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Magnetic field studies of elastic scattering and optic-phonon emission in resonant-tunneling devices

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The current-voltage characteristics of a series of double-barrier structures based on *n*-type GaAs/(Al,Ga)As are investigated in the presence of a quantizing magnetic-field perpendicular to the barriers. Landau-level structure arising from elastic scattering and LO-phonon-assisted tunneling into the quantum well is clearly resolved. For well widths less than 6 nm, emission processes involving both the AlAs- and GaAs-like LO-phonon modes of the (Al,Ga)As barrier are observed.

Double-barrier resonant-tunneling devices based on semiconductor heterostructures exhibit one or more resonant peaks and associated negative differential conductivity (NDC) in their current-voltage characteristics. A commonly quoted figure of merit, though one which depends strongly on the current density, is the peak-to-valley ratio. This is obtained by dividing the maximum value of the current at the resonant peak by the minimum value at higher voltage. In double-barrier devices based on *n*-type GaAs/(Al,Ga)As, peak-to-valley ratios of 3.5 have been obtained at room temperature and 22 at liquid-nitrogen temperature.[1,2] Even higher values (14 at 300 K to 35 at 77 K) have been obtained in the pseudomorphic (Al,In)As/(In,Ga)As system.[3] However, calculations of the $I(V)$ characteristics based on the assumption that the electrons undergo no scattering during the tunneling process predict peak-to-valley ratios which are an order of magnitude (or more) higher than the best values realized to date.[4]

The relatively low values of the peak-to-valley ratios found in real devices are generally attributed to a combination of "over the barrier" thermonic current[2,5] and the effects of scattering processes on the tunneling electrons.[6,7] The former process is important only at and around room temperature and can be neglected at liquid-nitrogen temperature and below. Here we investigate the nature of the scattering processes that contribute to the current in the valley region of the $I(V)$ curve, at voltages beyond the resonant peak in the current. By applying a high magnetic field perpendicular to the plane of the tunnel barriers (i.e., $\mathbf{B} \parallel \mathbf{J}$), the density of electron states is quantized into discrete Landau levels. This allows us to investigate the scattering processes spectroscopically and to distinguish between contributions to the valley current arising from elastic scattering and from inelastic scattering processes due to the emission of longitudinal-optic (LO) phonons by the tunneling electron.

The structures used in this investigation were grown by molecular-beam epitaxy. Three structures with different well widths and barrier thicknesses were studied. Their compositions are given in Table I. The layers were fabricated into mesas of various sizes, using standard photolithographic techniques. Note that structure III is asymmetric, i.e., the tunneling barriers have different widths. The consequence of this asymmetry (intrinsic bistability) is discussed in detail elsewhere.[8,9]

A schematic potential-energy profile of a double-barrier structure under bias is shown in the inset of Fig. 1. Note that the contact regions adjacent to the barriers in all three structures are lightly doped. This appears to enhance the peak-to-valley ratio.[1] It also means that under bias a quasi-two-dimensional electron gas (2DEG) forms in the accumulation layer adjacent to the emitter barrier.[9] Electrons are continually removed from the accumulation layer by tunneling. Due to the relatively low current density the mean electron lifetime in the accumulation layer is long (3 μs for structure I at 1 V and 300 μs for structure III at 400 mV) compared to the energy relaxation time due to acoustic-phonon emission. Hence, incoming electrons have sufficient time to thermalize and at low temperatures the 2DEG in the accumulation layer is degenerate. This is confirmed by the existence of Shubnikov-de Haas-like oscillations in the tunnel current.[10]

Structure I, with the narrow quantum well, shows only one resonant peak in $I(V)$ at 470 mV; structure II exhibits three peaks at 70, 420, and 890 mV; structure III exhibits two peaks at 300 and 1300 mV in forward bias (substrate positive). In order to study the valley current it is necessary to suppress the current oscillations that can occur when a device is biased in the region of NDC. The dotted curve in Fig. 1 shows a typical $I(V)$ curve when the

TABLE I. Compositions, doping levels (cm^{-3}), and thicknesses of the three structures used in this study. The central five layers of each structure are undoped.

