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Magnetic field effects on the exchange instability of the 2D electron gas

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Abstract

We have studied the effect of an external magnetic field on the photoluminescence of a two-dimensional electron gas (2DEG) formed in a GaAs quantum well for the case of an incipient occupation of the first excited electron subband. As this subband becomes populated the 2DEG undergoes a first-order phase transition driven by exchange terms of the Coulomb interaction, for which a spontaneous spin polarization is expected to occur. For a magnetic field applied perpendicular to the 2DEG we obtain a strong g-factor enhancement due to many-body effects, as determined from Landau level splittings of the densely populated second subband. In contrast, the intensity of the emission peak associated with the spin-polarized phase decreases linearly with field, indicating an in plane spin polarization. From the field dependence of the degree of linear polarization of the emission line F in the parallel field configuration, we were able to estimate the average size of the spin-polarized domains to be about 200 nm.

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High-mobility two-dimensional electron gases (2DEG) realized in modulation-doped semiconductor quantum well structures offer a unique opportunity to study the many-body behavior of dilute electron systems. Recently, it has been shown that a 2DEG undergoes a first-order phase transition, when the first excited electron subband becomes populated [1]. Evidence was found in the abrupt renormalization of the subband energy and its sudden occupation, as determined from photoluminescence (PL) measurements. The first-order character of this transition was confirmed by theory [2], after the *exact* exchange potential in the self-consistent density functional calculation was included. The theory also predicted the occurrence of a spontaneous breakdown of the spin symmetry without magnetic field to take place in a narrow range of Fermi levels (FL) close to the transition. This leads to the formation of spin-polarized domains, which exhibit optical recombination at an energy slightly below that of the emission from the second electron subband [3]. Whereas the sudden renormalization of the first excited subband upon occupation is a consequence of *inter*subband exchange-energy terms, the spin-polarized phase is favored by *intra*subband exchange interaction, as long as its population remains low.

As previously reported [4], PL spectra of the 2DEG measured without magnetic field exhibit a *new* peak, denoted F, 1.2 meV below the energy of the optical transition from the second subband E_1, when the Fermi

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level comes into resonance with the bottom of the subband but before the abrupt renormalization occurs. This peak which is observed only in spectra taken at very low temperatures and laser powers has been associated with the predicted ferromagnetic phase [3]. By varying the electron density in the quantum well with a gate voltage, we were able to construct a phase diagram in FL-T space, in which a narrow stability range of the spin-polarized phase with a triple point at 13 K electron temperature is determined. The purpose of this work is to further characterize the spin-polarized phase. In particular, we have investigated the effects of an external magnetic field applied in plane as well as perpendicular to the 2DEG on the second subband and the spin-polarized domains.

The sample consists of a modulation-doped 25-nm wide GaAs single quantum well (SQW) with $Al_{0.33}Ga_{0.67}As$ barriers grown by molecular-beam epitaxy. The growth sequence is given in Ref. [5]. At 2 K the 2D electron gas has a mobility of 8×10^5 cm^2/Vs and without bias only the lowest subband is occupied with a density of about 5.6×10^{11} cm^{-2}. By applying a gate voltage between the 2DEG and a back contact, the electron density in the SQW increases such that the second subband becomes populated. Magnetoluminescence measurements up to 4 T were performed at different temperatures down to 2 K in Faraday as well as Voigt geometry by placing the sample in the cold bore of a split-coil superconducting magnet.

We study first the situation in which the Fermi level is slightly below the bottom of the second subband. Fig. 1(a) shows a series of PL spectra in the spectral range of the transition energy E_1 from the second electron subband to the first heavy-hole subband, measured at 2 K and with a magnetic field $B_\perp$ of 1 T applied perpendicular to the 2DEG. We distinguish two peaks, one is E_1 and the other labeled F corresponds to the spin-polarized phase [3]. With increasing the Fermi level a third peak appears, which we associate with the Fermi-edge singularity (FES). On the one hand, the quantization of the hole motion into Landau levels by the external field $B_\perp$ leads to localization of the photoexcited holes by the disorder potential of the SQW and hole recoil becomes suppressed [6]. On the other hand, interference between transitions at the Fermi level and at the empty conduction subband E_1 contribute to a strong enhancement of the probability for recombination processes at the Fermi surface resulting in the sharp peak in PL and/or absorption spectra known as Fermi-edge singularity

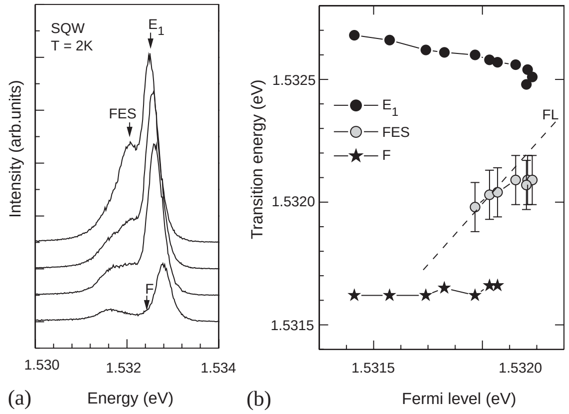

Fig. 1. (a) PL spectra of the GaAs SQW for different voltages measured at 2 K with a perpendicular magnetic field of 1 T. The assignment of the peaks to the optical transition between second electron and first hole subband (E_1), the spin-polarized phase (F) and the Fermi-edge singularity (FES) is indicated. (b) Plot of the peak energies as a function of the position of the Fermi level.

