

Room-temperature observation of resonant tunneling through an AlGaAs/GaAs quasiparabolic quantum well grown by molecular beam epitaxy

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(Received 2 December 1987; accepted for publication 23 February 1988)

We report the first room-temperature observation of resonant tunneling through a double-barrier diode with a 31.5-nm-wide AlGaAs/GaAs quasiparabolic quantum well grown by molecular beam epitaxy. As the bias voltage is scanned from 0 to 4 V, 11 resonant tunneling transitions are observed at room temperature. At 77 K, 13 resonant tunneling transitions are observed; 10 of them show negative differential resistance, and the highest peak-to-valley ratio is 1.4. At 4.2 K, 17 resonant tunneling transitions are observed; 15 of them show negative differential resistance, and the peak-to-valley ratio of the first tunneling peak is 3.6. Computer simulation indicates that for the 17 resonant tunneling transitions, the first 13 are likely due to resonant tunneling through quasibound states in the well, and the remainder are due to resonant tunneling through virtual states.

Resonant tunneling through a parabolic quantum well is of great interest because of its potential application in high-speed circuits. Unlike a square quantum well whose energy levels are quadratically spaced, a parabolic quantum well has equally spaced energy levels and therefore multiple equally spaced peaks in tunneling current. In 1984, Miller *et al.*¹ fabricated multiwell structures with quasiparabolic potential wells using molecular beam epitaxy (MBE). Their photoluminescence studies at 5 K showed that the energy levels in these structures are nearly equally spaced. Recently, Sen *et al.*² reported the observation of resonant tunneling transition through a quasiparabolic quantum well at ~ 100 K, and negative differential resistance at ~ 8 K. In this letter, we report the first room-temperature observation of resonant tunneling through diodes with a 31.5-nm-wide AlGaAs/GaAs quasiparabolic quantum well, and the first 77 K observation of negative differential resistance in these devices.

The quasiparabolic quantum well structure of our devices consists of two AlAs barriers, each 3 nm thick, and in between, a quasiparabolic quantum well of 31.5 nm width, which was formed by using a 21-period undoped AlGaAs/GaAs superlattice. Each period is 1.5 nm thick and consists of a layer of $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ and a layer of GaAs. The thickness of the AlGaAs layer in each period of the superlattice increases quadratically from the center of the well. Generally speaking, for a quasiparabolic well formed by $2N + 1$ periods of an $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ superlattice, the thickness of the AlGaAs in the n th period from the center of the well is given by

$$z = t(n/N)^2, \quad n = 0, 1, \dots, N,$$

where t is the thickness of the period. The thickness of GaAs in the n th period is therefore $t - z$. We call this quantum well structure quasiparabolic, not only because the well is formed by a superlattice, but also because there are two additional tall AlAs barriers.

The device structure was grown in a MBE chamber that has been devoted to high-purity n -type AlGaAs/GaAs growth work. There is no p -type dopant source in the chamber. Typically, background impurity level is $\sim 1 \times 10^{14} \text{ cm}^{-3}$ and mobility of undoped GaAs grown is 8500–9000

$\text{cm}^2/\text{V s}$. The best Hall mobility of undoped GaAs grown in this chamber is $163\,000 \text{ cm}^2/\text{V s}$ at 77 K.³ During the growth, the shutters were controlled by a computer. The device structure was grown on a silicon-doped (100) n^+ -GaAs wafer. The GaAs buffer layer underneath the structure and the contact layer on the top of the structure have a doping concentration of $1 \times 10^{18} \text{ cm}^{-3}$.

In device fabrication, mesas with areas varying from 25 to $400 \mu\text{m}^2$ were formed by wet etching. SiO_2 of a thickness of 40 nm was used for device passivation. Au/Ge/Ni was used for ohmic contact and annealed at 450°C for 30 s.

The devices were bonded to TO-5 integrated circuit packages and measured using a HP-4145 parameter analyzer. The devices were cooled down to 77 and 4.2 K by immersing them in liquid nitrogen and helium, respectively.

