КОНДЕНСАЦИЯЛАНҒАН КҮЙДІҢ ФИЗИКАСЫ
ФИЗИКА КОНДЕНСИРОВАННОГО СОСТОЯНИЯ
PHYSICS OF THE CONDENSED MATTER

Article

UDC 621.315.592, 621.03

https://doi.org/10.31489/2026PH2/6-12

Received: 13.01.2026
Accepted: 13.03.2026

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Unstable Waves in Two-Valley Semiconductors in the Presence of a Temperature Gradient and External Electric and Magnetic Field

A theory of unstable wave excitation in a two-valley semiconductor subjected to a temperature gradient and constant external electric and magnetic fields is developed. The effects of the external electric field, the temperature gradient, the magnetic field generated within the sample by hydrodynamic motion, and the electric field arising from charge-carrier redistribution are taken into account. It is shown that the sample size plays an important role in the excitation of unstable waves. The frequency of hydrodynamic waves is shown to be twice that of the thermomagnetic waves excited in the sample. Analytical expressions for the frequencies and growth rates of the unstable waves are obtained. Analytical conditions for the external magnetic field required to excite hydrodynamic unstable waves are derived, and the ranges of the external electric field corresponding to wave excitation are determined. It is established that the transition time of charge carriers from the lower valley to the upper valley is shorter than the transition time from the upper valley to the lower valley. The analysis is based on a linear theory and assumes that carrier mobilities differ only slightly from their equilibrium values. For the first time, the electric field generated within the semiconductor is taken into account, demonstrating the feasibility of developing new Gunn-effect devices, including generators and amplifiers. The proposed mechanisms are consistent with available experimental data on the Gunn effect. It is also shown that the combined action of a temperature gradient and an external magnetic field can facilitate the design and optimization of high-frequency devices and amplifiers.

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

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Introduction

In GaAs semiconductors, the energy spectrum of charge carriers at a wave vector value $k = 0$ has two minima. Between the two minima, the energy gap has a value of $\Delta = 0.36\,\text{eV}$. In the presence of an external electric field $\vec{E}$, charge carriers (in this case, electrons) receive energy from the electric field in order $\sim eEl$ (e refer to the elementary charge, l refer to the mean free path) and, using this energy, move into a high energy band. The mobility of charge carriers is $\mu_1 >> \mu_2$ (because $m_1^* << m_2^*$).

As one moves from the first valley to the second, the total current decreases. At certain values of the external electric field, the sample begins to emit energy at a certain frequency. This effect was first observed by the English scientist Gunn and is therefore called the Gunn effect [1]. In 1963, he discovered that the electric field $E \sim 2 \div 3 \cdot 10^3$ V/cm causes oscillations in the sample at certain values.

The electric current E_{kr}, following the electric field value $E \geq E_{kr}$, oscillates at a frequency of $\omega \sim 10^9 \div 10^{11}$ Hz. When the external electric field becomes greater than E_{kr} of the sample, it begins to emit energy, and the sample becomes an energy source. Based on the Gunn effect, amplifiers and generators were developed, which are called Gunn devices. The theory of the Gunn effect was developed in [1–4], and the physical basis of the effect was clarified. The energy spectrum of charge carriers in GaAs at Muller indices of [100] has the form (Fig. 1).

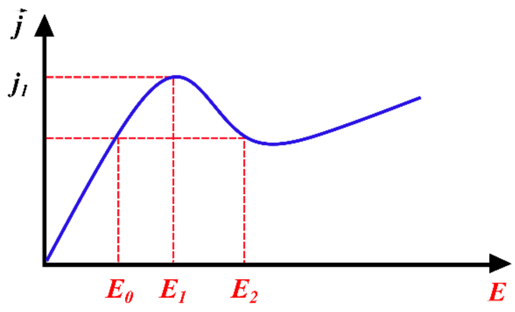

Figure 1. A plot of electric current as a function of the electric field

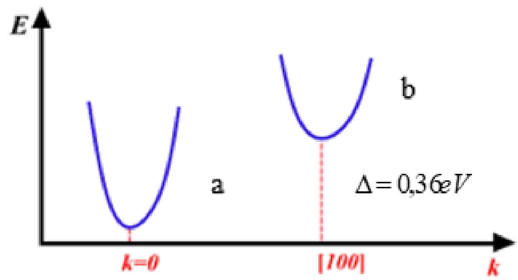

Figure 2. A plot of the energy of charge carriers as a function of the wave vector

