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The Effect of Non-Equilibrium Acoustic Phonons on the Tunnel Current in GaAs/AlAs Superlattices

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Abstract

We present the first study of the effect of ballistic acoustic phonons generated by a heated metal film on the tunnel current in GaAs/AlAs superlattices. The phonon-induced increase of the tunnel current as a function of applied voltage has a maximum at a voltage that varies linearly with heater temperature both in zero and applied magnetic field. The behaviour is consistent with phonon-assisted tunnelling by stimulated phonon emission. The system acts as a phonon spectrometer in the $<$ 1THz frequency region with a resolution of approximately 200 GHz.

The transport properties of double and multi-barrier tunnelling devices have been intensively studied and are now qualitatively understood. However, the role of phonon scattering, and in particular that by acoustic phonons, has been investigated to a much lesser extent. The first experimental investigation of the effect of acoustic phonons on a double barrier resonant tunnelling device (DBRTD) was made by measuring the change in tunnel current induced by a pulse of non-equilibrium acoustic phonons [1]. The measurements focused on tunnelling through donor levels in the quantum well. The signals were attributed to assisted tunnelling as a result of phonon absorption and stimulated phonon emission. This investigation has recently been extended to tunnelling through the ground state of the quantum well in magnetic fields [2] and the results were attributed to phonon assisted tunnelling between two Landau levels. These earlier experiments showed that DBRTDs have potential as phonon spectrometers. However, their resolution is rather modest because of level broadening (several meV). In this present work, we report the first measurements of assisted tunnelling in a superlattice (SL) produced by non-equilibrium phonons.

The principle of using a SL as a phonon spectrometer is illustrated in Figure1. Acoustic phonons induce assisted tunnelling transitions by absorption and stimulated emission of phonons that lead to changes of the tunnelling current through the SL. By changing the bias, V, across the SL it is possible, in principle, to change the energy of phonons which are active in tunnelling processes so the SL becomes a phonon spectrometer which can be tuned by changing the applied bias.

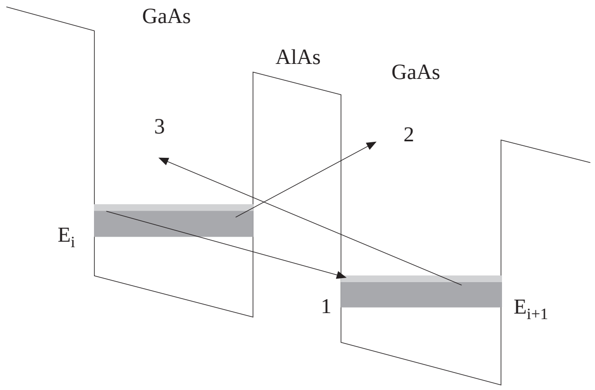

Figure 1. Possible phonon-assisted tunnelling transitions in a SL showing both stimulated phonon emission (1) and absorption (2,3) of phonons. For phonons with $\mathbf{q}$ perpendicular to the plane of SL and for $\hbar\omega = E_i - E_{i+1}$, only transition (1) is allowed.

The device consists of a 50 period weakly coupled GaAs/AlAs SL grown by molecular-beam epitaxy on a semi-insulating substrate. The 60 Å thick GaAs quantum wells and 40 Å thick AlAs barriers are both doped with Si to $2{\times}10^{16}$ cm^{-3}. The superlattice is separated from the n$^+$ ($2{\times}10^{18}$ cm^{-3}) contact layers by a 200 Å undoped spacer layer. The layers were etched to a $\pi \times (50 \times 50)$ μm^2 mesa and AuGe contacts were evaporated to the emitter and collector layers. The sample was immersed in liquid helium at 1.5K and non-equilibrium phonons were generated by applying 50-100 ns long electrical pulses through a constantan heater evaporated on the substrate opposite the device. A low repetition rate (<10kHz) was used to ensure minimal lattice heating even at the highest powers. The heater temperature, T_h, during the pulse is determined by acoustic mismatch theory [3]. The resulting transient change in tunnel current, $\Delta I(t)$, is measured as a function of applied bias, V, and heater temperature, T_h, using a high speed digitiser and signal averager. The experiments were also carried out in magnetic field of B=6 T.

The phonon-induced signal $\Delta I(t)$ in Figure 2 shows the arrival time of both longitudinal (LA) and transverse (TA) modes indicating the phonons are incident on the SL with a relatively narrow angular distribution and correspondingly well defined momentum $\mathbf{q}$.

