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Impurity Semiconductor as an Energy Radiator in Presence of Constant External Electric Field

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Abstract

It is shown that an impurity semiconductor in the presence of an external electric field can become an energy radiator with the certain frequency. Values of the frequency and external electric field, at which excited waves inside the semiconductor become instable, have been determined

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Introduction

Vibrational effects in semiconductors are associated with possibilities of practical use of the current instability phenomenon to produce high-frequency energy generators. Production of such devices would, first of all, requires theoretical predictions. When the vibrations of current carriers inside a semiconductor are instable, the energy radiation of the specific frequency starts from the semiconductor [1]. Therefore, the theoretical studies of the instability condition in concrete examples semiconductors are of special scientific interest. In this work we theoretically investigate the conditions of the occurrence of instable waves inside a concrete semiconductor in the presence of an external constant electric field.

Let us consider a semiconductor with concentrations of electrons n_- and holes n_+ being placed in an external constant electric field. Moreover, in the semiconductor there are one-fold N and two-fold N_- negatively charged traps, and $N >> N_-, n_+ << N, N_-, n_- << N, N_-$ inequalities hold. Electrons are captured, and holes are emitted by one-fold charged traps through the Coulomb energy barrier. The thermal generation of electrons and hole capture occur without a barrier. Then concentrations $n_\pm$ and N_- are determined by equations:

$$\frac{\partial n_\pm}{\partial t} \pm div j_\pm = (\frac{\partial n_\pm}{\partial t})_{rec}; \frac{\partial N_-}{\partial t} = (\frac{\partial n_+}{\partial t})_{rec} - (\frac{\partial n_-}{\partial t})_{rec}; j_\pm = \pm(n_\pm \mu_\pm E \mp D_\pm \nabla n_\pm);$$

$$divJ = ediv(j_+ - j_-) = 0; (\frac{\partial n_+}{\partial t})_{rec} = \gamma_+(E) n_{1+} N - \gamma_+(0) n_+ N_-; (\frac{\partial n_-}{\partial t})_{rec} = \gamma_-(0) n_{1-} N_- - \gamma_-(E) n_- N \tag{1}$$

Here and in the following $j_\pm$ are densities of flows of electrons and holes, $\gamma_-(0)$ is a coefficient of electron emission by two-fold negatively charged traps in the absence of an electric field, $\gamma_+(E)$ is the coefficient of hole emission by one-fold negatively charged traps in the presence of an electric field. For electron and hole concentrations $n_{1\mp}$ are determined from the stationary condition, i.e. $(\frac{\partial n_\mp}{\partial t})_{rec} = 0$ and $\gamma_\mp(E) = \gamma_\mp(0)$. We restrict ourselves to the one-dimensional case, i.e. directions of the wave vector $\vec{k}$ and electric field $\vec{E}_0$ are either parallel or anti-parallel.

Assuming that

$$n_\pm(x,t) = n_\pm^0 + \Delta n_\pm(x,t); N_-(x,t) = N_-^0 + \Delta N_-(x,t); E(x,t) = E_0 + \Delta E(x,t) \tag{2}$$

and introducing the following characteristic frequencies of capture and emission by equilibrium centers

$$\nu_- = \gamma_-(E_0) N_0; \nu_+ = \gamma_+(0) N_-^0; \nu_+^E = \gamma_+(E_0) N_0; \nu_-^1 = \gamma_-(E_0) n_-^0 + \gamma_-(0) n_{1-};$$

$$\nu_+^1 = \gamma_+(0) n_+^0 + \gamma_+(E_0) n_{1+}; n_{1+} = \frac{\gamma_+(0) n_+^0 N_-^0}{\gamma_+(E_0) N^0}; n_{1-} = \frac{\gamma_-(E_0) N^0}{\gamma_-(0) N_-^0}, \tag{3}$$

we can characterize dependences of coefficients of electron capture and hole emission by the following dimensionless parameters:

$$\beta_+^\gamma = 2\frac{d \ln \gamma_+(E_0)}{d \ln(E_0^2)}; \beta_-^\gamma = 2\frac{d \ln \gamma_-(E_0)}{d \ln(E_0^2)}. \tag{4}$$

Supposing $(\Delta n_\pm, \Delta N_-, \Delta E) \sim e^{i(kx - \omega t)}$, substituting (2) into (1) taking into account (3) and (4), we obtain the dispersion equation in oder to determine the frequency of energy irradiation from the semiconductor of the following form [2]:

$$\omega^3 + (\omega_1 + i\omega_2)\omega^2 + (\omega_3^2 + i\omega_4^2)\omega - \nu\omega_4^2 = 0. \tag{5}$$

