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Evidence for spin splitting in $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ heterostructures as $B \rightarrow 0$

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The splitting in zero magnetic field between the up- and down-spin electrons in a two-dimensional electron gas is obtained for a series of three different $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ modulation-doped heterostructures with high electron densities $[n_s \sim (1.5-1.8)\times 10^{12}\ \mathrm{cm}^{-2}]$. We have observed a characteristic beating modulation in the amplitude of the Shubnikov-de Haas oscillations in this system and up to six nodes have been measured in the Shubnikov–de Haas data for magnetic fields in the range $0.15\ \mathrm{T} < B < 1.0\ \mathrm{T}$. Analysis of these data indicates that one subband is primarily occupied and the two beating frequencies arise from a spin splitting of the lowest subband. A spin splitting of 1.5–2.5 meV as $B \rightarrow 0$ is deduced from the data. For magnetic fields applied at an angle θ to the interface, the beat positions scale as $\cos\theta$ for small angles but increase steeply after a critical angle.

The nonzero splitting between spin-up and spin-down electrons in a two-dimensional electron gas (2DEG) even as $B \rightarrow 0$ is a topic of current interest.[1,2] Two competing mechanisms are believed to be important: (i) a bulk k^3 term related to the inversion-asymmetry-induced splitting and (ii) an interface spin-orbit interaction. The effect of the uniaxial perturbation due to the quantum confinement of electrons in heterostructures on the spin splitting has recently been discussed.[1,3] However, experimental studies of the spin splitting as $B \rightarrow 0$ in heterostructures have been very few and the relative size and importance of the various mechanisms is yet to be established.

It seems that a very visible manifestation of the nonzero spin splitting will be two well-defined frequencies in the Shubnikov–de Haas (SdH) oscillations. This in turn will give rise to a series of beats in the amplitude of the SdH oscillations. In fact, it has long been known that "inversion-asymmetry splitting" leads to beating patterns in the SdH effect in bulk samples of some semiconductors.[4–6] The effect of spin splitting on the SdH oscillations has been reported for two-dimensional holes,[7] but not for two-dimensional electrons. The zero-field spin splitting for two-dimensional electrons has so far been investigated in $GaAs/Al_xGa_{1-x}As$ heterostructures only by ESR measurements.[8] An estimate of the zero-field splitting was made by extrapolating the high-magnetic-field data to $B=0$. Correct extrapolation requires knowledge of complicated effects like nonparabolicity; ignoring these effects may lead to erroneous estimations of zero-field spin splitting and g factor.[9] In this paper, we discuss the manifestation of zero-field spin splitting in the SdH effect for a two-dimensional electron gas in $In_xGa_{1-x}As$. Clear beats are observed at magnetic fields low enough that the effect of nonparabolicity is insignificant. The zero-field splitting is thus obtained in a straightforward manner.

A systematic study of the spin-splitting effect was performed in a series of three different $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ modulation-doped heterostructures with high electron densities $[n_s \approx (1.5-1.8)\times 10^{12}\ \mathrm{cm}^{-2}]$. This system is ideal for our study since (a) $In_xGa_{1-x}As$ is a narrow-gap material (relative to GaAs) with a correspondingly larger spin-orbit term, and (b) the high mobility of these materials facilitates SdH measurements at low magnetic fields ($B \gtrsim 0.15$ T). Moreover, strained layers of these materials with higher indium mole fractions have a sufficiently large conduction-band offset to permit high electron densities with the occupation of only one subband, thereby making the beating pattern in the SdH data clearly evident. As a result, we find a crisp and clear signature for a finite spin splitting as $B \rightarrow 0$ in this system. We have observed up to six nodes in the beating pattern in the SdH oscillations for magnetic fields in the range $0.15\ \mathrm{T} < B < 1.0\ \mathrm{T}$; a spin splitting of 1.5–2.5 meV as $B \rightarrow 0$ is deduced from the data.

Two of the samples used were pseudomorphic (sample A, $x=0.65$ and sample B, $x=0.60$) while one was lattice matched (sample C, $x=0.53$). The $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ modulation-doped heterostructures were grown on semi-insulating InP(Fe) substrates. Growth details, transport properties, and subband splittings of these structures are discussed elsewhere.[10] The schematic structural diagram and the energy-band diagram of the samples are shown in Fig. 1. The heterostructures were initially characterized by low-field van der Pauw measurements on samples having a clover-leaf geometry. The carrier densities and mobilities for the samples at 4.2 K are listed in Table I. Shubnikov-de Haas studies of the heterostructures were conducted on Hall bar samples fabricated using standard lithographic techniques. Temperatures down to 0.5 K and magnetic fields up to 8 T were used. The SdH oscillations disappear when the magnetic field is applied parallel to the $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ interface, confirming the two-dimensional nature of the carriers.

