Tr. J. of Physics
23 (1999) , 717 – 723.

Experimental Separation of Phonon and Extrinsic Scattering in 2D Carrier Gases in GaAs

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Received 01.03.1999

Abstract

A new method which separates phonon scattering from extrinsic scattering in 2D gases in GaAs is presented. In contrast to previous ones, the technique makes no assumptions about the temperature dependence of the extrinsic scattering. The preliminary measurements of the phonon limited mobility μ_{ph} on two electron gas samples show a Bloch-Grüneisen regime in the temperature range 1.2-4.5K and the results agree reasonably well with other experimental and theoretical work.

1. Introduction

The mobility of the two dimensional carriers (2D) formed at the interface $Al_xGa_{1-x}As$/GaAs is limited at low temperatures by extrinsic scattering (μ_{ex}), associated with remote and background impurities, and intrinsic scattering (μ_{ph}), associated with phonon scattering. Extrinsic scattering has been steadily reduced over the last two decades by advances and improvements in growth techniques and this has led to records mobilities at low temperatures [1,2]. However, phonon scattering is the ultimate intrinsic limit to the mobility at any temperature.

Phonon scattering has been studied, both theoretically [3, 4] and experimentally [1, 4] for some time. However, there are still unresolved questions such as the mechanism for the carrier-phonon interaction (deformation or piezoelectric potentials), the role of screening and the values of the coupling constants needed for agreement with experiments. At the lowest temperatures, known as the Bloch-Grüneisen (B-G) regime, $\mu_{ph} \propto T^{-7}(T^{-5})$ for screened deformation (piezoelectric) scattering. At high temperatures, $\mu_{ph} \propto T^{-1}$ and measurements on high mobility 2D gas are consistent with this dependence for T>5K [2]. So far, however, there have been no direct measurements of μ_{ph} at the lowest temperatures. Stormer et al [1] made measurements of μ_{ph} on very high mobility 2D electron samples ($\sim 1 \times 10^7$ cm^2/Vs). In these, it was assumed that the lowest temperature mobility (~0.3K) was due to impurity scattering and that the scattering for this process is temperature independent. μ_{ph} was obtained by subtracting a constant from the measured data.

In this paper, we present a new method that separates phonon and extrinsic scattering at low temperatures and allows each to be obtained as a function of temperature.

2. Phonon scattering in 2D gases

The energy relaxation rate P of hot 2D carriers due to phonons has been studied considerably both theoretically and experimentally [5, 7]. This system can be adequately described by a well defined carrier temperature, since thermalisation by carrier-carrier interaction occurs at a much faster rate than the carrier-phonon interaction and it is found that the power loss can be well approximated as $P \propto T_e^n - T^n$ (T_e and T are the carrier and lattice temperature respectively), where $n = 7(5)$ at the lowest temperatures in the B-G regime for screened deformation (piezoelectric) scattering and $n = 1$ at high temperatures. In our temperature range $n \sim 2 - 3$ [5, 7]. So if $T_e \gg T$, $P \propto T_e^n$ and the carrier temperature T_e is independent of T for a given P.

Assuming that Matthiessen's rule is valid in our temperature range, the device resistance R can be written as:

$$R = R_{ex} + R_{ph} \tag{1}$$

where R_{ex} and R_{ph} are the components due to extrinsic and phonon scattering respectively. R_{ex} is assumed to depend only on carrier temperature (ie independent of lattice temperature T). R_{ph} can in turn be expressed as $R_{ph} = R_{em} + R_{ab}$, where R_{em} and R_{ab} are the resistance components due to phonon emission and absorption respectively.

R_{em} and R_{ab} can be derived by evaluation the scattering rates due phonon emission and absorption and [3, 4, 6]

$$R_{em} \propto \sum_{\substack{k,k',\\ \omega,s}} f_k(1 - f_{k'})(n_q(T) + 1)\frac{(k - k')}{k} W_k^{k',q}$$

$$R_{ab} \propto \sum_{\substack{k,k',\\ \omega,s}} f_k'(1 - f_k)n_q(T)\frac{(k' - k)}{k} W_{k',q}^{k}$$

where k and k' denote the initial and final electron states respectively, q is the phonon wavevector with energy $\hbar\omega$ and mode s, f_k is the Fermi distribution function, $W_k^{k',q} \propto q(1/q)$ is the transition rate for the carrier-phonon interaction for deformation (piezoelectric) and $n_q(T)$ is the phonon occupation number defined by $n_q = [\exp(\hbar\omega_{q,s}/k_B T) - 1]^{-1}$.

