

Piezoreflectance characterization of double-barrier resonant tunneling structures

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The piezoreflectance technique has been used to optically characterize resonant tunneling structures that utilize isolated single quantum wells. The heavy- and light-hole transitions associated with the quantum wells were prominent in the spectra of samples with barrier widths ranging from 50 to 34 Å. Their spectral positions depended not only on quantum well and barrier thicknesses, but also significantly on the amount of carrier confinement produced by barrier height. Furthermore, variations in the magnitude of impurity transitions could be observed in the spectra of different samples.

In spite of the burgeoning interest in double-barrier resonant tunneling devices (see, for example, Refs. 1-5), no suitable techniques have emerged that can probe their isolated quantum well structures. The highly absorbing doped GaAs layers that cover the double-barrier regions permit electrical contact, but prohibit photoluminescence, electroreflectance, or photoreflectance measurements of the energy levels that aid in the tunneling process. This has necessitated the use of irregular characterization techniques. The growth parameters of these resonant tunneling devices have heretofore only been indirectly inferred from electrical measurements (i.e., current-voltage)⁵ or extrapolated from optical measurements performed on multiple quantum wells or near-surface structures.⁶

This letter reports on the viability of the piezoreflectance (PzR) technique for characterizing resonant tunneling devices that utilize isolated quantum well structures. The optical spectra not only indicate resonant energy levels, but clearly demonstrate their dependence on growth parameters. Moreover, the nondestructive nature and sensitivity to impurity levels establishes PzR as a valuable technique for characterizing double-barrier heterostructures prior and subsequent to device fabrication. It should be emphasized that although the piezoreflectance technique has been used in the past to characterize undoped single or multi-quantum well structures,⁷ it has never been used to characterize structures such as resonant tunneling diodes. Therefore, the information presented in this letter should benefit those involved in the design, fabrication, and characterization of these devices.

All four of the molecular beam epitaxially grown double-barrier resonant tunneling samples used in these experiments had 0.5 μm of Si doped n^+ -GaAs grown over the double-barrier regions. Two of them had 45 Å GaAs wells: one (sample UM1) with 34 Å AlAs barriers, the other (sample UM2) with 45 Å AlAs barriers. The second set of samples (grown at a separate facility) had 50 Å $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ barriers: one with a 40 Å well (PE1), the other a 50 Å well (PE2).

The piezoreflectance apparatus closely resembled that used elsewhere,^{7,8} and therefore, only relevant details will be presented here. Sample substrates were glued to lead-zirconate-titanate piezoelectric transducers (the cyanoacrylate ester glue could easily be removed with acetone without damaging the sample). A 400 Hz 185 V_{rms} square wave applied to the transducer produced strains ($<10^{-5}$) sufficient to modulate the electronic structure of the double-barrier samples, yet small enough to ensure a linear relation to $\Delta R/R$. Radiation from a tungsten-halogen lamp was dispersed through a 1/4 m monochromator and focused to a $\sim 250\mu\text{m}$ spot on the sample. The modulated reflectance signal was measured using a silicon p - i - n photodiode and lock-in amplifier, then normalized digitally to the dc reflectance.

Figure 1 shows the differences and similarities between typical PzR spectra obtained from the Physical Electronics (PE) (dashed) and University of Michigan (UM) (solid) samples. The PzR spectra of the PE samples always had features (labeled 1) attributed to impurity acceptor levels. The UM samples had similar impurity transitions (1'), but with significantly smaller magnitudes. Transitions involving

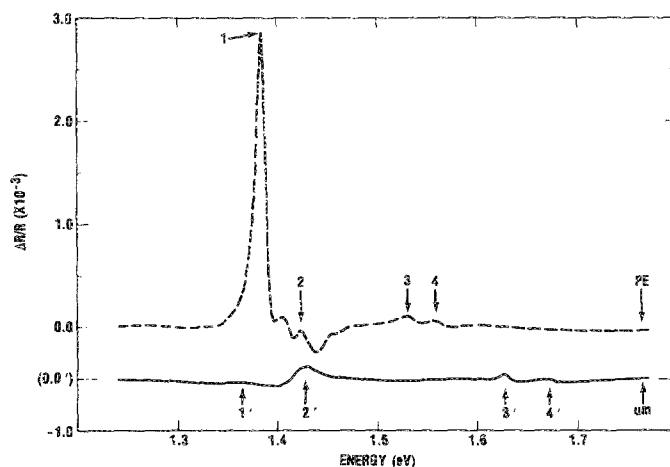


FIG. 1. Typical room-temperature piezoreflectance spectra of the PE (dashed) and UM (solid) samples.

carbon acceptor levels have previously been observed with low-temperature PzR measurements on MBE quantum well samples at energies ~ 20 meV below the GaAs level.⁷ However, the impurity transitions shown in Fig. 1 occurred ~ 35 meV below the GaAs feature (2 and 2'), implying that they resulted from Si acceptor levels.⁹ The difference in the magnitudes of these features suggested that the PE samples were grown under conditions that enhanced the amphoteric nature of Si.¹⁰ All PzR spectra obtained from these resonant tunneling samples had two features (labeled 3 and 4 or 3' and 4' in Fig. 1) attributed to the E_{11H} heavy-hole and E_{11L} light-hole transitions associated with the isolated single quantum wells.

Comparisons of PzR spectra obtained from a multiple quantum well sample (50 Å GaAs wells and 150 Å $\text{Al}_{0.3}\text{Ga}_{0.7}\text{As}$ barriers) with that from the PE2 sample (50 Å GaAs well and 50 Å $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ barriers) aided in identifying resonant energy levels associated with the double barriers. The maxima in the former spectra were previously shown to occur at the energies of transitions to excitonic states.¹¹ However, since the relative position of maximum with respect to the actual transition energy and the spectral line shape depend on the excitonic character of the final state,^{12,13} extrema in the spectra of resonant tunneling samples were only used as a first approximation to the energies of the E_{11HL} transitions.

