Suppression of deformation-potential electron–acoustic-phonon coupling in Si δ-doped GaAs structures

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We have used the heat-pulse technique to investigate phonon emission from two-dimensional electron gases formed in a series of molecular-beam-epitaxy- and metal-organic chemical-vapor-deposition-grown Si δ-doped GaAs structures with single subband occupation. By comparing the relative intensities of longitudinal and transverse acoustic-phonon emission over a wide range of input powers (0.01–1000 pW per electron) we suggest that deformation-potential coupling to longitudinal modes is suppressed in the acoustic regime ($T_e < 50$ K). In all samples the onset of optical-phonon emission was at input powers around 1.5 pW per electron, a value similar to that found in the heterojunction and quantum-well cases. Strong LA-mode emission is observed at all powers in contrast to previous observations in the heterojunction system.

In high-quality molecular-beam-epitaxy- (MBE) and metal-organic chemical-vapor-deposition- (MOCVD) grown modulation-doped $Al_xGa_{1-x}As/GaAs$ heterojunction and quantum-well (QW) structures, electron-phonon scattering can have a strong influence on electronic mobility down to very low temperatures. As a result, electron-phonon coupling has received considerable experimental and theoretical attention, particularly regarding the possible effects of confinement on the piezoelectric (PE) and deformation-potential (DP) coupling strengths.[1] It is generally accepted that in the heterojunction system, PE coupling to transverse-acoustic (TA) and longitudinal-acoustic (LA) phonons is dominant below $T_e \sim 1.5$ K. Above this temperature, DP coupling to LA modes takes over and for $T_e \geq 50$ K optical phonon scattering dominates. Conventionally, in such systems, the experimental approach has been with transport studies of temperature-dependent mobility. The transport approach, however, is difficult in the δ-doped case where the donor ions and two-dimensional electron gas (2DEG) are not separated and electron-ionized impurity scattering dominates the device resistance. The δ-doped system has a number of interesting differences from the heterojunction. Typically it is of considerably higher sheet carrier concentration and lower mobility. Perhaps most significantly, the electronic confinement is much weaker, that is, the effective 2DEG width is greater. An alternative experimental method is to examine the phonon emission directly using the heat-pulse/time-of-flight technique.[2] The 2DEG is briefly heated above the ambient lattice temperature and relaxation occurs by emission of phonons. With the sample held at sufficiently low temperatures these propagate ballistically across the sample and are detected by a bolometer at another crystal surface. Emission of LA and TA modes can be observed separately due to their different velocities and hence flight time to the detector. The technique has already been extensively employed in studies of the heterojunction[3] and QW (Ref. 4) systems. In the former, observation of strong TA- and negligible LA-mode emission is consistent with a dominance of PE coupling contrary to the transport data. A possible explanation of this anomaly may be connected with phonon focussing within the GaAs substrate. More recently, studies of double[5] and multiple[6] δ-doped structures have shown a number of features at high electric fields associated with real-space charge transfer of 2D electrons into higher-mobility extended bulk states. In these studies, the δ-doped layers were relatively closely spaced and interpretation of the results is complicated by interlayer tunneling. Indeed, in the multiple layer structure and in the absence of Hall and Shubnikov–de Haas data to the contrary it is not clear that the system will retain its 2D character. Here, we present a heat-pulse study of LA- and TA-mode emission from the 2DEG confined in a single Si δ-doped structure with single subband occupation. By the use of high-speed averaging techniques, we have been able to examine both modes at considerably lower input powers than has previously been possible (~ 0.01 pW per electron) in an effort to investigate the role of PE and DP coupling.

