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2011 J. Phys.: Conf. Ser. 334 012022

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Optical probing of quantum Hall effect of composite fermions and of the liquid-insulator transition

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Abstract. In the photoluminescence spectra of a two-dimensional electron gas in the fractional quantum Hall regime we observe the states at filling factors $\nu = 4/5, 5/7, 4/11$ and $3/8$ as clear minima in the intensity or area emission peak. The first three states are described as interacting composite fermions in fractional quantum Hall regime. The minimum in the intensity at $\nu = 3/8$, which is not explained within this picture, can be an evidence of a suppression of the screening of the Coulomb interaction among the effective quasi-particles involved in this intriguing state. The magnetic field energy dispersion at very low temperatures is also discussed. At low field the emission follows a Landau dispersion with a screened magneto-Coulomb contribution. At intermediate fields the hidden symmetry manifests. At high field above $\nu = 1/3$ the electrons correlate into an insulating phase, and the optical emission behaviour at the liquid-insulator transition is coherent with a charge ordering driven by Coulomb correlations.

1. Introduction

The two dimensional electron gas (2DEG) created in a modulation-doped semiconductor quantum well (QW) has been widely investigated using magneto-transport and magneto-optical techniques [1-4]. In particular, in magneto-photoluminescence experiments realized in an asymmetric modulation doped QW, the photo-excited holes are able to probe the plasma of interacting electrons, since the holes weakly affect the 2DEG when the separation between electrons and holes is large [5]. A magnetic field normal to the QW enhances many-body effects and gives access to the observation of quantum phenomena such as the integer and fractional quantum Hall effect (IQHE and FQHE, respectively). These phenomena have been explained within theories which invoke the many body

interactions that rule the arrangement of 2D electrons placed in high magnetic field, leading them to form highly correlated states. In particular, a solid theoretical scenario [6] which envisages the formation of Landau levels (LLs) and quasi-particles named composite fermions (CFs), has allowed the interpretation of several experimental results. However, FQHE at fractional filling factors that cannot be explained within the CFs theory has been observed in transport experiments [2] and very recently in optical experiments [7], and not all the features observed in the PL experiments are well understood but they keep on producing sources of research and discussion [8]. Besides, the presence of residual disorder is a fundamental ingredient for the observation of these quantum phenomena, and in samples with intermediate electron density ($\sim 10^{11} \text{ cm}^{-2}$) and sufficiently high mobility ($\sim 2 \times 10^6 \text{ cm}^2/\text{Vs}$) the interplay between disorder and Coulomb interactions can reveal interesting interaction-related effects. Among these, the two-dimensional metal-insulator transition represents an intriguing example, whose nature is still an open question. When the magnetic field exceeds a critical value B_c , the system from a quantum Hall liquid exhibiting the quantum Hall plateau becomes insulating, characterized by a diverging longitudinal resistance [9]. This transition to the insulating state has been studied by electrical transport in several semiconductor heterostructures [9, 10] and recently in graphene [11], and both the disorder-induced localization (Anderson) and the correlation-induced localization (Mott) have been invoked for the explanation of the phenomenon [12-13]. In particular in [12] the authors illustrate a scenario where the metal-insulator transition in the 2DEG can be attributed to strong correlations that are effectively enhanced even far away from integer filling, due to incipient charge ordering driven by non-local Coulomb interactions; optical results supporting this scenario have been obtained recently [14].

In this work we illustrate the results of our recent magneto-photoluminescence experiments, trying to enlighten the role of many body effects, strong correlations among the electrons and interaction-related effects. Analyzing the intensity and area of the 2DEG PL emission as a function of the magnetic field B at temperature down to 600 mK, we observe several structures in the spectra at integer and fractional filling factors ν , which we interpret within the CFs picture and taking into account the coulomb screening of the 2DEG [15]. At temperature down to 40 mK, studying the magnetic field dispersion of the emission energy and monitoring simultaneously the longitudinal and Hall resistances, we evidence a significant change in the PL in correspondence of the liquid-to-insulator transition of the 2DEG.

