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Resonant interband tunneling via Landau levels in polytype heterostructures

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The low-temperature ($T=1.4$ K) tunneling current of GaSb-AlSb-InAs-AlSb-GaSb heterostructures has shown sharp negative-differential-resistance features induced by a magnetic field parallel to the current. In addition, the zero-voltage tunneling conductance vanished at certain fields, in close analogy with the behavior of the in-plane conductance in the quantum-Hall-effect regime. These results, which strongly differ from similar experiments in GaAs-$Ga_{1-x}Al_xAs$ resonant-tunneling diodes, are explained in terms of resonant interband tunneling of GaSb holes through Landau levels in the conduction band of the InAs quantum well.

The unusual alignment between the conduction band of InAs and the valence band of GaSb has been exploited recently to implement tunneling devices with characteristics that might out-perform conventional resonant-tunneling diodes exemplified by GaAs-$Ga_{1-x}Al_xAs$ double-barrier heterostructures. Devices based on the polytype combination InAs-AlSb-GaSb (Ref. 1) have shown ratios of peak-to-valley currents that exceed 20:1 at room temperature,[2] with current levels as high as 28 kA/cm^2 (Ref. 3). The frequency response of these types of diodes has also been shown to be very promising.[4] This high performance results from an electronic-transport mechanism that, unlike in GaAs-$Ga_{1-x}Al_xAs$ structures, involves *interband tunneling* between conduction- and valence-band states.

Although such a process is also present in a p^+-n^+ tunnel diode,[5] the ability to combine two of these junctions back to back (as in, e.g., GaSb-AlSb-InAs-AlSb-GaSb) gives rise to the phenomenon of resonant interband tunneling, by which holes tunnel resonantly between two electrodes via an intermediate two-dimensional state in the conduction band of a thin layer placed in the tunneling barrier. In this paper we demonstrate that in the presence of a magnetic field the current-voltage (I-V) characteristics of (p)GaSb-AlSb-(n)InAs-AlSb-(p)GaSb structures show a behavior radically different from that observed in either tunneling or resonant-tunneling diodes.[5,6] The field induces new negative-differential-resistance (NDR) regions that shift to lower voltage as the field increases. Simultaneously, the zero-bias conductance oscillates periodically with the inverse of the field and becomes almost zero at certain fields. These resonant phenomena, the latter of which is the tunneling analog of the quantum Hall effect, are explained in terms of the large energy gaps in the two-dimensional density of states created by the magnetic field.

The existence of resonant interband tunneling in GaSb-AlSb-InAs-AlSb-GaSb heterostructures follows directly from the peculiar band alignment between GaSb and InAs: the top of the valence band of the former lies $\simeq$0.15–0.20 eV above the bottom of the conduction band of the latter. When the two semiconductors are put in contact, that alignment (normally called type II, to distinguish it from type I in GaAs-$Ga_{1-x}Al_xAs$ structures, in which the valence and conduction bands of GaAs are higher and lower in energy, respectively, than the corresponding bands of $Ga_{1-x}Al_xAs$) induces a transfer of electrons from GaSb into InAs, leaving holes behind. The charge transferred from one material to the other can be controlled by an intermediate layer of AlSb, which acts as a potential barrier. If this unit, GaSb-AlSb-InAs, is replicated in reverse order, one ends up with a symmetrical heterostructure whose band diagram is sketched in Fig. 1(a). InAs acts as a quantum well in which two-dimensional (2D) electrons are accumulated, and the GaSb cladding layers constitute p-type electrodes for the structure.

When a small voltage is applied between the electrodes, holes tunnel from one to the other through the hole-empty, 2D state in InAs, as indicated by the arrows in Fig. 1(a). This process combines the characteristics of both the tunnel and resonant-tunneling diodes. If the voltage is such that the 2D state is higher in energy than the top of the valence band of the emitter, holes are prevented from tunneling by the band gap of InAs and the current vanishes. This hole blocking, characteristic of the tunnel diode, is responsible for the large peak-to-valley ratios observed, whereas the resonant nature of the process contributes to a large current density.

