International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

March 2022	Issue 50	Volume 14	Number 1	Pages 228-232

INSTABILITY IN TWO GaAs VALLEY SEMICONDUCTORS IN ELECTRIC AND MAGNETIC FIELDS

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Abstract- It is shown that an unstable wave with a certain frequency and growth rate is excited in a GaAs-type crystal in a strong magnetic field. The crystal dimensions play an essential role for the excitation of this wave. It has been proven that it is possible to regulate the appearance of current fluctuations with a magnetic field. The interval of variation of the external electric field and the value of the frequency of the current oscillation are found. The values of the external electric field and the frequency of the current oscillation are determined at the initial point. In anisotropic media with an electronic type of charge carriers, an increasing thermomagnetic wave was excited under certain conditions. Analytical formulas have been found for the frequency and for the increment of this wave. A formula for the ratios of the temperature gradient has been found.

Keywords: Instability, Oscillations, Growth Rate, Frequency, Radiation.

1. INTRODUCTION

The phenomenon of electrical instability is a simple way to convert electromagnetic energy using semiconductors that do not contain either electron-hole transitions or any other artificially created microscopic inhomogeneities. From the point of view of radio engineering, a sample in which there are resting or moving domains is a system with a substantially nonlinear current-voltage characteristic (CVC). Depending on the conditions of the experiment, the generation and amplification of electromagnetic oscillations, stabilization of the current, the effect of "memory", etc. are possible here. Accordingly, the applied significance of the phenomenon of instability in semiconductors is great. The appearance of instabilities in solids (as well as in semiconductors) is associated with specific features of the solid.

For example, in a GaAs crystal, the volt-ampere characteristics and the energy spectrum of charge carriers are described by the bellowing graphs

An essential feature of the volt-ampere characteristic is that in a certain range of current values, the field strength is a multivalued function of the 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 sub-zone with higher energy and low mobility.

The effective mass of charge carriers in GaAs are:

$$m_a = 0.072 m_0 ,\quad m_b = 1.2 m_0 \tag{1}$$

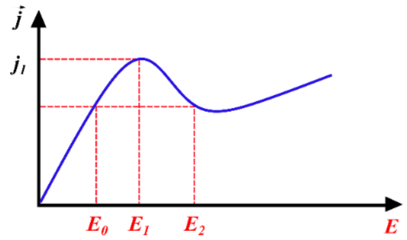

Figure 1. The dependence of the current density on the electric field is an N-shaped volt-ampere characteristic

We will mark the valleys 1-a, 2-b. The mobility of charge carriers in valleys is:

$$\mu_a = \frac{e\tau}{m_a} ,\quad \mu_b = \frac{e\tau}{m_b} \tag{2}$$

where, $\mu_a << \mu_b$. The total current has the form

$$\vec{j} = en_a\mu_a E + en_b\mu_b E = en\mu(E)E \tag{3}$$

$$n = n_a + n_b = \text{const} ,\quad \frac{dn}{dt} = 0 \tag{4}$$

Instability in GaAs in 1963 was discovered experimentally by the English physicist J. Gunn [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. The influence of a strong magnetic field on the Gunn effect has not been theoretically investigated.

In this theoretical work, we will investigate the influence of a strong magnetic field on the Gunn effect by applying the Boltzmann equation taking into account the intervalley scattering of charge carriers, and also calculate the frequency of current oscillations in the presence of a strong magnetic field.

$$\mu H_0 >> c \quad (5)$$

where, μ is mobility of charge carriers, H_0 is intensity of a constant magnetic field, and c is speed of light.

2. THEORY

The study of charge carriers in a nonequilibrium state, when they move in a crystal, under the influence of applied external fields, electric, magnetic and thermal, is of great theoretical and practical interest. In a stationary state, the electric field (as well as other physical quantities) does not depend on time. Under the influence of an electric field for the current to be stationary, electrons should be scattered on any lattice inhomogeneities (vibrations of atoms or crystal defects) and would give the solution to the energy accumulated in the electric field.

