INVESTIGATION OF PHOTONIC CRYSTAL LIGHT EMITTING DIODE USING SPECTROSCOPIC ELLIPSOMETRY

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1. Introduction

Light extraction efficiency (LEE) is the limiting factor in achieving high optical power output from light emitting diodes (LED) because a high fraction of the generated light is back reflected by total internal reflection at the GaAs-air interface. Therefore, plenty of efforts try to improve LEE which has also a positive environmental impact because of saving electrical energy. In the last years, the LEE improvement is employing an approach based on periodic structures, called photonic crystals (PhC), or photonic bandgap (PBG) crystals [1] patterned in the surface of the structure [2-3]. The PhC patterning in the LED surface is a very promising method for improving LEE and other properties. This study is focused on the ellipsometric measurements of the $Al_{0.295}Ga_{0.705}As$/GaAs light emitting diode (LED) structure with two dimensional photonic crystal structures patterned into the surface was studied by variable angle spectroscopic ellipsometry. Ellipsometric measurements of LEDs with and without photonic structures were performed. The resulting peaks and dips in the ellipsometry spectrum show the influence of the photonic structures and their relation with TE and TM modes is documented.

2. Experiments

The investigated LED structure under inverstigation is the $Al_{0.295}Ga_{0.705}As$/GaAs based structure with an $Al_{0.295}Ga_{0.705}As$ active region consisting of three GaAs quantum wells. The structure arrangement with layers thicknesses is shown in Fig. 1. The central wavelength of this LED is 845 nm. A patterned two dimensional (2D) PhC with square symmetry and circular shaped air holes was prepared using interference lithography. The grating period Λ is approximately 500 nm. The etching depth was determined from morphology analysis using atomic force microscopy to be approximately 200 nm. The real lattice of investigated 2D PhC with square symmetry and its reciprocal lattice with corresponding Brillouin zone are shown in Fig. 2. Ellipsometric investigations were made in ΓM and ΓX direction of the Brillouin zone.

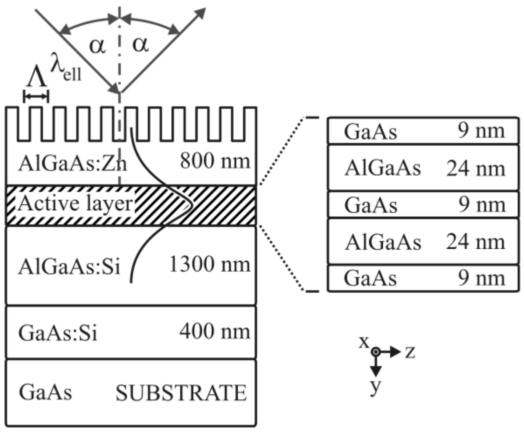

Fig. 1 Structure arrangement with layer thicknesses of the investigated 2D PhC LED structure and incident wave from ellipsometer with wavelength λ_{ell}.

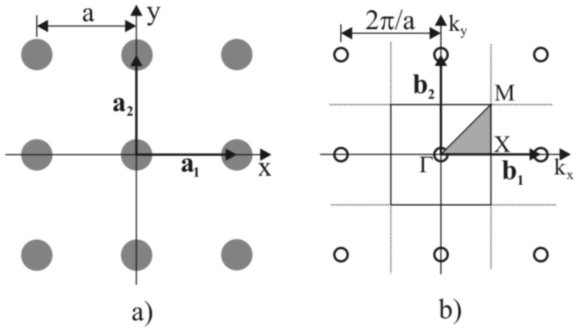

Fig. 2 a) Real lattice and b) reciprocal lattice with Brillouin zone of the 2D PhC with square symmetry. (after [11])

3. Results and discussion

The spectroscopic ellipsometry parameters can be used to characterize PBG structures because of the relationship between different polarization states. Ellipsometers in general can measure *tan(Ψ)* and *cos(Δ)* or *Ψ* and *Δ*, respectively. These parameters are defined as [4]

$$\tan(\psi)e^{j\delta} = \frac{E_{r,TM}/E_{i,TM}}{E_{r,TE}/E_{i,TE}} = \frac{\rho_{TM}}{\rho_{TE}}, \tag{1}$$

$$\tan(\psi) = \left|\frac{\rho_{TM}}{\rho_{TE}}\right|, \tag{2}$$

$$\cos(\delta) = real\left(\frac{\rho_{TM}/\rho_{TE}}{\left|\rho_{TM}/\rho_{TE}\right|}\right). \tag{3}$$

Ellipsometric parameters of the LED structure without PhC measured at three different angles of incidence α are shown in Fig. 3. There are peaks and dips in *tan(Ψ)* spectrum due to the interference bewteen particular layers of the multilayered structure. Ellipsometry measurements of the PhC LED in ΓX and ΓM directions are shown in Fig. 4 and Fig. 5 respectively. From these two figures it can be clearly seen that peaks and dips invoked by interference still remain but there are additional peaks and dips (labeled with black ellipses) which originate from different reflection coefficients of TE and TM modes for investigated PhC. This means, that the high reflection coefficient of TM modes in comparison to the TE modes reflection coefficient is responsible for peaks and high reflection coefficient of TE modes in comparison to the TM modes reflection coefficient is responsible for dips. This reflection difference is caused by bands in photonic band diagram of PhC for TE and TM modes according to Ref. [4]. Then, TE bandgaps would appear as a dip in the *tan(Ψ)* spectrum and TM bandgaps would lead to the peak value of *tan(Ψ)*.

