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LETTER TO THE EDITOR

Magnetophonon resonance effects in the phonon emission by a hot two-dimensional electron gas in a GaAs–AlGaAs heterojunction

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Abstract. The dominant energy relaxation process for hot electrons ($T_e > 50$ K) in GaAs–AlGaAs heterojunctions is generally believed to be through the emission of optical phonons. In magnetic fields satisfying the condition $nh\omega_c = h\omega_{LO}$ the energy relaxation rate is expected to be enhanced by magnetophonon resonance. We have heated the two-dimensional electron gas (2DEG) in a single GaAs–AlGaAs heterojunction by applying pulsed electric fields in the region of 10^4 V m^{-1} across the conducting channel. The optical phonons emitted rapidly decay into acoustic modes which we observe using CdS bolometers. Peaks in the amplitude of the detected phonon pulse as a function of magnetic field are observed which we attribute to magnetophonon resonant emission. The positions of the peaks are consistent with the LO phonon frequency in bulk GaAs.

Magnetophonon resonance is the resonant absorption or emission of optical phonons by electrons which occurs when the energy separation between two Landau levels equals the phonon energy.

$$nh\omega_c = h\omega_{LO}.$$

The cyclotron frequency $\omega_c = eB/m^*$, where m^* is the effective electron mass, and ω_{LO} is usually the LO phonon frequency. The resonant phonon emission or absorption leads to changes in the electron mobility and a corresponding oscillatory dependence of the device conductivity on applied magnetic field with period $1/B$. These conductivity changes have provided the exclusive means of studying magnetophonon resonance which was first predicted by Gurevich and Firsov (1961).

The first reported observations of magnetophonon resonance in two-dimensional electronic systems formed in a GaAs–AlGaAs heterojunction were made by Tsui *et al* (1980) who observed periodic variations in ρ_{xx} of amplitude $\Delta\rho_{xx}/\rho_0 \simeq 0.7\%$. The periodicity was consistent with scattering by bulk LO phonons but suggested that the electronic effective mass was somewhat larger than the band edge value of $0.665\, m_e$. This initial work was followed by a number of experimental and theoretical studies (Brummell *et al* 1988, Warmenbol *et al* 1988 (and references therein)). The mass enhancement being attributed to a combination of band non-parabolicity and to polaron effects. More recently it has been suggested that TO phonon scattering is also contributing and producing a small shift in the position of the resonance (Brummell *et al* 1988).

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The changes in resistivity produced by magnetophonon resonance are small, rarely exceeding 1% amplitude, much larger effects might be expected in the energy relaxation rate of hot electrons in these systems. This has recently been pointed out by Warmenbol *et al* (1988) who predict increases at resonance of up to two orders of magnitude. Experiments have been carried out by Chin *et al* (1984) to investigate the energy relaxation of hot electrons in zero magnetic field. They used heat pulse techniques to observe directly the phonons emitted by the hot electrons and found evidence of acoustic phonon emission at low pulse powers. It was not possible for them to observe directly the optical phonons emitted at higher pulse powers because the LO phonon lifetime in GaAs is too short, but a broad signal was seen and attributed to decay products from the optical phonons. It is believed that optical phonons in GaAs decay rapidly (approximately 10^{-11} s) into zone boundary LA phonons which on a timescale of tens of nanoseconds undergo further anharmonic decay to zone boundary TA modes (Ulbrich 1985). Three phonon decay processes are forbidden for the TA modes, it is likely that some propagate dispersively across the sample to reach the detector (Ulbrich *et al* 1980) and some mode convert at isotope scattering centres the products eventually reaching the detector. The arrival of the phonons is thus spread over a relatively long time giving the characteristic broad heat pulse signal.

In the present work we have investigated the phonon emission in quantising magnetic fields ($B < 7$ T). The experimental arrangement used is shown in figure 1. The GaAs–$Al_xGa_{1-x}As$ heterostructure was grown by MBE on a 5 mm thick SI GaAs wafer. The 2DEG had a sheet concentration of 9.3×10^{15} m^{-2} and a 4.2 K mobility of 10^2 m^2 V^{-1} s^{-1}. A 1 mm $\times$ 1 mm conducting channel was defined by etching and ohmic contacts formed by alloying tin. After fabrication of the device the sample was polished down to 3 mm thick to remove any traces of indium that may have diffused into the back of the wafer during growth and to shorten the phonon propagation distance. The bolometer was fabricated from CdS on the wafer opposite the device, this type of bolometer can be used in fields of up to 11 T or more (Ishiguro and Morita 1974). The sample was maintained at a temperature of 2 K in a flow of helium gas, electrical pulses of 100 ns duration and 10 V amplitude were applied across the contacts. The bolometer signal was pre-amplified and fed to a signal averaging system based on a digital storage oscilloscope. Figure 2 shows typical bolometer signals obtained at two different values of magnetic field. The signals have similar characteristics to the slow pulses seen in zero field by Chin *et al* (1984).

