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Intrinsic bistability by charge accumulation in an L-valley state in GaSb-AlSb resonant-tunneling diodes

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We have observed intrinsic bistability in the current-voltage characteristics of GaSb-AlSb double-barrier heterostructures at 4 K and under a hydrostatic pressure of 7 kbar. We explain this phenomenon by the accumulation of electrons in the L-point valley of the GaSb quantum well, after they tunnel from the electrode to a Γ-point quantum state and then scatter into the L point. Our model, which takes into account the various scattering and tunneling times involved in the process, is confirmed with magnetotunneling experiments up to 20 T. At this field, bistability completely disappears because of the field-induced reduction of Γ-L scattering.

Two different mechanisms[1,2] can explain the presence of bistability in the negative differential resistance (NDR) region of the current-voltage (I-V) characteristic of a double-barrier heterostructure: one intrinsic, due to the electrostatic feedback of the charge in the well on the energy of its confined two-dimensional (2D) -quasibound states; the other extrinsic, due to the presence of a parasitic series resistance in the bias loop. In conventional double-barrier heterostructures, such as GaAs-$Al_{1-x}Ga_xAs$-GaAs-$Al_{1-x}Ga_xAs$-GaAs, these two mechanisms are difficult to separate, since the design strategies that enhance the intrinsic mechanism (e.g., an increase of the collector barrier width or height[3]) also increase the bias at which resonance occurs. As a result, the NDR peak current increases and the extrinsic bistability is also enhanced.

In this paper, we show bistability phenomena in GaSb-AlSb-GaSb-AlSb-GaSb double-barrier heterostructures[4,5] that are unambiguously intrinsic. The problem of the GaAs system is overcome due to the presence of two different potential profiles (one following the Γ point, the other following the eight equivalent L points) in the relevant band diagram of the structure [see Fig. 1(a)], and, more specifically, because of the different values of the effective mass and density of states in each valley.

GaSb offers a unique opportunity to study the physics of the quantum transport of electrons. Although the bottom of its conduction band lies in the highly symmetric Γ point of the first Brillouin zone, just as in many other III-V compounds, its eight equivalent anisotropic L valleys [(111)-directions] are located only 60 meV above the Γ-point minimum. Lying at different positions in k space, these two sets of valleys (Γ and L) exhibit different pressure-dependent energy coefficients. Hence, by applying a moderate hydrostatic pressure (*lower than 10 kbar*) we can alter the relative band ordering of the Γ and L profiles, thereby changing the relative concentration of electrons populating them.

In the past,[5] we have observed simultaneously NDR due to resonant tunneling through the Γ-Γ-Γ-Γ-Γ and through the L-L-L-L-L paths. In this paper, we make use of this capability and take advantage of the presence of three different quantized states, L_1, Γ_1, and L_2, within a very short energy interval, to demonstrate the possibility of observing intrinsic bistability.

The basic idea of the experiment is the following: Applying an intermediate pressure to the GaSb-AlSb-GaSb-AlSb-GaSb double-barrier heterostructure, say, 7 kbar [see Fig. 1(b)], we can reach a situation in which electrons populate both the Γ and L valleys of the GaSb electrode. In tunneling through the Γ-Γ-Γ_1-Γ-Γ path (the subscript referring to the state in the well through which they tunnel), electrons will have a finite probability of scattering via phonon emission into the lower-lying L_1 state, from which they will take a relatively long time to escape due to the strong confinement of the L_1 state. Consequently, charge will be stored in this L_1 state and intrinsic bistability will be enhanced. An analo-

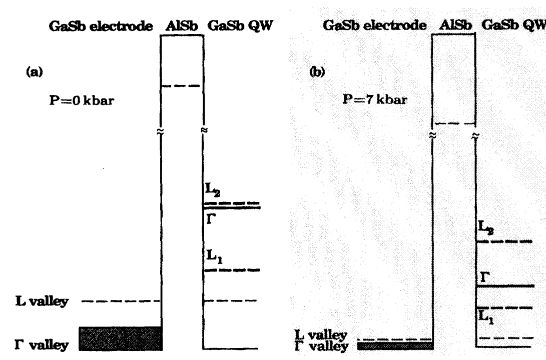

FIG. 1. Band profile of a GaSb-AlSb double-barrier heterostructure at (a) $P=0$ kbar and (b) $P=7$ kbar. Only half of the symmetric structure is shown.

