The investigation of vertical transport in semiconductor heterojunction systems has recently undergone a renaissance due to improved epitaxial techniques in a number of material systems. By using resonant tunneling, we can perform electronic spectroscopy not only of the double barrier structure itself, but of any system (with quantized well states) suitably coupled to a resonant tunneling spectrometer. In designing such systems, an important degree of freedom is introduced by utilizing multi-component structures; for example, a GaAs contact - AlGaAs barrier - InGaAs quantum well. In this structure, the high electron affinity of the quantum well creates a "deep" quantum well, in which we demonstrate that quantum well states can be hidden from transport. Finally, we present results from microfabricated quantum well structures ("quantum dots") which are sufficiently small in the lateral dimension to introduce size effects. Telegraph noise due to the lateral size of these structures has been observed, and the first indications of lateral quantization in all three dimensions in a semiconductor quantum well are presented.

1. Introduction

Resonant tunneling in double barrier heterostructures, first investigated in the GaAs/AlGaAs system by Chang, Esaki, and Tsu, has recently been the subject of intense investigation. The remarkable submillimeter wave experiments of Sollner et al. has generated remarkable interest and success due to improvements in GaAs epitaxial growth techniques. Peak-to-valley tunnel current ratios as large as 3.9:1 at 300K, and 21.7:1 at 77K have been demonstrated in the GaAs/AlAs system. Resonant tunneling by holes, sequential resonant tunneling through a multiquantum well superlattice, double superlattice barrier resonant tunneling structures, and resonant tunneling in triple barrier structures are only among a few of the intriguing investigations that have been performed.

In this paper, we present investigations on vertical transport in a number of new systems primarily to demonstrate the spectroscopic ability of resonant tunneling. The ability to "engineer" the structures allows for interesting electronic spectroscopy, previously available only with optical techniques. We also present results on transport in submicron structures that are sufficiently small in the lateral dimensions (as well as in the vertical dimension) such that size effects are observable.

2. Review: Quantum Well Spectroscopy and Deep Quantum Wells

The phenomena of resonant tunneling is characterized by the appearance of negative differential resistance regions in the I-V characteristics due to resonant tunneling through the quantum well state of the double barrier structure. Figure 1 illustrates a typical example of resonant tunneling in a GaAs/AlGaAs structure grown by MBE. Experimental details have been described previously. In this case the quantum well width and tunnel barrier height have been adjusted such that there are two states in the well (ground and first excited state) that will be available to transport with the structure under bias. The two well-defined peaks in the characteristics of Figure 1 correspond to these resonances. The calculated peak positions of the structure (83 meV for the ground state and 350 meV for the first excited state) are in excellent agreement with the experimentally observed peaks, when a series resistance of 40Ω is taken into account. Although suitably designed structures (like the one illustrated here) are easily fit by an effective series resistance, a more precise determination of the peak positions demand a detailed modeling of the accumulation and depletion regions in the contacts. This is especially important in view of the recent trend in these structures; i.e., inserting undoped GaAs "spacers"
between the doped GaAs contact and the AlGaAs barrier to prevent Si diffusion into the double barrier region. Figure 2 shows the shifting of the resonant peak to higher voltages with increasing GaAs spacer thickness, as expected.

The design of these structures need not be limited to the simple "double square barrier" case; in addition to being able to substitute complex barrier shapes, it has been demonstrated that the central quantum well can be replaced by a material with higher electron affinity than the surrounding GaAs contact regions, specifically, a strained-layer InGaAs quantum well. Figure 3 illustrates the gradual shifting of the ground state resonance to lower voltages as In is incorporated into the well of a nominally identical resonant tunneling structure. It should be noted that the lowest voltage structure (c) has a finite zero-bias conductance since the quantum well state has been lowered below the Fermi level of the GaAs contacts.

Figure 4 illustrates the effect of adding sufficient In to the quantum well that not only lowers the quantum well ground state below the Fermi level, but below the GaAs contact conduction band edge. In this case, the ground state is hidden from transport and resonant tunneling proceeds only through the excited states. Notice here that the conduction band edge of the InGaAs was lowered sufficiently to observe the n = 3 state of the quantum well, which was virtual in the GaAs quantum well case.

3. Tunneling from Quantized Regions

The ability to engineer peak positions in multicomponent systems now allows us, in
Figure 4. (a) I-V characteristics of a 85Å GaAs quantum well / double 35Å AlAs barrier structure at 77K. The ground and first excited state are visible. The inset is an expanded view of the ground state resonance. (b) I-V characteristics of a 85Å In$_{0.5}$Ga$_{0.5}$As quantum well / double 35Å AlAs barrier structure at 77K. The ground state is hidden, and the first (n=2) and second (n=3) excited states are visible. Note the absence of the low bias resonance seen in (a).

general, to use double barrier structures as spectrometers on suitably designed quantum well or superlattice structures. Specifically, we demonstrate here that we can perform spectroscopy on large quantum wells placed between different GaAs (or InGaAs) quantum well, double barrier structures. The different resonant positions of the peaks, tunable by In content instead of changing the quantum well width (which introduces other complexities), discriminates which region of the epitaxial structure is being examined. This insertion of these resonant tunneling regions throughout a complex epitaxial structure gives us a microscopic spectrometer to examine the energy states in the structure.

