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Low-field diffusion magnetothermopower of a high-mobility two-dimensional electron gas

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The low-magnetic field-diffusion thermopower of a high-mobility GaAs heterostructure has been measured directly on an electrostatically defined micron-scale Hall-bar structure ($4\ \mu\mathrm{m}\times 8\ \mu\mathrm{m}$) at low temperature ($T=1.6$ K) in the field regime ($B\leqslant 1.2$ T) where the formation of edge states does not influence the measurements. The sample design allowed the determination of the field dependence of the thermopower both parallel and perpendicular to the temperature gradient, denoted respectively by S_{xx} (longitudinal thermopower) and S_{yx} (the Nernst-Ettinghausen coefficient). The experimental data show clear oscillations in S_{xx} and S_{yx} due to the formation of Landau levels and reveal that $S_{yx}\approx 120 S_{xx}$ at a magnetic field of 1 T, which agrees well with the theoretical prediction that the ratio of these tensor components is dependent on the carrier mobility: $S_{yx}/S_{xx}=2\omega_c\tau$.

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Thermopower experiments have been used extensively to obtain information on electron transport and scattering in two-dimensional electron gases (2DEGs) in compound semiconductors (for reviews, see Refs. 1 and 2). Because of the strong electron-phonon coupling in these systems, the experimental signal is usually dominated by phonon drag. Hence, apart from the desired electronic transport contributions, the signal also contains a very significant contribution due to details of the electron-phonon interaction. In order to extract the diffusion thermopower, usually drastic approximations have to be made.[1,2] It would thus be very desirable to have an experimental approach that is not influenced by phonon-drag effects and directly yields the diffusion thermopower. In this paper we describe the realization of such an experiment.

We present direct measurements of the magnetic field dependence of the diffusion thermopower using current heating techniques in specially designed micro-Hall bar structures. The samples were fabricated from high mobility GaAs-AlGaAs heterostructures $[\mu\approx 100\ \mathrm{m}^2/(\mathrm{V\ s})]$ using split-gate techniques. A current passing through an electron channel adjoining the Hall structure is used to exclusively heat the electron gas, leaving the lattice temperature unchanged. This current-heating technique has previously been successfully used to determine the diffusion thermopower of mesoscopic systems such as quantum point contacts[3] and quantum dots.[4–6] The present sample design allows the direct measurement of the tensor components of the thermopower both parallel (S_{xx}) and perpendicular (S_{yx}) to the temperature gradient in the x direction. The results are discussed in the framework of theoretical models developed for the magnetic field regime where the formation of Landau levels leads to a modulation of the density of states,[7] but does not yet induce the formation of edge states. Therefore, the magnetic field in the present study is restricted to the low field regime ($B\leqslant 1.2$ T) where the influence of the quantum Hall effect can be neglected.

Figure 1 shows a scanning electron microscopy (SEM) photograph of the sample structure, including a schematic diagram of the measurement. The micro-Hall bar and the electron heating channel are defined by Schottky gates, thus forming the quantum point contacts (QPCs), which are used as voltage probes. Gates *A*, *D*, *E*, and *F* form the micro-Hall bar and gates *A*, *B*, *C*, and *D* the heating channel. Utilizing the fact that the thermopower of a QPC is quantized,[3] QPC_4 and QPC_5 are used to determine the electron temperature in the channel T_{ch} as a function of the heating current by measuring the voltage drop $V_{25}\equiv V_5-V_2$ across the electron channel, while gates *E* and *F* are not defined. This thermovoltage is given by $V_{25}=(S_{QPC_5}-S_{QPC_4})\Delta T_{ch}$, where ΔT_{ch} equals the temperature difference between the electrons in the channel (T_{ch}) and in the surrounding 2DEG ($T_l\approx 1.6$ K), which is in thermal equilibrium with the crystal lattice:

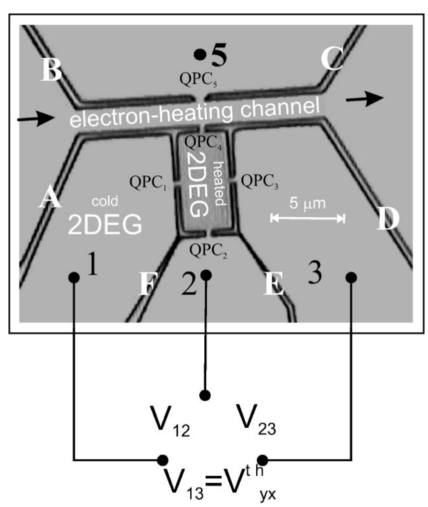

FIG. 1. SEM photograph of the split-gates structure and the scheme of the measurements.

