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E.R. Hasanov[1, 2], Sh.G. Khalilova[2, 1✉], A.H. Sultanova[3]

[1]*Baku State Uviversity, Baku, Azerbaijan;*
[2]*Institute of Physics, Baku, Azerbaijan;*
[3]*Nakhchivan State University, AZ7012, University Campus, Nakhchivan, Azerbaijan*

Excitation of Thermomagnetic Waves in Multi-Valley Semiconductors of the GaAs Type

It has been shown that in two-valley semiconductors, in the presence of a temperature gradient, a thermomagnetic wave is excited, which propagates perpendicularly to the temperature gradient. Such an unstable wave is excited at an electric field value where ionization, recombination and generation processes do not occur. Then the total concentration of charge carriers remains constant. The Gunn effect in GaAs was discovered in samples with ohmic contacts. However, obtaining true ohmic contacts in experiments is difficult; therefore, the injection of charge carriers at the contacts must be considered. It is necessary to calculate the impedance of the crystal in the presence of injection and to determine the capacitive and inductive nature of this impedance. The excited wave in GaAs, under the conditions considered, depends on the frequency of hydrodynamic wave. The electric field acts between the valleys The Gunn effect was observed in GaAs at values of crystals of the axes. For other crystallographic orientations, the frequency and growth rate take different values. In our theoretical study, an isotropic sample was used, following Gunn's experiments. Of course, theoretical investigations in anisotropic samples are also of significant scientific interest.

Keywords: thermomagnetic waves, growth, frequency, increment, dynamics, carrier concentration, characteristic frequencies, characteristic electric field, Gunn's effect, semiconductor

✉*Corresponding author*: Khalilova, Shahla, shahlaganbarova@gmail.com

Introduction

The conditions for excitation of thermomagnetic waves in a nonequilibrium plasma were first obtained in the presence of hydrodynamic motions of charge carriers [1]. In this work it was stated that hydrodynamic motions of charge carriers in the presence of a constant temperature gradient ($\vec{\nabla}T$) excite an alternating magnetic field and in this case a so-called thermomagnetic wave with a frequency $\omega_T = -c\Lambda\vec{k}\vec{\nabla}T$ arises in the plasma (where c is the speed of light, Λ is the Nernst-Ettinishausen coefficient, $\vec{k}$ is the wavevector). In [2] the velocity and the thickness of the wave front are estimated, and the inclusion of an external magnetic field affects the thermomagnetic wave profile only slightly.

The reflection wave depends on the initial voltage, magnetic field and fractional parameter in the semiconductor photothermal diffusion medium [3]. Maxwell's equations were applied considering the absence of infinite conducting and bias current medium. In addition, it applies the boundary settings for Maxwell and mechanical stress, diffusion, chemical reaction, and temperature gradient at the interface near the vacuum [3].

Thermomagnetic waves can propagate along the wave vector or perpendicular to the wave vector. Such transverse and longitudinal thermomagnetic waves were theoretically investigated in isotropic and anisotropic conducting media in [4–7]. Of particular interest is the study of transverse and longitudinal thermomagnetic waves in semiconductors. In semiconductors, the flow of charge carriers creates hydrodynamic movements, and an alternating magnetic field is excited in the medium without an external magnetic field (that is $\vec{H}_0 = 0$).

Impurity semiconductors are special media, because in them, considering two types of charge carriers (electrons and holes). The conditions for excitation of thermomagnetic waves require several limiting cases. It is known that in multi-valley semiconductors, unstable states of the medium are ensured by the creation of generators or amplifiers. Of course, the Gunn effect in two-valley semiconductors of the GaAs type is of particular interest. In GaAs semiconductors, the appearance of thermomagnetic waves can change. Experimental conditions and, of course, the creation of Gunn amplifiers and generators. In this theoretical work, we will investigate the appearance of thermomagnetic waves in two-valley semiconductors in the presence of an external constant electric field and in the presence of a constant temperature gradient. The studies will be carried out at a specific direction of the temperature gradient relative to the wave vector and without an external magnetic field.

