Photoluminescence of a two-dimensional electron gas in a modulation-doped GaAs/Al_xGa_{1-x}As quantum well at filling factors $\nu<1$

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The evolution of the 2DEG-hole magneto-photoluminescence (PL) with decreasing 2DEG density is studied in a high quality 25 nm-wide modulation-doped GaAs/AlGaAs quantum well in magnetic fields $B\leqslant 7$ T and lattice temperature $T_L=1.9$ K. The 2DEG density was varied by optical depletion (with He–Ne laser illumination) in the range of $n_{2D}=(1-7)\times 10^{10}$ cm^{-2}. As the filling factor decreases below $\nu=1$, a high-energy PL band (H) emerges; its evolution with B and electron density n_{2D} is studied. At $\nu\sim 0.4$, two additional PL lines split off the H-band, and these are assigned to the charged triplet X_t^- and neutral exciton X^0 PL. The evolution from free-hole–2DEG to charged exciton PL with decreasing n_{2D} and with increasing magnetic field (at $\nu<0.4$) is attributed to the appearance of regions containing localized electrons in the *photoexcited* quantum well. Localization results in simultaneous presence of the free-hole–2DEG PL from the electron puddles (H-band) and the charged exciton PL lines (spin-singlet, X_s^- and spin-triplet, X_t^-) from areas containing localized electrons.

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I. INTRODUCTION

The remarkable transport properties of the two dimensional electron gas (2DEG) in the quantum Hall regime have stimulated an extensive investigation of the photoluminescence (PL) in modulation-doped quantum wells (MDQWs) and heterojunctions.[1,2] The low-temperature PL spectra of GaAs/AlGaAs MDQWs subjected to a perpendicular magnetic field B, show singularities in the magnetic field dependence of the peak energies, oscillations of intensity and linewidth at both integer and fractional Landau level (LL) filling factors, ν.[1–5]

PL spectra are very sensitive to the quality of the studied heterostructure, and their reported evolution with 2DEG density and magnetic field as well as its interpretation, differ significantly in various experiments. Some of the PL features, in particular the PL intensity and linewidth oscillations, are due to the ‘‘extrinsic effect’’ caused by a magnetic field modulation of the screening efficiency of the electron–hole interaction in the presence of nonradiative recombination channels and fluctuating potential of impurities.[3,5]

One of the most remarkable features of the MDQW magneto-PL is the emergence of high-energy lines at filling factors $\nu<1$.[1,2,6] Previously, these PL lines were attributed to the radiative recombination of valence hole and the fractionally charged 2DEG quasiparticles.[1,2] Similar PL lines were observed in the magneto-PL of strongly depleted 20–30-nm-wide GaAs MDQWs and were attributed to negatively charged X^- and neutral X^0 excitons.[7] The X^- complex consists of two electrons and one hole. In a magnetic field, two bound states, electron spin-singlet X_s^- and spin-triplet X_t^- , are observed.[7,8] The dependence of the X_s^- , X_t^- , X^0 PL line energies on B has been extensively studied, and it turns out that the charged and neutral exciton luminescence dominates the PL spectrum of a *high density* 2DEG under strong magnetic field in *various* MDQWs.[7,9–11]

However, the charged exciton PL spectra are not yet fully understood even in the low-density limit. Due to the exact optical selection rules,[12] the lowest triplet X_t^- state must be dark in any quasi-2D state, and it may become optically-active in the presence of any mechanism that breaks the in-plane translational invariance. These mechanisms can be either scattering by disorder, interface roughness,[12] by the 2DEG itself[10] or X^--localization. In recent experiments, one more PL line[9] was observed at $\nu<1/3$ and T_L below 1 K (see also Ref. 13). This PL line and the commonly observed X_t^- line have been attributed to ‘‘dark’’ and ‘‘bright’’ triplet states of X^-, respectively. The existence of the excited ‘‘bright’’ triplet state X_{tb}^- was predicted in numerical simulations.[14] However, a relatively large predicted binding energy[14] of the ‘‘bright’’ triplet is not consistent with the results of high-accuracy calculations.[15] The latter show that the binding energies of the *dark triplet* X_t^- in 300 Å wide GaAs QWs are consistent with the experimentally determined values while the ‘‘bright’’ triplet X_{tb}^- state is at best only ‘‘marginally bound’’ in 100 Å GaAs QWs (binding energy 0.15–0.1 meV) and is unbound in 300 Å wide GaAs QWs.

