Exchange-driven instability and spin polarization of the two-dimensional electron gas

P Giudici, A R Goñi, U Haboeck, C Thomsen
Institut für Festkörperphysik, Technische Universität Berlin, Berlin, Germany

K Eberl
Max-Planck-Institut für Festkörperforschung, Stuttgart, Germany

F A Reboredo, C R Proetto
Comisión Nacional de Energía Atómica, Centro Atómico Bariloche, S.C. de Bariloche, Argentina

Abstract. We show that at low temperature and zero magnetic field a two-dimensional (2D) electron gas formed in a GaAs single quantum well undergoes a first-order phase transition, as the first excited electron subband becomes populated with electrons by rasing the Fermi level using a dc voltage. The evidence is found in the abrupt renormalization of the energy of the first excited subband and its sudden population, as determined from photoluminescence (PL) measurements. Self-consistent density-functional calculations with exact exchange potential for a 2D electron system reveal that this transition is driven by intersubband exchange interactions. This theory also predicts the spontaneous breakdown of the spin symmetry at the phase transition without magnetic field. In fact, PL spectra measured at 2 K and with very low laser powers exhibit a new peak below the energy of the optical transition from the first excited subband, which is associated with the spin-polarized phase.

1. Introduction

High-mobility two-dimensional electron gases (2DEG) fabricated in semiconductor quantum well structures are particularly suitable for studies of electronic correlations in reduced dimensions [1]. Exchange effects are a fundamental manifestation of electron-electron interactions in many-particle systems like 2DEGs. Exchange and correlation, for instance, are at the origin of a great variety of fascinating phenomena, for example, fractional quantum Hall states, spin excitations, magnetic ordering, excitonic binding and band-gap renormalization among others. A topic which has attracted much attention recently is the observation of ferromagnetism in a low-density free-electron gas formed in electron-doped calcium hexaboride (CaB_6) with a very high magnetic ordering temperature of 600 K [2]. The origin of the observed magnetic polarization is still a matter of speculation. Based on results of Monte-Carlo calculations [3] it has been argued that this is just a consequence of the spontaneous spin polarization of a diluted electron gas due to spin-spin correlations steaming from the Coulomb interaction between electrons [4].

Recently we have shown experimentally as well as theoretically that at low temperatures and zero magnetic field a 2D electron gas realized in a GaAs single quantum well (SQW) undergoes a first-order phase transition, as the first excited electron subband becomes populated [5]. The evidence was found in the low-temperature photoluminescence (PL) spectra which displayed the abrupt renormalization of the subband energy and its sudden population with electrons. The first-order character of the transition was confirmed by theory when the exact exchange potential for a 2D system was included in the self-consistent density-functional calculations [6]. In this work we have investigated the existence of a spin-polarized phase of the 2DEG in the vicinity of the first-order transition at zero magnetic field when the Fermi level comes into resonance with the bottom of the first-excited electron subband, as further predicted by the exact-exchange theory. For that purpose we performed PL measurements at 2 K using low laser excitation powers by varying the electron density with a dc gate voltage. We have also studied the influence of an external magnetic field on the PL signature of spin polarization.

2. Experimental

The sample consists of a modulation-doped 25-nm-wide GaAs SQW with $Al_{0.33}Ga_{0.67}As$ barriers grown by molecular-beam epitaxy. The growth sequence is given elsewhere [7]. At 4 K the sample has a 2D electron density of about 5.6$\times 10^{11}$ cm^{-2} and a mobility of 8×10^5 cm^2/V s. Without bias only the lowest subband is occupied with electrons up to the Fermi energy $E_F \approx 22$ meV. The energy separation to the second subband is $E_{01} \approx 28$ meV. The electron gas is contacted from the top surface by In alloying in order to apply a dc voltage up to 70 V between it and a metallic back contact.

Photoluminescence spectra were excited either with a tunable Ti:sapphire laser or with the 514 nm line of an Ar-ion laser and recorded with optical multichannel detection. Magnetoluminescence measurements up to 5 T were done at 2 K in Faraday as well as Voigt configuration, i.e. with the magnetic field perpendicular ($B_\perp$) and parallel ($B_{||}$) to the plane of the 2DEG, respectively, by inserting the sample in the cold bore of a superconducting split-coil magnet.

