Dominance of Fermi-Surface Holes in *p*-Type Tunneling

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(Received 13 February 2001; published 6 March 2002)

In-plane uniaxial stress is used to tune continuously the mixing between the heavy-hole (HH) and light-hole (LH) states in a *p*-type double-barrier structure. The LH1 and HH2 resonant tunneling peaks shift at almost the same rate with stress, in contrast to the corresponding exciton peaks observed by photoreflectance, which exhibit a strong Fano-related anticrossing. Comparison between the observed shifts and a four-band $\boldsymbol{k} \cdot \boldsymbol{p}$ calculation of the state energies in the well provides the first experimental proof that the flow of holes through off-zone center states dominates the resonant tunneling current in *p*-type structures.

DOI: 10.1103/PhysRevLett.88.126802 PACS numbers: 73.40.Gk, 72.80.Ey, 73.20.At

Tsu and Esaki [1] were the first to investigate the resonant tunneling of electrons in superlattices of $GaAs/Ga_{1-x}Al_xAs$. Since then, an enormous amount of both theoretical and experimental work has been reported on resonant electron tunneling, principally in double-barrier structures (DBSs), e.g., Refs. [2–4]. Resonant tunneling of holes was first investigated about ten years after Tsu and Esaki by Mendez *et al.* [5]. They found that the behavior of holes was more complex, and it was not possible to explain their results without considering the mixing between light holes (LH) and heavy holes (HH). It was quickly recognized that to consider the tunneling properly a multiband model must be employed, e.g., Refs. [6–9]. In such models, the momentum parallel to the layers, $k_{\parallel}$, needs to be taken into account since the mixing between LH and HH states is very sensitive to this parameter, and the mixing can change the transmission probability dramatically. In spite of this fact, it has not yet been proved experimentally that the current through *off-zone center states* in fact completely dominates the *I-V* characteristics. This has led to the widespread practice of continuing to treat resonant hole tunneling as if it occurred at the zone center, e.g., [10–13]. The lack of proof is because it is simply not reliable to compare the shapes and peak positions of experimental and calculated *I-V* curves, although such a comparison has recently been attempted [14]. In such a case, either a 1 monolayer difference in the well or barrier thickness, or a slight change in the emitter doping, can lead to a huge change in the shape of the predicted *I-V* characteristic or its peak positions. Also, the accumulation and depletion regions, charge buildup in the well, and any inelastic tunneling processes are very difficult to model reliably.

In this work an in-plane uniaxial stress is applied parallel to the [100] direction and is used to tune the mixing between HH and LH states in the quantum well (QW) of a resonant tunneling DBS grown along the [001] direction. If the energy positions of the LH1-E1 and HH2-E1 excitons are observed as a function of stress in a similar QW, for example, by photoreflectance spectroscopy as in Fig. 1, a strong Fano-related anticrossing is seen between LH1 and HH2 [15–17]. In resonant tunneling, however, we show that no such anticrossing occurs. By comparing the tunneling results not with the predicted *I-V* trace but rather with the calculated dispersion relation at various uniaxial stress values, we demonstrate that the tunneling is totally dominated by states at *finite* in-plane wave vector, near the Fermi surface of the emitter hole distribution. This contrasts with the exciton case, where zone-center states dominate [16]. The absence of an anticrossing in the tunneling thus provides the definitive proof that the off-zone-center current is dominant. We also obtain good agreement between our four-band $\boldsymbol{k} \cdot \boldsymbol{p}$ calculation of the tunneling current and key features of the observed resonant current components, in particular, the stress dependence of their amplitudes and bias positions.

A uniaxial stress modifies both the subband dispersions and the degree of mixing between valence-band states. To calculate the subband dispersions and the current, the four-band $\boldsymbol{k} \cdot \boldsymbol{p}$ Hamiltonian (including uniaxial stress terms) [16] was solved by a finite element approach [8], which is known to be numerically stable, in contrast to a transfer matrix approach [6]. The transmitted current density through the DBS is

$$J = e\,\frac{2 \times 4}{(2\pi)^3} \int_{k_{\parallel}=0}^{k_F} \int_{k_z=0}^{k_F} \int_{\theta=0}^{\pi/2} T(k_{\parallel}, \theta, k_z) \times v(k_{\parallel}, \theta, k_z) f_E (1 - f_C) k_{\parallel}\, dk_{\parallel}\, dk_z\, d\theta \qquad (1)$$

where v is the emitter group velocity in the z direction, and f_E and f_C are the hole occupation factors in the emitter and the collector, respectively. The transmission coefficient, T, was calculated from the probability flux, J_p, in the emitter and collector. By applying the continuity equation to the four-band Hamiltonian, it can be shown that