The GaAs sample is assumed to be pure and free of impurities. Therefore, electrons are the only charge carriers, and their total concentration remains constant

$$n = n_1 + n_2 = const \, . \tag{1}$$

The Gunn effect theory in the presence of an external magnetic field was first developed in [5] and it was proven that if there is an external magnetic field $\vec{H}$, current oscillations begin at lower electric field values, i.e., $E \sim 2 \div 3 \cdot 10^2$ V/cm.

This is due to the fact that electrons in the presence of a magnetic field twist and are quickly distributed non-uniformly throughout the sample. In 1963, it was demonstrated in [6] that the hydrodynamic motion of charge carriers in the presence of a temperature gradient generates a new wave, called a thermomagnetic wave. In [6] the frequency of the thermomagnetic wave was calculated and the cause of its occurrence was determined.

In [7–9] it was demonstrated that thermomagnetic waves can be excited in solids, and this wave does not interact with sound waves. In [6] an expression for the effective electric field in a medium was obtained.

$$\vec{E}^* = \vec{E} + \frac{[\upsilon H]}{c} + \frac{T}{c}\frac{\nabla n}{n} \, . \tag{2}$$

Here $\vec{E}$ refer to the external electric field, refer to the electric field generated as a result of hydrodynamic movements with velocity υ, and $\frac{T}{c}\frac{\nabla n}{n}$ refer to the electric field due to the redistribution of charge carriers within the medium.

The Gunn effect was studied in the presence of an electric field *E*. A theoretical study in the presence of external electric and magnetic fields was conducted in [5].

However, no theoretical study has been conducted taking electric fields (2) into account.

In this theoretical work, we will investigate the oscillations of physical quantities in GaAs semiconductors, taking into account electric fields (2), the presence of a constant temperature gradient, and an external magnetic field H_0. We will analyze the conditions for the emergence of unstable waves within the sample and the relationship of the excited waves to the thermomagnetic wave.

Materials and Methods

Under the influence of external forces (this is $\vec{H}, \vec{E}, \vec{\nabla}T$), the charge carrier moves from the first valley (Fig. 2) to the second valley in time τ_{12}, and the reverse transition from the second valley to the first valley takes time τ_{21}. Therefore, the continuity equation in each valley is [9]:

$$\frac{\partial n_1}{\partial t} + \operatorname{div}\vec{j}_1 = \frac{n_1}{\tau_{12}};$$
$$\frac{\partial n_2}{\partial t} + \operatorname{div}\vec{j}_2 = \frac{n_2}{\tau_{21}}. \qquad (3)$$

Considering that the total concentration of charge carriers is constant, this is

$$n = n_1 + n_2 = const; \qquad (4)$$

$$n_1' = -n_2', \qquad (5)$$

$\vec{j}_1$ and $\vec{j}_2$ the current flow density in both valleys [9]:

$$\vec{j}_1 = n_1\mu_1 E^* + n_1\mu_1'\left[E^*\vec{H}\right] - \alpha_1\left[\vec{\nabla}T\vec{H}\right] - \alpha_1'\vec{\nabla}T;$$
$$\vec{j}_2 = n_2\mu_2 E^* + n_2\mu_2'\left[E^*\vec{H}\right] - \alpha_2\left[\vec{\nabla}T\vec{H}\right] - \alpha_2'\vec{\nabla}T. \qquad (6)$$

The relationship between the magnetic field and the electric field is determined by Maxwell's equation

$$\frac{\partial \vec{H}}{\partial t} = -c\operatorname{rot}E^*, \qquad (7)$$

c refers to speed of light.

