

## RESONANT TUNNELING IN DOUBLE SUPERLATTICE BARRIER HETEROSTRUCTURES

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We have investigated resonant tunneling in double barrier heterostructures in which the tunnel barriers have been replaced by short period superlattices, and have shown for the first time quantum well confinement in a single quantum well bounded by superlattices. These results also demonstrate the first utilization of short period binary superlattices as effective tunnel barriers to replace the conventional  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  barriers. The superlattice structure does not exhibit the asymmetry around zero bias in the electrical characteristics normally observed in the conventional  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  barrier structures, suggestive of reduced roughness at the inverted interface by superlattice smoothing. The superlattice barrier also exhibits an anomalously low barrier height. The performance of this symmetric superlattice structure is compared with an intentionally constructed asymmetric double barrier superlattice structure, which exhibits pronounced asymmetry in the electrical characteristics. The observed behavior supports the view that resonant enhancement occurs in the quantum well.

Negative differential resistance (NDR) devices utilizing double barrier resonant tunneling structures<sup>1</sup> have recently undergone a renaissance<sup>2-4</sup> due to improved GaAs-AlGaAs molecular beam epitaxy (MBE) techniques. In these devices, the essential carrier transport mechanism is electron (or hole) tunneling, specifically through ultrathin ( $\sim 50\text{\AA}$ )  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  tunnel barriers and a GaAs quantum well. This renewed interest has led to the observation of large room temperature peak to valley tunnel current ratios,<sup>4</sup> resonant tunneling of holes,<sup>5</sup> the observation of multiple negative differential resistance (NDR) peaks due to resonant tunneling<sup>6</sup> and the observation of sequential resonant tunneling through a multi-quantum well superlattice.<sup>7</sup>

Until now, investigation of this structure in the GaAs/AlGaAs system has been limited to quantum well confinement barriers that have a constant Al mole fraction. There exist a number of intriguing structures that can be fabricated with barriers that are tailored in real space. However, there exist practical constraints on the rate in which the Al mole fraction (i.e., the height of the barrier with respect to the GaAs conduction band) can be changed, thus limiting the structures that can be investigated. To solve the Al mole fraction gradient constraint, we have investigated the possibility of replacing the AlGaAs alloy barrier with a superlattice of fixed Al mole fraction. Thus, tailoring of the barrier height

reduces to a simpler problem of dimensional control of the superlattice layers.

We present the first study of such a heterostructure utilizing superlattice barriers, in this case binary superlattices. It should be pointed out that the additional degree of freedom of an Al mole gradient in a superlattice barrier structure adds tremendous superlattice miniband tailoring possibilities. This report is the first demonstration that a quantum well state can be created in the single quantum well structure with superlattices, and that confinement can be achieved with thin superlattices. Though quantum well confinement by superlattices has been previously investigated by photoluminescence,<sup>8</sup> the superlattices were much thicker, had a longer period, and was investigated in a multiple quantum well structure.

The samples used in this study were grown by molecular beam epitaxy in a Riber MBE-2300 on a 2-inch (100)  $n^+$  Si-doped Sumitomo GaAs substrate. The substrate was directly heated in a rotating substrate holder. Following a highly doped ( $n$ -type, Si @  $\sim 1 \times 10^{18} \text{ cm}^{-3}$ ) buffer layer, the active resonant tunneling structure region was then grown. For the alloy barrier structure, the undoped  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  barrier (50Å,  $x = .35$ ), undoped GaAs quantum well, and similar  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  barrier were then grown, followed by a similar top contact  $\sim 0.5$  micron thick. For the superlattice barrier structure, the same procedure was used, replacing the superlattices for the alloy

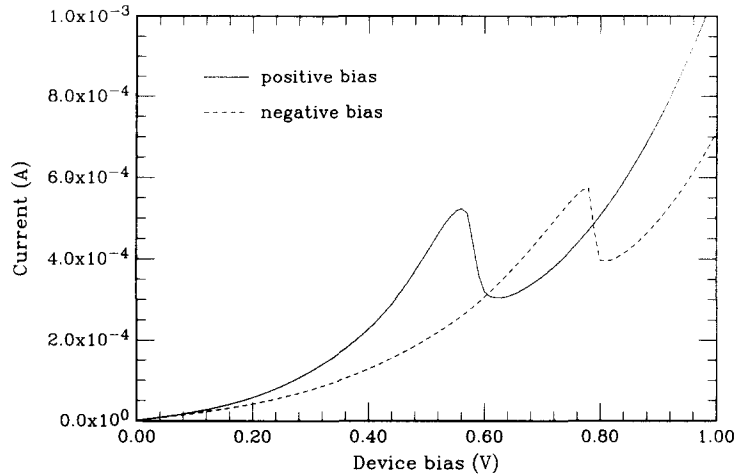


Figure 1. Current - voltage characteristics of a 50 Å GaAs quantum well / 50 Å Al<sub>0.35</sub>Ga<sub>0.65</sub>As double barrier heterostructure. The device mesa area =

