Evidence of inter-layer interaction in magneto-luminescence spectra of electron bilayers

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Magneto-luminescence studies in electron bilayers reveal the hallmarks of the even-denominator and other quantum Hall states in the intensities and energies of the inter-band optical recombination lines. In the presence of a small tunneling gap between the layers the magneto-optical emission from the lowest anti-symmetric subband, not populated in a single-electron picture, displays maxima at filling factors 1 and 2/3. These findings uncover a loss of pseudospin polarization, where the pseudospin describes the layer index degree of freedom, that is linked to an anomalous population of the anti-symmetric level due to excitonic correlations. The results demonstrate a new realm to probe the impact of inter-layer Coulomb interaction in quantum Hall bilayers.

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The terms of Coulomb interaction that arise from the spatial separation of electrons in double layer semiconductor heterostructures are at the origin of several new phenomena that occur in the quantum Hall (QH) regime. The prominent physics linked to the impact of inter-layer electron interaction dramatically manifests in the even-denominator QH state at total filling factor $\nu_T = 1$. Much attention was devoted to the quantum phase diagram of bilayers at $\nu_T = 1$ as a function of $\Delta_{SAS}/E_c$ and $d/l_B$ ($\Delta_{SAS}$ is the tunneling gap, $E_c = e^2/\epsilon d_B$, $l_B$ is the magnetic length, $d$ is the inter-layer distance). The description of inter-layer correlated states frequently employs a pseudospin degree of freedom that labels the electron occupation of the left and right layers. In pseudospin language, for example, the inter-layer correlated QH state at $\nu_T = 1$ and $\Delta_{SAS} = 0$ is described as an easy-plane pseudospin ferromagnetic phase with a spontaneously broken symmetry. Alternatively, this quantum phase can be regarded as an inter-layer exciton condensate.

Several experiments have highlighted the unique properties of the intriguing $\nu_T = 1$ state that emerges at $\Delta_{SAS} = 0$. These experiments have uncovered evidence of counterflow superfluid-like behavior and have established the existence of a finite-temperature phase transition. At finite values of the tunneling gap, on the other hand, the pseudospins align along a specific direction in the plane, in a manner that is linked to the electron occupation of the symmetric combination (S) of the lowest-energy quantum-well Landau levels (LL). However, if the tunneling gap remains sufficiently small, quantum fluctuations can lead to a suppression of the pseudospin ordering, which in turn leads to an anomalous occupation of the lowest antisymmetric spin-up (AS↑) Landau level. Indeed a loss of pseudospin order was probed at $\nu_T = 1$ by inelastic light scattering methods.

While extensive investigations of quantum Hall bilayers were carried out by magneto-transport techniques, light scattering and NMR, little efforts were devoted to studies of magneto-photoluminescence (magneto-PL). This is surprising since in single layers the magneto-PL is a powerful probe of electron-correlation and of spin polarization in the regimes of the integer and fractional quantum Hall effects. Some impacts of Coulomb interactions in magneto-PL, however, are hidden in symmetric modulation-doped heterostructures where the optical emission lines display a cross-over from Landau-level (linear) to excitonic (quadratic) behavior that, irrespective of the electron density, occurs exactly at $\nu = 2$. This effect, termed hidden symmetry (HS), results from a cancellation between the Coulomb interaction among the electrons in the conduction band and with the photo-generated hole in the valence band. It requires the square modulus of the electron and hole envelope functions to be similar in shape.

Motivated by this scenario, here we report the magneto-PL study of QH states in coupled electron bilayers. For the bilayer with vanishing tunneling gap the intensity minima of the lowest energy emission line at $\nu_T = 1$ and at $\nu_T = 1/2$ represent unambiguous manifestations of the occurrence of such inter-layer correlated quantum Hall states in magneto-PL. The evolution of the magneto-PL line intensities in a bilayer with a finite value of the tunneling gap confirms the loss of pseudospin polarization at $\nu_T = 1$ that arises from excitonic correlations in the ground state and reveals a similar but more pronounced effect at $\nu_T = 2/3$. In addition, in both samples we observe the characteristic signature of the hidden-symmetry transition which, contrary to conventional single layer systems, is seen at $\nu_T = 4$ due to the impact of the pseudospin degree of freedom. Indeed the HS requires both electrons and holes to be in the lowest LL. In double layers, because of the simultaneous presence of spin and pseudospin degrees of freedom, each LL consists of four sublevels with similar envelope function...
A nominally symmetric modulation-doped AlAs/GaAs double quantum well structure is designed, where the electron mobility is above $10^{11}$ cm$^{-2}$/Vs. The total electron density is $n_F \sim 1.1 \times 10^{11}$ cm$^{-2}$ and electron mobility above $10^6$ cm$^2$/Vs. A perpendicular magnetic field was applied to the electron bilayer. The magneto-PL spectra were measured after excitation with a single-mode tunable Ti-Sapphire laser at 795 nm. Laser power densities were kept at $10^{-4}$ W/cm$^2$ to avoid electron heating effects and circularly-polarized configurations were exploited to have access to spin states. A triple-grating spectrometer equipped with a CCD detector was used to detect the emitted light.

