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

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Abstract
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 μm × 8 μm) at low temperature (T = 1.6 K) in the low magnetic field regime (B ≤ 1.2 T) where delocalized quantum Hall states do 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} (Nernst-Ettinghausen coefficient). The experimental data show clear oscillations in S_{xx} and S_{yx} due to the formation of Landau levels for 0.3 T < B ≤ 1.2 T and reveal that S_{yx} ≈ 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} = 2ω_{c}τ.

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Thermopower experiments have been used extensively to obtain information on 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 true electronic or “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 development 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 [μ ≈ 100 m²/(Vs)] 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]. 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 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 ≤ 1.2 T) where the influence of the quantum Hall effect can be neglected.

Fig. 1 shows an 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], QPC4 and QPC5 are used to determine the electron temperature in the channel T_{ch} by measuring the voltage drop V_{25} = V_{5} - V_{2} across the electron channel, while gates E and F are not defined. We then have V_{25} = (S_{QPC5} - S_{QPC4})ΔT_{ch}, where ΔT_{ch} equals the temperature difference between the electrons in the channel (T_{ch}) and in the surrounding 2DEG (T_{l} ≈ 1.6 K), which is in thermal equilibrium with the crystal lattice: ΔT_{ch} = T_{ch} - T_{l} [3]. Note that the temperature difference ΔT_{ch} enters here rather than a gradient, since the thermovoltage across a QPC can only be measured globally. Experimentally, one observes that ΔT_{ch} ∝ I², where I is the net heating current, as expected from a simple heat balance equation that is valid for not too large current values [3]. Fig. 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 QPC4 was adjusted.
to $S_{QPC4} = 20 \, \mu V/K$ and the thermopower of QPC$_5$ was set at a minimal value ($S_{QPC5} \approx 0$). The temperature calibration is given on the right axis of Fig. 2.

For a thermopower experiment on the micro-Hall bar, QPC$_3$ was adjusted into the tunneling regime ($G_{QPC4} \approx 3 \times 10^{-5} \, \Omega^{-1} < e^2/h$). 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 minimal ($S_{QPC1,2,3} \approx 0$). The channel current was set to $\sim 10 \, \mu A$ which yields an electron temperature in the channel of $T_{ch} \approx 6.6 \, K$ [c.f. Fig. 2]; this current value gave a good compromise between pronounced thermovoltage signals and the avoidance of lattice heating effects. The inset of Fig. 2 shows the longitudinal resistance of the channel at this current level of $10 \, \mu A$; evidently the Shubnikov-de Haas oscillations are nearly suppressed, which 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 an $^4$He cryostat equipped with a 10 T superconducting magnet. The 2DEG carrier density ($2.8 \times 10^{15} \, m^{-2}$) and mobility ($\approx 100 \, m^2/(Vs)^{-1}$) 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 2DEG heating is proportional to $I^2$. Using ac-currents ($I = i_0 \cos(\omega t)$) and a lock-in detection of the second harmonic ($2\omega$), the measured signal solely depends on the thermovoltage $[V_{th} \propto I^2 = (i_0 \cos(\omega t))^2 \propto i_0^2 \cos(2\omega t)]$.

Fig. 1 indicates how the two tensor components of the thermopower can be obtained in our current heating experiment. First, we note that the thermopower of a 2 DEG in a magnetic field is a local property, so that the thermovoltages we measure are proportional to a temperature gradient, $V_{th} = S \nabla_x T dx$. We assume that the temperature gradient across the micro-Hall bar coincides with the line 4-2 connecting QPC$_4$ and QPC$_2$ defining the $x$-direction. 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 ($T_{ch}^{max} \approx T_{ch}$) and the surrounding 2DEG ($T_i$). In zero order approximation a constant temperature gradient along the line connecting QPC$_2$ and QPC$_4$ would have the following form: $\nabla_x T_e = (T_{ch}^{max} - T_1)/x_0 \approx 5 \, K/\mu m = 0.625 \, K/\mu m$, where $x_0$ is the extension of the micro-Hall bar in $x$-direction ($x_0 = 8 \, \mu m$).

