Energy Spectra of Isolated Trions in Asymmetric Quantum Wells

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

Keywords: trion, exciton, photoluminescence, quantum well

PACS: 71.35.Pq, 71.35.Ji

INTRODUCTION

The photoluminescence (PL) spectra of two-dimensional electron gases (2DEG’s) formed in doped quantum wells show recombination of trions (charged excitons) \(X^\pm\) [1,2]. The trion consists of two electrons \(e\) and a (heavy) hole \(h\). Especially at low 2DEG concentration \(n\), it can be considered a well-defined quasiparticle with binding energy \(\Delta\) and emission intensity \(\tau^{-1}\) independent of the surrounding electrons. 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 \(\lambda = \sqrt{\hbar c/\mu B}\). The condition for a dilute system is \(\nu \ll 1\), but the trions may remain bound even at \(\nu \sim 1\), when electrons form an incompressible Laughlin liquid [5]. A recent calculation [6] shows that emission from this state is due to recombination of fractionally screened trions ("quasiexcitons").

In weakly doped wells [7,8], trion spectra contain several bound states, distinguished by two-electron spin \(S\) and relative angular momentum \(M\). Only those trions with \(M = 0\) are optically active, and the most important ones are [9,10,11]: "bright singlet" \(X^\pm_{sb}\) with \(\langle S,M\rangle = (0,0)\), "dark triplet" \(X^\pm_{sd}\) \((1,-1)\), "bright triplet" \(X^\pm_{tb}\) \((1,0)\), and "dark singlet" \(X^\pm_{td}\) \((0,-2)\). Depending on material, well width \(w\) and magnetic field \(B\), the ground state is either \(X^\pm_{sb}\) or \(X^\pm_{td}\). The latter is favored by higher \(B\), and in GaAs wells the crossing occurs at \(B \sim 30\) T.

Understanding trion dynamics at \(n > 0\) is essential to establish PL as another (in addition to transport) microscopic probe of incompressible electron liquids [12,13]. The trion immersed in a 2DEG is affected in two ways: (i) the charge of confined electrons is compensated by a distant doping layer producing an electric field acting on the trion; (ii) the trion couples to the excitations of the surrounding 2DEG.

In Ref. [6] we show that the coupling of a trion to the Laughlin liquid depends on the particular trion wavefunction, leading to a qualitatively different behavior of PL at \(\nu = \frac{1}{2}\) in different wells. The dependence of the trion ground state on \(w\), \(n\), and \(B\) is addressed here. We report realistic calculations of the \(X^-\) binding energy in GaAs/AlGaAs wells doped on one side. We show that effect (i) is significant and must be accounted for when interpreting PL in terms of trion–2DEG coupling.

MODEL

In numerics we use spherical geometry [14]. The monopole strength defined in the units of flux quantum as \(2Q(\hbar c/e) = 4\pi R^2 B\), the total magnetic flux through a sphere of radius \(R\) (equivalently, \(Q\lambda^2 = R^2\)). The LL’s have the form of angular momentum shells with \(l \geq Q\).

The lowest-subband \(e\) and \(h\) densities \(\rho(z)\) are calculated self-consistently [15] as a function of \(w\) and \(n\). For \(n = 2 \times 10^{11} \text{cm}^{-2}\) (typical for GaAs), the splitting between the maxima of \(\rho_e(z)\) and \(\rho_h(z)\) is only \(\delta = 1.3\) nm for \(w = 10\) nm, but as much as \(\delta = 7\) nm for \(w = 20\) nm.

The densities are used in the calculation of \(e-e\) and \(e-h\) Coulomb matrix elements. The \(\Delta\’s\) are obtained from diagonalization of \(2e + h\) hamiltonians for \(2Q \leq 30\). LL’s with \(n \leq n_{\text{max}} = 4\) for both \(e\) and \(h\) are included, with the (heavy) hole cyclotron energies taken from Ref. [16]. Regular dependence on \(2Q\) and \(n_{\text{max}}\) allows accurate extrapolation of \(\Delta\) to the \(\lambda/R = 0\) and \(n_{\text{max}}^{-1} = 0\) limits.

RESULTS AND DISCUSSION

The \(\Delta\’s\) plotted in the following plots do not include the electron Zeeman energy \(E_z\), which must be subtracted from \(\Delta\) to give the binding energy of singlet states. In
Remarkably, the (triplet) trion has lower binding energy than the singlet, responsible for the shift of the singlet–triplet crossing to shorter wavelengths. The peak splitting varies from 10 to 40 T. Neglecting Zeeman energy, the crossing the X state occurs at $B \approx 28$ T in this well. Assuming a small $E_Z \sim 0.2$ meV [11], the crossing moves to just about $B \geq 25$ T.

In Fig. 2, $w$ and $B$ are constant, while $n$ changes from 0 to $3 \cdot 10^{11}$ cm$^{-2}$. Clearly, the $X_{ab}$ state looses binding energy more rapidly than $X_{cd}$ 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 $\Delta > 1$ meV $\sim 10$ K even at the largest $n$.

In Fig. 3, $n$ and $B$ are constant, and $w$ varies from 10 to 25 nm. The $X_{ab}$ state is the ground state in narrow wells, crossing the $X_{cd}$ state 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 $X_{cd}$ state [6], we find that wells with $w = 15$ to 25 nm are most suitable for PL studies of Laughlin incompressibility.

ACKNOWLEDGMENTS

We thank M. Potemski, P. Hawrylak, W. Bardyszewski, and L. Bryja for helpful discussions. Work supported by Grants DE-FG 02-97ER45657 of the U.S. Dept. of Energy and 2P03B02424 of the Polish MENiS.

REFERENCES