Excitonic Fock-Darwin Spectra in Quantum Dots

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Applying a magnetic field on an electronic system where levels are quantized has the effect of lifting angular momentum state degeneracies. If one has access to magnetic fields such that the cyclotron energy becomes comparable to or greater that the inter-level separation in the system, a criss-cross pattern of energy levels in the Energy vs Magnetic field diagram may be observed. For specific magnetic fields, positive angular momentum states of lower levels can become degenerate with negative angular momentum states of higher levels, thus prompting one to expect interesting physical phenomena related to mixing of states.

However, to observe the criss-cross pattern in natural atoms would typically require fields in the range of several hundreds to thousands of Teslas. Instead, artificial atoms or quantum dots with smaller interlevel spacing allows us to access this type of physics with fields of few to tens of Teslas. Since for Quantum Dots the electronic energy spectrum is often that of two-dimensional harmonic oscillators, the criss-cross pattern is referred to as the Fock-Darwin spectrum.[1]

Observation of the Fock-Darwin spectrum in QDs can be achieved in two ways. First, it can be deduced from Coulomb blockade spectroscopy of a single microfabricated sub-micron electrostatic quantum dot.[2] However, in that case electronic charges are added one by one in the QD, causing it to be strongly negatively charged. In the end, the spectrum needs to be separated from an additional charging energy term which usually dominates the addition spectrum. This difficulty can be overcomed by following the interband emission of charge-neutral electron-hole pairs in QD ensembles. Within the dipole approximation, radiative recombination occurs between an electron and a hole with the same quantum numbers (see arrows in fig. 1a). Summing up the energy of such an electron-one hole pair, one can define an excitonic particle which can couple directly to photons. By following the energy of such photons with increasing magnetic field, one can build an excitonic FD spectrum (fig. 1b). The limitation in such experiments comes from inhomogeneous broadening of the QD ensemble, which tends to broaden optical features and makes it difficult to resolve physical effects.

Here, We demonstrate that a well-controlled strain-driven self-assembly technique combined with a simple annealing procedure is capable of producing large ensembles of virtually identical semiconductor quantum dots analogous to the precise assembly of identical molecular structures in molecular electronics. Performing optical spectroscopy on these highly homogeneous QD arrays in ultra-high magnetic fields, an unprecedently well resolved Fock-Darwin spectrum is observed. The existence of up to four degenerate electronic shells is demonstrated, where the magnetic field lifts the initial degeneracies which reappear when levels with different angular momenta come into resonance.

By comparing a non-interacting FD spectrum (fig. 1b) with the experimental results (fig. 1c), differences can be observed which are attributed to many-body effects. At the resonances, exciton states become hybridized between states with opposite angular momentum, causing the magnetic field dependency to vanish for a small magnetic field range. Moreover, it can be shown that symmetry in the electron and hole wavefunctions lead to excitonic condenstation within a degenerate shell, whereby the energy to add/remove and exciton is the same, irrespective of the number of excitons pre-existing in the shell. Experimentally, this results in strong overlap of the emission lines at the resonances, where the peak emission intensity of a degenerate shell is much higher than that in a separate shell.

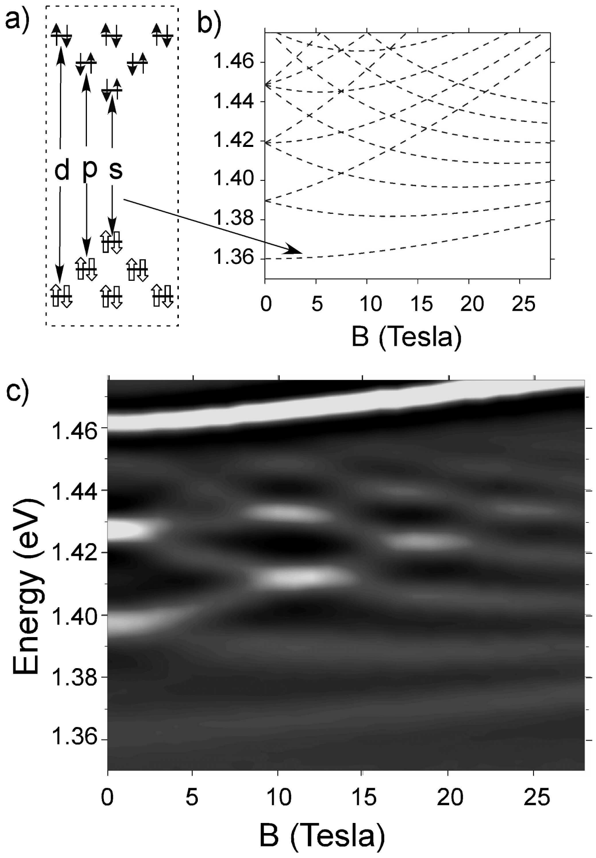

Figure 1. Using the electron and hole energy shell shown in a), one can build the excitonic FD spectrum shown in b). This is to be compared to the experimental result in c)

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[2] S. Tarucha, D. G. Austing, T. Honda, R. J. Van der Hage and L. P. Kouwenhoven, Phys. Rev. Lett. 77, 3613 (1996); M. Ciorga, A. S. Sachrajda, P. Hawrylak, C. Gould, P. Zawadzki, S. Jullian, Y. Feng and Z. Wasilewski, Phys. Rev. B 24, R16315 (2000).