25  $\mu\text{m}^2$  and  $T = 300^\circ\text{K}$ . Both positive and negative bias are shown for comparison. The asymmetry around zero bias is evident.

barriers. Devices were fabricated by defining mesas on the surface with conventional photolithography and microfabrication techniques, bonded for mechanical stability, and inserted into a variable temperature cryostat for measurements in the range 1.2°K to 300°K.

Figure 1 shows the static current-voltage (I-V) characteristics of a typical conventional alloy barrier, 50 Å wide quantum well resonant tunneling structure at 300°K. The structure exhibits a peak to valley tunnel current ratio of 1.75:1 (which increases typically to 7:1 at  $T > 100^\circ\text{K}$ ). For comparison purposes, the negative bias data has been reflected into the first quadrant. There exists a noticeable asymmetry in the electrical characteristics about zero bias. This asymmetry has been attributed to the inverted interface morphology of the quantum well and contact region.<sup>4</sup> This is consistent with our observations; positive bias implies electron injection from the superior backside GaAs contact. However, it is also possible to ascribe this asymmetry to dopant redistribution at the contacts due to the difference in diffusion times for the top and bottom contacts.

A superlattice barrier structure was fabricated and a cross-sectional TEM is shown in Figure 2. For this structure, each barrier consists of three 7 Å layers of AlAs and two 7 Å layers of GaAs. The GaAs quantum well width is 45 Å. Figure 3 shows the static current-voltage (I-V) characteristics of this structure at 300°K. The structure exhibits a peak to valley tunnel current ratio of 1.8:1. The symmetry for positive and negative bias is excellent. This implies that the inverted interface is indeed responsible for the observed asymmetry. The possibility of dopant diffusion through the structure has been eliminated by observing that, with the application of intense broadband light

there is negligible peak shift due to the effect of DX centers in the barriers.

The observed resonant bias positions can be compared with the theoretical predictions of a transfer matrix model<sup>9</sup> if the effects of the parasitic series resistances can be eliminated. However, there exists an unambiguous method to determine the energetic position of the quantum well state relative to the Fermi level of the contacts. Applying the technique of low bias thermal activation<sup>10</sup> to the double barrier structure, we see that the effective barrier height presented to the contact electrons is not the entire barrier but the nearby  $\Gamma$ -point of the quantum well state. This was applied to the 50 Å quantum well alloy barrier structure and is shown in Figure 4. This method gave an activation energy of 70 meV, which is in excellent agreement with a calculated value of 116 meV when adjusted for the energy of the Fermi level, approximately 50 meV.

The thermal activation analysis of the superlattice barrier structure is shown in Figure 5 for two different device mesa sizes. This gives a quantum well state of 121 meV. Using this energy to determine the energy of the effective barrier height  $\Delta E_c^*$ , assuming equal barriers and that the envelope function approximation for thick barriers is valid, we obtain a  $\Delta E_c^*$  of 290 meV. This was checked against comparing the transmitted resonant tunneling current densities of the superlattice barrier structure to the conventional alloy barrier structure. This gave a  $\Delta E_c^*$  of 240 meV. A monolayer fluctuation of the GaAs quantum well gave 275 meV, in good agreement with the envelope function approximation.

The superlattice barrier height is much lower than one would expect from a naïve averaged alloy composition of 0.60, which gives a barrier

