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Requirements for white LEDs for future Solid State Lighting applications

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During the last decade solid state lighting (SSL) has entered nearly every area in our everyday life by opening new lighting applications in professional lighting domains as well as in our homes. The markets for application of semiconductor-based LED technology, in particular for automotive, industrial and SSL applications, has grown tremendously and will continue to grow mid and long term.

Key parameters for white LEDs: Efficacy and quality of light

Two key parameters need to be considered for most of the lighting applications: the efficacy (efficiency folded with the sensitivity of the human eye, measured in lm/W) and the color rendering index (CRI). The CRI is defined as quantitative measure of the ability of a light source to reproduce colors of various objects in comparison to an ideal reference source [1]. For a maximum CRI of 100, the colors of objects can be expected to be seen as they would appear under daylight spectrum. Therefore, different applications require different combinations of efficacy and CRI as depicted in Fig.1a. For example, for outdoor and industrial applications light efficacies of more than 140lm/W are necessary at relatively low CRI, whereas for shop and museum illumination vivid colors realizable with CRI higher than 90 at moderate efficacy will be employed.

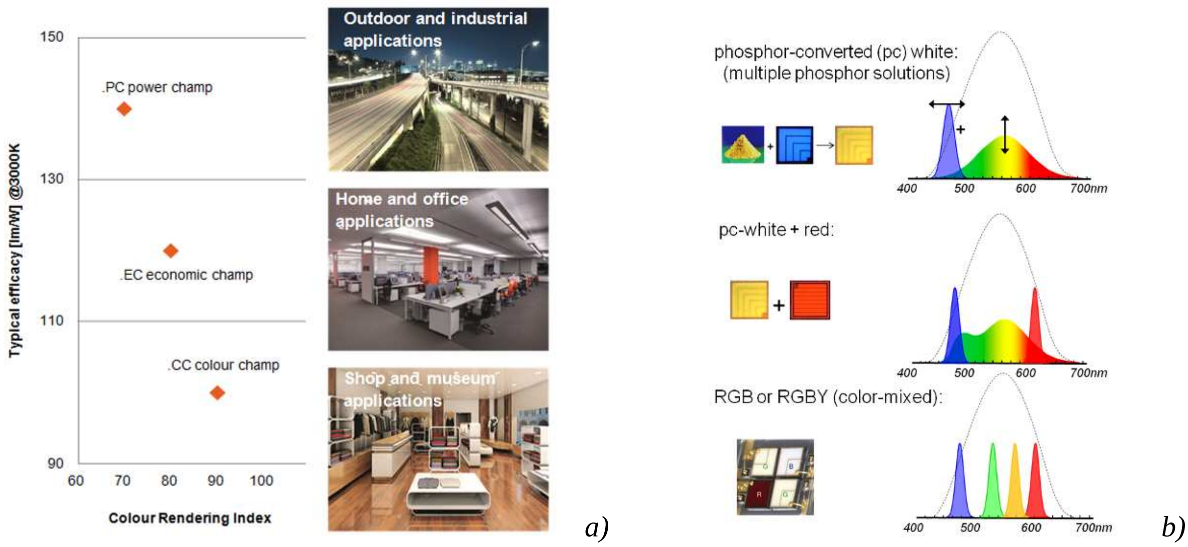

FIG. 1: a) For specific SSL applications, such as outdoor, home and/or shop illumination, typical efficacies in lm/W are plotted versus the typical CRI values. b) Description of white light generation by phosphor converted (pc) solution and by combination of LEDs emitting at different wavelengths.

The CRI can be adjusted by the correct combination of LEDs. For the generation of white light the main approaches are a) conversion of light emitted by a blue LED by at least one phosphor component, so called pc-conversion and b) the mixing of LED light emitting at various wavelengths, preferably red, blue and green, so-called RGB solution (Fig.1b). Especially, the second option requires high efficacies of each LED component.

Prerequisites for high-quality white LEDs: Highly efficient AlGaInP- and InGaN-based LEDs

With the increasing penetration of the general lighting market by semiconductor-based devices, the red LED necessary for the RGB solution (see Fig. 1b) experienced a renaissance. These red LEDs are based on the AlGaInP material system and grown lattice matched on GaAs substrates. Maximum luminous efficacies of 204lm/W at a current of 40mA and still 166lm/W at typical operating currents at a wavelength of ~610nm could be achieved [2] by

- Exact control of epitaxial growth parameters such as substrate misorientation, specific V/III ratios and correct doping profiles to avoid the formation of atomic ordering and reduce current leakage, respectively [3,4] and
- Perfect interplay between epitaxy, chip processing and design [2,4].

Nevertheless, the most important color in visible LEDs determining the efficacy is the blue LED chip. It is the major building block for both the PC as well as the RGB solution. Also here, the know-how in epitaxial processes, modeling and device design lead to control all aspects of external and internal quantum efficiency (EQE, IQE), such as injection efficiency and material quality in the low current range, and carrier density and transport control at high current densities. Despite tremendous progress concerning brightness and operation voltages - 235 lm/W at peak currents and 175 lm/W at operating currents were reported for white LEDs [5] - the physical understanding of some of the most fundamental properties of the (AlGaIn)N material system has remained rather limited. This is particularly true for the so-called efficiency ‘droop’, the decrease in generated photons per injected electron with rising operating current density (Fig.2). The internal losses caused by the ‘droop’ still account for more than 20% at typical operating currents. Therefore overcoming the ‘droop’ is the key for the improvement of white LEDs. Auger recombination and injection losses remain as the most likely root causes after years of intense research. [6,7]. Today, the effects of the droop are not solved but rather mitigated. The currently favored solution is the reduction of the carrier density by an improved carrier spreading among the active light generating volume (multi quantum wells or 3D nanostructures).

