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DIMENSIONAL RADIATION OF A TWO-VALLEY SEMICONDUCTOR IN AN EXTERNAL ELECTRIC AND STRONG MAGNETIC FIELDS

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Abstract- By theoretical investigation of the current fluctuations in two-valley semiconductors, it has been proven that the crystal size is the main factor. Analytical expressions are obtained for the radiation frequency and for the oscillation increment. The intervals of variation of the external electric field during radiation are found. Analytical expressions are obtained for the transition times between the valleys. It has been proven that in order to excite current oscillations in multi-wavelength semiconductors, the size of the sample must be certain. The critical value of the electric field, when the current fluctuations appear, is almost the same as the value of the electric field obtained by the Gunn experiment.

Keywords: Transition Time, Upper Valley, Lower Valley, Crystal Size, Current Density, Electric Field, Frequency.

1. INTRODUCTION

In 1963, Gann, studying the behavior of gallium arsenide in the region of strong fields, discovered a phenomenon consisting in the occurrence of current oscillations with a frequency of 10^9-10^{10} Hz when a constant electric field is applied to the crystal. This phenomenon is called the Gunn effect. Many semiconductors, including gallium arsenide (GaAs), have a fairly complex band structure.

For the first time, the Gunn effect was observed in samples of gallium arsenide GaAs and indium phosphide InP with n-type electrical conductivity. The threshold field strength for GaAs is 0.3 MV/m, and for InP it is about 0.6 MV/m. To explain the Gunn effect, it is necessary to take into account the complex structure of the conduction band of semiconductors, which is not reflected by the simplest energy diagrams.

Let us consider the mechanism of instability leading to high-frequency oscillations of the current using the example of the Gann experiment. Let an external voltage be applied to a semiconductor of length *L*. If the semiconductor is homogeneous, then the electric field in the sample is also homogeneous, but any real crystal has inhomogeneities. This leads to the fact that in this place of the sample the field strength has an increased value. With an increase in the strength of the external field, the critical value here is reached earlier than in the rest of the sample. Because of this, in the region of inhomogeneity, transitions from minimum *A* to minimum *B* begin PCS Figure 1, i.e., heavy electrons appear. Mobility here decreases, and resistance further increases. This leads to an increase in the field strength at the point of inhomogeneity and a more intense transition of electrons to the *B* minimum. The field in the sample becomes sharply inhomogeneous. If the curve has a convexity downwards, $m>0$. If the curve has a convexity upwards, then $m<0$. In this case, the particle will accelerate in the direction opposite to the direction of electron acceleration, i.e., it will behave like some imaginary particle with positive mass and charge. Within the framework of the method, this particle is called a "hole".

In the central minimum, corresponding to the point $k=0$, electrons have a significantly lower effective mass and greater mobility than in the side valleys. When exposed to a weak field, electrons populate the lower valley, since their drift velocities and quasi-momenta are small. In strong electric fields exceeding a certain threshold value, most of the electrons acquire additional energy and go to the side valley. Such a transition is accompanied by a decrease in the mobility of charge carriers, and since the current density is proportional to the mobility, a section of negative differential conductivity appears on the current-voltage characteristic.

In multi-valley semiconductors, radiation begins in the presence of a certain critical value of the external electric (E_{kr}) field. In the Gunn effect in two-valley semiconductors of the GaAs type, the electric field E_{kr} is approximately 2×10^3 V/cm. In theoretical works [1-7] it is proved that under the influence of a strong magnetic field ($\mu H >> c$, μ is mobility of carriers, H is magnetic field, c is speed of light), it is possible to reduce the values E_{kr} at which energy radiation starts from the sample. This process, on the one hand, creates the possibility of obtaining alternative energy, on the other hand, leads to the creation of high-frequency devices (generators, amplifiers, etc.) [8-11]. Therefore, a theoretical study of the phenomenon of energy radiation is promising and very important. In the Gunn effect, the emission from a two-valley semiconductor GaAs occurred depending on the sample size.

Therefore, it is gentle, theoretically, to investigate the radiation conditions of a two-valley semiconductor at different crystal sizes. In this theoretical work, we will investigate some possible conditions for the radiation of a two-valley semiconductor (GaAs type) in the presence of an external constant electric and strong ($\mu H >> c$) constant magnetic field. Let us prove that the dimensions of the crystal (L_x, L_y, L_z) play an important role for the radiation of the crystal.

