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Heat Pulse Studies of the Emission and Absorption of Acoustic Phonons in GaAs Quantum Wells and Wires

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Abstract

This paper reviews some recent experiments in which heat pulse techniques have been used to study the interaction of acoustic phonons with electrons in semiconductor quantum wells and wires. Heat pulse experiments provide temporal and spatial resolution of the phonons that are emitted or absorbed by the electrons and so give more detailed information about the electron-phonon interaction than can be obtained by other methods (e.g. transport measurements). Phonon experiments demonstrate clearly the effect of the electron confinement on the carrier-phonon interaction and the overall energy loss rate due to acoustic phonon emission. A qualitative explanation of the results is given in terms of the reduction of phase-space available for electron-phonon scattering when the electrons are confined in one and two dimensions. It is also shown how phonons can be used as spectroscopic probes of the electronic states in semiconductor nanostructures.

1. Introduction

Electron-phonon interactions play an important rôle in the physical behaviour of semiconductor devices [1]. Phonon emission and absorption processes relax the momentum and energy and so contribute to the electron mobility and power dissipation in devices. In the Gallium-Arsenide (GaAs) based devices considered in this paper, acoustic phonon scattering is expected to dominate at low temperatures ($\lesssim$20 K). Above 50 K processes involving optic phonons take over. In the intermediate temperature range other processes, e.g. emission of plasmon-optic phonon coupled modes, may make a significant contribution [2]. There are a number of ways of studying electron-phonon interactions experimentally, which include transport and optical measurements. However, the most appealing methods at low temperatures are direct phonon emission and absorption measurements using ballistic heat pulses. In phonon emission experiments, the electrons are heated above the lattice temperature by applying a short electrical or optical pulse. The electrons cool by emitting phonons that travel ballistically through the substrate which is semi-insulating, of high crystal quality and at liquid helium temperatures. The phonon pulse is detected using superconducting transition-edge bolometers. If the heating pulse is shorter than the difference in time for longitudinal (LA) and transverse (TA) acoustic phonons to propagate across the substrate (i.e. about 30 ns for a standard, 380 μm-thick, GaAs wafer), then it is possible to resolve the two modes separately. This gives information about the relative strengths of the different electron-phonon coupling mechanisms, deformation potential (DP) and piezoelectric (PE). The angular dependence of the emission can be studied by changing the position of the bolometer with respect to the device.

Phonon emission experiments hitherto proved very useful in the study of the energy relaxation by warm two-dimensional (2D) electrons and holes in GaAs heterostructures. The power dissipation and carrier temperature at which the onset of optic phonon emission occurred were measured [3, 4]. In the case of the 2D electron system, the surprising result was the complete absence of the LA mode in the detected signal [3], in stark contradiction to contemporary theories which predicted that the emission of the DP coupled LA mode should be much stronger. This has remained a mystery until only very recently when it was found that thorough consideration of the effects of (i) acoustic anisotropy on the electron-phonon matrix elements; (ii) screening of the DP and PE interaction; and (iii) the finite "thickness" of the 2D layer could lead to a theoretical explanation of all the observations [5]. In this paper phonon emission experiments on GaAs quantum wells are described. The measurements, made using wells of differing width, clearly demonstrate the influence of changing electron confinement on the phonon emission processes. Also discussed are some recent experiments on phonon emission by quasi-1D electrons in quantum wires. The results indicate that reducing the dimensionality of the electrons leads to a suppression of the acoustic phonon coupling and the onset of optic phonon emission at a much smaller power dissipation per electron than in a 2D system.

The most common type of phonon absorption measurements use the so-called phonoconductivity technique. Nonequilibrium phonons are generated by applying short electrical pulses to thin-metal-film heaters on the back surface of the substrate. After traversing the substrate, the phonons are incident on the device under investigation. The electron-phonon interaction is observed through the change in electrical conductivity of the device induced by the phonon pulse. This technique has been used to study 2D electron systems in the integer and fractional quantum Hall regimes [6, 7] and 2D hole systems [8]. In this paper phonoconductivity measurements in quantum wire devices are described. It is shown that such measurements not only give direct information about the electron-phonon interaction, but also give new information concerning the 1D electronic states.

