

EXCITED STATE RESONANT TUNNELING IN $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ DOUBLE BARRIER HETEROSTRUCTURES

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Resonant tunneling through the ground and first excited state of single quantum well, double barrier $\text{GaAs-Al}_x\text{Ga}_{1-x}\text{As}$ heterostructures is reported. Negative differential resistance from both quantum well states is observable up to room temperature in one of these structures. The observed positions of the quantum well states agree well with theory, though there exists an asymmetry in the current-voltage characteristics about the origin.

Negative differential resistance (NDR) devices utilizing double barrier resonant tunneling structures¹ have recently undergone a renaissance²⁻⁴ 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. The potential for millimeter wave oscillators,⁵ mixers, and logic devices utilizing resonant tunneling devices are intriguing. The ability to vary the NDR bias position and device current density independently, through dimensional control during MBE growth, is an attractive feature of these structures to device designers.

A class of devices,⁶ such as frequency multipliers, multistate memories, and high speed analog-to-digital converters become possible if designers can utilize multiple NDR regions in resonant tunneling devices. Measurements by other workers^{1,3} have established the existence of resonant tunneling through multiple states in quantum wells, but the effects were weak and observable only at low temperature. This paper reports NDR for transport through the ground and excited states of single well, double barrier resonant tunneling structures and the existence of excited state resonant tunneling at room temperature.

The prototype resonant tunneling structure is a one-dimensional, double barrier, single quantum well heterostructure.^{1,4} The center quantum well has a spectrum of discrete, higher allowed eigenstates (relative to the GaAs conduction band edge) than the electrons in the highly doped contacts. At low device bias, the eigenstate (band) in the central quantum well is too high in energy to allow resonant tunneling of electrons through the eigenstate. Tunneling through the entire structure is allowed, but

exponentially small. As the device bias increases, the quantum well state is lowered with respect to the Fermi level of the input contact, and carriers are allowed to tunnel through the structure. When the device bias is increased to the point that the allowed state in the quantum well is lower in energy than the conduction band edge of the input contact, elastic tunneling is no longer allowed due to the conflicting requirements of energy and momentum conservation. This decreases the tunneling current, producing NDR. Higher energy eigenstates will produce the same phenomena as they are biased to the Fermi level. An eventual increase in current at high device bias will be seen due to Fowler-Nordheim tunneling. The search for NDR from these higher states is the subject of this investigation.

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. Following a highly doped (n -type, Si @ $2 \times 10^{18} \text{ cm}^{-3}$) buffer layer, the active resonant tunneling structure region was then grown. The undoped $\text{Al}_x\text{Ga}_{1-x}\text{As}$ barrier (50 \AA , $x = .3$), 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 ~ 0.5 micron thick. The substrate was directly heated in a rotating substrate holder. Samples with quantum well widths of 50 \AA and 100 \AA were studied to observe the positions of the quantum well eigenstates as a function of well width.

Mesa diodes with diameters ranging from 2 to 225 microns were fabricated by conventional photolithography techniques. Ohmic contacts covered the top surface of the mesa and were made by evaporating Au-Ge, Ni, then Au, followed by an anneal. For devices too small to accommodate a direct bond, a silicon nitride layer (for isolation) was deposited over the sample followed by an Au evaporated bonding pad. Both backside and

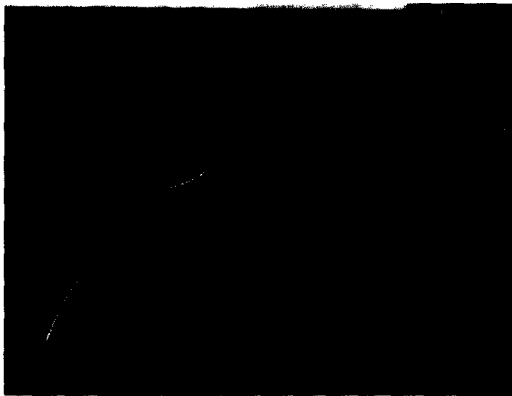


Figure 1. I-V characteristic of a 50 Å quantum well resonant tunneling device at room temperature. The active device area is 100 square microns.

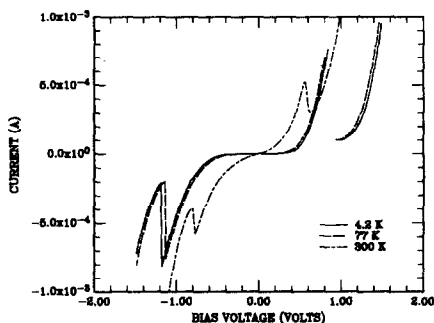


Figure 2. Temperature dependence of the I-V characteristics of a 50 Å quantum well resonant tunneling device. The active device area is 25 square microns.

planar contacts were used. The devices were either probed on a 77°K cold chuck or inserted into a variable-temperature helium-flow Janis cryostat for measurements in the temperature range 1.2°K to 300°K.

