Optica Applicata, Vol. XXXVII, No. 4, 2007

Optical characterisation of vertical-external-cavity surface-emitting lasers (VECSELs)

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The purpose of this paper is to outline the principles of optical characterisation of the new kind of semiconductor devices: vertical-external-cavity surface-emitting lasers (VECSELs). Realisation of high efficiency semiconductor devices requires high accuracy of epitaxial process. Gain characteristic of VECSEL structure is strongly affected by the precise placing of the quantum wells within the multilayer structure. Detailed optical characterisation of particular parts of the structure allows growth errors to be identified and gives insight into the lasing behaviour. In this work, we present an approach taking advantage of two spectroscopic techniques, photoluminescence and reflectance measurements, to study properties of VECSEL structure based on InGaAs/GaAs active region, designed for emission wavelength at 980 nm.

Keywords: vertical-external-cavity surface-emitting laser (VECSEL), DBR, quantum well, semiconductor laser, photoluminescence, reflectance.

1. Introduction

The vertical-cavity surface-emitting lasers (VCSELs) [1], thanks to their unique geometry and high quality of output beam, have wide range of applications, especially in optical communication, data storage and laser printing. In the simplest description, VCSEL structure is based on semiconductor multi-quantum well (MQW) active region bounded by two high reflectivity distributed Bragg mirrors (DBR), which form resonant cavity. Emission of radiation occurs vertically from the chip surface. However, the output power of single-mode VCSELs is limited to a few hundreds of miliwatts in TEM_{00} mode [2]. Further increasing of this value requires enlarging the active region, which leads to some disadvantages, such as problems with homogeneous pumping of the structure as well as multi-mode behaviour. To get around this, the external cavity can be used; the top Bragg mirror is replaced by external, partially transmitting spherical mirror. Such geometry allows for using optical pumping, which is an alternative to conventional, electrical pumping and ensures uniform distribution of pump power over the active region, especially in the case of high power operation. This leads to the idea of optically pumped semiconductor vertical-external-cavity surface-emitting lasers (VECSELs), which combine flexible spectral coverage and high output power with high quality, circular near-diffraction--limited output beam [3]. The architecture of such a laser provides direct access to laser modes and allows additional optical elements to be employed, *e.g.*, filters for single-frequency operation, nonlinear crystals for intracavity frequency doubling or wavelength tuning, or saturable absorbers for passive mode locking.

The absorption of excitation energy in the active region of VECSEL during optical pumping is estimated at several percent. To increase this value two methods can be applied. First of them is based on using special optics to realize multiple pump beam passing through the structure [4]. In the second method, the mode of sub-cavity formed inside the device by the active DBR and the semiconductor-air interface can be used to enhance the absorption. A standing wave pattern of the electrical field exists inside such a structure. To take advantage of this, the quantum wells have to be placed at the antinodes of this pattern with the separation of $\lambda_{\text{laser}}/2$, which is called resonant periodic gain (RPG) arrangement [5]. Thus the field intensity at the QWs is enhanced by the factor $\Gamma_{\text{RPG}} = 2$, in comparison with the average intensity. The influence of the internal cavity is expressed in additional intensity enhancement by the factor Γ_{cav} determined by the reflectance of the mirrors forming this cavity and the absorption within the cavity. The effective gain of the structure can be expressed as:

$$g_{\text{eff}}(\lambda, \alpha) = \Gamma_{\text{RPG}}(\lambda, \alpha)\, \Gamma_{\text{cav}}(\lambda, \alpha) g_0(\lambda)$$

where $g_0(\lambda)$ is the intrinsic gain of the QW without the cavity. It has to be stressed that the growth precision strongly affects the effective gain of the VECSEL. It puts the string demands on the epitaxial process, but we can test the wafer quality during particular stages of making device using some spectroscopic techniques. However, in the case of VECSEL structures the interpretation of measurement results requires different approach than in the case of conventional semiconductor lasers and is not trivial.

In this paper, we present the key principles of VECSEL optical characterisation. The information that can be extracted from reflectance (R) and photoluminescence (PL) measurements allows us to analyse VECSEL wafers and to identify growth errors. Additionally, due to non-destructive character of the above characterisation techniques epitaxial material, after measurements, can be used for further processing.

2. Optical characterisation

We have begun the investigation of VECSEL structure with testing two simpler kinds of the structure: the DBR active mirror, formed by 15 pairs of alternately arranged AlAs and GaAs layers and the structure containing device active region (formed by 6 comprehensively strained 8 nm-thick $In_{0.2}Ga_{0.8}As$ quantum wells separated by 131 nm-thick GaAs barriers).

