An Anderson-Fano Resonance and Shake-Up Processes in the Magneto-Photoluminescence of a Two-Dimensional Electron System

M. J. Manfra and B. B. Goldberg

Dept. of Physics, Boston University, Boston MA 02215

L. Pfeiffer and K. West

Bell Laboratories, Lucent Technologies, Murray Hill, NJ 07974

(March 24, 2022)

Abstract

We report an anomalous doublet structure and low-energy satellite in the magneto-photoluminescence spectra of a two-dimensional electron system. The doublet structure moves to higher energy with increasing magnetic field and is most prominent at odd filling factors $\nu = 5$ and $\nu = 3$. The lower-energy satellite peak tunes to lower energy for increasing magnetic fields between $\nu = 6$ and $\nu = 2$. These features occur at energies below the fundamental band of recombination originating from the lowest Landau level and display striking magnetic field and temperature dependence that indicates a many-body origin. Drawing on a recent theoretical description of Hawrylak and Potemski, we show that distinct mechanisms are responsible for each feature.
Over the last decade a substantial body of work has focused on the investigation of the photoluminescence spectra originating from the recombination of a two-dimensional electron system with a valence-band hole in the quantum Hall regime. In conjunction with transport measurements, much of this work has concentrated on examining the nature of the incompressible ground states that arise at integral and fractional filling. More recently, optical techniques have proven sensitive to excited states of the 2DEG inaccessible to transport. In particular, two groups have recently reported on new low-energy structure in the magneto-photoluminescence in GaAs structures occurring at energies below the fundamental recombination from the lowest Landau level (LLL). While clearly indicative of many-body effects, these new experimental results have led to differing proposals for the mechanisms responsible for the various spectral anomalies and a consensus has yet to be reached. These features have alternatively been attributed to a perturbative many-body shake-up process and to a non-perturbative final state resonance of the 2DEG. It is the purpose of this paper to present the results of a comprehensive experimental study of the polarization, magnetic field and temperature dependence of these optical anomalies and elucidate the distinct mechanisms responsible for each.

We report on the observation of unusual low-energy structure in the magneto-photoluminescence spectra for filling factors $\nu > 2$. We identify and analyze two distinct features: (i) a doublet structure in the fundamental recombination from the lowest Landau level develops at odd integral filling factors $\nu = 5$ and $\nu = 3$, (ii) a significantly smaller satellite peak which red shifts for increasing magnetic field between $\nu = 6$ and $\nu = 2$ is observed at approximately 2meV below the doublet structure. While these features are separated by rather small energy differences and occur roughly in the same regime of magnetic field, we shall show that the data conclusively point to distinct mechanisms for each process.

The two-dimensional electron system under investigation is a single-side $n$-modulation doped Al$_x$Ga$_{1-x}$As-GaAs 250Å single quantum well (SQW). Samples from three different wafers have been studied with similar behavior seen in all samples. All three samples are of extremely high quality: electronic densities $n_s$ range from $1.4 - 1.8 \cdot 10^{11} cm^{-2}$ and mobilities
\( \mu \) range from 2.6 – 3.0 \( \cdot 10^6 \text{cm}^2/\text{Vs} \). The samples were excited at 740nm with the output of a tunable Ti:sapphire laser. The laser was stabilized and the incident power density was kept below \( 10^{-4} \text{W/cm}^2 \). We have verified that all measurements were made in the linear regime by collecting data with incident power densities at \( 10^{-6} \text{W/cm}^2 \) with no change in the observed spectra. Excitation delivery and signal collection were accomplished via an optical fiber system that resides in He\(^3\) refrigerator mounted in a 13T magnet. Base temperature of our configuration is 500mK. All measurements were made in the transmission geometry and polarization analysis is done in situ with a circular polarizer placed immediately following the sample but prior to the collection fiber. The signal is dispersed in a 0.64m monochromator and detected with a liquid nitrogen-cooled charged-coupled-device (CCD) camera with 0.2meV resolution.

