Enabling cost-competitive mass production of micro-LED displays

ALLOS Semiconductors explains how GaN-based micro-LEDs grown by MOCVD on 200mm or 300mm silicon wafers offers huge cost and yield advantages compared with GaN-on-sapphire.

The challenge to bring micro-LEDs into mass production

The quest to use micron-sized light-emitting diodes (micro-LED) for the next generation of high-performance displays has led to dramatic progress in recent years. After the first demonstrators of these novel displays in 2012, the potentially huge advantages of this technology for end-product design, shape and performance have been recognized quickly. Compared with conventional liquid-crystal displays (LCDs) and organic light-emitting diode (OLED)-based displays, micro-LED displays promise higher brightness including readability in sunlight, better contrast, higher speed, wider viewing angles as well as improved lifetime, ruggedness and environmental stability. More importantly, micro-LED displays are extremely energy-efficient, which will boost the battery run-time – essential to mobile applications like smart watches, augmented reality (AR) glasses or smartphones – and curb the ever increasing electricity consumption of displays in general.

In a micro-LED display each pixel is made of three tiny LEDs emitting red, green and blue (RGB) light. Despite being as small as 2μm in edge length compared with 60μm diameter for a human hair or 300μm for a typical conventional LED, these LEDs are still sufficiently bright. This means that high-resolution displays can be transparent and thus seamlessly integrated even into glasses or contact lenses. At the same time there is plenty of space between the pixels that product designers want to utilize for example for sensors or solar cells. This will change the way we build and use displays: Virtually any surface can become a display while any ‘display’ can also have a multitude of functionalities. The first demonstrators already show micro-LED displays integrated into windows of cars or buildings, furniture, textiles or even wallpaper.

Realizing this disruptive potential, huge corporations like Sony and Apple (as well as many start-ups) began to invest early in micro-LED development. However, given the technical challenges — but also the constant improvements in conventional LCD and OLED displays — skeptical observers asked two questions: Firstly, can micro-LED-based products really deliver broad and decisive customer benefits or will they be limited to some niche applications? And secondly, can such products achieve the yield and cost levels that actually allow profitable mass production anytime soon?

Regarding the first question, companies like Samsung, Plessey, PlayNitride, X-Celeprint, Rohinni and many others have answered with a wide range of impressive micro-LED-based display prototypes and first flagship products. As Eric Virey of market research company Yole Développement observes: “We see two hot candidates for early micro-LED adaptation: Very small and very big displays. Very small displays (e.g. for AR glasses) benefit from the tiny micro-LED dimensions and corresponding high pixel density and they even offer unmatched high brightness. This is enabling a truly new consumer experience. In contrast, very large displays have the benefit of micro-LED displays’ unique cost structure. While the cost of conventional TVs depends largely on the display area, the cost of micro-LED displays is driven mainly by the number of pixels and thus micro-LED chips. This means that the cost for a 4K display with a size of 100-inches can be almost the same as for a 73-inch display. These unique economics can drive down the cost of large high-quality displays and thus generate a huge new market demand.” The success of such products would provide an initial critical volume to reduce the cost of micro-LED displays and mature the technology for other products like smartphones or automotive applications.

This makes it even more urgent to address the second question of how to improve the yield and cost levels to enable mass production. Although developers increasingly find solutions for individual production challenges like the processing accuracy of tiny micro-LED chips or for assembling them using so-called mass-transfer technologies, the end-to-end yield of the entire manufacturing chain remains insufficient. The biggest hurdle for manufacturability is the sheer amount of chips of constant quality needed for a single display: A 4K display consists of over 8 million pixels, and thus a total of almost 25 million so-called sub-pixels (consisting of micro-LED chips for red, green and blue light emission) are required. And of course, all these chips have to work after the display has been assembled, as consumers would not tolerate any pixels that are dead or light up in the wrong color.