In a plasma with a constant temperature gradient, a magnetic field arises. Unlike ordinary plasma, such a plasma has oscillatory properties and thermomagnetic waves are excited and oscillations occur only in the magnetic field. In this case, the wave vector of thermomagnetic waves is perpendicular to the magnetic field or lies in the plane [7]. The speed of thermomagnetic waves is comparable to the speed of sound and the speed of the Alfven wave. These waves are transverse magnetohydrodynamic waves propagating along the lines of force of the magnetic field. Alfven wave oscillations involve not only the electromagnetic field, but also particles of the conducting medium, this is Oscillations in them are possible only in the presence of a magnetic field and a conducting medium that behaves like a single liquid or gas [8].

Electromagnetic oscillations are periodic changes in the field strength E and induction B. Maxwell showed theoretically, and Hertz proved experimentally, that a changing magnetic field generates an alternating electric field, in turn, an alternating electric field generates an alternating magnetic field. This changes (oscillations) in the characteristics of the electromagnetic field occur in space [9]. In semiconductors, the temperature gradient leads to the emergence of a thermoelectric field. In metals, due to the strong degeneracy of electrons, their distribution generally depends very weakly on temperature, and therefore the thermoelectric field is less than in semiconductors in the ratio kT/ε_F (ε_F — Fermi energy), this is by three orders of magnitude. However, the same temperature gradient creates a flow of phonons that implement thermal conductivity; the scattering of electrons on these phonons leads to their “increase”, this is to the appearance of a noticeable drift velocity. Because of this, the thermo-emf can increase many times [10]. The concept of magnification was introduced by L.E. Gurevich [11], who applied it to metals in the absence, and later in the presence, of a magnetic field.

Fundamental in the field of kinetics of plasma processes are the works of L.D. Landau, who established the kinetic equation for plasma, and B.I. Davydov, who investigated the properties of plasma in a strong electric field. Due to the peculiarity of Coulomb forces in plasma, collisions with large impact distances are significant, at which the scattering angle and the transferred momentum are small, and therefore the collision integral can be transformed to an integro-differential form [11].

Instability of the hydrodynamic type in a plasma can also arise in the presence of an external magnetic field and a temperature gradient. It was considered in the case when the magnetic field is parallel to the electric field creating a constant ethical current, and in the perpendicular direction there is a temperature gradient. At certain values of the parameters, aperiodic instability occurs in the plasma. The case when the magnetic field is parallel to the temperature gradient and there is no current was also considered. Circularly polarized waves called thermomagnetic waves can propagate in the plasma along the magnetic field [11]. Under certain conditions, these waves become unstable and begin to grow. In a weak magnetic field, the instability is drift, and in a strong field, it is absolute. In L.E. Gurevich and B.L. Gelmont constructed a nonlinear theory of amplifying thermomagnetic waves. Instability, which can be called kinetic, and which is associated with the features of the distribution function of electrons and ions in the plasma, can arise in rarefied inhomogeneous plasma. Yu.A. Tserkovnikov investigated such instability in the presence of a non-uniform external magnetic field, in the case of non-isothermal plasma. In non-isothermal plasma the electron temperature significantly exceeds the ion temperature, and in the presence of a plasma density gradient [11].

When the wavelength of the emerging fluctuations significantly exceeds the Larmor radius, instability occurs within a certain range of carrier concentrations and magnetic field values. In the case of shorter waves, comparable to the Larmor radius, instability arises for all parameter values and is therefore considered “universal” [11].

If a semiconductor is in an external electric field, then the electrons receive a directed motion and drag phonons along with them [11].

Under certain steady-state conditions, the current in solids can be unstable. In this case, increasing oscillations arise.

If a conducting medium is in an external electric and magnetic field, then a new branch of oscillations (longitudinal) appears in its spectrum. These waves are weakly damped at frequencies significantly lower than the characteristic inverse relaxation times. In the presence of a gradient of any parameter determining the distribution of the field or current, these waves can become unstable and grow like an avalanche. This instability, which is often called a gradient, was observed in one particular case for plasma by Lehnert and theoretically explained by B.B. Kadomizev and A.V. Nedospasov [11]. In semiconductors it was discovered by Yu.L. Ivanov and S.M. [11] and most generally investigated by L.E. Gurevich and co-workers [12], who formulated the above principle and constructed a nonlinear theory for one case.

