Magnetophonon resonance in high-density high-mobility quantum well systems

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We have investigated the magnetophonon resonance (MPR) effect in a series of single GaAs quantum well samples which are symmetrically modulation doped in the adjacent short period AlAs/GaAs superlattices. Two distinct MPR series are observed originating from the Γ and X electrons interacting with the GaAs and AlAs longitudinal optic (LO) phonons respectively. This confirms unequivocally the presence of X electrons in the AlAs quantum well of the superlattice previously invoked to explain the high electron mobility in these structures [Friedland *et al.*, Phys. Rev. Lett **77**, 4616 (1996)]

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Ultrahigh conductivity ($\sigma = ne\mu$) two-dimensional electron gas (2DEG) systems have important applications in low-noise, high-frequency devices. Increasing the doping level, in order to increase the carrier density (n_s), often reduces σ, due to the significant decrease in mobility (μ) which is a direct result of the increased scattering from the remote ionized donors. For modulation doped two-dimensional (2D) structures based on the GaAs/AlAs system, the use of short period superlattices for the incorporation of the remote doping layer has been shown to lead to significant enhancement of the mobility for high density ($\sim 1\times 10^{12}$ cm^{-2}) 2DEG samples.[1] The achieved mobilities, up to $\sim 3 \times 10^6$ cm^2 V^{-1} s^{-1}, have been attributed to a screening of the Coulomb potential of the remote dopants by localized X electrons in the AlAs quantum well adjacent to each Si δ-doped GaAs layer in the short period superlattice. This hypothesis was based on self consistent calculation of the space charge distribution in the structure and capacitance-voltage measurements which indicated the presence of carriers outside the center GaAs quantum well and near to the Si δ-doping region.

The expected Bohr radius of the X electrons ($a_B \approx 2$–3 nm), together with the nominal distance of 1.7 nm from the δ-doped layer means that the X electrons can efficiently screen the ionized Si donors atoms whose average separation is ≈ 8–9 nm. The X electrons are effectively localized at low temperatures ($T \leqslant 10$–20 K) and do not contribute to transport (the absence of parallel conduction). However, at higher temperature, the X electrons should become delocalized. An unmistakable signature of a contribution of the X electrons to transport would be the observation of a magnetophonon resonance (MPR) in the electrical transport properties. This resonant scattering with longitudinal optic (LO) phonons in the presence of an applied magnetic field is well known in both bulk[2,3] and 2D semiconductors.[4–6]

The main result presented in this work is the observation of two distinct MPR series in our samples, which, due to the very different effective masses and phonon energies, we can identify with Γ and X electrons in the GaAs and AlAs quantum wells, respectively. The observation of the AlAs MPR clearly validates the important role played by X electrons in screening the long range potential of the remote ionized Si donors.

The four different structures investigated here were grown by solid source molecular beam epitaxy on semi-insulating (001) GaAs substrates. The barriers consist of two short period superlattices each with 60 periods of 4 ML of AlAs and 8 ML of GaAs. Carriers are introduced into the central 10–13 nm GaAs quantum well by a single Si δ-doping sheet with a concentration of 2.5×10^{12} cm^{-2} placed in a GaAs layer of each short period superlattice. Full details of the growth protocol are available elsewhere.[1] The sample properties are summarized in Table I. Hall bars were fabricated using conventional photolithography and chemical wet etching. Ohmic contacts were formed by evaporating AuGeNi followed by an anneal at 450 °C.

For the magnetotransport measurements the samples were placed on a rotation stage in a variable temperature cryostat installed on a water cooled, 28-T, 20-MW dc magnet. Transport measurements were performed using conventional phase sensitive detection at 10.66 Hz with a current of 1–5 μA. For the very high-field measurements a 60-T pulsed magnet

TABLE I. Electron density n_s and mobility μ measured at $T = 300$ mK for different samples with quantum wells of width L_{QW} at a distance d_δ from the remote δ-doping layers.

