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THE INTERACTION BETWEEN ACOUSTIC PHONONS AND ELECTRONS IN A 2-DIMENSIONAL ELECTRON GAS[1)]

RAMPTON, V. W.,[2)] NEWTON, M. I.,[2)] CARTER, P. J. A.,[2)] HENINI, M.,[2)] HUGHES, O. H.,[2)] HEATH, M.,[2)] DAVIES M.,[2)] CHALLIS, L. J.,[2)] KENT, A. J.,[2)] Nottingham

Experiments have been made using surface acoustic waves (SAW) at 200 MHz and bulk longitudinal ultrasonic waves at 9.36 GHz to study the electron-phonon interaction in a 2-dimensional electron gas (2-DEG) at a GaAs/AlGaAs heterojunction. The bulk waves were incident either normally or at 35° to the 2-DEG. Quantum oscillations are found in the SAW attenuation as a magnetic field is applied and follows the Shubnikov—de Haas oscillations in conductivity. Three magnetic field dependent attenuation phenomena are found with 9.36 GHz bulk waves. A relaxation attenuation because of a strain dependent effective mass occurs for both angles of incidence. Quantum oscillations at the same period as the Shubnikov—de Haas oscillations and a magnetoacoustic geometrical resonance for which the electron orbit diameter matches the component of ultrasonic wavelength in the plane of the 2-DEG occur when the angle of incidence is 35°.

I. INTRODUCTION

The availability of MBE grown semiconductor layers has stimulated interest in the 2-dimensional electron gas (2-DEG). This shows interesting new properties and there are many new device possibilities. The electron-phonon interaction is of considerable importance in devices which may be produced from MBE material. The electron-phonon interaction is likely to determine the electron relaxation time and thus many of the high frequency transport properties.

Studies of the interaction between surface acoustic waves at 70 MHz and the 2-DEG at a GaAs/AlGaAs heterojunction have been made by Wixforth et al. [1]. They found that the SAW attenuation oscillated as a magnetic field was applied to the 2-DEG and the oscillations had the same period as the Shubnikov—de Haas oscillations; the results could be interpreted in terms of a piezo-

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[2)] Department of Physics, University of Nottingham University Park, NOTTINGHAM NG7 2RD, U.K.

electric electron-phonon coupling and the measured electrical conductivity of the 2-DEG.

The electron-phonon interaction in a 2-DEG has also been investigated using heat pulses [2, 3] and also by observing the phonons emitted by the 2-DEG when a surcedrain current flows in a HEMT device [4, 5].

We have investigated the electron-phonon interaction in a GaAs/AlGaAs heterostructures using ultrasonic waves and surface acoustic waves. Bulk longitudinal utrasonic waves at 9.36 GHz were used and surface acoustic waves at 200 MHz.

II. EXPERIMENTS

GaAs/AlGaAs heterostructures have been grown by MBE on semi-insulating GaAs wafers. Standard wafers of 0.45 mm thickness were used for the experiments using surface acoustic waves but wafers 5 mm thick were used for the experiments with bulk ultrasonic waves. Layers of GaAs and AlGaAs were grown on the (100) faces of the wafers to produce a heterojunction at which the 2-dimensional electron gas (2-DEG) would form just below the surface of the wafer. The set of layers grown is shown in figure 1; similar layers to this have given an electron mobility of about 15 $m^2 V^{-1} s^{-1}$ and had carrier concentrations of about 4.5×10^{15} m^{-2}.

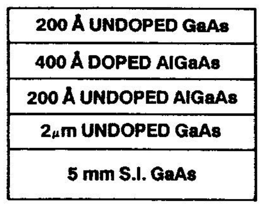

Fig. 1. MBE grown layer structure.

II.1. Surface acoustic waves

A device with source and drain electrodes but no gate was formed on the surface of the wafer and the surroundings etched back to the semi-insulating substrate. Surface acoustic wave transducers were formed on the surface of the substrate on either side of the device to generate waves at 200 MHz. The propagation direction was [110] and the path length between transmitter and

receiver was 10 mm. The experimental arrangement is shown in figure 2. The transducers were excited with rf pulses at 200 MHz and pulse length 500 nsec. The transmitted pulses were amplified and detected and examined with a box-car circuit which was used to improve the signal to noise ratio. The samples were in a vacuum can in a bath of liquid He at 4.2 K. A magnetic field up to 5 T could be applied normal to the surface of the wafer.

