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Thermomagnetic effect in a two-dimensional electron system with an asymmetric quantizing potential

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In a two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterojunction an electromotive force (EMF) was experimentally observed in the presence of a magnetic field parallel to the 2DEG plane and in the presence of a heating of the 2DEG with respect to the crystal lattice. The origin of this effect is the asymmetric quantizing potential of heterojunctions in the presence of a magnetic field which leads to an asymmetrical electron energy spectrum in the plane of 2DEG in the direction perpendicular to the magnetic field. The asymmetry of the electron energy spectrum leads to an asymmetrical electron-phonon interaction which results in the appearance of the EMF investigated. The value of the measured EMF is in agreement with theoretical estimations.

In a two-dimensional electron gas (2DEG) with asymmetric quantizing potential $U(z)$ in the presence of a magnetic field H_y parallel to the 2DEG plane, the electron energy spectrum becomes asymmetrical:

$$\varepsilon(k_x) \neq \varepsilon(-k_x), \tag{1}$$

where k_x is the wave vector of an electron in the direction perpendicular to the magnetic field.[1] The macroscopic properties of a 2DEG having an asymmetrical energy spectrum (1) are different for the directions $\langle x \rangle$ and $\langle -x \rangle$, leading to unusual physical effects.[2–5] Possible phenomena connected with this spectrum (1) were analyzed in recent theoretical studies[6,7] where different interactions between the 2DEG and elementary excitations (photons, acoustic phonons, etc.) having wave vectors q_x and $-q_x$ was demonstrated. This asymmetry of elementary electron interactions results in a universal quantum macroscopic effect: Any isotropic perturbation of any electron system having an asymmetrical energy spectrum (1) leads to the emergence of an electromotive force along the x axis.[8] In particular, this EMF appears for isotropic heating of the 2DEG with respect to the crystal lattice. The microscopic physical reason for this phenomenon is as follows. When the electron system is heated (for instance, by an electric field parallel to the 2DEG plane) the temperatures of the electron and phonon systems are different and energy transfer from the electron system to the phonon system by phonon emission takes place. Due to the difference of electron interactions with phonons having wave vectors q_x and $-q_x$, the energy transfer is accompanied by a momentum transfer from the phonons to the electrons along the x axis, leading to the emergence of an EMF $\mathcal{E}_x(H_y)$. The existence of this EMF was predicted in Ref. 9 and analyzed theoretically in more detail in Ref. 10. The aim of the present work is the experimental observation of this EMF.

For the investigations, Hall bars were fabricated from a 2DEG in a GaAs/AlGaAs heterojunction grown by molecular beam epitaxy. Two opposite probes 1, and 2, of the Hall bar were used to apply the heating current I, oscillating with the frequency f, such that the current parallel to the y axis crosses the bar that is parallel to the x axis (the geometry of the setup is presented in the inset of Fig. 1). The voltage drop U_{34} from the part of the bar at a distance $l = 100\ \mu$m from the crossing point was measured at frequency $2f$ as a function of magnetic field. The distance between the probes 3 and 4 was $d = 1$ mm. The same technique was previously used for measurements of thermopower of 2DEG microstructures in GaAs.[11] The Joule heat of the applied current produces a heating of the electron system with respect to the lattice temperature T. For low enough frequencies f, the temperature difference ΔT between the lattice and electron system oscillates with a frequency $2f$. Thus, for the magnetic field parallel to the y axis the voltage drop measured is proportional to the EMF $\mathcal{E}_x(H_y)$ directed perpendicular to the magnetic

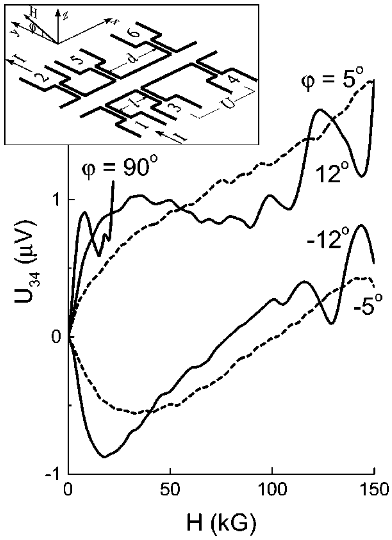

FIG. 1. Voltage drop U_{34} measured from probes 3 and 4 for different angles φ as the function of the absolute value of magnetic field. Inset shows the geometry of experiment.

field and the heating current line. The density and electron mobility of the 2DEG are $n_s = 4.6 \times 10^{11}$ cm^{-2} and $\mu = 4 \times 10^5$ cm^2/Vs. The measurements were carried out at temperatures T of about 20 K in magnetic fields up to 150 kG. We used $f \approx 7$ Hz and the power of the heating current was $P = 2.5 \times 10^{-4}$ W/mm^2 in our experiments. The magnitude of temperature oscillations ΔT was about 4 K in the region of the heating current. The measurements were carried out at different angles φ between the plane of 2DEG and the direction of the magnetic field. The transverse component of magnetic field H_z (and thus the angle φ) was determined using the measurements of the Hall signal proportional to H_z by passing the current through contacts 1 and 4, and measuring the voltage drop between contacts 3 and 5.

