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Observation of Resonances by Individual Energy Levels in InGaAs/AlAs Triple-Barrier Resonant Tunneling Diodes

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Current-voltage characteristics in InGaAs/AlAs triple-barrier resonant tunneling diodes were investigated. Our data show that a current peak is observed when any of the quantum well energy levels is resonant with the emitter level, without level alignment between neighboring wells. When one of the well widths was increased, some peak voltages shifted, while others remained unchanged. This indicates that the peak positions are associated to a specific well. When the temperature was lowered, some peaks became stronger, while others became weaker. Our analysis shows that the weaker peaks are caused by the resonances between the emitter and the far side well. At low temperatures, current injection to the far side well is more difficult, and the current peak becomes weaker. These results indicate the conculsion that neighboring energy levels are not aligned in these structures.

KEYWORDS: level alignment, resonant tunneling, charge build-up, temperature dependent current, electric field distribution, triple-barrier diode

1. Introduction

Electric field distribution in a superlattice structure is important for determining the performance of vertical transport devices. At low-bias voltage, the electric field is uniformly distributed within the structure. At higher voltages, the electric field is no longer uniform because a high field domain is formed.[1] It was previously thought that the electric field in a superlattice always aligns the energy levels of the neighboring wells at the same height. Recently, there was an experimental report that the electric field in a superlattice is lower than the field for resonant alignment.[2] The report showed that resonant alignment of energy levels occurred only for a narrow region of bias. In order to investigate electric field distribution, we studied the current-voltage (I-V) characteristics of triple-barrier resonant tunneling diodes.[3] Although this structure has only two wells, it demonstrates the interactions between quantum wells. Our data show that a current peak is observed when any energy level in the two wells is resonant with the emitter level, but shows no energy level alignment between neighboring wells. Peak voltage shift could be related to the well width change, and current peaks showed two different types of temperature dependence. These results indicate the conculsion that energy levels in neighboring wells are not aligned.

2. Experiments

The structures used in this study are made of $In_{0.53}Ga_{0.47}As$ wells and AlAs barriers, grown by MBE on n^+ InP substrates. The triple barrier structure consists of (starting from the substrate side) an AlAs barrier, narrow InGaAs well, AlAs barrier, wide InGaAs well, and AlAs barrier. Three different structures; A, B and C were studied. In these structures, the width of the narrow well is fixed to 58 Å. The wide-well width is 71 Å for sample A, and 65 Å for samples B and C. The barrier thickness is 25 Å for A and B, and 35 Å for C. The contacting layers on the top and the substrate side are InGaAs layers with 7×10^{17} cm^{-3} Si doping density. An Au disk of 100-μm diameter was deposited for an ohmic contact. Current-voltage characteristics were measured using a Hewlett-Packard 4142B dc source-monitor.

We calculated the energy levels and wavefunctions by numerically solving the Schrödinger equation. The calculation results show two energy levels in each well, and the calculated energies for sample B are 134 and 389 meV for the wide well, and 159 and 435 meV for the narrow well.

Figure 1 shows the I-V characteristics measured at room temperature. At positive bias the top side is positively biased, and electrons flow from the substrate through the narrow and wide wells. In this figure, the peak voltages are similar for the three samples, although the current scale is very different. At low temperature, one more current peak was resolved at 0.3 V (shown in Fig. 4 inset), and the position is indicated by a dashed line in Fig. 1. Sample C has thicker barriers, so that the peak positions are slightly higher than those of sample B. Figure 2 shows the I-V data of sample C taken

