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Instability in multi-valley semiconductors in external electric and magnetic fields

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. The paper takes into account that the time of transition from the lower valley to the upper valley differs from the time of transition from the upper valley to the lower valley. It means $\tau_{12} \neq \tau_{21}$ In the sample, the total concentration is constant, and therefore, $n_0 = n_a + n_b = const$. The changes in the corresponding concentrations are equal to each other and have the opposite sign, i.e. $n'_a = -n'_b$. It is taken into account that at critical values of the electric and magnetic fields and the corresponding concentrations they change as a monochromatic wave. And the change in these quantities differs little from their equilibrium value. For simplicity of mathematical calculations, the external electric and magnetic fields are directed in the same way, i.e. in x direction. Since the current oscillations in one direction (for example, along x) are studied in the experiment, the following equalities were taken into account $j'_y = 0, j'_z = 0$. In the vicinity of the critical field at the beginning of the current oscillation in the sample, the current oscillation frequency is $\varpi = \varpi_0 + i\varpi_1$, $\varpi_1 << \varpi_0$. In addition, the magnitude of the critical electric field, at which the current fluctuation changes depending on the magnetic field as follows $E_{kr} \sim \dfrac{1}{H^4_{external}}$.

Keywords: growth, oscillation, frequency, increment, valley, mobility, effective mass, Gunn's effect.

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 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 valley τ_{21}, i.e.

$$\tau_{12} \neq \tau_{21} . \tag{1}$$

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_b differ significantly

$$m_a << m_b \tag{2}$$

(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 $2 \cdot 10^3 \, V/cm$ or $3 \cdot 10^3 \, V/cm$. In these critical values of the electric field, the inequality

$$eE_0 L >> D\nabla n \quad (3)$$

(L is electron mean free path, e is elementary charge, D is diffusion coefficient, ∇n is electron 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 (1-3). Under the conditions of execution (1-3) and taking into account the direction of the external electric and magnetic fields, we will theoretically investigate the frequency of current oscillations in the above semiconductors and the critical value of the external electric field. We will investigate current oscillations in two-valley semiconductors at different directions of external electric and magnetic fields.

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:

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

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

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

$$\frac{\partial H'}{\partial t} = -irot\vec{E}' \quad (9) .$$

Theory

To determine the dispersion equation from (5, 6), taking into account (7-9), we will assume that all variable quantities change as monochromatic waves, i.e.

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

[8]

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

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

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

$$\vec{E}_0 = \vec{i}E_0, \vec{H}_0 = \vec{i}H_0 \quad (11)$$

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

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

$\vec{j}'_b$ 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:

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

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

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

We easily obtain the following dispersion equation

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

(15)

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

From (15) it turns out:

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

Here $\omega_x=\frac{16\pi cE_0}{H_0L_x}$, $\alpha_a=2\Phi_a+\frac{2cL_y}{\mu_aH_0L_x}$, $\alpha_b=2\Phi_b+\frac{2cL_y}{\mu_bH_0L_x}$, $\omega_a=\frac{4\pi\mu^0_aE_0}{\Phi_aL_y}$.

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 ω_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 $\Omega_0=\mu^0_{2b}E_0k_x$, $\Omega_1=\frac{m_a}{m_b}\cdot\frac{1}{\tau_{12}}$, $\gamma_0^2=\frac{64\pi^2}{\Phi_au}\cdot\frac{\left(\mu_aE_0\right)^2}{L_xL_y}$; $\gamma_1^2=\frac{8\pi}{\tau_{12}u}\cdot\frac{\mu_aE_0}{k_x}$; $\delta_0^3=\frac{32\pi^2}{u}\sigma^0_{2b}\frac{\mu^0_{2a}\mu_aE_0^2}{L_x^2}$, $\delta_1^3=\frac{64\pi^2}{4}\frac{\left(\mu_aE_0\right)^2}{\Phi_aL_xL_y}\cdot\frac{2}{\tau_{12}}\cdot\frac{m_a}{m_b}$.

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

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

Analysis of equation (17-18) shows that for

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

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

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

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

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 $E_{kr} \sim \frac{1}{H^4}$. 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

$$\omega_0 \sim 10^9\,Hz\,,\ \omega_1 \sim 2\cdot 10^7\,Hz\,,\ E_{kr} \sim 10^2\,V/cm\,,\ \tau_{21} \approx 6\tau_{12}\,.$$

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

$$\vec{E}_0 = \vec{i}E_0\,,\ \vec{H}_0 = \vec{j}H_0\,. \quad (22)$$

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

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

Here

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

From (23) is the electric field

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

Supplying (24) to (23) with

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

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 $\vec{E}_0 \perp \vec{H}_0$.