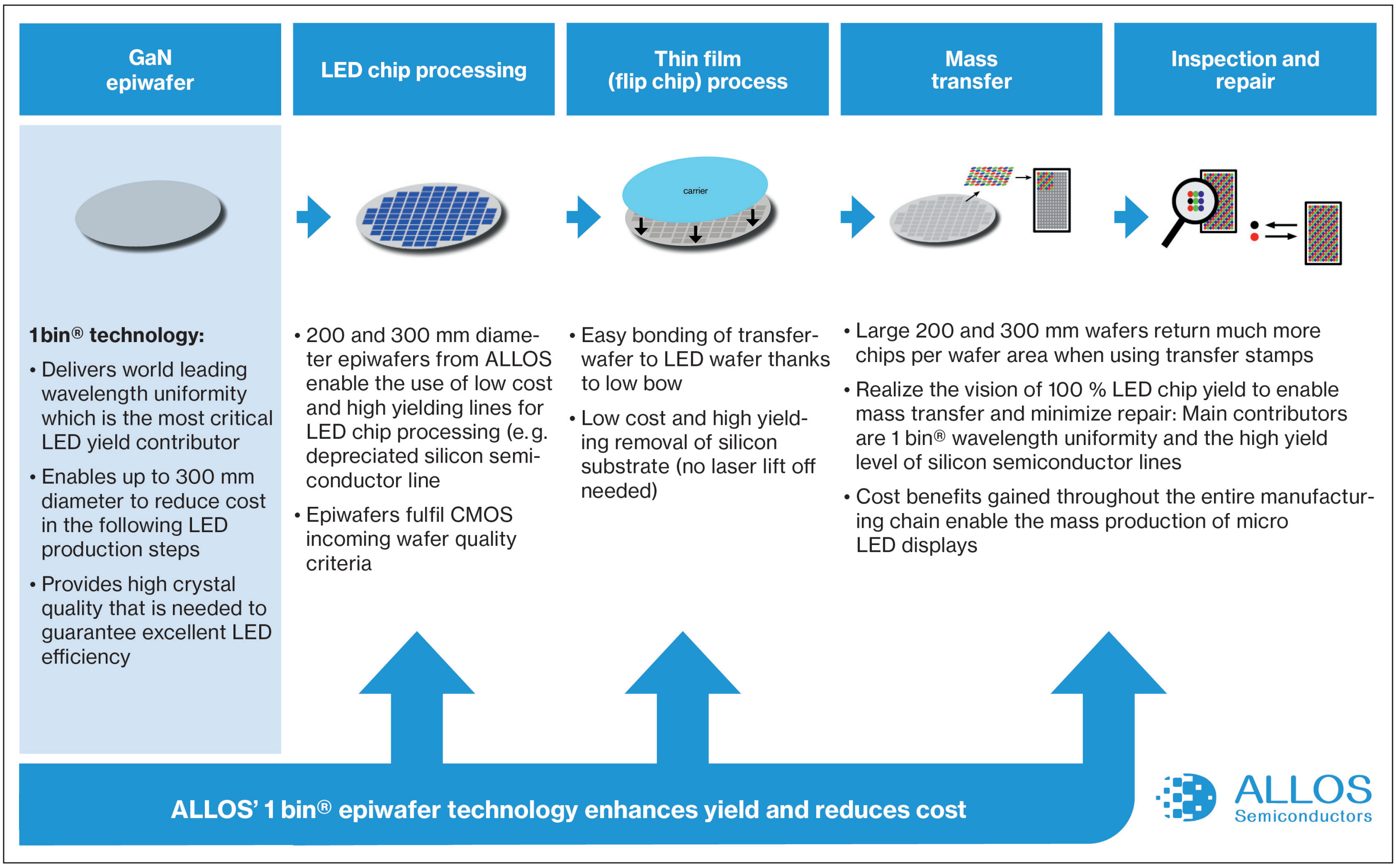
The problem with conventional LED technology

Conventional blue and green LEDs are manufactured by specialized LED vendors using gallium nitride (GaN)-on-sapphire epiwafers while red LEDs are mostly based on aluminium gallium indium phosphide (AlGaInP)-on-GaAs material. These technologies are mature for conventional LEDs and widely available. Additionally, several color conversion technologies could turn inexpensive GaN-based LEDs into red LEDs. One could thus expect that conventional LEDs are providing a solid foundation for micro-LED chip production as well.

But, despite large investments by leading LED suppliers, sapphire-based micro-LED manufacturing remains far from being ready for mass production. To start with, sapphire substrates are limited to 100mm and 150mm diameters, as larger substrates remain very expensive and result in too much GaN-on-sapphire wafer bow. Such wafer bow causes yield losses that eat up all theoretical cost savings of moving to larger diameters. This is in contrast to processes in the silicon semiconductor industry, where going to larger substrates is traditionally a key driver for cost savings.