2. BASIC EQUATIONS OF THE PROBLEM

An essential feature of the characteristic in Figure 1 is that in a certain range of current values, the field strength is a multivalued function of the current density. In this range of current variation, the system can be in one of three spatially homogeneous states. The Gann effect is related to the N-shaped characteristic. With negative differential conductivity, electric charges in the system are distributed unevenly, i.e., spatial regions with different charge values appear in the system (i.e., electric domains appear). One of the mechanisms for the emergence of domains is the Ridley-Watkins-Hilsum mechanism. In electronic gallium arsenide GaAs, the dispersion law has the following form

The dependence of the energy of charge carriers on the wave vector in GaAs has the form:

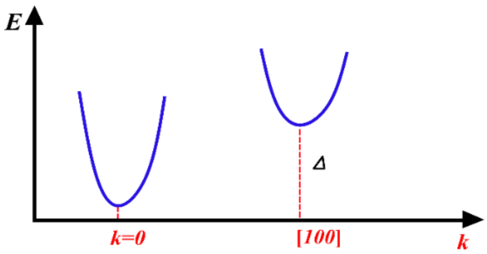

Figure 1. Energy dependence on the wave vector

Since the energy distance between the minima is relatively large ($\Delta = 0.36$eV , $\Delta \gg T_p$ is lattice temperature), under thermodynamic equilibrium conditions, the presence of upper valleys (minima) has practically no effect on the electron statistics. However, with a sufficiently strong heating of electrons by an electric field, some of them go to the upper minimum. The effective mass of electrons in the lower valley m_a is much less than the mass of electrons in the upper valley m_b. Therefore, the electron mobilities in the corresponding valleys are related by the relation.

Energy gap is $\Delta = 0.36$eV between valleys in GaAs. Charge carriers between two collisions receive energy from an external electric field eEl (e is electric charge, E is electric field, l -length of free path of charge carriers) and when $eEl = \Delta$ from valley "*a*" of charge carriers pass into valley "*b*". The effective masses and mobility in the GaAs crystal in the valleys have the following values.

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

where, m_0 is free electron mass.

$$\mu_a >> \mu_b \tag{2}$$

During the transition of charge carriers from valley "*a*" to valley "*b*", current fluctuations occur and radiation of the crystal begins. The concentration of the crystal is constant and has the form: $n = n_a + n_b = \text{const}$.

The current flux densities in the corresponding valleys j_a and j_b , and the total current j

$$\vec{j} = j_a + j_b \tag{3}$$

The equations of continuity in the valleys "*a*" and "*b*" are as follows:

$$\frac{\partial n_a}{\partial t} + \text{div}\vec{j}_a = \frac{n_a}{\tau_{ab}}, \quad \frac{\partial n_b}{\partial t} + \text{div}\vec{j}_b = \frac{n_b}{\tau_{ba}} \tag{4}$$

The τ_{ab} is time of transition of charge carriers from valley "*a*" to valley "*b*". The τ_{ba} is the time of the reverse transition of charge carriers.
where, $\tau_{aб} \neq \tau_{бa}$. The current flux densities in the presence of electric and magnetic fields are as follows:

$$\vec{j}_a = \sigma_a \vec{E} + \sigma_{1a}\left[\vec{E}\vec{H}\right] + \sigma_{2a}\vec{H}\left[\vec{E}\vec{H}\right], \quad \vec{j}_b = \sigma_b \vec{E} + \sigma_{1b}\left[\vec{E}\vec{H}\right] + \sigma_{2b}\vec{H}\left[\vec{E}\vec{H}\right] \tag{5}$$

In (5), the diffusion terms are not taken into account and the inequality

$$\sigma_{a,b}\vec{E} >> D_{a,b}\vec{\nabla} n_{a,b} \tag{6}$$

Maxwell's equation defines the relationship between alternating electric and alternating magnetic fields:

$$\frac{\partial \vec{H}'}{\partial t} = -\text{rot}\vec{E}'$$

3. THEORY

When studying the Gunn effect on GaAs samples, no dependence on orientation was found, which speaks in favor of this assumption. We will assume that for the lower valley intervalley scattering prevails over intravalley scattering, and for the upper valley intravalley scattering prevails over intervalley scattering.

