PHYSICAL REVIEW B **68**, 045325 (2003)

Exchange-enhanced energy shifts in the polarized photoluminescence of a two-dimensional hole system in the integer quantum Hall regime

T. B. Kehoe,[1] C. M. Townsley,[1,*] A. Usher,[1] M. Henini,[2] and G. Hill[3]
[1]*School of Physics, University of Exeter, Stocker Road, Exeter, EX4 4QL, United Kingdom*
[2]*Department of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, United Kingdom*
[3]*Department of Electronic and Electrical Engineering, University of Sheffield, Mappin Street, Sheffield, S1 4DU, United Kingdom*

(Received 19 June 2002; revised manuscript received 19 May 2003; published 30 July 2003)

Polarized photoluminescence spectroscopy studies have been performed on two-dimensional hole systems in GaAs-(Al,Ga)As one-side modulation-doped quantum wells in the integer quantum Hall effect regime. Energy shifts of the photoluminescence are observed at integer filling factors. For $\nu \geqslant 2$, the energies of the photoluminescence in the right- and left-circular polarizations are almost equal near even filling factors and maximally separated near odd filling factors. This behavior is attributed to a combination of many-body effects in the screening of the correlation hole of the photoexcited electrons and an exchange-enhanced Zeeman splitting at odd filling factors. At $\nu = 1$ upward energy shifts are seen in both polarizations; in contrast to the behavior at other odd filling factors, the transition energies in the two polarizations are almost equal instead of being maximally separated. This is attributed to the occurrence of filling factor $\nu = 1$ in a region of magnetic field where there is strong mixing of the heavy-hole and light-hole states.

DOI: 10.1103/PhysRevB.68.045325 PACS number(s): 73.43.−f, 78.55.−m, 78.67.De

I. INTRODUCTION

Photoluminescence (PL) spectroscopy is well established as a useful technique in the study of the physics behind the integer and fractional quantum Hall effects (IQHE and FQHE) in two-dimensional electron systems. The optical signatures of the quantum Hall effects can consist of spectral energy shifts and line splittings, together with intensity modulations, coinciding with integer and fractional Landau-level occupancies. The origin of the PL of a two-dimensional (2D) electron or hole system in the IQHE regime depends on the carrier density, the separation between the recombining electron and hole, and the amount of disorder in the sample. For system carrier densities greater than about 10^{15} m^{-2}, the regime under investigation in the present paper, the PL arises from the recombination of free electrons and holes.

In a 2D electron system (2DES) in narrow (250 Å) quantum wells, where the separation between the 2D electron system and the photoexcited holes is small, upward shifts in the energy of the PL line at integer filling factors are observed.[1] In wider (400 and 500 Å) quantum wells and single heterojunctions (SHJ's) where the 2D electron-hole separation is larger, downward energy shifts are observed.[1] These energy shifts have been interpreted as manifestations of the effects of screened many-body interactions.[2] The theoretical work[2] considered only spinless systems; if we include spin-split Landau levels, we would expect shifts in the recombination energy at every integer filling factor when the spin-split Landau levels are full. The behavior of the spin-split levels can be investigated through polarized PL studies. A polarization analysis of the photoluminescence from 2DES's in GaAs single quantum wells of different well widths and in a GaAs single heterojunction was presented by Goldberg *et al.*[1] They concentrated on the PL contributions from the spin-split electron states around filling factor $\nu = 1$, but also discussed the behavior at $\nu = 2$ and 2/3. For a 250-Å quantum well they observed similar shifts to higher energy for both polarizations near $\nu = 1$ where the low-energy spin-split state is completely full and the high-energy spin-split state is almost empty. The results were explained using the many-body effects of exchange and correlation. The hole exchange energy was taken to be negligible, given the low density of photoexcited holes. They argued that since the energy shifts were similar in the two polarizations, the exchange energy for the electron, which is population dependent and so different for the two spin-split states, must be almost exactly canceled by the electron correlation energy. This leaves the hole correlation energy as the dominant factor in determining the electron-hole recombination energy. As the quality of samples improved, anomalies in the optical spectroscopy were observed. For instance, the PL from low-disorder 2DES's in a 400-Å quantum well showed discontinuous shifts to lower energy in the PL at $\nu = 1$ and 2, and splitting of the PL line near odd filling factors for $\nu > 2$.[3] To explain these shifts and splittings, Hawrylak and Potemski[4] addressed the theory of PL for a low-disorder system in the IQHE regime. The discontinuous redshift in the PL is explained as the difference between the Coulombic electron-electron interactions as the system is brought through the integer filling factors. They found that final-state interactions are responsible for the splitting of the PL line at odd filling factors.

Munteanu *et al.*[5] recently presented polarized PL of a 2DES in a wide (1480 Å) GaAs parabolic quantum well. They observed differences between the discontinuous redshifts in the σ^+ and σ^- polarizations. Following the theory of Hawrylak and Potemski[4] and Cooper and Chklovskii,[6] they found that the ratio of the redshifts at $\nu = 1$ and 2 for the σ^- polarization agreed with the theory, but that, for the σ^+ polarization, the magnitude of the redshifts was smaller and the ratio of the redshifts at $\nu = 1$ and 2 was about 3 times the predicted value. It was suggested that valence-band mixing

©2003 The American Physical Society

might lead to an increased binding energy for the initial exciton state involved in the σ^+ polarization transition at $\nu=2$. This more tightly bound exciton would then capture another electron, forming a negatively charged exciton, and so lead to a greater overall lowering of the σ^+ polarization energy at $\nu=2$.

