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Fermi-edge singularities and enhanced magnetoexcitons in the optical spectra of GaAs/(Ga,Al)As single quantum wells

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Pronounced many-body exciton effects have been observed through photoluminescence in modulation-doped n-type GaAs quantum wells where a near-resonance coincidence exists between a transition involving two-dimensional electrons at the Fermi level in the first conduction subband and an exciton transition from the second conduction subband. Under these conditions, strong and distinct Fermi-edge singularities can be observed near $\mathbf{k}\approx\mathbf{0}$. A magnetic field induces further enhancement of the effect, but also leads to very large, B^{-1}-periodic amplitude variations in the photoluminescence, with excursions over 3 orders of magnitude.

There has been a surge of interest in the study of a two-dimensional (2D) electron gas in quantizing magnetic fields by optical methods, motivated in part by attempts to develop spectroscopic probes of the quantum Hall effect[1-3] For example, we have reported recently on results in (In,Ga)As single quantum wells[3] (SQW) where the connection to the integer QHE was argued to have been realized for a particular sample design in terms of optimizing its optical properties as a probe of the 2D electron gas. This design calls for a one-sided modulation-doped quantum well where the Fermi level (E_F) lies very near a particular unoccupied conduction subband (typically $n_c=2$). Under such circumstances, the dominant features in the recombination spectrum for such a nearly degenerate circumstance can show pronounced many-body exciton effects,[3] which are closely related to the "Fermi-edge singularities" (ES) observed through photoluminescence or absorption in modulation-doped quantum wells[4] (MDQW), albeit now under specific conditions.[5] In terms of an optical probe, apart from the near energetic degeneracy between the second conduction subband ($n_c=2$) and E_F, the details of the heterostructure design also include careful consideration of the electron-hole (e-h) wave-function overlap.[1-3] In the asymmetric heterostructures considered here, this overlap can, in principle, be adjusted over a large range by constraining the carriers to opposite sides of the SQW. Hence, the e-h Coulomb (excitonic) energy is also "tunable."

The principal aim of this paper is to show how, within a relatively narrow range in the electron-sheet density (n_s) and the e-h separation, pronounced many-body contributions to interband excitonlike transitions are present in n-type GaAs MDQW's, as viewed through photoluminescence (PL). The application of magnetic fields produces striking effects for hybridized "magnetoexciton" resonances both in terms of amplitude and spectra. Our data suggest that the ES effects are, if anything, enhanced in magnetic fields in ways which suggest their use as an optical probe of the 2D electron gas. At the same time, the experiments also raise questions about the photoholes in terms of their perturbation of the 2D system. This is, needless to say, a critical issue in optical studies of collective 2D electron phenomena such as the fractional QHE and the Wigner crystallization.

Figure 1 shows a portion of the photoluminescence spectrum recorded from a one-sided, asymmetric GaAs/(Ga,Al)As MDQW with an equilibrium electron density of $n_s=9.1\times10^{11}$ cm^{-2} at $T=2.5$ K. The spectral range corresponds to a recombination of electrons occupying phase space in the vicinity of the $n_c=2$ subband with thermalized $n_v=1$ photoholes in the GaAs SQW. We mention in passing that the recombination from GaAs buffer layers (which are a necessary part of the sample structure) gives rise to spectral features which strongly interfere with the PL at the $n_c=1$ subband edge. The SQW layer thickness is $L_w=200$ Å and the Al concentrations