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 a stationary current, electrons should be scattered on any inhomogeneities of the lattice (vibrations of atoms or crystal defects) and would give the lattice the energy accumulated in the electric field. Under the action of external forces, the state of charge carriers cannot be described by an equilibrium distribution function $f_0(\varepsilon)$, however a non-equilibrium distribution function $f\left(\vec{k},\vec{r}\right)$

must be introduced, which is the probability that electrons with a wave vector $\vec{k}$ (quasi-momentum $\hbar\vec{k}$) are near a point $\vec{r}$.

The distribution function $f\left(\vec{k},\vec{r}\right)$ 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.

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. By applying the Boltzmann 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, we will calculate the frequency of current oscillations in the presence of a strong magnetic field.

$$\mu H_0 >> c \tag{7}$$

(μ is the mobility of charge carriers, H_0 is the strength of a constant magnetic fields, c is the speed of light).

An essential feature of the *I-V* 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 electron gallium arsenide is two-valley. With the help of an electric field, a charge carrier is heated in a sub band with high mobility, as a result, they acquire a sufficiently high energy and pass into a sub band with high energy and low mobility. The effective mass of charge carriers in GaAs are $m_a = 0.072m_0$, $m_b = 1.2m_0$

The join solution of equations (2-7) determines the frequency of current oscillation in the sample. We choose the following coordinate system

$$\vec{E}_0 = \vec{i}E_{ox},\ \vec{E}_0 = \vec{i}E_{ox}$$

where, $\vec{i},\vec{h}$ are unit vectors and

$$\vec{j} = \vec{j}_a + \vec{j}_b \tag{8}$$

We find j'_x, j'_y, j'_z and under the condition

$$j'_x \neq 0,\ j'_y = j'_z = 0$$

$$\begin{aligned} j'_{ax} &= \sigma_a E'_x + \sigma_{1a} H_0 E'_y + \sigma_{2a} E'_z \\ j'_{bx} &= \sigma_b E'_x + \sigma_{1b} H_0 E'_y + \sigma_{2b} E'_z \end{aligned} \tag{9}$$

Supplying (9) to (4) taking into account (2) we easily obtain:

$$\frac{divj'_{ax}}{divj'_{bx}} = \frac{i\omega\dfrac{\tau_{ba}^2}{\tau_{ab}}\left(1-\dfrac{\tau_{ab}}{\tau_{ba}}\right)-\dfrac{\tau_{ba}}{\tau_{ab}}-\left(\omega\tau_{ba}\right)^2}{1+\left(\omega\tau_{ba}\right)^2} \tag{10}$$

The dispersion equation obtained from (10) has the form:

$$\begin{aligned} &\left(1+\omega^2\tau_{ba}^2\right)\left(\sigma_a\Omega_1+\sigma_{1a}\Omega_1-\sigma_{2a}\frac{\sigma_1}{\Omega}\frac{ck_z}{\omega}\frac{E_0}{H_0}\Omega_1\right)= \\ &=\left(\sigma_b\Omega_1+\sigma_{1b}\Omega_2-\sigma_{2b}\frac{\sigma_1}{\Omega}\frac{ck_z}{\omega}\frac{E_0}{H_0}\Omega_1\right)\times \\ &\times\left[\frac{i\omega^2\tau_{ba}^2}{\tau_{ab}}\left(1-\frac{\tau_{ab}}{\tau_{ba}}\right)-\frac{\tau_{ba}}{\tau_{ab}}-\omega^2\tau_{ba}^2\right] \end{aligned} \tag{11}$$

where,

$$\Omega = \sigma_2 + \frac{\sigma_1 ck_x}{\omega}\frac{E_0}{H_0};\ \Omega_2 = \omega - \frac{ck_y E_0}{H_0} + \frac{ck_z E_0}{H_0}\frac{\sigma_2}{\Omega};$$

$$\Omega_1 = \frac{\sigma}{\sigma_1}\omega - \frac{ck_x E_0}{H_0}$$

We denote $\omega_x = ck_x\dfrac{E_0}{H_0}$, $\omega_y = ck_y\dfrac{E_0}{H_0}$, $\omega_z = ck_z\dfrac{E_0}{H_0}$ and taking into account that $\left(\sigma_b,\sigma_{1b},\sigma_{2b}\right) << \left(\sigma_a,\sigma_{1a},\sigma_{2a}\right)$, $\tau_{ab} << \tau_{ba}$ from (11) we obtain:

$$\begin{aligned} &\left(1+\omega^2\tau_{ba}^2\right)\left(-\sigma_a\sigma_1\omega_x^2+\sigma_{1a}\sigma_2\omega^2-\sigma_{1a}\sigma_2\omega_y\omega\right)= \\ &=\left(-\sigma_b\sigma_1\omega_x^2+\sigma_{1b}\sigma_2\omega^2-\sigma_{1b}\sigma_2\omega_y\omega\right)\frac{i\omega\tau_{ba}^2}{\tau_{ab}} \end{aligned} \tag{12}$$

$$\frac{L_y}{L_z} = \frac{\sigma_{1a}}{\sigma_{2a}} = \frac{\sigma_{1b}}{\sigma_{2b}}$$

