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Studies of Phonon-Assisted Tunnelling in a δ-Doped Double Barrier Resonant Tunnelling Device

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We report measurements of the change in current induced by non-equilibrium phonons in a δ-doped double barrier resonant structure. In addition to the anti-Stokes and Stokes peaks resulting from tunnelling through the ground state of Si donors present in the well, two further peaks, C and D, are observed in magnetic fields >5 T. Peak D is attributed to phonon-assisted tunnelling between two Landau levels, while C may be attributable to heating effects.

The transport properties of double barrier resonant tunnelling devices (DBRTDs) have been the subject of considerable attention over a number of years although studies of the role of the electron–phonon interaction have only taken place rather more recently. Initially these concentrated on the pronounced feature above resonance caused by LO phonon emission [1] but these were followed by theoretical analysis of the effects of acoustic phonon scattering [2]. More recently, Bø and Galperin [3] calculated the effect of nonequilibrium acoustic phonons on tunnelling through the ground state of the quantum well in the presence of quantizing magnetic fields parallel to the direction of the current. The first experimental measurements on the role of acoustic phonons were made by firing phonon pulses at the DBRTD and observing the resultant change ΔI in tunnel current [4]. The investigation focussed on the tunnelling through the ground state level of Si donors present as impurities in the well. Phonon replicas (satellite peaks) in ΔI were observed either side of the donor peak in $I(V)$ and attributed to assisted tunnelling as result of phonon absorption (anti-Stokes) and emission (Stokes). In the present work this earlier investigation has been extended to studies of phonon-induced tunnel currents in δ-doped DBRTDs in zero magnetic field and in fields up to 15 T.

The experimental system consists of a $GaAs/Al_{0.4}Ga_{0.6}As$ DBRTD grown at 550 °C on a 400 μm semi-insulating substrate. The barrier and quantum well (QW) thicknesses are 5.6 nm and 9 nm, respectively. The centre of the well was δ-doped with Si donors to a concentration of 4×10^9 cm^{-2} and the Si doping of the contact layers was varied from

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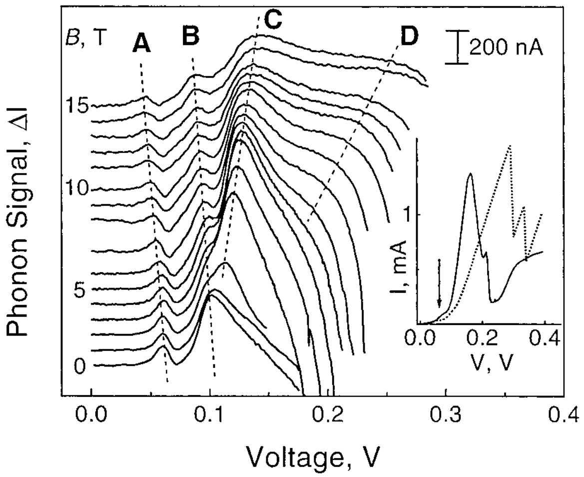

Fig. 1. The change in current $\Delta I(V)$ induced by non-equilibrium phonons for magnetic fields up to 15 T applied parallel to I. Inset: The $I(V)$ characteristics for $B = 0$ T (solid line) and 15 T (dotted line). The arrow shows the donor peak

2×10^{16} cm^{-3} to 1×10^{18} cm^{-3} to ensure that the electron gas that forms under applied bias is two-dimensional. Each barrier is separated from the nearer n^+ doped contact by a 20 nm thick GaAs spacer layer to minimise Si diffusion during growth. The device was immersed in helium at 4.2 K and non-equilibrium phonons were generated by passing ≈ 1 μs current pulses through a constantan heater evaporated onto the substrate opposite the DBRTD. The heater temperature T_h is estimated from mismatch theory [5]. The resulting transient change in tunnel current, ΔI, is measured as a function of applied voltage, V, in magnetic fields B up to 15 T applied parallel to the tunnelling current.

The $I(V)$ characteristics of the DBRTD are shown in the inset to Fig. 1 for $B = 0$ and $B = 15$ T. The pronounced increase with increasing B in the bias voltage at which the main resonant peak occurs is consistent with earlier studies [6] and is attributable to a decrease in the Fermi energy (E_F) in the emitter caused by an increase with B in the density of states in the lowest Landau level (LL) combined with an increase in charge build-up in the well. The vertical arrow near the onset of the main resonance shows the resonant peak due to tunnelling through the ground state of the Si donors in the QW [7]. From the oscillations in $I(B)$ apparent for $V > 0.14$ V we found the electron density in the emitter to increase approximately linearly with applied bias with $n_s \approx 1.5 \times 10^{11}$ cm^{-2} at 0.18 V and the electron mobility in the 2D emitter to be $\mu \approx 4 \times 10^4$ cm^2 V^{-1} s^{-1} near the main resonance. The ratio of the potential drop acrosss the first barrier to the total bias is estimated to be 0.3 at the donor peak. It decreases strongly with current, however, because of increasing charge build-up and falls to $\approx$0.01 at the main resonance.