In the presence of a temperature gradient in a conducting medium, a new type of instability phenomenon is possible. In the case of plasma, it was considered in a special review; in solids, it is possible only in very good conductors at hydrogen and lower temperatures. Under such conditions, weakly damped transverse waves (thermomagnetic) arise, associated with oscillations of the magnetic field. In the presence of an external magnetic field, these waves begin to grow. The work [12] describes an experiment by which it is possible to detect thermomagnetic waves and their amplification.

The theory of fluctuations in a nonequilibrium state, for example, for a system in an external electric field, was developed by V.L. Gurevich [13], using the kinetic equation for correlation functions of a certain type.

Soviet theoretical physicists investigated the phenomenon in semiconductors with a falling volt-ampere characteristic of an N-shaped connection. Such a characteristic can be caused either by the capture of electrons in deep traps, or by the transition of electrons under the influence of an electric field to higher states with lower mobility. The possibility of obtaining high-frequency oscillations gave rise to numerous studies throughout the world. A.F. Volkov and Sh.M. Kogan considered nonlinear oscillations in the case of an s-shaped characteristic. M.I. Iglitsii, E.G. Pel, L.Ya. Pervova and V.I. Fistul investigated oscillations not associated with the space charge, arising in semiconductors with a carrier of both signs, if the differential resistance for one of the carriers is negative [13, 14].

L.E. Gurevich and V.I. Vladimirov [14] investigated the kinetics of plasma with high radiative pressure and showed that the phenomenon of mutual increase of electrons and photons significantly changes the kinetic coefficients. The conditions of thermal instability of the type investigated by A.V. Gurevich also change. A special group of works in plasma kinetics is devoted to the so-called drift approximation, which describes the behavior of a rarefied plasma in an external magnetic field that slowly changes in space or time. In this case, the rapid motion of electrons along Larmor "circles" is accompanied by a slow displacement and change in the radius of these circles due to a change in the magnetic field. Averaging over the fast motion leads to the drift approximation. The theory of plasma oscillations based on this equation was developed by L.D. Landau, who showed that the problem of oscillations should be solved based on a certain initial state of the plasma, that is, its initial distribution function [15–19]. It turned out that even in the absence of collisions, plasma oscillations attenuate, roughly speaking, due to the transfer of wave energy to electrons, whose speed coincides with the phase velocity of the wave. This peculiar attenuation, called Landau attenuation, subsequently became the object of numerous studies.

We will consider excitation of thermomagnetic waves in the above semiconductors (in double-valley) without an external magnetic field and in the presence of a constant electric field. The crystals are under the influence of a constant temperature gradient. The temperature gradient is directed specifically along the external electric field. Between the valleys of the energy gap δ — when compared with the energy eEl obtained from the electric field of charge carriers, where l is the mean free path.

Basic equations of the problem

If the environment is under the influence of an external electric field $\vec{E}$ and a constant temperature gradient $\vec{\nabla}T = const$, then the electric field in the environment has the form:

$$\vec{E}^* = \vec{E} + \frac{\left[\vec{\upsilon}H\right]}{c} + \frac{T}{c}\frac{\nabla n}{n}. \tag{1}$$

Equation (1) shows the full effect of the electric field inside the sample. Here $\vec{E}$ is the electric field inside the medium due to the electric charge, $\frac{\left[\vec{\upsilon}H\right]}{c}$ is the electric field arising due to hydrodynamic movements with $\vec{\upsilon}$ the velocity of the charge carriers, $\frac{T}{c}\frac{\nabla n}{n}$ is the electric field created due to the redistribution of uneven charges inside the medium. It is known that in GaAs semiconductors the first and second valleys have an energy gap between them $\Delta = 0.36$ eV. The mobility of charge carriers receiving energy of the order of eEl (l is the mean free path of charge carriers) from the electric field can move to a high energy level if $eEl \sim \Delta$. If we denote the time of transition from the first valley to the second valley τ_{12} and back by τ_{21}, then $\tau_{21} > \tau_{12}$, because the carriers in the second valley after scattering cannot move back to the first valley in an elastic manner. The mobility of charge carriers $\mu_1 >> \mu_2$ due to the effective masses

