

Nanooptics and nanophotonics

Exciton states in semiconductor and dielectric quantum dots

Sergey I. Pokutnyi

Chuiko Institute of Surface Chemistry, Natl. Acad. of Sci. of Ukraine. General Naumov str., 17, Kiev-03164, Ukraine.

E-mail: Pokutnyi_Sergey@inbox.ru

In [1] we developed within the modified effective mass method the theory of an exciton formed from spatially separated electron and hole (the hole is in the dielectric (semiconductor) spherical QD volume, and the electron is localized at the outer spherical surface of the QD–dielectric matrix interface. It was shown that the short wavelength shift of the peak of the low temperature luminescence spectrum of samples containing zinc-selenide QDs, observed under the experimental conditions of [2], is caused by quantum confinement of the ground state energy of the exciton with a spatially separated electron and hole. The effect of significantly increasing the binding energy of an exciton (with a spatially separated electron and hole) in a nanosystem containing zinc-selenide and Al_2O_3 QDs in comparison with the binding energy of an exciton in a zinc-selenide single crystal (by a contribution factor of 4.1–72.6) was detected. It was shown that nanosystems consisting of zinc-selenide QDs grown in a borosilicate glass matrix can be used as the active region of dielectric (semiconductor) QD lasers.

The results of variational calculation of the exciton ground-state energy $E_0(a)$ (spherical QD of the radius a) [1] are obtained for a nanosystem containing zinc-selenide QDs, synthesized in a borosilicate glass matrix, studied in the experimental work [2]. In the experimental work [2], borosilicate glass samples doped with zinc selenide with concentrations from $x = 0.003$ to 1%, obtained by the sol–gel method were studied. According to X-ray diffraction measurements, the average radii a of ZnSe QDs formed in the samples are within $a \approx 2.0\text{--}4.8$ nm. In this case, the values of $\tilde{a}\tilde{a}$ are comparable to the exciton Bohr radius $a_{ex} \approx 3.7$ nm in a zinc-selenide single crystal. At low QD concentrations ($x = 0.003$ and 0.06%), their interaction can be disregarded. The optical properties of such nanosystems are mainly controlled by the energy spectra of electrons and holes localized near the spherical surface of individual QDs synthesized in the borosilicate glass matrix.

In [2], a peak in the low-temperature luminescence spectrum at an energy of $E_1 \approx 2.66$ eV was observed at the temperature $T = 4.5$ K in samples with $x = 0.06\%$; this energy is lower than the band gap of a zinc-selenide single crystal ($E_g = 2.823$ eV). The shift of the peak of the low-temperature luminescence spectrum with respect to the band gap of the ZnSe single crystal to the short-wavelength region is

$\Delta E_1 = (E_1 - E_g) \approx -165$ meV. The authors of [2] assumed that the shift ΔE_1 is caused by quantum confinement of the energy spectra of electrons and holes localized near the spherical surface of individual QDs and is associated with a decrease in the average radii a of zinc- selenide QDs at low concentrations ($x = 0.06\%$). In this case, the problem of the quantum confinement of which electron and hole states (the hole moving within the QD volume and the electron localized at the outer spherical QD–dielectric matrix interface or the electron and hole localized in the QD volume) caused such a shift of the luminescence-spectrum peak remained open.

Comparing the exciton ground-state energy ($E_0(a) - E_g$) [1] with the energy of the shift in the luminescence-spectrum peak $\Delta E_1 \approx -165$ meV, we obtain the average zinc-selenide QD radius $a_1 \approx 4.22$ nm. The QD radius a_1 may be slightly overestimated, since variational calculation of the exciton ground-state energy can give slightly overestimated energies. The determined average QD radius a_1 lies within the range of the average radii of zinc-selenide QDs ($a \approx 2.0\text{--}4.8$ nm), studied under the experimental conditions of [2].

To apply semiconductor nanosystems containing zinc- selenide QDs as the active region of lasers, it is required that the exciton binding energy $|E_{ex}(a)|$ [1] in the nanosystem be on the order of several kT_0 at room temperature T_0 (k is the Boltzmann constant). Nanosystems consisting of zinc- selenide QDs grown in a borosilicate glass matrix can be used as the active region of semiconductor QD lasers [1,2]. In the range of zinc-selenide QD radii a , the parameter $|E_{ex}(a, \varepsilon)/kT_0|$ take significant values in the range from 3.1 to 56 [1].

The effect of significantly increasing the binding energy of the exciton ground state in a nanosystem containing zinc-selenide and Al_2O_3 QDs with radii a was detected; in comparison with the exciton binding energy in a zinc-selenide single crystal, the increase factor is 4.1–72.6 [1]. It was shown that the effect of significantly increasing the binding energy of the exciton ground state in the nanosystem under study is controlled by two factors: (i) a substantial increase in the electron–hole Coulomb interaction energy and an increase in the energy of the interaction of the electron and hole with “foreign” images (the “dielectric enhancement” effect); (ii) spatial confinement of the quantization region by the QD volume; in this case, as the QD radius a increases, starting from $a \geq a_c^{(2)} a_c^{(2)} \approx 29.8$ nm, the exciton becomes two-dimensional with a ground-state energy that exceeds the exciton binding energy in a zinc-selenide single crystal by almost two orders of magnitude [1].

1. Pokutnyi S.I. On an exciton with a spatially separated electron and hole in quasi – zero – dimensional semiconductor nanosystems // Semiconductors. - 2013.- **47**. –P.791-798.
2. Bondar N.V., Brodyn M.S. Optical properties semiconductor quantum dots // Semiconductors. - 2010. - **44**. – P.884 – 890.