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E−beam longitudinal pumped laser on MOVPE−grown hexagonal CdSSe/CdS MQW structure

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Abstract

CdSSe/CdS multi quantum well structures were grown by metalorganic vapor phase epitaxy (MOVPE) on a CdS substrate misoriented by 12−15° from (0001) towards (10$\underline{1}$0). Microcavities with dielectric oxide mirrors were fabricated on the basis of these structures. Lasing in the 535−590 nm spectral range was achieved on different structures under longitudinal electron beam pumping at room temperature. The relatively high threshold of the laser and the blueshift from the spontaneous emission peak to lasing wavelength were explained by taking into account the type−II band alignment of the active region.

1. Introduction

A new trend in II−VI compound technology is to grow multi quantum well (MQW) structures with hexagonal crystal form, in order to solve the life time problems associated with ZnSe−based lasers which possess a cubic crystal lattice [1,2]. The stable hexagonal modification is realized in CdS, CdSe single crystals and their solid solutions. These single crystals are used successfully in laser cathode−ray tubes [3]. However it is difficult to produce hexagonal crystals at the relatively low temperatures used in epitaxy. In previous work, we presented mirror−like hexagonal CdS, ZnCdS films and CdS/ZnCdS QW structures grown on hexagonal CdS and ZnCdS substrates with exact (000$\underline{1}$)−orientation [4,5]. Here we present new results on the further improvement of CdSSe/CdS structures by using misoriented CdS substrates and the achievement of lasing on such structures under e−beam pumping.

2. Sample fabrication

The CdS substrates were cut from monocrystals, produced by free growth method using seeded physical transport [6]. The dislocation density was about 10^4 cm^{-2}, while the small−angle−boundary density on the (0001) surface did not exceed 15 cm^{-1}. It has been found that the morphology of the growth surface is improved dramatically when one uses substrates misoriented by 10−15º from (0001) orientation towards (10$\underline{1}$0). The cathodoluminescence (CL) efficiency at room temperature (RT) also increases. Therefore we adopted a 12−15º misorientation for the CdS substrates used in this work The substrate surface was polished after cutting and then etched in a solution of CrO_3 in HCl and H_2O. MOVPE was carried out at atmospheric pressure in a home−made quartz reactor of vent−run type without substrate rotation. $CdMe_2$, Me_2Se and Et_2S were used as precursors and hydrogen as the carrier gas. The heterostructures were grown at a temperature of 370º C.

CdSSe/CdS QW structures, containing 25−40 $CdS_{1-x}Se_x$ QWs with x = 0.2−0.6 and width of 1.5−3.5 nm, were introduced into the 2−4 μm thick CdS epilayer. A few of these structures were used for making a vertical cavity surface emitting laser (VCSEL). One such structure and the VCSEL made from it are sketched in Fig. 1. The fabrication steps were as follows. The structure was first bonded to a glass support by optical wax. The CdS substrate was removed in part by polishing, followed by etching in CrO_3−HCl−H_2O solution. Ten pairs of quarter wave SiO_2 and ZrO_2 layers were coated on the structure to form the first mirror of the cavity. This sample was then glued by high−temperature epoxy to a sapphire holder. The glass substrate was removed by heating the assembly up to the melting temperature of the wax. The free surface was cleaned and a second 10.5 pair mirror

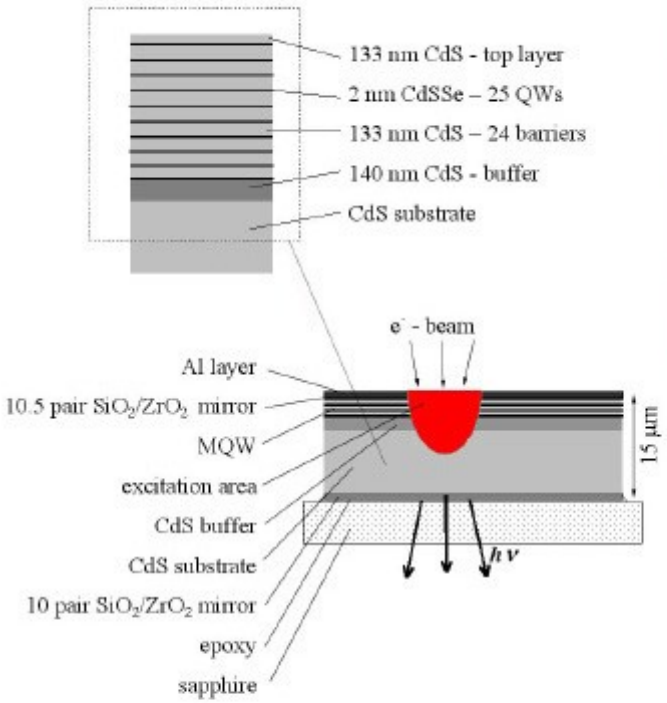

Fig. 1. Sketch of CdSSe/CdS MQW structure #74 and e-beam laser made on its basis.

