Evidence for LO-phonon-emission-assisted tunneling in double-barrier heterostructures

V. J. Goldman and D. C. Tsui
Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

J. E. Cunningham
AT&T Bell Laboratories, Holmdel, New Jersey 07733
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We report on our observation of a structure in the valley region of the current-voltage characteristic of a double-barrier resonant-tunneling structure. We attribute this feature to the LO-phonon-emission-assisted tunneling of electrons from the emitter electrode to the well. In addition, we observe magnetoquantum oscillations in the valley region, which we interpret as due to a momentum-nonconserving component of the tunneling current.

Previous studies of double-barrier resonant-tunneling structures (DBRTS) focused on the elastic tunneling of electrons from the emitter electrode to the resonant states in the well.[1-7] Such tunneling, when the component of the electron momentum transverse to the direction of tunneling ($\hbar k_\perp$) is conserved, is manifested by a peak in the current-voltage (I-V) characteristic of DBRTS.[1,2] In this paper we report the observation of a replica peak in the I-V curves of a high-quality DBRTS. The replica peak occurs at a higher bias voltage and is interpreted as due to the LO-phonon-emission-assisted (inelastic) tunneling of electrons through the emitter barrier. In addition, we observe oscillations in the differential magnetoconductance of the same devices when biased to the current valley. We attribute these oscillations to a $k_\perp$ nonconserving, but elastic resonant tunneling through the Landau-quantized states in the well.

Our DBRTS were grown by molecular-beam epitaxy on an n^+-type ⟨100⟩ GaAs substrate and have a 56-Å GaAs well sandwiched between two 85-Å-thick $Al_{0.40}Ga_{0.60}As$ barriers. The GaAs emitter and collector regions (each 0.5 μm thick) have net donor concentrations $\sim 2\times 10^{17}$ cm^{-3}. The devices were defined by Au-Ni-Ge Ohmic contacts which served as masks for mesa etching.[3] Figure 1 shows the I-V characteristics[8] of a DBRTS device (area 4.5×10^{-6} cm^2) which was immersed in liquid helium. The rf oscillations in the measuring circuit[8] were suppressed as described in Ref. 5. The I-V curve, including the two bistable regions, has been interpreted in Ref 5.

An interesting, previously unreported feature is a replica peak seen clearly in the blown-up I-V and in the dI/dV-V curves at $V \simeq -0.3$ V. The conduction-band (CB) energy diagram of the device at such biases is shown in Fig. 2. We calculated ΔE, the energy separation between the emitter E_F and the bottom of the E_0 subband in the well, within the sequential tunneling picture as described in Ref. 6. The LO-phonon-emission-assisted tunneling becomes possible at $\Delta E = \hbar\omega_0$, the LO-phonon energy, and the probability of such process peaks at $\Delta E \simeq \hbar\omega_0 + E_F$.[9]

In general there are three types of LO phonons which could be emitted in an inelastic-tunneling event in DBRTS. First is the GaAs LO phonons ($\hbar\omega_0 \simeq 36$ meV); the other two are the GaAs-like and the AlAs-like LO phonons in the $Al_{0.4}Ga_{0.6}As$ barrier ($\simeq 35$ and $\simeq 47$ meV, respectively).[10] The replica peak is shifted by $\simeq 45$ meV (in ΔE) from the elastic peak; however, there is no evidence for a similar structure shifted by $\simeq 35$ meV. This indicates that the inelastic tunneling is accompanied by emission of the AlAs-like LO phonons in the barrier with no appreciable contribution from the two other possibilities. The magnitude of the inelastic-tunneling-current peak is $\simeq 0.04$ of the elastic one.

Figure 3 shows the same feature in the I-V and the dI/dV-V curves for the opposite bias polarity. Also in Fig. 3 is shown the dI/dV-V curve taken in the magnetic field $B = 8.5$ T (parallel to the direction of tunneling).

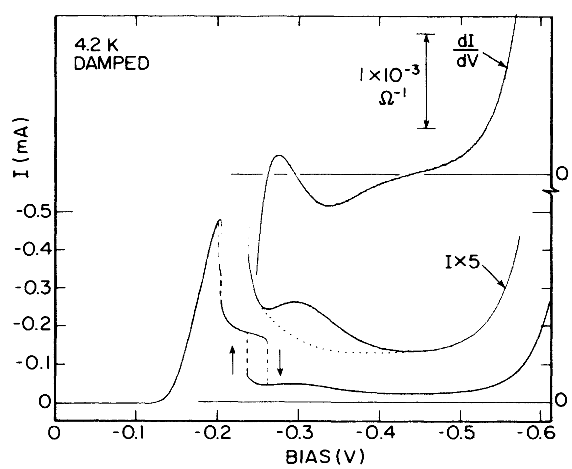

FIG. 1. The I-V and dI/dV-V curves of the DBRTS (Ref. 8). The dashed vertical lines show the switching between the high and low current states (Ref. 5). The dotted line (drawn by hand) indicates the background current in the replica peak region.