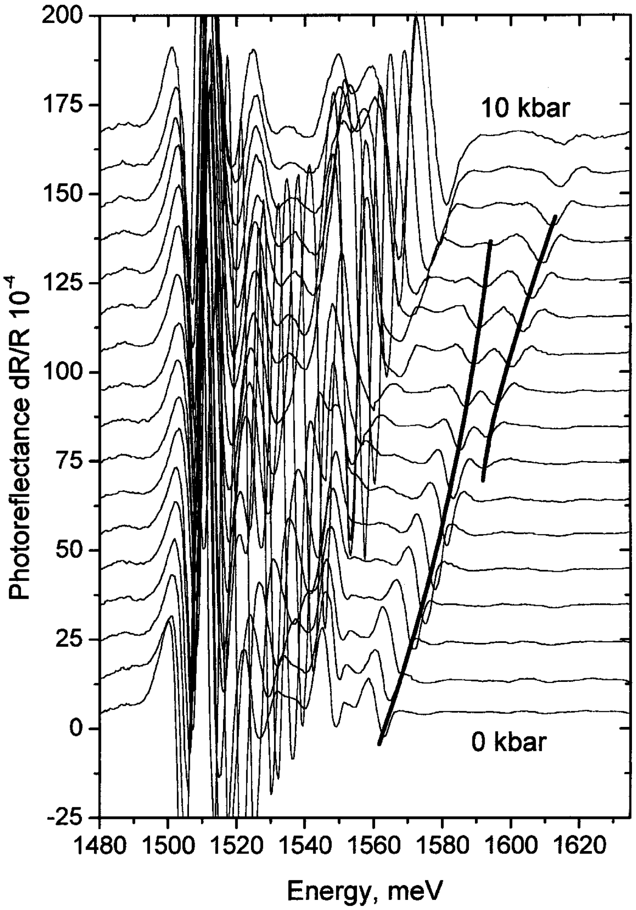

FIG. 1. Photoreflectance (PR) spectra at 80 K for a 100 Å $GaAs/Ga_{0.8}Al_{0.2}As$ QW grown along [001] and subject to a uniaxial stress along [100]. The polarization is perpendicular to the stress. The stress is increased in increments of ~0.6 kbar up to a maximum value of 10 kbar. The densely overlapping features on the left-hand side are bulk PR features, which are split by the stress. However, the optically allowed LH1-E1 exciton feature in the QW is clearly resolved and shifts upward in energy where a strong anticrossing may be seen with the HH2-E1 optically forbidden *p*-state continuum at ~6 kbar (indicated by solid line guides for the eye) [15].

$$J_p = \frac{i\hbar}{2}\sum_{r=1}^{4}\left(\phi_r^*\frac{\partial\phi_r}{\partial z} - \frac{\partial\phi_r^*}{\partial z}\phi_r\right)\Big/ m_r + \frac{i}{\hbar}[S^*(\phi_1\phi_2^* - \phi_3\phi_4^*) - S(\phi_1^*\phi_2 - \phi_3^*\phi_4)]. \tag{2}$$

Here, $\phi_1, \ldots, \phi_4$ are the envelope functions of the four crystal periodic functions with spin components $|3/2\rangle$, $|1/2\rangle$, $|-1/2\rangle$, and $|-3/2\rangle$, respectively, $S = -\sqrt{3}(\hbar^2/m_0)\gamma_3(k_x - ik_y)$, and $m_0/m_r = (\gamma_1 \pm 2\gamma_2)$ in which the positive sign is for $r = 2$ and $r = 3$. The Luttinger parameters are γ_1, γ_2, and γ_3, and values for GaAs were used [16].

Figure 2 shows the calculated dispersions of the subbands for a 60 Å GaAs well at different values of stress. The LH1 and HH2 states at the zone center cross at a stress just below 8 kbar. On the other hand, the LH1 and HH2 states with in-plane wave vectors in the range $k_y \sim 0.01$ to $0.02 \times 2\pi/a_0$ (a_0 is the cubic lattice parameter) do not cross. Instead, their energies decrease at about the same rate.

