EFFECT OF WEAK MAGNETIC FIELD ($\sim$300 Gs) ON THE INTENSITY OF TERAHERTZ EMISSION OF HOT ELECTRONS IN *n*-Ge AT HELIUM TEMPERATURES

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Experimental results of studying the effect of a weak magnetic field ($\sim$300 Gs) on the intensity of the terahertz emission ($\lambda \approx$100 μm) of hot electrons in n-Ge (crystallographic orientation $\langle 1,0,0\rangle$) at helium temperatures ($T \sim$5 K) are presented and discussed. It is shown that the strong influence of this field (decrease of the emission intensity by 500÷1000%) is related to a decrease of the carrier concentration at weak electric fields and the appearance of the magnetoresistance at stronger fields. The longitudinal magnetoresistance becomes significant due to the anisotropy of the energy dispersion law of electrons and a strong deformation of the electron velocity distribution function by the electric field (which is beyond the framework of the diffusion approximation).

1. Introduction

Recently, the peculiarities of mechanisms of generation and absorption of terahertz light attract still more attention of investigators [1]. In [2–4], we studied the angle dependences of the terahertz emission of hot electrons in n-Ge. This semiconductor has a cubic symmetry, but, in the case where the electric field is directed non-symmetrically with respect to valleys (minima in the conduction band), electrons in different valleys can have different temperatures. This results in the symmetry violation and, consequently, the appearance of the polarization dependence of the hot electron emission. We studied the relation between the polarization dependences and anisotropic scattering mechanisms [4, 5] characteristic of many-valley semiconductors. It was a surprise to discover that, under certain conditions (low temperatures, strong electric fields), the polarization dependences of the hot electron emission appear in the case where the electric field is oriented along the $\langle 1,0,0\rangle$ direction, i.e. symmetrically with respect to valleys. It was established that, in this case, the appearance of the polarization dependences is related to the symmetry violation of the even part of the electron velocity distribution function under the action of an electric field. In other words, this effect can be explained going beyond the bounds of the traditional so-called diffusion approximation. As is known (see, e.g., [6]), this approximation is based upon the smallness of the ratio of the drift velocity of an electron to its mean thermal velocity. At low temperatures and strong electric fields, the diffusion approximation appeared invalid. Another surprise was aroused by an extremely high sensitivity of the hot electron emission intensity to weak magnetic fields ($H \sim 300$ Gs) at low temperatures ($T \sim 5$ K). The emission intensity can fall by an order of magnitude due to the application of the magnetic field. This work is devoted to the study and explanation of this phenomenon.

2. Experimental Part

All measurements were performed on the set-up described in [4] supplemented with an attachment allowing one to subject an emitting sample to the action of the magnetic field of the required direction and magnitude – from zero to the maximum value. This field was created with the use of a permanent magnet with the corresponding devices used to regulate the field intensity. The arrangement of the units is schematically shown in Fig. 1.

The n-Ge samples were cut off in the crystallographic directions $\langle 1,1,1\rangle$ or $\langle 1,0,0\rangle$, had a standard size of $7\times1\times1$ mm^3, and were treated using the standard technique [4]. The electric field was created by pulses with a duration of 0.8 μs and a repetition rate of 6 Hz. After that, the signal of a semiconductor detector was amplified, integrated, and converted to the direct-current voltage proportional to the intensity of the hot electron emission of the sample in the region $\lambda \approx$100 μm. The

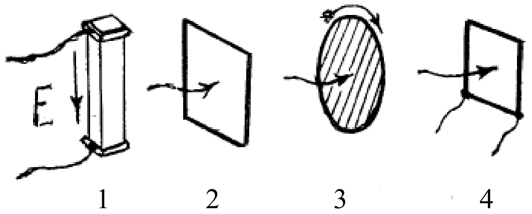

Fig. 1. Diagram of the experiment. *1* – n-Ge sample; *2* – filter limiting high frequencies; *3* – rotating polarizer; *4* – Ge(Ga) receiver

ohmicity of the contacts to n-Ge was provided using St alloy with a 5-% fraction of Sb.

