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Evidence of phonon drag in the thermopower of a GaAs-$Ga_{0.68}Al_{0.32}As$ heterojunction

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We report the first experimental demonstration that phonon drag is present in the thermopower of a two-dimensional electron gas at a GaAs-$Ga_{0.68}Al_{0.32}As$ heterojunction in both zero and high magnetic fields. The experiment involves polishing the rear surface of the GaAs plate on which the junction is grown in order to increase the phonon mean free path. This results in an increase of the thermopower by about a factor of 2 even though the electrical resistivities are unaffected.

The study of the quantization of two-dimensional electron gases in high magnetic fields has revealed unexpected phenomena, the most striking of which are the integer and fractional quantum Hall effects.[1-3] The thermopower $S_{xx}=E_x/(\partial T/\partial x)$ also reflects the complete quantization of the carriers and oscillates with magnetic field B in a fashion similar to that of the resistivity ρ_{xx}. Assuming that the separation of the Landau levels $\hbar\omega_c \gg kT$, all theories of S_{xx} appropriate to high B in the disorder free limit predict that $-eS_{xx}$ is a measure of the entropy per electron[4-6] (where $-e$ is the electronic charge); when $kT>\Gamma$, where Γ is the broadening of the Landau levels, the magnitude of S_{xx} should be given by

$$S_{xx}=-\frac{k}{e}\frac{\ln 2}{n+\frac{1}{2}}=-\frac{60\mu\mathrm{V\,K^{-1}}}{n+\frac{1}{2}}\,. \tag{1}$$

Here n is the quantum number of the level in which the Fermi energy lies ($n=0,1,\ldots$) and spin splitting is assumed to be unresolved. Some published experimental work[7-11] gives results in approximate agreement with these predictions. On the other hand, much larger magnitudes of S_{xx} (~ 1 mV K^{-1}) have been reported.[12,13] The origin of the differences in reported magnitudes is not understood but the latter data have been supported by thermal conductivity measurements on the GaAs substrates which yielded phonon mean paths Λ_p of the expected magnitudes; this lends confidence to the thermometric techniques which are particularly difficult on these small samples. The large magnitudes reported for S_{xx} suggest the possibility of phonon drag and this Rapid Communication describes experiments which confirm this possibility. It should be mentioned that the theories leading to Eq. (1) are based on diffusion models. Phonon drag arises from the nonequilibrium flow of phonons (in the bulk GaAs) down the temperature gradient. The phonons exchange momentum with the two-dimensional (2D) electrons and augment their thermopower. Cantrell and Butcher[14] have investigated this mechanism for $B=0$ and found agreement both with the large magnitudes of S_{xx} and the rapid temperature dependence reported in Refs. 12 and 13. In particular, they found that the phonon-drag part of S_{xx} should be proportional to Λ_p, the mean free path of the bulk phonons. In the present work we use the simple technique of polishing the rear surface of the GaAs plate (i.e., the surface opposite to that which has the 2D gas) to increase Λ_p and determine the effects on the transport properties.