Figure 1(a) shows a representative left-circularly-polarized ($\sigma^-$) PL spectrum at a magnetic field of 6 T from the sample with a finite tunneling gap. The main PL lines (magenta and blue) are assigned to recombination from the spin-up ($I^S$) and spin-down ($I^D$) levels, respectively, while the higher energy peak (red line) is linked to recombination of electrons in the AS$^\uparrow$ level ($I^A$). This assignment is supported by the circularly-polarized analysis reported in Fig. 1(b), which shows that the magenta and red peaks are left circularly polarized ($\sigma^-$), as opposed to the right circularly polarized ($\sigma^+$) blue peak. Furthermore, the energy separation of the blue and magenta lines displays a linear dependence on the magnetic field as expected from Zeeman-split lines with an effective Landé factor of $g_{eff} \approx 1.4$ (data not shown). The additional low-energy shoulder (green line in Fig. 1(a)) follows the evolution of the main PL line. We ascribe it to a disorder-assisted recombination and it will not be further discussed in the following.

Figure 1(c) is a color plot of the magneto-PL in $\sigma^-$ polarization. We can identify two different regions: a low-field region ($B < 1.5$ T) where a Landau fan of three peaks can be noticed, and a high-field region ($B > 1.5$ T) where the main emission line deviates from the linear behavior and in addition it displays several intensity oscillations. The plots of the peak energies and intensities, are shown in Figs. 2(a),(b).

If $(n,m)$ denotes the optical recombination of the electron in the $n$ LL with the heavy-hole in the $m$ LL, then the linear energy variations of the blue-magenta, orange and black peaks in Fig. 2(b) are compatible with the (0,0), (0,2) and (1,1) recombinations, respectively.

At $\nu_T = 4$ the magnetic-field dependence of the blue-magenta line energy changes abruptly from linear to quadratic, indicating the formation of a bound exciton. In analogy to magneto-PL studies in single layers, we interpret this changeover as due to the onset of the HS. This observation extends the validity of the HS to coupled bilayers where the lowest LL consists of four sublevels owing to the presence of both spin and pseudospin degrees of freedom.

Figure 2(b) reveals several intensity oscillations of the lowest energy emission line from the electrons in the lowest symmetric (pseudospin-up) LL. The maxima at 2.6,
4.8 and 7.1 T are linked to the occurrence of QH states with \( \nu_T = 2, 1 \) and \( 2/3 \), respectively, which are also observed in transport measurements (data not shown here). In addition, the emission from the antisymmetric (pseudospin-down) spin-up level displays maxima around \( \nu_T = 1 \) and \( \nu_T = 2/3 \), suggesting that at these two QH states a fraction of electrons populates the \( \sigma \) level as a consequence of a loss of pseudospin polarization. At \( \nu_T = 1 \) the loss of pseudospin polarization was previously observed in inelastic light scattering spectra \(^{19}\) and interpreted as a result of the formation of electron-hole excitonic pairs across \( \Delta_{SAS} \). At \( \nu_T = 2/3 \) no evidence was reported so far.

The emission intensity from the AS state increases by a factor of two passing from \( \nu_T = 1 \) to \( \nu_T = 2/3 \), suggesting that the loss of pseudospin polarization is more pronounced for the 2/3 state. Indeed a simple estimate based on the ratio of the relative intensities of the S and AS emission lines and on the \( \nu_T = 1 \) pseudospin polarization value of 36% reported previously\(^{10}\) suggests that for the 2/3 state the loss of pseudospin polarization is complete. This result is in agreement with numerical studies\(^{22}\) that describe this state through the pseudospin unpolarized Halperin (3,3,0) wavefunction for \( d/I_B \) above some critical value depending on \( \Delta_{SAS} \). In fact, for sufficiently large \( d/I_B \) the energetic advantage of localizing electrons in opposite layers (as in the (3,3,0) state) outweighs the tunneling energy cost.

