Vol. **114** (2008) *ACTA PHYSICA POLONICA A* No. 5

Proc. XXXVII International School of Semiconducting Compounds, Jaszowiec 2008

# Angular and Temperature Tuning of Emission from Vertical-External-Cavity Surface-Emitting Lasers (VECSELs)

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In this paper we demonstrate how the tuning of the VECSEL heterostructure can be precisely determined. Since the VECSEL active region is embodied in a microcavity, the photoluminescence signal collected from the chip surface is modified by the resonance of this cavity. The angle resolved photoluminescence measurements combined with the temperature tuning of the structure allowed us to precisely determine VECSEL emission features. The investigated structure consists of GaAs cavity with six InGaAs quantum wells and is designed for lasing at 980 nm.

PACS numbers: 42.55.Px, 85.35.Be, 78.67.De, 42.55.Sa, 42.55.Xi

## 1. Introduction

Vertical-external-cavity surface-emitting lasers (VECSELs) [1] are the newest kind of surface-emitting semiconductor devices. The VECSEL design is based on the well-known vertical-cavity surface-emitting laser (VCSEL) idea [2], where a quantum well gain medium is enclosed between two distributed Bragg reflectors (DBRs) which form a vertical cavity, 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 mirror which is used to form a laser cavity. Such an open resonator makes possible the efficient optical pumping of the laser chip and takes the direct access to the laser modes, 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 single mode operation in large diameter devices to join high power with the ability to produce a circular, diffraction-limited beam.

Within VECSEL heterostructure an additional microcavity is formed between the DBR and the semiconductor–air interface, thus a standing wave pattern of the electrical field exists inside the laser structure. To take the advantage of this, the specific quantum wells (QWs) of the active region have to be placed at the antinodes of the field pattern, which is called resonant periodic gain (RPG) arrangement [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 $\Gamma_{\text{RPG}} = 2$, in comparison with the average intensity [4].

The advantages offered by optically pumped VECSELs can be fully explored only under high power pumping conditions. An excess of the pump beam energy is dissipated within the chip as a heat, increasing its temperature, which is inevitably accompanied by changing the optical properties of the structure. Thus, for obtaining the laser action, the emission from the active region has to be properly aligned with the cavity resonance at operating conditions, i.e. at the threshold carrier density and at the increased active region temperature, both generated by the pump beam. It requires epitaxial fabrication of the heterostructure which is to a certain degree detuned at room 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. These thermal coefficients are reported in some papers [5, 6], however their values were determined by changing the temperature of the heat-sink, on which the laser chip has been mounted. In fact, the effects generated by the pump beam are more complicated and the thermal coefficients have to be determined in real operating conditions of the device. Photoluminescence (PL) spectroscopy provides an easy way to monitor the evaluation of the detuning degree with excitation intensity and the temperature. However, the active region of the VECSEL is embodied in a microcavity, so that the photoluminescence signal collected from the chip surface is modified by the resonance of this cavity [7]. Since the VECSEL internal cavity finesse is low, the cavity mode and the QW signals are comparable in spectral width and amplitude, thus a direct examination of quantum well emission is impossible. Emission properties of a microcavity structure strongly depends on the angle of observation [8], according to

$$\lambda_d = \frac{n}{l}\sqrt{n^2 - \sin^2\theta},$$

where $\theta$ is an angle of observation, $\lambda_d$ is a wavelength of the cavity mode, $l$ is the cavity width and $n$ is the refractive index of the cavity material. Combining the measurements that are dependent upon both the temperature and angle has allowed us to precisely determine the optical properties of the emission from the device active region.

## 2. Experiment

The investigated heterostructure consists of GaAs cavity with six InGaAs QWs located in the adjacent antinodes of the internal GaAs cavity resonant wave. This cavity is enclosed from the substrate side by DBR of 27 GaAs/AlAs pairs and from the surface side by AlGaAs window layer. This $\lambda/2$-thick window layer is to suppress the surface nonradiative recombination of the photocarriers generated by the pump beam. Designed detuning of the structure is about 20 nm at room temperature.

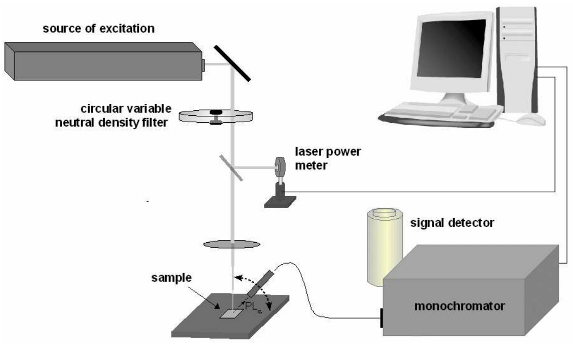


Fig. 1. Scheme of the experimental setup used in the angle resolved photoluminescence measurements. The inserted diagram presents the simple idea of angle resolved measurements of a microcavity.

