Article
https://doi.org/10.31489/2025PH1/45-52
UDC 621.315.592, 621.03

Received: 11.11.2024
Accepted: 21.01.2025

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Growing Waves in Semiconductors with Two Energy Minima of the GaAs Type

In two-valley semiconductors of the GaAs type, under the influence of external electric E_0 and magnetic fields H_0 at certain orientations $\vec{E}_0$ and $\vec{H}_0$, a current oscillation with a specific frequency and growth rate was obtained. The orientation of the electric E_0 and magnetic fields H_0 plays a significant role in the excitation of growing waves in semiconductors of the GaAs type. The frequencies and growth increments are determined when exciting current oscillations in a circuit. The dimensions of the crystal are determined by $L_z >> L_x$, L_y, $L_x = L_y$. If the dimensions of the sample differ from the condition $L_z >> L_x$, L_y, $L_x = L_y$, the growing waves can fade or grow. And in this case, the frequencies of the oscillation growth and the value of the electric E_0 and magnetic H_0 fields will be different. The values of the magnetic field in the valley "a" are strong, i.e. $\mu_a H_0 >> c$, and in the valley "b" are weak $\mu_b H_0 >> c$. If the magnetic field values in the valleys "a" and "b" are strong, then electromagnetic waves with other frequencies will also be excited. The theory for other values of the magnetic, electric field and, of course, for other values of the crystal dimensions will show other values for the frequency and growth increment. When preparing semiconductor devices (generators, amplifiers, etc.), the dimensions of the sample play a significant role. In this work, analytical expressions for the electric and magnetic fields for certain sample sizes L_x, L_y, L_z were obtained.

Keywords: unstable waves, fluctuations, Gunn effect, external electric field, semiconductor, magnetic field

Introduction

Among physical effects, one very interesting phenomenon stands out, which was called the Gunn effect, after the English physicist John Gunn, who discovered it in 1963. It is currently accepted that the Gunn effect [1] in n-type GaAs is due to the volumetric negative resistance arising as a result of the induced action of the electron transfer field from the conduction band valley with high carrier mobility to the valley with low mobility, i.e., it is an effect whose existence was previously predicted by Ridley and Watkins [2] and Hilsum [3]. The main confirmation of this mechanism is a decrease in the threshold electric field when the energy gap is placed between the valleys with high and low carrier mobility, caused either by uniform compression [4], or changes in GaP concentration in GaAs-GaP alloys [5]. The various characteristics of the Gunn effect identified by threshold field researchers are consistent with a two-valley mechanism.

Typical current-voltage characteristics for a plate and a notched sample made from the same ingot ($n = 4.6 \cdot 10^{15}$ cm^{-3} and $\mu = 3750$ cm^2/V·s) are presented in the Gunn experiment. In both cases, instability appears or disappears very abruptly, and no hysteresis phenomena were observed with changes in V. The plate characteristic deviates significantly from the ohmic one, apparently due to a decrease μ_L with increasing E. In the case of notched samples, any curvature of the characteristic is masked by the series resistance of the outer regions.

The measured values of the threshold field E_T for plate and notched samples with a thickness of 0.025 cm were almost the same: 2130 ± 100 V/cm for the first and 2440 ± 120 V/cm for the second. This indicates that the instability is primarily a volume effect and is not significantly related to the contacts. However, the consistently slightly lower value for plates suggests that in plate samples, the domains become affected in the high-field region near the cathode. The value of the threshold speeds ϑ_T, determined either by the magnitude E_T or by the threshold current density J_T, is mutually consistent and for the above-mentioned samples they are $9.15 \cdot 10^6$ and $9.24 \cdot 10^6$ cm/s. Such agreement was observed, as a rule, for all samples except those that were shorter than approximately 0.025 cm.