$$m_1^* << m_2^*. \tag{2}$$

Since in the Gunn effect there was no ionization and generation of charge carriers, the total concentration in the medium was constant, that is

$$\begin{aligned} n &= n_1 + n_2 = const; \\ n_1' &= -n_2'. \end{aligned} \tag{3}$$

The sample under consideration is without impurities and generation and recombination of charge carriers are absent. The external electric field is applied to the crystal in such a way that ionization of atoms is absent, therefore the concentration of charge carriers in the medium is constant.

Considering τ_{21} and τ_{12} the continuity equation in the valleys will have the form

$$\begin{aligned} \frac{\partial n_1}{\partial t} + \operatorname{div} j_1' &= \frac{n_1}{\tau_{12}}; \\ \frac{\partial n_2}{\partial t} + \operatorname{div} j_2' &= \frac{n_2}{\tau_{12}}. \end{aligned} \tag{4}$$

Here j_1' and j_2' are the current flux densities in the valleys. Equations (2), (3) and (4) describe the law of transition of charge carriers between valleys. The Gunn effect in two-valley semiconductors was observed at external electric fields of the order of $2 \div 3 \cdot 10^3$ V/cm and therefore at room temperature

$$eEl >> k_0 T, \tag{5}$$

(k_0 — Boltzmann constant). Equation (5) is the condition of a strong electric field.

In the environment, the current flow density is created by electric current E^* and therefore the current flow density in each valley has the form:

$$\begin{aligned} \vec{j}_1 &= n_1\mu_1\vec{E}^* + n_1\mu_1'\left[\vec{E}^*\vec{H}\right] - \alpha_1\vec{\nabla}T - \alpha_1'\left[\vec{\nabla}T\vec{H}\right]; \\ \vec{j}_2 &= n_2\mu_2\vec{E}^* + n_2\mu_2'\left[\vec{E}^*\vec{H}\right] - \alpha_2\vec{\nabla}T - \alpha_2'\left[\vec{\nabla}T\vec{H}\right]. \end{aligned} \tag{6}$$

Thus, to obtain the dispersion equation, we must jointly solve the system of equations (4) taking into account (3) and (6). Equation (6) is the flux density of each valley.

Theory

We must find the expression of the electric field $E^{*'}$ from the variable concentration of charge carriers. Therefore, equation (7), (8) will determine the expression E^* from n'.

First, we define $\vec{E}^*$ from (1) as follows

$$\begin{aligned} &\frac{\partial H}{\partial t} - c\operatorname{rot} E^*; \\ &\vec{H}' = \frac{c}{\omega}\left[\vec{k}E^*\right]; \end{aligned} \tag{7}$$

$$J = \vec{j}_1 + \vec{j}_2 = \left(n_1\mu_1 + n_2\mu_2\right)E^* + \left(n_1\mu_1' + n_2\mu_2'\right)\left[E^*\vec{H}\right] - \left(\alpha_1 + \alpha_2\right)\vec{\nabla}T - \left(\alpha_1' + \alpha_2'\right)\left[\vec{\nabla}T\vec{H}\right]; \tag{8}$$

$$J = \frac{c}{4\pi\sigma}\operatorname{rot}\vec{H}'. \tag{9}$$

Equations (7), (8) and (9) are Maxwell's equation and the expression for the total current.