After further manipulations and adding the two contributions [6], R_{ph} can be written as

$$R_{ph} \propto \sum_{w,s}(n_q(T_e)+n_q(T))\sum_{k,k'}(f_{k'}-f_k)\frac{(k-k')}{k}W_k^{k',q}$$

Following a similar procedure to that used for the energy loss rate and noting that the summation over ω is peaked at particular frequencies [5,6], it is possible to obtain a power law for R_{ph} and

$$R_{ph} \propto T_e^n + T^n \tag{2}$$

Where n varies from 7(5) for screened deformation (piezoelectric) scattering to 1 depending on the temperature.

Eq.2 shows that R_{ph} can be separated into two terms, the first represents phonon emission at T_e while the second represents phonon absorption at T.

3. A new technique for separating phonon and extrinsic scattering in 2D

To estimate the phonon contribution to the resistance at a lattice temperature T, we measure:

(i) The resistance R in equilibrium at $T, R(T)$, by passing a very low current through the device so that $T_e = T$.

(ii) R in the hot carrier regime for the **same** input power through the device P_e at two lattice temperatures:

(a) R_a at T and **(b)** R_b at $T_0 < T$.

We assume the carrier temperature are $(T_e)_a$ and $(T_e)_b$ respectively.

In **(b)**, T_0 =1.2K is the minimum lattice temperature and is chosen to be low enough for phonon scattering to be negligible.

If the power P_e is high enough so that $(T_e)_a \gg$T and $(T_e)_b \gg T_0$, the carriers have approximately the same temperature T_e both in **(a)** and **(b)**.

If the resistance of the device is solely dependent on the carrier temperature T_e, which is the case when phonon scattering is negligible, $R_a \approx R_b$, If, however, phonon scattering cannot be neglected, $R_a > R_b$ and R_{ph} can be determined from R_a and R_b using the following:

In (i), When $T_e = T$, the net rate of phonon emission by the 2D is zero so the phonon emission rate from the 2D carriers equals that for absorption or $R_{em} = R_{ab}$ (eq.2) and the resistance in eq.1 can be written as

$$R(T) = R_{ex}(T) + 2R_{ab}(T) \tag{3}$$

In (ii), when $T_e \gg T, T_0, R_{em}$ is independent of the lattice temperature T and depends only on the carrier temperature T_e (eq 2) [5]. Assuming that the phonon absorption depends on the lattice temperature only [5] (eq 2) and that it does not change with P which is reasonable since the change in the local lattice temperature with P is negligible in our experiments, R_a and R_b can be expressed as:

$$R_a = R_{ex}(T_e) + R_{em}(T_e) + R_{ab}(T) \tag{4}$$

and

$$R_b = R_{ex}(T_e) + R_{em}(T_e) + R_{ab}(T_0) \approx R_{ex}(T_e) + R_{em}(T_e) \tag{5}$$

Since phonon scattering is assumed to be negligible at T_0, ie $R_{ab}(T_0) \approx 0$. Hence

$$\Delta R(T) = R_a - R_b \approx R_{ab}(T) \tag{6}$$

which represents the resistance caused by phonon absorption at a temperature T. Using eqs.3 and 4, R_{ph} and R_{ex} can then be calculated as

$$R_{ph}(T) = 2\Delta R(T) \tag{7}$$

$$R_{ex}(T) = R(T) - 2\Delta R(T) \tag{8}$$

4. Experiments and preliminary results

The technique has been applied to a 2D electron gas in GaAs in the temperature range 1.2-4.5K and preliminary measurements on two modulated doped GaAs/$(Al_{0.4}Ga_{0.6})$As heterojunctions devices are presented. Sample A had an electron density 1K mobility of n_s=2.85×10^{15} cm^{-2} and a 5.5×10^5 cm^2/Vs while sample B contained n_s=0.85×10^{15} cm^{-2} electrons and had a mobility of 3.6×10^6 cm^2/Vs. The samples were immersed in liquid helium and four terminal measurements of the DC resistance of the device were made to avoid any contact resistance problems.