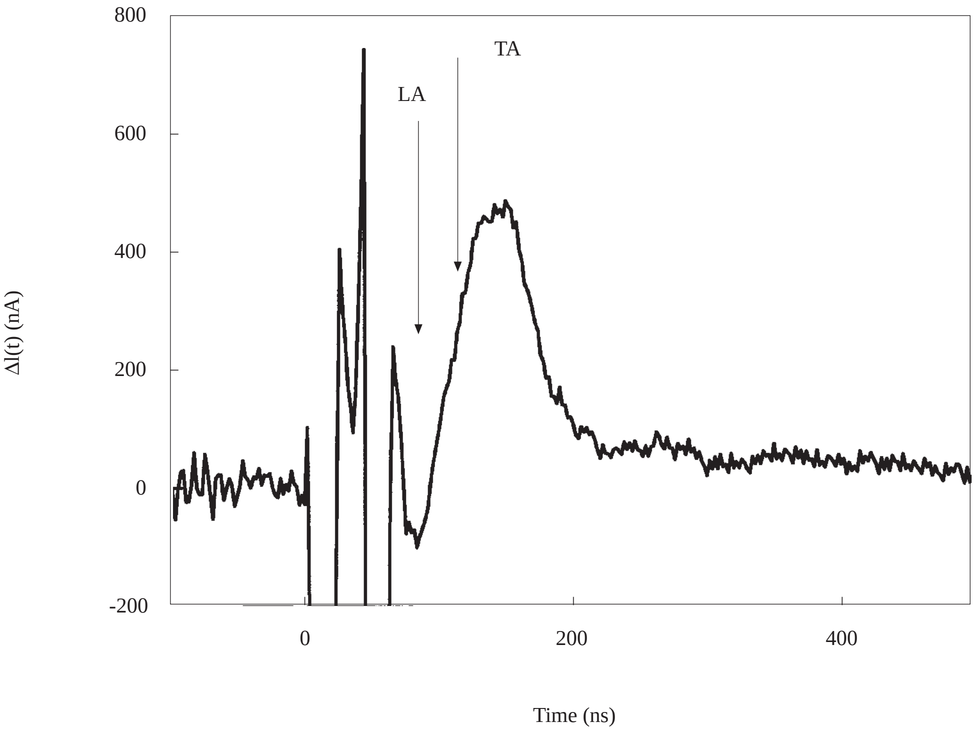

Figure 2. Time dependence of the phonon-induced signal $\Delta I(t)$ for V=200mV, B=0T and T_h=13.35 K. The vertical arrows show the expected arrival time of LA and TA phonons.

Figure 3 shows the dependence of the phonon-induced (TA) current changes $\Delta I(V)$ on applied bias, V for $7 < T_h < 13$ K and B=0. The bias, V_{max}, at which the peak in $\Delta I(V)$ occurs increases linearly with heater temperature, T_h, as can be seen more clearly from Figure 4. Results at B=6T are very similar. At these biases, the potential should be uniformly distributed in the SL and the energy separation between corresponding levels in neighbouring quantum wells $E = eV/n$ (n is the number of periods in SL) at $V = V_{max}$ has a value of a few meV which is close to the phonon energy at the maximum of the Planckian distribution with $T_h \sim 10$ K. The bias $V_0(1) = 50$mV at which $\Delta I(V)$ rises from zero (see Figure 3) is attributed to the voltage drop across the contacts and also possible fluctuations in the potential in the SL at low V.

We believe that the increase in V_{max} with T_h is due to the shift in the phonon energy distribution with T_h and suggests the phonon-induced signal is mostly governed by stimulated phonon emission (transition 1 in Figure 1). For simplicity we consider non-equilibrium phonons with momentum q perpendicular to the SL plane. Assuming in-plane momentum is conserved, the phonon-induced tunnelling can only occur between electron states with the same momentum involving phonons with energy $\hbar\omega = \hbar sq = E_i - E_{i+1} \approx eV/n$, where s is the sound velocity (Figure 1). Hence the phonon-induced changes in current $\Delta I(V) \propto W(\mathbf{q})g(q)N_q$, where $W(\mathbf{q})$, the stimulated emission rate, is determined by the type of electron-phonon interaction, g(q) is the density of phonon states and $N_q \propto \left(\exp\frac{\hbar\omega}{k_B T_h} - 1\right)^{-1}$ is the occupation number of phonons $\hbar\omega$ **at the SL**. For deformation potential coupling $W(\mathbf{q}) \propto q$ and in the Debye approximation $g(q) \propto q^2$ so that $\Delta I(V) \propto V^3 N_q$ which corresponds exactly to a Planckian energy distribution with a maximum at $\hbar\omega_{\max} \approx 3k_B T_h$.