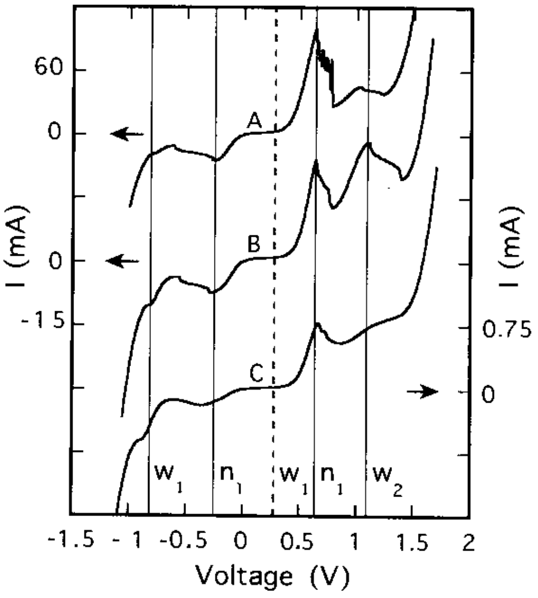

Fig. 1. Current-voltage characteristics of the three samples measured at room temperature.

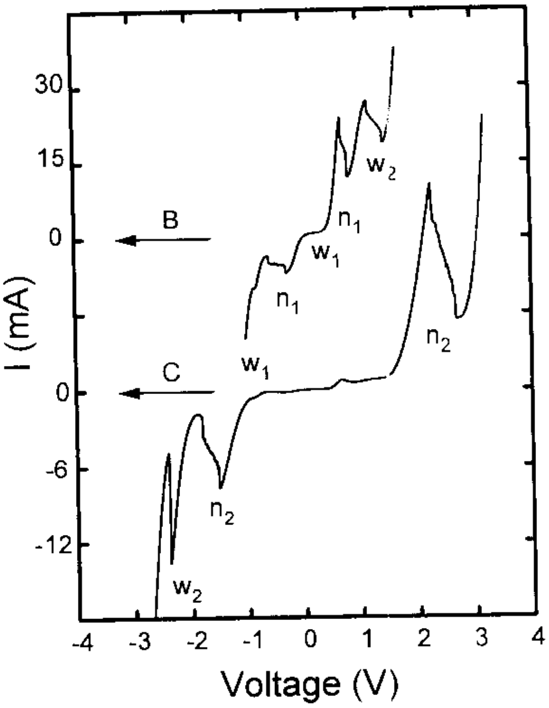

Fig. 2. Current-voltage data for a larger bias range, measured at room temperature.

at higher bias range. Samples A and B did not exhibit any peaks in the higher voltage region. In this figure, four peaks are observed in one polarity of bias for sample C. If the levels were aligned, the maximum number of peaks would be three. Therefore, we can infer that the four peaks in our data are from the resonances of the four energy levels with the emitter level, and the peaks in the figure are named by the associated energy levels. They are n_1, w_1, n_2 and w_2 on the negative side, and w_1, n_1, w_2 and n_2 on the positive side.

Figure 3 shows how the peak positions respond to well-width change. In this figure, the *I*-*V* data of samples A and B are compared. Samples A and B are different only in wide-well width. The width of the wide well is 71 Å for sample A and 65 Å for sample B. In Fig. 3(a) the n_1 position is nearly fixed, but the w_2 position shifted to lower voltage when the wide-well width was increased in sample A. Figure 3(b) shows negative-side peak positions. In this figure the w_1 peak also shifted to lower voltage in sample A. The Fig. 3(c) 77 K *I*-*V* data clearly show that the w_1 peak position is shifted to lower voltage. Figure 3(c) also shows that the two peaks on the negative side (sample A) are merged into one peak with one wide negative differential resistance region. The shift of the peaks in sample A indicates that they are related to the wide-well width change. When the wide-well width was increased, the energy levels of the wide well were lowered, and the peak voltages were shifted to lower values. If the neighboring well levels are aligned, the change of well width in one of the wells should affect all of the peak positions. Our data show that the level alignment does not occur in this case.