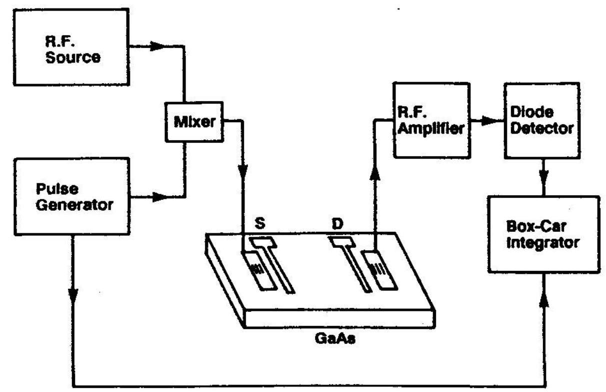

Fig. 2. Block diagram of the apparatus for surface acoustic wave experiments. The sample was cut from a wafer of GaAs 0.450 mm thick.

II.2. Bulk ultrasonic waves

The samples for experiments with bulk ultrasonic waves were 5 mm thick. Two samples were prepared; one for propagation along the [100] direction normal to the 2-DEG and the second for propagation along the [111] direction at an angle of 35.3° to the 2-DEG. Quartz rod transducers 3 mm in diameter were used to generate the ultrasound. The quartz rod was cemented to the back face of the first sample using epoxy; the second sample had the quartz rod cemented to a face cut at the appropriate angle on the wafer. Figure 3 shows the two samples and a block diagram of the apparatus. The end of the quartz rod was placed into a resonant cavity which was excited with microwaves from a 100 W pulsed magnetron. Longitudinal ultrasonic waves at 9.36 GHz were generated in pulses of length 500 nsec. The ultrasonic pulses were detected using a CdS bolometer (see [6]) on top of the wafer after the waves had travelled through the 2-DEG. The box-car circuit was used to improve the signal to noise ratio. A magnetic field up to 2 T could be applied to the sample and could be rotated to make any angle with the 2-DEG. The resonant cavity and sample were in a pumped bath of liquid He at about 2 K.

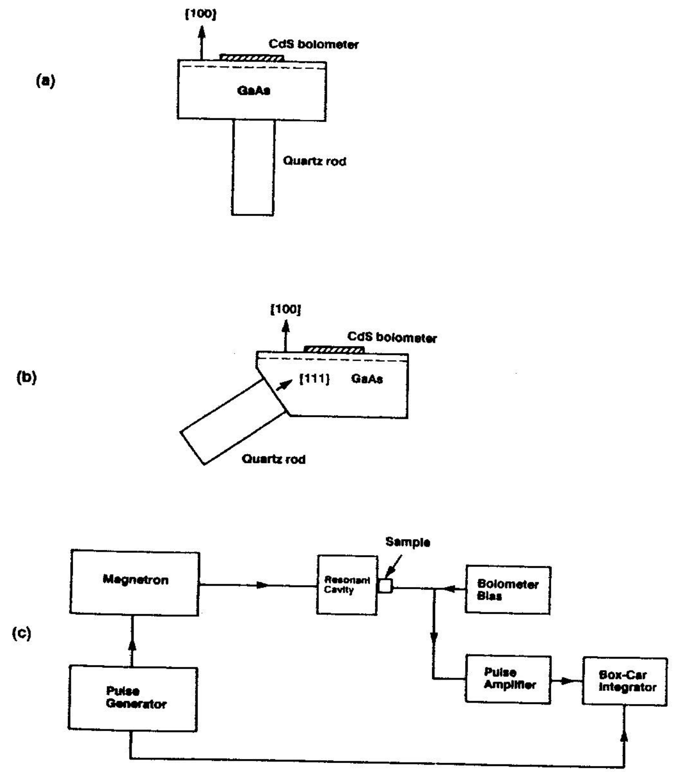

Fig. 3. (a) Sample for 9.36 GHz bulk ultrasonic wave experiment with ultrasound incidence normally on the 2-DEG. (b) Sample for 9.36 GHz bulk ultrasonic wave experiment with ultrasound incident at an angle to the 2-DEG. (c) Block diagram of the bulk ultrasonic wave apparatus.

III. RESULTS

III.1. Surface Acoustic Waves

The results obtained using surface acoustic waves at 200 MHz are shown in figure 4. We also show the source-drain conductance of the 2-DEG device. There are oscillations in the transmitted SAW amplitude which follow the oscillations in the conductance.

