Cathodoluminescence of laser $A^{II}B^{VI}$ heterostructures

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(Получена 16 октября 2006 г. Принята к печати 30 октября 2006 г.)

A cathodoluminescence (CL) method has been used for the studies of ZnSe-based heterostructures with CdSe fractional-monolayer recombination region. Electron beams with the energies of 1−25 keV provides the ability to analyze the CL bands associated with the different layers of the heterostructure and revealed on the CL spectrum at different electron beam penetration depth. The comparative analyses of the CL bands both from the recombination region and the upper layers have been used to characterize the transport properties of the structure. The correlation between the density and size distribution of quantum dots and full width on the half of maximum and spectral position of the CL bands has been studied in detail.

PACS: 78.60.Hk, 73.40.Lq, 73.63.Kv

1. Introduction

Cathodoluminescence (CL) can be used as an express and nondestructive tool for the diagnostics of different heterostructures. Among the most important characteristics of ZnSe-based heterostructures with CsSe fractional-monolayer recombination region are transport properties of excitation. These properties were studied earlier by photoluminescence technique [1]. In the case of cathodoluminescence the excitation is formed by beam-medium interaction, and the generation depth is governed mainly by the electron beam energy. The comparative analysis of the CL bands intensities from different layers of the structure associated with different electron beam penetration depth allows one to investigate the transport of carriers generated in the upper layers of the heterostructure and moved towards the recombination region. In the case of a weak transport the CL spectrum relates to the different layers of the structure corresponding to the different penetration depth of the electron beam. In the case of a good transport the carriers produced in upper layers migrates to the recombination region, leading to the dominance of CL band associated with the CdSe-based recombination region at any beam energies.

This paper consists of two parts. The first part of the paper demonstrates the abilities of CL technique to analyze the transport properties of ZnSe-based heterostructures consisted of ZnSe/ZnSSe superlattice (SL) and thick ZnMgSSe upper layer. The second part of the paper is devoted to the CL studies of CdSe-based quantum dot (QD) structures to reveal the correlation between the density and size distribution of QDs and CL spectra of the samples (full width on the half of maximum (FWHM) and spectral position of the CL bands). It should be noted the influence of molecular beam epitaxy (MBE) growth parameters (e.g. temperature) on the QD properties was studied earlier in ref. [2].

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2. Experimental details

The Cd(Zn)Se/ZnMgSSe structures were grown pseudomorphically by MBE on GaAs (001) substrates in two-chamber MBE system EP-1203. Two types of the structures have been grown: the structures for the studies of transport properties and the structures with a single QDs sheets grown at different temperature.

The structures of the first type contain the similar 2.5 ML (mono-layer) CdSe/ZnSe QD recombination region. Different types of upper layers have been studied, namely a symmetric ZnSSe/ZnSe alternately-strained superlattice (SL) of 0.7 μm thickness (sample A) and the thick (1.2 μm) ZnMgSSe-cap layer (sample B). Fig. 1 presents the schematic diagram of these samples. The structures studied

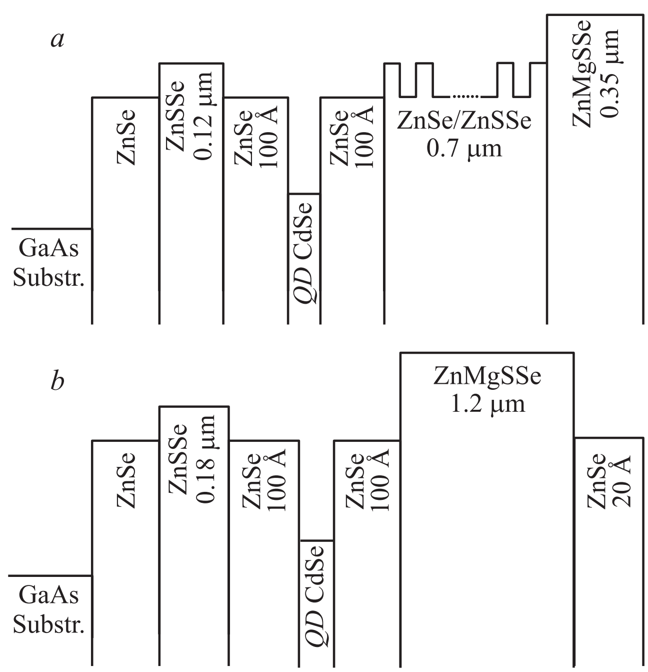

Figure 1. The schematic band diagram of the samples A and B.

