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IMPEDANCE OF A DEEP-TRAPPED SEMICONDUCTOR IN EXTERNAL CROSSED ELECTRIC AND MAGNETIC FIELDS

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The appearance of external instability in impurity semiconductors (i.e., the appearance of current fluctuations in an external circuit) is of practical importance from the point of view of preparing amplifiers and generators. Impurities (i.e., deep traps) in semiconductors, depending on their charge states, can capture or emit charge carriers.

Some impurities in a semiconductor create centers that can be in several charged states (singly, doubly, etc. positively or negatively charged). For example, a gold atom (Au) in germanium (Ge) can, in addition to the neutral state, be singly positively charged and singly, doubly, triply negatively charged centers.

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

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

Assuming that

$$\vec{E} = \vec{E}_0 + \Delta\vec{E}, n_{\pm} = n_{\pm}^0 + \Delta n_{\pm}, N_- = N_-^0 + \Delta N_-$$

And introducing the following characteristic frequencies

$\nu_- = \gamma_-(E_0)N_0$ - Electron capture frequency,

$\nu_+ = \gamma_+(0)N_-^0$ - Hole capture frequency,

$\nu_+^E = \gamma_+(E_0)N_0$ - Hole emission frequency, and we denote the numerical factors determined by the dependencies $\gamma_{\pm}(E_0), \mu_{\pm}(E_0)$.

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

$$\frac{\partial\Delta n_-}{\partial t} + div\Delta\vec{j}_-' = -\nu_-\Delta n_- + \nu_-'\Delta N_- - \nu_- n_-^0\beta_-^{\gamma}\frac{\vec{E}_0\Delta E}{E_0^2} = \left(\frac{\partial(\Delta n_-)}{\partial t}\right)_{rek}$$

$$\frac{\partial\Delta n_-}{\partial t} + div\Delta\vec{j}_+' = \nu_+\Delta n_+ + \nu_+'\Delta N_- + \nu_+^E n_{1+}\beta_+^{\gamma}\frac{\vec{E}_0\Delta E}{E_0^2} = \left(\frac{\partial(\Delta n_+)}{\partial t}\right)_{rek}$$

Where $\nu_-' = \gamma_-(E_0)n_-^0 + \gamma_-(0)n_{1-}, \nu_+' = \gamma_+(0)n_+^0 + \gamma_+(E_0)n_{1+}$

$$\begin{cases} C''_{-}\Delta n''_{-} + C''_{+}\Delta n''_{+} = C\Delta J \\ D''_{-}\Delta n''_{-} + D''_{+}\Delta n''_{+} = D\Delta J \end{cases}$$

$$\begin{cases} C'_{-}\Delta n'_{-} + C'_{+}\Delta n'_{+} = 0 \\ D'_{-}\Delta n''_{-} + D'_{+}\Delta n''_{+} = 0 \end{cases}$$

$$\Delta n''_{-} = \Delta J \frac{n^0_{-}\nu'_{-}\beta^{\gamma}_{-}\left(\nu^2_{-} + \omega^2\right)\left(\nu_{-} + i\omega\right)\left(\alpha_{+}\mu^2_{-} - \alpha_{-}\mu^2_{+}\right)c^2}{\omega^4_1\left(\mu_{-}\mu_{+}\right)^2 H^2}$$

$$\Delta n''_{+} = \Delta J \frac{n^0_{+}\nu'_{+}\beta^{\gamma}_{+}\left(\nu^2_{+} + \omega^2\right)\left(\nu_{+} + i\omega\right)\left(\alpha_{+}\mu^2_{-} - \alpha_{-}\mu^2_{+}\right)c^2}{\omega^4_1\left(\mu_{-}\mu_{+}\right)^2 H^2}$$

The variable potential difference across the ends of the crystal and the impedance can be calculated.