2. Phonon emission by warm electrons in quantum wells

To investigate in detail the effect of the 2D confinement of the electrons, the phonon emission from several GaAs/AlGaAs quantum well samples with well widths ranging from 3 - 15 nm was studied using heat pulse techniques. The parameters of the quantum wells used are shown in Table 1. Devices having an active area of 120 μm $\times$ 50 μm were fabricated out of each of the wells using standard photolithographic techniques. On the back face of the substrate, centrally opposite the device, a bolometer having active dimensions 100 μm $\times$ 10 μm was made. The power dissipated in the device and its resistance, R_d, during the excitation pulse were determined from pulse reflection measurements on the transmission line connecting the pulse generator to the device. Comparison of R_d with the steady-state resistance versus temperature characteristics of the device enables the electron temperature, T_e, to be determined [3].

Table 1. Parameters of quantum well samples

Wafer No.	NU665S	NU590S	NU535S	NU667S	NU666S
Well width (nm)	3	5.1	6.8	12	15
2DEG density ($\times 10^{15} m^{-2}$)	1.8	1.8	2.0	3.7	3.6
Mobility ($m^2 V^{-1} s^{-1}$)	4.4	6.2	15	48	53
Ratio LA/TA at 1 pW/electron	1.0	1.3	1.1	0.50	0.16

Figure 1 shows the heat pulse signals from the 6.8 and 15 nm wells at a dissipation of 1 pW/electron. Pulses due to both LA and TA mode emission are seen at both well widths. This is in stark contrast to earlier experiments on heterojunctions where the LA mode was not seen. The ratio of LA/TA is much larger in the narrower well. This ratio is given for all the wells in Table 1.

To a first approximation, ignoring acoustic anisotropy, in GaAs only the LA mode interacts with the electrons in GaAs via the DP interaction and the TA mode couples to electrons via the PE interaction [9]. The strength of DP coupling is proportional to the phonon wavevector q, whereas the strength of PE coupling is proportional to q^{-1}. For electrons confined in a well of width w, the emission of phonons perpendicular to the well is sharply cutoff for $q_c \geq 1/w$. This is because, to conserve momentum, the perpendicular component of phonon momentum must lie within the bounds of uncertainty in the perpendicular component of the electron momentum ($\sim \hbar/w$). Narrowing the well increases q_c and hence the proportion of DP coupled LA phonons relative to PE coupled TA. In the narrowest wells the ratio LA/TA stops increasing. This is because the cutoff has moved above the peak in the thermal distribution of phonons emitted by the electrons at $q_{\max} = 3k_BT_e/\hbar s$, where s is the phonon phase speed.

Figure 2 shows examples of heat pulse signals for the $w = 6.8$ nm well at $T_e < 50$K and $T_e > 60$ K (excitation powers: 3 pW/electron and 300 pW/electron respectively). The two signals have been normalised so that the total intensity in the ballistic modes is the same. Compared with the $T_e < 50$ K trace, for $T_e > 60$ K the 'TA' peak increases in relative amplitude and appears to shift by about 5 ns to a later time. The tail after the TA peak is also increased relative to the low power trace. The result of these changes is that, at high power, a larger proportion of the emitted energy reaches the bolometer at times later than the ballistic TA peak. Similar results are obtained for all well widths, except the changes in the signal occur at different power levels. By analogy with the work on heterojunctions [3], the growth of the TA tail at high power is associated with the emission of LO phonons followed by their decay ending in large-wavevector TA modes which eventually reach the bolometers.

