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Magnetic-field-induced charged exciton studies in a GaAs/Al$_{0.3}$Ga$_{0.7}$As single heterojunction

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The magnetophotoluminescence (MPL) behavior of a GaAs/Al$_{0.3}$Ga$_{0.7}$As single heterojunction has been investigated to 60 T. We observed negatively charged singlet (X_s^-) and triplet (X_t^-) exciton states that are formed at high magnetic fields beyond the $\nu=1$ quantum Hall state. The variation of the charged exciton binding energies are in good agreement with theoretical predictions. The MPL transition intensities for the X_s^- and X_t^- states showed variations (maxima and minima) at the $\nu=1/3$ and 1/5 fractional quantum Hall states as a consequence of a large reduction of electron-hole screening at these filling factors.

The formation of negatively charged magnetoexcitons in quasi-two-dimensional (2D) heterostructures[1–5] compared with the 3D systems is facilitated by the imposed confinement. In the 2D case, the binding energy of the second electron will be enhanced about ten times[1] compared with the value found in the 3D systems. Finkelstein *et al.*[3] showed for the GaAs/Al$_x$Ga$_{1-x}$As quantum wells (QW's) that there is a strong correlation between the metal-insulator (MI) transition and the appearance of neutral excitons (X^0) and negatively charged excitons (X^-). They concluded that the electrons become less effective in screening at the onset of the MI transition, allowing the formation of the bound states between electrons and holes. Calculations performed by Whittaker and Shields[6] proved that higher-Landau-level corrections are important in obtaining an accurate value for the binding energy of the X^- states. They showed that the singlet state and not the triplet state would be the fundamental state at large magnetic fields. This result contradicts the usual expectation that the triplet state is the one that becomes the fundamental state at high fields. Chapman *et al.*[7] predicted that quasi-2D systems that approximate to a biplanar system (e.g., heterojunctions) are unlikely to exhibit photoluminescence (PL) effects due to charged excitons. This result is inconsistent with our observations and with those of others.

In this paper we report the results of magnetophotoluminescence (MPL) measurements on a very-high-mobility modulation doped GaAs/Al$_{0.3}$Ga$_{0.7}$As single heterojunction (SHJ). Our polarized MPL measurements enable us to clearly resolve evidence of both singlet (X_s^-) and triplet (X_t^-) states of X^- that are formed at high magnetic fields, for $\nu<1$. The singlet remains the fundamental state with no indication of any crossover between the X_t^- and the X_s^- states in the high-field limit of 58 T. We found that the binding energies of the X_s^- and X_t^- states in our SHJ more closely approximate the results expected for a wide QW.[6] The intensity of the neutral exciton displays minima at filling factors $\nu=1$, 2/5, 1/3, and 1/5, a behavior similar to that reported earlier by Turberfield *et al.*[8] Also, the intensity of the X_t^- peak presents a local maximum at $\nu=1/3$ and a local minimum at $\nu=1/5$, while the intensity of the X_s^- peak undergoes a local maximum at the filling factors $\nu=1/5$.

The sample used in this study is a molecular beam epitaxy–(MBE) grown GaAs/Al$_{0.3}$Ga$_{0.7}$As SHJ with a dark electron density of 1.1×10^{11} cm^{-2} and a mobility greater than 3×10^{6} cm^2/Vs. In our PL experiment, the 2D electron gas (2DEG) density increased to 2.2×10^{11} cm^{-2} under constant laser illumination. The high magnetic fields were generated using a 20-T superconducting (SC) magnet and a 60-T quasicontinuous (QC) magnet, which has a 2-s field duration. A ^{4}He flow cryostat and a ^{3}He exchange gas system were used to achieve 2–4-K temperatures in a 20-T SC magnet and 0.4–4 K in the 60-T QC magnet, respectively. For PL experiments, a 632.8-nm low-power diode laser was used for the excitation source and a single optical fiber (600 μm diameter, 0.16 numerical aperture) technique was employed to provide both the input excitation light onto sample and the output PL signal to the spectrometer.[9] The spectroscopic system consisted of a 300-mm focal length $f/4$ spectrograph and a charge-coupled device (CCD) detector, which has a fast refresh rate (476 Hz) and high quantum efficiency. This fast detection system allowed us to collect approximately 1000 PL spectra during the 2-s duration of the QC magnet field pulse.

