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Interaction of an electron gas with photoexcited electron–hole pairs in modulation-doped GaAs and CdTe quantum wells

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Abstract

The nature of the correlated electron gas and its response to photo-injected electron–hole pairs in nominally undoped and modulation-doped multiple quantum-well structures was studied by experiment and theory, revealing a new type of optically active excitation, magnetoplasmons bound to a mobile valence hole. These excitations are blue-shifted from the corresponding transition of the isolated charged magnetoexciton X^- . The observed blue-shift of X^- is larger than that of two-electron negative donor D^- , in agreement with theoretical predictions. © 2002 Elsevier Science B.V. All rights reserved.

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Since the initial observation of the negatively charged exciton X^- in CdTe/CdZnTe QWs [1] there has been considerable interest in charged electron–hole (e – h) complexes in quasi-two-dimensional semiconductor systems. X^- , the semiconductor analog to the negatively charged hydrogen ion H^- in atomic physics, differs from its superficially similar relative, the negatively charged donor ion D^- [2] in some very important respect: the positive charge in X^- , the hole, is free to move around. A symmetry associated with the resulting center-of-mass motion leads to a new

electric-dipole selection rule [3], which prohibits, in particular, certain bound-to-bound X^- transitions [4] that dominate the absorption spectra of D^- . The evolution of the spectra in 2D e – h systems with electron density n_e from isolated neutral excitons, via isolated X^- , to a plasma consisting of many electrons and a few holes, and the effects of magnetic fields on this evolution have been the subject of many studies. Magneto-photoluminescence (PL) spectra of such systems show bandgap-renormalized Landau-level (LL)-to-LL transitions at high filling factors (FF) $\nu = 2\pi l_B^2 n_e$, $l_B = (\hbar c/eB)^{1/2}$ and a discontinuity in the slope of the PL energy vs. field for the $N = 0$ LL transition at $\nu = 2$. For $\nu < 2$ the dominant PL is depressed below the extrapolated $N = 0$ LL transition and has an “exciton-like” field dependence (see, e.g. Refs. [5,6] and references therein). Internal transitions of excitons (IETs) can yield important insight into the ground and excited states of excitons [7] and thus

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offer another method of probing the excitonic state in the dilute situation and its evolution with n_e and magnetic field. In this study we have used the internal transitions of negatively charged excitons X^- [4] and the effects of many-electrons on these spectroscopic signatures to probe the many-body state of the system.

Three GaAs/Al_{0.3}Ga_{0.7}As MQW samples (Samples 1, 2, and 3) and one CdTe/Cd_{0.7}Mg_{0.3}Te MQW sample (Sample 4) were studied. The structures of these samples are [(well/barrier-thickness in Å) × repetitions]: Sample 1—(200/600) × 20, Sample 2—(240/480) × 20, modulation-doped at $8.0 \times 10^{10} \text{ cm}^{-2}$, Sample 3—(240/240) × 10, modulation-doped at $3.2 \times 10^{11} \text{ cm}^{-2}$ and Sample 4—(80/330) × 10, modulation-doped at $3.5 \times 10^{11} \text{ cm}^{-2}$. The dopant in the GaAs (CdTe) samples was silicon (iodine). These structures were studied by photoluminescence (PL) and optically detected resonance (ODR) spectroscopy [4,7] at low (4.2 K) temperatures in magnetic fields up to 15 T. The range of doping densities chosen for this experiment puts the magnetic field corresponding to FF $\nu = 2$ well within the range of the superconducting magnet used in this study. The observed resonances were studied at several discrete far-infrared (FIR) laser photon energies ranging from 2.87 to 17.6 meV. Fig. 1 shows magneto-photoluminescence (MPL) data for Sample 3. Overlaying the contour plot are datapoints indicating peak positions that were obtained by peak-fitting the individual MPL spectra. The solid lines indicating LL-to-LL recombination are guides to the eye. After peak-fitting the MPL data, an ODR spectrum was obtained by recording the intensity changes (induced by the absorption of FIR radiation) of the main PL feature (indicated by the upright triangles) as a function of magnetic field. Figure 2a shows ODR spectra for Sample 2 for several FIR laser photon energies as indicated in the graph. The magnetic field corresponding to FF $\nu = 2$, 1.66 T, is indicated by the arrow at the bottom axis. The sharp feature present in all traces and marked by the upward pointing arrowhead is identified as the electron cyclotron resonance (e-CR) transition with energy $\hbar\omega_{ce}$. Note that no feature is observed in any scan at a higher magnetic field than that of e-CR, in agreement with the selection rule [3], prohibiting bound-to-bound IETs of X^- . Two other features are observed in the ODR spectra recorded for high FIR photon energies. These features, which are blue-shifted from those

