Nonresonant magnetotunneling in asymmetric GaAs/AlAs double-barrier structures

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The characteristic differences in nonresonant magnetotunneling processes measured from a number of asymmetric GaAs/AlAs double-barrier resonant-tunneling structures under two opposite biases have systematically been studied, and ascribed to the different dwell times of traversing electrons in the well as they tunnel in opposite directions.

Recently, magnetotunneling has proved to be a powerful tool to study the dynamics of electrons in double-barrier resonant-tunneling structures (DBRTS).[1–3] By applying a high magnetic field perpendicular to the plane of (Al,Ga)As barriers, Leadbeater *et al.*[3] were able to investigate spectroscopically the scattering processes in the valley reigon of the *I-V* curves of GaAs/(Al,Ga)As DBRTS and to distinguish between the tunneling transitions stemming from elastic scattering and from inelastic scattering. However, magnetotunneling spectra observed in experiments were versatile. LO-phonon-assisted tunneling could prevail over elastic-scattering-induced tunneling under certain circumstances or vice versa in other cases. The physical reason for that remains elusive. As LO-phonon-mediated tunneling involves an inelastically scattering event, it is not only dependent on electron-phonon coupling strength but also dominated by the interaction time of tunneling electrons with LO phonons in traversing the DBRTS. It thus is important to find out, from the various tunneling times introduced in previous work,[4–7] which one is the true time-limiting factor for the LO-phonon-assisted tunneling.

With the above motivation, similar studies on the magnetotunneling processes in the current valley region have been carried out in a number of asymmetric GaAs/AlAs DBRTS.

As we shall show in present work, the characteristic differences of the oscillatory series observed under two opposite biases give certain clues to the actual temporal process controlling the LO-phonon-assisted tunneling.

Our DBRTS diodes were grown by molecular-beam epitaxy on an n^+-type ⟨100⟩ GaAs substrate, Si doped to 2×10^{18} cm^{-3}, and had a 75-Å undoped GaAs well sandwiched between undoped AlAs barriers with thickness of 25 and 17 Å (the latter adjacent to the substrate). Two undoped GaAs spacers were placed on the two sides of the double-barrier structure to separate it from the top contact region (a 1000-Å GaAs layer with Si-doping graded from 2×10^{17} to 2×10^{18} cm^{-3} and a 5000-Å n^+-type GaAs cap layer of 2×10^{18} cm^{-3} Si doping) and the contact region on the substrate side (a 1000-Å GaAs layer with Si doping graded from 2×10^{17} to 2×10^{18} cm^{-3} and a 0.8-μm GaAs buffer of 2×10^{18} cm^{-3} Si doping). The devices were defined by 150×150 μm^2 or 200×200 μm^2 Au-Ni-Ge Ohmic squares which also served as masks for mesa etching. The *I-V* curves of DBRTS were measured at 4.2 K by a pseudo-four-terminal technique with a 1.5-nF capacitor in parallel with and close to the device to eliminate the biasing circuit oscillation.[8] As seen in Fig. 1, the *I-V* characteristic reported here displays a current peak-to-valley ratio of 20 in the forward bias (referring to the top contact being positively biased with respect to the substrate) and that of 5 in the reverse bias, as the bias voltage is forward swept. In both bias directions there exist pronounced bistable regions, the intrinsic nature of which will be proved later by our magnetotunneling data. The inset of Fig. 1 gives the sketched band diagram of our DBRTS under forward bias beyond the main resonant peak. The differential conductance dI/dV of the device was measured using a conversional ac technique with a constant modulation voltage of 1 mV applied on it. The lowest trace in Fig. 2 gives dI/dV as a function of the reverse bias voltage V at 4.2 K and $B=0$ T. Here we shall concentrate on the valley region, where, for clearness, the bistable region is simply indicated by two vertical dotted-dashed lines. At zero magnetic field, only a humped feature shows up immediately after the main resonant peak. This broad feature, observed first by Goldman *et al.*,[9] has previously