Substituting (1), (7), (9) into (8) and expanding the vector dedication, we easily obtain j_1' and j_2' the equation of continuity of divergence will have the following form (10)

$$E^* = \left[\frac{iT}{e}\vec{k}\frac{n'}{n_0} + \Lambda_0\beta\vec{\nabla}T\frac{\vec{E}_0\vec{E}^*}{E_0^2}\right]\frac{1}{\alpha};$$

$$\alpha = 1 + \frac{2\vec{k}\upsilon_0}{\omega} + \frac{2\omega_T}{\omega} + i\frac{c^2k^2}{2\pi\sigma\omega}; \tag{10}$$

$$\beta = 2\frac{d\ln\Lambda}{d\ln E_0^2}.$$

From (10) it is evident that the propagation of thermomagnetic waves (finite excitation) depends very strongly on the wave vector and on the temperature gradient. We consider the case $\vec{k} \perp \vec{\nabla}T$ because the frequency of thermomagnetic waves has the form

$$\omega_T - c\left(k\nabla T\right)\lambda',$$

λ' is the Nerst-Ettinshausen's coefficient. Considering that all variable physical quantities have a monochromatic form after that is

$$\left(E'^*, n'\right) \sim e^{i\vec{k}\vec{x}-\omega t}$$

after linearization (4) we easily obtain:

$$\vec{k}\vec{j}_1' = \mu_{10}n_{10}\left(\vec{k}\vec{E}^{*'}\right) + \vec{k}\vec{u}_{10}n' + \frac{2\sigma_1'c\vec{k}\vec{E}_0}{e\omega}\left(\vec{k}\vec{E}^{*'}\right) + \left(\vec{k}\upsilon_{10}n_{10}\delta_1 - \alpha_{10}\gamma_1\vec{k}\vec{\nabla}T\right)\frac{iT\vec{k}\vec{E}_0}{E_0^2 e\alpha\phi}\frac{n'}{n_{10}};$$

$$\vec{k}\vec{j}_2' = \mu_{20}n_{20}\left(\vec{k}\vec{E}^{*'}\right) - \vec{k}\vec{u}_{20}n' + \frac{2\sigma_2'c\vec{k}\vec{E}_0}{e\omega}\left(\vec{k}\vec{E}^{*'}\right) + \left(\alpha_{10}\gamma_2\vec{k}\vec{\nabla}T - \vec{k}\upsilon_{20}n_{20}\delta_2 - \right)\frac{iT\vec{k}}{E_0^2 e\alpha\phi}\frac{n'}{n_{20}}; \tag{11}$$

$$\phi = 1 - \frac{\Lambda_0\beta\vec{E}_0\vec{\nabla}T}{\alpha E_0^2}.$$

From (11) the solution to equation (11) is too complicated, and therefore we will consider the following approximations

$$\frac{\mu_{20}n_{20}}{\mu_{10}n_{10}}\cdot\frac{1}{\tau_{12}} = \frac{1}{\tau_{21}}. \tag{12}$$

The time of transition from the first valley to the second τ_{12} and the reverse τ_{21} transition are different and $\tau_{21} > \tau_{12}$. We consider the case when they are related to the relation (12).

Choosing the direction $\vec{\nabla}T$ and $\vec{k}$ as follows $\vec{k} \perp \vec{\nabla}T$ and substituting (10) into equation (4) we

$$\left[-i\omega^2 - 2i\vec{k}\upsilon_0\omega - 2i\omega_T\omega + \frac{c^2k^2}{4\pi\sigma}\omega - \frac{\omega}{\tau_{12}} - \frac{2\vec{k}\upsilon_0}{\tau_{12}} - \frac{2\omega_T}{\tau_{12}} - i\frac{c^2k^2}{2\pi\sigma\tau_{12}} + i\vec{k}\upsilon_1\omega + \right.$$

$$\left. + 2i\vec{k}\upsilon_0\vec{k}\upsilon_{10} + i\vec{k}\upsilon_1\omega_T - \frac{c^2k^2}{4\pi\sigma}\vec{k}\upsilon_1\right]\left(\mu_{20}n_{20}\omega + 2ck\mu_1'n_{10}\right) - \left[i\omega^2 + 2i\vec{k}\upsilon_0\omega + 2i\omega_T\omega - \frac{c^2k^2}{4\pi\sigma}\omega + \frac{\omega}{\tau_{21}} + \right.$$