Additionally, the cost per mask layer is actually higher in the LED industry compared with, for example, 200mm silicon foundries. This means that silicon foundries not only produce many more chips per wafer (due to the increased wafer size) but total cost per chip is significantly lower compared with in-house chip making at LED companies. To make matters worse, LED companies would need to invest heavily to upgrade their fabs to larger diameters and to meet the precision and particle requirements which are not needed for conventional LEDs but are unavoidable for micro-LED production.

In parallel, micro-LED manufacturing needs to address another even more severe issue: Due to inhomogeneity in the emission wavelength of the typical GaN-on-sapphire LED epiwafer, each LED chip needs to be tested and sorted into one of several bins to ensure that the respective sub-pixel will emit the desired light color. Already for conventional LEDs this represents a huge cost burden, but when facing the 25 million chips for a 4K display, this so-called 'binning' approach becomes technically impractical and cost-wise a show-stopper for volume production. What is needed instead is an epiwafer technology that allows for the production of larger epiwafers resulting in low-cost micro-LED chips with better wavelength uniformity to avoid binning and increase yield.



GaN epiwafer

1 bin® technology:
- Delivers world leading wavelength uniformity which is the most critical LED yield contributor
- Enables up to 300 mm diameter to reduce cost in the following LED production steps
- Provides high crystal quality that is needed to guarantee excellent LED efficiency

LED chip processing
- 200 and 300 mm diameter epiwafers from ALLOS enable the use of low cost and high yielding lines for LED chip processing (e. g. depreciated silicon semiconductor line
- Epiwafers fulfil CMOS incoming wafer quality criteria

Thin film (flip chip) process
- Easy bonding of transfer-wafer to LED wafer thanks to low bow
- Low cost and high yielding removal of silicon substrate (no laser lift off needed)

Mass transfer

Inspection and repair
- Large 200 and 300 mm wafers return much more chips per wafer area when using transfer stamps
- Realize the vision of 100 % LED chip yield to enable mass transfer and minimize repair: Main contributors are 1 bin® wavelength uniformity and the high yield level of silicon semiconductor lines
- Cost benefits gained throughout the entire manufacturing chain enable the mass production of micro LED displays

ALLOS' 1 bin® epiwafer technology enhances yield and reduces cost

Figure 1: Cost & yield effects of ALLOS' 1 bin® large-diameter GaN-on-Si LED epiwafers on entire production chain.

High yield and low cost with GaN-on-Si based micro-LEDs

To answer these demands for better emission wavelength uniformity and larger epiwafers, ALLOS Semiconductors of Dresden, Germany has developed its 1 bin® LED epiwafer technology. Instead of sapphire, it uses a proprietary and patented hetero-epitaxial process to grow GaN on silicon (GaN-on-Si) substrates in a standard metal-organic chemical vapor deposition (MOCVD) reactor. When comparing ALLOS' GaN-on-Si with market-leading GaN-on-sapphire, both materials have the same crystal quality with threading dislocation density of $2x10^8cm^{-2}$ and thus allow the manufacturing of micro-LED chips with high emission efficiency. Also, the cost per mm^2 epiwafer area before chip processing is similar.

The key advantage of ALLOS' 1 bin® GaN-on-Si technology is that it provides larger diameters and much better uniformity. This allows the realization of huge cost and yield advantages along the entire production chain, as shown in Figure 1.