The experimental setup is shown in detail in Fig. 1. All PL measurements were collected in an environment corresponding to the designed working conditions of the device, i.e. at room temperature and without any temperature stabilisation. The increase in the chip temperature was a direct result of high density of excitation. The 808 nm line of Coherent Ti:sapphire tunable laser was used as an excitation source and the laser beam was focused on the chip surface by the microscopic objective to the spot about 10 $\mu$m in diameter. The power of the laser light was controlled by Coherent laser power meter before each part of the measurements. PL signals were collected by the optical fibre mounted on the arm which was rotated around the investigated sample. The signal was driven to the slit of monochromator (Jobin-Yvon HR460 with 1200 l/mm grating) equipped with liquid-nitrogen cooled multichannel silicon detector (Jobin-Yvon CCD3000 camera). All spectra were measured at the same experimental parameters, i.e. the same width of slits and the time constant.

## 3. Results and discussion

Figure 2 shows a set of three experimentally obtained photoluminescence signal maps measured at various observation angles from 10° to 89°. In the first case the density of excitation power was relatively low (about 625 W/cm$^2$). The maximal enhancement of the emission was observed at the angle of 57° for the wavelength of 960 nm. It corresponds with room temperature PL emission from the quantum wells region. Low power excitation did not influence the temperature of the structure.

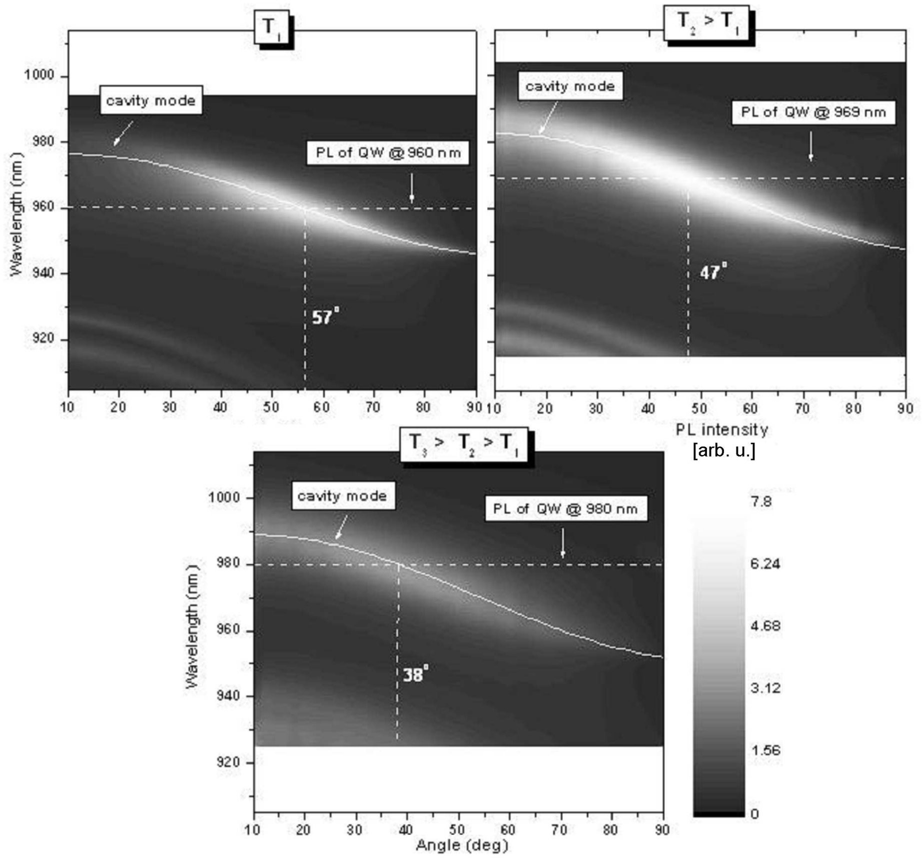


Fig. 2. The set of three maps of PL signals collected at the angles of observation from the range 10°–89°. Each map was obtained at different power of excitation beam.

In the second case (T2) the density of excitation power was about 1875 W/cm$^2$, which resulted in the increase in the chip temperature. Both the cavity mode and the peak of emission from the QWs were red-shifted in comparison with the first case. The spectral position of the cavity mode changed about 7 nm for small angles of observation, while the QW PL emission enhancement was observed at 969 nm, 9 nm more than previously. It indicates that the thermal coefficients of the cavity mode and QW emission spectral shift are different. Thus, increase in the chip temperature reduces the spectral separation between the QW emission and the cavity mode, which results in the decrease in the emission enhancement angle to 47°. In comparison with the first case the increase in the emission intensity was also observed.