Next, we have investigated complete VECSEL structure, consisting of the active region described above, enclosed between the AlAs/GaAs Bragg reflector (27 repeats) and the AlAs window layer, protected against the air oxidation by the GaAs cup layer. The epitaxial layers were undoped to minimise absorption losses. All the three structures have been grown by molecular beam epitaxy (MBE), on the GaAs substrate and GaAs buffer layer. The structure has been designed for the emission at 980 nm.

The Ti-Sapphire Coherent Innova solid state laser has been used as a source of photoluminescence excitation. The excitation wavelength 808 nm has been chosen because the VECSEL structure under investigation has been designed to be optically pumped by a semiconductor laser of that particular wavelength. The PL signal has been dispersed by a Jobin–Yvon HR460 spectrometer of 0.025 nm spatial resolution and detected by a Jobin–Yvon CCD3000 camera. The monochromatised light of a quartz-tungsten halogen lamp has been used for reflectance measurements. The radiation reflected from the sample has been focused on a Si-detector and the reflectance signal has been amplified using standard synchronous lock-in technique. For ensuring conditions similar to the device working conditions all optical measurements were performed at room temperature.

2.1. Characterisation of DBR structure

As has been pointed out above, the properties of the VECSEL active Bragg mirror strongly affect the effective gain of the structure. It is well known that the non-uniformity in the thickness of DBR layers causes modification of reflectivity spectrum. According to this and taking into account specificity of MBE growth process [6] we can expect that the changes in DBR reflectance spectrum will be radially distributed on the wafer.

An example of DBR reflectivity spectrum is shown in Fig. 1. Solid line represents experimental data and the open circles – results of simulation. In our case, the nominal layer thickness is 93.5 nm and 71.3 nm for GaAs and AlAs layers, respectively. For such thickness values the reflectivity spectrum should show stop-band plateau centred at 980 nm and about 100 nm wide. The spectrum shown in Fig. 1 is centred at 970 nm and is shifted to the shorter wavelengths compared to the spectral position designed. On the basis of the results of numerical simulation we have determined the values of the layer thickness at this measurement point as 82.10 nm and 68.74 nm for GaAs and AlAs layers, respectively.

In the case of test structures, such investigation allows us to identify growth errors and to correct growth process. On the other hand, the inhomogeneity of the DBR layer thickness makes a kind of post-growth selection possible for a structure with proper parameters. Especially, if we examine complete VECSEL structure, we can select those parts of the waver which meet design criteria best. For that purpose we need to

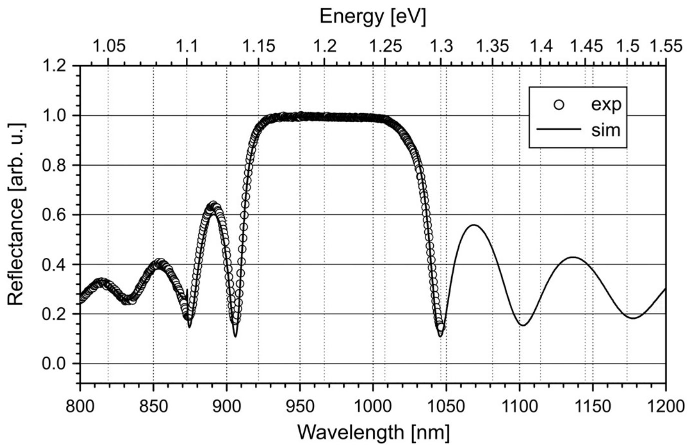

Fig. 1. Experimentally determined (dots) and calculated (solid line) reflectance spectrum of active DBR mirror.

determine stop-band dependence on the position on the wafer. The results of the DBR reflectance measurements along the radius of 2-inches wafer are shown in Fig. 2. In the middle of the wafer a characteristic stop-band of R spectrum is centred about 1065 nm and it shifts to the shorter wavelengths when we move the measurement point across the wafer, to its edges. The difference in the stop-band position between extreme measurement points is 106 nm, but the dependence is not linear. However, it can be