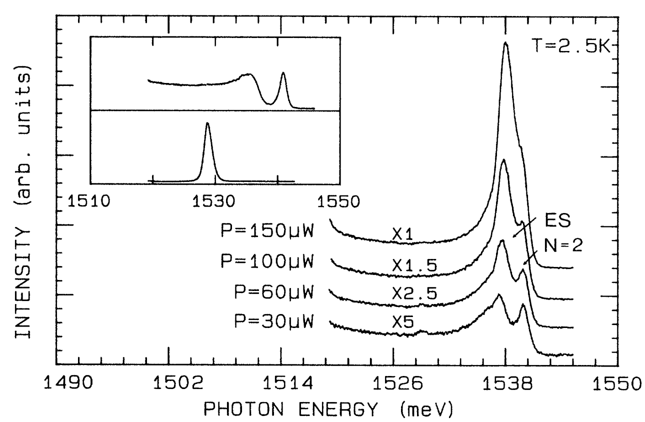

FIG. 1. Photoluminescence spectra from the n-type GaAs SQW in the region of the $n=2$ conduction to $n=1$ heavy-hole transition at $T=2.5$ K, showing the ES and its dependence of optical excitation level, as well as the $N=2$ exciton. The curves are displaced vertically for clarity and show incident optical power. The inset shows spectra from two other samples of different electron density.

are $x=0.3$ and 0.15 in the doped and undoped barrier layers, respectively. Low-temperature mobility is $\mu \approx 3\times10^5$ cm^2/Vs. We concentrate in this paper on the particular sample of Fig. 1 chosen from several structures grown with slightly different parameters. For this sample, E_F lies within 3 ± 0.3 meV *below* the $n_c=2$ subband as determined from a combination of optical and transport data.

At low levels of photoexcitation ($\Delta n_s \sim 10^6$ cm^{-2}, based on the measured excitation power and lifetime measurements by time-resolved optical techniques), the PL spectrum in Fig. 1 shows two clearly defined spectral features. The peak labeled "$N=2$" is an exciton composed of nonthermal (photoexcited) electrons in the $n_c=2$ subband with $n_v=1$ photoholes, whereas the peak labeled "ES" is interpreted involving *equilibrium* electrons at E_F and is subject to a distinct ES enhancement. In the low-excitation regime, the ES peak shows an approximately square dependence on the intensity of excitation, while that of the $N=2$ exciton is approximately linear (this dependence for the latter is also seen in undoped QW's and may contain a contribution from weak exciton localization and trapping). The power levels shown in Fig. 1 are measured at the sample position (of area 2×2 mm^2). At higher power levels than those in Fig. 1, the $N=2$ exciton becomes the dominant transition and the ES peak is no longer discernible. The ES feature is strongly temperature dependent as seen in Fig. 2, where it is strongly attenuated by $T\approx5$ K, beyond which the spectrum is dominated by excitons formed from thermally elevated electrons into the $n_c=2$ subband.

This observation of the ES signature is in strong contrast with PL spectra measured in samples in which the equilibrium sheet density is either too low or too high. That is, E_F is initially either too far (> 5 meV) below the $n_c=2$ subband, or lies within the subband. In the former case, the $n_c=1 \rightarrow n_v=1$ PL signal shows an abrupt fall off in amplitude at an energy E_F above the renormalized band gap without a distinct ES enhancement; in the second case, one sees a strong $N=2$ exciton which is not particularly sensitive to temperature or a magnetic field. The inset of Fig. 1 shows the low-temperature PL spectra for these cases, corresponding to sheet densities of $n_s=7\times10^{11}$ and 1.05×10^{12} cm^{-2}, respectively. The key point below is that in neither case are the effects induced by an external magnetic field, either qualitatively or quantitatively matched with the pronounced effects which occur for the structure of choice. In practical terms, we have found that an energy separation $\Delta E = E(n_c=2) - E_F$ of the order of 2–3 meV and $L_w \approx 200$ Å leads to PL spectra where the ES aspect plays a dominant role. The origin of the ES enhancement in such circumstances (near $k=0$) is due to the hybridization of the two nearly degenerate interband transitions[3] and has been analyzed theoretically in terms of virtual scattering of the electrons from E_F to the $n_c=2$ subband, intermediated by the Coulomb interaction with the photohole[5] (see also below). In this context, the exact origin of the pronounced superlinear intensity dependence of the ES peak in Fig. 1 may be due to a finite-hole wave vector increase or hole-induced nonlinearities in the many-body Coulomb scattering process.

