Interaction of Magnetoexcitons and Two-Dimensional Electron Gas in the Quantum Hall Regime

W. Chen, M. Fritze, and A. V. Nurmikko

Division of Engineering and Department of Physics, Brown University, Providence, Rhode Island 02912

D. Ackley, C. Colvard, and H. Lee

Siemens Laboratories, Princeton, New Jersey 08540

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We have investigated the influence of a two-dimensional electron gas on interband optical transitions in an (In,Ga)As modulation doped single quantum well under conditions where the Fermi level is very near the $n=2$ conduction subband and a many-body exciton is observed from this subband. Strong variations occur in external magnetic fields in both the exciton spectrum and its amplitude of which the latter correlates with the longitudinal Hall resistance in the quantum Hall regime.

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Magneto-optical studies of a quasi-two-dimensional (2D) electron or hole gas in semiconductor heterostructures have been widely applied to obtain information about details of Landau quantization,[1] valence-band complexities,[2] screening, many-body interactions,[3] and so on, including spectroscopy in the quantum-Hall-effect (QHE) regime[4] where recent work of Heiman *et al.* and Pinczuk *et al.*[5] suggests a connection between an optical probe and transport measurements in quantizing magnetic fields; a point of basic interest, for example, when considering the generally different statistical and spatial averaging these contrasting experimental measurements involve in a given sample.

In this Letter we present experimental results for a 2D electron system in an (In,Ga)As quantum-well structure, which strongly suggests a direct link between specific features in photoluminescence (PL) spectra and the longitudinal Hall resistance in the QHE regime. We demonstrate an optical effect where an excitonlike interband transition can be used as a sensitive probe of the equilibrium 2D electron gas. This transition originates from a normally unoccupied $n=2$ conduction-subband level which lies very near the Fermi level (E_F) of the 2D gas in the $n=1$ subband. In zero magnetic field, the transition is similar to the recently studied many-body "Fermi-edge singularity" in the interband spectra of doped (In,Ga)As and GaAs quantum wells.[6,7] In finite fields, the Coulomb coupling of this exciton to the 2D electron gas in our case is strongly field dependent; a feature which, as argued below, is correlated with 2D electron occupancy within the localized or delocalized states of a Landau level.

The structures used in this study were one-sided modulation doped n-type $Ga_{0.70}Al_{0.30}As/In_{0.15}Ga_{0.85}As/GaAs$ single quantum wells (MDSQW), with (In,Ga)As quantum-well thickness $L_w = 150$ Å.[8] The low-temperature electron mobility was approximately 8×10^4 $cm^2/V\,sec$ including samples with electron sheet density exceeding 1×10^{12} cm^{-2}. Figure 1 shows low-temperature, low-excitation (<10 mW/cm^{-2}) PL traces of two samples with electron densities $n_s = 8.0\times10^{11}$ and 1.1×10^{12} cm^{-2} (obtained from Hall measurements). The spectrum of the former for the $n_c=1$ conduction-band to $n_v=1$ valence-band transition shows a well-defined cutoff at an energy indicative of the Fermi level in the $n_c=1$ conduction subband. For the latter, the contribution from the $n_c=1$ subband merges into intense, strongly excitation-power-dependent emission from the $n_c=2$ conduction subband. The MDQW structures are asymmetric both from their compositional structure and the one-sided doping; hence the parity selection rule ($\delta n=0$) is weakened and the PL spectra at

