

# Resonant tunneling through a HgTe/Hg<sub>1-x</sub>Cd<sub>x</sub>Te double barrier, single quantum well heterostructure

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Resonant tunneling has been demonstrated through a double barrier, single quantum well HgTe/Hg<sub>1-x</sub>Cd<sub>x</sub>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,<sup>1</sup> has recently been the subject of intense investigation. The remarkable submillimeter wave experiments of Sollner *et al.*<sup>2</sup> and the achievement of large peak to valley tunnel current ratios<sup>3,4</sup> due to improvements in GaAs epitaxial growth techniques have 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,<sup>5</sup> multiple negative differential resistance peaks due to resonant tunneling through excited states,<sup>6</sup> sequential resonant tunneling through a multiquantum well superlattice,<sup>7</sup> and resonant tunneling in a double superlattice barrier heterostructure.<sup>8</sup> Investigations of these structures, however, have been confined to the III-V material systems and almost exclusively to the GaAs/AlGaAs system.

The recent achievement of epitaxial superlattices in the HgTe/CdTe system,<sup>9,10</sup> has led to the speculation that resonant tunneling can be observed in this system.<sup>11</sup> 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-hole and heavy-hole band structure, HgTe has a symmetry-induced inverted band structure with the  $\Gamma_8$  conduction band and the  $\Gamma_8$  heavy-hole valence bands degenerate at the zone center, producing a zero-gap semimetal. The  $\Gamma_6$  light-hole band lies 0.3 eV below the  $\Gamma_8$  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,<sup>12,13</sup> an intrinsic interface state has been proposed to form.<sup>14</sup> The observation of resonant tunneling in this system would provide important experimental evidence for the verification of the interface state model. In this letter, we report the first observation of resonant tunneling in a HgTe/Hg<sub>1-x</sub>Cd<sub>x</sub>Te double barrier heterostructure.

The epitaxial HgTe/Hg<sub>1-x</sub>Cd<sub>x</sub>Te double barrier structure studied was grown by molecular beam epitaxy on a CdTe (112) Te substrate. The CdTe surface was prepared for deposition with a 0.5% Br<sub>2</sub>-methanol static etch for 30 s followed by a 10 min anneal *in vacuo* at 275–300 °C to re-

move any excess tellurium. A 0.40- $\mu$ m CdTe buffer layer was then deposited using a CdTe effusion cell at 1.1  $\text{\AA}/\text{s}$  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  $180 \pm 5$  °C with a HgTe growth rate of 4.70  $\text{\AA}/\text{s}$  and a Hg<sub>1-x</sub>Cd<sub>x</sub>Te barrier layer growth rate of 0.63  $\text{\AA}/\text{s}$ .

An epitaxial HgTe layer was also grown under nominally identical conditions as in the double barrier structure and exhibited an electron carrier density of  $4.7 \times 10^{17} \text{ cm}^{-3}$  and a carrier mobility of  $2.75 \times 10^4 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  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  $9.3 \times 10^{12} \text{ cm}^{-3}$  and a carrier mobility of  $2.5 \times 10^3 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$  at 300 K. Electron microprobe measurements (5–10 kV) indicated the film had incorporated approximately 20% HgTe. None of the epilayers was 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 illustrates the layer dimensions for the double barrier structure. Following the CdTe buffer layer growth, the bottom contact of 1.01  $\mu\text{m}$  HgTe was deposited. The double barrier structure followed, consisting of 38  $\text{\AA}$  Hg<sub>0.2</sub>Cd<sub>0.8</sub>Te barriers and a 66  $\text{\AA}$  HgTe quantum well. The top contact, identical to the bottom contact, was then grown, followed by a 380- $\text{\AA}$  Hg<sub>0.2</sub>Cd<sub>0.8</sub>Te protective capping layer.

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 photoresist protection of the In contacts, the mesas were created by etching the structure in a 1/8% Br-methanol solution until the double barrier structure was 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

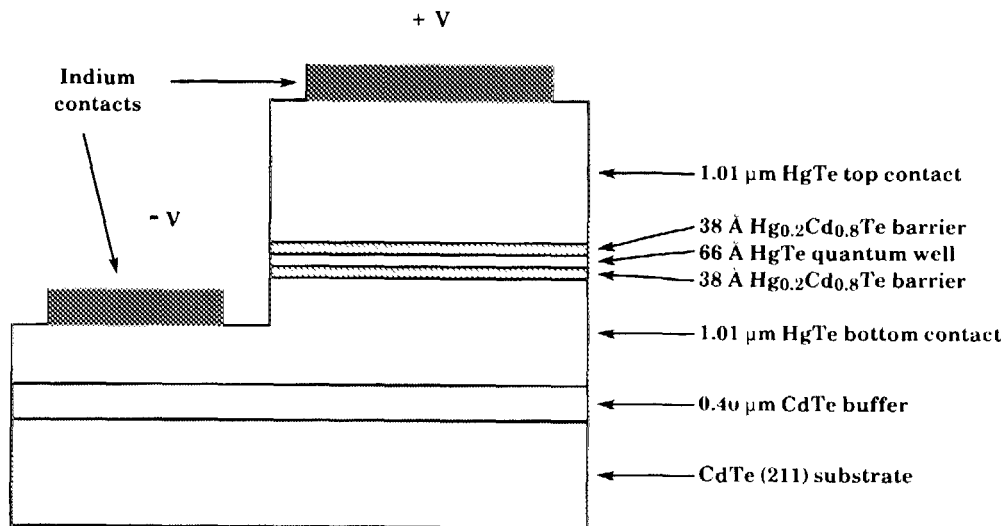


FIG. 1. Cross-sectional schematic of the  $\text{HgTe}/\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  double barrier, single quantum well heterostructure. Top mesa and backside indium contacts are diagrammed. A 380-Å  $\text{Hg}_{0.2}\text{Cd}_{0.8}\text{Te}$  protective cap was removed prior to device fabrication.

