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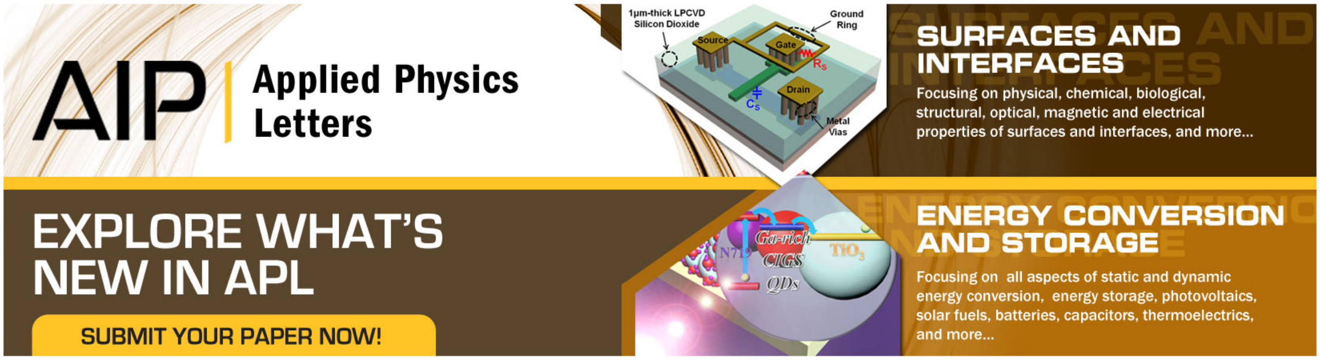

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Resonant tunneling through quantum wells at frequencies up to 2.5 THz

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Resonant tunneling through a single quantum well of GaAs has been observed. The current singularity and negative resistance region are dramatically improved over previous results, and detecting and mixing have been carried out at frequencies as high as 2.5 THz. Resonant tunneling features are visible in the conductance-voltage curve at room temperature and become quite pronounced in the *I-V* curves at low temperature. The high-frequency results, measured with far IR lasers, prove that the charge transport is faster than about 10^{-13} s. It may now be possible to construct practical nonlinear devices using quantum wells at millimeter and submillimeter wavelengths.

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Quantum wells are the subject of considerable theoretical and experimental study. They consist of thin (<100 Å) layers of material, usually a semiconductor confined between two layers of a different material with a larger band gap. In this way carriers are confined to the lower band-gap material. The most studied system uses molecular beam epitaxy (MBE) to fabricate GaAs wells adjacent to $Ga_{1-x}Al_xAs$ barriers. The properties of the wells are usually studied optically or characterized by their transport behavior. If the barriers are sufficiently thin, then carriers can tunnel through them, and it becomes possible to probe the quantum wells with carriers. We have studied resonant tunneling through a single quantum well of such a system.

In this letter we report the first observation of resonant tunneling at room temperature and a broad region of negative resistance which is already observable at 200 K. At 25 K we have observed the largest peak to valley ratio yet reported (6:1). By comparing high-frequency current response measurements with the observed dc characteristics we have established that response times are less than 10^{-13} s and are thus consistent with tunneling. In addition, we have carried out mixing experiments in these devices at various millimeter and submillimeter wavelengths down to 119 μm.

Tsu and Esaki[1] have shown that a large peak in the tunneling current should occur when the injected carriers have certain resonant energies. Figure 1 shows schematically how resonance occurs with applied dc bias. The electrons originate near the Fermi level to the left of the first barrier of height ΔE, tunnel into the well, and finally tunnel through the second barrier into unoccupied states. Resonance occurs when the electron wave function reflected at the first barrier is cancelled by the wave which leaks from the well in the same direction or, equivalently, when the energy of the injected carrier becomes approximately equal to the energy level of the electrons confined in the well.

Previous measurements of heterojunction quantum well structures have shown evidence of resonant tunneling. At low temperatures Chang *et al.*[2] have observed structure in the conductance (dI/dV) voltage curve, and occasionally negative resistance for a single quantum well in the $Ga_{1-x}Al_xAs$ system grown by MBE. Vojak *et al.*[3] have also observed negative resistance at 77 K in multilayer $Al_xGa_{1-x}As$ heterostructures grown by metalorganic chemical vapor deposition using a *p-n* junction for charge injection. These previous measurements, however, have shown only small regions of negative resistance, if any, and near unity peak to valley ratios. No resonant tunneling features were observed at room temperature. Also no measurements of response time were reported.

