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Extreme *g*-factor anisotropy induced by strain

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Magnetotransport measurements as a function of *B*-field orientation are studied on *p*-type strained-layer (001) GaAs/$In_{0.20}Ga_{0.80}As$/GaAs quantum wells at temperatures from 4.2 to 0.4 K. It is shown that the two-dimensional holes are derived from the $m_j=\pm\frac{3}{2}$ subbands and that the Zeeman splitting between the $m_j=\frac{3}{2}$ and $m_j=-\frac{3}{2}$ states of the same Landau level depends on the components of *B* perpendicular to the strained layer and not the total *B*. This *g*-factor anisotropy is shown to be a consequence of the large unaxial strain in the $In_{0.20}Ga_{0.80}As$ layer.

The Lande *g* factor of electrons in semiconductor materials is of fundamental interest. It is the parameter that determines the lifting of the spin degeneracy of electronic energy levels in the presence of a magnetic field. In a two-dimensional (2D) electron system, it is well known that the Landau-level splitting is determined by the magnetic-field component $B_\perp$ perpendicular to the surface, while the Zeeman spin splitting $\Delta E^{\pm}$ is proportional to the total magnetic field *B*. Thus, by tilting a sample in a magnet, the ratio of $\Delta E^{\pm}$ to Landau splitting can be varied continuously. This was first done in the magnetotransport experiment by Fang and Stiles in 1968,[1] and the technique has since become an established method to distinguish spin from Landau splittings in 2D electron systems. It has been applied to determine the effective *g* factor of 2D electron gases (2DEG) in a wide range of materials, including the Si metal-oxide-semiconductor structure,[1,2] the InSb inversion layer,[3] and the $Al_xGa_{1-x}As$/GaAs,[4,5] the $In_xGa_{1-x}As$/InP,[6] the $In_xAl_{1-x}As/In_yGa_{1-y}As$,[7] and the InAs/GaSb (Ref. 8) heterostructures. So far, this technique has not been tested in experiments on 2D hole systems. This is due to the inherent complexities of the energy structure of holes in these semiconductors, arising from spin-orbit coupling and mixing of the heavy- and light-hole bands away from the zone center.[9,10] The former splits the valence-band (VB) edge into fourfold and twofold degenerate bands and, as a result, the hole eigenstates are no longer pure spin states. The latter, in the presence of *B*, gives rise to four Landau ladders, each of which consists of a mixture of four different harmonic-oscillator wave functions.

In this paper, we wish to report our experimental study of the *B*-field orientation dependence of the Shubnikov–de Haas (SdH) oscillations from the 2D holes in the (001) $In_{0.20}Ga_{0.80}As$/GaAs strained-layer quantum-well structure. We find that, contrary to the 2D electrons, $\Delta E^{\pm}$ of 2D holes in the strain-split $m_j=\pm\frac{3}{2}$ VB does not depend on the total *B*, but rather on its component along the uniaxial strain, which is perpendicular to the heterojunction interface. This observation suggests that the *g* factor of the 2D hole gas (2DHG) is extremely anisotropic. The effective magnetic moment is oriented along the interface normal; it cannot align freely with a *B* in the plane of the heterojunction interface. We show that this extreme *g*-factor anisotropy is a natural consequence of the large strain along the ⟨001⟩ crystal symmetry axis of the $In_{0.20}Ga_{0.80}As$ layer.

Our samples are from two *p*-type modulation-doped heterostructures grown by molecular-beam epitaxy on semi-insulating, (001)-oriented GaAs substrates. The heterostructure consists of a 1.2-μm GaAs buffer layer, a *p*-type quantum well, and a GaAs cap layer. The quantum-well structure is a 100-Å undoped $In_{0.20}Ga_{0.80}As$ layer, sandwiched on both sides by an undoped GaAs spacer and a 25-Å Be-doped GaAs with a doping concentration of $2\times10^{18}/cm^3$. The spacer thickness is 150 Å for one sample and 300 Å for the other. The $In_{0.20}Ga_{0.80}As$ layer is thinner than the critical-layer thickness to avoid dislocation formation.[11] The samples are Hall bridges and Van der Pauw patterns, and Ohmic contacts to the 2DHG are made by alloying an In:Zn mixture at 420 °C for 10 min in a hydrogen ambient. The magnetotransport measurements are performed in a pumped liquid-helium system and a He^3 system, with *B* up to 10 T, using a rotating sample holder which can be tilted over an angle θ up to 90°, with respect to the direction of *B*.

