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Measurement of diffusion thermopower in the quantum Hall systems

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ABSTRACT

We have measured diffusion thermopower in a two-dimensional electron gas at low temperature ($T = 40\,\mathrm{mK}$) in the field range $0 < B < 3.4\,\mathrm{T}$, by employing the current heating technique. A Hall bar device is designed for this purpose, which contains two crossing Hall bars, one for the measurement and the other used as a heater, and is equipped with a metallic front gate to control the resistivity of the areas to be heated. In the low magnetic field regime ($B \leq 1\,\mathrm{T}$), we obtain the transverse thermopower S_{yx} that quantitatively agrees with the S_{yx} calculated from resistivities using the generalized Mott formula. In the quantum Hall regime ($B \geq 1\,\mathrm{T}$), we find that S_{yx} signal appears only when both the measured and the heater area are in the resistive (inter-quantum Hall transition) region. Anomalous gate-voltage dependence is observed above $\sim 1.8\,\mathrm{T}$, where spin-splitting in the measured area becomes apparent.

1. Introduction

The thermopower of a two-dimensional electron gas (2DEG) [1–5] has been attracting interest not only as a route to access its thermodynamic properties but also as a sensitive tool to probe various quantum phenomena that take place in a quantizing magnetic field (see, e.g., Refs. [6,7]). The thermopower in a 2DEG contains contributions from two separate mechanisms: diffusion and phonon drag. It is well known that the latter is by far the dominant contribution in standard experiments using an external heater to introduce temperature gradient [3]. This is because the heater raises both the lattice and the electron temperatures alike; the heat current is thus predominantly carried by phonons, which generates the phonon-drag thermovoltage through the electron–phonon interaction. However, it is the diffusion thermopower that is expected to be more sensitive to the phenomena taking place in a 2DEG. Furthermore, the experimental results for diffusion thermopower will be much easier to interpret, since external complications, the phonons, are not involved. Therefore, it is desirable to have a method sensitive only to the diffusion contribution. This can be achieved by employing current heating technique, which induces gradient only in the electron temperature T_e, leaving the lattice temperature intact. The technique was applied to a micro-scale ($4 \times 8\,\mu\mathrm{m}^2$) Hall bar by Maximov et al. [8] to obtain diffusion contribution to the longitudinal (S_{xx}) and transverse (S_{yx}) thermopower in the low magnetic field regime $B \leq 1.2\,\mathrm{T}$ at a temperature $T = 1.6\,\mathrm{K}$. Their use of the micro-Hall bar, however, resulted in rather large slowly varying background attributable to the quasiballistic motion of electrons. In the present paper, we describe our attempt to acquire diffusion thermopower at dilution-refrigerator temperatures $\sim 40\,\mathrm{mK}$, using a Hall bar designed to be well suited for the measurement of the thermopower, and having dimensions larger than the mean-free path of the electrons to avoid the intervention by the ballistic electrons. We make an attempt to extend the measurement to the quantum Hall regime, $B \geq 1\,\mathrm{T}$, employing a Hall bar device equipped with a front gate on the section used as a heater to circumvent the problem (to be discussed below) encountered in the quantum Hall regime.

2. Sample and measurement method

A conventional GaAs/AlGaAs 2DEG wafer with the carrier density and mobility $n_e = 4 \times 10^{15}\,\mathrm{m}^{-2}$ and $\mu = 70\,\mathrm{m}^2/(\mathrm{V\,s})$, respectively, is patterned into the device geometry illustrated in Fig. 1. The device is composed of two crossing Hall bars. The main Hall bar (between ohmic contacts 7 and 13) has a width $W = 50\,\mu\mathrm{m}$ and length $L = 279\,\mu\mathrm{m}$ and contains three sets of the voltage probes (with contacts 4–6 and 8–10) to measure the longitudinal (V_{xx}) and transverse (V_{yx}) voltages at three different locations (or with different inter-probe distances for V_{xx}). Both W and L, and distances between voltage probes ($L_1 = 23\,\mu\mathrm{m}$ or $L_2 = 153\,\mu\mathrm{m}$), are designed to be much larger than the mean-free path $L_{\mathrm{mfp}} = 7.3\,\mu\mathrm{m}$ of the electrons. The secondary Hall bar (between contacts 3 and 11), $170\,\mu\mathrm{m}$–long and $50\,\mu\mathrm{m}$–wide, is used as a heater by driving an ac heating current $I_h = 50-200\,\mathrm{nA}$, with frequency $f = 13\,\mathrm{Hz}$. The current I_h used is much larger than that in the ordinary resistivity measurement ($I = 0.5-10\,\mathrm{nA}$) and raises the electron temperature T_e through Joule heating, but is