2. Experimental

The experiments were performed on a 20 nm-thick asymmetric modulation-doped GaAs/AlGaAs single QW with carrier density $n = 1.8 \times 10^{11} \text{ cm}^{-2}$ and mobility $\mu = 1.6 \times 10^6 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$. Indium contacts were placed with a Hall bar geometry on a rectangular sample of millimetre size, allowing simultaneous transport and optical experiments. The sample was excited with the light from a Ti:sapphire laser at the energy of 1.748 eV, with an excitation power smaller than 300 μW . The experiments were performed in the temperature range 40 mK - 1.5 K.

3. Results and discussion

In Fig. 1 (top) is reported the low temperature PL emission deriving from the recombination of the 2DEG electrons in their first Landau level L_0 with photo-created valence holes in their first LL. The intensity of the L_0 emission varies markedly and in particular it exhibits clear minima at specific values of the magnetic field B , as can be seen in Fig. 1 (bottom) which shows the intensity of the PL peak as a function of B . Strong suppression of the PL intensity is observed at $\nu = 1$ ($B = 7.6 \text{ T}$), while a strong step is present at $\nu = 2$ at $B \sim 3.8 \text{ T}$; a weak minimum and a small step are also observed at $\nu = 3$ at $\nu = 4$, respectively. These behaviours, and similar ones reported by other authors [3,8], can be traced back to the influence by the electrons in the higher LLs on the emission from L_0 . At higher fields when $\nu < 1$, the emission is suppressed at values of the magnetic field that can be differentiated in two groups: i) the ones corresponding to fractional filling at $\nu = 2/3, 3/5, 2/5, 1/3, 2/7$ and at ν on both side of $1/2$, and ii) the ones corresponding to the filling factors $\nu = 4/5, 5/7, 4/11$ and $3/8$ (for the

last two see in particular Fig. 2). Fractions in group i) agree with the ones expected by the theory of CFs [6,16], according to which the FQHE for the electrons is seen as the IQHE of CFs, quasi-particles originating from the mutual interaction of the electrons in the magnetic field and formed by the bounding of an electron with an even number of magnetic flux quanta. The net result is the passage from a system of interacting electrons in a magnetic field B to another of vanishing interacting CFs in a residual magnetic field B^* which leads to the formation of LLs for the CFs. This allows to rescale the known picture for the IQHE of electrons to the case of the quasi-particles described by J. K. Jain [6]. The analysis of the PL intensity minima, with simultaneous monitoring the areas under the PL curves, allow to give a physical interpretation of the results, basing on the argument that the overlap between the wave-functions of the 2D electrons and photo-created holes depends on the Coulomb screening efficiency of the 2DEG [15]. The fact that the CFs form LLs, in analogy to what happens for electrons, makes possible to extend this interpretation for the behavior of the electrons in the IQH regime [4,15] to the case of FQHE PL intensity minima such as the ones observed in group i).

