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Study of Influences of Strong Electrostatic Field on Crystal Conductivity and Current

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Abstract: The frequencies of wave oscillations at internal and external instability in semiconductors of electron-hole conductivity with taking under consideration the relaxation of charge carriers have been calculated. The intervals of change of external electric field, at which the electric instability in the sample take place, have been found In this paper, the theory of external instability will be conducted at the presence of electrostatic field, when conductivities of electrons and holes have relaxation character.

Key words:

INTRODUCTION

The conductivity oscillations can appear in the crystal in which electron and hole components of conductivity are non-linear ones. The current oscillations of such type in the circuit can lead to electric instability. If relaxation times of electrons and holes $\tau_\pm$ are different and nonlinearity coefficients of conductivity of electrons and holes $\beta_\pm = \frac{E_0^2}{\sigma_\pm} \cdot \frac{d\sigma_\pm}{d\left(E_0^2\right)}$ have opposite signs, then current oscillations take place either because of electron decrease at the expense of electric field (hole increase), or because of electron increase (hole decrease) at the expense of electric field. Such process is studied experimentally [1], the frequencies of appearing current oscillations are estimated and critical electric field, at which the current oscillations start, is found. It is known, that energy with high frequency radiates from the crystal at oscillation mode. These oscillations are caused either by electron capture by the impurity centers (in impurity semiconductors) in electric field (hole radiation), or electron transitions into high energy states (in multi-domain semiconductors) [2].

Theory of External Instability at Presence of Electrostatic Field: The external instability appears at semiconductor energy radiation and sample resistance becomes complex. At such process current density decreases with the electric field increase and negative volt-ampere characteristic is observed.

In this paper, we will construct the theory of external instability at the presence of electrostatic field, when conductivities of electrons and holes have relaxation character, i.e.

$$\sigma_\mp = \sigma_\mp + \sigma'_\mp\,, \quad \frac{d\sigma'_\mp}{dt} + \frac{\sigma'_\mp}{\tau_\mp} = \frac{1}{\tau_\mp}\frac{d\sigma'_\mp}{d\left(E_0^2\right)} 2E_0\vec{E}' \qquad (1).$$

The net current is

$$\vec{J} = \sigma_+\vec{E} + \sigma_-\vec{E} + D_-\nabla\rho_- - D_+\nabla\rho_+ \qquad (2).$$

Linearizing (1-2) at $E = E_0 + E'$; $\rho = \rho_0 + \rho'$; E', $\rho' \sim e^{i\omega t}$ and taking into consideration that $divE' = \frac{4\pi e}{\varepsilon}\left(n_+^0 - n_- + N_0\right)$, where ε is dielectric constant, $N_0 = n_+^0 - n_-^0$, we obtain the equation for definition of electric field E′

$$\frac{\partial^2 E'}{\partial x^2} + \frac{4\pi\left(D_- - D_+\right)}{\varepsilon D_+}\frac{en_-^0\varphi_-}{E_0}\left(1 + \frac{\beta_-}{1+\alpha} - i\frac{\beta_-\alpha}{1+\alpha}\right)\frac{\partial E'}{\partial x} - \frac{4\pi\sigma_0}{\varepsilon D_+}\cdot$$
$$\cdot\left\{1 - \frac{\sigma_-^0\beta_-}{\sigma_0(1+\alpha)} + \frac{\sigma_+^0\beta_+}{\sigma_0(1+\delta)} - i\left[\frac{\sigma_+^0\beta_+}{\sigma_0(1+\delta)} - \frac{\sigma_-^0\beta_-\alpha}{\sigma_0(1+\alpha)}\right]\right\}E' = -\frac{4\pi J'}{\varepsilon D_+} \qquad (3)$$

Here, $\omega\tau_- = \alpha$, $\omega\tau_+ = \delta$, $\beta_+ \succ 0$, $\beta_- \prec 0$; $\varphi_- = \frac{d\ln\mu_-}{d\ln E_0^2}$.

Calculations: At the development of equation derivation (3), we took into consideration the small parameter $\frac{T}{eE_0L} \prec\prec 1$, where (T is temperature, L is sample length).

