New negative differential resistance device based on resonant interband tunneling

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(Received 30 May 1989; accepted for publication 6 July 1989)

We propose and demonstrate a novel negative differential resistance device based on resonant interband tunneling. Electrons in the InAs/AlSb/GaSb/AlSb/InAs structure tunnel from the InAs conduction band into a quantized state in the GaSb valence band, giving rise to a peak in the current-voltage characteristic. This heterostructure design virtually eliminates many of the competing transport mechanisms which limit the performance of conventional double-barrier structures. Peak-to-valley current ratios as high as 20 and 88 are observed at room temperature and liquid-nitrogen temperature, respectively. These are the highest values reported for any tunnel structure.

Semiconductor tunnel structures with negative differential resistance (NDR) have been extensively studied for many years. The reasons for this interest are applications such as microwave and fast digital devices. The tunnel diode (Esaki diode), in which carriers tunnel through the band gap of a forward-biased *p-n* junction, was invented in 1958.[1] In 1974 the double-barrier resonant tunneling (DBRT) diode was first demonstrated.[2] In this structure NDR arises from electrons tunneling through a quantum well state. Recently the single barrier tunneling (SBT) diode was introduced as another NDR device.[3,4] Electrons tunnel through this structure at energies close to the valence-band edge of the barrier layer, yielding a decrease in transmission probability as the voltage increases.

For many potential applications, NDR devices must have a large peak current density and a low valley current density. Hence, the peak-to-valley current (P/V) ratio is used as a figure of merit. The Esaki diode has produced P/V ratios larger than 50.[5] AlGaAs/GaAs DBRT diodes have been observed to display a P/V ratio of 3.9 (21),[6] while InGaAs/AlAs structures have yielded 14 (35)[7] at room temperature (77 K). The SBT structure (InAs/AlGaSb) has thus far produced P/V ratios of 1.6 (3.4) at room temperature (77 K).[8,9]

In this letter we propose and demonstrate a new tunnel structure with characteristics that outperform the previous tunnel structures. This device is the resonant interband tunneling (RIT) diode in which electrons tunnel from the conduction band of the contact layer, through a barrier and into a quantized hole state in the valence band of the quantum well layer. This structure can be considered as a combination of the Esaki diode and the DBRT diode, with the individual advantages (i.e., the high P/V ratio of the former and the high-frequency properties of the latter) combined in one device. We demonstrate the RIT diode for an InAs/AlSb/GaSb/AlSb/InAs heterostructure. Three samples were studied, all displaying strong NDR. P/V ratios as high as 20 and 88 are observed at room temperature and 77 K, respectively. These are the highest values reported for any tunnel structure.

A schematic diagram of the valence- and conduction-band (Γ point) edges of the InAs/AlSb/GaSb/AlSb/InAs heterostructure is shown in Fig. 1.[10,11] The important feature of this heterostructure is that the valence-band edge of the GaSb layer is higher in energy than the conduction-band edge of the InAs contact layers, allowing electrons to tunnel into the valence-band quantum well. As in the case of the DBRT structure, the tunneling electrons have a peaked transmission probability at the energy of the quantized state in the well. This process is normally called "resonant tunneling." Observe that we do not with this name distinguish between coherent and noncoherent tunneling of electrons.[12] The electron wave function in the InAs couples primarily to the light hole state in the well. Coupling to the heavy holes is expected to be much weaker since, in a homogeneous bulk crystal, such coupling would be forbidden by symmetry. For the present we assume that the electrons tunnel through the quantized light hole state in the well.

The maximum current will be obtained at a voltage where the maximum number of electrons can participate in the tunneling through the quantum state. In a DBRT this occurs when the quantized state is lined up in energy with the conduction band of the contact layer. For the RIT structure we have a more complicated situation since the energy bands in the direction parallel to the surface are pointing in opposite directions: up for the InAs conduction-band and down for the GaSb valence-band quantum well. Thus, we have an overlap of the bands at zero bias. The maximum number of tunneling electrons will occur somewhere between zero bias and the point where the quantized state drops below the InAs conduction-band edge. At higher voltages, electron tunneling through the quantized state is impossible due to energy conservation and consequently the current is lower (NDR). The RIT structure is similar to the DBRT structure in that the current peak is caused by tunneling through a quantum state. However, the size of the total barrier (as experienced by tunneling electrons) in the DBRT structure decreases as voltage is applied. The electrons in the RIT structure, on the other hand, have to tunnel

