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EFFECTS OF IONIZED IMPURITIES ON BINDING AND RECOMBINATION OF POSITIVE AND NEGATIVE QUASI-TWO-DIMENSIONAL MAGNETO-TRIONS

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Binding energies of negative and positive trions in high magnetic fields are compared. Simultaneous inclusion of several Landau levels and quantum well subbands in exact numerical diagonalization allowed quantitative description of the coupling between in-plane dynamics (governed by interplay of cyclotron quantization and Coulomb interactions) and single-particle excitations in the normal direction. Symmetric and asymmetric GaAs quantum wells of different widths were considered, as well as the effect of a possible binding of trions by sparse ionized impurities nearby the quantum well.

Keywords: Photoluminescence; trion; impurity.

1. Introduction

Negative trions ($X^- = 2e + h$) form in n-doped low-dimensional semiconductor structures from neutral excitons ($X = e + h$) by the capture of another electron. Analogously, positive trions ($X^+ = 2h + e$) form from excitons in p-doped nanostructures through the capture of a second hole. Dynamics of a three-body trion problem in a quasi-two-dimensional quantum well of finite width w, in the presence of strong magnetic field B and electric field induced by a layer of ionized donors or acceptors in asymmetrically doped structures is not at all trivial. Competition of several energy scales (Coulomb, cyclotron, subband, and Zeeman) and coupling of the translationally invariant in-plane motion (involving Landau quantization and electrostatic binding) with the strongly quantized motion in the normal direction make for the complexity of the trion problem.

The combination of photoluminescence (PL) experiments[1] and numerical calculations[2] led over a few recent years to the basic understanding of the trion energy and recombination spectrum. Specifically, the trion spectrum is known to include several bright and dark bound states, distinguished by the total (pseudo)spin $S = 0$

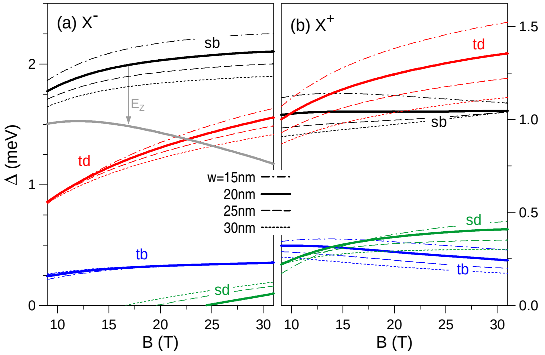

Fig. 1. Comparison of Coulomb binding energy Δ of negative (a) and positive (b) trions as a function of magnetic field B, in symmetric GaAs quantum wells of various widths $w = 15-30$ nm. Various trion bound states, distinguished by the total spin S of the pair of like carriers and the relative angular momentum M (recalculated for the planar geometry), are: *sb* – "bright singlet" $(S = 0, M = 0)$, *td* – "dark triplet" $(1, -1)$, *tb* – "bright triplet" $(1, 0)$, *sd* – "dark singlet" $(0, -2)$.

or 1 of the pair of like carriers and the relative angular momentum M. The most stable trions are the bright singlet $X^{\pm}_{\mathrm{sb}}$ $(S = M = 0)$ and two triplets $X^{\pm}_{\mathrm{tb}}$ and $X^{\pm}_{\mathrm{td}}$ ($S = 1$ and $M = 0$ and -1 for the "bright" and "dark" state, respectively). A weak dark singlet $X^{\pm}_{\mathrm{sd}}$ ($S = 0$ and $M = -2$) has also been proposed theoretically.

The Coulomb binding energy of a trion is defined as $\Delta = E_X + E_e - E_{X^-}$ or $E_X + E_h - E_{X^+}$, i.e., the difference between the given trion energy and the ground state energy of an unbound configuration, neglecting the Zeeman terms. The true binding energy of a singlet state must be further decreased by a Zeeman splitting E_{Z} of the second carrier that must flip its spin to become bound to the exciton.

It can also be expected that local perturbations such as quantum well width fluctuations[4] or sparse nearby ionized impurities[5] should affect their stability or recombination spectrum. The latter effect is also addressed here.

2. Results and Discussion

We carried out large-scale exact-diagonalization calculations, including single-particle states from several Landau levels (LLs) and quantum well subbands (yielding Hamiltonian matrices of several 10^9 nonzero elements, diagonalized with simultaneous resolution of spin and parity).[3] Inclusion of the electron and hole excitations both in the plane of the well (intra- and inter-LL) and normal to the plane (inter-subband) allowed unprecedented accuracy of the trion energies and wave functions.