It is clear that detailed information about the valence-band structure is necessary for the interpretation of the optical measurements. Theoretical studies[7] have revealed something of the rich structure of the valence band in heterostructures, including the mixed states of the light- and heavy-hole subbands, the zero-field spin splitting of the hole levels, and the electronlike dispersion of the excited subbands which leads to the crossing and anticrossing behavior of the intrasubband and intersubband hole Landau levels. However, experimental investigations were limited by the low quality of the systems available. In recent years, advances in the growth of *p*-type heterostructures on $(311)A$-oriented substrates has led to the production of high-quality 2DHS's, with mobilities comparable to those of 2DES's, and an increased interest in the study of these systems. The improvement in the hole mobility has made it possible to observe the FQHE in these systems and to study the transition from the incompressible liquid state to the magnetically induced Wigner solid state, which is more accessible because of the larger effective mass of the holes compared to electrons.[8] Investigations of the PL from 2DHS's have not been as extensive as those for 2DES's; however, a number of groups have reported PL measurements of 2DHS's in the QHE regime.[9–11] Butov and colleagues[9] and Davies *et al.*[10] presented unpolarized PL studies of 2DHS's in the extreme quantum limit $\nu<1$. In these studies, the shifts of the PL energy in magnetic field were characteristic of exciton recombination and no modulations of the recombination energy were observed at integer or fractional filling factors.

We have previously presented a detailed analysis of the density dependence of the PL from a 2DHS in a 151-Å quantum well.[11] For carrier densities greater than about $10^{15}\ \mathrm{m}^{-2}$ the PL was attributable to the recombination of free carriers in the quantum well. Modulations in the intensity correlated with integer and fractional filling factors. The PL energy dispersion was linear in magnetic field, and for the highest densities upward shifts were seen in the PL energy, similar to those seen for 2DES's, and attributed to the dominance of the screened Coulomb correlation hole of the photoexcited electrons as discussed above. As the hole density was reduced, the PL dispersion became superlinear as the excitonic effects dominated the recombination and the modulations of the PL energy disappeared. The intensity modulations were more robust and survived down to low densities.

Here we report *polarized* PL spectroscopy measurements of high-mobility 2DHS's in GaAs/(Al,Ga)As quantum wells in which a clear response can be seen in the recombination energy modulations to many-body effects in the IQHE regime. For filling factors $\nu\geqslant 2$ the energies of the two polarizations are maximally separated at odd filling factors, due to an exchange-enhanced spin splitting of the corresponding energy levels at these filling factors, and are almost equal at even filling factors. Superimposed on this spin splitting is an additional energy modulation due to the oscillating self-energies of the two-dimensional holes and the photoexcited electrons. These additional modulations are clearer in the unpolarized PL where the exchange-enhanced spin splitting is averaged out and the many-body interactions are manifested in the upward energy shifts of the PL at integer filling factors. At $\nu=1$, upward energy shifts are seen in both polarizations and the transition energies in the two polarizations are almost equal. This is attributed to the coincidence of filling factor $\nu=1$ with a region in magnetic field where there is strong mixing of the light- and heavy-hole states and the subsequent breakdown of the PL transition selection rules.

II. SAMPLE AND EXPERIMENTAL DETAILS

The samples used in this study were *p*-type one-side modulation-doped GaAs/$\mathrm{Al_{0.33}Ga_{0.67}As}$ quantum wells grown by molecular-beam epitaxy on $(311)A$ semi-insulating GaAs substrates. In each sample the undoped (Al,Ga)As spacer layer separating the acceptors from the 2DHS was 202 Å wide. A 2-μm GaAs buffer layer and a superlattice consisting of a series of eight (Al,Ga)As layers alternating with seven GaAs layers were grown between the substrates and the quantum wells. Sample NU2169 had a well width of 101 Å; samples NU2168 and NU1171 had well widths of 151 Å. The 2DHS densities p_s were in the range $2.0-2.3\times10^{15}\ \mathrm{m}^{-2}$. The PL measurements were made both on uncontacted samples and on samples with Hall-bar geometry which were used to make simultaneous PL and transport measurements. The hole mobilities with the samples under illumination were in the range 35–40 $\mathrm{m}^2/(\mathrm{V\,s})$.

The PL was excited using a 750-nm, $2-\mathrm{W\,m}^{-2}$ diode laser and detected using a charge-coupled-device (CCD) camera attached to a spectrometer. The overall system resolution was ~0.03 meV. Optical fibers with 600-μm-diam core were used to deliver the excitation radiation to the sample and to collect the luminescence. For the polarized PL measurements a circular-polarization analyzer was situated between the sample and the PL collection fiber. The right- and left-circularly polarized contributions to the signal were obtained by reversing the direction of the magnetic field. The simultaneous optical and transport measurements were made on a sample with Hall-bar geometry, ensuring that the active area of the Hall bar was illuminated by the PL excitation radiation. The transport measurements were made using standard low-frequency lock-in techniques. Two superconducting magnets provided magnetic fields of up to 15 T, and the sample was cooled in a ^{3}He cryostat with a base temperature of 0.3 K.

