Materials And Nano Optics For Solid-State Lighting

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With the dramatic performance increase of high-power light emitting diodes (LEDs) the door for general lighting application is open, as an expected fasted growth market segment for LEDs. In return also general illumination will be effected considerably by LEDs, which enable new lighting concepts driven by miniaturization, lifetime and sustainability.

The development of lighting technology was always driven by the improvement of the energy efficiency for generation of visible light. Since the human eye is most sensitive in a very narrow spectral range from about 430 to 650 nm the challenge is to transfer energy to electromagnetic radiation within that narrow region.
From a principle point of view semiconductor technology as employed in solid-state lighting devices (SSL) has the capability to release all energy from the recombination of electrons and holes, injected into a forward biased semiconductor p-n junction, as visible light within a narrow spectral range. However, even with 100 percent power-conversion efficiency, the so-called lumen-efficacy, in units of lumens (a factor of the eye response to different wavelength) per watt has to be compromised with the desired color rendering. For a reasonable color rendering (CRI) of 80, lamp efficacy is limited to about 300 to 400 lm/W. The target of a roadmap for SSL /1/ is to achieve 200 lm/W in 2020, i.e. a power conversion efficiency of 50% for a so-called lumen equivalent of 400 lm/W.

SSL technology is divided into inorganic light emitting diodes (LEDs) and organic light emitting diodes (OLEDs), relating to the materials employed for light generation. For both technologies highly efficient devices have been demonstrated producing light spanning the visible spectrum. Today inorganic LEDs are clearly ahead in lighting applications and will certainly never be surpassed by OLEDs in stability and achievable brightness. However, the demonstration of nearly 100 percent internal conversion efficiency /2/ and the potential for low cost production make also OLEDs attractive for SSL applications. October 1, 2004, 24 partners from 8 European countries started developments for breakthroughs in materials, deposition- and device technology in an Integrated Project, funded by the IST program of the European Commission’s 6th Framework to achieve a dominant position in OLED lighting /3/.

Next to all advantages of LED technologies, the generation of light within a solid with refractive index above 1 imposes a big challenge for extracting light efficiently into air. And realization of superior external efficiencies for both LEDs and OLEDs requires efficient light extraction mechanisms. The highest external quantum efficiency for a visible LED reported to date is 55% at 650 nm with a power conversion efficiency of 45 percent. The AlInGaP LED with these efficiency values was realized with a waver bonded GaP substrate formed to the shape of a truncated inverted pyramid, minimizing the number of reflections and absorption in the die /4/.
Gallium nitride (GaN) LEDs, which emit from the UV to the blue-green spectral region, today are the most promising solution for efficient SSL solutions. Here efficient light extraction has been demonstrated with a so-called flip-chip /5/ and surface roughened LED technology /6/. State of the art InGaN LEDs do have an estimated extraction efficiency of about 50 percent. Another potential solution for efficient light extraction are photonic crystals, which were studied intensively over many years. Photonic crystal structures close to the light generation layers in LEDs can be used in multiple ways: They can modify the spontaneous emission rate (i.e. alter internal quantum efficiency); prevent emission into (lost) guided modes; act as a diffraction grating to extract guided

light and, most important for étendue limited applications, increase the directionality of extracted light to increase LED radiance /7/.

Although technologies for realization of photonic crystals and nano-optics computation algorithms are well developed, gains realized in extraction efficiency for blue LEDs are in the order of 1.5-1.6 only. Research is going on to investigate the exact action of the photonic crystal and structures for modification of guided modes to maximize interaction with the optical structures further /8/.

Organic LEDs (OLEDs) are facing almost identical light extraction challenges, and also photonic crystal structures made with sub micron lithography have been realized. However, due to the large light emitting area involved, cost effective solutions for realization of optical structures in sub wavelength dimensions have to be developed /9/.

SSL white light can be generate by properly mixing LED devices emitting appropriate blue, green, yellow, amber and red light. A novel feature of these SSL lamps is a wide variability of colors. But also light mixing and color control are both major optical and electrical engineering tasks.

Another way to realize white light is the combination of a blue or UV emitting LED with a phosphor layer. The combination of a blue emitting LED and an yttrium aluminium garnet phosphor ($YAG:Ce^{3+}$) results in emission of white light if mixed properly. The success of this concept in combination with superior properties of blue emitting LEDs re-vitalized phosphor research into chemically stable and efficient phosphors converting blue light into green to red colors. Recently a new class of nitridosilicates and oxonitridosilicates activated with Eu^{2+} has been discovered with unprecedented thermally stable emission properties. White LEDs made with a combination of green and red emitting phosphors were realized with outstanding color rendering and spectral coverage, fully stable over the accessible temperature and drive current range of a 3 W LUXEON LED /9/.

References:

[1] J. Y. Tsao, Ed., Light Emitting Diodes (LEDs) for General Illumination Update 2002 (Optoelectronics Industry Development Association) (2002).
[2] C. Adachi, M. A. Baldo, M.E. Thompson, S. R. Forrest, J. Appl. Phys., 90, (2001) 5048.
[3] see www.olla-project.org.
[4] M. R. Krames et al., Appl. Phys. Lett. 75 (1995) 2365
[5] J. J. Wierer, D. A. Steigerwald, M. R. Krames, J. J. O'Shea, M. J. Ludowise, G. Christenson, Y.-C. Shen, C. Lowery, P. S. Martin, S.Subramanya W. Gotz, N. F. Gardner, R. S. Kern, S. A. Stockman, Appl. Phys. Lett. 78 (2001) 3379.
[6] T. Fujii, Y. Gao, R. Sharma, E. L. Hu, S. P. DenBaars, and S. Nakamura, Appl. Phys. Lett. 84 (2004) 855.
[7] J. J. Wierer, M. R. Krames, J. E. Epler, N. F. Gardner, M. G. Craford, Appl. Phys. Lett. 84 (2004) 3885.
[8] A. David, T. Fujii, R. Sharma, K. McGroddy, S. Nakamura, S. P. DenBaars, E. L. Hu, C. Weisbuch, H. Benisty, Appl. Phys. Lett. 88 (2006) 061124-1.
[9] H. Bechtel, W. Busselt, J. Opitz, Proceedings of SPIE 5519 (2004) 194.
[10] R. Mueller-Mach, G. Mueller, M.R. Krames, H.A. Höppe, F. Stadler, W. Schnick, T. Juestel, P. Schmidt, phys. stat. sol. (a) 202 (2005) 1727.