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Two-dimensional spin confinement in strained-layer quantum wells

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We show that a two-dimensional spin system can occur for "heavy," $m_J = \pm \frac{3}{2}$ holes resulting from a reduction to tetragonal symmetry produced by biaxial strain or confinement in a quantum well. Evidence is produced from magnetotransport measurements on strained $Ga_{1-x}In_xSb/GaSb$ quantum wells, in which the spin splitting is determined only by the component of magnetic field in the growth direction, and from published work on unstrained $GaAs/Al_xGa_{1-x}As$ heterojunctions. Complementary behavior is predicted for "light" holes.

In the wide variety of two-dimensional (2D) systems studied to date it has always been the orbital electron motion which is quantized into a fixed plane with spin remaining as a 3D variable.[1–3] Consequently the spin splitting is proportional to the total magnetic field while the Landau-level structure depends only on the component normal to the 2D electron gas (2D EG). In this Rapid Communication we demonstrate a two-dimensional spin quantization in which the angular momentum of a free 2D hole gas is projected in the direction perpendicular to the 2D plane by uniaxial stress. The resultant decoupling of the degenerate valence band is found to produce a considerable simplification of the band structure, as has been discussed by a number of authors in relation to improved optical and laser performance in strained layers.[4,5] In practice we show that the introduction of 2D spin and decoupled bands can also introduce considerable simplification in the picture of p-type heterostructures in general, especially at low carrier densities and close to the valence-band edge.

We have recently demonstrated[6] that it is possible to produce a high-quality 2D hole gas in the strained $Ga_{0.85}In_{0.15}Sb/GaSb$ system. The in-built uniaxial strain component ($\epsilon_{zz} - \epsilon_{xx} = 1.9\%$) is sufficient to decouple the $m_J = \pm \frac{3}{2}$ states of the valence band from the $m_J = \pm \frac{1}{2}$ ones. As a result, the $m_J = \pm \frac{3}{2}$ states are highest and are exclusively populated by holes,[7] with in-plane effective mass falling as low as $0.07 m_e$, yielding mobilities of order 10^4 cm^2/Vs. In $GaSb/Ga_{1-x}In_xSb$ the spin-magnetic-field coupling parameter κ is relatively large (equal to 4 and 5.7, respectively) and hence spin effects are particularly significant in this system.

We have studied magnetotransport in a number of strained single quantum well structures consisting of a single layer ~8 nm thick of $Ga_{0.85}In_{0.15}Sb$, grown onto a 5-μm-thick GaSb buffer layer with 60–100-nm GaSb cap layers. The substrate used is GaAs, with the buffer layer sufficiently thick to reduce the influence of dislocations. The samples are grown using metalorganic vapor-phase epitaxy (MOVPE), as described earlier.[6] Typical 2D carrier concentrations and mobilities fall in the range $(0.7–2.4)\times10^{11}$ cm^{-2}, and 10^3–10^4 cm^2/Vs, respectively. We shall concentrate on the results from one sample (449), which has the highest mobility, 9270 cm^2/Vs at 4.2 K, with a carrier concentration of 1.45×10^{11} cm^{-2}. All samples showed similar, if less well-resolved behavior. These figures are obtained following excitation of a weak persistent photoconductivity, the origin of which is not yet explained. The samples showed two-dimensional conduction only at temperatures below 20 K, since above this the p-type (2.7×10^{16} cm^{-3} at 300 K) GaSb buffer layer was no longer frozen out.

