Phonon-drag effect in GaAs-$Al_xGa_{1-x}As$ heterostructures at very low temperatures

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The thermoelectric power of high-mobility GaAs-$Al_xGa_{1-x}As$ heterojunctions has been investigated in the temperature range from 0.1 to 10 K in order to study the phonon-drag effect. The phonon-drag contribution to the Seebeck coefficient can be well described by the classical T^3 dependence below 2.5 K. At very low temperatures ($T<0.6$ K), the phonon drag becomes vanishingly small and a linear temperature dependence of the diffusion thermoelectric power was resolved. In addition, the thermoelectric power was measured in magnetic fields up to 7 T and different temperature dependences were found for the maxima of the thermoelectric power oscillations at different Landau levels.

I. INTRODUCTION

During the past few years there has been an increasing interest in the thermoelectric and thermomagnetic properties of the two-dimensional electron gas (2D EG) of semiconductor heterostructures. Such experiments turned out to be one of the major points for a detailed understanding of quantum effects in solids. Theoretical calculations have centered on the diffusion component of the Seebeck coefficient for both zero and nonzero magnetic fields.[1-6] In the limit of small Landau-level broadening in quantizing magnetic fields, the diagonal diffusion thermoelectric power S_{xx}^d shows Shubnikov–de Haas-type oscillations and becomes proportional to the entropy of the 2D EG.[2] Therefore, by measuring S^d at half-filled Landau levels one can calculate the width of the density of states.[1,7] However, there have been only a few experimental studies of the zero-field and magnetothermoelectric power.[7-15] In particular, as far as we know, no experimental results at very low temperatures (i.e., below 1 K) have been reported. It has been pointed out by Nicholas[16] that in semiconductor heterostructures having a small lattice mismatch, the phonon-drag effect may give a significant contribution to the total thermoelectric power even at temperatures below 10 K. In the meantime this has been confirmed experimentally.[7,12,13] Recently, detailed calculations of the phonon-drag contribution to the thermoelectric power of quasi-2D electrons coupled to the 3D phonons have been presented by Cantrell and Butcher.[17,18] The results of these authors are in good qualitative agreement with the data measured by Fletcher and co-workers.[12]

To recapitulate the present situation, it is likely that the total thermoelectric power of GaAs-$Al_xGa_{1-x}As$ heterostructures must be described by two contributions, namely a diffusive part S^d proportional to temperature,[19] and an additional one, the phonon-drag contribution S^{ph},[20] which is expected to increase as T^3: $S^{tot}=S^d+S^{ph}=aT+bT^3$. The expected linear temperature dependence of S^d in the case of a degenerate electron gas was only observed in zero magnetic field for samples with rather low mobility[7,15] ($\mu<5\times10^4$ cm^2/V s), whereas for the high-mobility samples ($\mu>1\times10^5$ cm^2/V s) the Seebeck coefficient S^{tot} is dominated by the phonon-drag contribution S^{ph} and shows a maximum in the range 5–10 K.[7,9,12,13] Obviously, the phonon-drag effect is enhanced with increasing mobility that implies increasing mean free paths of the carriers. The expected T^3 temperature behavior of the phonon-drag component has not yet been observed. Experimentally the temperature variation of S^{ph} for GaAs-$Al_xGa_{1-x}As$ heterostructures between 1.5 and 5 K was found to be[7] $S^{ph}\sim T^m$ with $m<2$.

In this paper we present the first measurements of the magnetothermoelectric power of GaAs-$Al_xGa_{1-x}As$ heterostructures below 1 K in order to help to elucidate the main issue, namely the temperature dependence of both S^d and S^{ph}. We will demonstrate that at these very low temperatures the total thermoelectric power in zero magnetic field agrees with the expected behavior, whereas in quantizing magnetic fields a new effect appears that has not yet completely been understood.

