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Thermoelectric power in the quantum-Hall regime at very low temperatures

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Abstract

We have measured the thermoelectric power (TEP) of high mobility 2DEGs in the integer and fractional quantum Hall regime down to 100 mK. At low temperatures, fluctuation-like structures in the TEP are observed. Below 160 mK the TEP diverges around the filling factor $\nu = \frac{1}{5}$ where the resistivity enters the insulating phase. The temperature dependence of the TEP at filling factors $\nu = \frac{1}{2}$ and $\frac{1}{4}$ resembles that of the zero field TEP enhanced by a constant factor. This is interpreted in terms of the phonon drag of composite fermions.

1. Introduction

The galvanomagnetic properties of two-dimensional electron gases (2DEGs) display a number of interesting phenomena such as the integer quantum-Hall-effect (IQHE) [1], the fractional quantum-Hall-effect (FQHE) [2], and the appearance of an insulating phase (IP) at low filling factors which has been attributed to a pinned Wigner solid [3].

Because the thermoelectric power (TEP) of 2DEGs in GaAs–$Ga_{1-x}Al_xAs$ heterostructures is usually dominated by phonon drag, it provides a direct measure of the electron–phonon interaction [4, 5] and can therefore yield complementary information on the nature of the 2DEG compared to resistivity (which is determined by electron-impurity scattering). The recent review by Gallagher and Butcher [6] on the TEP of 2DEGs provides a good introduction to the present work. The relation between the applied temperature gradient (which supplies the driving force) ∇T and the induced electric field $\boldsymbol{E}$ defines the TEP tensor $\boldsymbol{S}$: $\boldsymbol{E} = \boldsymbol{S}\nabla T$. With a magnetic field $\boldsymbol{B}$ applied perpendicular to the 2DEG there are only two independent components of $\boldsymbol{S}$, the thermopower S_{xx} and the Nernst–Ettingshausen coefficient S_{yx}.

In this paper we will report the first experimental results concerning the $\boldsymbol{S}$ of a 2DEG at temperatures T down to 100 mK in high magnetic fields. We will show that with decreasing temperature additional structures in the TEP appear and, at the lowest temperatures, a diverging TEP is observed at filling factors where the IP in resistivity measurements shows up. Furthermore, we will present the temperature dependence of the TEP at $\nu = \frac{1}{2}$ and $\nu = \frac{1}{4}$ and compare it to the zero field TEP in the framework of the composite fermion model. We will mainly concentrate on S_{xx} but most statements also apply to S_{yx}.

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2. Experimental

We investigated three high mobility ($\mu \simeq 200\ m^2/V\,s$) $GaAs$–$Ga_{1-x}Al_xAs$ heterostructures (kindly supplied by Philips Research Laboratory, Redhill, England) labeled G645 ($n = 0.75 \times 10^{11}\ cm^{-2}$), G647 ($n = 0.43 \times 10^{11}\ cm^{-2}$), and G650 ($n = 1.0 \times 10^{11}\ cm^{-2}$). Each 2DEG was grown on a semi-insulating GaAs substrate and was formed into a Hall bar with eight AuGeNi diffused ohmic contacts.

The experiments were carried out in the vacuum space of a ^3He–^4He dilution refrigerator adapted for use in high magnetic fields by having no metallic heat exchangers [7]. To avoid further eddy current heating, the sample holder was made of plastic and the only metal parts were in the thermal anchoring of the sample to the mixing chamber. The free-standing sample was In-soldered to the cold finger and the thermal gradient was produced by a heater glued to the free end. Typical temperature differences were a few tens of mK across the 2DEG and never exceeded 10% of the absolute temperature. Both ∇T and T were measured with two RuO_2 film resistors mounted on the rear side of the substrate. Special care was taken to eliminate all extraneous sources of heat loss from the sample.

As a check for the thermometry we have measured the thermal conductivity λ of the samples. λ is determined by the phonons in the three-dimensional substrate. Experimentally, λ follows the T^3-dependence expected for a constant phonon mean free path which is limited by boundary scattering.

The TEP was measured using pulsed heating and detected at twice the frequency of the electrical heater current using a lock-in technique. The measuring frequencies were in the range 2–12 Hz. We verified the thermal response time being fast enough by obtaining the same results (within 10%) for different frequencies.

3. Results and discussion

Although at $T > 400$ mK the TEP is very much smaller in the IQH regime than in the FQH regime,[1] the IQH TEP becomes comparable to, and even bigger than, the FQH TEP for $T < 350$ mK (see Fig. 1). At the lowest temperatures, the most pronounced structure is the peak between filling factors $\nu = 1$ and $\nu = 2$, i.e. between the two lowest spin-split Landau levels.

With decreasing T the TEP increasingly exhibits fluctuation-like structure. This is very reproducible for

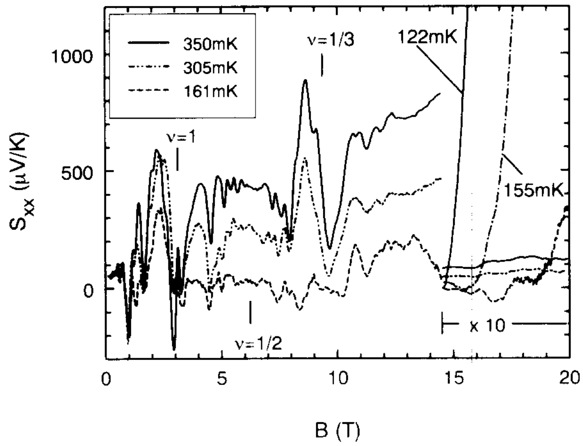

Fig. 1. The low-T thermopower S_{xx} of G645. With decreasing T reproducible fluctuation-like structures appear. In the field range of the insulating phase in the resistivity the TEP is diverging. For clarity the low-B parts of S_{xx} below 160 mK are omitted.

