

# Resonant tunneling in a GaAs/AlGaAs barrier/InGaAs quantum well heterostructure

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Resonant tunneling through a GaAs contact/double AlGaAs barrier/single InGaAs quantum well strained-layer heterostructure was investigated. The structure exhibits negative differential resistance up to 275 K due to tunneling through the first excited state of the quantum well. Comparison of the observed peak positions with theory indicates that the conduction-band offset of the AlGaAs/InGaAs heterojunction is nearly 100%. Using the magnetic field dependence of the current-voltage characteristics, we have measured the effective mass of an electron while transiting a multicomponent quantum well tunneling structure. An effective mass for electrons in the InGaAs quantum well of approximately half the bulk effective mass is obtained.

InGaAs/(Al,Ga)As strained-layer heterostructures have been extensively studied in recent years for both optical and electronic device applications. Laser diodes,<sup>1,2</sup> and recently InGaAs/AlGaAs modulation-doped field-effect transistors (MODFET's),<sup>3</sup> have been demonstrated. In this letter, we report a detailed investigation of the first reported<sup>4</sup> AlGaAs double barrier/single InGaAs quantum well resonant tunneling heterostructure. The ability to lower quantum well states with respect to GaAs contact layers (due to the higher electron affinity of InGaAs with respect to GaAs) is an important degree of freedom in tunneling device design. A previous investigation<sup>5</sup> of tunneling in a strained-layer heterostructure system exhibited catastrophic degradation upon thermal cycling. The high-temperature performance and stability of these strained-layer quantum well structures will be an important area of investigation.

The conduction-band diagram of the resonant tunneling structure at zero and applied resonant bias is illustrated in Fig. 1. The sample used in this study was grown by molecular beam epitaxy in a Riber MBE-2300 on a 2-in. (100)  $n^+$  Si-doped GaAs substrate. The structure consists of two undoped  $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$  barriers on either side of an undoped  $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$  quantum well. The active structure was clad between two 0.6- $\mu\text{m}$ -thick  $n^+$ -GaAs contact layers. Cross-sectional transmission electron microscopy of this structure revealed AlGaAs barrier thicknesses of 40 Å ( $\pm 10$  Å) and an InGaAs quantum well thickness of 60 Å ( $\pm 10$  Å). No misfit dislocations were found during an extensive search of the quantum well structure.

Devices ranging from 2 to 100  $\mu\text{m}^2$  were fabricated by defining mesas on the sample surface with conventional photolithography techniques. AuGe/Ni/Au Ohmic contacts covered the top surface of the mesa device. Variable temperature measurements were performed in a helium-flow Janis cryostat or in a stabilized oven for higher temperature measurements.

Figure 2 shows the temperature variation of the static current-voltage characteristics of a typical device. The struc-

ture exhibits a 2.6:1 peak-to-valley ratio at low temperatures, which starts to degrade at approximately 100 K, the same temperature at which conventional GaAs/AlGaAs alloy barrier structures also start to exhibit a degradation. Negative resistance persists up to 275 K, and to 300 K in a small number of devices. The absence of peak shift with temperature indicates the absence of any parasitic contact resistance. These devices were cycled repeatedly to low temperatures and did not show any thermal degradation that was noted in a similar strained-layer structure.<sup>5</sup>

The asymmetry in the electrical characteristics noted in the conventional GaAs/AlGaAs double barrier structures also appears in this structure. One unusual aspect of this structure not seen in the GaAs/AlGaAs structures is the negative thermal activation of low bias current<sup>6</sup> (i.e., decreasing current with increasing temperature), indicative that the quantum well state at zero bias does not lie below the Fermi level of the GaAs contact but above the GaAs conduction-band edge. This situation is achievable due to the negative conduction-band offset (with respect to the GaAs conduction band) of the InGaAs.

The expected resonant peak position was calculated by using a transfer matrix method<sup>7</sup> and is shown in Fig. 3 as a function of In fraction in the InGaAs quantum well. Two parameters which have a degree of uncertainty are the quantum well thickness (due to the attainable resolution of the cross-section micrograph) and the conduction-band offset of the AlGaAs/InGaAs heterointerfaces: these are treated as free parameters. We have used effective masses linearly extrapolated between the pure binary effective masses, a composition of 0.25 for the Al content and a 65% conduction-band offset for the GaAs/AlGaAs heterojunctions. The error bars in the observed peak position in the figure indicate the width of the experimental resonant peak (for all temperatures) and the uncertainty in the In fraction obtained from growth data.