In Figs. 4 and 5 we show the temperature dependence of *I*-*V* data. In Fig. 4, the w_2 peak at 1.2 V became weaker at low temperature, while the n_1 peak at 0.7 V became stronger. On the negative side, n_1 became weaker, while w_1 became stronger. Similar behavior is observed in the *I*-*V* data of sample C shown in Fig. 5. We believe that these results also support our individual resonance model. If current peaks show up as a result of individual level resonance, the peaks can be divided into two groups. One group contains the resonances between the emitter and the near side well, and the other group contains the resonances between the emitter and the far side well. For positive bias, the wide well is the far side well in our structures, and in Figs. 4 and 5 we can see that the w_2 peak is weaker at low temperature.

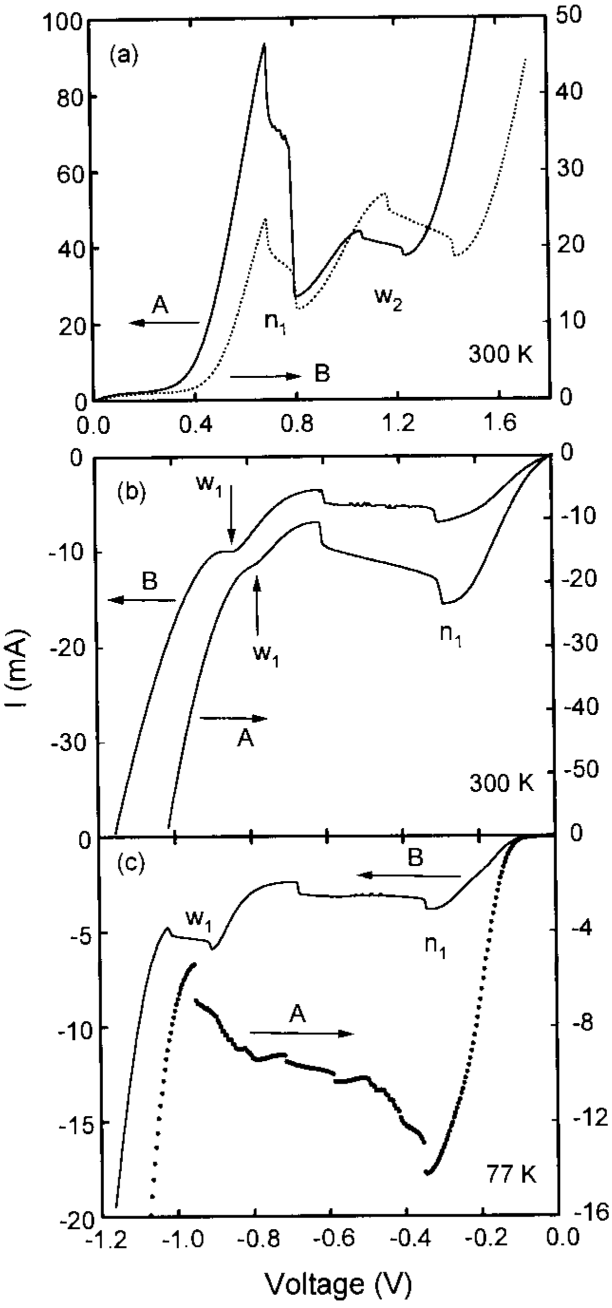

Fig. 3. Comparison of peak positions for samples A and B. (a) is for positive bias and (b) and (c) are for negative bias. The wide-well resonances (w_1 and w_2) clearly show shift when the width was increased from 65 Å to 71 Å.

When the structure is at the far resonance, the first well can be considered to be a barrier to the far side well. The transmission through the first well can be altered by temperature, since the transmission depends on the energy level position and thermal activation. The energy levels in the first well are