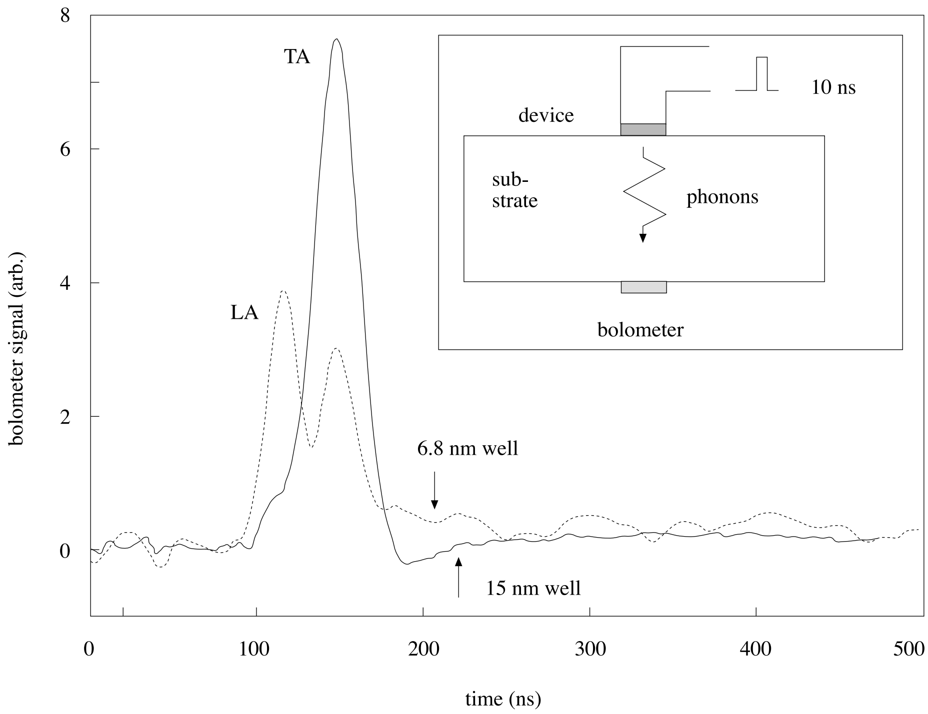

Figure 1. Heat pulse signals from 15 and 6.8 nm wide wells.

By extrapolating the high T_e data back to the power at which the "optic" tail just starts to grow out of the intrinsic tail due to the bolometer and electronic time constants, the power at which the onset of optic phonon emission occurs, P_{opt}, is determined. The results for all the wells are shown in Figure 3. It is clear that P_{opt} increases as w decreases. This means for $T_e < 50$ K, acoustic phonon emission is a more effective energy loss mechanism in the narrower wells.

The total acoustic phonon emission rate is proportional to the volume of phase-space available for electron scattering. This increases as w^{-1} owing to the perpendicular cutoff. The energy loss rate also depends on the energy spectrum of the emitted phonons which, at high T_e, is dominated by a peak at the cutoff, $\hbar\omega_{\max} \sim \hbar s/w$. Therefore, $P_{opt} \propto w^{-2}$ as shown by the solid line in Figure 3. The variation in 2D electron density between the different width wells does not affect this result significantly because, after taking into account the thermal smearing of the Fermi surface at $T_e \approx 50$ K, the in-plane, $2k_F$, momentum conservation cutoff does not vary much between samples. Also shown in Figure 3 are the results of numerical calculations of the energy loss by acoustic phonon emission at $T_e = 50$ K. Although the well width dependence is accurately predicted, the absolute values of P_{opt} are about an order of magnitude smaller than the experimental results. A possible reason for this difference is that another energy loss mechanism, e.g. emission of plasmon-optic phonon coupled modes [2], is dominant close to $T_e = 50$ K.