3. Experimental Results and Their Discussion

Figure 2,*a*–*c* presents the experimental results of studying the effect of a weak magnetic field on the intensity of the hot electron emission in n-Ge. One can see that, at small electric fields, the magnetic field reduces the emission amplitude by almost an order of magnitude. With increase in the electric field, the effect of the magnetic field on the emission intensity becomes considerably weaker. Such changes in the emission intensity under the action of the weak magnetic field cannot be explained by its influence on the dispersion law or scattering mechanisms. Simple estimates demonstrate that, during the mean free time between collisions of a carrier with scattering centers, its trajectory changes insignificantly. In this connection, it was necessary to search for other reasons of such a strong effect of the weak magnetic field on the terahertz emission intensity.

For this purpose, we studied the electrophysical characteristics of the n-Ge samples investigating their emission at helium temperatures. We took volt-ampere characteristics and carried out Hall measurements in order to determine the carrier concentration starting from low voltages, at which not all donors are ionized [7]. The measuring results are given in Fig. 3 and Table. As follows from the behavior of the volt-ampere characteristic of the sample in the absence and in the presence of the magnetic field (we recall that the magnetic field is weak, close to 300 Gs), the resistance of the sample in such a field grows almost by an order of magnitude at an electric field of ∼5 V. With increase in the electric field, the resistance of the sample grows much more slowly: only by tens of percent. One can trace a direct connection between the increase of the sample resistance and the fall of the emission intensity.

Thus, the first part of our task aimed at clarifying the reasons of a decrease of the terahertz emission in-

Fig. 2. Receiver signal: *1* – without magnetic field *2* – with weak magnetic field; heating electric fields: 15 V/cm (*a*), 25 V/cm (*b*), 200 V/cm (*c*)

V	2	3	4	5	9	15	30	45
n	$3.21{\times}10^9$	$7{\times}10^9$	$2.8{\times}10^{12}$	$1.41{\times}10^{13}$	$9.3{\times}10^{13}$	$1.7{\times}10^{14}$	$6.7{\times}10^{14}$	$2.3{\times}10^{14}$

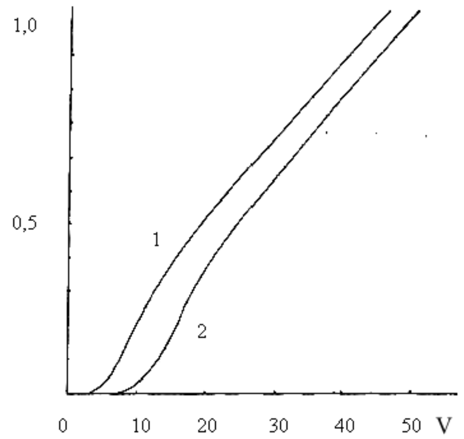

Fig. 3. Volt-ampere characteristic of the sample: *1* – without magnetic field *2* – with weak magnetic field (~300 Gs)

tensity under the action of the weak magnetic field is solved, though far from exhaustively. Now, we need to explain the large growth of the sample resistance under the action of such a weak magnetic field at helium temperatures. It turned out that similar phenomena have been already studied and were explained by the hopping conduction in the impurity band. According to the existing conceptions (see, e.g., [8]), the main contribution into the conduction at low temperatures (at which the majority of electrons are localized at impurities) is made by the hopping mechanism. The effect of the weak magnetic field on this mechanism is explained by its influence on the "tails" of the wave function of electrons localized at donors. The overlapping of these "tails" determines the probability of hops of electrons to vacancies.

It is worth noting that the thermal introduction of carriers into the conduction band is ineffective at low temperatures, that is why the hopping conduction over vacancies is provided by the compensation effect. This compensation is present in practically any material. Assuming that the impurity breakdown starts according to the Zener mechanism, it is easy to understand the effect of the magnetic field on the free carrier concentration in the conduction band on the stage where all donors are non-ionized. In turn, this explains the influence of the weak magnetic field on the hot electron emission at low temperatures.

In addition, the "attachment" of the carriers already introduced into the conduction band to neutral donors, the inverse process, and the dependence of both processes on the magnetic field are possible.

All the above-said concerns a decrease of the emission under the action of a magnetic field at low electric fields $10{\div}15$ V/cm (Fig. 2,*a*).

At strong electric fields, this decrease is much smaller (Fig. 2,*c*) and amounts to ~10% of the initial value. Such a behavior of the observed phenomenon can be explained by a deformation of the velocity distribution function in the case where the electric field is oriented along the $\langle 1,0,0\rangle$ direction and develops into the heating one. In this case, the diffusion approximation can explain fine characteristics of the discussed phenomena not always, and one should use a more accurate distribution function.