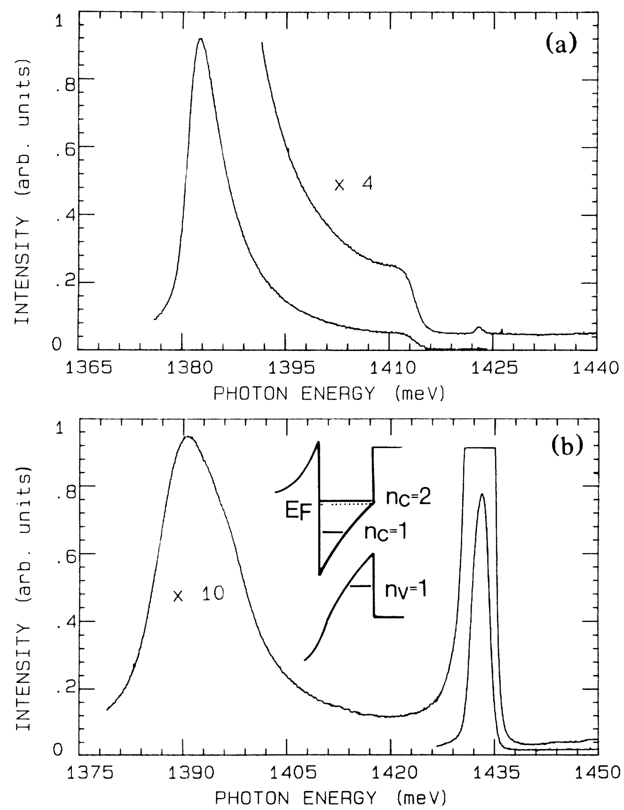

FIG. 1. Photoluminescence spectra of two (In,Ga)As MDQW's at $T=1.8$ K of different electron density (two magnifications): (a) $n_s=8.0\times10^{11}$ cm^{-2} and (b) $n_s=1.1\times10^{12}$ cm^{-2}. Inset: A schematic of the quantum-well band profile and relevant energy levels at $B=0$.

low temperatures involve thermalized holes in the $n_v=1$ valence subband (see inset of Fig. 1). Furthermore, the lattice-mismatch strain splits the valence-band extremum by approximately 60 meV so that only the "light-hole" band (with in-plane "heavy-hole" dispersion) is of relevance here.

The behavior of the $n_c=2 \rightarrow n_v=1$ emission in magnetic fields is the central feature in this paper. In particular, for the sample with higher sheet density in Fig. 1, the electron density is such that E_F is near the $n_c=2$ subband edge but *slightly below it*. We have determined this energy separation to be 4 ± 1 meV for this sample in zero field. Under such circumstances the $n_c=2 \rightarrow n_v=1$ emission, involving nonequilibrium electron-hole pairs, is excitonlike while very strongly influenced by (many-body) Coulomb effects of the energetically proximate 2D equilibrium electron gas. In zero field, the Coulomb interaction of photoholes with electrons in a single subband has been detailed as the Fermi-edge singularity.[6,7] In PL studies this involves electrons at $k=k_F$ with holes at $k\sim 0$; wave-vector conservation permits the singularity to be observable as a distinct peak only with strong hole localization. In our case, the $n=2$ exciton is analogous to an *edge singularity occurring at* $k\sim 0$ and the need for hole localization is relaxed. Figure 2 shows the zero-field temperature dependence of the $n_c=2 \rightarrow n_v=1$ emission. In strong contrast with exciton PL from an undoped (In,Ga)As quantum-well control sample, we observed a pronounced decrease with temperature of the amplitude (with a small blueshift) and the eventual appearance of a Boltzmann-like high-energy tail, as expected also in the case of the first subband-edge singularity.[7]

In an external magnetic field (perpendicular to the QW layer plane), our PL spectra show well-resolved Landau quantization for the $n_c=1$ subband ($n_c=1 \rightarrow n_v=1$ transition), yielding the following electron and hole effective masses (in layer plane), respectively: $m_e=0.0648m_0$ and $m_h=0.157m_0$.[9] The PL originating from the $n_c=2$ subband in the sample with $n_s=1.1 \times 10^{12}$ cm^{-2}, on the other hand, shows that it represents a Coulombically bound state being subject to only diamagnetic shifts while retaining its narrow linewidth.

