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Observation of the zero-field spin splitting of the ground electron subband in GaSb-InAs-GaSb quantum wells

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A group of GaSb-InAs-GaSb quantum wells with 75-Å well thickness are studied via magnetotransport. A beating pattern in the Shubnikov–de Haas oscillation is observed. Analysis of the data yields two carrier densities $n_1 = 5.1\times10^{11}$ cm^{-2} and $n_2 = 4.7\times10^{11}$ cm^{-2}. Both are identified as electrons and are attributed to the population of the ground electron subband whose twofold spin degeneracy is lifted due to the lack of inversion symmetry of the system. A zero-field spin splitting of 3.5 meV is deduced from the electron densities. The evolution of the beating pattern with a tilted magnetic field is also discussed.

In artificial modulated semiconductor structures such as quantum wells or heterostructures, two-dimensional (2D) electron (or hole) gases exist at the interface since the carriers are confined in one dimension and are free to move in the other two dimensions.[1] When the confining potential well is asymmetric, there is an electrical field perpendicular to the layer, which is equivalent to a magnetic field in the rest frame of an electron moving along the layer. This equivalent magnetic field lifts the twofold spin degeneracy of the electron energy band, leading to a finite spin splitting in the absence of external magnetic field. Experimental evidence of this zero-field spin splitting has been reported on n-type GaAs heterostructures and on p-type GaAs inversion layers.[2,3] In this Rapid Communication, we report an investigation of the Shubnikov–de Haas (SdH) oscillations of GaSb-InAs-GaSb quantum wells in both normal and tilted magnetic field. The results demonstrate that the ground electron subband spin degeneracy is lifted via the spin-orbit coupling in the presence of the interface electric field or that related to the bulk asymmetry.

The samples have standard Hall geometry and consist of 75 Å of InAs sandwiched between two GaSb layers. The InAs/GaSb system is especially interesting because of the unusual band-edge alignment at the interface, the so-called type-II heterojunction. The GaSb valence band is 150 meV above the bottom of InAs conduction band, which facilitates electron transfer from GaSb into InAs. In an ideal GaSb-InAs-GaSb quantum well, the number of electrons in the InAs layer is equal to the sum of the holes in the two GaSb barriers and the potential for the electrons is symmetric with respect to the well center. However, a large excess concentration of electrons in the InAs layer with respect to holes were usually observed in the quantum wells,[4] indicating that the transfer from the GaSb valence band is not the only source of electrons. Such an imbalance in carrier densities suggests the existence of positively charged centers in the vicinity of the interfaces with energy in the GaSb gap region.

The samples used in this experiment are those where nearly all electrons are balanced by the interfaces charges. Since the electron subband energy is above the valence band of GaSb for the well width $d_z = 75$ Å, there should be no free holes on the GaSb side of the interface. Experimental evidence has also shown that most of the interface charges are distributed at one of InAs/GaSb interface as the result of the epitaxial growth process.[5] The interface electric field would be of the order 10^5 V/cm for a typical sample with an electron density 10^{12}/cm^2 if all the positive charges are distributed at one interface. The energy band diagram is shown in Fig. 1.

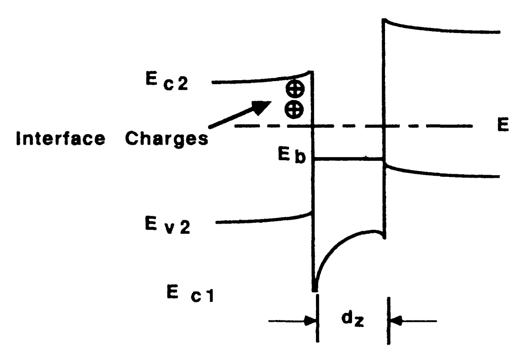

FIG. 1. The energy band diagram of the GaSb-InAs-GaSb quantum wells studied. The well is asymmetric due to the uneven distribution of the charged centers among the two InAs/GaSb interfaces. The surface electric field is perpendicular to the layer.