[7]. Fig. 1(b) displays the dependence of the peak energies on Fermi level. We note that the third peak follows the FL, which supports its interpretation as FES, whereas the position of the E_1 and F lines remains almost constant. We also point out that in the absence of a perpendicular magnetic field the high mobility of the 2DEG and the finite hole mass smear out the singularity and the FES peak is no longer observed.

As a function of $B_\perp$ but with the second subband still empty, the E_1 transition exhibits the typical diamagnetic shift and Zeeman splitting of exciton recombination. The latter is calculated according to $H^e_{\rm Zee} = g_e \mu_{\rm B} B m_j$ and $H^h_{\rm Zee} = -g_h \mu_{\rm B} B m_j$ for electrons and holes, respectively, where g_i are the g-factors and $\mu_{\rm B}$ is the Bohr magneton. The spin projections for the conduction and heavy-hole subbands are $m_j = \pm\frac{1}{2}\hbar$ and $\pm\frac{3}{2}\hbar$, respectively. In Faraday geometry the emission from the growth direction is σ_+, σ_- circularly polarized. The transition for σ_+ polarization is detected at higher energy than that of the σ_- one, from which a negative effective g-factor $g^* = (g_e - 3g_h)/2$ is inferred. From the measured g^* factor and assuming that $g_e = -0.44$ is close to the GaAs bulk value, as expected for a 25-nm-wide well, we obtain $g_h = 0.26 \pm 0.07$ which is in good agreement with the literature data [8].

The situation changes if the second subband E_1 is densely populated, becoming paramagnetic again after renormalization of its energy. For a FL about 10 meV

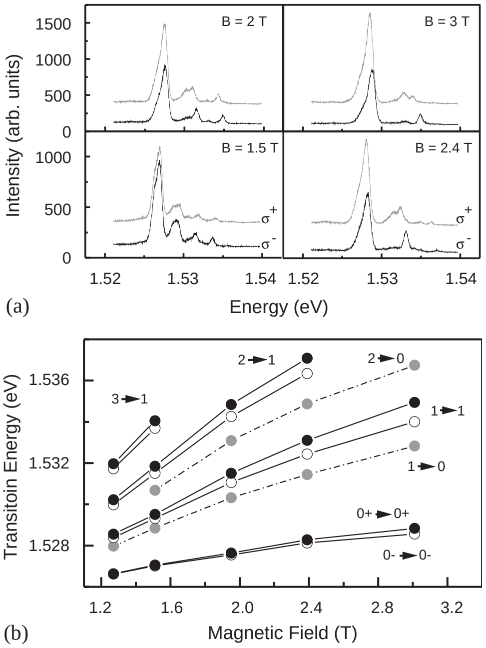

Fig. 2. (a) Circularly polarized PL spectra of the SQW measured at 2 K for different magnetic fields $B_\perp$. (b) Landau level fan diagram. Open (closed) symbols correspond to $\sigma_+(\sigma_-)$ circular polarization. Gray symbols represent features with no clear polarization.

above E_1 the magneto-PL spectra show a series of peaks with well-defined circular polarization corresponding to transitions between Landau levels (LLs), as seen in Fig. 2(a). The LL-fan diagram is illustrated in Fig. 2(b), where open(closed) symbols represent data for $\sigma_+(\sigma_-)$ polarization. Gray dots correspond to apparently depolarized emission lines which, we believe, are due to the superposition of two nearby peaks with different circular polarization. The marked nonlinear magnetic field dependence of the transition energies is a consequence of the strong mixing between heavy and light-hole Landau levels [9].