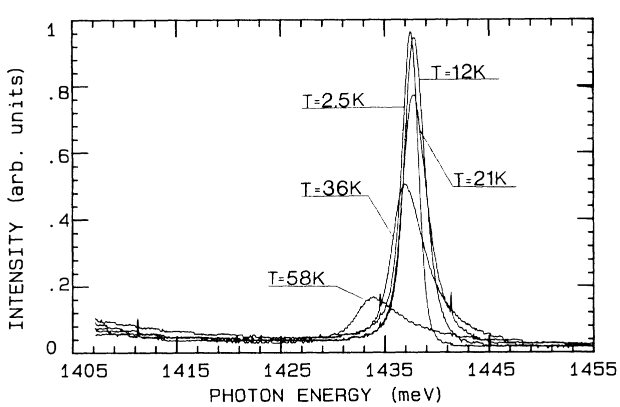

FIG. 2. Temperature dependence of the PL spectra for sample of $n_s=1.1\times 10^{12}$ cm^{-2} in the vicinity of the $n_c=2 \rightarrow n_v=1$ transition.

The most striking effect of the magnetic field, however, pertains to the *amplitude* of the $n=2$ excitonlike transition (termed "magnetoexcitation" below). Figure 3 shows a portion of the PL spectrum (including Landau levels of the $n_c=1 \rightarrow n_v=1$ transition adjacent to the $n_c=2$ related transition) over approximately a 1.5-T range. With increasing field in Fig. 3, two sequential events occur. First, the overlap of an $n=1$ Landau-level transition with the $n_c=2 \rightarrow n_v=1$ magnetoexciton transition develops. Second, at a distinctly higher-field value, the amplitude of the latter transition builds up rapidly, followed by a precipitous quenching. This sequence occurs repeatedly in the field, producing pronounced amplitude variations strictly periodic in $1/B$. The width of the peaks (in $1/B$) is approximately one-third of the field equivalent width of the $n=1$ Landau levels.

We have established a link between the amplitude variations of the magnetoexciton and transport phenomena in simultaneous Hall measurements as shown in Fig. 4. Note the correlation between the longitudinal Hall resistance ρ_{xx} in the QHE regime and what we term here as the "optical Shubnikov–de Haas" oscillations (OSdH) in the exciton amplitude. The (electrical) SdH effect gives a check on the electron density of 1.1×10^{12} cm^{-2}, in full agreement with the OSdH. The OSdH oscillations remain very well defined with an excellent signal-to-noise ratio to low magnetic fields ($B\sim 1$ T) while yielding large-amplitude ratios of maxima to minima (in excess of 1000:1 for the highest oscillation in Fig. 4). We emphasize the difference between these measurements and other magneto-optical experiments where interband PL amplitude variations $1/B$ are seen through a narrow spectral window due to Landau-level spectral shifts and level-population effects.[10] Such effects are generally much less pronounced than those in Figs. 3 and

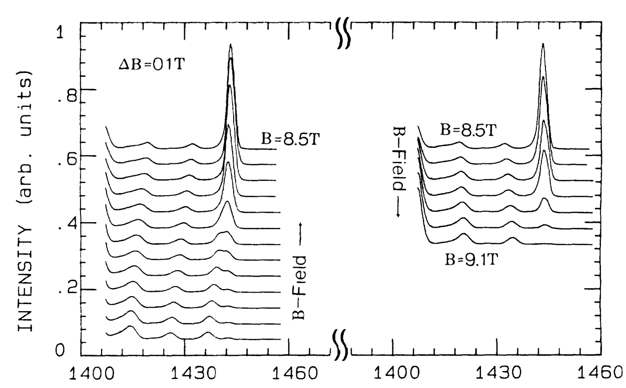

FIG. 3. Influence of the magnetic field on a portion of the PL spectrum at $T=1.8$ K, highlighting the highest Landau levels and the second conduction-subband-related transition. The magnetic field increases in steps of 0.1 T (upwards in the left-hand side of the figure and downwards on the right).

