Free versus localized hole magnetophotoluminescence in semiconductor heterojunctions near integer filling factors

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The influence of hole localization on the magnetoluminescence emission of a two-dimensional electron gas present in a semiconductor modulation-doped heterojunction is studied. For holes localized at a dilute delta layer of Be acceptors at large distances from the interface a narrow emission line is observed due to a Fermi-edge singularity involving electrons in the second confined state. The evolution of this line in a perpendicular magnetic field shows common characteristics with previous results in high mobility samples not containing Be, which are indicative of a general behavior of the electron system in heterojunctions involving localized holes. At filling factor 2 the emission intensity is abruptly transferred to the recombination of electrons in the lowest Landau level with free valence holes, irrespective of the presence of Be. The abruptness of this transition, which is also observed in some samples at filling factor 1, reveals a coherent change in the electron system over a macroscopic sample area. The new optical emission shows marked deviations with respect to the single-particle behavior, which are tentatively interpreted as the formation of a complex state involving a free photocreated hole and the electron system. This complex unbinds when the Fermi level crosses the mobility edge.

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I. INTRODUCTION

Electron interactions in two-dimensional electron-gas systems (2DEG) subjected to a perpendicular magnetic field are known to play a key role, both in the fractional and the integer quantum Hall effects (F-IQHE). In the past, a renewed interest emerged into interaction effects in Landau levels (LL's) higher than one, where significant deviations of the single-particle physics are observed. The occurrence of collective states without translation invariance in the 2DEG, as stripe and bubble phases, charge-density waves, and the Wigner crystal,[1,2] at or around high integer filling factors are good examples of interaction effects in the IQHE. Recent experiments on microwave absorption[3] suggest the formation of a two-dimensional Wigner crystal close to integer filling factors 1 and 2. These findings are in accordance with the idea that carriers in filled LL's are "inert" for dynamical screening in a similar way as are electrons in closed atomic shells. The few remaining electrons (holes) in the highest occupied LL slightly above (below) integer filling factors are responsible for the main collective response of the 2DEG.[1–4] Optical studies in high mobility 2DEG have been performed since a long time[4–12] to get insight into the interaction effects. Optical methods aim to overcome the possible influence of electrical contacts, which are present in transport experiments, and to probe electron states at energies away from the Fermi level. However, the inherent drawback of photoluminescence (PL) studies is the possible perturbation of the 2DEG by the photocreated holes (PCH's). One way to minimize this perturbation is to use modulation-doped semiconductor heterojunctions (HJ's) instead of quantum wells, where the electrons and holes are in the same (or in a nearby) spatial region. In HJ's the PCH's tend to escape away from the interface due to the built-in electric field. Then the PL emission from the 2DEG vanishes unless the hole is kept near the interface. This can occur either by trapping at defects due to uncontrolled disorder, by screening of the electric field (band flattening) due to weak *n*-type residual doping,[4] or by trapping at a δ layer of acceptors (normally Be) located at a certain distance from the HJ.[7,10] In the latter case, this distance determines the 2DEG interaction with the PCH's, and therefore influences the optical response of the system, as shown both experimentally[10] and theoretically.[13,14]

Magneto-PL (MPL) emission from samples involving (in principle) *free* holes have also been reported.[4,5,8,9] They show marked deviations from the single-particle trend in either the energy or the intensity of the PL emission at integer filling factors. In the case of recombination with *free* holes one would expect that conservation of the LL index is satisfied. In most experiments low power excitation is used, so that the few created PCH's relax quickly to their ground state and hence, only recombination with electrons in the lowest LL is possible.

In this paper we address the role of hole localization in the MPL response of a 2DEG in a semiconductor single HJ. Our approach is to compare samples having a dilute δ-doping layer of Be acceptors in the GaAs side at a given distance from the HJ interface, with Be-free samples. The two types of samples display some specific PL properties and some common ones. It is therefore important to compare both for a proper elucidation of the role played by hole localization in their optical properties. Simultaneous optical and transport measurements in Be-doped samples reveal

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TABLE I. Growth parameters and transport properties of the three studied samples: doping density [Si], doping layer width D, spacer width L, electron density n, Fermi energy E_F, and mobility μ. Sample A has a δ-doping layer of Be in the GaAs side, as explained in the text.