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 electron with a wave vector (quasimomentum $\hbar\vec{k}$) is near a point $\vec{r}$. 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: 1) under the influence of external factors; 2) under the influence of collisions of electrons with lattice vibrations (phonons) and crystal defects.

Current fluctuations (instability) in semiconductors are of interest from several points of view. First, it provides an easy way to convert electromagnetic energy using semiconductors. From the point of view of radio engineering, a sample in which there are resting or moving valleys is a system with a substantially nonlinear current-voltage characteristic (CVC). Generation and amplification of electromagnetic oscillations are possible here, depending on the experimental conditions. Second, the mechanisms responsible for the onset of instability reflect one or another specific feature of a solid. Finally, thirdly, we have here a case when physics came face to face with the properties of an essentially nonequilibrium macroscopic system.

In theoretical works [1-4], current oscillations in two-valley and impurity semiconductors are investigated. Typical examples of the dependence of the current density in a spatially homogeneous system on the field strength under conditions when there is a falling section on the volt-ampere characteristics are shown in Figure 2.

An essential feature of the characteristic in Figure 1 consists in the fact that in a certain range of currents, the field strength is a multivalued function of the current density. When $E=E_1$ and $E=E_3$ the differential conductivity is positive, when $E=E_2$ it is negative. In Figure 2 the current density is an inhomogeneous function at $E=E_p$ and $E=E_\upsilon$ the differential conductivity becomes infinite.

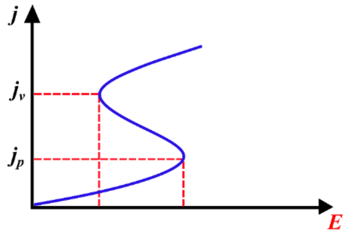

Figure 2. N-shaped current voltage characteristic

We will theoretically investigate the instability in semiconductors with a characteristic in Figure 1. In these semiconductors, under the influence of external factors (electric field, magnetic field), valleys appear in which the charge densities differ. A typical example of these semiconductors is GaAs. In a GaAs compound in 1964, the English scientist Gunn first observed current fluctuations (i.e., instability). The physical mechanism of the Gunn effect was explained in [6-7]. This mechanism leads to the appearance of a falling section on the volt-ampere characteristics due to the peculiarities of the energy spectrum of charge carriers. The idea is to use an electric field to heat the carriers in a sub band with high mobility, as a result of which they, having acquired a sufficiently high energy, will pass into a sub band with high energy and low mobility. In GaAs, the carrier dispersion law is as follows.

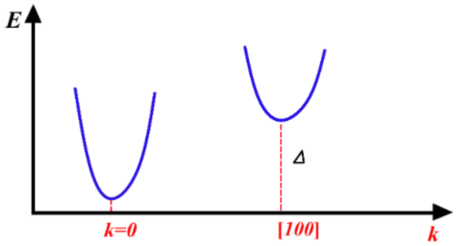

Figure 3. Energy dependence on the wave vector in GaAs

The dispersion law near the main minimum is isotropic. The effective masses are as follows $m_a = 0.072 m_0$, $m_b = 1.2 m_0$. Energy distance between $\Delta = 0.36\text{eV} >> k_0 T$ is minimum. With a sufficiently strong heating of the electrons, some of them pass into the upper minimum. The mobility of carriers in valleys is very different and $\mu_a >> \mu_b$.

On the basis of the Gunn effect, generators are prepared that operate the entire volume of the sample. In all theoretical works in the literature on the Gunn effect, it is assumed that intervalley scattering is small compared to intra-valley scattering. In this theoretical work, on the basis of solving the Boltzmann kinetic equation, taking into account intervalley scattering under the influence of an external electric field, we calculate the total current in two-valley (GaAs) semiconductors and determine the critical electric field at which the current oscillates.