The current-voltage (I - V) characteristic of a device with an area of $5 \times 4.5 \mu\text{m}^2$ at room temperature is shown in Fig. 1(a). Clearly, several resonant tunneling (RT) transitions can be seen. To accentuate these RT transitions, the derivative dI/dV is shown in Fig. 1(b). There are 11 RT transitions; however, there is no negative differential resistance. The characteristics of the devices were found to be quite uniform over the entire substrate (a quarter of a 2 in. wafer) and were essentially independent of device size. The fabrication yield is better than 90%.

Figures 2(a) and 2(b) show the I - V characteristic and its derivative of the same device at 77 K. There are a total of 13 RT transitions, and 10 of them show negative differential resistance. Figure 2(b) also shows that each negative-differential-resistance dip consists of, in fact, two narrow dips. This is due to the oscillation in the measurement circuit and not counted in counting peaks. The I - V characteristic of the device at 4.2 K is shown in Fig. 3. Compared with 77 K, there are four additional peaks in the low collector bias region and 17 RT transitions in total. Fifteen of these transitions show negative differential resistance. The peak-to-valley current ratio of the first peak is 3.6, which is the highest value reported for tunneling through such a wide AlGaAs/GaAs quantum well. The peak-to-valley ratios at 4.2 and 77 K are plotted in Fig. 4.

Comparison of Figs. 2 and 3 shows that as temperature

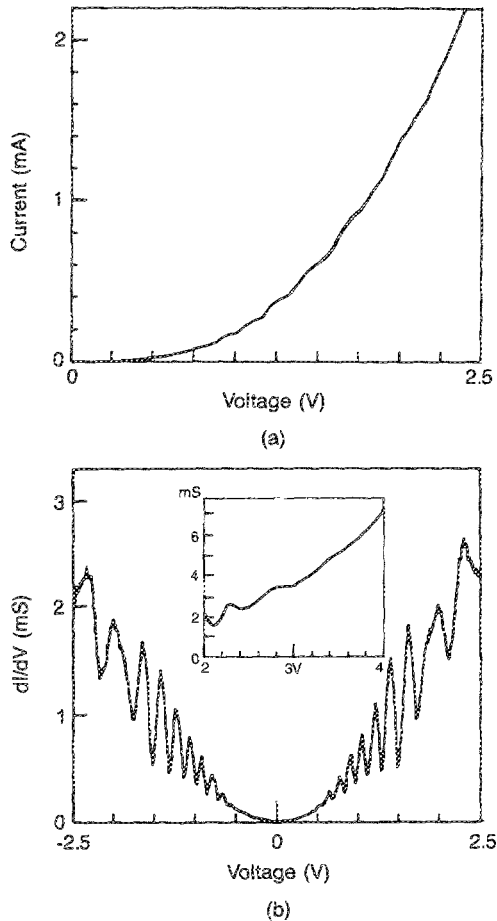


FIG. 1. At 300 K, (a) the I - V characteristic of a device of an area of $5 \times 4.5 \mu\text{m}^2$, when biased forward; (b) the derivative of the device, dI/dV , when biased both forward and backward. The inset in (b) is the derivative for a bias from 2 to 4 V.

is lowered from 77 to 4.2 K, there is basically no shift of peak position within the measurement accuracy ± 2.5 mV. The current for a peak at 77 K is only $\sim 2\%$ smaller than that of the same peak at 4.2 K. Comparison of Figs. 1 and 2 shows that when temperature is lowered from 300 to 77 K, the peak positions are reduced by a few millivolts. We believe that this reduction is caused by the change of the Fermi level and depletion width.

As shown in Fig. 5, the positions of the RT transitions at 4.2 K, V_p , can be fitted approximately into the equation, $V_p = 69.2 + 17.5n + 7.5n^2$ mV, where n is the peak number. As expected, for low collector bias, electrons see a more paraboliclike well; therefore, the energy of a level with small n is approximately proportional to n . For high collector bias, electrons see the potential well more like a square well because of the two tall AlAs barriers; thus the energy of a level with large n is essentially proportional to n^2 . In counting the number of RT transitions, the transition between 1.72 and 2.08 V, which exists in all tested devices, is not counted, because of its "strange" behavior, namely, it does not fit the peak position curve nor show a negative differential resistance as the peaks before and after it. The reason for this transition is unclear at the moment.