Figure 1 shows the dependence of the measured signal U_{34} on magnetic field H for different angles φ. At $\varphi = \pi/2$ the origin of the signal is the transverse Nernst-Ettingshausen EMF $\mathcal{E}_y^{NE}(H_z)$, that appears in lead 3 along the y direction due to the electron temperature gradient along x. This EMF is not compensated by the Nernst-Ettingshausen effect near lead 4 due to the exponential decay of the temperature gradient with the distance from the heating current line. One can see that the curve for $\varphi = 12°$ shows oscillations which are periodic in $1/H_z$. The origin of the oscillations is the feature of $\mathcal{E}_y^{NE}(H_z)$ driven by the transverse component of magnetic field and connected with the crossing of Landau levels by the Fermi energy. The electron density determined from these oscillations is $n_s = 4.6 \times 10^{11}$ cm^{-2} in agreement with that obtained from usual Hall measurements. Figure 2 shows the dependence of the measured signal on the transverse (H_z) and longitudinal (H_y) components of magnetic field. One can see from Fig. 2(a) that the signal measured for $\varphi = 5°$ and 12° is much larger than $U_{34}(\varphi = \pi/2) = \mathcal{E}_y^{NE}$ for corresponding values of H_z. This means that for small φ the main contribution to U_{34} is connected with the H_y component of the magnetic field, i.e., for small φ the voltage drop $U_{34} \approx \mathcal{E}_x(H_y)$.

It should be noted that the presence of a temperature gradient in a 2DEG along x can lead to ordinary thermomagnetic effects. However, any ordinary thermomagnetic effect connected with the H_y component should be an even function of magnetic field, with the sign of the effect determined by the sign of the temperature gradient. In contrast, the direction of the EMF of interest is determined by the vector product $[\vec{n} \times \vec{H}]$ (where $\vec{n}$ is the vector normal to the plane of 2DEG), and provided that the directions $\vec{n}$ and $-\vec{n}$ are not equivalent due to asymmetry of the quantizing potential of 2DEG, this EMF can be nonzero and should be an odd function of magnetic field. Figure 3 shows the dependence of $U_{34}(H)$ measured for the two signs of the magnetic field. One can clearly see that the high field part of the EMF connected with the H_y component changes sign when the magnetic field is reversed. This is convincing evidence that the observed EMF is not connected with ordinary thermomagnetic effects, but originates from the asymmetry of the quantizing potential of the 2DEG.

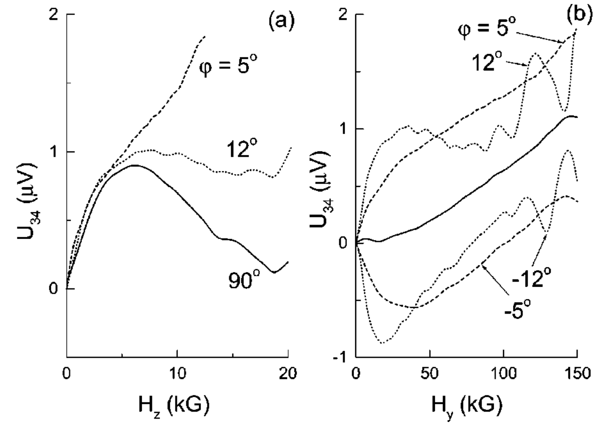

FIG. 2. The dependence of the measured signal U_{34} as a function of (a) H_z and (b) H_y components of magnetic field for different angles φ. The solid line is the $\mathcal{E}_x(H_y)$ dependence.

Since the measured signal can be presented as the linear sum of the two contributions $[U_{34} = \mathcal{E}_y^{NE}(H_z) + \mathcal{E}_x(H_y)]$ and taking into account that $\mathcal{E}_y^{NE}(H_z)$ is an odd function of H_z, one can obtain $\mathcal{E}_x = [U_{34}(\varphi) + U_{34}(-\varphi)]/2$. The corresponding curve calculated from the data measured at $\varphi = \pm 5°$ is

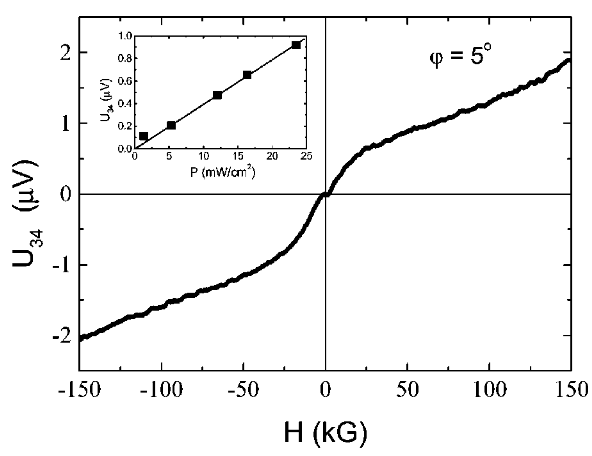

FIG. 3. The dependence of the signal $U_{34}(H)$ measured at $\varphi = 5°$ on the sign of the magnetic field. Inset shows the power dependence of EMF $\mathcal{E}_x(H_y)$ at $H_y = 100$ kG. Solid line is theoretical fit based on Eqs. (4) and (5).