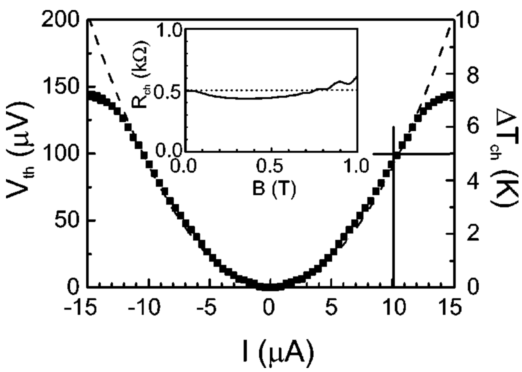

FIG. 2. Electron temperature as a function of the channel heating current. The squares represent the experimental data; the dashed line is a parabolic fit. Inset: The solid line shows the suppression of the SdH oscillations in the channel at a heating current of 10 μA. The dotted line is an arbitrary line drawn parallel to the magnetic field axis. The difference between the dotted line and the minimum of the SdH oscillations is about 15%.

$\Delta T_{ch}=T_{ch}-T_l$.[8] Note that the temperature difference ΔT_{ch} enters here rather than a gradient, since the thermovoltage across a QPC can only be measured globally. The essential ideas of the current heating technique have been documented in Refs. 8 and 9. By considering an equilibrium state between the heat flux into the electron-heating channel and the channel electrons it was shown that $\Delta T_{ch}\propto I^2$. Thus it follows that for a thermopower measurement of a QPC the thermovoltage is proportional to the square of the heating current, $V_{th}\propto I^2$, if the conductance is set to a constant value in the vicinity of a conductance step, i.e., $S_{QPC}(T)=S_{QPC}=\text{const}\neq 0$. Figure 2 shows the experimentally determined thermovoltage as a function of the channel heating current. It can be seen that the parabolic dependence is valid for currents up to 12 μA. For the temperature calibration, the thermopower of QPC_4 was adjusted to $S_{QPC_4}=20\ \mu\text{V/K}$ (Refs. 8 and 9) and the thermopower of QPC_5 was set at a minimal value ($S_{QPC_5}\approx 0$). The resulting calibration of the electron temperature in the channel as a function of heating current is given on the right axis of Fig. 2.

For a thermopower experiment on the micro-Hall bar, QPC_4 was adjusted into the tunneling regime ($G_{QPC_4}\approx 3\times 10^{-5}\ \Omega^{-1}<e^2/h$). QPC_1, QPC_2, and QPC_3 were set to higher conductance values ($G_{QPC}\approx 10\times 2e^2/h$) in order to keep their thermopower contribution as small as possible ($S_{QPC_{1,2,3}}\approx 0$). The channel current was set to $\sim$10 μA which yields an electron temperature in the channel of $T_{ch}\approx 6.6$ K [cf. Fig. 2]; this current level gave a good compromise between pronounced thermovoltage signals and the avoidance of lattice heating effects. The inset of Fig. 2 shows the longitudinal magnetoresistance of the channel at this current level of 10 μA. Evidently, the Shubnikov–de Haas oscillations are considerably suppressed; this ensures an approximately constant heat dissipation over the field range studied.

The experiments were carried out at a temperature of about 1.6 K in a ^{4}He cryostat equipped with a 10 T superconducting magnet. The 2DEG carrier density (2.8×10^{15} m^{-2}) and mobility [$\approx$100 m^2(V s)$^{-1}$] were obtained from Hall and Shubnikov–de Haas (SdH) measurements. Standard lock-in amplifier measurement techniques were used to measure the thermoelectric effects. As mentioned above, the heating of the channel electrons is proportional to I^2. Thus using an ac heating current $[I=i_0\cos(\omega t)]$ the second harmonic of the lock-in detector signal is proportional solely to the thermoelectric properties of the sample.

