Qubits based on the exciton degrees of freedom of a semiconductor quantum dot

V V Samartsev, T G Mitrofanova
Zavoisky Physical-Technical Institute, FRC Kazan Scientific Center of RAS, Sibirsky tract, 10/7, 420029, Kazan, Russia

Corresponding author: samartsev@kfti.knc.ru

Abstract. We have studied theoretically a possibility to construct a quantum gate on the basis of semiconductor quantum dots of a core/shell type.

1. Introduction

This work is devoted to a theoretical study of a possibility to create the quantum gate which operates using qubits based on the exciton degrees of freedom of a semiconductor quantum dot (QD). As far as the authors know, for the first time this problem was solved in the experimental work [1], the results of which are also presented in the monograph [2]. Later, experimental work by Japanese authors [3] appeared which also showed that in order to create a QD quantum gate, at least two interacting excitons of different polarizations and opposite spins should be excited in it.

Since the excitation of a QD is short-pulse (and therefore coherent), it is appropriate to note that the problem of exciton coherence creation was discussed by one of the authors of this article a long time ago, starting with the prediction of exciton-echo [4] and other non-linear exciton phenomena (see the review [5]). Now, our interest in this problem arose again because our colleagues in two experimental groups (from our institute and from the Institute of Spectroscopy of RAS in Moscow) recently reported on the synthesis of the semiconductor QDs of CdSe – CdS type in polymethyl methacrylate (PMMA) [6] and of CdSe – CdS – ZnS type in toluene [7]. The role of the core in these QDs is played by CdSe [8], and the role of the shell – by the wide-gap semiconductors CdS and ZnS. Thus, there appeared a real prospect that in the nearest future they will attempt to create a quantum gate in practice.

Note that for a semiconductor such as CdSe with a band gap in the infrared region, the fluorescence spectrum lies in the visible range (since the CdSe nanoparticles are small and have a size of about 5 nm) [2]. Moreover, the number of atoms in QDs is small enough and, therefore, the absorption of light by a QD is very weak [8]. But the CdS – ZnS substrate, into which the CdSe core of the QD is wrapped, contains a large number of atoms. Thus the idea arose to excite QDs to the excitation band of a shell, where an electron-hole pair corresponds to almost every photon of laser radiation. At the same time, the photoelectron absorption cross section is approximately four orders of magnitude greater than the photon absorption cross section of the QD core. In the monograph [8], even the type of laser (argon laser) is indicated, the radiation of which should excite the ZnS substrate. In this case, when QD luminescence is excited through the absorption band of the substrate, its intensity will increase by four orders of magnitude.
2. On the possibility to create a quantum gate with the exciton and biexciton energy transitions

According to [8], laser light excites in a wide-gap semiconductor substrate (for example, ZnS) several free electron-hole pairs, which then partially lose their energy and turn into coupled pairs, i.e., excitons. Of course, we are talking about Wannier – Mott excitons [9, 10], which resemble a hydrogen atom. However, there is a fundamental difference between the Wannier – Mott exciton and the hydrogen atom. The Wannier – Mott exciton annihilation differs from the disappearance of the hydrogen atom. When no hydrogen atoms are left in the cuvette of the spectrograph, all spectral absorption lines of hydrogen will disappear from the sample spectrum. In contrast, in the semiconductor, peaks of exciton absorption are observed with the formal absence of the excitons themselves. The intensity of the peaks is proportional to the concentration of all valence electrons that could participate in the formation of exciton states. Therefore, a semiconductor in which excitons are absent but can be formed must be characterized by a concentration of the filled zero exciton states \( N_{\text{EO}} \) that is equal to the number of valence electrons per unit volume of the crystal (~ \( 10^{22} \) cm\(^{-3} \)). The state called as the ground state of the exciton will be simultaneously the excited state of the crystal as a whole. The Wannier – Mott exciton radius is usually \( 10^{-7} \) cm or more and coincides, as a rule, with the QD radius.

In semiconductor QDs, the exciton plays the role of a qubit [2], and exciton states are controlled by ultrashort pulses, which transfer the exciton to a superposition state. It was noted above that in order to create the QD-based quantum gate, one should excite at least two interacting excitons inside the QD. The Coulomb interaction of excitons lowers the total energy of the biexciton state by \( \Delta \), due to which the energy scheme of the quantum gate (figure 1) becomes four-level (\( \{00\}, \{01\}, \{10\}, \{11\} \)) and nonequidistant. In this case, the performing of short-pulse experiments requires a “two-color” excitation scheme since the exciton and biexciton excitation energies differ by \( \Delta \).

![Diagram](image)

**Figure 1.** The scheme of the energy levels of a quantum gate on QDs. \( P_x \) and \( P_y \) are the polarizations of the exciting pulses. \( |10\rangle \) is one of the states of the quantum gate. The energy transitions \( |10\rangle \leftrightarrow |11\rangle \) and \( |00\rangle \leftrightarrow |01\rangle \) are biexciton transitions while \( |00\rangle \leftrightarrow |10\rangle \) and \( |01\rangle \leftrightarrow |11\rangle \) are excitonic ones.