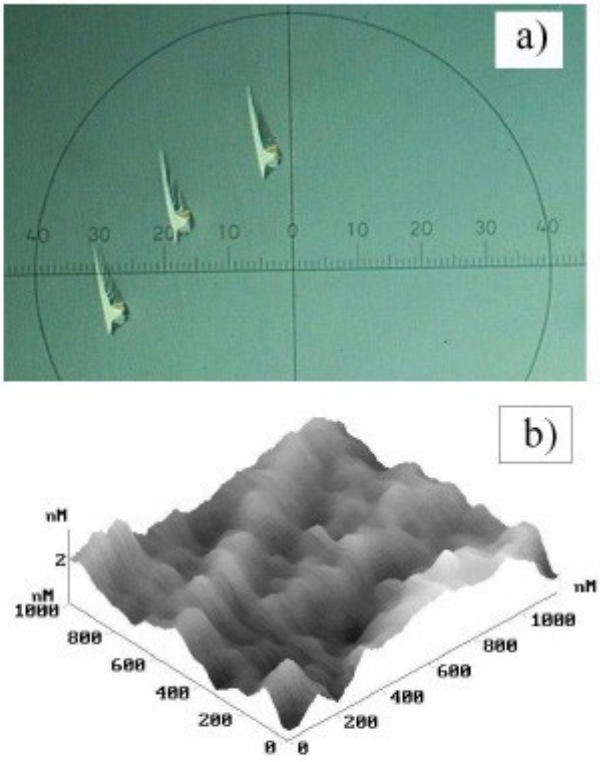

Fig. 2. Optical (a) and AFM (b) images of the CdSSe/CdS MQW structure #177. Small scale division of optical image is 2.5 μm. MRS roughness is 0.48 nm.

stack of the same design. Al layer was deposited on this surface to complete the etalon. The cavity was pumped by a scanning electron beam with energy E_e = 25−50 keV and current I_e = 0−1.7 mA with an e−beam diameter d_e = 20−50 μm, depending upon the electron energy and current. The scan velocity was about $4 \cdot 10^5$ cm/s. The repetition rate of the scan was 50 Hz. Laser characteristics were studied at RT and T = 80 K. CL spectra were measured at RT and T = 14 K under CW e−beam pumping with E_e = 10 and 30 keV, I_e = 1 μA and d_e = 0.03 and 1 mm.

3. Experimental results and discussion

Fig. 2a shows a typical optical microscope plan view of as−grown structure made with interference contrast. There are three hillocks on the surface, due to defects on the substrate surfaces. The concentration of the hillocks is as small as 10^4 cm^{-2}. The area between the hillocks appears flat. Fig. 2b presents a photographic image of a flat region made by atomic−force microscopy (AFM). The RMS roughness is smaller than 0.5 nm on area of 1.0x1.0 μm^2, showing that scattering of generated light on the structure interfaces will be small enough in the cavity.

The CL spectrum of as−grown structures at RT contained one line whose maximum and FWHM changed with QW composition and QW thickness. A FWHM for structures emitting in the 540−550 nm green spectral range of about 90 meV increased to about 150 meV for structures emitting in orange. The structures emitting in red range had typically small CL intensity at RT because of misfit dislocation formation.

Laser action at RT was achieved in the 535−590 nm spectral range for different structures. Fig. 3 compares emission spectra for two VCSEL just above threshold with CL spectra of the corresponding structures obtained at low excitation level at RT. As seen, lasing occurs at 550 nm and 587 nm, respectively, on the short wavelength side of the spontaneous spectra in both cases. Additional longitudinal modes of the cavity appear in the laser spectrum at higher pump powers. The best parameters were obtained for the VCSEL containing 25 QWs and emitting at 550 nm . The threshold current was about 0.2 mA at E_e= 40 keV. It corresponds approximately to current density of 40 A/cm^2. The output power was 0.1 W at RT and increased up to 1.5 W at T = 80 K.

