GaN-Based Devices – A Challenge in Semiconductor Lighting

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The rapid development of GaN-based devices since 1993 initiated a numerous amount of new, innovative applications in semiconductor lighting. In 1996 the estimated annual growth rate was about 30%. In reality the market growth rate almost tripled to about 80% for the time period from 1995 to 1999. The major markets were full color displays and automotive, mainly using green and blue LEDs. In future an even more interesting market for GaInN-LEDs will develop, the application of LEDs in general lighting. In 1999 this market had a share of only 0.5%. The general lighting market will be based mainly on white LEDs, using both three chip solutions (RGB) and single chip solutions in combination with luminous converters. The solution of choice will be defined by application, focusing on cost and performance as discussed in this paper.

1. Market Development

1.1 General GaN-Market

First light emitting devices based on GaN were presented in 1993, immediately entering the market. At that time, the market for GaN-based devices was almost zero, and production was driven by estimated market potentials. First market reports were published in 1995/1996, indicating an annual growth potential of approximately 30%, starting at 30 Million US$ in 1995 and reaching 150-200 Million in 1999. One of the early starters was OSRAM Opto Semiconductors (former Siemens HL) strongly developing the automotive market for blue/green GaN-based LEDs.

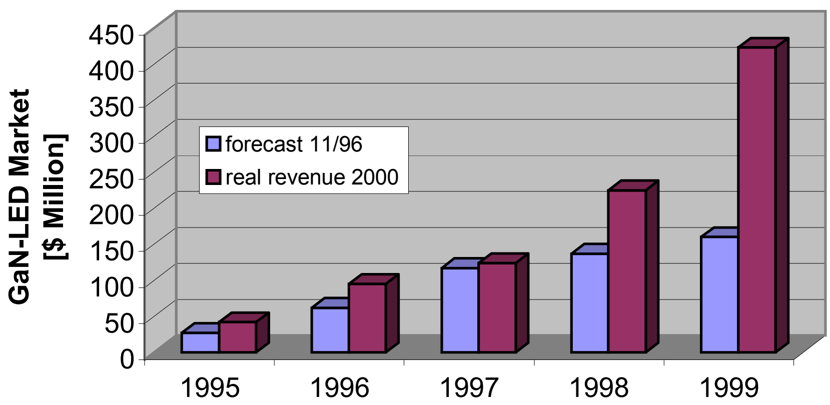


Fig. 1: Comparison of historical market forecast of 1996 and market growth by revenue reported in May 2000.

Today the automotive market with a share of about 20% developed to become one of the two major market segments. There is only one market which is bigger today. This is the segment of full color displays, taking a share of approximately 30%. These two market segments absorb about 50% of today's GaN-LED production with a total volume of more than 400 Million US$. Comparing these numbers with the estimated numbers from 1995/96, the annual growth rate of 30% was even conservative compared to the real growth of the Nitride market, reaching an approximate growth rate of about 80% per year as indicated in Fig. 1.

Other market segments such as traffic lights or general lighting have a rather negligible market share below 1% in 1999. Yet especially general lighting is expected to become one of the major driving forces for GaN-based light emitting devices. For general lighting mainly white light emitting devices will be needed, utilizing the advantages of both technologies, three chip solutions (RGB) and single chip solutions with fluorescent converters. The preference of using single or multi chip solutions strongly depends on the application. Major driving forces for the lighting market will be energy and labor saving on one hand. On the other hand expected lifetimes exceeding 50.000 h for LED solutions will become an important issue.

1.2 White LED Market and Requirements

According to R. Haitz (Agilent Technologies) the energy consumption related with illumination is as high as 20% of the total electrical power consumption in North America. For total replacement of incandescent and fluorescent lamps in the US savings of several billion US$ only on electrical energy are discussed, not even taking into account reduced labor costs. This rough estimate gives an indication of the market potential for solid state lighting.

Today's luminous efficiency for single chip white LEDs is in the order of 15-20 lm/W, independent of the substrate. A plug efficiency of about 20% for today's chips in a 5 mm radial housing is realistic. Corresponding converter materials show conversion efficiencies of 75 – 95%, the most. Therefrom it becomes obvious that the LED-chip shows the largest potential for improvement to achieve efficiency values of 50 – 80 lm/W and more as are reported for fluorescent lamps. Besides the increase of brightness levels, it is very important to further reduce the forward voltage. Both brightness and forward voltage requirements will lead to new vertical device structures and chip designs within the next couple of years. One possibility to reduce forward voltage is to increase chip size, reducing series resistance and thermal loss. Such large chips can be driven at higher currents combined with even lower current densities as today's devices.

