EFFECTS OF LOCALIZED PHONON MODES ON ELECTRONIC TRANSPORT IN GaAs/AlAs DOUBLE BARRIER STRUCTURES

P. J. Turley, C. R. Wallis and S. W. Teitsworth
Department of Physics
Duke University
Durham, NC 27706

Abstract

Experimental current-voltage measurements have been performed at 4.2K on asymmetric GaAs/AlAs double barrier structures (with device layer widths 33Å - 80Å - 45Å) which also incorporate large spacer layers with graded doping profile. The samples possess unusually large satellite peaks in the valley current due to phonon-assisted tunneling. These large currents are well-explained by a relatively simple calculation which includes the effects of optical phonon localization using a dielectric continuum model. Symmetric interface modes (with the energy of bulk AlAs optical phonons, 50.1 meV) and confined modes in the well (with the energy of bulk GaAs optical phonons, 36.2 meV) are found to dominate the phonon-assisted tunneling current.

It has been suggested that in GaAs/AlAs heterostructures optical phonons can become localized, either in one of the semiconducting layers (confined phonons), or near the interface between two layers (interface phonons) [1-3]. Unfortunately, experimental data which can provide direct evidence of phonon localization or the interaction of localized phonons with electrons is mostly limited to optical measurements, which cannot always provide the information needed to calculate the effect of localized phonons on electronic transport [2,3].

One process which can provide information about localized phonons through purely electronic measurements is phonon-assisted tunneling in double barrier structures. Recent experiments have noted satellite peaks in the current through double barrier structures for voltages just above the main resonant tunneling peak, and have attributed these peaks to phonon-assisted tunneling [4–9]. When a magnetic field is applied parallel to the current, it becomes clear that at least two types of phonons participate in the reaction, one with an energy of bulk GaAs phonons, 36.2 meV, and the other with an energy of bulk AlAs phonons, 50.1 meV [5-7]. Phonon-assisted tunneling should provide a good experimental determination of certain properties of localized phonons. Phonon energies can be estimated, and since at least two different types of phonon participate in the reaction, comparing the magnitudes of the current peaks may give relative phonon-electron couplings. The most commonly used model of localized phonons is the dielectric continuum model, a macroscopic model of localized phonons which has been shown to approximate more detailed microscopic models accurately [1-3]. In this paper, we will show that the dielectric continuum model can give calculated current-voltage curves in quantitative agreement with experiments in asymmetric structures.

In the phonon-assisted tunneling process, electrons in the emitter are coupled with the resonant state in the well through the emission of an optical phonon [9-13]. The phonon emission rate is calculated using a golden rule approach with the appropriate electron-phonon interaction Hamiltonian, which is derived with the dielectric continuum model [1]. In previous papers we have predicted and shown that two types of phonons are preferentially emitted during phonon-assisted tunneling: confined modes in the well, with energy 36.2 meV, and symmetric interface phonons, with energy of 50.1 meV in the long wavelength limit

[9,11-13]. The emission rate must be placed into an appropriate current formula, which depends strongly on the nature of the electronic states in the emitter. In typical calculations a three-dimensional density of states is used [10-13]. In most experimental structures, however, large spacer regions will result in a large amount of band bending, leading to the formation of a quasi-bound state in the emitter with a two-dimensional density of states. The current density is then given by

$$J(V) = \frac{e}{A}\int W(E_z,k_{\parallel};V)\, g_e(k_{\parallel})\, f_e(E_z,k_{\parallel})\, dk$$

where E_z is the z-directional energy of the quasi-bound state in the emitter, $k_{\parallel}$ is the momentum of the initial electron projected onto the plane of the interfaces, $W(E_z,k_{\parallel};V)$ is the total emission rate, $g_e(k_{\parallel}) = 2(A/(2\pi)^2)$ is the density of states in the emitter, A is the cross-sectional area of the device, and $f_e(E_z,k_{\parallel})$ is the Fermi distribution of electrons in the emitter.

We have self-consistently calculated E_z and the Fermi energy E_F, using a simple approximation scheme. Given the electric field $\mathcal{E}$ in the emitter barrier, the energy of the lowest quasi-bound state is calculated using the triangular well approximation $E_z \approx 2.338\,(\hbar^2/2m)^{1/3}\,(e\mathcal{E})^{2/3}$, where E_z is measured relative to the bottom of the triangular well. Then, assuming that the electric field is completely screened by the electrons in the lowest quasi-bound state, the Fermi energy at T = 0 is given by $E_F = \pi\hbar^2 e\mathcal{E}/(em^*)$. Since the experimental current densities are reasonably small we assume that the effect of current flow on occupation factors is negligible. The voltage drop across the collector spacer layer is calculated using the depletion layer approximation. While this approximation scheme may seem relatively simplistic, is gives close predictions for the onset of resonant tunneling in the structure given here and in others we have investigated.