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

$$\left(\frac{\partial f}{\partial t}\right)_{\text{external}}+\left(\frac{\partial f}{\partial t}\right)_{\text{collision}}=0 \quad (6)$$

In the presence of external electric and magnetic fields, Equation (6) has the form

$$\vec{V}\vec{\nabla}f+\frac{e}{\hbar}\left(E+\frac{1}{c}\left[\vec{V}\vec{H}\right]\right)\vec{\nabla}_{\vec{k}}f=\left(\frac{\partial f}{\partial t}\right)_{\text{collision}} \quad (7)$$

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

When solving this problem, we neglect the anisotropic one, because in studies of the Gunn effect on GaAs samples, no orientation dependence was found. 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

$$\left(\frac{\partial f^a}{\partial t}\right)_{\text{external}}+\left(\frac{\partial f^a}{\partial t}\right)_{\text{intravalley}}=0 \quad (8)$$

$$\left(\frac{\partial f^b}{\partial t}\right)_{\text{external}}+\left(\frac{\partial f^b}{\partial t}\right)_{\text{intravalley}}=0 \quad (9)$$

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

$$f=f_0+\frac{\vec{P}}{p}\vec{f}_1 \quad (10)$$

where, $\vec{P}$ is momentum. Then for the valley "*a*" and "*b*" we write:

$$f^a=f_0^a+\frac{\vec{P}}{p}\vec{f}_1^a,\ f^b=f_0^b+\frac{\vec{P}}{p}\vec{f}_1^b \quad (11)$$

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

$$f_0^b=Be^{-\alpha_b(\varepsilon-\Delta)^2} \quad (12)$$

$$f_1^b=-\frac{em_bl_b}{p}\vec{E}\frac{\partial f_0^b}{\partial p} \quad (13)$$

$$l_b=\frac{\pi\hbar^4\rho u_0^2}{D^2m_b^2k_0T},\ \alpha_b=\frac{3D^4m_b^5k_0T}{e^2\pi^2\hbar^8\rho^2u_0^2E^2} \quad (14)$$

where,
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:

$$f_1^b=-\frac{el_bm_b}{p}\frac{\partial f_0^b}{\partial p}\times\frac{\vec{E}+\frac{el_b}{cp}\left[\vec{E}\vec{H}\right]+\left(\frac{el_b}{cp}\right)^2\vec{H}\left(\vec{E}\vec{H}\right)}{1+\left(el_bH/cp\right)^2} \quad (15)$$

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

where, B is normalization constant.

$$\alpha_b=\frac{3D^4m_b^5k_0T\left[1+\left(\frac{el_bH}{cp}\right)^2\right]}{e^2\pi^2\hbar^8\rho^2u_0^2\left[E^2+\left(\frac{el_b}{cp}\right)^2\left(\vec{E}\vec{H}\right)^2\right]} \quad (16)$$

$$f_0^a=Ae^{-\alpha_a\varepsilon^2} \quad (17)$$

We calculate the total current density

$$\vec{j}=\vec{j}_a+\vec{j}_b \quad (18)$$

$$\begin{aligned}\vec{j}_a&=\frac{e}{3\pi^2\hbar^3m_a}\int_0^\infty f_1^a p^3dp=\frac{e^2l_a\alpha_aA}{3\pi^2\hbar^3m_a^2}\times\\&\times\left\{\vec{E}\left(\frac{cH}{el_a}\right)^2p^7e^{-\frac{\alpha_ap^4}{4m_a^2}}dp+\right.\\&+\frac{el_a}{c}\left(\frac{cp}{el_aH}\right)^2\int_0^\infty p^6e^{-\frac{\alpha_ap^4}{4m_a^2}}dp\left[\vec{E}\vec{H}\right]+\\&\left.+\left(\frac{el_a}{c}\right)^2\left(\frac{cpH}{el_a}\right)^2\int_0^\infty p^5e^{-\frac{\alpha_ap^4}{4m_a^2}}dp\vec{H}\left(\vec{E}\vec{H}\right)\right\}\end{aligned} \quad (19)$$

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 (19) are calculated by the following formula (gamma function).