In figure 3 we show the variation of the maximum amplitude of the signal with magnetic field up to 7 T. The peaks near 5.4 T and 4.5 T are in approximately the same position as magnetophonon resonance peaks in the resistivity of similar samples (Brummell *et al* 1987). They are superimposed on a monotonically decreasing signal amplitude which is due to the reduction in input power caused by the increasing magnetoresistance of the device. We also measured the device conductivity as a function of field with 10 V across the channel to check that the peaks were not simply due to changes in the input power caused by conductivity oscillations. Only very weak (<1% amplitude) Shubnikov–de Haas oscillations were detected certainly not large enough to account for the size of the peaks in the signal amplitude. We therefore attribute these peaks to enhanced phonon emission due to magnetophonon resonance. We were unable to detect magnetophonon conductivity oscillations to compare directly with the phonon data, these are normally much smaller in amplitude than the Shubnikov–de Haas oscillations and specialised techniques are required to extract them from the background.

Further evidence for an enhancement of the energy loss rate by resonant phonon

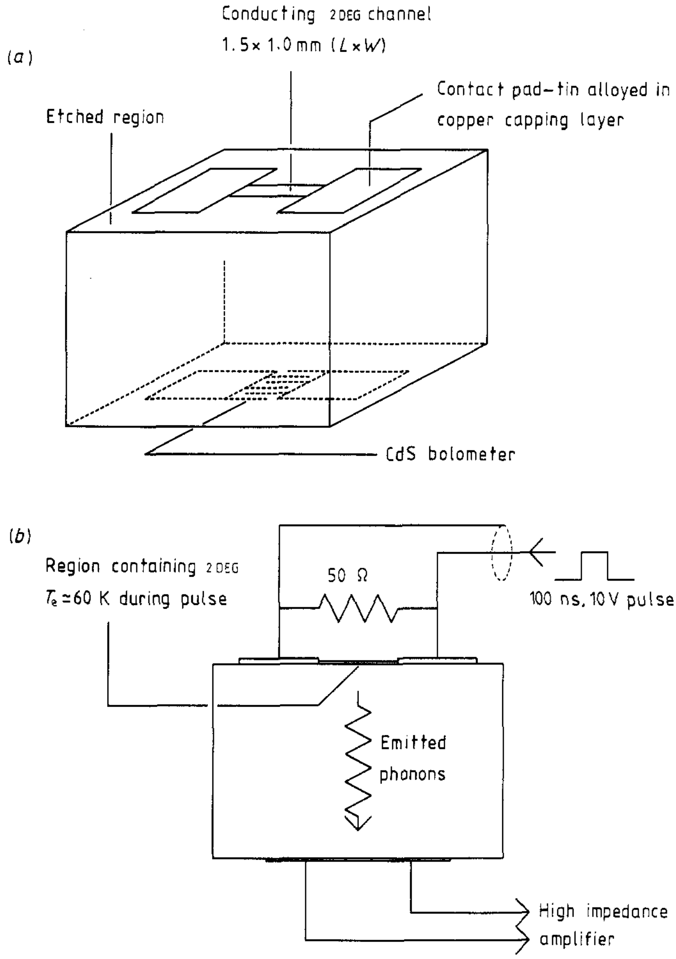

Figure 1. Experimental arrangement, showing (*a*) the sample geometry and (*b*) the electrical connections.

emission is observed in the time traces in figure 2. The trace taken on resonance at 5.4 T has a noticeably shorter rise time than that taken off resonance at 6.3 T, indicating that relatively more phonon energy is reaching the bolometer at shorter times when the resonance condition is satisfied. This is consistent with an increase in the hot-electron energy relaxation rate. Figure 4 was obtained by integrating over the leading edge of the time traces. The magnetophonon resonances are clearly enhanced in this plot. Warmenbol *et al* (1988) calculated values of the off-resonance energy loss rate in the region of 10^{-11} W/electron. In our case there are about 10^{10} electrons in the device and the peak electrical input power is about 50 mW during the 100 ns pulse. This implies overall energy relaxation times of the order 50 ns, much less than the width of the signal peak. Furthermore the signal does not narrow appreciably when the resonance condition is satisfied, suggesting that the length of the signal is primarily due to bottlenecks in the phonon down-conversion processes.

The positions of the magnetophonon peaks imply a fundamental field of

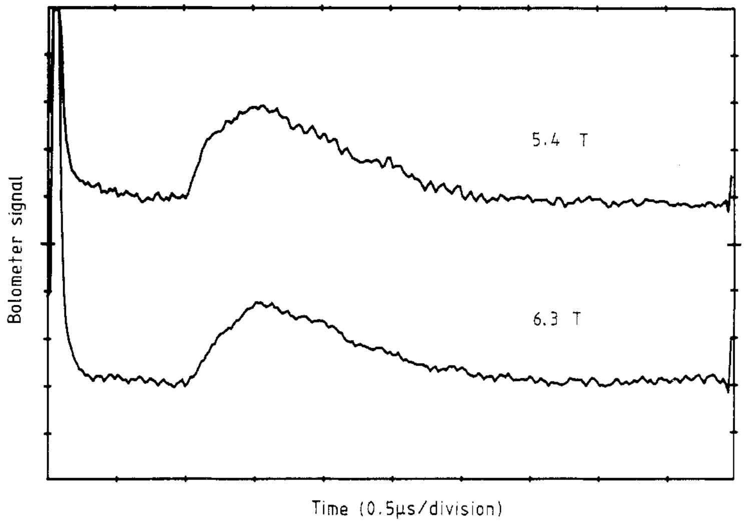

Figure 2. Bolometer signals at two values of magnetic field, these signals were obtained after averaging over 5000 traces. The large peak at the start of the trace is due to electrical pickup of the excitation pulse.

