Electron transport in an AlSb/InAs/GaSb tunnel emitter hot-electron transistor

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We report preparation of high quality AlSb/InAs/GaSb heterostructures by molecular beam epitaxy. Using this crystal growth technique we have fabricated unipolar AlSb tunnel emitter transistors and used them to explore electron transport as a function of electron injection energy E_i across a 100-Å-thick InAs quantum well base. A low-energy threshold for collector current is observed for $E_i > \phi_{bc}$, where ϕ_{bc} is the base/collector potential barrier. A maximum collection efficiency of ~ 0.9 is obtained at $E_i \cong 1.5$ eV and at larger values of E_i, the collection efficiency decreases due to wave function symmetry and velocity mismatch across the abrupt base/collector heterointerface.

There is interest in exploring the possible use of unipolar hot-electron transistors (HETs) in high-speed device applications. The superior transport properties of In-containing compounds such as strained $In_{0.15}Ga_{0.85}As$ on a GaAs substrate or $In_{0.53}Ga_{0.47}As$ on InP result in HETs with acceptable low-temperature ($T = 77$ K) current gains[1] and high-frequency operations.[2] Materials with higher In content, such as the binary compound InAs, might be expected to out perform ternary HET structures. With this in mind we have undertaken a study of transport in the AlSb/InAs/GaSb material system. The AlSb/InAs heterostructure has the advantage of a 1.3 eV conduction-band offset which is much larger than ambient thermal energy at $T = 300$ K ($k_B T \cong 0.025$ eV), and a reduced electron scattering rate in the InAs base region due to a low density of states. Recently, we demonstrated the first room-temperature ($T = 300$ K) operation of a unipolar double-heterojunction HET with a current gain in excess of 10 and a two-dimensional electron gas forming the base region.[3] The device uses thermionic emission from an indirect, wide band-gap AlSbAs emitter, the transistor base is a 100-Å-thick InAs layer, and the collector is GaSb. In this letter we report the preparation of an AlSb/InAs/GaSb heterostructure and the results of a study using a tunnel emitter to explore electron transport as a function of injection energy in this device.

There are several problems inherent to the preparation of AlSb/InAs/GaSb heterostructures. The optimal growth temperatures for each layer are significantly different. Under continuous growth conditions, an atomically smooth interface requires an abrupt change in the group V species stablizing the growth. In addition, the relatively large lattice mismatch may introduce threading dislocations for layers exceeding the critical thickness. The expitaxial layer structure shown in Fig. 1(a) is grown in a molecular beam epitaxy (MBE) system on (001) oriented Te-doped GaSb substrates using elemental sources. Te is used as n-type dopant for GaSb. The substrates are chemically polished and etched using 3% bromine-methanol solution prior to epitaxial growth. The antimony and arsenic tetramers are thermally cracked into dimers to improve the incorporation efficiency of group V elements. For example, an As/In flux ratio of 3 is sufficient for the As-stablized InAs growth at 500 °C, compared to a ratio over 10 if As_4 is used.[4]

The growth temperature is optimized to achieve high quality heterointerfaces and antimonide compounds under continuous growth conditions. At 500 °C, the exchange of Sb and As at the heterointerface when switching the stablizing

