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Semiconductor laser based on a CdS/ZnSe heterostructure with longitudinal optical pumping by a laser diode

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Abstract. **An optically pumped semiconductor laser based on a CdS/ZnSe heterostructure containing 10 coupled quantum wells is studied. The structure is grown by metalorganic vapour phase epitaxy on a GaAs substrate. A microcavity with interference dielectric mirrors is fabricated based on this structure. At room temperature under longitudinal pumping by an InGaN/GaN pulsed laser diode with a wavelength of 438 nm, the peak power of the microcavity reaches 100 mW at a wavelength of 508 nm and a pulse duration of 65 ns.**

Keywords: *metalorganic vapour phase epitaxy, CdS/ZnSe heterostructure, quantum wells, optical pumping.*

1. Introduction

Semiconductor disk lasers (SDLs), or vertical-external-cavity surface-emitting semiconductor lasers with, in particular, optical pumping, can generate high-power radiation with a good beam quality [1–4]. At present, SDLs are mainly based on A3B5 structures emitting in the near-IR region. The final goal of the present study was to fabricate a SDL with the fundamental wavelength in the blue–green spectral range (480–560 nm). In this case, conversion to the mid-UV spectral range (240–280 nm), which is most popular for some applications, can be achieved by relatively simple intracavity frequency doubling. As an active laser medium, it is necessary to use resonant periodic structures of wide-gap compounds, for example, the CdS/ZnSe heterostructure [5–8].The advantages and disadvantages of this heterostructure in comparison with other known heterostructures emitting in the blue–green spectral range, namely, ZnCdSe/ZnMgSSe and InGaN/GaN, were previously discussed by us in [6, 7]. We succeeded to achieve lasing of CdS/ZnSe heterostructures both in a microcavity [6] and in a SDL [7] under pumping by a repetitively pulsed N_2 laser. However, due to a short pulse duration of the N_2 laser (~8 ns), the SDL cavity length did not exceed 3 mm. In addition, the great difference between in the energies of the pump (~3.7 eV) and emission (~2.5 eV) photons strongly restricts the laser efficiency. In the present work, we study a microcavity laser with longitudinal pumping by a commercial laser diode (LD) based on an InGaN/GaN heterostructure with a wavelength of 438 nm (2.83 eV) and a pulse duration of ~200 ns. At the next stage of investigations, we plan to study a SDL under pumping by the same diode.

A blue laser diode has already been used to pump a laser based on a heterostructure of A2B6 compounds, in particular, on the CdSe/ZnSe/ZnSSe heterostructure [9]. However, the authors of [9] used transverse pumping of a waveguide structure, whose design considerably differs from the design of structures for longitudinal pumping.

2. Experiment

The CdS/ZnSe nanostructures were grown by metalorganic vapour phase epitaxy on a GaAs substrate in a hydrogen flow at atmospheric pressure in a quartz reactor. As initial compounds, we used dimethyl selenide $(CH_3)_2Se$, dimethyl cadmium $(CH_3)_2Cd$, diethyl sulphide $(C_2H_5)_2S$, and diethyl zinc $(C_2H_5)_2Zn$. The structures were grown on GaAs substrates disoriented from the (001) to the (111)A plane by 10°. The substrate temperature was 440 °C. The structure contained sequentially grown layers of a ZnS_xSe_{1-x} buffer 190 nm thick and ten periods consisting of layers of ZnSe (3 nm thick), CdS (2 nm), ZnSe (2 nm), CdS (2 nm), ZnSe (3 nm), and a ZnSSe barrier layer (82 nm). The CdS and ZnSe layers formed quantum wells (QWs) for electrons and holes, respectively. Thus, the structure in the region of QWs has type-II band offsets. The thicknesses of layers could smoothly vary over the structure surface due to inhomogeneity of the hydrogen flow with initial components in the reactor. The elastic stresses formed by QWs were compensated by increasing the sulphur concentration in the barrier layers to 11 %. The total thickness of the heterostructure with 10 QWs was approximately 1.2 μm. The heterostructure had a mirror-smooth surface.

To fabricate the active element of the microcavity laser, the first dielectric mirror consisting of 11 $HfO_2–SiO_2$ layer pairs with a calculated reflection coefficient of 99 % at a wavelength of 508 nm and a transmittance of 73 % at 438 nm was deposited on the structure. A sapphire substrate 5 mm thick was glued on this mirror with EPOTEK-301 optical epoxy. Then, the GaAs growth substrate was removed by grinding and selective etching and the free structure surface was coated with the second dielectric mirror consisting of 12 $Ta_2O_5–SiO_2$ layer pairs with a calculated reflection coefficient of 99.6 % at a wavelength of 508 nm.

