Interplay of Rashba, Zeeman and Landau splitting in a magnetic two dimensional electron gas

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The transport properties of a magnetic two dimensional electron gas consisting of a modulation doped n type Hg_{0.98}Mn_{0.02}Te/Hg_{0.3}Cd_{0.7}Te quantum well, QW, have been investigated. By analyzing the Shubnikov-de Haas oscillations and the node positions of their beating patterns, we have been able to separate the gate voltage dependent Rashba spin-orbit splitting from the temperature dependent giant Zeeman splitting. It has been experimentally demonstrated that the Rashba spin-orbit splitting is larger than or comparable to the \( sp-d \) exchange interaction induced giant Zeeman splitting in this magnetic 2DEG even at moderately high magnetic fields.

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The study of a two dimensional electron gas, 2DEG, in a system with additional interactions has lead to interesting new physics. One example is the Rashba spin-orbit, s-o, interaction which has been the subject of numerous investigations of III-V heterostructures. More recently, Rowe et al. showed that magneto-intersubband scattering, MIS, may cause similar beating patterns in the magneto-resistance of InAs. Zhang et al. have demonstrated that MIS is not present in narrow gap II-VI materials, i.e. HgTe based quantum wells, due to the strong non-parabolicity of the conduction band. The Rashba s-o coupling is strong in such HgTe QWs, which exhibit an inverted band structure when the well width is greater than approximately 6 nm. The exceptionally large zero field Rashba splitting of up to 17 meV observed in this material is due to the heavy hole character of the first conduction band, which is usually labelled as \( H1 \) (see Ref. 6 for details).

Another example of novel 2DEG physics is the recently introduced magnetic heterostructures in which magnetic ions (usually Mn ions) are exchange coupled to the 2DEG. These structures have previously been employed to investigate spin interactions, spin dependent transport and localization, quantum phase transitions, as well as to measure the magnetization of a magnetic 2DEG.

So far, magneto-transport studies of a magnetic two-dimensional electron gas in narrow-gap heterostructures have not been reported. Such structures offer the intriguing possibility to probe the interplay of Rashba, Zeeman and Landau effects, which all may lead to level splittings of comparable magnitude: the 2D electrons are coupled to the local moments of magnetic ions via a ferromagnetic \( sp-d \) exchange interaction, resulting in spin splitting energies, \( \Delta E_S \), of tens of meV, which are comparable to or larger than the Landau level splitting, \( \hbar/\omega_c \), and finally, as discussed above, the Rashba s-o interaction is of a similar magnitude in type III heterostructures.

In this letter, we report on an investigation of the gate voltage and temperature dependent Shubnikov-de Haas, SdH, oscillations in \( n \) type Hg_{0.98}Mn_{0.02}Te/Hg_{0.3}Cd_{0.7}Te QWs. The observed beating patterns in SdH oscillations show the effects of a combination of Rashba s-o interaction and \( sp-d \) exchange interaction. The resulting total spin splitting energy is consistent with the calculated Rashba s-o splitting energy and a temperature dependent Zeeman component. The Rashba splitting energy can be varied by a factor of 3.5 in the low carrier concentration range by means of the gate voltage. The population difference between the two subbands has been determined from a fast Fourier transformation, FFT, of the SdH oscillations. Results for the QW discussed in detail here, Q1697, and similar QWs are comparable. Q1697 was modulation doped symmetrically on both sides of the Hg_{0.98}Mn_{0.02}Te quantum well using CdI_{2} as a doping material. The Hg_{0.98}Mn_{0.02}Te well width is 12.2 nm and the Hg_{0.3}Cd_{0.7}Te barriers are composed of a 5.5 nm thick spacer and a 9 nm thick doped layer. Standard Hall bars were fabricated by wet chemical etching. A 200 nm thick Al_{2}O_{3} film was deposited on top of the structure, which serves as an insulating layer. Finally Al was evaporated to form a metallic gate electrode. Ohmic indium contacts were fabricated by thermal bonding.

Magneto-transport measurements were carried out in a \(^3\)He cryostat using dc techniques with currents of 1 \( \mu \)A in magnetic fields ranging up to 7 T and temperatures down to 0.38 K. The carrier concentration, \( n_{H1} \), and the mobility of the first conduction band were determined to be \( 2.4 \times 10^{12} \text{ cm}^{-2} \) and \( 5.2 \times 10^{4} \text{ cm}^{2}/(\text{Vs}) \) at 4.2 K for zero gate voltage.

Figs. 1 and 2 show the temperature dependence and gate voltage dependence of SdH oscillations for Q1697. Beating patterns are observed in the SdH oscillations because of the existence of two closely spaced frequency components with similar amplitudes due to level split-
It is well known that a splitting of the Landau levels leads to a modulation of the SdH amplitude according to

\[ A \propto \cos(\pi \nu) \]  

where \( \nu \) is given by

\[ \nu = \frac{\delta}{\hbar \omega_c} \]  

\( \hbar \omega_c \) is the Landau level separation energy and \( \delta \) is the energy splitting of each Landau levels. Nodes in the beating pattern in the SdH oscillations will occur at half-integer values of \( \nu \); \( \pm 0.5, \pm 1.5, \) etc.; where \( A \) is zero. Three nodes are observed at higher charge carrier concentrations, whereas their number decreases at lower concentrations. Experimentally, we find that the first node corresponds to \( \nu = 1.5 \), and the successively lower nodes occur at \( \nu = 2.5 \) and 3.5.

