INVESTIGATIONS OF EFFECT OF THE ACTIVE REGION DESIGN ON EMISSION SPECTRA AND EFFICIENCY OF HETEROSTRUCTURES FOR MONOLITH MULTI-COLOR LEDS.

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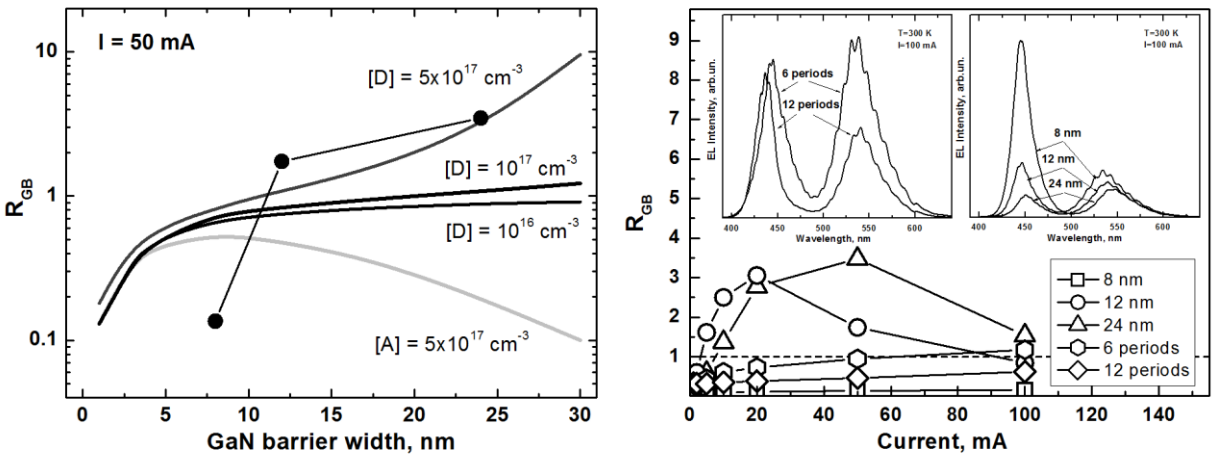
Progress in the development of light emitting diodes (LEDs) based on InAlGaN material system during last two decades has allowed to produce high-performance, high-efficiency long lifetime solid state white light sources. The traditional approach to obtain white LEDs is still based on partial conversion of emission of the blue (450 - 470 nm) LEDs based on *group III nitrides* to long wavelength emission by using of phosphors. Another approach of obtaining white light sources is based on RGB color mixing concept, because InAlGaN LEDs allow to obtain emission in the whole visible spectral range from blue to red.

The one of perspective approaches in frame of the the RGB concept is monolith LEDs, which active region contains a few InGaN quantum wells (QWs), emitting in the spectral range from blue to red. The main difficulties restricting the fabrication of these monolith LEDs are low emission efficiency of heterostructures with InGaN QWs having high indium content and emitting in green and yellow spectral ranges. The external quantum efficiency reduction of InGaN based LEDs emitting with emission wavelengths more than 530 nm is mainly due to build-in piezoelectric fields and generation of a defects caused by large lattice mismatch between GaN and InN. Another significant problem is to provide effective charge carrier injection in QWs with different indium content. Due to low hole mobility the radiative recombination in such MQWs active region occur mainly in one or two QWs adjacent to p-GaN region.

Epitaxial monolith LED structures were grown on (0001) sapphire substrates using AIX2000HT metalorganic vapor phase epitaxy system. The active regions of these LED heterostructures contain two ~3 nm-thick InGaN QWs, separated by ~10 nm-thick GaN barriers, emitting in blue (440-450 nm) spectral region ("blue" QWs) grown on 12-period InGaN/GaN short-period superlattice (SPSL), and one ~3 nm-thick InGaN QW, emitting in green (540-570 nm) spectral region ("green" QW). The details of the epitaxial growth procedures and the properties of the "blue" and "green" QWs, and InGaN/GaN short-period superlatticies (SPSL) have been described previously in [i],[ii] and [iii], respectively.