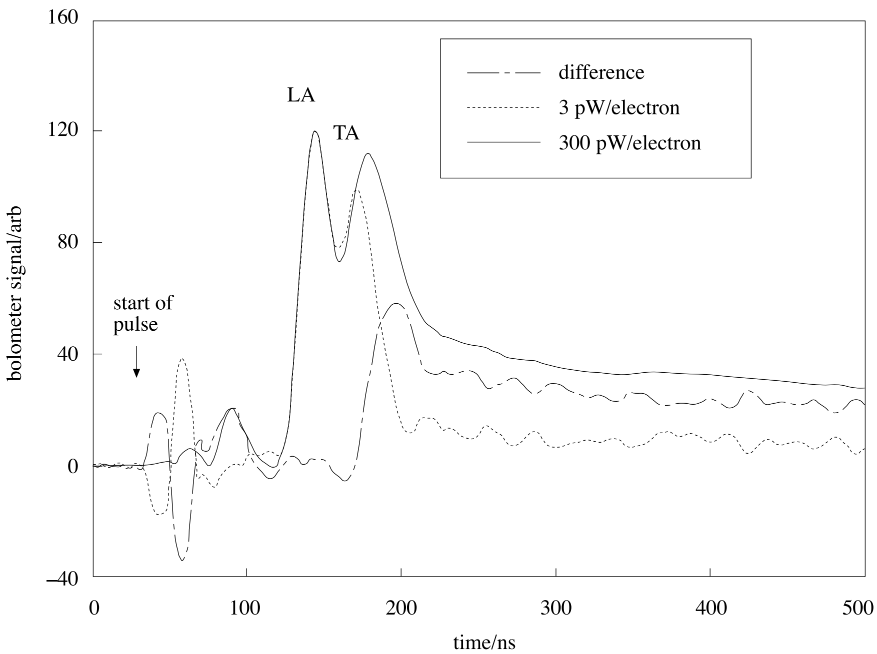

Figure 2. Heat pulse signals at different excitation powers, below and above the onset of optic phonon emission

3. Phonon emission by warm 1D electrons in a quantum wire array

With improvements in signal averaging technology, it has recently become possible to observe directly the phonons emitted by electrically heated electrons in quantum wires.

The device, (see Figure 4) was based on a 2DEG, having 4.2 K mobility 95 $m^2V^{-1}s^{-1}$ and areal density $4 \times 10^{15}m^{-2}$, in a modulation-doped GaAs/AlGaAs heterojunction grown by molecular-beam-epitaxy. An array of $100 \times 100 \mu$m-long QWRs were defined by a variant of the well-known split-gate technique as used in, for example, [10]. Magnetotransport measurements were used to characterise the array [11]. At a gate bias, $V_{gate} = -1.5$ V, an average wire width $\Delta x \approx 50$ nm and a 1D electron density $n_{1D} = 1.5 \times 10^8 m^{-1}$ were measured. The electrons were heated by applying voltage pulses of up to a few tens of mV amplitude and 20 ns duration to the wires, and the emitted phonons detected by superconducting aluminium bolometers.

Figure 5 shows some example heat pulse signals at different excitation powers. The signals are similar to those obtained using a 2DEG device. They are dominated by a strong TA mode peak. At higher powers, the signals develop a long tail after the TA mode peak. By analogy with the case of a 2D electron system this is identified with the onset of optic phonon emission. In this case, however, the onset of optic phonon emission appears to occur at about 0.2 pW/electron, about one order of magnitude less than for a heterojunction. A possible explanation for this lies in the reduction in phase-space for electron scattering due to the additional confinement. This leads to the phonon emission in the x-direction (Figure 4) being cutoff for $q_x \gtrsim 1/\Delta x$, corresponding to just 11 GHz for TA phonons. For the equivalent 2DEG, the cutoff is for $q_x \gtrsim 1/2k_F$ or about 170 GHz. The restriction of the acoustic phonon emission to lower frequencies means that it is a less efficient process for relaxing the energy of hot carriers. The temperature of the carriers is therefore more easily raised to 50 K by the applied electrical power, whereupon optic phonon emission can take place.