Sample	[Si] (cm^{-3})	D (nm)	L (nm)	n (cm^{-2})	E_F (meV)	μ(cm^2/V s)
A	1.0×10^{18}	40	45	3.16×10^{11}	11.3	
B	1.5×10^{18}	45	80	3.24×10^{11}	11.6	2×10^{6}
C	1.5×10^{18}	45	80	1.96×10^{11}	7.0	0.9×10^{6}

sharp peaks in the MPL spectrum at integer filling factors, which are due to Fermi-edge singularities (FES) associated to electrons in the weakly populated second confined subband recombining with localized holes.[10] The details of their intensity dependence on magnetic field strikingly coincide with data reported[4] in a high-mobility, low-density 2DEG, thus indicating that hole localization by residual disorder can play a key role even in very high mobility samples. Below filling factor $\nu=2$ an abrupt onset of the MPL emission occurs involving *free* valence-band holes in both Be-containing and Be-free samples. At low temperature this emission shows marked deviations from the expected LL trend, both in the energy and intensity dependence on the magnetic field. This anomalous behavior disappears when the Fermi level crosses the mobility edge[9] and is observed in some cases also at $\nu=1$. This behavior is tentatively attributed to the formation of a complex state involving a small number of LL holes (electrons missing in one of the spin branches of the lowest LL) and the valence-band hole. By small number we mean a density for which the inter LL-hole distance is larger than the magnetic length.

II. EXPERIMENT

The modulation-doped $Al_{0.33}Ga_{0.67}As/GaAs$ single HJ's are grown by molecular-beam epitaxy on GaAs (001). The layer stack consists of a GaAs/AlGaAs short-period superlattice buffer layer, a 1000 nm thick GaAs layer, an undoped $Al_{0.3}Ga_{0.7}As$ spacer layer, a Si-doped $Al_{0.3}Ga_{0.7}As$ layer, and a thin undoped GaAs cap layer. The numerical values of the spacer thickness L, the doped layer thickness D, and the doping level (Si) are listed in Table I for the three samples studied. In one of the samples (sample A) a dilute Be δ-doping layer (1×10^{9} cm^{-2}) is located in the GaAs side at a distance $d=60$ nm from the HJ interface. The other samples (samples B and C) have no Be layer. The diagram of the band structure is shown in the inset of Fig. 1. Two electron states (E_0,E_1) are confined at the HJ with the Fermi level E_F slightly above E_1, as it will be shown later. The arrows indicate the PL transitions discussed in the following section. A Hall bar was fabricated on some of the samples to allow simultaneous measurement of PL and transport properties.

The electron densities determined from transport measurements under experimental illumination conditions are listed in Table I together with the Fermi energies and electron mobilities. PL measurements were performed at 280 mK in the ^{3}He-immersion insert of a cryostat with a superconducting magnet providing magnetic fields up to 12 T. The samples were optically accessed through windows located at the bottom of the cryostat. A Ti-sapphire laser was used for PL excitation below the band gap of the AlGaAs barrier. The excitation power was kept below 30 mW/cm^2, and the emitted light was detected with a double spectrometer and a charge coupled device detector.

III. RESULTS AND DISCUSSION

A. Zero magnetic field

The PL spectrum at zero field of sample A is shown in Fig. 1. The most intense peaks around 1.514 eV (marked X) are due to bulk excitons of the GaAs layer. Recombination of electrons at the ground state E_0 with valence-band holes (see inset) is hindered by the built-in electric field. However, it can be observed due to hole trapping at residual disorder as a small step at 1.505 eV. Its low intensity (two orders of magnitude smaller than the X peak) indicates that residual disorder in the sample is marginal for hole trapping. As shown later, recombination of the E_1 electrons with valence-band holes, which is also expected to be weak, occurs at nearly the same energy as the X excitons, and is hidden by them. In the