In the measurement, the forward bias is the bias at which electrons travel from the top electrode to the substrate electrode. When the devices are biased backward, at 4.2 K

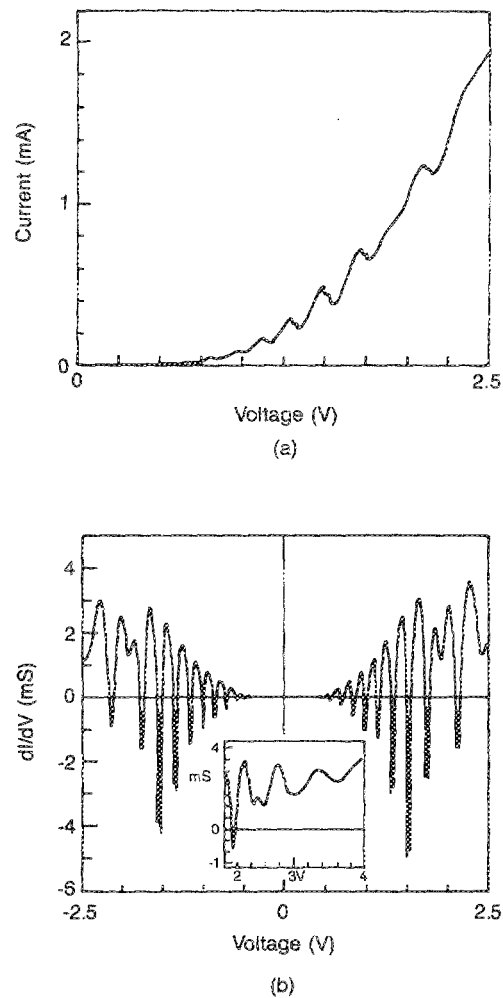


FIG. 2. At 77 K, (a) the I - V characteristic of the same device, when biased forward; (b) the derivative dI/dV when biased both forward and backward. The inset in (a) is the log plot of I - V characteristics, and the inset in (b) is the derivative for a bias from 2 to 4 V.

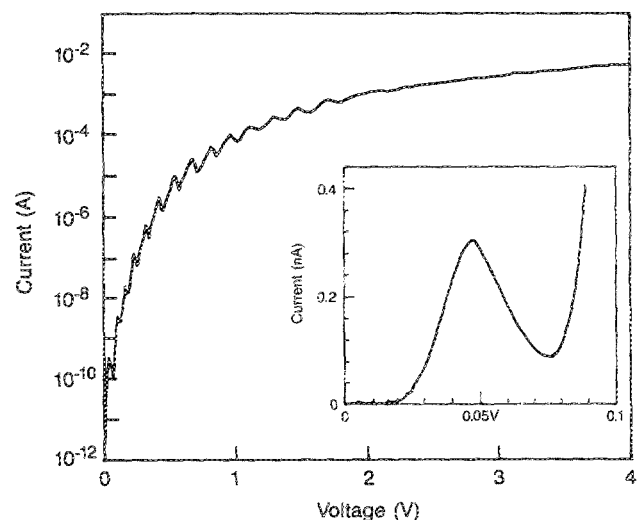


FIG. 3. Log plot of I - V characteristic of the same device at 4.2 K. The inset is the first peak.