Figure 1 shows the power dissipated per electron P as a function of the device resistance R at the minimum lattice temperature T_0=1.2K, where phonon scattering is assumed negligible, but also at a number of higher temperatures $T(1.25 < T < 4.5K)$. R_b is the resistance at $P = P_e$ and T_0.

For each lattice temperature $T, \Delta R(T) = R_a - R_b$, where R_a is the value of R at the same power P_e but at T. To ensure that $(T_e)_a \gg T$ and $(T_e)_b \gg T_0$ for all temperatures, $\Delta R(T)$ is measured at $P_e \geq 10^5$ eV/s which corresponds to heating the electrons to $T_e \sim 10K \gg T_0, T$ [4,7]. $R_{ph}(T)$ is then estimated using eq.5 and the corresponding variation of phonon limited mobility μ_{ph} with T is shown in Fig 2. μ_{ph} varies approximately as T^{-n}, where n varies from about 4.7 at the lowest temperatures to about 3 near 4.2K for sample A and from 4.3 to 2 for sample B, which suggests that a B-G regime is observed for both samples for T<4.5K. Also shown in Fig.2, are the numerical calculations by Karpus, which include both deformation and piezoelectric scattering but exclude screening [4], and the experimental measurements of Stormer *et al* [1]. As can be seen, reasonable agreement is obtained at 4.2K. However their temperature dependence are both somewhat weaker.

Figure 3 shows the variation of the device resistance with temperature at equilibrium ($T_e = T$) for both samples. The extrinsic scattering, R_{ex} estimated from eq.6 is also shown. As seen, for both samples, R_{ex} varies as as -T^2 and the data from both samples suggest that relative change in R_{ex} with temperature $\delta R_{ex}/R_{ex}$ is approximately $\propto -(k_BT/E_F)^2$ (E_F is the Fermi energy). This dependence is consistent with other measurements [8] and is explained by a decrease in impurity scattering as a result of thermal smearing of the Fermi surface [8,9]. It is of note that for both samples, the temperature dependence of the resistance is dominated by phonon scattering as expected in these high mobility samples. Finally using these results, it is possible to use the resistance of the device to measure the electron temperature and hence the energy loss rate of the 2D carriers by phonon emission. The method and results will be presented and discussed elsewhere [10].

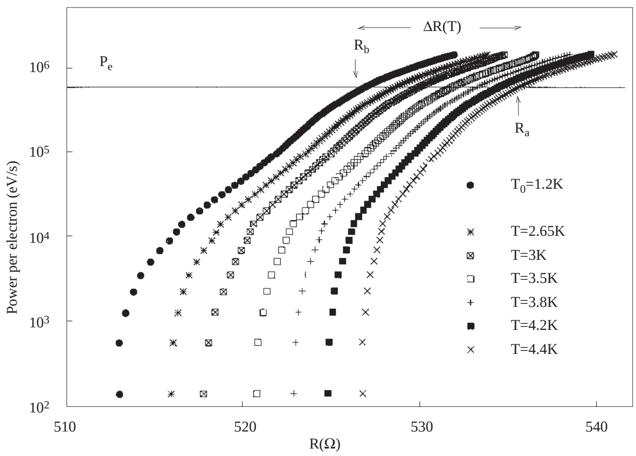


Figure 1. The power per electron P vs the resistance of the device R at the minimum lattice temperature T_0=1.2K but also at higher temperatures T for sample A. R_b is measured for $P = P_e$ and T_0. For each lattice temperature T, ΔR(T)=$R_a - R_b$, where R_a is measured at the same power P_e but at T.