Taking into account (4) from (3), we easily find

$$\operatorname{div}\vec{j} = \left(\frac{1}{\tau_{12}} - \frac{1}{\tau_{21}}\right)n_1'. \qquad (8)$$

Where $\vec{j} = \vec{j}_1 + \vec{j}_2$.

Substituting (6) into (8), we easily obtain:

$$\operatorname{div}\left\{\sigma\vec{E}^* + \frac{\sigma}{c}[\nu H] + \frac{T}{e}\left(\frac{\sigma_1}{n_{10}} - \frac{\sigma_2}{n_{20}}\right)\nabla n_1 + \sigma'\left[E^*H\right] + \frac{T}{e}\left(\frac{\sigma_1}{n_{10}} - \frac{\sigma_2}{n_{20}}\right)\left[\nabla n_1 H\right] - \alpha\nabla T - \alpha'\left[\vec{\nabla}T\vec{H}\right]\right\} =$$
$$= \left(\frac{1}{\tau_{12}} - \frac{1}{\tau_{21}}\right)n_1'. \qquad (9)$$

Where $\sigma = \left(\frac{n_1\mu_1 + n_2\mu_2}{e}\right), \sigma_1 = \frac{n_1\mu_1}{e}, \sigma_2 = \frac{n_2\mu_2}{e}, \sigma' = \left(\frac{n_1\mu_1' + n_2\mu_2'}{e}\right), \alpha = \alpha_1 + \alpha_2, \alpha' = \alpha_1' + \alpha_2'$.

Determining from Maxwell's equations

$$\vec{j}_1 + \vec{j}_2 = \frac{\varepsilon c}{4\pi}\operatorname{rot}\vec{H}.$$

Let's put $\vec{j}_1$ and $\vec{j}_2$ from (6), and we easily obtain an equation of the following type:

$$\vec{x} = \vec{a} + \left(\vec{b}\vec{x}\right), \vec{x} = \vec{E}^*. \qquad (10)$$

Due to the cumbersome nature of the expression $\vec{a}$ and $\vec{b}$, we will not write out the vectors.

By multiplying equation (10) once as a vector $\vec{E}^*$ and a second time as a scalar $\vec{E}^*$ with a weak magnetic field (this is $\mu_{10}H_0 << c$), we easily obtain

$$\vec{E}^* = -\frac{[\upsilon H]}{c} - \Lambda'[\nabla TH] + \frac{c}{4\pi\sigma}\operatorname{rot}H + \frac{T}{e}\left(\frac{1}{n_{10}} - \frac{1}{n_{20}}\right)\nabla n' + \Lambda\vec{\nabla}T. \qquad (11)$$

Where $\Lambda' = \frac{\alpha'\sigma - \sigma'\alpha}{\sigma^2}$ refer to Nernst-Ettingshausen coefficient

$$\Lambda = \frac{\alpha}{\sigma}, \alpha = \alpha_1 + \alpha_2, \alpha' = \alpha'_1 + \alpha'_2;$$

$$\vec{E}^* = \frac{T}{e\gamma}\left(\frac{1}{n_{10}} - \frac{1}{n_{20}}\right) i\vec{k} n'_1 + \Lambda \nabla T \frac{\vec{E}_0 E^*}{E_0^2};$$

$$\vec{E}_0 E^* = \frac{T}{e\gamma}\left(\frac{1}{n_{10}} - \frac{1}{n_{20}}\right) i\vec{k}\vec{E}_0 n'_1 + \frac{\Lambda \vec{\nabla} T \vec{E}_0}{E_0^2} \vec{E}_0 E^*; \tag{12}$$

$$\gamma = 1 + \frac{\vec{k}\vec{\upsilon}}{\omega} - \frac{2\omega_T}{\omega} - i\frac{c^2 k^2}{4\pi\sigma}.$$

To obtain the dispersion equation for the frequency of the excited waves inside the sample, equations (9, 10, 11) must be solved simultaneously.