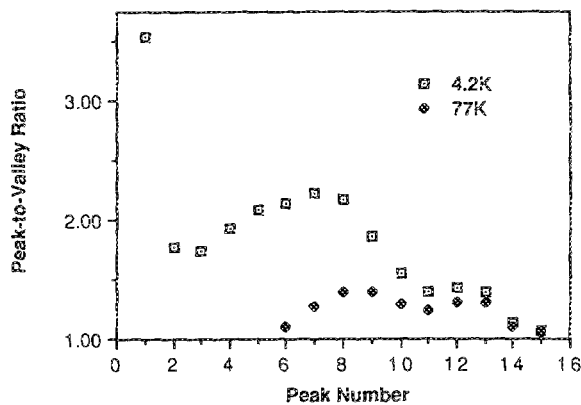


FIG. 4. Peak-to-valley ratio vs peak number of the device at 77 and 4.2 K.

and for a given peak, the peak-to-valley ratio is $\sim 10\%$ smaller, the peak current is $\sim 25\%$ higher, and the peak positions shift to higher voltage by ~ 20 mV. The variation of the peak-to-valley ratio and peak current becomes much less as the peak number becomes higher, as well as when temperature increases. We believe these variations and shift indicate that the actual doping concentration next to the quantum well structure is lower at the top electrode and higher at substrate electrode.⁴

Computer simulation of the electron probability for tunneling through the quasiparabolic quantum well shows that the minimum spacing of the energy levels is 46 meV, which is almost two times larger than the thermal excitation energy at room temperature, $kT \sim 26$ meV. This is one of the two reasons that resonant tunneling through this quasiparabolic quantum well can be observed at room temperature. The second reason is that the energy spread due to scattering, estimated using the mobility of undoped GaAs (~ 8700 cm²/V s) and the uncertainty principle, is ~ 2 meV, which is less than the minimum energy spacing. An intuitive way to see this is that at room temperature and assuming a velocity of 1×10^7 cm/s, the mean free path is ~ 33 nm, which is longer than the length of the quantum well. Hence the wave function of electrons can, even at room temperature, extend over the entire quantum well.

The computer simulation also indicates that if all the energy levels in the well can be resolved, the first 13 current peaks observed at 4.2 K are due to the tunneling through the quasibounded states in the well, and the rest of peaks are due to the tunneling through the virtual states which are above the AlAs barrier at the collector side. Two experimental evi-

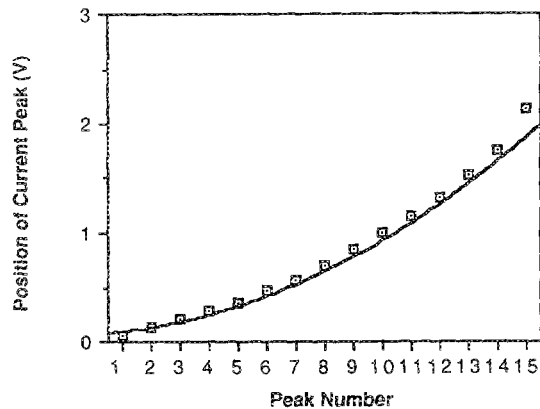


FIG. 5. Position of RT transition vs peak number of the device at 4.2 K. The solid line is the curve fitting of the equation, $V_p = 69.2 + 17.5n + 7.5n^2$ mV.

dences add support to this argument. First, as shown in Fig. 2(b), the negative differential resistance increases with peak number first and reaches the maximum at the 13th peak ($V = 1.525$ V), then decreases with the peak number. Second, the peak-to-valley ratio, as shown in Fig. 4, drops sharply after the 13th peak.

In summary, we have observed, at room temperature, 11 resonant tunneling transitions through a double-barrier diode with a 31.5-nm-wide AlGaAs/GaAs quasiparabolic quantum well grown by MBE. At 77 K, 13 resonant tunneling transitions are observed; 10 of them show negative differential resistance, and the highest peak-to-valley ratio is 1.4. At 4.2 K, 17 resonant tunneling transitions are observed; 15 of them show negative differential resistance, and the peak-to-valley ratio of the first tunneling peak is 3.6.

We wish to thank E. Larkins for useful discussions regarding MBE growth, K. Lear for designing the device mask set, and E. Wolak for his comments on the manuscript. The work was supported by Defence Advanced Research Projects Agency under contract Nos. N00014-86-K-0530 and N00014-86-K-0077.

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⁴S. Y. Chou and J. S. Harris (unpublished).