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Selection-rule breakdown in coherent resonant tunneling in a tilted magnetic field

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We report on a study of resonant-tunneling in a magnetic field tilted with respect to the current direction on a double-barrier structure. A splitting of the resonant current peak into several satellites is observed and corresponds to tunneling with nonconservation of the Landau-level index. We propose a simple coherent-tunneling model that accounts very well for both positions and magnitudes of the observed features and we show that these experiments clearly evidence new selection rules for tunneling in a tilted magnetic field.

In recent years, there has been an increased interest for magnetotunneling studies in GaAs-Ga$_{1-x}$Al$_x$As double-barrier diodes with the magnetic field **B** either parallel or perpendicular to the current **J**. Magnetotunneling experiments in a parallel magnetic field $B_\parallel$ have been reported by many authors and have provided useful information: In the resonant regime, weak oscillations of the current are observed in the $I(B_\parallel)$ curves[1-4] from which it is possible to deduce the charge buildup in the well and the dimensionality of the emitter. In the off-resonance regime, the analysis of the valley-current magneto-oscillations provides a very good determination of the different scattering mechanisms contributing to this current.[5-9] Translational invariance in the plane of the layers implies conservation of Landau-level index for coherent tunneling from the emitter into the well. Breakdown of this selection rule is only observed in the valley current and corresponds to incoherent elastic- or inelastic-scattering processes. In a transverse magnetic field $B_\perp$, a shift of the resonance towards higher voltages and a strong broadening of the peak are observed.[10-12] These effects have been explained by the action of the Lorentz force coupling the parallel and perpendicular motions.

We report here magnetotunneling studies performed in a double-barrier structure with a two-dimensional emitter under tilted magnetic field, the angle θ between **B** and **J** varying from 0 to 90°. In the resonance regime, giant oscillations are observed in the $I(V)$ characteristic and correspond to a splitting of the resonant peak into several satellites, whose positions depend on $B_\parallel$ and relative intensities vary dramatically with $B_\perp$. These peaks correspond to tunneling from the emitter into the well with nonconservation of the Landau-level index which, surprisingly, becomes the dominant contribution to the resonant current for large $B_\perp$. We present a simple coherent-tunneling model using a perturbational approach which accounts perfectly for both the positions and the intensities of the satellite peaks. These experiments clearly evidence new selection rules for coherent magnetotunneling in a tilted magnetic field.

The symmetric double-barrier structure used in this work was grown by molecular-beam epitaxy on an n^+-type GaAs substrate. Both emitter and collector consisted of 0.3 μm of GaAs, Si doped to 10^{18} cm^{-3}, and of a large spacer layer (600 Å) of nonintentionally doped GaAs. The barriers are 100-Å-thick Al$_{0.31}$Ga$_{0.69}$As layers and the well is a 50-Å nonintentionally doped GaAs layer. A 60×60 μm^2 device is defined by standard mesa etching techniques. $I(V)$ characteristics of this sample and magnetotunneling experiments with magnetic field parallel to the current have been previously reported in Ref. 9. At 4.2 K and $B=0$, the resonant peak voltage is $V_p=0.33$ V, the peak current density is 12.2 A cm^{-2}, and the peak-to-valley current ratio is ~ 12. Figure 1 shows the calculated band structure of the device at resonance obtained by solving the Poisson equation in the Thomas-Fermi approximation in both contacts and assuming a constant Fermi level in the whole emitter. Due to the doping profile, a two-dimensional (2D) accumulation layer forms at the emitter side with a bound level $E_{\rm acc}$. E_w is the energy of