We linearize equations (9, 10, 11) with respect to the physical quantities as follows:

$$\vec{E}^* = E_0^* + E^{*\prime}, E^{*\prime} << E_0^*, \vec{H} = \vec{H}_0 + \vec{H}', \vec{H}' << \vec{H}_0, n_1 = n_{10} + n'_1, n'_1 << n_{10} \tag{13}$$

and the total current flow

$$\vec{j} = \vec{j}_0 + \vec{j}'.$$

We select the following coordinate system: $\vec{H}_0 = \vec{k} H_{oz}, \vec{E}_o = \vec{i} E_{0x}, \vec{\nabla} T = \vec{i} \nabla_x T$, $\vec{i}, \vec{k}$ — unit vector.

Considering conditions (13) from (9, 10, 11), after algebraic calculations:

$$j'_x = \sigma_0 E_x^{*\prime} + E_0 \sigma' + \frac{\sigma_0}{c}\left(\upsilon_{0y} H'_z - \upsilon_{0z} H'_y\right) + E_1 i\left(\frac{\sigma_1}{n_{10}} - \frac{\sigma_2}{n_{20}}\right) n'_1 + \sigma'_0 E_y^{*\prime} + $$
$$+ E_1 \frac{k_y}{k_x} i\left(\frac{\sigma_1}{n_{10}} - \frac{\sigma_2}{n_{20}}\right) H_0 n' - \Lambda\delta \nabla_x T \frac{E_x^{*\prime}}{E_0}, \tag{14}$$

$$E_1 = \frac{T}{e} k_x;$$

$$j'_y = \sigma E_y^{*\prime} - \frac{\sigma_0 H_0}{c}\upsilon'_x - \frac{\sigma' H_0}{c}\upsilon_{x0} + E_1 \frac{k_y}{k_x} i\left(\frac{\sigma_1}{n_{10}} - \frac{\sigma_2}{n_{20}}\right) n'_1 + \sigma'_0 E_*^{*\prime} - E_1\left(\frac{\sigma_1}{n_{10}} - \frac{\sigma_2}{n_{20}}\right) n'_1 = 0; \tag{15}$$

$$j'_z = \sigma E^{*\prime} + \frac{\sigma_0}{c}\left(\upsilon_{x0} H'_y - \upsilon_{y0} H'_x\right) + E_1 \frac{k_z}{k_x} i\left(\frac{\sigma_1}{n_{10}} - \frac{\sigma_2}{n_{20}}\right) n'_1 + \sigma'_0 \frac{E_0}{H_0} H'_y - \alpha \nabla_x T H'_y = 0; \tag{16}$$

$$H'_x = \frac{c}{\omega}\left(k_y E_z^{*\prime} - k_z E_y^{*\prime}\right),\ H'_y = \frac{c}{\omega}\left(k_z E_x^{*\prime} - k_x E_z^{*\prime}\right),\ H'_z = \frac{c}{\omega}\left(k_x E_y^{*\prime} - k_y E_x^{*\prime}\right). \tag{17}$$

At

$$H_0 = \frac{c}{\mu_{10}} \frac{L_y}{L_x} \frac{n_{20}}{n_{10}}. \tag{18}$$

The dispersion equation has the form:

$$\left(\Omega + i k_x \upsilon_{10}\right)\omega^2 + \left[\Omega\left(\vec{k}\vec{\upsilon}_0 - 2\omega_T\right) + k_x \upsilon_{10} \frac{c^2 k^2}{4\pi\sigma_0} + i\left(k_x \upsilon_{10} \vec{k}\vec{\upsilon}_0 - k_x \upsilon_{10} 2\omega_T - \Omega \frac{c^2 k^2}{4\pi\sigma}\right) - \right.$$
$$\left. - k_x^2 \upsilon_1 \upsilon_{oy} \eta\left(\frac{n_{10}}{n_{20}} + i\eta\right)\right]\omega - k_x^2 \upsilon_{10} \upsilon_{oy}\left(\frac{n_{10}}{n_{20}} + i\eta\right)\left(\vec{k}\vec{\upsilon}_0 - 2\omega_T - i\frac{c^2 k^2}{4\pi\sigma_0}\right) = 0; \tag{19}$$

$$\Omega = k_x \upsilon_1 \frac{n_{10}}{n_{20}} - \eta k_x \upsilon_1 - \omega(\tau).$$