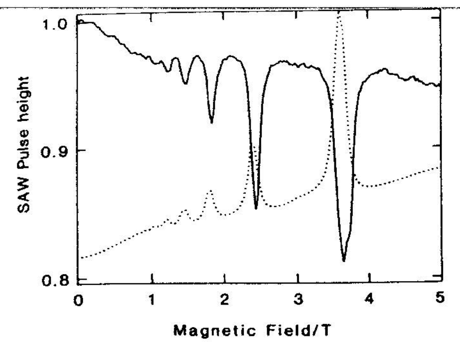

Fig. 4. Results of the SAW experiments. The solid line shows the height of the transmitted SAW pulse as a function of applied magnetic field; the dotted line shows the source-drain conductance of the device. The frequency was 200 MHz, the temperature 4.2 K and the magnetic field was normal to the surface of the sample.

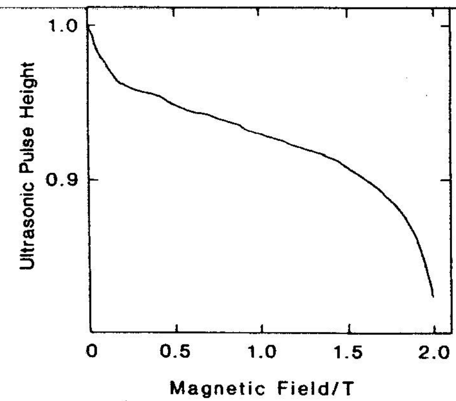

Fig. 5. Results of the bulk ultrasonic wave experiment. The detected ultrasonic pulse height is shown as a function of applied magnetic field when the angle between the ultrasound and the 2-DEG was 90°. The temperature was 2 K and the magnetic field was normal to the surface of the sample.

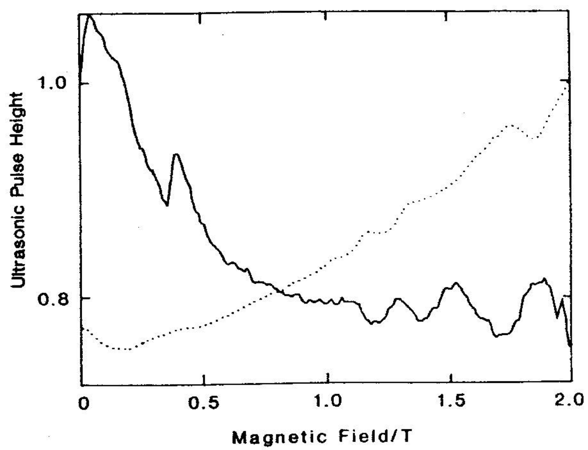

Fig. 6. Results of the bulk ultrasonic wave experiment. The solid line shows the detected ultrasonic pulse height as a function of applied magnetic field when the angle between the ultrasound and the 2-DEG was 35°. The dotted line shows the source-drain conductance of the device. The temperature was 2 K and the magnetic field was normal to the surface of the sample.

III.2. Bulk ultrasonic waves

The results obtained using 9.36 GHz longitudinal bulk waves are shown in figures 5 and 6 for the two orientations and with the magnetic field normal to the 2-DEG. The results are different for the two cases. When the phonons are incident normally on the 2-DEG the attenuation increases as the magnetic field increases and no oscillations are found at least up to 2 T, the limit of the magnetic field we could use in the bulk wave experiments. When the ultrasonic waves are incident along the [111] direction — that is making an angle of 35° with the 2-DEG — then we find oscillations in the attenuation as the magnetic field is varied. These oscillations have the same period as the Shubnikov—de Haas oscillations in the source-drain resistance of the device. In addition, when the ultrasonic waves are incident along the [111] direction and there is a component of the ultrasonic wave vector in the plane of the 2-DEG, an extra minimum in the detected ultrasonic pulse height appears at 0.36 T. When the angle between the magnetic field and the 2-DEG was changed, the results were consistent with all the observed effects depending on the component of field normal to the 2-DEG.

IV. DISCUSSION

When a magnetic field is applied to a 2-DEG, the electronic states split up into Landau levels. Thus the density of states at the Fermi level depends on whether the Fermi energy coincides with a Landau level or is between the Landau levels. The density of states at the Fermi level oscillates at the applied magnetic field is increased and any phenomenon, such as source — drain resistance, which depends on the density of states at the Fermi surface oscillates as the magnetic field is increased.

IV.1. Surface acoustic waves

The results of the SAW experiments follow those of Wixforth et al. [1] obtained at the lower frequency of 70 MHz. We find an attenuation which follows the Shubnikov—de Haas oscillations in conductance. Our measurements of conductance are only two terminal measurements so we are not able to derive the longitudinal and transverse conductivities of the 2-DEG. The frequency is too low to give a wavelength short enough to show effects dependent on electron orbit size.

