Subband dispersion of holes in AlAs/$In_{0.10}Ga_{0.90}As$/AlAs strained-layer quantum wells measured by resonant magnetotunneling

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Magnetotunneling of holes through the double-barrier AlAs/$In_{0.10}Ga_{0.90}As$ strained-layer structure is investigated with magnetic fields up to 23 T to determine the in-plane dispersion of the two-dimensional subbands in the $In_{0.10}Ga_{0.90}As$ quantum well. Mass reversal, nonparabolicity, anticrossing, and anisotropy are observed. The lack of electronlike dispersion in the lowest-energy light-hole subband is attributed to the large biaxial compressional strain in the $In_{0.10}Ga_{0.90}As$, which suppresses the mixing of heavy and light-hole states even at finite in-plane wave vectors.

Charge transport through a double-barrier resonant tunneling structure (DBRTS) depends explicitly on the energy levels of the heterostructure,[1,2] and therefore can give direct information about the energy structure of the two-dimensional (2D) subbands in the quantum well. When a strong magnetic field B is applied parallel to the tunneling direction, it induces oscillatory features in the current-voltage I-V characteristic. These features arise from resonant tunneling into the Landau levels in the quantum well and thus provide a way to determine the effective mass of the carriers.[3,4] When B is applied transverse to the tunneling direction ($B_\perp$), the charge carriers will acquire a transverse momentum $\Delta K_\perp$ in the course of tunneling through the emitter barrier. This additional transverse momentum induces a shift in the voltage position V_p of the resonance peak in the I-V.[5] Since the shift in V_p and the change in $K_\perp$ are directly related to the subband energy-momentum (E-$K_\perp$) dispersion, resonant magnetotunneling can be a tool to probe the subband in-plane dispersion. It is particularly useful for studying complex energy structures since it probes specific values of the $K_\perp$, not an average over K space.

The application of this technique to study the complex valence-band (VB) dispersion has recently been reported by Hayden *et al.*[6] in p-type AlAs/GaAs/AlAs and by Gennser *et al.*[7] in p-type $Si/Si_{1-x}Ge_x/Si$. We wish to report in this letter the first magnetotunneling measurements on p-type AlAs/$In_{0.10}Ga_{0.90}As$/AlAs strained-layer structures and the in-plane dispersion of the VB determined with $B_\perp$ up to 23 T. The large biaxial strain in the $In_{0.10}Ga_{0.90}As$ layer splits the fourfold degenerate VB edge ($K=0$) and modifies the energy structure of the strain split-off subbands.[8] For $K_\perp \lesssim 2\times10^8$ m^{-1}, we observe a strong in-plane dispersion (i.e., light effective mass) for the heavy-hole (HH) ground subband of the $In_{0.10}Ga_{0.90}As$ well and about three times weaker dispersion (i.e., heavy effective mass) for the light-hole (LH) ground subband. Surprisingly, we did not observe the electronlike states in the LH_0 subband of the strained $In_{0.10}Ga_{0.90}As$ well for $K_\perp$ up to 5×10^8 m^{-1}. This observation is contrary to the theoretically predicted and recently reported LH_0 subband dispersion in the lattice-matched $Al_xGa_{1-x}As$/GaAs structures. Our result is a direct consequence of the large biaxial compressive strain in the $In_{0.10}Ga_{0.90}As$ layer which effectively decouples the HH-LH bands even at finite $K_\perp$. The observation of a light in-plane mass for the HH_0 subband and a heavy in-plane mass for the LH_0 subband at small $K_\perp$ is also consistent with this effective decoupling of HH-LH bands by the strain. In addition, large in-plane anisotropy is observed and estimated to be $\approx$20% for the HH_0 and LH_0 subbands in the $In_{0.10}Ga_{0.90}As$ well.

Two DBRTS device structures, grown by molecular-beam epitaxy on a (001) p^+-GaAs substrate, were investigated. The active region of device 1 consists of (1) 0.2 μm of GaAs, Be doped to 2×10^{18}/cm^3, (2) 0.1 μm of GaAs, Be doped to 1×10^{18}/cm^3, (3) 0.1 μm of GaAs, Be doped to 5×10^{17}/cm^3, (4) 500 Å of undoped GaAs, (5) 60 Å of undoped AlAs barrier, (6) $W=42$ Å of undoped $In_{0.10}Ga_{0.90}As$ well, (7) 70 Å of undoped AlAs barrier, (8) 500 Å of undoped GaAs, (9) 0.1 μm of GaAs, Be doped to 5×10^{17}/cm^3, (10) 0.1 μm of GaAs, Be doped to 1×10^{18}/cm^3, and (11) 0.3 μm of GaAs, Be doped to 2×10^{18}/cm^3. Device 2 differs only in the quantum-well thickness, $W=34$ Å. The undoped spacer layers outside the barriers are intended to prevent dopant diffusion into the quantum well. The barrier asymmetry is designed to prevent significant charge buildup in the well at the forward bias.[5] The devices were defined by the 45×45-μm^2 contact pads of Au-Zn-Au square dots which were used as a mask for the mesa etching. Ohmic contacts were formed by alloying at 400 °C in hydrogen ambient. The magnetotunneling measurements were performed at 4.2 K with $B_\perp$ to 9 T in a superconducting magnet and to 23 T in a Bitter magnet. The sample was mounted in a rotating sample holder; its I-V and the derivatives were measured using conventional ac lock-in technique.