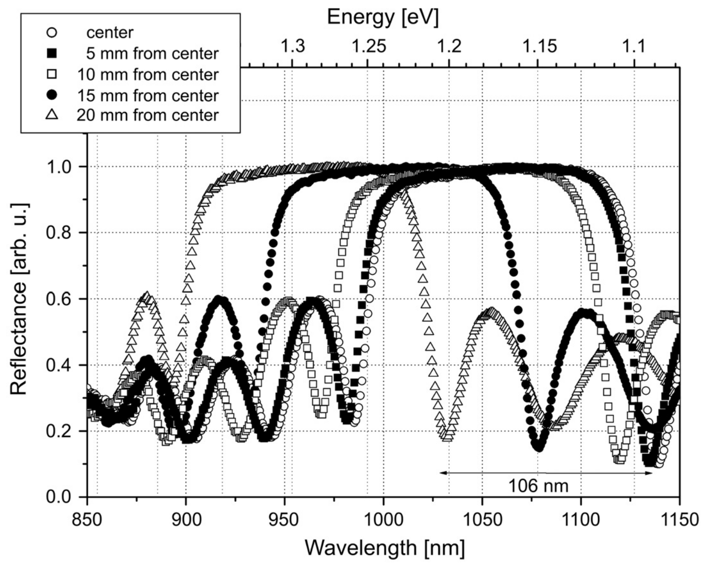

Fig. 2. Distribution of reflectivity spectra on the DBR sample. Particular symbols mark spectra taken at different measurement points along radius of the wafer.

easily estimated that the area meeting design criteria with satisfactory accuracy is between 15 and 20 mm from the centre of the wafer (about 5 to 10 mm from its edge).

2.2. Characterisation of active region

In the complete VECSEL structure the quantum well active region is placed inside sub-cavity formed by the DBR and the interface between the semiconductor and the air. Such geometry of the device causes modification of PL signal registered from the wafer surface; the emission from quantum well region is modulated by interference effects within the multilayer structure [3]. In order to obtain information about optical properties of the active region, before completing device preparation, we have studied the test structure consisting of quantum wells only; without DBR.

As with the DBR investigation, we have performed the PL measurement at various points across the wafer. The spectra collected this way are very similar, so, for clarity, we present only two extreme results, measured at the centre of the wafer and near its edge (Fig. 3). The strong PL peaks at about 990 nm correspond to electron–heavy hole (1e–1hh) recombination in quantum wells. On the basis of numerical calculations we have attributed the features marked in the figure at shorter wavelengths to the transitions with participation of light-holes and the transitions from higher energy levels in QWs.

Maximum of the emission from QWs is shifted to long wavelengths in comparison to designed 980 nm. Spectral position of the emission maximum from such a kind of active region depends on two factors: indium content in InGaAs layer and/or QW thickness resulting from the QW layer growth velocity. In the case of MBE grown structures these two factors are correlated and there is no possibility of stating without additional studies which of them had stronger influence on the energetic structure of

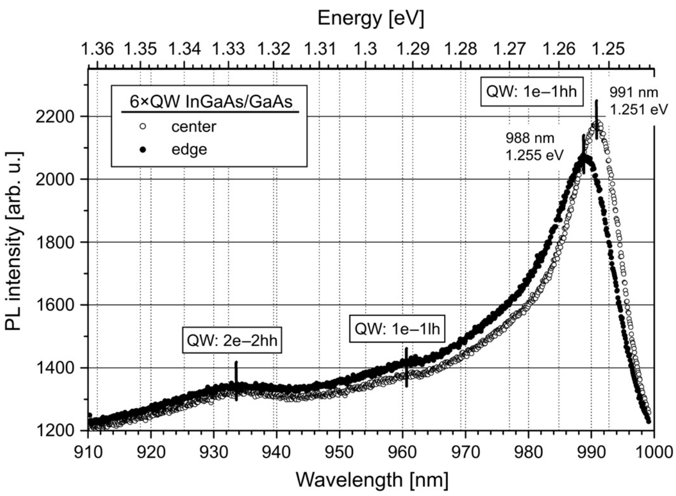

Fig. 3. PL spectrum of the structure containing 6 quantum wells forming the active region of VECSEL.

quantum well. However, the difference in the peak position of QW emission with respect to intended wavelength of the order of 10 nm is considered to be contained in the range of tolerance resulting from thermal tuning of the device. In our case, the above difference is 8 nm (10 meV) in the centre of the wafer and 11 nm (14 meV) near the edge.

Spectral shift between two extreme PL spectra measured at distant points of wafer is negligible, thus we can conclude that the changes in layer thickness do not influence emission properties of active region as strongly as the DBR optical properties.