The experimental double barrier structure was grown by molecular beam epitaxy (MBE) on a n^+ GaAs (100)-orientated substrate by P.K. Bhattacharya and W. Li at the University of Michigan. The core of the structure consists of an 80 Å undoped GaAs well surrounded by a 33 Å undoped AlAs barrier on the emitter side and a 45 Å undoped AlAs barrier on the collector side. On either side of the device are 950Å spacer layers with a doping graded up to 1×10^{18} cm^{-3}. Results shown here are for 500 μm diameter mesas. Current-voltage (I-V) curves were measured using a four-terminal circuit with the sample immersed in liquid helium at 4.2 K. Current was measured by monitoring the voltage across a 1.00 Ω series resistance.

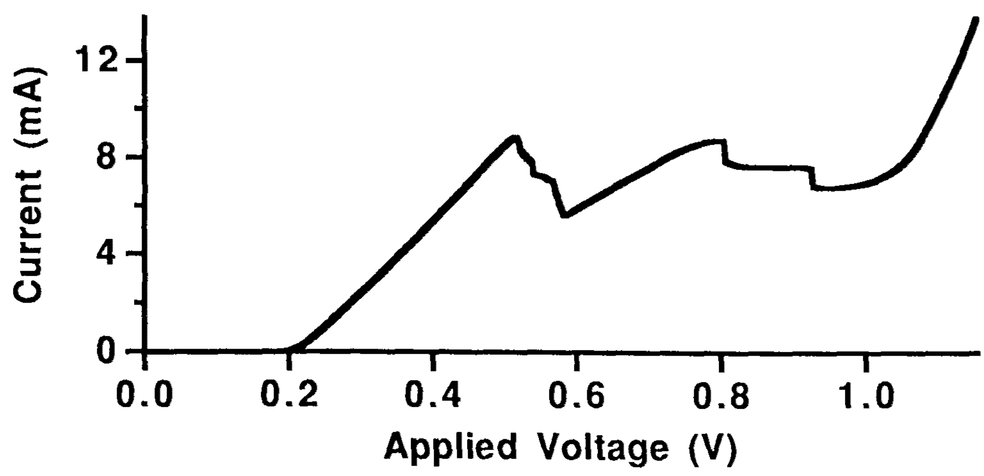

Fig. 1 - Experimental current-voltage curve in the forward bias direction, i.e. the 33 Å barrier as the emitter barrier.

Figure 1 shows a typical experimental I-V curve for these samples at 4.2 K in the forward bias direction, i.e., the 33 Å barrier as the emitter barrier. The presence of this unusually large phonon-assisted tunneling peak at 0.8 V is due in part to the unequal barrier layer thicknesses. In typical structures the ordinary resonant tunneling current is dependent on the thicknesses of both the emitter and collector barriers. The phonon-assisted tunneling current, however, is essentially dependent on the thickness of the emitter barrier alone. The thickness of the collector barrier will only become important if it is thick enough to cause a significant amount of charge build-up in the well, filling up the resonant electronic states and inhibiting the phonon emission process. The plateaus observed in the I-V curves for voltages just above the resonant tunneling peak and the phonon-assisted tunneling peak correspond to time-averages of the oscillating current.

Figure 2(a) shows an expansion of the I-V curve of Fig. 1, focusing on the phonon-assisted tunneling peak. The calculated I-V curve in Fig 2 (b) includes the direct phonon-assisted tunneling contribution discussed above and several other effects which will be important in real devices. For instance, the quasi-bound state in the emitter will have a small width in energy due to scattering in the emitter layer and the coupling to the resonant state in the well. For this calculation we assume a broadening of 10 meV [15].

In addition, there are other processes which can lead to an excess current. For the voltage range 0.6 V – 0.8 V we believe that the most important of these is quasi-elastic scattering by acoustic phonons, which also couples the quasi-bound state with the resonant state. Other processes such as Γ to X conversion in the AlAs barriers and ionized impurity scattering can also lead to excess current, but are not as important in the range of interest. We model the excess current due to acoustic phonon emission by adding a constant background current of 3.8 mA to our calculation in order to bring the calculated and experimental peak heights to the same value.