But there is also another phenomenon which should be taken into account especially for structures like the investigated $Al_{0.295}Ga_{0.705}As$/GaAs multi-quantum well LED whose approximated refractive index [5-7] of active layer is higher than the refractive index of ambient layers. Such an active layer acts like a core of the planar waveguide with $Al_{0.295}Ga_{0.705}As$ layers as a cladding [7,8]. Thus PhC patterned in the LED surface acts like

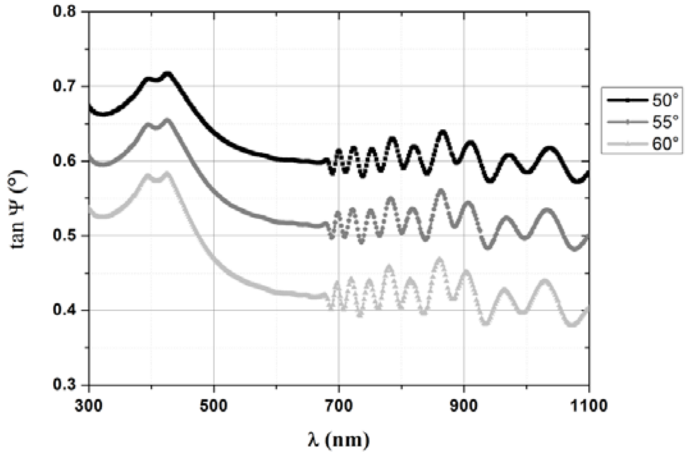

Fig 3 Ellipsometry parameter *tan(Ψ)* for LED without PhC for three different angles.

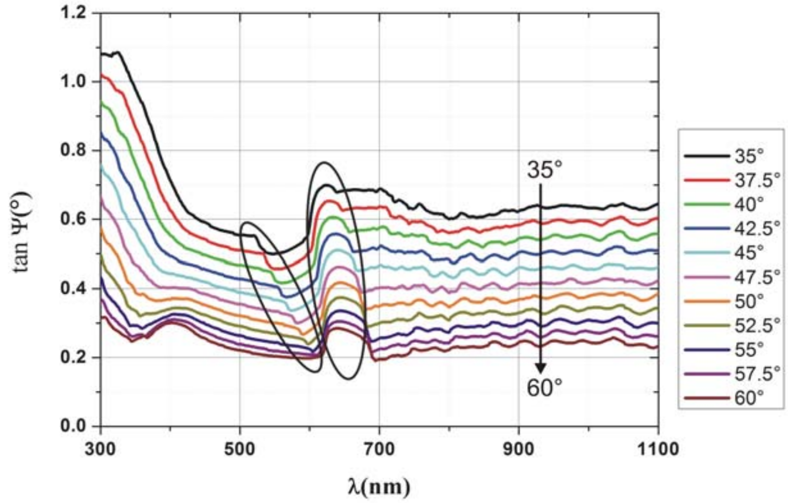

Fig 4 Ellipsometry parameter *tan(Ψ)* for PhC LED in ΓX direction for different angles.

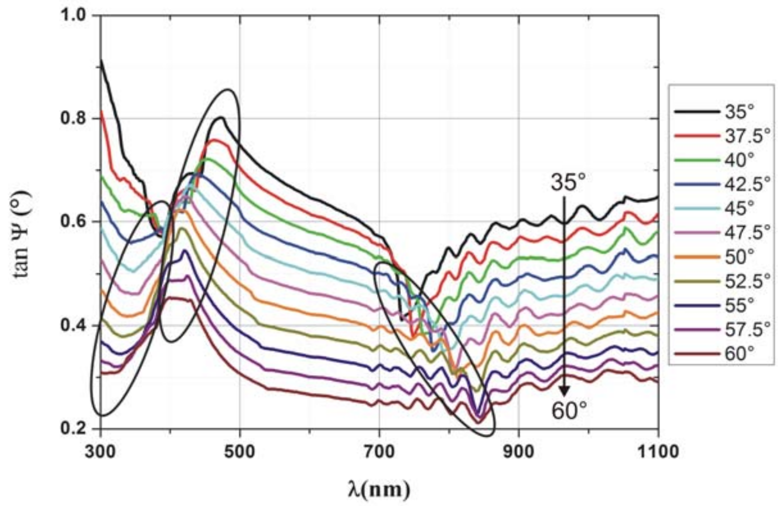

Fig. 5 Ellipsometry parameter *tan(Ψ)* for PhC LED in ΓM direction for different angles.

a coupling grating [9,10], which can couple incident light from ellipsometer to the waveguide consisting of layers of the LED structure. Because this waveguide has different coupling condition for TE (κ_{TE}) and TM (κ_{TM}) modes the *tan (Ψ)* spectrum should be related to the ratio of coupling coefficient for TE and TM modes as

$$\tan(\psi) = \left|\frac{\rho_{TM}}{\rho_{TE}}\right| \approx \left|\frac{\kappa_{TE}}{\kappa_{TM}}\right|. \quad (4)$$

4. Conclusion

Properties of PhC $Al_{0.295}Ga_{0.705}As/GaAs$ MQW LED structure were investigated by spectroscopic ellipsometry. Analysis of the *tan(Ψ)* spectrum showed that a PhC patterned surface strongly affects the polarization properties of the investigated sample. By comparison of structures with and without PhC it is possible to specify which peaks and dips in the spectra are invoked by PhC. These are caused by bands in photonic band diagram of PhC for TE and TM modes, what was confirmed from ΓX and ΓM directions measurements. Based on these results, forthcoming studies should reveal the relation of photonic band gaps and ellipsometric spectra. It was also shown, that individual layers of the investigated structure create a waveguide with the active layer as a core and thus PhC can couple modes to this waveguide which has also effects on the polarization behavior of the sample measured by ellipsometry and this effect should be taken into account in next exact ellipsometric analysis.

Acknowledgement

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