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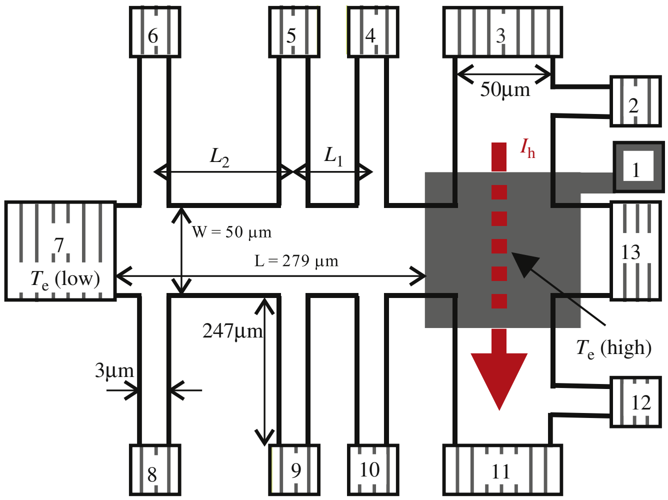

Fig. 1. Schematic diagram of the sample. Hatched rectangles are the ohmic contacts. Main (horizontal, from 7 to 13) Hall bar ($50 \times 279\,\mu m^2$) contains three pairs of voltage probes (4–6, 8–10). Secondary (vertical, from 3 to 11) Hall bar ($170 \times 50\,\mu m^2$) is employed as the heater; the voltage probes (2,11) are used for the SdH measurement. A (gray) shaded rectangle is a metallic front gate to control the resistance of the area to be heated.

kept small enough to prevent the heating of the lattice. We can probe the electron temperature in the heater section by the voltage probes (contacts 2 and 12), exploiting the amplitude of the Shubnikov–de Haas (SdH) oscillation. Thus the difference in the electron temperature $\Delta T_e = T_e$ (high) $- T_e$ (low) is introduced to the main Hall bar, between T_e (high) at the crossing region shared with the secondary Hall bar (dubbed as "heater area" henceforth) and T_e (low) at the ohmic contact (contact 7) composed of diffused NiAuGe alloy, the latter assumed to be in equilibrium with the lattice temperature, or the temperature of the mixing chamber of the dilution refrigerator. Strictly speaking, ohmic contacts for the voltage probes (contacts 4–6 and 8–10) are also at T_e (low), and therefore the temperature gradient is also directed from the heater area toward these contacts, resulting in rather complicated temperature distribution. To minimize the disturbance by the voltage-probe contact pads, arms are designed to be thin (3 μm) and long (247 μm), and the pads are made much smaller than that of contact 7 to diminish their efficiency as the heat sink.

Since $\Delta T_e \propto I_h^2$, thermopower S_{xx} and S_{yx} are obtained by detecting the component of V_{xx} and V_{yx} having the frequency $2f = 26\,\text{Hz}$ by using a lock-in amplifier; then we have $S_{xx} = (V_{xx}/\Delta T_e)(L/L_{1(2)})$ and $S_{yx} = (V_{yx}/\Delta T_e)(L/W)$. The component of voltages with the frequency f, on the other hand, yields non-local resistance. We note in passing that since we are using a Hall bar, we can, of course, also measure the longitudinal and the Hall resistances (which can readily be translated to the resistivities ρ_{xx} and ρ_{yx}) for the same area of the sample as the thermovoltages are acquired, simply by passing (small) current between contacts 7 and 13.