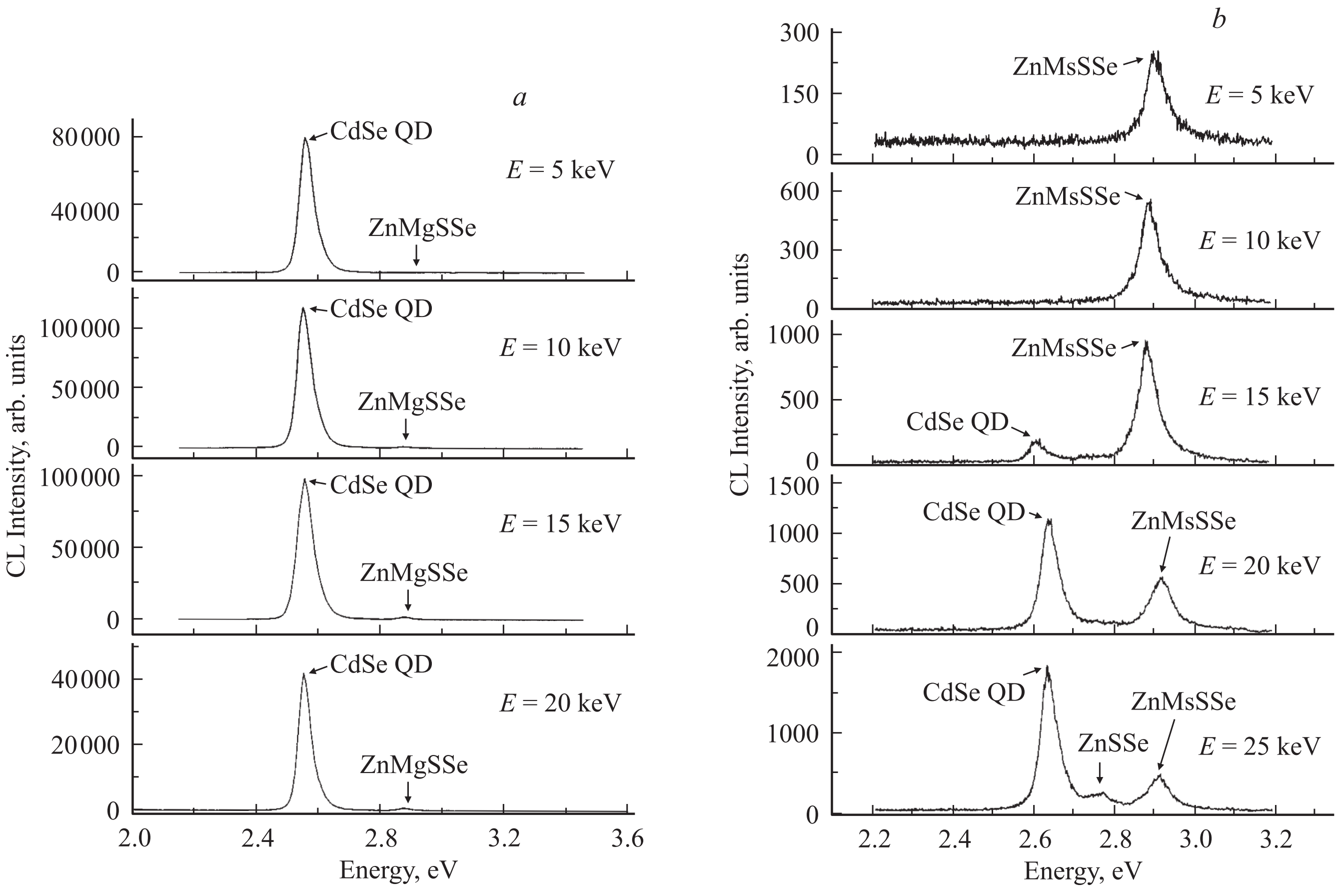

Figure 2. The CL spectra of samples A (*a*) and B (*b*) registered at different electron beam energies.

in the second part of the paper have the similar design comprising ZnSSe buffer layer, 100 nm thick, 10 nm bottom ZnSe layer, single CdSe QD region grown in a standard MBE growth mode and a cap ZnSe layer of 20 nm thick. The growth temperature during CdSe deposition was varied from $T_{sub} = 280°C$ (sample C) to $T_{sub} = 340°C$ (sample D). The CdSe sheets of both structures were deposited at an average CdSe growth rate of ~ 0.6 Å/s (0.2 ML/s).

