Vol. **108** (2005) *ACTA PHYSICA POLONICA A* No. 4

Proceedings of the XXXIV International School of Semiconducting Compounds, Jaszowiec 2005

Trion Binding Energies and Wave Functions in Doped Quantum Wells

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The energy spectra of negative trions ($X^- = 2e + h$) in one-sided doped GaAs quantum wells are calculated. The maps of the trion binding energy Δ as a function of well width w, electron concentration n, and the magnetic field B are obtained. The dependence of the trion ground state ("bright singlet" versus "dark triplet") on those parameters is established.

PACS numbers: 71.35.Pq, 71.35.Ji

1. Introduction

The photoluminescence (PL) spectra of two-dimensional electron gases (2DEGs) formed in doped quantum wells contain peaks corresponding to recombination of trions (charged excitons) X^- [1, 2]. The trion is a bound state of a pair of conduction electrons e and a valence (heavy) hole h. Whether trions can be considered as well-defined quasiparticles (with binding energy Δ and emission intensity τ^{-1} independent of the surrounding electrons), it depends on the 2DEG concentration n.

In the absence of a magnetic field, the PL spectrum as a function of n evolves from a trion peak to the "Fermi-edge singularity" [3]. The transition depends on the relation between the characteristic lengths or energies of the trion and of the 2DEG (Bohr radius a_{B}^* vs. $n^{-1/2}$, or Δ vs. Fermi energy).

In high magnetic fields B, the electrons fill only a fraction $\nu = 2\pi\lambda^2 n$ of the lowest Landau level (LL), and the trion radius scales with a magnetic length $\lambda = \sqrt{hc/eB}$. The "radius<distance" diluteness condition is equivalent to $\nu < 1$, suggesting [4] that the trions might remain bound even at n corresponding to

$\nu \sim \frac{1}{3}$, when electrons form an incompressible Laughlin liquid [5]. Indeed, a recent calculation [6] shows that emission from this state is due to the recombination of *fractionally* screened trions ("quasiexcitons").

The X^- spectra in empty wells [7, 8] are understood quite well. Several bound trion states (with a positive $\varDelta = E_{\mathrm{X}} + E_{\mathrm{e}} - E_{\mathrm{X}^-}$) are distinguished by two-electron spin S and relative (with respect to the center of mass) angular momentum M. Only those trions with $M = 0$ are optically active (photon emission conserves M, and the left over electron has $M \equiv 0$). The most important states are [9–11]: "bright singlet" $\mathrm{X}^-_{\mathrm{sb}}$ with $(S, M) = (0, 0)$, "dark triplet" $\mathrm{X}^-_{\mathrm{td}}$ $(1, -1)$, "bright triplet" $\mathrm{X}^-_{\mathrm{tb}}$ $(1, 0)$, and "dark singlet" $\mathrm{X}^-_{\mathrm{sd}}$ $(0, -2)$. Depending on material, well width w, and magnetic field B, the ground state is either $\mathrm{X}^-_{\mathrm{sb}}$ or $\mathrm{X}^-_{\mathrm{td}}$. The latter is favored by higher B, and in GaAs wells the singlet–triplet crossing occurs at $B = 20$ to 30 T.

The situation at larger concentrations is quite different. The understanding of emission from such states as Laughlin $\nu = \frac{1}{3}$ liquid is essential to establish PL as another (in addition to transport) probe of their microscopic properties [12, 13]. Therefore, most important is the *change* of the trion recombination compared to the empty well, possibly related to electron incompressibility. The trion immersed in a 2DEG is affected in two ways: (E1) The charge of confined electrons is compensated by a distant doping layer. The resulting electric field F penetrating the 2DEG forces the electrons and holes toward opposite walls of the well, weakening the e–h attraction compared to e–e repulsion within the trion, and thus affecting its binding. (E2) The trion is screened by the surrounding (mobile) electrons.

Only E2 is sensitive to the electron correlations. In Ref. [6] we show that the coupling of a trion to the Laughlin liquid depends on the particular trion wave function, leading (because of E1) to a qualitatively different behavior of PL at $\nu = \frac{1}{3}$ in different wells. Namely the emission energy is discontinuous only when the trion coupled to a 2DEG is the $\mathrm{X}^-_{\mathrm{td}}$ (and not an $\mathrm{X}^-_{\mathrm{sb}}$).