The SdH and Hall measurements were performed typically at 1.2 K. The resistivity ρ_{xx} and ρ_{xy} were recorded as a function of the magnetic field (B) perpendicular to the 2D layer. Several samples with similar carrier concentrations were examined and the beating pattern observed in the data were reproducible. Figure 2(a) shows the typical results for ρ_{xx} and ρ_{xy} obtained with a sample c which has an electron density $n_s \sim 10^{12}/\mathrm{cm}^2$ and a low-field mobility of $\sim$20 000 $\mathrm{cm}^2/\mathrm{V\,s}$ at 1.2 K. The most important features of the SdH data are the beats between 0.5 and 2.0 T, which are shown in Fig. 2(b).

It is well known that the SdH oscillations for an ideal 2D system are periodic in the inverse field, whose period, with spin degeneracy 2, is given by $\Delta(1/B) = (e/\hbar\pi)n_s^{-1}$, where n_s is the carrier concentration. The beat in SdH data, arising from the participation of two sets of oscillations with slightly different frequencies, directly reflects the presence of two carriers in the system. As the number of rapid oscillations between adjacent amplitude minima (the nodes) is about 10, the densities of the two carriers differ by about 10% from the average. A fast Fourier transform (FFT) was performed on the SdH data. The resulting spectrum displays two distinct peaks at the frequencies corresponding to the two carrier densities: $n_1 = 5.1\times10^{11}$ cm^{-2} and $n_2 = 4.7\times10^{11}$ cm^{-2}.

In order to identify whether the two carriers are electrons or holes, the low-field magnetoresistance and Hall resistance were carefully analyzed. From 0 to 0.5 T, ρ_{xx} shows a positive magnetoresistance of about 20% and the ρ_{xy} is essentially linear with B, and the slope yields a carrier concentration of $(1.0\pm0.2)\times10^{12}$ cm^{-2}, identical to the total carrier concentration (n_1+n_2) obtained from the ρ_{xx} oscillations. This indicates that we have a two-carrier system with same charge polarity—electrons from two subbands. Moreover, even if holes exist in these samples, it is unlikely that they participate in the SdH oscillations at B fields as low as 0.5 T and with the amplitude as significant as that of the electrons, since their mobility is usually an order of magnitude lower than that of electrons in such quantum-well systems.[4]

When the temperature was increased from 1.2 to about 7.0 K, the highest temperature at which the beat can be resolved, the overall oscillation amplitude decreased proportionally and there was no distortion of the beat pattern. The oscillation amplitude at the beat node, which equals the difference between the amplitudes of the two sets of oscillations, vanishes at all temperatures. This suggests that the two sets of oscillations respond to the temperature change in the same fashion or that the effective masses of the two carriers are nearly the same at the Fermi level. It also implies that the carrier relaxation times are similar for both subbands. The mass is determined to be $m^* = (0.055\pm0.003)m_0$ from the temperature dependence of the oscillation amplitude. Here m_0 is the free-electron mass.

The observed SdH patterns reveal the existence of two sets of electrons with the same mass and concentrations ratio $n_1/n_2 \sim 1.1$. A simple model to account for the data is to assume that the electrons are associated with the occupation of two 2D subbands. Since the relative carrier concentrations obtained are independent of magnetic field, the energy splitting Δ can be treated as a constant in the field window where the beats are observed. In this case, Δ is related to the carrier densities by the following equation: $\Delta = (n_1 - n_2)/D(E) \sim 1.7$ meV, where $D(E) = m^*/\pi\hbar^2$ is the density of states including spin degeneracy. According to Bastard, Mendez, Chang, and Esaki,[6] the energy separation between the ground electron subband and the first excited subband for a 75 Å well is of the order 100 meV, which is more than an order of magnitude larger than the 1.7 meV obtained. Thus, it is unlikely that the observed beating behavior is due to the occupation of two 2D subbands. Rather, it strongly suggests that the two carriers result from the removal of the ground electron subband spin degeneracy in the absence of magnetic field. A possible reason for the removal of spin degeneracy is due to spin-orbit interaction at the interface.