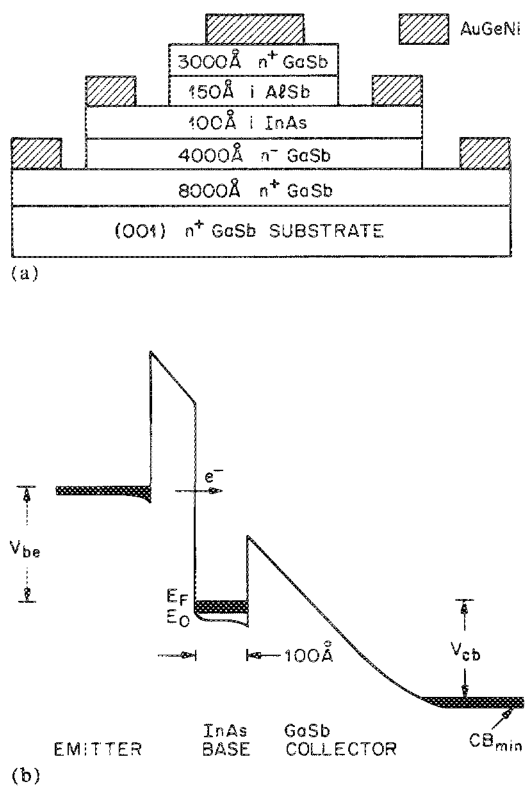

FIG. 1. (a) Schematic diagram of the epitaxial layer sequence and two-level transistor mesa structure for transport measurements. (b) Conduction-band diagram of the AlSb/InAs/GaSb heterostructure under base/emitter bias V_{be} and collector/base bias V_{cb}.

group V beam from arsenic to antimony or vice versa is not very fast. Using a growth rate of 1 μm/h, the interface can be buried quickly, preventing any surface vacancy-enhanced exchange of As and Sb. This is important because if, for example, the GaSb surface is exposed to an As beam for 10 s at 500 °C, the reflection high-energy electron diffraction (RHEED) pattern shows slight faceting indicating the formation of some GaAs-like area on the surface. Overgrowth of a thick InAs layer on such a surface generally gives poor InAs morphology with many pyramidal defects, and the mobility of the two-dimensional electron gas in an InAs quantum well structure grown this way is much lower compared to material obtained using continuous growth. Similar observations of mobility reduction resulting from heterointerface characteristics have been reported very recently.[5] In this work, abrupt interfaces are characterized by the immediate transition of the RHEED pattern from (1×1) for InAs to (1×3) for AlSb or GaSb without any faceting stage. Meanwhile, maintaining a V/III flux ratio close to stoichiometry at this growth temperature is important for growing high quality GaSb and AlSb.[6] The lattice mismatch is accommodated by elastic deformation in the thin emitter and base regions. This deformation has little effect on the conduction-band structure of interest here and is ignored in the subsequent discussion.

To study electron transport across the heterojunctions, the wafer is processed into a two-level transistor mesa structure. In Fig. 1(b) we show a schematic diagram of the structure's conduction band under bias. Electrons in the n-type GaSb emitter tunnel through a 150-Å-thick AlSb tunnel barrier into a 100-Å-thick InAs base. The tunneling process ensures that an essentially monenergetic beam of electrons is injected perpendicular to the heterointerface in a cone with small angular spread. The probability of phonon scattering which could broaden the electron energy distribution is small. After traversing the base, electrons impinge on the GaSb collector. If the electron injection energy E_i is less than the base/collector barrier energy, $\phi_{bc}\sim0.8$ eV, no electrons are collected and all the injected current I_e flows in the base. For $E_i>\phi_{bc}$, some electrons traverse the base and subsequently contribute to the collector current I_c.

An important scattering mechanism determining collector efficiency is quantum reflection from ϕ_{bc}. It is well known that quantum reflection is determined, in part, by electron velocity mismatch across the abrupt InAs/GaSb heterointerface.[3,7] For example, for an electron velocity $v^{\rm InAs}$ in InAs and $v^{\rm GaSb}$ in GaSb the reflection coefficient is $R=[(v^{\rm InAs}-v^{\rm GaSb})/(v^{\rm InAs}+v^{\rm GaSb})]^2$. In this simplified example we assume that there is no contribution to R from a mismatch in the character (symmetry) of the electron wave function across the interface. Since in our structure $E_i\propto eV_{be}$ to within ±0.1 eV, we may explore electron collection efficiency as a function of injection energy by plotting the ratio I_c/I_e with base/emitter voltage bias V_{be}. Typical results of such a measurement at a temperature $T=200$ K are shown in Fig. 2. As may be seen, for injection energy E_i less than ϕ_{bc}, no electrons are collected. For $E_i>\phi_{bc}$, the ratio I_c/I_e increases rapidly with decreasing velocity mismatch at either side of the heterointerface. The sharp rise at