$$\left. + \frac{2\vec{k}\upsilon_0}{\tau_{21}} + \frac{2\omega_T}{\tau_{21}} + i\frac{c^2k^2}{2\pi\sigma\tau_{21}} - i\vec{k}\upsilon_2\omega - -2i\vec{k}\upsilon_0\vec{k}\upsilon_2 - 2i\vec{k}\upsilon_2\omega_T + \frac{c^2k^2}{4\pi\sigma}\vec{k}\upsilon_2\right]\left(\mu_{10}n_{10}\omega + 2ck\mu_2'n_{20}\right) = 0$$

$$\upsilon_1 = \mu_1\vec{E}_0, \upsilon_2 = \mu_2\vec{E}_0$$

From (11) it is clear that the solution to equation (11) is too complicated, and therefore we will consider the following approximations. Equation (11) is the dispersion equation for determining the frequency (13) of the waves arising under the condition (12).

Considering (12), from solution (11) we obtain:

$$\omega_{1,2}=\frac{\tau_{12}}{2\tau_{21}}\left(i\Omega-4\omega_T-\omega_x\right)\pm\sqrt{\left(\frac{\tau_{12}}{2\tau_{21}}\right)^2\left(i\Omega-4\omega_T-\omega_x\right)^2+\frac{2}{\tau_{21}}\left(2\omega_T 2\vec{k}\vec{\upsilon}_0+i\frac{c^2k^2}{4\pi\sigma}\right)};\qquad(13)$$

$$\Omega=\frac{1}{\tau_{21}}-\frac{1}{\tau_{12}},\omega_x=4\vec{k}\vec{\upsilon}_0+\frac{c^2k^2}{2\pi\sigma}.\qquad(14)$$

Equation (14) is a characteristic notation. From the analysis of (13) considering (14) we obtain and we will select the imaginary and real parts of the oscillation frequency as follows:

$$\omega_{1,2}=-\frac{i}{2\tau_{21}}-\frac{\tau_{12}}{2\tau_{21}}\left(4\omega_T+\omega_x\right)\pm\left(x+iy\right);$$
$$x=\frac{1}{\sqrt{2}}\left[\sqrt{\Omega_1^4+\Omega_2^4}+\Omega_1^2\right]^{1/2},\ y=\frac{1}{\sqrt{2}}\left[\sqrt{\Omega_1^4+\Omega_2^4}-\Omega_1^2\right]^{1/2}.\qquad(15)$$

Then from (15)

$$\Omega_1^2=\left(\frac{\tau_{12}}{2\tau_{21}}\right)^2\left(4\omega_T+\omega_x\right)^2-\left(\frac{\tau_{12}}{2\tau_{21}}\right)^2\Omega^2+\frac{2}{\tau_{21}}\left(2\omega_T+2\vec{k}\vec{\upsilon}_0\right);$$
$$\Omega_2^2-\left(\frac{\tau_{12}}{2\tau_{21}}\right)^2\cdot 2\left(4\omega_T+\omega_x\right)+\frac{1}{\tau_{21}}\frac{c^2k^2}{2\pi\sigma}.\qquad(16)$$

In (15) it is to see that one wave is decaying, and the second wave can grow if

$$\frac{1}{\sqrt{2}}\left[\sqrt{\phi_1^2+\phi_2^2}-\phi_1\right]^{1/2}>\frac{1}{2}\qquad(17)$$

$$\phi_1=\frac{\tau_{12}^2\left(4\omega_T+\omega_x\right)^2}{4}+4\tau_{21}\left(\omega_T+\vec{k}\vec{\upsilon}_0\right)-\frac{1}{4};$$
$$\phi_2=\frac{\tau_{12}^2\left(4\omega_T+\omega_x\right)}{2}+\frac{c^2k^2\tau_{12}^2}{2\pi\sigma\tau_{21}}.\qquad(18)$$

