Nonequilibrium Acoustic Phonon-Assisted Tunneling in GaAs/(AlGa)As Double Barrier Devices

F. F. Ouali, N. N. Zinov'ev,* L. J. Challis, F. W. Sheard, M. Henini, D. P. Steenson, and K. R. Strickland
Physics Department, University of Nottingham, NG7 2RD, United Kingdom
(Received 21 March 1995)

We report the first observations of nonequilibrium phonon-assisted tunneling in a double barrier resonant tunneling device in GaAs. The change in tunnel current produced by the phonons occurs at a bias voltage, which depends on the phonon energy showing that the device has potential as a phonon spectrometer.

PACS numbers: 73.40.Gk

There has been considerable progress in the understanding of resonant tunneling structures including double barrier structures and an increasing interest in their potential as devices [1]. Somewhat less attention, however, has been given to the component of the tunnel current arising from inelastic phonon-assisted tunneling. It is known that the broad satellite peak in tunnel current above the resonant peak is attributable to phonon-assisted tunneling involving the emission of longitudinal optic (LO) phonons [2], and this has been confirmed by theoretical analysis [3] and further studied experimentally by a number of other authors [4]. Assisted tunneling associated with acoustic phonons is also assumed to take place [5,6], and the current will also be affected by changes in electron distribution caused by a rise in electron temperature.

In this Letter, we report the first measurements of assisted tunneling caused by nonequilibrium acoustic phonons. The sample is a GaAs/$(Al_{0.4}Ga_{0.6})$Al double barrier resonant tunneling device (DBRTD) in which barriers of (AlGa)As are located on either side of a GaAs layer, which acts as a quantum well. The results provide information on the potential variation across the DBRTD and demonstrate this type of device could have value as a phonon spectrometer. The sample used (NU165) was grown by molecular beam epitaxy on a (100) semi-insulating substrate at a temperature of 630 °C. The substrate was Cr free and grown by the liquid-encapsulated Czochralski method. The structure consists of two 5.5 nm thick $Al_{0.4}Ga_{0.6}As$ barriers, separated by a 5 nm thick GaAs well. The barriers are separated from the doped n^+ GaAs contact regions by a 2.5 nm thick GaAs spacer layer. The doping on each side varies from $\sim 1 \times 10^{16}$ cm^{-3} at the edge of the spacer layer to 2×10^{18} cm^{-3} 50 nm away from the edge. When a bias voltage is applied, accumulation occurs on one side resulting in a two-dimensional emitter, while the collector remains three dimensional as shown schematically in the inset to Fig. 1. The layers were etched down to a 3×80 μm^2 mesa, and contacts were made to emitter and collector. The back face of the 400 μm substrate was polished, and a 600×60 μm^2 constantan heater evaporated opposite the mesa using back-to-front alignment.

The current-voltage characteristics of the DBRTD, $I(V)$ and dI/dV, are shown in Fig. 1. Since both energy and in-plane wave vector $k_{\|}$ are conserved, the resonant (main) peak occurs when eV_b equals the difference in the energies of the subband minima of the electrons in the well E_0 and emitter E_e (V_b is the voltage between the emitter and the center of the well as shown in the figure). The asymmetry of the peak in $I(V)$ and its large "half-width" (80 mV) below the peak are attributable to charge storage in the well, which also reduces the component V_b of the total bias voltage V [2].

The phonon signals are observed by applying current pulses of duration 10–30 μs to the heater with the substrate at 4.2 K. These generate pulses of nonequilibrium phonons which cross the substrate and strike the DBRTD. The resulting change in tunnel current ΔI produces a voltage pulse across a series resistor, which is recorded as a function of bias voltage V. Measurements were made for seven pulse powers from 5 to 130 mW and a slow repetition rate ~500 Hz was used to minimize sample heating. The charge buildup in the DBRTD results in

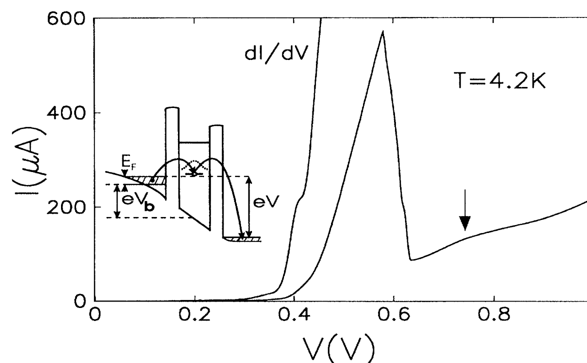

FIG. 1. The current-voltage characteristics $I(V)$ and dI/dV of the DBRTD at 4.2 K. The arrow shows the satellite peak attributed to LO phonon-assisted tunneling. The inset gives the energy band diagram of the DBRTD showing a phonon-assisted transition.