Figure 1 shows the dependence of the Hall resistance ρ_{xy} and the diagonal resistivity ρ_{xx}, in the integer quantum Hall effect (IQHE) regime, on *B*, which is applied perpendicular to the sample surface (i.e., $\theta=0°$). The sample has a 2DHG density $p_{2D}=2.5\times10^{11}/cm^2$ and a low-field mobility $\mu=2.5\times10^4$ cm²/V s. At integer Landau-level filling factors *i*, the data shows the characteristic features of the quantized plateaus, h/e^2i, in ρ_{xy} and the vanishing of ρ_{xx}, when the Fermi energy is pinned in the gap between two adjacent levels. The occurrence of these features at odd integers, $i=3$, 5, 7, and 9, indicates the removal of spin degeneracy for $B\geq1.0$ T. In contrast

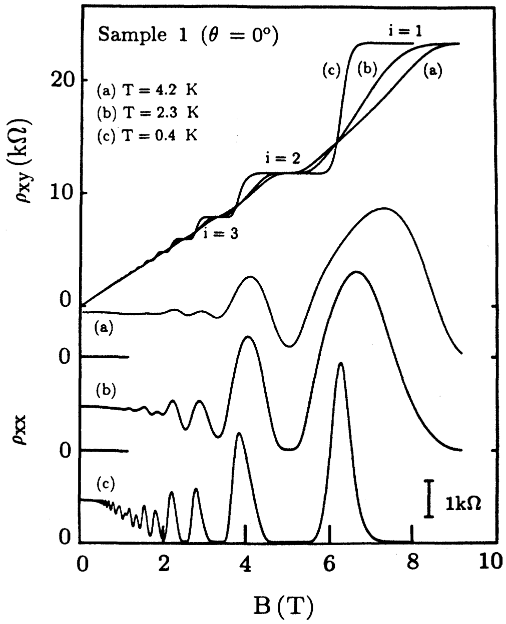

FIG. 1. Hall resistance ρ_{xy} and the diagonal resistivity ρ_{xx} as a function of magnetic field B at (a) $T=4.2$ K, (b) $T=2.3$ K, and (c) $T=0.4$ K. Sample 1 has a spacer thickness of 300 Å and the 2DHG has a density of $p_{2D}=2.5\times10^{11}/\text{cm}^2$ and a mobility of 2.5×10^4 cm^2/V s.

to the 2DHG in the lattice-matched Al$_x$Ga$_{1-x}$As/GaAs heterostructure,[12,13] in which two sets of SdH oscillations are reported, we observe only one set of oscillations, suggesting that only one subband is populated.

We have also made cyclotron resonance (CR) measurements on the same sample using an optically pumped, linearly polarized, far-infrared molecular gas laser at 4.2 K.[14] The effective mass from the CR is $m^*=0.15m_e$. This hole mass is considerably smaller than the GaAs hole mass of $\sim0.35m_e$. For our sample structure, the In$_{0.20}$Ga$_{0.80}$As layer is under biaxial compression and the fourfold degeneracy at the VB edge is split into a $m_j=\pm\frac{3}{2}$ doublet and a $m_j=\pm\frac{1}{2}$ doublet. The estimated strain-induced splitting is $\sim$60 meV,[15] and the $m_j=\pm\frac{3}{2}$ band with a light in-plane mass is expected to be the uppermost VB. From the observation of a light in-plane hole mass in our CR experiment, we conclude that the 2DHG is in the $m_j=\pm\frac{3}{2}$ band of the In$_{0.20}$Ga$_{0.80}$As layer. Our SdH data show that the 2DHG occupies one single subband.

In the IQHE regime, the dissipation in transport at integer fillings is thermally activated and the activation energy is a measure of the energy gap between the neighboring Landau levels. In Fig. 2, we show this thermally activated behavior by plotting as a function of $1/T$, on a semilog scale, the diagonal conductivity $\sigma_{xx}(=\rho_{xx}/\rho_{xx}^2+\rho_{xy}^2)$ of the sample at the $i=3$, 4, 5, 6, and 7 minima. The straight lines are fits to the linear portions of the data to $\sigma_{xx}(T)=\sigma_{xx}^0e^{-\Delta/2kT}$. The activation energy Δ, obtained from the data at the odd integer fillings, is a direct measure of the spin splittings at $B=3.3$, 2.0, and 1.43 T. Our data yield $\Delta=13$, 4.0, and 1.7 K which correspond to

