DETERMINATION OF FREQUENCY IN TWO VALLEY SEMICONDUCTORS SUCH AS GaAs

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It is shown that the dimensions of the crystal play an essential role in the excitation of an unstable wave with a certain frequency and growth rate, and it is possible to regulate the appearance of current oscillations with a magnetic field. The values of the frequency of the current oscillation are found. The value of the external electric field and the frequency of current oscillation are determined at the initial point.

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INTRODUCTION

A simple way to convert electromagnetic energy using semiconductors that do not contain any electron-hole junctions is the phenomenon of electrical instability. The current-voltage characteristic (CVC) of such a sample is linear. Generation and amplification of electromagnetic oscillations, current stabilization, "memory" effect, etc. are possible. Instability depends on the characteristics of the solid. For example, in a GaAs crystal, the I–V characteristics and the energy spectrum of charge carriers are described by the following graphs

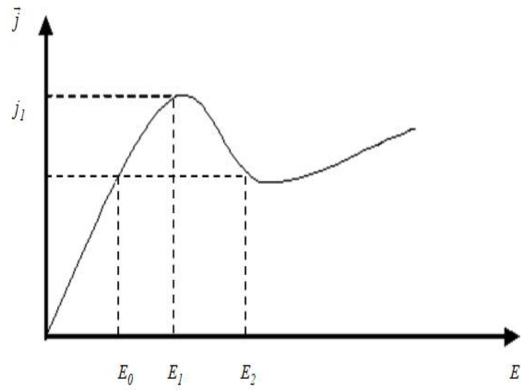

Fig. The dependence of the current density on the electric field is an N-shaped volt-ampere characteristic.

Field strength is a multivalued function of current density. The energy spectrum of electronic gallium arsenide is two-valley. With the help of an electric field, charge carriers are heated in the sub-zone with high mobility, as a result, having acquired a sufficiently high energy, they pass into the sub-zone with higher energy and low mobility.

The effective mass of charge carriers in GaAs are important $m_a = 0{,}072m_0$ $m_b = 1{,}2m_0$, and the mobility of charge carriers in the valleys are $\mu_a = \frac{e\tau}{m_a}$ and $\mu_b = \frac{e\tau}{m_b}$ ($\mu_a \ll \mu_b$, μ is the mobility of charge carriers). We will designate valleys 1-a, 2-b.

The total current has the form

$$\vec{j} = en_a\mu_a E + en_b\mu_b E = en\mu(E)E \qquad (1)$$

$$n = n_a + n_b = const \quad \frac{dn}{dt} = 0 \qquad (2)$$

Instability in GaAs in 1963 was discovered experimentally by the English physicist J. Gann [1]. In theoretical works [2-3], the Gunn effect is investigated in the presence of an external electric field. All theoretical studies are calculated without carrier diffusion. However, in the scientific literature there are no theoretical works devoted to theoretical studies of the Gunn effect taking into account intervalley scattering based on the solution of the Boltzmann kinetic equation. In this theoretical work, we will calculate the frequencies of current oscillations in the presence of a strong magnetic field by applying the Boltzmann equation, taking into account the intervalley scattering of charge carriers.

$$\mu H_0 >> c \qquad (3)$$

(H_0 is intensity of a constant magnetic field, c is speed of light)

THEORY

In a stationary state, the electric field is independent of time. Under the influence of an electric field for the current to be stationary, electrons must be scattered on any lattice inhomogeneities (vibrations of atoms or crystal defects). Under the action of external forces, the state of charge carriers cannot be described by the equilibrium distribution function $f_0(\varepsilon)$, but it is necessary to introduce a nonequilibrium distribution function $f(\vec{k},\vec{r})$, which is the probability that an

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electron with a wave vector (quasimomentum $\hbar\vec{k}$) is near a point. The distribution function $f(\vec{k},\vec{r})$ is found from the kinetic Boltzmann equation. It is assumed that the distribution function can change under the influence of two reasons, either under the influence of external factors, or under the influence of collisions of electrons with lattice vibrations (phonons) and crystal defects.