structures were measured at room-temperature in conventional swept voltage mode. The room temperature  $I$ - $V$  characteristics of a device with mesa area  $50\ \mu\text{m} \times 50\ \mu\text{m}$  are shown in Fig. 2(a). Positive bias corresponds to the top mesa contact positive with respect to the backside contact. The

structure exhibits a 1.4:1 peak to valley tunnel current ratio, a resonant voltage  $\leq 440\ \text{meV}$ , an asymmetry of the resonant positions about zero bias, and a current density at resonance of  $1.5 \times 10^3\ \text{A cm}^{-2}$ . More than 25 similar devices over a  $4\ \text{mm} \times 7\ \text{mm}$  area were sampled and all devices exhibited negative differential resistance. There was negligible variation in resonant peak position for the devices sampled, but the peak to valley characteristics varied from 1.1:1 to 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.<sup>15</sup> The resistance in the present case is due to the probe apparatus, independently measured to be  $5\ \Omega$ . This gives a corrected (true) resonant voltage for the heterostructure of  $240\ \text{mV}$ . The effect of the extra voltage drop across the series resistance can be minimized, as shown in Fig. 2(b), for a device of smaller mesa area ( $25\ \mu\text{m} \times 25\ \mu\text{m}$ ). This device exhibits a resonant voltage  $\leq 240\ \text{mV}$ , which gives a corrected resonant voltage of  $230\ \text{mV}$ . In this case the negative resistance is directly observable and is  $\leq -1.4\ \Omega$ . The resonant peak positions are in good agreement with the interface state calculations of Schulman and Anderson<sup>11</sup> and clearly exclude the use of single band models using the CdTe (or HgCdTe) conduction-band minimum (which gives a resonant energy of  $832\ \text{meV}$ ). This observation provides direct evidence for the existence of the proposed interface state.

All the  $\text{HgTe}/\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  structures exhibit an asymmetry in the  $I$ - $V$  characteristics (specifically, the resonant voltages) around zero bias. This observation is common in the GaAs/AlGaAs system, and has been ascribed either to the inferior inverted interface morphology of the quantum well and contact region<sup>4</sup> or the redistribution of dopants in the contact regions. It has recently been shown<sup>8</sup> that the inverted surface is probably the responsible mechanism for the asymmetry in the GaAs/AlGaAs system. However, it is not clear from the present data which (if either) suggestion is the responsible mechanism in the  $\text{HgTe}/\text{Hg}_{1-x}\text{Cd}_x\text{Te}$  system. Additionally the role of interface diffusion, absent in the GaAs/AlGaAs system, must be considered.

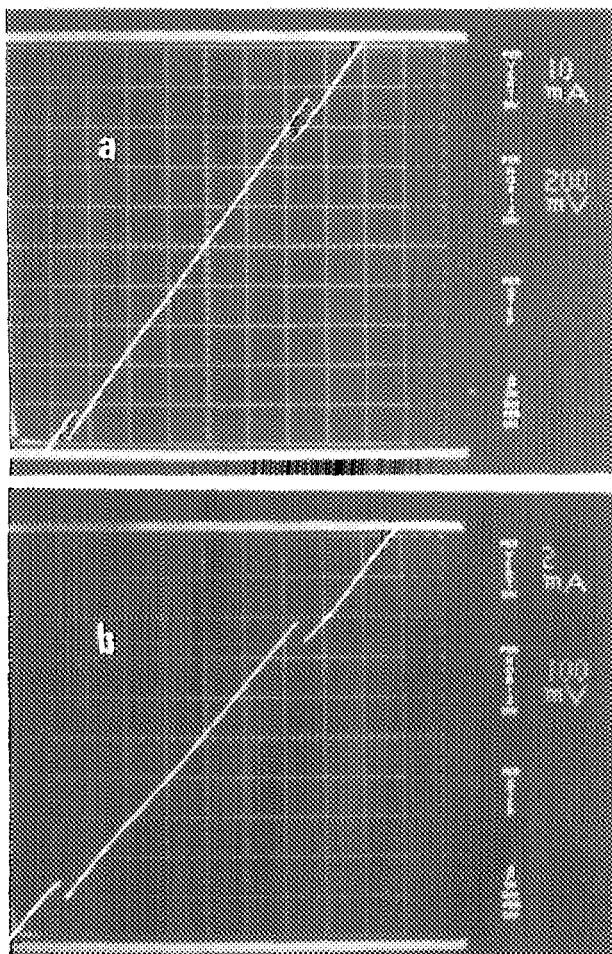


FIG. 2. (a) Static  $I$ - $V$  characteristics of a mesa structure measured at room temperature. Mesa area =  $50\ \mu\text{m} \times 50\ \mu\text{m}$ . Positive bias corresponds to the top mesa contact positive with respect to the backside contact. (b) Static  $I$ - $V$  characteristics of a mesa structure measured at room temperature. Mesa area =  $25\ \mu\text{m} \times 25\ \mu\text{m}$ .

The demonstration of resonant tunneling in the HgTe/Hg<sub>1-x</sub>Cd<sub>x</sub>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  $\Gamma_6$  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 behaviors of these structures around the transition ( $x = 0.16$ ) value are sensitive probes of the Hg<sub>1-x</sub>Cd<sub>x</sub>Te heterojunction band structure.

In summary, we report the first observation of resonant tunneling in a HgTe quantum well, double Hg<sub>0.2</sub>Cd<sub>0.8</sub>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 positions are in good agreement with the interface state calculations of Schulman and Anderson, though the structure exhibits asymmetry in the resonant peak positions around zero bias.

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