For $B_\perp < 2$ T the field dependence of the LLs is almost linear and given by $E_i = \hbar\omega_c(i + \frac{1}{2})$, where $i = 0, 1, 2\ldots$ is the level index and $\omega_c = eB/m_{e,h}c$ is the cyclotron frequency. The energy of a transition between the nth electron level with effective mass m_e and the lth hole state with mass m_h, denoted $n \to l$, is calculated as $E_1 + E_n + E_l$. The assignment of the series of peaks on the basis of their energy and circular polarization, assuming that photoexcited holes occupy only the first two states, is indicated in Fig. 2(b). The set of data points $n \to 0$ is well fitted using the known electron and heavy-hole masses $m_e = 0.068m_0$ and $m_{hh} = 0.4m_0$, respectively. For the $n \to 1$ transitions, however, a smaller hole mass is needed, indicating a strong light-hole admixture [9]. For the $0 \to 0$ transitions which we suppose of pure heavy-hole character, we obtain an effective g factor of $g^* = -1.33 \pm 0.15$. This value is twice as large as for the case of the empty subband. The contribution to the g-factor enhancement steeming from the reduction of the subband energy due to renormalization and the consequent increase in electron effective mass is at most of the order of 10%. This led us to the conclusion that many-body effects play a fundamental role in the gyromagnetic properties of the 2DEG probably in a similar way as observed in the quantum Hall regime [10] and for self-assembled quantum dots [11].

Going back to the ferromagnetic phase, a further confirmation of its in plane spin polarization [3] is the absence of Zeeman splitting for finite $B_\perp$ and the fact that the intensity of the peak F decreases linearly with magnetic field disappearing at about 1.5 T. A spin polarization of the electronic domains formed in the second subband is the result of a net gain in exchange energy due to Pauli repulsion between electrons with parallel spins [2]. A perpendicular magnetic field modifies the wave function overlap and the ferromagnetic order within the excited subband gets destroyed.

We now turn to the discussion of the effects of a magnetic field $B_\parallel$ applied in Voigt configuration in the plane of the 2DEG. The main difference with the perpendicular field case concerns the independence of the intensity of peak F on field, which speaks for the stability of the spin-polarized phase, and the absence of the feature associated with the FES. In Voigt geometry, light emitted with circular polarization with respect to the magnetic field is detected vertically polarized. We define the degree of linear polarization as $\mathrm{DP} = (I_V - I_H)/(I_V + I_H)$, where I_V and I_H stand for the intensity of the peak F in vertical and horizontal polarization, respectively (the field is applied in horizontal direction). Thus, DP weights up the proportion of domains with spin polarization pointing in field direction, i.e. it is a measure of the magnetization of the domain ensemble along $B_\parallel$. As shown in Fig. 3, the DP of peak F increases linearly with field. In the low-field limit, DP is well described by a Brillouin function $\mathrm{DP} = g\mu_B(J+1)B_\parallel/3k_BT$, where J is the average total spin of the domains in units of $\hbar$. By fitting this function to the experimental data using $g_e = -0.44$

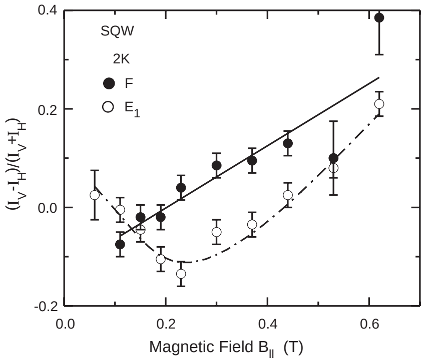

Fig. 3. Dependence on in plane magnetic field of the degree of linear polarization for the emission from the spin-polarized phase F and the second subband E_1.

and an effective electron temperature $T = 4$ K, we obtain a total average spin $J \sim 25$, which corresponds to about 50 electrons per domain. For an electron density of 5×10^{10} cm^{-2} corresponding to the jump at the sudden occupation of the first excited subband, the mean radius of a domain should be around 200 nm.

In contrast, the degree of linear polarization of the E_1 line displays an initial decrease with a minimum at about 0.24 T, above which DP increases with $B_{||}$ in a similar way as for the F peak. At this point we can only speculate about this striking behavior. We recall that the E_1 peak arises from *hot* luminescence from the empty second subband. The Fermi level which is close below the bottom of the subband increases slightly with $B_{||}$. The consequent tiny increase in thermally activated population seems to be important enough to cause an appreciable renormalization of E_1 of a few tenths of meV, bringing this subband closer to the upper spin state of the spin-polarized domains [3]. A transfer of electrons with predominantly spin component along $B_{||}$ sets in from paramagnetic subband states to the excited domain level, such that the I_V component of the emission at E_1 diminishes, contributing to the initial reduction of DP.

In summary, we have investigated the influence of the magnetic field on the phenomenology of the 2D electron gas associated with the sudden occupation of an excited subband. The effective g factor of the optical transition at E_1 doubles its value due to many-body effects, when the second subband becomes populated. A field applied perpendicular to the 2DEG plane inhibits the formation of spin-polarized domains but favors the observation of the Fermi-edge singularity, and vice-versa for an in plane magnetic field. Finally, we note that for finite in plane fields an additional peak is apparent in PL spectra at intermediate energies between the F and E_1 emissions, which we have attributed to a skyrmionlike excitation of the spin-polarized domains. Details of this observation are given in Ref. [3].

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