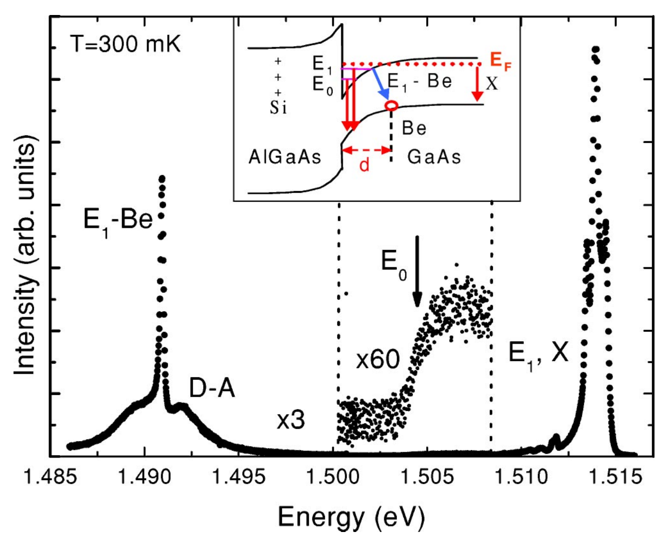

FIG. 1. (Color online) PL spectrum of sample A at zero magnetic field. Note the enlargement factors of the different regions. The inset shows the band diagram of the sample. The electron states and the optical transitions discussed in the text are indicated.

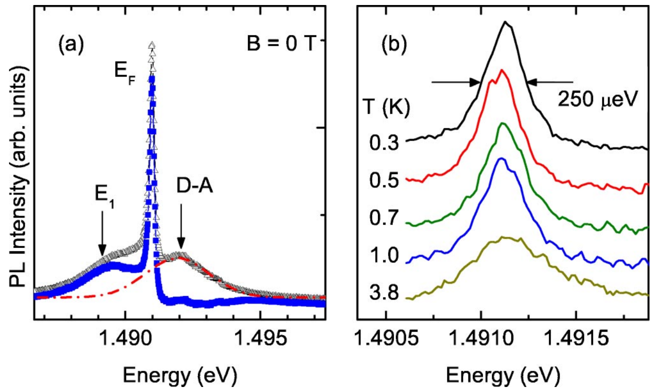

FIG. 2. (Color online) (a) Line shape of the E_1-Be emission (closed square, blue) obtained by subtracting a Gaussian (dashed, red) representing the donor-to-acceptor emission of carbon from the raw spectrum (open triangle, black). (b) Temperature dependence of the E_1-Be emission at the Fermi level.

low-energy part of the spectrum a very sharp line appears at 1.491 eV on top of the broad emission of donor-to-acceptor transitions $(D\text{-}A)$ due to carbon impurities. The sharp line is due to E_1 electrons recombining to PCH trapped at Be acceptors.[10] At difference with previous work,[7,15] where the distance from the Be layer to the HJ interface was lower, we do not observe E_0 electron recombination with Be-trapped holes due to their poor wave function overlap. The E_1-Be emission line shape is obtained in Fig. 2(a) (closed square, blue) by subtracting from the raw data (open triangle, black) a Gaussian (dashed red line) representing the *D-A* emission, as taken from the spectra of Be-free samples. The E_1-Be line shape is characteristic of a FES, which has been thoroughly studied[5,7,16] in high mobility 2DEG's with localized holes. Indeed, the PL line shape associated to recombination of E_1 electrons bears a strong resemblance with the result reported in Ref. 5 for E_0 recombination. In our case the PL emission starts at the E_1 band edge (marked by an arrow) and shows a strong narrow peak [0.25 meV full width at half maximum (FWHM)] at the Fermi level. The possible coupling of electrons at the Fermi level to the quasicontinuum of empty states above E_1 would support this interpretation.[17] The occupied E_1 bandwidth is $E_F - E_1 = 2.1$ meV. To confirm that the sharp E_1-Be emission corresponds to a FES, its temperature dependence has been measured. The results are shown in Fig. 2(b), where a rapid intensity decrease is observed in the temperature range between 0.3 and 3.8 K. This decrease is due to the smearing of the Fermi surface at temperatures of the order of a few tenths of the Fermi energy.[16,17]

B. Be-doped sample in a magnetic field

The E_1-Be emission is an adequate tool to investigate the optical response of the 2DEG in a magnetic field, as it will provide the signature of the MPL response when the PCH's are localized. This will allow, as shown below, to identify other emission processes as involving free 2D holes. The intensity of the E_1-Be emission and the longitudinal (ρ_{xx}) and transverse (ρ_{xy}) resistivities have been simultaneously measured as a function of the magnetic field in sample *A* at