Then, in the considered stationary state, these factors compensate each other.

$$\left(\frac{\partial f}{\partial t}\right)_{external} + \left(\frac{\partial f}{\partial t}\right)_{collision} = 0 \qquad (4)$$

In the presence of external electric and magnetic fields, equation (4) has the form

$$\vec{V}\vec{\nabla}f + \frac{e}{\hbar}\left(E + \frac{1}{c}[\vec{V}\vec{H}]\right)\vec{\nabla}_{\vec{k}}f = \left(\frac{\partial f}{\partial t}\right)_{collision} \qquad (5)$$

$$\vec{V} = \frac{1}{\hbar}\nabla_{\vec{k}}\varepsilon(\vec{k})$$

Neglecting the anisotropic one, we solve the equation. We assume that for valley “a” with intravalley, and for valley “b”, intravalley scattering prevails over intervalley one. Then the Boltzmann equations for the valley "a" and "b" can be written in the following form

$$\left(\frac{\partial f^a}{\partial t}\right)_{external} + \left(\frac{\partial f^a}{\partial t}\right)_{intravalley} = 0 \qquad (6)$$

$$\left(\frac{\partial f^b}{\partial t}\right)_{внеш} + \left(\frac{\partial f^b}{\partial t}\right)_{внутридол} = 0 \qquad (7)$$

In [2] Davydov showed that in a strong electric field the distribution function can be represented in the form

$$f = f_0 + \frac{\vec{P}}{p}\vec{f}_1 \qquad (8)$$

($\vec{P}$ -momentum)

Then for the valleys “a” and “b” we write

$$f^a = f_0^a + \frac{\vec{P}}{p}\vec{f}_1^a,\ \ f^b = f_0^b + \frac{\vec{P}}{p}\vec{f}_1^b \qquad (9)$$

In [3], from solution (9), the distribution function f^b was found in the presence of an electric field

$$f_0^b = Be^{-\alpha_b(\varepsilon-\Delta)^2} \qquad (10)$$

$$f_1^b = -\frac{em_b l_b}{p}\vec{E}\frac{\partial f_0^b}{\partial p} \qquad (11)$$

Here

$$l_b = \frac{\pi h^4\rho u_0^2}{D^2 m_b^2 k_0 T},\ \alpha_b = \frac{3D^4 m_b^5 k_0 T}{e^2\pi^2 h^8\rho^2 u_0^2 E^2} \qquad (12)$$

l_b - the length of the free path in the valley «b», D - deformation potential, T- grate temperature,
p -the density of the substance, u_0 - sound speed.

It was shown in [2] that in strong electric and magnetic fields in the case of intravalley scattering, the function f_1^b has the form:

$$f_1^b = -\frac{el_b m_b}{p}\frac{\partial f_0^b}{\partial p}\cdot\frac{\vec{E}+\frac{el_b}{cp}[\vec{E}\vec{H}]+\left(\frac{el_b}{cp}\right)^2\vec{H}(\vec{E}\vec{H})}{1+\left(\frac{el_b H}{cp}\right)^2} \qquad (13)$$

$$f_0^b = Be^{-\alpha_b(\varepsilon-\Delta)^2} \qquad (14)$$

(B -normalization constant)

$$\alpha_b = \frac{3D^4 m_b^5 k_0 T\left[1+\left(\frac{el_b H}{cp}\right)^2\right]}{e^2\pi^2 h^8\rho^2 u_0^2\left[E^2+\left(\frac{el_b}{cp}\right)^2(\vec{E}\vec{H})^2\right]} \qquad (15)$$

$$f_0^a = Ae^{-\alpha_a\varepsilon^2} \qquad (16)$$

We calculate the total current density

$$\vec{j} = \vec{j}_a + \vec{j}_b \qquad (17)$$

$$\vec{j}_a = \frac{e}{3\pi^2\hbar^3 m_a}\int_0^\infty f_1^a p^3 dp = \frac{e^2 l_a\alpha_a A}{3\pi^2\hbar^3 m_a^2}\left\{\vec{E}\left(\frac{cH}{el_a}\right)^2 p^7 e^{-\frac{\alpha_a p^4}{4m_a^2}}dp + \right.$$
$$\left. + \frac{el_a}{c}\left(\frac{cp}{el_a H}\right)^2\int_0^\infty p^6 e^{-\frac{\alpha_a p^4}{4m_a^2}}dp\left[\vec{E}\vec{H}\right] + \left(\frac{el_a}{c}\right)^2\left(\frac{cpH}{el_a}\right)^2\int_0^\infty p^5 e^{-\frac{\alpha_a p^4}{4m_a^2}}dp\vec{H}\left(\vec{E}\vec{H}\right)\right\} \qquad (18)$$

It can be written in $\vec{j}_b$ a similar way, only it is necessary to replace the index "a" with "b" and A with B. The integrals in (18) are calculated by the following formula (gamma function).