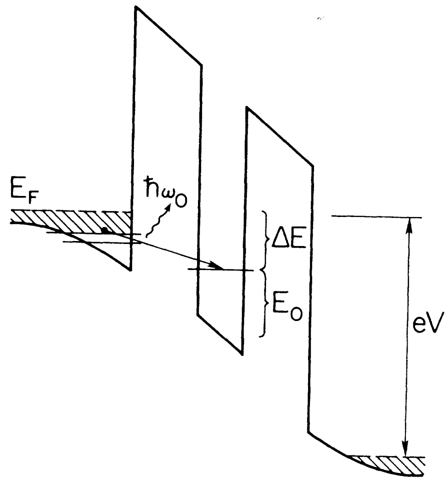

FIG. 2. The conduction-band energy diagram of a DBRTS under bias. Shown schematically is a LO-phonon-emission-assisted tunneling event. Subsequently, the electron leaves the well by tunneling through the collector barrier.

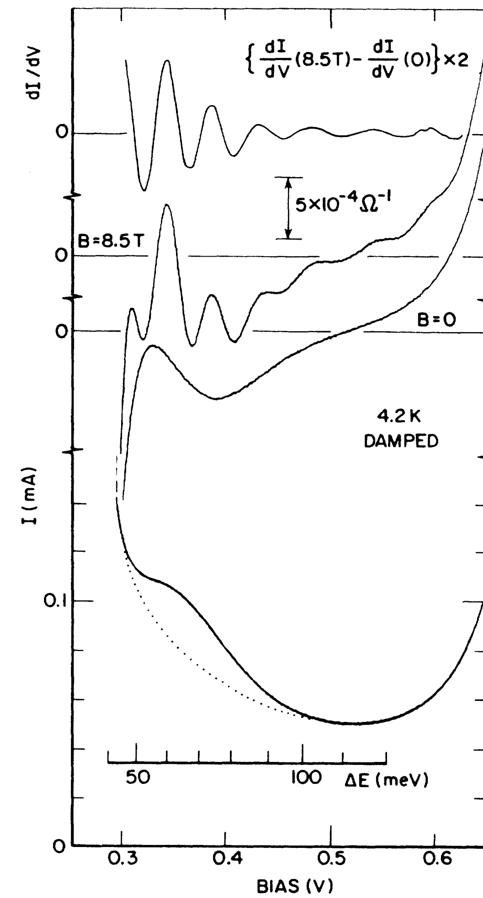

FIG. 3. The I-V and dI/dV-V curves in the positive bias polarity. The top curve gives the difference between the differential conductivities at 8.5 and 0 T. The ΔE scale was calculated as described in Ref. 6.

The most striking feature of the magnetoconductance curve is the oscillations which become observable at $B \simeq 2.5$ T. Since these oscillations extend through the whole bias range between the E_0 and the E_1 tunneling peaks, we conclude that they are due to a $k_\perp$ nonconserving, but elastic tunneling from the occupied states in the emitter electrode to the Landau-quantized states of the lowest (E_0) subband in the well. The ionized-impurity scattering appears to be the most likely mechanism which lifts the $k_\perp$ conservation rule in this DBRTS. This interpretation is supported by the general shape of the valley region of the I-V curve which, except for the inelastic-tunneling peak, appears to be composed of the tails of the E_0 and E_1 tunneling peaks.

In the positive bias polarity the "background" valley current, relative to the E_0 elastic-tunneling peak current, is about 20% greater than that in the negative polarity.[11] In Ref. 6 we have proposed that the asymmetry in the I-V curves with respect to the bias polarity in nominally symmetrical DBRTS can be explained, at least partially, by a difference in the dopant concentrations (and, therefore, E_F) in the two electrodes. This is consistent with the interpretation of the valley current as due, mostly, to the $k_\perp$ nonconserving but elastic tunneling induced by the ionized-impurity scattering since, in the positive bias, electrons tunnel from the heavier doped electrode.[6] The ratio of the amplitudes of the magnetoquantum oscillations in the opposite bias polarities is approximately equal to the ratio of the valley, and not the peak, currents.[12]

In conclusion, we would like to stress the difference between the LO-phonon emission by "hot" electrons *after* a tunneling process,[13] and the LO-phonon-emission-assisted tunneling, reported in this paper. In fact, the LO-phonon-emission-assisted tunneling, although present, is very difficult to observe in a single-barrier tunneling structure since it is masked by the much larger elastic tunneling.[14]

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[11]The current peak-to-valley ratios for this device at 4.2 K are 14.7 and 17.7 for the positive and negative bias, respectively.
[12]We note here that in a DBRTS with thinner barriers the nonresonant tunneling (directly from the emitter to the collector electrode) or, at higher temperatures, the thermoionic emiision can dominate the valley current.
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