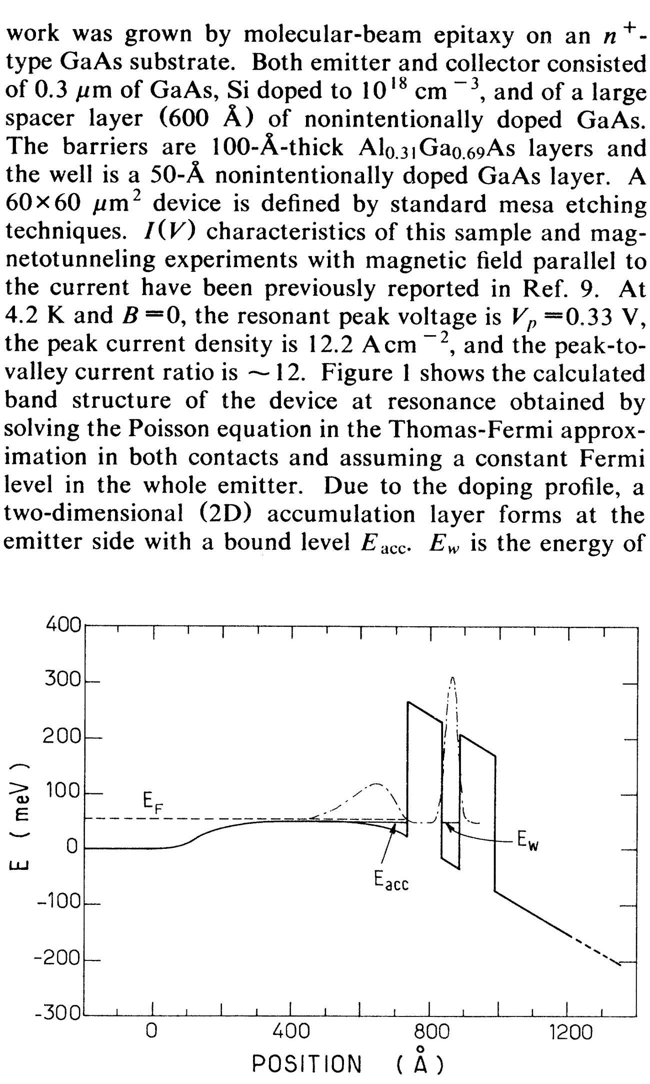

FIG. 1. Calculated band structure at the resonance voltage. The dashed line indicates the emitter Fermi level. Wave functions $\chi_{\rm acc}(z)$ and $\chi_{w'}(z)$ are shown by the dot-dashed line.

the bound level in the well and the current resonance condition[3,6,9] at zero magnetic field is $E_{\mathrm{acc}}(V)=E_w(V)$. The electron wave functions in the 2D emitter and in the well are also shown[13] in Fig. 1. The variations $E_{\mathrm{acc}}(V)$ and $E_w(V)$ have been obtained from the analysis of the magnetotunneling experiments with $\mathbf{B}\|\mathbf{J}$ in good agreement with the theoretical dependence deduced from the calculated profile of the structure.[9] A linear variation $\Delta(E_{\mathrm{acc}}-E_w)/\Delta eV\approx 0.23$ has been measured in the voltage range 0.3–0.7 V.