III. RESULTS AND DISCUSSION

A. PL energy shifts

We present the data for the 101-Å quantum well in magnetic fields up to 8 T and then compare the results for 151-Å quantum wells.

Typical PL spectra taken at 350 mK for the 101-Å quantum well are shown in the inset of Fig. 1(a). At zero mag-

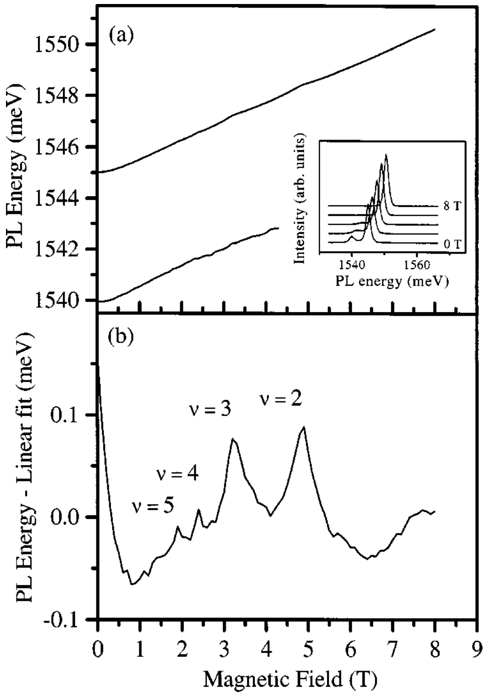

FIG. 1. Inset: typical PL spectra from sample NU2169 at magnetic fields from 0 to 8 T. (a) Energy of the PL peaks as a function of magnetic field. (b) PL energy of the main peak with a straight-line fit to the data subtracted vs magnetic field, showing upward energy shifts of the PL energy at integer filling factors.

netic field the spectrum consists of two peaks, with one peak at 1.545 eV and a second, lower intensity peak about 5 meV below the main peak. The main peak arises from the recombination of 2D holes with photoexcited electrons in the quantum well. We believe that the second peak is also associated with the recombination of the two-dimensional holes, but its exact origin is not known. The intensity of the second peak is greatly reduced when the PL is excited with low levels of radiation having energy above the (Al,Ga)As band gap and disappears when this level is increased. The intensity is also reduced and the line disappears as the magnetic field is increased. The energy shift of the second peak with applied magnetic field is almost linear with the same slope as the main PL peak, which would indicate that they are related. The second peak does exhibit energy and intensity modulations with magnetic field similar to the main 2DHS PL, but this might be due to the influence of the low-energy side of the main PL peak. In the PL spectra from 2D electron systems in similar quantum well structures a second PL peak on the low-energy side of the 2D PL peak has been reported previously.[12,13] In the PL of multi-quantum-well structures, with wells slightly wider than the wells studied here, a second peak has been seen and attributed to defect related PL.[12] For a one-side modulation-doped 150-Å quantum well a second peak in the spectra was identified as PL arising from a GaAs buffer layer.[13] The energy of the second PL peak in the spectra from the 100-Å quantum well presented here is above the bulk GaAs band-to-band recombination energy, which suggests that the PL arises from the recombination of 2D holes at a defect. This is further supported by recent photoluminescence excitation spectroscopy experiments on this sample. In the rest of this paper we focus our attention on the main PL peak.

Figure 1(a) shows the dependence of the peak position of the lines in the unpolarized PL spectra on applied magnetic field. The peaks shift almost linearly to higher energies as the magnetic field is increased. This linear shift is characteristic of the free carrier recombination associated with transitions from electron and hole Landau levels which have a linear dependence on magnetic field, neglecting hole Landau-level mixing. The linear shifts of the lines rule out the possibility of the PL being excitonic in nature. Small upward shifts in the energy of the main peak can be seen at magnetic fields near 4.8 and 3.2 T. These shifts can be seen more clearly by subtracting from the data a linear fit to the data which corresponds to the sum of the Landau-level separations of the recombining electron and hole. The data minus the linear fit, shown in Fig. 1(b), reveal upward shifts in energy at magnetic fields which are associated with the integer quantum Hall effect at filling factors $\nu=2$, 3, 4, and 5 as indicated. Simultaneous transport measurements confirm these assignments. The upward energy shifts at every integer filling factor are consistent with the theory of PL from a disordered system, as outlined above.[2]

We turn now to the polarized PL. Considering again only the main PL peak, the energy shift of the PL in each polarization shifts almost linearly to high energy with increasing magnetic field. If we subtract from the data for each polarization a straight line which fits the average energy of the peaks in the two polarizations, we see that the transition energies of the two polarizations are almost equal at even filling factors, but well separated at odd filling factors, Fig. 2(a). Figure 2(b) shows the integrated intensity of the PL for both polarizations and will be discussed later.