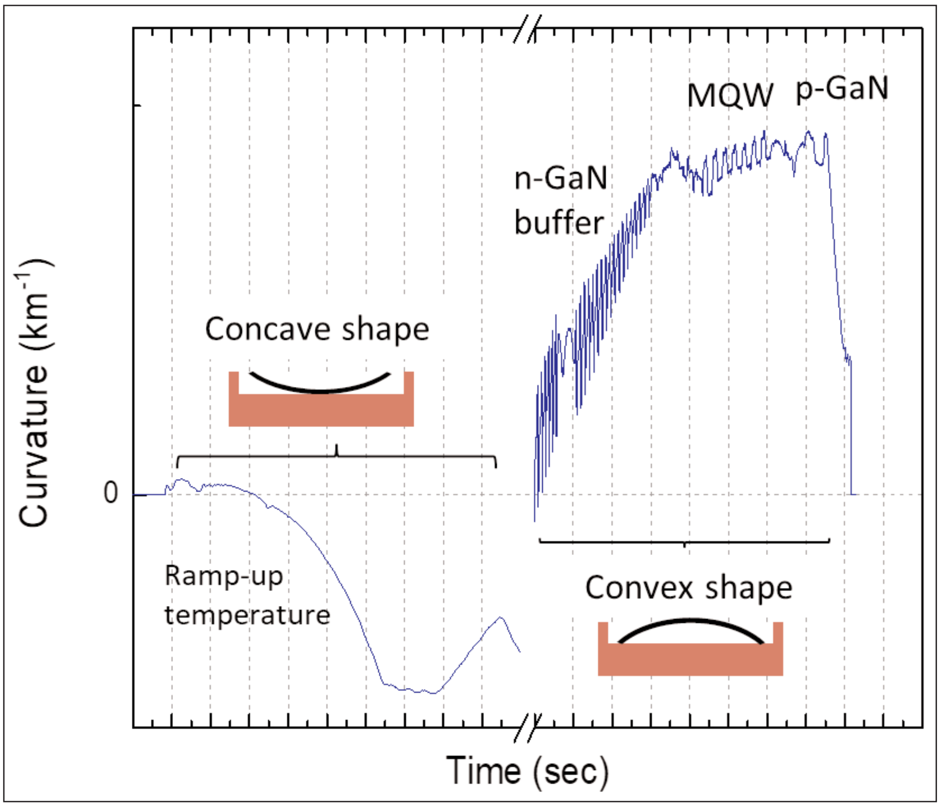


Figure 2: Typical curvature profile during GaN-on-Si LED epi growth.

Driven by customer demand, ALLOS has worked mainly on 200mm but recently has also successfully demonstrated its technology on 300mm wafers. Both wafer sizes enable the use of low-cost, high-yield silicon processing lines for micro-LED chip manufacturing. This can be realized either by acquiring depreciated 200mm hardware or by sub-contracting chip processing to foundries. This might also lead to new forms of cross-industry cooperation: While LED companies could use their technological expertise and IP to design and deliver good micro-LEDs, the manufacturing excellence of silicon semiconductor companies in delivering unmet yield levels at low cost plus their available manufacturing capacity qualifies them as perfect contributors to overcome the yield and cost challenges for micro-LED chip production.

To benefit from the advantages of standard silicon processing lines the 1 bin® epiwafer technology is — unlike sapphire — fulfilling all incoming wafer quality criteria of CMOS lines. For example, the epiwafers are crack-free, thin (725µm at 200mm and 775µm at 300mm) and have only minimal bow (<30µm), which also enables high-yielding bonding. In combination with the well-established capabilities in silicon lines to remove the silicon substrate by grinding and etching, this facilitates much better yield than with the laser lift-off used for sapphire for so-called thin-film chip processing, which is required for micro-LEDs. Because most micro-LED manufacturing techniques use so-called transfer stamps, large wafers enable further cost-savings as the area utilization improves significantly with larger wafer diameters. Comparing for example 200mm with conventional 100mm wafers and assuming a transfer stamp size of 20mm x 20mm, the total wafer area increases by a factor of four while better area utilization allows for five times more usable chips. This better area utilization alone enables a reduction of LED chip cost per display of 25%, which increases to a staggering 40% when migrating further to 300mm.

Finally, using a silicon foundry and matching LED wafer sizes also offers the opportunity for integration with silicon technology processes, e.g. for the so-called monolithically integrated micro-LED displays, where CMOS driver wafers are bonded to LED wafers.

Precise strain engineering enabling large epiwafers

In light of these huge advantages of GaN-on-Si for micro-LED production, the question arises how to achieve the necessary and decisive epiwafer properties. For ALLOS the technological answer lies in the strain engineering that is at the core of its 1 bin® technology.