Equations (15), (16), (17) and (18) are the distinguished real and imaginary parts of the corresponding quantities. By putting (18) into (15) we easily obtain:

$$\omega=\omega_0+i\omega_i\qquad(19)$$

In the notation (18) the obtained imaginary and real parts of the frequencies

$$\omega_0=\omega_T\left\{\frac{\sqrt{2}\tau_{12}}{\tau_{21}}\left[\sqrt{1+\left(2\tau_{21}\omega_T\right)^2}+1\right]^{1/2}-\frac{\tau_{12}}{\tau_{21}}\right\};\qquad(20)$$

$$\omega_1=\omega_T\left\{\frac{\sqrt{2}\tau_{12}}{\tau_{21}}\left[\sqrt{1+\left(2\tau_{21}\omega_T\right)^2}-1\right]^{1/2}-\frac{1}{2\tau_{21}}\right\}.\qquad(21)$$

Equation (20)–(21) define the expression for the part for the increment after theoretical calculation. Analysis (21) shows that for a wave to grow with frequency (20), the inequality must be satisfied

$$8\sqrt{2}\pi\omega_T\sigma\left(\omega_T\tau_{12}\right)^2>c^2k^2\qquad(22)$$

Under the conditions of Gunn's experiment, an increase in thermomagnetic waves is obtained under condition (23). It should be noted that the condition for excitation of thermomagnetic waves in the above-mentioned two-valley semiconductors was investigated for the first time and there is no experimental evidence for the excitation of thermomagnetic waves in two-valley semiconductors.

Using experimental data of the Gunn effect, that is $L=0.25$ mm, $n\approx 3\cdot 10^{16}$ cm^{-3} is the length of the sample, it is easy to prove that (22) is well satisfied. When obtaining (20), (21) and (22), it was taken into account that

$$\tau_{12}\omega_T > \frac{1}{4}, \frac{c^2k^2\tau_{12}}{2\pi\sigma\tau_{21}} < 2\tau_{12}\omega_T, \tau_{21} > \tau_{12}, \quad (23)$$

which are easily achieved under experimental conditions. Inequality (22) is the condition of excited thermomagnetic waves, inequality (23) is the relationship between the transition times between the valleys.

In our theoretical work, the conditions for observing thermomagnetic waves in two-valley semiconductors of the GaAs type are indicated and corresponding experiments can be carried out.

Results

Thus, in two-valley semiconductors, when charge carriers transition between valleys, a thermomagnetic wave is excited, the wave vector of which is directed perpendicular to the temperature gradient. The frequency of this wave is thermomagnetic in nature. The growth increment of this wave is less than the frequency of the wave. The frequency and growth increment of this wave depend on the times τ_{21} and τ_{12}. Such instability is a purely thermomagnetic instability. The growth criterion of the excited wave is well satisfied when using the data of the Gunn experiment.

Conclusion

For the preparation of high-frequency amplifiers, our theoretical calculation shows an improvement in the quality factor of the devices.

Evaluation of frequencies ω_0 and growth increment ω_1 taking into account the Gunn experiment data shows that the frequency ω_0 of excited waves is of the order of 10^8 Hz, and the growth increment ω_1 of this wave is much smaller, this is 10^7 Hz. It should be noted that the excited thermomagnetic wave propagates with a higher frequency than the frequency of hydrodynamic waves (kv_0) and a lower frequency of electromagnetic waves $\omega_T < ck$. The results of our theoretical work, this is the expression for the frequency, the expression for the increment is valid when the waves propagate perpendicular to the temperature gradient. Of course, under the conditions $k \parallel \nabla T$ of excitation of the corresponding waves and the expression for them as a function of the external electromagnetic field and as a function of the total concentration in the medium will be different. The conditions of excitation of thermomagnetic waves in anisotropic crystals were theoretically investigated in [7]. To obtain the frequencies of current oscillations, it is necessary to calculate the total resistance of the sample, this is the impedance of the crystal.