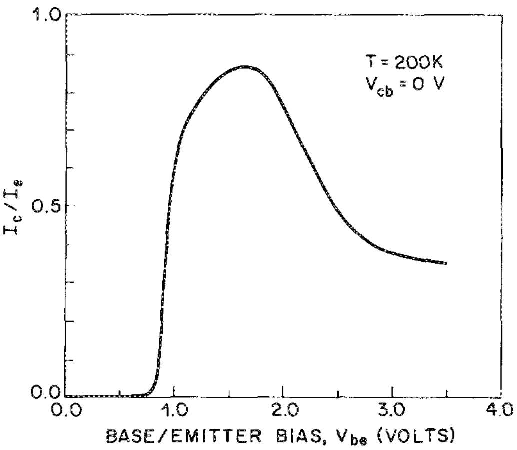

FIG. 2. Ratio of the collector and emitter currents, I_c/I_e, as a function of base/emitter bias voltage V_{be}.

threshold indicates that contribution from phonon scattering is within our energy resolution of about 0.1 eV. Maximum base transport efficiency occurs for $E_i\sim1.5$ eV. With further increase in E_i, collection efficiency decreases and finally for $E_i\sim2.5$ eV, less than 50% of electrons are collected.

We may obtain a qualitative understanding of these facts by examining Fig. 3 where the InAs (solid curve) and GaSb (broken curve) band structures are shown for the (001) crystal direction.[8] In this diagram the electron velocity for an electron of energy $E_i\sim\hbar\omega_i$ and wave vector k_i may be obtained from the slope $\partial\omega_i/\partial\hbar k_i$. Thus, as mentioned above, the extent of mismatch in slope of the curve for InAs and GaSb is a measure of quantum reflection from the InAs/GaSb interface. At energies greater than 2.5 eV, electrons

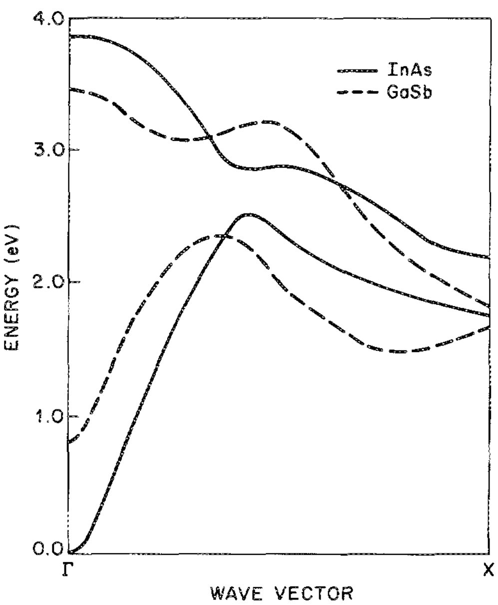

FIG. 3. Offset conduction-band structures for InAs and GaSb taken from Ref. 7. The electron velocity for a given injection energy may be obtained from the slope $\partial\omega_i/\partial\hbar k_i$.

are injected into electronic states above the lowest conduction band in which both velocity *and* wave function character mismatch and therefore quantum reflection is high. Hence, for $E_i \gtrsim 2.5$ eV, electron collection efficiency decreases dramatically. Numerical evaluation of $1 - R$ from the band diagram in Fig. 3 is qualitatively similar to the experimental result in Fig. 2. However, we note that a quantitative comparison between experiment and theory requires a detailed calculation, for example, using techniques similar to those developed by Stiles and Hamann.[9]

In summary, we have described the preparation of an AlSb/InAs/GaSb tunneling hot-electron transistor by MBE. For injection energy E_i less than the base/collector potential barrier, no electrons are collected. At larger E_i, the collection efficiency is determined by the electron velocity and wave function character mismatch across the base/collector heterojunction.

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