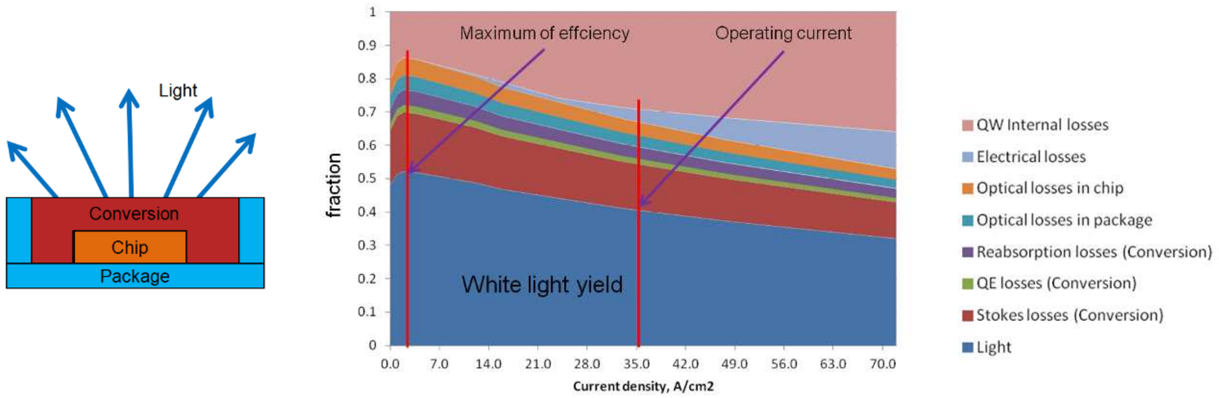

FIG. 2: Analysis of the efficiency of a white LED, where the main losses are found to be in epitaxy and conversion efficiency [8].

Thus, the detailed understanding of the InGaN quantum well growth is essential. To enable a better insight in the effects of the basic growth parameters on the material properties, thick InGaN layers have been analyzed. The identification of basic growth mechanisms will be applied for the improvement of LED epitaxy [9]. The application of slow growth rates result in smooth layers while higher growth rates induce a meandering surface morphology. Using low-temperature cathodoluminescence, a direct correlation of the morphology to local luminescence properties is obtained: the top of meandering structures reveals a spectrally red-shifted emission compared to the emission wavelength expected from the average indium content determined by X-ray diffraction (Fig.3). This shift can be explained by increased indium incorporation on top of the meander due to a spatially localized compositional pulling effect.

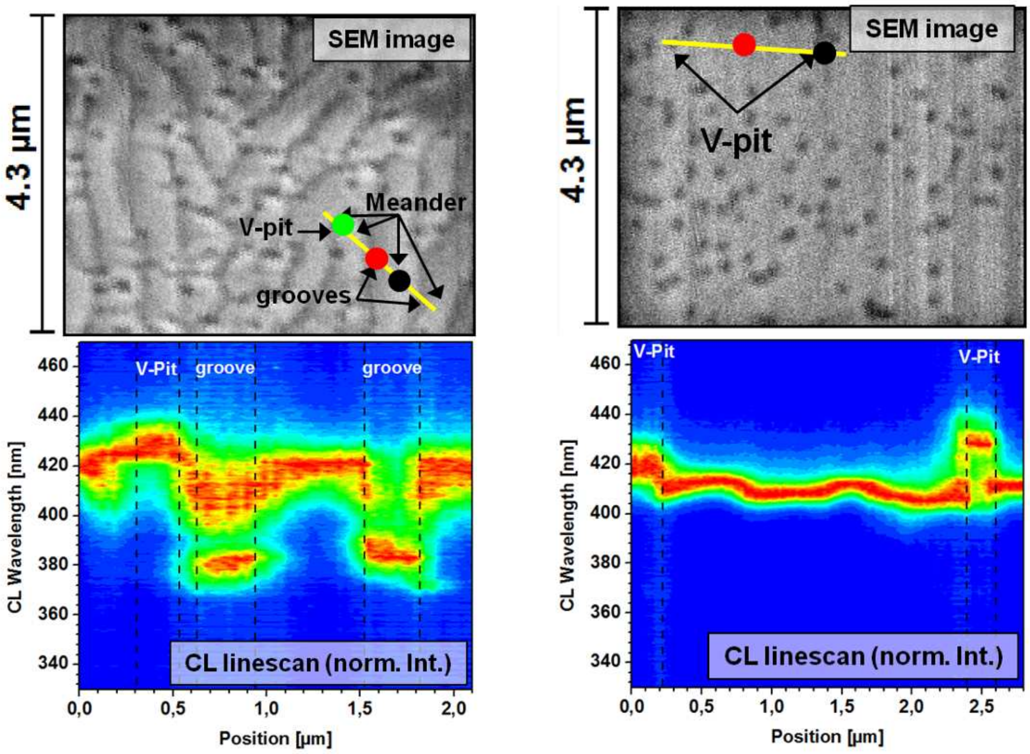

FIG. 3: The SE image (top) shows the spatial origin of the spectral line scan (dashed line) taken by cathodoluminescence (bottom) for the fast grown sample with growth rate of 433nm/h (left) and for the very slowly grown InGaN bulk layer by 133nm/h (right).

Not only the surface morphology and its impact on the luminescence behavior are important, but also the Indium concentration and the profile of InGaN quantum wells are prerequisites for transport calculations. At this conference a comprehensive simulation of growth conditions will be presented at the poster session. Indium composition profiles of InGaN QW grown at different growth conditions such as various temperatures and V/III ratios and derived by dark-field electron holography TEM are evaluated to validate a two dimensional reactor model [10].

Acknowledgements

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