presented as the solid line in Fig. 2(b). The nonlinearity of the curve near zero magnetic field is connected with an error in determining the angle at $|\varphi|<5°$, the influence of which on the resultant curve is stronger in weak magnetic fields where the $\mathcal{E}_y^{NE}(H_z)$ dependence is stronger [see Fig. 2(a)].

It follows from Ref. 9 that the EMF considered is

$$\mathcal{E}_x(H_y)=\left(\frac{\hbar}{en_s}\right)\int_{x_3}^{x_4} dx \sum_{\boldsymbol{q}} q_x[(w_e(\boldsymbol{q})-w_a(\boldsymbol{q})], \tag{2}$$

where $w_a(\boldsymbol{q})$ and $w_e(\boldsymbol{q})$ are, respectively, the probabilities of the acoustic phonon absorption and the acoustic phonon emission per unit time and per unit area of the 2DEG, $\boldsymbol{q}$ is the phonon wave vector, and the integration over x extends between coordinates of the probes 3 and 4. In the condition of the present experiment, Eq. (2) has the form[10]

$$\mathcal{E}_x(H_y)\approx(k_BT)^5\left(\frac{\Xi m d_0}{\pi\hbar^4}\right)^2\left(\frac{12k_B}{\rho v_l^5 e n_s c}\right)\left(\frac{H_y}{E_z}\right)\times\int_{x_3}^{x_4} dx\Delta T(x), \tag{3}$$

where Ξ is the deformation potential of the GaAs conduction band, m is the effective electron mass, ρ is the crystal density, v_l is the velocity of the longitudinal acoustic wave in crystal, $d_0=(3\hbar^2\pi^2/16meE_z)^{1/3}$ is the characteristic thickness of the 2DEG, $E_z=4\pi e n_s/\epsilon$ is the electrical field at the heterojunction along the z axis, and ϵ is the dielectric constant. Using the thermal conductance equation for the degenerate 2DEG and the Weidemann-Franz law, the heating of the 2DEG between probes 3 and 4 can be written in the form:

$$\Delta T(x)=\Delta T_0 \exp\left(-\frac{x}{L}\right), \tag{4}$$

where x is the distance from the heating current line,

$$\Delta T_0\approx\frac{P\tau}{n_s k_B}$$

is the amplitude of temperature oscillations in the region of the heating current,[12]

$$L=\pi\sqrt{\frac{\mu\tau k_B T}{3e}}$$

is the characteristic length of the thermal conduction process in the 2DEG, and τ is the energy relaxation time in the electron-phonon system. Substituting Eq. (4) into Eq. (3) yields

$$\mathcal{E}_x(H_y)\approx(k_BT)^5\left(\frac{\Xi m d_0}{\pi\hbar^4}\right)^2\left(\frac{12k_B}{\rho v_l^5 e n_s c}\right)\left(\frac{H_y}{E_z}\right)\Delta T_0 \times\exp\left(-\frac{l}{L}\right)L\left[1-\exp\left(-\frac{d}{L}\right)\right]. \tag{5}$$

For a 2DEG in GaAs the energy relaxation time τ is about 10^{-9} s.[13,14] Then, for $H_y\sim10^5$G, Eq. (5) gives $\mathcal{E}_x(H_y)\sim10^{-7}$ V. One can see from Fig. 2(b) that this value is in reasonable agreement with experimental results.

The inset of Fig. 3 shows the power dependence of the EMF $\mathcal{E}_x(H_y)$ measured at $H_y=100$ kG. One can see that the dependence is linear in accordance with Eqs. (4) and (5) except for the lowest value of power where the accuracy of measurements is not high due to the small magnitude of the signal.

In conclusion, the effect considered is based on the asymmetry of the interaction of electrons with phonons q_x and $-q_x$. This asymmetry is a direct consequence of the simultaneous breaking of the inversion symmetry due to the asymmetric quantizing potential of heterojunction, and time-inversion symmetry due to magnetic field. As was previously shown,[2] the breaking of these fundamental symmetries results in analogous asymmetry of electron-photon interaction. However, in contrast to the effects originating from this asymmetry, namely the enhancement of photovoltaic effect, the asymmetry of electron-phonon interaction, considered in the present work, results in an EMF, which is completely absent in a 2DEG with symmetrical quantizing potential or in zero magnetic field.

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