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Probing of InAs/AlSb double barrier heterostructures by ballistic electron emission spectroscopy

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InAs/AlSb resonant tunneling heterostructures have been studied by ballistic electron emission spectroscopy. Current thresholds attributed to quasibound states in the quantum well and emission over the AlSb barriers are observed. The observed shape of thresholds is consistent with inelastic processes in the InAs layers of the structures, where a high number of electron–hole pairs are generated. A threshold consistent with the generation of electron–hole pairs in quantum well states is observed. © *1997 American Institute of Physics.* [S0003-6951(97)03626-7]

Ballistic electron emission spectroscopy (BEES) is a potentially useful technique for characterizing heterostructures, or BEES could be used to determine energy levels that are difficult to measure by other methods. BEES measurements on double barrier tunneling structures have been reported for GaAs/AlGaAs structures.[1,2] Thresholds in current–voltage ballistic characteristics ($I_c - V$) were observed at voltages consistent with the quasibound quantum well state and the height of the AlGaAs barriers. These thresholds were observed at both 300 and 77 K.[1,2]

We report the BEES measurements on InAs/AlSb resonant tunneling structures, which are of significant interest for the fabrication of high-speed circuits.[3,4] We have examined two structures that differ in quantum well thickness, i.e., different resonant state energies. These differences should be manifested as different BEES thresholds. Furthermore, the narrow energy gap of InAs should yield strong electron–hole ($e-h$) pair creation, producing an additional BEES threshold.[5–8]

Our BEES apparatus is described elsewhere.[9] We used the Mo tip prepared by etching in KOH solution. The sample is biased during the measurement. The ratio of ballistic current to tunneling current (I_c/I_t) is measured as a function of the voltage, (V), between the tip and sample, reducing the effects of instabilities in the tunneling current. (I_t) is held constant during the measurements. (I_t) is held at approximately 1 nA, although it varies slightly from one characteristic to the next. Each of the ($I_c/I_t - V$) characteristics presented here is an average of 20 characteristics taken at 300 K. Increased averaging (to 40 scans) did not alter the observed peak positions in any of our experiments. For each single characteristic, a step size of 0.01 V over the range 0.1–2.3 V is used, with each (I_c/I_t) value determined by taking the average of 10 000 measurements. This procedure yields a measurement time of approximately 2 h per resulting presented characteristic, so that to obtain the BEES spectra, we use the same acquisition time as was reported for similar measurements in Ref. 6. The zero for ballistic current is defined as the value at the lowest bias used. Variations across the sample surface and with illumination have been studied.

Prior to testing of the InAs/AlSb heterostructures, the BEES apparatus was tested by comparing measurements on an Au–GaAs(n) Schottky barrier sample to the published BEES spectra, Ref. 10.

Two InAs/AlSb double barrier heterostructure samples grown by molecular beam epitaxy, Sb640 and Sb663, have been used to acquire the data presented here. The samples were grown on (100)-oriented semi-insulating GaAs substrates. Growth commenced with a 150 nm GaAs buffer layer and continued with a five-period, 2 ML/2 ML, InAs/GaAs superlattice, 1 μm InAs buffer layer, 2 nm AlSb barrier, 4 nm (sample Sb640) or 12 nm (sample Sb663) InAs quantum well, 2 nm AlSb barrier, and 3 nm InAs cap layer. All layers are nominally undoped; background doping of the InAs layers is approximately 1×10^{16} cm^{-3}, n type. Schematic band-edge diagrams of samples Sb640 and Sb663 are provided in Fig. 1. The first and second quantum well energy levels, E_1 and E_2, are shown relative to the estimated Fermi level, E_F, which lies 0.2 V from the bottom of the conduction-band edge of bulk InAs. The energy gaps of InAs and AlSb are labeled G_1 and G_2, respectively. The height of the AlSb barriers above E_F is labeled E_B.