Sample	n_s (cm^{-2})	μ (cm^2/V s)	L_{QW} (nm)	d_δ (nm)
1038	1.28×10^{12}	1.14×10^6	10	14
1201	9.4×10^{11}	2.80×10^6	13	22
1200	7.4×10^{11}	2.20×10^6	13	30
1416	6.4×10^{11}	2.18×10^6	13	34

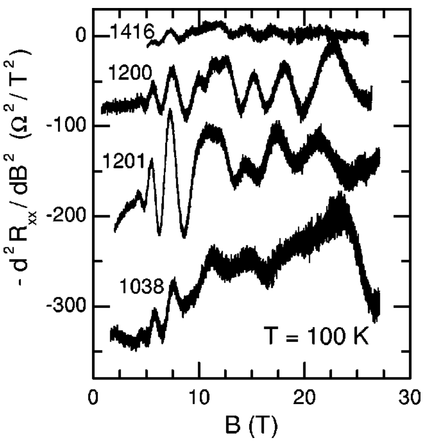

FIG. 1. Second derivative of the longitudinal resistance vs magnetic field measured at $\theta = 0$ and $T = 100$ K for the four samples investigated. Curves have been shifted vertically for clarity

was used with conventional dc detection ($I = 100$ μA) and a low-pass preamplifier to limit the transient component of the signal induced by the magnetic field pulse. In both cases the longitudinal sample resistance R_{xx} and Hall resistance R_{xy} were simultaneously measured as a function of magnetic field (B). The tilt angle of the sample with respect to the applied magnetic field can be precisely determined from R_{xy} which depends only on the perpendicular magnetic field ($B_{\perp}$).

The application of a magnetic field quantizes the electron motion and to a first approximation resonant absorption of an LO phonon can occur whenever

$$\hbar \omega_{LO} = N \hbar \omega_c = N \hbar e B_{\perp} / m^*,$$

where $N = 1,2,3 \ldots, \hbar \omega_{LO}$ is the LO phonon energy and m^* is the electron effective mass. The changed scattering rate at resonance gives rise to oscillations in the resistance[4,5] which are periodic in $1/B_{\perp}$. The optimum temperature for observing MPR oscillations is a compromise between having the lowest temperature possible in order to reduce Landau level broadening and having the highest temperature possible in order to have a large thermal phonon population. Even under optimum conditions MPR oscillations are weak[7] with a typical amplitude $\delta R/R \sim 1\%$.

In order to extract the weak MPR oscillation from the monotonically increasing background magnetoresistance we have numerically calculated the second derivative d^2R_{xx}/dB^2. Results for the four samples measured at $T = 100$ K (the optimum temperature for our samples) and with the magnetic field applied perpendicular to the layers ($\theta = 0$) are shown in Fig. 1. All samples show more or less pronounced MPR oscillations with two distinct series. A low magnetic field series corresponding to the scattering of the Γ electrons in the center quantum well with GaAs LO phonons and a second series which develops at higher magnetic fields ($B \gtrsim 10$ T) which we identify with the scattering of X electrons with AlAs LO phonons in the AlAs layer next to each Si δ doping in the short period superlattice. The fundamental magnetic field (corresponding to $N = 1$) for each series of

TABLE II. Fundamental magnetic fields for the MPR oscillations in Fig. 1. The phonon energies have been calculated assuming $m^*/m_e = 0.072$ for the Γ electrons in GaAs and $m^*/m_e = 0.21$ for the light (in plane) mass X electrons in AlAs

Sample	B_F(GaAs) (T)	B_F(AlAs) (T)	$\hbar\omega_{LO}$(GaAs) (meV)	$\hbar\omega_{LO}$(AlAs) (meV)
1038	22.5 ± 0.7	-	36.7 ± 1.1	-
1201	21.1 ± 0.6	89.2 ± 1.5	34.4 ± 2.1	49.9 ± 2.3
1200	22.9 ± 0.5	88.4 ± 2.3	37.3 ± 2.0	49.4 ± 2.8
1416	23.3 ± 1.2	89.5 ± 5.5	38.0 ± 3.0	50.1 ± 5.0

oscillations can be obtained from either an analysis of the period of the oscillations in $1/B$ or from a Fourier transform of d^2R_{xx}/dB^2 versus $1/B$. Both methods give identical results within experimental error. The fundamental fields deduced for each sample (where possible) are indicated in Table II.