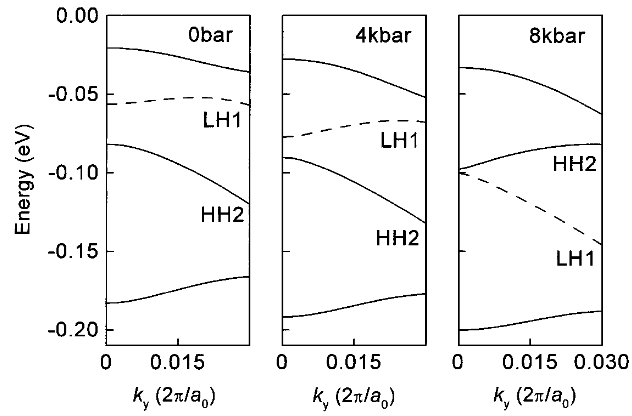

FIG. 2. Subband dispersions of a 60 Å GaAs well, grown along [001] (*z* direction) and subjected to uniaxial pressure along [100] (*x* direction), as indicated.

A GaAs/AlAs DBS was grown by MBE along [001] with 51 Å undoped AlAs barriers, a 60 Å undoped GaAs well, and 51 Å undoped GaAs spacer layers. The surrounding GaAs layers were doped, $p = 5 \times 10^{17}$ cm^{-3}, with beryllium atoms. Circular mesas of 200 μm diameter were fabricated on 3.2 mm × 12 mm rectangular specimens of the 0.4 mm thick GaAs wafer, whose sides were parallel to the in-plane ⟨100⟩ directions. The specimens were mounted at the end of a stainless steel uniaxial stress cell, which was immersed under liquid helium [18]. The shorter sides of the specimens were supported on grooved stainless steel holders with stycast epoxy resin. Uniaxial stress was applied to the sample along [100] by pressing these holders with a piston driven by a room temperature helium gas pressure system. To check the uniformity of the applied stress across the sample, *I*-*V* measurements were carried out on several mesas at each of several different stress values. The variation of the bias and current values at the resonant peaks was found to be less than 5% at 7.5 kbar. This shows that the applied uniaxial stress was quite homogeneous throughout the sample, considering that such variations can also be introduced by the nonuniformity of the layer dimensions in the double-barrier structure. Hysteresis between raising and lowering the stress was also found to be negligible.

Figure 3(c) shows how the LH1 and HH2 current peaks are shifted by the applied uniaxial stress. From the dispersion of the subbands in the well (Fig. 2), it can easily be seen that for a current flowing principally through the zone center states, the peak positions behave as in Fig. 3(a), with the LH1 peak crossing the HH2 peak at around 7 kbar. Such a crossing between zone center HH and LH states can be observed in optical experiments, such as the photoreflectance spectra of Fig. 1. Surprisingly, the tunneling results show no evidence of such a crossing. However, the experimental results agree rather well with Fig. 3(b), which shows the confinement energies of the subbands

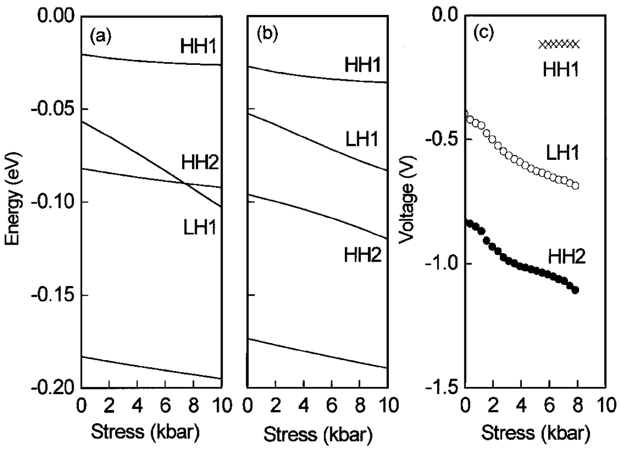

FIG. 3. Calculated confinement energies for a 60 Å wide GaAs well as a function of uniaxial stress, at (a) $k_y = 0$ and (b) $k_y = 0.016 \times 2\pi/a_0$. (c) Measured positions of the HH1, LH1, and HH2 current peaks.

at $k_y = 0.016 \times 2\pi/a_0$, a wave vector comparable with typical Fermi wave vectors in the emitter. It has long been thought that current through off-zone center states is dominant for hole tunneling structures since the transmission coefficient, T, increases with $k_{\parallel}$ by several orders of magnitude [6]. The good agreement between Figs. 3(b) and 3(c) provides the first definitive experimental proof of this principle.

