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RESONANT TUNNELING STUDIES OF VARIABLY SPACED MULTIPLE QUANTUM WELL STRUCTURES IN THE AlGaAs SYSTEM

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ABSTRACT

In this paper we report experimental and theoretical studies of resonant tunneling and the first observation of resonant tunneling in variably spaced multiple quantum well structures designed for electron injection at voltages between 0.1 and 0.2V. The experiments are in good agreement with a resonant tunneling theory developed for these structures.

In a series of recent papers we proposed and discussed the use of a new device structure, the variably spaced superlattice energy filter (VSSEF). In this device, the width of the quantum wells are progressively decreased through the superlattice (SL) such that under an appropriate bias, the confined quantum levels in adjacent wells become aligned. Incident electrons can then resonantly tunnel through the SL and be injected at a higher energy relative to the conduction band minimum of an adjacent semiconductor layer. Thus, a nearly monoenergetic stream of high energy electrons is produced providing carrier heating at relatively low bias voltages. Possible applications of this structure are to optimize the efficiency of interband or intraband impact ionization, impact excitation of bound electrons, and injection of carriers from a small bandgap semiconductor into a larger bandgap semiconductor. These properties have application in improving the performance of avalanche photodiodes, microwave devices and thin film electroluminescent devices.

The underlying physical principle in the operation of devices made using a variably spaced superlattice is the existence of a resonant tunneling channel in the multiquantum well structure under bias. Optimization and design of these devices requires a detailed understanding of the physical mechanisms controlling carrier transport in strongly coupled MQW/SL systems. We have recently developed such a model to design VSSEF devices which exhibit resonant tunneling under an appropriate bias. The most unequivocal experimental verification of resonant alignment is provided by negative differential resistance (NDR) measurements. At present, NDR has only been observed in single quantum well devices following the pioneering work of Sollner, et al. In this paper, we...
report the first experimental observation of NDR phenomena by resonant tunneling in multiquantum well structures consisting of two and three well devices, and thus prove experimentally the feasibility of a wide range of new device concepts.

At present, the theory of resonant tunneling in single quantum structures is still being refined and requires considerable development in order to unambiguously describe all of the experimental observations. For example, a complete theory must include transient carrier effects as well as the proper treatment of the boundary conditions. Also, it is apparent from some of the soft I-V curves reported that the observed NDR effects attributed to resonant tunneling are partially due to thermionic emission over the second AlGaAs barrier. To minimize both space-charge and depletion effects, we have, therefore in this study, reduced the barrier doping to relatively low concentrations and designed structures using the simplest proven theories.

The structures required for this investigation were designed using a theory which employs a transfer matrix solution of the resonant tunneling problem including self-consistent effects arising from the carrier charge. The Schroedinger equation is solved exactly using linear combinations of Airy functions and the solutions are then matched at each interface by assuming that the wavefunctions and its first derivative divided by the electron effective mass are continuous across each interface. A series of 2 x 2 matrices is formed from the continuity of the wavefunctions and their derivatives. Successive multiplication of these matrices then couples the ingoing wavevector to the outgoing wavevector of the heterostructure stack. Self-consistent effects are added by simultaneously solving the Poisson and Schroedinger equations. Thus, the transmission coefficient is obtained as a function of the incident electron energy on the first barrier.

A schematic of the band structure and the calculated transmissivity of a two well VSSEF device using Al$_{0.35}$Ga$_{0.65}$As barriers and GaAs QWs designed for electron injection of 0.20 V are shown in Figure 1. For an incident carrier energy of 0.02 eV, it is apparent that exact alignment of the n=1 subband level: in the first and second QWs is obtained for well widths of 59.44 Å and 31.09 Å, respectively. In all of these calculations, the dimensions are multiples of the monolayer thickness (2.8266 Å) for GaAs so as to represent a physically realizable device structure. As indicated in Figure 1b, the calculation is for 50.88 Å thick barriers and the band parameters for the AlGaAs/GaAs heterointerface given by Adachi and Miller, i.e. effective masses of 0.067m$_0$ in the wells and 0.096 m$_0$ in the barriers, nonparabolicity factors of 0.61 for GaAs and 0.484 for AlGaAs, and a conduction band discontinuity of 0.27 eV for an x-value of 0.35.