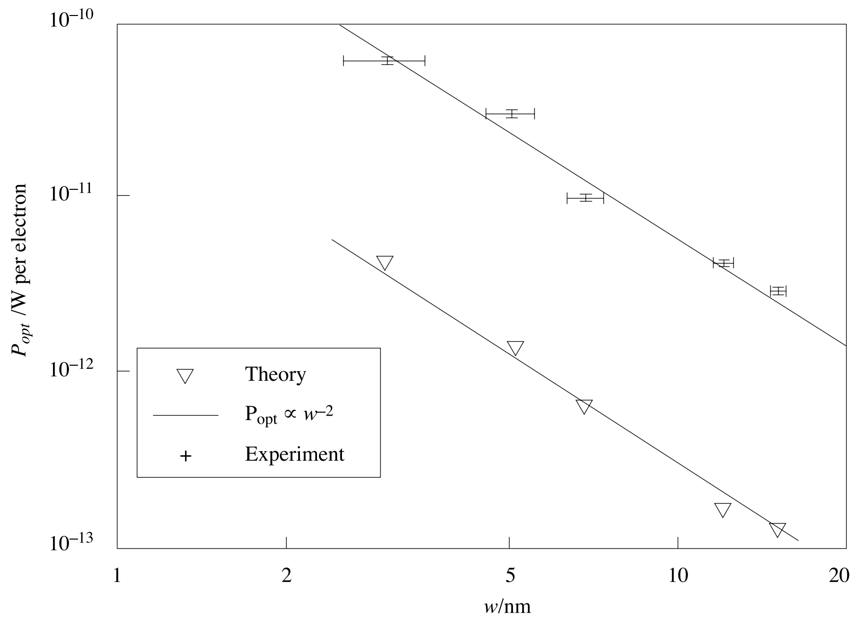

Figure 3. P_{opt} as function of w.

4. Phonoconductivity of quantum wires

Figure 6 shows the experimental arrangement for phonoconductivity measurements. Two split-gate devices were studied: one had a single channel of length, $L = 10\mu$m, which is comparable to the electron mean-free-path in the heterostructure ($\approx 5\mu$m); the other had a very short "point-contact" channel. Opposite the device, a $100 \times 10\mu$m CuNi heater was fabricated. The samples were cooled to 1.2 K in a liquid-helium cryostat and pulses of nonequilibrium phonons were generated by applying 20 ns electrical pulses to a heater. A constant bias current, $I_{DS} = 100nA$ was passed through the device. When the phonons were incident upon it, the phonon-induced change in device conductance was manifested as a small transient voltage signal which was amplified and averaged over many traces to improve the signal to noise ratio. A typical signal after 10^6 averages is shown in Figure 6 (inset).

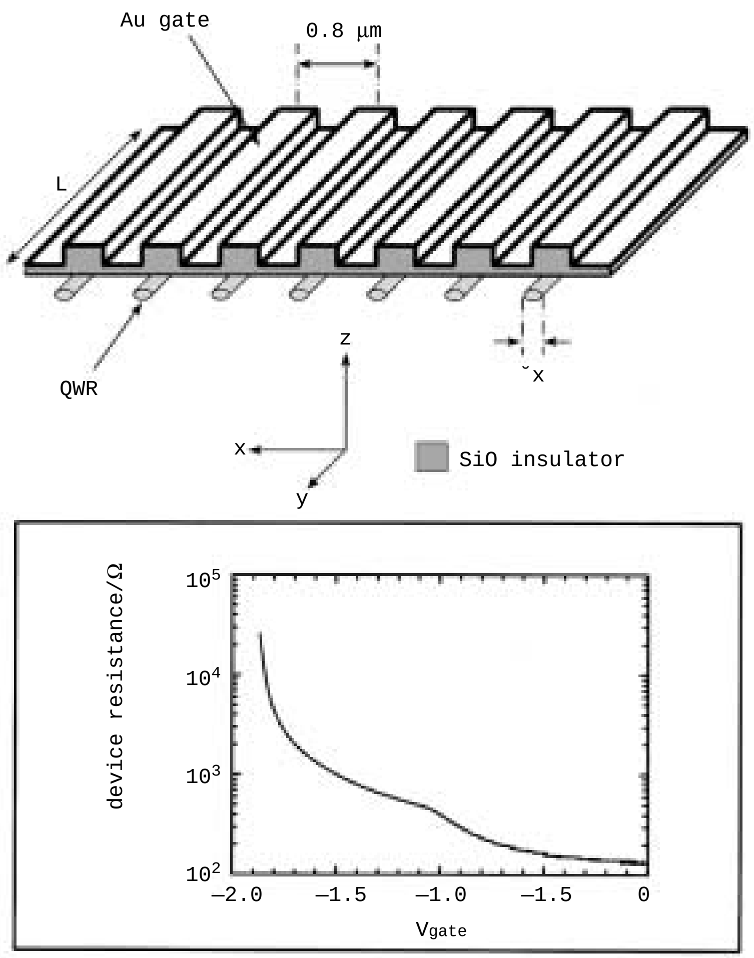

Figure 4. Quantum wire array and gate characteristics (inset)

The results for the 10 μm channel were reported in [12]. The phonons caused an increase in the conductance of the channel which was attributed to phonon-induced delocalization of weakly localized electron states in the wire.

