Resonant tunneling through a HgTe/Hg$_{1-x}$Cd$_x$Te double-barrier, single-quantum-well heterostructure

M. A. Reed, R. J. Koester, M. W. Goodwin, and H. F. Schaake

Central Research Laboratories, Texas Instruments Incorporated, Dallas, Texas 75265

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Resonant tunneling has been demonstrated through a double-barrier, single-quantum-well HgTe/Hg$_{1-x}$Cd$_x$Te heterostructure for the first time. Negative differential resistance is observable at room temperature, exhibiting a 1.4:1 peak-to-valley tunnel current ratio. The observation provides direct evidence for the existence of the proposed intrinsic interface state.

Resonant tunneling in GaAs/AlGaAs double-barrier heterostructures, first investigated in the seminal work of Chang, Esaki, and Tsu,\textsuperscript{1} has recently been the subject of intense investigation. The remarkable submillimeter wave experiments of Solntsev et al.\textsuperscript{2} and the achievement of large peak-to-valley tunnel current ratios\textsuperscript{3,4} due to improvements in GaAs epitaxial growth techniques has renewed interest in these structures as negative differential resistance devices. This interest has led to a number of intriguing observations: resonant tunneling in a double-barrier heterostructure by holes,\textsuperscript{5} multiple negative differential resistance peaks due to resonant tunneling through excited states,\textsuperscript{6} sequential resonant tunneling through a multiquantum well superlattice,\textsuperscript{7} and resonant tunneling in a double superlattice barrier heterostructure.\textsuperscript{8} Investigations of these structures, however, have been confined to the III-V materials systems and almost exclusively to the GaAs/AlGaAs system.

The recent achievement of epitaxial superlattices in the HgTe/CdTe system\textsuperscript{9,10} has led to the speculation that resonant tunneling can be observed in this system.\textsuperscript{11} However, the basic physics of resonant tunneling in the HgTe/CdTe system is distinctly different from the now familiar GaAs/AlGaAs system. Although CdTe (or the alloy HgCdTe for sufficiently small Hg concentration) has a normal $\Gamma_6$ conduction band and $\Gamma_8$ degenerate light- and heavy-hole band structure, HgTe has a symmetry-induced inverted band structure with the $\Gamma_6$ conduction band and the $\Gamma_8$ heavy-hole valence bands degenerate at the zone center, producing a zero-gap semimetal. The $\Gamma_8$ light-hole band lies 0.3 eV below the $\Gamma_6$ edges due to relativistic corrections. Thus, the conduction and light-hole valence bands have inverted symmetries. Since the light $\Gamma_8$ mass changes sign across the heterojunction, and since the valence-band offset is conjectured to be small relative to the CdTe band gap and negative with respect to the HgTe heavy-hole valence band,\textsuperscript{12,13} an intrinsic interface state has been proposed to form.\textsuperscript{14} The observation of resonant tunneling in this system would provide important experimental evidence for the verification of the interface state model. In this paper we report the first observation of resonant tunneling in a HgTe/Hg$_{1-x}$Cd$_x$Te double-barrier heterostructure.

The epitaxial HgTe/Hg$_{1-x}$Cd$_x$Te double-barrier structure was grown by molecular-beam epitaxy on a CdTe (112) Te substrate. The CdTe surface was prepared for deposition with a 0.5% Br$_2$-methanol static etch for 30 s followed by a 10-min anneal in vacuo at 275–300 °C to remove any excess tellurium. A 0.40-$\mu$m CdTe buffer layer was then deposited using a CdTe effusion cell at 1.1 A/s with the substrate temperature near 275 °C. To assure a uniform Hg vacancy concentration, the composition modulation in the double-barrier structure was achieved by alternating the Te and CdTe cell shutters with a fixed open Hg cell shutter. The double-barrier structure was deposited at a substrate temperature of 180 ± 5 °C with a HgTe growth rate of 4.70 Å/s and a Hg$_{1-x}$Cd$_x$Te barrier layer growth rate of 0.63 Å/s.

An epitaxial HgTe layer was also grown under nominally identical conditions as in the double-barrier structure and exhibited an electron carrier density of $4.7 \times 10^{13}$ cm$^{-3}$ and a carrier mobility of $2.75 \times 10^4$ cm$^2$ V$^{-1}$ s$^{-1}$ at 300 K by low-field Hall measurements. Similarly, an epitaxial CdTe layer was grown in the presence of a Hg flux under nominally identical conditions as in the double-barrier structure and exhibited an electron carrier density of $9.3 \times 10^{13}$ cm$^{-3}$ and a carrier mobility of $2.5 \times 10^4$ cm$^2$ V$^{-1}$ s$^{-1}$ at 300 K. Electron microprobe measurements (5–10 kV) indicated the film had incorporated approximately 20% HgTe. None of the epitaxial layers were intentionally doped. The 10-kV reflection high-energy electron diffraction patterns with sharp streaks and intense Kikuchi bands for all the layers were indicative of high-quality single-crystal growth.