Figure 1 displays the low temperature magneto-photoluminescence spectra in the left-circular \((\sigma^-)\) polarization in the field range of 0T to 4T for a sample with \( n_s=1.8 \cdot 10^{11} \text{cm}^{-2} \) and \( \mu = 2.6 \cdot 10^6 \text{cm}^2/\text{Vs} \). The use of polarization analysis is crucial since the high quality of these samples results in narrow line-widths in which spin-splittings are resolved above 1.5T. Detecting in the \( \sigma^- \) polarization guarantees that the fundamental recombination from the LLL occurs between a \( m_z = 1/2 \) electron level and a \( m_z = 3/2 \) hole level. The application of a quantizing magnetic field causes the zero field spectrum to split into the Landau fan structure. The gross behavior of these spectra and its relationship to the quantum Hall effect have been studied extensively. We focus our discussion on the low energy structure between \( \nu = 5 \) and \( \nu = 2 \) appearing below the main peak labeled LL\(_0\) in Figure 2. Within the context of a non-interacting model, LL\(_0\) is associated with the ground-state recombination of an electron and hole, each sitting on the lowest Landau level. Figure 2 shows an individual spectra taken at \( \nu = 3 \) and \( T=0.53\text{K} \) in which two distinct low-energy features are visible below the fundamental ground-state recombination LL\(_0\). Our analysis will focus on the origin of these two optical anomalies, labeled OA\(_0\) and OA\(_1\).

We begin our discussion with the lowest energy feature, labeled OA\(_1\), which we attribute to the process of shake-up in a magnetic field. In a shake-up process a recombining
electron-hole pair perturbs the electron gas causing another electron to be excited across the cyclotron gap from the lowest Landau level to the first Landau level. Energy conservation requires that the emitted photon’s energy be lower than the fundamental recombination by $\sim \hbar \omega_c$. Shake-up in a magnetic field has been studied experimentally with similar behavior reported in InGaAs-InP quantum wells, and most recently, in GaAs structures. The theory of shake-up has also been extensively investigated. Most theoretical approaches have assumed a significant amount of disorder in which electron-electron interactions can be treated perturbatively and only cyclotron gaps are considered. Zeeman gaps, which are typically unresolved in such systems, are ignored, and consequently the shake-up process is independent of the spin configuration of the 2DEG. As shown in Figure 3, OA$_1$ moves to lower energy for increasing magnetic fields with a slope approximately equal to $-1.65$meV/T, corresponding to an inter-Landau level excitation in GaAs. We note that the absolute separation between OA$_1$ and LL$_0$ is actually greater than $\hbar \omega_c$: at $\nu = 3$ the recombinations are separated by $\sim 6$meV while $\hbar \omega_c$ at this field is approximately 4meV. This behavior has been observed previously in the InGaAs-InP system and attributed to the fact that for non-zero wave-vectors the excitation energy of the $n=1$ magneto-plasmon mode actually exceeds $\hbar \omega_c$. For comparison, we have drawn in Figure 3 a line through OA$_1$ that corresponds to an excitation dispersing with a slope equal to the ideal (non-interacting) Landau level separation in GaAs of 1.65meV/T. The correspondence is quite good. The intensity of OA$_1$ is also quite small; its peak intensity is only $\sim 6\%$ of the peak intensity seen in LL$_0$, and between $\nu = 6$ and $\nu = 2$, OA$_1$ shows very little intensity variation. The smallness of the observed intensity in OA$_1$ and its complete lack of significant variation over this field range clearly identify it as a perturbative shake-up process.