At strong electric fields (at which the concentration of carriers in the conduction band does not change anymore), the effect of a magnetic field on the hot electron emission is related to the appearance of the longitudinal magnetoresistance. The latter is connected with a decrease in the electron heating and therefore a fall of the emission. The mechanism of the formation of the longitudinal magnetoresistance in many-valley semiconductors is considered in the following section.

4. Longitudinal Magnetoresistance

For today, the general theory of galvanomagnetic phenomena in many-valley semiconductors with regard for the anisotropy of the dispersion law of carriers and mechanisms of their scattering is well developed and solidly substantiated (see, e.g., [9]). However, the general formulas of this theory are rather cumbersome. The situation becomes still more complicated when trying to allow for the possibility of the electron heating by the electric field.

The purpose of this work is narrower – to explain the reasons for the appearance of the longitudinal magnetoresistance and estimate its magnitude in the case where arbitrary electric and weak magnetic fields are oriented along the direction symmetric with respect to valleys ($\langle 1,0,0\rangle$ in n-Ge). That is why we can employ a rougher but simpler model. The essence of this approximation is to characterize the hot electrons by a velocity-shifted Maxwellian distribution function [10] or (in the case of degeneracy) by the Fermi [11] function with the effective electron temperature. In many-valley semiconductors, such a function is to be introduced for electrons of each valley. In the general case where there exists the possibility of a degeneracy of the electron gas in the α-th ellipsoid, we can write [11]

$$f_\alpha = \left\{ 1 + \exp\left(+ \frac{\varepsilon(\boldsymbol{v}) - \mathbf{p}\mathbf{u}^{(\alpha)} - \mu^{(\alpha)}}{kT^{(\alpha)}} \right) \right\}^{-1}, \tag{1}$$

where v is the electron velocity, $\varepsilon(v)$ and $\mathbf{p}$ are its energy and momentum, respectively, $T^{(\alpha)}$ denotes the effective electron temperature, $\mu^{(\alpha)}$ is the chemical potential, and $\mathbf{u}^{(\alpha)}$ is the drift velocity. The quantities $\mu^{(\alpha)}$, $T^{(\alpha)}$, and $\mathbf{u}^{(\alpha)}$ must be determined from the equations for the concentration, energy, and momentum balance, respectively. In what follows, we will consider the case where the electric field $\mathbf{E}$ and the magnetic field $\mathbf{H}$ are oriented along the direction symmetric with respect to valleys ($\langle 1,0,0\rangle$ for n-Ge), so the parameters $\mu^{(\alpha)}$ and $T^{(\alpha)}$ will be the same for all valleys. As concerns the drift velocity $\mathbf{u}^{(\alpha)}$ in the given symmetric case, it will have the same absolute value but different directions for different valleys. That is why we do not present explicitly the balance equations for the electron concentrations in valleys and their energies and restrict ourselves to the momentum balance equation. In the principal axes of the α-th mass ellipsoid, in which the energy dispersion law has the standard form

$$\varepsilon(\boldsymbol{v}) = \frac{P_\perp^2}{2m_\perp} + \frac{P_\parallel^2}{2m_\parallel}, \tag{2}$$

the momentum balance equation is

$$e\left\{ E_i + \frac{1}{c}\left[\mathbf{u}^{(\alpha)} \times \mathbf{H}\right]_i = \frac{m_\perp}{\tau_\perp}\, u_i^{(\alpha)}, (i = x, y) \right\}, \tag{3}$$

$$e\left\{ E_z + \frac{1}{c}\left[\mathbf{u}^{(\alpha)} \times \mathbf{H}\right]_z = \frac{m_\parallel}{\tau_\parallel}\, u_z^{(\alpha)} \right\}, \tag{4}$$

where e is the electron charge, c is the light velocity, while $\tau_\parallel$ and $\tau_\perp$ are the longitudinal and transverse relaxation times, respectively.