Figure 1 is a schematic of the double-barrier structure. Following the CdTe buffer layer growth, the bottom contact of 1.01-$\mu$m HgTe was deposited. The double-barrier structure followed, consisting of Hg$_{0.5}$Cd$_{0.5}$Te barriers and a HgTe quantum well. The top contact, identical to the bottom contact was then grown, followed by a 380-Å Hg$_{0.5}$Cd$_{0.5}$Te protective capping layer. Figure 2 shows a cross-sectional transmission electron micrograph (TEM) of the double-barrier structure with the dimensions of the barriers and the quantum well.

Mesa devices of various mesa size were fabricated by first removing the protective cap layer and then evaporating an In alloy onto the ion-milled HgTe surface to define Ohmic top contacts. Following a photosist protection of the In contacts, the mesas were created by etching the structure in a 1/8% Br$_2$-methanol solution until the double-barrier structure is isolated. The electrical isolation of mesas was verified by noting an increase in resistance between mesas after the etch due to removal of the (shorting) top conductive layer.
between topside In contacts. Backside contact was defined by an identical In evaporation onto the etched HgTe surface. A schematic of the mesa structure is also diagrammed in Fig. 1.

Static current–voltage (I–V) characteristics of the mesa structures were measured at room temperature in conventional swept voltage mode. The room-temperature I–V characteristics of a device with mesa area 50 × 50 μm is shown in Fig. 3(a) for positive and negative bias. An expanded I–V characteristic for just positive bias is shown in Fig. 3(b). Positive bias corresponds to the top mesa contact positive with respect to the backside contact. The structure exhibits a 1.3:1 peak to valley tunnel current ratio, a resonant voltage <840 meV, an asymmetry of the resonant positions about zero bias, and a current density at resonance of 1.5 × 10^7 A cm⁻². More than 25 similar devices over a 4 × 7 mm area were sampled and all devices exhibited negative differential resistance. Peak-to-valley characteristics varied from a minimum of 1.1:1 to a maximum of 1.4:1.

The apparent hysteresis in the I–V characteristic (i.e., multivalued current at voltages around resonance) is the well-known effect of the addition of a parasitic series resistance with a negative resistance device. The resistance in the present case (large here due to the low impedance of the

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**Fig. 2.** Cross-sectional TEM of the HgTe/Hg₁₋ₓCdₓTe double-barrier structure.

**Fig. 3.** (a) Static I–V characteristics (positive and negative bias) of a mesa structure measured at room temperature. Mesa area = 50 × 50 μm. Positive bias corresponds to the top mesa contact positive with respect to the backside contact. (b) Expanded I–V characteristic (positive bias) of (a).
device) is due to the probe apparatus, independently measured to be 16 Ω. This gives a corrected (true) resonant voltage for the heterostructure of 240 mV. The same value of 240 mV is obtained for the negative bias peak, indicating that the asymmetry in the $I-V$ characteristic about zero bias is due to a difference in the transmitted resonant current presumably due to the asymmetric barrier thicknesses. The mechanism for the current asymmetry is presently under investigation.

A systematic survey of a number of devices, when corrected for the parasitic series resistance, gave a resonant voltage of $235 \pm 5$ mV. The resonant peak position is in good agreement with the interface state calculations of Schulman and Anderson\textsuperscript{11} (for these dimensions, ~200 mV) and clearly excludes the use of single-band models using the CdTe (or HgCdTe) conduction-band minimum (which gives a resonant voltage of 832 mV). This observation provides direct evidence for the existence of the proposed interface state.

The demonstration of resonant tunneling in the HgTe/Hg$_{1-x}$Cd$_x$Te system makes possible a number of important investigations. A careful study of the resonant peak current densities and resonant voltages as a function of quantum well and barrier width can give an accurate determination of the valence-band offset. Alternatively, moving the shifted $\Gamma_8$ valence band in the contact and quantum well layers by uniformly varying the Cd mole fraction not only gives the offset but allows the transition to a “GaAs-like” resonant tunneling structure for $x > 0.16$. The behavior of these structures around the transition ($x = 0.16$) are sensitive probes of the Hg$_{1-x}$Cd$_x$Te heterojunction band structure.

In summary, we report the first observation of resonant tunneling in a HgTe quantum well, double Hg$_{0.2}$Cd$_{0.8}$Te barrier heterostructure. Negative differential resistance is observable at room temperature, producing peak-to-valley tunnel current ratios as high as 1.4:1. The observed resonant peak position for a 41-Å Hg$_{0.2}$Cd$_{0.8}$Te barrier/71-Å HgTe quantum well/41-Å Hg$_{0.2}$Cd$_{0.8}$Te barrier structure is $235 \pm 5$ mV, in good agreement with the interface state calculations of Schulman and Anderson.

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