$$\int_0^\infty x^ne^{-xdx}=\Gamma(n+1) \quad (20)$$

Applying formulas (20), we obtain expressions for the total current density of the expression

$$\begin{aligned}&\vec{j}=\sigma\vec{E}+\sigma_1\left[\vec{E}\vec{h}\right]+\sigma_2\vec{h}\left(\vec{E}\vec{h}\right)\\&\sigma=\frac{8nc^2m_a^{1/2}\alpha_a^{-1/4}}{3\sqrt{2}l_a\Gamma(3/4)}\times\frac{1}{H^2}\times\left(\frac{m_b}{m_a}\right)^3\left(\frac{m_0}{m_a}\right)^{1/2}\\&\sigma_1=\frac{4enc}{H}\frac{\Gamma(7/4)}{\Gamma(3/4)}\\&\sigma_2=\frac{4e^2nl_a\alpha_a^{1/4}}{3\sqrt{2}m_a^{1/2}}\times\frac{\Gamma(3/2)}{\Gamma(3/4)}\times\left(\frac{m_b}{m_0}\right)^{1/2}\end{aligned} \quad (21)$$

After calculating (σ,σ_1,σ_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 ($\mu H >> c$).

3. CURRENT OSCILLATION FREQUENCY IN A STRONG MAGNETIC FIELD ($\mu H >> c$)

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

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

and we will equate the expressions of currents (20-22), as a result we will receive the following expressions

$$\frac{c}{4\pi}\operatorname{rot}\vec{H}' + \frac{1}{4\pi}\frac{\partial E'}{\partial t} = \sigma\vec{E} + \sigma_1\left[\vec{E}\vec{h}\right] + \sigma_2\vec{h}\left(\vec{E}\vec{h}\right) \quad (23)$$

We have chosen the following coordinate system

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

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

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

Considering $H' \sim e^{i\left(\vec{k}x - \omega t\right)}$ and $E' \sim e^{i\left(\vec{k}x - \omega t\right)}$ from (23), taking into account (25), we obtain the following dispersion equations for determining the frequency of current oscillations.

$$\Omega^2\vec{E}' + \left(\vec{i}\sigma_1 H_0 E'_y - \vec{h}\sigma_2 H_0^2 E'_z\right)\omega -$$
$$-2\sigma_2 E_0 H_0 c\left[\vec{k}\vec{E}'\right] + \quad (26)$$
$$+\left[\sigma_1 c E_0 E'_z - \frac{ic^2}{4\pi}\left(\vec{k}\vec{E}'\right)\right]\vec{k} = 0$$

Writing down the components of the vector Equation (26), we obtain the following three Equations

$$\begin{cases} \Omega_1^2 E_x{}' + \Omega_2^2 E_y{}' + \Omega_3^2 E_z{}' = 0 \\ \delta_1^2 E_x{}' + \delta_2^2 E_y{}' + \delta_3^2 E_z{}' = 0 \\ \theta_1^2 E_x{}' + \theta_2^2 E_y{}' + \theta_3^2 E_z{}' = 0 \end{cases} \quad (27)$$

where,

$$\Omega_1^2 = \Omega^2 - \frac{ic^2 k_x^2}{4\pi}$$

$$\Omega_2^2 = \sigma_1 H_0\omega + 2\sigma_2 E_0 H_0 k_z c - \frac{ic^2 k_x k_y}{4\pi}$$

$$\Omega_3^2 = \sigma_1 E_0 c k_x - 2\sigma_2 E_0 H_0 c k_y - \frac{ic^2 k_x k_z}{4\pi}$$

$$\delta_1^2 = -2\sigma_2 E_0 H_0 c k_z - \frac{ic^2 k_x k_y}{4\pi}$$

$$\delta_2^2 = \Omega^2 - \frac{ic^2 k_y^2}{4\pi}$$

$$\delta_3^2 = 2\sigma_2 E_0 H_0 c k_x + \sigma_1 E_0 c k_y - \frac{ic^2 k_y k_z}{4\pi} \quad (28)$$

$$\theta_1^2 = 2\sigma_2 E_0 H_0 c k_y - \frac{ic^2 k_x k_z}{4\pi}$$

$$\theta_2^2 = -2\sigma_2 E_0 H_0 c k_x - \frac{ic^2 k_y k_z}{4\pi}$$

$$\theta_3^2 = \Omega^2 - \sigma_2 H_0^2\omega + \sigma_1 E_0 c k_z - \frac{ic^2 k_z^2}{4\pi}$$

