Substrate Conformal Imprint Lithography for nanophotonics in applications

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Nanoimprint lithography (NIL) is seen as a promising technology for the cost effective fabrication of sub-micron and nano-patterns on large areas. Real world conditions such as substrate bow and particle contaminants rule out the use of hard/rigid stamps over wafer scale areas. Hence soft- rubber-like stamp are required and previous soft-lithography methods could not achieve nm resolution and low pattern deformation to allow mix-and-match integrating with existing production. Furthermore, before industry will commit to a new production technology the value chain must be clearly defined with professional tooling, consumables and process development. Substrate Conformal Imprint Lithography (SCIL)[1] combines the low cost, flexibility and robustness of PDMS rubber working stamps, with the resolution and low pattern deformation of small rigid stamps. We will demonstrate that large area nano-pattens can deliver enhanced performance for LEDs, VCSEL lasers, thin film - and wafer based photo-voltaics.

Light sources based on reliable and energy-efficient light-emitting diodes (LEDs) are instrumental in the development of solid-state lighting (SSL). Modifying the emission profile of an LED from a Lambertian source to a collimated emission with increased brightness can open up new applications in etendue limited applications. This has to be accomplished for the pump LED by applying photonic crystal patterns[2] and on the phosphor level by using plasmonic coupled fluorescent emitters.[3]

For the blue pump light which is generated in high index GaN this can be accomplished by nano-structuring (photonic crystal) the GaN semi-conductor material. To achieve optimal mode overlap and thus light extraction, the crystal

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[1] Ph.D. Thesis Utrecht University, **2010**, Substrate Conformal Imprint Lithography for Nanophotonics, M.A. Antonius Verschuuren

[2] J.J. Wierer, A. David, and M.M. Megens, *III-nitride photonic-crystal light-emitting diodes with high extraction efficiency*, Nature Photonics **3**, 163 (2009)

[3] G. Lozano, D.J. Louwers, S.R.K. Rodríguez, S. Murai, O.T.A. Jansen, M.A. Verschuuren and J. Gómez Rivas, *Plasmonics for solid-state lighting: Enhanced excitation and directional emission of highly efficient light scources, Light Science and applications,* (2013) (accepted for publication)

has to be applied on pre-selected LEDs (emission wavelength, thickness) that match the photonic crystal lattice. We demonstrate that we can apply the nano-patterns on individual LEDs, which are already mounted on a sub-mount, which is possible due to the flexibility of our stamp. See Figure 1. Here, we demonstrate a very large improvement in phosphor emission (60-fold directional enhancement for unpolarized emission) using nanophotonic structures. (Fig. 2) This is attained by coupling emitters with quantum efficiencies (>80%) to collective plasmonic resonances in periodic arrays of aluminum nanoantennas. This opens new paths for fundamental and applied research in SSL in which plasmonic nanostructures are able to mold the spectral and angular distribution of the phosphor emission. The approach is general and we demonstrate this by efficient coupling for YAG:Ce, quantum dots and organic phosphors. This allows for optimal tuning of color point and matching the eye-sensitivity for ultimate efficiency.
Attention will be given to the boundary conditions for SCIL to be applied in terms of process flow, throughput, and cost of ownership.

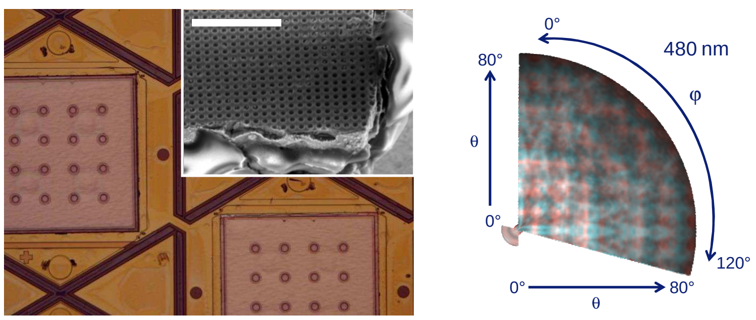

Figure 2: Patterning non-continuous substrates: Submount with separated 1mm^2 flip-chip LEDs, the inset shows a SEM image of an LED dye corner with the transferred hole pattern. Scale bar: 5μm.

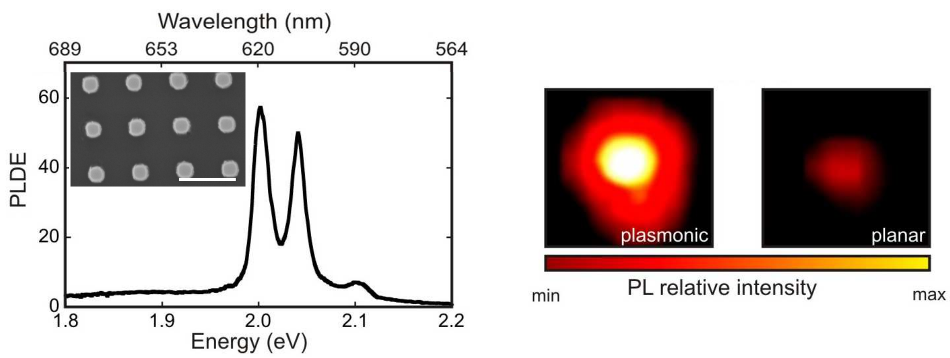

Figure 2: Plasmonic enhanced emission: Photoluminescence directional enhancement (PLDE) as a function of photon energy measured at θ_{in}=0 deg and θ_{em}=0 deg. The inset shows a SEM top view of aluminum particles arranged in an ordered periodic lattice. Scale bar indicates 500 nm. Right shows a digital camera image of the emission from a red dye applied on a plasmonic lattice and the same layer on glass as reference under equal pumping conditions.