Another important and only partially understood issue is the origin of the PL lines observed at finite electron filling factors $0.5<\nu<2$. In some experiments,[16,17] it appears as if the X_s^-, X_t^-, and X^0 lines still dominate in spite of strong many-body effects that are important for the 2DEG being in the lowest LL. The reported insensitivity of the magneto-PL spectrum to ν may be explained[18] by a "hidden symmetry"[19] when though large, the many-body contributions to the energies involved in the transition between the initial and final many-electron states, cancel. This cancellation is *exact* in quasi-2D systems with electron–hole symmetry in strong magnetic fields, when electrons and holes occupy the same (partially filled) LL's.[19] Because of this "hidden symmetry," magneto-PL from such many-body systems carries essentially no information about many-body effects. It should be stressed, however, that this is only a partial explanation because in realistic quasi-2D systems (with different electron and hole effective masses and wave functions, and mixing of LL's at finite fields B), the "hidden symmetry" is only approximate.

In this work, we study the magneto-PL of a MDQW in which the 2DEG density n_{2D} is reduced by optical depletion. This method has the advantage over n_{2D} variation by electric bias. The reason is that photovoltages appearing at electrical contacts may increase the interband transition linewidth by inducing in-plane inhomogenities in n_{2D}. Thus, our experiments reveal very narrow PL lines ($\sim$0.2 meV) even at $T_L \sim 2$ K and allow an accurate study of the PL line energy, intensity and shape in large ranges of n_{2D} and B. A comprehensive investigation of the evolution from the free-hole–2DEG to the X_s^-, X_t^-, and X^0 PL with varying B and n_{2D} is carried out and a qualitative discussion of the nature of the PL lines at filling factors $0.4<\nu<2$ is given. We propose that at $\nu\sim0.4$, a metal-insulator transition occurs in the photoexcited MDQW, and there is a spatial separation between QW regions that contain the 2DEG (2DEG puddles) and regions with localized electrons that give rise to the X_s^-, X_t^-, and X^0 PL. A broad PL band (H) that emerges as electron filling factor ν decreases below one, originates in the 2DEG puddles whose total area shrinks as ν reduces below 0.4.

II. EXPERIMENTAL PROCEDURE

The PL study was performed on a sample containing a single 25 nm wide GaAs/AlGaAs MDQW grown by molecular beam epitaxy on (001)-oriented undoped GaAs substrate. The n-type δ-doped layer was separated from the QW interface by a 100-nm-wide undoped $Al_{0.13}Ga_{0.87}As$ spacer layer. The 2DEG density and the dc mobility in the dark and at 4 K were $n_{2D}^0 = 7\times10^{10}$ cm^{-2} and $\mu > 2\times10^6$ cm^2/V s, respectively. The sample was illuminated by a He–Ne laser light whose photon energy $E_L = 1.96$ eV is greater than $Al_{0.13}Ga_{0.87}As$ band gap. The electron–hole (e–h) pairs photoexcited in the $Al_{0.13}Ga_{0.87}As$ are spatially separated by the built-in heterojunction electric field. The holes accumulate in the GaAs QW and recombine with the 2D-electrons, thus n_{2D} is reduced. By using this optical depletion method,[2,20] we vary n_{2D} from 7×10^{10} cm^{-2} down to 1×10^{10} cm^{-2} by increasing the He–Ne light intensity (I_L did not exceed 10 mW/cm^{-2}). The PL spectra obtained with the lowest He–Ne excitation coincide with the spectra measured under

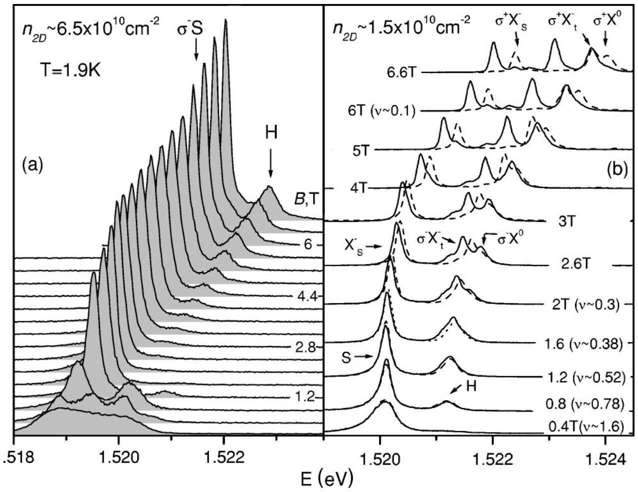

FIG. 1. The evolution of the PL spectrum with increasing B for the 25-nm MDQW, $T_L = 1.9$ K. (a) $n_{2D} = 6.5\times10^{10}$ cm^{-2}, PL spectra measured in σ^--polarization with the interval of 0.4 T. (b) $n_{2D} = 1.5\times10^{10}$ cm^{-2}, σ^- (solid lines) and σ^+ (dashed lines).