The structure, shown schematically in Fig. 1, was pre-

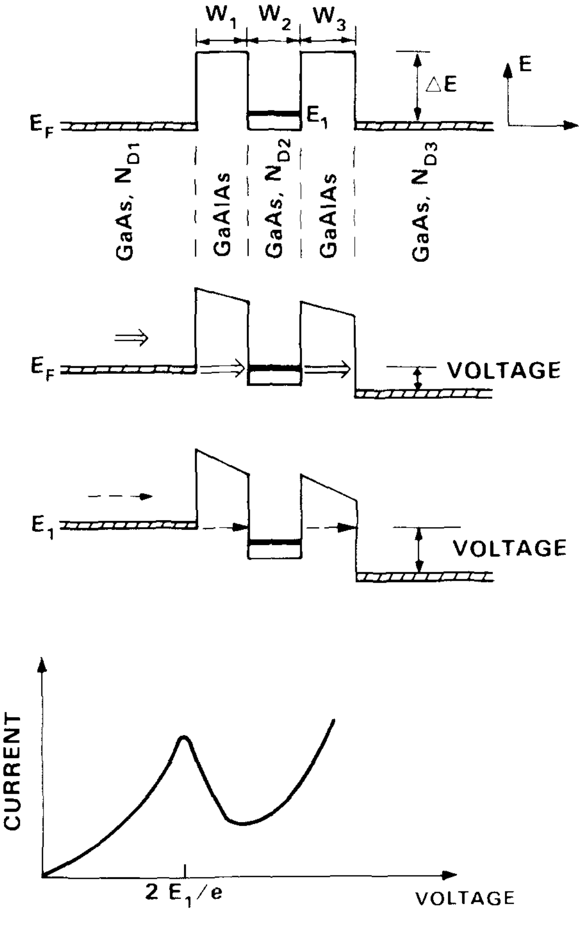

FIG. 1. Electron energy as a function of position in the quantum well structure. The parameters are $N_{D1} = N_{D3} = 10^{18}$ cm^{-3}, $N_{D2} = 10^{17}$ cm^{-3}, and $W_1 = W_2 = W_3 = 50$ Å. The doping level in the well center is an average value achieved by placing a layer of 10^{18} cm^{-3} material in the central 10% of the well. The energy level E_1 occurs above the bottom of the bulk conduction band because of confinement in the x direction. From the aluminum concentration ($x \simeq 25\%$–30%) we estimate $\Delta E = 0.23$ eV.

pared by molecular beam epitaxy on an n-type wafer of GaAs. The net donor concentration (Si) in the GaAs outside the barriers is 10^{18} cm^{-3}, and the GaAs well was doped to an average concentration of 10^{17} cm^{-3} by placing a layer of 10^{18} cm^{-3} material in the central 10% of the well. The resulting band bending within the well is negligible compared to kT. The top layer of GaAs is about 5000 Å thick. The barriers of $Ga_{0.75}Al_{0.25}As$ were not intentionally doped and are presumed to be semi-insulating owing to defect compensation. The substrate growth temperature was 680 °C and the flux ratio of As to Ga as measured from an ion gauge placed at the substrate growth position was 19:1. The Al concentration was measured by analysis of scanning transmission electron induced x rays from the barriers and from measurements of thicker films grown under similar conditions. Both methods gave $x = 25\%–30\%$. The barrier and well dimensions of 50 Å were determined by transmission electron microscopy.

Arrays of mesas, 5 μm square, were etched into the completed wafer with Ohmic contacts top and bottom. The wafers were then diced into 10-mil square chips and mounted in a corner cube detector mount with a whisker contacting the mesas. The corner cube structure has been used routinely in our laboratory for mounting Schottky diodes to be used as detectors and mixers and is well characterized at submillimeter wavelengths.[4]

The observed dc current-voltage and conductance-voltage curves are shown in Fig. 2 for several temperatures. Notice that even at 300 K there are features in the conductance curve, and that a broad region of negative differential resistance exists at 200 K. At temperatures below 50 K the transmission peaks occur at an average voltage of 0.218 V. The peak to valley ratio is 6:1 on the positive side and 4.8:1 for negative voltages. The asymmetry may be due to slightly different barrier thicknesses, or heights, and may also involve interface states at the GaAs-GaAlAs interface.