II. EXPERIMENT

The samples were grown by molecular-beam epitaxy (MBE) on GaAs substrates. A Hall bar, suitable for measurement of the electrical and Hall resistivities ρ_{xx} and ρ_{xy} as well as the Seebeck coefficient S_{xx} was then produced by selective etching. We investigated two high-mobility samples from different sources with comparable carrier densities and mobilities. They were contacted with indium soldered 100 μm superconducting Nb-Ti wires, which had no appreciable heat leak to the surrounding. The experiments were carried out in a dilution refrigerator. The sample holder was a thin copper disk (thickness $d=2$ mm, diameter $d=4.5$ cm) which had

several radial cuts to avoid heating by eddy currents. For the same reason, the sample holder was mounted about 30 cm beneath the mixing chamber by use of a bundle of 20 oxygen-free high-conductivity (OFHC) copper rods ($\phi = 1$ mm). In order to ensure a good thermal contact to the sample support and to guarantee sufficient mechanical stability, the samples were screwed at one end directly to the sample holder, thus forming the cold sink. Temperature gradients across the samples were produced by applying current to a 600-Ω strain gauge heater glued to the free end. The samples were hanging freely in the vacuum can. This experimental setup also enables the determination of the thermal conductivity. The temperature gradient ΔT across the samples and the mean sample temperature were measured with Au–0.03%Fe/Nb-Ti thermocouples. One end of both thermocouple leads was soldered with Indium to the sample, the other was isothermally connected to the mixing chamber. The absolute temperature of the sample support was measured and controlled by several independent thermometers: a calibrated Ge resistor and an Allen-Bradley carbon resistor, one of each on the mixing chamber and on the sample holder. The calibration of these sensors was checked by a superconducting transition device from the National Bureau of Standards (NBS). The thermocouples were calibrated against a carbon resistor in a separate run. The results of the thermoelectric power of Au–0.03%Fe/Nb-Ti were in good agreement with the data reported by Chaussy *et al.*[21]

In zero magnetic field the thermovoltages of the thermocouples and of the samples were measured using battery driven dc nanovoltmeters (EM Electronics Ltd., Model N1a) whereas the magnetic field dependence of the thermal emf was detected using an ac technique: a low-frequency ($f < 10$ Hz) ac voltage was applied to the strain gauge heater and the resulting thermovoltage was recorded with a lock-in amplifier (Ithaco Model 393) at double the frequency. The resolution thus achieved was about 2 nV.

III. THERMAL CONDUCTIVITY

To check the experimental setup we first studied the thermal conductivity, given as $\lambda = (P/\Delta T)(l/A)$, where P denotes the heater power ($P = UI$), and l and A are the length and the cross section of the samples. The major heat leak is via the 100-μm-thick and 30-cm-long Au-Fe wires. But an estimate of the heat losses showed that at least 99% of the total heat current was flowing across the samples. Our results are represented in Fig. 1. Between 0.2 and 7 K the thermal conductivity $\lambda(T)$ fits well a T^3 law, as expected theoretically for low-temperature boundary scattering.[22] The data also agree well with those given by Fletcher *et al.*[12] in the overlapping temperature range (2–6 K). Below 7 K umklapp processes can be neglected and the phonon mean free path Λ in the sample shown was determined approximately using the general equation for the thermal conductivity ($\lambda = \frac{1}{3} c_p v \Lambda$, with c_p the specific heat of the lattice and v the sound velocity) to be of the order of 80 μm. We conclude from these first $\lambda(T)$ data for heterostructures below 1 K that the applied

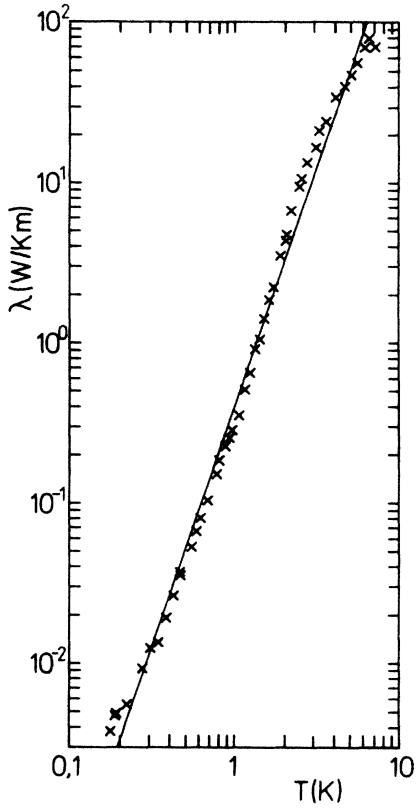

FIG. 1. Thermal conductivity of GaAs-$Al_xGa_{1-x}As$ heterostructure as a function of temperature.

