Photoluminescence studies of optical properties of VECSEL active region under high excitation conditions

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Abstract. In this paper we demonstrate results of photoluminescence studies of the active region of vertical-external-cavity surface-emitting lasers. The investigated structure has been designed for lasing at 980 nm. The gain medium consists of six In_{0.18}Ga_{0.82}As quantum wells embedded in a microcavity enclosed from the substrate side by distributed Bragg reflectors formed by 27 pairs of GaAs/AlAs and from the surface side by a \( \lambda/2 \) thick AlGaAs window layer. The quantum well emission collected from the chip surface is modified by the resonance of this cavity. However, unequivocal information about optical properties of the active region can be provided by the photoluminescence signal measured from a cleaved edge of the epitaxial wafer. The density of excitation influences the spectral position of emission from the quantum wells forming the active region. On the basis of our studies of edge emitted PL signal we have determined the dependence between the intensity of the quantum well emission and the density of excitation power. The optimal excitation conditions of investigated structure have been also determined.

1. Introduction

Vertical-External-Cavity Surface-Emitting Lasers (VECSELs) [1] are the newest kind of surface-emitting semiconductor lasers (SELs). The VECSEL design is based upon the well-known VCSEL (vertical-cavity surface-emitting lasers) idea [2], in which a quantum well gain medium is embodied in a vertical cavity formed by a pair of distributed Bragg reflectors (DBRs) and an emission of radiation occurs vertically from the wafer surface. In VECSEL structure, the upper epitaxial mirror is replaced by an external output coupler which closes a laser cavity from the opposite side. An open resonator makes possible an efficient optical pumping of the laser chip and provides the direct access to the laser mode, enabling one to employ intra-cavity optical elements, e.g. filters for single-frequency operation, nonlinear crystals for intracavity frequency doubling or wavelength tuning, or saturable absorbers for passive mode locking. Thanks to the non-conventional geometry and several other unique features, VECSELs have a wide range of applications, especially in optical communication, data storage and laser printing. But the main advantage of VECSELs is that they enable high power single mode operation in large diameter devices with the ability to produce a circular, diffraction-limited beam.

Within VECSEL heterostructure, a Fabry-Perot microcavity is formed between DBR and the semiconductor-air interface and a standing wave pattern of the electric field exists inside the structure. To take the advantage of this the quantum wells forming the device active region have to be placed at the antinodes of the field pattern with the separation of \( \lambda_{\text{res}}/2 \), what is called the resonant periodic gain arrangement (RPG) [3]. The wavelength of the cavity resonance \( \lambda_{\text{cav}} \) should correspond with the
wavelength of the quantum well emission. In this way the field intensity at the QWs is enhanced by the factor $\Gamma_{RPG} = 2$, in comparison with the average intensity [4].

The advantages offered by optically pumped VECSELs can be fully explored only under high power pumping conditions, what is inevitably accompanied by both a band filling due to photogenerated carriers and a band shrinkage due to heating. A majority of the pump beam energy is dissipated within the chip as a heat, increasing its temperature. Both the cavity mode and the quantum well emission change their spectral position with the temperature, however each of them has a different thermal coefficient. Additionally, band filling and band shrinkage due to heating shift QW emission in opposite directions in a quite complicated manner. For the laser action it is necessary to have the QW emission properly aligned with the cavity resonance at the operating conditions, i.e. the threshold carrier density and the active region temperature. This requires an epitaxial fabrication of the heterostructure which is to a certain degree detuned at room temperature. PL spectroscopy allows determination of initial detuning of the above and provides an easy way to monitor the evaluation of the amount of detuning with the excitation intensity and the temperature.

On the basis of PL measurements we have analyzed the optical properties of the investigated heterostructure under high density of excitation and have determined the optimal operating conditions of the device. It should be noticed that direct examination of VECSEL active region on the basis of PL measurements, in which the signal is collected from the chip surface is impossible due to the fact that QW emission is modified by the resonance of the microcavity [5]. Only measurements of PL signal emitted directly from the VECSEL active region provide unequivocal information. It can be obtained by collecting the PL signal from a cleaved edge of the epitaxial wafer. In this paper we report the results of excitation dependent photoluminescence investigation of the VECSEL active region consisting of InGaAs/GaAs quantum wells.