Examples of the I-V characteristics for resonant interband tunneling are shown in Fig. 2. The experimental curves correspond to a GaSb-AlSb-InAs-AlSb-GaSb heterostructure at low temperatures ($T=1.4$ K), under a magnetic field H parallel to the current. The AlSb barriers, 40 Å thick, and the InAs well, 150 Å wide, were grown by molecular-beam epitaxy on a p-type GaSb substrate. The structure was capped with a top GaSb layer doped with acceptors to 1×10^{17} cm^{-3}. Similar structures with smaller well widths were also studied but will not be discussed in detail here.

The bottom trace, for $H=0$, exhibits a monotonic increase of current up to $\simeq$0.20 V followed by a pronounced NDR and then by a very small residual current up to at least 0.5 V. As in type-I resonant tunneling, the voltage at which NDR occurs gives direct information on

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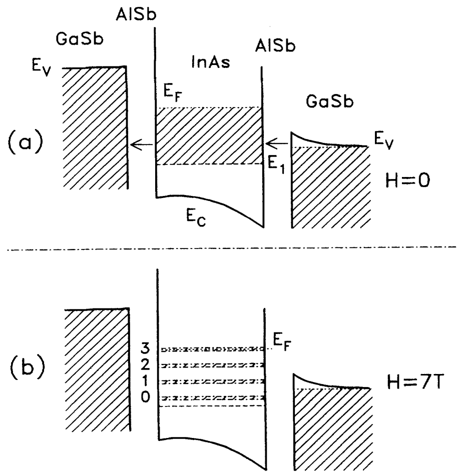

FIG. 1. (a) Schematic band profile of a GaSb-AlSb-InAs-AlSb-GaSb heterostructure under an external bias. Holes in GaSb tunnel resonantly through the empty (of holes) states in InAs as long as the quantum state E_1 is lower in energy than the top of the valence band of the emitter electrode. (b) Effect of a magnetic field H parallel to the tunneling current on the electronic density of states in the InAs quantum well. Resonant tunneling is possible only when the energy of holes in the emitter coincides with that of a Landau level in InAs.

the energy of the resonant state E_1 once space-charge effects are taken into account. If we assume that under bias the quasi-Fermi level of the 2D electrons in InAs is equidistant from the quasi-Fermi levels of the GaSb electrodes and that E_1 is not affected by the electric field, then the NDR at 0.20 V implies that E_1 is, under equilibrium conditions, $\simeq 0.10$ eV below the valence-band edge of GaSb. This result is in fair agreement with the value 0.08 eV obtained from a calculation that includes mass nonparabolicity, finite barrier height, and band-bending effects due to charge accumulation in the InAs well.

The application of a magnetic field parallel to the tunneling current alters the I-V characteristics drastically. As the traces in Fig. 2 show, several NDR features are induced by fields as low as 3 T. Each of them is labeled with a number, pertaining to the index of the Landau level involved in the tunneling process, as will be discussed below. With increasing field, these structures increase in intensity and shift to lower voltages until they gradually disappear at zero bias. Thus, the number of NDR regions decreases with increasing H from four (at 6 T) to two (above 12 T). The voltage positions of the field-induced features are summarized in Fig. 3 for a large set of magnetic fields. The values at low fields ($H < 3$ T) were determined from minima in the conductance characteristics, measured by superimposing a small ac signal to the dc bias. The higher sensitivity of the conductance permitted the resolution of Landau levels up to $N = 20$, down to 0.7 T (not shown in Fig. 2).