3. Results and discussion

3.1. Zero-field measurements

The electron density in the SQW increases with bias shifting the Fermi level towards degeneracy with the bottom of the first excited subband. Representative PL spectra in the energy range of optical transitions from the first excited electron subband to the heavy-hole ground state in the well are displayed in Fig. 1 for different gate voltages. As previously reported in Ref. [5], the PL peak at E_1 exhibits an abrupt and strong redshift in excess of 10 meV when the Fermi energy almost equals the intersubband spacing E_{01}. This reduction of E_1, which is observed in part in the spectra of Fig. 1 for the higher bias values, is a consequence of band-gap renormalization effects in electron gases due to many-body exchange-correlation corrections [8, 9]. Moreover, the occupation of the second subband proceeds discontinuously indicating the occurrence of a first-order phase transition, which is driven by intersubband exchange-correlation terms of the Coulomb interaction between electrons in both lowest subbands [5, 6].

A striking result concerns the appearance in PL spectra of a new sharp peak labeled FP (see Fig. 1) at about 1 meV below the energy E_1 of the emission from the first excited subband. We note that this peak can only be observed at lattice temperatures below 5 K and for low excitation power densities, such that the effective temperature of the electron gas is not higher than about 10 K, as determined from the width of the Fermi edge in the PL spectrum. This behavior of the FP feature is in contrast to that of the E_1 peak, which increases in intensity in proportion to the excitation power since it arises from hot luminescence due to the recombination of photoexcited carriers. We point out that the phenomenology of our

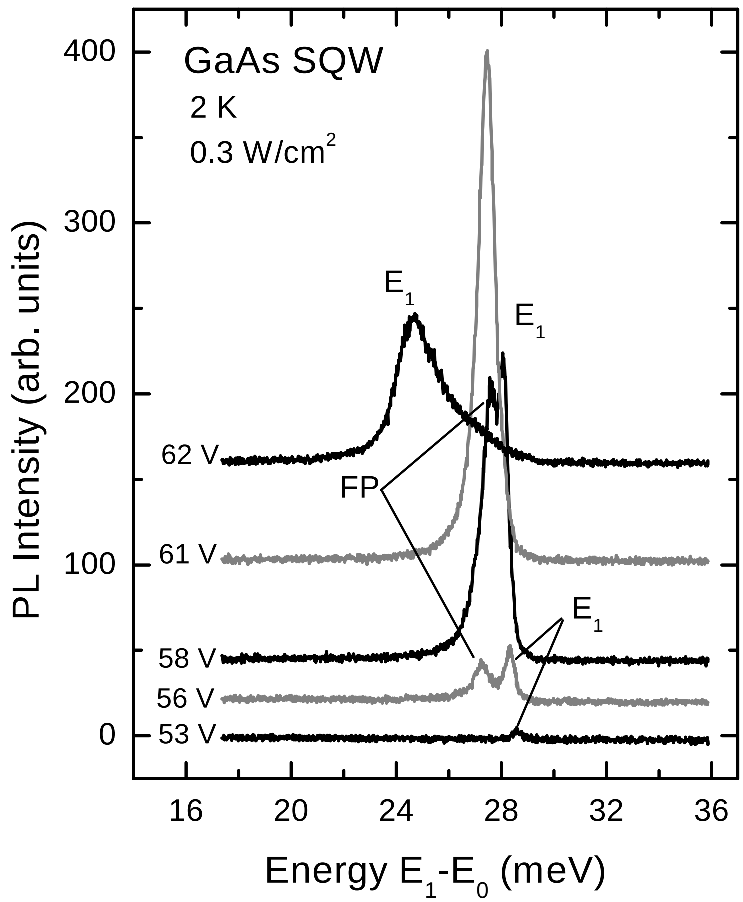

Figure 1. Photoluminescence spectra of the modulation-doped single quantum well in the energy range of the optical transition from the first excited electron subband E_1 measured at 2 K and a low power density of 0.3 W/cm^2 for different gate voltages. The peak denoted FP is associated with the ferromagnetic phase.

observations does not correspond to that of the Fermi-edge singularity (FES), as reported in Ref. [10, 11] for thinner GaAs SQWs with a different barrier structure and one order of magnitude less mobility. In our case, the energy of the FP peak is independent of the position of the Fermi edge which can be tuned across the energy range of E_1 by changing the applied bias.