Consider, for example, a biexciton transition \( |00\rangle \leftrightarrow |01\rangle \), the states of which (\( |00\rangle \) and \( |01\rangle \)), for simplicity of further presentation, we denote as \( |0\rangle \) and \( |1\rangle \). According to [11], a qubit has two
computational basis vectors $|0\rangle$ and $|1\rangle$ belonging to the Hilbert space, and an arbitrary (superposition) state of the qubit $|\varphi\rangle$ is a linearly weighted combination of computational basis vectors:

$$|\varphi\rangle = a|0\rangle + b|1\rangle = a\begin{bmatrix} 0 \\ 1 \end{bmatrix} + b\begin{bmatrix} 0 \\ 1 \end{bmatrix},$$

where the coefficients $a$ and $b$ are the probability amplitudes that satisfy the relation $|a|^2 + |b|^2 = 1$.

So, before the measurement, the qubit is in both states of the computational basis simultaneously, and the measurement allows the qubit to collapse into one of these states. The quantum gate can be considered [11] as the simplest quantum-mechanical device that implements a certain unitary transformation over selected qubits (in our case, biexcitons and excitons of QD) during a certain period of time. In turn, a quantum network is a quantum computing device consisting of quantum gates, synchronized in time. Returning to the experimental work [1], we note that the $\pi$-pulse will excite the biexciton energy transition $|10\rangle \rightarrow |11\rangle$ only if the another ultrashort pulse almost simultaneously excited the exciton to the state $|10\rangle$. In this case, the $\pi$-pulse generates a state with a certain population, which can be read using a weak probe pulse. This gives us the opportunity to construct the dependence of this population on the area of the $\pi$-pulse, which is oscillating with the Rabi frequency. One can prepare the state of biexciton in any superposition of states $|10\rangle$ and $|11\rangle$ by changing the pulse duration. We note that the authors of [1] admit that, at exciton transitions, laser excitation can be continuous (“stimulated”) in order to provide the simultaneous character of lasers actions in a “two-color” excitation scheme. Since the variety of superpositions of levels is huge, the number of possibilities of such a quantum gate is great.

Another example of such studies was realized by Japanese authors [3] using the photon echo technique on excitons and biexcitons of quantum dots (GaAs) at 2 K placed in various magnetic and electric fields. As in the case of [1], two excitons with opposite spins and polarizations were excited in each QD. Therefore, the energy scheme of the quantum gate levels most likely coincided with that shown in figure 1, and the exciton binding energy in biexciton was equal to 4.1 MeV. Using a two-pulse sequence of ultrashort pulses, exciton and biexciton transitions were excited, their superposition was achieved, and exciton and biexciton echo signals were observed, the decay of which varied in various magnetic and electric fields. The decay times of these curves ranged from 20 to 60 ps. Thus, the set of oscillating (with the Rabi frequency) dependences of the populations on the pulse duration from [1] is replaced by the set of the photon echo decay curves in various magnetic and electric fields in the experiment [3].

3. Conclusion

Since the research groups in which the experiments [6] and [7] were carried out possess the necessary short-pulse technique and have experience in working on it, an attempt can be made to create a quantum gate in the semiconductor QDs they have grown, similar to that created in [1] and [3]. This work was intended to draw their attention to this possibility.

Acknowledgments

The authors are grateful to the Program of the Presidium of the Russian Academy of Sciences “Actual problems of low temperature physics” for financial support.

References

[1] Li X, Wu Y, Steel D, Gammon D, Stievater T H, Katzer D S, Park D, Piermarocchi C and Sham L J 2003 Science 301 809
[2] Novotny L and Hecht B 2006 Principles of nano-optics (Cambridge: Cambridge University Press)
[3] Ikezawa M, Nair S, Suto F, Masumoto Y, Uchiyama C, Aihara M and Ruda H 2007 J. Lumin.
[4] Samartsev V V 1972 Phys. Lett. 38A 363
[5] Samartsev V V and Sheibut Yu E 1991 Laser Physics 1 482
[6] Shmelev A G, Leontyev A V, Zharkov D K, Nikiforov V G, Lobkov V S and Samartsev V V 2017 Bulletin of the Russian Academy of Sciences: Physics 81 557
[7] Karimullin K R, Knyazev M V, Arzhanov A I, Nurtdinova L A and Naumov A V 2017 Jour. of Physics: Conf. Ser. 859 012010
[8] Osadko I S 2011 Fluctuating Fluorescence of Nanoparticles (Moscow: Nauka)
[9] Davydov A S 1978 Solid State Theory (Moscow: Nauka)
[10] Gribkovskiy V P 1988 Semiconductor Lasers (Minsk: University Publishing House)
[11] Imre S and Balazs F 2005 Quantum Computing and Communications: An Engineering Approach (Budapest: John Wiley & Sons)