To grow GaN-on-Si is challenging because of the large mismatch in both lattice constant and thermal expansion coefficient (CTE) between GaN and silicon. A technology to overcome these issues is needed as otherwise these forces will result in a high degree of strain, causing wafer bow, cracks and wafer breakage as well as insufficient crystal quality. To add further complexity,

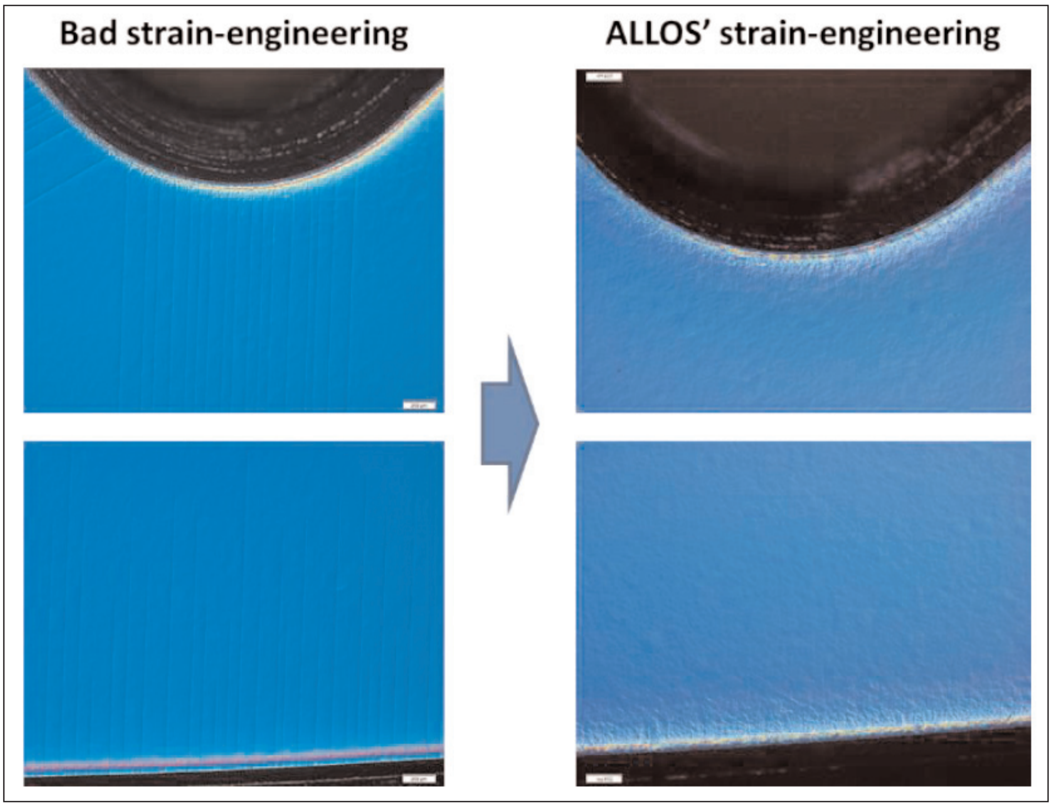


Figure 3: Nomarski images of notch and opposite round edge of 200mm GaN-on-Si epiwafers. With ALLOS’ strain engineering cracks can be reliably prevented even at the very edge of the wafer which is otherwise often seen in GaN-on-Si growth (left image).

there are several trade-offs between these attributes and other LED properties, like wavelength uniformity — the crucial contributor to high yield. This means that producing ‘hero results’ for individual parameters might be possible even with immature technologies, but the real challenge lies in achieving good values for all crucial properties at the same time.

Figure 2 shows the typical curvature profile of GaN-on-Si during growth. When cooling down from growth temperature (~1000ºC) to room temperature, huge tensile strain is induced into the structure. With ALLOS’ strain engineering this is compensated by purposely inducing a precisely defined amount of compressive strain during growth. This results in flat epiwafers after cooling down. Additionally, the epiwafer bow during growth can be controlled with a high accuracy of ±5µm and can be adjusted to accommodate external factors too. If needed, this in-line process control capability can, for example, be used to adjust to unexpected shifts in the bow of the incoming substrate, as detected by an in-situ monitor at the beginning of the growth. The same strain engineering enables the growth on large diameters and is used to reliably prevent cracks (see Figure 3). It enables growing much thicker GaN layers (7µm and more) than competing technologies and delivers epiwafers that have the standard substrate thickness used in silicon lines (e.g. 725µm for 200mm).

Excellent and stable wavelength uniformity is essential for high yield

Achieving superior wavelength uniformity is the key to address the need for high yield, as inhomogeneities on the epiwafer level multiply yield-losses throughout the manufacturing chain. There are two critical parameters for achieving excellent wavelength uniformity:

(1) temperature uniformity across the epiwafer during the multiple-quantum-well (MQW) growth and

(2) gas flow uniformity inside the MOCVD reactor.