Samples *A* and *B* show striking beats in the SdH oscillations. The magnetoresistance of sample *A* at 0.5 K is shown in Fig. 2. Six distinct null points in the beat pattern can be seen in the trace. The last null point occurs at a magnetic field of 0.873 T. High-field measurements up to 8 T do not show any more beats after 0.873 T. In the high-field measurement a very low background frequency of ~0.83 T is observed in the SdH oscillations, indicating that the next higher subband is slightly populated; a carrier density of $\sim 4\times10^{10}$ cm^{-2} was estimated for this subband. The small positive magnetoresistance seen in the trace is attributed to a low-mobility parallel path in the sample caused by incomplete freezeout of the n^+ $In_{0.52}Al_{0.48}As$ layer or the n^+ $In_{0.53}Ga_{0.47}As$ cap layer. Sample *B* has magnetoresistance characteristics very similar to sample *A*.

In contrast to samples *A* and *B*, which were pseudomorphic strained heterostructures, sample *C* is lattice matched and unstrained. The magnetoresistance of sample *C* at 0.5 K is shown in Fig. 3. Two distinct frequencies arising from the population of two subbands are evident in the SdH oscillations. A careful inspection of the data reveals clear evidence of beating in the high-frequency component. The positions of the nulls are shown in the figure. The presence of nulls in the SdH oscillations in sample *C* suggests that strain is not an essential factor in producing the beats. From Table I, sample *C* has a smaller mobility than either samples *A* or *B*, presumably due to increased intersubband scattering[11] and higher alloy scattering. In comparison to samples *A* and *B*, sample *C* has considerably higher population in the second subband. This is due to the smaller conduction-band discontinuity in sample *C* which leads to a smaller separation between the subbands.[10]

n	In-Ga-As	$N_D=3\times10^{18}$	200 Å
i	In-Al-As		300 Å
n	In-Al-As	$N_D=3\times10^{18}$	200 Å
i	In-Al-As		100 Å
i	In(x)Ga(1-x)As		150 Å
i	In-Ga-As		400 Å
i	In-Al-As		4000 Å
i	In-Al-As/In-Ga-As		SL
	SI InP(100)		

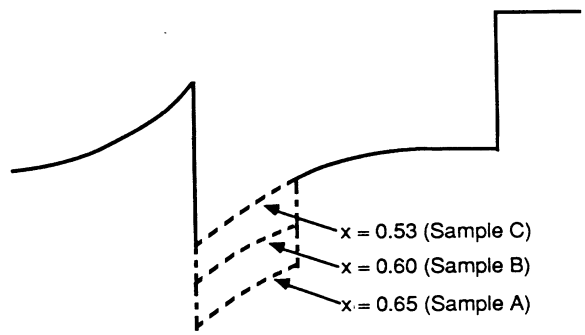

FIG. 1. Schematic and band diagrams of the $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ heterostructures investigated. The dashed line shows the position of the 2DEG.

The observation of this pronounced beating effect in the $In_xGa_{1-x}As/In_{0.52}Al_{0.48}As$ system should be contrasted to other low-field SdH measurements reported earlier in a lattice-matched $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ sample.[12] These previous measurements do not show evidence for a nonzero spin splitting. One important difference is the much higher carrier density in our samples [in Ref. 12, $n_s \approx (6\text{–}8)\times10^{11}$ cm^{-2}]. As discussed above, a higher carrier density is expected to produce a larger and, hence, more observable splitting, especially if the k^3 term dominates the splitting.

Various explanations for the beating effects in the ex-

TABLE I. Transport data at 4.2 K obtained from Hall and SdH measurements and the spin splitting as $B\to 0$ for the three heterostructures. Effective mass m^*/m_0 obtained from temperature dependence of the SdH oscillations for all three structures is 0.046 ± 0.002.

Sample (x)	Hall data μ_H ($cm^2/V s$)	n_H (10^{12} cm^{-2})	N_0[a] (10^{12} cm^{-2})	N_1[b]	Spin splitting (δ_0) as $B\to 0$ (meV)
A (0.65)	134000	1.75	1.65	~0.04	2.37
B (0.60)	95000	1.65	1.53	~0.04	2.50
C (0.53)	67900	1.46	1.12	~0.26	1.50

[a]Carrier density in the lowest subband.
[b]Carrier density in the next higher subband.