In an ideal homogeneous sample E_T, the value should be equal to E_c, the field corresponding to the maximum velocity ϑ_c. In real samples, inhomogeneities in the distribution of impurities can easily lead to field fluctuations of two to three times, or even more over several microns near the electrodes or within the bulk. Therefore, a moderate average field can locally reach a value E_c, causing the nucleation of a domain, the movement of which will then be supported in the average field [6]. Thus, the measured values E_T, depending on the degree of field inhomogeneity, can range from E_c to field E_s, requiring a fully formed domain to maintain movement. The instability may be localized in some region of the crystal, although if the extent of this region is too small, the field distribution will be distorted, forming a new stable configuration [7, 8]. In most samples, due to heterogeneity, the value of E_T is lower than the value of E_s. A more interesting mechanism for the occurrence of negative differential resistance in the bulk of a semiconductor was proposed by Ridley and Watkins [2] and independently by Hilsum [3]. These authors drew attention to the fact that in n-type gallium arsenide, which has two minima (or valleys) in its conduction band, the carrier mobility in the upper minimum is much lower than in the lower one. For this reason, during field heating of the electron gas, the electron mobility begins to drop sharply as soon as their energy is sufficient to move to the upper minimum. This leads to the appearance of negative differential resistance. Since the time constant in this case is of the order of 10^{-11} seconds, the negative resistance is maintained up to very high frequencies.

Later, the phenomenon of the occurrence of electrical oscillations associated with the movement of domains in such a semiconductor in a strong electric field was experimentally discovered by Gunn and was called the Gunn effect [9–13]. Many studies have been conducted. Soviet scientists made a significant contribution to the creation of the Gunn effect theory [9–13]. The generation frequency in a Gunn diode is determined by the domain travel time from the formation site to the corresponding contact. Since the domain is usually formed near the cathode, this time is equal to the domain travel time through the sample. The domain velocity is about 10^7 cm/s, so with a sample thickness of 10 microns, the travel time will be about 10^{-10} s, and therefore the generated frequency is about 10^{10} GHz. However, a slightly different generation mechanism is possible that allows obtaining higher-frequency oscillations. This mechanism is not directly related to the domain travel time through the entire sample. Since the domain is not formed instantly, but over a time of about 10^{-10} s, using an external resonator with sufficiently high impedance, it is possible to prevent its complete formation. As soon as the domain begins to form, it immediately becomes an active element of the circuit, capable of delivering power to an external load. If the load is large enough (i.e., high), the voltage on the semiconductor begins to decrease and falls below the threshold value at which the domain can exist. Then the domain begins to dissipate, and the resistance of the semiconductor decreases. At some point, the voltage across it becomes higher than the critical value again, and domain formation begins anew, continuing in this manner. This mode is called the limited space-charge accumulation mode (LSA). The frequency is determined by the characteristics and size of the crystal. Therefore, in this mode, it is much easier to achieve high generation frequencies than in conventional Gunn diodes.

The discovery of the Gunn effect in 1963 stimulated intensive research of this effect in many countries around the world. At the same time, many companies began to develop serial samples of high-frequency oscillation generators based on this effect, and already in 1966, the company “International Semiconductor” (USA) released Gunn generators with a generation frequency of 2–3 GHz and a power in continuous mode of 50–70 mW [9–13].

Essence of Gunn’s effect is that if an electric field is applied to a homogeneous sample made of a special material with existing electrical contacts, the magnitude of which exceeds a certain threshold value (the effect was observed by the discoverer on gallium arsenide and indium phosphide crystals; for the first, the electric field strength should be 3 kV/cm, and for the second — 6 kV/cm), then current oscillations begin to be observed in the external electrical circuit. Moreover, it was discovered that the period of these oscillations is approximately equal to the flight time of electrons from the cathode to the anode, and the oscillation frequency was quite high and was in the microwave range: $T_0 \approx L/u_g$, here: L is the length of the sample; u_g is the drift velocity of electrons [14–16].

Another option for using the Gunn diode is to create high-speed logic circuits and memory elements due to its ability to generate pulses in one period of the operating frequency. The response time of such elements will not exceed several tens of nanoseconds. In addition, the Gunn diode can also be used as a current stabilizer, which is based on the property of its volt-ampere characteristic, which describes the possibility of saturation when certain conditions are reached. That is, in other words, a stabilizer based on it can be used as a means of stabilizing relatively small currents at high frequencies or stabilizing relatively large currents at low frequencies.

The advantages of its operation as a stabilizer are the fast time to establish the stabilization mode and the ability to operate in a very wide range of voltages and currents. Another application of the Gunn diode is the creation of so-called “neuristors”, which are physical devices that imitate an axon — a long process of a nerve fiber coming from a nerve cell.

The transformation of electromagnetic energy using semiconductors is of theoretical and practical interest from the point of view of radio engineering. Therefore, the mechanisms responsible for the occurrence of current oscillations in the image were studied in various experimental and theoretical works. The dependence of the current density (*j*) on the external electric field *E* of a GaAs semiconductor has the form.