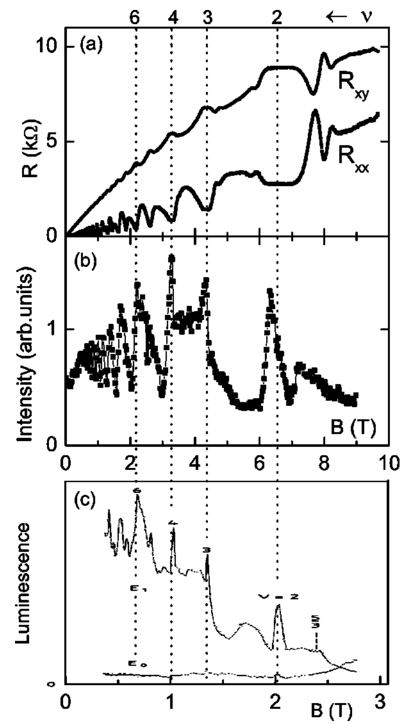

FIG. 3. (a) Longitudinal $(R\text{xx})$ and transverse $(R\text{xy})$ resistance of sample *A* for increasing magnetic field simultaneously measured with the PL emission. Some integer filling factors are indicated. (b) E_1-Be emission intensity versus magnetic field. (c) MPL intensity data taken from Ref. 4 in a low-density, high-mobility HJ sample. The horizontal scale has been stretched to compare equal filling factors.

300 mK. The results of transport measurements presented in Fig. 3(a) show distinct IQHE plateaus in ρ_{xy} and minima in ρ_{xx}. The increasing background at high magnetic fields arises from parallel conductance due to carriers in the doping layer produced by the sample illumination.[18] Figure 3(b) shows intensity maxima of the E_1-Be emission at integer filling factors, which become very sharp at high fields. These peaks have the same temperature dependence as in the zero-field case [Fig. 2(b)]. They are due to the joint effects of electron population of the E_1 state and the many-body interaction leading to the FES mentioned in the preceding section. Indeed, the weak E_1 population changes with increasing field whenever the Fermi level jumps from E_1 to the successive LL's of E_0,[7,10,19] originating intensity changes which are periodic in the E_0 filling factor. The sharp peaks in Fig. 3(b) do not reflect exclusively the E_1 population, but rather they result from the FES enhancement of the emission probability as in the zero-field case. The increased level coupling near the crossings of E_1 with the E_0-LL can contribute to the FES enhancement. The intensity of the E_1-Be emission depends strongly on the Be-HJ distance. It can be observed[10] up to $d = 100$ nm, thus indicating the large extension of the E_1 wave function away from the interface.

Figure 3(c) shows the MPL results of Ref. 4 for a similar HJ containing a 2DEG with $n = 9.7 \times 10^{10}$ cm^{-2} and $\mu = 9 \times 10^6$ cm^2/V s. The horizontal scale is set to compare both samples at equal filling factors. The similarity of the two PL data sets is striking considering the very different electron