From a lineshape analysis of the PL spectra we were able to determine the electron densities in both subbands and the position of the Fermi level, i.e. the Fermi energy E_F measured from the bottom of the lowest subband at E_0. The results for the peak maxima of the E_1 and FP features are plotted in Fig. 2 as a function of the Fermi energy. In this plot we distinguish between data points obtained by increasing (triangles pointing to the right) and decreasing (triangles to the left) voltage. The data display a clear hysteresis upon changes in the Fermi level near the first-order phase transition, whose signature is the sudden renormalization of E_1. The FP feature becomes apparent in PL spectra a few meV before the phase transformation of the electron gas occurs.

We attribute the observation of the FP peak to the appearance of ferromagnetic ordering in the very diluted 2D electron gas which forms as the first excited subband starts to become populated when the Fermi energy is shifted into resonance with E_1 by increasing

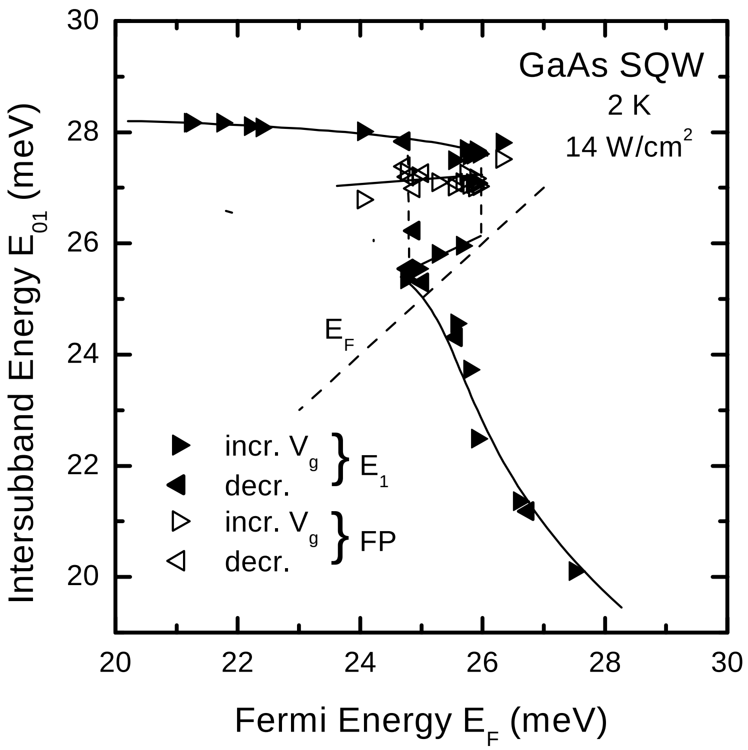

Figure 2. Energy separation between the two lowest electron subbands as a function of the Fermi energy E_F measured from the bottom of the lowest one at E_0 for increasing (right triangles) and decreasing (left triangles) gate voltage V_g. Full and open symbols correspond to the paramagnetic (E_1) and ferromagnetic (FP) phase, respectively, of the 2DEG formed in the first excited subband. Lines are a guide to the eye. The dashed line corresponds to the position of the Fermi energy.

the gate voltage. Our exact-exchange theory predicts that at very low densities the exchange interaction between electrons would lead to a spontaneous breakdown of the spin symmetry, hence, the electron system becomes spin polarized even in the absence of an extermnal magnetic field. By these means the overall Coulomb repulsion is lowered within a spin-polarized domain with respect to the paramagnetic spin-degenerate phase, giving rise to the redshift of about 1 meV of the FP feature as compared to E_1. We notice that the results of our self-consistent density-functional calculations for the redshift are in good quantitative agreement with the experimental ones.

3.2. Magneto-PL measurements

For further characterization of the properties of the spin-polarized phase we measured magneto-PL spectra of the SQW at 2 K and in Faraday as well as in Voigt configuration, i.e. with the magnetic field applied perpendicular or parallel to the plane of the 2DEG, respectively. Figure 3 shows the results for the peak energy positions obtained with external magnetic fields up to 4 T. Another interesting result concerns the observation of an additional PL feature labeled P^* at a slightly higher energy than FP, which exhibits a similar behavior as a function of laser power, temperature and gate voltage than the peak of the ferromagnetic phase. It is important to note that the P^* peak only appears for finite magnetic fields, indicating the violation of an optical selection rule due to a symmetry breakdown induced by the applied field. The different energy position of the E_1 peak for parallel and perpendicular