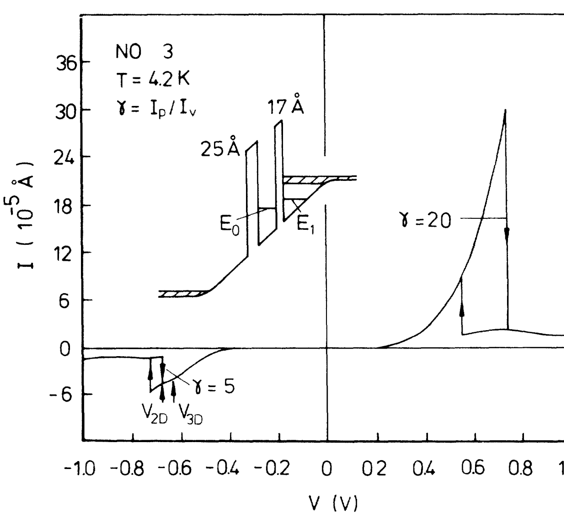

FIG. 1. The *I-V* curve of asymmetric DBRTS No. 3 at 4.2 K. $\gamma=I_p/I_v$, the current peak-to-valley ratio. The inset shows a schematic band-edge profile of the structure under positive bias.

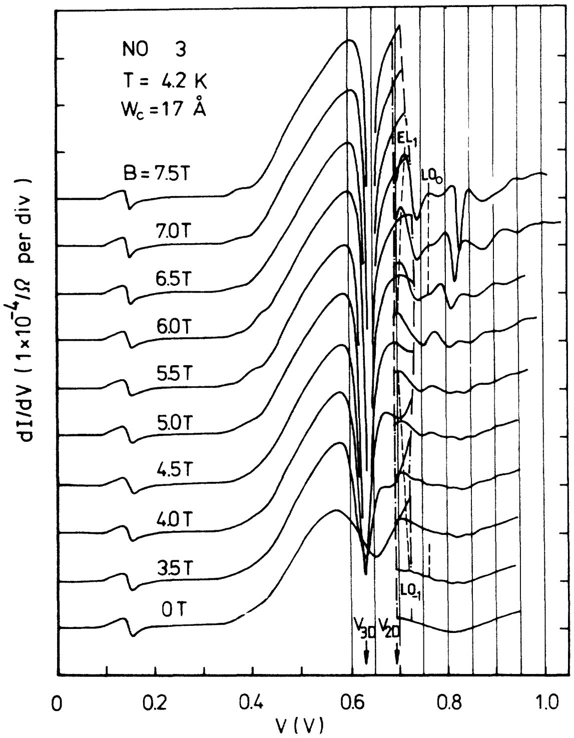

FIG. 2. The differential conductance dI/dV of DBRTS No. 3 measured as a function of negative bias at 4.2 K for different B fields. W_c is the thickness of collector barrier. The other labeling is defined as in the text.

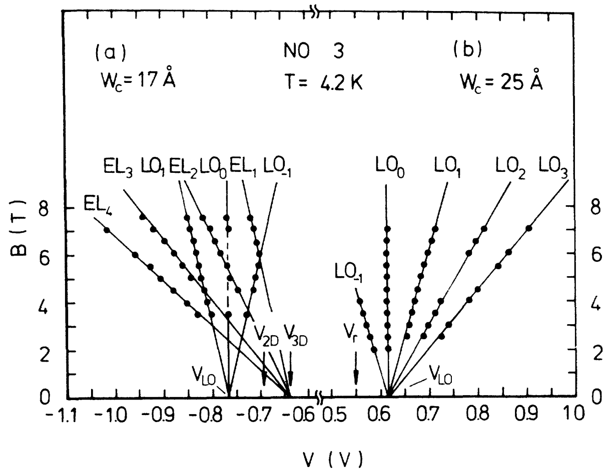

FIG. 3. (a) Fan chart in terms of the B field dependence (**B**‖**I**) of the peaks in dI/dV vs V for positively biased DBRTS No. 3 with $W_c = 25$ Å. (b) Fan chart for negatively biased DBRTS No. 3 with $W_c = 17$ Å. LO_p, EL_p and V_{3D}, V_{2D} are described in the text.