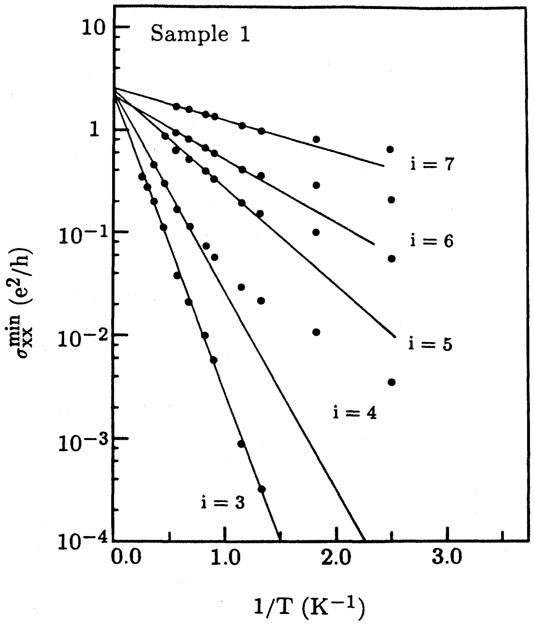

FIG. 2. Semilog plot of σ_{xx} minimum as a function of $1/T$ at filling factors $i=3$, 4, 5, 6, and 7.

an effective g factor $g^*=5.7$, 3.1, and 1.7, respectively (from $\Delta=g^*\mu_BB$, where μ_B is the Bohr magnetron). We should also note that σ_{xx}^0, obtained from the extrapolated intercepts in Fig. 2, is $\sim2e^2h$, which is more than twice the value reported for 2DEG in the Al$_x$Ga$_{1-x}$As/GaAs heterostructure.[16]

In Fig. 3(a), we show the SdH oscillations as a function of B for four different tilt angles at $T=4.2$ K. For $\theta=0°$, the dips in ρ_{xx} at $B=5.0$, 3.33, and 2.5 T correspond to filling factors $i=2$, 3, and 4 (as identified by their respective quantum Hall plateaus in ρ_{xy}). As θ is increased, the dip positions shift to higher B according to $B_\perp/\cos\theta$, but

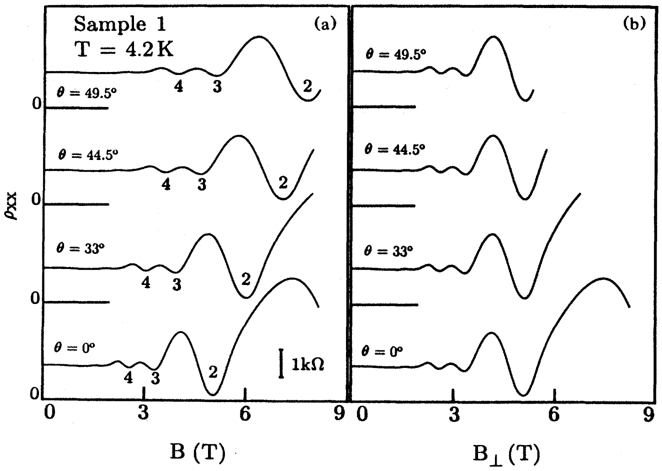

FIG. 3. (a) ρ_{xx} vs total B and (b) ρ_{xx} vs $B_\perp=B\cos\theta$ at four different tilt angles θ. The data are from sample 1 at $T=4.2$ K and θ is the angle between B and the surface normal of the sample.

the absolute magnitude of ρ_{xx} at the minima remains unchanged. This observation is surprising in that, in contrast to the well-known 2DEG case, $\Delta E^{\pm}$ depends only on $B_{\perp}$, not the total B. More specifically, if the splitting is proportional to B, ρ_{xx} at the $i=3$ minimum should decrease exponentially with increasing B, following $\rho_{xx}^{\min} \sim \exp(-g^*\mu_B B/2kT)$. Since the $i=3$ minimum at $B=3.33$ T at $\theta=0°$ is observed at $B=5.13$ T at $\theta=49.5°$, $\rho_{xx}^{\min}$ is expected to decrease by more than a factor of 2, which is not the case in our experiment. In Fig. 3(b), the same data are plotted versus $B_{\perp}$ for a direct comparison. It is clear that not only the positions of the ρ_{xx} minima stay at the same $B_{\perp}$ for all θ's, but the entire SdH spectrum remains identical within our experimental accuracy of 0.4%. Thus, $\Delta E^{\pm}$, as well as the cyclotron splitting of the 2DHG, are determined by $B_{\perp}$, not by the total B.