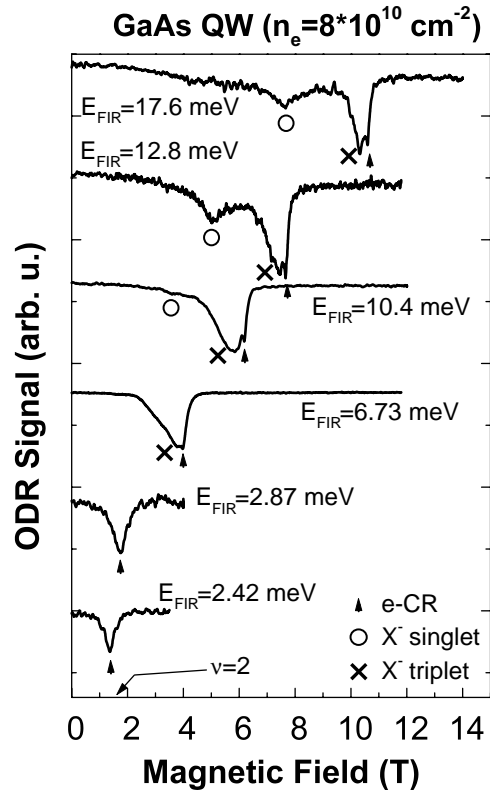


Fig. 1. ODR spectra of Sample 2.

observed in the undoped GaAs sample, are attributed to bands of ionizing singlet- (circles) and triplet-like (crosses) internal transitions of X^- [4]. The resonant fields for both singlet- and triplet-like X^- transitions occur *above* the field corresponding to $\nu = 2$. At lower FIR photon energies, the triplet feature remains strong, but the singlet feature weakens and is not observable at 6.73 meV (the predicted field position corresponds to $\nu > 2$). For the heavily doped Sample 3 these features become generally weaker and are further blue-shifted. In the modulation-doped CdTe-based MQW (Fig. 2b), only a triplet-like band below e-CR was observed for FF $\nu < 2$. The field position of this feature is also blue-shifted with respect to the position in a nominally undoped sample.

Theoretically, we consider intraband excitations from the ground state of a 2D system “the hole embedded in a sea of electrons” in strong magnetic fields with integer fillings of electron LL’s $\nu = 1, 2$. In the presence of a compensating background, intraband

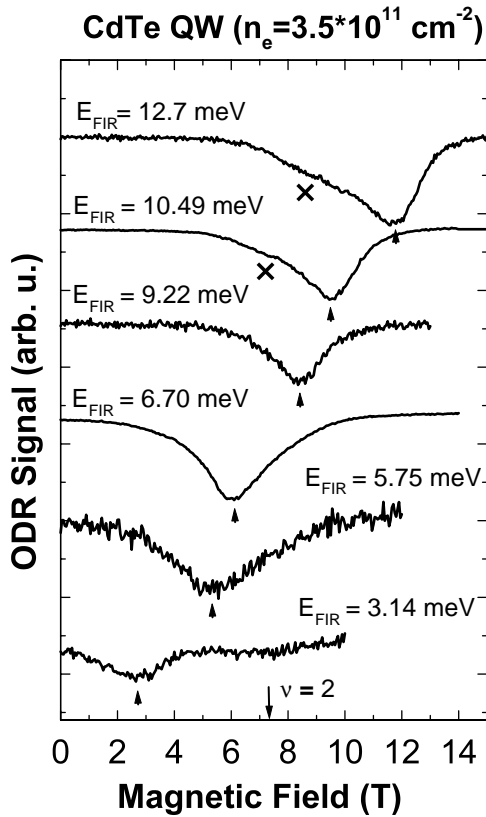


Fig. 2. ODR spectra of Sample 4.

collective excitations from the ground state can be described to be resonances involving a correlated e–h final state consisting of the conduction band electron in the empty $N = 1$ LL, e_{1cb} , a conduction band hole in an otherwise filled $N = 0$ LL, h_{0cb} , and a mobile valence band hole in the $N = 0$ LL, h_{0vb} . Therefore, the final state can be considered to be a positively charged 2h–e complex, which closely resembles the positively charged trion X^+ . The peculiarity of the present situation is the strong exchange interaction between the particles e_{1cb} and h_{0cb} . In the absence of the valence band hole, such a collective excitation is a 2D magnetoplasmon [8,9] Magnetoplasmons, like charge-neutral excitations, can be characterized by the conserved center-of-mass momentum $\mathbf{K} = (K_x, K_y)$. When $|\mathbf{K}|$ ranges from zero to infinity, the magnetoplasmon dispersion $E(\mathbf{K})$ forms a band of finite width $E_0/2$, where $E_0 = \sqrt{\pi/2}e^2/\epsilon l_B$. An eigenstate of the magnetoplasmon with a fixed \mathbf{K} is characterized by