The large separation of the PL lines for the two polarizations at odd filling factors is indicative of a large separation between the spin-split energy levels at odd filling factors. This is reminiscent of the enhanced Zeeman splitting of the spin-split Landau levels seen in the PL of a two-dimensional electron system.[14] In the electron system, the Landau level associated with the low-energy spin-split level experienced an enhanced shift to lower energy, due to the exchange enhancement of the *g* factor, when that level was nearly full and the high-energy spin-split level was nearly empty. Only the low-energy spin-split level was observed in that system, but the high-energy component was expected to experience an enhanced upward shift as the level was emptying. Once the level was depopulated, no transition from that level would be observed. It would appear then that the upward shifts in the recombination energy expected at every integer filling factor due to the oscillation of the screening by the two-dimensional hole system of the correlation-hole of the photoexcited electrons are accompanied by an exchange-enhanced spin splitting at odd filling factors.

It should be noted that in the case of the electron system it was pointed out[14] that the enhancement of the spin splitting will only occur at the Landau levels near the Fermi energy and that the Landau levels below the Fermi energy should maintain their original linear shift. The PL we observe con-

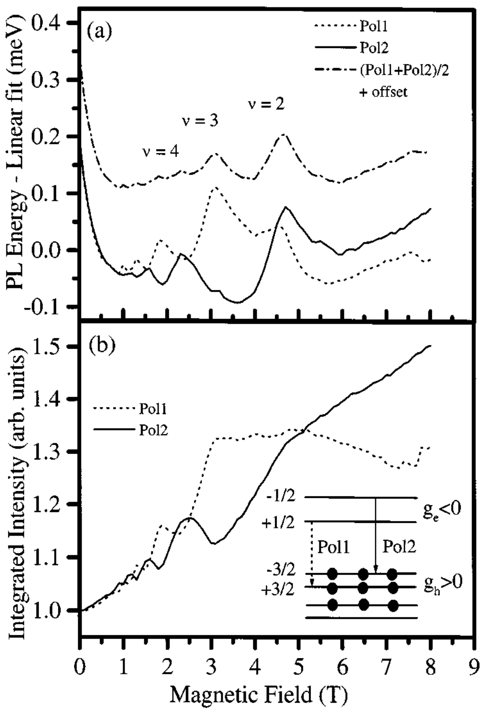

FIG. 2. Energy and intensity of the polarized PL from sample NU2169 vs magnetic field. (a) The PL energy in the two polarizations with a straight-line fit to the average energy of the two polarizations subtracted. The average energy of the two polarizations with a straight-line fit subtracted is shown with an offset (dot-dashed line). (b) Intensity of the PL in the two polarizations. Inset: electron and hole energy-level diagram identifying the transitions associated with each PL polarization. The solid circles represent the holes filling the three lowest-energy hole levels for $\nu=3$.

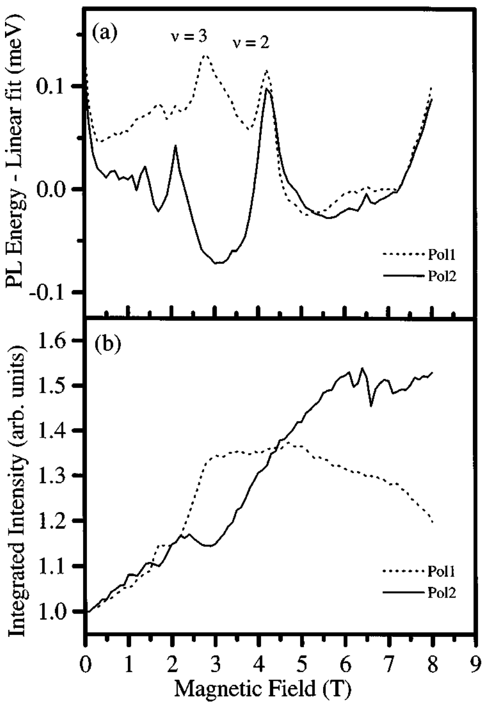

FIG. 3. (a) Energy of the PL from sample NU2168 vs magnetic field in the two polarizations with a straight-line fit to the average energy of the two polarizations subtracted. (b) Intensity of the PL in the two polarizations.

sists of one peak which we attribute to a recombination between the lowest-energy hole and electron Landau levels, with no resolved higher Landau levels. Our observation of enhanced spin splitting of the lowest Landau level at $\nu=3$ and 5 demonstrates that there is a coupling of the exchange enhancement to pairs of levels below the Fermi energy as proposed by MacDonald *et al.*[15]

We propose the energy-level diagram shown in the inset of Fig. 2(b) to explain the observed energy shifts and to identify the transitions associated with the two PL polarization components. For the 101-Å quantum well we take the electron g factor, g_e, to be about -0.2.[16] If the hole g factor has a small positive value $g_h<|g_e/3|$, the recombination of an electron in the $+1/2$ spin-split electron level with a hole in the $+3/2$ spin-split hole level will be the lower energy of the two transitions shown. We associate this transition with the data labeled Pol1 and the higher-energy transition involving the recombination of an electron in the $-1/2$ spin-split electron level with a hole in the $-3/2$ spin-split hole level with Pol2. Above 4.5 T and below 0.5 T the data of Fig. 2(a) support this assignment. At intermediate magnetic fields the exchange enhancement of the hole g factor at odd filling factors increases the energy separation between the $+3/2$ hole level and the $-3/2$ hole level, which increases the transition energy of Pol1, while decreasing the transition energy of Pol2. This exchange enhancement of the spin splitting of the hole levels also increases the expected upward energy shift of the low-energy transition (Pol1), but produces a downward energy shift of the high-energy transition (Pol2) which acts to cancel the expected upward shift and accounts for the observed crossing of the transition energies of the two polarizations. The energies of the spin-split components at even filling factors are unaffected; an upward shift is evident in both polarizations at $\nu=2$. The average of the PL energies of the two polarizations is also shown, with an offset for clarity, in Fig. 2(a). By taking the average energy of the PL in the two polarizations the effect of the enhanced spin-splitting is canceled, which allows the remaining contribution from the many-body interactions to be seen as upward energy shifts at integer filling factors, consistent with the upward energy shifts seen in the unpolarized PL shown in Fig. 1(b).