The characteristic features of the dependence of the current density on the external electric field are that one value of the current density corresponds to several values of the electric field. This characteristic was obtained by Gunn at Mueller values.

In valleys “*a*” and “*b*” the effective mass of electrons has the value

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

(m_0 — mass of a free electron). In GaAs $\Delta = 0.36\,\text{eV}$ based on (1) the mobility of electrons in the corresponding valleys satisfies the condition

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

In 1963, the English scientist Gunn experimentally [11] discovered in GaAs current oscillations with a frequency of $\omega \sim 10^9$ Hertz at fields $E \sim 3\cdot 10^3$ V/cm. This effect was called the Gunn effect. Microscopic theories of the Gunn effect are constructed in several theoretical works. However, the frequency of current oscillations in calculations and the critical values of the electric field obtained in these theoretical works correspond to the experimental values approximately. In some theoretical works using the Balsman kinetic equation, the mean free path of charge carriers was calculated, and analytical expressions for the electric field at which current oscillations begin in two-valley semiconductors of the GaAs type were obtained. The conductivities in both zones were also calculated in the presence of an external magnetic field. However, in this theoretical work we calculated the frequencies of current oscillations in two-valley semiconductors taking into account the time of transitions between two valleys, and we will calculate the values of these times depending on the size of the GaAs semiconductor. Current oscillations begin at certain values of external electric and magnetic fields. Theoretical studies of the Gunn effect in an external constant electric and magnetic field have not been investigated. Therefore, the excitation of electromagnetic waves in GaAs semiconductors with constant electric and magnetic fields is of great scientific interest. In this theoretical work, we will calculate the value of the electric and magnetic fields. At the point of the beginning of excitation of electromagnetic waves in GaAs semiconductors. We calculated the critical values of the electric and magnetic fields at the point of excitation of the waves. The values of the electric and magnetic fields are needed to prepare semiconductor devices (generators, amplifiers, etc.) For electric and magnetic fields, we will clean out the analytical expressions at which the current oscillation begins in the semiconductor. The theoretical method for studying the Gunn effect is the solution of the equation of continuity of the current flux density in individual valleys and Maxwell’s equation for alternating electric fields inside the sample.

Main Equations of the Problem

In the Gunn effect experiment in two-valley GaAs semiconductors, the electron concentration n is constant, and therefore,

$$n_a = n_a^0 + n'_a, n_b = n_b^0 + n'_b\,. \tag{3}$$

The transition between the valleys occurs under the condition

$$n'_a = -n'_b\,. \tag{4}$$

The transition times between the valleys τ_{12} and τ_{21} are determined by the continuity equations

$$\frac{\partial n'_a}{\partial t} + \operatorname{div} j'_a = \frac{n'_a}{\tau_{12}}, \frac{\partial n'_b}{\partial t} + \operatorname{div} j'_b = \frac{n'_b}{\tau_{21}}\,. \tag{5}$$

Here n'_a — concentration of electrons after transition from one valley to another; n'_b — concentration of electrons after transition from one valley to another; j'_a — current density of electrons after transition from one valley to another; j'_b — current density of electrons after transition from one valley to another.

The current flux densities in the presence of an external magnetic field are determined by the following equations:

$$\vec{j}_a = \sigma_a \vec{E} + \sigma_{1a}\left[\vec{E}\vec{H}\right] + \sigma_{2a}\vec{H}\left[\vec{E}\vec{H}\right];$$
$$\vec{j}_b = \sigma_b \vec{E} + \sigma_{1b}\left[\vec{E}\vec{H}\right] + \sigma_{2b}\vec{H}\left[\vec{E}\vec{H}\right]. \quad (6)$$

In (6) the condition is considered $eE_0 l >> k_0 T$ for the electric field (where e is the elementary charge, E_0 is the electric field, k_0 is the Boltzmann constant, T is the temperature of the sample). Therefore, there are no diffusion terms for the current density.

The magnetic field is determined by Maxwell's equation

$$\frac{\partial \vec{H}}{\partial t} = -\operatorname{crot}\vec{E} \quad (7)$$

The electrical conductivities $\sigma_a, \sigma_{1a}, \sigma_{2a}, \sigma_b, \sigma_{1b}, \sigma_{2b}$ are calculated in [17, 18].