Figure 1 indicates how the two tensor components of the thermopower can be obtained in the current heating experiment. First, we note that the thermopower of a 2DEG in a magnetic field is a local property, so that the thermovoltages we measure are proportional to a temperature gradient. We define the line 4-2 connecting QPC_4 and QPC_2 as the x direction, the direction along which the temperature gradient driving the thermopower is applied. An important parameter for the experiment is the electron temperature at the crossing of line 4-2 and the line connecting QPC_1 and QPC_3 (line 1-3 defining the y direction). If the electron temperature outside the micro-Hall bar is assumed to be equal to the lattice temperature, a temperature gradient is expected to develop between the side which is in contact with the heating channel ($T_e^{max}\approx T_{ch}$) and the surrounding 2DEG (T_l). If electron-electron scattering is regarded as the dominant mechanism for the electron energy relaxation, an exponential decay of the electron excess energy determines the local electron temperature in the heated micro-Hall bar. Thus taking the electron-electron scattering length according to Ref. 10 an electron temperature of $\sim$3.5 K is expected for the central area of the present micro-Hall structure.

From Fig. 1, it is clear that V_{yx}^{th}, the thermovoltage perpendicular to the temperature gradient, can be determined directly by measuring the voltage difference between the areas 1 and 3, $V_{yx}^{th}\equiv V_{13}\equiv V_3-V_1$, provided the intrinsic thermopower of QPC_1 and QPC_3 can be neglected. For V_{xx}^{th} however, the required voltage probe at the crossing point of the lines 1-3 and 4-2 is not available. Instead, we can obtain V_{xx}^{th} from measuring the signals present at $V_{12}\equiv V_2-V_1$ and $V_{32}\equiv V_2-V_3$. Since V_{12} and V_{23} contain contributions from V_{xx}^{th} as well as V_{yx}^{th}, V_{xx}^{th} can be determined by adding V_{12} and V_{23} and subtracting $V_{13}\equiv V_{yx}^{th}$. This allows us to compare V_{xx}^{th} and V_{yx}^{th} directly without an exact knowledge of the temperature gradient in the micro-Hall structure.

The measured thermovoltage components V_{xx}^{th} and V_{yx}^{th} are shown in the insets of Figs. 3 and 4, respectively. The thermopower values, S_{xx} and S_{yx}, have been calculated from the thermovoltage signal assuming an estimated average electron temperature of 3.5 K as mentioned above. Apart from a smooth variation of the thermopower, clear oscillations become visible for magnetic fields larger than 0.3 T for both components. In order to analyze these oscillations the smooth background variation has been subtracted (Figs. 3 and 4). The observed background signal corresponds qualitatively to the expected behavior for the magnetothermopower in the intermediate regime between weak localization and Landau quantization ($0.04<B<0.3$ T) (Ref. 11)

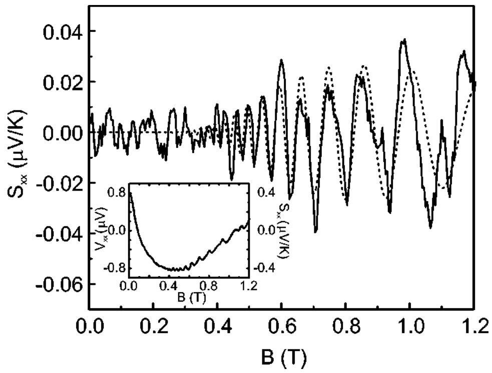

FIG. 3. Thermopower S_{xx} parallel to the temperature gradient after subtracting a smooth background. The solid line corresponds to the experimental data for an average electron temperature of $T=3.5$ K and the dotted line represents a fit according to Eq. (1). Inset: Measured thermovoltage V_{xx}^{th} parallel to the temperature gradient.

where the quasiballistic motion of the electrons in the microstructure and the deflection induced by the magnetic field account for additional contributions. This latter effect will be discussed in detail elsewhere.[12] However, the thermopower values observed for zero magnetic field [$S_{xx}(B=0)\approx 0.4\ \mu$V/K and $S_{yx}(B=0)=0$] correspond well to the values which are expected from the solution of the steady-state Boltzmann equations for the diffusion thermopower of a 2DEG [cf. Eqs. (18) and (19) in Ref. 11]. The small thermopower fluctuations in the range of $B<0.3$ T which are visible for the S_{xx} component in Fig. 3 can also be attributed to quasiballistic electron motion.[12] Similar fluctuations of the same order of magnitude are also present for S_{yx} (Fig. 4) but are not visible on the presented scale. In the following, we will present a detailed quantitative discussion of the second magnetic field regime $(0.3<B<1.2\ \text{T})$.