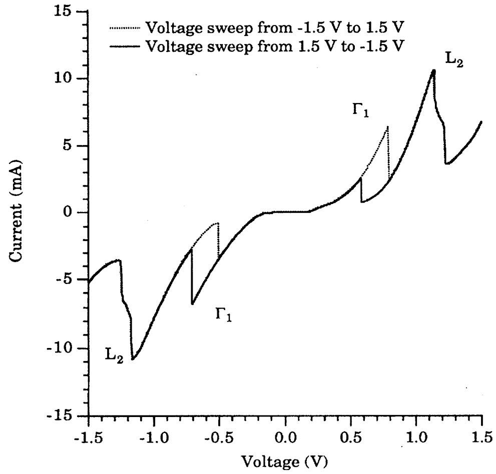

FIG. 2. Measured *I-V* characteristic of a 6-nm well 3.4-nm barriers GaSb-AlSb-GaSb-AlSb-GaSb resonant-tunneling diode at 4 K and 7 kbar.

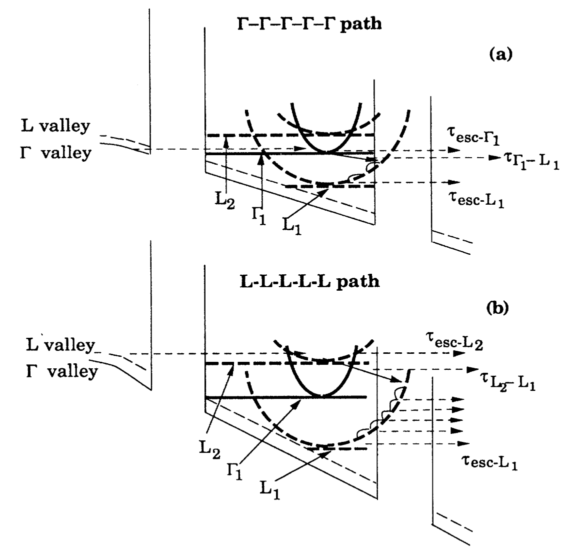

FIG. 3. Schematic representation of the different times involved in the resonant-tunneling process through (a) the Γ-Γ-Γ_1-Γ-Γ path and (b) the L-L-L_2-L-L path.

gous process will occur when electrons tunnel through the L-L-L_2-L-L path. However, the L_2 state lies at a higher energy and electrons tunneling through this path confront a lower AlSb L barrier. Hence, the escape time from the L_2 state is shorter and the probability of being scattered into the L_1 state smaller. (Note that in comparison with the Γ-Γ-Γ_1-Γ-Γ path, the intersubband scattering rate from the L_2 state should not change significantly, since the additional scattering process from the L_2 state into the Γ_1 state is negligible due to the different density of states in the two valleys.) As a result, a stronger NDR feature showing less or no bistability region should be expected for the L-L-L_2-L-L path.

We have tested these ideas on transport experiments in samples grown by molecular-beam epitaxy on (100)-oriented n^+-type GaSb substrates. The basic double-barrier structure is formed by two 3.4-nm undoped AlSb barriers and a 6-nm undoped GaSb well. The electrodes are also of GaSb doped to 1×10^{17} cm^{-3}. A more detailed description of the device, the device processing, and the pressure apparatus can be found in Ref. 5.

Figure 2 shows the typical *I-V* characteristic of one of these devices at a temperature of 4 K and under 7 kbar of pressure for opposite bias sweeping directions. Increasing the bias voltage from -1.5 to 1.5 V, we observe two different sets of NDR features: One, symmetric in position, at -1.16 and 1.16 V, with peak currents of -11 and 11 mA, respectively; the other, very asymmetric, at -0.5 and 0.8 V, with peak currents of -3.6 and 6.4 mA, respectively. Sweeping the bias voltage in the opposite direction, from 1.5 to -1.5 V, again the same two sets of features are observable. The symmetric set at -1.16 and 1.16 V does not change with bias sweeping direction. However, the second set appears at new positions, -0.7 and 0.6 V, and exhibits different peak currents, -2.4 and 6.8 mA, respectively.

The features at -1.16 and 1.16 V are the result of electrons tunneling from the L valley of the GaSb electrode through the second quantized L state in the quantum well. The other NDR set, in the regions between -0.7 and -0.5 V and between 0.6 and 0.8 V, comes from electrons tunneling from the Γ valley of the GaSb electrode through the first quantized Γ state in the well. These paths have been identified through the pressure dependence of their peak currents.[5] (Note that an additional weak feature at 0.2 V, resulting from electrons tunneling from the L valley of the GaSb electrode through the first quantized L state in the quantum well, is also observed. However, the presence of this feature is not essential for this work.)