The dependence of the trion ground state on w, n, and B is addressed in this note. We report realistic, exact-diagonalization calculations of the X^- binding energy in GaAs/AlGaAs wells doped on one side, taking into account E1. The results prove that the effect of F on X^- recombination (E1) is significant and must be accounted for when interpreting the PL spectra in terms of trion–2DEG coupling (E2). They should also help to design structures suitable for the PL studies of incompressible electron liquids.

2. Model

In numerical calculations we use spherical geometry [14]. The monopoly strength defined in the units of flux quantum as $2Q(hc/e) = 4\pi R^2 B$, the total magnetic flux through a sphere of radius R (equivalently, $Q\lambda^2 = R^2$). The LLs have the form of degenerate angular momentum shells with $l \geq Q$.

The e and h densities $\varrho(z)$ are calculated self-consistently [15] as a function of w and n. Two sample results are shown in Fig. 1, showing splitting of e and h layers in the wider well. These densities are used in the calculation of e–e and e–h Coulomb matrix elements. The Δs are obtained from diagonalization of 2e + h and e + h Hamiltonians for several values of $2Q \leq 30$. Five LLs for both e and h are included, and the hole cyclotron energies are from Ref. [16]. In Fig. 2 we plot Δ as a function of squared surface curvature $(\lambda/R)^2 = Q^{-1}$, for X^-_{sb} and X^-_{td} in a $w = 20$ nm well with $n = 2 \times 10^{11}$ cm^{-2} and $B = 25$ T. Regular dependence allows accurate (quadratic) extrapolation of the binding energies to the $\lambda/R = 0$ limit.

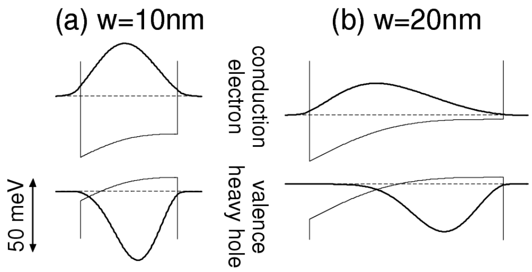

Fig. 1. Band energy and carrier density profiles along normal (z) direction for $w =$ 10 nm (a) and 20 nm (b) GaAs wells, doped on one side to $n = 2 \times 10^{11}$ cm^{-2}.

The values of Δ plotted in this and the following plots do not include the electron Zeeman energy E^{e}_{Z}, which must be subtracted from Δ to give the binding energy of singlet states. In PL spectrum, the sum $E^{e}_{Z} + E^{h}_{Z}$ splits the peaks for ω_+ and ω_- polarizations, but the splitting between the corresponding peaks for different trions is (for constant E_Zs) unaffected.

3. Results and discussion

The extrapolated binding energies of all four trions are compared in the next four plots. Motivated by a recent experiment of Byszewski et al. [13], for a reference system we choose parameters of Fig. 2, for which the Laughlin $\nu = \frac{1}{3}$ state occurs at a high, but experimentally accessible B.

In Fig. 3, w and n are constant and B varies from 10 to 50 T. Neglecting Zeeman energy, the X^-_{sb} crosses X^-_{td} at $B \approx 10$ T and unbinds at $B \approx 30$ T in this well. Assuming $E^{e}_{Z} \sim 0.2$ meV [11], the only bound trion at $B \geq 20$ T is X^-_{td} with $\Delta \approx 0.8$ meV. It is the ground state in the whole $\nu < 1$ regime.

In Fig. 4, w and B are constant, while n changes from 0 to 3×10^{11} cm^{-2}. Clearly, the X^-_{sb} looses binding energy more rapidly than X^-_{td} as a function of n. This is responsible for the shift of the singlet–triplet crossing to lower B in doped wells compared to the earlier estimates [11]. Remarkably, the (triplet) trion has $\Delta > 0.5$ meV ~ 5 K even at a very large n.

