Electric field control of exciton states in quantum dot molecules

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A central focus of current research is finding physical implementations for quantum bits and gates, in particular on the basis of semiconductor quantum dots [1, 2]. The most critical aspect in these activities is the search for controllable physical interactions between pairs of quantum dots. Here we demonstrate such a controllable interaction by studying the exciton states in quantum dot molecules with an electric field along the molecule axis. For this demonstration we use single quantum dot molecule spectroscopy and compare the experimental data with the results of detailed calculations. The overlap of the electron and hole wavefunctions and the Coulomb interactions between electron and hole lead to coupling between excitons in these structures. Thus excitons form linear combinations of the four possible electron-hole single particle configurations: carriers can be in the same, upper or lower dot (direct exciton) or they can be in opposite dots (indirect exciton). In our experiments we focus on the two energetically lowest lying states, that result from mixing of the single particle configurations through Coulomb interactions. For flat-band situation (U=0), the ground state is orbitally symmetric and therefore optically active, while the higher lying state is orbitally antisymmetric and dark.

Calculations show that by applying an electric field the ground state is converted into a state in which electron and hole are located in different dots and thus becomes dark. The excited state, on the other hand, converges into a direct exciton with considerable optical activity. These expectations are in good accord with the experimental data, observed by photoluminescence spectroscopy of a single dot molecule for different electric fields in reverse bias. The low energy emission line at low electric field is a coupled, optically active state and approaches a decoupled, optically inactive state for increasing electric field. The high energy emission line at low electric field is a coupled, optically dark state and approaches a decoupled, optically bright state for increasing electric field. The voltage for obtaining the transformation into intradot and interdot excitons increases with decreasing barrier width between the dots, as tunneling of carriers becomes stronger and thus the coupling. These results demonstrate that the carrier wave functions in quantum dot molecules can be controlled on a detailed level, a necessary prerequisite for controllable interactions between exciton quantum bits in such structures.

[1] The Physics of Quantum Information, eds. D. Bouwmeester, A. Ekert and A. Zeilinger, Springer, Berlin, 2000.

[2] P. Hawrylak, S. Fafard, and Z.R. Wasilewski, Condens. Matter News 7, 16 (1999).