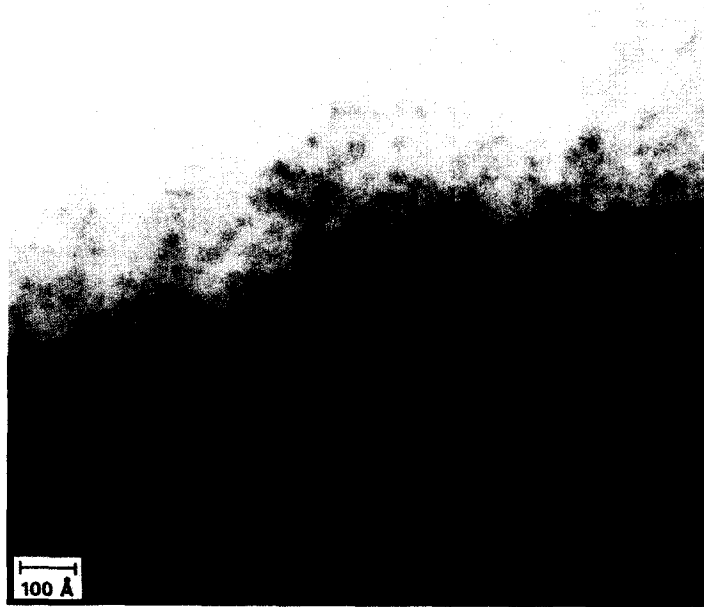


Figure 2. Cross-sectional TEM of the binary superlattice barrier resonant tunneling structure. The width of the quantum well is 45 Å and the widths of the two GaAs and three AlAs superlattice barrier components are 7 Å. I-V characteristic of a 100 Å quantum well resonant

tunneling device at 77°K. The peak at 150 mV is due to resonant tunneling through the ground state of the quantum well, and the peak at 1.45 V is due to resonant tunneling through the first excited state of the quantum well.

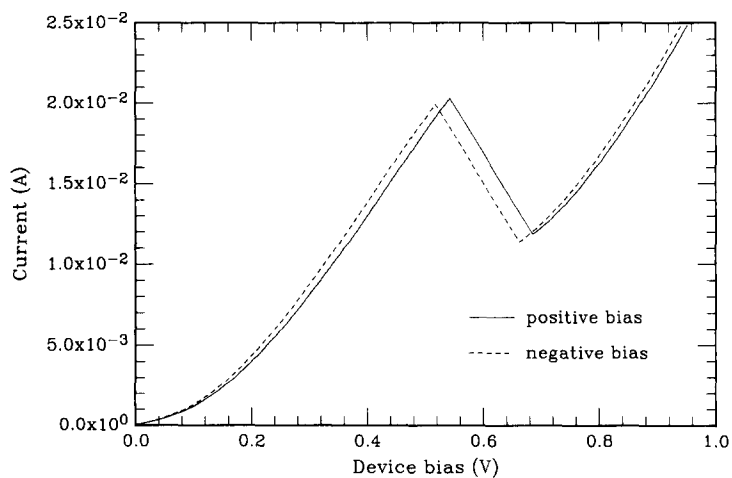


Figure 3. Current - voltage characteristics of the superlattice double barrier heterostructure. The device mesa area =  $25 \mu\text{m}^2$  and  $T = 300^\circ\text{K}$ . Both

positive and negative bias are shown for comparison. The symmetry around zero bias is excellent.

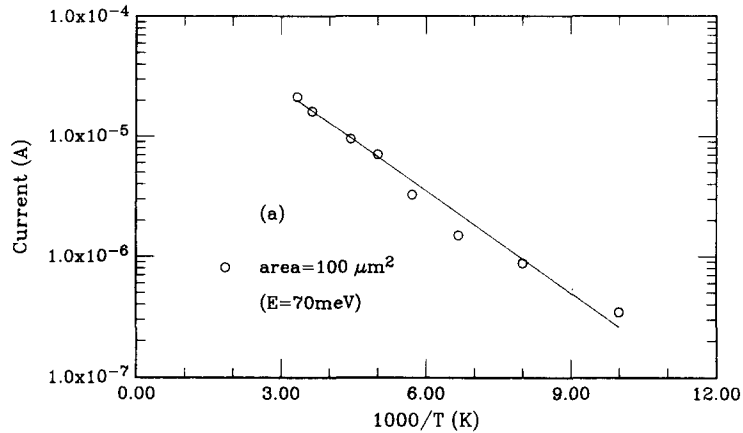


Figure 4. Low bias thermally activated current for the 50 Å alloy barrier structure. The device

mesa area = 100  $\mu\text{m}^2$ . The results are in excellent agreement with theory.

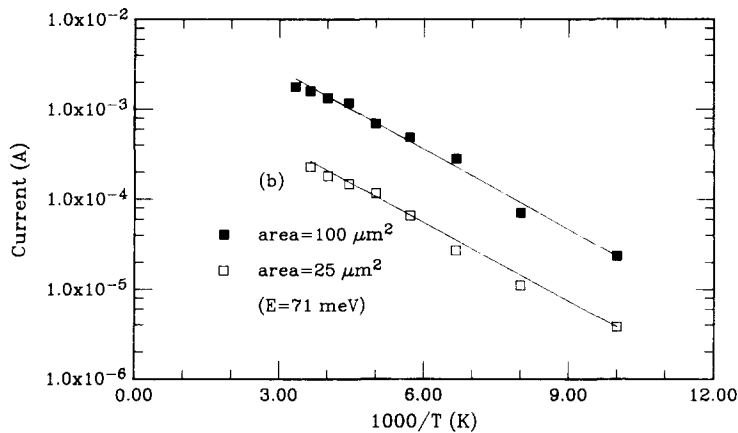


Figure 5. Low bias thermally activated current for the superlattice barrier structure. The device

mesa areas = 25  $\mu\text{m}^2$  and 100  $\mu\text{m}^2$ . The activation energy = 71 meV.

