

Anderson-Fano resonance and shake-up processes in the magnetophotoluminescence of a two-dimensional electron system

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We report an anomalous doublet structure and low-energy satellite in the magnetophotoluminescence 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 [Phys. Rev. B **56**, 12 386 (1997)], we show that distinct mechanisms are responsible for each feature. [S0163-1829(98)51516-0]

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.¹ More recently, optical techniques have proven sensitive to excited states of the two-dimensional electron gas (2DEG) inaccessible to transport. In particular, two groups have recently reported on a low-energy structure in the magnetophotoluminescence in GaAs structures occurring at energies below the fundamental recombination from the lowest Landau level (LLL).^{2,3} While clearly indicative of many-body effects, these 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 process³ and to a non-perturbative final state resonance of the 2DEG.^{2,4} 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 magnetophotoluminescence 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 $\nu=3$, and (ii) a significantly smaller satellite peak which redshifts for increasing magnetic field between $\nu=6$ and $\nu=2$ and is observed at approximately 2 meV 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 $\text{Al}_x\text{Ga}_{1-x}\text{As-GaAs}$ 250 Å 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 $1.4\text{--}1.8\times 10^{11}\text{ cm}^{-2}$ and mobilities μ range from $2.6\text{--}3.0\times 10^6\text{ cm}^2/\text{Vs}$. The samples were excited at 740 nm with the output of a tunable Ti:sapphire laser. The laser was stabilized and the incident power density was kept below 10^{-4} 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} 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 He³ refrigerator mounted in a 13-T magnet. Base temperature of our configuration is 500 mK. 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 0.64-m monochromator and detected with a liquid-nitrogen-cooled charged-coupled-device (CCD) camera with 0.4-meV resolution.

Figure 1 displays the low-temperature magnetophotoluminescence spectra in the left-circular (σ^-) polarization in the field range of 0 T to 4 T for a sample with $n_s=1.8\times 10^{11}\text{ cm}^{-2}$ and $\mu=2.6\times 10^6\text{ cm}^2/\text{Vs}$. The use of polarization analysis is crucial since the high quality of these samples results in narrow linewidths in which spin splittings are resolved above 1.5 T. Detecting in the σ^- 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 their relationship to the quantum Hall effect have been studied extensively.¹ We focus our discussion on the low-energy structure between $\nu=5$ and $\nu=2$ appearing below the main peak labeled LL_0 in

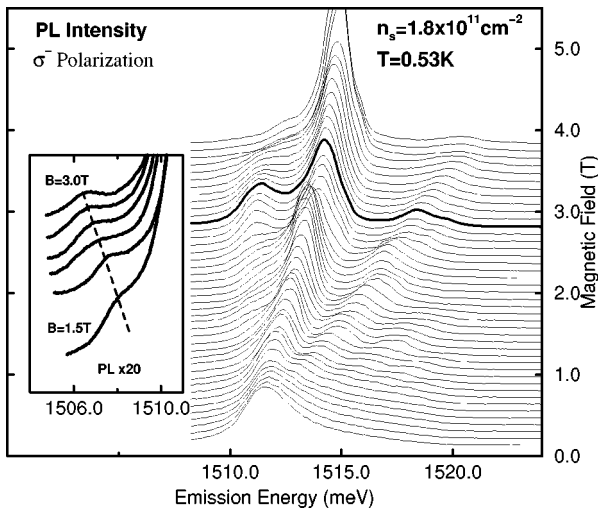


FIG. 1. Photoluminescence spectra in the LCP (σ^-) polarization at $T=0.53$ K for the SQW with $n_s=1.8 \times 10^{11} \text{ cm}^{-2}$ and $\mu=2.6 \times 10^6 \text{ cm}^2/\text{Vs}$. The spectra at $\nu=3$ is highlighted to show the low-energy fine structure. The inset to Fig. 1 displays the lowest-energy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

Fig. 2. Within the context of a noninteracting 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 $T=0.53$ 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 low-