Figure 3(a) shows the PL peak energy dispersion in magnetic field for the two polarizations, with a straight line subtracted, for the 151-Å quantum well NU2168. We keep the same polarization labeling as for the 101-Å quantum well data and use the same energy-level diagram to explain the data. However, in this case, following Snelling *et al.*,[16] we expect g_h to have a larger positive value, g_e to be more negative, and $g_h>|g_e/3|$. This inequality means that the splitting of the hole spin states in field is larger than the splitting of the electron spin states for the same field, which increases the energy of the transition between the $+1/2$ electron level and the $+3/2$ hole level (Pol1), while the energy of the transition between the $-1/2$ electron level and the $-3/2$ hole level (Pol2) is decreased so that the latter transition is now expected to be the lower-energy transition. This is borne out by the low-field ($B < 4$ T) data of Fig. 3(a)—in particular, the transition energies in the two polarizations are clearly diverging with field at low field, at a much higher rate than for the 101-Å quantum well, and with Pol2 the lower-energy transition. In this case, an exchange-enhanced splitting of the hole energy levels again increases the energy of transitions to the $+3/2$ hole level, while decreasing the energy of transitions to the $-3/2$ hole level. So Pol1 is the higher-energy transition at low fields and remains the higher-energy transition at odd filling factors, while Pol2 is the low-energy transition at low fields and remains the low-energy transition at odd filling factors without any crossings of the transition energies, in contrast to the case for the 101-Å quantum well. In Pol1 we see an upward energy shift at integer filling factors $\nu = 2,3,4,5$ due to the screening of the photoexcited electron, with an increased upward energy shift at odd filling factors due to the exchange-enhanced splitting of the hole energy levels, while in Pol2 we see upward energy shifts at even filling factors, but at odd filling factors the upward shifts expected due to the screening of the correlation hole of the photoexcited electron are canceled by the downward energy shift produced by the enhanced splitting of the hole levels.

Assuming a linear dispersion of the electron and hole energy levels in magnetic field, we would expect the two transitions to continue to separate in energy with increasing field. We note that for the 151-Å-wide well in magnetic fields greater than about 4.2 T the energies of the two transitions begin to merge. We attribute this to a crossing and anticrossing of the two lowest hole Landau levels. Calculations of the Landau levels for 2DHS's in quantum wells grown on (311)*A*-oriented samples show a complicated structure of hole Landau levels with both crossing and anticrossing behavior for Landau levels arising from different subbands, including a crossing of the two lowest Landau levels in the lowest heavy-hole subband.[17] For a 151-Å well a crossing of the two lowest Landau levels is predicted to occur at a magnetic field of approximately 3 T and the crossing point moves to higher fields as the well width is reduced. The calculation of the Landau levels was performed in the axial approximation, and it was noted that if full Landau-level mixing is included, the crossing of the two lowest levels is expected to become an anticrossing. In the calculations, shown in Fig. 6 of Ref. 17, it is the first excited Landau level which changes direction as the magnetic field increases and crosses the lowest Landau level to become the ground state at high magnetic fields. In our data we see that the transition energies in the two polarizations become equal for magnetic fields above about 4.2 T and then start to diverge again, with Pol1 remaining the higher-energy transition. This behavior is seen in Fig. 4(a), in which the PL for sample NU1171 is presented, up to 15 T. This would suggest that the two lowest hole Landau levels do not cross, but approach each other and then separate again. This crossing and anticrossing behavior is expected to occur over a range of magnetic fields around the calculated crossing point and produce a mixing of these states in this range. We note that we see the crossing and anticrossing behavior at higher field than theoretically predicted; this discrepancy may be due to the approximations in the calculations. From the calculations, the crossing and anticrossing point is expected to occur at a higher field for the 101-Å quantum well, which is consistent with our data where there is no evidence for the crossing and anticrossing of the hole levels for magnetic fields up to 8 T.

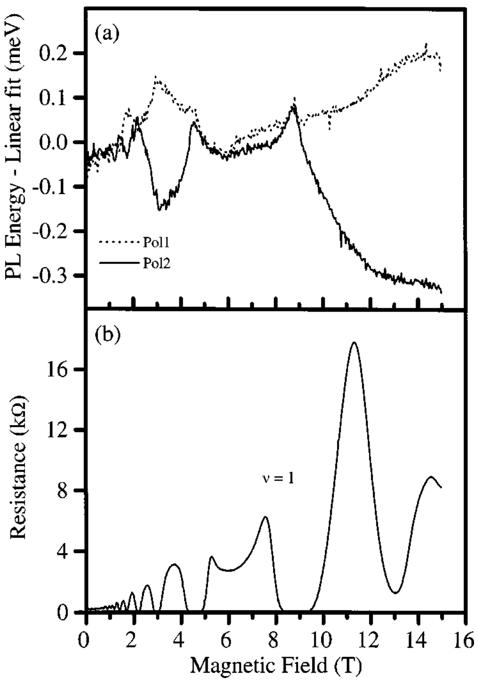

FIG. 4. (a) Center-of-mass energy of the PL from sample NU1171 as a function of magnetic field in the two polarizations with a straight-line fit to the average energy of the two polarizations subtracted. (b) Simultaneously measured longitudinal resistance.