a Ti–sapphire laser excitation at $E_L = 1.56$ eV (when e–h pairs are photoexcited inside the QW). The PL spectra were detected in two circular polarizations (σ^- and σ^+) and were measured with high spectral resolution ($\simeq$0.03 meV) by using a Dilor-spectrometer and a CCD camera. The sample was immersed in liquid He at 1.9 K, and a magnetic field ($B \leqslant 7$ T) was applied perpendicularly to the 2DEG layer.

III. EXPERIMENTAL RESULTS

Figure 1 displays the PL spectral evolution with increasing B for two He–Ne-laser light photoexcitation intensities. The PL spectra at $B=0$ originate from the recombination of the 2D-electrons with free photoexcited holes. The 2DEG Fermi energy determines the spectral width. A narrowing of the PL spectral band with increasing I_L [Figs. 1(a), 1(b)] demonstrates the reduction of n_{2D} with I_L. As B increases, this band splits into lines that are due to inter-Landau level (LL) transitions [Fig. 1(a)]. The n_{2D} values estimated from the PL band widths at $B=0$ (Ref. 21) coincide with those obtained from the B values corresponding to the disappearance of the second Landau level in the PL spectra (filling factor of $\nu=2$). These n_{2D} values are given in Figs. 1–3.

At $\nu\sim1$, a new, broad (linewidth of 0.5 meV) PL band (H) emerges in σ^--polarization at the high-energy side of the main (S) PL band, and its intensity increases with increasing B [Fig. 1(a)]. For $n_{2D} = 6.5\times10^{10}$ cm^{-2}, the H-band appears at $B\sim3$ T ($\nu\simeq1$). As n_{2D} is reduced, the H-band emerges at lower magnetic fields and then, with further increasing B, it splits into three bands [see Figs. 1(b) and 2(a)]. The two additional, high energy, narrow PL lines are X_t^- and X^0. These lines are also observed in σ^+-polarization [Figs. 1(b) and 2(a)]. For the lowest n_{2D}, the H-band is separated from the S-band by 1 meV, it becomes visible at $B\simeq0.6$ T ($\nu \sim 1$), and the X_t^- and X^0 lines can be resolved at $B\geqslant1.5$ T ($\nu\sim0.4$) [Fig. 1(b)].

Figure 2(a) shows the evolution of the σ^- and σ^+ PL

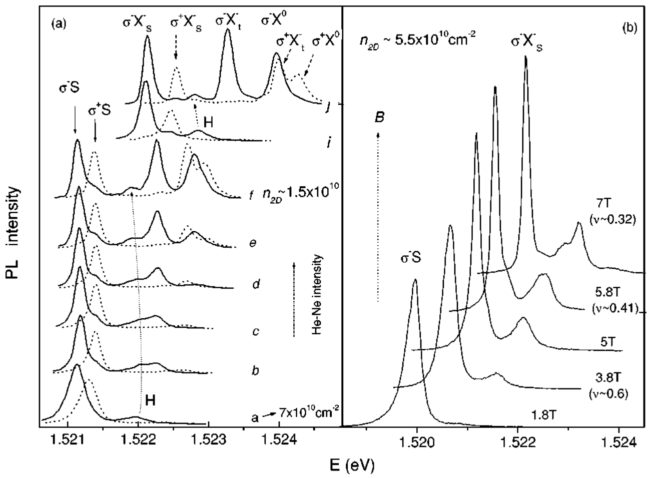

FIG. 2. (a) PL spectra in σ^- and σ^+ polarizations (solid and dotted lines, respectively) for several He–Ne laser light intensities, I_L. Curves a, b, c, d, e, f are obtained at $B=5$ T with increased I_L (n_{2D} varies from 7 to $1.5\cdot 10^{10}$ cm^{-2}). Curves i and j are measured at $B=7$ T at the lowest and highest I_L, respectively. Dotted curve (with arrow) shows a slight shift of the H-PL peak with n_{2D}. (b) The spectral evolution of the σ^- PL spectra with increasing magnetic field from 1.8 up to 7 T at $n_{2D}\simeq 5.5\cdot 10^{10}$ cm^{-2} (estimated filling factors are given in the brackets).