Figure 5 illustrates an experimental embodiment of such a structure. The structure consists of a 40Å Al$_{0.8}$Ga$_{0.2}$As double barrier (90Å In$_{0.9}$Ga$_{0.1}$As quantum well) / 750Å GaAs quantum well / 40Å Al$_{0.8}$Ga$_{0.2}$As double barrier (90Å GaAs quantum well), with a n$^+$ GaAs contact on the other side of the GaAs quantum well resonant tunneling structure. The large GaAs quantum well (750Å) will have a small energy splitting in comparison to the quantum wells of the double barrier structures (90Å). In this specific case, the GaAs quantum well resonant tunneling structure has a n$^+$ contact region so as to provide a “source” or “sink” of available carriers. Thus, when the structure is biased such that carriers tunnel from the large quantum well into the double barrier structure, they will be injected from a ladder of states in the large quantum well. For simplicity, we will discuss results using the GaAs quantum well resonant tunneling structure as the spectrometer (though similar results are also obtained from the InGaAs resonant tunneling structure, at a different bias position). In addition, the heavily doped contact on the right hand side and the intrinsic region on the left hand side (in Fig. 5(b)) create accurately the band structure schematically illustrated in Figure 5; a more detailed self-consistent solution of the band structure is remarkably similar. Thus, the intrinsic region simply acts as a lever arm for the applied voltage, as well as being quantized.

Figure 6(a) shows a I-V characteristic at T=4.2K corresponding to electron injection from the large GaAs quantum well. A series of peaks corresponding to electron injection from the states in the 750Å quantum well through the state in the 90Å quantum well are clearly observable. The structure appears on the low bias side of the major peak only. The experimentally observed splittings are 59 meV, 103 meV, 143 meV, and 238 meV. No peaks corresponding to n=4 in the large quantum well are observed, indicative of the position of the Fermi level in this region. The ratios of the splittings to the ground state splitting (1:1.74:2.42:4.03) are in excellent agreement with calculated values (1:1.69:2.36:3.01) except for the n=4 level, presumably due to band bending. Clearly this technique can be generalized to more complex regions, such as parabolic injectors to verify equal splitting in such structures.

Now consider electron injection from the n$^+$ GaAs region, through the 90Å GaAs quantum well double barrier structure, into the 750Å GaAs quantum well region. Below the resonant peak, the tunneling current is a sum of elastic scattering to available states on the other side of the structure, and inelastic tunneling through the entire structure or through the intermediate quantum well state (which should be negligible at these temperatures). Thus, no structure in the I-V
characteristic below the resonant peak should be seen due to the large quantum well. However, when the structure is biased beyond the major resonant peak position, elastic scattering can then occur via the 90 Å quantum well state; i.e., elastic scattering to the 90 Å quantum well ground state subband, relaxation to the bottom of this band, then tunneling out of the structure. Thus, peaks in the I-V characteristic should occur at biases greater than the major resonant peak bias.

Figure 6(b) shows the I-V characteristic of this structure at \( T = 4.2 \text{K} \) corresponding to electron injection from the n+ GaAs region. There are no observable peaks at biases less than the resonant bias. However, a series of oscillations appear at biases greater than the resonant bias in accordance with the mechanism described above. The spacings of these oscillations (\( \sim 130 \text{meV} \)) are approximately constant, corresponding to the asymptotic energy level spacing of a large quantum well, and quantitatively are in good agreement with the size of the splittings of these levels when the asymmetry of the resonant peak positions is taken into account. However, there is insufficient resolution of the splitting to allow an exact determination of the quantum numbers of these levels.

4. Transport through Quantum Dots

The resonant tunneling devices discussed so far operate by virtue of the quantum size effect in the quantum well imposed by the lower electron affinity tunnel barriers. The dimension of the structure in the plane of the quantum well is essentially infinite on this scale. However, microfabrication techniques have advanced to the degree that lateral dimensions can approach the dimensions determined by the epitaxial growth layers. In this case, splitting of the quantum well state (band) will occur due to lateral quantization imposed by a microfabricated potential. We have produced such structures, and have measured transport through these laterally confined quantum wells, i.e., "quantum dots".

The microfabrication approach used to produce these microstructures is summarized in Figure 7.
The initial structure (substrate) is a resonant tunneling diode structure, grown by MBE on a n+ GaAs substrate and consisted of a 0.5 micrometer-thick Si-doped (2x10^{18} \text{ cm}^{-3}) GaAs buffer layer graded to less than 10^{16} \text{ cm}^{-3}, a 50Å undoped GaAs spacer layer, a 50Å Al_{0.27}Ga_{0.73}As tunnel barrier, and a 50Å undoped GaAs quantum well. The structure was grown to be nominally symmetric about a plane through the center of the quantum well. Large area (2 micrometers x 2 micrometers) devices fabricated in a conventional manner exhibit a 1.6:1 peak to valley tunnel current ratio and a current density at resonance of 1.6 \times 10^{4} \text{ A/cm}^2.

