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APPEARANCE OF UNSTABLE WAVES IN SEMICONDUCTORS WITH TWO TYPES OF CHARGE CARRIERS IN THE PRESENCE OF CERTAIN IMPURITY LEVELS

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Abstract- In semiconductors with two types of charge carriers, radiation of energy occurs. For each case, the values of the electric field are determined for a magnetic field $\mu_+ H >> C$ identification. The sign of the scattering constant of charge carriers is determined. Analytical expressions are found for the parameters of recombination and generation of charge carriers $\beta_\pm^\gamma$. The values of the frequency $(\omega_1 < \omega_2 < \omega_3)$ and the electric field $(E_1 < E_2 < E_3)$ are consistent with the experimental data. Semiconductors with above properties can be used in preparation of amplifiers and microwave generators.

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

1. INTRODUCTION

In [1-5], a theory of current oscillations in electric and magnetic fields, was constructed. In these researches

$$\beta_\pm^\gamma = 2\frac{d\ln\gamma}{d\ln\left(E_0^2\right)}$$

$$\beta_\pm^\mu = 2\frac{d\ln\mu_+}{d\ln\left(E_0^2\right)}$$

were taken as positive constants.

However, we will show below that β_+^μ depending on the nature of scattering charge carriers can be negative value and β_+^γ remain positive. In this theoretical work, we construct a theory of current oscillations in strong electric $v_d > S$ and magnetic $\mu_\pm H_0 >> C$ fields at

$$\beta_\pm^\mu < 0$$

$$v_d = \mu_\pm E_0$$

where, v_d is the drift velocity of charge carriers, $\mu_\pm$ is the motilities 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 crystal.

For β_+^γ we have obtained analytical expansions as a function of the electric field, magnetic field, the current frequency oscillations.

2. 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 $eE_0 l$ (e is positive elementary charge, and l is 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 transfer process increases the number of electrons, and the capture process decreases the number electrons in the conduction band. Number of holes increases due to the capture of electrons by deep traps from the valence band.

However, number of holes decreases due to capture of electrons from deep traps by holes. Electrons and holes signs with concentrations n_- and n_+, respectively. In addition, in semiconductor there are negatively charged deep traps with a concentration of N_0.

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

where, N_+ and N_- are the concentration of once negatively charged traps and of double negatively charged traps, respectively.

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

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

where, $j_\pm$ 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, and $\gamma_-(E)$ is electron capture coefficient of negatively charged traps once for the presence of an electric field. At E=0 we have $\gamma_-(E)=\gamma_-(0)$. 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 $\left(\frac{\partial n_-}{\partial t}\right)_{rek}$ and $\gamma_-(E)=\gamma_-(0)$ 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

$$\begin{aligned}\overrightarrow{J_-}&=-n\mu\vec{E}+n\mu_{1-}\left[\vec{E}\vec{h}\right]-n\mu_2\vec{h}\left[\vec{E}\vec{h}\right]-\\&-K_-\vec{\nabla}+K_{1-}\left[\vec{\nabla}n\vec{h}\right]-K_2\vec{h}\left[\vec{\nabla}n_-\vec{h}\right]\end{aligned} \quad (3)$$

where, $\vec{h}$ is a unitary vector by the magnetic field, μ is Ohmic, μ_{1-} is Hall's, μ_2 is focusing mobility of electrons, K_-, K_{1-}, K_{2-} are 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 [6] is

$$K_\pm=\frac{T_{eff}}{e}\mu_\pm$$

$$T_{eff}=\frac{T}{3}\left(\frac{CE_0}{SH_0}\right)^2$$

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

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

The continuity equation for holes will be

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

$$\begin{aligned}\overrightarrow{J_+}&=n_+\mu_+\vec{E}+n_+\mu_{1+}\left[\vec{E}\vec{h}\right]-n_+\mu_2\vec{h}\left(\vec{E}\vec{h}\right)-\\&-K_+\vec{\nabla}n_++K_{1+}\left[\vec{\nabla}n\vec{h}\right]-K_{2+}\vec{h}\left(\vec{\nabla}n_-\vec{h}\right)\end{aligned} \quad (4)$$

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

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:

$$\begin{aligned}&\frac{\partial N_-}{\partial t}=\left(\frac{\partial n_+}{\partial t}\right)_{rek}-\left(\frac{\partial n_-}{\partial t}\right)_{rek}\\&\vec{E}(\vec{r},t)=\overrightarrow{E_0}+\Delta\overrightarrow{E_0}(\vec{r},t)\end{aligned} \quad (5)$$

On an axis X the electric field, and on axis Z the magnetic field is directed.