$$Z = \frac{\Delta V}{\Delta J}$$

By isolating the real and minimum parts of the impedance, we obtain

$$\frac{\mathrm{Re}\, Z}{Z_0} = \left(\frac{\mu_+ H}{c}\right)^2 \frac{1}{\alpha_+}\left(a + A\cos\alpha + B\sin\alpha\right)$$

$$\frac{JmZ}{Z_0} = \frac{\mu_+ H}{c\theta}\left(D + e\upsilon_0\delta\left(\frac{\mu_+}{\mu_-}\right)^2 \frac{\mu_+ H}{c}\frac{\beta_-^\gamma}{}\cos\alpha\right)$$

Where

$$a = 1 - \frac{\omega^3}{\Omega_1^3}\cdot\frac{1}{\beta_+^\mu}\left(\alpha_- + \frac{\nu_-^2}{\omega^2}\right) - \frac{\omega^3}{\Omega_2^3}\left(\alpha_+ + \frac{\nu_-^2}{\omega^2}\right)\frac{\mu_+}{\mu_-\beta_+^\mu}$$

$$\Omega_1^3 = \frac{n_0\mu_+ H\theta\omega_1^4}{2n_-\nu_- c\beta_-^\gamma\alpha_+}, \Omega_2^3 = \frac{n_0\mu_+ H\theta\omega_1^4}{2n_+\nu_+^E\beta_+^\gamma\alpha_-}$$

$$\theta = \frac{2L_x\nu_-\left(n_+\nu_+^E\beta_-^\mu\beta_+^\gamma + n_-\nu_-\beta_+^\mu\beta_-^\gamma\right)}{n_0 k_y\upsilon_0^2\left(\beta_-^\mu + \beta_+^\gamma\right)} = \left(\frac{E_x}{E_0}\right)^2$$

$$\delta = \delta_+^0 + \delta_-^0 + \delta_+^L + \delta_-^L$$

$$\upsilon_0 = \mu_- E_0, n_0 = n_-^0 + n_+^0, Z_0 = \frac{L_x}{\sigma_0 s}, \sigma_0 = e\left(n_-^0\mu_- + n_+^0\mu_+\right)$$

s is crystal cross-section, L_x is crystal length.

$$A=\frac{1}{\alpha_x}\left[\frac{\omega^3}{\Omega_1^3}\left(\alpha_x+\frac{\nu_+^2}{\omega^3}\right)\frac{1}{\beta_x^{\mu}}+\frac{\omega^3}{\Omega_2^3}\cdot\frac{\mu_+}{\mu_-}\cdot\frac{\nu_+\omega^2+\nu_-^2\nu_+^E}{\beta_+^{\mu}\nu_+^E\omega^2\alpha_x}\right]\frac{\mu_+H}{c}\cos\alpha,\alpha=\frac{\mu_-H}{c}\theta$$

$$B=\left(\frac{\mu_+H}{c}\right)^2\frac{1}{\alpha_x}\left[\frac{\nu_-}{\omega\alpha_x\beta_+^H}\frac{\omega^3}{\Omega_1^3}-\frac{\omega^3}{\Omega_2^3}\left(1+\frac{\nu_-^2}{\omega^2}\right)\frac{\nu_+}{\omega}\cdot\frac{\mu_+}{\mu_-\alpha_x\beta_+^H}-\frac{\omega^3}{\Omega_2^3}e\upsilon_-\delta\cdot\frac{\mu_+H}{c}\cdot\frac{\mu_+}{\mu_-}\frac{1}{\alpha_x\theta}\right]\left(\frac{\mu_+H}{c}\right)^2\sin\alpha$$

$$D=\frac{\mu_+H}{c\theta}\left[\frac{3\omega^3}{\Omega_3^3}\frac{eE_0}{Tk_y}\left(\frac{\mu_-sH}{\mu_+cE_0}\right)^2\left(\alpha_x\nu_+^E\mu_+\beta_+^H\left(\alpha_x+\frac{\nu_-^2}{\omega^2}\right)-n_-\nu_-\mu_-\beta_-^{\gamma}\frac{\nu_-^2}{\omega^2}\left(\alpha_x+\frac{\nu_-^2}{\omega^2}\right)\right)\right]$$