The presence of strong field-induced NDR peaks and their shifts with field contrast with magnetotunneling results obtained in type-I resonant-tunneling devices. In the latter, even at the strongest fields, current changes associ-

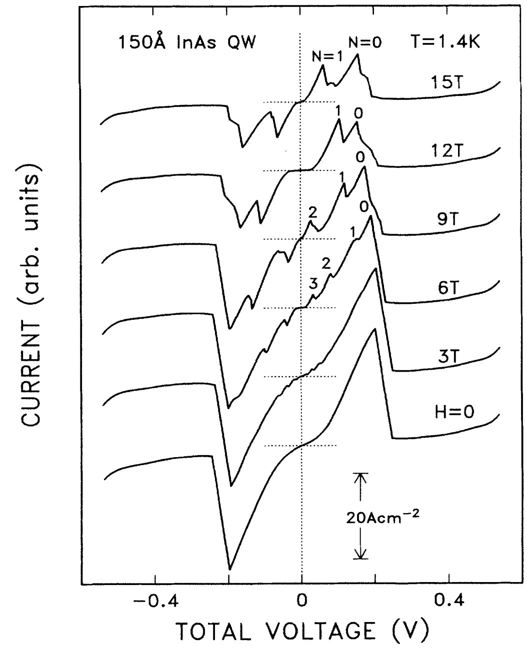

FIG. 2. Current-voltage characteristics of a GaSb-AlSb-InAs-AlSb-GaSb heterostructure with 40-Å AlSb and 150-Å InAs layers, under various magnetic fields parallel to the current direction. The single-peak characteristic at $H = 0$ evolves into a series of NDR features whose strengths increase with field, simultaneously shifting to lower voltages. Each structure corresponds to resonant tunneling via a Landau level of index N in the InAs quantum well.

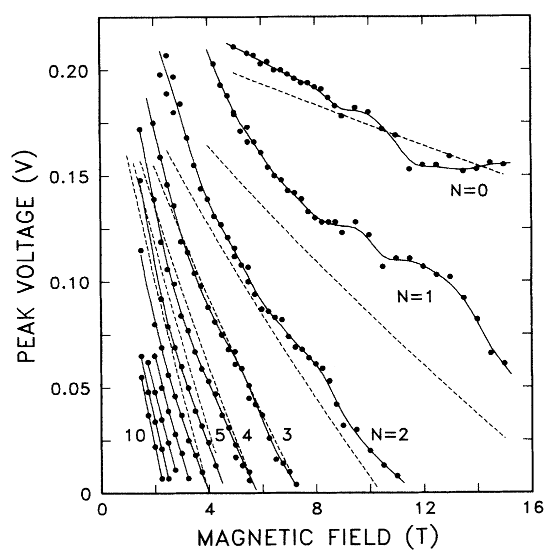

FIG. 3. Plot of the peak voltages (dots) for the NDR features in Fig. 2 as a function of magnetic field. The continuous lines are guides for the eye. Each peak decreases monotonously with increasing field at low and moderate fields. Above 8 T the traces for the peaks corresponding to low-index Landau levels ($N = 0$, 1, 2) show oscillations related to field-induced transfer of charge between GaSb and InAs. The discontinuous lines are the result of a non-self-consistent calculation of the Landau levels in InAs.

ated with direct Landau-level tunneling can be clearly resolved only in the conductance-voltage characteristics.[6] In addition, these weak features shift to higher voltages with increasing field. The different behavior of type-II structures under a magnetic field stems from the fact that tunneling involves both electrons and holes and that they have very different effective masses. Thus, the strong NDRs in Fig. 2 are a consequence of the large cyclotron energy of InAs compared to the Fermi energy of the GaSb emitter.

The process is easily understood if we consider first the high-field regime of Fig. 1(b). As the voltage increases, the small energy window of the emitter passes successively through Landau levels in the well. Every time a level below the Fermi energy is aligned with that window, resonant tunneling is possible and the current increases. As the increasing voltage misaligns them the current drops, and eventually vanishes (at least ideally) when the accumulation layer of the emitter is in the energy gap between Landau levels. When the next level comes within the range of the energy window the process starts again, resulting in multiple sharp NDR features in the I-V characteristic such as those observed in Fig. 2 at, or above, 9 T. At low fields, the energy window encompasses several Landau levels and resonant tunneling can take place through all of them simultaneously. When, with increasing voltage, one of these channels is completely outside the accumulation layer, the current drops slightly and produces a weak NDR structure.