$L_+(\vec{r_1}t)=L_+^0+\Delta L_+(\vec{r},t)$, $N_-(\vec{r},t)=N_+^0+\Delta N_-(\vec{r},t)$

The deviation of a magnetic field from an equilibrium value is equal to zero as we consider longitudinal vibrations.

We will ignore the badge (0) meaning an equilibrium value of the corresponding values further. We linearize the Equations (2) and (4) taking into account (6) and we enter the following characteristic frequencies

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

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

we will designate numerical constants defined by dependences on an electric field

$$\begin{aligned}\beta_\pm^\gamma&=2\frac{d\ln\gamma_+(E_0)}{d\ln\left(E_0^2\right)}\\\beta_\pm^\mu&=2\frac{d\ln\mu_+(E_0)}{d\ln\left(E_0^2\right)}\end{aligned} \quad (7)$$

where, $\beta_\pm^\gamma$ is dimensionless parameter, depending on scattering of charge carriers β_+^γ can have the negative sign, i.e. $\beta_+^\gamma<0$. In [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.

$$\text{div}\vec{I}=e\,\text{div}\left(\overrightarrow{j_+}-\overrightarrow{j_-}\right)=0 \quad (8)$$

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

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

where, $a_1,\overrightarrow{a_2},\overrightarrow{a_3}$ 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 $a_1,\overrightarrow{a_2},\overrightarrow{a_3}$ we will be limited to the indication of the scheme of the decision

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

$$\Delta L_+(\vec{r},t)=\Delta L_+'e^{i(\vec{k}\vec{r}-wt)}+\Delta L_+''e^{-iwt} \quad (10)$$

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

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

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

From the decision (10), we define $\Delta n''_-$ and $\Delta n''_+$.

To we find wave vectors from the dispersive equation

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

Write (10) in the following form

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

where, k_j are roots of the dispersive Equation (13).

Constants λ_+^j are defined from the following boundary conditions [8].

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

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

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

$$\frac{\operatorname{Re} Z}{Z_0} = x_+^2\left\{1 + \varphi\left[(\cos\alpha - 1) + \frac{\nu_-}{w\beta_+^\mu}\sin\alpha\right] + \right.$$
$$+\varphi_+(\cos\alpha) - \frac{ev\delta x_+}{\theta}\beta_+^\mu\left(\frac{\mu_+}{\mu_-}\right)\sin\alpha - \quad (17)$$
$$\left. -\left(1 + \frac{\nu_-^2}{w^2}\right)\left[\frac{\mu_+}{\beta_+^\mu\beta_-^\mu\mu} + \frac{\nu_+}{\beta_+^\mu w\mu}\sin\alpha\right]\varphi_+\right\}$$

$$\frac{\operatorname{Im} Z}{Z_0} = \frac{x_+}{\theta}\left[Bn_+\nu_+^E\mu_+\beta_+^\gamma\left(1 + \frac{\nu_-^2}{w^2}\right) - \right.$$
$$\left. -Bn_-\nu_-\mu_-\beta_-^\gamma\left(1 + \frac{\nu_+^2}{w^2}\right) + \frac{ev\delta x_+}{2}\left(\frac{\mu_+}{\mu_-}\right)^2\cos\alpha\right] \quad (18)$$

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

$$\theta = \frac{2L_x\nu_-}{n_0 k_y v^2\left(1 + \frac{\beta_+^\mu}{\mu_-^\mu}\right)}\left(n_+\nu_+^E\beta_+^\gamma + n_-\nu_-\frac{\beta_+^\mu}{\beta_-^\mu}\beta_-^\gamma\right);$$

$$n_0 = n_+ + n_-,\ \varphi_- = \frac{2n_-\nu_-w^3}{n_0 w_1^4 x_- + \theta}\beta_-^\gamma,\ \varphi_+ = \frac{2n_+\nu_+w^3}{n_0 w_1^4 x_+ + \theta}\beta_+^\gamma,$$

$$w_1^4 = w^2\left(\nu_-^2 + \nu_+^2\right) + w^4 + \nu_-^2\nu_+^2,\ x_+ = \frac{\mu_+ H}{c} >> 1,\ k_y = \frac{2\pi}{L_y}$$

We used the following known expressions of mobility in the stronger magnetic field [9]

$$\mu_\pm(H) = \left(\frac{c}{H}\right)^2\frac{1}{\mu_\pm^0}$$

$$\mu_{1\pm} \approx \sqrt{2}\frac{c}{H} \quad \mu_{2\pm} \approx \mu_\pm^0$$

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

$$-\frac{\operatorname{Re} Z}{Z_0} + R = 0 \quad (19)$$

$$\frac{\operatorname{Im} Z}{Z_0} + \frac{R_1}{Z_0} = 0 \quad (20)$$

We find an electric field where are happened fluctuations of current in a chain.