2.3. Characterisation of final VECSEL structure

The photoluminescence spectrum of full VECSEL structure measured at the centre of the wafer and recorded perpendicularly to its surface is shown in Fig. 4. As has been mentioned earlier, in such geometry of measurement the observed PL signal is

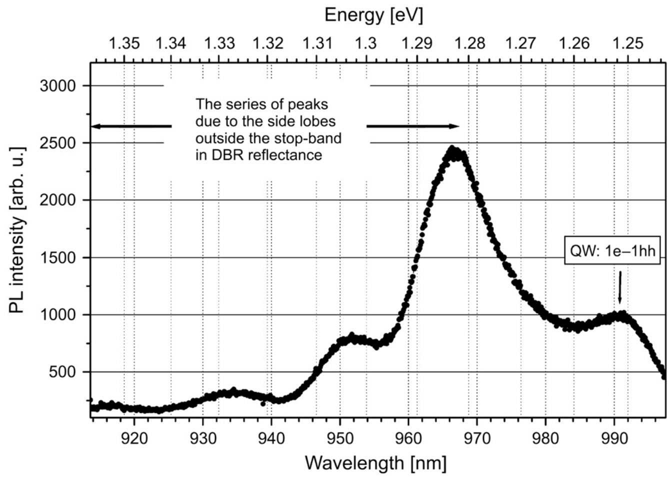

Fig. 4. Surface-emitted PL signal of final VECSEL structure.

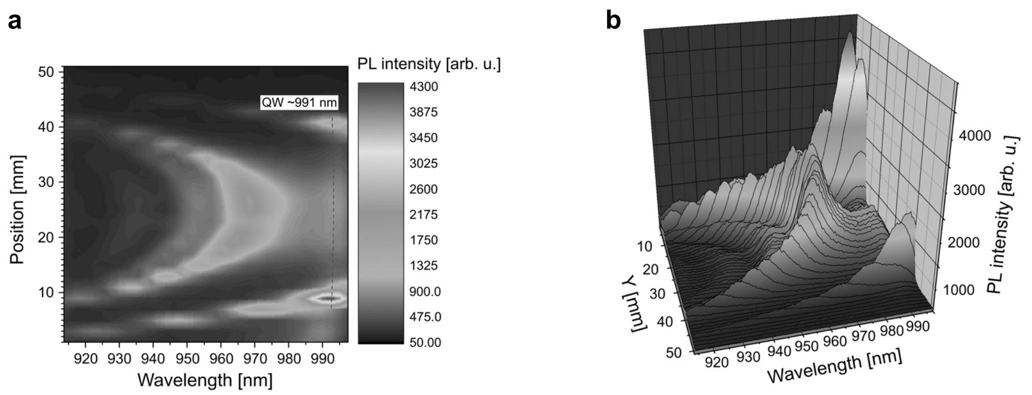

Fig. 5. Map (**a**) and 3D graph (**b**) of PL signal distribution along radius of the VECSEL wafer.

a function of the QW emission and the spectral filtering caused by the sub-cavity resonance. Additional studies should be performed in order to unequivocally clarify the origin of particular peaks in PL spectrum. One of the good ways is to analyse spatial distribution of PL spectra on the wafer. Results of such investigation along radius of the wafer are shown in Fig. 5. It can be noticed that the peak near 991 nm does not shift with the position, whereas the spectral position of peaks in short-wavelength parts of PL signal strongly depends on the measurement point. Taking into account the above dependence of DBR reflectance on the position on the wafer we can conclude that the series of peaks at shorter than $\lambda = 980$ nm wavelengths comes from the side lobes outside the stop-band in DBR reflectance spectrum. The peak at 991 nm corresponds to electron–heavy hole recombination in quantum wells, but its

