Electron-Hole Magnetoplasmas in Quantum Wells

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The coupling of a photon probe to electron-hole magnetoplasmas in quantum wells is calculated for the first time including electron-hole pairing and excitonic effects. Optical experiments on modulation-doped quantum wells support the validity of the mean-field approximation involved. The condensation of quasi-two-dimensional, neutral, electron-hole plasmas into an excitonic-insulator state is accompanied by strong modifications of magneto-optical spectra. Significant magnetic field and well-width dependences of dynamical Stark effect and exciton saturation are predicted.

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Because of the attractive interparticle interaction, an electron-hole plasma in semiconductors or semimetals is expected to condense into a so-called excitonic-insulator state.[1-3] Analogously to the superconducting ground state of simple metals electrons and holes are paired in the condensed phase in such a way that the polarization $\langle \psi_e \psi_h \rangle$ is nonzero, where ψ_e and ψ_h denote the annihilation field operators of electrons and holes. In direct-gap semiconductors an electromagnetic field couples directly to this order parameter and the condensation phenomenon can be studied by the response to a probing light field (though the electron-hole pairing, which modifies the one-particle density of states, must not be confused with the photon vertex correction or exciton effect, which is a two-particle property). Pairing correlations in low-density plasmas have been successfully identified in recent years.[4] Of special interest are many-body effects on the dynamical (optical or ac) Stark effect,[2,4-6] resulting from a strong, below-band-gap light field which drives the electron-hole pairing externally. $GaAs/Al_xGa_{1-x}As$ quantum wells were found to be ideally suited to detect these effects.[4]

Based on the results of mean-field theory it is suggested in the present Letter that magnetic fields can be employed advantageously for the study of electron-hole pairing in quantum wells. The predicted effects of condensation on the magneto-optical properties of quasi-2D, high-density, electron-hole plasmas should be observable and are hoped to lead to the experimental identification of the excitonic-insulator state. Confidence in the reliability of the theory is derived from the favorable comparison with experiments on modulation-doped quantum wells. Magnetic field effects on the exciton saturation and dynamical Stark effect are also discussed for the first time.

The effects of an applied magnetic field on the optical response of modulation-doped quantum wells have been experimentally studied in some detail.[7-9] Potemski *et al.*[10] found that excitonic correlations persist even in highly excited quantum wells. Magnetic fields have not yet been employed to study electron-hole pairing phenomena, but femtosecond pump-and-probe magnetospectroscopy experiments have been announced for the near future.[11] The number of relevant theoretical papers is limited. Mean-field theory of a strictly two-dimensional, neutral, electron-hole plasma has been shown to be exact in the limit of infinite magnetic fields,[12] and the magnetoluminescence of modulation-doped quantum wells has been investigated.[13,14] Optical oscillator strengths and gain and absorption spectra of magnetoplasmas have, to the best of my knowledge, not been calculated at all.

The present mean-field (Hartree-Fock) treatment of the optical properties of quasi-2D magnetoplasmas takes into account the finite extension of the subband envelope function, the interaction with higher Landau-level states, the electron-hole pairing, and the exciton effect. The lowest-subband envelope functions are taken to be Gaussians with a half-width obtained by minimizing the total Hartree energy.[15] The Bethe-Salpeter equation, which determines absorption and gain spectra and emission spectra,[2,3] is generalized to quasi-2D systems and the presence of magnetic fields using the matrix elements from Refs. 16 and 17. The parameters for GaAs $m_e = 0.067$, $m_h = 0.3$, $\epsilon = 12.5$ for well and barrier material and a valence/conduction-band offset ratio of 0.3/0.7 are used. Nonparabolicities, valence-band mixing, and spin splittings are disregarded, as well as higher-order scattering effects (e.g., screening, lifetime broadening, and shakeup). Unless stated otherwise the calculations are done for a 100-Å $GaAs/Al_{0.3}Ga_{0.7}As$ quantum well and compared with the strictly 2D limit where appropriate. With a basis of up to 1200 Landau-level pair wave functions, fully converged results are obtained for fields down to $\simeq 0.2$ T ($\simeq 3$ T in the strictly 2D limit). Preliminary results have been reported in Ref. 18.