Here σ_a — electrical conductivity in valley "*a*"; σ_{1a} — Hall electrical conductivity in valley "*a*"; σ_{2a} — focusing electrical conductivity on valley "*a*"; σ_b — electrical conductivity in valley "*b*"; σ_{1b} — Hall electrical conductivity at valley "*b*"; σ_{2b} — focusing electrical conductivity on valley "*b*".

Theory

By solving the system of equations (5, 6, 7) taking into account (3, 4), we can determine the frequencies of current oscillations in two-valley GaAs semiconductors. For small values of physical quantities $\vec{E}, \vec{H}, n$, i.e. $\vec{E} = \vec{E}_0 + \vec{E}', \vec{H} = \vec{H}_0 + \vec{H}', n = n_0 + n'$, frequencies of current oscillations will be determined.

$$\left(\vec{E}', \vec{H}', n'\right) \sim e^{i\left(\vec{k}\vec{r} - \omega t\right)}. \quad (8)$$

The fluctuation values of the electric and magnetic fields and the concentration of charge carriers when a current appears inside the sample are small compared to the constant thermodynamic values of the electric and magnetic fields and the concentration of carriers.

Selecting a coordinate system

$$\vec{E}_0 = \vec{i}E_{0x}, \vec{H}_0 = \vec{i}H_{0x}.$$

From (6) we easily obtain

$$j'_{ax} = \left(\sigma_a + \sigma_{2a}H_{0x}\right)E'_x - \sigma_{1a}H_{ox}E'_z; \quad (9)$$

$$j'_{ay} = \sigma_a E'_y + \frac{\sigma_{1a}c}{\omega}\left(k_y - k_x\right)E'_y + \sigma_{1a}H_{ox}E'_z + \frac{2\sigma_{2a}cE_{ox}H_{ox}}{\omega}\left(k_z E'_x - k_x E'_z\right); \quad (10)$$

$$j'_{by} = \sigma_b E'_y + \frac{\sigma_{1b}c}{\omega}\left(k_y - k_x\right)E'_y + \sigma_{1b}H_{ox}E'_z + \frac{2\sigma_{2b}cE_{ox}H_{ox}}{\omega}\left(k_z E'_x - k_x E'_z\right). \quad (11)$$

From (6) provided that $\vec{E}_0 = \vec{i}E_{0x}, \vec{H}_0 = \vec{i}H_{0x}$, the corresponding components of the current density in the valleys "*a*" and "*b*" have the form (10, 11), and in the valleys "*b*" the corresponding values (9, 10, 11) have the same form when "*a*" is replaced by "*b*".

In the experiment, the values of current density are measured in different directions. We will write expressions for the fluctuation current density along the *X* axis, equating to zero (10, 11) we find E'_y and E'_z, and substituting into (9)

$$j'_{ax} = \left(\sigma_a + \sigma_{2a}H_{0x} + \frac{\sigma_{1y}^a\sigma_z^a - \sigma_1^a\sigma_{1z}^a}{\sigma_{1y}^a\sigma_{2z}^a - \sigma_{2y}^a\sigma_{1z}^a}\right)E'_x;$$
$$j'_{bx} = \left(\sigma_b + \sigma_{2b}H_{0x} + \frac{\sigma_{1y}^b\sigma_z^b - \sigma_{1z}^b\sigma_1^b}{\sigma_{1y}^b\sigma_{2z}^b - \sigma_{2y}^b\sigma_{1z}^b}\right)E'_x. \quad (12)$$

The current densities along the *X* and *Z* axes, of course, have certain values, following the experiment, we consider them equal to zero, i.e. $j_x = j_y = 0$. Therefore, the values of the corresponding electrical conductivity have the following form

$$\sigma_{1y}^{a,b}=\sigma_{a,b}+\frac{\sigma_{1a,b}c}{\omega}\left(k_y-k_x\right),\sigma_{ya,b}=\frac{2\sigma_{2a,b}cE_{ox}}{\omega H_{0x}}k_z\,;$$
$$\sigma_{2y}^{a,b}=\sigma_{1,a,b}k_x-\frac{2\sigma_{2a,b}E_{ox}c}{\omega H_{0x}}k_x,\sigma_{za,b}=\frac{\sigma_{1a,b}ck_zE_{ox}}{\omega H_{0x}}-\frac{2\sigma_{2a,b}cE_{ox}}{\omega H_{0x}}k_y, \qquad (13)$$
$$\sigma_{1z,a,b}^{a,b}=\frac{2\sigma_{2a,b}E_{ox}c}{\omega H_{0x}}k_x+\sigma_{1,a,b},\sigma_{2za,b}=\sigma_{a,b}-\frac{\sigma_{1a,b}ck_xE_{ox}}{\omega H_{0x}}-\frac{2\sigma_{2a,b}cE_{ox}}{\omega H_{0x}}k_y.$$