At $\vec{k}\vec{\upsilon}_0 = -2\omega_T$

$$\left(\Omega + ik_x\upsilon_{10}\right)\omega^2 + \left[k_x\upsilon_{10}\frac{c^2k^2}{4\pi\sigma_0} - i\left(k_x^2\upsilon_1\upsilon_{0y}\eta^2 + \Omega\frac{c^2k^2}{4\pi\sigma}\right) - k_x^2\upsilon_1\upsilon_{oy}\eta\frac{n_{10}}{n_{20}}\right]\omega - \\ -k_x^2\upsilon_{10}\upsilon_{oy}\left(i\frac{n_{10}}{n_{20}} - i\eta\right)\frac{c^2k^2}{4\pi\sigma_0} = 0. \quad (20)$$

At

$$\frac{c^2k^2}{4\pi\sigma_0}E_0 = k_x\upsilon_{oy}\eta E_1\frac{n_{10}}{n_{20}}. \quad (21)$$

At $\tau_{12} = \frac{\upsilon_{oy}}{E_0\mu_{10}}\frac{4\pi\sigma_0}{c^2k^2}$ solution of (20) is

$$\omega_0 = k_x\upsilon_{0y}\left[\left(\frac{c^2k^2}{\upsilon_{0y}4\pi\sigma}\frac{n_{10}}{2n_{20}}\right)^2 - \frac{E_1}{2E_0}\eta^2\right];$$

$$\omega_1 = k_x\upsilon_{0y}\left(\frac{c^2k^2}{\upsilon_{0y}4\pi\sigma}\frac{n_{10}}{2n_{20}}\right)^{1/2}.$$

This is $\omega_0 < \omega_1$.

In this case, the growing wave of a hydrodynamic nature has a greater increment than the frequency of propagation of this wave.

Results and Discussion

Thus, when a two-valley GaAs semiconductor is exposed to external energy, magnetic fields and a temperature gradient with a specific direction, a hydrodynamic wave is excited instead of a thermomagnetic electromagnetic wave. The excited wave is growing, and with increasing electromagnetic wave frequency, the frequency of this wave increases. The sample size can be any value, and the ratio to the concentrations is $\frac{n_{10}}{n_{20}} > 1$. The transition time from the first valley to the second valley satisfies the condition $\tau_{12} < \tau_{21}$. The magnetic field has specific values and satisfies the condition

$$\mu_{10}H_0 << c.$$

The frequency of hydrodynamic waves is twice that of thermomagnetic waves. The electric field, under increasing conditions of excited waves, has a certain range. During unstable states of the sample, the electric field must exceed a certain characteristic field, this is $E_0 > \Lambda\nabla_x T$.

Conclusion

The direction of the external electric field and the temperature gradient are the same. The direction of the external magnetic field is perpendicular to the electric field of the temperature gradient. All theoretical calculations were performed for oscillations of physical quantities within the sample. Thus, internal instability was theoretically investigated. When oscillations of physical quantities are released externally, that is, when current oscillations in the circuit begin (i.e., external instability) and energy is emitted from the sample, the sample's resistance decreases. To calculate the oscillation frequency during external instability, it is necessary to calculate the impedance with a real frequency and a complex wave vector. This problem requires a different type of theoretical calculation. Taking into account the temperature gradient and external magnetic field simplifies the process of manufacturing high-frequency devices and amplifiers.