Figure 4 shows the experimental and calculated *I-V* characteristics for various uniaxial stress values. In the calculations, the emitter and collector are treated as flat bands and no inelastic tunneling or charge buildup in the well is considered. To calculate the current density, the Fermi energy and the Fermi surface in the emitter are reevaluated at each uniaxial stress value, since the density of states changes due to the stress. At ambient pressure, the current flowing through the double-barrier structure is dominated by the incoming HH states in the emitter since the maximum $k_{\parallel}$ value for the lowest energy HH state is much larger than that of the lowest energy LH state at a given doping concentration. Also when stress is applied, the hole band splits into two components, with energies shifted by $(A - 2B)X$ and $(A + 2B)X$, respectively. Here $A = 3.54$ meV/kbar, $B = 1.31$ meV/kbar, and X is the stress value which is negative for compressive stress [19]. Hence the holes all occupy the upper band at a pressure of only a few kbar. In the present experiment, the doping concentration of the emitter was $p = 5 \times 10^{17}$ cm^{-3} which gives a value of 3.5 meV for the Fermi energy at ambient pressure. Thus even at around 1 kbar hardly any holes exist in the lower band. Therefore, in our calculations, we have considered only incoming waves of the upper band (or only heavy hole states for the case of ambient pressure). The calculated *I-V* characteristics are shown in Fig. 4(b). This figure shows that the calculated peak positions follow the same trend as in the experimental results of Figs. 4(a) and 3(c), and as in the calculated *finite* k_y energies in Fig. 3(b). This clearly demonstrates that the current through off-zone center states is dominant.

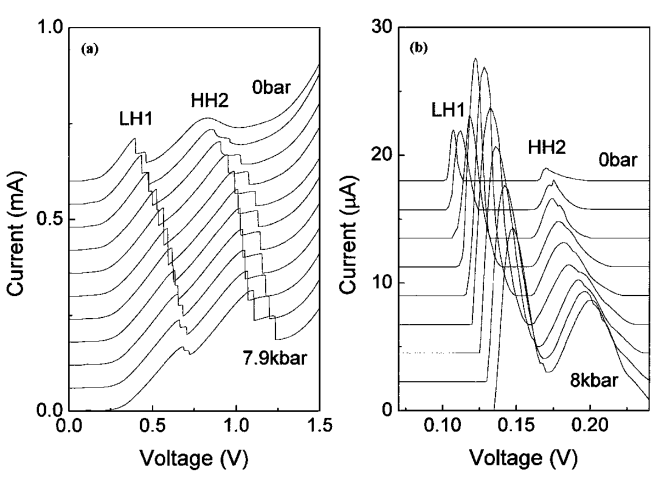

FIG. 4. (a) Experimental and (b) calculated *I-V* traces.

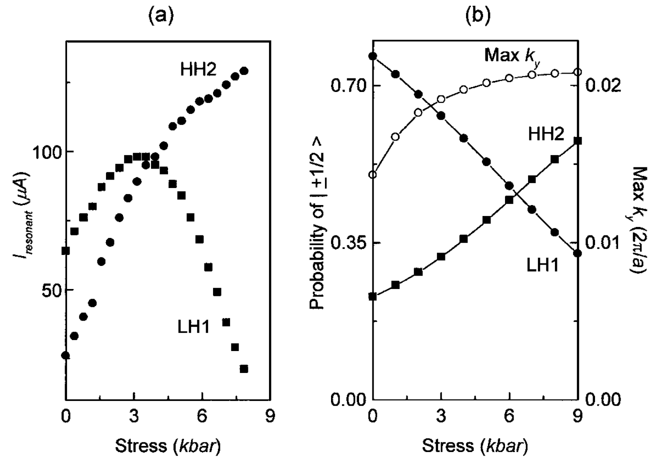

FIG. 5. Stress dependence of (a) the measured resonant tunneling currents through the LH1 and HH2 states and (b) the maximum parallel momentum k_y and the integral (along z) of the sum of the squares of the $|\pm 1/2\rangle$ envelope functions for the LH1 and HH2 states at $k_y = 0.016 \times 2\pi/a_0$.