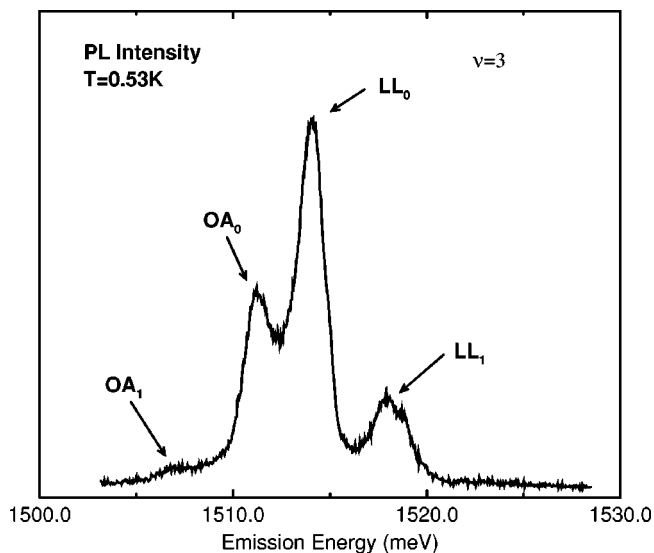


FIG. 2. Individual spectra at $\nu=3$ displaying low-energy anomalies OA_0 and OA_1 . The fundamental recombinations from the 0th and 1st Landau level are labeled LL_0 and LL_1 respectively. Note the strong intensity of the OA_0 peak relative to the fundamental LL_0 .

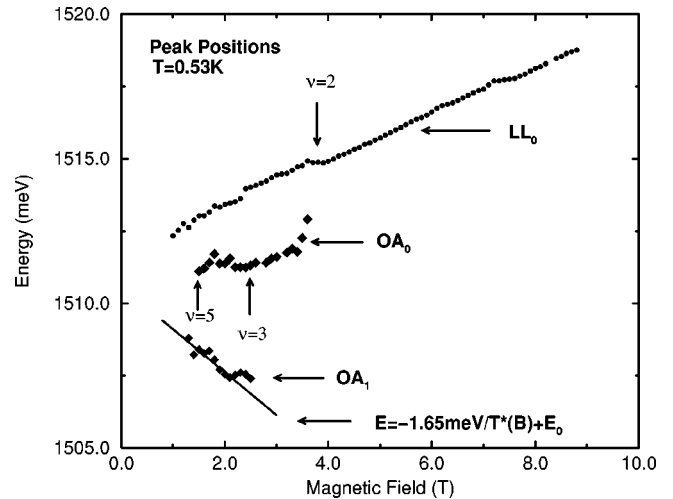


FIG. 3. Recombination peak positions as function of magnetic field at $T=0.53$ K. The low-energy features are labeled OA_0 and OA_1 . The fundamental recombination from the 0th Landau level is labeled LL_0 . Also shown is the line $E = -1.65 \text{ meV/T} \times B + E_0$ as explained in the text.

est 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 $\text{In}_x\text{Ga}_{1-x}\text{As-InP}$ quantum wells,⁵ and most recently, in GaAs structures.³ The theory of shake-up has also been extensively investigated.^{6,7} 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 Fig. 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.⁸ 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 $\sim 6 \text{ meV}$ while $\hbar \omega_c$ at this field is approximately 4 meV . This behavior has been observed previously in the $\text{In}_x\text{Ga}_{1-x}\text{As-InP}$ system⁵ and attributed to the fact that for nonzero wave vectors the excitation energy of the $n=1$ magnetoplasmon mode actually exceeds $\hbar \omega_c$.⁹ For comparison, we have drawn in Fig. 3 a line through OA_1 that corresponds to an excitation dispersing with a slope equal to the ideal (noninteracting) Landau level separation in GaAs of 1.65 meV/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 Fig. 2. At $\nu=3$, OA_0 contains nearly 50% of the spectral weight seen in the fundamental recombination band, LL_0 . The intensity of OA_0 exhibits a complicated magnetic-field dependence which is clearly seen in Fig. 4. At $\nu=6$