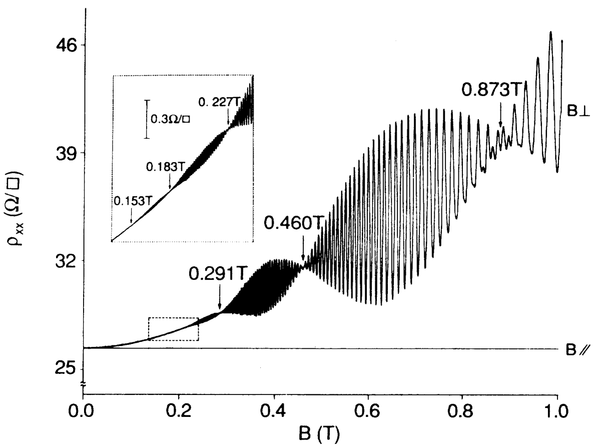

FIG. 2. The resistance for sample A as a function of magnetic field at $T=0.5$ K. Node positions in the SdH oscillations are marked by arrows. The magnetoresistance for $B<0.25$ T is shown by the dotted inset.

perimental data have been considered. It is well known that beating effects can be produced by gross inhomogeneities of the electron concentration in the sample.[13] This possibility, however, proved untenable after studies of different samples cut from different regions of the wafers yielded identical data. The structures investigated have a high density of localized states (higher than GaAs/$Al_xGa_{1-x}As$ and $In_xGa_{1-x}As$/InP systems) due to interface roughness, alloy disorder, strain, etc.;[14] however, our analysis shows that this cannot explain the beats in the range of magnetic fields involved.

Since the beating effect implies the existence of two closely spaced frequency components with similar amplitudes, it is important to identify the origin of the two frequency components. There are two possibilities: (1) either two subbands are occupied, each having electron concentrations given by n_1 and n_2, or (2) one subband is spin split and has carrier concentrations $n_1^{\downarrow}$ and $n_1^{\uparrow}$ in the two levels. In either case, the Hall voltage will measure the total electron concentration which we call n_H. If we assume that two subbands are occupied, the average of the electron concentration in each level can be calculated from the measured average frequency of the SdH oscillations $F_{\rm av}$:

$$n_{\rm SdH}=2\frac{e}{h}F_{\rm av}\,. \tag{1}$$

However, if there is one spin-split subband, the spin-degeneracy factor of 2 must not be included in the derivation of Eq. (1), and the average of the electron concentration in each level will be given by

$$n_{\rm SdH}=\frac{e}{h}F_{\rm av}\,. \tag{2}$$

Since the total carrier density in the sample obtained from SdH analysis should agree with the Hall voltage value n_H and since there are two levels, we should have $n_H \approx 2n_{\rm SdH}$. From our experimental data, this is true only if $n_{\rm SdH}$ is calculated from Eq. (2). From this analysis, we infer that the two frequency components originate from one spin split subband.

In order to extract estimates for the spin splitting from this data, a convenient model is required. It is well known that a spin-split Landau level gives rise to two closely spaced frequencies with similar amplitudes leading to a modulation of the SdH amplitude given by

$$A\sim\cos\pi\nu\,, \tag{3}$$

where

$$\nu=\frac{\delta}{\hbar\omega_c}\,, \tag{4}$$

and δ is the energy separation between the spin-split Landau levels. Nodes in the beat pattern in the SdH oscillations will occur at half-integer values of $\nu(\pm 0.5, \pm 1.5$, etc.) where A is zero. The total spin splitting δ can be expressed in the form

$$\delta=\delta_0+\delta_1\hbar\omega_c+\delta_2(\hbar\omega_c)^2+\cdots\,, \tag{5}$$

where δ_0 is the zero-field spin splitting, $\delta_1\hbar\omega_c$ is the linear splitting and the second- and higher-order terms become important at high magnetic fields. For low magnetic fields, only the first two terms of Eq. (5) are required. In our analysis, we have assumed this to be the case. If $\delta_0=0$ then $A\sim\cos\pi\delta_1$ which is simply a multiplicative constant independent of B and no beating effects are expected. However, if $\delta_0\neq 0$, then ν decreases as the magnetic field is increased so that the factor A oscillates. The last node occurs when $|\nu|=0.5$. Equation (4) then gives the total spin splitting at each magnetic field where a null is observed.