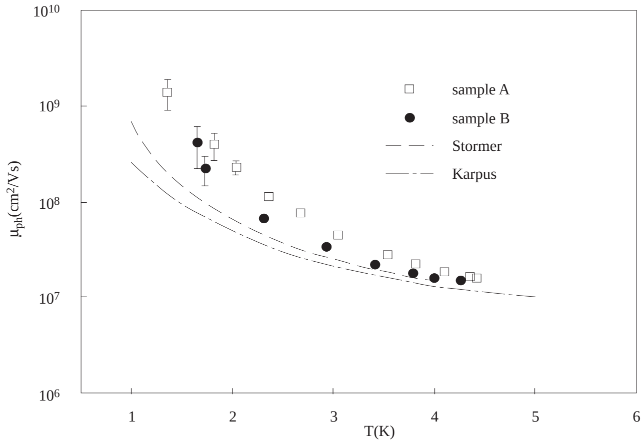
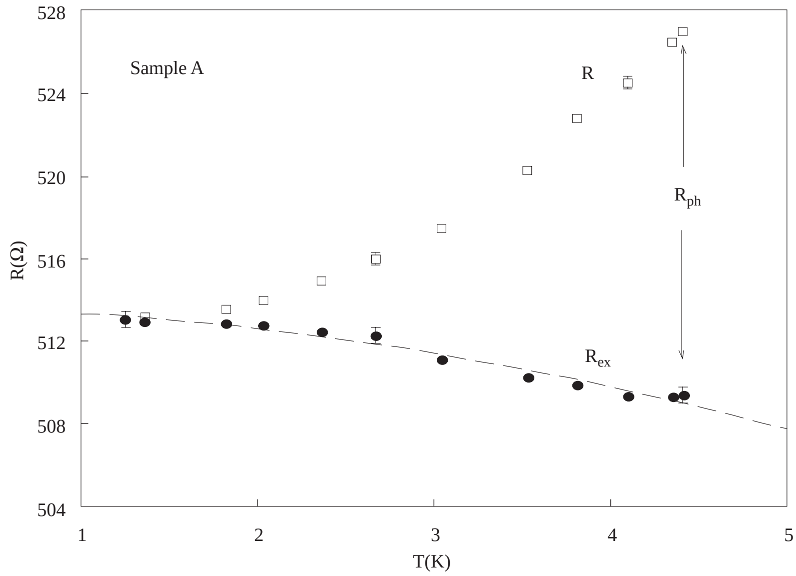


Figure 2. The temperature dependence of the phonon limited mobility μ_{ph} for samples A and B. Also shown are the theoretical calculations by Karpus for a density n_s=2×10^{11} cm^{-2} and measurements by Stormer *et al* on a sample with n_s=2.2×10^{11} cm^{-2}.



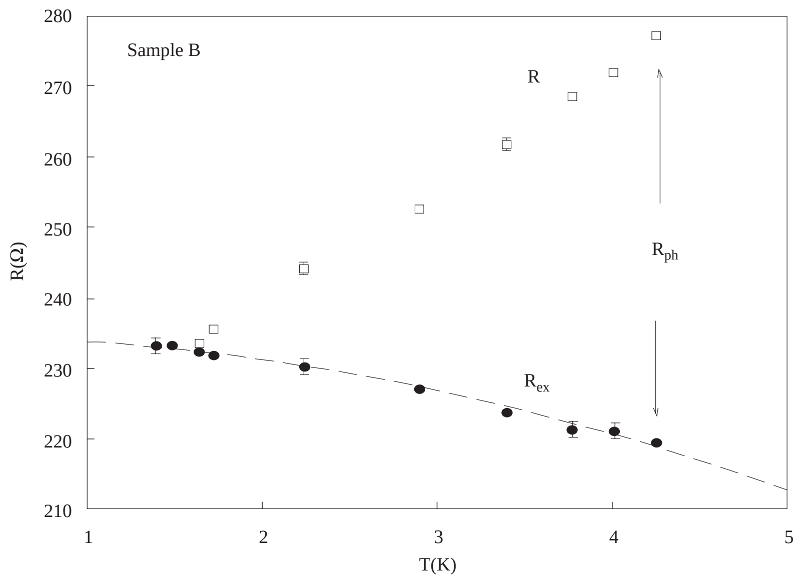


Figure 3. The variation of the device resistance R and the resistance component due to extrinsic scattering R_{ex} with temperature for both samples (A and B). The dashed line indicates a $-T^2$ dependence both for A and B.

5. Summary

In summary, we have proposed a new method to separate phonon scattering and extrinsic scattering in 2D and which allows each to be obtained as a function of temperature. The technique has been applied to a 2D electron gas in GaAs in the temperature range 1.2-4.5K and preliminary measurements of the phonon limited mobility μ_{ph} agree reasonably well with other experimental and theoretical works. In addition, the temperature dependence of the extrinsic scattering is also consistent with other measurements and theory. Further work is in progress to improve the accuracy of the measurements and to extend them to 2D electron gases with lower mobilities. It is also planned to make measurements on hole gases.

We would like to thank L.J. Challis for valuable discussions, M. Henini and C.T. Foxon for supplying the devices and finally A.J. Kent and S.A. Cavill for their help with the experimental set up.

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