THE SEMICONDUCTORS WITH DEEP TRAPS IN STRONG ELECTRIC AND MAGNETIC FIELDS

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The energy radiation with different values of radiation frequencies takes place in the semiconductors with definite deep traps and both signs of charge carriers in electric and magnetic fields. The values of electric field strength at magnetic one $\mu_{\pm}H \gg C$ are defined for each case. The sign of the scattering constant of charge carrier is defined. The analytical expressions for the parameters of recombination and generation of charge carriers $\beta_{\pm}^{\gamma}$ are found. The current oscillation theory is constructed in linear approximation. The values of $(\omega_1, \omega_2, \omega_3)$ frequency and (E_1, E_2, E_3) strength of the electric field are well agree with existing experimental data. The given semiconductors can be used at the preparation of generators and amplifiers.

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1. INTRODUCTION

The current oscillation theory in semiconductors with deep traps and two types of charge carriers is described in works [1-5]. The following constants $\beta_{\pm}^{\gamma} = 2\frac{dln\gamma_{\pm}U}{dln(E_0^2)}$, $\beta_{\pm}^{\mu} = 2\frac{dln\gamma_{\pm}\mu_{\pm}}{dln(E_0^2)}$ are taken as the positive ones in the given works.

However, below we will show that $\beta_{\pm}^{\mu}$ can be negative values in the dependence on scattering character of charge carriers and $\beta_{\pm}^{\gamma}$ constants stay positive ones.

In this theoretic work we will construct the oscillation current theory in the semiconductors with concrete deep traps and two types of charge carriers in strong electric $v_d > S$ and magnetic $\mu_{\pm}H_0 \gg C$ fields at $\beta_{\pm}^{\mu} < 0$.

The drift velocity of charge carriers v_d is defined by formula $v_d = \mu_{\pm}E_0$ where $\mu_{\pm}$ are mobilities of holes and electrons, E_0 is strength of constant electric field, H_0 is strength of external magnetic field, S is velocity of sound in the crystal.

For $\beta_{\pm}^{\gamma}$ constants we obtain the analytical expressions as the functions of electric fields, magnetic fields, oscillation current frequencies.

2. SEMICONDUCTOR MODEL AND TASK MAIN EQUATIONS

The electrons (and also holes) at the existence of electric field receive the energy of eE_0l order (e is positive elementary charge; l is length of electron free path).

That's at existence of electric field the electrons can overcome Coulomb barrier of singly charged center and recombine with this center.

Besides, as a result of heat transfer process, the electrons can regenerate from impurity centers (from deep traps) to the conduction band. The capture process decreases the electron number and transfer process increases it in conduction band.

The number of holes increases because of electron capture by deep traps from valence band and decreases because of the electron capture by the holes from deep traps. The different probabilities of generation and recombination lead to carrier concentration change in the crystal. We will mind that the semiconductor with carriers of both signs, i.e. electrons and holes with concentrations n_- and n_+ correspondingly. Besides, the negatively charged deep traps with N_0 concentration from which N is concentration of singly negatively charged traps and N_- is concentration of double negatively charged traps

$$N_0 = N_+ N_- \tag{1}$$

The continuity equation for the electrons in the semiconductors with above mentioned types of the traps has the form:

$$\frac{\partial n_0}{\partial t} + divj_- = \gamma_-(0)n_{1\_}N_- - \gamma_-(E)n_-N = (\frac{\partial n_-}{\partial t})_{rec} \tag{2}$$

Here and further $j_{\pm}$ are flux densities of electrons and holes, $j_{-(0)}$ is radiation value of electrons by double negatively charged traps in the absence of electric field. It can be called the coefficient of thermal generation coefficient. $\gamma_-(E)$ is coefficient of electron capture by singly negatively charged traps at the presence of electric field. $\gamma_-(E) = \gamma_-(0)$ at $E=0$.