The microcavity structure was longitudinally excited through the sapphire substrate by a pulsed LD with λ = 438 nm. The LD radiation stripe was focused by a minilens on the heterostructure surface. The excited region had the shape of a

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stripe with a length of 150 μm and a width less than 15 μm. The used design of the active element did not allow us to study the laser under cw pumping due to the low thermal conductivity of the glue layer, dielectric mirror, and sapphire substrate. Because of this, the LD operated in a repetitively-pulsed regime with a pulse repetition rate of 10–20 Hz and a pulse duration at half maximum of 200 ns. However, we expect that a cw regime will be achieved in the future by sandwiching the heterostructure (without the growth substrate) between two diamond plates as has already been done in membrane-type SDLs based on the GaInAs/GaAs heterostructure [10]. As a pulsed LD driver, we used a driver for Schottky diodes (IXDD630CI). The scheme of the laser and recording the pump and laser pulses is presented in Fig. 1.

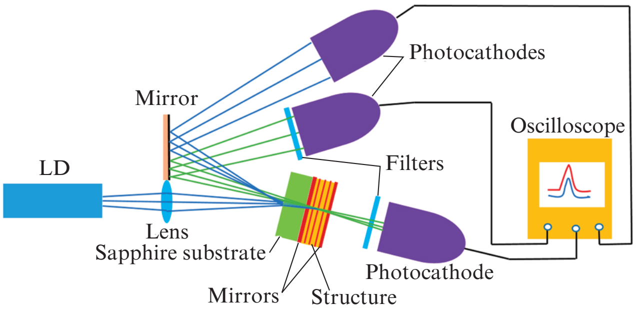

Figure 1. (Colour online) Scheme of the laser and of recording the pump and laser pulses.

The structure was excited through the sapphire substrate so that the thick buffer layer was maximally distant from the region of the maximum absorption of LD radiation. The pump pulse was controlled using a calibrated coaxial photodetector FEK-29, which recorded the pulse of LD radiation partially reflected from the substrate and the structure. This pulse triggered the oscilloscope sweep. The laser radiation of the structure was coupled out through both the second mirror and the sapphire substrate. The radiation from both sides was recorded by calibrated FEK-22. To cut the scattered pump radiation, we placed ZhS-17 filters with transmittances of 70% at $\lambda = 508$ nm and below 1% at $\lambda = 438$ nm in front of these photodetectors.

The near-field laser radiation was photographed from the side of the second mirror using a microobjective and a digital camera. The far-field radiation intensity distribution from the same side was studied using photographs of laser spots on a white paper sheet. The radiation spectrum was recorded with a fibre-coupled S-100 spectrometer (Solar Laser Systems)

3. Experimental results and discussion

Figure 2 shows the spectra of the microcavity structure.

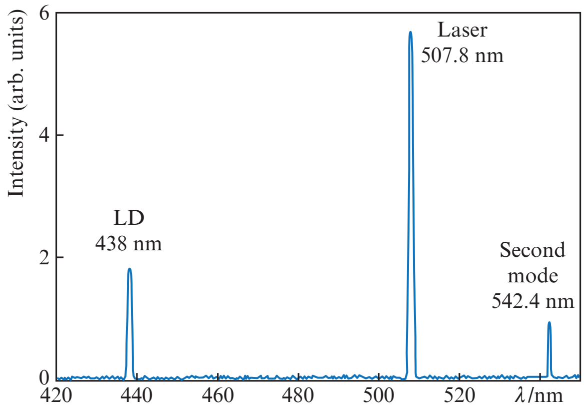

Figure 2. (Colour online) Emission spectra of the LD and the microcavity structure.

The laser diode emitted at $\lambda = 438$ nm. The fundamental radiation of the structure had the wavelength $\lambda = 507.8$ nm and a width of 1.2 nm at half maximum. The radiation spectrum also exhibits the second mode at $\lambda = 542.4$ nm. The spectrum slightly changes as the excited region shifts over the structure surface due to an inhomogeneity of the structure thickness, and the second mode is often not seen. The near- and far-field images of the structure radiation are presented in Fig. 3. The near-field image corresponds to the image of the LD emission region and has a length of about 150 μm. The width of this region is difficult to measure. It does not exceed 15 μm. The near-field pattern of laser radiation at a slight excess over the threshold consists of a line of bright points (Fig. 3a), which are mutually incoherent. Therefore, the radiation divergence is determined by the size of these points. The total radiation divergence angle was ~10°.

