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Investigation of the features of electronic spectrum of quantum dots in narrow-gap semiconductors

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Samples with quantum dots (QDs) of narrow-gap semiconductors of the A_3B_5 group (indium antimonide) and the A_2B_6 group (mercury selenide) have been studied. The absorption spectra of the investigated QDs are analyzed and the correspondence of the maxima in the spectral characteristics to the model representations of the calculated electronic energy spectrum for this materials is assessed. It is concluded that used model representations requires refinement, primarily due to the fact that studied objects are nanocrystals with complex geometry.

Keywords: quantum dots, indium antimonide, mercury selenide, electronic energy spectrum.

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One of the most promising and interesting objects of research in the light of practical applications are quantum dots (QDs) of semiconductor materials from the groups A_3B_5 and A_2 At $_6$. A_3B_5 compounds (primarily InSb) and some of the A_2B_6 compounds (HgTe, HgSe) have characteristic features of the energy spectrum (small width of forbidden band $\sim$ 0.2 eV) and extremely small values of the effective mass of conduction electrons. Therefore specific phenomena associated with size quantization of the electron energy spectrum can manifest themselves in relatively large structures (for example, up to 30 nm for InSb), which can significantly simplify the technology for obtaining and working with such objects [1–4].

QD electronic spectrum can be controlled in various ways: by introducing impurity atoms (doping), by introducing structural defects, by physical actions, etc. [5–9]. Owing to the appearance of additional discrete electron energy levels in QDs, as well as under certain additional conditions, these structures can realize such a type of electromagnetic radiation absorption, which is associated with optical transitions between levels of the same energy quasiband. This absorption can be called interlevel.

Absorption of this type has the following properties.

1. The spectrum of this absorption is selective, i. e. absorption takes place at certain values of photon energy:

$$\hbar\nu \approx \varepsilon_{ci+1} - \varepsilon_{ci},$$

where ε_{ci} — i-th discrete level of an electron in the quasi-conduction band.

2. The frequencies of the this absorption spectrum will lie in the IR region, since

$$\hbar\nu \sim \frac{(\pi\hbar)^2}{2m^* a^2},$$

where m^* is the effective mass of the conduction electron, a is the characteristic size of the QD. For example, for InSb QDs with a characteristic size from 25 to 30 nm, the wavelength of the interlevel transition quantum will lie in the range from 9 to 14 μm. This is an important range for detecting electromagnetic radiation, taking into account applications in the field of electronic technology and medicine.

A distinctive feature of QDs in narrow-band-gap semiconductors is that the energy gap between discrete levels (for example, $\varepsilon_{ci2} - \varepsilon_{ci1}$) can noticeably exceed the width of the forbidden band (ε_g) of a bulk material [5]. This can significantly expand the functionality of devices using QD-like materials, as well as provide the possibility of a controlled change in their absorption spectrum.

Samples with quantum dots of semiconductors of the A_3B_5 group (indium antimonide) and A_2B_6 (mercury selenide), because the quantum limitation in the selected materials makes it possible to control the width of forbidden band in a wide spectrum of IR range [10,11]. The technologies for obtaining the investigated QDs are described in detail in the papers [12,13].

Layers with QDs were deposited on glass substrates and studied using a transmission electron microscope Libra 120 (Zeiss, Germany), a scanning probe microscope SOLVER NANO (NT-MDT, Russia), and Fourier spectrometer IRAffinity-1 IR (Shimadzu Corp., Japan).).

Typical images of transmission electron microscopy (TEM) for InSb QDs are shown in Fig. 1.

The characteristic dimensions of QDs were 10−12 nm. Quantum dots were defined as nanocrystals with a complex geometry, but still closer to a cubic shape. This made it possible to use the „cubic“ model„ [14] as the most adequate for calculating the QD energy spectrum.