$$\int_0^\infty x^n e^{-xdx} = \Gamma(n+1) \qquad (19)$$

Applying formulas (19), we obtain expressions for the total current density of the expression

$$\vec{j} = \Sigma\vec{E} + \Sigma_1\left[\vec{E}\vec{h}\right] + \Sigma_2\vec{h}\left(\vec{E}\vec{h}\right) \qquad (20)$$

$$\Sigma = \frac{8nc^2 m_a^{1/2}\alpha_a^{-1/4}}{3\sqrt{2} l_a \Gamma(3/4)} \cdot \frac{1}{H^2} \cdot \left(\frac{m_b}{m_a}\right)^3 \left(\frac{m_0}{m_a}\right)^{1/2}$$

$$\Sigma_1 = \frac{4enc}{H}\frac{\Gamma(7/4)}{\Gamma(3/4)} \qquad (21)$$

$$\Sigma_2 = \frac{4e^2 n l_a \alpha_a^{1/4}}{3\sqrt{2} m_a^{1/2}} \cdot \frac{\Gamma(3/2)}{\Gamma(3/4)} \cdot \left(\frac{m_b}{m_0}\right)^{1/2}$$

After calculating ($\Sigma, \Sigma_1, \Sigma_2$), the frequencies of the current oscillation can be calculated. In work [4-5], we calculate the frequency of the current oscillation in the presence of a weak magnetic field ($\mu H >> c$)

To calculate the oscillation frequency, we find from Maxwell's equation the current density

$$\vec{j}' = \frac{c}{4\pi} rot\vec{H}' + \frac{1}{4\pi}\frac{\partial \vec{E}'}{\partial t} \qquad (22)$$

and we will equate the expressions of currents (19-22), as a result we will receive the following expressions

$$\frac{c}{4\pi} rot\vec{H}' + \frac{1}{4\pi}\frac{\partial E'}{\partial t} = \Sigma \vec{E} + \Sigma_1\left[\vec{E}\vec{h}\right] + \Sigma_2 \vec{h}\left(\vec{E}\vec{h}\right) \qquad (23)$$

We have chosen the following coordinate system

$$\vec{H}_0 = \vec{h}H_0, \vec{E}_0 = \vec{h}E_0 \qquad (24)$$

To determine the variable part of the magnetic field, we will use the Maxwell equations

$$\frac{\partial \vec{H}'}{\partial t} = -crot\vec{E}', \vec{H}' = \frac{c}{\omega}\left[\vec{k}\vec{E}'\right] \qquad (25)$$

Considering $H' \sim e^{i(\vec{k}x-\omega t)}$ and $E' \sim e^{i(\vec{k}x-\omega t)}$ from (24), taking into account (25), we obtain the following dispersion equations for determining the frequency of current oscillations

$$\Omega^2 \vec{E}' + \left(\vec{i}\,\Sigma_1 H_0 E_y' - \vec{h}\Sigma_2 H_0^2 E_z'\right)\omega - 2\Sigma_2 E_0 H_0 c\left[\vec{k}\vec{E}'\right] + \left[\Sigma_1 c E_0 E_z' - \frac{ic^2}{4\pi}\left(\vec{k}\vec{E}'\right)\right]\vec{k} = 0 \qquad (26)$$

Writing down the components of the vector equation (26), we obtain the following three equations

$$\begin{cases} \Omega_1^2 E_x' + \Omega_2^2 E_y' + \Omega_3^2 E_z' = 0 \\ \Xi_1^2 E_x' + \Xi_2^2 E_y' + \Xi_3^2 E_z' = 0 \\ \Theta_1^2 E_x' + \Theta_2^2 E_y' + \Theta_3^2 E_z' = 0 \end{cases} \qquad (27)$$

Here:

$$\Omega_1^2 = \Omega^2 - \frac{ic^2 k_x^2}{4\pi},\ \Omega_2^2 = \Sigma_1 H_0 \omega + 2\Sigma_2 E_0 H_0 k_z c - \frac{ic^2 k_x k_y}{4\pi},\ \Omega_3^2 = \Sigma_1 E_0 c k_x - 2\Sigma_2 E_0 H_0 c k_y - \frac{ic^2 k_x k_z}{4\pi},$$