From Fig. 1, it is clear that $V_{yx}^{th}$, the thermovoltage perpendicular to the temperature gradient, can be determined by measuring the voltage difference between the areas 1 and 3, $V_{yx}^{th} = V_{13} - V_1$ or $V_3$, provided the intrinsic thermopower of QPC$_1$ and QPC$_3$ can be neglected. For $V_{yx}^{th}$, 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 $V_{12} = V_2 - V_1$ and $V_{32} = V_2 - V_3$. 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 $V_{13} = V_{yx}^{th}$. This allows us to compare $V_{xx}^{th}$ and $V_{yx}^{th}$ directly without an exact knowledge of $\nabla_z T_e$ in the micro-

**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 solid line with squares represents the measured data; the dotted line is a parabolic fit. Inset: Suppression of the SdH oscillations in the channel at a heating current of 10 $\mu A$. The difference between the dotted line and the minimum of the SdH is about 15%.
Hall structure.

For both components, the experiments show clear oscillations in the thermopower with magnetic field (Figs. 3 and 4). The thermopower signal has been calculated from the thermovoltage measurement assuming the linear temperature gradient as mentioned above. The presented field range studied can be separated into two parts: First, \( B < 0.3 \) T; the electrons are considered as classical particles which are deflected by the applied magnetic field and scattered elastically at the device boundaries (mean free path \( l_{mf} \approx 8 \) \( \mu m \))\(^{10}\), and second, \( 0.3 < B < 1.2 \) T where the oscillations correspond to the formation of Landau levels in the 2DEG and hence to the magnetic field dependent modulation of the density of states. In the following, we will present a detailed quantitative discussion of the second magnetic field regime \((0.3 < B < 1.2 \) T).

According to Ref.\(^{7}\) the magnetic field behaviour of the thermopower oscillations can, in the regime of Landau level formation, be described by the following equations:

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

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

where \( T_D \) is the Dingle temperature, \( \omega_c \) the cyclotron frequency, \( \tau \) the transport relaxation time, and \( f \) is the frequency of the oscillations \((f/B = E_F/\hbar \omega_c, \text{where } E_F \) 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 \( X = 2\pi^2 k_BT/\hbar \omega_c \). 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.\(^{12}\) have shown that Eqs. (3) and (4) are valid up to much higher field values \((B \sim 1 \) T) when localization effects can be neglected (as it is the case for high mobility 2DEGs).

The results of the measurements up to 1.2 T are presented in Fig. 3 and Fig. 4 together with fits using Eqs. (1) and (2). For the fits, the carrier density \( n \) and the mobility \( \mu \) were taken from the transport characterization. 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\(^{7,12}\). The thermal smearing was fitted by a free parameter \( T_e \), which can be interpreted as the average electron temperature in the micro-Hall bar. The best fits for an average electron temperature of \( T_e = 4 \) K is in very good agreement with the estimates made above concerning the temperature gradient.

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. (3) and (4), 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 \( \approx 120 \). Again, this value agrees well with the expected value of 160. To our knowledge this is the first successful measurement of the diffusion thermopower for a semiconductor 2DEG system. The current heating approach allows us to avoid the influence of phonon-drag effects\(^{13,15}\). From the consistency of the average

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**FIG. 3:** Thermopower \( S_{xx} \) parallel to the temperature gradient: The solid line corresponds to the experimental data for \( \Delta T = 2.5 \) K and the dashed dotted line represents the calculation according to Eq. 3.

**FIG. 4:** Thermopower \( S_{yx} \) perpendicular to the temperature gradient: The solid line corresponds to the experimental data for \( \Delta T = 2.5 \) K and the dashed dotted line represents the calculation according to Eq. 4.
temperatures and the temperature gradients, which are obtained from the fitting and the channel temperature calibration, it can be concluded that the chosen geometry and the measurement configuration are suitable for investigating the diffusion thermopower of high mobility samples.

Summarizing, the results presented here demonstrate that electron heating techniques can be used to measure directly the longitudinal and transverse components of the diffusion thermopower. For low magnetic fields, thermopower fluctuations are observed which originate from quasi-ballistic electrons; for higher fields, the modulation of the electron density of states due to Landau level formation determines the oscillatory part of the diffusion thermopower. Current theories [2, 7] describe this oscillatory behavior to a large extent and can be used to independently gauge the electron temperature. The consistency of these measurements with theory opens up the way for an alternative method for studying the diffusion thermopower in the QHE as well as in the fractional quantum Hall effect regime, where currently, experimental data are discussed controversially [11, 16, 17, 18].

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