We obtain the following dispersion Equations for determining the frequency of the current oscillation from the solution of the system of Equations (27).

$$\Omega^2 = 16\pi^2\sigma_2^2\left[\frac{\sigma^2}{ck_z} - \frac{2ck_z}{\sigma^2} + i2\pi^2\left(\frac{L_z}{L_x}\right)^2\right] \quad (29)$$

where, L_z, L_x are corresponding sample lengths.

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

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

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

$$\sigma_2^2 = \sigma_{20}^2\alpha^{1/2} = \sigma_{20}^2\cdot\frac{E_x}{\Delta E_0}$$

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

$$L_x = L_y$$

By supplying (30) to (29), we obtain the following Equations for determining the frequency of the current oscillation.

$$\omega^2 - 4\pi i\left[\sigma - \frac{4\pi^2\sigma_2 L_z}{L_x}\left(\frac{1}{2} + i\right)\right]\omega + 4\pi c^2k^2 = 0 \quad (32)$$

From solution (32), taking into account (31), we easily obtain:

$$\omega_0 = \frac{8\pi^3\sigma_2 L_z}{L_x},\ \omega_1 = 2\sqrt{\pi}ck \quad (33)$$

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

$$ck >> \pi\sqrt{2}\sigma\frac{E_x}{E_0} \quad (34)$$

e.g.

$$E_0 >> E_x\frac{\pi\sqrt{2}\sigma}{ck} \quad (35)$$

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

4. CONCLUSION

Thus, by applying the kinetic equation in two-valley semiconductors of the GaAs type, the intervals of variation of the external constant electric field, at which the radiation of electromagnetic energy occurs, are determined. Such an unstable state occurs in a sample, the dimensions of which are $L_x = L_y$, $L_z >> L_x, L_y$ - where, our chosen coordinate system

$$\vec{H}_0 = \vec{h}H_{0z},\ \vec{E}_0 = \vec{h}E_{0z},\ \mu H_{0z} >> c \quad (36)$$

Not the only coordinate system in which current fluctuations occur. With another choice of coordinate systems $\left(E_0 \perp H_0, \vec{E}_0\vec{H}_0 = E_0 H_0\cos\alpha, \left[\vec{E}_0\vec{H}_0\right] = E_0 H_0\sin\alpha\right)$, a different amount of theoretical research is needed. For the system we have chosen, the frequency and growth rate (33) of the definition and it is easy to verify that $\omega_1 << \omega_0$., when the experimental data of Gann $\omega_0 \sim 10^9$ Hz are taken into account, and is in agreement with the experiment.

It can be seen from the volt-ampere characteristic that the point $\frac{dj}{dE}=0$ is the beginning of the oscillation, i.e., Increment

$$\omega_1 = 0 \tag{37}$$

Taking into account (37), i.e., $\omega = \omega_0$ from (32) we obtain

$$\omega_0 = 2\pi\sigma \tag{38}$$

$$E_0 = E_{char}\cdot\frac{c^2k^2}{\pi\Delta u_0^2} \tag{39}$$

$$u_0 = \frac{8nc^2 m_a^{1/2} m_0^{1/2}}{3\sqrt{2}\Gamma(3/4)H^2}\cdot\left(\frac{m_b}{m_a}\right)^3 \tag{40}$$

It can be seen from (33-40) that with an increase in the magnetic field, the electric field increases in a square, and this makes it difficult for the appearance of the radiative state of the sample. This means that instability can be regulated with a magnetic field.

Analytical formulas are found for the frequency and increment of a growing thermomagnetic wave in anisotropic media with an electronic type of charge carriers, as well as a formula for the temperature gradient ratios.

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BIOGRAPHIES

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