 0031-9007/95/75(2)/308(4)$06.00 © 1995 The American Physical Society

bistability in $I(V)$ near to the main peak [this is not apparent in Fig. 1, which shows $I(V)$ for one direction of voltage sweep only], which complicates the response of the device to nonequilibrium phonons, and these initial studies focus on the small shoulder in $I(V)$ at a voltage $V \simeq 420$ mV, ~ 160 mV below the main peak. The shoulder is more clearly observable in dI/dV and, by fitting with an exponential the smooth background due to tunneling into the confined state, subtracting, and integrating, we obtain the small peak in tunnel current $I_i(V)$ shown in Fig. 2. This peak, of height 2 μA, centered at $V \simeq 415$ mV, and of half-width 15 mV, is attributable to tunneling into a Si donor state in the well [7] of energy $E_i \sim 10-15$ meV less than E_0 [8]. The Si impurities in the well are caused by diffusion from the doped emitter and collector regions during growth [9], and the impurity tunneling mechanism has been discussed in detail elsewhere [7,10]. The in-plane confinement of the donor wave function within a length a_0 ($a_0 \sim 10$ nm is the Bohr radius in GaAs) implies a range of in-plane wave vectors $k_{\parallel} \sim 1/a_0$ rather than a well-defined value as in the main confined state. So the selection rule becomes $\Delta k_{\parallel} \leq 1/a_0$ and, since the Fermi wave vector k_F is believed to be $>1/a_0$, this allows tunneling within an energy range $\sim \hbar^2/2m^* a_0^2 \sim 6$ meV, which is responsible for much of the width of the impurity peak.

The phonon signal ΔI_i resulting from this impurity peak and its shift with phonon energy is attributable to phonon-assisted tunneling resulting from phonon absorption. For a monoenergetic beam of phonons of energy $\hbar\omega$ incident normal to the emitter, energy conservation requires that the peak in ΔI_i should be displaced from the peak in $I_i(V)$ by an amount given by $e\delta V_b = \hbar\omega$. So, since for deformation potential coupling, the distribution of the phonon-assisted tunneling, emitted by a heater at temperature T_h, has a maximum at $\hbar\omega \sim 3k_BT_h$, the peak in ΔI_i should be displaced from that in $I_i(V)$ by $e\delta V_b \sim 3k_BT_h$. The phonon peak should be slightly broader than $I_i(V)$ because of the distribution of phonon frequencies and their spread in incident angles around the normal to the emitter.

Figure 2 shows the phonon signal for a power input to the heater of $P = 80$ mW. The peak has a height of 60 nA and half-width of 15 mV and corresponds to an increase of $\sim 0.4\%$ in the total current $I = 15$ μA. The temperature of the heater T_h during the pulse can be calculated from the input power using acoustic mismatch theory [11] and, for $P = 80$ mW, $T_h = 8.5$ K so that, if scattering in the substrate can be neglected (as seems likely for $T_h < 12$ K [12]), the phonons causing tunneling have a frequency distribution which peaks at $\hbar\omega \sim 3k_BT_h \sim 2$ meV and a half-width ~ 1 meV. This is appreciably less than that of $I_i(V)$, which accounts for the similar widths of $\Delta I_i(V)$ and $I_i(V)$. Figure 3 shows that the peak positions fall linearly with T_h as expected for phonon-assisted tunneling, and the inset compares data for $T_h = 5.0$ and 8.5 K and shows Gaussian fits to the data points. If the tunneling peak occurs at $\hbar\omega \sim 3k_BT_h$, the slope of the line, $dV/dT_h \sim 9.3k_B/e$, indicates $dV_b/dV \sim 1/3.1$, which is broadly consistent with our estimate for this structure based on electrostatics. It is also similar to the value $dV_b/dV \sim 1/3.3$ above the main peak determined from the 117 mV displacement of the satellite due to assisted tunneling from the emission of LO phonons of energy 36 meV, although this neglects the change in position of the main peak due to charge storage. The probability of phonon-assisted tunneling can be deduced from the size of $\Delta I_i(V)$. For $P = 80$ mW, this indicates that the number of phonon-assisted transitions is 4×10^{11} s^{-1}. The phonon flux incident on the DBRTD can be estimated to be $\sim 1.5 \times 10^{17}$ s^{-1} from the fraction $240/2\pi \times 400^2 \sim 2.5 \times 10^{-4}$ of the total solid angle 2π it subtends at a point in the heater, which is then increased by ~ 3 [13] because the TA modes are focused along the [100] direction by elastic anisotropy. So this