The calculated peak positions have two sets of curves for a given set of parameters (AlGaAs/InGaAs conduction-band offset and quantum well width); the set at low In fraction corresponds to resonant tunneling through the ground state of the quantum well, whereas the high In fraction set corresponds to resonant tunneling through the first excited

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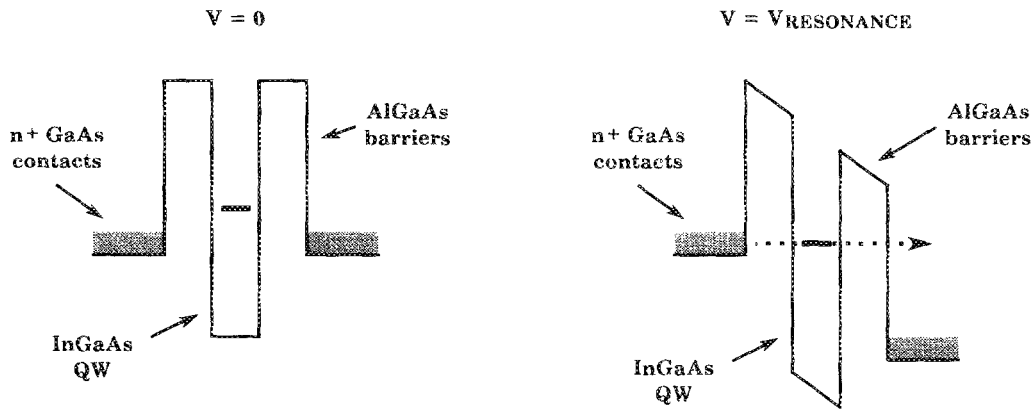


FIG. 1. Schematic conduction-band diagram for the GaAs contact/AiGaAs double barrier/InGaAs quantum well resonant tunneling structure under no bias (left) and resonant bias (right).

state of the quantum well. Clearly the observed peak is due to resonant tunneling through the first excited state. Additionally, it can be seen that the fit to a 60-Å well [labeled "100% (60 Å)"] is bad for any value of the conduction-band offset for the AlGaAs/InGaAs heterojunction (given in terms of the percentage of the band-gap difference that occurs in the conduction band). Using the maximum uncertainty in the well width (which gives 70 Å), we have plotted the fits for 100% conduction-band offset and 84% conduction-band offset (which had previously been measured in a GaAs/InGaAs heterojunction<sup>8</sup>). The observed peak position is quite bad for the 84% conduction-band offset, but is in excellent agreement with a maximum conduction-band offset of 100%. These measurements imply a InGaAs/AiGaAs conduction-band offset very close to 100%.

The presence of a multiple component system presents the unique opportunity to easily measure the effective mass of the tunneling electrons in the quantum well. Application of a magnetic field parallel to the current direction (perpendicular to the plane of the quantum well) offsets the  $N=0$  Landau level of the InGaAs quantum well with respect to the Fermi level in the GaAs contact due to the different effective masses of the two materials. Thus the resonant peak will shift with applied magnetic field, a mechanism that is physically distinct from the weak oscillations observed<sup>9</sup> in the binary component system where the effective mass is the

same in the contact and the quantum well. Treating the effective mass of the GaAs as known, the effective mass of the InGaAs quantum well electrons,  $m_{\text{InGaAs}}^*$ , can be expressed by

$$\frac{1}{m_{\text{InGaAs}}^*} = \frac{1}{m_{\text{GaAs}}^*} + \frac{2a}{\hbar} \frac{\Delta V}{\Delta B}, \quad (1)$$

where  $(\Delta V/\Delta B)$  is the change in the resonant peak position as a function of applied magnetic field,  $a=1$  if the applied bias is dropped totally across the double barrier structure and assuming that the bottom of the well shifts under bias by 1/2 eV.