Submillimeter measurements were made at 138 GHz, 761 GHz, and 2.5 THz with a carcinotron and far IR lasers, respectively. We measured the current response as a function of dc bias voltage. The calculated current responsivity $\mathscr{R}_i$ is given by

$$\mathscr{R}_i = \frac{\Delta I}{\Delta P_{\text{avail}}} = \frac{I'' Z_A}{(1 + Z_A/R_s)^2}\left(\frac{1}{\omega R_s C}\right)^2. \qquad (1)$$

This expression is obtained following Torrey and Whitmer,[5] but accounting for the mismatch between the antenna impedance Z_A of the corner cube and the device impedance in the limit $\omega R_s C \gg 1$ and $R_s \ll (dI_{\text{dc}}/dV)^{-1}$. Here, I'' is the second derivative of the dc I-V curve, C the device capacitance, ω the angular frequency, and R_s the series resistance. We have used $Z_A = 50\,\Omega$ from model measurements on the corner cube at 10 GHz. This value is uncertain by perhaps a factor of 2 because of the large scaling factor. The series resistance was calculated from the sum of the spreading resistance ($2\,\Omega$), resistance of the overgrown GaAs ($4\,\Omega$), and skin resistance of the chip ($5.5\,\Omega$). The capacitance is just the barrier capacitance of 290 fF as calculated from the device dimensions.

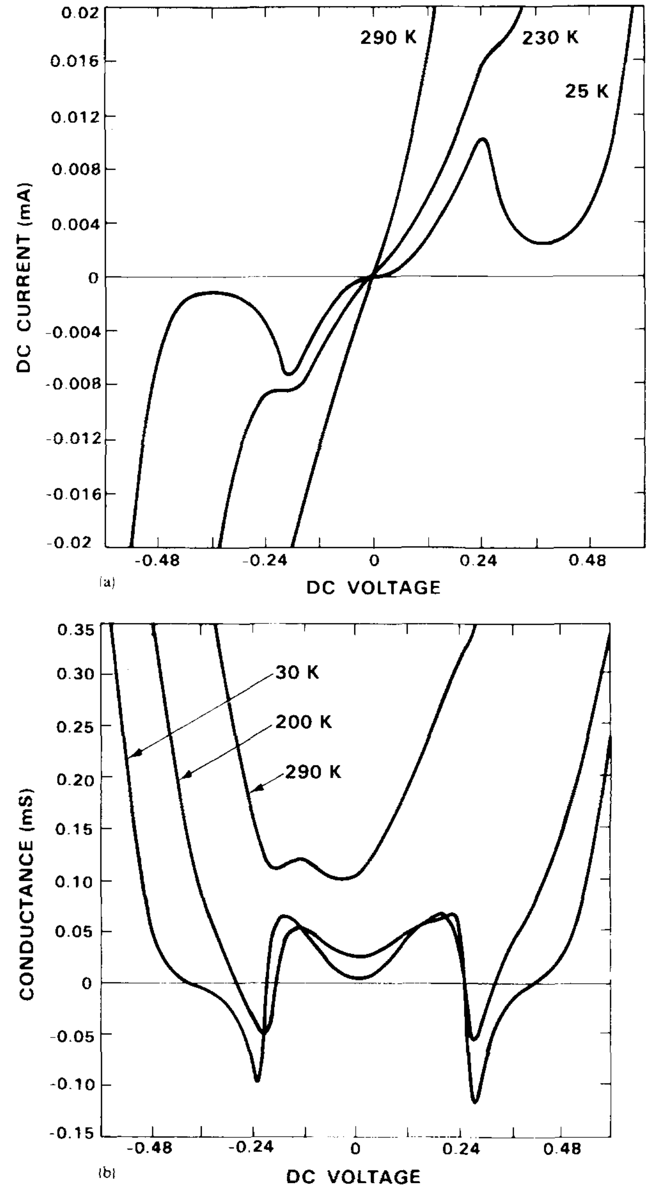

FIG. 2. (a) Current-voltage and (b) conductance (dI/dV)-voltage curves at three temperatures. Notice that resonant tunneling features can be seen even at room temperature.