spectra with decreasing n_{2D} (for $\nu<0.6$) at $B=5$ T (curves a–f) and at $B=7$ T (curves i and j). For high n_{2D} (curves a and i), the σ^- PL spectrum consists of S and H-bands while only the S-band is seen in the σ^+ spectrum. Both σ^- and σ^+ S bands are asymmetrically broadened on the low-energy side at $\nu>0.4$ (Fig. 2). The S and H-bands slightly shift to higher energy with reducing n_{2D}. As the energy shift saturates, the S-band becomes narrower and symmetric. Then, the X_t^- and X^0 PL lines emerge in both σ^- and σ^+ polarizations. With further reduction in n_{2D}, the S and H-PL intensities decrease while the X_t^- and X^0 intensities increase. This spectral modification is attributed to a transition from the 2DEG–hole recombination to the singlet X_s^-, triplet X_t^- negatively charged and neutral X^0 exciton recombination. The 2DEG–hole PL (S-band) transforms into the X_s^- line with decreasing n_{2D} and/or increasing B [Fig. 1(b)].

Figure 2(b) displays the PL evolution with increasing B for an intermediate n_{2D} value. Now, the H-band appears and the evolution to X_t^- and X^0 PL occurs at a higher B than in Fig. 1(b); therefore, the higher electron density n_{2D} is, the higher field B is needed for such a transition. One can clearly see the transformation of the asymmetric S-band into a narrow X_s^- line. The X_s^-, X_t^-, and X^0 linewidths are less than 0.2 meV.

The magnetic field dependence of the PL peak energies, $E(B)$ was measured for various n_{2D} [Fig. 3(a)]. The $E(B)$ for the S-PL peak is shown for two n_{2D} values. At low B, the $E(B)$ depends on n_{2D} while it is nearly independent of n_{2D} for $B>4$ T. The S-line shifts to higher energy with decreasing n_{2D} due to a reduced 2DEG exchange energy (band gap renormalization).[21] At $\nu\simeq 2$, a change in the magnetic field dependence $E(B)$ of the S-PL peak occurs—from linear at $\nu>2$ to "diamagnetic" (approximately square root of B) at $\nu<2$ as was previously reported.[16,17] The energy position $E(B)$ of the H-band is also shown for two n_{2D}-values. At high n_{2D}, the separation between the S and H peaks is 0.7 meV; it does not vary with B. At low n_{2D}, the separation decreases from 1 meV at $B=1$ T to 0.65 meV at $B=7$ T. The $E(B)$ dependencies of the X_s^- ($B>4$ T), X_t^- and X^0 lines are very similar to that previously reported.[7–11] It is noted here that the positions of the X_s^-, X_t^-, and X^0 lines do not vary with n_{2D}.

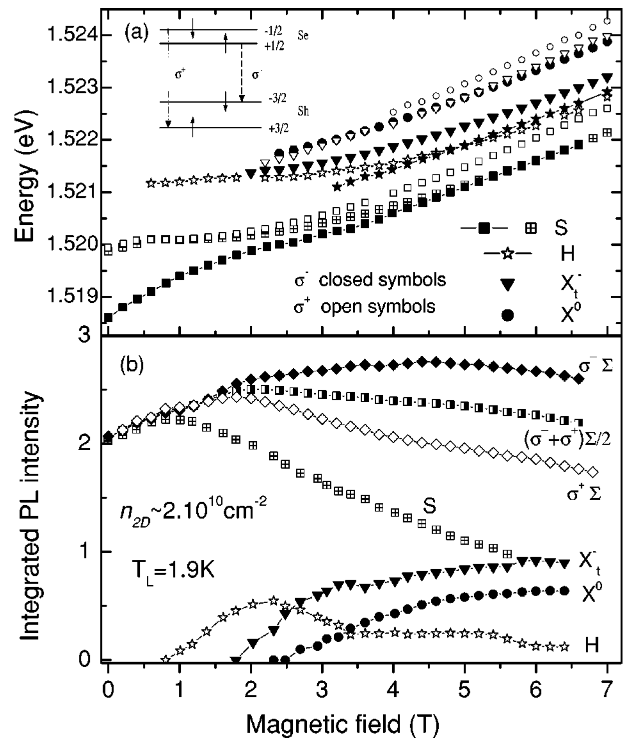

FIG. 3. (a) The magnetic field dependence of the PL peak energies. S and H-peak dependencies are shown for two n_{2D} values, $7\cdot 10^{10}$ cm^{-2} and $\simeq 1.5\cdot 10^{10}$ cm^{-2} (dark and crossed symbols, respectively). Inset defines the conduction-valence band transitions probed by σ^- and σ^+ circularly polarized PL. (b) The integrated PL intensities of the each σ^- lines and the entire spectral integrated σ^--PL ($\sigma^-\Sigma$), σ^+-PL ($\sigma^+\Sigma$), and the total PL ($\sigma^-\Sigma+\sigma^+\Sigma$).