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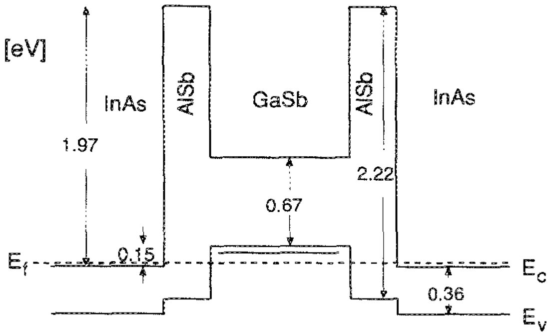

FIG. 1. Band-edge diagram (Γ point) for the RIT structure at room temperature. Experimental band offset values have been reported for the InAs/GaSb interface ($\Delta E_v = 0.51$ eV) (see Ref. 9) and the AlSb/GaSb interface ($\Delta E_v = 0.40$ eV) (Ref. 10) only. The valence-band edge of the GaSb and the quantized hole state of the well are both above the InAs conduction-band edge at zero bias. In this figure the band bending has been neglected.

not only through the band gap of the AlSb layers but also through the band gap of the GaSb layer at voltages past resonance. Thus, the electrons experience a very thick barrier, virtually eliminating valley current contributions arising from tunneling.

The samples are grown on GaAs (100) substrates in a Perkin–Elmer 430 molecular beam epitaxy (MBE) system. An As cracker and an Sb cracker were used to produce dimers instead of tetramers in the molecular beam. Details of bulk growth parameters for InAs and GaSb can be found elsewhere.[13] Due to the large lattice mismatch (7.2%) between the substrate and the epilayer, a thick buffer layer was grown. The buffer layer consisted of 2500 Å GaAs grown at 600 °C, a five-period $In_{0.7}Ga_{0.3}As$/GaAs (2 monolayers/2 monolayers) superlattice grown at 500–520 °C, and 1.0 μm InAs (heavily Si doped) grown at 500 °C. The superlattice at the GaAs/InAs interface reduces the number of strain-induced dislocations which penetrate into the InAs layer.[13,14] This buffering scheme has previously been used for double-barrier structures,[15] single-barrier structures,[9] and infrared superlattices[16] with very good results.

The RIT structure was grown at 500 °C on top of the buffer layer and consisted of a GaSb quantum well sandwiched between AlSb barriers, 100 Å undoped InAs spacer layers, and 500 Å lightly doped ($n = 2\times10^{16}$ cm^{-3}) InAs spacer layers. The two-step spacer layer technique is used to reduce the number of Si donors in the barrier region and has previously been used for AlGaAs/GaAs double-barrier structures.[5] Finally a 2500-Å-thick heavily doped ($n = 2\times10^{18}$ cm^{-3}) InAs cap layer was grown. The three samples had the following thickness for the AlSb/GaSb/AlSb layers: sample A, 25 Å/65 Å/25 Å; sample B, 25 Å/65 Å/15 Å; sample C, 25 Å/100 Å/15 Å (the thinner barrier being closest to the substrate).

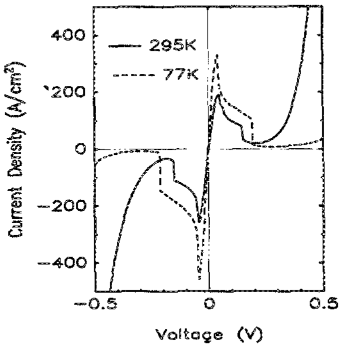

FIG. 2. Current-voltage characteristics of sample A (25 Å AlSb barriers; 65 Å GaSb well) at room temperature and liquid-nitrogen temperature. The curve is fairly symmetric around zero bias with slightly larger currents in the reverse direction. The P/V ratios are 9.5 and 65 at room temperature and 77 K, respectively.