Data from the beat positions is shown in Fig. 4 where we have plotted the total spin splitting as a function of $\hbar\omega_c$ for the three samples. In each case we have assumed that the last (highest-field) null corresponds to $\nu=0.5$, and that successively lower nulls occur at $\nu=1.5$ 2.5, etc. The intercept with the $\hbar\omega_c=0$ axis of a straight line fitted to the lowest few field points gives us δ_0; the zero-field spin splittings obtained in this way for samples A, B, and C are

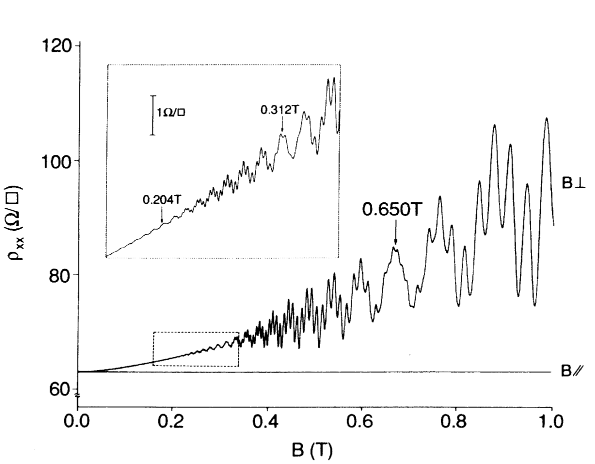

FIG. 3. The resistance of sample C as a function of magnetic field at $T=0.5$ K. Node positions in the SdH oscillations are marked by arrows. The magnetoresistance for $B<0.35$ T is shown by the dotted inset.

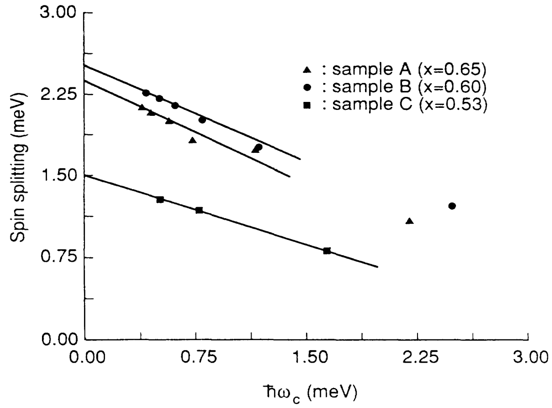

FIG. 4. Total spin splitting for samples A, B, and C (calculated from the positions of the SdH nulls) as a function of $\hbar\omega_c$. Line segments show the intercepts used to estimate δ_0: ▲, sample A; ●, sample B; ■, sample C.

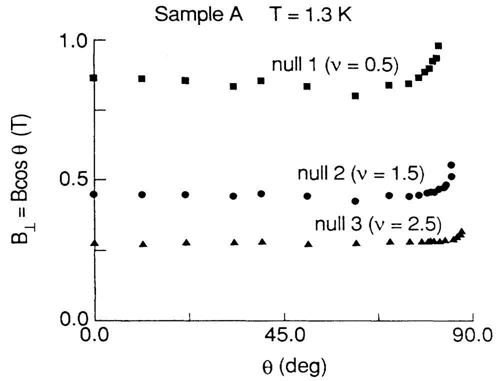

FIG. 5. Perpendicular magnetic fields $B_\perp$ at which the last three nulls in the beat occur as a function of θ, the angle of tilt of the sample with respect to the applied magnetic field.

2.37, 2.5, and 1.5 meV, respectively.

As shown by Lommer *et al.*,[9] nonparabolicity cannot be ignored if an attempt is made to extrapolate δ_0 and g^* from high-field measurements of spin splitting.[8] All our experimental data is at low magnetic fields ($\lesssim 1$ T), and δ_0 was estimated from the lowest field data points ($\lesssim 0.3$ T). At these low magnetic fields we expect the nonlinearity to be insignificant. This is certainly true in GaAs.[9] The nonlinearity could be more pronounced in $In_xGa_{1-x}As$, but we do not expect this to significantly change the values for δ_0 quoted above.

The clarity of the beating pattern allows us to make measurements by varying the angle of the sample with respect to the applied magnetic field, allowing the spin splitting to be adjusted by the total field while the SdH oscillations are only affected by the component of B perpendicular to the 2DEG. Since the beats are influenced by the total spin splitting of a Landau level, we expect to see the location of the nulls move to higher magnetic fields whenever $g^*\mu_B B_{tot}$ becomes comparable to δ_0. Experimentally, the locations of the last three nulls were measured as a function of magnetic field as sample A was tilted. The angle of tilt was determined in the usual way by accurately measuring the SdH frequency and comparing to the known frequency for zero tilt. The results of this experiment are plotted in Fig. 5. The uncertainty in determining the magnetic field at which the zero occurred is $< \pm 0.02$ T. It is evident from the data that the perpendicular component of B required to produce a beat null is constant up to a certain angle and then increases sharply as we might expect. A detailed analysis of this data may allow us to discriminate between the different microscopic theories for the origin of spin splitting.

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