From (5) we obtain

$$\left(1-i\omega\tau_{21}\right)\operatorname{div} j'_{ax}=\left(1+i\omega\tau_{12}\right)\operatorname{div} j'_{bx}. \qquad (14)$$

Considering, $\mu_aH_{ox}>c$ and $\mu_bH_{ox}<c$, and choosing the dimensions of the sample

$$L_x=L_y,L_z>>L_x,L_y \qquad (15)$$

the dispersion equation under the above conditions (15) have the following form:

$$\tau_{21}\frac{\mu_a}{\mu_b}\phi_a^3\omega^4+\left(i\frac{\mu_a}{\mu_b}\phi_a^3-10\tau_{12}\omega_x\phi_a^3-3\tau_{12}\omega_x\phi_a^2\right)\omega^3-\left(i6\phi_a^2\frac{\mu_b}{\mu_a}+3\tau_{21}\omega_x\phi_a^2\frac{\mu_a}{\mu_b}+\right.$$
$$\left.+4\tau_{21}\omega_x\phi_a^2\frac{\mu_b}{\mu_a}-i3\phi_a^2+\tau_{12}\omega_x\phi_a^2\frac{4\mu_b}{\mu_a}+\tau_{21}\omega_x\phi_a\frac{12\mu_a}{\mu_b}-i3\phi_a+\tau_{12}\omega_x\phi_a^2\frac{18\mu_b}{\mu_a}\right)\omega_x\omega^2+ \qquad (16)$$
$$+\left(i\phi_a^3 4-3\tau_{21}\omega_x\phi_a-i32\phi_a\frac{\mu_b^2}{\mu_a^2}-24\tau_{12}\omega_x\phi_a^2\frac{\mu_b}{\mu_a}-i2\frac{\mu_a}{\mu_b}\phi_a^2+\tau_{21}\omega_x\frac{24\mu_a}{\mu_b}-\right.$$
$$\left.-4i_x\phi_a^2\frac{\mu_b}{\mu_a}-12\tau_{12}\omega_x\phi_a^2\right)\omega_x^2\omega-8\tau_{21}\omega_x^4\phi_a^3\frac{\mu_a}{\mu_b}-i\left(\frac{\mu_a}{\mu_b}\phi_a^3 48-12\phi_a^3\frac{\mu_b}{\mu_a}\right)12\phi_a^3\frac{\mu_a}{\mu_b}=0$$

Here $\phi_a=\dfrac{\mu_aH_{ox}}{c}$, $\omega_x=ck_x$.

We can estimate the values of the magnetic and electric fields using the formula

$$E_0=2H_0\frac{\mu_b}{\mu_a},\ H_0=\sqrt{\frac{2}{3}}\frac{c}{\sqrt{\mu_a\mu_b}}\,; \qquad (17)$$
$$\mu_a=10^5,\mu_в=10^4,\ x=\frac{\omega}{\omega_x}.$$

Then the fourth-order dispersion equation with respect to the frequencies of current oscillations has the following algebraic form

$$x^4+\left(\frac{i}{\tau_{21}\omega_x}-\frac{9\tau_{12}}{\tau_{21}}\right)x^3+\left[\frac{6}{\tau_{21}\omega_x}\left(\frac{\mu_b}{\mu_a}\right)^3-i\frac{3}{\phi_a}\frac{\mu_b}{\mu_a}+\frac{4\tau_{12}}{\tau_{21}\phi_a}+12\left(\frac{\mu_b}{\mu_a}\right)^2+\frac{2\tau_{12}}{\tau_{21}}\frac{\mu_b}{\mu_a}\right]x^2+ \qquad (18)$$
$$+\left[24-12\frac{\tau_{12}}{\tau_{21}}\left(\frac{\mu_b}{\mu_a}\right)^2\right]x-8\tau_{21}\omega_x-i48=0$$