In Fig. 1 we present two different circular polarization, σ^+ (right circularly polarized, RCP) and σ^- (left circularly polarized, LCP), measurements of MPL spectra taken at the same magnetic field (17 T). Both plots are normalized to the

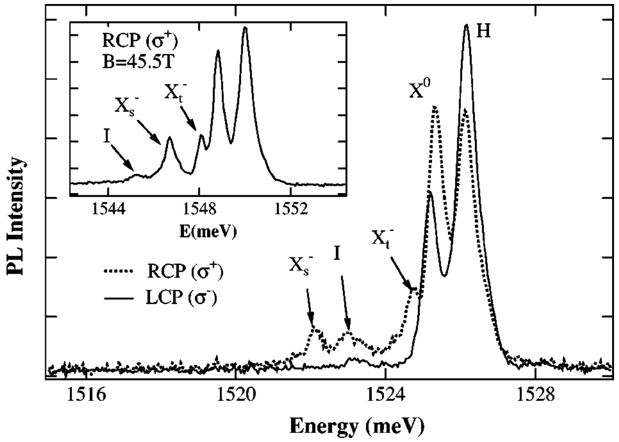

FIG. 1. Spin-polarized MPL spectra at $B=17$ T and $T=1.5$ K. Both spectra were normalized with respect to the zero-field data. The RCP spectrum (solid line) shows X^- peaks, whereas they are not present in the LCP spectrum. The small peak labeled I is an artifact. It appears in both polarizations and is field independent. Near the $\nu=1/5$ state (inset), the X_s^- and X_t^- state intensities are comparable and well resolved.

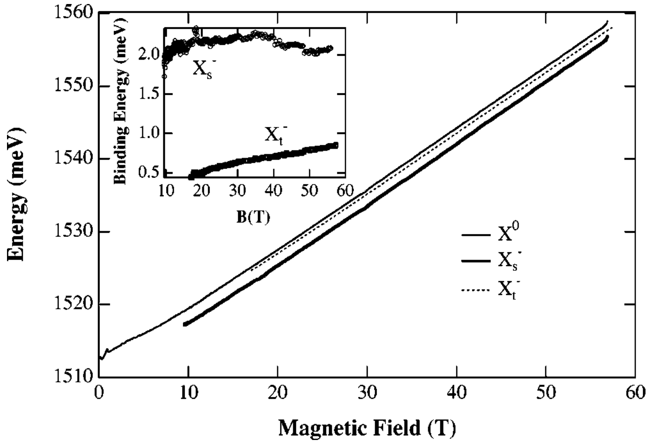

FIG. 2. Transition energy vs magnetic field at $T=1.5$ K. The X_s^- state appears at $\nu\approx0.9$ (10 T), whereas the X_t^- state does not appear until $B\approx17$ T. The inset shows the binding energies of charged excitons relative to the neutral exciton. The binding energy of the X_s^- state remains almost constant up to 58 T. The X_t^- state binding energy increases slightly with increasing magnetic field.