The samples were grown by MBE and MOCVD with a single δ-doped sheet of donor concentration 6×10^{11} cm^{-2} placed at the center of a nominally undoped 2000-Å GaAs layer grown on a semi-insulating 0.38-mm GaAs ⟨100⟩ substrate. A 100-Å GaAs n^+ capping layer was added to improve contacting and reduce surface depletion. A Hall bar (0.5×0.1 mm^2 $L \times W$) was defined by etching, with AuGe annealed contacts. On the opposite crystal surface, two thin-film superconducting aluminum bolometers were deposited by thermal evaporation, on and at 50° to the device normal. Shubnikov–de Haas

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measurements showed single subband occupation with sheet carrier concentration typically around 4.5×10^{11} cm^{-2}, indicating that approximately three-quarters of the donor atoms were ionized in all samples.

With the sample held at the bolometer's superconducting transition temperature, 20-ns electrical pulses of 20-mV to 60-V amplitude and 10-kHz repetition rate were applied to the device. Emitted phonons arriving at the bolometer caused a small resistance change, which could be detected as a voltage signal with a constant current applied. A high-speed averaging oscilloscope was then used to capture the phonon time-of-flight traces. As the devices were not well matched to the 50-Ω feeder cable, net input power was taken as the difference between the forward and reflected powers. In previous experiments on the heterojunction system[3] carrier temperatures were estimated by a comparison of the pulse and dc resistance values. However, this is not possible in this system as the device resistance is dominated by ionized impurity scattering and varies only weakly with temperature. In the acoustic regime, the carrier temperature varies from 1.5 to 50 K, above which optical phonon coupling is predominant. All input powers quoted are in pW per electron, calculated by dividing the total input power by the total electron concentration, allowing comparison of samples with different sheet carrier densities. Hall and Shubnikov–de Haas transport measurements were used to characterize the devices electrically.

Figure 1 shows a typical phonon time-of-flight trace for a bolometer at 50° to the device normal taken at an input power of 100 pW per electron. The LA- and TA-mode peaks are relatively broad, due to the finite size of the device and bolometer, but well resolved. (We shall restrict our discussion to the 50° bolometer results, as for the normal direction the flight time is considerably shorter and accurate separation of the individual LA and TA amplitudes is not possible.) In Fig. 2 we plot the TA-mode signal amplitude versus input power per electron,

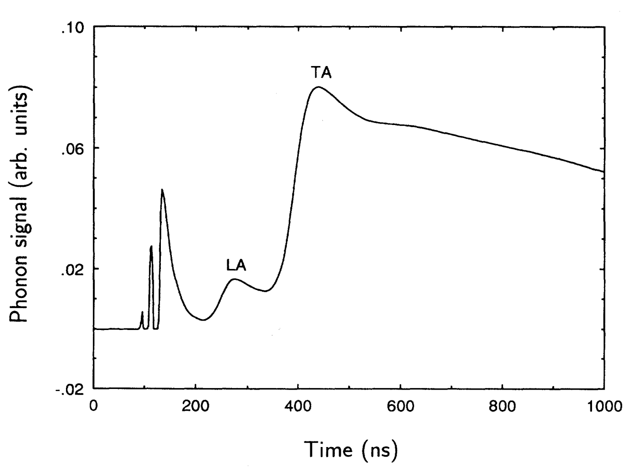

FIG. 1. Typical phonon time-of-flight trace taken in the optical emission regime (100 pW per electron) showing the characteristic TA peak tail of phonons arriving later than the ballistic flight time.

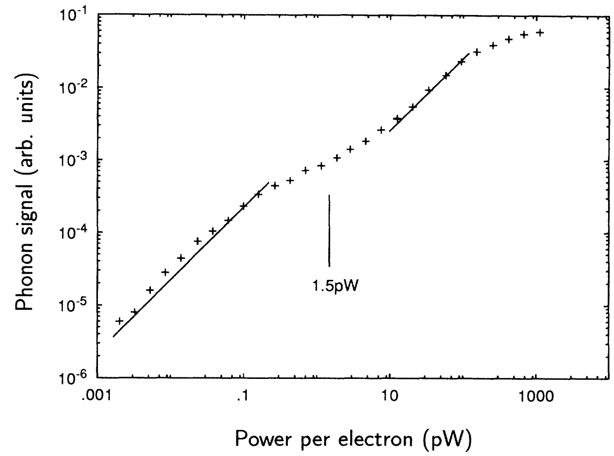

FIG. 2. TA-mode signal height vs input power. The break at 1.5 pW per electron has been shown previously in the heterojunction system to occur for a carrier temperatures around 50 K and is associated with the onset of LO mode emission. The flattening off above approximately 100 pW per electron is due to bolometer saturation.