The NDR features at -1.16 and 1.16 V, with the highest peak current, do not show any bistability region. In contrast, the other set, at -0.7 to -0.5 V and 0.6 to 0.8 V, exhibits the lowest peak current and, at the same time, a strong bistability region. Since extrinsic bistability, when present, is due to the voltage drop on the parasitic resistance of the bias loop, and this voltage drop is directly proportional to the current flow, we can immediately rule out the possibility of the series resistance as the origin of the bistability phenomenon.

To explain these experimental results, we have to include in the resonant-tunneling picture the different scattering mechanisms electrons are exposed to after entering the well from the GaSb emitter electrode and before leaving it to the GaSb collector electrode. These processes are schematically represented in Fig. 3. In tunneling through the Γ-Γ-Γ_1-Γ-Γ and L-L-L_2-L-L paths, three different times are relevant: the escape times from the resonant quasibound Γ_1 and L_2 states into the GaSb electrodes, $\tau_{\text{esc-}\Gamma_1}$ and $\tau_{\text{esc-}L_2}$, respectively; the intersubband scattering times from the quasibound Γ_1 and L_2 states into the L_1 state due to the emission of longitudinal acoustical and optical phonons, $\tau_{\Gamma_1\text{-}L_1}$ and $\tau_{L_2\text{-}L_1}$, respectively; and the escape time from the bottom of the quasibound L_1 state, $\tau_{\text{esc-}L_1}$. (Note that, in principle, one should expect two other times to be important, the intraband relaxation time in the L_1 state, $\tau_{\text{relax-}L_1}$, and the escape time of electrons from the L_1 band before reaching its bottom, $\tau^{\text{exc}}_{\text{esc-}L_1}$. However, since the density of states in the L bands is very high, we can consider the intraband relaxation process instantaneous, and, as a result, these two times unimportant.)

The rate equations associated with these processes are given by

$$\frac{dN_{\Gamma_1}}{dt}=\frac{J_{\Gamma_1}}{e}-\frac{N_{\Gamma_1}}{\tau_{\text{esc-}\Gamma_1}}-\frac{N_{\Gamma_1}}{\tau_{\Gamma_1\text{-}L_1}},$$

$$\frac{dN_{L_1}}{dt}=\frac{N_{\Gamma_1}}{\tau_{\Gamma_1\text{-}L_1}}-\frac{N_{L_1}}{\tau_{\text{esc-}L_1}},$$

for resonant tunneling through the Γ-Γ-Γ_1-Γ-Γ path; and

$$\frac{dN_{L_2}}{dt}=\frac{J_{L_2}}{e}-\frac{N_{L_2}}{\tau_{\text{esc-}L_2}}-\frac{N_{L_2}}{\tau_{L_2\text{-}L_1}},$$

$$\frac{dN_{L_1}}{dt}=\frac{N_{L_2}}{\tau_{L_2\text{-}L_1}}-\frac{N_{L_1}}{\tau_{\text{esc-}L_1}},$$

for the process involving the L-L-L_2-L-L path. From these equations, one can obtain the accumulated charge in steady state in each resonant path:

$$N^{\text{total}}_{\Gamma_1\text{-path}}=N_{\Gamma_1}\left(1+\frac{\tau_{\text{esc-}L_1}}{\tau_{\Gamma_1\text{-}L_1}}\right)=\frac{J_{\Gamma_1}}{e}\left(\frac{\tau_{\text{esc-}\Gamma_1}(\tau_{\Gamma_1\text{-}L_1}+\tau_{\text{esc-}L_1})}{\tau_{\Gamma_1\text{-}L_1}+\tau_{\text{esc-}\Gamma_1}}\right),$$

$$N^{\text{total}}_{L_2\text{-path}}=N_{L_2}\left(1+\frac{\tau_{\text{esc-}L_1}}{\tau_{L_2\text{-}L_1}}\right)$$

$$=\frac{J_{L_2}}{e}\left(\frac{\tau_{\text{esc-}L_2}(\tau_{L_2\text{-}L_1}+\tau_{\text{esc-}L_1})}{\tau_{L_2\text{-}L_1}+\tau_{\text{esc-}L_2}}\right).$$

These equations just tell us that the difference in the accumulated charge in the well in the Γ-Γ-Γ_1-Γ-Γ and L-L-L_2-L-L processes is the result of the difference in the escape times $\tau_{\text{esc-}\Gamma_1}$ and $\tau_{\text{esc-}L_2}$ and in the intersubband scattering times $\tau_{\Gamma_1\text{-}L_1}$ and $\tau_{L_2\text{-}L_1}$.