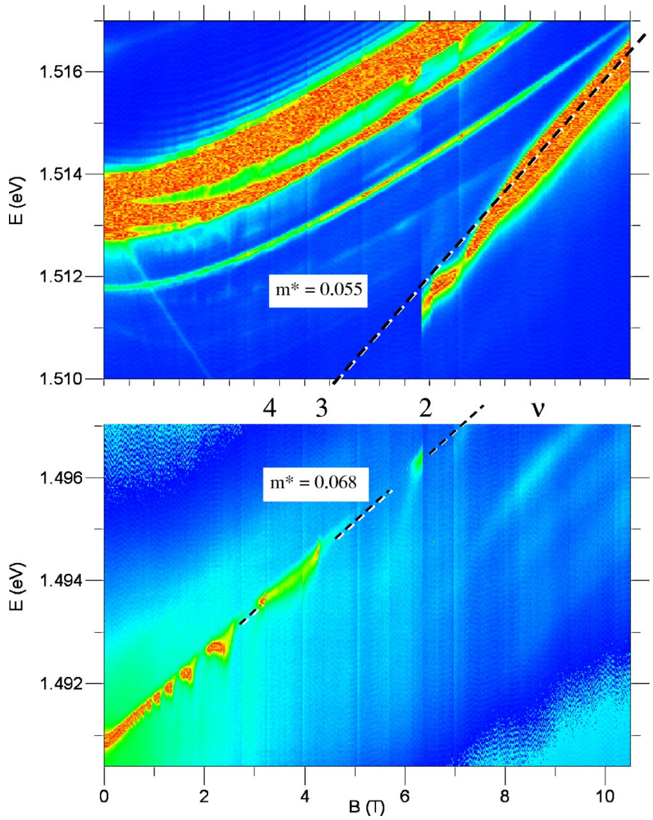

FIG. 4. (Color online) Energy and intensity (color scale) of magneto-PL of sample *A* versus magnetic field at 300 mK. The reduced effective masses of the E_1-Be and the E_0 emission lines are obtained from the slopes (see text).

densities and mobilities. This seems to indicate that, in spite of the very high mobility of the 2DEG, the E_1 recombination reported in Ref. 4 probably involves holes localized at residual disorder. These localization sites must be far enough from the HJ interface (remember the large E_1 wave function extension) to have a negligible effect on mobility.

The evolution of the spectrum in Fig. 1 with increasing magnetic field is shown in Fig. 4, where the emission intensity is represented as a color scale. The lower part of the figure shows again the E_1-Be MPL sharp emission with the intensity variations described above. Its energy increases linearly with a slope of 0.89 meV/T. Considering the energy dependence of the uppermost Zeeman level of a hole localized at a Be acceptor [0.041 meV/T (Ref. 20)], one obtains a conduction effective mass $m_e^*=0.068$, which coincides with the bulk GaAs value ($m_e^*=0.067$) within the experimental error. This clearly indicates that the E_1-Be emission involves free conduction E_1 electrons and localized holes. The magnetic field and temperature dependence of the E_1-Be emission bears some resemblance with the *E*-line reported in Ref. 12, although the intensity of the latter grows monotonically with the field. This is consistent with the interpretation of the *E* line as a recombination of the 2DEG with localized holes.[12] In the upper part of Fig. 4 the *X* emissions display the typical parabolic trend of excitons. At low fields one can observe a faint line with negative slope starting at 1.513 eV. It is attributed to shake-up (SU) processes, which are well known in other 2DEG systems.[21] They involve an E_1 electron recombination with a valence-band hole (probably localized by disorder, as in the case of the E_0 emission shown in Fig. 1). The recombination energy is shared between the emitted photon and an inter-LL electronic excitation. The SU extrapolation to zero field indicates precisely the E_1 band-edge position, which is 9.2 meV above E_0. The fact that the SU intensity does not change appreciably with the field is quite intriguing. It could be due to the coupling of E_1 and E_0 electrons, making the SU intensity sensitive to the overall E_0+E_1 electron population.

When the magnetic field increases, an abrupt intensity transfer occurs at $\nu=2$ from the E_1-Be band to a new emission line at 1.512 meV. The origin of this new recombination is attributed to the formation of a many-electron complex state including electrons in the lowest LL of E_0 and a free valence-band hole,[10] as discussed below. In fact, the E_0 emission energy at high fields varies linearly and extrapolates to its value of 1.505 eV at zero field, shown in Fig. 1. Its slope indicates a reduced effective mass of 0.055. The linear energy decrease of the E_0 transition with magnetic field is confirmed by its weak reappearance between filling factors 3 and 4 in Be-free samples.[9] This, together with the temperature dependence shown below, excludes excitons as a possible origin of the E_0 emission. At difference with the E_1-Be luminescence, this corresponds to free electrons ($m_e^*=0.067$) and *free* valence-band holes ($m_h^*=0.34$) in GaAs.[22] The intensity changes of the E_0 emission are correlated with small changes in the *X* emission, indicating that part of the excitonic emission occurs near the HJ interface.[11] The appearance of the E_0 luminescence involving free holes only below $\nu=2$ is consistent with LL index conservation. It also shows the "inert" behavior of filled LL's for recombination.[4,9,10] However, the abruptness of the emission onset at $\nu=2$ and its strong intensity compared with the E_0 emission at zero field indicates that an efficient coupling mechanism appears below $\nu=2$ between the 2DEG and the valence-band hole, which is in an extended state, at least in a plane parallel to the HJ. This mechanism is strong enough to prevent PCH trapping at Be acceptors and occurs simultaneously over a macroscopic area of the sample (at least of the order of the laser spot size, i.e., around 100 μm). This surprising uniformity of the electron system response in the vicinity of $\nu=2$ has been also reported for even filling factors in photon statistics measurements.[23] The remaining features of the E_0 emission in Be-doped samples and in Be-free ones have many common points and will be treated in the following section.