The range of energies available for the outgoing holes of the accumulation layer in the emitter increases with the total bias applied, but since the electronic cyclotron energy in InAs is large ($\simeq 5$ meV/T), the high-field limit can be achieved at moderate fields for all voltages. This dependence on bias explains why for a given field, especially if it is moderately low (see, e.g., the I-V characteristic for $H=3$ T in Fig. 2), the field-induced features are stronger for small voltages than for high biases.

From the above physical picture, the shift of the various NDR features to lower biases with increasing magnetic field follows naturally. This behavior represents the signature for magnetotunneling in type-II heterostructures, and provides the best proof that both the valence and conduction bands are involved in the process.

Fully consistent with interband resonant tunneling is the effect of a perpendicular magnetic field, under which the field-induced NDR features of Fig. 2 were completely absent. Instead, as the perpendicular field increased, the intensity of the single NDR at $H=0$ decreased and its peak shifted to lower voltages. This decrease in voltage, associated with a diamagnetic shift of the quantum level E_1, had the opposite sign to that found in type-I resonant-tunneling structures, as expected when the conduction band of InAs and valence band of GaSb participate in the tunneling process.

In our simplified model we have ignored the fact that the holes in the accumulation layer of the emitter are two dimensional, so that their longitudinal (to the tunneling direction) energies are quantized, while the magnetic field quantizes their transverse energies into Landau levels. This quantization raises the issue of parallel-momentum conservation, which in the presence of a field translates into conservation of the Landau-level index during the tunneling process. In type-I heterostructures it has been demonstrated that, in general, this condition holds experimentally,[6] although phonon-assisted magnetotunneling has also been observed.[7]

Our results suggest the validity of the conservation of Landau-level index in type-II structures as well. Because of the small cyclotron energy of heavy holes in GaSb ($\simeq 0.35$ meV/T), at low fields level broadening will smear out the discrete energy spectrum. At high fields, however (e.g., > 10 T), a well-defined hole Landau ladder is possible, in which case, if the Landau index is conserved, NDR will occur only when the Nth electron level passes its corresponding hole level. If the index was not conserved and the cyclotron energy of holes was much larger than their level broadening it would be possible to observe additional NDR structures every time the Nth electron level passes an occupied hole level. The absence of these features in the I-V characteristics suggests that the Landau-level index is indeed conserved. (The structures beyond the $N=1$ and $N=2$ NDRs at 15 T, in Fig. 2, are likely due to circuit instabilities and not to intrinsic causes.)

The dependence with field of the NDR structures can be predicted theoretically. The discontinuous lines in Fig. 3 summarize the results of a calculation of the Landau-level energies in which nonparabolicity effects were included. Simplifying assumptions were equal voltage drop in the two AlSb barriers, no effect of the perturbing electric field on the quantum state E_1, independence of the transferred charge on magnetic field, and no spin effects. Hole quantization was also ignored. As seen in the figure, the simple calculation satisfactorily reproduces the general trends and is in fair agreement with the experiment for low biases and moderate magnetic fields.

The most important effect ignored in the calculation is the dependence on the magnetic field of the electronic charge transferred from GaSb to InAs. A self-consistent model for GaSb-InAs-GaSb structures (under no electric bias) has predicted appreciable oscillations in the charge, especially at high fields, which can even lead to a semimetal-semiconductor transition in the quantum limit.[8,9] Although that heterostructure lacks the AlSb barriers of our experimental system, aside from a different value in the charge transfer the results of the model should be applicable to the present situation. The self-consistent calculations show that the electronic charge in InAs reaches a minimum whenever a magnetic level becomes fully empty, is equal to the zero-field value when the Fermi level is in the center of the gap between levels, and is maximum when a level is about to start being depopulated.[9]

At 10 T the oscillations are estimated to be $\simeq \pm 15\%$ of the zero-field charge, an effect that should noticeably affect the Landau-level energies. Indeed, for $H > 8$ T the plot in Fig. 3 shows fluctuations in the smooth dependence of the resonant voltages that very likely are manifestations of variations in the charge, as Landau levels are progressively emptied of carriers. A detailed analysis of these fluctuations would require complete calculations that include the effects of an external bias to the structure.