A spin-orbit Hamiltonian, $H_{\mathrm{s.o.}}$, was proposed by Rashba and Bychov[7,8] to represent such spin orbit interaction in the presence of interface confinement:

$$H_{\mathrm{s.o.}} = \alpha(\sigma\times\mathbf{k})\cdot\mathbf{z}\,.$$

In this equation $\mathbf{k}$ is the wave vector, σ are the Pauli matrices, and $\mathbf{z}$ is the unit vector in the direction normal to the layer. The spin-orbital coupling constant α depends implicitly on the strength of the surface electric field. Calculation shows that the $H_{\mathrm{s.o.}}$ leads to a significant spin splitting at finite k. In small B field ($B < 2.0$ T), the total

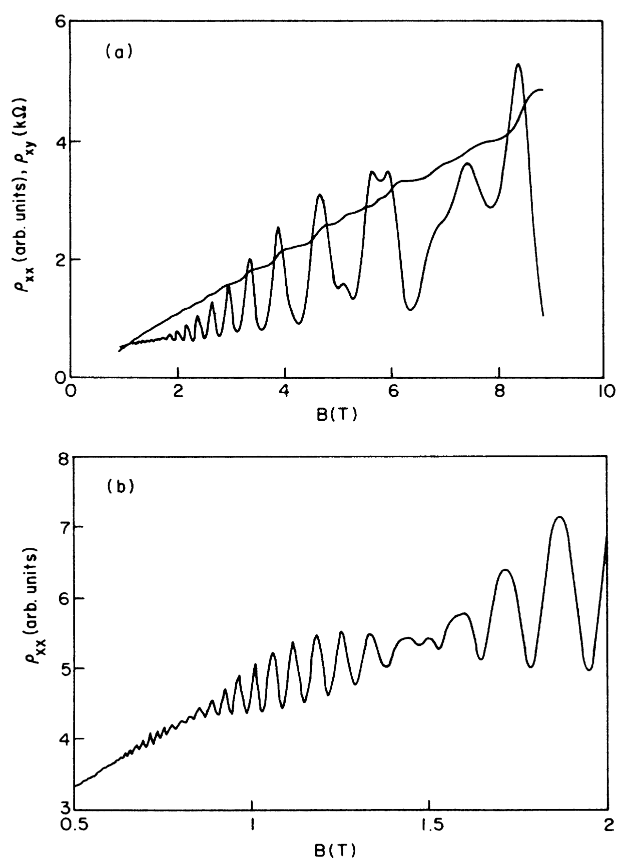

FIG. 2. (a) The transverse magnetoresistance ρ_{xx} and Hall resistance ρ_{xy} as a function of magnetic field B (T) at 1.2 K. (b) The beating pattern in ρ_{xx} between 0.5 and 2.0 T.

spin splitting is dominated by the spin orbital interaction and is relatively independent of the magnetic field. It follows that at zero external field, the spin splitting is about 3.5 meV, about twice the 1.7 meV estimated above because we have only half the value of $D(E)$ in this case.

Despite its simplicity, this model captures the essential features of the system in terms of demonstrating the existence of a finite zero-field spin splitting. Explicitly, we made two assumptions: negligible external field induced Zeeman splitting and a parabolic InAs conduction band. Judging from the measured effective mass of $0.055m_0$, which is substantially greater than the bulk conduction band edge mass $0.023m_0$, a correction to the nonparabolicity effect is necessary. Also, according to Rashba's calculation, the spin splitting exhibits nonlinear field dependence when the spin orbit term $H_{\rm s.o.}$ is included. A more elaborate model that accounts for both effects will be discussed elsewhere.