Figure 2 shows $I(V)$ characteristics measured at 4 K for several values of $B_\perp$ and a constant parallel field $B_\|=6.9$ T. These conditions are experimentally achieved by adjusting the total magnetic field when varying the angle θ. The most striking point observed with changing $B_\perp$ is that the resonant current peak splits into satellite peaks whose number increases with $B_\perp$. It is clear in Fig. 2 that the voltage positions of the observed features are independent on $B_\perp$ while their relative intensities are extremely sensitive to $B_\perp$. The weaker oscillations observed in Fig. 2 in the valley current correspond to inelastic magnetotunneling assisted by LO phonons as previously analyzed in Ref. 9. Such measurements have been realized for several values of $B_\|$ in the range 5–12 T and we have plotted in Fig. 3(a) (dots) the voltage positions of the resonant current satellite peaks as a function of $B_\|$. These positions are nearly independent of $B_\perp$. The dots in Fig. 3(a) group themselves into a set of straight lines converging near the resonant peak voltage $V_p=0.33$ V as $B_\|$ goes to zero. The origin of these satellite resonant peaks is explained as follows. Under the longitudinal magnetic field $B_\|$ the transverse motion of 2D electrons in both accumulation layer and well is quantized into Landau orbits and the component $B_\perp$ gives rise only to a small diamagnetic shift of the Landau-level energies.[14] Note that only the $n=0$ Landau level is occupied in the emitter for $B_\| > 3$ T since the effective Fermi-level energy $E_F-E_{\mathrm{acc}}\approx 5$ meV in the resonance regime (Fig. 1). Since the dependence $E_{\mathrm{acc}}-E_w$ as a function of bias voltage is known, one can easily calculate the voltages for which the occupied emitter Landau level is aligned with the mth Landau level in the well. These calculations, shown by the solid lines in Fig. 3(a) for $m=0,1,\dots,4$, account perfectly for the experimental data and the satellite peaks labeled by m in Fig. 2 correspond, therefore, to elastic tunneling with nonconserving Landau-level index. Note that for high $B_\perp$, peaks associ-

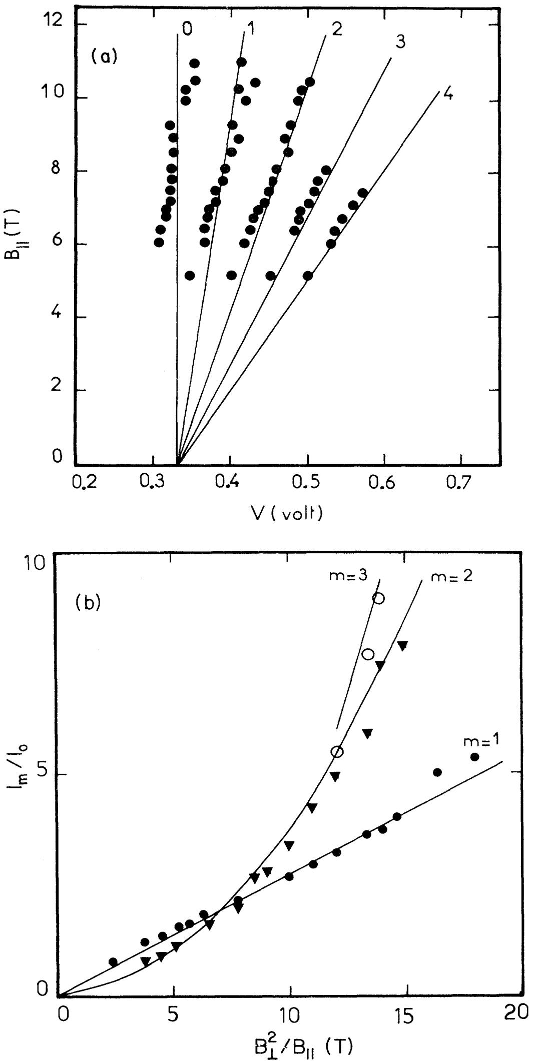

FIG. 3. (a) Voltage positions of the resonant current satellite peaks as function of $B_\|$ (dots). Solid lines are the calculated $B_\|(V)$ dependence of the current maxima for $m=0,1,\dots,4$. (b) Experimental intensity ratio I_m/I_0 of the satellite peaks for $m=1$, 2, and 3 (symbols). Solid lines are the theoretical ratio I_m/I_0 calculated as a function of $B_\perp^2/B_\|$.