In the last case the density of excitation power was increased to 3125 W/cm$^2$ which caused further rise of the sample temperature. Therefore, further spectral red-shift of both the cavity mode and the QW emission was observed. The spectral separation between them was about 10 nm for small observation angles, while in previous cases it had been 18 nm and 14 nm, respectively. The angle at which we observed the enhancement of PL emission was 38°, which is 9° less than previously. However, the intensity of the chip emission significantly decreased. High temperature of the structure resulted in intensification of nonradiative recombination of excited carriers and in a decrease in the quantum well photoluminescence.

Figure 3 summarizes the angular dependence of PL intensity for the wavelengths of emission enhancement. At the angles at which the structure is tuned (the spectral position of the cavity mode and the emission of QWs is the same) the emission intensity increases. In the last case (T3) the enhanced emission intensity is lower according to the previous ones.

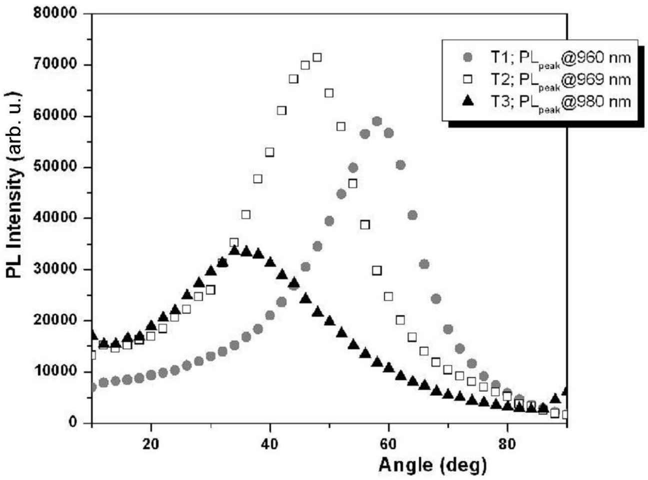


Fig. 3. The angular dependence of the PL signals intensity for the wavelengths of emission enhancement, at three chip temperatures (three values of the excitation power densities).

Analysis of the results obtained in this experiment allowed us to determine changes in spectral position of the cavity mode and the QWs emission caused by various excitation conditions (Fig. 4). It is seen clearly that the thermal coefficient of the cavity mode differs from the one of QW emission. At higher temperature the spectral separation between the cavity mode position and the maximum of active region emission is smaller and the detuning of the structure becomes lower. Thus, using only the temperature factor one can tune the structure to resonance.

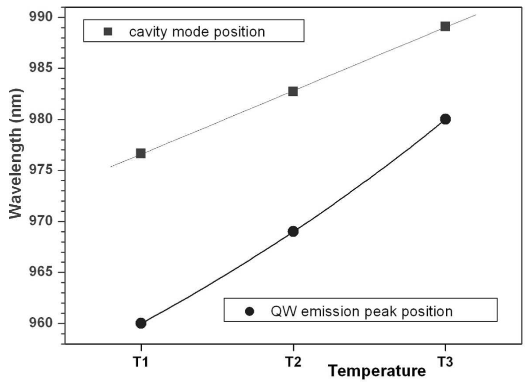


Fig. 4. The changes in the spectral position of the cavity mode (squares) and the peak of emission form QWs (circles), for three different operation temperatures.

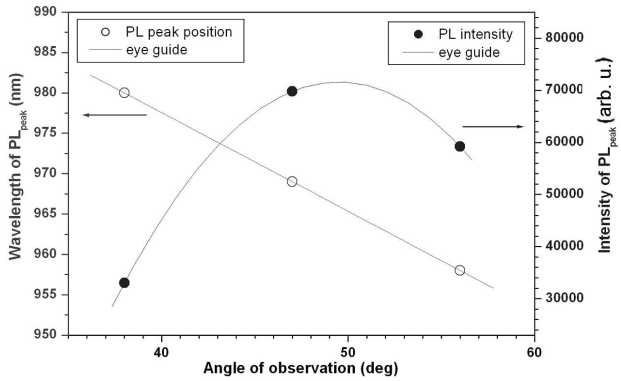


Fig. 5. The angular dependence of the spectral position (open circles) and the intensity of the emission from the VECSEL chip (black circles).

However, as it was mentioned above, the temperature increase causes reduction of the PL intensity. It was observed during this experiment that for the highest excitation density (corresponding with T3) the intensity of the PL signal decreases and is low even if the structure is in tune (Fig. 5).

## 4. Summary

We used the angle resolved photoluminescence measurements performed at various excitation conditions to precisely determine VECSEL emission features. Changing the angle of observation we can tune the structure to the resonance. Another tuning factor is the temperature of the chip. The difference in thermal coefficients of the cavity mode and the QW emission causes that for higher temperatures the detuning is lower and the enhancement of the emission can be obtained at lower angles of observation. However, the chip temperature rise results in a decrease in the photoluminescence intensity as well as the spontaneous emission of the device. It is particularly important to take into consideration these two effects in designing the VECSEL structures.

## Acknowledgments

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

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