Electrical studies of charge build-up and phonon-assisted tunneling in double-barrier materials with very thick spacer layers

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Double barrier heterostructure materials containing very thick, low-doped layers adjacent to the barriers have been studied. In particular, charge build-up in the quantum well has been investigated along with the effects on this of a magnetic field perpendicular to the barriers. Phonon-assisted tunneling has also been observed from both localized and delocalized states in the emitter.

For many years it has been realized that the performance of double-barrier material can be enhanced by undoped[1] or lightly doped[2] spacer layers adjacent to the barriers, which act both to reduce the capacitance of the devices and to prevent excessive diffusion of dopant atoms into the barrier and well layers. Such spacer layers typically range between 1.5 and 50 nm in thickness; while thin layers show few other effects, thicker spacer layers can have more far-reaching consequences. The light doping allows band bending to occur, leading to appreciable charge accumulation on the emitter side of the barriers and depletion on the collector side of the barriers.[3] The band bending in the emitter can be sufficient to form a triangular quantum well on the outside of the emitter barrier,[4] in which case tunneling occurs from two dimensional (2D) localized states in the emitter rather than from the more usual 3D Fermi sea.

Recently, interest has been shown in the fabrication of variable-area resonant tunneling diodes (RTDs)[5–7] and such devices require materials in which the low-doped layers adjacent to the barriers are of much greater thickness. We might therefore expect that such materials would exhibit similar but more extreme properties to those found in more conventional structures containing spacer layers. This communication reports new results found during an investigation into two such materials containing highly doped *n*-type contact layers at 5×10^{18} cm^{-3}, with the doping concentrations being lowered over several layers to 1×10^{16} cm^{-3} close to the barriers. The graded doping is similar in both, with the principal difference being the thicknesses of the barrier and quantum-well layers which affects the mean lifetime of the electrons in the well. The details of the low-doped and active layers are as follows: material 1 (short lifetime) -380 nm 1×10^{16} cm^{-3} GaAs, 4.2 nm undoped GaAs, 4.2 nm undoped AlAs, 6.0 nm undoped GaAs, 4.2 nm undoped AlAs, 4.2 nm undoped GaAs, and 380 nm 1×10^{16} cm^{-3} GaAs; material 2 (long lifetime) -350 nm 1×10^{16} cm^{-3} GaAs, 10.0 nm undoped GaAs, 5.0 nm undoped AlAs, 7.0 nm undoped GaAs, 5.0 nm undoped AlAs, 10.0 nm undoped GaAs, and 350 nm 1×10^{16} cm^{-3} GaAs. Experiments were performed on 2-terminal RTD devices fabricated by wet chemical etching of circular mesas with diameters between 6 and 20 μm.

The current-voltage (*I-V*) characteristics for 12-μm-diam devices in forward bias are shown for each material in Fig. 1, with the reverse-bias characteristics being very similar. This shows results for upward (solid line) and downward (dashed line) sweeps of the voltage, with a large amount of hysteresis being apparent. There are several possible reasons for such bistability. The most basic, the effect of series contact resistance, can be discounted both from other measurements of the contact resistances and from the similarity of the hysteresis curves despite the large difference in currents involved. The other two possibilities, parasitic oscillation[8] and charge build-up[9] are harder to distinguish but, for reasons outlined below, we attribute the hysteresis seen here to charge build-up.

The application of a magnetic field perpendicular to the barriers splits any accumulated charge in the emitter into Landau levels, and this can be used to measure the amount of charge present.[9] Magneto-conductance measurements have been performed for various fixed biases, and the results of these for material 2 are given in Fig. 2. This shows that the charge accumulated in the emitter remains roughly constant from 300 mV up to the resonance voltage of 650 mV, at which it undergoes a step increase by a factor of 1.4 corresponding to the device switching off-resonance. Similar results were obtained for material 1. Such a result is entirely consistent with charge build-up in the quantum well. Accumulation of charge in the well acts to screen the emitter barrier from the increasing electric field across the collector, and while this is occurring the charge accumulation in the emitter remains constant. However, once the device switches off resonance, all charge is lost from the quantum well and, due to electrostatic feedback, the increase in the emitter accumulated