showing two linear regions with a break around 1.5 pW per electron characteristic of the changeover from acoustic to optical-phonon emission. This has been previously observed in the heterojunction system at approximately the same power and corresponds to a carrier temperature of $T_e \sim 50$ K. Below 1.5 pW TA phonon emission is via piezoelectric coupling. Above this power, emission into longitudinal-optic (LO) phonons dominates. These have very short lifetimes, of order 1 ps, and decay through a series of steps to high-frequency TA modes, the whole process taking around 20 ns. It is these phonons that reach the bolometer. The break at 1.5 pW results from the different angular dependencies of the acoustic and optical emission processes and hence the different proportion of emission falling on the bolometer in the two regimes. The high-frequency TA phonons associated with optical emission propagate diffusively due to strong isotope scattering and arrive at the bolometer later than the ballistic flight time, producing the pronounced tail seen in Fig. 1. This long tail in the time-of-flight experiments was widely observed in 2D systems for $T_e > 50$ K.[3,5]

Figure 3 gives the ratio of LA- to TA-mode signal heights versus power. In the acoustic regime ($P < 1.5$ pW per electron), the ratio is approximately constant while above it drops rapidly as the optical decay TA phonons increase in intensity. The observation of such a relatively large LA-mode signal is unusual in that it has not been previously observed in heterojunction studies. Partly this may be due to the 50° bolometer being along a slight focusing direction for LA modes and a defocussing direction for TA modes. The absolute value of the LA/TA ratio is sensitively dependent on phonon focussing[2,7,8] for a given propagation direction. However, in our case this will introduce a fixed geometrical factor and the important feature is that the ratio is constant with power.

In GaAs two mechanisms of electron–acoustic-phonon coupling are possible: DP coupling to LA modes only,

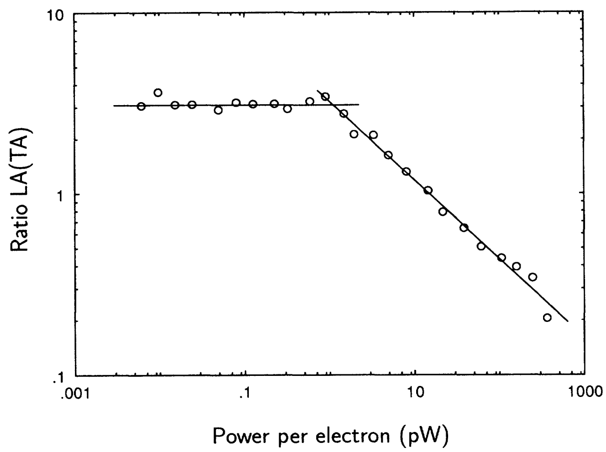

FIG. 3. Ratio of LA- to TA-mode peak heights vs power. The straight lines are shown as a guide to the eye.