With the method described so far, we succeeded in measuring the transverse (Nernst) component S_{yx} of the diffusion thermopower for low magnetic fields $B \le 1\,\text{T}$, as will be shown in the next section. The measurement of the longitudinal (Seebeck) component S_{xx} is still suffering from the effect of electron deflection due to the magnetic field, which causes the mixing-in of the transverse component asymmetrically between $B > 0$ and $B < 0$. We therefore focus on the S_{yx} component, acquired by using contacts 4 and 10 as voltage probes, in the present paper. A problem arises in applying the current heating technique in a magnetic field: since the longitudinal resistance varies with magnetic field also in the heater area, the temperature difference ΔT_e generated by the Joule heating also varies with magnetic field. This does not cause serious trouble in low magnetic fields where the resistance variation is not so large. In the quantum Hall regime, however, resistance variation is phenomenal, ranging from ~ 0 at the quantum Hall states to $\sim \text{k}\Omega$ in between. To avoid the difficulties, we placed a metallic front gate on the heater area, as shown in Fig. 1. This enabled us to control the carrier density, hence the resistance, of the heater area independent of whether or not the measured area is in the quantum Hall states.

3. Results

Fig. 2 shows the transverse thermopower S_{yx} at low magnetic fields ($B \le 1\,T$) measured by the method described in the previous section, with a heating current $I_h = 200\,\text{nA}$. (A sample without the metallic front gate is used for this measurement.) Note that S_{yx} oscillates around zero, without any noticeable background.

The diffusion thermopower is related to the longitudinal and transverse conductivities σ_{xx} and σ_{yx} by the generalized Mott formulas [9],

$$S_{xx} = -L_0 eT \frac{d}{d\varepsilon_F} \ln\sqrt{\sigma_{xx}^2 + \sigma_{yx}^2}, \tag{1}$$

$$S_{yx} = -L_0 eT \frac{d}{d\varepsilon_F} \arctan\frac{\sigma_{yx}}{\sigma_{xx}}, \tag{2}$$

where $L_0 = \pi^2 k_B^2/3e^2$ is the Lorenz number and ε_F the Fermi energy. If we assume that properties of the system are mainly determined by the location of the Fermi energy with respect to the Landau levels, we can identify the energy derivative with the derivative with respect to the magnetic field as

$$\frac{d}{d\varepsilon_F} = -\frac{B}{\varepsilon_F}\frac{d}{dB}. \tag{3}$$

Using this relation, Eqs. (1) and (2) are rewritten as

$$S_{xx} = \frac{L_0 eTB}{\varepsilon_F}\frac{d}{dB}\ln\sqrt{\rho_{xx}^2 + \rho_{yx}^2}, \tag{4}$$

$$S_{yx} = \frac{L_0 eTB}{\varepsilon_F}\frac{d}{dB}\arctan\frac{\rho_{yx}}{\rho_{xx}}, \tag{5}$$

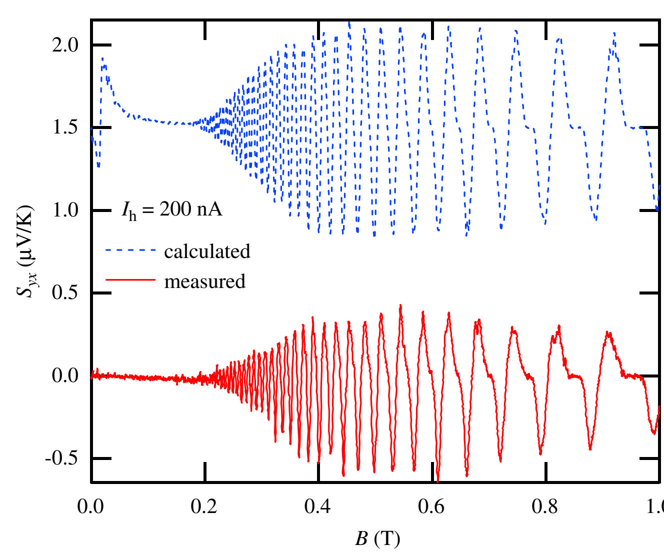

Fig. 2. Transverse thermopower S_{yx} measured directly (solid line) and that calculated from the measured ρ_{xx} and ρ_{yx} using Eq. (5) (dotted line), at $T = 40\,\text{mK}$. The latter is offset by 1.5 μV/K for clarity.