Preparation of the samples for BEES measurements was performed as follows: A 10 nm Au layer was evaporated in

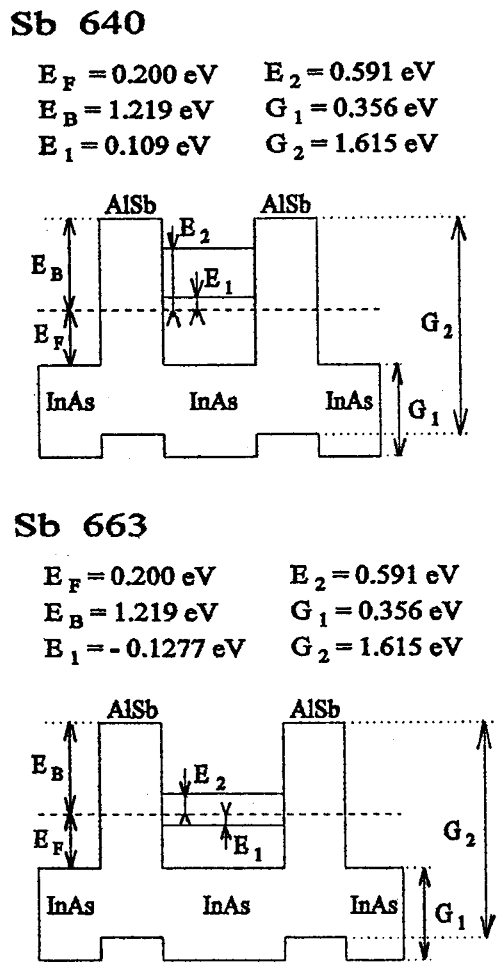

FIG. 1. Schematic band-edge diagrams corresponding to InAs/AlSb double barrier heterostructure samples Sb640 and Sb663. G_1 and G_2 are the energy gaps of InAs and AlSb, respectively. E_1 and E_2 are the first and second resonant states. E_B is the height of the AlSb barrier, and E_F is the Fermi energy.

ultrahigh vacuum through a shadow mask placed on top of each sample. The ''back'' contact was made either directly to the substrate, or to the 1 μm thick InAs buffer layer after removing the double barrier structure by etching. In a few cases, the substrate was bombarded from the back side by 50 keV Ar^+ at a dose of 10^{15} ions/cm^2 to improve the back contact. Silver paste was used to make a large back side contact to the substrate, while gentle silver springs were used to make contacts to the InAs buffer layer and to the evaporated Au layer.

Initial measurements were performed on sample Sb663 in the energy region 0.7 to 1.7 eV. The shape of the threshold most frequently observed in the energy region corresponding to the height of the AlSb barriers is shown in Fig. 2, where the labeled $E_B = 1.219$ V is attributed to the height of the barriers in the structure (see Fig. 1). At different measured places of the sample the voltage at which the current begins to increase significantly varies by less than ± 0.05 V around E_B. The sharp peaks observed in the BEES spectrum have been previously attributed to strong inelastic processes, such as scattering and $e-h$ pair creation, which result in a decrease in the ballistic current with voltage significantly greater than the threshold. This was demonstrated experi-

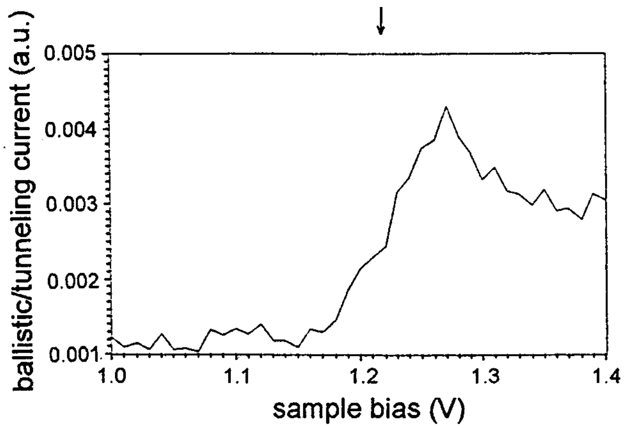

FIG. 2. BEES characteristic from Sb663 in the barrier energy region. (I_c/I_t) is taken to be zero for eV=0.7 eV. The sample was prepared by evaporating 10 nm of Au on top of the sample, the back contact is made for the 50 keV Ar^+ ion bombarded GaAs substrate. The threshold due to transport over the AlSb barriers is indicated by an arrow.