From (18) we will express β_+^γ via β_-^γ.

$$\beta_+^\gamma = \frac{n_-\nu_-\mu}{n_+\nu_+^E\mu_+}\frac{w_+^2\nu_+^2}{w_+^2\nu_-^2}\beta_-^\gamma \quad (21)$$

then

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

Write (17) in the following form

$$-\frac{\operatorname{Re} Z}{Z_0} = \Phi_0 + \Phi_1\sin\alpha + \Phi_2\cos\alpha \quad (23)$$

Define β_+^γ and β_-^γ from (23) as following form: $\Phi_0 = 0, \Phi_1 = 0$, then we will get:

$$\beta_+^\gamma = \frac{x_+^2}{A_+\left[1 + \frac{\nu_+}{w}\left(\frac{w}{\nu_-} + \frac{\nu_-}{w}\right)\right]}$$

$$\beta_-^\gamma = \frac{x_+^2\left(1 + \frac{\nu_-^2}{w^2}\right)}{A_-\left[\frac{\nu_-\nu_+}{w^2} + \frac{\nu_-^2}{w^2} + 1\right]}$$

$$A_+ = \frac{2n_0\nu_+^E\alpha x_+}{n_0 w\theta\beta_+\mu}\frac{\mu_+}{\mu_-} \quad (24)$$

$$A_- = \frac{2n_-\nu_-\alpha x_+}{n_0 w\theta\beta_+\mu}$$

$$\alpha = \frac{w}{w_1^4}$$

$$w_1^4 = w^4 + w^2\left(\nu_-^2 + \nu_+^2\right) + \nu_-^2\nu_+^2$$

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

$$y^3+\frac{\nu_+}{\nu_-}y^2-\frac{\nu_+^2}{\nu_-^2}y+\frac{\mu_+}{\mu_-}=0$$
$$y=\frac{w}{\left(\nu_-\nu_+\right)^{\frac{1}{2}}} \tag{25}$$

The analysis of the decision the equation shows roots the Equation (26) $\left(\nu_- > \nu_+\right)$

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

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

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

Substituting cosα from (27) in the equation of $\frac{\operatorname{Re} Z}{Z_0}+\frac{R}{Z_0}=0$, we will get expressions for an electric field in the presence of fluctuation of current in chain as Figure 1.

$$E_0\left(w_1\right)=E_1=\frac{\left|R_1\right|\mu}{R\left|\beta_-^{\mu}\right|\mu_+}\frac{1}{ev\delta}$$
$$E_2=\frac{4\left|R_1\right|\mu}{R\left|\beta_-^{\mu}\right|\mu_+}\frac{1}{ev\delta}\frac{\nu_-}{\nu_+}$$
$$E_0\left(w_3\right)=E_3=\frac{6\left|R_1\right|\mu}{R\left|\beta_-^{\mu}\right|\mu_+}\frac{1}{ev\delta}\frac{\nu_-}{\nu_+}$$

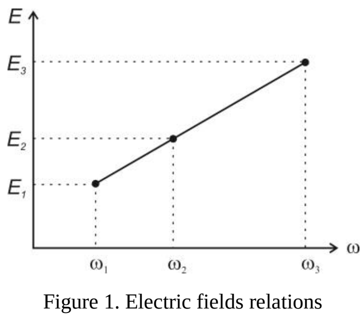

Figure 1. Electric fields relations

3. 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 β_+^{μ} have a negative sign. With current oscillations in the circuit, resistance of a negative nature occurs.

If

$$R=\left|R_1\right|,\ \frac{\mu}{\mu_+}\approx 10,\ \frac{\nu_-}{\nu_+}\sim 10,\ ev\delta\sim 10^{-1}$$
$$E_1\sim 10^3\ \text{V/cm},\ E_2\sim 4\times 10^3\ \text{V/cm},\ \ E\sim 6\times 10^3\ \text{V/cm}$$

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

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

It means that microwave current oscillations occur i.e. microwave radiation energy from the above semiconductor. The magnetic field is determined from the inequality $\mu_+ H >> C$. 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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