E-beam lithography was used to define an ensemble of quantum dots (including single and multiple dot regions) nominally 0.25, 0.15, and 0.1 micrometer in diameter, in a bi-layer PMMA resist spun onto the structure. This pattern was then transferred to a AuGe/Ni/Au (500Å / 150Å / 600Å) dual-purpose Ohmic top contact and etch mask by lift-off. Highly anisotropic reactive ion etching (RIE) using BCl₃ as an etch gas defined columns in the structure. A SEM of one of these etched structures is seen in Figure 8. To make contact to the tops of the column(s), an insulating polyimide was spun on the wafer, cured, and then etched back by oxygen RIE until the tops of the columns were exposed. A gold contact layer was lifted off which
Figure 9 shows a I-V characteristic of a single quantum dot resonant tunneling structure at 100K. The lateral dimensions of this single dot structure is 0.15 micrometers x 0.25 micrometers. The structure clearly shows NDR, though the peak to valley is degraded from the large area structure, probably due to process damage. The I-V clearly exhibits a "noise" that is far above the system background noise. The origin of this noise is the so-called "single electron switching" phenomena that has been observed in narrow Si MOSFET wires. Traps in or near the narrow conduction channel and are near the Fermi level can emit or capture electrons with a temperature-dependent characteristic time. The lowering of specific traps through the Fermi level is clearly evident (at .6V, .8V through .85V, 1.0V through 1.1V). This phenomena is seen up to room temperature (though for a different set of traps), and is usually "frozen out" by 4.2K.

Provision bonding pads for contact to either single dots or arrays of them.

Figure 10 shows a time-dependent trace of a similar device at fixed bias voltage. The switching between two discrete states is evident. In all regions of Figure 9 where a trap is biased near the Fermi level, switching similar to Figure 10 is observable, provided that the temperature is in the correct range. The switching rate for different traps are in general unique, and are dependent on temperature and bias. Under the appropriate temperature/bias conditions, a superposition of these phenomena can be seen (for example, see Fig. 9, ~1.1V).

If the mechanism for the telegraph noise is scattering from traps of varying occupancy as suggested, then the trap(s) should have a well-defined activation energy measurable by the switching rate between discrete values as a function of temperature. This was measured by taking the same device as shown in under constant bias (specifically, the same as for Figure 10) and varying the temperature. Figure 11 shows that the behavior is indeed activated, with a measured activation energy of of 280 meV for this particular trap.

It is curious that telegraph noise can be seen for the physical dimensions (0.15 micrometer x 0.25 micrometer) of the structure. However, the effects of depletion at the etched mesa side surfaces due to pinning of the Fermi level has not been taken into account. Taking the observed current at resonance and assuming that the current density must be the same as in the large area device (assuming that the switching is a perturbation), we calculate that the effective (circular) conduction path diameter is ~500Å, consistent with the observation of the switching phenomena. This implies a depletion layer of approximately 500Å. However, transport and switching phenomena have also been observed in an array of dots 2000Å by 1000Å suggesting a depletion layer smaller than 500Å.

At these lateral dimensions, splitting of the quantum well resonance due to lateral size quantization imposed by the depletion depth potential should be observable. Very recent results
Figure 12. I-V characteristic of a single quantum dot nanostructure at 4.2K, showing resonant tunneling through the discrete states of the quantum dot.

of one of these structures, epitaxially similar with lateral dimensions of 1000Å round, is shown in Figure 12. The I-V characteristics show well defined negative differential resistance peaks at low temperature, which disappear at high temperature. This is due to resonant tunneling through the 0-D density of states in the quantum "dot", and is the first indication of lateral quantization in all three dimensions in a semiconductor quantum well. Detailed measurements of this structure are in progress.10

5. Summary

The range of new phenomena in the vertical transport of heterostructure and microfabricated heterostructure systems is rapidly expanding. The above provides some techniques useful for the design and spectroscopy that is available in these structures. We also have described the techniques for the fabrication of microstructured multilayers, which already show interesting size effect phenomena and the first indication of lateral size quantization to all three dimensions in a semiconductor quantum well. These structures should provide a unique laboratory for the investigation of localization and quantum size effect phenomena.

Acknowledgments - I am indebted to J. W. Lee and R. J. Matyi for MBE growth, to J. N. Randall for quantum dot microfabrication, to T. M. Moore for e-beam lithography, to H.-L. Tsai for cross-section TEMs, to R. T. Bate, W. R. Frensley and A. E. Wetsel for analysis and discussions, and to R. K. Aldert, D. A. Schultz, P. F. Stickney, J. R. Thomason, A. E. Wetsel, and J. A. Williams for technical assistance. This work was sponsored by the Office of Naval Research, the Army Research Office, and the Air Force Wright Aeronautical Laboratory.

References