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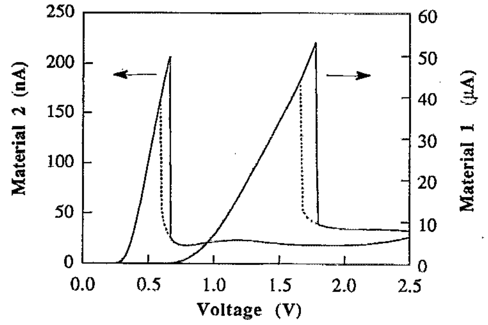

FIG. 1. *I-V* characteristics of the two materials used in these experiments at 4.2 K. Note the different current scales.

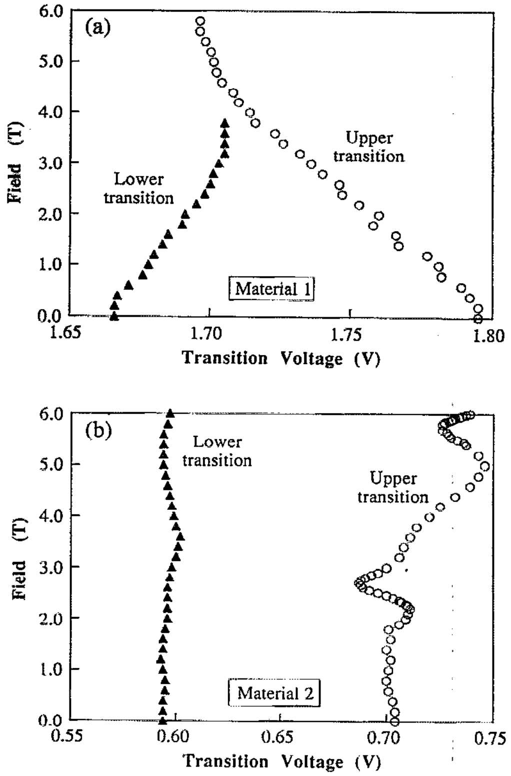

FIG. 3. Transition voltages vs magnetic field for (a) material 1 and (b) material 2 at 4.2 K showing the magnetic field dependence of the hysteresis.

charge should match that lost from the well. For equal barrier transparencies the accumulation in the well is just half that in the emitter, so the step change should be by a factor of 1.5, in good agreement with that observed.

Figure 3 shows the effect of a magnetic field applied perpendicular to the barriers on the hysteresis in the *I-V* characteristics. Results similar to those seen in material 2 have been observed by Eaves *et al.*[10] who attributed the increase in the hysteresis with applied field to rapid inter-Landau-level scattering in the quantum well leading to an increase in the effective density of states. This increases the capacity of the well to store charge without affecting the emitter barrier, so that a greater screening of the applied potential can occur. For such a mechanism, the periodic structure observed should be associated with the filling of the Landau levels in the emitter. Electrons tunnel from the emitter into empty states in the quantum well from which they may relax. The number of empty states available to receive tunneling electrons therefore depends upon the number of occupied (or partially occupied) Landau levels in the emitter and the occupation of the levels in the well. As each successive Landau level in the emitter becomes depopulated, the number of the empty states in the well aligned with occupied levels in the emitter is reduced, and so we expect a minimum in the field-dependent hysteresis. Thus the minima in the hysteresis versus field curve should correspond to filled Landau levels in the emitter. The minima occur at 2.7 and 5.7 T and, assuming an electron density of 2.6×10^{11} cm^{-2} in the emitter (10% higher than that previously measured), these values correspond to 0.96 and 2.02 filled Landau levels. The agreement is not expected to be exact since the charge build-up in the accumulation region is both bias and field dependent.