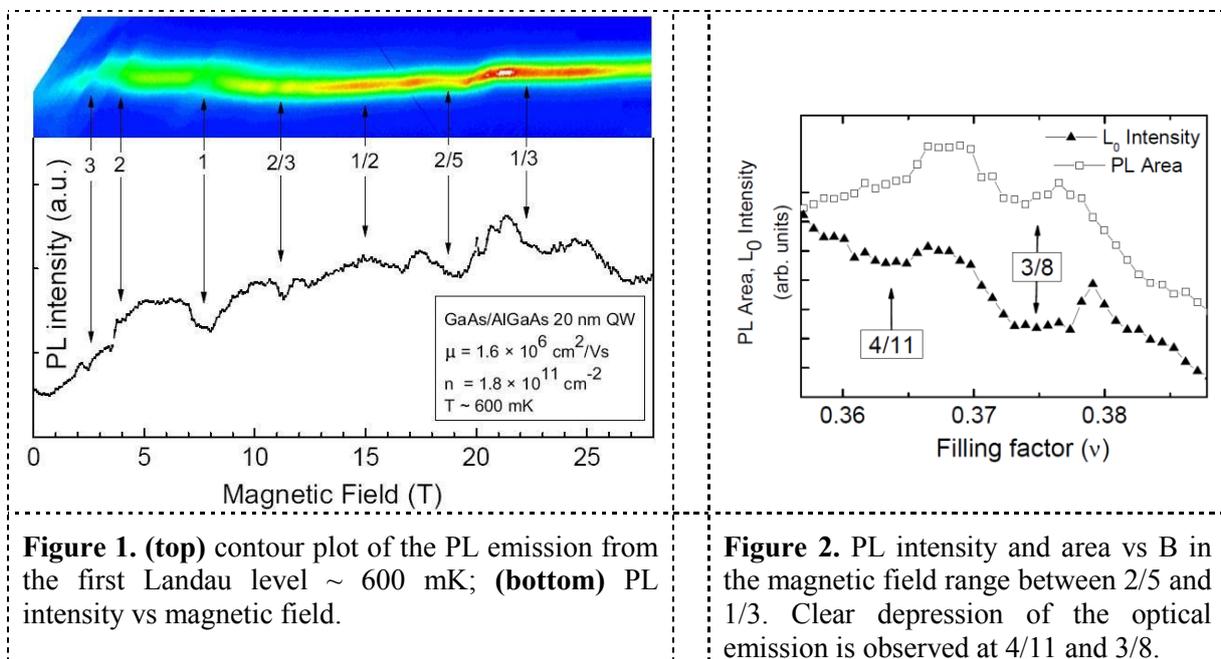


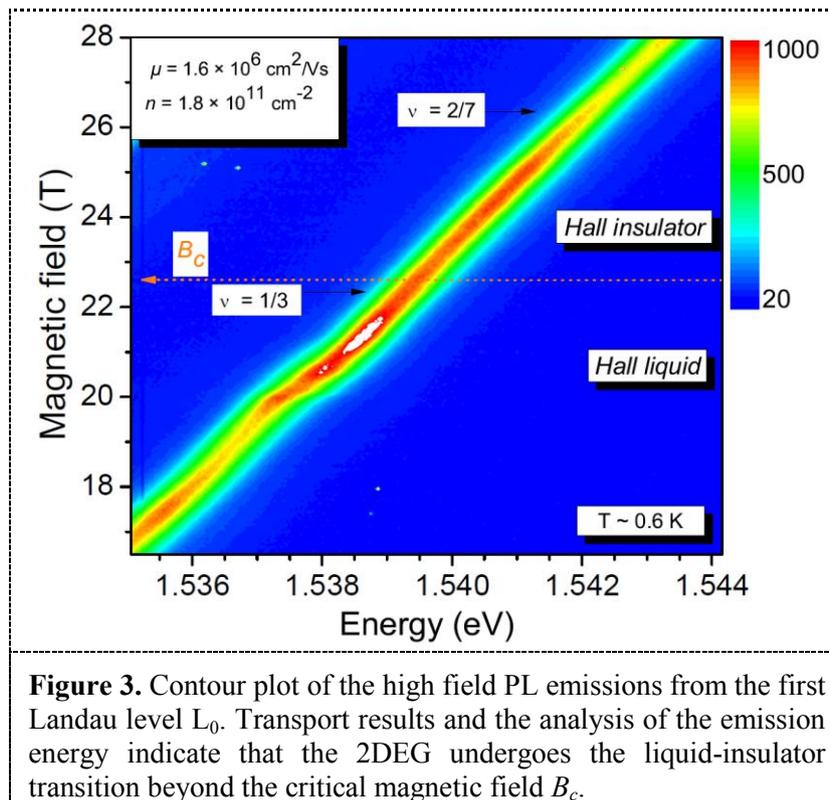
Figure 1. (top) contour plot of the PL emission from the first Landau level $\sim 600 \text{ mK}$; **(bottom)** PL intensity vs magnetic field.

Figure 2. PL intensity and area vs B in the magnetic field range between $2/5$ and $1/3$. Clear depression of the optical emission is observed at $4/11$ and $3/8$.