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Э.Р. Гасанов, Ш.Г. Халилова, А.Х. Султанова

GaAs типті көп аңғарлы жартылай өткізгіштердегі термомагниттік толқындардың қозуы

Екі аңғарлы жартылай өткізгіштерде температура градиенті болған кезде температура градиентіне перпендикуляр таралатын термомагниттік толқын қозғалатыны дәлелденді. Мұндай тұрақсыз толқын иондану, рекомбинация және генерация жүрмейтін электр өрісінің мәнінде қозғалады. Сонда заряд тасымалдаушылардың жалпы концентрациясы тұрақты болады. GaAs-тағы Ганн эффектісі сынамада омдық контактілер болған кезде анықталды. Тәжірибеде омдық контактілерді алу қиын, сондықтан контактілерге заряд тасымалдаушылардың инъекциясын қарастыру қажет. Инъекция болған кезде кристалдың кедергісін есептеп, кедергінің сыйымдылық және индуктивті сипатын анықтау қажет. Қарастырылып отырған жағдайда GaAs-тағы қозған толқын гидродинамикалық толқынның жиілігіне байланысты. Аңғарлар арасында жүзеге асырылатын электр өрісі Ганн эффектісі GaAs-та осьтерінің кристалдарының мәндерінде анықталды. Кристалдық осьтердің басқа мәндерінде жиілік пен өсу өсімінің басқа мәндері болады. Біздің теориялық зерттеуімізде Ганның тәжірибелерінен кейін изотропты үлгі қолданылды. Әрине, анизотропты үлгілердегі теориялық зерттеулер ғылыми қызығушылық тудырады.

Кілт сөздер: термомагниттік толқындар, өсу, жиілік, өсу, динамика, тасымалдаушы концентрациясы, сипаттамалық жиіліктер, сипаттамалық электр өрісі, Ганн эффектісі, жартылай өткізгіш

Э.Р. Гасанов, Ш.Г. Халилова, А.Х. Султанова

Возбуждение термомагнитных волн в многодолинных полупроводниках типа GaAs

Доказано, что в двухдолинных полупроводниках при наличии градиента температуры возбуждается термомагнитная волна, распространяющаяся перпендикулярно градиенту температуры. Такая неустойчивая волна возбуждается при значении электрического поля, при котором не происходит ионизация, рекомбинация и генерация. При этом общая концентрация носителей заряда остается постоянной. Эффект Ганна в GaAs был обнаружен при наличии в образце омических контактов. Длина образца в эксперименте Ганна составляла $L \approx 0{,}25$ мм. Получение омических контактов в эксперименте затруднено, поэтому необходимо учитывать инжекцию носителей заряда через контакты. Необходимо рассчитать импеданс кристалла при наличии инжекции и определить емкостную и индуктивную природу импеданса. Электрическое поле осуществляет переход между долинами. Эффект Ганна был обнаружен в GaAs при значениях кристаллографических осей. При других значениях кристаллографических осей частота и инкремент роста будут иметь другие значения. В нашем теоретическом исследовании использовался изотропный образец, следуя экспериментам Ганна. Конечно, теоретические исследования в анизотропных образцах представляют научный интерес. В наших работах представлены исследования термомагнитных волн в анизотропных образцах. Однако в наших работах не учитываются переходы между долинами.

Ключевые слова: термомагнитные волны, рост, частота, инкремент, динамика, концентрация носителей, характеристические частоты, характеристическое электрическое поле

Information about the authors

Hasanov, Eldar — PhD in Physics, Associate Professor of Department of Solid State Physics, Baku State University, Leader of Department of Encyclopedia and Terminology, Institute of Physics, Baku, Azerbaijan; e-mail: egasanov065@gmail.com; ORCID ID: https://orcid.org/0009-0009-6900-6148.

Khalilova, Shahla (*corresponding author*) — PhD in Physics, Leading researcher of Department of Encyclopedia and Terminology at Institute of Physics, teacher of Department of Structure of Matter at Baku State University Physics, Baku, Azerbaijan; e-mail: shahlaganbarova@gmail.com; ORCID ID: https://orcid.org/0000-0003-4302-9674.

Sultanova, Aygun — PhD in Physics, Associate professor of Department of General and Theoretical Physics, Nakhchivan State University, Nakhchivan, Azerbaijan; e-mail: aygunsultanova60@gmail.com ORCID ID: https://orcid.org/0009-0006-7406-6055