The PzR spectra of Fig. 2 demonstrate the energy dependence of the E_{11H} and E_{11L} transitions on quantum well width. The $n = 1$ light- and heavy-hole transitions associated with the 40 Å well not only occurred at energies greater than those from the 50 Å well, but also their energy separation increased.

A reduction in barrier width (while maintaining barrier height and well width) reduced carrier confinement, thereby decreasing the energy of the heavy- and light-hole transitions as indicated in Fig. 3. Both of these PzR spectra were obtained from samples with 45 Å wells, but only had 34 Å barriers (solid curve); the other had 45 Å barriers (dashed curve). Also, note the increased linewidth of the E_{11L} fea-

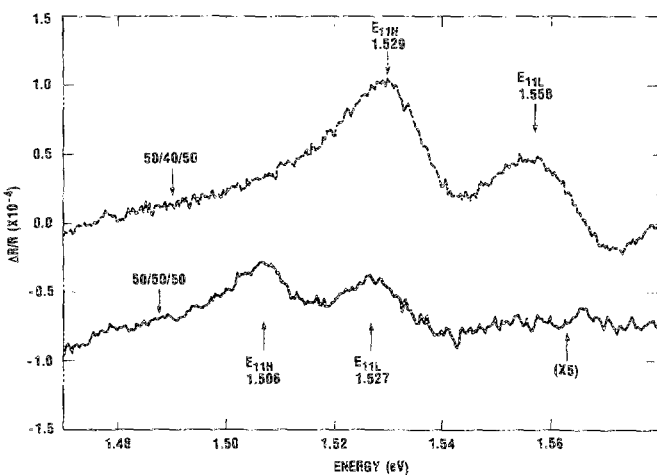


FIG. 2. PzR spectra of the PE samples having 40 Å (dashed) and 50 Å (solid) wells. Note that the increase in confinement shifted the $n = 1$ transitions toward greater energies.

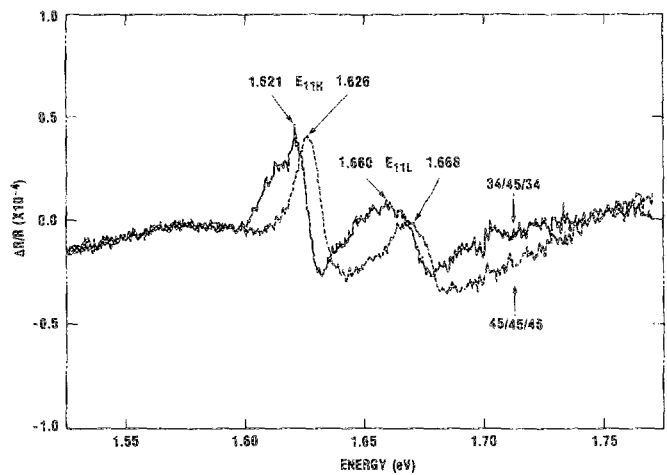


FIG. 3. PzR spectra clearly show the effects of barrier width on carrier confinement. The samples had 34 Å (solid) and 45 Å (dashed) AlAs barriers.

ture and the shoulder on the low-energy side of the E_{11H} feature in the spectrum of the 34 Å barrier sample. Additional features such as these have previously been ascribed to interface irregularities that occur during growth.⁶

Figure 4 illustrates the shift in energy of the $n = 1$ levels that accompanied an increase in barrier height. The E_{11HL} features in the UM2 spectrum (AlAs barriers) occurred at energies ~ 100 meV greater than those of the PE1 sample ($\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ barriers). The energy split between the light- and heavy-hole transitions increased as well. The minor difference in the well and barrier width between the PE1 and UM2 samples only decreased the separation of the corresponding $n = 1$ transitions compared to that which would have occurred had only their barrier height differed. These spectra, therefore, demonstrate the significance of barrier height to carrier confinement.

In conclusion, the PzR technique has proven useful for directly determining energy levels associated with quantum wells deeply buried ($\sim 0.5 \mu\text{m}$) below regions of heavily

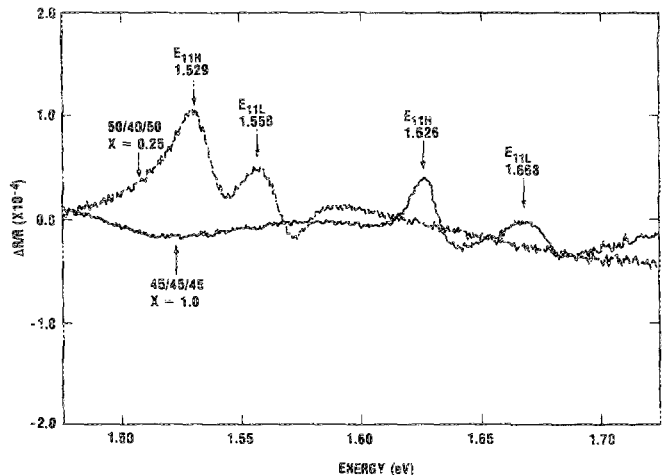


FIG. 4. PzR spectra illustrating the effects of barrier height on carrier confinement. The samples had $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}$ (dashed) and AlAs (solid) barriers.

doped GaAs. The sensitivity of PzR to subtle differences in growth parameters, impurity levels, and surface inhomogeneities makes it useful for predicting device performance prior to fabrication. Furthermore, the dependence of PzR line shapes on excitonic contributions provides a means to study carrier confinement and system dimensionality.

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