Composition	Structure I	Structure II	Structure III
n-type GaAs	0.5 μm, 2×10^{18}	0.5 μm, 2×10^{18}	0.5 μm, 2×10^{18}
contact	50 nm, 2×10^{16}	50 nm, 2×10^{16}	50 nm, 1×10^{17}
			50 nm, 1×10^{16}
GaAs	2.5 nm	2.5 nm	3.3 nm
$Al_{0.4}Ga_{0.6}As$	5.6 nm	5.6 nm	11.1 nm
GaAs	5.0 nm	11.7 nm	5.8 nm
$Al_{0.4}Ga_{0.6}As$	5.6 nm	5.6 nm	8.3 nm
GaAs	2.5 nm	2.5 nm	3.3 nm
n-type GaAs	50 nm, 2×10^{16}	50 nm, 2×10^{16}	50 nm, 1×10^{16}
contact	1.0 μm, 2×10^{18}	2.0 μm, 2×10^{18}	50 nm, 1×10^{17}
			2.0 μm, 2×10^{18}
		n-type GaAs substrate, 2×10^{18} cm^{-3}	

device is not stabilized against oscillations. (Note the region of extrinsic bistability.[2,8-10]) Stability is achieved by connecting, in parallel with the device, a small chip resistor r ($=25$ Ω) of sufficiently low impedance that $r < |dV/dI|$ throughout the region of NDC.[11] The stable $I(V)$ characteristics of the tunneling device are calculated by subtracting the current V/r flowing through the parallel resistor from the total current. Typical results obtained at zero magnetic field are shown for the three structures in Fig. 1 (solid curve) and in Figs. 2 and 3. Due to its high impedance, structure III did not require a parallel resistor to stabilize the current.

The $I(V)$ curves for all three structures exhibit a subsidiary peak (or shoulder) beyond the main resonant peak. Goldman, Tsui, and Cunningham[6] and Bando *et al.*[12] have attributed this feature to LO-phonon-assisted tunneling into the quantum well. Note also that LO-phonon-assisted scattering between the subbands of the quantum well has been observed in resonant tunneling structures.[10,13]

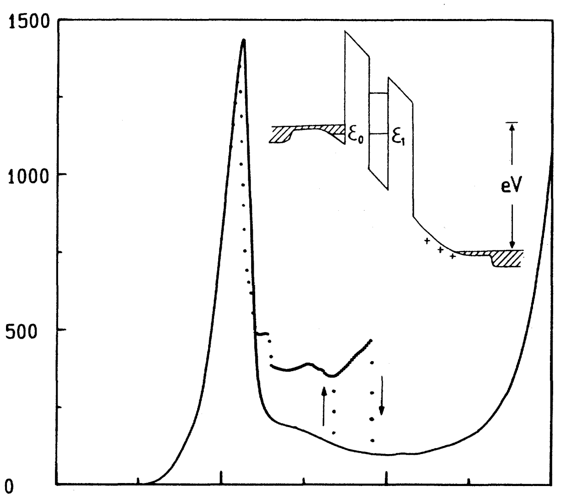

FIG. 1. The current-voltage characteristics at 77 K of a 5-μm-diam mesa fabricated from the double-barrier structure I (5-nm well). The dotted curve was measured when the device was oscillating and the full curve when the oscillation and current bistability were suppressed by connecting a small resistor (25 Ω) in parallel with the device. The inset shows a schematic potential-energy profile of a double-barrier device under bias.

If an electron traverses the barriers without scattering, which is assumed to be the case for the majority of electrons contributing to the main resonant peak, the k-vector component, $k_\perp$, perpendicular to the tunneling direction is conserved. The emission of an LO phonon (energy $\hbar\omega_{LO}$) or an elastic-scattering process violates this conservation rule. The LO-phonon-assisted peak and the contribution to the valley current of elastic scattering can be revealed more clearly by applying a quantizing magnetic field B parallel to the direction of the tunnel current. This quantizes the energy of motion in the plane of the barriers so

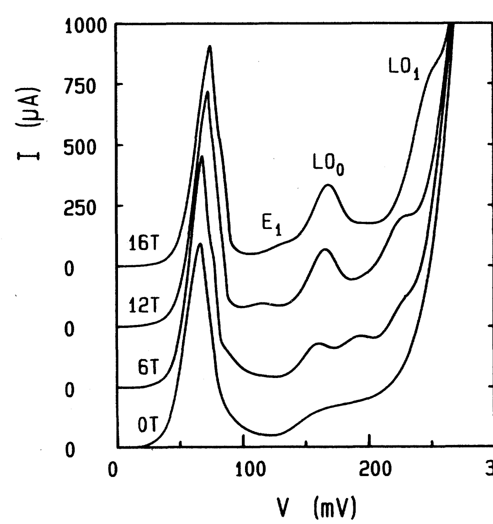

FIG. 2. The current-voltage characteristics at 4 K and at various magnetic fields B‖J of a 100-μm-diam mesa fabricated from structure II (11.7-nm well). The curves show only the region of the first resonance.