All samples were studied using CL spectroscopy. An original spectrometer [3] was installed on the optical microscope port of a Camebax electron microprobe. CL (300 K) measurements were done with different penetration depth into the layer varying the beam energy from 1 to 25 keV. The electron beam diameter was $\sim 0.5\,\mu$m.

Transmission electron microscopy (TEM) measurements were carried out using the JEM-T6 (JEOL) electron micro-

Table 1. The calculated beam penetration depth for the samples A and B

The energy of electron beam, keV	The penetration depth for sample A, μm	The penetration depth for sample B, μm
5	0.2	0.3
10	0.6	0.6
15	1.3	0.7
20	1.4	1.0
25	1.8	1.5

Table 2. Cathodoluminescent characteristics and the properties of QD, sample C

Growth temperature T_{sub}	The spectral band maximum, eV	FWHM, eV	Quantum dot density, 10^{10} cm^{-2}	Quantum dot lateral sizes, nm	Average quantum dot size, nm
280°C	2.20	0.06	8.5	2−5	3−4
340°C	2.18	0.07	7.0	3−8	5−6

scope. The density of QDs in the films was determined using a plain-view bright-field TEM images. Two-beam mode was applied in order to reveal dislocations with different Burgers vectors.

3. Transport properties characterization

Experimental CL data for the samples A and B are presented in Fig. 2. The constant energy loss method was used to calculate the beam penetration depth for each sample [4] (Tabl. 1).

For the sample B a single band with the energy of 2.89 eV is observed at the beam energies 5−10 keV. This band corresponds to the ZnMgSSe and agrees well with penetration depth calculations. Maximum penetration depth expected for this energy range is about 0.6 μm, and the carriers are generated inside the ZnMgSSe layer. Due to weak transport properties the generated carriers are recombined in the ZnMgSSe quaternary layer. At the beam energy of 15 keV the penetration depth increases up to 1.3 μm and exceeds the total thickness of ZnSSe/ZnSe SL and ZnMgSSe layers. At this energy the second spectral band (2.62 eV) corresponding to the CdSe QDs appears in the spectrum. Further increase in the beam energy leads to the increase of QDs/ZnMgSSe CL intensity ratio due to the shift of the center of irradiated area towards the substrate. As a result the band corresponding to the ZnSSe buffer layer appears in the CL spectrum.

For the sample A QD band in CL spectrum dominates at any electron beam energies though the calculated beam penetration depth reached the QD layer at beam energy of 20 keV. This fact is explained by the good transport properties of ZnSe/ZnSSe superlattice. The intensity of this band is about two orders of magnitude higher than that of sample B. One can also observe a small peak from ZnMgSSe cap layer. The dependence of Cl band intensities on electron beam energy for the samples A and B is presented in Fig. 3.

Summarizing, the ratio between QDs and cap layer CL band intensities can be used for the characterization of transport properties of heterostructures.

4. QD properties

We also tried to investigate the correlation between structural properties of QDs and CL spectra. The results of CL study and TEM investigations were examined together to understand the dependence of emission properties on densities and size distributions of QDs. For this purpose two samples (C and D) having the similar design have been used. TEM plain-view images (Fig. 4) were used to estimate both size distribution and density of quantum dots in the samples. The results are collected in Tabl. 2. The histograms of QD size distributions for the samples C and D is presented on Fig. 5.

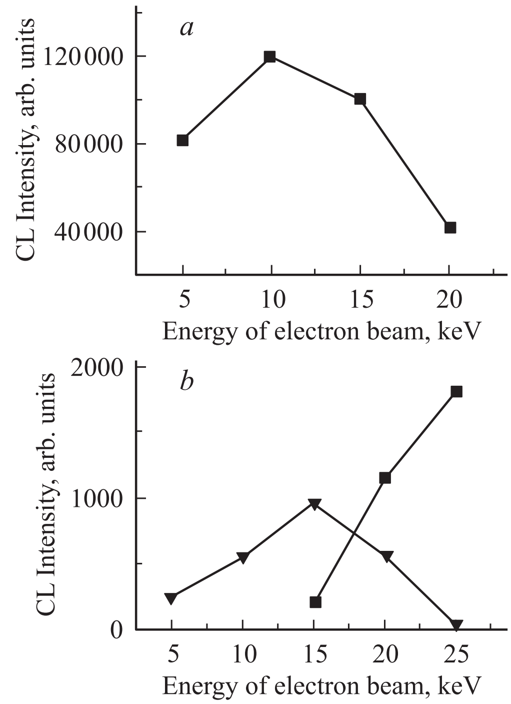

Figure 3. The dependence of CL band intensity on the electron beam energy for the samples A (a) and B (b). The intensities of CL band associated with CdSe QDs are plotted as black squares; the data on ZnMgSSe CL band of sample B are plotted as black triangles.