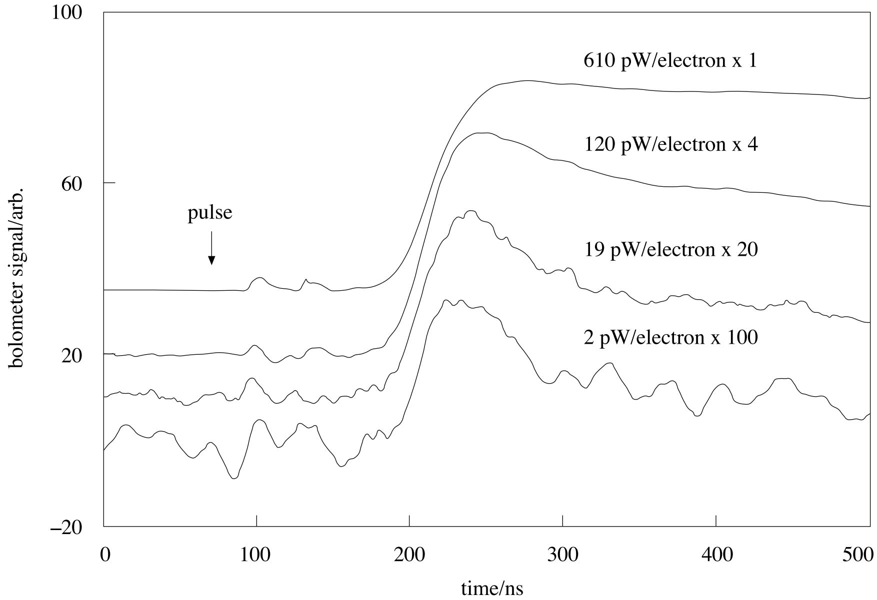

Figure 5. Phonon signals from quantum wire array.

The phonoconductivity response of the short wire (point contact) as a function of split gate bias, V_{gate}, is shown in Figure 7. Giant oscillations in the phonoconductivity are observed. The maxima in the oscillations coincide with the "steps" in the DC conductance. Increasing the (negative) gate bias has the effect of narrowing the 1D channel and so the energy separation of the 1D electronic subbands increases. A step in the DC conductance occurs when the Fermi energy, E_F, is coincident with a 1D subband edge [10]. The oscillations in the phonoconductivity are believed to be due to fluctuations in the 1D density of states (DOS) at E_F. The 1D DOS is sharply peaked close to the edge of any 1D subband and this is reflected in the phonon scattering rate. Such strong effects are not seen in the transport data because the DC conductance is proportional to the integral of the DOS.

The phonoconductivity is negative, i.e. the phonons cause a *decrease* in the conductance. This can be qualitatively understood if we note that phonons can only influence the conductance of the point contact by backscattering electrons in the channel. However, at present, the large size of the response $\sim 0.01G_0$ cannot be accounted for. Theoretical estimates of the conductance change due to direct backscattering [13], predict a response some two orders of magnitude weaker than observed. This is because the phonons, originating from a heater located directly opposite the wire, have insufficient in-line momentum to backscatter the electrons. One possible explanation is that, due to the nonuniform potential along the channel, the in-line momentum conservation condition is relaxed, thus opening up phase space for electron scattering. Another possibility is that electrons gain energy by absorbing phonons in the 2D "contact" region before entering the wire. Once in the wire an electron may relax by emitting a phonon and so, to conserve momentum, it may be backscattered. Further theoretical work is in progress with the aim of giving a quantitative account of the observed conductance changes.