In Fig. 1 we present a number of curves illustrating the magnetic field dependence of the binding energy, $\Delta(B)$, for both negative and positive trions confined in symmetric GaAs quantum wells of different widths. For the X^-, the bright singlet has the largest Δ for all shown parameters, but inclusion of electronic E_{Z} reveals a singlet–triplet crossing (e.g., at $B \approx 22.5$ T for $w = 20$ nm). For the X^+, the bright singlet is bound less strongly, and inclusion of the hole's E_{Z} (not shown) leads to

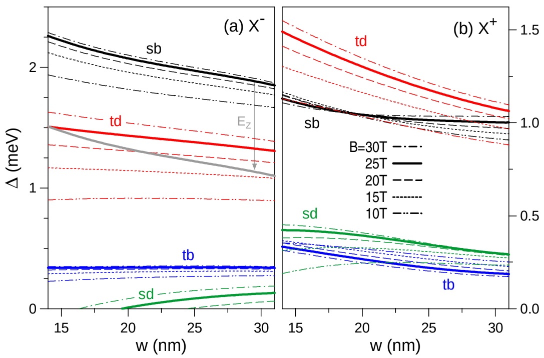

Fig. 2. Same as Fig. 1, but with the trion Coulomb binding energies Δ plotted as a function of width w of a symmetric GaAs quantum well for several different magnetic fields $B = 10 - 30$ T.

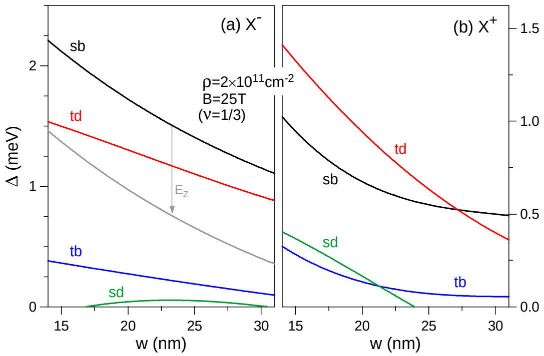

Fig. 3. Similar to Fig. 2, dependence of positive (a) and negative (b) trion Coulomb binding energy Δ on width w, but for an asymmetric GaAs quantum well, doped one side to electron or hole concentration $\varrho = 2 \cdot 10^{11}$ cm^{-2}, at magnetic field $B = 25$ T, corresponding to filling factor $\nu = 1/3$. $E_Z = 0.75$ meV in frame (a) is electron Zeeman energy that must be subtracted from Δ to obtain the total binding energy of the singlet in order to determine the trion ground state.

emergence of a dark triplet ground state for all shown parameters. The (negative or positive) bright triplet is relatively less field dependent than the two more strongly bound trions, with $\Delta < 0.5$ T.

In Fig. 2 we show similar curves, but plotted as a function of well width, $\Delta(w)$. While in some cases the trion binding weakens with widening of the well, in others, somewhat surprisingly, it is nearly independent of w. For example, the binding of $X^-_{\rm tb}$ appears nearly constant through $w = 10 - 30$ nm for all studied magnetic fields, and so is the binding of $X^-_{\rm td}$ – at sufficiently weak fields $B \le 15$ T.

In Fig. 3 we also show $\Delta(w)$, but for the asymmetric quantum wells, doped on one side to the typical areal carrier concentration $\varrho = 2 \cdot 10^{11}$ cm^{-2} (at the chosen high magnetic field $B = 25$ T, corresponding to the Landau level filling factor $\nu = 1/3$, at which a Laughlin incompressible liquid forms). The reduction of binding with increasing width is now a strong effect, caused largely by a quantum

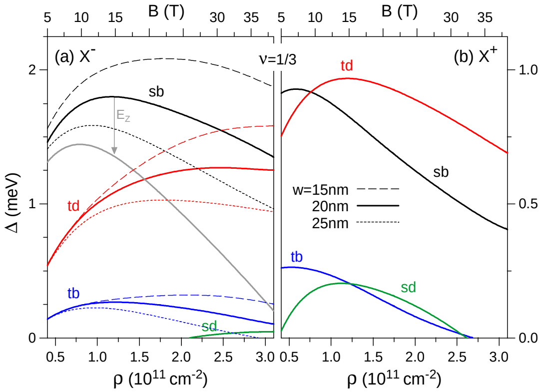

Fig. 4. Similar to Fig. 3, but with the trion Coulomb binding energies Δ plotted as a function of magnetic field B and concentration ϱ (proportional to each other at a fixed filling factor, $\nu = 1/3$), for three different widths $w = 15 - 25$ nm of a one-sided doped GaAs quantum well.

