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Excitation of unstable waves in two-valley semiconductors of the GaAs type in external electric and magnetic fields

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Abstract

It is theoretically proved that the excited wave in two-valley semiconductors is growing. It is indicated that the directions of external fields play an essential role for the appearance of growing waves in the sample. It is shown that oscillations can occur at certain values of the sample dimensions L_x, L_y, L_z. Analytical formulas for the frequency of the growing waves are obtained. The interval of variation of the external electric field in a strong magnetic field $\mu H >> c$ has been determined.

Keywords: growth, oscillation, frequency, increment, valley, mobility, effective mass

1. Introduction

In [1-5], current oscillations in semiconductors with one type of charge carriers and in semiconductors with two types of charge carriers were theoretically investigated. In these theoretical studies, analytical expressions were obtained for the vibration frequency and for the critical electric field at the onset of vibration inside the sample. It is known that fluctuations in the current in the Gunn effect occurs due to the transition of electrons from a low energy level to a higher energy

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level. Of course, after the transition of electrons from the lower energy level to the upper energy level, the number of charge carriers in the lower valley decreases, and in the upper valley their number increases. After the inelastic interaction of charge carriers, losing the energy received from the electric field, they return to the lower valley. The transition time from the lower valley to the upper valley τ_{12} differs from the time of the transition from the upper valley to the lower valleyτ_{21}, i.e.

$$\tau_{12} \neq \tau_{21} \quad (1)$$

Under the influence of external electric magnetic fields, current fluctuations in the circuit occur due to the presence of inequality (1). The effective mass of charge carriers m_a in the lower valley, and the effective mass of charge carriers m_6 differ significantly

$$m_a << m_b \quad (2)$$

(in GaAs, $m_a = 0{,}072m_0$, $m_b = 1{,}2m_0$, m_0 is the mass of a free electron) In the Gunn effect [6], current oscillations begin at a critical value of the external electric field, approximately $2 \cdot 10^3 \frac{V}{sm}$or $3 \cdot 10^3 \frac{V}{sm}$. In these critical values of the electric field, the inequality

$$eE_0L >> D\nabla n \quad (3)$$

(L is electron mean free path, e is elementary charge, D is diffusion coefficient, is ∇nelectron concentration gradient). In force (3), during the transition from valley a to valley b, diffusion currents do not play the main role. In this theoretical work, we will investigate current oscillations in semiconductors of the GaAs type under the action of an external constant electric and magnetic fields, taking into account inequalities (1,2,3). We will investigate current oscillations in two-valley semiconductors at different directions of external electric and magnetic fields

2. Basic equations of the problem

The electron concentration in GaAs is constant, therefore

$$n_0 = n_a + n_b = const$$
$$n'_a = -n'_b \quad (4)$$

The equation of continuity in the valleys "a" and "b" is as follows:

$$\frac{\partial n'_a}{\partial t} + div\vec{j}'_a = \frac{n'_a}{\tau_{12}} \quad (5)$$

$$\frac{\partial n'_b}{\partial t} + div\vec{j}'_b = \frac{n'_b}{\tau_{21}} \quad (6)$$

Taking into account (3) in the presence of external electric and magnetic fields, the expressions for the flux density in the valleys “a” and “b” have the form:

$$\vec{j}_a = \sigma_a \vec{E} + \sigma_{1a}\left[\vec{E}\vec{H}\right] + \sigma_{2a}\vec{H}\left[\vec{E}\vec{H}\right] \tag{7}$$

$$\vec{j}_b = \sigma_b \vec{E} + \sigma_{1b}\left[\vec{E}\vec{H}\right] + \sigma_{2b}\vec{H}\left[\vec{E}\vec{H}\right] \tag{8}$$

Here $\sigma_{a,b} = en_{a,b}\mu_{a,b}$; $\sigma_{1a,b} = en_{a,b}\mu_{1a,b}$; $\sigma_{2a,b} = en_{a,b}\mu_{2a,b}$, $\mu_{a,b}, \mu_{1a,b}, \mu_{2a,b}$ corresponding to electron mobility

$$\frac{\partial H'}{\partial t} = -irot\vec{E}' \tag{9}$$

3. Theory

To determine the dispersion equation from (5.6), taking into account (7.8.9), we will assume that all variable quantities change as monochromatic waves, i.e.

$$(E', H', n'_a, n'_b) \sim e^{i(\vec{k}\vec{r} - wt)}$$

($\vec{k}$ is wave vector, $\omega$is vibration frequency within the sample)

$$\vec{E} = \vec{E}_0 + \vec{E}', n_a = n_a^0 + n'_a, n_b = n_b^0 + n'_b, \vec{H} = \vec{H}_0 + \vec{H}' \tag{10}$$