At all three frequencies the measured current response agrees with the calculated value within a few decibels. In Fig. 3, expanding on an approach used first by Small *et al.*,[6] we show the measured and calculated current response at 2.5 THz. Since the general shape of the two curves is the same, it follows that the I-V curve at 2.5 THz must be very similar to the dc I-V curve. In addition, the magnitude of the calculated current response agrees rather well with the measured curve considering the uncertainties in the parameters of Eq. (1). The somewhat greater discrepancy between measured and calculated values at large voltages may be due to quantum effects of photon assisted tunneling. The agreement is sufficient to show that the charge transport mechanism is at least as fast as the angular period of 2.5 THz, i.e., $\tau = 6 \times 10^{-14}$ s. Further verification has been obtained by mixing two sources near 140 GHz in the device, as well by the observation of far infrared laser mode beats at 434 and 119 μm. These first quantum well structures were not meant to compete with Schottky diodes as detectors. (The responsivity is smaller by over an order of magnitude.) But with dif-

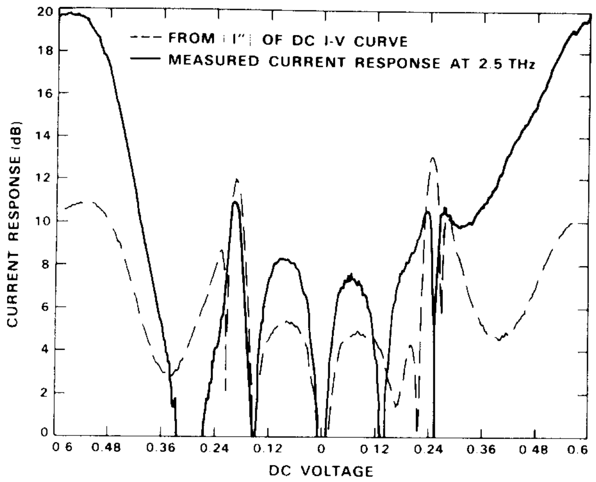

FIG. 3. Current response at 2.5 THz as a function of dc bias voltage. (Sample is at 25 K.) The dashed curve is calculated on the basis of the dc *I-V* curve. Zero decibels corresponds to 0.3 μA/W and 10 dB is 3 μA/W. The general agreement shows that the *I-V* curve at 2.5 THz is very similar to the dc curve, and thus the charge transport is fast.

ferent structure parameters and a reduction in capacitance, high-frequency sensitivity can probably be improved.

The time required for electrons to transit both barriers and the well can be estimated by assuming that tunneling times are approximately given by the uncertainly relation, $\tau \leqslant h/\Delta E$. From our estimate of the Al concentration ($x \simeq 25\%$–30%) in the barriers, and optical measurements of barrier heights,[7] $\Delta E \approx 0.23$ eV. The electrons outside the barrier region have a Fermi velocity of 5×10^7 cm/s, so we assume for simplicity that they move through the well region at the saturation velocity of about 10^7 cm/s. This yields a total transit time estimate of order 10^{-13} s. Other estimates of the tunneling time[8] reduce the total transit time estimate by about a factor of 2.

The tunneling current density of these devices is rather low for practical applications in view of the large capacitance ($RC = 3 \times 10^{-12}$ s). Chang *et al.*[2] have shown that a decrease of barrier width by a factor of 2 results in an increase in current density of two orders of magnitude. We will investigate the lower limits of barrier thickness in the future.

We have fabricated a second MBE wafer of nominally identical configuration to that of Fig. 1 and find very similar results. The quantum well thickness and the barrier heights seem to be reproducable within 10%–20%. Three devices randomly chosen from the same wafer were found to be virtually identical.

The existence of a large negative resistance at very high frequencies suggests applying these devices to millimeter and submillimeter amplifiers and oscillators by designing appropriate resonance circuits and matching the device to the resonator. Since these devices can be fabricated with planar technology, feedback and antenna elements could be placed very near the active area, reducing losses. Also, arrays of elements could be used in distributed circuits.

In conclusion, fabrication of high quality, reproducible, high speed resonant tunneling structures has been demonstrated. It now appears feasible to construct practical nonlinear solid state devices using quantum wells at millimeter and submillimeter wavelengths.

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