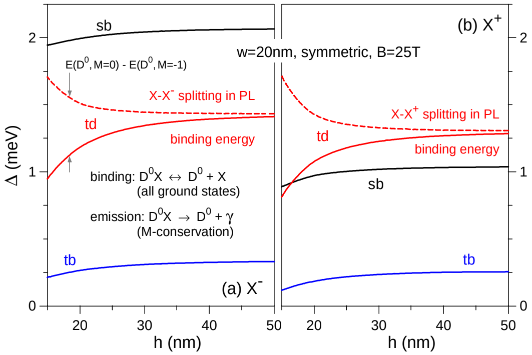

Fig. 5. Comparison of Coulomb binding energy Δ of negative (a) and positive (b) trions as a function of distance h of a point charge impurity (ionized donor or acceptor) from the center of a symmetric GaAs quantum well of width $w = 20$ nm, in magnetic field $B = 25$ T. For the trions with $M \neq 0$, binding energy Δ (shown with a solid red line for the "dark triplet") is distinguished from the trion–exiton splitting in the PL spectrum (dashed line), as explained in the text.

confined Stark shift. Interestingly, when X^- and X^+ are compared, it is always the most strongly bound state that is most sensitive to the Stark effect ($X^-_{\rm sb}$ and $X^+_{\rm td}$).

In Fig. 4 we show $\Delta(B)$ for one-sided doped wells, calculated at a fixed filling factor $\nu = 1/3$ (i.e., at concentration ϱ proportional to B). This graph allows design of a quantum well with a desired trion ground state to be used as a probe of a Laughlin liquid (it was shown[6] that only a dark triplet trion leads to discontinuities in PL at $\nu = 1/3$). The singlet–triplet crossing in the X^- spectrum clearly shifts to lower fields due to the Stark effect, especially in wider wells. For X^+, the dark triplet appears to be a robust trion ground state regardless of B, w, ϱ, or E_Z.

The reduction of all binding energies in the presence of a nearby ionized impurity is clear in Fig. 5, showing Δ as a function of its distance h from the well center.

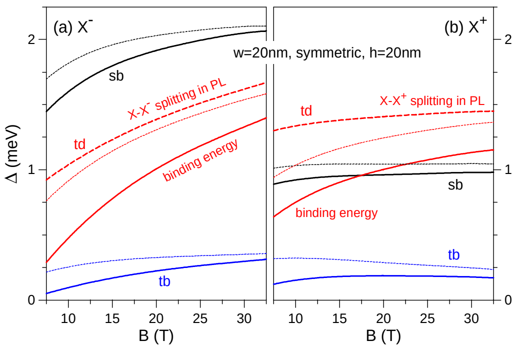

Fig. 6. Similar to Fig. 1, comparison of Coulomb binding energy Δ of negative (a) and positive (b) trions as a function of magnetic field B, but in the presence of an ionized donor or acceptor at a distance $h = 20$ nm from the center of a symmetric GaAs quantum well of width $w = 20$ nm. As in Fig. 5, for the "dark triplet", binding energy (solid lines) is distinguished from the trion–exiton splitting in PL (dashed lines). For comparison, thin dotted lines give the data without an impurity.

Note that the binding energy is now defined as $\Delta = E_X + E_{D^0} - E_{D^0X}$ or $E_X + E_{A^0} - E_{A^0X}$, where D^0X or A^0X denotes an X^- bound to an ionized donor or an X^+ bound to an ionized acceptor. This quantity is equivalent to the PL splitting of the bound trion (D^0X or A^0X) line from the free exciton line – only for the bright trion states with $M = 0$. For others (e.g., the dark triplet), the impurity-bound carrier left over after the recombination of an impurity-bound trion retains the initial angular momentum $M \neq 0$, and thus also some excitation energy. The PL splitting of the dark triplets, different from Δ, is shown with dashed lines. In Fig. 6 we also show a sample field dependence, $\Delta(B)$, calculated in the presence of an impurity at a distance $h = 20$ nm.

Acknowledgments

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