High magnetic field studies of the confined hole states in quantum wells grown on novel substrate orientations

Evidence for a ‘camel’s back’ structure in the energy subbands

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Magnetic fields are used to examine the anisotropic in-plane energy dispersion of the quantum well states of an AlAs/GaAs/AlAs double-barrier diode grown on a (3 1 1)A substrate. The measurements reveal biaxial anisotropy in some subbands. These features are confirmed by a six-component envelope-function calculation of the subbands of a (3 1 1) valence band quantum well.

We have investigated the form of the energy versus in-plane wavevector $\epsilon(k_{\parallel})$ dispersion of quasi-bound hole states in a GaAs/AlAs (3 1 1)A quantum well using resonant magnetotunnelling spectroscopy [1]. This technique allows both the magnitude and direction of $k_{\parallel}$ to be selected, so it can also be used to examine the anisotropy of the carrier dispersion curves with respect to the crystalline axes. Calculations [2,3] and our measurements reveal a much greater anisotropy for some of the hole subbands than is observed for those of a similar (1 0 0) quantum well [4]. Some of the higher energy subbands exhibit a ‘camel’s back’ structure with a saddle-point at $k_{\parallel} = 0$. However, the ground state subband is found to be isotropic for $k_{\parallel} < 1 \times 10^6 \text{ cm}^{-1}$. It is well known theoretically that the dispersion curves of confined holes are complicated [5–8] due to the presence of a second-order spin–orbit term in the effective Hamiltonian [9]. This term admixes the light and heavy hole valence bands and can lead to hole energy decreasing with increasing in-plane wavevector $k_{\parallel}$.

Details of the composition and growth of the device studied here have been given elsewhere [10]. Briefly, it consists of a 4.2 nm wide GaAs quantum well between two 5.1 nm wide AlAs barriers. Resonant tunnelling from the emitter accumulation layer occurs when the energy $eV_e$ at which holes are injected into the quantum well is equal to the energy $\epsilon(k_{\parallel})$ of a quasi-bound state of the quantum well. In the absence of scattering, resonant tunnelling can only occur with the conservation of energy and in-plane wavevector $k_{\parallel} = (k_x, k_y)$. In a magnetic field $B$ applied parallel to the $x$-axis, the tunnelling holes acquire an additional in-plane wavevector component along the $y$-axis, $\Delta k_{\parallel} = eB\Delta s/\hbar$, where $\Delta s$ is the average separation between hole...
states in the emitter accumulation layer and in the quantum well [1]. The voltage positions $V_p$ of the resonant peaks in the current–voltage characteristics $I(V)$ are measured as a function of both the direction and magnitude of $B$. Hence the in-plane energy dispersion of the confined quantum well states can be mapped out.

Figure 1 shows the $I(V)$ characteristics of the device at various values of in-plane magnetic field. Seven features, each corresponding to resonant tunnelling into a quasi-bound subband of the quantum well, are labelled (i) to (vii) on the 17 T curves. Two of the quantum well subbands produce very weak resonances, (iv) and (vi), which only become visible directly in $I(V)$ at higher magnetic fields; they are clear features in the conductance, $dI/dV$, as shown. The other five resonances are much stronger. Peaks (i) and (ii) have a very weak $B$-dependence indicating a small $\varepsilon(k_{||})$ dispersion. Similar weak dispersion is also found for the two lowest energy subbands of a (100) quantum well [1,6–8]. Some of the peaks show a very strong subband anisotropy. For example, as $B$ is increased from 0 to 17 T, resonance (vii) moves rapidly to higher voltages, by more than 150 mV, for $B \|[011]$ the up-shift is only 90 mV.