The solution of this equation in the general case (i.e. without assumption is not possible). Therefore, we will use the conditions and from (18)

we obtain

$$x^4-15x_0x_1-\frac{9\tau_{12}\omega_x}{5}x_0^3+\left(\frac{20\tau_{12}\omega_x}{\phi_a}+12\frac{\mu_b^2}{\mu_a^2}\right)x_0^2+\left(24+60\tau_{12}\omega_x\frac{\mu_b^2}{\mu_a^2}\right)x_0+\frac{2\mu_b}{\mu_a}x_1-\frac{8}{5}=0\,; \qquad (19)$$

$$4x_0^3x_1+5x_0^3-\frac{27\tau_{12}\omega_x}{5}x_0^2x_1+2\left(\frac{20\tau_{12}\omega_x}{\phi_a}+12\frac{\mu_b^2}{\mu_a^2}\right)x_0x_1+\left(24+60\tau_{12}\omega_x\frac{\mu_b^2}{\mu_a^2}\right)x_1-\frac{2\mu_b}{\mu_a}x_0-48=0\,. \qquad (20)$$

Then after isolating the real and imaginary parts of equation (18), we obtain the following two equations (19-20). When obtaining (19-20), we assumed for the transition times from valley “*b*” to valley “*a*” from the condition

$$\tau_{21}\omega_x = 5. \tag{21}$$

From the joint (19-20) the real and imaginary parts of the frequency oscillation are obtained as follows

$$x_0 = \frac{9}{5}\tau_{12}\omega_x. \tag{22}$$

Substituting (22) into (20), we easily obtain:

$$x_1 = \frac{3}{20}\tau_{12}\omega_x. \tag{23}$$

The ratio $\frac{x_1}{x_0} << 1$, this follows explicitly $\sigma_{12} << \sigma_{21}$.

Comparing (22) and (23), we obtain

$$\frac{\tau_{12}}{\tau_{21}} = \left(\frac{2}{27}\right)^{1/3}\frac{1}{2} << 1.$$

And this indicates that the transition time from valley "*a*" to valley "*b*" is less than the transition time from valley "*b*" to valley "*a*".

Thus, the frequency of current oscillations

$$\omega_0 = \frac{9}{5}\tau_{12}\omega_x^2,$$

the frequency of increase

$$\omega_1 = \frac{3}{20}\tau_{12}\omega_x^2.$$

With another value of the solution τ_{21}, the frequency and the increment of increase will have a completely different value.

Discussion

Thus, the conditions for excitation of increasing waves in two-valley semiconductors depend significantly on the choice of coordinate systems relative to external electric and magnetic fields. Of course, these conditions depend on the size of the sample. The obtained analytical formulas for the electric and magnetic fields correspond to the Gunn experiment. The time of transition from the second valley to the first valley $\tau_{21} = \frac{1}{5\omega_x} = \frac{1}{5ck_x} = \frac{L_x}{10c\pi}$ for $\tau_{21} \sim 10$. The characteristic time of transition from "*a*" to "*b*" and from "*b*" to "*a*" in addition to the specified values, other values can be obtained. However, the condition $\tau_{21} \sim \tau_{12}$ is not violated when obtaining current oscillations in the specified semiconductors. The orientation of the electric and magnetic fields plays a role in obtaining the corresponding oscillations. Of course, from all possible orientations, it is necessary to choose the orientation for which the required value is less than the value of the external electric field. This means that the direction of the magnetic and electric fields coincides and is directed along the electric field and the excitation of current oscillations occurs as in the Gunn experiment. To reduce the electric field, it is necessary to check other orientations $\vec{E}_0$ and $\vec{H}_0$. For the preparation of corresponding devices based on GaAs type semiconductors, it is practically advantageous at lower values of the external electric field.

Results

Analytical formulas for the purity of excited waves and for the growth increment of these waves are obtained. The dependence of the frequency and the growth increment of the growing wave on the external electric and magnetic fields is not the only one for obtaining a growing wave in the specified semiconductors. The obtained forms for the electric and magnetic fields are quite consistent with the Gunn experiment. The experimental data of the Gunn effect for the electric field are in good agreement with our theoretical studies for the electric field. However, there are no experimental values of the magnetic field and therefore the values of the magnetic field obtained by us theoretically were not compared with the experimental data. Numerical estimates of the transition times from valley "*a*" to valley "*b*" are of the order of the electron relaxation time. The value of the transition time from valley "*a*" to valley "*b*" and back, depending on the value of the external electric and magnetic fields may be different. However, in all cases, the transition time from valley "*b*" to valley "*a*" is greater than the transition time from valley "*a*" to valley "*b*", i.e. $\tau_{21} > \tau_{12}$. This condition proves that the charge carriers (in this case, electrons) are scattered by the crystal lattice, lose energy and pass from the outer energy valley to the lower valley. There are no theoretical studies of the Gunn effect in alternating electric and magnetic fields. For such a theoretical analysis, it is necessary to solve nonlinear differential equations, for example, using the mathematical method of Bogolyubov-Metropolsky [18, 19, 20]. Such a study of the Gunn effect leads to the determination of the amplitude of the current oscillation, and, of course, to determine the amplitude of the emerging waves as a function of time.