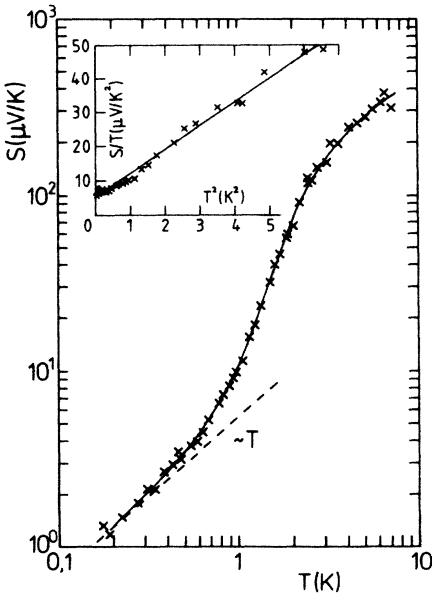

FIG. 2. Typical temperature dependence of the Seebeck coefficient S_{xx} at zero magnetic field. The electron density n and mobility μ of the presented sample are $n = 3.3 \times 10^{11}$ cm^{-2} and $\mu = 8.1 \times 10^5$ cm^2/V s, respectively, at $T = 4.2$ K.

experimental arrangement, in particular the determination of the temperature difference across the heterostructure, is reliable and correct for the study of the thermoelectric properties even at temperatures below 1 K.

IV. TEMPERATURE DEPENDENCE OF THERMOELECTRIC POWER IN ZERO MAGNETIC FIELD

The total emf S^{tot} as a function of temperature is displayed in Fig. 2. We distinguish three regions in the temperature dependence of $S^{tot}(T)$: (i) very low temperatures $T<0.6$ K, where an almost linear dependence $S^{tot}\sim T$ is observed; (ii) an intermediate range 0.6 K $<T<2.5$ K in which S^{tot} increases rapidly according to $S^{tot}\sim T^3$; and (iii) high temperatures $T>2.5$ K, for which the temperature dependence of S^{tot} again weakens with rising temperature.

At sufficiently low temperatures, we expect to see, according to current theories, the following temperature dependence for the total thermoelectric power: $S^{tot}=S^d+S^{ph}=aT+bT^3$. This is best visualized by a plot of S^{tot}/T versus T^2 as shown in the inset of Fig. 2. Our experimental results indicate that at temperatures below 0.6 K the phonon-drag effect becomes negligible and the thermoelectric power displays a linear temperature dependence which we attribute to the pure electronic contribution. With increasing temperature (here 0.6 to 2.5 K) the phonon-drag contribution dominates the thermoelectric power with a T^3 dependence. We emphasize that both the linear and the cubic temperature dependences are in agreement with the theoretically expected behavior and are verified for the first time. The prefactors a and b can be calculated from the finite intercept and the slope of S^{tot}/T versus T^2. The resulting values are $a=5.1\ \mu V/K^2$ and $b=7\ \mu V/K^4$.

Our linear term is a factor of 5 larger than the value found by Davidson *et al.*[10,15] for their samples ($a=1\ \mu V/K^2$). The different a values could be explained either by the energy dependence of the scattering mechanisms or by the influence of subbands. Assuming an energy-dependent conductivity $\sigma(E)=n_s e^2\tau_0 E^{(p+1)}/m^*$ one can calculate[16] the exponent of this energy dependence by substituting into Motts formula for the diffusion thermoelectric power.[19] We obtain $(p+1)=1.2$ for the sample shown. This is only a bit larger than $(p+1)=1.0$ which we calculate for the Davidson samples. From this result we conclude that energy-dependent scattering mechanisms have to be considered in interpretation of the diffusion thermoelectric power. The influence of the subband structure on the electronic contribution to the thermoelectric power was recently discussed.[23]

Above 2.5 K the temperature dependence of S^{tot} deviates from the T^3 behavior. A most likely explanation for this is the onset of additional scattering processes, such as phonon-phonon or phonon-impurity interactions which limit the mean free path of phonons and lead to the observed maximum in the phonon drag and S^{tot}, respectively.

V. THERMOELECTRIC POWER IN QUANTIZING MAGNETIC FIELDS

The phonon-drag effect not only contributes to the thermoelectric power of a 2D EG at zero magnetic field but also enhances significantly the diagonal and off-diagonal components of the thermoelectric tensor S_{ij}, in quantizing magnetic fields, e.g., at about $T=5$ K the maxima of the magneto-Seebeck coefficient S_{xx}^{max} have been found to be up to a factor of 100 larger than in the case of thermoelectric power without any phonon-drag