The integrated intensity of each PL band as a function of B [Fig. 3(b)] and as a function of photoexcitation intensity (n_{2D}) were studied in both circular polarizations. Together with a high spectral resolution, this allowed us to correctly identify the higher energy Zeeman-split components of the X_s^-, X_t^-, and X^0 lines. The $E(B)$ dependencies for the σ^+-components are shown by open symbols in Fig. 3(a). The energy separation between σ^- and σ^+ components vary nearly linearly with B, and thus, we measured the Zeeman splitting for the charged X_s^-, X_t^-, and neutral X^0 excitons: $\triangle E=g\mu_B B$, where μ_B is the Bohr magneton and g is the corresponding effective g-factor. As seen from Fig. 3(a), the Zeeman splitting of the triplet state X_t^- is larger than that of the singlet X_s^- and of the neutral exciton X^0. We obtained the effective g-factors to be 1.7, 1.1, and 0.8 for the X_t^-, X_s^-, and X^0 states, respectively. The exciton g-factor is very close to that measured previously.[23]

Figure 3(b) shows the spectrally integrated PL intensities $\sigma^{+/-}\Sigma$, as a function of B. We observe an intensity redistribution between the PL bands, but, there is no observable variation of the total PL intensity $I_{\sigma^-}+I_{\sigma^+}$ with increasing B. Thus, the quantum PL efficiency of the QW does not change in the entire range of B.

IV. DISCUSSION

A remarkable feature of the studied PL spectral evolution is the appearance of the high energy broad H-band at $\nu \leqslant 1$ with a subsequent transformation of the 2DEG–hole PL (S and H-bands) into X_s^-, X_t^-, and X^0 lines. The studied PL behavior at filling factors $\nu < 0.4$ is similar to that previously reported for the dilute 2DEG in various 10–30-nm-wide GaAs MDQWs of various qualities.[7,11] In line with these studies, we assign the three lines to charged X_s^-, X_t^-, and neutral X^0 excitons. We will analyze the PL evolution at $\nu < 2$, proposing that the PL transformation at $\nu \simeq 0.4$ is due to a magnetic field-induced localization of the 2DEG in the *photoexcited* MDQW.[24]

It is important to stress that the PL of MDQWs depends to a large degree on the kinetics of photocreated electrons, holes, and excitons, and that the PL essentially involves nonthermalized carriers. This is because of the short recombination times of the photoexcited particles.[2,25] Nonthermalized valence band holes were detected in the PL spectra obtained at $B=0$. Indeed, for $n_{2D} > 5\times 10^{10}$ cm^{-2} the electron–hole interaction is screened by the 2DEG, and the observed PL spectra at $B=0$ can be well fitted by a product of the 2D electron and hole distribution functions characterized by effective electron T_e and hole T_h temperatures.[21] Such a fitting procedure allowed us to estimate electron density n_{2D} and to obtain the values of T_e and T_h. T_e is found to be always close to the lattice temperature $T_L = 1.9$ K and T_h exceeds T_L.[22] Even at the lowest photoexcitation intensity, the hole temperature T_h was higher than T_L, and thus, the valence band holes are nonthermalized and occupy excited states before they recombine with the 2DEG. It should be noted that the PL intensity on the high-energy side of the spectrum at $B=0$, near the Fermi-energy, is higher than that found from the fitting.[22] This is known as the Fermi-edge singularity when the 2D-electrons of the Fermi wave-vector recombine with nonthermalized valence band holes having the same value of the wave vector (see, e.g., Ref. 26).