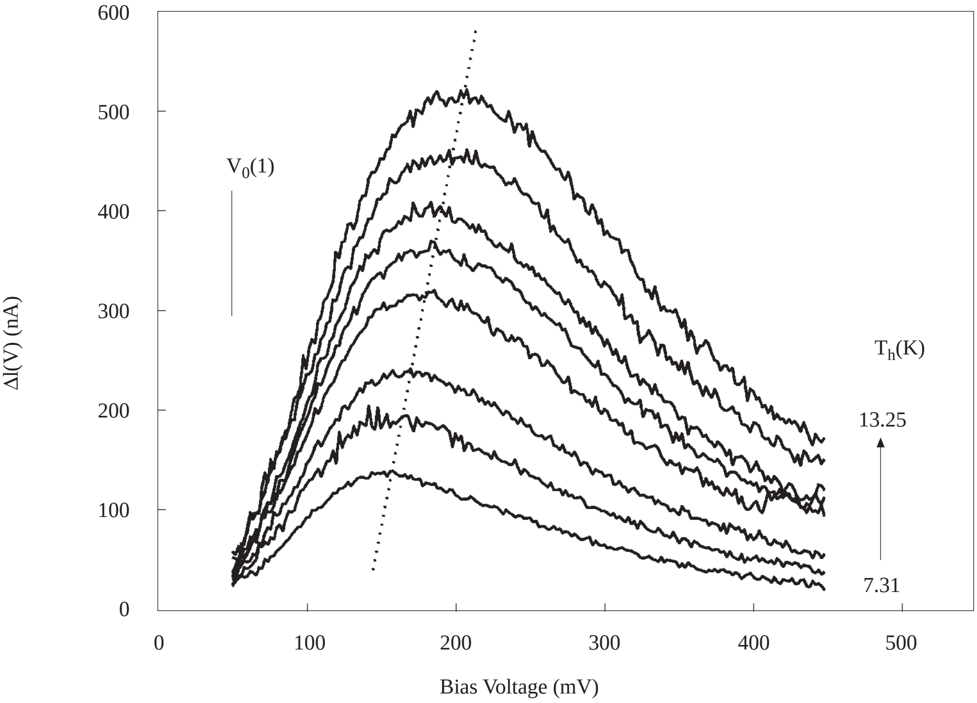

Figure 3. Dependence of phonon (TA) induced signal on bias voltage for different heater temperatures, T_h. This was obtained by measuring the signal at the maximum in $\Delta I(t)$. The dashed line shows the shift of the maximum in $\Delta I(V)$ with T_h.

The experimental data is in good qualitative agreement with the above analysis. Figure 4 shows that V_{max} is proportional to T_h. However, the slope of $E_{max}(T_h)$ (solid curve in Figure 4) is less $(1.9k_B T_h)$ than in the case of deformation potential coupling. This seems likely to be due to the contributions of other types of electron-phonon interaction mechanisms in the SL (piezoelectric, ripple [4]) for which $\Delta I(V) \propto VN_q$. It is of note that the offset, $V_0 = 90$mV, obtained by extrapolating $V_{max}(T_h)$ to $T_h = 0$ is larger than the voltage $V_0^{(1)}$ at which conductance starts. We attribute the difference, $V_0^{(2)} = 40$mV, to tunnelling transitions to states up to 0.8meV $(eV_0^{(2)}/n)$ above the Fermi level which could arise through electron scattering or in-plane phonon momentum. This shifts V_{max} to a somewhat higher value and leads to an additional contribution to V_0. The spectrometers resolution is therefore ≈ 0.8meV.

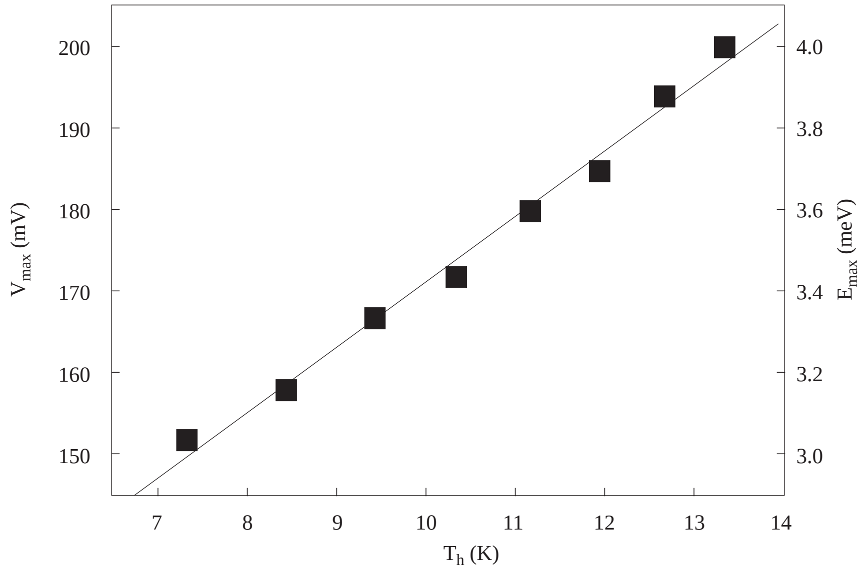

Figure 4. The position of the maximum, V_{max}, in $\Delta I(V)$ as a function of heater temperature T_h. The right hand scale shows the corresponding phonon energy $E_{max} = eV_{max}/n$. The line shows a linear fit $E_{max} = ak_BT_h + eV_0/n$ with $a = 1.9$ and $V_0 = 90$mV.

In summary we show that the changes in the tunnel current in a SL induced by ballistic acoustic phonons may be explained by stimulated phonon emission. The system may be used as magnetic field-independent phonon spectrometer of THz phonons with a resolution less than 1 meV.

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