With the application of magnetic fields we find that the ES effect is, under these circumstances, considerably enhanced on the average while it displays pronounced amplitude variations periodic in $1/B$. Here we highlight the low-field and high-field regimes, leaving a more-extended presentation of data elsewhere. In the low-field regime ($B\leq2$ T), we find that well before the Landau levels (LL) of the 2D electrons in the $n_c=1$ subband are fully isolated, strong variations are seen in the ES spectrum. Figure 3 shows such spectra at $T=1.4$ K up to $B\approx2$ T. We have chosen the incident power level so that the ES feature and the $N=2$ exciton are comparable at $B=0$ T in order to follow both of these resonances with the field. The incipient formation of a LL structure well below the ES peak shows normal orbital quantization of the one-electron states in the $n_c=1 \rightarrow n_v=1$ transition. The situation is considerably more complex, however, in the ES and $N=2$ exciton spectral regime. In particular, the ES transition is subject to large amplitude variations, while its spectral position is not significantly changed. Note the

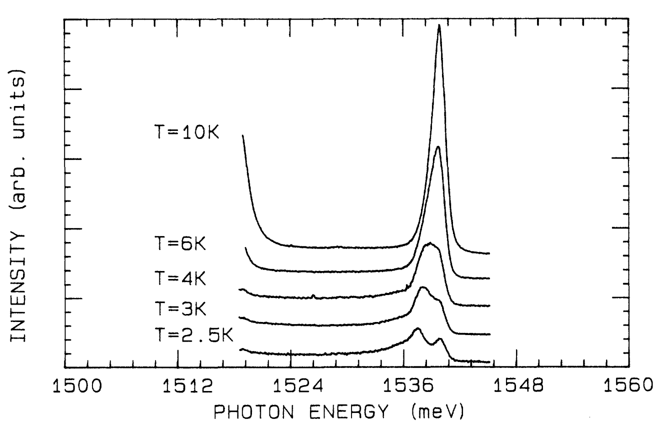

FIG. 2. Temperature dependence of the PL spectrum showing the quenching of the ES emission and buildup of the $N=2$ exciton from thermal excitation of electrons into the $n_c=2$ subband.

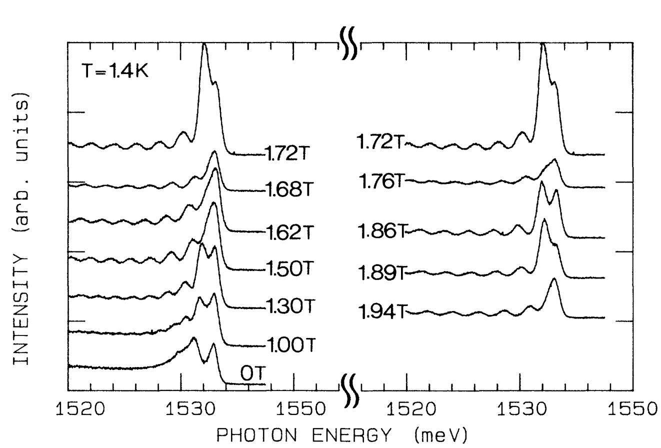

FIG. 3. PL spectrum at $T=1.4$ K in the low-field regime showing the variations in the ES signal and the incipient Landau quantization within the $n_c=1$ subband.

changes which occur, e.g., in the interval of 0.04 T between 1.72–1.76 T. It is important to note that the dominant changes apply to the ES feature and *not* to the $N=2$ exciton peak, which is only weakly affected. The ES amplitude changes occur within a field range which is a fraction (~0.3 or less) of the equivalent width of the LL's. Furthermore, the $n_c=1$ LL emission *below* the ES also varies in close synchronism with the ES. In other words, the ES feature extends in its influence well below E_F, deeper into the Fermi sea, through the extended 2D electron states, which in this field range are not yet separated into isolated LL's.