We focus now on the sample with vanishing tunneling gap. A representative \( \sigma^- \) polarized emission spectrum from this sample at \( B = 6 \) T is shown in Fig. 3(a). Four emission lines are identified, which we label \( I_0^- \), \( I_0^+ \), \( I_1^- \), and \( I_1^+ \), in increasing order of energy. The polarization analysis shown in Fig. 3(b) indicates that the \( I_0^- \), \( I_1^- \), and \( I_1^+ \) lines are \( \sigma^- \) polarized and we link them to the recombinations of electrons in the lowest spin-up LL (see inset to Fig. 3(a)) with different heavy-hole levels. The \( I_0^+ \), on the contrary, involves the recombination of spin-down electrons. The magnetic field variation of the energy difference between \( I_0^- \) and \( I_0^+ \) is linear as expected for Zeeman-split lines and yields an effective Landé fac-

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**FIG. 2.** (Color online) (a) Peak energies and (b) integrated intensities vs magnetic field for the \( \sigma^- \) polarized PL spectra from the finite tunneling gap sample at 50 mK. The filling factors of the QH states observed in transport experiments are indicated in the upper axis. The short-dashed lines in (b) represent the best linear fits to the energy data at low magnetic fields.

**FIG. 3.** (Color online) PL data from the sample with vanishing tunneling gap at 50 mK. (a) Representative spectrum in \( \sigma^- \) polarization at \( B = 6 \) T fitted with Gaussian lines. The inset represents a schematic of the spin-split states in the lowest Landau level in the conduction and valence bands. Each spin state has a double pseudospin degeneracy. (b) Spectrum resulting from the difference between the \( \sigma^- \) and the \( \sigma^+ \) polarized emissions at 6 T. (c) Color plot of the \( \sigma^- \) polarized spectra in the range 0 - 9.5 T.
The peak energies for all four lines are shown in Fig. 4(a). At low magnetic fields, the PL energies vary linearly with B. Using the same values as above for the electron and heavy-hole effective masses, we attribute the $I_0^+$ and $I_1^+$ emissions to the $(0,0)$, $(0,1)$ recombinations, respectively. Again the lowest energy line ($I_0^+$) displays an abrupt change-over from linear (single particle) to quadratic (excitonic) behavior at $\nu_T = 4$, suggesting the impact of the HS and of the pseudospin degree of freedom also in this case. The linear-to-quadratic change occurs at $\nu_T = 2$ for the $I_1^+$ line. Indeed this emission line involves holes from a higher LL ($m = 1$) and therefore it is not subject to the HS mechanism. The different behavior between the lowest and the higher energy lines was also observed in single layers.\textsuperscript{20}

The magnetic field positions of the QH states at $\nu_T = 4, 2, 1, 2/3$ and $1/2$ as identified in magneto-transport data (not shown) are indicated with arrows in Fig. 4. The lowest energy line $I_0^+$ displays intensity minima (see Fig. 4(b)) in correspondence to the occurrence of such QH states. The intensity minima appear independently from the value of the laser excitation wavelength (data not shown), which rules out the possibility that they could result from magnetic field-induced changes in the absorption. The quenching of the emission is indeed a manifestation of the QH states and can be linked to the reduction of the optical matrix element associated with the onset of QH phases. The latter follows from the localization of electrons and holes in the disorder potential, which increases in the gapped QH phases because of the reduced electron screening.\textsuperscript{27} We remark that the observed QH states with $\nu_T = 1$ and $1/2$ are genuinely linked to the impact of inter-layer correlations. In particular the $\nu_T = 1/2$ state has no counterpart in single-layer single-component systems.

Finally the magneto-PL energies vary smoothly with B for $\nu_T < 4$ in both samples (see Figs. 2(a) and 4(a)) and do not provide evidence of QH states. This behavior is a consequence of the HS.

In conclusion we have studied the magneto-PL spectra in coupled bilayers in the QH regime. The evolution of the intensities of the emission lines in a magnetic field reveals a loss of pseudospin polarization at $\nu_T = 1$ and $2/3$ in a sample with a finite moderate value of $\Delta_{SAS}$ and signals the occurrence of inter-layer correlated QH states at $\nu_T = 1$ and $1/2$ in the vanishing $\Delta_{SAS}$ sample. The energy evolution of the emission lines reveals the role of the hidden symmetry at magnetic fields above $\nu_T = 4$. Magneto-PL appears as a promising technique to investigate the role of inter-layer correlation in bilayers. Future experiments in slightly asymmetric double layers can finely probe the role of inter-layer electron interactions at $\nu_T = 1$ or in the fractional QH regime.

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