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Э.Р. Гасанов, Ш.Г. Халилова, Р.Г. Мустафаева

Температура градиенті және сыртқы электр мен магнит өрістері бар жағдайда екі аңғарлы жартылай өткізгіштердегі тұрақсыз толқындар

Жартылай өткізгіштердің көрсетілген екі аңғарында белгілі бір бағыттағы температура градиенті және белгілі бір бағыттағы сыртқы тұрақты электр және магнит өрістері болған жағдайда қозатын тұрақсыз толқындардың теориясы жасалды. Сыртқы электр өрісінің, температура градиентінің, гидродинамикалық қозғалыстар нәтижесінде үлгі ішінде пайда болатын магнит өрісінің, сондай-ақ заряд тасымалдаушылардың қайта таралуынан туындайтын ішкі электр өрісінің әсерлері ескерілді. Тұрақсыз толқындардың қозуында үлгінің өлшемі маңызды рөл атқаратыны көрсетілді. Гидродинамикалық толқындардың жиілігі аталған үлгі ішінде қозатын термомагниттік толқындардың жиілігінен екі есе жоғары екені дәлелденді. Пайда болатын тұрақсыз толқындардың жиілігі мен өсіміне арналған аналитикалық өрнектер алынды. Гидродинамикалық табиғаттағы тұрақсыз толқындарды қоздыру үшін қажетті сыртқы магнит өрісінің аналитикалық өрнектері анықталды. Бұл толқындарды қоздыруға арналған сыртқы энергетикалық өрістің аралықтары белгіленді. Заряд тасымалдаушылардың төменгі аңғардан жоғарғы аңғарға өту уақыты екінші аңғардан бірінші аңғарға қарағанда қысқа екені айқындалды. Сызықтық теория құрылып, тасымалдаушылардың қозғалғыштығы олардың тепе-теңдік мәндерінен шамалы ғана айырмашылығы бар деп қабылданды. Алғаш рет осы жартылай өткізгіш ішінде туындайтын электр өрісін есепке алу жаңа Ганн аспаптарын, яғни генераторлар мен күшейткіштерді жасау мүмкіндігінің практикалық жүзеге асырылатынын көрсетті. Жұмыста сипатталған мұндай аспаптарды жасау мүмкіндіктері Ганн эффектісі бойынша тәжірибелік деректермен толық сәйкес келеді. Температура градиенті мен сыртқы магнит өрісін ескеру жоғары жиілікті құрылғылар мен күшейткіштерді жасауға мүмкіндік беретіні көрсетілді.

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

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Нестабильные волны в двухдолинейных полупроводниках в присутствии температурного градиента и внешнего электрического и магнитного поля

Разработана теория возбуждения неустойчивых волн в присутствии температурного градиента заданного направления, а также внешних постоянных электрического и магнитного полей заданного направления в двух указанных долинах полупроводников. Учтено влияние внешнего электрического поля, температурного градиента, магнитного поля, возникающего внутри образца вследствие гидродинамических движений, а также влияние электрического поля, возникающего внутри образца вследствие перераспределения носителей заряда. Показано, что размер образца играет важную роль при возбуждении неустойчивых волн. Доказано, что частота гидродинамических волн в два раза выше частоты термомагнитных волн, возбуждаемых внутри указанного образца. Получены аналитические выражения для частоты и инкремента возникающих неустойчивых волн. Определены аналитические выражения для внешнего магнитного поля, необходимого для возбуждения неустойчивых волн гидродинамической природы. Установлены интервалы внешнего энергетического поля для возбуждения этих волн. Установлено, что переход носителей заряда из нижней долины в верхнюю происходит быстрее, чем переход из второй долины в первую. Построена линейная теория, при этом предполагалось, что подвижности носителей заряда незначительно отличаются от их равновесных значений. Впервые учет электрического поля, генерируемого внутри данного полупроводника, демонстрирует практическую возможность создания новых приборов Ганна, то есть генераторов и усилителей. Возможности создания таких приборов, описанные в работе, полностью согласуются с экспериментальными данными по эффекту Ганна. Показано, что учет температурного градиента и внешнего магнитного поля способствует созданию высокочастотных приборов и усилителей.

Ключевые слова: термомагнитные волны, рост, частота, инкремент, динамика, концентрация носителей, характерные частоты, характерное электрическое поле, эффект Ганна, полупроводник

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