The samples used in these experiments were grown by molecular-beam epitaxy. A single heterojunction was grown on a pure GaAs semi-insulating substrate and consists of 1.5 μm of p-type GaAs ($\simeq 10^{15}$ cm^{-3}), a 110-Å spacer of undoped $Ga_{0.68}Al_{0.32}As$, a 200-Å layer of Si-doped (3×10^{18} cm^{-3}) $Ga_{0.68}Al_{0.32}As$, and a 140-Å GaAs cap layer. At 4.2 K the 2D carrier density was 2.3×10^{15} m^{-2} and the mobility was about 4.0 m^{2}V^{-1}s^{-1}. Under illumination with a red light emitting diode the carrier density increased to about 6.5×10^{15} m^{-2} and the mobility to 18.5 m^{2}V^{-1}s^{-1}. The results reported here are for the unilluminated sample only, but all the same features are present with the illuminated sample, which is evidence that the results to be described are not limited to a particular range of carrier density or mobility. The measurements were carried out on two pieces of the same sample which we label A and B. Each of samples A and B measured about $12\times6\times0.42$ mm^3 and had a large Hall bar pattern etched into the active surface with overall dimension of about 4×5 mm^2. Electrical contacts were made using 0.3-mm-diameter Sn balls. The experimental techniques were similar to our previous description[13] and details need not be repeated here. The major difference from the earlier work is that the current measurements were limited to the ^{4}He temperature range and all thermometer calibrations were made using ^{4}He vapor pressure. Also, we have used a completely different cryostat. Typical temperature gradients were 130 mK cm^{-1} at 4 K and 20 mK cm^{-1} at 1.6 K. We found, as before,[13] that it was difficult to produce good thermal contact to GaAs so that with the He bath at 1.1 K we were limited to a heat current $\lesssim 15$ mW to keep the sample at less than 4.2 K. Under these conditions we had a temperature difference of

only 0.15 K across the sample and a difference of about 2.75 K at the cold junction to the copper. Of the total of 8–10 samples we have examined so far, all have behaved in this way. The use of Cr-doped substrates increases the thermal resistivity of the samples,[13] and thus temperature gradients, but the junction resistance remains much the same. We note that Davidson, Dahlberg, Valois, and Robinson[11] have not taken this junction resistance into account; this can increase the magnitudes they report for S_{xx} by more than a factor of 10.

Sample A was measured as received, i.e., the rear surface had a matt finish. The rear surface of sample B was optically polished before attaching the thermometers; we will refer to this as sample BP. After taking a series of data, the rear surface of sample BP was carefully abraded using 5 μ diamond paste until a matt finish was produced everywhere (except of course where the thermometers were attached, which corresponds to two strips each about 0.35 mm wide across the full width of the sample). All measurements were then repeated on this sample, which is referred to as sample BM. The intention was that sample A would provide a check on the results from sample BM. Since both are taken from the same wafer, and they are physically similar we expect them to have similar properties. On the other hand sample BP will have a higher thermal conductivity λ than the other two samples, providing boundary scattering of phonons is significant; if the electronic properties depend on the phonon mean path Λ_p, then this sample should behave differently. It should be stressed that the two sets of measurements on BP and BM were made with no changes in the wiring or thermometry (other than the routine recalibration of the carbon resistors against the vapor pressure of ^{4}He); hence we expect excellent relative accuracy between these two sets of data, probably at the level of 2%–3%. On the other hand, sample A can be compared with B only at the level of $\sim$10%–15% for λ and $\sim$20% for S_{xx} because of the independent geometrical factors involved.

Figure 1 shows the thermal conductivity λ for samples BP and BM. We see that λ for sample BP is typically 50% larger than that for sample BM, and it is closer to 100% larger at the lowest temperatures. For sample A we find λ to be 15% larger than that for sample BM but otherwise it follows the same curve; this is reasonable agreement in view of the quoted accuracies. We also note that these data on the matt samples are in good agreement with those for sample 4 of Ref. 13 which was also grown on a pure GaAs substrate. When Λ_p is limited by boundary scattering we expect $\lambda \propto T^3$. The exponents for samples A, BP, and BM at $T \simeq 2$ K are 2.8, 2.4, and 2.8, respectively, each ± 0.1. Using the elastic constants of GaAs (Ref. 15) we estimate $\Lambda_p \sim 1.5$–2.0 mm at $T \simeq 2$ K for samples A and BM which is not unreasonable for boundary scattering in a sample of cross section 0.42×6 mm^2, with the active face highly polished. For sample BP, Λ_p is presumably higher by the ratio of the relevant λ but the rather strong departures of λ from T^3 are not understood at present.