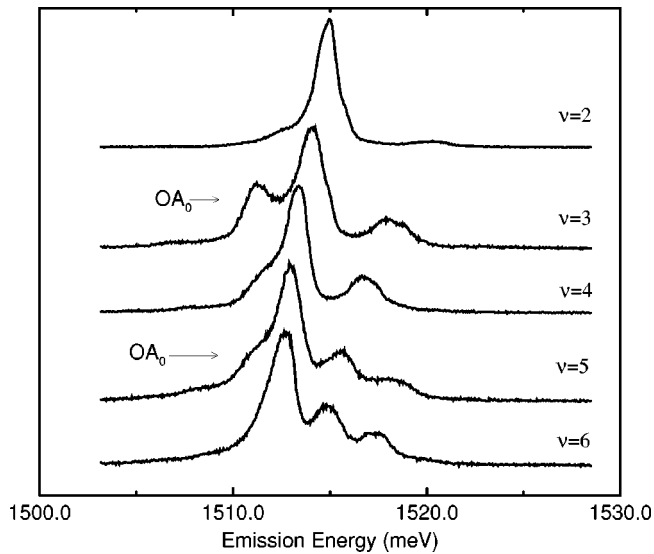


FIG. 4. Magnetic-field development of optical anomalies between $\nu=6$ and $\nu=2$. All spectra are taken in the σ^- polarization at $T=0.53$ K. For ease of comparison, all spectra have been normalized to have the same peak intensity in the LL_0 transition.

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 0.1 T. 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 0.1 T. For higher magnetic fields the feature is greatly suppressed and largely gone at $\nu=2$. This behavior is summarized in Fig. 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 structure is also quite telling and is displayed in Fig. 5. OA_0 , which appears as a broad shoulder to the LL_0 recombination

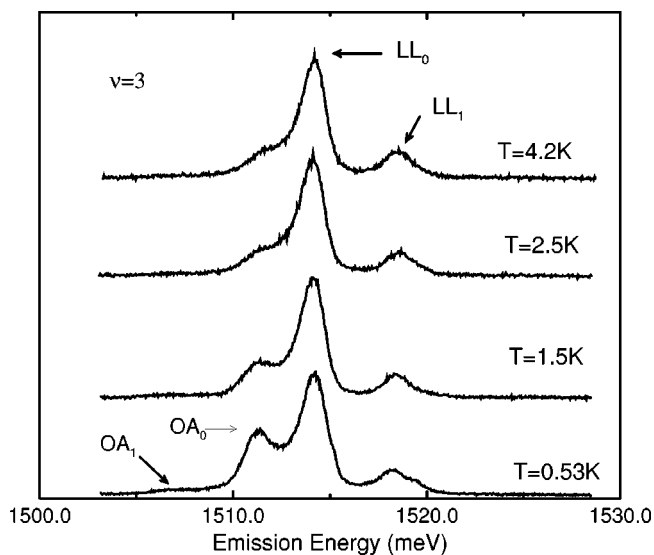


FIG. 5. Temperature dependence of low-energy structure between 4.2 and 0.53 K. All scans are taken at $B=2.5$ T, $\nu=3$.

at $T=4.2$ K, doesn't change significantly down to temperatures of 2 K. The most dramatic changes occur between 1.5 and 0.53 K. This energy scale of 1 K \sim 0.08 meV 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.*⁴ which has been used to explain a similar behavior seen in the data of Gravier and co-workers.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 noninteracting 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 noninteracting system. This is the fundamental finding of Hawrylak's work: the doublet structure observed in luminescence at odd filling factors is due to the nonquasiparticle 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 numerically⁴ and the lower-energy peak of the doublet is found to contain 60% 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 fac-

tors is shown to be related to a nonperturbative splitting of the final state spectral function of the 2DEG.¹⁰

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