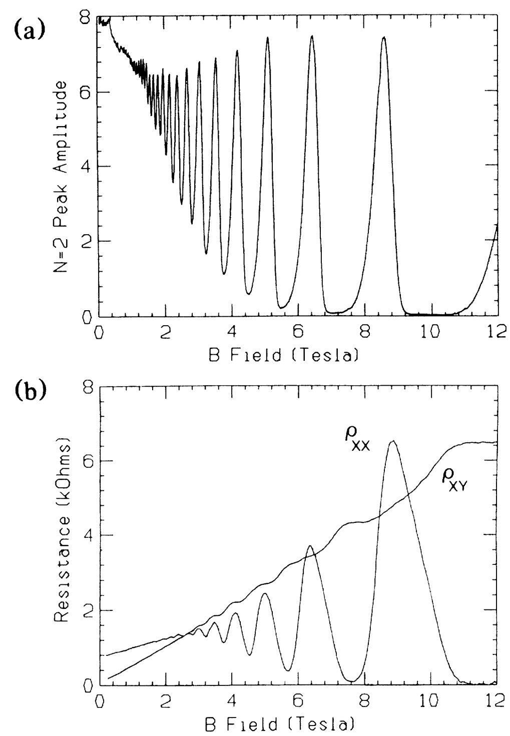

FIG. 4. Variations of the $n_c=2$ magnetoexciton amplitude as a function of magnetic field (a) at $T=1.8$ K and (b) compared with Hall measurements on the same sample. A scale factor of 2.5 is applied to ρ_{xx}.

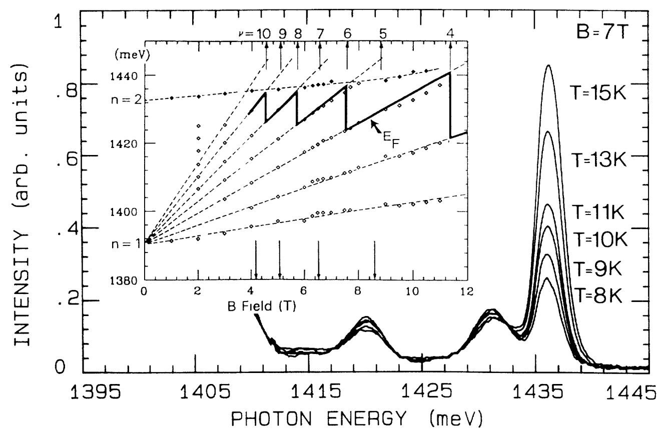

FIG. 5. Illustration of temperature dependence of the magnetoexciton transition over the interval of $T=8$–15 K in a field of 7 T. Inset: The fanplot of the $n=1$ and 2 transition energies (dashed lines are to guide the eye) together with the OSdH maxima (arrows at bottom) and filling factors (arrows at top) as well as the calculated position of E_F at $T=0$ K over the field range of interest (bold line).

4 and without such a commensurate connection to QHE data as in our case. In Fig. 4, while there is an excellent one-to-one correspondence between the ρ_{xx} and OSdH maxima, a finite discrepancy is evident for the highest-field maximum. From initial studies to fields beyond 12 T it appears that lifting of the spin degeneracy complicates the magnetoexciton interaction.

The strong-field-induced modulation of the magnetoexciton requires that a Coulomb coupling between the 2D electron gas and the nonequilibrium electron-hole pair exists; that is, zero-field conditions where E_F is very near the $n_c=2$ subband edge but where negligible equilibrium electron density resides in the $n_c=2$ subband. Apart from the Coulomb or many-body exciton enhancement at $k\sim 0$, the interband optical-transition probability for a $n_c=2\rightarrow n_v=1$ transition is also enlarged by the strong quantum-well asymmetry. The asymmetry in our one-sided modulation doped SQW samples can be approximated as a potential consisting of an asymmetric triangular part (containing the $n_c=1$ and $n_v=1$ subbands) and a square-well part (for the $n_c=2$ subband).

