Spin-polarized quantum transport and magnetic field-dependent carrier density in magnetic two-dimensional electron gases

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Abstract

Low-temperature magneto-transport and magneto-photoluminescence measurements are reported in magnetic two-dimensional electron gas samples formed by modulation doping shallow (Zn,Cd,Mn)Se single quantum wells. The small Fermi energy (~1–2 meV) and large exchange-induced spin splitting (~10 meV) results in a completely spin-polarized electron gas at filling factors as high as v = 12. Further, the spin splitting significantly perturbs the confinement potential, resulting in a magnetic field-dependent carrier density. © 2000 Published by Elsevier Science B.V. All rights reserved.

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Magnetic semiconductor quantum structures, in which confined carriers interact via exchange with magnetic ions (such as Mn2+), exhibit a rich variety of phenomena such as spin-dependent quantum confinement, enhanced magneto-optical effects and carrier-induced ferromagnetism [1,2]. In “magnetic” two-dimensional electron gases (M2DEGs) derived by modulation doping magnetic semiconductor quantum wells [3–7], the s–d exchange interaction greatly amplifies the spin splitting (ΔEs) which easily exceeds the cyclotron energy (ℏωc)k. Depending on the relative values of ΔEs, (ℏωc)k and the Fermi energy (EF), a M2DEG can be highly spin polarized, with consecutive Landau levels (LLs) separated by a cyclotron gap rather than a spin gap. Such M2DEGs effectively act as “spinless” fermion gases in which to study phenomena such as insulator–quantum Hall liquid transitions and plateau-to-plateau transitions [6,7].

Although initial samples based on ZnSe/(Zn,Cd,Mn)Se single quantum wells (SQWs) have provided insights into spin-dependent transport and localization in M2DEGs, their low mobility (~3000 cm²/V s) obscures detailed explorations of any new underlying physics. In contrast to these quartenary quantum well samples, M2DEGs derived from the dilute ternary (Cd,Mn)Te have significantly higher mobilities (up to 40 000 cm²/V s) (Ref. [7]).
ing both the sample growth and design. The increased mobility is produced in part by employing a smaller Cd concentration in the (Zn,Cd,Mn)Se SQW, hence reducing both alloy disorder and strain. Quantum transport in these M2DEGs may be studied at carrier densities as low as $6.5 \times 10^{11} \text{cm}^{-2}$ where $E_F < \Delta E_S$, resulting in complete spin polarization at filling factors as high as $v = 12$. In addition, the shallow depth of the SQW ($\sim 50 \text{meV}$) has the unusual consequence that the spin splitting ($\sim 10 \text{meV}$) itself creates a sizeable perturbation on the confinement potential, resulting in a magnetic field-dependent carrier density.

We focus on two modulation-doped SQWs of (Zn,Cd,Mn)Se, fabricated by molecular beam epitaxy on (100) GaAs substrates after the growth of a $\sim 1.5 \mu\text{m}$ ZnSe buffer layer. The n-type dopant (Cl) is introduced in two 20 nm thick regions of the ZnSe barrier, located symmetrically on each side of the SQW with a 12 nm undoped spacer of ZnSe. The samples are capped by an 80 nm undoped ZnSe layer followed by a thin ($\sim 10 \text{nm}$) region of highly doped n-ZnSe ($N \sim 10^{18} \text{cm}^{-3}$). The SQW is 10.5 nm thick and is grown "digitally" as a short-period superlattice of $(\text{Zn}_0.95\text{Cd}_{0.05}\text{Se})_m\text{f(MnSe)}_f$, where $m$ is an integer and $f$ is a fraction. Sample A has $m = 5$, $f = \frac{1}{5}$, while sample B has $m = 5$, $f = \frac{1}{10}$. Magneto-transport measurements are carried out using DC Hall bar techniques down to temperatures of $\sim 320 \text{mK}$ and magnetic fields up to 5 T. Contacts are made by annealing In dots in a forming gas atmosphere for 15 min. Magneto-photonoluminescence (magneto-PL) measurements are carried out in the Faraday geometry in magnetic fields up to 40 T and temperatures down to 2.2 K.

The exchange-enhanced spin splitting $\Delta E_S$ in our samples is estimated from the Zeeman shift $\Delta E_{PL}$ in the magneto-PL spectrum that arises from electric-dipole allowed transitions between the lowest spin–electron and heavy hole LLs.\(^2\) The Zeeman shift of the PL peak from its value at zero field is related to $\Delta E_S$ as follows:

$$
\Delta E_{PL} = 2.63(\Delta E_S) + 1/2(\hbar \omega_c)_e
+ (\hbar \omega_c)_{hh} + g_e\mu_B B + g_{hh}\mu_B B,
$$

\(^2\) In the presence of a magnetic field, the PL spectrum consists of two peaks, only one of which survives beyond $v = 1$. We attribute this higher-energy peak to the band-edge emission.

where $(\hbar \omega_c)_e$ and $(\hbar \omega_c)_{hh}$ are the cyclotron energies for electrons and heavy holes respectively, the last two terms in the equation are the respective intrinsic Zeeman terms and are typically negligible compared to $\Delta E_S$. The prefactor multiplying $\Delta E_S$ arises from the known ratio of the s–d and p–d exchange interactions \([8]\). The spin splitting $\Delta E_S$ is proportional to the sample magnetization, so that $\Delta E_S = (\Delta E_S)_{MAX} B_{5/2} (5\mu_B B/kT_{eff})$, where the Brillouin function is empirically modified by an effective temperature $(T_{eff} = T + T_0)$ to account for Mn–Mn interactions \([1]\). The magneto-PL shift can hence be fit to the sum of a modified Brillouin function and a term linear in magnetic field. The respective fitting parameters for samples A and B are: $(\Delta E_S)_{MAX} = 11$, 8.3 meV and $T_0 = 1.3$ and 0.63 K.