mentally and by Monte Carlo simulation (Refs. 5 and 11). It is expected that $e-h$ pair creation occurs mainly in the InAs layers of the structure due to the narrow energy gap of this material.

Examples of measured BEES characteristics over the full voltage range are shown in Figs. 3 and 4 for samples Sb663 and Sb640, respectively. The top characteristic in Fig.

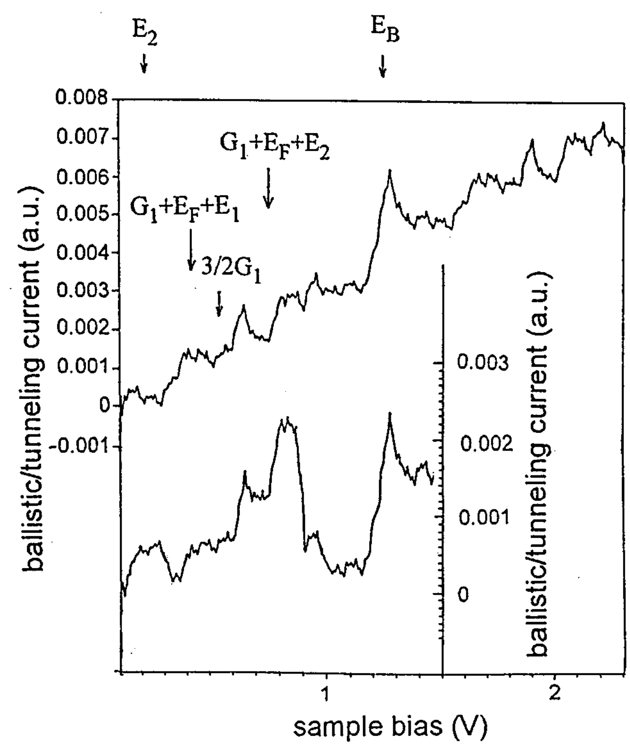

FIG. 3. BEES characteristics from Sb663. The top characteristic is from the sample prepared using the same procedure as described in the caption of Fig. 2; the characteristic below is from the sample with the back contact made for a 1 μm thick InAs layer. The arrows indicate anticipated thresholds near the experimentally measured thresholds. G_1 is the energy gap of InAs. E_1 and E_2 are the first and the second resonant states, E_B is the height of the AlSb barriers, and E_F is the Fermi energy. (I_t) for the lower lying characteristic is three times larger than for the top characteristic.

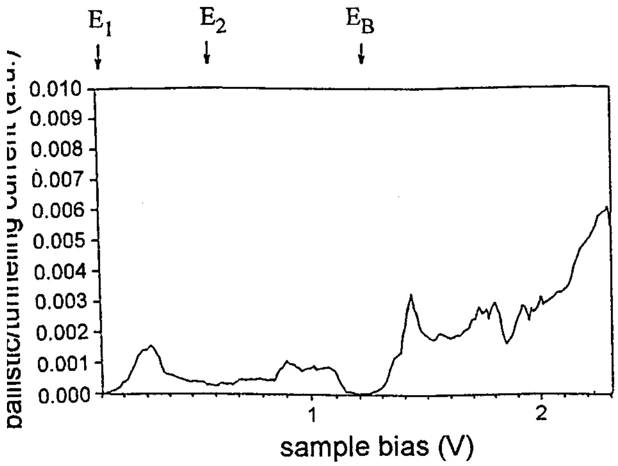

FIG. 4. BEES characteristic from Sb640. The sample was prepared by evaporating 10 nm of Au on top of the sample, the back contact is made for the 1 μm thick InAs layer below the double barrier heterostructure. The arrows indicate anticipated thresholds near the experimentally measured thresholds. G_1 is the energy gap of InAs. E_1 and E_2 are the first and second resonant states. E_B is the height of the AlSb barriers, and E_F is the Fermi energy.