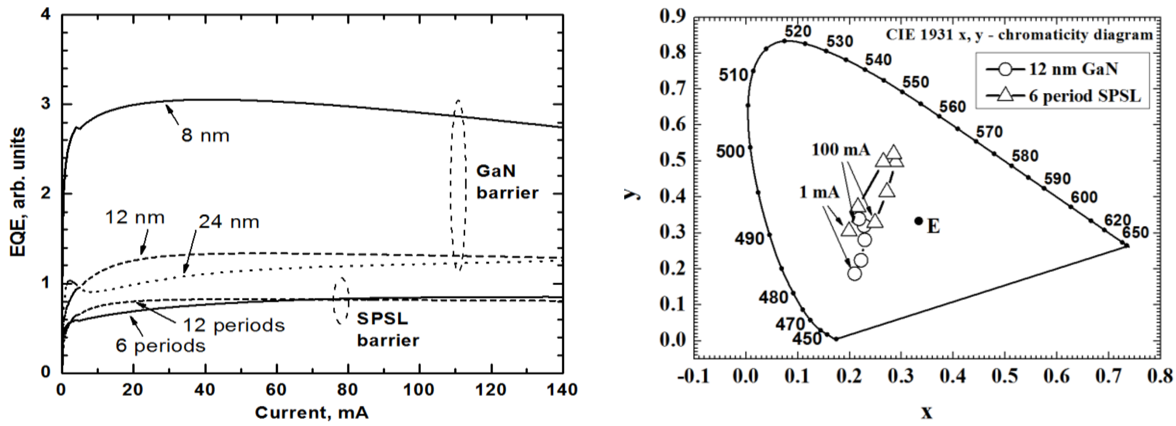
The evolutions of structural and optical properties of monolith LED heterostructures with different barriers between "blue" and "green" QWs were investigated. The first set of LEDs contain GaN barrier layer with thickness range from 8 to 24 nm. The second set of LEDs were grown with 6 and 12 period InGaN/GaN SPSLs as the barrier layer. The structural properties of active regions were investigated using high resolution transmission electron microscopy (HRTEM) technique. From the analysis of HRTEM images it was shown that the "blue" quantum wells have thickness varying from 0 to 3 nm with two-dimensional islands formed. The islands have a lateral size varying from 50 to 100 nm with indium composition of 18±5%. The "green" QW thickness is about 3 nm with indium composition of 30±4%. The overall InGaN SPLS thickness is about 27-28 nm with average indium composition of ~10-11%.

Ratios of "green" and "blue" electroluminescence peak intensities (R_{GB}) with different GaN barrier thickness and barrier doping type and levels were analysed using commercial software package SiLENSe [iv]. At small barrier thickness low than 10 nm, the R_{GB} is determined mainly by filling of "blue" and "green" quantum wells by nonequilibrium charge carriers and weakly dependent on barrier doping level (Fig. 1a). At GaN barrier thickness more than 10 nm, the R_{GB} is determined by charge carrier transport between quantum wells and strongly influenced by doping type and concentration (Fig. 1b). Electroluminescence investigations carried out on a wafer using indium contacts show that the decrease of GaN barrier thickness from 24 to 8 nm leads to increase of intensity ratios of blue and green emission lines R_{BG} of electroluminescence spectra (Fig. 1b). In case of barrier based on InGaN/GaN SPSL, the increase of a number of periods from 6 (12 nm) to 12 (24 nm) leads to increase "blue" emission line intensity with respect to "green" emission line intensity at large currents caused by charge carriers injection in active region.



a) b)

Figure 1. Calculated electroluminescence peak intensity ratios with different GaN barrier thickness and barrier doping (curves) and experimental data (solid circles). Donor and acceptor concentrations are shown (a). Current dependences of electroluminescence peak intensity ratios and electroluminescence spectra (on insert) for LED structures with two "blue" and one "green" InGaN QWs, separated by SPLS or GaN barriers (b).



a) b)

Figure 2. Current dependences of external quantum efficiency for LED structures with two "blue" and one "green" InGaN QWs, separated by SPLS or GaN barriers (a). CIE 1931 color diagram with color coordinates of emission of LED structures, which contain in active region two "blue" InGaN QWs and one "green" InGaN QW, separated by 3 nm-thick GaN barrier (squares) or 12-period InGaN/GaN SPSL (triangle) (b).

The LED structure with 8 nm-thick GaN barrier shows maximal external quantum efficiency caused by maximal intensity of predominated "blue" emission line (Fig. 2a). The electroluminescence spectra of the LED structures with 12 nm and 24 nm-thick GaN barriers shows approximately equal intensity of "blue" and "green" emission lines. The EQE of these LED structures are lower than for LED with 8 nm-thick GaN barrier. EQE of the LED structures with GaN barriers is 20-25% higher than that of the LED structures with SPSL barriers. The higher values of EQE might be related to lower indium content and lower density of defects in the active regions with GaN barriers. Investigated LED structures with barriers based on 6-period and 12-period InGaN/GaN SPSL demonstrate very close values of EQE. So increase of a number of periods from 6 to 12 in SPSL does not affect structural quality of the monolith LED active region.

Current dependence of the R_{GB} leads to current dependence of color characteristics give rise to control of color parameters of the white monolith LEDs emission (Fig. 2b). Color coordinates of the emission of the LED structure with 12 nm-thick 6-period InGaN SPSL barrier are shifted to green spectral region at low values of current and then shifted again to blue spectral region at high currents.

The LED structure with three InGaN QWs, separated by 8 nm-thick GaN barriers, was grown in order to increase color rendering index of emission of the monolith structures. Electroluminescence spectra of the LED has three peaks at ~430 nm, ~485 nm and ~550 nm with practically equal intensities *caused by* emission from InGaN QWs with different indium content. The equality of emission intensities indicate effective charge carriers injection in active region with three quantum wells in spite of lower efficiency compared with 2-QWs active region LED structure emitting at the same wavelengths (430-440 and 550-560 nm).

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[iv] http://www.str-soft.com/products/SiLENSe/.