The direction of the magnetic field $\vec{H}_0$ relative to the electric field $\vec{E}_0$is essential for determining the dispersion equation. First, we obtain the dispersion equation from (5-6) with the orientation of the electric and magnetic fields by the following sample

$$\vec{E}_0 = \vec{\imath}E_0, \vec{H}_0 = \vec{\imath}H_0 \tag{11}$$

($\vec{\imath}$ is unit vector in x). On the basis of (11) from (7) it is easy to obtain:

$$\vec{j}'_a = \sigma_a^0 \vec{E}' + \vec{\imath}2E'_x(\sigma_a^0\varphi_a + \sigma_{2a}^0\varphi_{2a}) + \vec{\imath}\frac{n'_a}{n_{a0}}E_0(\sigma_a^0 + \sigma_{2a}^0) + \vec{\imath}\sigma_{2a}^0 E'_x + \frac{\sigma_{1a}^0 cE_0}{\omega H_0}\left(E'_x\vec{k} - k_x\vec{E}'\right) + \frac{2\sigma_{2a}^0 cE_0}{\omega H_0}\left[\vec{k}\vec{E}'\right] \tag{12}$$

$\vec{j}'_b$ has the form (12) only "a" must be replaced by "b". Writing down the components (12) ($\vec{j}'_{ax}, \vec{j}'_{ay}, \vec{j}'_{az}$) and from the condition $j'_{ay} = 0, j'_{az} = 0$ finds the components E'_y and E'_z then supplying the values $E'_y$and E'_z in j'_{ax} we find:

$$j'_{ax} = \left[\sigma_{2a}^0(1 + 2\varphi_{2a}) + 2\varphi_a\sigma'_a - \frac{2\sigma_{2a}ck_zE_0}{\omega H_0}\cdot\frac{1}{\frac{\sigma_a^0\sigma_{1a}^0}{2(\delta_{2a}^0)^2}\cdot\frac{\omega H}{ckyE_0} - 2} - \frac{2\sigma_{2a}^0 ck_yE_0}{\omega H_0}\left(\frac{2L_y}{L_x} + \frac{1}{u^2}\right)\right]E'_x + \frac{n'_a}{n_{a0}}\sigma_{2a}^0 E_0 \tag{13}$$

j'_{bx}has the form (13) if "a" is replaced by "b". Supplying $j'_{ax}$and j'_{bx}in (14) taking into account (4)

$$divj'_{ax}=\frac{n'_a(1+i\omega\tau_{12})}{\tau_{12}}$$
$$divj'_{bx}=\frac{n'_b(1+i\omega\tau_{21})}{\tau_{21}} \quad (14)$$

We easily obtain the following dispersion equation

$$\left(\frac{i}{\tau_{21}}-\omega+\mu_{2a}^{0}k_xE_0\right)\sigma_{2a}^{0}\left[\Phi_a\left(\frac{L_y\omega^2}{2\pi\mu_aE_0}-2\omega\right)-\frac{4\pi cE_0}{H_0L_z}-\frac{8\pi cE_0}{L_yH_0}\cdot\frac{1}{u^2}\left(\frac{1}{4\pi}\cdot\frac{\omega L_y}{\mu_aE_0}-2\right)-\frac{8\pi cE_0}{H_0L_x}\left(\frac{1}{4\pi}\cdot\frac{L_y\omega}{\mu_aE_0}-2\right)\right]+$$
$$+\left(\frac{i}{\tau_{12}}+\mu_{2b}^{0}k_xE_0\right)\sigma_{2b}^{0}\left[\Phi_b\left(\frac{1}{4\pi}\frac{L_y\omega^2}{\mu_bE_0}-2\omega\right)-\frac{4\pi cE_0}{H_0L_z}-\frac{8\pi cE_0}{L_yH_0}\cdot\frac{1}{u^2}\left(\frac{1}{4\pi}\cdot\frac{\omega L_y}{\mu_bE_0}-2\right)-\frac{8\pi cE_0}{H_0L_x}\left(\frac{1}{4\pi}\cdot\frac{L_y\omega}{\mu_bE_0}-2\right)\right] \quad (15)$$