We turn now to OA$_0$, the largest and most striking feature in Figure 2. At $\nu = 3$ OA$_0$ contains nearly 50 percent of the spectral weight seen in the fundamental recombination band, LL$_0$. The intensity of OA$_0$ exhibits complicated magnetic field dependence which is clearly seen in figure 4. At $\nu = 6$ there is no indication of the OA$_0$ but at $\nu = 5$ it is clearly developed. This change happens quite dramatically; the feature appears with a change of
magnetic field of only 0.1T. The feature doesn’t disappear at $\nu = 4$ but rather its intensity is suppressed relative to $\nu = 5$ and it blueshifts towards LL$_0$. OA$_0$ rapidly gains spectral weight at $\nu = 3$, again in a very narrow regime of magnetic field of approximately 0.1T. For higher magnetic fields the feature is greatly suppressed and largely gone at $\nu = 2$. This behavior is summarized in Figure 3 where the magnetic field dependence of all recombinations is displayed. OA$_0$ does not move to lower energy for increasing field as one would expect from a simple shake-up process: it shows very little dispersion except for blueshifts seen at $\nu = 4$ and $\nu = 2$. The temperature dependence of this novel structure is also quite telling and is displayed in Figure 5. OA$_0$, which appears as broad shoulder to the LL$_0$ recombination at T=4.2K, doesn’t change significantly down to temperatures of 2K. The most dramatic changes occur between 1.5K and 0.53K. This energy scale of 1K $\sim$ 0.08meV is much smaller than any cyclotron gap and indicates the importance of many-body and/or spin effects.

The most striking aspects of OA$_0$ are its huge intensity at odd filling factor $\nu = 3$ and the complex dependence of its intensity and energy position on magnetic field. The strong resonance seen at odd filling suggests that the spin of the electron system plays an important role. Our understanding of this doublet structure follows the recently developed model of Hawrylak et al.\textsuperscript{6} which has been used to explain a similar behavior seen in the data of Gravier and co-workers.\textsuperscript{2} This model has the advantage that it is applicable in the limit of low disorder in which both Zeeman and cyclotron gaps are resolved and electron-electron interactions are expected to be of prime importance. The recombination of a conduction-band electron and valence-band hole leaves a hole in the final state of the electron system. In the non-interacting limit this hole represents a well-defined quasiparticle. Nevertheless, this hole left behind in the final state of the 2DEG lies well below the Fermi level and constitutes a highly excited state. If this hole is degenerate with other elementary excitations of the electron gas and electron-electron interactions are strong, the spectral function of the fully interacting hole may not be perturbatively related to the hole in the non-interacting system. This is the fundamental finding of Hawrylak’s work: the doublet structure observed in luminescence at odd filling factors is due to the non-quasiparticle behavior of the 2DEG hole.
spectral function. The two peaks observed in luminescence are shown to be due to a resonant many-body interaction of the hole in the electron gas with a continuum of spin-wave excitations. Thus spin plays a crucial role in the physics of this model; the splitting of the spectral function only occurs at odd fillings where a continuum of low-lying spin waves is resonant and the spin of the hole can be compensated for by a spin-flip excitation. Hawrylak has deemed this situation an “Anderson-Fano” resonance in which the hole strongly interacting with the continuum of low-lying spin waves is mapped onto the classic solid-state physics problem of a localized state interacting with an unbound continuum.

We believe that such theoretical considerations describe qualitatively our experimental observations of the doublet LL$_0$ and OA$_0$, and clearly distinguish it from the perturbative shake-up process OA$_1$. The hole spectral function has been calculated numerically and the lower energy peak of the doublet is found to contain 60 percent of the spectral weight of the fundamental recombination band at $\nu = 3$. This splitting into a resonant doublet structure is consistent with the experimentally observed behavior. Additionally this theory accounts well for the observed blueshifts and intensity reductions seen in OA$_0$ at even filling $\nu = 4$ and $\nu = 2$ where the spectral function is expected to collapse to a single peak in the absence of low-lying intra-Landau level spin wave excitations. Both experiment and theory point to the important role played by the spin magnetization of 2DEG for final state interactions.