the finite relative motion (a bound e_{1cb} – h_{0cb} pair) and by the extended motion of the center-of-mass. In the presence of the valence band hole, the classification of states changes drastically: the three-particle state X^+ is charged and cannot be characterized by the conserved center-of-mass momentum \mathbf{K} . Instead, charged complexes in \mathbf{B} can be characterized [3] by two exact quantum numbers—the total angular momentum projection M_z and the oscillator quantum number k . The latter physically determines the center-of-rotation of the charged complex as a whole in the plane perpendicular to \mathbf{B} ; correspondingly, there is Landau degeneracy in k . The relative motions of three particles can be either finite (on average, all particles are at finite distances from each other) or infinite. In the latter case the states belong to the three-particle continuum, which is formed by two partly overlapping bands: one band is formed by the magnetoplasmon (the bound e_{1cb} – h_{0cb} pair) plus a valence band hole h_{0vb} in a scattering state. The second band is formed by the states of an interband magnetoexciton X_{10} (a bound e_{1cb} – h_{0vb} pair) plus a conduction-band hole h_{0cb} in the scattering state. When all relative motions are finite, a truly bound X^+ -like state is formed; such states lie outside the continuum. There also exists a third possibility: quasi-bound states—the three-particle 2h–e resonances—may exist in the continuum. Depending on the width of the resonances and on the coupling to the continuum, such states may resemble bound X^+ states and may exhibit sharp peaks or Fano-resonances in optical measurements.

We performed calculations of the eigenspectra of the three-particle 2h–e excitations and matrix elements of intraband optical transitions $h_{0vb} + photon \rightarrow 2h$ –e following the method that has been described elsewhere [3]. In this paper, we describe the spectra of transitions that have energies larger than the e–CR energy $\hbar\omega_{ce}$. For electron FF $\nu=1$, there exists one rather sharp, optically active 2h–e resonance that lies within the continuum. For FF $\nu = 2$, due to the enhanced exchange-correlation effects, this state shifts upward in energy, moves out of the continuum, and becomes a truly bound 2h–e state. Simultaneously, it loses oscillator strength. Physically, for both $\nu=1$ and 2, the optically active state describes a magnetoplasmon bound to the mobile valence band hole h_{0vb} . The corresponding energies of collective excitations are larger than the energy of the internal triplet X^- transition (see

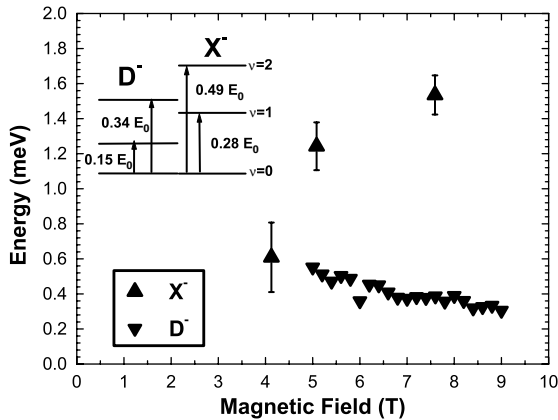


Fig. 3. Summary plot showing the blue shift of X^- and D^- . $E_0 = \sqrt{\pi/2}e^2/\epsilon l_B$ is the characteristic energy of Coulomb interactions in strong magnetic fields.

inset to Fig. 3). The latter transition corresponds to the vanishing FF $\nu = 0$. Therefore, the X^- transitions are blue-shifted in the presence of excess electrons. The calculated blue shifts of the X^- triplet at $\nu = 1$ and 2 are $0.28E_0$ and $0.49E_0$, correspondingly.

This behavior resembles the blue shift of the two-electron negative donor center D^- in the presence of excess electrons [10], which is understood in terms of magnetoplasmons localized on fixed donor ions D^+ [11,12]. The qualitative difference for a mobile valence hole is the presence of an additional dynamical symmetry, magnetic translations, and the corresponding exact optical selection rule [3,4]. Quantitatively, the blue shifts of the X^- and D^- are comparable. In agreement with experiment, the predicted blue shift of the X^- is larger than that of the D^- (Fig. 3). This can be explained by the diminished negative contribution of the Coulomb e–h attraction to the energy of the final 2h–e state containing a mobile valence band hole.

In conclusion, we have theoretically shown that in a photo-excited, quasi-2D system, in the presence of an electron gas, there exists a new type of optically active excitation, a magnetoplasmon bound to a mobile valence hole, and we have obtained experimental

evidence for this transition in ODR experiments. This excitation, depending on the electron filling factor ν , lies either within or above the band of free neutral magnetoplasmons and is blue shifted from the corresponding transition of the isolated charged magnetoexciton X^- . Theoretical results provide a qualitative explanation of the experimental findings, the blue shift of internal X^- transitions for fillings $\nu < 2$, in terms of a collective many-body excitation of the system.

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