3 is the ballistic current versus voltage characteristic of Sb663 prepared by making a back contact to the ion bombarded GaAs substrate. Figure 4 presents the characteristic obtained from Sb640 prepared by making the ''back'' contact to the 1 μm InAs buffer layer. Thresholds corresponding to the height of the AlSb barriers are labeled E_B above both Figs. 3 and 4. Similar thresholds are expected when the Fermi energy of the STM tip is aligned with the energy levels in the quantum well of the structure. These energies are labeled as E_2 in Fig. 3 and as E_1 and E_2 in Fig. 4. The threshold near E_1 in Fig. 4 is more pronounced than the threshold near E_2; however, the relative strength of these features has been observed to vary with the lateral position for the measurement. The thresholds corresponding to E_1 and E_2 have also been observed to vary by up to 0.1 V with the lateral position. The results are in accordance with the expected influence of noise on room-temperature measurements of such low laying thresholds as E_1 and E_2.

Three other thresholds are observed in Fig. 3 in addition to those described above. These additional thresholds are observed independent of the method used for back contact to the sample, and are most likely caused by $e-h$ pair creation. Three thresholds are marked with arrows at voltages $G_1+E_F+E_1$, $3/2G_1$, and $G_1+E_F+E_2$ below the barrier threshold in Fig. 3. The first and third of these thresholds are associated with $e-h$ pair creation at the ground and first excited states in the well. The second threshold is associated with the onset of impact ionization in semiconductors at $3/2G_1$ (Refs. 5 and 12).

The thresholds are better observed when the ''back'' contact is made to the 1 μm InAs buffer layer of the sample. An example of the measurement on such a sample in the range of 0.1 to 1.5 eV is shown in the bottom of Fig. 3. (I_t) for this case was 3 nA.

In contrast, we could not attribute any thresholds associated with $e-h$ pair creation below the barrier threshold from the sample with the thin (4 nm) InAs quantum well, as shown in Fig. 4. As the two samples differ only in InAs quantum well thickness, we conclude that $e-h$ pair creation in the sample with a 12 nm quantum well actually occurs in the well rather than in the InAs cladding layers.

The reliability of our results depends on the strength of the peaks in the ballistic current characteristics after individual thresholds. The lowest ratio of the height of the peak to background in the barrier region was observed for samples with back contact to GaAs, and it was about 2. This ratio differs for different measured points because of the existence of grains in the Au layer and partly because of inhomogeneities of Au/InAs and InAs/AlSb interfaces. The lowest ratio was about 35% below the highest ratio for samples with the back contact made to GaAs. The observed ratio of the height of the peak to background in the barrier region for samples with the back contact made to the 1 μm InAs buffer layer is always higher than 2. The lowest value is 75% below the observed maximum value. The ratio for other peaks increases with decreasing the ratio for the peak in the barrier region and vice versa.

In summary, this letter reports the BEES study of InAs/AlSb double barrier heterostructures. We have successfully observed a few ballistic current features at room temperature and in air. We are able to conclusively resolve the threshold due to the AlSb barrier height and most of the measured characteristics also yield thresholds in agreement with anticipated values for transport through resonant states of the structure, even though some of them are affected by noise. An additional threshold is consistent with $e-h$ pair creation in InAs with energy $3/2G_1$. Finally, we are able to identify thresholds due to the creation of $e-h$ pairs at resonant energy levels from a sample with a relatively thick InAs quantum well.

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