Light extraction technologies for high efficiency GaInN-LED devices

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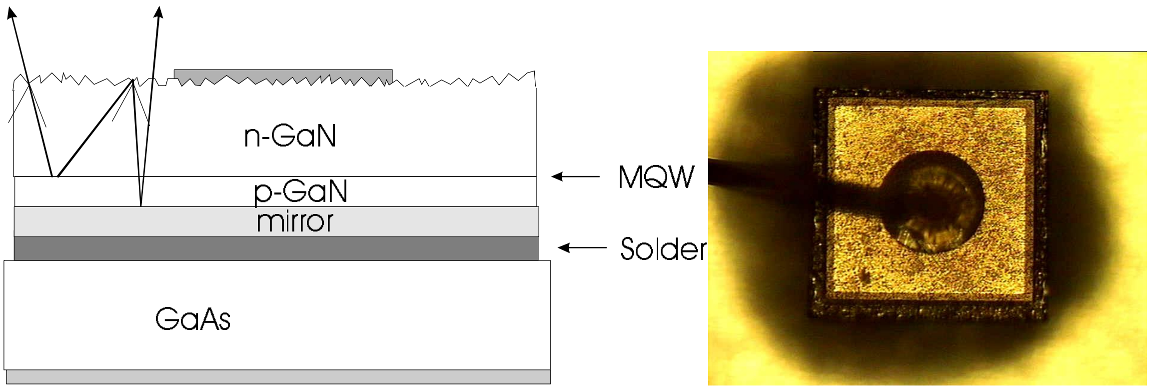
ABSTRACT

Data are presented for an GaInN based thinfilm LED. The LED is fabricated by transferring the epilayers with laser lift off from sapphire to a GaAs host substrate. In combination with efficient surface roughening and highly reflective p-mirror metallisation an extraction efficiency of 70% and wall plug efficiency of 24% at 460nm have been shown. The chips showed 12mW @ 20mA with an Voltage of 3.2V. The technology is scalable from small size LEDs to high current Chips and is being transferred to mass production.

Solid state lighting has seen a rapid development over the last decade. They compete and even outperform ligth sources like incandescent bulbs and halogen lamps. LEDs are used in applications where brightness, power consumption, reliability and costs are key parameters as automotive, mobile and display applications. In the future LEDs will also enter the market of general lighting. For all of these new applications highly efficient, scalable and cost efficient technologies are required.

Up to now there have been two main technologies used for the fabrication of GaInN based LEDs: On the one hand the widely used sapphire based technology. This technology allows the growth of high quality epilayers on a relative inexpensive substrate. As sapphire is non conductive, a horizontal device geometry with two top contacts has to be used. Sapphire is hard to dice and elaborate techniques for providing a homogenous current distribution at the pn junction have to be applied. These LEDs are top emitters and easy to mount. An inherent problem of GaN technology is the low conductivity of p-GaN, which allows light generation only under the p-metallisation. This characteristic demands semitransparent contacts for the standard design where 50% of the generated light is absorbed. The problem can be overcome by flip chip mounting of the LEDs **[1]**. In this case the light is extracted via the sapphire substrate without absorbing losses. The absorbing p-contact is replaced by a reflective contact. The light extraction can be doubled compared to the standard design. The technology allows also the realization of large area chips with special contact geometries. A major drawback of flipping sapphire devices is the expensive and technical demanding mounting. The light extraction out of the GaN into the sapphire substrate is also limited by the difference in the index of refraction (GaN=2.5; Sapphire=1.8)



(a) **(b)**

Figure 1 (a) A schematic cross section view of the InGaN thinfilm LED. The mirror acts also as p-contact (b) top view of the LED

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SiC based technology on the other hand provides a true vertical current structure. The propagation of light into the substrate is also more effective due to the high index of diffraction of SiC, which on the other hand makes the light extraction into the casting more difficult. This problem has been overcome by the ATON technology developed by OSRAM OS in the year 2000 **[2]** **[3]**. This chip shaping technology allows high extraction efficiencies (approx. 50%) and easy to handle mounting technolgy. The efficiency can be further improved by flipping the device and substituting the semitransparent top contact by an reflective contact. This flip chip is scalable, allows as well a small chip size (200µm) as high current chips (1000µm) with a light flux of up to 150 mW at a current of 350 mA **[4]**. However, the substrate is costly and the minimum operation voltage is limited by the series resistance of the substrate.