been attributed to LO-phonon-assisted tunneling into the well. Actually, as the B field is increased from zero, it develops into different series of the magneto-oscillations which involve contributions from both the elastic-scattering-induced transition and the LO-phonon-assisted transition. As pointed out by Leadbeater *et al.*,[3] the magnetotunneling beyond the main resonant peak, for which the wave-vector component $k_\perp$ perpendicular to the tunneling direction is not conserved, only needs to obey the following energy conservation, given by

$$E_1 = E_0 + \frac{p\hbar eB}{m^*} + i\hbar\omega_{LO} . \quad (1)$$

Here, by E_1 we denote the two-dimensional (2D) subband in the emitter, in which the electrons are quantized by the interfacial potential well in the accumulation layer due to the wide GaAs spacer used in our DBRTS. E_0 is the quasibound state inside the well. $\hbar\omega_{LO}$ labels the LO-phonon energy. p is equal to the change in the Landau index before and after the tunneling. When $i = 0$, the magnetotunneling involves only the elastic-scattering-induced transitions. $i = 1$ represents single LO-phonon-mediated transitions. From the expression (1) one can easily identify the oscillatory peaks, the positions of which do not change with B field, with the LO-phonon replica peaks ($p = 0, i = 1$). The fan chart in Fig. 3 summarizes all these clearly distinguishable series in both bias directions. As shown in the figure, all the series of the peaks marked LO_p extrapolate back to the LO-phonon replica peaks at $V_{LO} = 0.615$ V for the forward bias and at $V_{LO} = -0.765$ V for the reverse bias in the limit $B \to 0$. The arrows indicate the cut-off positions of the different resonances V_r, V_{2D}, and V_{3D}. Here, V_{3D} is the voltage where the bottom of the subband E_0 in the well is lowered just below 3D states in the emitter so that the resonantly enhanced tunneling from the 3D states into the quasi-2D states E_0 ceases. V_{2D} indicates the biasing condition for which E_0 breaks away from being in alignment of E_1 so that resonant tunneling from 2D states to 2D states is no longer possible as well. In Fig. 2 V_{2D} corresponds to the main discontinuity at $V = -0.69$ V. V_{3D} is visualized as the deep minimum at $V = -0.63$ V; they differ from each other. Actually, the shoulder labeled V_{3D} in the reverse I-V curves, as shown in Fig. 1, is to be resolved as a sharp jump of tunneling current in high magnetic field, leading to a doublet peak structure. Similar identifications for V_{3D} and V_{2D} were vaguely discussed by Goldman *et al.*[8] The details about the I-V curve of our GaAs/AlAs DBRTS will be reported elsewhere. Up to now, most of our data measured under forward bias from the GaAs/AlAs DBRTS reproduce the main features of the magneto-oscillations in the valley region of the I-V curve, reported previously by Leadbeater *et al.*[3] in GaAs/(Al,Gs)As DBRTS except for the LO_{-1} peaks. The newly observed LO_{-1} peaks arise from nonresonant tunneling transition of electrons from the $(n+1)$th Landau level in the accumulation layer to the nth Landau level in the well with the emission of a LO phonon. Instead of moving away from the main resonant peak, as the other LO_p peaks do, the LO_{-1} peaks merge into it with increasing B field.

At this point, we turn to the main issue of the present work. Figure 3(a) illustrates the typical fan chart in the reverse bias region measured from the same sample. In comparison with the fan chart in the forward bias [Fig.

3(b)], the following important features are worth mentioning.