Under an applied magnetic field, the energy and spin relaxation rates decrease,[25] leading to a nonthermal redistribution of photogenerated particles between spin-split ($n_{LL}=0$) Landau Levels as well as between the excitonic (X_s^-, X_t^-, X^0) states. This is detected by a low degree of the polarization of the X_s^-, X_t^-, and X^0 lines. At $B=7$ T, for example, the polarization of the lowest ($n_{LL}=0$) inter-LL (S-band) transition (defined as the ratio $P=(I_{\sigma^-}-I_{\sigma^+})/(I_{\sigma^-}+I_{\sigma^+})$) is $\simeq 0.3$, and it decreases down to $\simeq 0.2$ as n_{2D} is reduced. The presence of the high-energy peaks in the low-temperature magneto-PL is also due to incomplete relaxation of photoexcited carriers before they recombine. Thus, the observed PL spectrum is determined not only by the lowest energy states but it is also strongly controlled by the formation and decay processes for various entities such as X^0, X_s^-, and X_t^-.

Now we turn our attention to the origin of the S and H PL bands. At $\nu < 2$, the σ^- PL component probes the transitions between the lower, fully occupied spin-up ($S_e = +1/2$) electron state and the valence band ($S_h = -3/2$) [see inset in Fig. 3(a)].[3,27] When the spin-up electron recombines with the hole, the empty state that is left in an otherwise filled lowest electron Landau level, may be described as a spin-hole. The corresponding PL peak in the σ^- polarization occurs at energy $E_s^- = E_{gap}^- - E_{ee}$, where E_{gap}^- is the ($S_e = +1/2$ to $S_h = -3/2$) band gap energy and E_{ee} is the electron exchange energy (the energy needed to create one spin-hole in the lowest electron LL).

In the studied 25-nm-wide MDQW, the valence band hole is closer to the 2DEG layer than the average e–e separation ($d_{ee} \geqslant 30$ nm), and excitonic effects are important[27,28] in interpreting the PL spectra for $\nu = 1 \pm \varepsilon$. At $\nu = 1+\varepsilon$, there are spin-down electrons in the upper spin Landau level, and one needs to take into account (1) the binding energy E_X of the interband exciton formed by a valence band hole and a spin-down electron in the initial state, and (2) the energy that is needed to create the spin-wave excitation, SW (or "spin-exciton"-spin-hole in the lowest electron LL bound to a spin-down electron in the upper LL level) in the final state. The latter energy is $(E_{ee} - E_{SW})$, where E_{SW} is the spin-wave energy (or the binding energy of the "spin-exciton"), which depends on the SW momentum and forms a band of finite width. Thus, in this case, the recombination energy is $E_s^- = E_{gap}^- - E_X - (E_{ee} - E_{SW}) = E_{gap}^- - E_{ee} + (E_{SW} - E_X)$. For the studied case of the closely situated valence band hole and the 2DEG, $E_X \simeq E_{SW}$,[5,27] and therefore, $E_s^- = E_{gap}^- - E_{ee}$. The same PL energy E_s^- is expected at $\nu = 1-\varepsilon$ for the recombination in a "free-hole state"[27] when the valence band hole recombines with an electron from the lowest spin-up LL. As a result, a singularity in the PL peak energy or intensity is not expected theoretically at $\nu = 1$, and this is corroborated in the present experiment [see the behavior of the S PL peak in Fig. 3(a)]. The σ^+ S PL corresponds to the recombination of a spin-down $S_e = -1/2$ electron with a valence band hole having $S_h = +3/2$. Therefore in the σ^+ polarization, the energy of the S peak E_s^+ is lowered with respect to E_{gap}^+ by the interband exciton binding energy E_X.[27]

Because of the presence of non-thermalized spin-down electrons, both σ^+ and σ^- S PL components persist at $\nu < 1$ (Figs. 2 and 3), and the nature of the S-PL at $\nu = 1 \pm \varepsilon$ is the same.

At $\nu = 2$, the magnetic field dependence $E(B)$ of the S-PL peak changes from linear to "diamagnetic" [Fig. 3(a)] as was previously observed and associated[16,17] with a transition to isolated charged exciton X^-. This assumed that X^- is bound despite screening and other many-body effects. It should be stressed that at finite filling factors, when the mean separation between electrons becomes comparable with (or even less than) the size of the X^- complex, describing X^- as isolated few-body complexes X^- is physically unsatisfactory and one should turn to an appropriate many-body picture as discussed above. An explanation of this $E(B)$ dependence may partially be attributed[18] to breaking (at $\nu>2$) of the "hidden" symmetry in 2D systems. At $\nu<2$, the many-body contributions to the energies of the initial and final electron states involved in the PL are large, but they cancel out, and the magneto-PL from such many-body systems carries essentially no information about many-body effects. At $\nu>2$, electrons start to occupy the first and higher LL's while the hole resides in its zero LL. In this situation, no exact cancellation occurs, and many-body effects manifest themselves fully in the PL spectra. It is worth noting that the recent calculations of the band gap renormalization due to e–e interaction,[29] indicate the change of the energy dependence from linear to the square root of B at $\nu\simeq 2$.

