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Investigation of the electron-phonon interaction in the fractional quantum Hall regime using the thermoelectric effect

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In the fractional quantum Hall regime (filling factor $\nu < 1$) the measured longitudinal and transverse components of the thermopower of the two-dimensional electron gas in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions behave qualitatively differently from those in the integer quantum Hall regime and also quite differently from the tensor components of the resistivity. They are both found to be almost field independent, making a jump of approximately a factor of 2 at $\nu = \frac{1}{3}$. Since the thermopower is experimentally shown to be caused by phonon drag, this result implies a different electron-phonon coupling to the quasiparticle states below and above $\frac{1}{3}$.

Experimental investigations as well as theoretical models of thermoelectric effects of two-dimensional electron gases (2DEG) in GaAs-$Ga_{1-x}Al_xAs$ heterojunctions in a quantizing magnetic field have been intensively pursued in recent years.[1–7] As the thermoelectric power (TEP) in such systems was shown to be due to phonon drag, TEP data can give a direct insight into the electron-phonon coupling. In this paper we present experimental TEP data appropriate to the fractional quantum Hall (FQH) regime of these systems.

We will show that, down to the lowest measured temperatures (350 mK), the TEP is still dominated by phonon drag and thus probes the electron-phonon coupling to the fractional states. This is in contrast to resistivity which is sensitive to electron impurity scattering. The different behavior of the thermoelectric power as compared to the resistivity is demonstrated by the totally different field and temperature dependence of these two quantities. Furthermore, in the quantum limit both tensor components of the TEP are found to behave similarly as a function of field, in contrast to their behavior at integer filling factors. In particular, at the lowest temperatures, both components are found to be almost field independent, with a constant value which below filling factor $\nu = 1/3$ is roughly two times higher than above $\nu = 1/3$. These results show a difference in the electron-phonon coupling between integer and fractional states, and within the fractional regime between different quasiparticle states. The only calculation appropriate to the FQH regime so far reported[7] falls far short of explaining our data.

We studied three molecular-beam epitaxy grown GaAs-$Ga_{1-x}Al_xAs$ heterojunction samples (samples 1, 2, and 3 with mobilities of 230, 270, and 190 $m^2\,V^{-1}\,s^{-1}$ and electron concentrations of 0.86, 0.43, and 1.0 $\times 10^{15}$ m^{-2}) in the standard eight-contact Hall bar geometry on a rectangular GaAs substrate of about $10 \times 3 \times 0.5$ mm^3. Manganin wires, 100 μm diameter and about 1 cm length, were connected to the eight contacts (NiAuGe) of the sample with silver-filled epoxy. The wires were thermally anchored to the ^{3}He bath. The thermal conductance of all the wires was at least two orders of magnitude smaller than that of the samples, implying a negligible heat leak. The sample was supported at one end by soldering with indium to a copper arm inside a vacuum can, which in turn was thermally connected to the ^{3}He bath, and a heating resistor was epoxied to the other end.

An ac temperature gradient of between 10 and 100 mK was established between the source and the drain of the 2DEG with 12-Hz pulsed heating, and the components of the thermoelectric power parallel and perpendicular to the gradient were measured with a phase-sensitive lock-in technique. We checked that the thermal response of the system was fast enough by verifying that for 5–30 Hz the same results were obtained. Sample temperatures between 350 mK and 2 K could be produced by varying the heating power and the temperature of the ^{3}He bath. In order to calibrate the temperature T and the temperature gradient ∇T we applied an equivalent dc heating current before and after each recording of TEP data. T and ∇T were then determined under steady-state conditions by measuring the resistances of two calibrated thinfilm resistors glued on the rear side of each sample. For the measurements in a magnetic field we stabilized the temperature of the bath and the heating power. Furthermore, we also held the field steady at 5, 10, 15, and 20 T in order to check T and ∇T during a TEP measurement. Because we had also investigated the magnetoresistance of the thermometers we were able to estimate the corrections required to account for this. The resulting data showed that the thermal conductivities of the substrate had no significant field dependence and allow us to conclude that the uncertainty in our measured T and ∇T is at worst 5%. The same thermal conductivities were obtained for all three substrates and these were in good agreement with previous data on semi-insulating GaAs.[1] The cryostat was mounted in either a 12-T superconducting magnet or a 20-T Bitter magnet.