First, a series of the magneto-oscillations labeled EL_p appears as the tunneling transition involving only elastic processes.[3] Apparently, asymptotes of the EL_p group towards zero B field have to merge into the main resonant peak. As is known, the dynamic storage of electron charges in the well is an important feature of the resonant tunneling and to make the dependence on the external bias of the level separation, E_1-E_0, substantially different from that when the DBRTS diode is biased out of the resonance. Generally speaking, one cannot know for certain that a linear extrapolation of the EL_p group into the bias region prior to the discontinuity of the resonant current should necessarily be a good practice. As a result, we do not intend to distinguish whether the appearance of EL_p peaks corresponds to the $(n+p)$th discrete Landau level in the well being aligned with the bottom of the nth Landau subband of 3D electrons or in line of the nth discrete Landau level of 2D electrons in the emitter. Anyhow, EL_p series represents the elastic-scattering-induced tunneling between Landau levels in the emitter and in the well.

Second, the elastic-scattering-induced tunneling, marked EL_p, tends to dominate over the LO-phonon-assisted tunneling, marked LO_p in reverse bias condition. Only two branches of LO_p peaks, LO_{-1} and LO_1, remain well defined in contrast to the case in the forward bias, where up to five branches of LO_p peaks are fully developed and no peak of EL_p type appears. What is more, the LO_0 peak in the reverse bias appears to vanish before the B field reaches 7 T.

Third, in the bias region between V_{2D} and V_{LO}, there is the intriguing coexistence of the LO_{-1} and EL_1 peaks in different B field regions.

Fourth, the weak peaks appear at low reverse biases (0.15 V) in Fig. 2, the origin of which will be studied elsewhere.

It is of great importance to understand the underlying physics responsible for the pronounced distinctions observed with opposite bias on our asymmetric DBRTS. Assuming the electron-LO-phonon interaction to be restricted to the resonant site, Wingreen *et al.* recently[10] applied the S-matrix scattering formulation to explicitly derive the LO-phonon-mediated tunneling probability through DBRTS and confirmed the experimental observation of the LO-phonon replica peak in the current valley region. Following the same line, we suppose that the electron-LO-phonon interaction mainly takes place in the well. Then, it is natural to think that dynamic processes like the LO-phonon-assisted tunneling should depend essentially on the dwell time (or the lifetime) of the traversing electron in the well. In a sequential tunneling approach, it is expressed by[8,11]

$$\tau=\frac{2W}{T_c}\left[\frac{m^*}{2E_0}\right]^{1/2}, \tag{2}$$

where W is the width of the well, E_0 is the quasibound level in the well, and T_c denotes the transmission probability of the collector barrier. Clearly, the larger T_c is (i.e., the thinner is the collector barrier), the shorter is the lifetime τ. For tunneling under forward bias, we have the thicker collector barrier (25 Å). As a result, the longer electron lifetime in the well leads to a higher probability to interact with LO phonons, hence stronger LO_p peaks. In fact, all the observed magnetotunneling peaks under forward bias are LO-phonon mediated. Under reverse bias the situation is just opposite. The thinner collector barrier (17 Å) and shorter lifetime weakens the LO-phonon-assisted tunneling (LO_p), while, relatively speaking, magnetotunneling with the participation of elastic scattering only (EL_p peaks) is becoming dominant.

On the other hand, the asymmetry of the EL_p series observed with opposite bias is presumably associated with the possible differences of scattering processes (such as interface roughness or ionized impurities, etc.) for electrons traversing DBRTS along the opposite directions. Most likely, the thinner barrier close to the substrate has the interfaces of better quality than the out thick barrier so that the EL_p tunneling channel could be greatly suppressed under the forward bias. This is qualitatively in accordance with the theoretical prediction made recently by Leo *et al.*[12]

In conclusion, we have systematically studied the nonresonant magnetotunneling processes involving both elastic and inelastic scattering in deliberately made asymmetric DBRTS. We have proposed that the characteristic differences in nonresonant magnetotunneling observed with opposite bias are likely attributed to the different lifetimes that the traversing electrons expend in the well for tunneling in the two opposite directions. More work in this direction, both theoretical and experimental, needs to be done in the future.

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