The absolute values of the calculated current and bias positions for the resonant peaks are not directly comparable to the experimental values, since the calculation does not include any band bending, charge accumulation in the emitter, or nonresonant tunneling effects. Nevertheless, from the calculated results, it can clearly be seen that the peak current through the confined LH1 state has its maximum value at around 4 kbar, while that through the confined HH2 state increases monotonically. Figure 5(a) shows the measured resonant currents of the LH1 and the HH2 resonances as a function of stress. The resonant current was taken to be the difference between the peak and valley current values, because the valley current is normally introduced by nonresonant tunneling processes and also by the onset of the next resonance if the carrier concentration in the emitter is high enough. The calculated current values are about 10 times smaller than the resonant current derived from the experimental curves. This is mainly due to the lack of consideration of an accumulation layer in the emitter and also to differences between nominal structure parameters (barrier width, well width, etc.) and the parameters used in calculation. Nevertheless, the experimental results in Fig. 5(a) show very good qualitative agreement with the calculation in Fig. 4(b).

The applied uniaxial stress increases the mixing between the LH1 and HH2 states, resulting in an increase (decrease) of the amplitudes of the $|\pm 1/2\rangle$ components of the HH2 (LH1) wave function inside the well. This is shown in Fig. 5(b), which plots the stress dependence of the integral (along z) of the sum of the squares of the $|\pm 1/2\rangle$ envelope functions for $k_y = 0.016 \times 2\pi/a_0$. An increase in the amplitudes of the $|\pm 1/2\rangle$ components of the wave function in the well should enhance the tunneling, since these components should tunnel more easily through the barrier than the $|\pm 3/2\rangle$ components. Hence increasing the stress should increase the current for HH2 states and vice versa for LH1 states. However, the experimental results for LH1 below 3.5 kbar are contradictory to this simple argument. In this pressure range, the peak current increases rather than decreases. The reason for this behavior is that the effect of the stress on the emitter Fermi surface must also be considered. The applied uniaxial stress deforms the heavy hole Fermi surface, compressing it along the applied uniaxial stress direction and expanding it in the perpendicular directions. This increases the maximum in-plane wave vector normal to the stress (k_y) as shown in Fig. 5(b). This figure shows that the k_y Fermi wave-vector component increases rapidly up to 4 Kbar but then starts to saturate at a value which depends on the emitter carrier concentration. Since the $|\pm 1/2\rangle$ components of the LH1 wave function decrease almost linearly, there must be another contribution to the transmission coefficient that increases more rapidly in order to make the tunneling current increase with increasing stress. Thus this is direct evidence that the transmission coefficient indeed increases very rapidly with increasing parallel momentum and is the main reason why off-zone center current, near the Fermi surface of the emitter hole distribution, in fact dominates the tunneling in p-type structures. Above 3.5 kbar the LH1 peak current starts to decrease because the maximum parallel momentum then starts to saturate while the light-hole component of the wave function is still decreasing. For the HH2 resonance, the peak current increases rapidly up to 4.5 kbar since both the maximum parallel momentum and the $|\pm 1/2\rangle$ components of the wave function in the well are both increasing. Once the maximum parallel momentum starts to saturate the rate of increase is slowed down. We also have observed a monotonic increase with increasing stress of the peak current for the much weaker HH1 resonance. In this case the increase of the k_y Fermi wave-vector component should be the dominant effect.

Finally, we note that our analysis shows that tunneling in a typical DBS occurs at $k_{\parallel} = (0.01\text{–}0.02)2\pi/a_0$, depending on the details of the emitter accumulation layer. This is comparable to the wave vectors of dispersion anomalies in the valence band, for example, the maximum for LH1 in Fig. 2(a). Thus quantitative interpretation of experiments which map out such anomalies should be carried out with caution, e.g., [10–13].

In conclusion, the dependence of the resonant tunneling of holes on an in-plane [100] uniaxial stress has been demonstrated. Stress allows the dispersions of the LH and HH states, and their intermixing, to be tuned continuously. Our results provide the first clear experimental confirmation that the current through a p-type tunneling device is dominated by off-zone center tunneling of states near the Fermi surface in the emitter.

This work was supported by the Engineering and Physical Sciences Research Council (E.P.S.R.C.) of the U.K. We thank L. E. Bremme for useful discussions. T. R. acknowledges support from the Friedrich Flick Förderungsstiftung.

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