C. Be-free samples

The abrupt transition at $\nu=2$ has been also observed in Be-free HJ samples having different electron densities.[8,9] Consequently, it is not related to the peculiarities of the valence-band structure, nor, as just shown, to hole localization. The energy and intensity dependence of the E_0 emission on the magnetic field at filling factors below 2 shows significant deviations from the LL behavior at low temperatures, as shown in the inset of Fig. 5 for the Be-free HJ (sample *B*). Comparison of Figs. 4 and 5(inset) indicate that the "anoma-

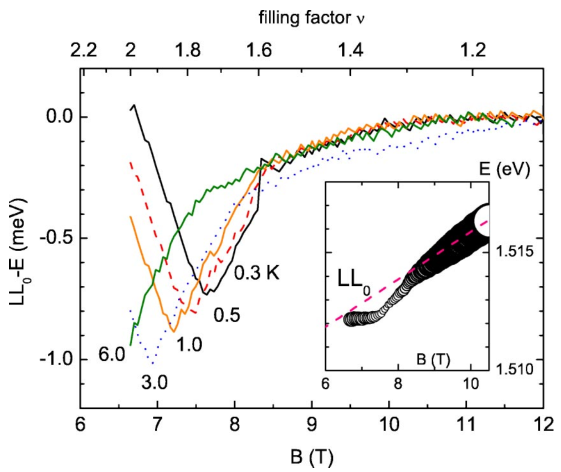

FIG. 5. (Color online) Temperature dependence of the E_0 energy of sample *B* versus magnetic field subtracted from the linear LL_0 trend as shown in the inset.

lous behavior" is less marked in sample *A*. Although anomalies are generally observed in our samples, their specific details (the amount of deviation with respect to the LL linear trend and the abruptness of the change of the emission intensity as a function of the field) change from sample to sample. In some cases these changes might be related to the influence of the electrical contacts on the 2DEG in samples prepared for transport measurements. However, the presence of the Be layer has no systematic influence on the anomalies. The energy deviation of the E_0 emission of sample *B* with respect to the linear LL trend is represented in Fig. 5 for increasing temperatures. At 0.3 K it has a marked dip near $\nu=1.8$ and progressively disappears at a field corresponding to $\nu \cong 1.6$. For increasing temperatures, the dip moves to lower fields and finally disappears. By simultaneous transport and optical measurements in a similar sample, the magnetic-field value at the dip has been shown[9] to coincide with the crossing of the mobility edge and the Fermi level. This suggests that the reported "anomaly" can be due to the formation of a complex state including the 2DEG system and the extended hole, which is unbound by screening when the 2DEG becomes compressible.

Similar measurements have been performed in sample *C*, with a lower electron density. Figure 6 displays the simultaneous (a) optical and (b) transport measurements. In addition to the abrupt PL onset at $\nu=2$, there is a sudden jump to lower energies at $\nu=1$ followed by a similar field dependence. The kinks of the energy versus magnetic-field curves (the magnetic fields at which the deviation with respect to the LL linear trend is maximum) coincide in both cases with the crossing of the mobility edge with the Fermi level, i.e., $\nu=1.8$ and $\nu=0.9$, respectively. The main trend of Fig. 6(a) is similar to the results reported in Ref. 8 for the high-electron-density case. However, the abruptness of the changes in the present case indicates again a change of the optical response at both integer filling factors, *which is coherent over a macroscopic area of the sample*. Results in Fig. 6(a) indicate that similar mechanisms control the behavior of the MPL at both $\nu=1$ and $\nu=2$. The jump at $\nu=1$ has been interpreted in terms of a change in the lowest-energy state before recombination from an "excitonic" state above $\nu=1$ formed by the electron system and the valence hole to a "free hole" state below $\nu=1$.[8,13] However, it is not clear whether this interpretation can be applied to $\nu=2$.