We have measured the $I(V)$ characteristics at regular intervals of $\Delta \theta = 22.5^\circ$ in the (311) plane and in 1 T steps up to 17 T, corresponding to a maximum in-plane wavevector component $\Delta k_{||} = 1.0\pi \times 10^6$ cm$^{-1}$. In this way, we can construct $V_p(k_{||}, \theta)$ plots of the dispersion curves for each of the quantum well subbands. These can be classified into two groups: subbands (i), (iii), (v) and (vii) have a small anistropy with the minimum of hole energy occurring at $k_{||} = 0$; subbands (ii), (iv) and (vi) exhibit strongly the biaxial symmetry of the (311) plane, the latter two with a ‘camel's back’ structure in which two minima of the hole energy occur along the [011] axis in the $k_{||}$ plane. Figure 2(a)–(c) shows the measured dispersion curves $V_p(B)$. It can be seen that subband (i) is weakly dispersed and isotropic for $k_{||} < 1 \times 10^6$ cm$^{-1}$, similar in form to the lowest-energy heavy hole subband of a (100) quantum well [8]. This result is of interest as an anisotropy of the Hall mobility has been observed for the two-dimensional hole gas in very high mobility p-type heterostructures grown on (311)A [11]. These low density (4 x 10$^{11}$ cm$^{-2}$) heterostructures have a Fermi wavevector $k_F = 1.2 \times 10^6$ cm$^{-1}$. Our results indicate that this mobility anisotropy is probably due to growth-related corrugations [12] along [233] rather than a band structure effect. The figure shows the pronounced ‘camel's back’ structure of subband (iv) with minima in hole energy along [011] at $k_{||} = \pm \pi \times 10^6$ cm$^{-1}$. Thus for the range of $k_{||}$ achievable with our maximum available magnetic field, this subband has electron-like character for $k_{||}$ along [011] and hole character for $k_{||}$ along [233]. This type of subband with a saddle-point at $k_{||} = 0$ is not found for unstrained (100) GaAs quantum wells [13,14]. Subbands

![Figure 1. Current–voltage characteristics at 4.2 K of a p-type resonant tunnelling device (grown on a (311)A substrate) at various values of the in-plane magnetic field $B$. Solid curves are for $B \|[011]$ (that is $k_{||}$ along [233]), dashed curves are for $B \|[233]$ (that is $k_{||}$ along [011]).](image-url)
Fig. 2. (a)–(c) Experimental dispersion curves, $V_p(B)$ for resonances (i), (iv) and (v) respectively observed in $I(V)$. The values of $k_\parallel$ are obtained from the equation in the text. The regions outside the white circles are an extrapolation beyond the range of the measurements. (d)–(f) Energy dispersion $\varepsilon(k_\parallel)$ of the corresponding quantum well subbands calculated for zero electric and magnetic fields, using a six-component envelope-function formalism. The vertical axes correspond to $k_\parallel$ along $[213]$, the horizontal axes correspond to $k_\parallel$ along $[011]$. For subbands (i) and (v) the hole energy and $V_p$ increase steadily with increasing $k_\parallel$. In the contour plots (b) and (e) of subband (iv) the saddle-point at $k_\parallel = 0$ corresponds to $V_p = 870$ mV and a hole energy of 131 meV.

(iii), (v) and (vii) are weakly anisotropic paraboloids with the major axis in $k$-space along $[213]$.

Figure 2 compares our data with the calculated subbands of an isolated AlAs/GaAs/AlAs valence band quantum well of width 6 nm on a (311) plane in the absence of applied electric and magnetic fields. The envelope-function calculations [13–15] use the six-band Luttinger-Kohn Hamiltonian [9], which includes the heavy-hole, light-hole and spin-orbit split-off bands. The Luttinger parameters used are quoted in ref. [10]. For all seven subbands, there is good qualitative agreement between the general forms of...
the observed and calculated dispersions. In particular, our observation of the ‘camel’s back’ dispersion for subband (iv) is confirmed. The anisotropy of subband (i) is only evident in the calculated dispersion curves at large \( k_{||} \), beyond the range achievable with our maximum available field. We noted earlier that resonant tunneling into subbands (iv) and (vi) produces only weak features in \( I(V) \), as can be seen in fig. 1. The calculated \( \varepsilon(k_{||}) \) surface of subband (vi) has a ‘camel’s back’-shaped dispersion similar to that of subband (iv) [15]. We account qualitatively for the weakness of these two resonances as follows. Holes tunnel into the quantum well from the lowest energy subband of the emitter accumulation layer, which at low temperatures is occupied up to its quasi-Fermi energy. This subband has a small dispersion similar to that shown in fig. 2(d) for the quantum well ground state. Increasing the applied bias has the effect of sweeping the emitter \( \varepsilon(k_{||}) \) surface through that of the quantum well subband. Due to the ‘camel’s back’-shaped dispersion of the quantum well subband and the requirements of energy and wavevector conservation, the resonance is spread over a wide range of applied bias and corresponds to a broad but weak feature in \( I(V) \).

In conclusion, we have used resonant magnetotunnelling spectroscopy to study the complicated energy dispersion and anisotropy of the states in a (3 1 1)A valence-band quantum well. Our measurements reveal the marked anisotropy and biaxial symmetry of some of the confined hole subbands. The dispersions of some of these subbands have a ‘camel’s back’ shape. However, the ground state subband is fairly isotropic. We have compared our results with calculated (3 1 1) quantum-well hole subbands and obtain qualitative agreement.

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References