Here

$$\nu = \nu_+^1 + \nu_-^1; \omega_1 = \frac{k(\sigma_+^\mu v_- - \sigma_-^\mu v_+)}{\sigma^\mu}; v_\pm = \mu_\pm E_0; \sigma_\pm^\mu = e n_\pm^0 \mu_\pm^0 \beta_\pm^\mu; \beta_\pm^\mu = 1 + 2\frac{d \ln \mu_\pm(E_0)}{d \ln(E_0^2)};$$

$$\sigma^\mu = \sigma_+^\mu + \sigma_-^\mu; \omega_2 = \frac{\sigma_+^\gamma \nu_+^E - \sigma_-^\gamma \nu_-}{\sigma^\mu}; \omega_3^2 = \frac{\sigma_-^\gamma \nu_- \nu_+^1 - \sigma_+^\gamma \nu_+^E \nu_-^1 \frac{\mu_+}{\mu_-}}{\sigma^\mu}; \tag{6}$$

$$\omega_4^2 = \frac{\sigma_-^\gamma \nu_- k v_+ + \sigma_+^\gamma \nu_+^E k v_-}{\sigma^\mu} ; \sigma_\pm^\gamma = e n_\pm \mu_\pm \beta_\pm^\gamma .$$

Exact solutions of (5) in a general form are extremely bulky and therefore we restrict ourselves by cases that are feasible in experiment. Let us present vibration frequencies as [3]

$$\omega = \omega_0 + i\gamma \text{ and } \gamma << \omega_0 . \qquad (7)$$

Separating real and imaginary parts of Equation (5) and taking into account (7) we get the following two equations:

$$\omega_0^3 + \omega_1 \omega_0^2 - 2\omega_0 \omega_2 \gamma + \omega_3^2 \omega_0 - \omega_4^2 \gamma - \nu \omega_4^2 = 0 , \qquad (8)$$

$$3\omega_0 \gamma + 2\omega_0 \omega_1 \gamma + \omega_2 \omega_0^2 + \omega_3^2 \gamma + \omega_4^2 \omega_0 = 0 . \qquad (9)$$

It is seen from Equations (8) and (9) that values of ω_0 and γ depend on values and signs of characteristic frequencies $\omega_1, \omega_2, \omega_3$. We consider the case

$$\omega_3^2 > 0, \omega_1 < 0, \omega_2 < 0 \text{ and } \omega_0 > \frac{\omega_3^2}{2|\omega_1|} . \qquad (10)$$

Then from (8) and (9) we obtain

$$\omega_0^3 - \omega_1 \omega_0^2 + 2\omega_0 \omega_2 \gamma - \omega_4^2 \gamma - \nu \omega_4^2 = 0 , \qquad (11)$$

$$3\omega_0 \gamma - 2\omega_1 \gamma - \omega_2 \omega_0 + \omega_4^2 = 0 . \ (12)$$

The vibration inside the semiconductor is growing (i.e. instable) as $\gamma > 0$. Then (12) has the form

$$\omega_0 = \frac{2\omega_1}{3} , \ \omega_4^2 = \frac{2\omega_1 \omega_2}{3} . \qquad (13)$$

Substituting values of ω_0 and ω_4^2 from (13) into (11) we obtain

$$\gamma = \nu + \frac{4}{27} \cdot \frac{\omega_1^3}{\omega_4^2} . \qquad (14)$$

From (14) it is seen that the value of γ can essentially vary depending on the validity of the following inequalities: 1)$\nu > \frac{4}{27} \cdot \frac{\omega_1^3}{\omega_4^2}$ and 2)$\nu < \frac{4}{27} \cdot \frac{\omega_1^3}{\omega_4^2}$.

Then the frequency of energy radiation from the semiconductor has got the value $\omega_0 = \frac{2\omega_1}{3}$ and the condition $\omega_0 >> \gamma$ is fully satisfied when the external electric field is determined from

$$\omega_4 > \frac{1}{\sqrt{2}} \nu . \qquad (15)$$

Positive ness of ω_3^2 leads to

$$\frac{n_-}{n_+} \cdot \frac{\nu_-}{\nu_+^E} \cdot \frac{\nu_+^1}{\nu_-^1} \cdot \frac{\beta_-^\gamma}{\beta_+^\gamma} \cdot \frac{\mu_-}{\mu_+} > 1 . \qquad (16)$$

The condition (16) of energy radiation from an impurity semiconductor with frequency (15) at possible experimental conditions is fully satisfied.

Dependences of mobilities $\mu_{\pm}^{0}$ on an electric field depend on charge carrier scattering. In the case of scattering by acoustic vibrations of the lattice $\mu_{\pm} \sim E^{-1/2}$ and $\frac{d\ln\mu_{\pm}}{d\ln E_0^2} = -\frac{1}{2}$, and in the case of scattering by lattice optical vibrations $\frac{d\ln\mu_{\pm}}{d\ln E_0^2} \approx \frac{1}{2}$.

To evaluate dimensionless parameters $\beta_{\pm}^{\gamma}$ the determination of the Coulomb potential around negative impurities is needed. However, so far as $\mu_{-} >> \mu_{+}$ and $\nu_{+}^{1} \sim \nu_{-}^{1}$ in the case of $n_{-}^{0} \geq n_{+}^{0}$ condition (16) is fulfilled. Thus, in impurity semiconductors considered by us, (for example, gold-doped germanium, $GeAu$), an instable wave arises under the certain constant electric field. In these conditions the semiconductor becomes a source of energy radiation of the specific frequency and with a specific wave growth increment inside the semiconductor.

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