The I-V of two DBRTS devices in forward bias at $B=0$ are shown as the lower two traces in Fig. 1. The d^2I/dV^2-V for device 1 ($W=42$ Å) is shown as the top

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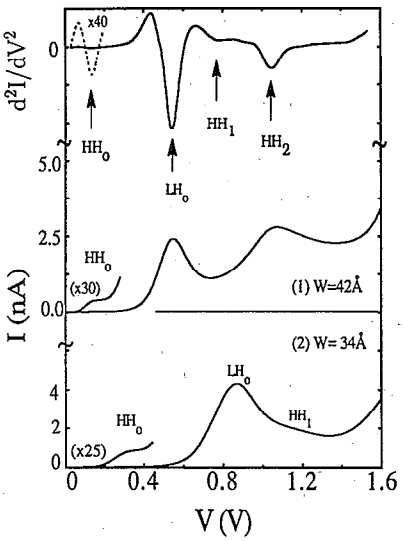

FIG. 1. I-V characteristics of two AlAs/$In_{0.10}Ga_{0.90}As$/AlAs DBRTS devices at 4.2 K. W is the thickness of the $In_{0.10}Ga_{0.90}As$ layer. The lower two traces are I-V. The top trace is the d^2I/dV^2-V of device with $W=42$ Å.

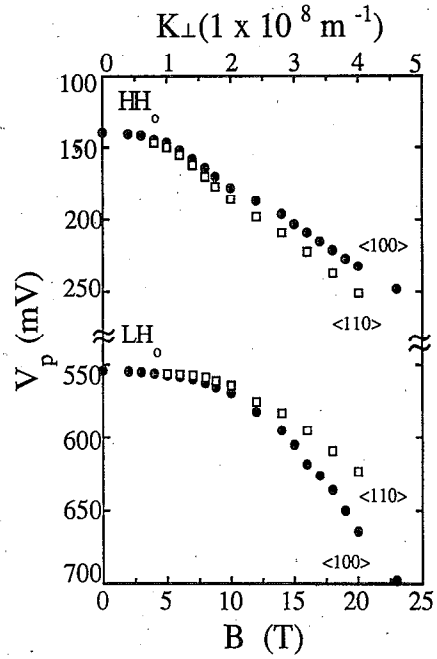

FIG. 2. Voltage position V_p of the HH_0 and LH_0 resonance peak as a function of $B_\perp$, applied along a ⟨100⟩ direction (closed dots) and a ⟨110⟩ direction (open squares) in the plane of the AlAs/$In_{0.10}Ga_{0.90}As$ interface.

trace. In device 1, the tunneling current rises at $V\approx 60$ mV, showing a weak but clear shoulder at ≈ 150 mV. At higher biases, two resonance peaks are seen at $V=553$ and 1080 mV. In the d^2I/dV^2-V, the two strongest minima labeled LH_0 and HH_2 correspond to the two resonance peaks in the I-V. The HH_0 minimum at $V=145$ mV is the ground subband resonance. In addition, a weak minimum, not apparent in the I-V, is resolved at $V=780$ mV and is labeled HH_1. For device 2, which has a narrower well width ($W=34$ Å), all the resonances are shifted to higher biases. The HH_0 and the LH_0 resonances are observed at $V=306$ and 820 mV, respectively, and the HH_1 resonance is discernible in the I-V as a shoulder at $V\approx 1.2$ V. Since both the quantum confinement and the biaxial compressive strain in the well act to split the HH-LH subbands at Γ ($K=0$) and push the HH subband upward in energy, the HH subband must be the uppermost valence-band states in the $In_{0.10}Ga_{0.90}As$ well. We therefore assign the HH_0 resonance to tunneling of holes into the HH ground subband. Moreover, the current level at the LH_0 resonance is about two orders of magnitude higher than that at the HH_0 resonance in both devices. Since the tunneling probability of holes into the LH ground subband is expected to be orders of magnitude larger than that into the HH ground subband,[9] we assign the LH_0 resonance peak to the LH ground subband. The HH_1 and HH_2 resonances are assigned to the first and second HH excited subbands, respectively. This assignment is based on an energy-level calculation using the band parameters deduced from the HH_0 and LH_0 resonances and assuming a band offset of 480 mV (Ref. 10) for HH at the AlAs/$In_{0.10}Ga_{0.90}As$ heterojunction.