We have made similar measurements on another sample having $p_{2D}=5.2\times10^{11}/\text{cm}^2$ and $\mu=2.2\times10^4\ \text{cm}^2/\text{V s}$. The data taken at 2.5 K for three different θ's are plotted as a function of the total B in Fig. 4(a) and of $B_{\perp}$ in Fig. 4(b). At $\theta=0°$, when B is perpendicular to the interface, the $i=7$ and 5 minima occur at $B=3.0$ and 4.2 T, respectively. At $\theta=48.5°$, these same minima occur at $B=4.5$ and 6.3 T. If $\Delta E^{\pm}$ is determined by B, not $B_{\perp}$, the ρ_{xx} at these minima should decrease by two and four times that at $\theta=0°$. Again, the SdH spectrum, when plotted versus $B_{\perp}$ [Fig. 4(b)], is identical for all θ and it indicates an extreme g-factor anisotropy.

It is well known that exchange interaction is important in $\Delta E^{\pm}$ in transport and the value of g^* is enhanced from its bare band-structure value.[1,17,18] However, the origin of the observed anisotropy can be understood, quite apart from the exchange enhancement, by considering the energy structure of the VB edge of the strained $\text{In}_{0.20}\text{Ga}_{0.80}\text{As}$ layer. If the uniaxial strain direction is $\boldsymbol{\tau}$, which is along the ⟨001⟩ crystallographic axis normal to the $\text{In}_{0.20}\text{Ga}_{0.80}\text{As}$ layer, the strain Hamiltonian of the VB, given by

$$H_{\epsilon}=(a+\tfrac{5}{4}b)\epsilon-b\sum_{i=1}^{3}J_i^2\epsilon_{ii}-\frac{1}{\sqrt{3}}d\sum_{i,j}[J_i,J_j]\epsilon_{ij}\,,$$

commutes with $j_z=\mathbf{J}\cdot\boldsymbol{\tau}$.[19] Since the strain is large in our samples, the degeneracy of the VB at $k=0$ is split into two pairs of Kramers doublets, having definite spin eigenstates with eigenvalues of j_z: $m_j=\pm\frac{3}{2}$ or $m_j=\pm\frac{1}{2}$. This splitting will be further increased by the quantum-well confinement.[20] For $\mathbf{B}\parallel\boldsymbol{\tau}$ (i.e., $\theta=0°$), the spin Hamiltonian, $H_{\mathbf{B}}=\kappa g_0\mu_B(\mathbf{J}\cdot\mathbf{B})$, of the holes also commutes with j_z.[19] Here, g_0 is the free-electron g factor and κ is a Luttinger VB parameter. As a result, each doublet is further split into two levels, either $m_j=+\frac{3}{2},-\frac{3}{2}$ in one energy band or $m_j=\pm\frac{1}{2},-\frac{1}{2}$ in the other. The Zeeman splitting is the energy difference between two spin-split states of the same Landau level.[21] The effective g factor, defined by $\Delta E^{\pm}=g\mu_b B$, is equal to $3\kappa g_0$ for the $m_j=\pm\frac{3}{2}$ band.[22]

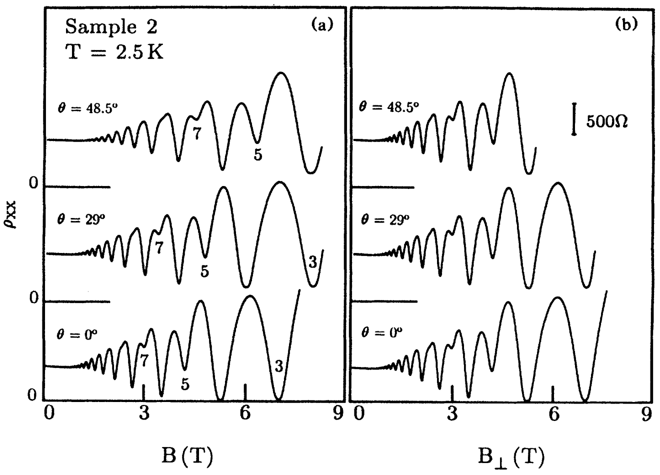

FIG. 4. (a) ρ_{xx} vs total B (b) ρ_{xx} vs $B_{\perp}$ for three different tilt angles. The data are from sample 2 which has a 150-Å spacer, a $p_{2D}=5.2\times10^{11}/\text{cm}^2$, and a $\mu=2.2\times10^4\ \text{cm}^2/\text{V s}$ at $T=2.5$ K.