The large temperature shift of the nodes observed in Q1697 and shown in Fig. 1 is caused by the strong sp – d exchange interaction between the conduction electrons and the Mn ion spins, as discussed by Gui et al.\(^8,16\) for bulk Hg\(_{1-x}\)Mn\(_x\)Te. The temperature dependence stems from the reduction in magnetization of the Mn ions with increasing temperature. Phenomenologically, the effective \( g^* \) factor in dilute magnetic semiconductors can be expressed as

\[ g^* = g_0 - \frac{(\Delta E)_{\text{max}}}{\mu_B B} B_{5/2} \left[ \frac{5g_{\text{Mn}} \mu_B B}{2k_B(T + T_0)} \right] \]  

where \( g_{\text{Mn}} = -2 \) is the \( g \) factor for Mn, \( B_{5/2}(x) \) is the Brillouin function for a spin of \( S = 5/2 \), which has been empirically modified by using a rescaled temperature, \( T + T_0 \), in order to account for antiferromagnetic spin-spin interaction, and \( (\Delta E)_{\text{max}} \) is the saturated spin splitting energy caused by the sp – d exchange interaction. \( g_0 \) is the \( g \) factor for a HgTe QW without the presence of Mn,\(^8\) i.e., \( g_0 = -20 \).

An experimental estimate for \( (\Delta E)_{\text{max}} \) can be obtained from the results displayed in Fig. 1, where the differences in experimental level splitting energies, \( \delta \), between 0.38 K and temperature \( T \) are plotted versus the Landau level splitting energy, \( \hbar \omega_c = \hbar(e/m^*)B \). The electron effective mass employed here has been determined by means of self-consistent Hartree calculations.\(^8\) The Hartree calculations are based on a 8 \( \times \) 8 \( \mathbf{k} \cdot \mathbf{p} \) band structure model\(^8\) including all second order terms. The energy gap of Hg\(_{0.98}\)Mn\(_{0.02}\)Te has been taken into consideration; however, \( sp – d \) interaction of the Mn spins has been neglected. The inherent bulk inversion asymmetry of Hg\(_{0.98}\)Mn\(_{0.02}\)Te and Hg\(_{0.3}\)Cd\(_{0.7}\)Te has also been neglected, since this effect has been shown to be very small in Hg\(_{1-x}\)Cd\(_x\)Te.\(^8\) We find \( m^* = 0.047 \) to 0.051 \( m_0 \) for the carrier concentrations observed in the experiments, i.e., \( n_{H_1} = 2.2 \times 10^{12} \) cm\(^{-2} \) for \( V_g \) between \(-3.75 \) and \(+4.75 \) V. The curves in Fig. 1 are results of least square fits of Eq. 3 at the corresponding temperatures. The agreement is reasonable and results in \( (\Delta E)_{\text{max}} = 4.3 \pm 0.5 \) meV and \( T_0 = 2.6 \pm 0.5 \) K. In principle, these parameters depend only on the Mn composition.

However, the giant Zeeman effect can not explain why the observed nodes also shift with gate voltage, i.e.,
FIG. 3: Experimental values of the difference in level splitting energies, $\delta$, between 0.38 K and the temperature $T$ versus the Landau level splitting energy for the symmetrically modulation doped Q1697 with $V_g = 1.0$ V. The curves are the results of a least square fit of values of $g'\mu_B B$ by means of Eq. 3.

The asymmetry of the QW structure, as can be seen in Fig. 5, is nearly linear with magnetic field. This behavior is typical for level splitting due to the Rashba $s$-$o$ component, as was discussed for non-magnetic HgTe quantum wells by Zhang et al. A fast Fourier transformation, FFT, of the SdH oscillations as a function of $1/B$ has been used to determine the carrier concentration of the spin split H1 subbands. A double peak structure is clearly resolved in the FFT spectra (not shown here) of the SdH oscillations for different temperatures and gate voltages shown in Figs. 1 and 2 for Q1697. The node at the highest field shifts from 2.25 T ($V_g = -3.75$ V) to 3.72 T ($V_g = 4.75$ V) while the carrier concentration for the first conduction subband, $H_1$, changes only from 2.24 to 2.65 x $10^{12}$ cm$^{-2}$ and the total carrier concentration from 2.73 to 3.56 x $10^{12}$ cm$^{-2}$.

Fig. 4 shows the relative experimental and theoretical population differences, $\Delta n_{H1}/n_{H1}$, together with the results of self-consistent Hartree calculations versus the total carrier concentration for the first conduction subband, $H_1$. As demonstrated below, their magnitude of up to 13 meV is greater than that of Zeeman and Landau level splitting for high Landau numbers can be expressed to a first approximation as a function of the magnetic field according to:

$$\delta \approx \left[ (\hbar \omega_c - g'\mu_B B)^2 + \Delta_R^2 \right]^{1/2} - \hbar \omega_c \quad (4)$$

where $\Delta_R$ is the Rashba spin-orbit splitting energy. In spite of their strong nonparabolic band structure, experimental and theoretical values of $\hbar \omega_c$ for HgTe QWs are nearly linear with magnetic field. Using the theoretical value of $\Delta_R$ and the values of the effective $g$ factor according to Eq. 3, the total spin splitting energy, $\delta$, has
have experimentally demonstrated that the Rashba effect in the magnetic 2DEG can be effectively controlled by means of the structure inversion asymmetry via the gate voltage. These results may be useful in realizing and designing future spintronic devices.

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For some gate voltages, additional population of the second (E2) conduction band is observed. This does not, however, influence the analysis of the H1 level splitting discussed here.

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