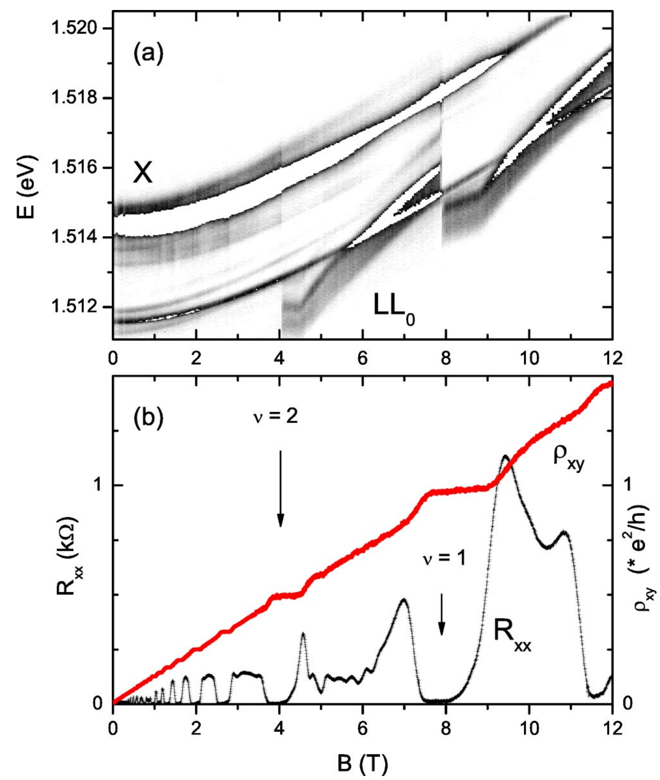

FIG. 6. (Color online) (a) MPL energy and intensity (gray scale) of sample *C* versus magnetic field at 300 mK. The exciton (*X*) and the lowest Landau level LL_0 are indicated. (b) Longitudinal and transverse magnetoresistances simultaneously measured with the PL emission.

The nature of the complex state involving the 2DEG and the PCH, suggested to be the origin of the reported "anomalies," is unknown and needs further investigation, including theory. One can exclude the formation of charged excitons (as in the recent work on fractionally charged quasiholes[24]) because of the high electron concentration of our samples. Instead, an hypothetical complex formed by the few missing electrons in the spin-down state of the lowest LL index at $\nu<2$ (LL holes), or spin-up missing electrons at $\nu<1$, and the extended hole, could be considered as the origin of the anomalies. Charged complex states of this kind have been proposed[13] for a small number of quasiparticles. Considering sample *B*, at $\nu=1.8$ the LL-hole density is $n_{LLh}=4.2\times 10^{10}$ cm^{-2}, corresponding to an average inter-LL-hole distance five times larger than the magnetic length l_B ($l_B=9.3$ nm for 7.5 T). This gives a value of the parameter r_s (which measures the ratio of the Coulomb energy to the kinetic energy) of $r_s=(\pi n_{LLh})^{-1/2}(a_B)^{-1}=2.7$, where a_B is the effective Bohr radius. Similar values are obtained for samples *A* and *C*. Thus, the LL holes can be regarded as an ensemble of independent particles subject to Coulomb interaction, which would form the complex state with the valence hole when the filling factor is slightly below 1 or 2.

IV. SUMMARY

In summary, in a comparative study of samples containing a high mobility 2DEG, with and without the presence of a dilute layer of Be acceptors, we report a narrow many-body emission line in samples with the Be acceptor layer. This line corresponds to the E_1-Be recombination. The evolution of this line in a perpendicular magnetic field reveals common characteristics with previous results in high-quality samples, which are indicative of a general behavior of 2DEG recombination with localized holes. At filling factor 2 an abrupt transfer of emission intensity occurs to the lowest E_0-LL recombination with free valence holes, irrespective of the presence of Be. The deviations of the energy dependence on the magnetic field with respect to the single-particle LL behavior is found also at $\nu=1$. It is tentatively interpreted in terms of the formation of a complex state involving the free photocreated hole and the dilute gas of LL holes. This complex, whose exact nature is unknown, unbinds at higher magnetic fields, when the Fermi level crosses the mobility edge.

ACKNOWLEDEMENTS

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