different field sweeps and is similar at different T, but the details of the structure are different when $\boldsymbol{B}$ is reversed. This means that the measured S_{xx} and S_{yx} have contributions which are both even and odd in $\boldsymbol{B}$. S_{xx} is expected to be even under reversal of $\boldsymbol{B}$ and S_{yx} should be odd, but experimentally there is usually some admixture of the one into the other because of imperfect contact alignment. However, in the present experiments such a geometric effect can be excluded as being responsible for the observed behaviour because the unexpected contributions are essentially only seen in the IQH regime and not in the FQH regime, e.g. the odd part of S_{xx} vanishes for $\nu < 1$ (with some deviation around $\nu = \frac{1}{3}$) even though the amplitude of S_{yx} in the FQH range is rather large.

Another interesting feature is that we find a similar behaviour for the T dependence of S_{xx} at filling factors of $\frac{1}{2}$ and $\frac{1}{4}$ as we do with the zero field TEP (see Fig. 2). At $\nu = \frac{1}{2}\ (\frac{1}{4})$, S_{xx} is about a factor of 20 (50) larger than at zero B. We interpret the measured TEP at $\nu = \frac{1}{2}$ and $\frac{1}{4}$ as the "zero field phonon drag TEP" of the composite Fermions (CF) at these points [8] and deduce that the CFs have a stronger interaction with the phonons than noninteracting electrons. CFs are quasi-particles consisting of an electron bound to an even number of flux quanta. The effective magnetic field for CFs is zero at filling factors with even denominator ($\nu = \frac{1}{2}$, $\nu = \frac{1}{4}$, etc.) [9].

At zero B, the phonon drag TEP S^g, which is usually the main contribution to the TEP [4,5] can be expressed [10,6] as

$$S^g = -\frac{vLm^*}{eT\tau_{ep}} = -\rho^{ph}\frac{nevL}{T}, \tag{1}$$

[1] For a detailed description of the TEP in this temperature range, see Ref. [5].

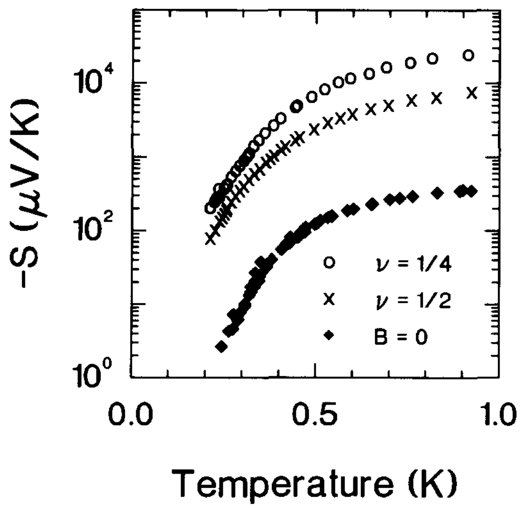

Fig. 2. The temperature dependence of S_{xx} at filling factors $\nu = \frac{1}{2}$ and $\nu = \frac{1}{4}$ compared the zero field TEP of G647.

where v is the sound velocity in the GaAs substrate, L the phonon mean free path, m^* the effective mass of the electrons, τ_{ep} the scattering time between the three-dimensional phonons and the 2DEG, and $\rho^{ph} = m^*/ne^2\tau_{ep}$ is the resistivity due to electron–phonon scattering. A similar relation still holds with B present [11]. Eq. (1) can be applied to CFs in which case $m^*\tau_{ep}^{-1}$ is replaced by $m_{cf}^*\tau_{cfp}^{-1}$, with m_{cf}^* being the effective mass of the CFs and τ_{cfp}^{-1} the CF-phonon scattering rate [12]. Leadley et al. [13] report a slightly B-dependent effective mass $m_{cf}^* \approx 0.5m_e$ for the $\nu = \frac{1}{2}$ CF, where m_e is the free electron mass, and a similar value at $\nu = \frac{1}{4}$ but with a stronger B dependence. According to Eq. (1), an increase of m^* from 0.067 to $0.5m_e$ results in an increase of S_{xx} by about a factor of 8. The experimentally found enhancement of S_{xx} by ~ 20 and ~ 50, respectively, would imply a phonon scattering rate which is about 2–3 times stronger for the $\nu = \frac{1}{2}$ CF than for non-interacting electrons and, with the same m_{cf}^*, another factor of 2–3 stronger for the $\nu = \frac{1}{4}$ CF.

At $T < 160$ mK a diverging TEP is observed (see Fig. 1) in the field range where the IP develops in resistivity measurements (around $\nu = \frac{1}{5}$). At $T > 200$ mK the TEP decreases strongly with T in this field range. A diverging S_{xx} has been reported in Ref. [14] in a 2DHG for filling factors around $\nu = \frac{1}{3}$. Essentially the same behaviour is shown by S_{yx} but we note that the diverging part does not change sign when $\boldsymbol{B}$ is reversed, whereas the rest of the structure in the FQH regime does.

4. Conclusions

We have measured the TEP of 2DEGs in $B \leq 20$ T and down to 100 mK. At low T we observe field-dependent fluctuations, mainly in the IQH regime, and a diverging TEP around $\nu = \frac{1}{5}$. The T dependence at $\nu = \frac{1}{2}$ and $\nu = \frac{1}{4}$ is found to be similar to the zero field TEP and is interpreted using the composite fermion model. Further experimental as well as theoretical investigations concerning these observations are in progress.

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