Figure 4 presents the oscillograms of pump and laser pulses. The laser pulse peak coincides with the maximum of the pump pulse. The complex shape of the pump LD pulse is caused by imperfection of the used driver. The microcavity

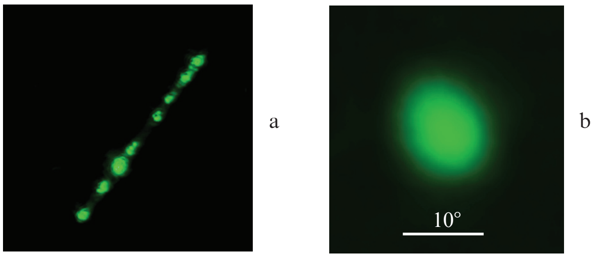

Figure 3. (Colour online) (a) Near- and (b) far-field patterns of laser radiation.

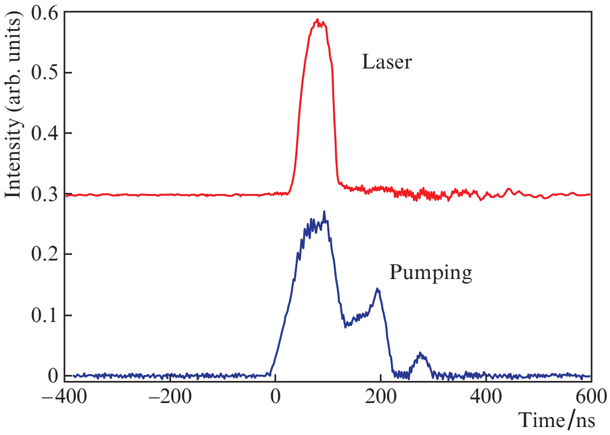

Figure 4. (Colour online) Oscillograms of the pump and laser pulses.

laser pulse width at half maximum was 65 ns. The measurements showed that the amplitude of the generated pulse coupled out through the sapphire substrate is threefold higher than the amplitude of the radiation pulse coupled out through the second mirror.

Figure 5 shows the dependence of the laser peak power on the pump peak power absorbed in the structure.

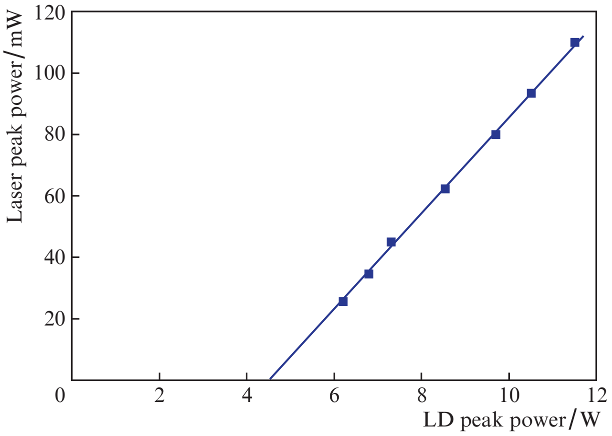

Figure 5. (Colour online) Dependence of the laser peak power on the pump peak power absorbed in the structure.

The maximum peak output power emitted in both directions is 110 mW. The threshold absorbed pump power is estimated as 4.5 W. A slight excess over the threshold is achieved. The slope efficiency is 1.6%.

The relatively low laser power and efficiency can be explained by several reasons. First of all, it is a mismatch between the microcavity mode and the gain line maximum. Due to the small thickness of the structure, the spectral distance between modes may exceed the gain line width. The structure period (distance between QWs) may not coincide with the period of the cavity mode nodes, which leads to a decrease in the mode gain. It is also necessary to decrease the internal losses in the structure and to optimise the reflection coefficients of mirrors. In addition, it is unclear how well nonequilibrium electrons are captured at high pump levels due to the appearance of barriers on heteroboundaries of the CdS layer as a result of band bending and how well nonequilibrium holes are captured due to the relatively low depth of QWs formed in ZnSe layers. All these questions require additional investigations.

Thus, in the present work, we have developed for the first time a semiconductor laser based on the CdS/ZnSe/ZnSSe nanoheterostructure with type-II band offsets, which emits in the green spectral range under longitudinal pumping by a blue (438 nm) InGaN LD. The obtained results give hope for developing a green SDL with optical LD pumping. The reasons for the insufficiently high laser characteristics require additional investigations.

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