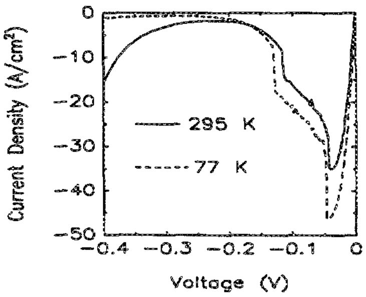

FIG. 3. Current-voltage characteristics of sample B (25 Å and 15 Å AlSb barriers; 65 Å GaSb well) in the reverse direction. The P/V ratios are as high as 20 (72) at room temperature (77 K).

Mesa structures (area 100 μm^2) with Au/Ge contacts on top were prepared using standard photolithography, lift-off, and chemical etch techniques. Au/Ge deposited on the etched InAs buffer layer served as "back" contact. No annealing was necessary since Au/Ge forms an ohmic contact to InAs. The mesas were probed with a thin gold wire to establish electrical contact to the devices.

The current-voltage (I-V) characteristic of sample A is shown in Fig. 2. A current peak corresponding to tunneling through the valence-band quantized hole state can be seen for both forward and reverse bias. There is no threshold voltage for drawing current from the structure due to the fact that the bands overlap at zero bias, as discussed previously. The P/V ratios are 9.5 at room temperature and as high as 65 at 77 K.

Samples B and C were both grown intentionally asymmetric with the thinnest barrier closest to the substrate. In these samples the peak currents in the forward direction (mesa contact positive relative to substrate) were about six times larger than for reverse bias. Thus the largest current is obtained with electrons tunneling through the thinner barrier into the quantum well and out through the thicker barrier. This has previously been noted for AlGaAs/GaAs double barriers. The explanation has been that the maximum transmission probability is achieved when the barriers have equal sizes at resonance.[17] The P/V ratios at forward bias for these two samples were about 9 (28) at room temperature (77 K). The best P/V ratios, however, were obtained for reverse bias and these I-V curves can be seen in Figs. 3 and 4. Sample B (65 Å well) had a room-temperature P/V ratio as high as 20. Sample C (100 Å well) had the best P/V ratio at 77 K of all samples with the very large value of 88. This value is much larger than any previously reported for tunnel structures.

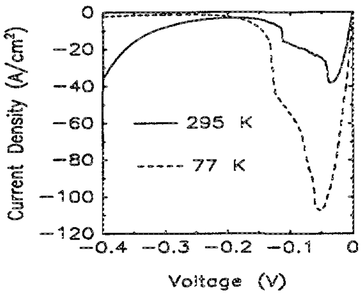

FIG. 4. Current-voltage characteristics of sample C (25 Å and 15 Å AlSb barriers; 100 Å GaSb well) in the reverse direction. The room-temperature P/V ratio is 13 while at 77 K the large value of 88 is obtained.

One important feature in all the I-V curves is that the low valley current extends to relatively high voltages. We believe that this is due to the band gap of GaSb being pushed down to the energy of the tunneling electrons as discussed previously. Thus the electrons experience a very thick barrier, which keeps the current low even at higher voltages.

In all three samples the currents at 77 K are larger than at room temperature. This is most obvious in sample C. This may be caused by reduced thermal spreading of the carriers which would allow more states to participate in the tunneling process, or possibly the variations of band gaps with temperature.

The results presented show that the RIT diode is a promising alternative for future applications of NDR devices. In this early stage of development we have already demonstrated very high P/V ratios and a wide, low current, valley region. The best peak current density is presently about 600 A/cm^2 but is expected to increase as we optimize the device structure. This novel structure can also be used for three-terminal NDR devices with additional possibilities for making base contacts to those previously reported.[18]

At present no theoretical modeling of the structure has been done. The RIT structure is a bit more complicated than the standard double-barrier structure since both the valence and conduction bands have to be considered. We are working on this problem in order to obtain a more thorough understanding of the tunneling process.

In summary, we have proposed and demonstrated the novel resonant interband tunneling (RIT) structure as a NDR device. We have observed peak-to-valley current ratios as high as 20 and 88 at room temperature and 77 K, respectively. These values are much higher than any previously reported for tunneling structures. We attribute the low valley current to the band gap of GaSb acting as a barrier for electrons at voltages past resonance. The RIT structure has a large potential in microwave and digital applications and for construction of three-terminal NDR devices.

This work was supported by the Office of Naval Research under contract No. NO0014-89-J-1141. One of us (JRS) wishes to thank the Boncompagni–Ludovisi foundation for financial support. Another (DHC) is thankful to TRW for financial support.

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