2. Experiment

The investigated heterostructure consists of six 8 nm $\text{In}_{0.18}\text{Ga}_{0.82}\text{As}/\text{GaAs}$ quantum wells located in the adjacent antinodes of the internal microcavity resonant wave. This cavity is enclosed from the substrate side by 27 pairs of GaAs/AlAs layers of DBR and from the surface side by AlGaAs window layer. This $\lambda/2$ thick window layer suppresses the surface nonradiative recombination of the photo-carriers generated by the pump beam.

The experimental set-up is shown in details in figure 1. All PL measurements were performed in an environment corresponding to the designed working conditions of the device, i.e. at room temperature and without any temperature stabilisation. The 808 nm line of the Coherent Ti:Sapphire tunable laser was used as an excitation source and the laser beam was focused on the chip surface by the microscope objective to the spot about 10 µm in diameter. The power of the laser light was controlled by Coherent laser power meter during each measurement.

![Figure 1. Experimental setup used for excitation dependent photoluminescence measurements of VECSEL active region](image-url)
The PL signal was collected from the cleaved edge of the VECSEL epitaxial wafer by the objective mounted on the microtranslators allowing a precise calibration of the objective position with respect to the sample. The CCD monochromatic camera was used for monitoring the picture of the wafer edge. The PL signal was analyzed by the monochromator (Jobin-Yvon HR460 with 1200 l/mm grating) equipped with LN2 cooled multichannel silicon detector (Jobin-Yvon CCD3000 camera). All spectra were measured at the same experimental conditions, i.e. the same slit width and the time constant.

3. Results

Figure 2 shows the photoluminescence signals measured at various excitation power densities. For a relatively low density of excitation (89 W/cm²) the spectral position of the PL peak is at 956 nm (1.3 eV), corresponding to 1e-1hh transition in In₀.₁₈Ga₀.₈₂As/GaAs quantum wells at room temperature. Thus, such a low excitation power did not influence the temperature of the structure. The high-energy tail of the PL spectrum is due to transitions from higher energy levels in quantum wells.

At higher excitation power large value of photoexcited carriers is generated within the region absorbing the excitation radiation, i.e. QW barriers. These carriers then recombine in the QW region contributing to the total PL intensity, which rapidly increases. On the other hand, high excitation conditions cause the increase of the VECSEL chip temperature. The temperature induced band gap narrowing in the materials forming the active region results in the QW levels shift to the lower energies and reduction of the transition energies. The PL peak is therefore red-shifted. The PL spectrum observed at the highest density of excitation (2089 W/cm²) is dominated by the 1e-1hh transition at 973 nm (1.274 eV), however, due to band filling, the contribution of the higher energy transitions is larger in comparison with low excitation conditions.

Figure 2. The photoluminescence spectra measured at various excitation power densities. The inserted graphs show PL signals obtained at the lowest (89 W/cm²) and the highest (2089 W/cm²) density of excitation.
The numerical analysis of the all measured PL spectra allows us to determine the dependence of the QW emission features on the excitation power. Figure 3 shows the PL peak wavelength, PL intensity and the value of integrated PL as a function of excitation power density. The spectral position of the PL peak depends almost linearly on the excitation power in the considered range of its values and the changes in the PL signal intensity and the integrated PL have the nonlinear character. Additionally, above the excitation density of about 1.7 kW/cm² both intensities start to decrease. It is due to the fact that high power excitation conditions result in the lattice temperature increase, which causes intensification of nonradiative recombination of photoexcited carriers and consequently decrease of the quantum well photoluminescence.

4. Summary
We have used the excitation dependent photoluminescence measurements for the precise determination of VECSEL active region emission features. The PL signals were collected from the cleaved edge of the epitaxial wafer in order to avoid the influence of the microcavity resonance on the emission from the quantum wells. The intensity and the line shape of the PL signal were found to be very sensitive to the changes in excitation intensity. We have determined that in the investigated range of excitation power the spectral shift of the emission from the VECSEL active region is almost the linear function of the excitation power density. Additionally, we have noticed that large increment of the chip temperature can result in reduction of emission from the VECSEL active region and, as a consequence, decrease of the lasing efficiency. Therefore, both effects have to be taken into consideration when the VECSEL structure is designed.

Acknowledgments
This work was partially supported by the Polish Ministry of Science and Higher Education under grant N515 003 31/0302. Authors thank Agata Jasik from the Institute of Electron Technology in Warsaw, who crystallised the investigated structure and made it available to examination.

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