Figure 2 shows ρ_{xx} and ρ_{yx} for sample BM. The data for sample BP are identical to within 2% except near $B = 0$ where ρ_{xx} for sample BM is 10% higher than that for

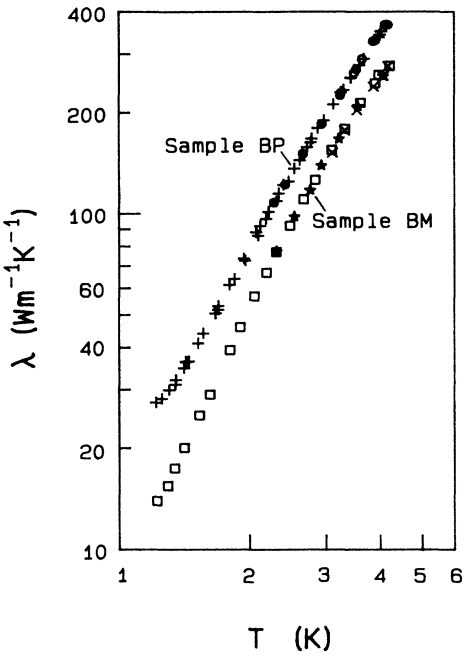

FIG. 1. The thermal conductivity λ of the polished sample BP and the matt sample BM. The different symbols correspond to different ^{4}He bath temperatures (which is not relevant except to show that this has no affect on the data).

sample BP. For sample A the data on ρ_{xx} are everywhere 5%–10% lower than that shown in Fig. 2 but ρ_{yx} is virtually unchanged. The data, in total, suggest that any changes to the resistivities caused by changing Λ_p are insignificant, at least for this sample. This is expected since impurity scattering is the dominant mechanism limiting the mobility at these temperatures.

Figure 3 reproduces our data on the zero-field variation of S_{xx} with temperature for all three samples. The two samples A and BM are in good agreement and are well

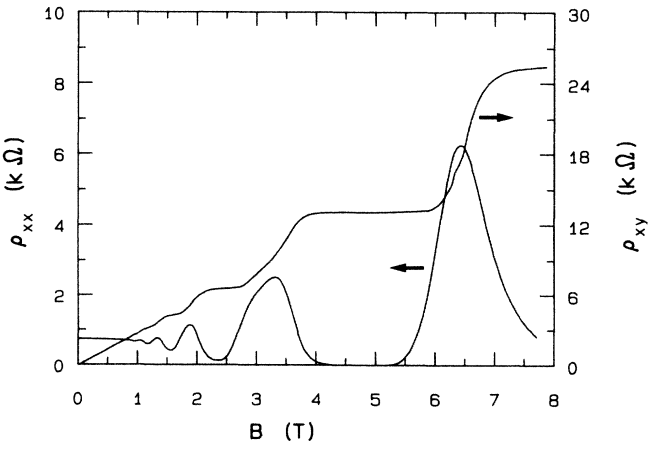

FIG. 2. The resistivity ρ_{xx}, left scale, and Hall resistivity ρ_{yx}, right scale, for sample BM. See text for differences with the other samples. These data are taken at 1.61 K.