Thermoelectric effects are caused by the application of a temperature gradient $\boldsymbol{\nabla} T$ to an electron system which leads to a thermally induced electron current $\mathbf{j}_{\rm th} = \overleftrightarrow{\epsilon}\, \boldsymbol{\nabla} T$ ($\overleftrightarrow{\epsilon}$ is the thermoelectric tensor). In equilibrium, this current has to be compensated by an electric current $\mathbf{j}_{\rm el} = \overleftrightarrow{\sigma}\, \mathbf{E}$ where $\overleftrightarrow{\sigma}$ is the conductivity and $\mathbf{E} = \overleftrightarrow{\mathrm{S}}\, \boldsymbol{\nabla} T$ the electric field produced as a result of the thermally induced current. For a two-dimensional (2D) system in a magnetic field there are two independent components of $\overleftrightarrow{\mathrm{S}}$: the thermopower S_{xx} in the direction of the thermal gradient and the Nernst-Ettingshausen coefficient S_{yx} in the perpendicular direction. Due to the Lorentz force, the thermally induced current $\mathbf{j}_{\rm th}$ is rotated by the Hall angle θ with respect to the temperature gradient $\boldsymbol{\nabla} T$. For low disorder where $\rho_{xx} \ll \rho_{xy}$, we can simplify $S_{xx} \approx -\epsilon_{yx}\rho_{yx}$ and $S_{yx} \approx \epsilon_{xx}\rho_{yx}$. These corrections are found to be valid experimentally within 2% for S_{xx} and 10% for S_{yx}. It is preferable to work with the quantity S_{xx} rather than ϵ_{yx} because the latter is expected to exhibit an underlying $1/B$ dependence due to the Lorentz force on the quasiparticles. This $1/B$ dependence is automatically eliminated in $S_{xx} \approx -\epsilon_{yx}\rho_{yx}$ (for sample 1 in the FQH regime the Hall resistivity ρ_{yx} deviates at most 2% from the classical linear B dependence, the deviations mainly being evident around the narrow $\nu = 1/3$ plateau). Similarly we have also chosen to work with S_{yx} rather than ϵ_{xx}.

At zero field the only thermoelectric coefficient is S in the direction of the gradient. S is governed by two mechanisms: diffusion of the charge carriers and the drag of these carriers by phonons. The diffusion term S^d is given by[8] $S^d = -(\pi^2 k/3e)(p+1)(T/T_F)$, where T_F is the Fermi temperature and p describes the energy dependence of the electron scattering rate expected to be about unity for this case. In a simple model, the phonon-drag TEP at zero field can be described by[6]

$$S^g = -\frac{1}{3}\frac{C}{(n/L_z)e}\frac{L}{v}\tau_{pe}^{-1} = -\frac{\lambda}{(n/L_z)ev^2}\tau_{pe}^{-1} \quad , \qquad (1)$$

where C ($\propto T^3$) is the phonon specific heat, n is the 2D electron concentration, L_z is the total specimen width in the confinement direction, L is the size-limited phonon mean free path, v is the speed of sound, and $\lambda = CvL/3$ is the thermal conductivity. The scattering rate τ_{pe}^{-1} represents a momentum transfer rate from the phonons to the 2DEG.

The experimental thermopower S, which is just the sum of S^g and S^d, is always found to be at least an order of magnitude larger than S^d, assuming $p = 1$, even at 0.5 K. If we use $S^g = S - S^d$ with $p = 1$, then Eq. (1) allows us to evaluate τ_{pe}^{-1}. The results for the three samples are shown in Fig. 1 as a function of the reduced temperature T/T_0. T_0 is the temperature where the dominant phonon wave vector for momentum transfer $q = 4.96kT/\hbar v$ ($v \approx 4000$ ms^{-1} is the sound velocity) equals the Fermi diameter $2k_F$ of the 2DEG.[6,9] As expected, τ_{pe}^{-1} shows a maximum near T_0 for the three different samples with different Fermi temperatures. These arguments show that the zero-field TEP is dominated by phonon drag. Since a magnetic field only influences the electronic states and not the phonons, measurements of the TEP in a magnetic field will reflect the field dependence of the coupling between the electrons and the phonons and, in the FQH region, the interaction between phonons and the quasiparticle states.

The measured thermopower S_{xx} and the Nernst-Ettingshausen coefficient S_{yx} of sample 1 as a function of magnetic field are shown in Figs. 2(a) and 2(b). For comparison, the resistivities ρ_{xx} and ρ_{xy} of the same sample with the position of several well-pronounced fractions are represented in Fig. 2(c). The TEP of all three samples show the same features, both qualitatively and quantitatively, as a function of magnetic field. The fractions 1/3 and 2/3 are clearly visible in S_{xx} and S_{yx}. Apart from this structure, Fig. 2(a) shows that the magnitude of S_{xx} at a given field decreases with decreasing temperature. The diffusion contribution to the S_{xx} is predicted to be given by the entropy per unit charge[4] and thus to be independent of T reaching a value of 120 μV K^{-1} at $\nu = 1/2$ and 280 μV K^{-1} at $\nu = 1/10$. (This assumes the Landau levels are narrower than kT, otherwise the magnitude becomes smaller and tends to a linear dependence on T.) The measured values are at least an order of magnitude