In (2) the unknown constant $n_{1\_}$ having the concentration dimension, is defined by the following method. At the absence of electric field and under stationary and equilibrium conditions,

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i.e. $(\frac{\partial n_-}{\partial t})_{rec} = 0$ and $\gamma_-(E) = \gamma_-(0)$ we obtain from (2):

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

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

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

Here $\vec{h}$ is unit vector along magnetic field, $\mu(E,H)$ is ohmic electron mobility, $\mu_{1_-}(E,H)$ is Hall electron mobility, μ_2 *(E, H)* is focused electron mobility, D_-, D_{1_-}, D_{2_-} are ohmic, Hall, focused electron diffusion coefficients correspondingly. For the simplifying of big calculations we consider the case when the carriers have the effective temperature. Then diffusion coefficient is:

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

C is speed of light in the crystal, *T* is temperature in energy units. Besides, we will consider the crystals the sizes of which satisfy to following relations:

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

The continuation equation for the holes has the form:

$$\frac{\partial n_+}{\partial t} + divj_+ = \gamma_+(E)n_{1_+}N_+ - \gamma_+(0)n_+N_- = (\frac{\partial n_-}{\partial t})_{чек} \quad (4)$$

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

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

As a result of recombination and generation in non-stationary conditions the number of single and double negatively charged traps changes (the general concentration of traps stay constant). The change of the number of double negatively charged traps by the time defines the change of the number single negatively charged traps by the time has the form:

$$\frac{\partial N_-}{\partial t} = (\frac{\partial n_+}{\partial t})_{rec} - (\frac{\partial n_-}{\partial t})_{rec} \quad (5)$$

The external electric field is directed along X axis and magnetic field is directed along Z axis.
Suppose that:

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

The inclination of magnetic field from equilibrium value is equal to 0 as we consider the longitudinal oscillations. (0) sign meaning the equilibrium value of corresponding values we will not write.

Let's linearize the equations (2) and (4) taking into consideration (6) and introduce the following character frequencies:

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

$$\acute{\nu}_+ = \gamma_+(0)n_+ + \gamma_+(E_0)n_{1_+}$$

and designate the numerical constants defining the dependences on electric field $\gamma_\pm(E_0)$ and $\mu_\pm(E_0)$

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

$\beta_\pm^\gamma$ is dimensionless parameter, $\beta_\pm^\gamma$ can have the negative sign, i.e. $\beta_\pm^\gamma < 0$ in the dependence on charge carrier scattering. In [7] it is shown that $\beta_\pm^\gamma = -0{,}8$ at scattering on optical and acoustic (mixed scattering) photons $\beta_\pm^\gamma = -0{,}8$. We will consider that $\beta_\pm^\gamma < 0$ in following theoretical calculations.

At absence of recombination and generation of carriers the condition of quazi -neutrality means that the number of electron changes is equal to the number of hole change, i.e. $\Delta n_- = \Delta n_+$. At presence of recombination and generation of charge carriers the condition of quazi-neutrality means that total current doesn't depend on coordinates but depends on time.

$$div\,\vec{j} = ediv\left(\vec{j}_\mp \vec{j}_-\right) = 0 \quad (8)$$

After linearization of equations (2), (4), (8) we will obtain the equation for electric field of the following type:

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

where a_1, a_2, a_3 are constant values depending on oscillation frequency, character frequencies, equilibrium values of charge carrier concentration, electric and magnetic fields and numerical multipliers $\beta_\pm^\gamma$, $\beta_\pm^\mu$. Because of big coefficients a_1, $\vec{a}_2$, $\vec{a}_3$ we write only the solution scheme.

Let's divide the functionals $\Delta n_\pm(\vec{r}, t)$, $\Delta N_-(\vec{r}, t)$, $\Delta E(\vec{r}, t)$ to parts proportional to oscillation current ΔJ in external circuit:

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

The analogous divisions we make for ΔN_-, ΔE. After simple algebraic calculations from (2, 4, 8, 9) taking into consideration (10), we will obtain two equation systems:

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

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

From solution (11) we obtain $\Delta n''_-$ and $\Delta n''_+$. The wave vectors we find from dispersion equation:

$$d'_- b'_+ + b'_- d'_+ = 0 \qquad (13)$$

We write (10) in the following form:

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

where k_j is dispersion equation root (13).