(21.6 ± 0.4) T, assuming that the electrons couple to the bulk GaAs LO phonon with frequency 296.4 cm^{-1} this implies an effective electron mass of $0.068 \pm 0.001 m_e$, slightly above the band-edge mass of $0.0665 m_e$. Theoretical calculations of the effects of screening on the polaron effective mass (Das Sarma and Mason 1985) predict that for the sheet concentration in our sample the polaron correction is less than 0.04%. This is less than our experimental error, suggesting that the mass enhancement might be almost entirely

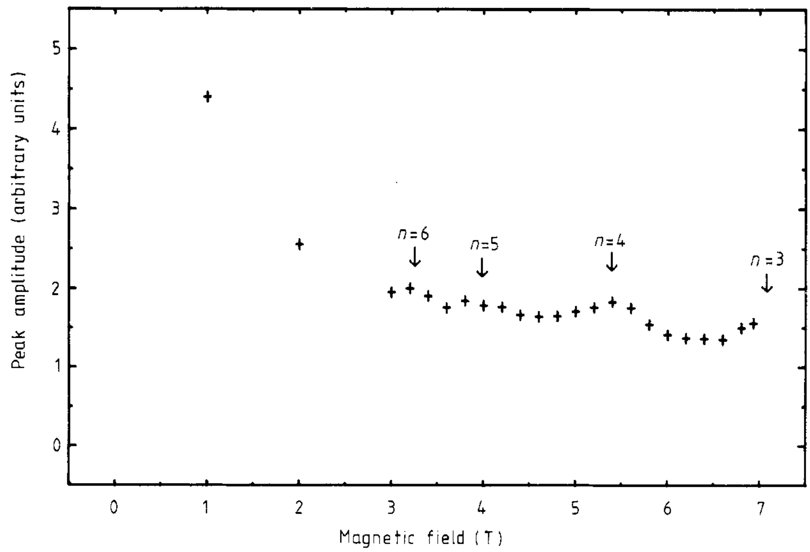

Figure 3. Variation of the maximum signal height as a function of the magnetic field.

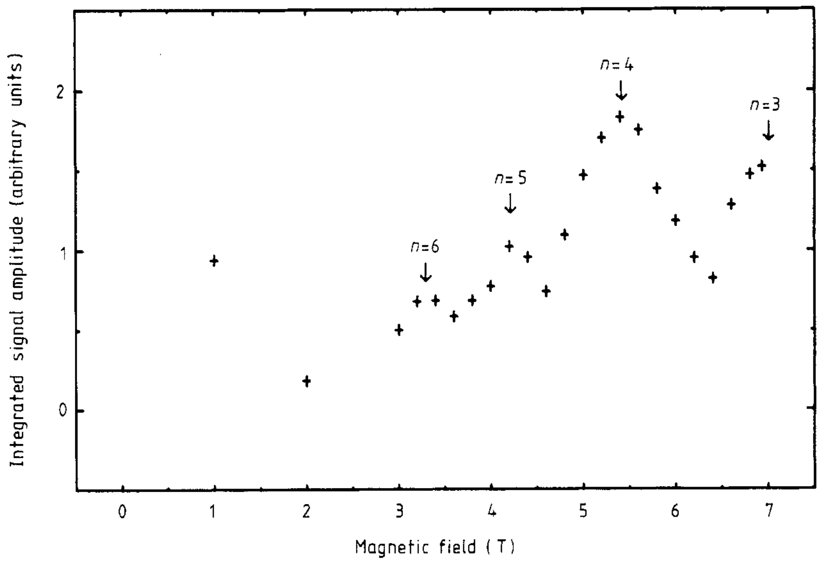

Figure 4. Phonon signal integrated over its leading edge as a function of magnetic field. The order of the resonance peak is indicated.

due to band non-parabolicity. However, Brummel *et al* (1988) calculate a much larger polaron contribution to m_e of 1.2% compared to a non-parabolicity correction of 2% in similar systems.

So in conclusion, observation of the phonons emitted by a heated 2DEG in GaAs–AlGaAs heterojunctions in a magnetic field shows more directly the resonant magnetophonon enhancement of the electron energy relaxation rate. The oscillations of up to 10% in amplitude are much stronger than those seen in the magnetoresistance typically 1%. This is consistent with theoretical results which predict changes in the energy relaxation rate by up to two orders of magnitude in these systems. From the resonance positions we deduce an effective electron mass of $0.068 \pm 0.001 m_e$ but are unable to reach any conclusion as to the relative contributions of resonant polaron and non-parabolicity effects to the mass enhancement. Further experiments are being planned to answer this question.

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