We have also examined the effect in the tilted magnetic field in order to incorporate the Zeeman term with the spin orbit term in the splitting. This technique, first applied by Fang and Stiles to measure the g factor in Si inversion layers,[9] has been widely utilized for studying the spin related effects in 2D systems. The magnetoresistance was recorded as a function of the tilting angle θ as the sample is rotated in a constant magnetic field B_T. The data were then plotted vs the inverse perpendicular magnetic field component $(1/B_\perp)$, where $B_\perp = B_T \cos\theta$. By increasing the total field B_T, one effectively increases the field induced spin Zeeman splitting and causes electrons to redistribute between the two spin levels. Figure 3 shows the data obtained at $B_T = 2.0$, 5.0, 11.3 T. For clarity, the oscillations are shifted to be around zero. The apparent change in the line shape reflects a change of the relative electron population of the two levels and demonstrates conclusively that the beat is caused by spin, not by other effects such as inhomogeneity or population of higher 2D subbands. Many detailed features of the tilted field data will de discussed in another publication. Here we summarize observations. (1) The onset of oscillations occurs at higher $B_\perp$ for larger B_T. This means the relaxation time decreases with the parallel field component. (2) As B_T increases, the amplitude of the oscillations at the "beat" minimum increases and also the number of oscillations between minima decreases. These results are due, respectively, to the increasing ratio of the relaxation times for the two split bands and increasing field-induced spin splitting $g\mu_B B_T$ with B_T. Here μ_B is the Bohr magneton. (3) The beating pattern finally disappears at $B_T \sim 8.0$ T, and above this field, the SdH oscillations in $B_\perp$ shows two distinct frequencies—the first near the onset of the oscillations and the second at higher quantizing fields $(B_\perp)$. We tentatively attribute it to be due to the resolution of the high-mobility spin band at low $B_\perp$ and both subbands at higher $B_\perp$.

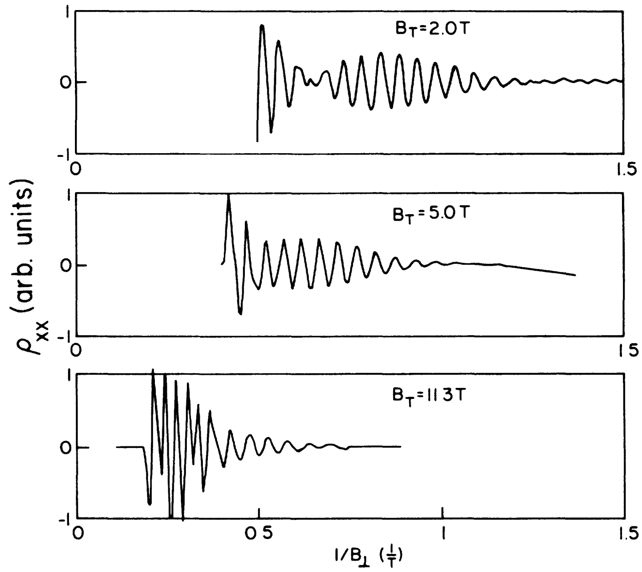

FIG. 3. Results in a tilted magnetic field: ρ_{xx} vs $1/B_\perp$ at three different total magnetic fields B_T. The apparent change in the line shape reveals the change in the relative electron population of the two spin bands as the result of the increased spin splitting in the field $B_T = 2.0$ to 11.3 T.

The origin of the observed spin splitting in these samples is attributed to the spin-orbit interaction in the presence of the interface electric field arising from the asymmetry of the well. It is also important to note that the lack of inversion symmetry in bulk InAs, which has a zinc-blende structure, also contributes to the removal of the spin degeneracy of bands for finite k. This bulk term, normally represented by a k^3 term Hamiltonian,[10] takes the similar form as $H_{\rm s.o.}$ in the special case of a quantum well due to the confinement of electron momentum in one dimension. Instead of the surface field strength, the spin-orbit constant α in $H_{\rm s.o.}$ for the bulk effect depends on the well width and is larger for narrower wells. The present experiment which probes only the total splitting, cannot distinguish the contributions from each of the two sources. However, the bulk splitting may be negligibly small based on the experimental observations on InSb,[11] which is similar in many ways with InAs. The experimental observations on InAs bulk asymmetry are not available.

In conclusion, SdH measurements of electrons in a GaSb-InAs-GaSb quantum well reveals that the spin degeneracy of ground electron subband is lifted in the absence of external magnetic field. The zero-field spin splitting (3.5 meV) is extrapolated from the splitting obtained in the field range 0.5–2 T, assuming that the field-induced Zeeman splitting is negligible. Future experiments on wells with different InAs thicknesses are needed to distinguish further the bulk and surface field effects.

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