An alternative approach to enhance light outcoupling efficiency is to apply thinfilm technology to GaInN. This approach has been proposed by Yablonovitch et al **[5]** and is a well estabilshed technology for high efficiency LEDs for the arsenide and phosphide based material systems**[6]**. The technology has already been commercialized by OSRAM OS for the AlInGaP material system**[7]**.

In this approach the extraction probability of photons is increased by giving the photons multiple opportunities to find the esacape cone out of the semiconductor. This means photons which have directions out of the extraction cone have to be redirected back into the extraction cone. A method of choice is to generate chaotic trajectories which lead to an ergodic distribution of light. This assures the maximum statistically feasible output coupling from the LED through the extraction cone.

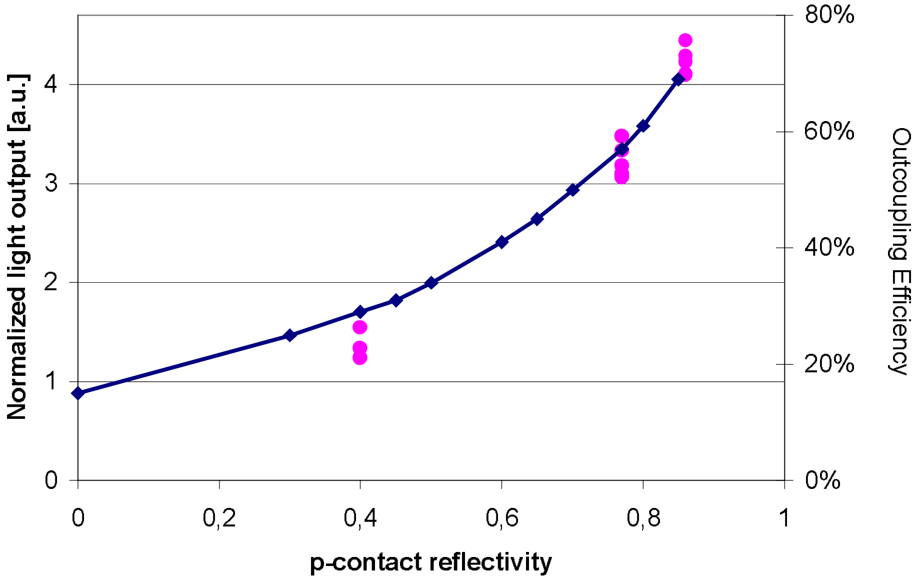


Figure 2 Calculated outcoupling efficiencies as function of p-contact reflectivity according to eq. (1) and (2). The calculated data are compared to normalized experimental data. The data were normalized using standard processed LEDs for estimation of the internal quantum efficiency.

For a simple model of such a LED we consider photon trajectories which are completely randomized with respect to internal angles in the semiconductor **[5**]. This means in steady state that the external efficiency is given by the ratio of the emission into the extraction cone to the total emission.

The photon loss rate through the top surface (=light extraction) is given by:

$$\int_0^{\theta_C}\int dAB_{Int}T(\theta)\cos\theta 2\pi\sin\theta d\theta = \frac{\pi B_{\text{int}}A\overline{T}}{n^2} \qquad (1)$$

where B_{Int} is the internal brightness in photons/cm^2/s/sr. θ is the polar angle, A is the surface area, θ_c is the critical angle given by $\sin\theta_C = 1/n$ and $\overline{T}$ is the angle averaged transmission coefficient through the top semiconductor surface.

The loss rate due to absorbtion at a mirror opposite to the emitting chip surface is given by :

$$\int\int_0^{\pi/2} dAB_{Int}R(\theta)\cos\theta 2\pi\sin\theta d\theta = \pi B_{Int}A\overline{R} \qquad (2)$$

Where $\overline{R}$ is the angle averaged reflectivity.