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For the solving of equation (3) it is necessary to take into consideration the boundary conditions for E′. We consider the homogeneous boundary conditions [3]

$$E'(0,t) = E'(L,t) = 0 \quad (4).$$

Taking into consideration the boundary condition (4) the solution of equation (3), we can obtain in the following form:

$$\begin{aligned} &E'(x_1 t) = c_1 e^{r_1} + c_2 e^{r_2} + c_2 e^{r_2} + \frac{4\pi J'}{\varepsilon \sigma_0 E_0} \\ &r_1 = k_1 x, \quad r_2 = k_2 x \end{aligned} \quad (5).$$

where r_1 and r_2 are roots of characteristic equation (3) at J'.

$$\begin{aligned} &r_1 = -\frac{E_1}{2E_0}\left(1 + \frac{\beta_-}{1+\alpha}\right) + x_0 + i\left[x_0 - \frac{E_1 \alpha \beta_-}{2E_0(1+\alpha)}\right] \\ &r_2 = -\frac{E_1}{2E_0}\left(1 + \frac{\beta_-}{1+\alpha}\right) - x_0 - i\left[x_0 + \frac{E_1 \alpha \beta_-}{2E_0(1+\alpha)}\right] \\ &E_1 = \frac{4\pi(D_- - D_+)}{\varepsilon D_+} \cdot \quad len\_\varphi_-, \quad x_0 = \frac{\sigma_0}{\sigma_-}(2\alpha)^{\frac{1}{2}}, \quad \sigma_0 = \sigma_-^0 + \sigma_+^0 \end{aligned} \quad (6).$$

Substituting (6) into (5) we find the constants $c_{1,2}$ taking into consideration boundary conditions (4) and obtain crystal impedance as follows:

$$Z(\omega) = \frac{1}{J(\omega)}\int_0^L E' dx = Z_0\left[1 + \frac{r_2 - r_1}{i r_1 r_2} \cdot \frac{(e^{r_1} - 1)(e^{r_2} - 1)}{e^{r_1} - e^{r_2}}\right] \quad (7).$$

where Z_0 is sample resistance without external electric field. Taking into consideration (6), one can easily emphasize the real and imaginary parts of impedance

$$\begin{aligned} &\frac{\mathrm{Re}\,Z}{Z_0} = 1 - \frac{2x_0^2}{(A^2 + B^2)(f^2 + N^2)}\left[(A+B)(\Phi f + FN) + (B-A)(Ff - \Phi N)\right] \\ &\frac{\mathrm{Im}\,Z}{Z_0} = \frac{2x_0^2}{(A^2 + B^2)(f^2 + N^2)}\left[(A-B)(\Phi f + FN) + (A+B)(Ff - \Phi N)\right] \end{aligned} \quad (8)$$

Here

$$\begin{aligned} &A = 2(x_0^2 - ab), \quad B = a^2 - b^2, \quad a = \frac{\sigma_0 E_1}{2E_0 \sigma_-}; \quad b = \frac{\sigma_0 E_1}{2E_0 \sigma_-}\alpha \\ &\Phi = 1 + e^{x_0 - a}\cos(x_0 - b) + e^{-2a}(\cos 2b + \sin 2x_0) \\ &F = e^{x_0 - a}\sin(x_0 + b), \quad f = e^{x_0 - a}\cos(x_0 - b), \quad N = e^{x_0 - b}\sin(x_0 - b) \end{aligned} \quad (9)$$

From (8) and (9) it is seen, that obtaining of conditions $\frac{\mathrm{Re}\,Z}{Z_0} \prec 0$ and $\frac{\mathrm{Im}\,Z}{Z_0} \prec 0$ are too complex and that's why we will find from (8) the conditions Re Z = 0 and I *m* Z = 0 [4], at which current oscillations start and sample radiates the energy.[5]

From (8) it is easily seen, that I m Z = 0 if following conditions are correct:

$$\sin b = \left[\frac{e^{-\frac{\pi}{2}}}{2\left(1-\sqrt{2}e^{-\frac{\pi}{4}}\right)} \right]^{\frac{1}{2}}; \quad E_0 \geq \frac{\pi\sigma_-^0}{4\sigma_0} E_1, \qquad (10).$$

$$E_1 = \frac{4\pi\left(D_- - D_+\right)}{\varepsilon D_+} l \sin_+^0 \varphi_1, \quad \varphi_1 = \frac{d\ln\mu_-}{d\ln E_0^2}.$$

$$\omega \geq \sqrt{2} \cdot \frac{E_0}{E_1} \cdot \frac{1}{\tau_-}$$

The radiation frequency ω increases with the increase of external electric field E0.

CONCLUSION

When electron relaxes faster (i.e. τ decreases), then ω increases and this process corresponds to more effective change of concentrations of current carriers. The electron transitions into higher energy states in multi-domain semiconductors and electron capture by negative impurity centers in electric field lead to decrease of relaxation time $\tau_{\pm}$.

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