IV.2. Bulk ultrasonic waves

There are at least three effects that we observe in these experiments. Firstly, we find an increase in ultrasonic attenuation as the magnetic field is increased for both directions of propagation, secondly we find oscillations in the magnitude of the attenuation for incidence at an angle and thirdly we find an increased attenuation at 0.36 T also when the ultrasonic waves reach the 2-DEG at non-normal incidence.

Let us consider the first of these which appears for both angles of incidence. We suggest that is a relaxation type of attenuation. The effective mass of the 2-DEG electrons is a function of compressional strains and the spacing of the Landau levels fluctuates as the longitudinal ultrasonic wave passes through. If the relaxation time for the restoration of thermal equilibrium between the Landau levels is comparable to the period of the ultrasonic wave, then a strong attenuation is to be expected. As the magnetic field is increased then the mean separation of the Landau levels increases and the relaxation time due to coupling to the thermal phonons will change. Hence a magnetic field dependent attenuation of ultrasound is expected as we find in our experiments.

The second phenomenon, the quantum oscillations in ultrasonic attenuation observed at magnetic fields above 1 T and coinciding with the Shubnikov—de Haas oscillations, can be explained as follows. When the longitudinal ultrasonic waves are travelling along the [111] direction, there is a component of shear strain present when refferred to the fourfold $\langle 100 \rangle$ axes. These strains in GaAs are piezoelectrically coupled to the electric field whereas a longitudinal ultrasonic wave along the [100] direction, having only compressional strains with respect to the $\langle 100 \rangle$ axes, is not coupled to the electric field. A longitudinal ultrasonic wave along [111] produces a component of electric field in the plane of the 2-DEG. Thus the ultrasonic attenuation is a function of the sheet conductivity of the 2-DEG for propagation of the ultrasound along the [111] direction and the attenuation follows the Shubnikov—de Haas oscillations.

The third phenomenon we have observed is the attenuation maximum at 0.36 T when the ultrasonic waves are incident at 35° to the 2-DEG. We believe this is the magnetoacoustic geometric resonance [7]. The distance, measured along [110], between the wavefronts of a longitudinal ultrasonic wave at 9.36 GHz, travelling along [111], in GaAs is 70 μm. If we fit this to the diameter of a circular electronic orbit at the Fermi surface, we find a Fermi wave vector of $1.9 \times 10^{8}\ m^{-1}$. We note however that the theory of Pippard [8] for a three-dimensional metal shows that in that case there is a phase factor and the maximum ultrasonic attention occurs when the circular electron orbit diameter is 1.25 times the wavelength. There are only a few Shubnikov—de Haas oscillations visible (figure 6, dotted line) but they enable an estimate to be made of the electron concentration as 3.7×10^{15} m^{-2}. This implies a Fermi wave vector for the electrons of 1.5×10^{8} m^{-1}. The agreement between the two values for the Fermi wave vector is not close but is sufficiently near to suggest that the interpretation of the results is correct. The assumption of a precisely circular orbit may not be justified; a circular electron orbit would be expected in GaAs where the conduction band minimum is at the zone centre and the 2-DEG is normal to a four-fold improper symmetry axis. A sample with higher mobility in which geometric resonances could be observed at lower magnetic fields and with more than one ultrasonic wavelength per electron orbit would enable the phase factor to be determined and hence give an unambiguous value for the orbit dimension. A full theory of the electron-phonon interaction in a 2-DEG is needed to completely account for the experimental results.

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ВЗАИМОДЕЙСТВИЕ ФОНОНОВ С ЭЛЕКТРОНАМИ В ДВУХМЕРНОМ ЭЛЕКТРОННОМ ГАЗЕ

Были произведены эксперименты с использованием поверхностных акустических волн (ПАВ) на частоте 200 MHz с целью изучить электрон-фононное взаимодействие в 2-мерном электронном газе (2-МЭГ) в гетеропереходах GaAs/AlGaAs. Объемные волны были падающими либо ортогонально, либо под углом 35° к 2-МЭГ. Были найдены квантовые осцилляции в затухании ПАВ под воздействием магнитного поля, которые следуют осцилляциям Шубникова—де Хааса в проводимости. Три явления затухания в зависимости от магнитного поля были найдены для 9.36 GHz объемных волн. Релаксационное затухание, обусловленное эффективной массой, зависимой от деформации, появляется для обоих углов надения. Показано, что появляются квантовые осцилляции на том же периоде, что и осцилляции Шубникова—де Хааса, если угол надения равен 35°.