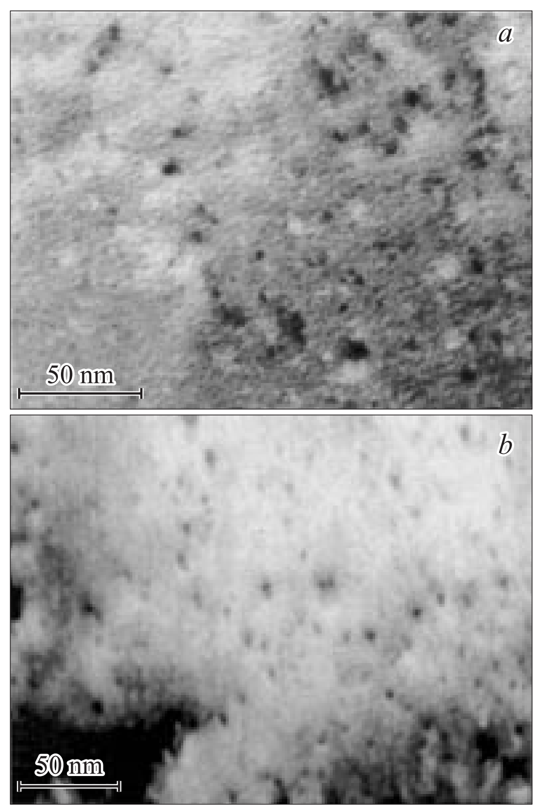

Figure 4. TEM plan-view images for the samples C (a) and D (b).

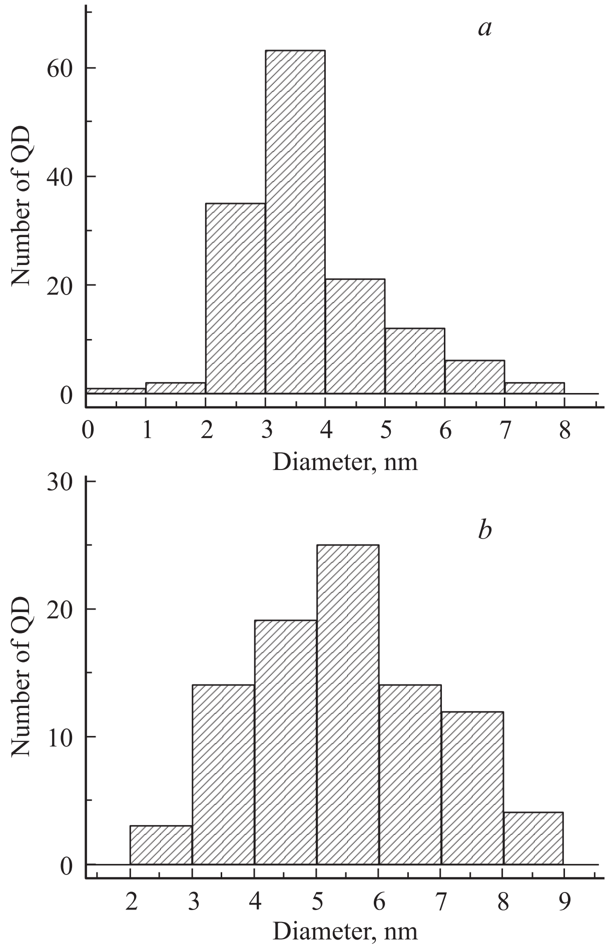

Figure 5. The histograms of CdSe QD lateral size distributions for the samples C (*a*) and D (*b*).

For the sample C the QD spectral band maximum and FWHM are 2.249 and 0.060 eV, respectively. For the sample D the QD band is of 2.243 eV and FWHM is of 0.071 eV. One can observe a correlation between the FWHM of QD CL band and QD lateral size distribution. With the increase of average QD size a small red shift of CL band position is observed (from 2.20 eV for the sample C to 2.18 eV for the sample D (see Tabl. 2)).

5. Conclusion

Cathodoluminescence method can be used as an express and nondestructive tool for the diagnostics of transport properties of ZnSe-based heterostructures. The introduction of the ZnSSe/ZnSe short-period SL instead of bulk ZnMgSSe provides good carrier transport to a QD recombination region. The correlation between CdSe QD lateral size distribution and CL emission band (spectral position, FWHM and band intensity) has been obtained.

The work was partly supported by RFBR grant No. 05-02-16568a.

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