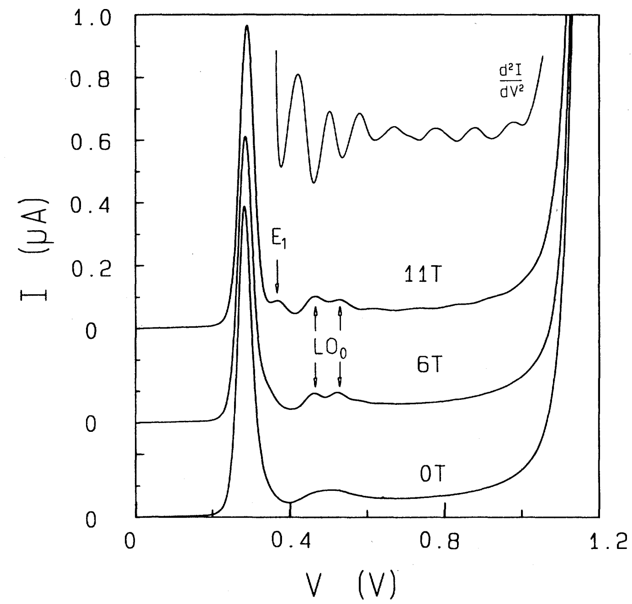

FIG. 3. The current-voltage characteristics of the first resonance in forward bias at 4 K and various magnetic fields **B**‖**J** for a 200-μm-diam mesa fabricated from structure III. The inset shows d^2I/dV^2 for the 11-T curve, emphasizing the magneto-oscillatory structure.

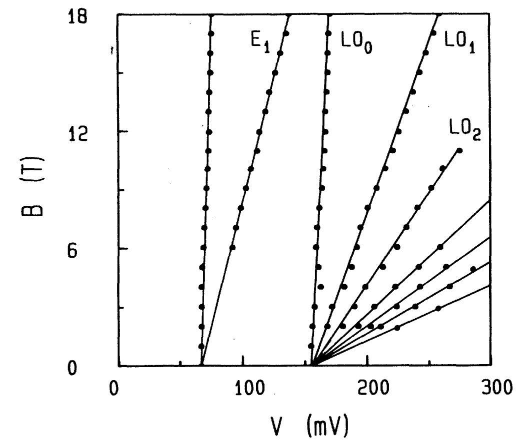

FIG. 4. Fan chart showing the magnetic-field dependence (**B**‖**J**) of the peaks in $I(V)$ for structure II. The elastic- and inelastic- (LO phonon) scattering processes giving rise to the oscillations are discussed in the text.

that the energy of electrons in the accumulation layer of the emitter and in the quantum well are given by

$$\varepsilon=\varepsilon_0+(n+\tfrac{1}{2})\hbar\omega_c \quad \text{(accumulation layer)},$$

and

$$\varepsilon=\varepsilon_1+(n'+\tfrac{1}{2})\hbar\omega_c \quad \text{(quantum well)},$$

where n and n' are the Landau-level quantum numbers, $\omega_c=eB/m^*$, and ε_0 and ε_1 are the lowest quasibound state energies in the emitter and well, respectively. The conservation of $k_\perp$ for $B=0$ corresponds to the requirement that $p=n'-n=0$ at finite B, so that resonant tunneling occurs at an applied voltage for which $\varepsilon_0=\varepsilon_1$, independent of B. Figure 2 shows the effect of a quantizing magnetic field **B**‖**J** on the $I(V)$ characteristics of structure II. The following features are noteworthy. First, the magnetic field increases the amplitude of the strongest LO-phonon-assisted peak, which has a peak-to-valley ratio of 2.6 at 18 T. Second, a weak secondary peak (E_1) emerges from the main resonant peak in the $I(V)$ curve as the magnetic field is increased. Similar subsidiary peaks also evolve from the LO-phonon feature with increasing B. Third, the magnetic field increases the peak-to-valley ratio (from 15 at $B=0$ to 25 at $B=18$ T). The fan chart in Fig. 4 shows the evolution of the magnetoquantum peaks in the $I(V)$ characteristics.