The technology has not been applied to nitride based LEDs, as most of the "musts" for the fabriaction of thinfilm LEDs demand new technological approaches:

- The performance is mainly limited by the reflectivity of the p-mirror metalisation. Fig.2 shows the calculated extraction efficiency as a function of p-mirror reflectivity according to equation (1) and (2). High performance can be only obtained with high reflectivities. The only metals which show good reflectivity in the blue spectral range are aluminum and silver. But these materials form only very poor electrical contacts on p-GaN. On the other hand metals which give good p-contacts as Pt, Ni or Au show only very poor reflectivities of 50% or less.

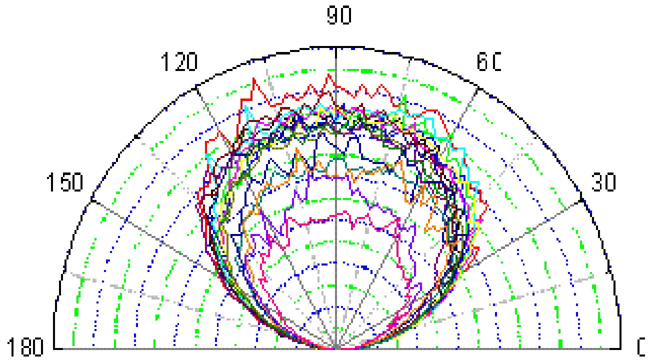
- Special care has to be taken for a surface structuring, which allows efficient redistribution of the reflected light at the emitting surface. As GaN is very resistive to etchants and also hard to dry etch, technologies as natural lithography **[8**] can not be used.

- For getting optimum light extraction and minimum absorbtion losses, the complete structure has to be thin. For conventional systems this can be achieved by removing the substrate using epitaxial lift off **[5**]. This technology can not be used for GaN based devices as the commonly used substrates SiC and sapphire are chemical resistive and also very difficult to machine mechanically. An approach is to use laser lift off, where a sacrificial layer of GaN at the GaN Sapphire interface is thermally decomposed with an UV laser**[9**]**[10**]. With this technology up to now only some square centimeters of GaN epilayer or single chips have been transferred without microcracks. For industrial applications lift off technolgies have to operate on wafer level.

All lift off technologies demand a mechanical support. The contacts have to be solderable and compatible with the lift off technology.

In the present work, these issues have been overcome. Here, we demonstrate for the first time high efficiency thinfilm devices based on GaInN. The design is beyond a simple vertical sapphire LED structure as shown by **[9**, as special care has been attributed to high extraction efficiency with mirror design and special surface texturing.

Fig. 1(b) shows a top view and Fig.1(a) a schematic cross section of the device. The processing is performed by first growing a GaInN multiple quantumwell structure on sapphire by MOVPE. A reflective Ag based p-contact is deposited on top of the GaN:Mg area and structured by photolithography. Then mesas are etched through the complete epi-structure defining a chip size of 290µmx290µm. The LEDs are subsequently bonded with eutectic AuSn bonding to a standard GaAs submount. Then the GaN is illuminated through the transparent substrate with a pulsed UV laser causing a decomposition of the GaN adjacent to the substrate as described by Kelly et. al **[10]**. By adjusting the laser parameters we can transfer reproducibly complete epi layers on wafer scale to the submount. The surface is defined by a patent pending surface process. The processing ends with the deposition of a standard TiAl n-contact on the laser etched surface.



(a)

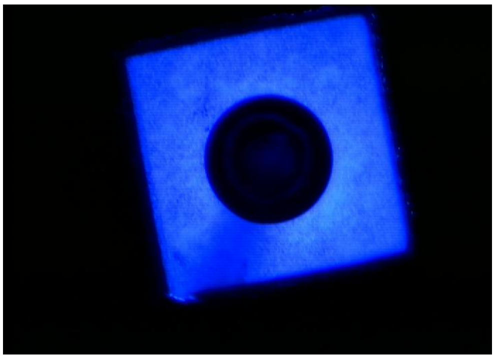

(b)

Figure 3 (a) The farfield shows a Lambertian emission. (b) The nearfield shows homogenous emission of the InGaN Thinfilm LED