Figure 1(a) shows a typical recording of the magne-

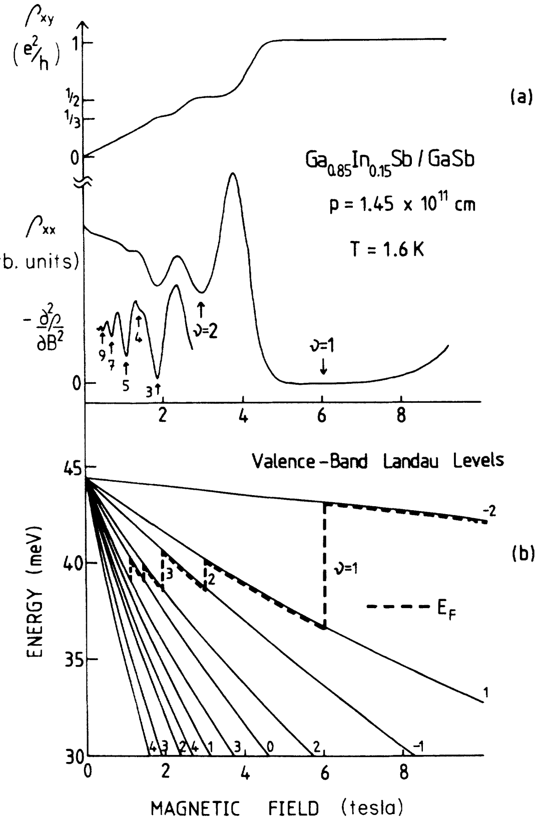

FIG. 1. (a) Magnetoresistance ρ_{xx} and Hall resistance ρ_{xy} at 1.6 K for the hole gas with $p = 1.45\times10^{11}$ cm^{-2}. Also shown at low field is $-d^2\rho_{xx}/dB^2$, which emphasizes the low-field minima. (b) $m_J = \frac{3}{2}$ Landau levels calculated from the effective Hamiltonian for $\kappa = 5.7$. Fermi-level motion is indicated by the dashed line, for zero broadening. The energy scale is measured from the GaSb band edge.

toresistance and quantum Hall plateaus at 1.6 K. One obvious feature stands out. There is a strong series of both minima and plateaus which occur at *odd* integer values of the Landau-level filling factor $\nu = nh/eB$, and can be detected up to $\nu = 15$ in the second derivative. By contrast the even minimum at $\nu = 2$ is relatively weak and no even features are detectable above $\nu = 4$. Thus the behavior appears to be that of a system with a series of Landau levels, each split by an effective spin splitting of over half the cyclotron energy, as can be achieved in n-type systems using tilted fields.[1–3] Using the effective mass measured in these structures ($\sim 0.07 m_e$) (Ref. 7) this requires an effective g factor of order 6 or greater with a resultant separation of $3g^* \mu_B B$ for the $m_J = \pm \frac{3}{2}$ states. The origin of this behavior is the large band-structure contribution to the spin splitting and the reduction in symmetry caused by the strain acting on the valence band.

Using a Kohn-Luttinger effective Hamiltonian approach[8,9] including quantum confinement[10] and strain,[11] we have calculated the Landau levels as a function of magnetic field for various values of the coupling parameter κ. One set can be seen in Fig. 1(b), calculated from valence-band parameters reported in Ref. 7. It is clear that they form two interleaved fans (with quantum numbers starting from -2 and 1, corresponding, in the completely decoupled limit, to $m_J = -\frac{3}{2}$ and $+\frac{3}{2}$ states) which have a large effective spin splitting. The motion of the Fermi energy as a function of field is shown assuming infinitely sharp levels and this confirms that the large steps do correspond to odd integer fillings, in agreement with the large minima found in the resistivity trace. The accuracy of the model is evidenced by the good agreement with the measured interband magnetophotoconductivity and cyclotron resonance spectra.[7] It is seen that strain greatly simplifies the level structure as compared with that associated with unstrained p-type heterojunctions and quantum wells.[12–17]

The quantitative results of the calculations were verified by making an activation measurement of the spin splitting at $\nu = 1$, which gave a value for $\Delta E = 5.2$ meV at 6.5 T from an Arrhenius plot of $\rho_{xx} = \rho_0 \exp(-\Delta E / 2k_B T)$. This represents good agreement with the calculated value of 6.5 meV, given the reduction often seen in activation measurements due to finite-level broadening,[18] and the existence of a mobility edge separating the localized and extended states.

The more dramatic result appears when we rotate the sample growth axis away from the magnetic field, as shown in Fig. 2. As expected the *positions* of the minima move upwards in total magnetic field as the level degeneracies are determined only by the perpendicular field component, B_z. The *amplitudes* of the spin-split minima at $\nu = 1,3,5,\ldots$, however, remain constant and are

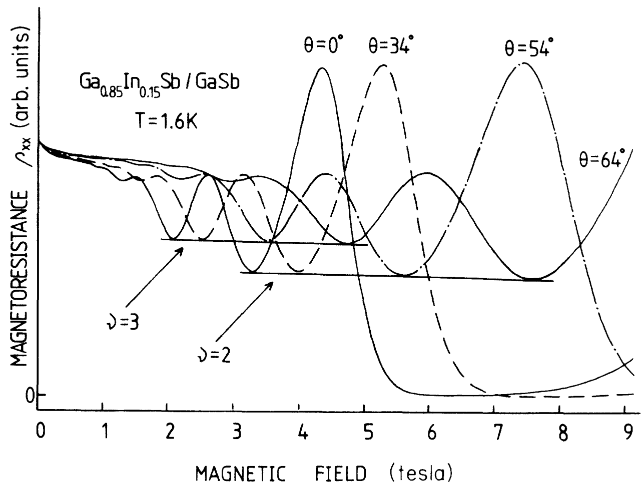

FIG. 2. Magnetoresistance in a tilted field demonstrating the independence of the strength of the resistivity minima from the total magnetic field. This can be seen by following the minimum values for $\nu = 3$ and 2 as shown in the figure. Angles are between field and growth direction.