Here $\Phi_a=2\varphi_a+1+2\varphi_{2a},\Phi_b=2\varphi_b+2\varphi_{2b}$

From (15) it turns out:

$$\omega^3-\left[\frac{i}{\tau_{21}}+\mu_{2b}^{0}k_xE_0+\alpha_{\ a}\omega_a+\frac{m_a}{m_b}\frac{\omega_{\mathrm{a}}}{\omega_b}\left(\frac{i}{\tau_{12}}+\mu_{2a}^{0}k_xE_0\right)\right]\omega^2+$$
$$+\left[\omega_a\left(\frac{i}{\tau_{21}}+\mu_{2b}^{0}k_xE_0\right)\alpha_a+\omega_x\omega_a+\alpha_b\omega_a\left(\frac{i}{\tau_{12}}+\mu_{2a}^{0}E_0k_x\right)\right]\omega- \quad (16)$$
$$-\omega_a\omega_x\left(\frac{i}{\tau_{21}}+\mu_{2b}^{0}E_0k_x\right)-\omega_x\omega_a\frac{m_a}{m_b}\left(\frac{i}{\tau_{12}}+\mu_{2a}^{0}k_xE_0\right)=0$$

Here $\omega_x=\frac{16\pi cE_0}{H_0L_x}$, $\alpha_a=2\Phi_a+\frac{2cL_y}{\mu_aH_0L_x}$, $\alpha_b=2\Phi_b+\frac{2cL_y}{\mu_bH_0L_x}$, $\omega_a=\frac{4\pi\mu_a^0E_0}{\Phi_aL_y}$

Supplying in (16) $\omega=\omega_0+i\omega_1$, taking into account $\omega_1<<\omega_0$ (17), we obtain the following two equations for determining $\omega_0$and ω_1

$$\omega_0^3-\Omega_0\omega_0^2+2\Omega_1\omega_0\omega_1+\gamma_0^2\omega_0-\gamma_1^2\omega_1-\delta_0^3=0 \quad (17)$$
$$3\omega_0^2\omega_1-2\Omega_0\omega_0\omega_1-\Omega_1\omega_0^2+\gamma_0^2\omega_1+\gamma_1^2\omega_0-\delta_1^3=0 \quad (18)$$

Here $\Omega_0=\mu_{2b}^{0}E_0k_x$, $\Omega_1=\frac{m_a}{m_b}\cdot\frac{1}{\tau_{12}}$, $\gamma_0^2=\frac{64\pi^2}{\Phi_{\mathrm{a}}u}\cdot\frac{(\mu_aE_0)^2}{L_xL_y}$; $\gamma_1^2=\frac{8\pi}{\tau_{12}u}\cdot\frac{\mu_aE_0}{k_x}$; $\delta_0^3=\frac{32\pi^2}{u}\sigma_{2b}^{0}\frac{\mu_{2\mathrm{a}}^{0}\mu_{\mathrm{a}}E_0^2}{L_x^2}$, $\delta_1^3=\frac{64\pi^2}{4}\frac{(\mu_aE_0)^2}{\Phi_aL_xL_y}\cdot\frac{2}{\tau_{12}}\cdot\frac{m_a}{m_b}$

When obtaining dispersion equations (17-18), we assumed that

$$\tau_{21} = \tau_{12}\frac{m_b}{m_a}, L_y = 4L_z, L_x >> \frac{1}{2}\left(\frac{m_b}{m_a}\right)^2 L_y$$

Analysis of equation (17-18) shows that for

$$E_0 >> E_{кр}, K_{кр} = \left(\frac{1}{\tau_{12}}\right)^2 \frac{L_x}{12\pi\sigma_{2b}^0\mu_{2a}^0} \tag{19}$$

$$\omega_0 = \frac{8\sigma_{2b}^0}{u}\frac{m_b}{m_a}\frac{\mu_a}{\mu_{2b}^0}, \omega_1 = \frac{1}{3}\frac{m_b}{m_a}\cdot\frac{1}{\tau_{12}} \tag{20}$$

And the condition$\omega_0 >> \omega_1$ is met if

$$\tau_{12} >> \frac{1}{24en_{0b}\mu_a}\left(\frac{m_a}{m_b}\right)^2 \tag{21}$$

It can be seen from (20) that the frequency of the growing oscillations decreases with ω_1 an increase in the external magnetic field as $\omega \sim \frac{1}{H}$, and the critical field decreases as $E_{кр} \sim \frac{1}{H^4}$. Thus, with an external magnetic field, it is possible to obtain current oscillations in two-valley semiconductors at lower values of the external electric field. This result was obtained in our previous theoretical works [7]. If we evaluate the existing experimental values (19-20), then we can easily get approximate values

$$\omega_0 \sim 10^9 Hz, \omega_1 \sim 2\cdot 10^7 Hz,\ E_{кр} \sim 10^2\frac{V}{sm}, \tau_{21} \approx 6\tau_{12}.$$