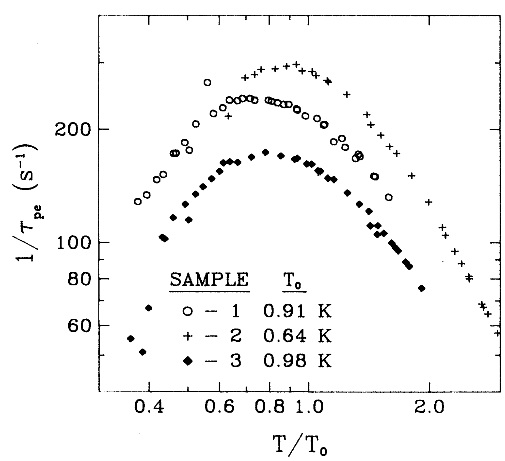

FIG. 1. The zero-field phonon-electron scattering rate τ_{pe}^{-1} determined from the ratio between the phonon drag TEP and the thermal conductivity for the three samples.

larger, even at 0.5 K. In addition, the experimental S_{xx} shows a strong temperature dependence similar to that at zero field. Both these arguments confirm that also in a magnetic field the phonon drag remains the dominant contribution to the TEP.

Our data show several features pointing to a different behavior of the experimental TEP below and above $\nu = 1$.

First, we see a remarkable increase in the magnitude of the TEP with B, reaching at the higher end of the temperature scale values of 70–100 mV K^{-1} at filling factors around $\nu = 0.2$. Theory, which gives correct values for $\nu > 1$,[5,6] predicts only about 2 mV K^{-1} at $\nu = 1/2$ and 2 K.[7]

The second observation is that in the integer regime ($\nu > 1$) S_{yx} resembles the derivative of S_{xx} with respect to the magnetic field, i.e., dS_{xx}/dB (as reported earlier on many different samples[1]) and, therefore, at the extrema of S_{xx}, S_{yx} changes sign. Conventional theory predicts the phonon drag part of S_{yx} to be zero[10] within the approximation $S_{yx} = \epsilon_{xx}\rho_{yx}$, but very recently[11] S_{yx} has been shown to vary as the energy derivative of σ_{xx} at constant B which would give a behavior similar to the experiments. On the other hand, in the present FQH regime data ($\nu < 1$), S_{yx} is found to be composed of a contribution proportional to S_{xx} (with a constant temperature and field-independent ratio of 0.4 ± 0.1 for all three samples) onto which a much smaller component proportional to dS_{xx}/dB is superimposed in the vicinity of the fractional states (Fig. 3).

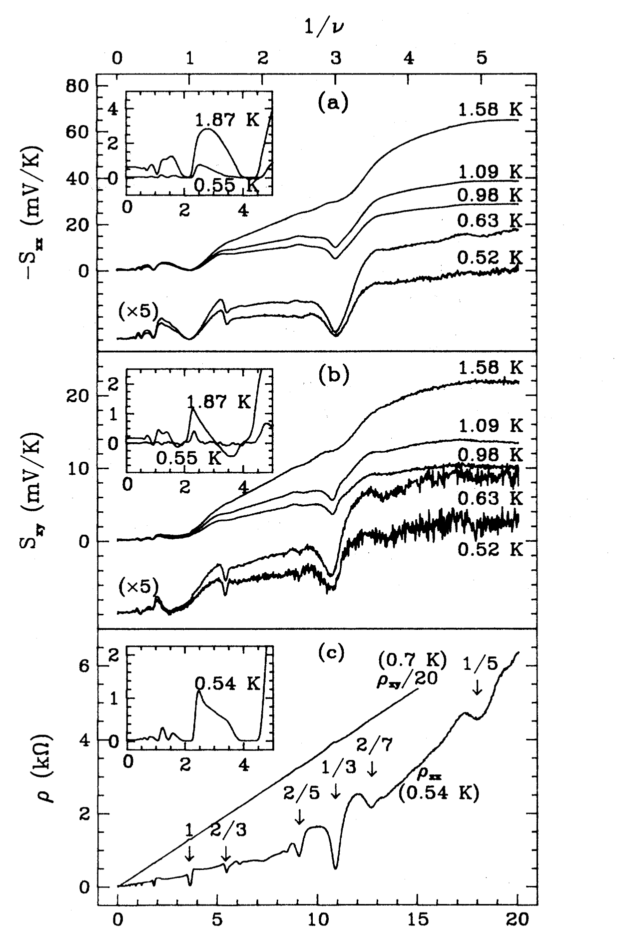

FIG. 2. The thermoelectric power S_{xx} (a) and the Nernst-Ettingshausen coefficient S_{yx} (b) of sample 1 at various temperatures (the graphs at 0.52 K and 0.62 K are shifted and enhanced by a factor of 5); the transverse magnetoresitivity ρ_{xx} (c) with fractional filling factors marked for $T = 0.52$ K and the Hall resisivity ρ_{xy} (c) for $T = 0.7$ K. The insets show the low-field data ($\nu > 1$) for sample 3 which has an electron concentration similar to sample 1.