The application of $B_\perp$ shifts the voltage position V_p of the resonances. We have investigated to 23 T this shift of the HH_0 and LH_0 resonances in both devices and plotted our data from device 1 as V_p vs $B_\perp$ in Fig. 2. The solid dots are the data taken with $B_\perp$ applied along a ⟨100⟩ axis of the sample and the open squares are with $B_\perp$ along a ⟨110⟩ axis. The shift in V_p arises from the change in the in-plane momentum, $\Delta K_\perp$, induced by $B_\perp$. If we take $\mathbf{B}_\perp$ to be along x axis and the tunnel current along z-axis, a hole in the emitter state (E, K_x, K_y) will tunnel elastically into the subband state (E, K_x, K_y-ΔK_y) of the well. ΔK_y is given by

$$\Delta K_y = eB_\perp\langle z\rangle/\hbar\,, \tag{1}$$

where $\langle z\rangle$ is the average hole traversal distance. Since the energy is conserved in the tunneling process, any gain in kinetic energy due to the change in ΔK_y must be supplied by a change in bias and thus cause a shift in V_p. Therefore, the plot of V_p vs $B_\perp$ in Fig. 2 is a display of the subband dispersion in the quantum well, and the difference in V_p for different orientations of $B_\perp$ in the plane of the interface is a direct measure of the subband anisotropy. The corresponding $K_\perp$, calculated from Eq. (1) using $\langle z\rangle = 125$ Å for the device,[11] is shown in the upper horizontal axis.

We first neglect the anisotropy and concentrate on the dispersion for $K_\perp$ along ⟨100⟩. It is clear from the data that for small $K_\perp$ ($B_\perp \leqslant 10$ T, corresponding to $K_\perp < 2\times 10^8$ m^{-1}) the HH_0 subband is much more dispersive than the LH_0 subband, as anticipated from the so-called diagonal approximation (which neglects mixing of HH and LH states) that the HH subband should display a light in-plane mass and the LH subband should display a heavy in-plane mass.[12] This valence-band mass reversal effect is well known in strained material[8,13] and has been a main reason for the interest in using p-type $In_xGa_{1-x}As$ strained-layer structure for high-speed electronic applications.[14] For

$B_\perp \geq 10$ T, in the large $K_\perp$ limit, the HH_0 subband becomes nonparabolic, showing an almost linear dispersion. Such a high degree of nonparabolicity in the HH_0 subband has also been deduced from magneto-luminescence experiments recently by Jones *et al.*[15] The LH_0 subband, on the other hand, takes on the lighter mass dispersion in this limit, suggestive of the anticrossinglike feature seen in several theoretical calculations.[12,16–18] This feature arises from mixing of the HH and LH states at finite $K_\perp$, when the off-diagonal terms are included in the valence-band Hamiltonian. We must also emphasize that the dispersion of our LH_0 subband is strictly holelike and there is no indication in the data of the electronlike dispersion (i.e., having camel-back shape or negative hole masses) predicted in these calculations. This may at first appear surprising in that electronlike dispersion has recently been seen in the lattice-matched $GaAs/Al_xGa_{1-x}As$ quantum-well structure.[6] Again, the electronlike dispersion results from the strong mixing of HH and LH hole states at finite $K_\perp$. In our strained-layer structure, the strain induced splitting is ≈ 25 meV, sufficiently large to decouple the HH and LH states to make the mixing due to quantum confinement negligible and, as a result, we do not expect the LH_0 subband to display the electronlike dispersion.

Finally, we have investigated the subband anisotropy (or warping) by rotating B in the interface plane. We find that both subbands are essentially isotropic for $B \leq 5$ T ($K_\perp \leq 1\times10^8$ m^{-1}). The anisotropy, which is expected when warping of the bulk valence bands is taken into account, is clearly resolved at ≈ 10 T for $K_\perp \approx 2\times10^8$ m^{-1} and increases to $\approx 20\%$ at $K_\perp \approx 4\times10^8$ m^{-1} or $B_\perp \approx 20$ T (see Fig. 2). Similar anisotropy of comparable magnitude has recently been observed in the $Si/Si_{1-x}Ge_x$ strained-layer structure by Gennser *et al.*[7] However, in the lattice-matched $GaAs/Al_xGa_{1-x}As$ structure, Hayden *et al.*[6] found only a very small anisotropy. Thus the large anisotropy observed in our samples and in the $Si/Si_{1-x}Ge_x$ must also be due to the large biaxial strain that alters the band mixing.[19]

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