For this study, special interrupted growth techniques and temperature profiles were used to obtain very abrupt interfaces and to minimize the diffusion of Si into the barriers. Dopant diffusion into the barriers was also inhibited by reducing the dopant concentration from 5 x 10$^{17}$ to 1.0 x 10$^{17}$cm$^{-3}$ near the VSSEF structure and by the growth of a 50.88 Å wide undoped GaAs layer on either side of the structure. The actual structures grown therefore consisted of: 1) an n$^+$-substrate; 2) a doped 25 period 14 Å spaced AlGaAs/GaAs SL (to act as a diffusion and dislocation barrier) and a 0.7 µm GaAs layer doped from 5 to 1 x 10$^{11}$cm$^{-3}$; 3) a 50.88 Å layer of undoped GaAs; 4) the VSSEF structure; 5) a 50.88 Å layer of undoped GaAs; and 6) 0.9 µm of GaAs doped from 1 to 5 x 10$^{17}$cm$^{-3}$. Devices were fabricated by evaporating Au:Ge/Ni/Au metallization layers and ohmic contacts were formed by alloying at 380°C for 2 minutes in an inert atmosphere. This was followed by electroplating with an overlayer of 1 µm of Au to increase the device's structural...
integrity. Mesas 20-50 µm in diameter were defined on the sample by using conventional photolithographic techniques. Measurements of the I-V characteristics were performed in a Vari-Temp dewar using a standard curve tracer.

Using the theory described previously, two and three well VSSEFs were designed for electron injection at 0.20 and 0.15 eV. In all designs, 50.88 Å barriers were used. In a two well VSSEF device operating at 0.2 eV injection energy, well sizes of 59.44 Å and 31.09 Å were calculated, and for the three well VSSEF structure, the well sizes were 67.84 Å, 39.57 Å, and 25.44 Å, respectively. For the 0.15 eV three well structure the well dimensions were 81.97, 50.85, and 36.75 Å, respectively.

Figures 2, 3 and 4 show the I-V characteristic measured for three structures at 77K. As expected, all devices exhibit strongly asymmetrical I-V curves in which, for positive bias, a resonance peak is observed very close to the voltage designed for tunneling. The NDR associated with these features produces a 77K peak-to-valley ratio of 4:1, 5.5:1, and 8:1 for the samples shown, respectively. These values are in good agreement with the data reported on single well devices. At higher bias voltages, additional structure is observed in some of the devices before the current begins to increase exponentially with increasing voltage. This latter characteristic is also observed in all devices in reverse bias and is attributed to breakdown in which the electrons tunnel through the first barrier and then are injected over the remaining barriers of the structure. Measurements at temperatures between 300-10 K show that similar features are present at room temperature, but appear to be smaller because of the increased flow from thermionic emission over the barriers. However, the position of the resonances occurs very close to their 77 K positions. Lower temperature measurements also show that the I-V characteristics change little with decreasing temperature. These results are strong evidence that the observed peaks in the I-V curves are caused by tunneling.

Examination of the specifics of each device confirms these general observations. The peak in the I-V curve for the two well VSSEF occurs at 0.24 V in excellent agreement with the transmissivity peak at 0.22 V (total voltage is the bias of 0.20 V plus injection energy of 0.02 eV). Similarly, excellent agreement is observed for the two three-well designs in which resonances were calculated for 0.20 and 0.15 V. The strong agreement between theory and experiment is also demonstrated in Figure 5, which shows the calculated dependence of the transmissivity on the incident electron energy and the I-V curve calculated for this last structure.

As pointed out by Goldman, the low-bias resistance is a good measure of device quality. As shown by Figure 2, this is reasonably large (500 K-ohm) for the two-well device, indicating some leakage current. However, larger low-bias resistance values were measured for the 0.20 and 0.15 V three-well VSSEF structures (1.2 and 1.5 M-ohm, respectively). This is attributed to the better quality of these devices and the fact that the larger number of barriers appears to increase both the low bias resistance and the breakdown voltage.

In summary, we have presented the first observation of resonant tunneling in several variably spaced superlattices consisting of coupled two- and three-well systems designed for electron injection at 0.15 and 0.20 V. The observed experimental resonances, their independence of temperature, and the very close correlation obtained with theory unambiguously confirm this interpretation. Thus, this work unequivocally illustrates the feasibility of a new class of devices based on the variably spaced superlattice energy filter; i.e. variably spaced superlattice electroluminescence displays, visible and infrared detectors, and because their NDR effects are
expected to be present up to 100-500 GHz frequencies, microwave oscillators.

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REFERENCES

Figure 1. Conduction-band profile of a two-well VSSEF structure designed for electron injection of 0.20 V.

Figure 2. Current-voltage characteristics of the two-well VSSEF structure shown in Figure 1 at 77K.

Figure 3. Current-voltage characteristics at 77K of a three-well VSSEF structure designed for electron injection at 0.20 V.

Figure 4. Current-voltage characteristics of a three-well VSSEF structure designed for electron injection at 0.15 V.

Figure 5. (a) Calculated transmissivity vs. incident electron energy for three-well VSSEF structure designed for electron injection at 0.20 V. (b) Calculated I-V curves for the same structure (smoothed).