

There is presently widespread interest in excitons, the fundamental interband excitations in semiconductors (Coulomb-correlated electron-hole pairs), in low-dimensional semiconductor systems. Both basic physics and applications drive this interest. In the case of quasi-2D systems much recent attention has been focused on charged excitons and magneto-excitons (trions), which have the lowest energy of the photo-excited system at low excitation intensities. Charged exciton complexes were originally predicted by Lampert [1958] but not observed experimentally until 1993 [Kheng *et al.* 1993]. Trions have since been studied intensively in GaAs and CdTe QW structures [*e.g.*, Finkelstein *et al.* 1995; 1996; Cox *et al.* 1998; Shields *et al.* 1995; Whittaker and Shields 1997], and by our group. The evolution of the exciton system in quasi-2D as a function of excess electron concentration from isolated neutral excitons to negatively charged excitons to a few-hole/many-electron plasma (the metal-insulator transition), and the effects of a magnetic field on these transitions have been the focus of some recent investigations [Finkelstein *et al.* 1995, 1996; Shields *et al.* 1995; Gekhtman *et al.* 1996]. However, there have been very few studies of internal exciton transitions (IETs) in such systems (except for ours). IETs provide distinct signatures of neutral and charged excitons, which can be used to distinguish between states of the system. We have utilized Optically Detected Resonance (ODR) spectroscopy, a sensitive technique that employs a visible excitation laser and a far infrared (FIR) probe laser, to make the first observation of IETs for both neutral and charged excitons. [Salib *et al.* 1995; Nickel *et al.* 1998; Dzyubenko *et al.* 1999]. In this technique the photoluminescence (PL) excited by the visible laser is modulated by resonant absorption of power from the FIR laser and these changes in PL are monitored as a function of either magnetic field or photon energy with magnetic field as a parameter.

Although there are many superficial similarities between neutral and charged excitons and neutral and charged shallow donors in semiconductors, we have shown that there are also surprising and fundamental differences. Thus we expect some similarities in the internal transitions in the presence of excess electrons, but we also anticipate some surprises. In the presence of excess electrons, donors in semiconductor quantum wells exhibit a large blue shift and oscillations in the transition frequency with maxima at integral filling factors (ν), and smaller changes at fractional ν . For $\nu < 1$, the blue shifts for all samples rapidly decrease, and the transition frequencies approach those of the isolated D^- -ion, even with as many as 16 electrons per positive donor ion. We have come to understand this behavior in terms of positive donor ions located at the minima of long-range lateral potential fluctuations [Jiang *et al.* 1998]. Based on this picture one would expect similar behavior to occur for localized excitons at high fields, and internal transitions can distinguish between localized and free X^- s [Dzyubenko and Sivachenko 1999]. There is presently no theoretical model that predicts the behavior of free excitons in the presence of a substantial density of electrons.

There have been many studies of PL and absorption/reflection in: 1) single-side modulation-doped heterostructures and wide QWs, and 2) symmetrically modulation-doped narrower QWs. In case 2) photoinjected electrons and holes are located in the same spatial region (in the GaAs wells), while in case 1) electrons and photo-injected holes are spatially separated due to the self-consistent potential. The mobilities of structures 2) are generally poorer than those of structures 1), and it is usually assumed that there is larger disorder and larger fluctuating potentials in the former (which account for observed differences in behavior). For these two types of structures two distinctly different behaviors of the interband magneto-optical spectra are observed. In case 1) PL features generally increase linearly with B except for cusp-like oscillations and discontinuities at integral ν and "anomalies" (discontinuities in slope and