In strongly quantizing magnetic fields (isolated LL's), the average intensity of the ES continues to grow while subject to amplitude excursions over more than 3 orders of magnitude. The lower trace of Fig. 4 shows such variations in fields up to 12 T under conditions that the PL signals at $B=0$ could not be detected at all, but the ES feature grew to become the spectrally dominant one by about $B=1$ T. (Experimentally, we used a spectral-windowing approach to isolate the ES feature for its amplitude determination.) In the regime of the large amplitude variations, the PL spectra again suggests an interplay of the ES (which is shifting approximately diamagnetically) with the $N=2$ exciton resonance, now modified with the Landau quantization of the 2D electron gas whose level filling factors are given in the figure. (In addition to the principal oscillations, smaller, periodic "satellites" are also evident. These appear to be associated with a higher-energy hole state which can be spectrally seen when the main PL signals are very weak.) Figure 5 shows some of the spectral details over a field range of $B=6.31$–7.20 T, corresponding to the early stages of the buildup of one of the amplitude maxima in Fig. 4. The overlap and the sharing of oscillator strength between the two interacting interband resonances suggests that these transitions hybridize periodically, excitonlike, in the magnetic field ($1/B$). The $N=2$ exciton state "pins" the ES resonance energy which is strongly influenced by the Landau quantization of the 2D gas. Note how the amplitude of luminescence involving electrons in the lower LL's of the $n_c=1$ subband (below the ES region) also varies strongly with magnetic field, showing minima when the Es state displays a maximum, and vice versa (upper panel in Fig. 4). This is opposite to the low-field regime described above. The temperature dependence of the amplitude oscillations is also quite pronounced as seen in the inset of Fig. 5. While the oscillations are virtually quenched by $T\approx 20$ K, very strong PL signals are still present in the form of the $N=2$ exciton due to the thermally excited electron population from the Fermi sea of the $n_c=1$ subband. (Experimentally, we could still isolate the ES component in the increasingly $N=2$ dominated emission at $T\sim 10$ K; beyond this, such distinct identification was no longer possible.)

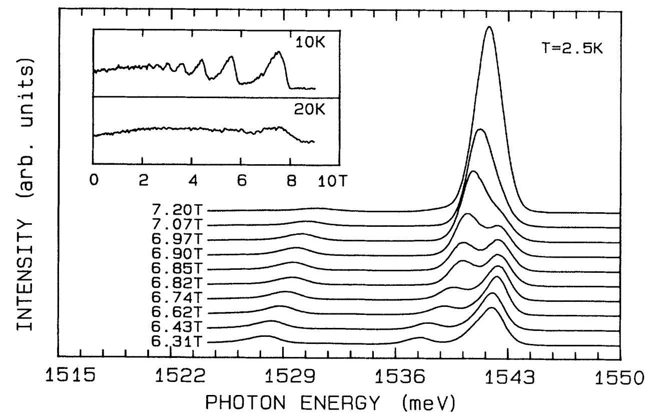

FIG. 5. Details of the spectrum within one period of the oscillations of Fig. 2, showing the hybridization of the ES with the nearby transition which has evolved from the highest Landau level in the $n=1$ subband. The inset shows temperature dependence of the oscillations in Fig. 4.

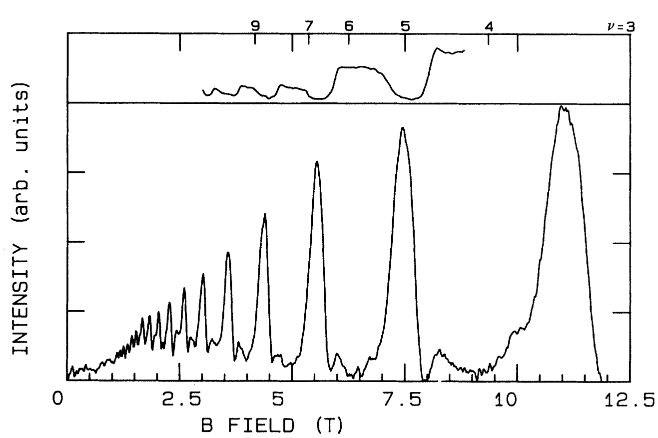

FIG. 4. Amplitude of the ES signal as a function of magnetic field at $T=2.5$ K reaching into the high-field regime (lower panel). The upper panel shows the variations in amplitude of the (much weaker) luminescence from electrons in the lower Landau levels of the $n=1$ subband.

