Magnetic Field Induced Charged Exciton Studies in a GaAs/Al$_{0.3}$Ga$_{0.7}$As Single Heterojunction

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(January 8, 2022)

Abstract

The magnetophotoluminescence (MPL) behavior of a GaAs/Al$_{0.3}$Ga$_{0.7}$As single heterojunction has been investigated to 60T. We observed negatively charged singlet and triplet 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 these states showed intensity variations (maxima and minima) at the $\nu=1/3$ and 1/5 fractional quantum Hall (FQH) state as a consequence of a large reduction of electron-hole screening at these filling factors.

In the last several years, many magneto-optical investigations have focused on the $\nu=1$ quantum Hall state due to drastic changes in its electronic properties in this magnetic field regime. In a doped quantum well system, screening within the two dimensional electron gas (2DEG) prevents the formation of excitons. Instead, the 2DEG shows...
distinct Landau level transitions in the presence of magnetic fields. However, whenever the Fermi energy sweeps from one Landau level to the next, the screening strength oscillates leading to non-linear behavior in the inter-Landau transitions observed in photoluminescence (PL). This non-linear behavior is attributed to a modulation of the hole self-energy. At $\nu=1$, when all the possible states are filled, the electron screening is greatly reduced which leads to formation of the metal-insulator (MI) transition. Finkelstein et al. showed that there is a strong correlation between the MI transition and the appearance of neutral excitons ($X^0$) and negatively charged excitons ($X^-$) based on optical measurements performed on GaAs/AlGaAs quantum wells. 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. More recently, calculations performed by Whittaker et al. showed that higher Landau level corrections are important in obtaining an accurate value for the binding energy of the charged exciton states. They showed that the singlet state and not of 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. predicted that quasi two dimensional (2D) systems that approximate to a biplanar system (e.g. heterojunctions) are unlikely to exhibit PL effects due to the charged excitons. This result is inconsistent with our observations and with those of others.

In this Letter, we report the results of PL measurements on a very high mobility modulation doped GaAs/Al$_{0.3}$Ga$_{0.7}$As single heterojunction. Our polarized MPL measurements enable us to clearly resolve evidence of both singlet and triplet states of $X^-$ that are formed at high magnetic fields beyond $\nu=1$. While the formation of the neutral exciton takes place near the filling factor $\nu=1$, the charged magneto-excitons are formed at higher fields. Our measurements also indicate that the singlet state does in fact remain the fundamental state. There is no indication in the MPL data of any cross-over between the triplet and the singlet state at least up to our high field limit of 58T. The binding energy of the singlet state ($X^-_s$) relative to $X^0$ is almost independent of magnetic field,
while that of the triplet state ($X^{-}_t$) increases slightly with increasing magnetic field. Theoretical calculations\textsuperscript{7} performed for the 2D negatively charged excitons predicted an increase of the binding energy of $X^{-}$ with decreasing well width owing to the enhancement of the Coulomb interactions induced by confinement. The binding energy is expected to increase with magnetic field due to the shrinkage of the outer electron orbital and an increase in the Coulomb interaction. Our experimental results indicate that the charged exciton binding energies in a single heterojunction more closely approximate the results expected for a wide quantum well (QW)\textsuperscript{7}. We also find that the intensity of the PL signal is sensitive to the formation of the incompressible quantum liquid (IQL) states at the filling factors $\nu=1/3$ and $\nu=1/5$.

The sample used in this study is a MBE grown GaAs/Al$_{0.3}$Ga$_{0.7}$As single heterojunction (SHJ) with a dark electron density of $1.1 \times 10^{11} cm^{-2}$ and a mobility greater than $3 \times 10^{6} cm^{2}/Vs$. In our PL experiment, the 2DEG density increased to $2.2 \times 10^{11} cm^{-2}$ under constant laser illumination. The high magnetic fields were generated using a 20 T superconducting (SC) magnet and a newly commissioned 60 T quasi-continuous (QC) magnet, which has a 2-second field duration. A $^4$He flow cryostat and a $^3$He exchange gas system were used to achieve 2-4 K temperatures in 20T SC magnet and 0.4-4 K in the 60T QC magnet, respectively. For PL experiments, a 630nm low power diode laser was used for the excitation source and a single optical fiber (600$\mu$m 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\textsuperscript{10}. 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 (476Hz) and high quantum efficiency. This fast detection system, allowed us to collect approximately 1000 PL spectra during the 2-second duration of the QC magnet field pulse.