Related to the characteristic motion with field of the NDR features of Fig. 2 is the presence of vanishing conductance at $V=0$ for certain magnetic fields, as illustrated in Fig. 2 for $H=6$ and 9 T. A detailed look at the zero-voltage conductance as a function of H reveals very strong oscillations, shown in Fig. 4 approaching vanishing values at high fields. These are reminiscent of the low-field Shubnikov–de Haas oscillations of the in-plane conductance of a 2D gas and the subsequent zero-conductance regions at high fields. The 2D character of these "vertical" oscillations was confirmed by a study of their dependence with the angle between the field and the tunneling direction, which also demonstrated that the doublets in the high-field oscillations are associated with spin splitting of the electron states. This behavior, and its resemblance with in-plane conduction, is not fortuitous but rather the result of a deep similarity between in-plane and resonant vertical transport.

In the former, conduction is finite when a Landau level is partially occupied, and vanishes when all the states are full. In the same way, tunneling is possible only when the Fermi level is within a magnetic state. If the Fermi level is in the gap between two Landau levels there are no states available for holes to tunnel through and the conductivity becomes zero. In a loose sense we can talk of a "vertical quantum Hall effect," because of the analogy with the zero-resistance (or zero-conductance) regions accompanying the in-plane quantum Hall effect.

Following this parallelism and taking into account the degeneracy of each magnetic level eH/h (e and h are the electron charge and Planck's constant, respectively), from the fields at which conduction vanishes it is possible to determine the filling factor ν and the number of 2D electrons in the InAs quantum well. For the 150-Å well discussed here, the 2D carrier concentration in the well was 1.2×10^{12} cm^{-2}, in good agreement with semiclassical calculations of the charge transferred from the GaSb layers. It should be noted that this determination of the electron density does not contradict the fact that the amount of charge accumulated oscillates with H since the value obtained here corresponds to the charge when the Fermi level is in the gap between Landau levels, which, as mentioned above, coincides with the charge at $H=0$.

This paper has focused on the prominent features in the tunneling-current characteristics of the GaSb-AlSb-InAs-AlSb-GaSb system under a parallel magnetic field. Equally, if not more, significant are the characteristics of a heterostructure in which the roles of InAs and GaSb are exchanged, that is, InAs-AlSb-GaSb-AlSb-InAs. In this case, electrons from the InAs electrodes tunnel resonantly via hole Landau levels in the GaSb well, giving rise to NDR features some of which shift to lower voltages with increasing magnetic field while others move in the opposite direction. Such a complicated behavior is undoubtedly related to the complex valence-band structure of GaSb and will be discussed in a future publication.

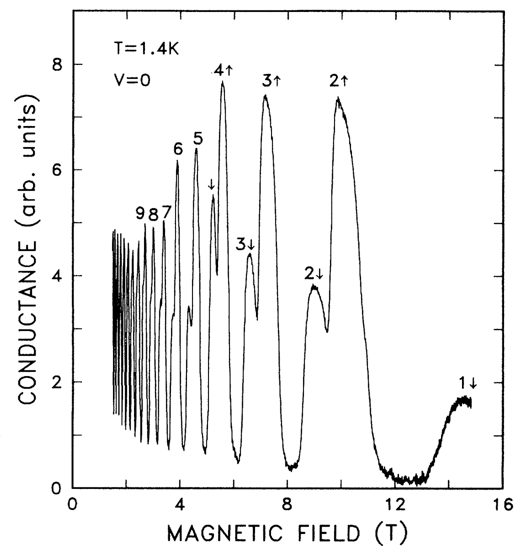

FIG. 4. Oscillations in the tunneling conductance, at $V=0$, as a function of magnetic field for the heterostructure of Fig. 2. In close analogy with the quantum Hall effect, the vanishing conductance at certain fields corresponds to a situation in which the Fermi level lies in the gap between two Landau levels of the InAs well.

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