Effect of ITO spreading layer on performance of blue light-emitting diodes

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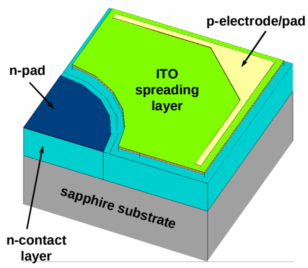
Motivation

- multi-functional ITO materials are used (i) as tunnel contacts to p-GaN, reducing contact resistance, (ii) to provide a better current density uniformity in the LED active region, and (iii) to avoid optical losses caused by emitted light reflection from low-reflective metallic electrodes (ohmic contacts)
- each of the functions utilizes different ITO properties, making non-trivial optimization of the materials parameters and overall chip design

this simulation study is aimed at finding correlations between the ITO properties and main LED characteristics

simulations carried out with SimuLED package: http://www.str-soft.com/products/SimuLED/

LED structure and chip design



300×300 μm^2 square-shaped LED die

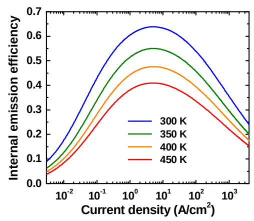
LED heterostructure:

- 3 μm n-GaN contact layer ($n=1\times10^{18}$ cm^{-3})
- MQW active region – four wells: 3 nm InGaN / 10 nm n-GaN ($n=5\times10^{16}$ cm^{-3}); emission wavelength of 450 nm
- 40 nm p-$Al_{0.2}Ga_{0.8}N$ electron blocking layer ([Mg]=1.5×10^{19} cm^{-3})
- 200 nm p-GaN contact layer ([Mg]=2.5×10^{19} cm^{-3})

ITO layer:

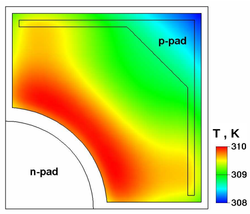
- electrical conductivity of 2000 S/cm
- thermal conductivity of 8 W/m·K
- refractive index $n_r = 2.02+0.01i$

Auger recombination is considered as the main non-thermal mechanism of internal quantum efficiency (IQE) droop at high current densities

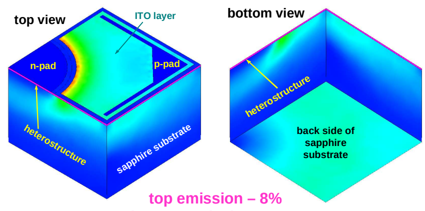


Factors affecting LED performance

I = 20 mA , d_{ITO} = 50 nm

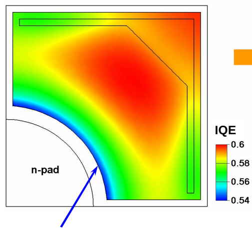


mean active region overheating is greater than temperature variation across the active region

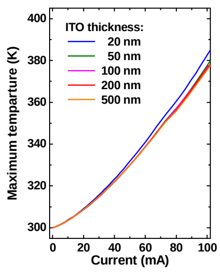


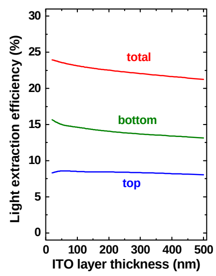
top emission – 8%
bottom emission – 15%
total emission – 23%

total light extraction efficiency (LEE) is ~1.5-2.0 times higher than LEE of similar LED with metallic electrodes

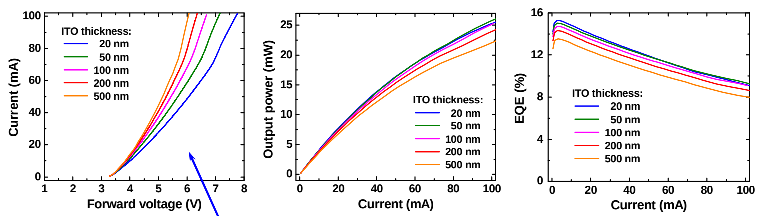


IQE reduction in the area of maximum current localization is primary caused by Auger recombination





Output LED characteristics



$$R_S \approx (L_{sp}/\sigma d_{n-GaN}\, p)^{-1}$$

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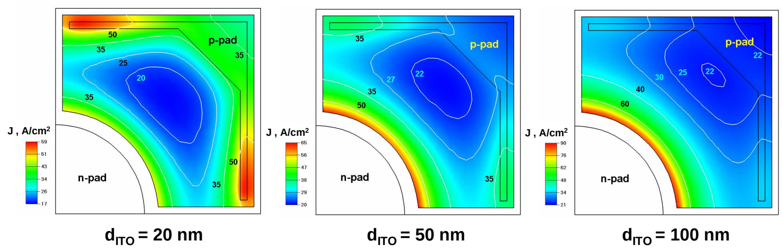
Current spreading in LED die at I = 20 mA



- current crowding occurs at the edge of p-electrode at a small ITO thickness, while the current concentrates at the edge of n-electrode at a large thickness
- a uniform distribution of the current density cannot be obtained by variation of the ITO layer thickness; moreover, the higher the ITO thickness (sheet electrical conductivity), the stronger is the current crowding

Conclusions

- optimization of light extraction and current spreading in LED die requires contradictory approaches: LEE grows but current crowding becomes stronger with the ITO thickness (or its electrical conductivity)
- increasing of ITO thickness improves the LED series resistance but does not provide a uniform current density distribution in the die
- control of intrinsic ITO properties, like electrical conductivity and electron concentration that determine the light absorption in the ITO film, is necessary to optimize the light extraction from LED die