According to Ref. 7 the magnetic field behavior of the thermopower oscillations can, in the regime of Landau level formation, be described by the following equations:

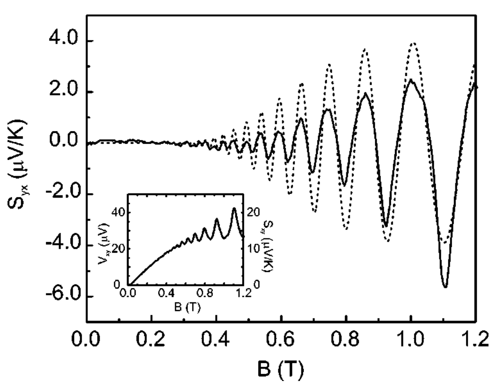

FIG. 4. Thermopower S_{yx} perpendicular to the temperature gradient after subtracting a smooth background. The solid line corresponds to the experimental data for an average electron temperature of $T=3.5$ K and the dotted line represents a fit according to Eq. (2). Inset: Measured thermovoltage V_{xx}^{th} parallel to the temperature gradient.

$$S_{xx}=\frac{2}{1+\omega_c^2\tau^2}\left(\frac{\pi k_B}{e}\right)D'(X)\exp\left(-\frac{2\pi^2 k_B T_D}{\hbar\omega_c}\right)\sin\left(\frac{2\pi f}{B}-\pi\right), \tag{1}$$

$$S_{yx}=\frac{4\omega_c\tau}{1+\omega_c^2\tau^2}\left(\frac{\pi k_B}{e}\right)D'(X)\exp\left(-\frac{2\pi^2 k_B T_D}{\hbar\omega_c}\right)\sin\left(\frac{2\pi f}{B}-\pi\right), \tag{2}$$

where T_D is the Dingle temperature, ω_c the cyclotron frequency, τ the transport relaxation time, and f the frequency of the oscillations ($f/B=E_F/\hbar\omega_c$, where E_F is the Fermi energy). The quantity $D'(X)$ is the derivative of the thermal damping factor $D(X)$, defined by $D(X)=X/\sinh X$ where $X=2\pi^2 k_B T/\hbar\omega_c$. These equations were originally[7] derived for conditions where $\omega_c\tau<1$, which would restrict the validity in our case to magnetic fields up to $B\sim 20$ mT. However, Coleridge *et al.*[14] have shown that Eqs. (1) and (2) are valid up to much higher field values ($B\sim 1$ T) when localization effects can be neglected (as is the case for high mobility 2DEGs).

The dotted curves in Fig. 3 and Fig. 4 are fits to the experimental data using Eqs. (1) and (2). For the fits, the carrier density n was taken from the transport characterization. The best fit according to Eqs. (1) and (2) was obtained for a slightly reduced mobility $\mu=80\ \text{m}^2(\text{V s})^{-1}$ compared with the measured value $[100\ \text{m}^2(\text{V s})^{-1}]$ for the macroscopic sample. This difference can be readily explained by considering the local probe character of the micro-Hall bar structure. The Dingle temperature was obtained from the assumption that the quantum mobility is approximately 10 times lower than the electron mobility, i.e., $T_D\approx 10\pi/\mu\approx 0.4$ K.[7,14] The thermal smearing was fitted by a free parameter $\overline{T_e}$, which can be interpreted as the average electron temperature in the micro-Hall bar. The best fits with an average electron temperature of $\overline{T_e}=4$ K are in good agreement with the estimates based on the energy relaxation due to electron-electron scattering. Both S_{xx} and S_{yx} can be fitted satisfactorily using the same set of parameters, even though the amplitudes are very different. According to Eqs. (1) and (2), the ratio of the thermopower perpendicular and parallel to the temperature gradient is given by $S_{yx}/S_{xx}=2\omega_c\tau$. For the present sample, the measured ratio at $B=1$ T is ≈ 120. This value agrees well with the expected value of ~ 160 for $\mu=80\ \text{m}^2(\text{V s})^{-1}$ which follows from the fitted thermopower curve.

This is a direct measurement of the diffusion thermopower oscillation in a GaAs-based 2DEG system. The use of electron heating techniques avoids lattice heating and therefore phonon-drag effects become negligible.[7,15,16] From the consistency of the average temperatures and the temperature gradients, which were obtained from the fitting and the channel temperature calibration, it can be concluded that the chosen geometry and the measurement configuration are suited for investigating the diffusion thermopower especially in high-mobility GaAs-2DEG structures. Note that for low-mobility samples, lattice heating occurs at lower current levels and the applicability of the current heating method has to be verified separately. This opens up the way for studying the diffusion thermopower in the integer and fractional quantum Hall effect regimes using the electron heating technique which provides an alternative method compared with the methods recently applied by other authors (see Refs. 1 and 17–21).

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