In our interpretation, the periodic buildup and quenching of the magnetoexciton amplitude is a consequence of two sequential factors as follows. First, the crossing of a $n_c=1$ Landau level with the $n=2$ exciton provides a means for hybridization of the two conduction-band states. As a zeroth-order approximation this hybridization can be expressed as a product wave function of the particular Landau level $|L\rangle$ and the exciton wave function $|X\rangle$ (in zero field), with the Coulomb interaction energy as $E_{\text{Coul}}=\langle L|\text{H}_{\text{Coul}}|X\rangle$. The hybridization provides a further means of enhancing the interband matrix element for the overlapping transitions, but more important, in our view, the maintenance of a Coulomb channel for coupling the magnetoexciton to the 2D electron gas. We are unaware of an existing theory applicable to these circumstances,[11] but our experimental data are directly indicative that such a channel must exist between the magnetoexciton "probe" and the 2D many-body system for states near the Fermi level. The overlap of the two transitions in Fig. 2 is seen to be at maximum at ~ 7.8 T; in general, such level overlaps occurred slightly above the extrapolated crossings drawn from low-field "fanplots" for the energies of the $n_c=1$ and 2 associated transitions. Such deviations are an indication of the interaction between the two levels. At the same time, it is clear from Fig. 3 that the pronounced changes in the magnetoexciton amplitude occur at field values which are *higher* than those for the actual level "crossing." The importance of the coincidence with the maxima in ρ_{xx} shows very clearly and intuitively that the coupling of the magnetoexciton with the free-electron gas (in the spirit of the edge singularity) occurs most effectively when the Fermi level is within the *delocalized* states of the uppermost occupied Landau level (excess electron-hole concentration is much lower than the 2D electron density). That is, the maxima in OSdH oscillations coincide with *odd* (delocalized) integer Landau-level filling factors in the $n_c=1$ conduction subband within 2%–3% accuracy (at field values where the spin degeneracy is not yet lifted). These key observations are summarized in the inset of Fig. 5 which shows the fanplot of the $n=1$

and 2 transition energies, together with the OSdH maxima and filling factors, as well as the calculated position of E_F at $T=0$ K for the equilibrium electrons over the field range of interest.

For the measured sheet density (1.1×10^{12} cm^{-2}) the corresponding level filling factors show that E_F, for example, in the spectra of Fig. 3 (with the filling factor reaching 5 at the maximum of the magnetoexciton amplitude) lies within the Landau level immediately below the one which is actually hybridizing with the $n=2$ magnetoexciton (note that because of the enhancement of the matrix element for the hybridizing Landau level its PL amplitude gives a much exaggerated impression of the actual level population). This observation was checked over several periods of the OSdH oscillations and is also consistent with the presence of only single oscillatory behavior in the electrical SdH data and the assumption that the magnetoexciton acts only as a weak probe of the 2D electron gas.

The role of the localized and delocalized states can be further seen from the temperature dependence of the OSdH oscillations. For example, by fixing the magnetic field at an amplitude minimum, thermally activated behavior is observed. As an example, Fig. 5 shows how this occurs at $B=7$ T where a finite overlap between a $n_c=1$ Landau level and the $n_c=2$ exciton already exists at $T=2$ K. Note the strong increase with temperature of the exciton amplitude (shown here for $T=8$–15 K) while Landau-level spectra are very little influenced. The temperature dependence of the exciton amplitude fits an exponential over nearly 2 orders of magnitude yielding an activation energy for the case of Fig. 5 of approximately 1.5 meV. Note that we are not simply observing the thermal excitation of electrons into the $n_c=2$ subband. Depending on the B-field "bias" value we have measured such energies in the range of 1–5 meV. This is in the range of values obtained from T dependence of ρ_{xx} (In,Ga)As MDSQW's,[12] suggesting that the data in Fig. 5 contain a contribution from thermal excitation of electrons from the localized states to extended states within a given Landau level. The OSdH effect is more complicated, however, as it is likely that the Coulomb channel which couples the 2D electron gas to the optical probe (exciton) is quite T dependent in its own right. In this sense, for example, our temperature dependences are less explicit than those of Heiman *et al.* in Ref. 5.

In summary, we have shown how an excitonlike transition with many-body coupling to an energetically proximate 2D electron gas suggests a useful linkage between optical and transport measurements, here in the integer QHE regime. However, substantive theoretical challenges remain for quantitative modeling of the Coulomb interaction of the exciton and the electron system under conditions where hybridization with Landau levels is responsible for providing a powerful channel for this field-dependent interaction.

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