For $\mathbf{B}$ in the plane of the strain layer, i.e., $\mathbf{B}\perp\boldsymbol{\tau}$ or $\theta=90°$, the problem is more complicated. However, if the magnetic energy associated with the Luttinger Hamiltonian is small compared to the strain energy Δ_{ϵ}, separating the $m_j=\pm\frac{3}{2}$ and $m_j=\pm\frac{1}{2}$ states at $k=0$, it is convenient to continue using the $m_j=\pm\frac{3}{2},\pm\frac{1}{2}$ representation (corresponding to $\mathbf{J}$ along $\boldsymbol{\tau}$), and project the 4×4 Hamiltonian matrix onto two 2×2 submatrices in the space of the $(\phi_{3/2},\phi_{-3/2})$ and $(\phi_{1/2},\phi_{-1/2})$ functions. The form of the matrix for $H_{\mathbf{B}}$ with $\mathbf{B}\parallel\langle010\rangle$ or $\langle100\rangle$ is

$$H_{\mathbf{B}}=\kappa g_0\mu_B B\left|\begin{array}{cccc}\phi_{3/2} & \phi_{-3/2} & \phi_{1/2} & \phi_{-1/2}\\ 0 & 0 & \sqrt{3}/2 & 0\\ 0 & 0 & 0 & \sqrt{3}/2\\ \sqrt{3}/2 & 0 & 0 & 1\\ 0 & \sqrt{3}/2 & 1 & 0\end{array}\right| \text{ or } \kappa g_0\mu_b B\left|\begin{array}{cccc}\phi_{3/2} & \phi_{-3/2} & \phi_{1/2} & \phi_{-1/2}\\ 0 & 0 & i\sqrt{3}/2 & 0\\ 0 & 0 & 0 & -i\sqrt{3}/2\\ -i\sqrt{3}/2 & 0 & 0 & i\\ 0 & i\sqrt{3}/2 & -i & 0\end{array}\right|. \tag{1}$$

In our samples, $\Delta_{\epsilon}\gg\hbar\omega_c$ or $g\mu_B B$. The contribution of the off-diagonal submatrices to the effective Hamiltonian in each subspace can be expanded in terms of $1/\Delta_{\epsilon}$. To first order, the contributions of the off-diagonal submatrix in $H_{\mathbf{B}}$ to the effective Hamiltonian in the $m_j=\pm\frac{3}{2}$ space is of the order $(\kappa\mu_B B)^2/\Delta_{\epsilon}$, which vanishes in the high-strain limit. Consequently, the projection of $H_{\mathbf{B}}$ in the $m_j=\pm\frac{3}{2}$ subspace is zero and $\Delta E^{\pm3/2}=0$. Another possible source of Zeeman splitting for $\mathbf{B}\perp\boldsymbol{\tau}$ is the higher-order q term in the spin Hamiltonian,[9] which is negligible in both GaAs and InAs.[23] Therefore the g factor of the $m_j=\pm\frac{3}{2}$ 2DHG is extremely anisotropic. Exchange enhancement will not change this result.

The above argument follows from the existence of a large uniaxial strain in the quantum-well layer and the preferrential population of the 2DHG in the $m_j = \pm \frac{3}{2}$ band. Consequently, the phenomenon should be observable in other strained-layer 2D hole systems, such as the Si/Si_xGe_{1-x} system.[24] However, this extreme *g*-factor anisotropy is uniquely associated with the 2DHG in the $m_j = \pm \frac{3}{2}$ bands, not in the $m_j = \pm \frac{1}{2}$ bands. Finally, we should note that since the activation energy is a measure of the enhanced splitting, it will be difficult to infer κ directly from our data.

In summary, we have studied the *B* orientation dependence of SdH oscillations of the 2DHG in the (001) $GaAs/In_{0.20}Ga_{0.80}As/GaAs$ strained-layer quantum-well structure. We find that $\Delta E^{\pm}$ of the 2DHG in the strain-split $m_j \pm \frac{3}{2}$ VB depends on *B* perpendicular to the heterojunction interface, not the total *B*. This *g*-factor anisotropy is shown to be a consequence of the large strain splitting of the VB at $k = 0$ due to the biaxial compression in the $In_{0.20}Ga_{0.80}As$ layer. Similar work has recently been reported by Martin *et al.*[25] on the $Ga_{1-x}In_xSb/GaSb$ and by Glaser *et al.*[26] on the $Si/Si_{1-x}Ge_x$ strained-layer structures. These authors have independently come to the same conclusion.

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