From a practical point of view, fundamental energy transitions ($\varepsilon_{c1} - \varepsilon_{v1}$) and transitions between the first and second discrete levels of the electron in the QD quasi-

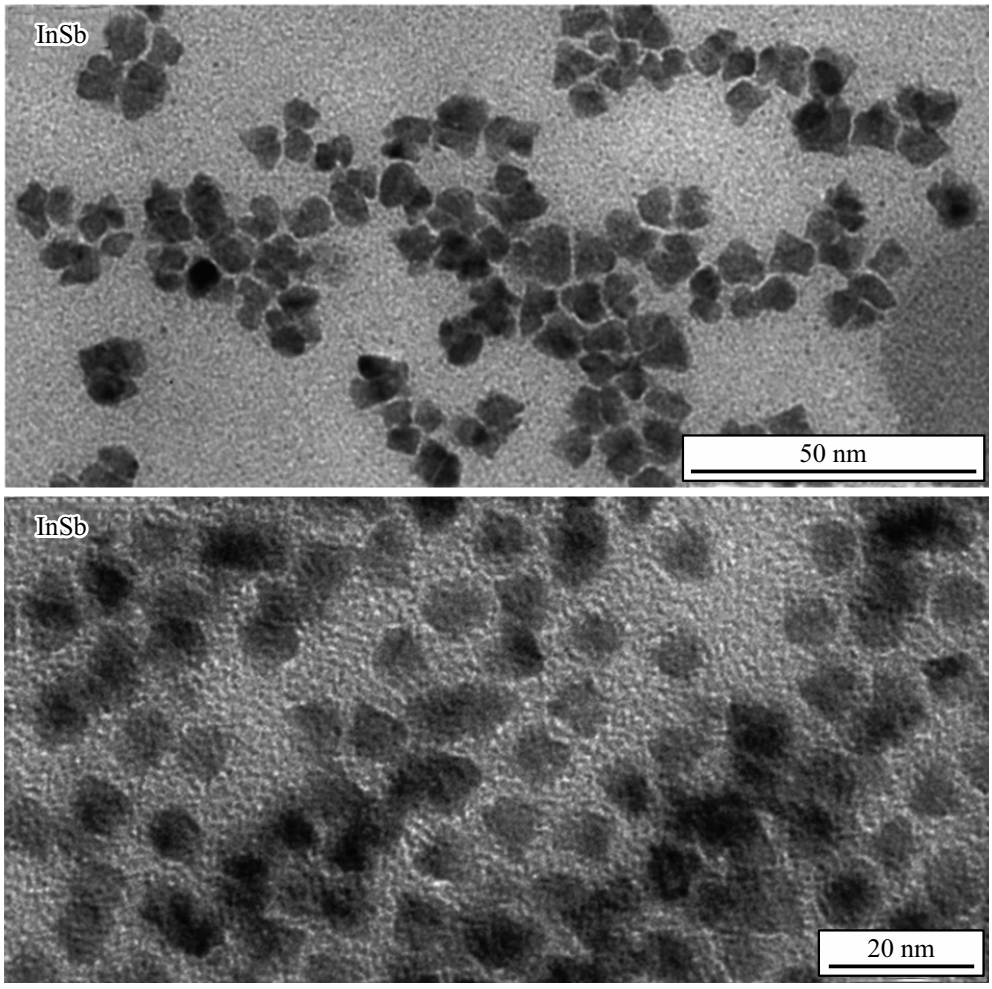

Figure 1. TEM images of InSb QDs.

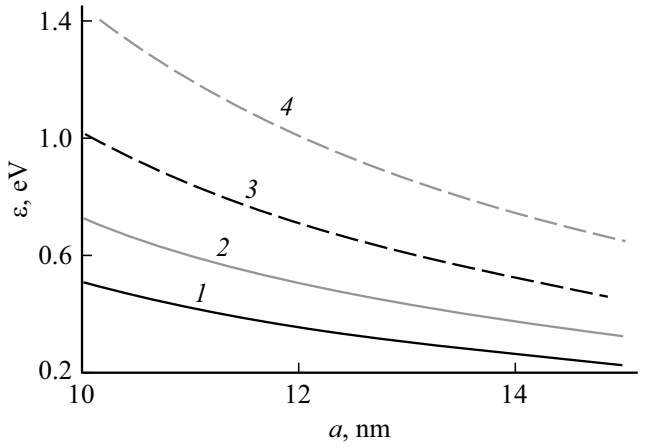

Figure 2. Calculated values of the energies of the first (solid lines) and second (dashed lines) electron levels in the QD. *1*, *3* — InSb; *2*, *4* — HgSe.

conduction band can be of most importance. Then,

$$\varepsilon_{c2} - \varepsilon_{c1} \approx \frac{3(\pi\hbar)^2}{2m^* a^2}. \qquad (1)$$

The calculated energy spectra for the conduction electrons of these QDs are shown in Fig. 2.