$\mathrm{Re}\,Z$ and JmZ can change sign in an oscillatory manner due to variations in the frequency ω, the electric field E_0, and the magnetic field H. However, depending on the values of the parameters a, A, B, D, a sign change $\mathrm{Re}\,Z$ and JmZ is also possible without oscillation. Since the current in the external circuit $\mathrm{Re}\,Z<0$ and JmZ can be either negative or positive, we proceed as follows to determine the oscillation frequency. At $D=0$

$$\omega^2=\frac{n_+\nu_+^E\nu_-\mu_+\beta_+^{\gamma}}{n_-\mu_-\beta_-^{\gamma}\alpha_-}$$

is obtained.

Then

$$\frac{JmZ}{Z_0}=\left(\frac{\mu_+ H}{c}\right)^2\left(\frac{E_0}{E_x}\right)^2 e\upsilon_-\delta\left(\frac{\mu_+}{\mu_-}\right)^2 \beta_-^{\mu}\cos\alpha$$

From

$$\frac{JmZ}{Z_0}=\frac{R_1}{Z_0}=0$$

is obtained.

$$\cos\alpha=-\frac{R_1}{Z_0}\left(\frac{\mu_+ H}{c}\right)^2\left(\frac{E_x}{E_0}\right)^3\left(\frac{\mu_+}{\mu_-}\right)^2\frac{1}{e\upsilon_-\delta},\upsilon_x=\mu_- E_x$$

$$\frac{\mathrm{Re}\,Z}{Z_0}=\frac{R}{Z_0}=0$$

At $E_0 > E_x$

$$\omega=\nu_+\left(\frac{\nu_+^E}{2\nu_-\beta_+^{\gamma}}\right)^{1/2}$$

is obtained.

$$\frac{n_+}{n_-} > \frac{\mu_+}{\mu_-}\frac{\left(\nu_-\nu_+^E\right)^{1/2}}{\nu_+}\frac{\beta_-^\gamma}{\alpha_-\beta_-^\gamma}$$

Thus, at $E_0 > E_x$, $\mathrm{Re}\,Z$ and JmZ are satisfied, they pass through zero, and the sample receives energy at frequency $\omega = \nu_+\left(\frac{\nu_+^E}{2\nu_-\beta_+^\gamma}\right)^{1/2}$

In this case, the numerical values of $\mathrm{Re}\,Z$ and JmZ are determined by the value of Z_0, i.e.

$$\left|\mathrm{Re}\,Z\right| = JmZ = Z_0$$

At $\mathrm{Re}\,Z < 0$ and $JmZ > 0$ or, $JmZ < 0$ and both differ from the value Z_0, it is necessary to solve a system of equations.

Conclusion

In extrinsic semiconductors with two types of charge carriers, energy emission occurs (i.e., an external instability is excited) in the presence of an external constant electric field and a strong external magnetic field oriented perpendicular to it ($\mu_{\pm}H >> c$). The crystal dimension $L_x >> L_y, L_z$ is larger along the x-axis. The electric field at which the external instability sets in exceeds a certain critical field value, which depends on the equilibrium carrier concentrations and the oscillation frequency of the current in the external circuit. The oscillations occur at a high frequency $\omega \sim 10^9\ Hz$. It should be noted that current oscillations in the GaAs semiconductor compound (the Gunn effect) also occur at a high frequency $\omega \sim 10^9 \div 10^{11}\ Hz$. Such semiconductors are advantageous for the fabrication of amplifiers and oscillators. The real and imaginary parts of the impedance have been calculated as functions of the equilibrium charge-carrier concentrations, characteristic frequencies, and the electric field.