The high magnetic field data for the 151-Å quantum well NU1171 are shown in Fig. 4(a), where the PL center of mass, instead of peak position, is plotted against applied magnetic field. The center-of-mass method, which gives a more reliable measure of the PL position, was used to find the peak position in the PL from sample NU1171. This method was not used for the PL from samples NU2168 and NU2169 due to the presence of the second peak to the low-energy side of the main peak in these samples, which made it necessary to use a curve fitting method to extract the peak position. The simultaneously measured longitudinal resistance is shown in Fig. 4(b). Clear minima in the resistance are observed at integer filling factors. In this paper we are primarily interested in the optical data. The transport measurements are used to check the association of features in the optical data with the occurrence of integer Landau-level filling.

In Fig. 4(a), we note that from $\nu < 2$ to $\nu = 1$ the transition energies of the two polarizations are equal (to within the experimental resolution), and at $\nu = 1$ there are upward shifts of the transition energies in both polarizations. At this filling factor the difference in the populations of the two hole spin states is at its maximum, with the lower-energy spin-split level completely full and the higher-energy spin-split level completely empty. The exchange-enhanced splitting of the two hole states is therefore also expected to be at a maximum, and only a transition to the lowest-energy hole level would be expected. We suggest that the observed behavior is due to the effects of heavy- and light-hole mixing, which, although negligible at low fields, become more significant at high fields. This mixing is further complicated by the mixing of the ground and first-excited heavy-hole Landau levels in this region of magnetic field, which makes these levels a mixture of all four possible hole states. The accidental coincidence of $\nu=1$ with this range of magnetic fields means that only one hole Landau level is occupied and this hole ground state is of a mixed state so that transitions from either one of the two spin-split electron states to this lowest hole state can give rise to PL in both polarizations. In this situation the transition energy in both polarizations would be equal. Transitions from either one or both spin-split electron levels are allowed, and so it is not possible to determine the transitions involved in producing the measured PL. As the magnetic field is further increased, the mixing between the heavy-hole states is reduced as the energy levels diverge and the ground state of the holes becomes a mixture of heavy- and light-hole states involving just one of the two possible heavy-hole states and one of the two possible light-hole states. Now transitions from either spin-split electron level can produce only one polarization of the PL. At high fields this mixing is further reduced and the hole ground state can be considered a pure heavy-hole state again. Note that this means that the splitting between Pol1 and Pol2 at high fields, where only one hole level is occupied, is entirely due to the electron g factor. On this assumption we estimate g_e from Fig. 4(a) and obtain $|g_e|=0.7\pm0.3$. This value is larger than the low-field value for g_e reported in Snelling *et al.*;[16] however, it is consistent with the picture of the splitting between the transition energies in the two polarizations arising from only the splitting between the electron levels since it is smaller than the combined electron and hole g factors which would be involved if the two polarizations arose from transitions between spin-split electron and spin-split hole levels.

We note that consideration of the effects of band mixing in the calculations[18] of hole Landau levels for two-dimensional hole systems in SiGe quantum wells has been shown to be sufficient to explain the observation of large gaps at mostly odd filling factors, as determined from magnetotransport measurements.[19] Only discrepancies between the experimental and calculated gaps at low filling factors were assigned to many-body effects. On the other hand, numerical simulations[20] of magnetotransport measurements on a p-type GaAs/(Al,Ga)As quantum well have shown that, while it is essential to include band mixing in the calculations, hole exchange interactions must also be included to obtain an accurate simulation of the data. The importance of hole exchange interactions in two-dimensional hole systems in GaAs/(Al,Ga)As quantum wells is further supported by the optical data presented here.

We now discuss the PL energy modulations in terms of the theory applicable to low-disorder systems developed by Hawrylak and Potemski.[4] In Fig. 3 of Ref. 4 they show the Hartree-Fock self-energy of the hole created in the electron Landau level, after recombination of the electron-hole pair, which will be reflected in the PL. They show both spin-state energies and find that the two spin-state energies are equal at even filling factors and separated at odd filling factors as expected from the exchange contribution. This corresponds to the main feature in our polarized PL data, with the transition energies in the two polarizations being almost equal at even filling factors and separated at odd filling factors due to the exchange interaction, Fig. 2(a).

Starting from this point, Hawrylak and Potemski show how in moving up in filling factor through a completely filled level an additional excitonic binding energy leads to a discontinuous jump in the PL energy at integer filling factors. They also show how the consideration of final-state interactions leads to a splitting of the PL near odd filling factors. Although we do see the broad exchange-enhanced splitting of the PL energies in the two polarizations, we do not see discontinuous jumps or splittings in either of the polarizations. We note that the jumps and splittings are expected to be smaller in energy for hole systems compared to electron systems, and since we are not able to resolve the broader spin splitting in the unpolarized PL, we would not expect to be able to see these additional jumps and splittings.