$\lambda_\pm^j$ are constants are defined from following boundary conditions:

$$\Delta n_\pm(0) = \delta_\pm^0 \Delta J,\ \Delta n_\pm(L_x) = \delta_\pm^{L_x}\Delta J \qquad (15)$$

After it we calculate the impedance Z:

$$Z = \frac{\Delta V}{\Delta J} = \frac{1}{\Delta J}\int_0^{L_x} E(x,t)dx = ReZ + JmZ \qquad (16)$$

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

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

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

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

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

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

We use the following known expressions of mobilities in strong magnetic field:

$$\mu_\pm(H) = (\frac{c}{H})^2 \cdot \frac{1}{\mu_\pm^0};\ \mu_{1\pm} \approx \sqrt{2}\frac{c}{H};$$

$$\mu_{2\pm} \approx \mu_\pm^0 \qquad [9]$$

When the current oscillations in external chain begin so the sample Volt-ampere characteristics becomes linear one. The real part of impedance ReZ has the negative sign. The impedance imaginary part ImZ can have any sign. Adding to R ohmic resistance from equation solution:

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

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

we will find the electric field at which the current oscillations in circuit takes place.

From (18) let's express β_+^γ through β_-^γ.

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

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

Rewrite (17) in the following form:

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

Using (23) we obtain β_+^γ and β_-^γ by the following way:

$\Phi_0 = 0, \Phi_1 = 0$, then we easily obtain:

$$\beta_+^\gamma = \frac{X_+^2}{A_+\left[1+\frac{v_+}{\omega}\left(\frac{\omega}{v_-}+\frac{v_-}{\omega}\right)\right]}\,,\ \beta_-^\gamma = \frac{X_+^2\left(1+\frac{v_-^2}{\omega^2}\right)}{A_-\left(\frac{v_- v_+}{\omega_2}+\frac{v_-^2}{\omega^2}+1\right)}$$

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

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

Equating the ratios $\frac{\beta_+^\gamma}{\beta_-^\gamma}$ from (21) and (24) we obtain the following equations for the definition of current oscillation frequency in circuit.

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

The analysis of solution of equation shows that the roots of equation (25) have the following form at $v_- > v_+$:

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

From equation $\frac{JmZ}{Z_0} + \frac{R_1}{Z_0} = 0$ we obtain: R_1 is resistance of capacity or inductive character

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

Substituting $cos\alpha$ from (27) into equation $\frac{Rez}{Z_0} + \frac{R}{Z_0} = 0$ we obtain the expressions for electric field at the presence of current oscillation in circuit.

$$E_0(\omega_1) = E_1 = \frac{|R_1|\mu}{R|\beta_-^\mu|\mu_+} \cdot \frac{1}{ev\delta}$$

$$E_2 = \frac{4|R_1|}{R|\beta_-^\mu|}\frac{\mu}{\mu_-} \cdot \frac{1}{ev\delta}\frac{v_-}{v_+} = E_2$$

3. CONCLUSION

In above mentioned semiconductors the waves with frequencies $\omega_1 < \omega_2 < \omega_3$ at electric fields $E_1 < E_2 < E_3$ are excited (fig.1).

Analytical expressions for current oscillation frequencies and for electric field show that constants of charge carrier scattering constants $\beta_\pm^\mu$ have the negative sign.

At current oscillations the resistance of negative character appears in the chain if $R = |R_1|$, $\frac{\mu}{\mu_+} \approx 10$, $\frac{v_-}{v_+} \sim 10, ev\delta \sim 10^{-1}$. Then we have:

$$E_1 \sim 10^3\ V/cm,\ E_2 \sim 4 \cdot 10^3\ {}^V\!/_{cm};$$
$$E_3 \sim 6 \cdot 10^3\ {}^V\!/_{cm}.$$

These values are well agree with existing experiments. The corresponding current oscillation frequencies have the following values:

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

It means that the high-frequency current oscillations, i.e. high-frequency radiation of energy from above mentioned semiconductor takes place. The magnetic field is defined from inequality $\mu_\pm H \gg C$. For the definition of region of electric field change and current oscillation frequency at further increase of electric field one can construct the nonlinear theory.

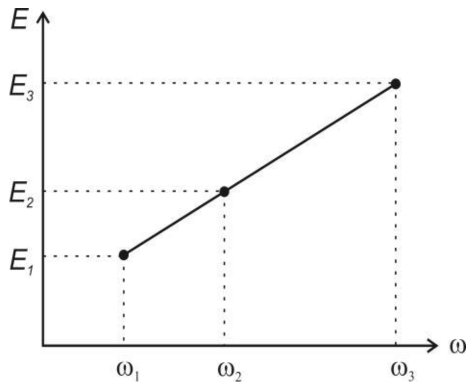

Fig.1. The dependence of electric field on current oscillation frequency.

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