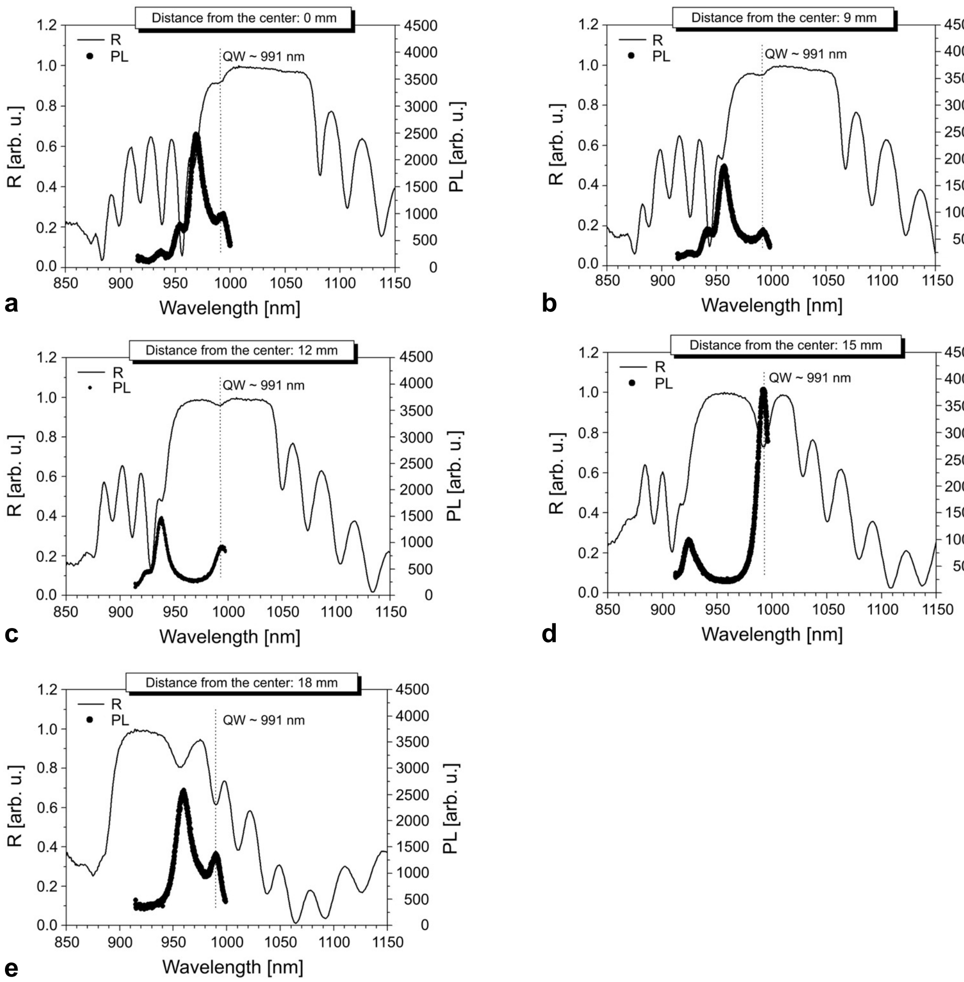

Fig. 6. Comparison of reflectance (left ordinate) and PL signal (right ordinate) of full VECSEL structure, measured at different points along the radius of the wafer.

profile is filtered by a sub-cavity resonance in the longitudinal confinement factor of the structure gain [3].

The photoluminescence and the reflectance data collected together at various points across the wafer are compared in Fig. 6. Such analysis allows one to determine the parts of the wafer where the emission from the structure is the strongest. The reflectance spectra show the break-in near 991 nm which exhibits no spectral shift over the whole area of the wafer. We have concluded that the dip in reflectance spectra in Figs. 6**a**–6**d** is rather due to the enhanced absorption on quantum wells than to the microcavity resonance. In our case, the sub-cavity is formed only by one DBR of high reflectivity ($R = 0.998$) and the semiconductor-air interface of low reflectivity ($R = 0.32$). The finesse of such cavity is $F = 2.45$. For such low finesse cavity the theoretically predicted dip depth in the reflectivity spectrum is $\sim 1\times 10^{-4}$ and it should not be observed. However, introducing even small absorption inside cavity, provided by the QW presence, causes the manifestation of resonant dip. Figure 6**d** presents the situation where the sub-cavity resonance wavelength overlaps the emission from active region. The intensity of the PL peak at 991 nm strongly increases due to enhanced quantum well absorption by resonant periodic gain arrangement of structure as well as coupling QW emission to the cavity mode and its resonance amplification. Figure 6**e** shows a dip which is not correlated with the main peak of emission from the active region. It originates from resonance of microcavity which occurs at shorter wavelengths than QW emission. It is enhanced by the absorption of the resonance radiation at the quantum wells.

3. Conclusions

In this paper, we present the approach to optical characterisation of VECSEL structures on particular stages of device realisation. Results of photoluminescence and reflectance investigations confirm that one of the major prerequisites to obtain high efficiency VECSEL device is proper tuning of the wavelength of radiation emitted from the active region, sub-cavity resonance and spectral position of stop-band in active mirror reflectance spectrum. We have found that even small non-uniformity in layer thickness of VECSEL structure strongly affects the optical properties of the device. Thus, growth process of surface-emitters which are perfectly tuned on the whole wafer area is very difficult and on-line spectroscopic diagnostics pays indispensable role in the device development.

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Received May 14, 2007
in revised form September 18, 2007