B. PL intensity modulations

Modulations in the intensity of the PL with magnetic field can be seen in the polarized PL data which show some structure associated with filling factors $\nu\geqslant 2$, Fig. 2(b). The PL intensities in the two polarizations are almost equal at even filling factors and at a maximum difference for odd filling factors. At odd filling factors the intensity of Pol1 is enhanced while that of Pol2 is reduced. The changes in the intensity are related to the integer filling factors and are sensitive to the difference in the populations of the two hole spin states at odd filling factors. The PL arises from transitions to the lowest spin-split hole Landau levels which will have equal populations for all filling factors $\geqslant 2$, so the variation in intensity of the PL is not simply related to the populations of these levels. From the energy-level diagram [inset Fig. 2(b)] we note that Pol2 is associated with the transition from the high-energy electron level and Pol1 with the transition from the low-energy electron level. We suggest that at odd filling factors the difference in the populations of the hole spin-split states, which gives rise to the enhanced spin splitting of the hole states, also induces an enhanced splitting of the electron states. This is perhaps a logical extension of the theory of MacDonald *et al.*[15] of the coupling between Landau levels. The two spin-split electron levels are populated by photoexcited carriers. However, there may also be a portion of the population of the carriers in the upper spin-split level maintained by thermal excitation of carriers from the lower-energy electron level to the upper-energy electron level, related to the energy difference between the two levels. At odd filling factors the separation between the spin-split electron levels increases, which reduces the thermally excited population of carriers. The upper electron level increases in energy and therefore depopulates, with a consequent reduction in the intensity of Pol2, while the lower-energy electron level decreases in energy and becomes more

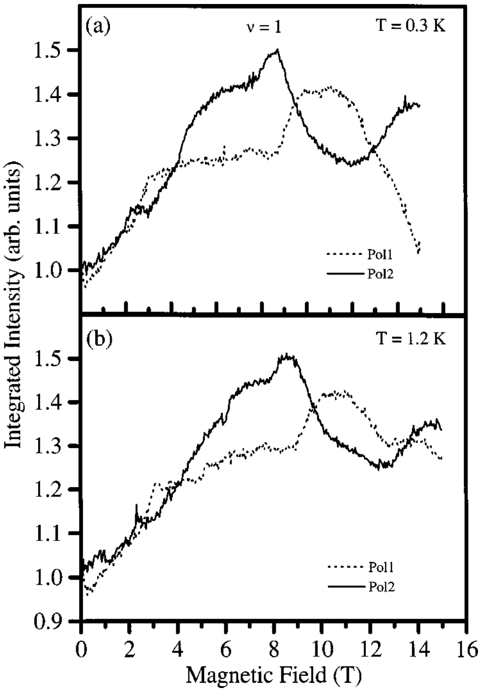

FIG. 5. Integrated intensity of the PL in the two polarizations as a function of magnetic field for sample NU1171 at temperature $T = 0.3$ K (a) and $T = 1.2$ K (b).

populated, which increases the relative intensity of Pol1. We expect the additional splitting of the electron levels to have relatively little effect on the transition energies. The same argument holds for the intensity variation of the PL from the 151-Å quantum well, Fig. 3(b). We note that although the relative energy positions of the polarization components are reversed in this case, it is still the PL in the polarization associated with transitions from the high-energy electron level (Pol2) which is reduced in intensity and that associated with transitions from the lower-energy electron level (Pol1) which is increased in intensity at odd filling factors.

Figure 5(a) shows the variation of the integrated intensity of the PL for the 151-Å quantum well NU1171 in magnetic fields up to 15 T. The behavior of the PL intensities for $\nu < 2$ may also show evidence of mixing of the lowest hole Landau levels. In the case of the 151-Å quantum well we expect a mixing of the hole states due to the anticrossing behavior for magnetic fields greater than about 4.2 T, which corresponds to a filling factor $\nu < 2$. For $\nu < 2$, the intensity of the transition associated with the upper spin-split hole Landau level (Pol1) should decrease as this level depopulates. However, the intensity of Pol1 remains constant, which is consistent with a continuation of transitions having this polarization due to mixing of the hole levels. At high fields (>12 T) the intensity of Pol1 begins to decrease as the upper spin-split hole level is completely depopulated and the mixing of the hole levels becomes less significant. This is further supported by the temperature dependence of the PL intensity. Figure 5(b) shows the PL intensity versus applied magnetic field at 1.2 K. At the higher temperature the first excited hole Landau level becomes thermally populated and the decrease in the intensity of Pol1 at high magnetic fields due to the unmixing of the hole levels is compensated by an increase of the PL from electrons recombining with the thermally excited holes in the $+3/2$ hole level.