unaffected by the increase in total field, as is the weaker $\nu = 2$ minimum. This remarkable characteristic has been observed by Iye *et al.*[19] in asymmetrically p-type doped narrow $GaAs/Al_xGa_{1-x}As$ quantum wells, although no simple explanation was given. This behavior is in marked contrast to the well-documented behavior seen in n-type systems, such as Si metal-oxide-semiconductor field-effect transistors and GaAs-based inversion layers[1–3] where a large increase is seen in the strength of structure attributed to spin-split levels as the sample is rotated relative to the magnetic-field direction. We will show that the origin of this behavior is a general result of 2D quantization of the spin caused by the strain and confinement in the structure. The energy levels are determined only by the perpendicular component of field, B_z, and the conceptual view of the system becomes much simpler. The strain projects the total angular momentum J associated with the valence band along the uniaxial strain axis (perpendicular to the layers), giving a splitting of 71 meV between the $m_J = \pm \frac{3}{2}$ and $m_J = \pm \frac{1}{2}$ band edges. The strong spin-orbit coupling ($\Delta = 0.8$ eV in GaSb) means that the spin and orbital motion remain coupled, and are both projected along the strain axis which is perpendicular to the 2D hole gas.

We now propose a theoretical model in which this behavior can be understood directly from an examination of the effective Hamiltonian H in the presence of strain and a tilted field:[10,20]

$$H = \begin{pmatrix} P_+ - 3\kappa\mu_B B_Z & 0 & Q - \sqrt{3}(\gamma_3 + \kappa)\mu_B B_- & R \\ 0 & P_+ + 3\kappa\mu_B B_z & R^\dagger & -Q^\dagger + \sqrt{3}(\gamma_3 - \kappa)\mu_B B_+ \\ Q^\dagger - \sqrt{3}(\gamma_3 + \kappa)\mu_B B_+ & R & P_- - \kappa\mu_B B_z & -2\kappa\mu_B B_- \\ R^\dagger & -Q + \sqrt{3}(\gamma_3 - \kappa)\mu_B B_- & -2\kappa\mu_B B_+ & P_- + \kappa\mu_B B_z \end{pmatrix} . \qquad (1)$$

The Hamiltonian is expressed in the basis $m_J=\frac{3}{2}$, $-\frac{3}{2},\frac{1}{2},-\frac{1}{2}$ using the following terminology:

$$P_{\pm}=-p_z^2(\gamma_1\mp 2\gamma_2)/2m-2B_z\mu_B(\gamma_1\pm\gamma_2)$$
$$\times(a_+a_-+\tfrac{1}{2})\mp\zeta+V(z)\,,$$
$$Q=\gamma_3 p_z\sqrt{(12\mu_B B_z)/m}\,a_-\,,$$
$$R=\sqrt{3}(\gamma_2+\gamma_3)\mu_B B_z a_-^2\,,$$
$$B_{\pm}=B_x\pm iB_y\,,$$

where $a_{\pm}$ are Landau ladder operators for cyclotron motion about B_z and $\gamma_1,\gamma_2,\gamma_3$ are the conventional Luttinger-Kohn parameters.

When the separation of the $m_J=\pm\frac{3}{2}$ and $\pm\frac{1}{2}$ states is large, caused by the well potential $V(z)$ and the uniaxial strain splitting 2ζ, then the terms $P_{\pm}$ are large compared with the off-diagonal elements and the matrix can be decoupled approximately into a pair of 2×2 diagonal blocks. This removes the influence of the transverse field components B_x and B_y on the low quantum number $m_J=\pm\frac{3}{2}$ states, leaving only a two-dimensional behavior resulting from the perpendicular component B_z. It is interesting to note that the opposite is true for the $m_J=\pm\frac{1}{2}$ levels which lie primarily in the transverse direction, and therefore should show an enhanced spin splitting due to the transverse field component. In the low-field, decoupled limit we find