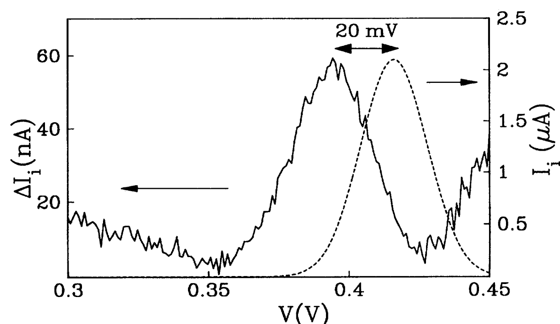

FIG. 2. The change in current $\Delta I_i(V)$ from the DBRTD produced by nonequilibrium phonons from a heater at $T_h = 8.5$ K. The dashed line shows the impurity peak I_i obtained from Fig. 1.

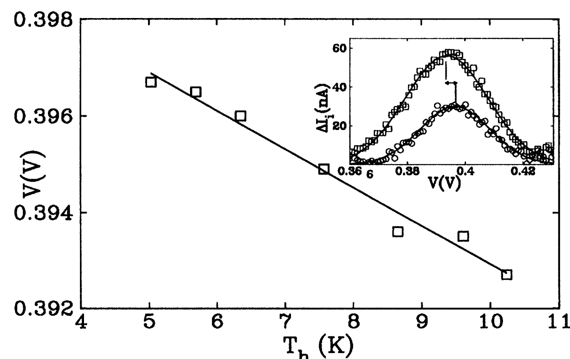

FIG. 3. The bias voltage at the peak of $\Delta I_i(V)$ plotted against the heater temperature T_h. The line fitted to the data has a slope $9.3k_B/e$. The inset shows examples of $\Delta I_i(V)$ for $T_h = 5.0$ (lower curve) and 8.5 K; the solid lines are Gaussian fits to the data points.

suggests that the probability of a phonon producing assisted tunneling is $\sim 4 \times 10^{11}/1.5 \times 10^{17} = 3 \times 10^{-6}$.

Although we attribute the phonon signal $\Delta I_i(V)$ to phonon-assisted tunneling it seems likely that the majority of the absorbed phonons induce transitions within the emitter rather than between the emitter and the well. Tunneling from unthermalized excited electrons would be difficult to distinguish from phonon-assisted tunneling. However, since the tunneling rate is estimated to be appreciably smaller than the electron-electron scattering rate, most of the excited electrons are thermalized before they can tunnel. The resulting rise in temperature can be estimated from the fraction $\sim 7.5 \times 10^{-4}$ of emitted phonons falling on the DBRTD. If the substrate were at 4.2 K, the phonon intensity falling on the DBRTD would rise, when the heater temperature is raised to 8.5 K, by $7.5 \times 10^{-4}(8.5/4.2)^4 \sim 1.2\%$. So, if the DBRTD emitter had an emissivity of 1, its temperature T_e would rise by $\sim 0.3\%$, which is 12 mK. However, since the emitter emissivity to phonons of this frequency and incident angle is estimated to be $\leq 1 \times 10^{-2}$ [14], the rises in T_e will be ≤ 0.1 mK and ≤ 0.01 mK for $T_h = 8.5$ and 5.0 K, respectively. It seems very unlikely that such small changes could produce the signals seen or could lead to linear dependences in their position with T_h, since T_e should vary as T_h^4.

Further evidence suggesting that the phonon peak is due to phonon-assisted tunneling rather than a temperature rise of the two-dimensional electron gas emitter comes from equilibrium measurements of $I(V)$. Figure 4 shows that the difference in the equilibrium value of the tunnel current for substrate temperatures of 4.2 and 1.3 K, $\Delta I(V) = I_{4.2} - I_{1.3}$, has a peak at 398 mV. This equals, to within experimental error, the voltage at which the phonon peak would occur for a heater at 4.2 K (with the substrate at $T \ll 4.2$ K) as can be seen by extrapolating the line in Fig. 3 (measurements on another sample confirmed that the peak moves linearly with substrate temperature as expected). Now when the substrate is at 4.2 K, the phonon intensity at the DBRTD is ~ 60 times larger $[\sim 60 \times 600/(400)^2 \times 4\pi]$ than when the phonons are coming from a heater at 4.2 K with the substrate at a much lower temperature. So clearly the position of the peak is independent of the intensity and only depends on the frequency of the incident phonons. This is consistent with phonon-assisted tunneling but not with a heating process. The size of the peaks should, however, be proportional to intensity, and this can be checked from the size of the signals in Fig. 4. The signal from a heater at 5.0 K is smaller by ~ 20 than the difference peak $I_{4.2} - I_{1.3}$ so that from a heater at 4.2 K would be ~ 40 times smaller, in reasonable agreement with the estimated ratio of intensities of ~ 60.