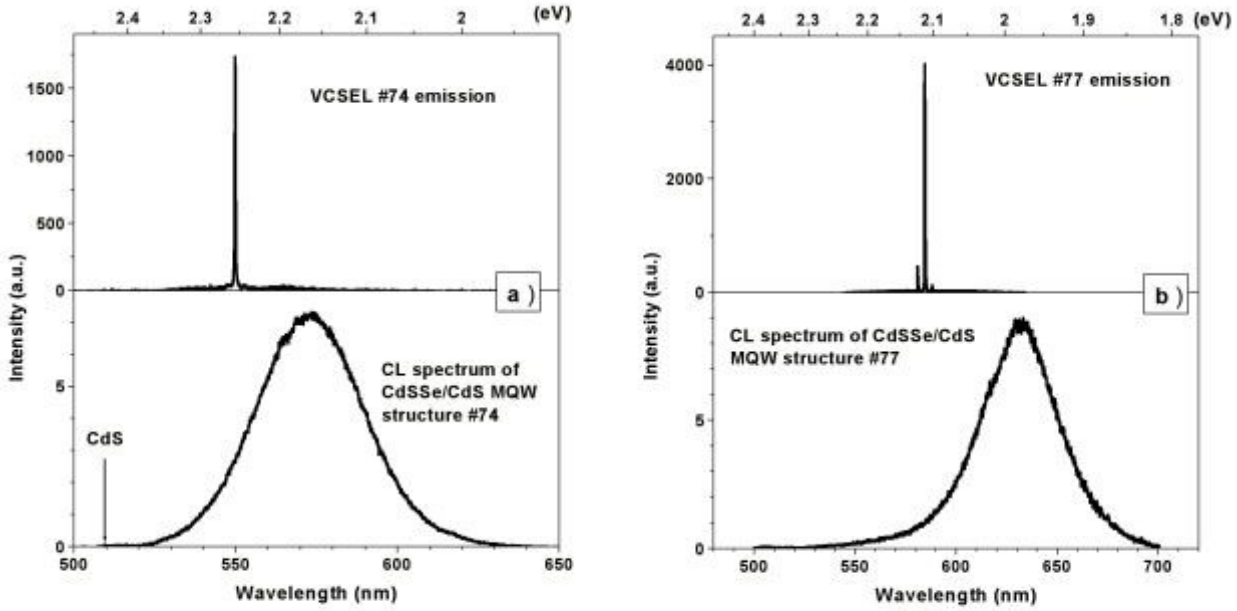

Fig. 3. CL spectra of as-grown CdSSe/CdS MQW structures at RT, E_e = 10 keV, I_e =1μA, d_e= 1 mm and emission spectra of e-beam pumped VSCELs made of these structures at RT, E_e = 40 keV, I_e=1.5·$I_{e,th}$ and d_e = 25 μm.

To obtain more details concerning the reason for the unusual blueshift of the lasing wavelength from the spontaneous emission maximum we studied the VCSEL emission below threshold. Fig. 4 shows the VCSEL emission spectra under longitudinal e−beam pumping at E_e = 45 keV, I_e = 1 mA, T = 300 K and various values of d_e. Decreasing d_e (increasing excitation intensity) leads to a widening of the emission line on the high−energy side until the onset of lasing. Lasing was observed in the 580−590 nm range for this etalon, which is 165 meV above the maximum of the spontaneous emission line.

These observations may be interpreted by taking into account a particular feature of the band alignment of the CdSSe/CdS structure used. According to [7] CdSe and CdS form heterostructures of type−II with a conduction band offset ΔE_c of 0.23 eV. For the $CdS_{0.5}Se_{0.5}$/CdS structure (Fig. 4) ΔE_c = 115 meV is expected. The intense emission lines in the CL spectra at low excitation level (λ_{max} = 635 nm at RT and 615 nm at T = 14 K) are thus due to recombination of electrons from the thick CdS layer with holes localized in the thin CdSSe layer. The band alignment of the structure at low excitation level is sketched in Fig. 5a. The probability of such a recombination is much less than one of direct transitions in QW because of small carrier function overlap. Therefore observation of high CL intensity means that quality of the structure studied is high enough and other recombination transitions are practically absent.

