Simulating an optically active gate-defined quantum dot

E. Olbińska, M. Gawełczyk

Institute of Theoretical Physics, Wroclaw University of Science and Technology, 50-370 Wroclaw, Poland

Quantum dots (QDs) of various types are currently used in many areas of quantum technologies and quantum information. Gate-defined QDs, created by applying electrodes over a quantum well allow for manipulating their properties by adjusting the potentials applied to the electrodes. High-quality many-qubit devices have been demonstrated within this approach [1]. However, dots of this kind can typically only confine one type of carrier simultaneously which means that they cannot directly couple with light and thus exchange information with flying photonic qubits. Conversely, self-assembled QDs can confine both electrons and holes and therefore can be optically active. Although easier to manufacture than gate-defined QDs, their properties tend to be harder to control, as they are characterized by randomness in their arrangement and defining features (size, shape, and details of chemical composition). Thus combining the advantages of both kinds of QDs, i.e., easily adjustable QD properties and controlled couplings between QDs with optical activity would be desirable.

Here, we propose to use the simplest possible geometry of circular electrodes whose combined potential would confine both holes and electrons. By numerical simulations, we show that it is theoretically possible to create an optically active gate-defined QD for this geometry.

Our calculations are carried out by numerically solving the Schrödinger equation in cylindrical coordinates. Direct discretization of the problem would lead to carrier wave functions exhibiting nonphysical behavior near the origin. We implement the improved discretization [2] to avoid this problem. Then we calculate the overlap integral of carrier wave functions, with a nonzero result indicating a theoretical possibility of both carriers occurring in the same volume, which is essential for optical transitions to take place. After achieving a nonzero overlap of the wave functions, we carry out an optimization process for the dimensions of the system and potentials applied to the electrodes to maximize the result. A key step in the optimization is to reject dot-defining parameters that result in electron wave functions that are not well-localized, meaning that in a real system, the electron would not get confined in the dot at all. From the optimized QD parameters we obtain an overlap of ~ 0.2 which is already a very promising result. Next, we include the electron-hole interaction in the model by solving self-consistently the Schrödinger and Poisson equations. Finally, for exciton states calculated in this manner, we calculate the optical properties in the dipole approximation.

Our results can be an introductory step in creating optically active gate-defined QDs. If this kind of dot was added to a linear array or a matrix of standard gate-defined QDs it could act as an interface with light for such a device. This additional component could open the door for long-distance quantum communication between gate-defined QD matrices.

[1] D. M. Zajac, T. M. Hazard, X. Mi, E. Nielsen, and J. R. Petta, Phys. Rev. Appl. **6**, 054013 (2016).
[2] V. Laliena and J. Campo, J. Phys. A: Math. Theor. **51**, 325203 (2018).