The luminescence energy of a charge plasma, consisting of the electron gas in a modulation-doped quantum well and a small number of photoexcited holes, is given in Fig. 1 as a function of magnetic field and electron density. The electron-hole pairing is negligible here, but excitonic effects are important when the filling factor (for one spin component) is smaller than 1. The apparent reduction of the masses due to the decrease of the

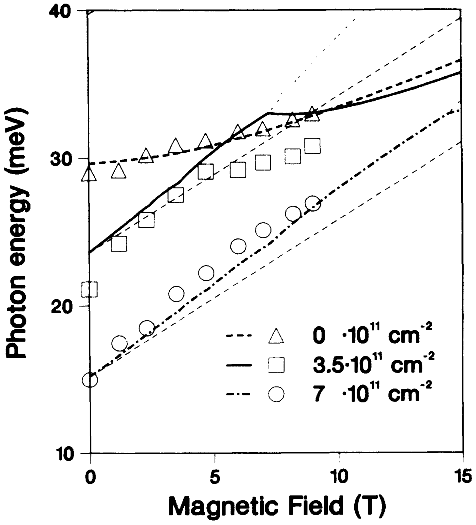

FIG. 1. Results of mean-field theory (bold lines) for the luminescence energy of a 107-Å $GaAs/Al_{0.4}Ga_{0.6}As$ modulation-doped quantum well as a function of magnetic field and electron densities, and the experiments (symbols) of Yoshimura and Sakaki (Ref. 8). The dotted line corresponds to the neglect of the exciton effect, while for the thin dashed lines the magnetic field dependence of the electron self-energy has also been neglected. To facilitate comparison with experiments the band edges at zero magnetic field as calculated in the Hartree approximation are adjusted to numerically exact Hartree results which take into account internal electric fields in the gated structure (Ref. 8). The zero-magnetic-field results differ by 0.6 and -1.3 meV from those calculated by local-density-functional theory (Refs. 18 and 25) for the densities 3.5×10^{11} and 7×10^{11} cm^{-2}, respectively.

electron self-energy with magnetic field and the transition from a linear (Landau-level-like) to parabolic (excitoniclike) diamagnetic shift with decreasing density and increasing field agree with experiments,[8] though theory appears to overestimate the field needed for the "magnetic freezeout." The introduction of a small magnetic field considerably simplifies solution of the Bethe-Salpeter equation at zero magnetic fields. At 0.2 T and an electron density of 4×10^{11} cm^{-2}, the absorption edge is found to be dominated by the so-called Mahan exciton[19] with a binding energy of 3.5 meV, which compares well with a binding energy of 4 meV measured recently by absorption experiments.[9] The above observations support the validity of mean-field theory and thus the conjecture of Schmitt-Rink, Chemla, and Miller[4] that screening is relatively unimportant in quantum wells. The results for neutral plasmas discussed in the following can therefore be expected to be reliable as well.

In Fig. 2 the calculated blueshift and saturation behavior of ground-state (1s) excitons due to a low electron-hole pair density of 10^{10} cm^{-2} is displayed as a function of magnetic field for the strictly 2D system and the 100-Å quantum well. The effect of the injected carriers is twofold.[4,20] The filling of the phase space by the