multiple lines) at fractional ν . Cusps are upward pointing and lie above the extrapolated low-field, bandgap-renormalized, Landau-level-to-Landau-level transitions [see e.g., Goldberg *et al.* 1992]. The discontinuities at integral ν are more complex, and can be both blue- and red-shifted relative to the extrapolated Landau level to Landau level (LL-LL) transitions [Goldberg *et al.* 1992; Hawrylak and Potemski 1997; Gravier *et al.* 1998; Osborne *et al.* 1998; Nicholas *et al.* 1998]. These anomalies are still not understood and are under active investigation [*e.g.* Nicholas 1999; Martinez 1999]. In case 2) the general behavior is very different. At low magnetic fields, LL-LL transitions (linear in B) shifted by bandgap renormalization are observed. Beginning at $\nu = 2$, the lowest observed transition is depressed below the extrapolated heavy-hole ($N_h = 0$) to electron ($N_e = 0$) transition. For $\nu < 2$ the field dependence appears to be excitonic, and this line has been attributed to X^- . Additional exciton-like features appear at higher fields where $\nu < 1$; these have been attributed to the triplet X^- and to the neutral free heavy-hole exciton, X . We believe that the PL features that have been attributed to X^- are more precisely described as X^- recombination in the presence of many electrons; this PL represents the response (in recombination) of the many-body system to the photoinjected electron-hole pair. This general behavior is very robust and is seen in samples from different sources over a very wide range of modulation doping, well-widths and mobilities. The appearance of the X^- -like feature at $\nu = 2$, and X for $\nu < 1$ is not fully understood, nor is the relationship between this behavior and the contrasting behavior of single heterostructures. The exciton-like behavior is never seen (to our knowledge) in single heterostructures or one-side-doped wide quantum wells. Localization definitely plays a role, but is not the whole story. We believe that the connection between these two behaviors lies in spatial separation of the electrons and photo-excited hole (and the electron-hole coulomb interaction); there is a large separation for single heterostructures and very small (or no) separation for narrow quantum wells. The correlation of magneto-optical behavior with spatial separation has been noted recently in careful magneto-PL studies around $\nu = 1$ [Osborne *et al.* 1998; Cooper and Chlovskii 1997]. Explanations invoking many-electron effects exclusively [Asano and Ando 1998; Hawrylak and Potemski 1997, and references therein], while perhaps appropriate for the "cleanest" single-heterostructure samples and wide, one-side-doped QWs, are not appropriate for the narrower, symmetrically doped QW situation. For narrow QWs or symmetric wide-wells, the Coulomb attraction of the electron and valence-band hole is larger than the electron-"spin-hole" interaction in the two-dimensional electron gas.

Using the new spectrometer system purchased under this grant, we have initiated studies of the effects of excess electrons on the internal transitions of photoexcited excitons in GaAs/AlGaAs symmetrically modulated-doped multiple-quantum-well structures. The goal of this work, supported by NSF DMR9722625, is to determine the effects of electron-electron interaction on the energy states and optical spectra of photo-injected electron-hole pairs in the presence of many excess electrons in quasi-2D electronic systems. Based on our experience in with internal transitions of X and X^- , and our recent major steps forward in understanding the optical signatures of charged complexes in a magnetic field (with our collaborators [Dzyubenko and Sivachenko, 1999]), we are using the internal transitions as a probe of the "state" of the many-body system. The goal is to unravel the complex field-dependent behavior described in the preceding paragraph. In particular, we hope to answer the following questions: 1) Are the high field states in quantum wells (QWs) with large densities of excess electrons negatively charged (X^-) and neutral (X) excitons, or do they represent a more complex collective response of the system? 2) What is the role of localization in the observed evolution of the magneto-PL of quantum wells (QWs) from bandgap-renormalized, band-to-band recombination at low fields to

X^- -like recombination at $FF = 2$, and finally to X -like recombination for $FF < 1$? 3) How can the distinctly different magneto-optical behaviors of different types of modulation doped heterostructures be reconciled?

In an attempt to answer some of these questions we have carried out a preliminary set of experiments on a series of modulation-doped GaAs/Al_{0.3}Ga_{0.7}As MQW structures with nominal donor (Si) doping levels of $3.2 \times 10^{11} \text{ cm}^{-2}$ (sample 1), $1.6 \times 10^{11} \text{ cm}^{-2}$ (sample 2), and $0.8 \times 10^{11} \text{ cm}^{-2}$ (sample 3); the well- and barrier- widths of these samples are 24 nm and 48 nm, respectively.

Examples of results are shown in Fig. 1. The approach that we have adopted is to take ODR spectra at a series of far IR laser wavelengths such that the critical region near $FF = 2$ is spanned, namely data are obtained at fields both below and above the field corresponding to $FF = 2$. In Fig. 1(b) we show a series of ODR spectra from sample 3 obtained by tracking the lowest energy feature in the magneto-

PL spectrum (attributed to recombination from an X^- -singlet ground state). At the shortest wavelength (highest photon energy) the ODR spectrum is very similar to that obtained in a nominally undoped, 20 nm MQW structure. [Dzyubenko *et al.* 1999] We have attributed the observed features to bands of ionizing internal transitions, singlet (indicated by the upward pointing blue arrows) and triplet (the line just below eCR). These bound-to-continuum transitions dominate the spectra for free X^- due to a hidden symmetry (magnetic translational invariance) of the Hamiltonian. [Dzyubenko and Sivachenko 1999] Note that the resonant fields for both the singlet- and triplet- X^- features occur above the field corresponding to filling-factor (ν) = 2. Just as in the previous work at low electron densities, in the present case there is no indication of the bound-to-bound triplet transition, which would dominate if the X^- complexes were strongly localized. This transition would occur on the high-field side of the eCR. As the photon energy is decreased, and the resonant features move to lower magnetic field, the triplet feature remains strong, but the singlet feature weakens and is not observable at a wavelength of 184 microns (photon energy = 54.3