$$\Xi_1^2 = -2\Sigma_2 E_0 H_0 c k_z - \frac{ic^2 k_x k_y}{4\pi},\ \Xi_2^2 = \Omega^2 - \frac{ic^2 k_y^2}{4\pi},\ \Xi_3^2 = 2\Sigma_2 E_0 H_0 c k_x + \Sigma_1 E_0 c k_y - \frac{ic^2 k_y k_z}{4\pi}, \qquad (28)$$

$$\Theta_1^2 = 2\Sigma_2 E_0 H_0 c k_y - \frac{ic^2 k_x k_z}{4\pi},\ \Theta_2^2 = -2\Sigma_2 E_0 H_0 c k_x - \frac{ic^2 k_y k_z}{4\pi},\ \Theta_3^2 = \Omega^2 - \Sigma_2 H_0^2 \omega + \Sigma_1 E_0 c k_z - \frac{ic^2 k_z^2}{4\pi}.$$

We obtain the following dispersion equations for determining the frequency of the current oscillation from the solution of the system of equations (28)

$$\Omega^2 = 16\pi^2 \Sigma_2^2\left[\frac{\Sigma^2}{ck_z} - \frac{2ck_z}{\Sigma^2} + i2\pi^2\left(\frac{L_z}{L_x}\right)^2\right] \qquad (29)$$

L_z, L_x - corresponding sample lengths.

Here

$$\Omega = \Sigma + \frac{ic^2k^2}{4\pi\omega} + \frac{i\omega}{4\pi} \qquad (30)$$

When deriving the dispersion equation, we used the inequality for the electric field

$$E_0 >> uE_{char},\ u = \frac{16\pi^2\sigma_{20}^2 k_y^2}{c^2 k_x^2 k_z^2 \Delta} \qquad (31)$$

$$\Sigma_2^2 = \Sigma_{20}^2 \alpha^{1/2} = \Sigma_{20}^2 \cdot \frac{E_x}{\Delta E_0}$$

$$E_x = \left(\frac{3D^4 m_0 m_a^3 m_b k_0 T}{\pi^2 e^2 \hbar^8 \rho^2 u_0^2}\right)^{1/2}$$

$$L_x = L_y$$

By supplying (30) to (31), we obtain the following equations for determining the frequency of the current oscillation

$$\omega^2 - 4\pi i\left[\Sigma - \frac{4\pi^2 \Sigma_2 L_z}{L_x}\left(\frac{1}{2} + i\right)\right]\omega + 4\pi c^2 k^2 = 0 \qquad (32)$$

From solution (33), taking into account (32), we easily obtain:

$$\omega_0 = \frac{8\pi^3 \Sigma_2 L_z}{L_x}, \;\; \omega_1 = 2\sqrt{\pi} ck \tag{33}$$

Formulas (33) for the frequency of the current oscillation and the growth rate of the oscillation are obtained at

$$ck >> \pi\sqrt{2}\Sigma \frac{E_x}{E_0} \tag{34}$$

e.g

$$E_0 >> E_x \frac{\pi\sqrt{2}\Sigma}{ck} \tag{35}$$

Comparison of (35) with (31) is in good agreement.

DISCUSSION OF THE RESULTS

The intervals of variation of the external constant electric field are determined by applying the kinetic equation in two-valley semiconductors of the GaAs type, at which radiation of electromagnetic energy occurs. Such an unstable state occurs in a sample, the dimensions of which are $L_x = L_y$, $L_z >> L_x, L_y$, the coordinate system $\vec{H}_0 = \vec{h} H_{0z}$, $\vec{E}_0 = \vec{h} E_{0z}$, $\mu H_{0z} >> c$ and, with a different coordinate system $E_0 \perp H_0, \vec{E}_0 \vec{H}_0 = E_0 H_0 \cos\alpha, \left[\vec{E}_0 \vec{H}_0\right] = E_0 H_0 \sin\alpha$, a different value of theoretical research is needed. It can be seen from the CVC graph that the point $\frac{dj}{dE} = 0$ is the beginning of the oscillation, i.e. $\omega_1 = 0$ is increment. Considering $\omega = \omega_0$, $\omega_0 = 2\pi\sigma$.

$$E_0 = E_{char} \cdot \frac{c^2 k^2}{\pi \Delta u_0^2} \tag{36}$$

$$u_0 = \frac{8nc^2 m_a^{1/2} m_0^{1/2}}{3\sqrt{2}\Gamma(3/4) H^2} \cdot \left(\frac{m_b}{m_a}\right)^3 \tag{37}$$

With an increase in the magnetic field, the electric field increases in a square, and this can be used to regulate the instability.

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