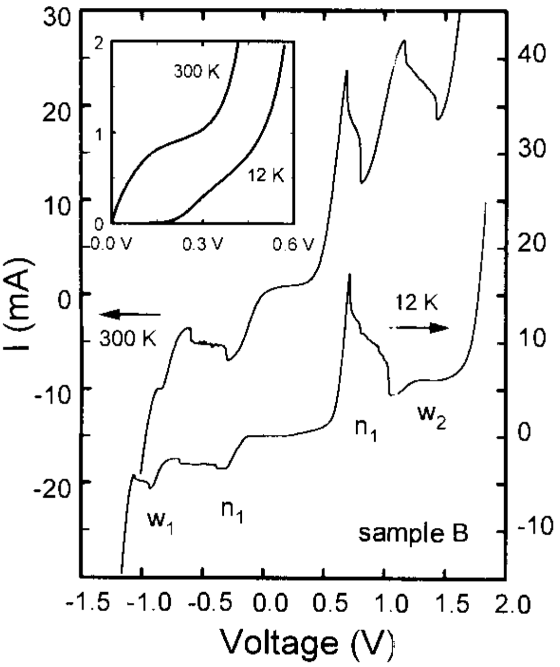

Fig. 4. Temperature dependence of the resonances in sample B. n_1 on the negative side and w_2 on the positive side became weaker at low temperatures. Inset: *I-V* characteristics of sample B on an expanded scale, between 0 and 0.6 V.

not resonant to the emitter, and at room temperature, current can flow via thermal excitation. At low temperature, thermal activation becomes difficult, and transmission through the first well decreases. In other words, the effective barrier becomes thicker at low temperature. This explains why the far resonance shows weaker resonance at low temperature.

3. Conclusion

We presented experimental evidence which supports our individual resonance model. The number of peaks, well-width dependence and temperature dependence indicate that the peaks in our data are due to resonances between the emitter and independent energy levels, without level alignment between neighboring wells.

We would like to note that this model does not deny the occurrence of charge accumulation in quantum wells. Charge accumulation in the wells could exist, but apparently the charge accumulation is not strong enough to align neighboring energy levels to the same height. In some of our low temperature *I-V* data we observed bistability, which we think is due to charge accumulation.

We demonstrated with our data that the resonance between wells with one well in between can show peaks, especially at room temperature. So far, only resonances between adjoining neighbors were considered in a superlattice structure. However, our data show that a well can inject electrons farther than to its joining neighbor. This can be explained by considering the length of the localized electron wavefunctions in a superlattice.[4] If the wavefunction covers more than one period of a superlattice, it will be possible to observe this type of resonance.

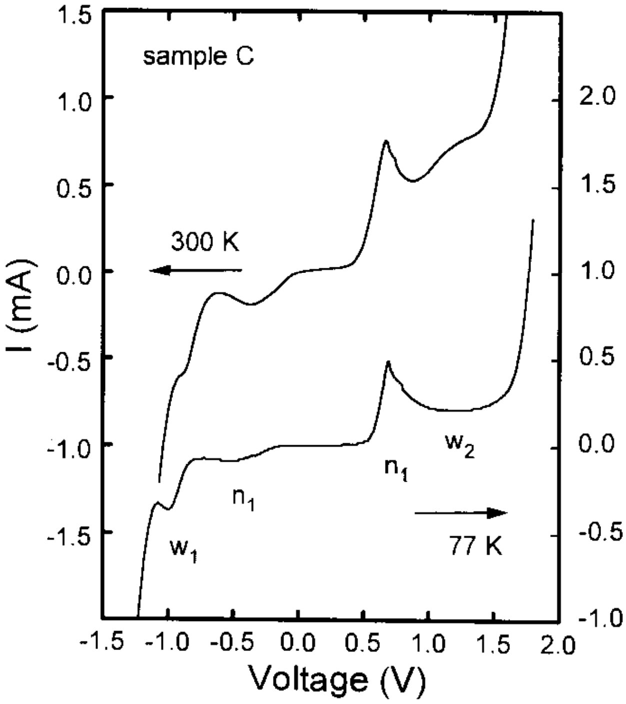

Fig. 5. Temperature dependence in sample C. The behavior is similar to those in Fig. 4.

In Fig. 3(c), two peaks were merged into one wide peak at 77 K (sample A). This behavior has not been previously reported. In a multi-barrier structure, it was not clear whether two closely spaced levels merge into one peak or remain separated by anti-crossing. Our data show that merging can occur in such a case.

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