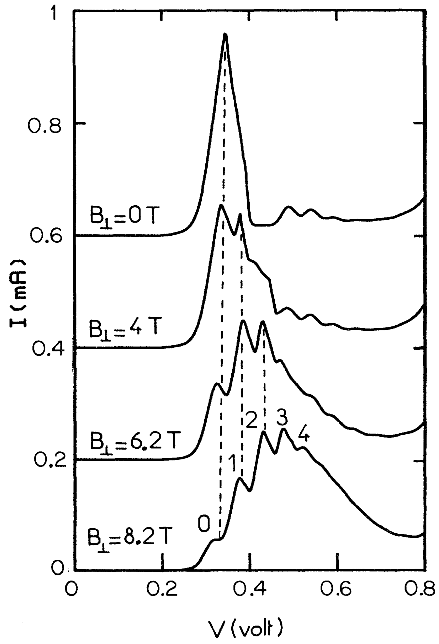

FIG. 2. Typical $I(V)$ characteristics obtained at 4.2 K for several values of $B_\perp$ and $B_\|=6.9$ T. The vertical scale is for $B_\perp=8.2$ T and each curve is shifted from the preceding one by 0.2 mA. Peaks are labeled by the Landau-level index m of the well state.

ated to nonconserving Landau-level index ($m \neq 0$) are more intense than the $m = 0$ one. Under a purely parallel magnetic field, weak features corresponding to elastic magnetotunneling with nonconserving Landau-level index are only observed in the valley current[9] and are explained by scattering processes coupling the parallel and the perpendicular electron motions.

In a tilted magnetic field, magnetotunneling with nonconserving Landau-level index becomes possible without the help of any scattering process. This can be shown by a simple theoretical approach in which $B_\perp$ effect is treated separately in the emitter and in the well as a perturbation of the Landau-level ladders. In a magnetic field $\mathbf{B} = (0, B_\perp, B_\parallel)$, the electron Hamiltonian using the gauge $\mathbf{A} = (B_\perp z, B_\parallel x, 0)$ for the vector potential is $H_0 + \delta H$, where H_0 is the Hamiltonian for $B_\perp = 0$ in the 2D emitter or in the well and δH represents the $B_\perp$ effect which is treated as a perturbation and is given by

$$\delta H = \frac{eB_\perp p_x z}{m_c} + \frac{(eB_\perp z)^2}{2m_c} . \tag{1}$$

Here p_x is the x component of the momentum operator, z the electron coordinate along the tunneling direction, and m_c the GaAs conduction mass. The eigenstates of H_0 gives the Landau levels in the emitter ($j = \text{acc}$) and in the well ($j = w$)

$$E_{j,n}(V) = E_j(V) + (n + \tfrac{1}{2}) \frac{\hbar e B_\parallel}{m_c} , \qquad n = 0, 1, \ldots , \quad j = \text{acc}, w . \tag{2}$$

The corresponding wave functions are

$$\psi_{j,n} = \exp(ik_y y) \chi_j(z) \phi_n(x - x_0) , \tag{3}$$

where $\chi_j(z)$ describes the quantized motion in the 2D system j and $\phi_n(x - x_0)$ is the usual Landau-level wave function.[14]

In a tilted magnetic field, the Landau levels are weakly coupled by the perturbation term δH leading to an energy shift

$$E'_{j,n}(V) = E_{j,n}(V) + \frac{(eB_\perp)^2}{2m_c} (\langle z^2 \rangle_j - \langle z \rangle_j^2) , \tag{4}$$

where $\langle z \rangle_j$ is the mean electron position in the 2D system j. We have considered a single bound level in the emitter and well and we have neglected any intersubband coupling in these calculations. The second term in Eq. (4) represents a diamagnetic shift whose order of magnitude is $(eB_\perp L)^2/2m_c$, where L is the characteristic length of the confinement potential.[14] For $L = 50$ Å, which is a realistic value in the accumulation layer (Fig. 1) and the well, a diamagnetic shift of 3×10^{-2} meV T^{-2} is calculated and is therefore much smaller than the energy separation $\hbar e B_\parallel / m_c = 1.7$ meV T^{-1} between the Landau levels in the experimental conditions used in this work. As a consequence, $B_\perp$ has only a weak effect on Landau-level energies in both the emitter and the well and a perturbation treatment of δH is justified. In particular, this model can explain the extremely weak $B_\perp$ dependence of the satellite peak positions, as it is seen in Fig. 2. The corresponding perturbed wave functions are given by[14]

$$\psi'_{j,n} = \psi_{j,n} \exp\left\{ -\frac{ieB_\perp}{\hbar} \left[\langle z \rangle_j \left(x + \frac{\hbar^2 k_y}{eB_\parallel} \right) \right] \right\} . \tag{5}$$