Conclusion

Two-valley semiconductors with valleys “a” and “b” effective masses of electrons are $m_a \ll m_b$. 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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Э.Р. Гасанов, Ш.Г. Халилова

Сыртқы электр және магнит өрістеріндегі көпжақты жартылай өткізгіштердегі тұрақсыздық

Екіжақты жартылай өткізгіштердегі қозған толқын біртіндеп артатыны теориялық түрде дәлелденді. Сыртқы өрістердің бағыттары үлгідегі артып келе жатқан толқындардың пайда болуы үшін маңызды рөл атқаратыны көрсетілген. Тербелістер үлгі өлшемдерінің белгілі бір мәндерінде L_x, L_y, L_z болуы мүмкін екендігі дәлелденген. Артып келе жатқан толқындардың жиілігі үшін аналитикалық формулалар алынды. Күшті магнит өрісі бар $\mu H >> c$ сыртқы электр өрісінің өзгеру аралығы анықталды. Жұмыста төменгі аймақтан жоғарғы аймаққа өту уақыты жоғарғы аймақтан төменгі аймаққа өту уақытынан өзгеше екендігі ескерілген. Бұл дегеніміз $\tau_{12} \neq \tau_{21}$. Үлгіде жалпы концентрация тұрақты, сондықтан $n_0 = n_a + n_b = const$. Тиісті концентрациялардың өзгеруі бір-біріне тең және қарама-қарсы таңбаға ие, яғни $n'_a = -n'_b$. Электр және магнит өрістерінің критикалық мәндерінде және тиісті концентрацияларда монохроматты толқын ретінде өзгеретіні ескерілді. Және бұл шамалардың өзгеруі олардың тепе-теңдік мәнінен аз ерекшеленеді. Математикалық есептеулердің қарапайымдылығы үшін сыртқы электр және магнит өрістері бір бағытта, яғни x бойынша бағытталған. Экспериментте токтың тербелістері бір бағытта (мысалы, x бойынша) зерттелгендіктен, келесі теңдіктер $j'_y = 0,\ j'_z = 0$ болатыны ескерілді. Үлгідегі бастапқы ток тербелісінің критикалық өрісінің айналасында ток тербелісінің жиілігі $\varpi = \varpi_0 + i\varpi_1, \varpi_1 << \varpi_0$. Сонымен қатар, критикалық электр өрісінің шамасы, токтың тербелісі магнит өрісіне байланысты келесідей өзгереді $E_{kr} \sim \dfrac{1}{H^4_{external}}$.

Кілт сөздер: арту, тербеліс, жиілік, өсу, жақты, қозғалыс, тиімді масса, Ганн эффектісі.

Э.Р. Гасанов, Ш.Г. Халилова

Неустойчивость в многодолинных полупроводниках во внешнем электрическом и магнитном полях

Теоретическим образом доказано, что возбуждаемая волна в двухдолинных полупроводниках является нарастающей. Указано, что направления внешних полей играют существенную роль для появления нарастающих волн в образце. Показано, что колебания могут происходить при определенных значениях размеров образца L_x, L_y, L_z. Получены аналитические формулы для частоты нарастающих волн. Определен интервал изменения внешнего электрического поля при сильном магнитном поле $\mu H >> c$. В статье учтено, что время перехода из нижней долины в верхнюю отличается от времени перехода из верхней долины в нижнюю. Это означает $\tau_{12} \neq \tau_{21}$. В образце общая концентрация постоянна, поэтому $n_0 = n_a + n_b = const$. Изменения соответствующих концентраций равны друг другу и имеют противоположный знак, то есть $n'_a = -n'_b$ Учтено, что при критических значениях электрического и магнитного полей соответствующие концентрации меняются как монохроматические волны. Изменение этих величин мало отличается от их равновесного значения. Для простоты математических вычислений внешнее электрическое и магнитное поля направлены в одном направлении, то есть по направлению *x*. Поскольку в эксперименте исследованы колебания тока в одном направлении (например, вдоль *x*), учитывались следующие равенства: $j'_y = 0, j'_z = 0$. В окрестности критического поля в начале колебания тока в образце, частота колебания тока $\varpi = \varpi_0 + i\varpi_1$, $\varpi_1 << \varpi_0$. Кроме того, величина критического электрического поля, при котором колебание тока изменяется в зависимости от магнитного поля, выглядит следующим образом: $E_{kr} \sim \dfrac{1}{H^4_{external}}$.

Ключевые слова: нарастание, колебание, частота, приращение, долина, подвижность, эффективная масса, эффект Ганна.