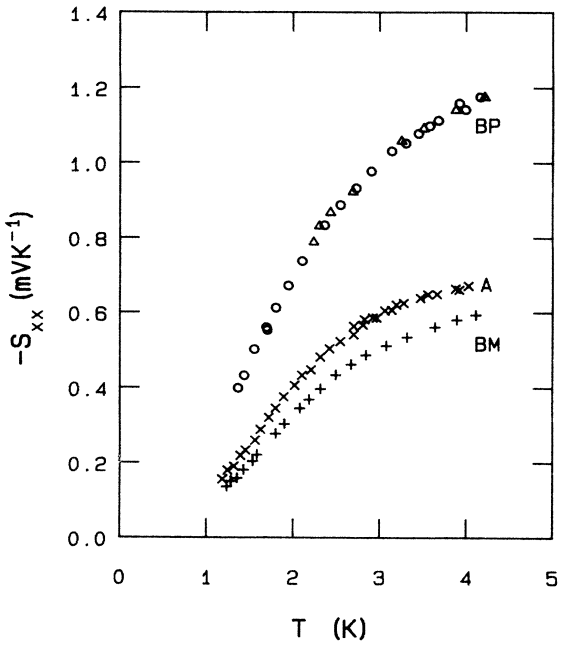

FIG. 3. The zero-field thermopower of all three samples. The diffusion thermopower is unlikely to exceed $-100\ \mu V\ K^{-1}$ in this temperature range.

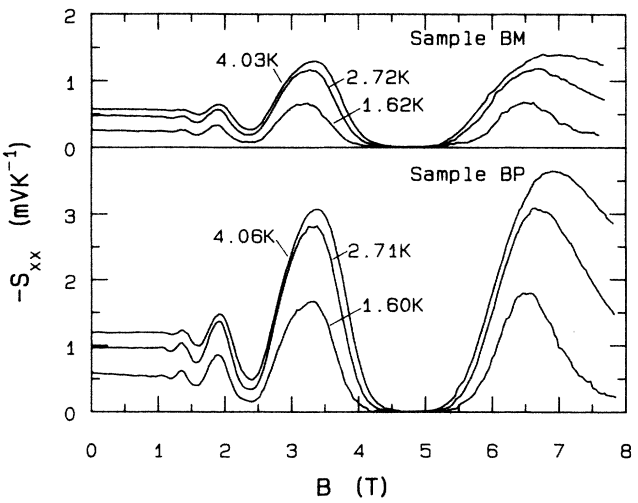

FIG. 4. The thermopower of samples BP and BM drawn to the same scale.

within the expected error limits. However, it is clear that the polished sample BP has a much larger magnitude of thermopower at any temperature compared to that of the matt finish samples, the difference being about a factor of 2. This behavior is in accord with that predicted by Cantrell and Butcher,[14] i.e., that the magnitude of S_{xx} will increase as Λ_p increases.

Finally Fig. 4 shows S_{xx} as a function of B for samples BP and BM. The data for sample A are very similar to those for sample BM but are everywhere 10% larger, just as the zero-field data were, and this agreement is well within the expected experimental errors. To put these data in perspective we note that according to Eq. (1) the height of the peak near 3 T should be about $-40\ \mu V\ K^{-1}$, which is between one and two orders of magnitude lower than that which was actually observed; this suggests that diffusion effects are insignificant here. Sample BP again has a thermopower which is about a factor of 2 larger than the other two samples (the factor is ~ 2 at $B=0$ but increases steadily at higher fields and is greater than 2.5 at 7 T). Polishing the rear surface of the GaAs clearly has a dramatic effect on S_{xx} even though the electrical resistivities are unaffected. The only theoretical results appropriate to this situation are those of Nicholas[16] which would predict a phonon-drag contribution of order $20\ \mu V\ K^{-1}$. We await the results of more rigorous calculations. Should there be any residual doubts about the thermometry in these experiments, we emphasize that the qualitative result of an increase in $-S_{xx}$ after polishing the rear surface is quite evident in the original experimental data even ignoring changes in temperature gradient (which accentuates the behavior). For a given heat current through the samples, the thermoelectric output voltages from sample BP were always clearly larger than for the other two samples. That this should be so is seen from Figs. 1, 3, and 4 where $-S_{xx}$ increases by at least a factor of 2, but where λ increases by typically only 50% for the polished sample. Thus the effect is real and independent of thermometry.

To summarize, these results prove that the thermopower of this heterojunction is very sensitive to the mean free path of the phonons in the bulk GaAs substrate even though the electrical resistivities are unaffected and are dominated by impurity scattering effects. This provides conclusive evidence that phonon drag is a major fraction of the measured thermopower in both zero and high magnetic field.

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