The evaluation of the intersubband scattering times $\tau_{\Gamma_1\text{-}L_1}$ and $\tau_{L_2\text{-}L_1}$ is rather difficult, due to the anisotropy of the L valley. In principle, however, one can suppose them similar, or at least of the same order, since both scattering rates are basically controlled by the same number of available states for scattering to, that is, those in the L_1 band.

The evaluation of the escape times $\tau_{\text{esc-}\Gamma_1}$ and $\tau_{\text{esc-}L_2}$ can be theoretically estimated from the energy width of the transmission resonance. However, a meaningful comparison of the two escape times in this way is often difficult due to the strong sensitivity of the transmission width not only on the different material and device parameters (effective masses, band discontinuities, or barrier widths) but also on any mechanism resulting in loss of coherence inside the well. (This is why, in spite of the simplicity of matching the NDR voltage, it is always difficult to properly simulate the peak current value of the NDR feature without using different unphysical fitting procedures, such as adjusting the effective mass in the barrier. This has been specially difficult in structures with high peak currents or with NDR features due to confined states at higher energies.)

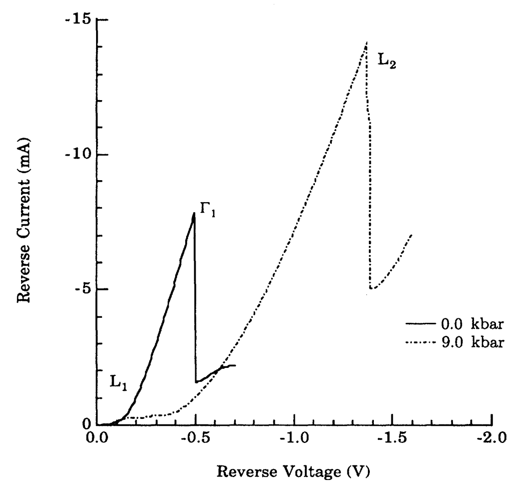

FIG. 4. Experimental I-V characteristic of a GaSb-AlSb-GaSb-AlSb-GaSb resonant-tunneling diode at 77 K under two different applied pressures, 0 and 9 kbar. Voltage sweeping direction is from -1.5 to 0 V.

Instead, we have opted to compare these times qualitatively, based only on the interpretation of the experimental measurements performed at two extreme pressures, 0 and 9 kbar, at which electrons populate only either the Γ or the L valley. Figure 4 shows the I-V characteristic of the double-barrier heterostructure at 77 K at two extreme pressures, 0 and 9 kbar. At 0 kbar, the bottom of the conduction band of the GaSb electrodes lies in the Γ valley. Consequently only resonant tunneling via the Γ-Γ-Γ_1-Γ-Γ path is observed (NDR feature at -0.45 V, peak current of -8 mA). At 9 kbar the situation has been inverted, the L valley becoming the bottom of the conduction band of the GaSb electrode. Hence only resonant tunneling through the L-L-L_2-L-L path is observed (NDR feature at -1.3 V, peak current of 15 mA).

Although the strength of these two NDR features is governed by three different parameters, the carrier concentration in the relevant valley of the electrodes (Γ valley in tunneling through the Γ state, L valley in tunneling through the L state), the velocity of these carriers and the transmission characteristic of the double-barrier heterostructure, only the last two are different in each of the resonant-tunneling paths. At $P=0$ kbar all the electrons are in the Γ valley, and consequently their perpendicular transport properties are controlled by the Γ effective mass ($m_\Gamma=0.0412$). At $P=9$ kbar, the supply electrons at the electrodes populate exclusively the L valley, hence their perpendicular transport properties are governed by the L-valley effective mass in the (100) direction:[6]

$$m_{L(100)}=\frac{3m_l m_t}{2m_l+m_t}\approx 0.2,$$

where subscripts l and t mean longitudinal and transverse. The presence at 9 kbar of a strong NDR feature (peak current of 15 mA, peak-to-valley difference of 10 mA) three times stronger than the Γ NDR feature at 0 kbar, even though the effective perpendicular mass has been increased about five times (and hence, the velocity of the carriers reduced by the same factor), is a clear sign that the transmission width of the resonant-tunneling characteristic of the L-L-L_2-L-L path is much wider than the equivalent width in the Γ-Γ-Γ_1-Γ-Γ path. Consequently, the escape time from the resonant L_2 state is much shorter and hence less charge is accumulated in the well. As a result, no intrinsic bistability is observed.