Denoting $Y = \omega\tau_{ba}$ considering, $y = y_0 + iy_1$, $y_1 << y_0$ form (12) we get:

$$\begin{aligned} &y_0^4 - \alpha_a y_0^3 + \alpha_a\frac{\sigma_{1b}}{\sigma_{1a}}\cdot\frac{1}{\tau_{ab}\omega_x}3y_0^2 y_1 - \\ &-\alpha_b^2 2y_0 y_1 - \omega_y\tau_{ba}y_0 - \frac{\sigma_b}{\sigma_a}y_1 - 1 = 0 \end{aligned} \tag{13}$$

$$\begin{aligned} &4y_0^3 y_1 - 3\alpha_a y_0^2 y_1 - \frac{\alpha_a}{\tau_{ab}\omega_x}\frac{\sigma_{1b}}{\sigma_{1a}}y_0^3 + \\ &+\alpha_b y_0^2 - \omega_y\tau_{ba}y_1 + \frac{\sigma_b}{\sigma_a}y_0 = 0 \end{aligned} \tag{14}$$

where, $\alpha_a = \left(\dfrac{\sigma_{1a}\sigma_2}{\sigma_a\sigma_1}\right)^{1/2}$, $\alpha_b = \dfrac{\sigma_{1b}\sigma_2}{\sigma_a\sigma_1}$, $\tau_{ba} = \dfrac{\alpha_a}{\omega_x}$

From (14) we find:

$$\tau_{ab} = \frac{L_x}{c}\left(\frac{1}{2\pi u}\cdot\frac{L_x}{L_y}\right)^{1/3}\left(\frac{H_0}{E_0}\right)^{2/3}\left(\alpha_a\right)^{1/6}$$

$$u = \left(\frac{2\pi}{3}\right)^2\frac{4^3}{\alpha_a^4}\frac{\sigma_{1a}}{\sigma_{1b}} \tag{15}$$

The $\tau_{ab} < \tau_{ba}$ leads to the following inequality:

$$E_0 > H_0\left(\frac{L_x}{L_y}\right)^{3/2}\left(\frac{1}{2\pi}\right)^2\left(\frac{9\alpha_a^4}{4^3}\right)^{3/2}\left(\frac{\sigma_a\sigma_1\sigma_{1b}}{\sigma_{1a}^2\sigma_2}\right)^{1/2} \tag{16}$$

Taking into account (16) from (13), we obtain:

$$y_0 = \alpha_a, \; y_1 = \frac{\sigma_{1a}}{3\sigma_{1b}\alpha_a} \times \tau_{ab}\tau_{ba}\omega_x\omega_y \quad (17)$$

$y_1 << y_0$ leads to inequality

$$E_0 >> H_0 \left(\frac{\sigma_{1a}}{\sigma_{1b}}\right)^{3/2} (2\pi)^{5/2} \left(\frac{1}{u}\right)^{1/2} \left(\frac{L_x}{L_y}\right)^2 \left(\frac{1}{\alpha_a}\right)^{1/2} \quad (18)$$

Equating the right side (16-18) we get:

$$\frac{L_x}{L_y} = \frac{u}{(2\pi)^5} \left(\frac{\sigma_{1b}}{\sigma_{1a}}\right)^3 \left(\frac{9\alpha_a^4}{4^3}\right)^3 \quad (19)$$

$$L_y = rL_x, \; L_x = L_z \frac{\sigma_{1a}}{\sigma_{2a}} \times \frac{1}{r}$$

We can easily verify that $r << 1$ and therefore,

$$L_x >> L_z, \; L_y \approx L_z \quad (20)$$

Thus, radiation occurs at a certain size (20) of the sample.