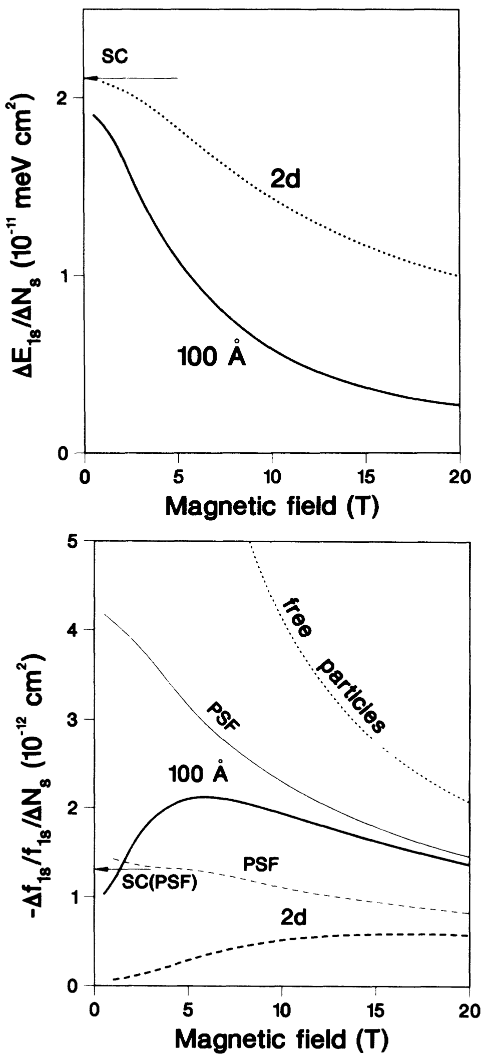

FIG. 2. (a) The blueshift of the ground-state exciton energy E_{1s} and (b) the saturation $-\Delta f_{1s}$ of its oscillator strengths f_{1s} due to an electron-hole pair density of $\Delta N_s = 10^{10}$ cm^{-2} as a function of magnetic field for a strictly 2D system and a 100-Å quantum well. The contribution of phase-space filling (PSF) to the decrease of f_{1s} is indicated by the thin lines. The neglect of the Coulomb interaction leads to the dotted line labeled "free particles." The exciton energy shift and the PSF contribution to the saturation of the oscillator strengths as obtained by Schmitt-Rink, Chemla, and Miller (Ref. 20) for strictly 2D systems and zero magnetic fields are indicated by arrows (labeled SC).

additional carriers destabilizes the exciton, but the exchange "molecular" field has a stabilizing effect so that the net result is fairly small. By extrapolating the curves in Fig. 2 it is seen that for zero magnetic fields this cancellation occurs for finite well width as well as for the 2D system in such a way that the total results do not differ much, which explains the satisfactory performance of the strictly 2D model in saturation studies.[4] *At finite magnetic field this balance is not maintained, however, and a*

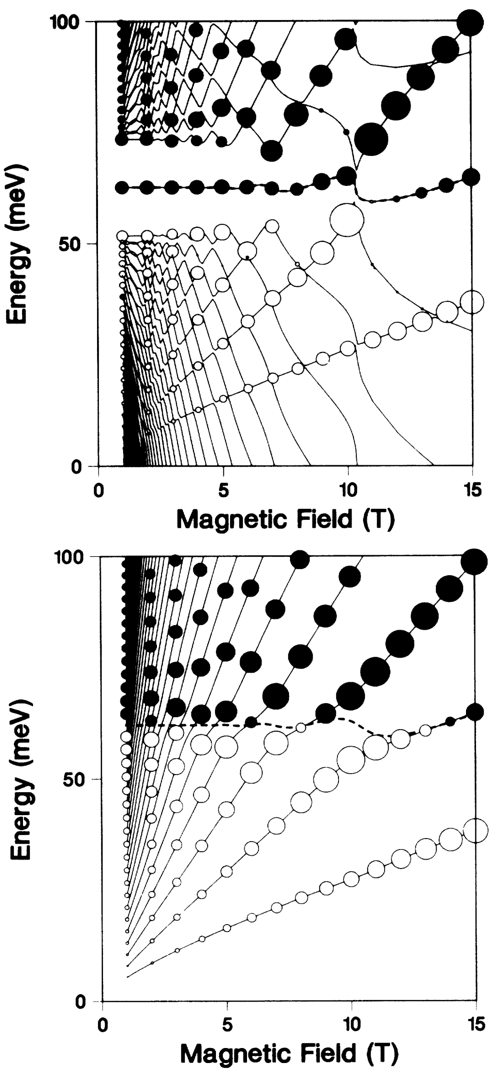

FIG. 3. Gain (open dots) and absorption (solid dots) spectra of an electron-hole plasma of density 10^{12} cm^{-2} confined to a 100-Å quantum well in (a) the condensed phase at 0 K and (b) normal phase at 50 K. The oscillator strengths at integer magnetic fields are proportional to the dot area. The chemical potential is given by the dashed lines.