zero-field spectrum (not shown). The appearance of the higher-energy peak labeled *H* with increasing magnetic field has been observed by others.[8,10] Its origin is unknown but it becomes the most dominant feature in the spectrum at very high fields. The weak peak labeled *I* is assumed to be due to an artifact/impurity in the spectrum, as it remains field and polarization independent. The two peaks of interest in Fig. 1 are the ones labeled X_s^- and X_t^- on the low-energy side of X^0. The peak located 2.1 meV below X^0 is first observed at $B\approx10$ T, and we associate it with the singlet state of the negatively charged exciton (X_s^-). Magnetoresistance studies taken simultaneously with the MPL confirm that this charged exciton peak first emerges at a magnetic field just slightly higher than the $\nu=1$ ($B=9.1$ T) state. The second peak, which lies at 0.6 meV below X^0, suddenly appears at 17 T, and we associate it with the triplet state of the negatively charged exciton (X_t^-). These bands are strongly σ^+ polarized, whereas X^0 remain unpolarized. All three peaks have intensity oscillations with magnetic field. At $B=45.5$ T, X_s^- and X_t^- are clearly resolved and have comparable intensities as seen in the inset in Fig. 1.

Our polarization observations are in agreement with the experimental results presented by Whittaker and Shields[6] up to 20 T. Shields *et al.*[11] show that the probability of having X^- in σ^+ polarization is larger than that of having X^- in σ^- polarization, due to the fact that in the $\nu<1$ regime the number of the spin-↑ electrons in the first Landau level is much higher than that of the spin-↓ state. In addition, the formation of the X^- in σ^+ polarization, in contrast with the σ^- polarization, requires the presence of the spin $+3/2$ hole states.

Figure 2 shows the PL transition energy versus magnetic field up to 58 T at $T=1.5$ K. The highest transition (solid line) at low fields is the 0→0 Landau transition from the 2DEG. Bauer[12] showed that at zero magnetic field the PL signal will be dominated by the recombination of the 2DEG with photoexcited holes, if the carrier density is higher than 1.0×10^{11} cm^{-2}. The excitonic character is recovered when the magnetic field is applied. In the case of our sample we estimate that the formation of the neutral X^0 exciton takes place around $\nu=1$. From the measurements performed on modulation doped QW's, Finkelstein *et al.*[4] found that the PL signal from X^- states emerge for filling factors $\nu>1$ after the appearance of the neutral exciton X^0. They also showed that for large-electron-density systems, the charged exciton states are destroyed because of the Coulomb screening of the free-electron gas. Hence, X^- transitions appear only if the screening of the interaction between a neutral X^0 and a free electron is substantially diminished. With increasing magnetic field, the screening factor oscillates,[13] reaching a minimum value at the filling factor $\nu=1$. Also, the cyclotron radius will become smaller (about 85 Å at $\nu=1$) than the X^0 radius, increasing the probability of formation of bound X^- states. As this occurs only at $\nu\approx0.9$ in our experimental data, we may conclude that the reduction in the screening factor at $\nu=1$ is not sharp, but rather of an Anderson type[14] when the electrons are still effective in screening, although this effect is small.

The singlet and triplet state spin wave functions that can be seen in σ^+ polarization are of the form[11]

$$S_0=(1/\sqrt{2})(e_\uparrow e_\downarrow - e_\uparrow e_\downarrow)h_\uparrow, \tag{1}$$

$$T_0=(1/\sqrt{2})(e_\uparrow e_\downarrow + e_\uparrow e_\downarrow)h_\uparrow, \tag{2}$$

with total spins of $+3/2$ for both of them. The other two possible triplet states are

$$T_{-1}=e_\downarrow e_\downarrow h_\uparrow, \tag{3}$$

$$T_{+1}=e_\uparrow e_\uparrow h_\downarrow, \tag{4}$$

and they will generate σ^+ and σ^- polarized signals, respectively. The T_{-1} state can be neglected due to the fact that its formation implies the existence of the two spin-down electrons. For magnetic fields higher than the one corresponding to the filling factor $\nu=2$, the population of the $-1/2$ electron level is strongly reduced.