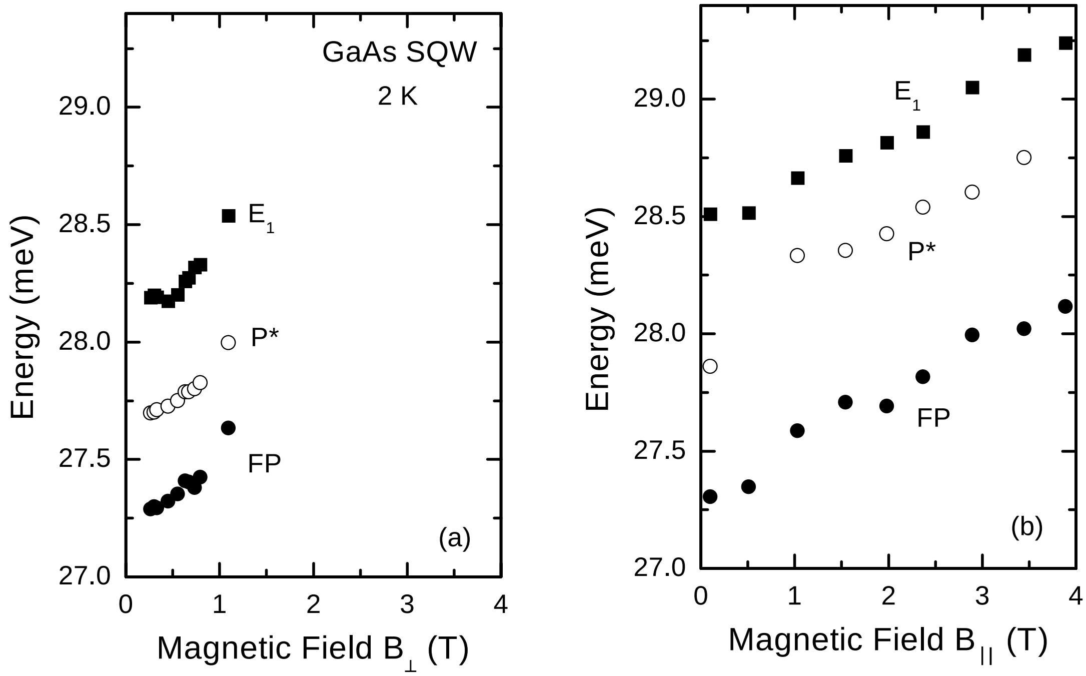

Figure 3. Energy positions of the peaks observed in magnetoluminescence spectra with the field (a) perpendicular and (b) parallel to the plane of the quantum well. P^* denotes the additional feature apparent in spectra with finite magnetic field.

magnetic fields is due to the fact that both measurements were performed with different gate bias, which strongly affects the renormalization of the second subband (see Fig. 2). As a function of magnetic field, all three features exhibit an initial diamagnetic shift of their energy followed by a linear dependence. This is the typical field behavior expected for optical transitions between Landau levels originating from confined states in quantum wells [12, 13]. The diamagnetic (quadratic in the field) term is more pronounced for an in-plane field since in this case the linear dependence sets in only when the magnetic length becomes smaller than the extension of the exciton wave function in growth direction, which is limited by the well width. For $B_\perp$, in contrast, the size of the magnetic orbit has to be compared with the large effective Bohr radius of the exciton at E_1, characterized by a small binding energy of about 1 meV due to strong screening effects in the 2DEG.

Up to now we are not able to give an explanation for the origin of the peak P^*. We tentatively assign it to optical transitions from a many-body state corresponding to a spin-flip excitation of the spin-polarized diluted electron gas formed in the second subband. For a ful assignment of this feature further investigations, for instance of the polarization of the emitted light with and without magnetic field, are necessary.

In conclusion, we have provided strong evidence for the existence of the ferromagnetic phase of a low-density 2D electron gas which forms when the first-excited electron subband of a single quantum well structure starts to become populated, as the Fermi level is raised with a gate voltage. The evidence is found in luminescence spectra taken at 2 K and with low laser excitation powers in order not to heat up the electron system. This result is in very good agreement with the prediction of an exact-exchange density-functional theory which indicates that spin-polarization is attained spontaneously (without external magnetic field) due to exchange-correlation interactions in the 2DEG.

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