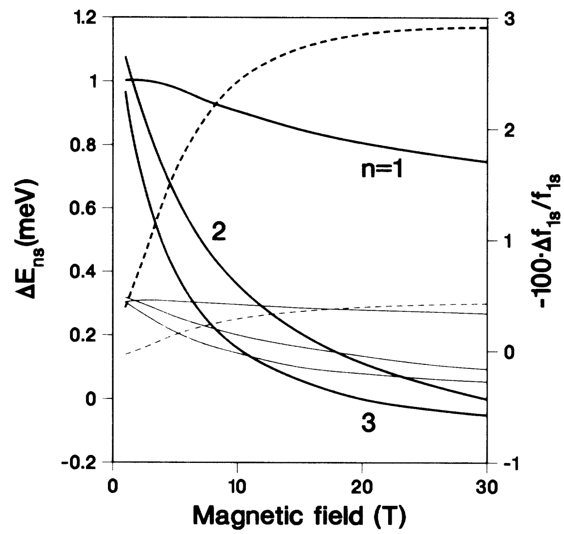

FIG. 4. The dynamical Stark effect on excitons in a 100-Å quantum well due to a monoenergetic pump field of 10 MW/cm^2 and a detuning of 20 meV (thick lines) and 50 meV (thin lines). The solid lines denote the exciton energy shift (referring to the left ordinate) for the lowest three allowed ($1s$–$3s$) exciton transitions, while the changes in oscillator strength (right ordinate) of the ground-state exciton are given by the dashed lines.

strong dependence on the well width follows. A valuable test of the present theory would be an experimental verification of the maximum in the saturation of the oscillator strengths predicted for intermediate magnetic fields [Fig. 2(b)].

The effect of pairing on the optical properties of high-density electron-hole plasmas can be inferred from Fig. 3, where gain and absorption spectra for the condensed state at 0 K and the normal phase at 50 K are compared. The gap of the condensed phase is easily identified in Fig. 3(a), being very insensitive to magnetic field until the Landau-level spacing exceeds the energy gap. The state in the middle of the gap (i.e., at the chemical potential μ) is a superposition of the excitons formed from empty pair states above and filled pair states below μ. Excited excitonic states close to both band edges of the insulating gap can also be identified. Another interesting phenomenon are the lines with a strong negative diamagnetic shift which reflect the oscillator strength of "antipair excitations" due to the hybrid character of the quasiparticles of the condensed ground state.

It has been shown by Schmitt-Rink, Chemla, and Haug[2] that the virtual electron and hole populations created by below-band-gap photons give rise to many-body corrections to the dynamical Stark effect which can be treated by mean-field theory. Self-consistent solutions of the Bethe-Salpeter equation in this case have been obtained recently[21–23] and are generalized here to the presence of magnetic fields, assuming that the detuning is large compared with the energetic pulse width.[21,23] Significant[24] effects of magnetic fields for ground as well as excited states are calculated (Fig. 4), which depend weakly on the detuning. By extrapolation of the results in Fig. 4 a slight enhancement of the oscillator strengths is found for zero magnetic fields. With increasing field a quenching of the oscillator strengths occurs, because the exchange molecular field is reduced and the destabilization of the excitons by the phase-space filling becomes dominant.

In conclusion, I have presented results of mean-field theory for the optical properties of confined, charged, and neutral magnetoplasmas. Experiments on modulation-doped quantum wells can be explained well. Results for low-density neutral plasmas have still to be confirmed by experiments on exciton saturation and dynamical Stark effect in magnetic fields. The elusive excitonic-insulator state in high-density plasmas will be easier to identify in the presence of magnetic fields because of the characteristic effects of condensation and the fact that discrete spectra are less sensitive to ever-present line broadenings. The present theory is hoped to stimulate a first experimental discovery of this fundamental state of matter.

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