The important thing is that after recombination, both S_0 and T_0 states will leave behind a spin-up electron. For this reason, the change in the Zeeman energy in the case of *both* these states will be the same:

$$\Delta E^s_{Z,RCP}=\Delta E^t_{Z,RCP}=-(1/2)(|g_h|-|g_e|)\mu_B B \\ =-\Delta E_Z(X^0), \tag{5}$$

where $\Delta E_Z(X^0)$ is the Zeeman splitting of the neutral exciton.[15] If we assume that the g_e and g_h factors do not depend on magnetic field in a different manner for the X^0 state than for the X_s^- and X_t^- states, then the energy differences between these two states and the neutral X^0 will reflect only the changes in their Coulomb energies. Recently, the B dependence of the g factors of the X^0 and the X_s^- states was measured experimentally[16] and was found to be small ($\cong$0.45) for magnetic fields in the range 0–8 T. We may also expect that the variation of the g factors with magnetic field for the X_s^- and X_t^- states should be almost identical. This is due to the fact that the main contribution to any differences would come from the mixing of the electron and hole wave functions from the higher Landau levels and higher subbands as a result of the large spatial extent of the X_s^- and X_t^- states.

The inset in Fig. 2 shows the binding energies of X_s^- and X_t^- transitions relative to that of X^0. The binding energy of the singlet state remains almost constant to 58 T (2.1 meV), whereas the binding energy of the triplet state increases from 0.6 meV at 17 T to 1.2 meV at 58 T with a saturation at high magnetic fields. In general, this observation may be considered unusual, as at very high fields the triplet state, in accordance with Hund's rules, has to be the ground state, implying that the singlet and triplet states have to cross each other. Palacios *et al.*[17] concluded from the result of calculations performed in the lowest-Landau-level (LLL) approximation that the X_s^- state will be bound only at zero magnetic field. When the magnetic field is applied, X_s^- will become unbound, and the only bound state will be X_t^-. However, more complete calculations performed by Whittaker and Shields[6] take into consideration both higher Landau levels and higher energy subbands. Their results lead to a different conclusion. For instance, they report that in the case of a 100-Å QW, the crossover of these two states is not expected to occur until around 35 T. As the well width is increased (e.g., to 300 Å), they find that the two charged exciton transitions show no crossing even at fields as high as 50 T. In our study on a modulation-doped SHJ we observe that the difference in energy between X_t^- and X_s^- states at high magnetic fields stays fixed at about 1 meV with no sign of a crossing. This behavior more closely resembles the predictions for a single-sided doped wide QW.[6] It has been pointed out before[18] that in the MI transition regime valence holes can move toward the interface, forming a bound state with the electrons. However, because of the Coulomb repulsion from the positive donors, the valence holes and the electrons will still be confined in different layers. For this reason, the spatially separated electron-hole pairs in a SHJ show behavior similar to a wide QW. This assumption is supported by the magnitude of the binding energies obtained experimentally. The inset in Fig. 2 indicates that the binding energies of the X_t^- and X_s^- at 17 T are of 0.5 and 2.1 meV, respectively. These values are comparable to those presented in some other publications.[2,6]

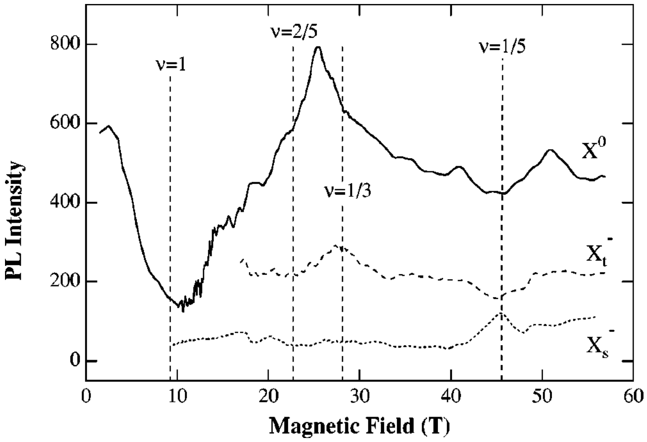

FIG. 3. MPL transition intensity vs magnetic field at $T=1.5$ K. The MPL intensity of X^0 shows minima at $\nu=1/3$, 1/5, and 2/5. The intensity of the X_s^- peak has a local maximum at $\nu=1/5$, whereas the intensity of the X_t^- transition has a minimum at $\nu=1/5$ and a maximum at $\nu=1/3$.