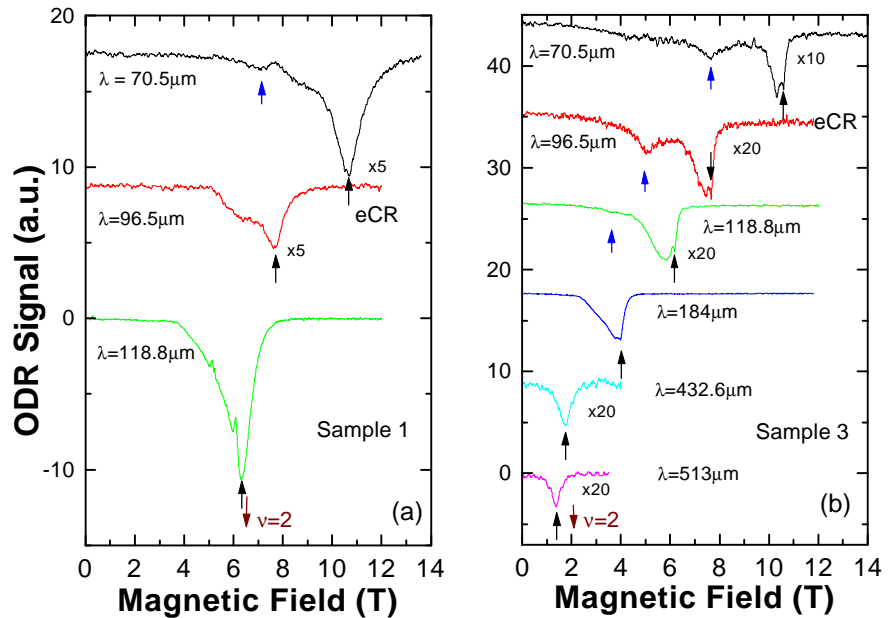


Fig. 1. ODR spectra comparing two modulation-doped samples: Sample 1 - $3 \times 10^{11} \text{ cm}^{-2}$; sample 2 - $0.8 \times 10^{11} \text{ cm}^{-2}$. (a) Results for sample 1 at three FIR laser wavelengths. (b) Results for sample 3 at seven FIR laser wavelengths. Electron cyclotron resonance is indicated by the up-point black arrows (eCR), and a feature that has been identified in lower density samples as a band of internal transitions of X^- (singlet ionizing transitions) is indicated by the upward-pointing blue arrows. The field corresponding to filling-factor (ν) = 2 is also indicated for each sample.

cm^{-1}). At this photon energy, the singlet feature should occur in the vicinity of the magnetic field corresponding to $\nu = 2$. At still longer wavelengths, there is no evidence of either singlet or triplet transitions; the photon energy is too small to excite any internal transitions.

In the case of the heavily doped sample 1 (Fig. 1 (a)) the behavior is rather different. At the highest photon energy, where the singlet-like feature in Fig. 1 (b) lies slightly above the field corresponding to $\nu = 2$ for this sample, there is a weak feature that appears to be a blue-shifted singlet-like band, and a band that lies just below the eCR. The latter is most probably the triplet-like band for this sample. However, at 96.5 microns there is no clear singlet-like feature, but rather a broad band that begins slightly below eCR and extends to lower fields. Similarly, at 118.8 microns there is no evidence of the singlet-like feature, which should occur below 4T, only a broad tail below eCR (apparently related to the triplet-like transitions).

These preliminary data lend strong support to the idea that at magnetic fields above $\nu = 2$, irrespective of the electron density, the states are exciton-like. The blue-shift of the corresponding singlet and triplet internal transitions as the electron density increases is strongly suggestive that the transitions are many-body excitations of the system, and not isolated X^- complexes. In addition, there is no evidence for strong localization, which should lead to bound-to-bound triplet transitions on the high field side of eCR. [Dzyubenko and Sivachenko 1999] Additional experimental work support by theory is needed to sort out the details of this complex situation.

We are still working on the software necessary to interface the CCD camera to the ODR set-up. Problems with compatibility and bugs in the commercial software have delayed our implementation of the CCD full-spectrum approach to these ODR studies.

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