The obtained analytical expressions of the electric and magnetic fields for certain sample sizes can be used in the preparation of semiconductor devices (generators, amplifiers, etc.).

References

1 Gunn, J.B. & Elliott, B.J. (1966). Measurement of the negative differential mobility of electron in GaAs, *Physics Letters, 22*, 369–3711.

2 Ridley, B.K. & Watkins, T.B. (1961). The Possibility of Negative Resistance Effects in Semiconductors. *Proc. Phys. Soc. 7*8, 17–36.

3 Hilsum, C. (1962). Transferred Electron Amplifiers and Oscillators. *Proceedings of the IRE, 50*, 2, 185–189.

4 Hutson, A.R., Jarayaman, A., Chynoweth, A.G., Corriell, A.S., & Feldmann, W.L. (1965). Mechanism of the Gunn Effect from a Pressure Experiment. *Phys. Rew. Letters, 14*, 639.

5 Shyam, M., Allen, L.W., & Pearson, G.L. (1966). Effect of variation of energy minima separation on Gunn oscillations. *IEEE Trans.*, *ED-13*, 63.

6 Heeks, L.S., Woode, A.D., & Sandbank, C.P. (1965). Wave propagation in negative resistance media. *Proc IEEE, 53*, 554.

7 McCumber, D.E. & Chynoweth, A.G. (1966). Hall effect in many-valley semiconductors at high electric field. *IEEE Trans., ED-13*, 4.

8 Kroemer, H. (1966). Hot-electron relaxation effects in devices. *IEEE Trans., ED-13*, 27.

9 Gunn, J.B. (1964). Current instabilities and potential distribution in GaAs and InP. *Plasma Effects in Solids*, 199–207.

10 Kozhevnikov, V.Y., Kozyrev, A.V., Konev V.Y., & Klimov A.I. (2022). The phase stability of nanosecond Gunn oscillators. *Vojnotehnicki glasnik — Military Technical Courier, 70*(2), 460–471.

11 Gunn, J.B. (1963). Microwave oscillations of current in a GaAs semiconductor. *Solid state comm, 1*, 88.

12 Ridley, B.K. (1966). The inhibition of negative resistance dipole waves and domains in n-GaAs. *IEEE Trans ED-13*, 41.

13 Pejman Taslimi (2005). An introduction to Gunn oscillator and electronics of TEDs, Shahed university of Tehran, 12.

14 Kalyon, G., Mutlu, S., Kuruoglu, F., Pertikel, I., Demir, I., & Erol, A. (2023). In GaAs-based Gunn light emitting diode. *Materials Science in Semiconductor Processing, 159*, 1, 107389.

15 Hua-Wei Hsu, Michael J. Dominguez, & Vanessa Si. H. (2020). Gunn threshold voltage characterization in GaAs devices with wedge-shaped tapering. *J. Appl. Phys., 128*, 074502.

16 Hasanov, E.R., Khalilova, Sh.G., Mammadova, G.M., & Mansurova, E.O. (2023). Excitation Of Unstable Waves In Semiconductors Such As Gaas Magnetic Fields. *JTPE, 15*, 2, 302–306.

17 Hasanov, E.R, Khalilova, Sh.G., & Mustafayeva, R.K. (2021). Instability in Two GaAs Valley Semiconductors in Electric and Magnetic Fields. *The 17th International Conference on "Technical and Physical Problems of Engineering"*, 60–63.

18 Bogolyubov, N.N., & Mitropolsky, Yu.A. (1955). Asymptotic methods in the theory of nonlinear oscillations Engineering, *Physics*, 408.

19 Richard, Krantz. (1990). Threshold Voltage and IV Characteristics of AlGaAs/GaAs MODFETs. Electronics Research Laboratory Laboratory Operations The Aerospace Corporation, 20.