It should be noticed also that the binding energy of the triplet state increases slightly with increasing magnetic field, whereas the binding energy of the singlet state remains approximately constant or even decreases. This behavior can be understood from the symmetry of the spatial wave functions for these states. The singlet spatial wave function is symmetric, while the triplet must be antisymmetric if it is to preserve an overall parity of -1 for the total wave function. This is equivalent to saying that in the singlet state, the two electrons are equally separated from the hole, while in the triplet case, they are located at different distances from the hole in order to minimize the repulsion between them. With increasing magnetic field, the orbit of the outer electron in the triplet state is more affected by the field compared with the orbit of the inner electron. The same is true for the orbits of the two electrons in the singlet state, which are located to maximize the attraction between each of them and the hole. Application of a magnetic field shrinks the orbits of the electron in neutral excitons and the two electrons in the singlet state, but it has a less significant effect on them than on the shrinkage of the outer electron in the triplet case. Thus the reduction in the orbits will lead to an enhancement of the binding energies that will be different for each of the three particles at hand.

Figure 3 shows the evolution of the peak intensities for X^0 and X^- with magnetic field. At the filling factors $\nu=1$, 2/5, 1/3, and 1/5, the intensity of the X^0 peak shows local minima. A similar behavior was first reported by Turberfield *et al.*[8] and was attributed to the localization of the electrons in these states concomitant with a reduction of the screening factor. Besides this, we notice local maxima and minima in the intensities of the X^- states at $\nu=1/3$ and 1/5, a result that, to the best of our knowledge, has not been reported before. From Fig. 3 we see that the X_t^- state transition intensity increases at the filling factor $\nu=1/3$, but there is a reduction at $\nu=1/5$. Conversely, the intensity of the X_s^- state has a local maximum at $\nu=1/5$ but remains unchanged at $\nu=1/3$. In our view, this intensity behavior is due to the reduction of the free-electron orbits at higher magnetic fields. This causes the population of the charged X^- to increase compared with that of the neutral X^0, especially in the case where the screening effect is small. The X_t^- state is more weakly bound compared with the X_s^- state, since the singlet state remains the lowest-energy state. For this reason, due to the reduction of the screening associated with the formation of the incompressible quantum liquid states (IQL), at $\nu=1/3$, the energy of the X_t^- state will be lowered more than the energy of the X_s^- , leading to an increase in population of this state. The results in an increase in the observed PL intensity of the X_t^- at $\nu=1/3$. At $\nu=1/5$, the Coulomb interactions for both neutral and charged excitons will be very strong, such that neither of these states will experience a significant decrease in energy at this filling factor. As a consequence, the population of the singlet state, which is the fundamental one, will be increased due to electron localization, leading to the observed peak in its intensity. Although data are only presented at 1.5 K, the spectra show the same features at 400 mK.

In conclusion, we have performed MPL spectral measurements on a high-quality low-modulation-doped GaAs/$\mathrm{Al}_{0.3}\mathrm{Ga}_{0.7}\mathrm{As}$ single heterojunction. The formation of singlet and triplet states of the X^- charged excitons takes place at high magnetic fields beyond the $\nu=1$ quantum Hall state. The binding energy of the X_s^- remains almost constant, whereas the binding energy of the X_t^- increases slightly initially and then tends to saturate with increasing magnetic field. Our experimental data support the theoretical prediction of a noncrossover behavior of these two states in the magnetic fields regime investigated (up to 58 T), so that the singlet state remains the fundamental ground state. The intensity of the X_t^- transition shows a maximum at $\nu=1/3$ and a minimum at $\nu=1/5$, while in contrast, the X_s^- transition shows a minimum at $\nu=1/5$ but little change at $\nu=1/3$.

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