$$E_{+3/2}-E_{-3/2}=6\kappa\mu_B B_z\,,$$
$$E_{+1/2}-E_{-1/2}=2\kappa\mu_B[B_z^2+4(B_x^2+B_y^2)]^{1/2}\,, \tag{2}$$

predicting that the $m_J=\pm\frac{1}{2}$ levels should show very different behavior. This could be observed by studying structures in which the uniaxial stress component is compressive. The simplification in spin structure is the analog of that to in-plane band structure well known to arise from the removal of degeneracy between the $m_J=\pm\frac{3}{2}$ and $\pm\frac{1}{2}$ levels.

The terms a_+a_- in $P_{\pm}$ include contributions from the in-plane field and produce small diamagnetic shifts similar to those familiar in n-type structures.[21] Corrections from the off-diagonal 2×2 blocks can be estimated from perturbation theory in which the first-order term vanishes. The second-order correction, for the $m_J=\pm\frac{3}{2}$ levels, for example, contains only one term because of the orthogonality of the Landau states. It is, at most, equal to

$$E^{(2)}_{\pm3/2}=3(\gamma_3\pm\kappa)^2\mu_B^2(B_x^2+B_y^2)/\Delta E\,, \tag{3}$$

with a further strong reduction from the overlap between the z-dependent part of the envelope functions of the $m_J=\pm\frac{3}{2}$ and $\pm\frac{1}{2}$ states, which are spatially separated owing to the type-II character of the $m_J=\pm\frac{1}{2}$ levels in the present system. The denominator ΔE is the energy separation between the $m_J=\pm\frac{3}{2}$ and $\pm\frac{1}{2}$ states and is dominated by the strain splitting and quantum confinement. In the present case the correction [Eq. (3)] is, at most, 1.3 meV for $m_J=+\frac{3}{2}$ and less than 0.1 meV for $m_J=-\frac{3}{2}$ for the highest recorded in-plane field of 8 T.

It is interesting to note that the spin/strain component of the Hamiltonian [Eq. (1)] and hence the behavior described by Eq. (2), is equivalent to that of a localized, paramagnetic, $S=\frac{3}{2}$ ion in a reduced-symmetry tetragonal environment[22] (as produced by the uniaxial strain and/or quantum confinement):

$$\mathcal{H}=g\mu_B\mathbf{B}\cdot\mathbf{S}+D[S_z^2-S(S+1)]\,, \tag{4}$$

where g and D are replaced by 2κ and $\Delta E/2$.

Other evidence for the 2D spin picture comes from work on strained $Ga_{1-x}In_xAs/GaAs$ structures stimulated by this analysis (Martin *et al.*[23]). Here the magnitude of the spin splitting is substantially smaller due to the smaller κ value of GaAs, and spin-split minima do not dominate the magnetoresistance. Nevertheless the structure is still found to be entirely 2D. In narrow unstrained $GaAs/Al_xGa_{1-x}As$ quantum wells Iye *et al.*[19] found that at low densities an asymmetrically doped well showed 2D behavior for both spin and Landau minima, while for higher densities an "anomalous" spin splitting appeared. We can now interpret the 2D behavior as due to the heavy-hole, light-hole decoupling produced by the strong confinement in the narrow well, and it is not necessary to ascribe this to the additional electric-field–induced lifting of the Kramers degeneracy[24] as thought previously.[19] It should be emphasized, however, that the conceptual simplicity breaks down once the decoupling becomes small compared to the in-plane energies, for example, in single p-type heterojunctions,[12,14–17,19,24] or systems with tensile stress such as GaSb/AlSb (Ref. 25) where the strain and confinement act in opposite senses to give only a small band-edge splitting.

We conclude that as a result of the large strain decoupling between the $m_J=\pm\frac{3}{2}$ and $\pm\frac{1}{2}$ states in these structures we have unambiguous evidence for the 2D quantization of *both* spin and orbital motion, which gives rise to Shubnikov–de Haas and quantum Hall effect structure. This decoupling results from a reduction to tetragonal symmetry and can be produced either by strain, as in the present case, or by the effect of quantum confinement.[19] In contrast to the n-type case, however, the spin splitting can be a dominant factor due to the fact that it separates the $m_J=\pm\frac{3}{2}$ states. The strong $\mathbf{L}\cdot\mathbf{S}$ coupling of the valence band then leads to a spin state projected along the normal to the 2D hole gas.

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