The absorption spectra of macrosamples with the studied quantum dots were studied. Typical results are shown in Fig. 3.

The maxima in the spectral dependences of the absorption coefficient can be interpreted as transitions between discrete levels of electron in the QD conduction quasi-band. As follows from the analysis, the experimental results are close to those calculated for QDs of the semiconductor materials under study with similar characteristic dimensions and values of the effective electron mass. This may be explained as follows.

The first maximum, corresponding to the absorption wavelength 1.5 μm, is related to the fundamental absorption:

$$\varepsilon_{\hbar\nu} = \varepsilon_{g_0} + \varepsilon_{c1} + \varepsilon_{v1}, \qquad (2)$$

where $\varepsilon_{\hbar\nu}$ is the quantum energy in the absorption maximum region, ε_{g_0} is the band gap of the bulk material, ε_{c1} is the value of the first energy level of the quantum dot electron, counted from the bottom of the conduction

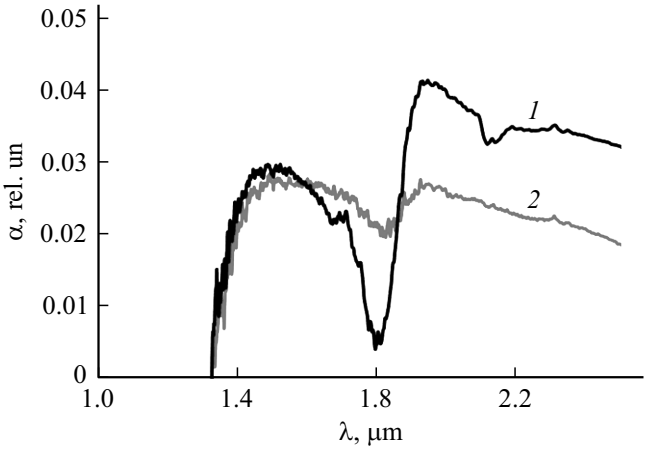

Figure 3. Typical spectral dependences of QD absorption coefficient. *1* — HgSe, *2* — InSb.

band of the bulk material, ε_{v_1} is the value of the first energy level of the hole, counted from the top of the valence bulk material zones.

The effective mass of electron in the materials under consideration (about $0.014m_0$ for InSb and $0.020m_0$ for HgSe, where m_0 is the mass of a free electron) is substantially less than the effective mass of hole, and in expression (2), ε_{v_1} can be neglected compared to ε_{c1}.

Taking into account that ε_{g_0} for InSb is approximately 0.18 eV, we can estimate the value of ε_{c1}, which is 0.64–0.65 eV. This value corresponds (with an accuracy of $2kT$) to the dimensions obtained by direct TEM measurement and the model used (Figs 1 and 2).

The position of the second maximum (Fig. 3), which can be interpreted as corresponding to the transition between the first and second levels of the QD electron energy spectrum, at the specified characteristic size of QD and use of expression (1) does not correspond to the calculated values of $\varepsilon_{c2} - \varepsilon_{c1}$. Estimates of the characteristic size of QDs based on the position of the maxima in the spectral characteristic and calculation by formula (1) give a value of at least 20 nm, which significantly exceeds the values measured using TEM (Fig. 1).

Thus, we studied samples with QDs of narrow-band-gap semiconductors of A_3B_5 group (indium antimonide) and A_2B_6 (mercury selenide). The absorption spectra of the investigated QDs are analyzed, and the correspondence of the maxima in the spectral characteristics to the model representations of the calculated electron energy spectrum for the materials under consideration is evaluated. The results corresponding to fundamental transitions between discrete levels, as follows from the analysis, are adequate for QDs of the studied semiconductor materials with similar characteristic sizes and values of the effective electron mass.

The position of the second maximum, which can be interpreted as corresponding to the transition between the first and second levels of the electron in QD conduction quasi-band, at the specified characteristic size of QD and used model does not correspond to the calculated values. This allows us to conclude that the model representations used in calculating the QD energy spectrum of the considered narrow-band-gap semiconductors (for the second and higher levels) require refinements, the need for which is primarily due to the fact that the objects under study are nanocrystals with a complex geometry.

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Conflict of interest

The authors declare that they have no conflict of interest.

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