Increasing the excitation level leads to an infill of the conduction band of the CdS layers by electrons while holes fill up the valence band in the CdSSe QWs. As a result of such an infill an internal space−charge field is induced by excited carrier separation [8]. In this case the band alignment becomes like the one presented in Fig. 5b. (Detailed quantitative modeling of the structure's energy levels under high excitation has not been completed). Quasi Fermi levels rise and the emission line widens to high−energy side with increasing excitation level. Laser action is achieved when the difference between quasi Fermi levels exceeds the energy of electron transition in the QW and optical gain compensates all cavity losses. It is clear that the first condition may be fulfilled only at a recombination energy higher than the energy of the spontaneous emission by the conduction band offset, ΔE_c = 115 meV. However fulfilling the second condition requires additional excitation that leads to a further energy shift of laser emission from the spontaneous emission energy. Therefore the observed 165 meV shift may be explained on the basis of this model.

It should be noted that the band bending increases with increasing total concentration of nonequilibrium carriers. This leads to increasing carrier wave function overlap and an enhancement of the optical matrix element [9].

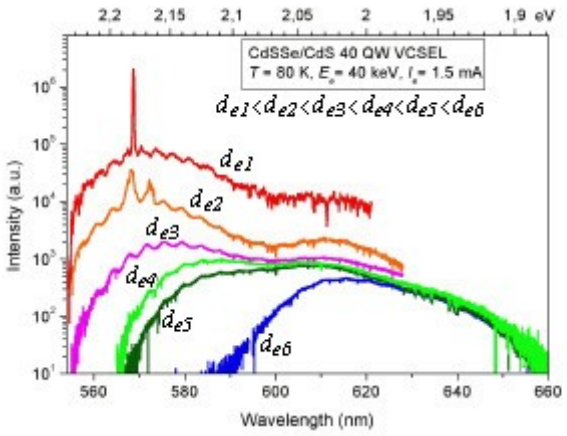

Fig. 4. Emission spectra of the VSCEL #77 at T = 80 K, E_e = 45 keV, I_e = 1 mA at different d_e.

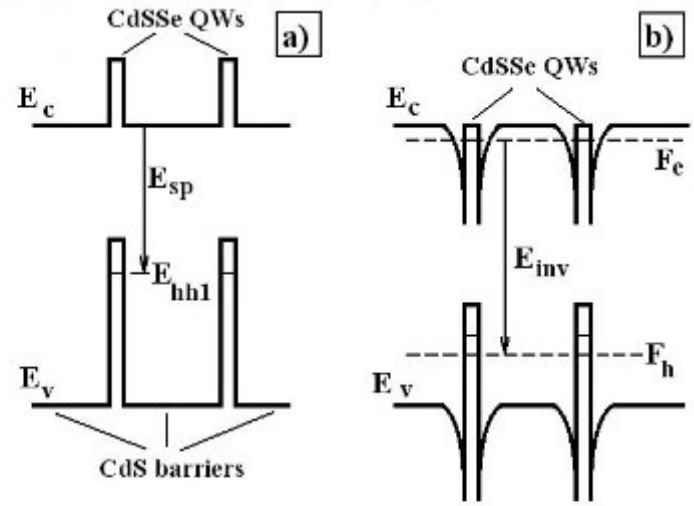

Fig. 5. Band alignment of the CdSSe/CdS MQW structure at low (a) and high (b) excitation level. E_{sp} is the spontaneous emission maximum, E_{inv} is an emission energy at inversion condition.

Besides, the band bending decreases the total number of electron levels that should be filled to achieve required quasi Fermi levels. So expected threshold may be quite small although the structure has the type−II band alignment. The relatively high threshold obtained in this work is likely to be due to the nonoptimal structure period used and mismatching of the QW positions with the cavity mode antinodes. Nevertheless the threshold achieved is smaller than the threshold of analogous VCSEL made using a bulk active CdSSe layer.

4. Conclusion

The first e−beam pumped VCSEL on CdSSe/CdS MQW structure grown by MOVPE was realized. Relatively high threshold of the laser is due to nonoptimal structure design and the type−II band alignment of the structure used. Low threshold lasing should be obtained by using CdS/ZnCdS or CdSSe/ZnCdS MQW structures which have a type−I band alignment. This work is in hand.

Acknowledgements

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