Having reached device characteristics and device parameters to meet the level of conventional light sources, costs per die and costs per lm/W will be the final parameter to enter the lighting market in large volumes either using a numerous amount of today's devices with small dimensions or using only a few enlarged devices with an area of 1 mm^2 or more.

2. LED Technology

2.1 Light Emitting GaInN-Chips

In principle, LED technology is mainly dominated by the development of vertical LED structures for light generation and light extraction, which is determined by chip-design and packaging technology. Focusing on the chip, the design of epitaxial layers for GaN devices is based on the buffer technology, the active region, and the multi layer p-side. Most important seems to be the control of the interfaces of the active region as well as the definition of the pn junction. In order to realize highly efficient layer packages, most of the structures are grown using MOVPE. The structures contain GaInN quantum wells with well thicknesses of 2 nm to 5 nm separated by 2 nm to 10 nm barriers either of GaN or GaInN with low In content. Many devices have AlGaN electron barriers on the p-side of the device with Al contents of about 10% to 20%, followed by p-doped GaN to form low resistance p-contacts.

For emission wavelengths between 450 nm – 470 nm carrier overflow from localized energy states within the quantum well is small due to a relatively high Indium content, minimizing the probability of carriers to reach non radiative recombination centers, e.g., threading dislocations. At the same time, the Indium content is still low enough to ensure the necessary overlap between electron and hole wavefunctions, which is affected by built-in piezoelectric fields resulting in the quantum-confined Stark effect.

At longer wavelengths two effects reduce quantum efficiency: On one hand, the high Indium content needed for long wavelengths intensifies the piezoelectric fields leading to a reduction of electron-hole wavefunction overlap. On the other hand, the quality of GaInN layers decreases with high Indium content, leading to more non-radiative recombination centers. In the short wavelength UV region, the efficiency also decreases as the confinement energy of carriers within localized states of lateral quantum well fluctuations is decreased, i.e. the probability is increased that carriers reach non-radiative recombination centers. To avoid the loss of efficiency of UV-LEDs, high band gap confinement layers containing aluminum have to be developed.

The major part of GaN-based devices is grown on sapphire substrates, only some organizations such as OSRAM-OS focus on SiC as a substrate. The advantage of sapphire is the availability and substrate costs. Not taking into account the fact of limited availability and costs, SiC has a lot of advantages as a material itself over sapphire, such as electrical and thermal conductivity, the thermal expansion coefficient as well as the reduced lattice mismatch to GaN. On top of that SiC shows additional advantages from a processing (yield, complexity, costs) as well as a manufacturing point of view.

Only recently improving the light extraction from the chips became a major topic. Since sapphire is difficult to shape due to its extreme hardness, most organizations working on sapphire try to enhance light extraction by using flip-chip or p-side down mounting techniques in combination with mirror contacts on the p-side. The generated light enters either directly into the transparent sapphire substrate or is reflected towards the sapphire side by the mirror. The efficiencies of such devices can be improved by enlarging the chip size to operate the device at lower current densities. Here the thermal saturation effects as well as band filling effects in the quantum wells do not limit the internal efficiencies. Figure 2 demonstrates the decrease of efficiency with increasing operation current density observed in a standard LED.