The ratio S_{yx}/S_{xx} is proportional to that of the transverse and longitudinal components of the thermally induced electric field. Since, apart from the fractions, this ratio is found to be constant, this implies that the effective electric field has a constant angle with respect to the thermal gradient. To understand this point it should be remembered that the thermoelectric field is set up to compensate the thermally induced current, and, due to the Hall effect, is perpendicular to it in a magnetic field. Therefore, one would normally expect the thermal current to be perpendicular to the thermal gradient and the thermoelectric field to be parallel to it, i.e., $S_{yx} = 0$ and $S_{xx} \neq 0$. Since S_{yx}/S_{xx} is found to be constant, the thermal current is not perpendicular to the gradient, but forms an angle of about 70° with it. We speculate that this may indicate an anisotropy in the electron-phonon coupling already observed at zero field[12] and which may be especially pronounced in a field where only the lowest Landau level is occupied.

The last and probably most important observation is the experimental indication that the 1/3 filling acts as a boundary between two different states. This can be seen very clearly for temperatures below 1 K where the B-field dependence of S_{xx} reveals two plateaus for $2/3 > \nu > 1/3$ and $\nu < 1/3$, the second being about two times higher than the first; again all three samples show this behav-

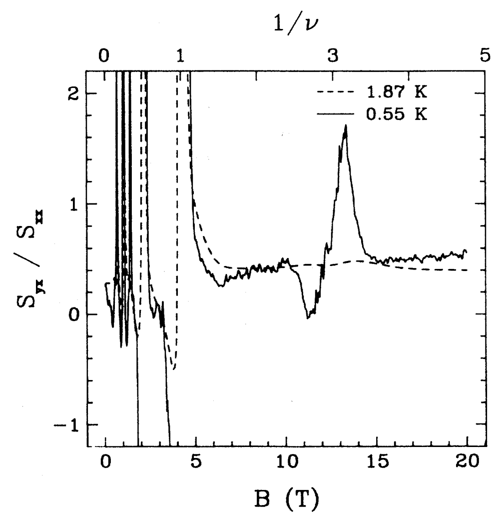

FIG. 3. Ratio S_{yx}/S_{xx} for sample 1 at two different temperatures.

ior. As ϵ_{yx} was shown to be accurately given by $\epsilon_{yx} = -S_{xx}/\rho_{yx}$, a strong change passing from above to below 1/3 also occurs in the fundamental thermoelectric property ϵ_{yx}. This jump is still visible at 1.09 K but for higher temperatures it is becoming masked by a high background TEP. In between these plateaus $-S_{xx}$ goes through the $\nu = 1/3$ minimum. Investigations of the FQH effect generally concentrate on the nature of the fractional states *at* $\nu = p/q$, whereas the TEP also distinguishes between states below and above $\nu = 1/3$. A possible explanation of this effect may be related to the nature of the electronic quasiparticle states. The average cohesive energy of the theoretically predicted states is drastically reduced passing from $\nu > 1/3$ to $\nu < 1/3$.[13] The experimental fact that the measured TEP is roughly two times bigger for $\nu < 1/3$ than for $\nu > 1/3$ may be related to a lower efficiency of phonon momentum transfer to quasiparticle states with higher cohesive energy. In this context it is interesting to note that although 2/5, 1/5, and 2/7 are well pronounced in the resistance data, they are much less visible in the thermopower taken at the same temperatures (see Fig. 2). The changes in the cohesive energy of the electrons at other fractions than 1/3 are much less significant[13] which would explain why they are not observed as distinct plateaus in the experimental TEP data. An alternative quite speculative explanation would be that the quasiparticle charge is different below and above 1/3. Equation (1) shows that the TEP is inversely proportional to the particle charge and assuming that this proportionality remains true in a magnetic field an increase in the TEP could be due to a decrease of the quasiparticle charge passing from above 1/3 to below.

In summary we have measured the TEP of two-dimensional electron gases at low temperatures and at high fields in three different samples. The zero-field data have shown that the TEP in all samples is dominated by phonon drag. The magnetic-field data show qualitatively different behavior for $\nu < 1$ as compared to $\nu > 1$. In the quantum limit, at values other than $\nu = 1/3$, the ratio S_{yx}/S_{xx} is constant with the same proportionality factor for all samples. The values of S_{xx} and S_{yx} below and above 1/3 are almost field independent and differ by roughly a factor of 2 for all samples. This may reflect the difference in cohesive energy of fractional states or the changes of the fractional charge. It would clearly be of great interest to extend these measurements to even lower temperatures.

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