As one can see from Figs. 1 and 2, both σ^-, σ^+ S-PL bands are asymmetric in the large range of filling factors $\nu<2$ until the X_t^- and X^0 PL lines emerge. The asymmetric S-PL with a tail at low energy is due to the presence of SW excitations in the final state.[27] Such a line shape and a S-PL shift to higher energy with decreasing n_{2D} caused by the reduced e–e exchange energy E_{ee}, clearly indicate the many-body nature of the S-PL band at $\nu>0.4$. Recently, a large renormalization (blue shift) in energies of the intraband transitions that originate (at $\nu\ll 1$) from the singlet and triplet X^- internal transitions, was observed at $\nu\sim 1$.[30] The many-body collective excitation responsible for the transitions that appear as "X^-" internal transitions, was attributed to a magnetoplasmon bound to a mobile valence band hole.[30,31] Together with the behavior of the highly resolved PL spectra obtained at $0.4<\nu<2$ in this work (see Figs. 1–3), this demonstrates the important role of the many-body effects at $\nu>0.4$ and indicates that the "hidden symmetry" is only approximately applicable to realistic quasi-2D systems (with different electron and hole effective masses and wave functions, and mixing of LL's at finite fields B).

The high-energy H-PL band emerges at $\nu<1$. A similar PL band was previously observed at temperatures below 1 K, and conflicting interpretations of its origin were given.[1,6,9,10] This PL line was initially attributed to a recombination of the valence band hole with fractional quantum Hall complexes[1] and later, to the "free hole state."[6,27] Recently, Yusa *et al.*[9] reported that the high-energy PL band emerges at $\nu<2/3$ and splits into two lines at $\nu<1/3$ (see also Ref. 13). These two PL lines were associated with the "dark" X_{td}^- and "bright" triplet X_{tb}^- charged exciton states (to avoid confusion we stress that we denote these lines as H-band and X_t^-, respectively). The assignment of the H-line at $\nu<2/3$ to the "dark" X_{td}^- state was based upon the similarity of the observed and calculated[14] binding energy of the "dark" triplet. On the other hand, the X_t^- line and its magnetic field dependence at $T_L=2$ K was attributed to the "dark" X_t^- exciton interacting with the excess electrons.[10]

In contrast to previous reports,[9,10,13] we clearly resolved four PL bands in the σ^- polarization (S or X_s^-, H, X_t^- and X^0) even at $T_L=1.9$ K and studied their evolution with electron density n_{2D} (Figs. 1 and 2). Several findings seem to rule out the H-band attribution to the "dark" triplet X_{td}^-. First, the H-band is clearly observed at $0.4<\nu<1$, when many-body effects play an essential role, and no isolated few-particle complexes X_t^- and X^0 can exist in a strongly-interacting system. Indeed, the H-band emerges at lower B than both X_t^- and X^0 [Fig. 3(b)]. Secondly, the H and X_t^- PL intensities vary in opposite directions with varying ν: The H-PL intensity decreases while that of X_t^- increases with increasing B [see Fig. 3(b) at $B>2.5$ T] or with decreasing n_{2D} [see Figs. 1(b) and 2(a)]. If the H and X_t^- PL originate in the same complex, X_t^- in either its dark or bright states, such a behavior would be impossible. Thirdly, the H-PL band is about twice broader than the X_t^- line. In addition, our preliminary study[24] showed a pronounced, different response of the (S and H) and (X_t^- and X^0) PL bands to microwave irradiation, which modifies the line shape of S and H-bands while only affecting the X_t^- and X^0 PL intensities.