Transitions, for which $k_\perp$ (or n) is not conserved, are governed only by energy conservation. Therefore,

$$\varepsilon_0=\varepsilon_1+\frac{p\hbar eB}{m^*}+i\hbar\omega_{\rm LO},$$

where $i=0$ for elastic scattering and $i=1$ for LO-phonon emission. We have no evidence for multiphonon emission ($i>1$). The chart shows two clearly identifiable groups of lines. In the limit $B\rightarrow 0$, peak E_1 extrapolates back to the main resonant peak at 70 mV. The peaks LO_p extrapolate back to the satellite corresponding to single LO-phonon emission at 160 mV. The main resonant peak, which shifts very slightly to higher bias with increasing B, corresponds to tunneling processes for which n is conserved. The slight shift may be due to the magnetoresistance of the contact layers. The weak peak marked E_1 is due to a nonresonant tunneling transition involving elastic (or quasielastic) scattering from the nth Landau level in the emitter contact to the $(n+1)$th Landau level in the well. Such a transition could be caused by scattering due to ionized impurities or interface roughness (elastic) or by acoustic-phonon emission (quasielastic). The peaks marked LO_p correspond to transitions of electrons from the nth Landau level in the emitter to the $(n+p)$th Landau level in the well, with the emission of an LO phonon. The relative intensities of the main resonant peak and peaks E_1 and LO_p provide a qualitative indication of the contribution of the various charge transport processes to the measured current.

It is interesting to note that the effect of the magnetic field is to suppress the (quasi-) elastic-scattering-induced transitions at certain voltages below and above E_1 and to enhance then at other voltages, corresponding to the peak E_1. In zero magnetic field such processes are allowed energetically for all voltages beyond the main resonant peak in the tunnel current. At these voltages the lowest energy bound state in the well is below the energy of the electrons in the emitter. However, a large magnetic field quantizes the electron motion in the plane of the barriers, thus giving rise to sharp peaks in the densities of states. Therefore, energy conservation allows elastic scattering into the well only at certain voltages (E_1) and inhibits it elsewhere. This explains the enhancement of the peak-to-valley ratio with increasing B which is evident in Fig. 2.

Figure 3 shows the forward bias $I(V)$ characteristics of the asymmetric double-barrier device (structure III) at $B=0$ and in the presence of a longitudinal magnetic field. The inset shows the second derivative, d^2I/dV^2, which reveals the magneto-oscillations more clearly. At 0 T the phonon satellite peak has a "flat top" structure. Application of a magnetic field clearly resolves two distinct phonon-assisted peaks at voltages (470 and 530 mV) which do not shift with increasing B. They must arise from optical-phonon emission with no change in Landau-level number. We attribute the two components to the two LO-phonon modes in (Al,Ga)As.[14] Structure due to the elastic-scattering process (E_1) and LO-phonon emission accompanied by a change of Landau quantum number is also observed, but is complicated by the overlapping of two different phonon series. Very similar structure is observed in structure I, with two LO-phonon-assisted peaks at 570 and 630 mV being resolved by the application of a magnetic field.

The difference in voltage between the phonon satellites and the main resonant peak is considerably larger than $\hbar\omega_{LO}$. This is because only a fraction (e.g., $\simeq 30\%$ for structure II) of the total applied voltage V is dropped between the emitter contact and the quantum well, with a large portion of the voltage being dropped across the collector barrier and the depletion layer in the collector contact. The potential distribution across the device varies with applied bias. Fairly accurate estimates of the potential difference V_1 between the emitter contact and the well can be obtained over a range of applied voltage V by noting that the separations between the main resonance and E_1 and between the peaks LO_p and LO_{p+1} correspond to $\Delta V_1 = \hbar\omega_c$. Using this procedure we can estimate the energy of the LO phonons involved in the phonon-assisted tunneling process. For structure II we obtain $\hbar\omega_{LO}=35$ meV, in good agreement with the LO-phonon energy of GaAs. For structure III the two phonon peaks correspond to $\hbar\omega_{LO1}=35.5$ meV and $\hbar\omega_{LO2}=48$ meV, and to $\hbar\omega_{LO1}=34.5$ meV and $\hbar\omega_{LO2}=48.5$ meV for structure I. These values are in good agreement with the energies of the GaAs-like and AlAs-like LO-phonon modes of (Al,Ga)As with [Al] $=0.4$.[14]

A possible explanation for the observation of two phonon modes in structures I and III but only one in structure II is that structures I and III have narrower quantum wells so the wave function of the quasibound state in the well penetrates further into the (Al,Ga)As barrier. Tunneling electrons would then couple more effectively to the AlAs-like mode. Note that structures I and II have the same barrier widths but only the narrower well shows the two phonon modes.

In conclusion, we have used a quantizing magnetic field to investigate elastic- and inelastic-scattering processes in the valley region of resonant tunneling devices. We have observed coupling of the tunneling electrons to both the GaAs-like and AlAs-like LO-phonon modes of the (Al,Ga)As barrier region.

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