20 Hasanov, E.R, Khalilova, Sh.G., & Mustafayeva, R.K. (2022). Instability in two GaAs valley Semiconductors in electric and magnetic fields. *International Journal on "Technical and Physical Problems of Engineering" IJTPE 14*(1), 228–232.

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GaAs типті екі энергия минимумы бар жартылай өткізгіштердегі өсіп келе жатқан толқындар

$\vec{E}_0$ сыртқы электрлік және H_0 магнит өрістерінің әсерінен GaAs типті екі жолақты жартылай өткізгіштерде белгілі бір бағыттар бойынша $\vec{E}_0$ және H_0 токтың тербелісі белгілі бір жиілікте және өсу қарқынымен алынады. $\vec{E}_0$ электрлік және H_0 магнит өрістерінің бағыты GaAs типті жартылай өткізгіштердегі өсу толқындарын қоздыру кезінде маңызды рөл атқарады. Электрлік және магниттік өрістердің мәндерін анықтау үшін аналитикалық өрнектер алынды. Тізбектегі токтың тербелісі қозған кезде өсу жиіліктері мен өсінділері анықталады. $L_z >> L_x$, L_y, $L_x = L_y$ кристалдың өлшемдері айқындалды. Егер үлгінің өлшемдері $L_z >> L_x$, L_y, $L_x = L_y$ жағдайдан өзгеше болса, толқындардың өсуі әлсіреуі немесе өсуі мүмкін. Бұл ретте тербелістің өсу жиілігі мен $\vec{E}_0$ электрлік және H_0 магнит өрістерінің мәндерін басқалар алады. Алқаптағы магнит өрісінің мәндері «*a*» күшті, яғни $\mu_a H_0 >> c$, «*b*» алқабында әлсіз, яғни $\mu_b H_0 >> c$. Егер «*a*» және «*b*» алқаптарындағы магнит өрісінің мәні күшті болса, онда электромагниттік толқындар басқа жиіліктермен де қозғалады. Магниттік, электр өрісінің және кристалл өлшемдерінің басқа мәндеріндегі теория жиілік пен өсу үшін басқа мәндерді көрсетеді. Жартылай өткізгіш құрылғыларды (генераторлар, күшейткіштер және т.б.) дайындау кезінде үлгінің өлшемдері маңызды рөл атқарады. Бұл жұмыста үлгілердің белгілі бір өлшемдерінде L_x, L_y, L_z электр және магнит өрісінің аналитикалық өрнектері алынды.

Кілт сөздер: тұрақты емес толқындар, флуктуациялар, Ганн эффектісі, сыртқы электрлік өрістер, жартылай өткізгіштік, магнит өрістер

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Нарастающие волны в полупроводниках с двумя минимумами энергии типа GaAs

В двухдолинных полупроводниках типа GaAs под влиянием внешнего электрического $\vec{E}_0$ и магнитного H_0 полей при определённых ориентациях $\vec{E}_0$ и H_0 получено колебание тока с определённой частотой и инкрементом нарастания. Ориентация электрического $\vec{E}_0$ и магнитного H_0 полей играет существенную роль при процессе возбуждения нарастающих волн в полупроводниках типа GaAs. Получены аналитические выражения для определения значений электрического и магнитного полей. Определены частоты и инкременты нарастания при возбуждении колебаний тока в цепи. Размеры кристалла определяются $L_z >> L_x$, L_y, $L_x = L_y$. Если размеры образца отличаются от условия $L_z >> L_x$, L_y, $L_x = L_y$, то нарастая, волны могут затухать или нарастать. При этом частоты нарастания колебания, а также значения электрического $\vec{E}_0$ и магнитного H_0 полей будут получаться другими. Значения магнитного поля в долине «*a*» является сильным, т.е. $\mu_a H_0 >> c$, а в долине «*b*» является слабым $\mu_b H_0 >> c$. Если значение магнитного поля в долинах «*a*» и «*b*» становится сильным, тогда возникают электромагнитные волны с другими частотами. Теория при других значениях магнитного, электрического поля и размеров кристалла покажет другие показатели для частоты и инкремента нарастания. При приготовлении полупроводниковых приборов (генераторов, усилителей и т.д.) существенную роль играют размеры образца. В данной работе были получены аналитические выражения электрического и магнитного поля при определенных размерах образцах L_x, L_y, L_z.

Ключевые слова: нестабильные волны, флуктуации, эффект Ганна, внешнее электрическое поле, полупроводник, магнитное поле

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