In summary, we have presented a systematic experimental study of the low energy structure of the photoluminescence spectra from a low disorder 2DEG at integral filling $\nu > 2$. Our findings identify two distinct features occurring below the fundamental band of recombination from the lowest Landau level. The lowest energy satellite is consistent with a perturbative shake-up process in a magnetic field. The splitting of the fundamental recombination line at odd filling factors is shown to be related to a non-perturbative splitting of the final state spectral function of the 2DEG.
ACKNOWLEDGMENTS

This work was supported by National Science Foundation Grant No. DMR-9701958. We thank Pawel Hawrylak for many insightful conversations.
REFERENCES

1 B.B. Goldberg, D. Heiman, A. Pinczuk, L. Pfeiffer, and K. West, Phys. Rev. Lett. 65, 641 (1990); A.J. Turberfield, S.R. Haynes, P.A. Wright, R.A. Ford, R.G. Clark, J.F. Ryan, J.J. Harris, and C.T. Foxon, Phys. Rev. Lett. 65, 637 (1990); H. Buhmann, W. Joss, K. von Klitzing, I.V. Kukushkin, G. Martinez, A. Plaut, K. Ploog, and V.B. Timofeev, Phys. Rev. Lett. 65, 1056 (1990).

2 L. Gravier, M. Potemski, P. Hawrylak, and B. Etienne — Preprint, submitted to PRL (1997).

3 Gleb Finkelstein, Hadas Shtrikman, Israel Bar-Joseph, Phys. Rev. B. 56, 10326 (1997).

4 Using an effective mass $m^* = 0.0699m_e$ for GaAs, the separation between Landau levels is $\hbar\omega_c = 1.65\text{meV}/T \cdot B$.

5 C. Kallin and B. Halperin, Phys. Rev. B. 31, 3635 (1985).

6 P. Hawrylak and M. Potemski, Phys. Rev. B. 56, 12386 (1997).

7 P. Hawrylak, Phys. Rev. B. 44, 11236 (1991).

8 P. Hawrylak, Phys. Rev. B. 42, 8986 (1990).

9 K.J. Nash, M.S. Skolnick, M.K. Saker, and S.J. Bass Phys. Rev. Lett. 70, 3115 (1993).

10 P. Hawrylak, N. Pulsford, and K. Ploog, Phys. Rev. B.46, 15193 (1993).
FIGURES

Figure 1. Photoluminescence spectra in the LCP ($\sigma^-$) polarization at $T=0.53K$ for the SQW with $n_s = 1.8 \cdot 10^{11} cm^{-2}$ and $\mu = 2.6 \cdot 10^6 cm^2/Vs$. The spectra at $\nu = 3$ is highlighted to show the low-energy fine-structure. The inset to Fig. 1 displays the lowest-energy feature tuning to lower energy for increasing magnetic field.

Figure 2. Individual spectra at $\nu = 3$ displaying low energy anomalies OA$_0$ and OA$_1$. The fundamental recombinations from the 0th and 1st Landau level are labeled LL$_0$ and LL$_1$ respectively. Note the strong intensity of the OA$_0$ peak relative to the fundamental LL$_0$.

Figure 3. Recombination peak positions as function of magnetic field at $T=0.53K$. The low energy features are labeled OA$_0$ and OA$_1$. The fundamental recombination from the 0th Landau level is labeled LL$_0$. Also shown is the line $E=-1.65meV/T \cdot B+E_0$ as explained in the text.

Figure 4. Magnetic field development of optical anomalies between $\nu = 6$ and $\nu = 2$. All spectra at taken in the $\sigma^-$ polarization at $T=0.53K$. For ease of comparison, all spectra have been normalized to have the same peak intensity in the LL$_0$ transition.

Figure 5. Temperature dependence of low energy structure between 4.2K and 0.53K. All scans are taken at $B=2.5T$, $\nu = 3$. 
Manfra, et al. Fig 1.
Magnetic Field (T)

Energy (meV)

$\nu = 2$

$\nu = 5$

$\nu = 3$

$E = -1.65 \text{meV}/T^*(B) + E_0$

Peak Positions

$T = 0.53 \text{K}$

Manfra, et al. Fig 3.
Manfra, et al. Fig 4.
Manfra, et al. Fig 5.