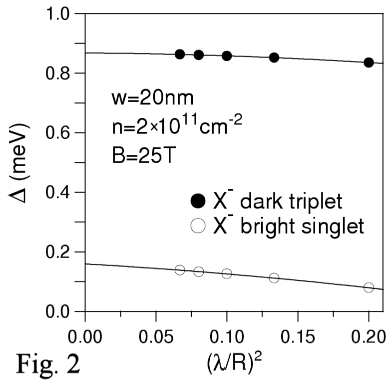

Fig. 2

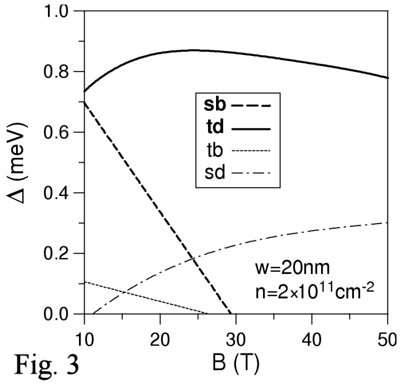

Fig. 3

Fig. 2. Trion binding energies Δ as a function of squared surface curvature $(\lambda/R)^2$.

Fig. 3. Trion binding energies Δ as a function of magnetic field B.

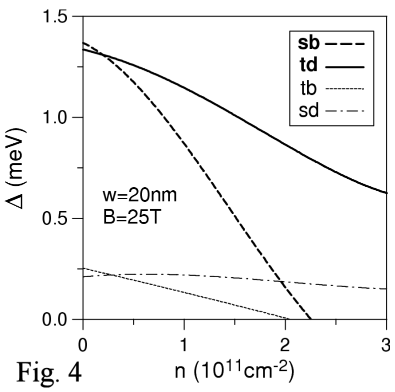

Fig. 4

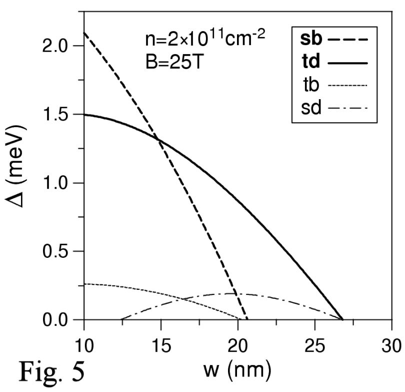

Fig. 5

Fig. 4. Trion binding energies Δ as a function of concentration n.

Fig. 5. Trion binding energies Δ as a function of well width w.

In Fig. 5, n and B are constant, and w varies from 10 to 30 nm. The X^-_{sb} is the ground state in narrow wells, crossing the X^-_{td} at $w \approx 15$ nm (neglecting E_Z). Knowing that emission from a trion coupled to a 2DEG shows discontinuity at $\nu = \frac{1}{3}$ only when this trion is an X^-_{td} [6], we find that wells with $w = 15$ to 25 nm are most suitable for PL studies of Laughlin incompressibility. The 20 nm well used in Ref. [13] seems ideal by having X^-_{td}s with a large $\Delta \sim 0.8$ meV and no other bound trions.

Figure 6 is an example of a map of $\Delta(n, B)$ for a constant w. The energy contours are only shown for X^-_{sb} and X^-_{td}, and the grey and white areas indicate two different ground states. The dependence of the singlet–triplet transition on B and n is evident, and the crossing of the ground state boundary with the $\nu = \frac{1}{3}$ line is found at $n \approx 1.2 \times 10^{11}$ cm^{-2} (neglecting E_Z).

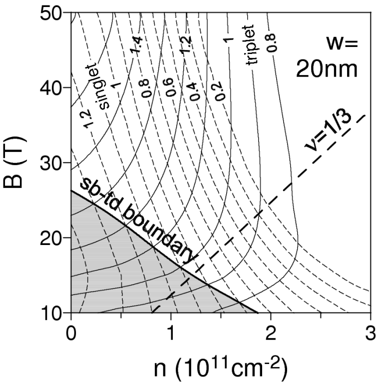

Fig. 6. Trion binding energies Δ as a function of concentration n and magnetic field B. Energy contours of X^-_{sb} and X^-_{td} are shown with dashed and solid lines.

Acknowledgment

We thank M. Potemski, P. Hawrylak, W. Bardyszewski, and L. Bryja for helpful discussions. Work supported by the grant DE-FG 02-97ER45657 of the U.S. Dept. of Energy and the grant 2P03B02424 of the State Committee for Scientific Research (Poland).

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