The results for the peak shift with magnetic field are shown in Fig. 4, where a shift of  $1.9 (\pm 0.2)$  mV/T for the positive bias peak and  $2.7 (\pm 0.4)$  mV/T for the negative bias peak is observed in these samples. This yields an effective mass of  $m_{\text{InGaAs},+}^* = 0.032 (\pm 0.002)m_0$ , for the positive bias peak and  $m_{\text{InGaAs},-}^* = 0.026 (+0.003, -0.002)m_0$ , for the negative bias peak. This result is approximately half of the expected value for  $0.058m_0$  for this composition material. Surprisingly the difference in the effective mass values for positive and negative bias conditions exceeds the experimental uncertainty. These results are probably experimental artifacts and imply that use of a sim-

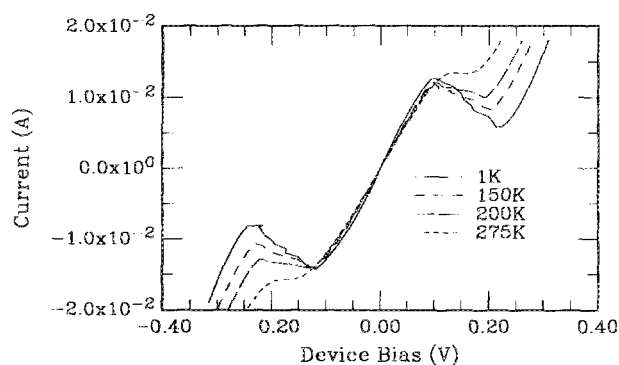


FIG. 2. Static current-voltage characteristics of the GaAs/AiGaAs/InGaAs double barrier resonant tunneling structure for different temperatures. Device mesa area = 25 ( $\mu\text{m}$ )<sup>2</sup>.

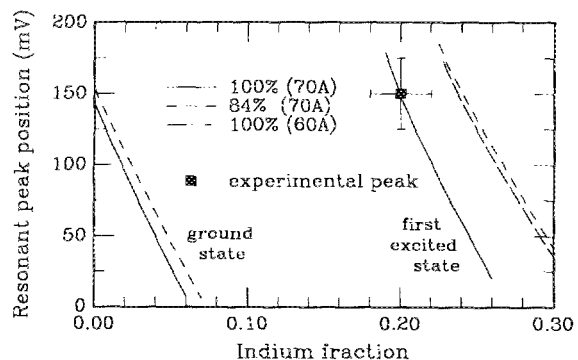


FIG. 3. Calculated resonant tunneling peak voltage vs In fraction for the double barrier structure. Plotted are the positions for tunneling through the ground and first excited state for quantum well sizes of 60 and 70 Å (in parenthesis), with AlGaAs/InGaAs conduction-band offsets of 84 and 100%. The data point is the observed peak position, with the error bars denoting the experimental width of the resonance and the uncertainty in the In fraction.

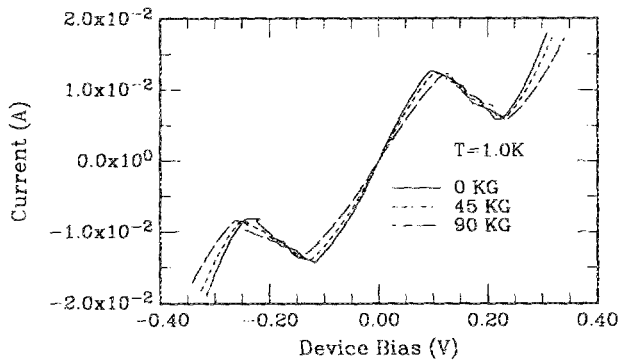


FIG. 4. Static current-voltage characteristics of the GaAs/AlGaAs/InGaAs double barrier resonant tunneling structure for the different magnetic fields. Device mesa area =  $25 (\mu\text{m})^2$  and  $T = 1.0 \text{ K}$ .

plistic model for a resonant tunneling structure [as applied in Eq. (1)] is inadequate. It is expected that the effects of accumulation and depletion regions are significant in these structures. It has been suggested<sup>10</sup> that the effects of these regions as well as the formulation of a space-charger layer by carriers in the quantum well can adequately account for such discrepancies.

In summary, we report the first study of a resonant tunneling structure where the center quantum well is of a different material than the contact or barrier regions, specifically a material that has a negative conduction-band offset with respect to the contact material. We have been able to fit the observed peak position for the AlGaAs/InGaAs heterojunc-

tion with a conduction-band offset of nearly 100%. We have also been able to measure the effective mass of electrons in this quantum well system and obtain an effective mass  $m_{\text{InGaAs}}^*$  of approximately  $0.03m_0$ , considerably less than the expected mass of 0.058. This result implies that accumulation and depletion regions in this structure are significant.

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