Due to the weakness of the magnetic field, we can solve Eqs. (3) and (4) using perturbation theory with respect to the parameter H. In the zero-order approximation (i.e. at $H = 0$), Eqs. (3) and (4) yield

$$\left\{ u_i^{(\alpha)} \right\}_0 = \frac{e\tau_\perp}{m_\perp} E_i, \quad i = x, y, \tag{5}$$

$$\left\{ u_z^{(\alpha)} \right\}_0 = \frac{e\tau_\parallel}{m_\parallel} E_z, \tag{6}$$

$$\mathbf{u}_0^{(\alpha)} = \frac{e\tau_\perp}{m_\perp}\mathbf{E} + \left(\frac{e\tau_\parallel}{m_\parallel} - \frac{e\tau_\perp}{m_\perp} \right)(\mathbf{i}_\alpha \mathbf{E})\, \mathbf{i}_\alpha, \tag{7}$$

where $\mathbf{i}_\alpha$ is the unit vector that specifies the orientation of the α-th ellipsoid (valley). From Eq.(7) (or Eqs.(5)–(6)), one can see that the direction of the drift velocity $\mathbf{u}^{(\alpha)}$ does not coincide with that of the electric field, unless this field is directed along the principal axis of the mass ellipsoid. As a result, the term $[\mathbf{u}^{(\alpha)} \times \mathbf{H}]$ will be non-zero in spite of the fact that $\mathbf{H} \parallel \mathbf{E}$. This is the reason for the appearance of the longitudinal magnetoresistance in n-Ge.

Then, one can develop the perturbation theory with respect to H, i.e. substitute the approximate value $\mathbf{u}_0^{(\alpha)}$in the term $[\mathbf{u}^{(\alpha)} \times \mathbf{H}]$ neglected when obtaining Eq.(7), which yields $\mathbf{u}_1^{(\alpha)}$ and so on. As a result, we obtain the series with respect to H for the drift velocity of electrons of the α-th valley (see Appendix):

$$\mathbf{u}^{(\alpha)} = \quad \mathbf{u}_0^{(\alpha)} + \mathbf{u}_1^{(\alpha)} + \mathbf{u}_2^{(\alpha)} + \ldots. \tag{8}$$

The term linear in H in the drift velocity (8) ($\mathbf{u}_1^{(\alpha)}$) determines the Hall current. Due to the symmetry of the problem, the total Hall current in all valleys is equal to zero. The component $\mathbf{u}_2^{(\alpha)}$ determines the magnetoresistance. Its $\langle 1,0,0\rangle$-projection and the sum over all valleys determines the addition ΔJ_2 to the current $J_0 = J(H = 0)$. As is shown in Appendix,

$$\frac{\Delta J_2}{J_0} = -\frac{(e^2\,\tau_\perp/m_\perp\,c^2)(\tau_\parallel/m_\parallel - \tau_\perp/m_\perp)^2 \cdot \mathrm{H}^2}{3(\tau_\parallel/m_\parallel + 2\tau_\perp/m_\perp)}, \tag{9}$$

where

$$J_0 = \frac{e^2 n}{3}\left(\frac{\tau_\parallel}{m_\parallel} + 2\frac{\tau_\perp}{m_\perp} \right), \tag{10}$$

and n is the total electron concentration (in all valleys).

For n-Ge,

$$m_\perp \ll m_\parallel, \quad \tau_\perp \sim \tau_\parallel. \tag{11}$$

In this case, formula (9) acquires the simplified form

$$\frac{\Delta J_2}{J_0} = -\frac{1}{6}\frac{e^2\,\tau_\perp}{m_\perp^2\,c^2} H^2. \tag{12}$$

Assuming for the estimate that $m_\perp \approx 0.7 \times 10^{-28}$ g, $\tau_\perp \approx 10^{-11}$ s, and $H \approx 300$ Oe, we obtain from Eq.(12) that $\Delta J_2 / J_0 \approx -1/12$, which is in good agreement with the experiment.

5. Conclusions

The performed studies allow us to make the following conclusions. At low temperatures and weak electric fields, at which the majority of electrons is localized at donor levels, the effect of a weak magnetic field on the volt-ampere characteristics and the emission is explained as follows. Both the hopping conduction and the Zener breakdown mechanism are sensitive to the influence of a magnetic field on the "tails" of the wave function of an electron localized at a donor. This explains the fast decrease of the current and the emission due to the application of a weak magnetic field. In strong electric fields, all donors are ionized and the electron concentration in the conduction band is constant. The effect of the magnetic field on the volt-ampere characteristics and the emission in strong electric fields is much weaker. In this case, such a weak influence is explained by the longitudinal magnetoresistance. The mechanism of the longitudinal magnetoresistance is related to the anisotropy of the dispersion law of electrons in n-Ge.