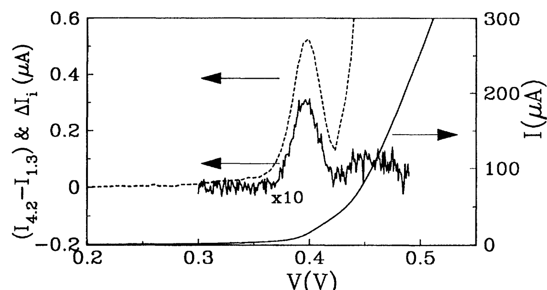

FIG. 4. The broken curve shows the difference, $I_{4.2} - I_{1.3}$, in the $I(V)$ characteristics for substrates at temperatures of 4.2 and 1.3 K. The two solid lines show the peak $\Delta I_i(V)$ produced by a phonon pulse from a heater at 5.0 K and the $I(V)$ characteristic at 4.2 K.

The linear dependence on phonon energy of the bias voltage at which the phonon peak occurs evidently does not extend to zero energy, $T_h = 0$, since this would lead to a bias voltage for the impurity peak $I_i(V)$ 15 mV less than that observed. We tentatively attribute this difference to a decrease in the donor binding energy by ~ 5 meV $(dV_b/dV \sim 1/3)$ caused by an increase in the number of mobile electrons in the well with increasing bias voltage. At low voltages the number of electrons in the confined states in the well will be too small, compared with the number of donors, to produce significant screening of the donor charge, but this will no longer be the case at higher voltages. For this to account for the departure from linear dependence in the voltage range 397−415 mV, the sheet density of the electrons in the well n_e must be comparable to or more than that of the donors n_d at 415 mV but significantly less at 397 mV. n_e is related to the tunnel current by $n_e = I\tau/Ae$, where A is the area of the DBRTD and τ is the tunneling time through the collector barrier, which for this structure we estimate to be $\sim 8 \times 10^{-11}$ s. So at 415 mV, where the tunnel current is 30 μA, $n_e \sim 6 \times 10^9$ cm^{-2}, but this falls to $\sim 3 \times 10^9$ cm^{-2} at 397 mV, where $I = 15$ μA. n_d can be estimated by comparing the size of the impurity peak $I_i = 2$ μA with the value $I_i = 1$ μA (adjusted for the difference in areas) from a comparable structure in which n_d was δ doped to 4×10^9 cm^{-2} [9]. The barriers of the present structure are thinner by 1 monolayer, and if allowance is made for this, the two values of I_i become very similar, suggesting the value of n_d in the present sample must also be $\sim 4 \times 10^9$ cm^{-2}, very comparable to the estimated values for n_e. It therefore seems reasonable to conclude that the shift in the position of the phonon peak takes place when the low current condition $n_e < n_d$ is replaced by the higher current condition $n_e > n_d$ leading to the screening of the donor potential and an increase in the energy of the impurity level.

The DBRTD remains sensitive to phonons in magnetic fields parallel to the direction of current, and Fig. 5 shows the field dependence of the phonon signal ΔI for $T_h = 8.5$ K. The bias voltage is held fixed at 400 mV, close

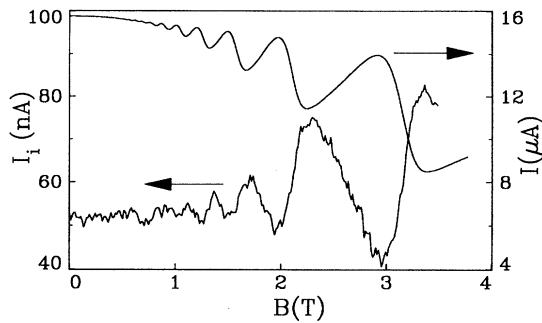

FIG. 5. The lower curve shows the change in current $\Delta I_i(V)$ produced by phonons from a heater at 8.5 K as a function of magnetic field B parallel to the current. The bias voltage $V = 400$ mV. The upper curve shows the oscillations in tunnel current I at the same bias voltage.