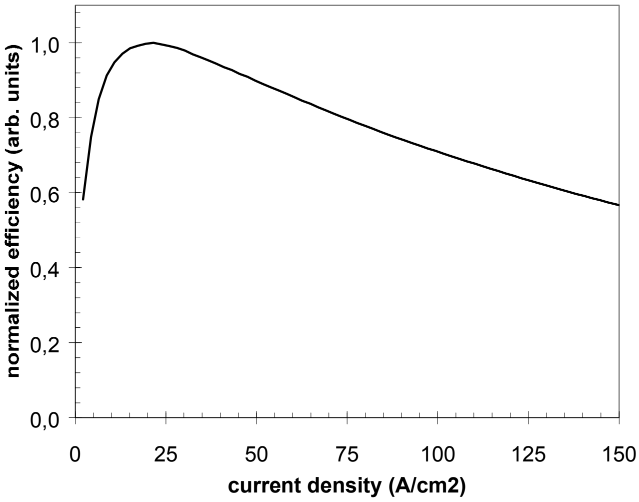
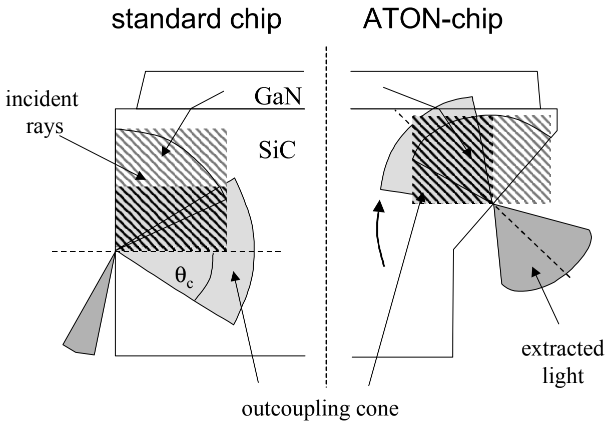


Fig. 2: External efficiency of an InGaN-LED with varying operation current density.



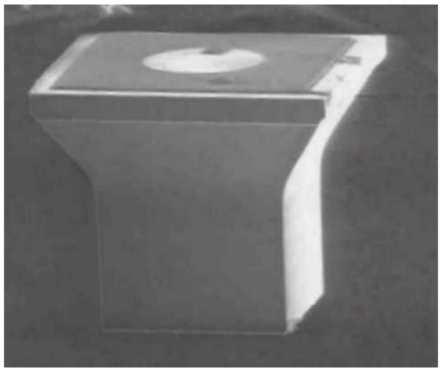


Fig. 3: Sketch of the improved light extraction conditions by the new chip design developed by OSRAM-OS, named ATON, compared to a standard GaN-LED on SiC-substrate. On the right a SEM micrograph of an ATON-chip is shown.

On SiC the situation is different. The material SiC is not as hard as sapphire and therefore can be shaped using standard processing technologies. At OSRAM-OS a technique was developed to shape devices in such a way that light extraction from the substrate is improved (Fig.3). This was achieved by designing a chip with an undercut on the side walls to generate inclined side facets. In a standard device with cubic geometry most of the light entering the substrate gets lost due to multiple total internal reflection and subsequent absorption. The limitations of geometrical optics on light extraction become clear in the sketch of the outcoupling conditions in Fig. 3. On one hand the angular range of rays entering the substrate is limited due to refraction at the GaN/SiC interface. On the other hand total reflection occurs for rays hitting the sidewall at grazing incidence, so that only a small angular range of incoming light can be coupled out. Using OSRAM's technique of shaping side walls (named ATON technology), the overlap of the incoming light cone with the outcoupling cone can be enlarged. This technique is suitable for the entire GaInN-product line with similar brightness improvements for wavelength from UV to green and even longer wavelengths.

The use of this technology at OSRAM-OS led to an increase in brightness of about 80%. The combination of improved facet design with advances of the epitaxy lead to a brightness level of up to 8.2 mW at an emission wavelength of 470 nm.

2.2 White Light Emitting Devices

For the generation of white light, different approaches using GaInN-LEDs can be derived. Four basic combinations are demonstrated in Fig. 4. In Fig. 4A a three-chip RGB-solution is shown. The advantage of this approach is the variable color when driving each chip separately. Such diodes are used, e.g., as pixels for full color displays. Diodes based on InGaN can be used to provide the blue and green colors, whereas GaInAlP-LEDs are used for red. If just the generation of white light is intended, the Multi-LED is not well suited because of its size, multiple driving voltages, costs and last but not least color rendering.

To be competitive with other light sources it is mandatory to provide a single chip LED suitable for high volume production. Therefore luminous conversion is a very valuable technology. Today white LEDs based on single converter solutions are commercially available. Here the blue GaN-chip is embedded in a phosphor, e.g. a rare earth doped garnet. The blue light emitted by the diode partially pumps the converter, and the yellow light emitted by the phosphor in combination with the blue light of the diode adds up to white light. The spectrum of such a diode is shown in Fig. 4B. The solid line shows the complete spectrum of the LED, whereas the dashed line gives the spectrum of the converter itself and the diode without converter, respectively (the intensity loss due to conversion is not drawn to scale in this figure).