4. CONCLUSION

Thus, theoretical studies of current fluctuations in two-valley semiconductors of the GaAs type show that the crystal size under conditions of current instability is the main factor. The dimensions L_x, L_y, L_z must have certain values for the radiation of the crystal. The transition time from the lower valley to the upper one is less than the time of the transition from the upper valley to the lower one. This physical fact is fully justified in Gunn's experiment. Charge carriers, receiving energy from an external electric field (order eEL), go to the upper energy level, and the transfer of energy in the lattice is weak. The resulting nonequilibrium state of the crystal is returned to its original state by radiation. This process is slower than the transition to a higher energy level, then $\tau_{ab} < \tau_{ba}$.

The values of a strong magnetic field ($\mu H >> c$) linearly depend on the external electric field ($E_0 \sim H_0$). The direction of the magnetic field can change the radiation conditions. In this theoretical work, the magnetic field is directed perpendicular to the electric field. In a different direction of the magnetic field, you will probably get different values for the oscillation frequency and for the current oscillation increment. Then, for radiation, crystals of other sizes will be needed. Thus, adjusting radiation with crystal sizes requires samples with different sizes for the experiment. The critical value of the electric field, when the current fluctuates, is almost the same as the value of the electric field obtained by the Gunn experiment. To excite a current oscillation in multi-wavelength semiconductors, the size of the sample must be defined.

REFERENCES

[1] E.R. Hasanov, R.K. Mustafayeva, G. Mammadova, S.G. Khalilova, E.O. Mansurova, "Excitation of Growing Waves in Impurity Semiconductors with Two Current Fluctuations in Two-Valley Semiconductors in Strong Electric and Magnetic Fields", IOSR Journal of Applied Physics (IOSR-JAP), Vol. 13, pp. 55-62, January 2021.

[2] E.R. Hasanov, E.O. Mansurova, S.G. Khalilova, K.N. Yusifova, G.M. Mammadova, "Unstable Thermomagnetic Waves in Anisotropic Media of Electronic Type of Charge Carriers", IOSR Journal of Applied Physics (IOSR-JAP), Vol. 13, pp. 13-17, January 2021.

[3] E.R. Hasanov, S.G. Khalilova, R.K. Mustafayeva, G.M. Mammadova, "Oscillations of Current in Two-Valley Semiconductors in a Strong Electric Field", Advanced Studies in Theoretical Physics, Vol. 15, No. 3, pp. 145-152, 2021.

[4] E.R. Hasanov, A.R. Hasanova, S.G. Khalilova, R.K. Mustafayeva, "Current Oscillations in Semiconductors with Deep Traps in Strong Electric and Magnetic Fields", IOSR Journal of Applied Physics, Issue 1, Vol. 11, No. 1, pp. 13-18, January 2019.

[5] E.R. Hasanov, S.G. Khalilova, Z.A. Tagiyeva, S.S. Asadova, "Current Oscillations in Semiconductors with Deep Traps in Strong Electric and Magnetic Fields", The 15th International Conference on Technical and Physical Problems of Electrical Engineering (ICTPE), pp. 103-107, Istanbul, Turkey, 14-15 October 2019.

[6] E.R. Hasanov, I.I. Mustafayev, "Non-Linear Fluctuations of Concentration of Charge Carriers and Electrical Field in Semiconductors", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 32, Vol. 9, No. 3, pp. 39-43, September 2017.

[7] E.R. Hasanov, V.M. Hajiyeva, A.S. Rikani, "Radiation Doped Semiconductors with Certain Impurities", The 14th International Conference on Technical and Physical Problems of Electrical Engineering (ICTPE), pp. 80-84, Nakhichevan, Azerbaijan, 15-17 October 2018.

[8] J.B. Gunn, "Microwave Oscillations of Current in III - V Semiconductors", Solid State Comm., Vol. 1, No. 4, pp. 88-91, September 1963.

[9] J.B. Gunn, "Current Instabilities and Potential Distribution in GaAs and InP Plasma Effects in Solids", pp. 199-207, Paris, France, 1964.

[10] J.B. Gunn, "Characteristics of the Electron Transfer Effect Associated with Instabilities, Proc. Int, Conf. Phys. Semi cond., pp. 505-509, Kyoto, Japan 1966.

[11] J.B. Gunn, " Effect of Domain and Circuit Properties on Oscillations in GaAs", IBM Journal of Research and Development, Vol. 10, pp. 310-320, July 1966.

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