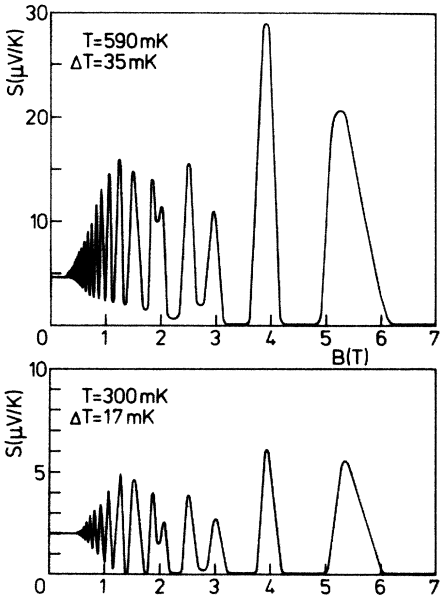

FIG. 3. Thermoelectric power oscillations in a magnetic field at different temperatures.

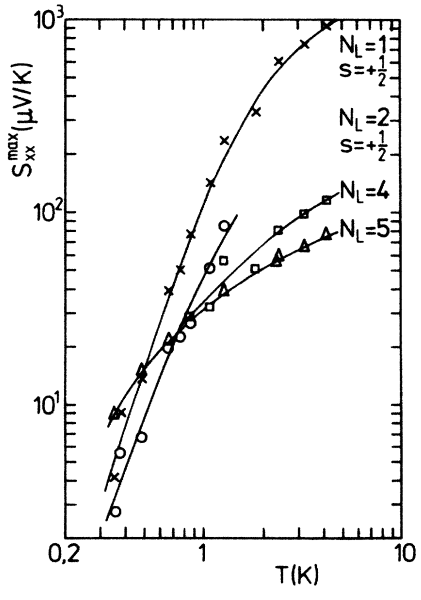

FIG. 4. Temperature dependence of S_{xx} maxima at different Landau levels.

contribution.[7] We investigated the diagonal component of the thermoelectric tensor S_{xx} as a function of magnetic field up to $B=7$ T and in the temperature range between 0.1 and 4 K. The experimental results of $S_{xx}(B)$ are shown in Fig. 3 for two different temperatures. With decreasing temperature the maxima of the diagonal component $S_{xx}^{\max}$ decrease very rapidly. So far, this is in qualitative agreement with theory because both the phonon-drag and the diffusion thermoelectric power vanish at zero temperature.[2] A more detailed inspection reveals a new phenomenon which is illustrated in Fig. 4 in the plot of $S_{xx}^{\max}$ as a function of temperature for different Landau levels. At low temperatures ($T<1$ K) the maxima of S_{xx} for low Landau levels ($N_L=1,2$) decrease much faster than those for higher Landau levels ($N_L=4,5$). This result was already indicated in former works,[7,12,15] but up to now, no experimental data below 1.5 K have been reported. Below this temperature the temperature dependence of $S_{xx}^{\max}$ for different Landau levels show "cross overs." Such an effect was not observed for the electrical resistance $\rho_{xx}^{\max}$ of the investigated sample. The maxima of the Shubnikov–de Haas oscillations for lower Landau levels are always larger than those for higher ones and the maxima saturate at certain values with decreasing temperature.

The unexpected behavior of $S_{xx}^{\max}$ occurred in high-mobility samples in which a strong phonon-drag contribution to the thermoelectric power is present. Therefore we assume that in quantizing magnetic fields the electron-phonon coupling becomes weaker. To the best of our knowledge, there exists no theory at present that gives a satisfactory explanation of the observed behavior. Preliminary results on another sample with high mobility confirm the dependence of $\lambda(T)$ described above and ascertain $S(T)$ and $S_{xx}^{\max}$. Further experiments are planned to gain a deeper understanding of this new effect.

VI. CONCLUSION

Our thermoelectric experiments provide for the first time clear evidence that the temperature dependence of the Seebeck coefficient of GaAs-$Al_xGa_{1-x}As$ heterostructures below 10 K arises from two major contributions: the diffusion thermoelectric power which increases linearly with temperature and the phonon-drag which exhibits a T^3 behavior and becomes dominant above 0.6 K. This picture is in agreement with theoretical predictions. In addition, we found at very low temperatures a new, not previously observed magnetic-field-dependent effect for $S_{xx}^{\max}$: The maxima of the thermoelectric power oscillations of unequal Landau levels show substantially different temperature dependences; in particular, cross overs have been observed at very low temperatures. In order to explain this behavior more theoretical calculations of the phonon-drag effect in magnetic fields are required. For the systematic variation of $S(T,B,\mu)$ much more data are needed on samples with a wider range of mobilities.

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