and PE coupling to both TA and LA modes. The matrix elements for emission of an acoustic phonon $\mathbf{Q}=(q,q_z)$ (in-plane component q, normal component q_z) are given by the expressions[9]

$$|U_{\rm LA}^{\rm DP}(Q)|^2=\frac{\eta E_D Q}{2\rho v_{\rm LA}}G(q_z)\ ,$$

$$|U_{\rm LA}^{\rm PE}(Q)|^2=\frac{32\pi^2\eta^2 e^2 e_{14}^2}{\kappa^2\rho v_{\rm LA}}\frac{(3q_xq_yq_z)^2}{Q^7}G(q_z)\ ,$$

$$|U_{\rm TA}^{\rm PE}(Q)|^2=\frac{32\pi^2\eta^2 e^2 e_{14}^2}{\kappa^2\rho v_{\rm TA}Q^5}\times\left[q_x^2q_y^2+q^2q_z^2-\frac{(3q_xq_yq_z)^2}{Q^2}\right]G(q_z)\ ,$$

where $v_{\rm LA}$ and $v_{\rm TA}$ are longitudinal and transverse sound velocities, respectively, E_D is the deformation coupling constant, and e_{14} is the piezoelectric coupling constant. $G(q_z)$ is a form factor for emission in the normal direction that drops rapidly to zero for $q_z>1/a_0$, where a_0 is a length characterizing the 2DEG "thickness." (From the uncertainty principle, if the electron z position is uncertain to within a_0, its z momentum will be uncertain to within $\hbar/a_0$, placing an upper limit on q_z.) At a given angle the Q dependencies reduce to

$$|U_{\rm LA}^{\rm DP}(Q)|^2\propto Q\ ,$$

$$|U_{\rm LA}^{\rm PE}(Q)|^2\propto\frac{1}{Q}\ ,$$

$$|U_{\rm TA}^{\rm PE}(Q)|^2\propto\frac{1}{Q}\ .$$

Thus, at low electron temperatures (emission of lower Q phonons) PE coupling should dominate, while DP coupling will become dominant at higher temperatures (emission of higher Q phonons), as has been noted in transport studies of heterojunction and QW systems. For our sample geometry the crossover occurs for $Q\sim1.7\times10^8\ {\rm m}^{-1}$, or a LA-mode frequency of ~140 GHz.[10]

In the acoustic regime we have noted that the LA/TA intensity ratio is approximately constant as a function of input power, that is, the individual LA and TA emission rates have the same temperature dependence. From this we can infer that the LA and TA emission-rate Q dependencies must be identical and hence that the observed LA and TA signals must both be PE coupled. If a significant proportion of the LA-mode signal resulted from DP coupling we would expect the ratio to rise with increasing input power (carrier temperature) as emission of higher Q phonons became energetically possible. DP coupling appears to have been suppressed in contrast to the heterojunction and QW 2D systems where transport studies have shown that DP-coupled phonon scattering play a major role.

A significant feature of the 2DEG at a δ-doped layer is that the confinement is relatively weak with a_0 typically in the range 20–100 nm. (In comparison a heterojunction might have $a_0\sim5$ nm.) It follows that the upper limit on q_z from $G(q_z)$ will be lower. Specifically, in the present case, for a 2DEG of sheet concentration $4.5\times10^{11}\ {\rm cm}^{-2}$ and $a_0=50$ nm, $q_z\leq2\times10^7\ {\rm m}^{-1}$. For in-plane emission $q\leq2k_f$ here k_f is the Fermi wave vector, or approximately $1.8\times10^8\ {\rm m}^{-1}$ in the example chosen. Thus, for emission at all but the largest angles to the normal, Q is limited to the regime where PE coupling will be dominant ($Q\leq1.7\times10^8\ {\rm m}^{-1}$). For a heterojunction of similar sheet concentration but $a_0=5$ nm, $q_z\leq2\times10^8\ {\rm m}^{-1}$ and hence DP coupling would no longer be strongly suppressed.

We have observed the phonon emission from the 2DEG formed in a series of MBE- and MOCVD-grown Si δ-doped GaAs samples with single subband occupation. In the acoustic regime, the ratio of LA- to TA-mode intensity is approximately constant consistent with a suppression of DP coupling, both the LA and TA signals observed resulting from piezoelectric coupling. This is in contrast to what has been seen with transport techniques in the heterojunction system.

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