In conclusion, the authors express their gratitude to O.G. Sarbey and S.M. Ryabchenko for the discussion of a number of questions.

APPENDIX

With the use of Eq.(7), we obtain:

$$[\mathbf{u}_0^{(\alpha)} \times \mathbf{H}] = e(\tau_\parallel/m_\parallel - \tau_\perp/m_\perp)(\mathbf{i}_\alpha\,\mathbf{E})\,[\mathbf{i}_\alpha \times \mathbf{H}]\,. \quad (A1)$$

Assuming that the vector $[\mathbf{i}_\alpha \times \mathbf{H}]$ is directed along the x axis and substituting Eq. (A1) into (3), one can put down

$$\mathbf{u}_1^{(\alpha)} = \frac{e^2\tau_\perp}{m_\perp c}\, e(\tau_\parallel/m_\parallel - \tau_\perp/m_\perp)(\mathbf{i}_\alpha\mathbf{E})\,[\mathbf{i}_\alpha \times \mathbf{H}]\,. \quad (A2)$$

After that, Eq. (A2) yields

$$[\mathbf{u}_1^{(\alpha)} \times \mathbf{H}] = \frac{e^2\tau_\perp}{m_\perp c}(\tau_\parallel/m_\parallel - \tau_\perp/m_\perp)(\mathbf{i}_\alpha\mathbf{E})\,[(\mathbf{i}_\alpha \times\, \mathbf{H}) \times \mathbf{H}] =$$

$$= \frac{e^2\tau_\perp}{m_\perp c}(\tau_\parallel\,/m_\parallel)(\mathbf{i}_\alpha\mathbf{E})\{(\,\mathbf{i}_\alpha\mathbf{H})\mathbf{H} - \mathbf{i}_\alpha\mathbf{H}^2\}. \quad (A3)$$

As one can see, the vector $[\mathbf{u}_1^{(\alpha)} \times \mathbf{H}]$ lies in the plane specified by the vectors $\mathbf{H}$ and $\mathbf{i}_\alpha$. If we take the direction $[\mathbf{i}_\alpha \times \mathbf{H}]$ in this plane as the x axis and the direction $\mathbf{i}_\alpha$ as the z axis (the normal to these vectors will be the y axis), then the components $[\mathbf{u}_1^{(\alpha)} \times \mathbf{H}]_y$ and $[\mathbf{u}_1^{(\alpha)} \times \mathbf{H}]_z$ will be non-zero. Their substitution into Eqs. (3) and (4), respectively, yields

$$\mathbf{u}_{2y}^{(\alpha)} = \frac{e^3\tau_\perp^2}{m_\perp^2 c^2}(\tau_\parallel/m_\parallel - \tau_\perp/m_\perp)(\mathbf{i}_\alpha\mathbf{E})(\mathbf{i}_\alpha\mathbf{H})\{\mathbf{H} - \mathbf{i}_\alpha(\mathbf{i}_\alpha\mathbf{H})\}, \quad (A4)$$

$$\mathbf{u}_{2z}^{(\alpha)} = -\frac{e^3\tau_\perp\tau_\parallel}{m_\perp m_\parallel c^2}(\tau_\parallel/m_\parallel - \tau_\perp/m_\perp)(\mathbf{i}_\alpha\mathbf{E})\{H^2 - (\mathbf{i}_\alpha\mathbf{H})^2\}\mathbf{i}_\alpha. \quad (A5)$$

Expressions (A4) and (A5) are put down in the vector form so that to be easy-to-use in the laboratory system of coordinates and to sum up over all valleys. Thus, $\mathbf{u}_{2y}^{(\alpha)}$ and $\mathbf{u}_{2z}^{(\alpha)}$ are related to the given ellipsoid α only through the unit vector $\mathbf{i}_\alpha$.