While the problem of edge singularities in the optical spectra of modulation-doped quantum wells has been discussed from a theoretical point of view in recent literature,[6,7] following the original idea of Mahan,[8] there is little published work on the influence of magnetic fields on this many-body exciton state. In connection with their study of the influence of the finite hole mass on edge singularities, Uenoyama and Sham have also calculated magneto-optical spectra for PL and absorption.[9] Their general trend shows that, as the hole mass is lowered (from infinity), the spectral strength in PL of the ES is strongly reduced. In our case, however, the presence of the extra scattering channel at the $n_c=2$ subband edge clearly strengthens the ES transition, especially in a magnetic field. Here, we present empirical suggestions about the nature of the ES transition in the circumstances of the second-subband proximity effect. First note that while ES features were observed in PL in zero field from (In,Ga)As quantum wells by Skolnick *et al.*,[4] they used the argument of hole localization in the alloy to endow sufficient wavefunction amplitude at $k=k_F$. The near resonance with the $n_c=2$ subband encountered in our case essentially allows the multiple Coulomb scattering processes to take place near $\mathbf{k}\approx 0$. Thus, sharp ES peaks, distinct from the

$N=2$ exciton, can be observed in PL for GaAs *without* a need to evoke localization or infinite-mass arguments. This is also clearly shown by the calculations of Mueller, Ruckenstein, and Schmitt-Rink.[5] In real space, the $n_c=1$ electrons and $n_v=1$ holes are spatially separated in the asymmetric quantum-well structures so that their Coulomb pair interaction is weak. However, the $n_c=2$ state has a substantially larger overlap with the $n_v=1$ state and we believe that the nearly degenerate condition in our experiments makes the $n_c=2$ subband to extend a "Coulomb bridge" for the enhancement of the ES effect. Qualitatively, while the $n_c=2$ state has a wave function which is orthogonal to the $n_c=1$ state in the one-electron limit, the coupling through the photohole (exciton aspect) opens up in effect a large number of Feynman paths for the electron-hole problem in terms of electrons at the Fermi edge. Naturally, the one-electron matrix element for the $N=2$ exciton state ($n_c=2 \rightarrow n_v=1$) is also enhanced ($|\mu|^2$), increasing by about a factor of 8. However, as shown clearly by the experiment, conditions of excitation and temperature can be chosen so that the ES transition, not the $N=2$ exciton, dominates the PL spectrum.

In external magnetic fields where the second-subband ES enhancement is subject to the large $1/B$ periodic changes as shown above, the theoretical problem becomes quite difficult. However, the PL spectra (Figs. 3 and 5) are still useful, at least in terms of suggestive insight to the field-induced effects. The fact that the electronic states near E_F now involve Landau orbitals has, of course, a direct impact on the ES amplitude and its spectral position; perhaps more appropriately, we may speak of hybridization involving the different magnetoexcitonlike transitions near the $n_c=2$ subband. The $N=2$ magnetoexciton establishes the upper limits to the photon energy of the hybridized ES state. This "clamping" can, in fact, be clearly identified by constructing a fan plot for the spectral positions of the observed PL energies.

We interpret the very-large-amplitude variations of Fig. 5 as changes in the stability of formation of the ES state. That is, at the minima of these oscillations the ES is unable to form, most likely because of the unavailability of free electrons in *extended* states of the uppermost occupied LL. This leads to the quenching of its PL signal as competing channels for recombination of the photoexcited carriers take over. In our high-field regime, this is clearly illustrated by the "out-of-phase" amplitude oscillations of the PL signals involving lower-lying LL's of the n_c subband (upper panel in Fig. 4); at a field for which the ES enjoys maximum enhancement, all the available photoholes are used up for this recombination channel so that the PL emission from the lower LL's is minimized. This out-of-phase behavior occurs in the field regime where the LL's are fully isolated from each other, in contrast to the low-field regime where the ES- and LL-based transitions are in synchronism in terms of their amplitude oscillations. We also note that the maxima in the ES amplitude follow approximately the odd filling factors in the integer regime of the QHE (the peak at $B \sim 11$ T showing evidence of spin splitting and corresponding to $\nu = 3\frac{1}{2}$). A more extensive account of our transport data will be presented separately.

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