The states belonging to group ii) do not belong to the IQHE of CF series, but at least the first three can be explained in the frame of the theory of J. K. Jain [6], imagining the corresponding quantum states as FQHE of CFs. This requires to assume that the CF-CF interaction is not vanishing, but the residual interaction manifests itself as FQHE, which implies composing CFs of CFs (see for example the experimental work of Gallais et al. [17]). On the contrary, the origin of $\nu = 3/8$ can neither be explained as IQHE nor as FQHE of CFs. Indeed, the enigmatic origin of this state, which has been observed only in few recent magneto-transport experiments as a small minimum in R_{xx} [2], is still under debate. For its explanation, a model invokes an instability in the Fermi sea with opening of a gap involving a p-wave pairing of CFs [18], with similarities to the pairing proposed to explain the minimum in R_{xx} observed at $\nu = 5/2$ due to the occurrence of a BCS-like ‘‘Pfaffian’’ state [19-21]. A different approach proposes the grouping of quasi-particles as a possible explanation [18]. Another picture suggests the clustering of composite bosons that carrying flux positive as well as negative quanta [22]. In the framework of all these theories describing the occurrence of a minimum in R_{xx} at $\nu = 3/8$, the optical observation of the $3/8$ state in the optical emission represents a cue for a better understandings of its nature.

We also investigated the magnetic field dispersion of the emission energy. We observe that the strongest L_0 emission is accompanied by the ones from higher LLs (at higher energy) and the one from

a shake-up (SU1) process [23] (at lower energy). All these emissions approximately follow a linear dispersion, but the accurate analysis of the L_0 energy vs B at very low temperature shows several interesting features [14]. At low field L_0 follows quite close the LL dispersion, while above $B_{\nu=2}$ it deviates and stays well below the linear behavior $1/2(\hbar\omega_{c-e} + \hbar\omega_{c-h})$, also exhibiting two small inflections or shifts at $\nu = 2/3$ and between $\nu = 2/5$ and $\nu = 1/3$ (also observed by I. Bar-Joseph et al. [23], and by M. Byszewski et al. [8]).



In this range we observe another change in the overall behavior of the energy dispersion: it becomes quadratic up to ~ 19 T, as typically observed for electron-hole bound states like neutral or charged excitons [24]. Above ~ 21 T the emission follows another dispersion law that we find out to be linear, suggesting that the system is evolving from a liquid phase to an insulating one [14]. Fig. 3 shows the contour plot of the emission at magnetic fields, below and above the critical field B_c of the liquid-to-insulator transition, obtaining B_c from the transport measurements, because at B_c the R_{xy} crosses the values h/e^2 [14]. In high mobility GaAs-AlGaAs samples the transition takes place beyond the $\nu = 1/3$ state (as in our case) or the $\nu = 1/5$ state [9]. The frame for the interpretation of our results, obtained in simultaneous optical and transport experiments also at ~ 40 mK [14], is provided by recent theoretical findings concerning the strong correlation effects in 2DEG [25], showing that the insulating phase results from the incipient charge ordering driven by Coulomb interactions, and also by experimental works showing that at intermediate density and close to criticality the electrons exhibit an increased effective mass [26] also due to the strong correlations.

4. Conclusions

In conclusion, the quantum states at several fractional ν have been observed in optical experiments as suppression of the PL emission and interpreted using a model based on the CFs picture and the Coulomb screening of the 2DEG ($\nu = 4/5, 5/7, 4/11$), or attributed to the weakening of the screening of the Coulomb interaction among the quasi-particles which compose the state ($\nu = 3/8$). The correlation

effects in our 2DEG have also been investigated by simultaneous optical and transport experiments, observing a drastic change in the emission energy when the system undergoes the metal-insulator transition.

Acknowledgments

We are grateful to M. Hilke, W. Pan, G. Pastori Parravicini and M. Potemski and for enlightening discussions. This work has been supported by the Cariplo Foundation *QUANTDEV*, the Spanish Ministry of Science and Innovation (FIS2009-07880, PPT310000-2009-6, PCT310000-2009-3), the Junta de Castilla y León (SA049A10), and by EuroMagNET, EU contract n° 228043.

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