height of 587 meV. The observed barrier height of 290 meV is equivalent to an averaged alloy composition of 0.30. An envelope function approximation to a superlattice of infinite extent gives 677 meV for the conduction miniband edge. Thus, the superlattice barrier structure exhibits an anomalously low barrier height. The observation of an anomalously low barrier height is indicative of an enhanced evanescent tail.

We have also investigated a structure that has an asymmetric superlattice barrier construction. Figure 6 shows a cross-sectional TEM of the asymmetric binary superlattice barrier resonant tunneling structure. The 5 component superlattice barrier is the same as in the structure

discussed previously, but the "asymmetric" barrier has 7 Å AlAs component, a 7 Å GaAs component, and a 15 Å AlAs component. The width of the quantum well is 45 Å. This structure is intriguing since the effective barrier, going from the quantum well to the GaAs contact, slopes "up" with respect to the conduction band of the GaAs contact. This implies that (1) the I-V should be asymmetric; (2) the resonance should have a smaller peak to valley ratio going from the asymmetric barrier to the symmetric barrier than in the reverse direction.<sup>9</sup>

Figure 7 shows a static I-V measurement of the asymmetric resonant tunneling structure at 300°K. Positive bias corresponds to electron

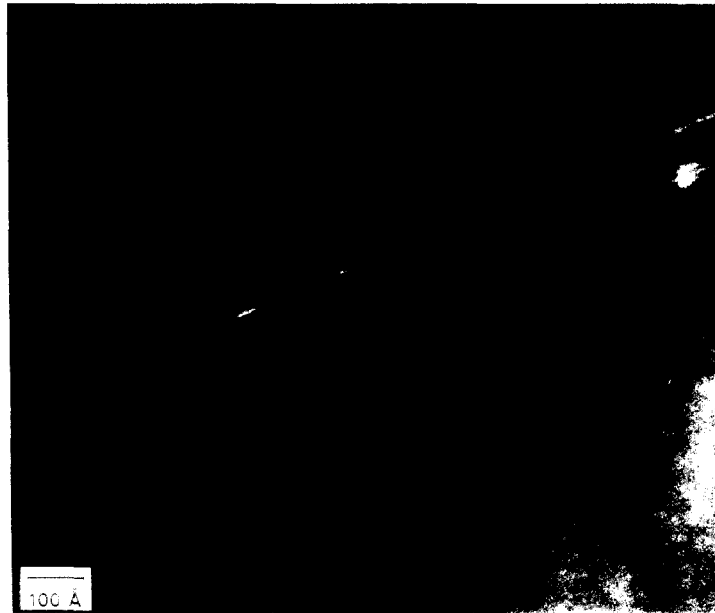


Figure 6. Cross-sectional TEM of the asymmetric binary superlattice barrier resonant tunneling structure. The width of the quantum well is 45 Å. The 5 component superlattice barrier has two

GaAs and three AlAs components of 7 Å each, and the asymmetric barrier has a 7 Å AlAs component, a 7 Å GaAs component, and a 15 Å AlAs component.



Figure 7. Current - voltage characteristics of the asymmetric superlattice resonant tunneling structure. The device mesa area =  $100 \mu\text{m}^2$  and  $T = 300^\circ\text{K}$ . Positive bias corresponds to electron injection first through the "asymmetric" barrier.

injection first through the "asymmetric" barrier. There exists negligible voltage difference in the peak positions, implying that the weighted barrier height at resonance is approximately the

same for both barriers. However, the peak to valley is quite different for the different bias directions. This observation supports the view that the observed negative differential resistance is due to resonant enhancement ("coherent" resonant tunneling) in the structure versus the recently proposed<sup>11</sup> model of sequential resonant tunneling.

In summary, we have investigated resonant tunneling in structures where the normal alloy barriers have been replaced by superlattices. The structures do not exhibit the asymmetry in the electrical characteristics seen in the alloy barrier structures, and have an anomalously low barrier height. An asymmetric superlattice structure exhibited different peak to valley ratios in opposite bias configurations, supporting the view that resonant enhancement does occur in double barrier structures.

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