The large spin splitting of conduction band states has important implications for the sheet density in the M2DEG since, in the presence of a magnetic field, the conduction band offset $\Delta E_{CB}$ is modified to $\Delta E_{CB} = (\Delta E_{CB})_0 + (\Delta E_S)/2$ for spin-down electrons. Hence, the depth of the spin-dependent confinement potential increases with increasing magnetic field and decreasing temperature, leading to an increased transfer of carriers, whether localized or free, from the barrier regions into the SQW. A detailed modeling of this picture requires a self-consistent calculation of the Schrodinger and Poisson equations, taking into account the change in the confinement potential with temperature and magnetic field, as well as the sample preparation-dependent surface states. However, the essential physics can be verified by measuring the temperature- and field-dependent sheet density $N_S(B, T)$ using magneto-transport, and correlating this with the measured $\Delta E_S$.

Fig. 1 shows the field- and temperature-dependence of the sheet resistance $(\rho_x)$ in both samples. In sample A, the zero-field sheet resistance decreases exponentially with increasing temperature, indicating a strongly localized 2DEG characterized by hopping transport between localized states. On the other hand, the weak temperature dependence of the zero-field resistivity in sample B indicates diffusive transport in a weakly localized electron gas. At low magnetic fields, both samples display the striking positive magneto-resistance characteristic of M2DEGs and attributed to changes in the diffusive and hopping transport caused by the large spin splitting of
Fig. 1. Sheet resistance $\rho_{xx}$ as a function of temperature and magnetic field for the two samples. Sample A has carrier concentration $N_S = 6.35 \times 10^{10}$ cm$^{-2}$ and mobility $4210$ cm$^2$/V$s$ at $4.2$ K. Sample B has carrier concentration $N_S = 1.3 \times 10^{11}$ cm$^{-2}$ and mobility $13700$ cm$^2$/V$s$ at $4.2$ K, both extracted from low-field measurements.

electronic states [4–6]. At higher fields, the quantum transport in both samples distinctly shows LLs corresponding to all integer values ($\nu = 1–5$ in sample A and $\nu = 1–12$ in sample B), again a consequence of the large $\Delta E_S$ in the samples. A careful analysis of the quantum oscillations in both samples indicates that $N_S(B,T)$ – as deduced from the location of the minima in $\rho_{xx}$ – increases with field. In addition, at fixed field, we find that $N_S(B,T)$ decreases with increasing temperature. A detailed study of $N_S(B,T)$ in sample B (Fig. 2) shows a clear correlation with $\Delta E_S$, providing strong support for the postulate that the exchange-enhanced splitting is responsible for the variation in sheet density. We note further that low field ($< 0.5$ T) Hall measurements clearly indicate a carrier concentration that is lower than that deduced from the Shubnikov–de Haas oscillations. Surprisingly, this low-field value of $N_S$ is higher than that extrapolated to zero spin splitting in Fig. 2.

The measured spin splitting can be also used to examine the LL structure in the M2DEG samples and to hence gain insights into the observed quantum transport. Since the s–d exchange by itself does not mix LLs of different spin, the relevant LL diagrams may be constructed by adding the experimentally determined spin splitting $\Delta E_S$ to the cyclotron energy ($\hbar \omega_c$). We note that we do not account for possible “floating” of the extended states at low magnetic fields [9]. The resulting LL level diagrams for samples A and B (Figs. 3(a) and (b), respectively) indicate complete spin polarization even at large filling factors (for instance, up to $\nu = 12$ in sample B). Further, sample A clearly undergoes transitions between insulator and quantum hall liquid states at both $\nu = 2$ and 1 (Fig. 1(a)). As usual, we define the insulating regime as one in which $\rho_{xx}$ decreases with increasing tempera-
Fig. 3. Landau level fan diagrams at 0.32 K as calculated from the spin splitting measured in magneto-PL experiments. The calculation uses an effective mass $m^*_\text{e} = 0.145 m_0$ and is obtained from cyclotron resonance measurements. Dotted lines are spin-down and solid lines spin-up, while the heavy solid line is the Fermi energy as calculated from the positions of the Shubnikov–de Haas minima in Fig. 2.

In summary, we have demonstrated that modulation-doped $\text{ZnSe/(Zn,Cd,Mn)Se SQWs}$ can be designed with high enough quality to permit quantum transport studies at low carrier densities. The shallow confinement required for an enhanced mobility leads to an unusual field- and temperature-dependent carrier density. Nonetheless, we are able to study the generic aspects of quantum transport in M2DEGs that are completely spin polarized right from the onset of quantum transport. Attempts at gating such samples are underway in order to map out the phase diagram in these model spinless fermion gases.

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References