The AlAs series has a considerably higher fundamental magnetic field due to both the larger effective mass of the X electrons and the larger LO phonon energy of AlAs. In order to take into account non parabolicity it is necessary to use slightly heavier effective masses than the band edge values[8] for GaAs ($m^*/m_e = 0.067$) and AlAs ($m^*/m_e = 0.19$). The calculated phonon energies which are summarized in Table II have been calculated assuming a mean value of $m^*/m_e = 0.072$ for the Γ electrons in GaAs and $m^*/m_e = 0.21$ for the light mass (in plane) X electrons in AlAs. The phonon energies found are to be in good agreement with the currently accepted values for bulk GaAs [$\hbar\omega_{LO}$(GaAs) $= 36.25$ meV] and bulk AlAs [$\hbar\omega_{LO}$(AlAs) $= 50.09$ meV].[8]

In two dimensions the coupling to phonon modes is expected to be modified, with the electrons coupling to the interface (slab) modes[7] or dressed modes due to dynamic screening[9] both of which are expected to have a slightly reduced energy compared to bulk. Far infrared absorption measurements at zero magnetic field in these samples confirm that the LO phonon energies are indeed close to the bulk values.[10] A precise determination of the phonon energy, for which the effective mass should be precisely known, is not the objective of this work.

To our knowledge, MPR has never been observed in bulk AlAs. In 2D systems MPR has been reported due to scattering between quantum well Γ electrons and evanescent AlAs barrier or interface LO phonons in GaInAs/AlInAs multiquantum wells[11] or AlGaAs/GaAs superlattice structures.[12] MPR between AlAs X electrons and GaAs LO phonons has been observed[13] in 1D GaAs/AlAs quantum wires, and in GaAs/AlAs superlattice samples when the magnetic field is applied along the growth direction. We stress here that it is not possible to identify the high-field MPR series with the scattering between Γ electrons (in the quantum well) and evanescent AlAs barrier or interface LO phonons, since using the light Γ mass $m^*/m_e = 0.072$ would imply a scattering with a phonon of energy ~ 150 meV which far too large to be physically meaningful. Therefore, the observation of the

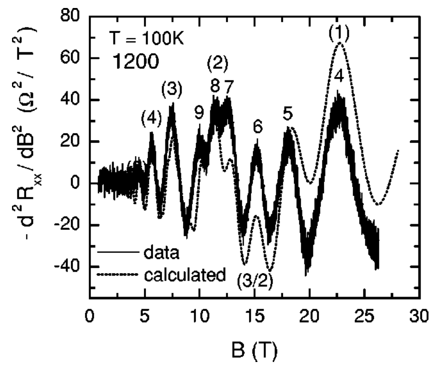

FIG. 2. Comparison of the MPR oscillations calculated using an exponentially damped cosine function and the data for sample 1200. A linear background has been subtracted from the raw data shown in Fig. 1. The minima are labeled to indicate the resonance condition for the GaAs LO phonon series, $N=1$, 2, 3, 4, and 5 (in brackets) and for the AlAs LO phonon series, $N=4$, 5, 6, 7, 8, and 9.

high-field MPR series clearly demonstrates the presence of X electrons located in the AlAs barrier which interact with AlAs LO phonons.

In bulk GaAs MPR oscillations have been described by an exponentially damped cosine series[14]

$$\Delta R_{xx}/R_{xx} \propto \cos(2\pi\omega_{LO}/\omega_c)\exp(-\gamma\omega_{LO}/\omega_c),$$

where γ is a magnetic field independent damping factor. In our case we can write

$$d^2R/dB^2 \approx -A_1\cos(2\pi\omega_{LO_1}/\omega_{c_1})\exp(-\gamma_1\omega_{LO_1}/\omega_{c_1}) - A_2\cos(2\pi\omega_{LO_2}/\omega_{c_2})\exp(-\gamma_2\omega_{LO_2}/\omega_{c_2}),$$