As we are interested in the longitudinal magnetoresistance, it is necessary to find the addition to the current J_0 quadratic in the magnetic field (in the direction $\mathbf{E} \parallel \mathbf{H}\mathbf{q}_0; \mathbf{q}_0 \equiv (1,0,0)$). This addition is evidently equal to

$$\Delta J_2 = -\frac{en}{4}\sum_{(\alpha)} \mathbf{q}_0\{\mathbf{u}_{2y}^{(\alpha)} + \mathbf{u}_{2z}^{(\alpha)}\}. \quad (A6)$$

Here, $\frac{1}{4}n$ is the electron concentration in one valley.

Substituting expressions (A4) and (A5) into (A6) and taking into account that the unit vectors $\mathbf{i}_\alpha(\alpha = 1,2,3,4)$ in n-Ge have the form

$$\mathbf{i}_1 = \frac{1}{\sqrt{3}}(1,1,1), \quad \mathbf{i}_2 = \frac{1}{\sqrt{3}}(-1,1,1),$$

$$\mathbf{i}_3 = \frac{1}{\sqrt{3}}(1,-1,1), \quad \mathbf{i}_4 = \frac{1}{\sqrt{3}}(-1,-1,1),$$

we obtain

$$\Delta\mathbf{J}_2 = -\frac{e^4 n}{9m_\perp c^2}\left(\frac{\tau_\parallel}{m\parallel} - \frac{\tau_\perp}{m_\perp}\right)^2 H^2\mathbf{E}. \quad (A7)$$

For isotropic scattering mechanisms and dispersion law, $\Delta J_2 = 0$.

1. V.E. Lyubchenko, Radiotekhn. No. 2, 5 (2002).
2. V.M. Bondar, O.G. Sarbey, and P.M. Tomchuk, Fiz. Tekhn. Polupr. **69**, 1540 (2002).
3. P.M. Tomchuk, Ukr. Fiz. Zh. **49**, 681 (2004).
4. V.M. Bondar and N.F. Chornomorets', Ukr. Fiz. Zh. **48**, 51 (2003).
5. P.M. Tomchuk and V.M. Bondar, Ukr. Fiz. Zh. **53**, 666 (2008).
6. I.M. Dykman and P.M. Tomchuk, *Transport Phenomena and Fluctuations in Semiconductors* (Naukova Dumka, Kyiv, 1981) (in Russian).
7. Yu.A. Astrov and A.A. Kastal'skii, *Peculiarities of Breakdown of Shallow Donors in Pure n-Ge* (Mantis, Vilnius, 1972).
8. B.I. Shklovskii and A.I. Efros, *Electronic Properties of Doped Semiconductors* (Springer, New York, 1984).
9. P.I. Baranskii, I.S. Buda, I.V. Dakhovskii, and V.V. Kolomoets, *Electric and Galvanomagnetic Phenomena in Anisotropic Semiconductors* (Naukova Dumka, Kyiv, 1977) (in Russian).
10. E.M. Conwell, *Kinetic Properties of Semiconductors in Strong Electric Fields* (Academic Press, New York–London, 1967).
11. F.G. Bass and Yu.G. Gurevich, *Hot Electrons and Strong Electromagnetic Waves in Semiconductors and Gas Discharge Plasma* (Nauka, Moscow, 1975) (in Russian).

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ВПЛИВ СЛАБКОГО МАГНІТНОГО ПОЛЯ ($\sim$300 Гс) НА ІНТЕНСИВНІСТЬ ТЕРАГЕРЦОВОГО ВИПРОМІНЮВАННЯ ГАРЯЧИХ ЕЛЕКТРОНІВ В n-Ge ПРИ ГЕЛІЄВИХ ТЕМПЕРАТУРАХ

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Р е з ю м е

У роботі наведено експериментальні результати та їх обговорення у вивченні впливу слабкого магнітного поля ($\sim$300 Гс) на інтенсивність терагерцового випромінювання ($\lambda \approx$100 мкм) гарячих електронів з n-Ge (кристалографічний напрямок ($\langle 1,0,0\rangle$) при гелієвих температурах T $\sim$5 K). Показано, що сильний вплив такого поля (зменшення інтенсивності) випромінювання (500–1000 %) пов'язаний зі зменшенням концентрації носіїв при слабких електричних полях та появою магнітоопору при сильніших полях. Поздовжній магнітоопір стає суттєвим завдяки анізотропії закону дисперсії енергії електронів і сильній деформації електричним полем функції розподілу електронів за швидкостями (вихід за межі дифузійного наближення).