To further confirm this model, we have applied a magnetic field along the growth direction. The application of a magnetic field is an excellent probe for phonon processes. The reason is simple: Under a magnetic field, the two degrees of freedom of a quantum well are reduced to one due to the formation of Landau levels. As a result, the two quasicontinuum quantum numbers k_x and k_y become only one, the quasicontinuum quantum number k_y. For a phonon, however, the presence of a magnetic field reduces the number of degrees of freedom one step further, from two to zero, since all the quantized states with the same quantum numbers E_z and n are degenerate in energy, regardless of the value of k_y.

In our structure, the application of a magnetic field along the growth direction should, therefore, reduce the scattering processes involving phonons, since the conservation of energy becomes more restrictive. Consequently, less charge will be transferred from the Γ_1 (L_2) state into the L_1 state, reducing the intrinsic bistability. This is confirmed in Fig. 5, where the I-V characteristic of one of these devices at 4 K and under 7 kbar of pressure is shown for different magnetic fields. At $B=0$ T, the Γ-based NDR exhibits a bistability region of 150 mV, between 0.45 and 0.6 V. Increasing the magnetic field reduces the bistability region (100 mV at 5 T, 40 mV at 12 T), which finally vanishes above 15 T. Meanwhile, no bistable region is observed at the L_2-based NDR at any magnetic field.

In summary, we have demonstrated the possibility of obtaining a bistable region in the I-V characteristic of a double-barrier heterostructure unambiguously related to the accumulation of charge in the well and hence due to the electrostatic feedback of the charge on the energy of the confined 2D-quasibound states. Unlike the GaAs-AlAs system, where resonant tunneling is mainly affected by a single Γ-Γ-Γ-Γ-Γ profile, resonant tunneling in GaSb-AlSb is a more complex process, controlled by two different band profiles, the Γ-Γ-Γ-Γ-Γ and the L-L-L-L-L, and in which scattering between the different valleys plays a definitive role. It is this scenario which has allowed us to observe simultaneously NDR features with peak current and bistability strength displaying opposite behavior, and, consequently, to exclude the extrinsic mechanism as the origin of the bistability.

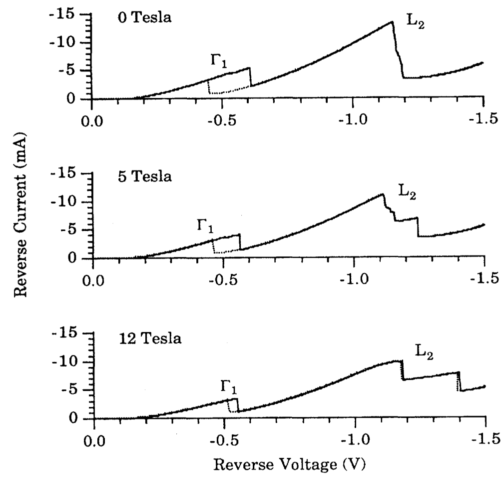

FIG. 5. Measured I-V characteristic of a 6-nm well 3.4-nm barriers GaSb-AlSb resonant-tunneling diode at 4 K and 7 kbar at different applied magnetic fields: (a) 0 T, (b) 5 T, (c) 12 T.

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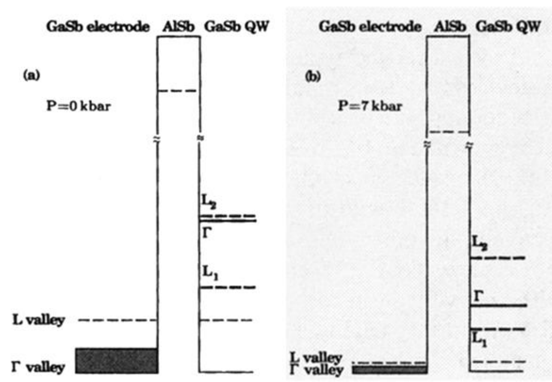

FIG. 1. Band profile of a GaSb-AlSb double-barrier heterostructure at (a) $P=0$ kbar and (b) $P=7$ kbar. Only half of the symmetric structure is shown.