There are many advantages of the thinfilm design for GaInN based LEDs. The light leaves the chip solely through the roughened chip surface. Therefore no losses in absorbing Ni/Au or Pt contacts as in standard sapphire and SiC based LEDs can occur. The thick metallisation of the p-mirror contact also allows a very efficient current distribution, with no ohmic losses in the p-contact metallisation. As the light is emitted through the randomizing surface, the LED emits in a true Lambertian pattern in contrast to SiC based LEDs. This emision pattern is favorable for casting and allows also a scalable chip design. First tests showed scalability for chip sizes between 150µm and 1000µm without scaling losses. The chips can be small compared to standard flip chip design, as a vertical structure is used and only one bondpad at a side is required. The horizontal configuration allows also easy mounting in standard packages with only one wirebond required or without technical demanding flip chip mounting.

The chip can be well described with the model according to equation (1-2). Fig. 2 shows the good coincidence of the experimental data and the model by varying the p-contact reflectivity.
The electrooptical parameters of the chips are shown in Fig.4. Maximum output of 11.2mW at 450 nm emission wavelength has been shown up to now. By processing epi wafers as standard sapphire wafers and thinfilm LEDs, we oberserved an enhancement of 260% of the optical output compared to standard LEDs. Raytracing analysis and calculations according to equ (1)+(2) showed extraction efficiencies of at least 70%. The LEDs are therefore even more efficient than sapphire based Flipchip LEDs and allow easier process in chip structuring as well as packaging.

The operation voltage of the LED is as low as 3.2V at 20mA. This can be mainly attributed to the use of thick metall layers for the p-contact, as no semitransparent contact are needed in the design. In the vertical design of the thinfilm LED there is also no need for current spreading layers to reach homogenous ligth generation.
The chips showed a wallplug efficienciy of 24% at 450nm. Standard degradation tests showed also high stability of the design.

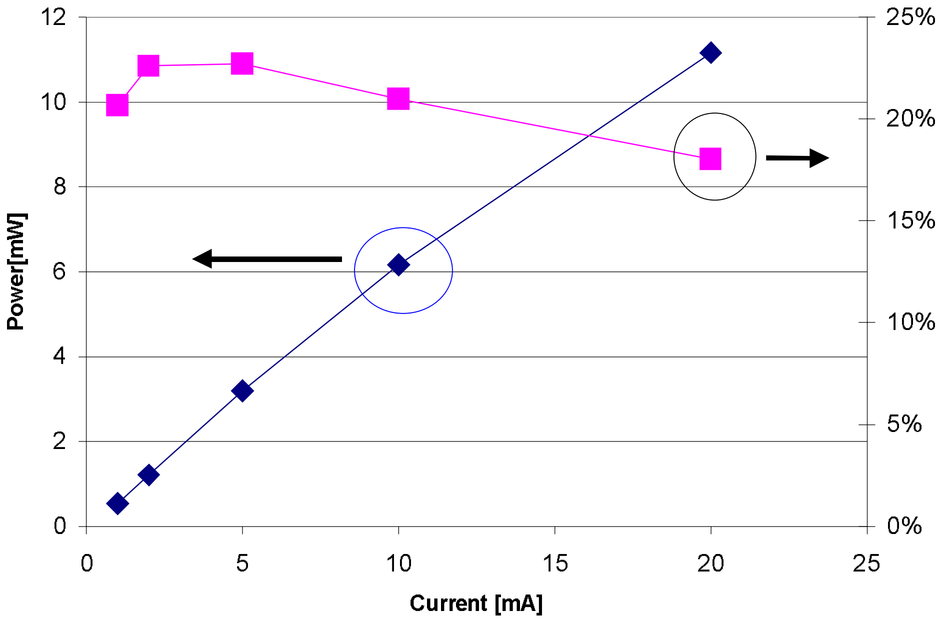


Figure 4 Measured total light output and wallplug efficiciency vs injection current of a 290µmx290µm device.

Summary

We have demonstrated the fabrication of GaInN based thinfilm LEDs on a full 2 inch wafer level. Their extraction efficiency is higher by a factor of 2.6 compared to standard top emitting AlGaInN LEDs. The technology is scalable and shows advantages in mounting as it offers a true vertical structure. The wallplug efficiency could be further enhanced by lowering the operation voltage to best values below 3.0V.

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