Thus, we conclude that the H-line is due to the recombination of a strongly-interacting many-body state involving one valence band hole and many electrons. The corresponding recombination may be thought of as that of the valence band hole with a spin-up electron which, roughly speaking, has an adjacent equilibrium spin-hole (missing spin-up electron). As the filling factor ν decreases below one, more equilibrium spin-holes appear on the lowest electron LL leading to the energy shift of this line. The H-PL peak energy is expected to be centered at the *high-energy* side of the S-PL peak. This is because the H-PL energy can be estimated to be $E_{\rm H}=E_{\rm gap}^- - E_e$, where E_e is the energy needed to remove one electron from the lowest LL in the presence of an adjacent spin-hole. E_e is likely to be less than electron exchange energy E_{ee} characterizing a completely filled electron LL. In this picture, the H energy and the line shape vary with decreasing ν [see Figs. 2(a) and 3(a)]. As $\nu<1$, the S-PL intensity decreases (it should go to zero in equilibrium case) while the H-PL intensity increases, and this may be associated with increasing number of the "spin-up electron–spin-hole pairs" in the lowest LL. It is important to mention that a qualitatively similar picture was proposed also by Rashba and Sturge,[18] who suggested that the PL spectrum at $\nu<1$ may consist of doublets similar to "the exciton spectra of mixed crystals where lattice sites are randomly occupied by two species." A more detailed and quantitative theory is needed for a complete understanding of the origin, energy and line shape of the H line at $\nu<1$. We also stress that both H and S PL lines are due to different recombination channels from a collective many-body state "valence hole plus many 2D electrons" (cf. with collective modes involved in intraband transitions at $\nu\simeq 1$).[30]

At $\nu\sim 0.4$, the S-PL line narrows, and two additional narrow lines emerge from the H-band. The higher is the 2DEG density, the higher is the magnetic field B at which such a transition occurs. It is important to underline that the broad H-band and the narrow X_s^-, X_t^-, and X^0 lines *coexist* in a wide range of filling factors ν [see, in particular, Fig. 3(b) at $B>2$ T)]. With reducing ν below 0.4, the integrated H-PL intensity decreases while the total integrated intensity of the X_t^-, X^0 lines increases.

This behavior may originate from the metal-insulator transition (MIT), which is accompanied by the appearance of spatially separated regions containing high and low density electrons. In the case of a strong long-range fluctuating potential, a magnetic-field induced localization is expected to occur at $\nu \sim 0.5$.[32,33] In high mobility GaAs MQDWs, the fluctuating potential due to the remote ionized donors (in the AlGaAs-doped layer) is not strong. However, there is an additional photoinduced fluctuating potential caused by *photoinduced localized charges* in the adjacent AlGaAs spacer layers and on the inverted QW interface. In the presence of this random potential, the MIT is likely to give rise to a formation of puddles containing the 2DEG and the regions with localized electrons. We propose that the evolution of the 2DEG–hole PL to the exciton PL is associated with a magnetic field-induced localization of the 2D electrons in *photoexcited MDQW*. Appearance of the 2DEG puddles in photoexcited QW with increasing B was previously discussed.[34,35] An approximate physical criterion for such a "percolation-type" MIT may be written, in analogy with the criterion for Mott transition, as $a_B \sim n_{2D}^{-0.5}$, where a_B is the effective Bohr radius. With increasing magnetic field, the effective Bohr radius decreases (and eventually reduces to the magnetic length l_B) and, thus, the transition occurs at higher 2DEG densities.

As n_{2D} decreases at a given B, the localization starts at $\nu \simeq 0.4$, and the area containing localized 2D-electrons increases while the 2DEG puddles area is reduced. Thus, the total intensity of the X_s^-, X_t^-, and X^0 PL originating in the localized 2D-electron area, increases, and that of the H-PL (from the 2DEG puddles) reduces with decreasing ν [Figs. 2 and 3(b)]. It should be noted that the electron localization is an essential condition for the existence of a strong *charged* exciton PL lines near the MIT transition. The neutral X^0 and charged triplet X_t^- exciton PL lines emerge approximately at the same B [see Fig. 3(b)]. It is clear that the 2D electron localization allows formation of negatively charged excitons when neutral excitons appear.

V. CONCLUSIONS

We studied the evolution of the photoluminescence spectra with varying n_{2D} and B for the 2DEG-hole system in high quality MDQW. A higher energy PL band (H) emerges as electron filling factor ν decreases below one. The evolution of the PL spectra with electron density n_{2D} and magnetic field B was studied. At filling factor $\nu \sim 0.4$, two additional PL lines split off the H-PL band, and these are the charged (triplet) and neutral exciton PL. We associate the transition from the 2DEG–hole to charged exciton PL with a localization of 2D-electrons in photoexcited MDQWs with decreasing n_{2D} or increasing magnetic field. A qualitative discussion of the nature of the PL lines at filing factors $0.4 < n_{2D} < 2$ has been given.

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