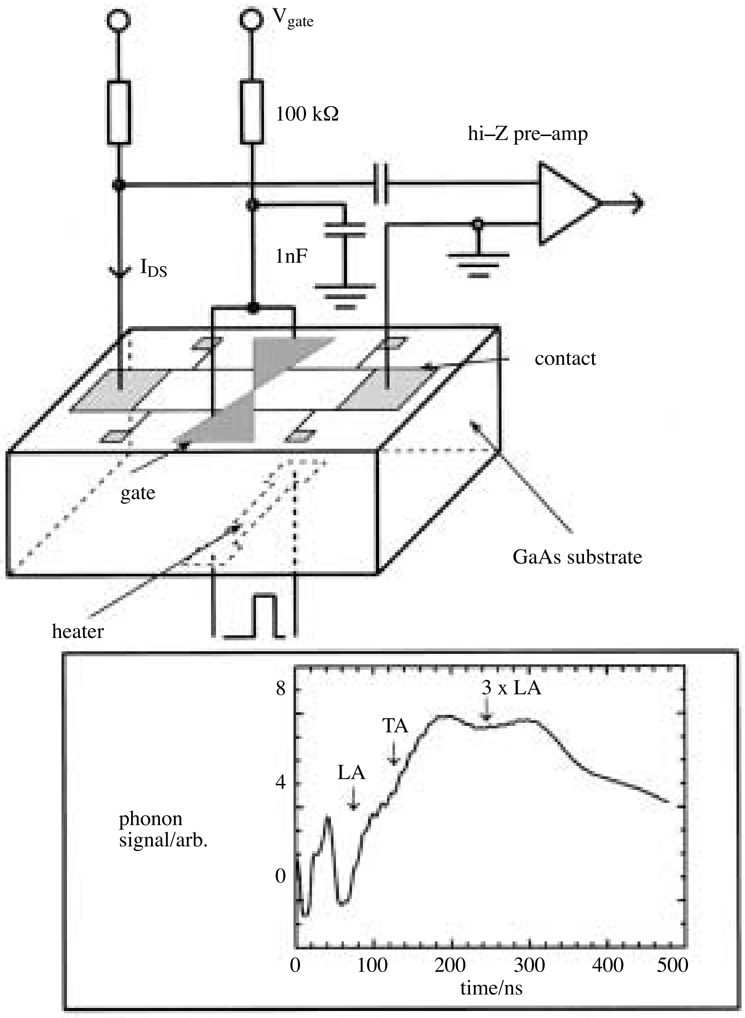

Figure 6. Phonoconductivity arrangement, the inset shows a typical signal.

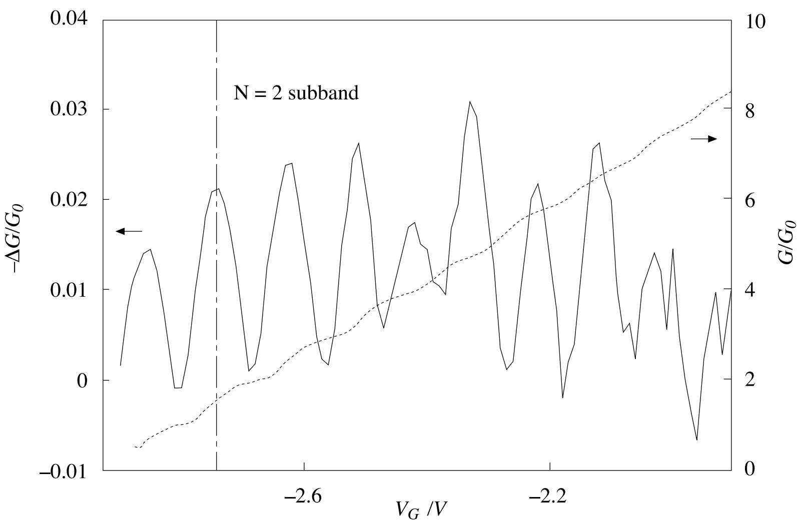

Figure 7. Phonoconductivity oscillations and DC conductance of a quantum point contact, $G_0 = 2e^2/h$ is the conductance quantum.

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