) we will get the following equations for definition of an oscillation frequency of current in chain.

$$y^3 + \frac{v_-}{v_+}y^2 - \frac{v_-^2}{v_+^2}y \quad + \frac{\mu_-}{\mu_+} = 0,\quad y = \frac{\omega}{(v_-v_+)^{1/2}} \qquad (25)$$

The analysis of the decision the equation shows roots the equation (26) ($v_- > v_+$)

$$Y_3 = -\frac{v_-}{2v_+}\left(\sqrt{5}+1\right), Y_2 = \frac{v_-}{2v_+}\left(\sqrt{5}-1\right), Y_1 = 1 \qquad (26)$$

From equation $\frac{ImZ}{Z_0} + \frac{R_1}{Z_0} = 0$ (the R_1 is resistance of capacitive or inductive character) we will get

$$cos\alpha = -\frac{R_1}{Z_0}\frac{2}{ev\delta}\left(\frac{\mu}{\mu_x X_+}\right)^2 \qquad (27)$$

Substituting cosα from (27) in the equation of $\frac{Rez}{Z_0} + \frac{R}{Z_0} = 0$ we will get expressions for an electric field in the presence of fluctuation of current in chain.

$$E_0(\omega) = E_1 = \frac{|R_1|\mu}{R|\beta_-^{\mu}|} \cdot \frac{1}{ev\delta} \quad, E_2 = \frac{4|R_1|}{R|\beta_-^{\mu}|}\frac{\mu}{\mu_-} \cdot \frac{1}{ev\delta}\frac{v_-}{v_+} = E_2$$

$$E_0 = E_3 = \frac{6|R_1|\mu}{R|\beta_-^{\mu}|\mu_+} \cdot \frac{1}{ev\delta}\frac{v_-}{v_+}$$

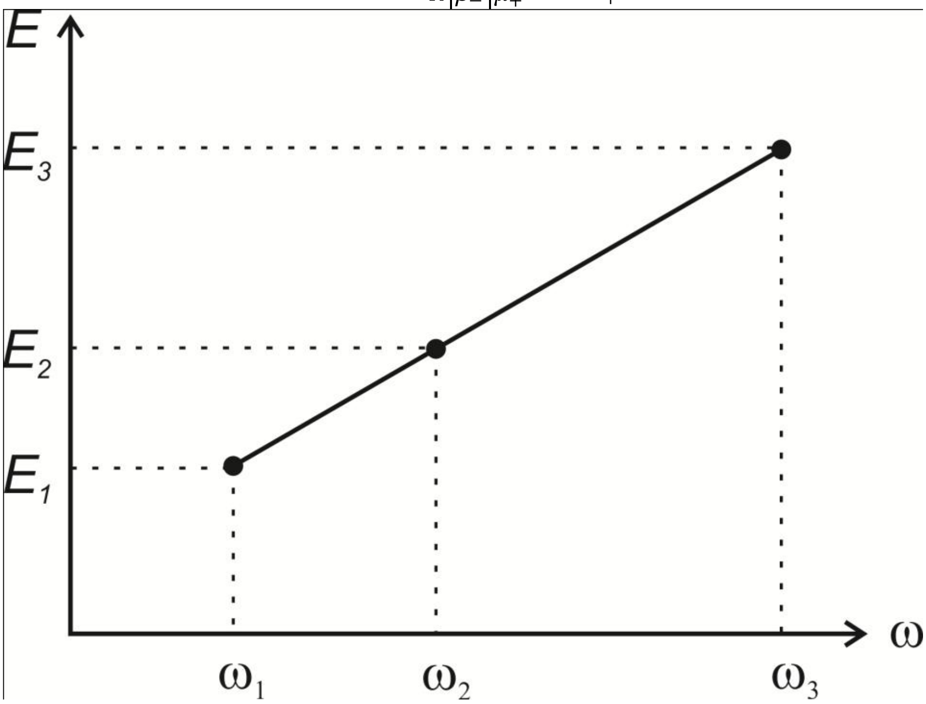

Fig.1.

III. Discussion

In the above semiconductors, waves with frequencies $\omega_1 < \omega_2 < \omega_3$ are excited at electric fields $E_1 < E_2 < E_3$. Analytically, expressions for the oscillation frequency of the current and for the electric field show that the carrier scattering constants $\beta_{\pm}^{\mu}$ have a negative sign. With current oscillations in the circuit, resistance of a negative nature occurs.

If $R = |R_1|$, $\frac{\mu}{\mu_+} \approx 10$, $\frac{v_-}{v_+} \sim 10, ev\delta \sim 10^{-1}$

$$E_1 \sim 10^3\, V/sm,\ E_2 \sim 4 \cdot 10^3\, V/sm;\ \ E_3 \sim 6 \cdot 10^3\, V/sm$$

and these values are in complete agreement with existing experiments (10). With these estimates, the frequency of oscillation

$$\omega_1 \sim 3 \cdot 10^7,\ \omega_2 \sim \frac{\sqrt{5}-1}{2} \cdot 10^9 \frac{1}{sec},\quad \omega_3 \sim \frac{\sqrt{5}+1}{2} \cdot 10^9 \frac{1}{sec}$$

It means that microwave current oscillations occur i.e. microwave radiation energy from the above semiconductor. The magnetic field is determined from the inequality $\mu_{\pm}H \gg C$. To determine the range of variation of the electric field, and the frequency of oscillation with a further increase in the electric field, we must construct a nonlinear theory.

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