In Fig. 1, we present two different polarization measurements of PL spectra taken at the same magnetic field (17 T). Two side bands are clearly observed in the $\sigma^+$ (right circularly polarized, RCP) measurements; these features are not present in the $\sigma^-$ (left circularly polarized, LCP) spectra. Magnetoresistance data taken simul-
taneously with MPL demonstrate that the magnetic field, where these side peaks first emerge, is just slightly higher than the \( \nu = 1 \) (B=9.1T) state. The side features are attributed to charged exciton transitions due to the charge imbalance between the conduction and valence bands in the MI transition regime. In the \( \sigma^+ \) spectra, the peak located 2.1meV below the E0(e1-hh) transition is first clearly observed at B=13T and is associated with the singlet state of the charged exciton (\( X^-_s \)). The other peak at 0.6meV below the E0 transition emerges around 17T. We believe this weaker feature to be from the PL from the triplet state of the charged exciton (\( X^-_t \)). The highest energy peak at 1526.3 meV and the weak peak at 1523 meV that appear in both polarizations are related to the response of the bulk GaAs free exciton (FX) transition and to an impurity transition, respectively.

Fig. 2 shows the PL transition energy vs. magnetic field up to 58T at T=1.5K. The highest transition (solid line) at low fields is the 0→0 Landau transition from the 2DEG; this transforms into the neutral E0 exciton at a field around \( \nu = 1 \). As previously reported by Finkelstein et al., the PL signal from charged excitons emerge for filling factors \( \nu > 1 \), after the appearance of the neutral exciton \( X^0 \). Finkelstein et al. 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 reaching a minimum value at the filling factor \( \nu = 1 \). For a SHJ, photocreated holes are forced to migrate towards the GaAs flat band region because the Coulomb repulsion between positive donors and valence holes is larger than the Coulomb attraction between electrons and holes. However, at the MI transition, where the screening effect disappears, holes move back to the junction region and form a strong bound state due to the recovered Coulomb attraction between electrons and holes. Consequently, this dynamical movement of the valence holes in a single heterojunction enables the formation of the \( X^- \) in the MI transition regime. As this occurs only at \( \nu < 1 \) in our experimental data, we may conclude that the reduction in the screening fac-
tor is not sharp, but rather of an Anderson type because the electrons are still effective in screening, although this effect is small.

Our spectral data show two $\sigma^+$ charged exciton states. It has been pointed out by Palacios et al., the probability of having $X^-$ in $\sigma^+$ polarization is larger than that of having $X^-$ in $\sigma^-$ polarization, due to the fact that in the $\nu<1$ regime the number of the spin-up electrons in the first Landau level is much higher than that of the spin-down state. For this reason, we expect the number of $X^-$ excitons formed by the capture of a spin up electron by a $X^0$ to be much higher than the number of those formed with a spin down electron. Shields et al. show that the singlet and triplet state spin wave functions that can be seen in $\sigma^+$ polarization are of the form:

$$S_0 = \frac{1}{\sqrt{2}}(e \uparrow e \downarrow - e \uparrow e \downarrow)h \uparrow$$
$$T_0 = \frac{1}{\sqrt{2}}(e \uparrow e \downarrow + e \uparrow e \downarrow)h \uparrow$$

with total spins of (3/2) for both of them. These spin wavefunctions have the lowest possible energies and their formation involves the presence of a ground state heavy hole state (3/2). The other two possible triplet states are,

$$T_{+1} = e \uparrow e \uparrow h \downarrow$$

and they will generate a $\sigma^+$ and $\sigma^-$ polarized signals respectively. The $T_{-1}$ state can be neglected due to the higher Zeeman energy.

The data allow us to determine the magnetic field dependence of the binding energy of the charged excitons. 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 58T (2.1meV), whereas the binding energy of the triplet state increases from 0.6meV at 17T to 1.2meV at 58T 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. concluded from the result of calculations performed in the lowest-Landau-level (LLL) approximation, that the $X^-$ ground state will change from the singlet at zero field to a triplet at high fields, while the singlet state will become unbound in the limit of strong magnetic fields. However, more complete calculations performed...
by Whittaker and Shields 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 quantum well (QW), the cross-over of these two states is not expected to occur until somewhere 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 these two negatively charged exciton states stays fixed at about 1 meV with no sign of a crossing. This behavior more closely resembles the result found for a single-sided doped wide quantum well.