The I-V characteristics of a typical device (an active area of 100 square microns) for the 50 Å quantum well MBE sample at 300°K is shown in Figure 1. The NDR region exhibits a 1.7:1 peak-to-valley current ratio to room temperature and 7:1 at 77°K. Figure 2 shows the I-V characteristics of a similar device, with an active area of 25 square microns (though perhaps as small as 16 square microns due to undercutting by the mesa definition etch), at 300°K, 77°K, and at 4.2°K. There is little difference in the characteristics of these devices below ~150°K. The peak shift with temperature is primarily due to the change of parasitic resistance with temperature, and the increase of the valley



Figure 3. 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.

current with increasing temperature is due to inelastic current generation. The breaks in the 4.2°K and 77°K data curves are regions where the device undergoes self-oscillatory phenomena. This device demonstrated a 3:2 NDR region at 300°K. The I-V characteristics exhibit a slight asymmetry about the origin seen elsewhere,⁴ which has been attributed to the inferior GaAs-on-AlGaAs inverted interface. No additional features in the I-V due to excited state tunneling were observable at any temperature.

Measurements were performed on similar devices for the 100 Å quantum well MBE sample. There was no observable NDR at room temperature, but two clear peaks were evident at 77°K as shown in Figure 3. The lower voltage peak can be identified with resonant tunneling through the ground state of the quantum well, and the higher voltage peak resonant tunneling through the first excited state. Figure 4 shows the lower voltage peak on an expanded scale, demonstrating clear NDR for resonant tunneling through the quantum well ground state. The low voltage peaks also exhibited a pronounced asymmetry (160 mV vs 300 mV) and the excited state peak was not observable on the 300 mV side.

The theoretical positions of the resonant peaks for the 100 Å well were derived using a transfer-matrix technique.⁷ In terms of device bias voltage, the resonant positions are 83 mV for the ground state and 0.35 V for the first excited state. The experimental results are in excellent agreement with theory when the series parasitic resistance of 16 Ω is taken into account. This resistance also explains the apparent "hysteresis" of the excited state peak, which is due to the resonant tunneling diode - parasitic resistor series combination. This apparent hysteresis will appear whenever the value of the series resistance



Figure 4. Expanded scale of Fig. 3 showing negative differential resistance due to resonant tunneling through the quantum well ground state.

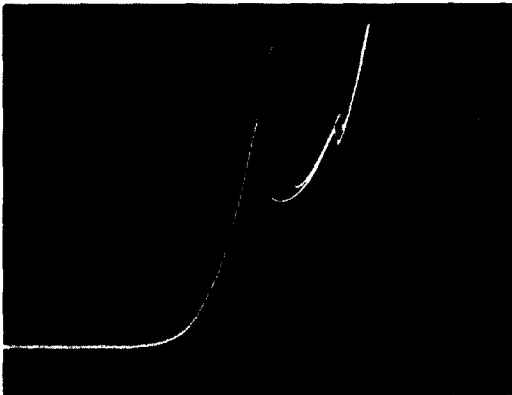


Figure 5. I-V characteristic of a 50 Å quantum well resonant tunneling device at 77°K. The higher voltage peak is due to resonant tunneling through the first excited state of the quantum well. Both of these peaks exhibited weak NDR (1 to 2%) at room temperature.

is less than the absolute magnitude of the negative resistance produced by resonant tunneling.

A second set of devices were fabricated from the 50 Å sample to search for any evidence of resonant tunneling through weakly bound or virtual states in narrow wells. In this case the bottom contact (i.e., the contact to the bottom of the mesa diode) was a topside planar Schottky barrier. Figure 5 demonstrates an observation made at 77°K in 2 out of 14 devices fabricated. The lower voltage peak agrees well with the

predicted value (0.24 V) of resonant tunneling through the ground state of the 50 Å well when the Schottky barrier and parasitic resistance are taken into account. The higher voltage peak is ascribed to tunneling through the first excited state. The transfer-matrix technique does not predict a second bound state in the well, though the approximations of this model cannot be considered valid at high bias voltage. The experimental bias position of the excited state indicates a state very near the top of the 50 Å quantum well. That this peak does not appear in all devices may be due to quantum well thickness fluctuations across the sample that are sufficient to unbind the loosely bound state. The peak-to-valley ratio of the excited state NDR, as well as the ground state, weakened with increasing temperature but was still observable as a 1-2% peak-to-valley NDR at room temperature. The inferior room temperature performance of the 100 Å quantum well sample should not be taken as intrinsic since no effort was made to iteratively optimize the structure, as was performed on the 50 Å structure.

In summary, NDR from resonant tunneling through quantum well excited states has been observed in two MBE samples of different quantum well size. The voltage positions of the resonant peaks agree well with theory. The NDR in the excited states of one sample was observable at room temperature.

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