In the Oppenheimer formalism,[15] the coherent-tunneling current is described by a Fermi "golden rule" expression of the barrier potential $\mathcal{V}(z)$ between wave functions of emitter and well.[16] The matrix element is proportional to the longitudinal part $\langle \chi_{\text{acc}} | \mathcal{V}(z) | \chi_w \rangle$ and to the overlap of the transverse parts. The main effect of $B_\perp$ is then to suppress the orthogonality of the transverse parts of the wave functions for $\Delta n \neq 0$. Indeed, after some calculations, the following nonzero matrix element is obtained:[13,17]

$$\langle \psi'_{\text{acc},n} | \mathcal{V}(z) | \psi'_{w,n+m} \rangle = \langle \chi_{\text{acc}} | \mathcal{V}(z) | \chi_w \rangle e^{-\alpha/2} i^m \alpha^{m/2} \times \left[\frac{n!}{(n+m)!} \right]^{1/2} L_n^m(\alpha) \tag{6}$$

with

$$\alpha = \frac{eB_\perp^2}{2\hbar B_\parallel} (\langle z \rangle_w - \langle z \rangle_{\text{acc}})^2 .$$

Here $L_n^m(\alpha)$ is the generalized Laguerre polynomial $[L_0^m(\alpha) = 1]$. The nonzero matrix element (6) shows that, in a tilted magnetic field, coherent tunneling becomes possible with nonconserving Landau-level index n between the 2D emitter and the well and therefore that the selection rule $\Delta n = 0$ breaks down. If I_m is the magnitude of the peak current associated with tunneling from Landau level $n = 0$ in the emitter to Landau level m in the well (peak labeled by m on Fig. 2), the following ratio is deduced immediately from (6), if we neglect the weak voltage dependence of the longitudinal part of the matrix element:

$$\frac{I_m}{I_0} = e^{-\alpha} \frac{\alpha^m}{m!} . \tag{7}$$

In Fig. 3(b), the experimental ratio I_m/I_0 is plotted as a function of α for $m = 1$, 2, and 3. Solid lines represent the calculated ratio using Eq. (7) and $d = \langle z \rangle_w - \langle z \rangle_{\text{acc}} = 190$ Å. Note that d is very close to the distance between the z coordinates of the $\chi_{\text{acc}}(z)$ and $\chi_w(z)$ maxima (see Fig. 1). We have neglected the extremely weak dependence of d on the bias voltage V. A quite remarkably good agreement is obtained between the experimental data and our simple model which indicates that magnetotunneling with nonconserving Landau-level index is the dominant contribution to the resonant current in tilted magnetic field, i.e., the ratio I_m/I_0 is larger than unity. Nevertheless, since elastic-scattering-assisted tunneling also has resonances when Landau levels of different index are aligned in energy,[13] it would require a more complete quantitative evaluation to decide whether tunneling is mainly coherent or incoherent in the resonance regime.

In summary, we have studied the Landau-level selection rules for resonant magnetotunneling in a high-quality double-barrier structure with a 2D emitter under a tilted magnetic field. A splitting of the resonance peak into several satellites is observed which corresponds to tunneling from 2D emitter into the well with nonconserving Landau-level index, and therefore, to a breakdown of the

Landau-level index conservation rule obtained for coherent tunneling in a purely parallel magnetic field. We have proposed a simple model which accounts perfectly for both positions and magnitudes of the satellite peaks and we have shown unambiguously that coherent magnetotunneling with nonconserving Landau-level index can be the dominant contribution to the resonant current in tilted magnetic field.

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