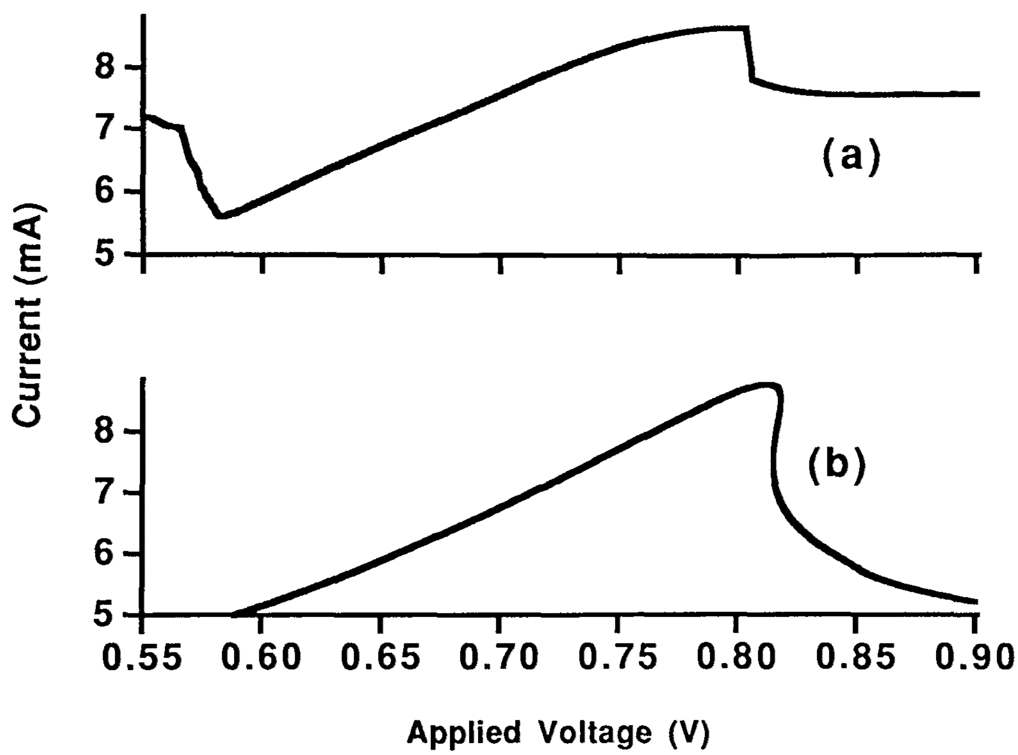

Fig. 2 - Comparison of the experimental phonon-assisted tunneling current versus dielectric continuum model prediction. (a) Expanded view of the experimental current-voltage curve of Fig. 1, focusing on the phonon-assisted tunneling region. (b) Calculated excess current.

Parasitic resistances in the device will also distort the experimental I-V curve [15]. Any real device will contain resistance associated with the contacts or in the lightly doped spacer region. The value of this resistance may be determined from the maximum value of the slope of the resonant tunneling peak. Using this we find a resistance of 31 Ω, a value that is independently confirmed with the magnetotunneling data [14].

Incorporating these effects into the phonon-assisted tunneling calculation results in Fig 2 (b). The voltages of the peak current in Figs. 2 (a) and (b) are remarkably close (0.80 Volts vs. 0.81 Volts) as are the slopes of the two curves. On the other hand, some interesting discrepancies remain between Figs 2(a) and (b). Perhaps the most striking of these is that the experimental curve has a broad concave-down region near the maximum of the phonon-assisted tunneling current, while the theory peak is considerably sharper. This difference could be due to the approximations implicit in the dielectric continuum model of localized phonons and may also be due to imprecise modeling of the quasi-bound emitter state.

In conclusion, we have measured the valley current in asymmetric GaAs/AlAs double barrier structures. The measured current is in close agreement with a simple model which includes the effects of localized phonons on phonon-assisted tunneling within a dielectric continuum model. The symmetric interface phonons (with the energy of bulk *AlAs* LO phonons) have been observed to dominate the phonon-assisted tunneling current with confined well phonons (with the energy of bulk *GaAs* LO phonons) also contributing significantly.

We thank Michael A. Stroscio for helpful conversations. This work has been supported by the National Science Foundation through Grant No. DMR - 9157539.

References

1. N. Mori and T. Ando, Phys. Rev. B **40**, 6175 (1989).
2. J. Menéndez, J. Luminescence **44**, 285 (1989).
3. P. Lugli, E. Molinari, and H. Rüker, Superlatt. Microstruct. **10**, 471 (1991).
4. V. J. Goldman, D. C. Tsui, and J. E. Cunningham, Phys. Rev. B **36**, 7635 (1987).
5. M. L. Leadbeater, E. S. Alves, L. Eaves, M. Henini, O. H. Hughes, A. Celeste, J. C. Portal, G. Hill, and M. A. Pate, Phys. Rev. B **39**, 3438 (1989).
6. G. S. Boebinger, A. F. J. Levi, S. Schmitt-Rink, A. Passner, L. N. Pfeiffer, and K. W. West, Phys. Rev. Lett. **65**, 235 (1990).
7. J. G. Chen, C. H. Yang, M. J. Yang and R. Wilson, Phys. Rev. B. **43**, 4531 (1991).
8. Y. Galvao Gobato, F. Chevoir, J. M. Berroir, P. Bois, Y. Guldner, J. Nagle, J. P. Vieren, and B. Vinter, Phys. Rev. B **43**, 4843 (1991).
9. P. J. Turley, C. R. Wallis, S. W. Teitsworth, W. Li and P. K. Bhattacharya, submitted to Appl. Phys. Lett.
10. F. Chevoir and B. Vinter, Appl. Phys. Lett. **55**, 1859 (1989).
11. P. J. Turley and S. W. Teitsworth, Phys. Rev. B **44**, 8181 (1991).
12. P. J. Turley and S. W. Teitsworth, Phys. Rev. B **44**, 12959 (1991).
13. P. J. Turley and S. W. Teitsworth, submitted to J. Appl. Phys.
14. P. J. Turley, C. R. Wallis and S. W. Teitsworth, W. Li, and P. K. Bhattacharya, unpublished.
15. J. Chen, J. G. Chen, C. H. Yang and R. A. Wilson, J. Appl. Phys. **70**, 3131 (1991).