Fig. 1 shows the change in current, ΔI, induced by a pulse of non-equilibrium phonons from a heater at temperature $T_h = 10$ K for fields B from 0 to 15 T. We discuss first the position of the minimum in ΔI occurring at $\approx$0.07 V for $B = 0$ T. This coincides exactly with the donor peak in $I(V)$ and this remains the case over the whole field range, both features moving to lower voltages with increasing B. At $B = 0$ T, two peaks occur either side of the minimum. As B increases, the first peak, A, follows the minimum to lower voltages while the second peak splits into two peaks, B and C. Peak B follows the minimum and hence the donor peak in $I(V)$ to lower voltages as B increases.

Peak C, which lies just above the threshold voltage for tunnelling into the ground state of the well, follows the threshold closely to higher voltages as B increases. For $B > 5$ T, a new peak, D, appears as a shoulder at a voltage just below that of the main resonant peak in $I(V)$ and follows it up to 15 T at an approximately fixed voltage below it. Peaks A and B are not present in a DBRTD of similar structure containing an undoped QW indicating that, in the doped device, A and B are caused by phonon-assisted tunnelling through donor levels. Peaks C and D are however also seen in the undoped structure indicating their intrinsic character. This rules out an earlier tentative interpretation for C involving an excited donor state [8].

We envisage two processes for acoustic phonons to induce changes in the tunnelling current. The first is *phonon-assisted tunnelling* in which an electron tunnels into the anti-Stokes or Stokes satellites of a level in the QW corresponding respectively to the simultaneous absorption or emission of an acoustic phonon. Peaks A and B are evidently consistent with this process and involve tunnelling through a Si donor level in the QW. For $B = 0$ T, their positions and the existence of a minimum in ΔI located at the donor peak in $I(V)$ are in qualitative agreement with a recent theoretical model for this process [9]. For $B > 3$ T, only the lowest LL is occupied in the emitter and we attribute peak D, which follows the position of the main resonant peak in $I(V)$ as B increases, to phonon-assisted tunnelling between $n = 0$ LLs in the 2D emitter and the QW as a result of phonon absorption (anti-Stokes). For $B > 6$ T we also observe a rich structure in $\Delta I(V)$ for voltages above that of the main resonant peak in $I(V)$ (not shown in Fig. 1). One of the lines may be the phonon emission (Stokes) peak of the main resonance but the structure may also involve phonon-induced peaks associated with the second confined level of the QW. More work on different structures is needed to distinguish these various possible contributions.

The second process envisaged is the *heating of the 2D electron gas in the emitter*. The incident phonons raise the electron temperature of electrons and so change the occupation of states with energies $E \approx E_{\mathrm{F}}$ but the phonons are not directly involved in the tunnelling process. The theoretical model [9] indicates that this electron heating is very unlikely to give rise to the observed form of $\Delta I(V)$ for phonons tunnelling into the donor level: two peaks, A and B, either side of a minimum coinciding with the donor peak in $I(V)$ [3]), although it could certainly give rise to changes in ΔI of the size observed through of very different form.

The reason why phonon-assisted tunnelling rather than heating effects appear to predominate for tunnelling through the donor levels might be accounted for if the tunnelling into the donors occurs from localised states in the low density emitter due to the donors in the well. This would reduce the effect of electron heating and may also increase the electron–phonon coupling and hence the probability of phonon-assisted tunnelling [8]. The contribution of heating may however be important at the threshold of the main resonance. We have modelled the process by considering tunnelling between two Gaussian LLs, one partly filled in the emitter and one empty in the well. The results show that the experimentally observed peak C is not inconsistent with this model and so may be due to heating rather than phonon-assisted tunnelling. Some support for

[3]) This form would certainly not occur from a homogeneous 2D emitter but the possibility that it could arise from particular forms of inhomogeneity in the emitter plane cannot be totally excluded.

this comes from the fact that at $\approx$5 T, the amplitude of D (attributed to phonon-assisted tunnelling), varies very differently with T_h than that of C, in particular becoming more pronounced at low T_h. This might suggest they involve different processes.

It was earlier shown experimentally [4] that the position of the anti-Stokes satellite peak of the donor level varied linearly with the heater temperature T_h and hence with the dominant frequency of the phonons incident on the DBRTD so that it could be used as phonon spectrometer. This result is qualitatively consistent with theory when the phonon energy is large compared with the linewidth of the level [3, 9]. In the present work however the dependence of the position of peak A, B, and D on T_h was always too small to measure but the reason for this difference in experimental behaviour is not understood. Insensitivity to phonon frequency can however, be explained in terms of inhomogeneous broadening: the widths of the donor level (several meV) and the LLs (up to 5 meV in 15 T) both being very much larger than the phonon energies involved.

In summary, we note that we have measured the change in current induced by non-equilibrium phonons in δ-doped DBRTDs. Peaks A and B either side of a minimum, which coincides in position with the donor peak in $I(V)$, are attributed to phonon-assisted tunnelling through the ground state of a Si donor in the QW as a result of phonon absorption and emission, respectively. These observations are qualitatively consistent with a recent theoretical model. Peak D is attributed to phonon-assisted tunnelling (phonon absorption) through the intrinsic ground state of the QW. Peak C, which occurs just above the threshold for tunnelling into this state, has a different character from D and may be due to phonon-heating of the electrons in the 2D emitter.

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