In the case of material 1, magneto-conductance measurements give an electron density of 3.7×10^{11} cm^{-2} in the emitter, and so minima might be expected at 3.8 and 8.1 T. However, no such enhanced hysteresis is seen. For the mechanism described above to hold, it is necessary for there to be time for the electrons in the quantum well to undergo inter-Landau-level transitions. Ferreira and Bastard[11] give a lifetime of order 2×10^{-10} s for intrasubband acoustic phonon transitions in similar systems, and the electron lifetimes have been measured to be 5×10^{-10} s and 1×10^{-7} s for materials 1 and 2, respectively. Thus, for material 2 the lifetime in the well is indeed much longer than the transition lifetime, while for material 1 the lifetimes are similar, consistent with the lack of enhancement of the hysteresis. Hence the contrasting properties of the two materials can be explained by the proposed mechanism and the different carrier lifetimes due to the different barrier thicknesses.

Both of the materials show distinct features in their valley currents from phonon-assisted tunneling[12,13] and the position of these versus a magnetic field perpendicular to the barriers is shown for material 2 in Fig. 4. Various definite trends can be seen on the fan diagram, as indicated by the lines which have been added in accordance with the energy conservation equation.[12] The energy scale beneath

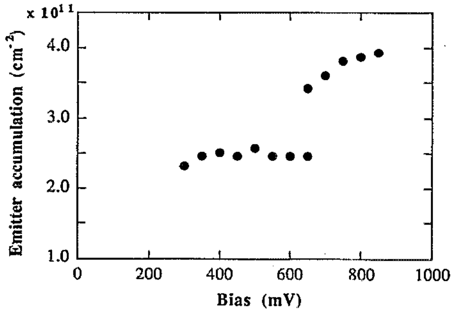

FIG. 2. Charge build-up in the emitter accumulation region for material 2 at 4.2 K measured from magneto-conductance oscillations.

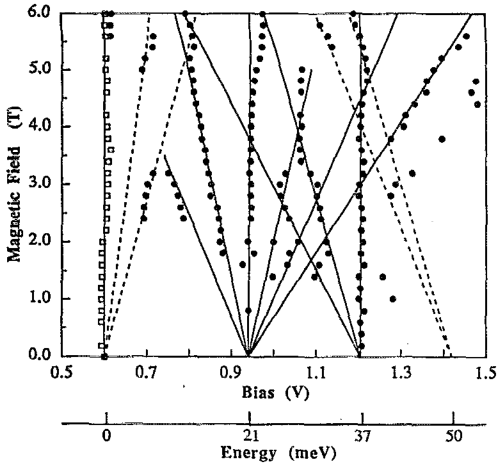

FIG. 4. Positions of features due to phonon-assisted tunneling in material 2 at 4.2 K plotted vs the magnetic field applied perpendicular to the barriers. The energy scale has been added according to the energy conservation equation (see Ref. 12).

the graph has also been added in accordance with the conservation equation so as to be consistent with both the position of the zero-field intercepts and the spread of the fans.

The experimental points do show good agreements with the theoretical lines. At zero field, tunneling can be mediated by either a GaAs-type phonon (37 meV) or an AlAs-type phonon (50 meV), and can occur from the 2D state in the emitter (0 meV) or from the 3D states in the emitter close to the Fermi energy (−15 meV). Combinations of these give the zero-field intercepts of 21, 37, and 50 meV seen in the diagram. The fan structures result from tunneling between Landau levels of different index, and should correspond to either the GaAs cyclotron energy (solid lines) or the AlAs cyclotron energy (dashed lines). The theoretical lines on the fan diagram agree well with the experimental results, either as definite trends in the peak positions or as perturbations on the larger peaks, with phonon-assisted tunneling being observed both from the 3D states just below the Fermi energy and the 2D localized states in the emitter. The energy difference between the bottom of the 3D states and the main 2D level in the emitter measured by this method is 15 meV. By comparing this with the energy difference of 20 meV between the 2D level and the Fermi energy at this bias (derived from magneto-conductance measurements) we can infer that the 3D states have a width of approximately 5 meV.

In conclusion, we have reported an investigation into double-barrier materials containing very thick low doped layers adjacent to the barriers. Studies into the enhancement of the hysteresis in the *I-V* characteristics by a perpendicular magnetic field have confirmed a mechanism for this previously suggested by Eaves *et al.*[10] Phonon-assisted tunneling has also been observed from both localized and delocalized states in the emitter.

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