Now we will choose the following orientation of the electric and magnetic fields

$$\vec{E}_0 = \vec{i}E_0, \vec{H}_0 = \vec{j}H_0 \tag{22}$$

With orientation (22), repeating calculations using equations (5.6) taking into account (4), we obtain the following dispersion equation

$$\omega^2 - \left[\omega_b + \omega_a\frac{\tilde{\sigma}_b}{\tilde{\sigma}_a} - \frac{\sigma_1^2+\sigma_2^2}{\tilde{\sigma}_a} + i\left(\frac{1}{\tau_{21}} + \frac{\tilde{\sigma}_b}{\tilde{\sigma}_a}\frac{1}{\tau_{12}}\right)\right]\omega - \frac{\sigma_1^2 u_{b_0} + \sigma_1^2 u_{a_0}}{\tilde{\sigma}_a} - \frac{i}{\tilde{\sigma}_a}\left(\frac{\sigma_1^2}{\tau_{21}} + \frac{\sigma_2^2}{\tau_{12}}\right) = 0 \tag{23}$$

Here

$$\sigma_1^2 = k_x\tilde{\sigma}_a u_{b_0}, \sigma_2^2 = k_x\tilde{\sigma}_b u_{a_0}, \tilde{\sigma}_a = \sigma_{a_0}(1+2\varphi_a); \tilde{\sigma}_b = \sigma_{b_0}(1+2\varphi_b); \varphi_a = \frac{d\,ln\,\mu_a}{d\,ln(E_0^2)}; \varphi_b = \frac{d\,ln\,\mu_b}{d\,ln(E_0^2)}$$

From (23) is the electric field

$$E_0 = \frac{2\sigma_{a_0}\sigma_{b_0}(1+\varphi_a+\varphi_b)}{en_0\mu_{a_0}\mu_{b_0}k_x} = 2\varphi\frac{en_{b_0}}{k_x} \tag{24}$$

Supplying (24) to (23) with

$$\left(\frac{1}{\tau_{21}}+\frac{\tilde{\sigma}_b}{\tilde{\sigma}_a}\cdot\frac{1}{\tau_{12}}\right)^2=8\,\varphi e n_{b_0}\frac{\sigma_1^2\mu_{b_0}+\sigma_2^2\mu_{a_0}}{\tilde{\sigma}_a} \quad (25)$$

We obtain the following expressions for the oscillation frequency in the above two-valley semiconductors

$$\omega_1=\frac{1}{\sqrt{2}}\left(\frac{1}{\tau_{21}}+\frac{\tilde{\sigma}_b}{\tilde{\sigma}_a}\cdot\frac{1}{\tau_{12}}\right)\left[\frac{i}{2}\left(1+\sqrt{2}\right)\right],\ \omega_2=-\frac{1}{\sqrt{2}}\left(\frac{1}{\tau_{21}}+\frac{\tilde{\sigma}_b}{\tilde{\sigma}_a}\cdot\frac{1}{\tau_{12}}\right)\left[\frac{i}{2}\left(1-\sqrt{2}\right)\right] \quad (26)$$

It can be seen from (26) that the excited wave with frequency $\omega_0=\frac{1}{\sqrt{2}}\left(\frac{1}{\tau_{21}}+\frac{\tilde{\sigma}_b}{\tilde{\sigma}_a}\cdot\frac{1}{\tau_{12}}\right)$and grows with the increment $\gamma=\frac{1}{\sqrt{2}}\left(\frac{1}{\tau_{21}}+\frac{\tilde{\sigma}_b}{\tilde{\sigma}_a}\cdot\frac{1}{\tau_{12}}\right)\frac{1+\sqrt{2}}{2}$

A wave with a frequency ω_2 is damped. This means that when the magnetic field is directed perpendicular to the electric field, a wave is excited with a frequency that is very different from the case $E_0 \perp H_0$

4. Conclusion

Two-valley semiconductors with valleys "a" and "b" effective masses of electrons $m_a \ll m_b$. In an external constant electric and magnetic fields, we radiate energy at a high frequency, at certain values of the electric field. Magnetic field values are $\mu_{a_0}H_0 >> c$ and $\mu_{b_0}H_0 >> c$. These fluctuations occur in the sample with certain values L_x, L_y, L_z. $H_0 \perp E_0$ the oscillation is excited with a different frequency and in a different value of the external electric field. Rough estimates of the electric field and vibration frequency within the existing experiments are quite satisfactory.

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