As pointed out above, in the MI transition regime, valence holes move toward the interface forming a bound state. However, due to the dynamics of the system, valence holes can only remain somewhere near the junction. For this reason, the spatially separated electron hole pairs in a SHJ show behavior similar to a wide quantum well. This assumption is in good agreement with the magnitude of the binding energies expected for the charged excitons for a wide QW. The inset in Fig. 2 indicates that the binding energies of the $X_{t}^{-}$ and $X_{s}^{-}$ at 17 T are of 0.5 meV and 2.1 meV, respectively. These values are comparable to those found by Shields et al. of 0.8 meV and 1.9 meV for $X_{t}^{-}$ and $X_{s}^{-}$, respectively, at 8 T for a wide QW.

Two important aspects emerge from our experimental data. We find 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 affect 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.

Fig. 3 shows the evolution of the peak intensities for $X^0$ and $X^-$ with magnetic field and it can be seen that both the neutral and charged excitons show non-linear behavior near the filling factors $\nu=1/3$ and $1/5$. At these filling factors, the $X^0$ transition intensity shows local minima. This behavior was first reported by Turberfield et al.\cite{14} and was attributed to the localization of the electrons in these states concomitant with a reduction of the screening factor. They found that this reduction in the intensity of the neutral exciton is accompanied by a similar increase in the intensity of the charged magneto-excitons. We observe an increase in the triplet state transition intensity at the filling factor $\nu=1/3$ and a reduction at $\nu=1/5$. The intensity of the singlet state transition, on the other hand, increases 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 to 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 $X^-_{s}$ state, since the singlet state remains the lowest energy state. For this reason, at $\nu=1/3$, the energy of the $X^-_{t}$ state will be lowered more than the energy of the $X^-_{s}$ leading to a an increase in population of this state; this results in an increase in the observed PL intensity. 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 the intensity. It is of note that this anomalous behavior can still be observed at temperatures as high as $T=1.5K$.

In conclusion, we have performed MPL
spectral measurements on a high quality low modulation-doped GaAs/Al_{0.3}Ga_{0.7}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 but tends to saturate with increasing magnetic field. Our experimental data support the theoretical prediction of a non-crossover behavior of these two states in the magnetic fields regime investigated (up to 58T), so that the singlet state remains the fundamental ground state. The intensity of the $X^-_t$ transition shows maxima at $\nu=1/3$ and $\nu=1/5$. In contrast, the $X^-_s$ transition shows a minima at $\nu=1/5$ but little change at $\nu=1/3$. These features can still be observed at temperatures as high as $T=1.5K$.

The authors would like to thank A. H. MacDonald for helpful discussions and gratefully acknowledge the engineers and technicians at NHMFL-LANL in the operation of the 60T QC magnet. Work at NHMFL-LANL is supported by NSF Cooperative Agreement # DMR-9527035, the Department of Energy and the State of Florida.
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FIGURES

FIG. 1. Spin polarized MPL spectra at B=17T and T=1.5K. The RCP spectrum (solid line) shows $X^-$ peaks whereas LCP spectrum does not show these features. The highest energy peak is assigned to the GaAs free exciton and a small peak located between singlet and triplet states, which appears in both polarization, is an impurity transition (indicated as I). Near $\nu=1/5$ state (inset), the singlet state intensity is comparable to that of the triplet state.

FIG. 2. Transition energy vs magnetic field at T=1.5K. The singlet state appears near $\nu=1$ (9.1T) whereas the triplet state does not appear until B 16T. The inset shows the binding energies of charged excitons relative to the neutral exciton. The binding energy of the singlet state remains almost constant up to 58T. The triplet state binding energy increases with increasing magnetic field.

FIG. 3. MPL transition intensity vs magnetic field at T=1.5K. The MPL intensities of $X^0$ and $X_{t}^-$ have peaks near $\nu=1/3$ state, whereas the intensity of the $X_{s}^-$ transition remains constant over that field region. However, at $\nu=1/5$, the opposite behavior is observed. The $X_{s}^-$ transition shows a peak in the intensity while the $X^0$ and $X_{t}^-$ transition show dips.