to the phonon peak in zero magnetic field, while the field parallel to the current is increased from 0 to 5 T. The upper curve shows the oscillations that occur in the tunnel current, and the lower curve shows the oscillations in phonon signal ΔI_i. The periods are the same but there is a striking difference in phase: the phonon signal falling to a minimum at the maximum in tunnel current. The current is dominated by off-resonance tunneling into the confined states for which $\Delta k_{\parallel} \neq 0$, and the largest contributions seem likely to be from the highest occupied states since they are closest to resonance. So the magneto-oscillations in resonant tunnel current should be due to oscillations in the density of states at the Fermi energy [1]. The phonon signal, however, is presumably due to phonon-assisted tunneling into the impurity state from all electrons of energy ≤ 6 meV, and the number of these should vary rather weakly with field. However, the transition probability of the phonon-assisted tunneling process is reduced by screening, so it will oscillate out of phase with the density of states at the Fermi surface leading to the out of phase oscillations seen in ΔI_i. Measurements are in progress to investigate the field dependence in more detail as a function both of bias voltage and of the angle between the field and the current.

We conclude that the change in tunnel current in a DBRTD produced by a nonequilibrium phonon pulse is caused by phonon-assisted tunneling. The variation in position of the signal with phonon frequency shows that, for bias voltages in the region of the phonon signal, $dV_b/dV \sim 1/3$ similar to its value in the region of the satellite peak due to LO phonon-assisted tunneling. The device may be useful as a phonon spectrometer. The resolution of the present arrangement is rather modest, however, and improvements on this may depend on whether it is possible to use the main tunnel peak where the in-plane momentum selection rule is stronger than for the impurity tunneling. If it is, the DBRTD should also be usable as a spectrometer in magnetic fields because of the conservation of Landau level index. Use of the main peak in both zero and nonzero magnetic fields will probably require the use of aymmetric structures to avoid the bistability of the present structure.

We are very grateful to Professor L Eaves and Dr. T. M. Fromhold for valuable discussions, Dr. A. V. Akimov and D.N. Hill for help with experiments, and to the Engineering and Physical Sciences Research Council for financial support.

---

*EPSERC visiting Fellow and on leave from Ioffe Physical Technical Institute, 194021 St. Petersburg, Russia.

[1] F. Capasso, S. Sen, F. Beltram, and Y. Y. Cho, in *Physics of Quantum Electron Devices,* edited by F. Capasso, Springer Series in Electronics and Photonics (Springer-Verlag, Berlin, 1990), Vol. 28, p. 181.
[2] V. J. Goldman, D. C. Tsui, and J. E. Cunningham, Phys. Rev. B **36**, 7635 (1987).
[3] N. S. Wingreen, K. W. Jacobsen, and J. W. Wilkins, Phys. Rev. Lett. **61**, 1396 (1988).
[4] M. L. Leadbeater, E. S. Alves, L. Eaves, M. Henini, O. H. Hughes, A. Celest, J. C. Portal, G. Hill, and M. A. Pate, Phys. Rev. B **39**, 4338 (1989).
[5] F. Chevoir and B. Vinter, Appl. Phys. Lett. **55**, 1859 (1989).
[6] C. H. Grein, E. Runge, and H. Ehrenreich, Phys. Rev. B **47**, 12 590 (1993).
[7] J. W. Sakai, T. M. Fromhold, P. H. Beton, L. Eaves, M. Henini, P. C. Main, and F. W. Sheard, Phys. Rev. B **48**, 5664 (1993).
[8] G. Bastard, *Wave Mechanics Applied to Semiconductor Heterostructures* (Les Editions de Physique, Paris, 1990), Chap. IV.
[9] M. Henini, J. W. Sakai, P. H. Beton, L. Eaves, and P. C. Main, J. Vac. Sci. Technol. B **11**, 958 (1993).
[10] M. W. Dellow, P. H. Beton, C. J. G. Langerak, T. J. Foster, P. C. Main, L. Eaves, M. Henini, S. P. Beaumont, and C. D. W. Wilkinson, Phys. Rev. Lett. **68**, 1754 (1992).
[11] W. Kappus and O. Weiss, J. Appl. Phys. **44**, 1947 (1973).
[12] M. T. Ramsbey, S. Tamura, and J. P. Wolf, Phys. Rev. B **46**, 1358 (1992); time of flight measurements on samples from the same wafer show a behavior consistent with this.
[13] A. J. Kent (private communication).
[14] P. J. Price, Physica (Amsterdam) **134B**, 164 (1985).