where the indices 1 and 2 refer to the relevant material parameters for GaAs and AlAs respectively. The predicted behavior is compared to the data for one of the samples in Fig. 2. Here we have used the phonon energies for bulk GaAs, $\hbar\omega_{LO_1}=36.25$ meV, and AlAs $\hbar\omega_{LO_2}=50.1$ meV, together with the relevant effective masses $m^*/m_e=0.072$ for the Γ electrons in GaAs and $m^*/m_e=0.21$ for the light (in plane) mass X electrons in AlAs. The only adjustable fitting parameters are then $A_1=50\ \Omega^2T^{-2}$, $A_2=100\ \Omega^2T^{-2}$, and $\gamma_1=\gamma_2=0.3$. The predicted behavior reproduces almost exactly the observed period(s) and amplitude of the oscillations except for a difference in amplitude at high magnetic field. This can be attributed to a strong damping of the $N=1$ maximum and the $N=3/2$ minimum of the GaAs series. This series is strongly damped at high magnetic fields due to self consistent corrections to the density of states.[15] This is a result of the dominance of elastic over inelastic (phonon) scattering at high magnetic fields when the Landau levels are extremely narrow. The Landau levels in the AlAs quantum well are significantly broader due to the inevitably much lower mobility associated with the proximity of Si δ-doping layer. This suggests that it is the Landau level broadening due to the presence of this short range scattering which explains the robustness of the AlAs MPR series at high magnetic field.

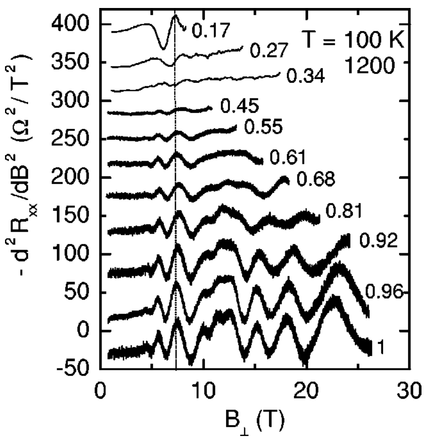

FIG. 3. Second derivative of the longitudinal resistance vs magnetic field measured at $T=100$ K and for different angles measured using static [$\cos(\theta)=0.45-1$] and pulsed [$\cos(\theta)=0.17-0.34$] magnetic fields for sample 1200. Curves have been shifted vertically for clarity. The dotted vertical line at the magnetic field corresponding to $N=3$ for the GaAs series is drawn as a guide to the eye.

In addition, rotation measurements have been performed to confirm the 2D nature of both series. Typical results for sample 1200 are shown in Fig. 3 where d^2R_{xx}/dB^2 versus the perpendicular component of the magnetic field is plotted for a number of different angles. With increasing tilt angle, for both series the peak positions do not shift with respect to $B_\perp$ as expected for 2D systems for which the cyclotron energy depends only on $B_\perp$. This is in agreement with the self-consistent calculations,[1] which state that the AlAs X electrons are localized in an AlAs quantum well and that there is no X-miniband formation in the short period superlattice. The small shift of the AlAs series to higher $B_\perp$ at large tilt angles is probably due to the anisotropic mass of the X valleys in AlAs.

For a given $B_\perp$, tilting the sample increases the in-plane component of the magnetic field ($B_\parallel$) which induces a mixing between different electrical subbands. In GaAs/AlGaAs heterojunctions this leads to a drastic reduction in the amplitude of the MPR oscillations.[16] The effect of $B_\parallel$ on the MPR oscillations is less marked in quantum well samples[11] due to the much larger energy separation of the electrical subbands. In Fig. 3 the high-field AlAs series is suppressed for tilt angles above 47 ° [$\cos(\theta)=0.68$]. The low field GaAs series survives at almost all angles and even apparently regains in amplitude at very high tilt angles [$\cos(\theta)\leq 0.17$]. It is not evident that this reemergence should be associated with MPR. At high tilt angles it is almost certainly not a good approximation to treat the system as being two dimensional since the magnetic length $\ell_B=\sqrt{\hbar/eB}$ is already significantly less than the width of the GaAs quantum well.

In conclusion, a series of high density 2DEG samples designed to reduce remote impurity scattering have been investigated using magnetophonon resonance. Two distinct MPR series are observed, one originating from Γ electrons interacting with GaAs LO phonons in the center GaAs quantum well, and one originating from X electrons interacting with AlAs LO phonons in an AlAs quantum well adjacent to the Si δ doping in the short period superlattice situated on either side of the center GaAs quantum well. This result clearly demonstrates the presence of X electrons in the AlAs quantum well which have previously[1] been invoked to explain the enhanced screening of the remote impurity potential required to explain the very high mobilities achieved in these high carrier density samples.

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