IV. SUMMARY

We have presented a PL investigation of two-dimensional hole systems in a range of quantum wells. In the unpolarized PL we observe upward shifts in the PL energy at integer filling factors which arise from many-body interactions dominated by the screening of the correlation hole of the photoexcited electrons by the 2D hole system. Polarized PL measurements show modulations in the energies and intensities of the PL from the spin-split levels. The energy separation of the PL in the two polarizations is maximum at odd filling factors and minimum at even filling factors, and this is attributed to an exchange-enhanced spin splitting, which masks any upward energy shifts in each polarization which would be expected at every integer filling factor and are seen in the unpolarized PL. We identify the main transitions which contribute to the PL in the two polarizations and see evidence for a crossing and anticrossing behavior of the two lowest hole Landau levels in the 151-Å quantum wells. Upward energy shifts are seen in both polarizations at $\nu = 1$ and, in contrast to the behavior at other odd filling factors, the transition energies in the two polarizations are almost equal. This is attributed to the coincidence of filling factor $\nu = 1$ with the region in magnetic field where strong mixing of the light- and heavy-hole states leads to a breakdown of the PL transition selection rules, thereby allowing PL of both polarizations to be seen when only one hole level is occupied. It is suggested that the modulations in the polarized PL intensities can be understood in terms of changes in the populations of the electron spin-split energy levels due to an enhanced splitting of these levels at odd filling factors.

ACKNOWLEDGMENTS

We would like to thank M.E. Portnoi and A.S. Plaut for useful discussions. This work was funded by the Engineering and Physical Sciences Research Council of the U.K. under Grant No. GR/L 78819.

---

*Present address: Clarendon Laboratory, University of Oxford, Oxford, OX1 3PU, United Kingdom.

[1] B. B. Goldberg, D. Heiman, M. Dahl, A. Pinczuk, L. Pfeiffer, and K. West, Phys. Rev. B **44**, 4006 (1991).

[2] T. Uenoyama and L. J. Sham, Phys. Rev. B **39**, 11 044 (1989); S. Katayama and T. Ando, Solid State Commun. **70**, 97 (1989); T. Tsuchiya, S. Katayama, and T. Ando, Jpn. J. Appl. Phys., Part 1 **34**, 4544 (1995).

[3] L. Gravier, M. Potemski, P. Hawrylak, and B. Etienne, Phys. Rev. Lett. **80**, 3344 (1998).

[4] P. Hawrylak and M. Potemski, Phys. Rev. B **56**, 12 386 (1997).

[5] F. M. Munteanu, Yongmin Kim, C. H. Perry, D. Heiman, D. G. Rickel, M. Sundaram, and A. C. Gossard, Phys. Rev. B **62**, 4249 (2000).

[6] N. R. Cooper and D. B. Chklovskii, Phys. Rev. B **55**, 2436 (1997).

[7] T. Ando, J. Phys. Soc. Jpn. **54**, 1528 (1985); D. A. Broido and L. J. Sham, Phys. Rev. B **31**, 888 (1985); U. Ekenberg and M. Altarelli, *ibid.* **32**, 3712 (1985).

[8] M. B. Santos, Y. W. Suen, M. Shayegan, Y. P. Li, L. W. Engel, and D. C. Tsui, Phys. Rev. Lett. **68**, 1188 (1992).

[9] L. V. Butov, A. Zrenner, M. Shayegan, G. Abstreiter, and H. C. Manoharan, Phys. Rev. B **49**, 14 054 (1994); L. V. Kulik, V. T. Dolgopolov, A. A. Shashkin, A. F. Dite, L. V. Butov, V. D. Kulakovskii, H. C. Manoharan, and M. Shayegan, *ibid.* **51**, 13 876 (1995).

[10] A. G. Davies, E. E. Mitchell, R. G. Clark, P. E. Simmonds, D. A. Ritchie, M. Y. Simmons, M. Pepper, and G. A. C. Jones, Phys. Rev. B **51**, 7357 (1995).

[11] Y. V. Ponomarev, A. Usher, P. J. Rodgers, B. L. Gallagher, M. Henini, and G. Hill, Phys. Rev. B **54**, 13 891 (1996).

[12] D. Heiman, B. B. Goldberg, A. Pinczuk, C. W. Tu, A. C. Gossard, and J. H. English, Phys. Rev. Lett. **61**, 605 (1988).

[13] M. H. Meynadier, J. Orgonasi, C. Delalande, J. A. Brum, G. Bastard, M. Voos, G. Weimann, and W. Schlapp, Phys. Rev. B **34**, 2482 (1986).

[14] I. Kukushkin, V. Timofeev, K. von Klitzing, and K. Ploog, in *Festkörperprobleme: Advances in Solid State Physics*, edited by U. Roessler (Vieweg, Braunschweig, 1988), Vol. 28, p. 21.

[15] A. H. MacDonald, H. C. A. Oji, and K. L. Liu, Phys. Rev. B **34**, 2681 (1986).

[16] M. J. Snelling, E. Blackwood, C. J. McDonagh, R. T. Harley, and C. T. B. Foxon, Phys. Rev. B **45**, 3922 (1992).

[17] B. E. Cole, J. M. Chamberlain, M. Henini, T. Cheng, W. Batty, A. Wittlin, J. A. A. J. Perenboom, A. Ardavan, A. Polisski, and J. Singleton, Phys. Rev. B **55**, 2503 (1997).

[18] L. G. C. Rego, P. Hawrylak, and J. A. Brum, Solid State Commun. **105**, 139 (1998).

[19] P. T. Coleridge, A. S. Sachrajda, P. Zawadzki, R. L. Williams, and H. Lafontaine, Solid State Commun. **102**, 755 (1997).

[20] M. Kemerink, P. M. Koenraad, and J. H. Wolter, Phys. Rev. B **57**, 6629 (1998).