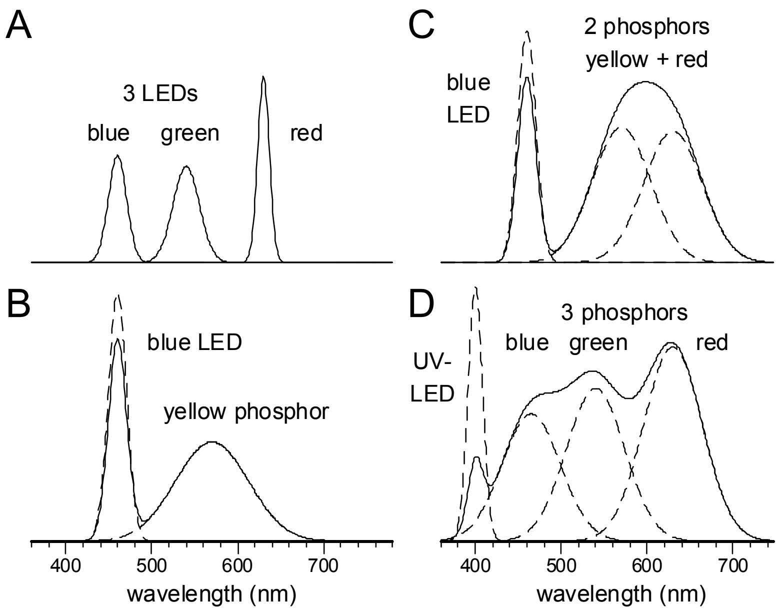


Fig. 4: Possible approaches for the fabrication of white LEDs: RGB-solution (A); blue chip combined with 1 (B) or 2 (C) converters; UV-LED with 3 converters (D).

One of the most important parameters for white light sources is color rendering. It is well known that a colored surface looks different when illuminated by an artificial light source or by daylight. With the color rendering index (CRI) a figure of merit R_a can be assigned to a light source, giving information on the color rendering of eight standard surfaces. For daylight the CRI has been normalized to $R_a = 100$. For comparison an incandescent bulb has an $R_a \approx 90$, a standard fluorescent bulb has an $R_a \approx 70 - 90$.

The CRI of the white converter LED depends of the emission wavelength of the blue LED. Using a single converter a maximum CRI of about $R_a = 80$ can be reached for an LED emitting in the wavelength range of 450 nm – 470 nm. The limitation on the CRI for the one converter solution is due to the large gap between the blue pump wavelength and the emission wavelength of the converter. Yet this gap cannot be avoided due to the laws of color mixing, where a blue source needs to be combined with a yellow source to yield white light.

The use of only a single converter imposes more or less stringent limitations on the properties of white LEDs. More flexibility can be gained by using an additional converter. So, e.g., red tones can be emphasized as shown in Fig. 4C. These diodes will give a more natural color to human skin. Yet the gap in the spectrum between the pump wavelength and the converter emission remains, because of the Stokes shift between absorption and emission of the converter.

In an even more advanced solution the visible part of the spectrum is completely generated by phosphors. With a spectral width of the converter emission between 70 nm – 120 nm a quasi-continuous spectrum can be simulated (Fig. 4D). With this technique a high color rendering index of $R_a > 90$ can be achieved for applications like photography, where a high quality of the illumination source is needed. Since in this solution visible light is generated by phosphors, the emission wavelength of the pump source can be moved into the UV spectral range. This is on one hand necessary for pumping the blue phosphor, on the other hand the choice of available converter materials is enlarged, because the pump wavelength now can be tuned to the absorption maximum of the converters. As a drawback it should be mentioned that three converters are not as efficient as the one phosphor solution from the energetic point of view, given by the down conversion of a 400 nm photon to blue 470nm, green 530nm and red 600 nm, where the photon energy is reduced down to 1/3 of the original energy.

If a white LED with high efficiency, high brightness and low costs is needed, the single chip solution with one converter will be used. By using two or three phosphors high end products can be obtained for special lighting applications.