The latter can be achieved through gas flow simulation and the use of latest-generation reactor types, like the Veeco Propel in the case of the data presented here. Achieving good epiwafer temperature uniformity is much more difficult, as during MQW growth the epiwafer is convex (see Figure 2), resulting in different distances between the heat source underneath and the epiwafer above (large distance at center and zero distance at the edge of the epiwafer). This problem increases with epiwafer size, which makes it challenging to obtain good wavelength uniformity on 200mm and 300mm GaN-on-Si LED epiwafers.

In combination with a specially designed domed wafer carrier, which is dissipating heat uniformly, ALLOS is utilizing the power of its strain engineering to control the shape of the epiwafer during MQW growth. This ensures that the distance between the domed wafer carrier and the epiwafer is equal across the entire epiwafer diameter. The resulting temperature uniformity leads to ALLOS’ industry-leading wavelength uniformity values.

Figure 4 shows the photoluminescence (PL) map of a 200mm GaN-on-Si LED epiwafer. The optimized growth conditions result in a standard deviation (STDEV) of only 0.566nm at an average wavelength of 446.4nm. The wavelength histogram shows that 97.6% of the coverage area is within the 2.5nm target bin. The min-max value of wavelength for the entire epiwafer is as low as 3.3nm. Even in the case that a further tightened ±1nm wavelength uniformity bin were applied, 92.1% of the epiwafer area is within that target already today.

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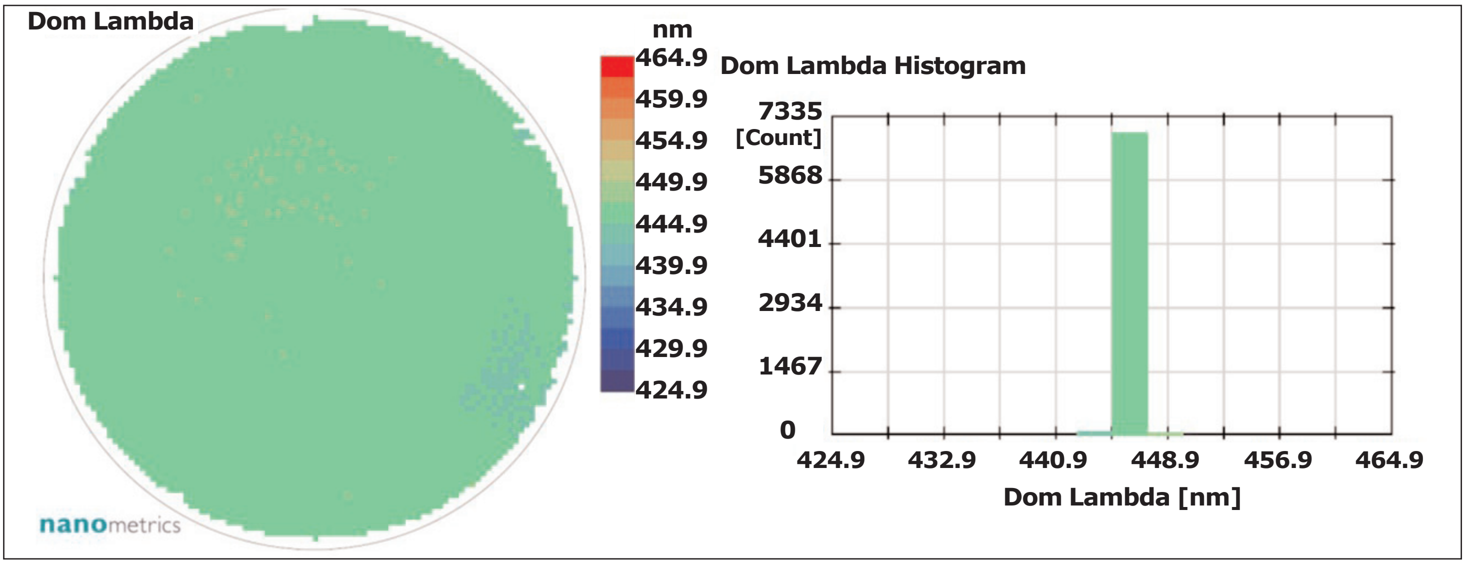

Figure 4: PL map of a 200mm GaN-on-Si LED epiwafer. Average wavelength of 446.4nm with STDEV of 0.566nm is achieved. The histogram with 2.5nm bin size shows 97.6% coverage area and min-max value is 3.3nm.

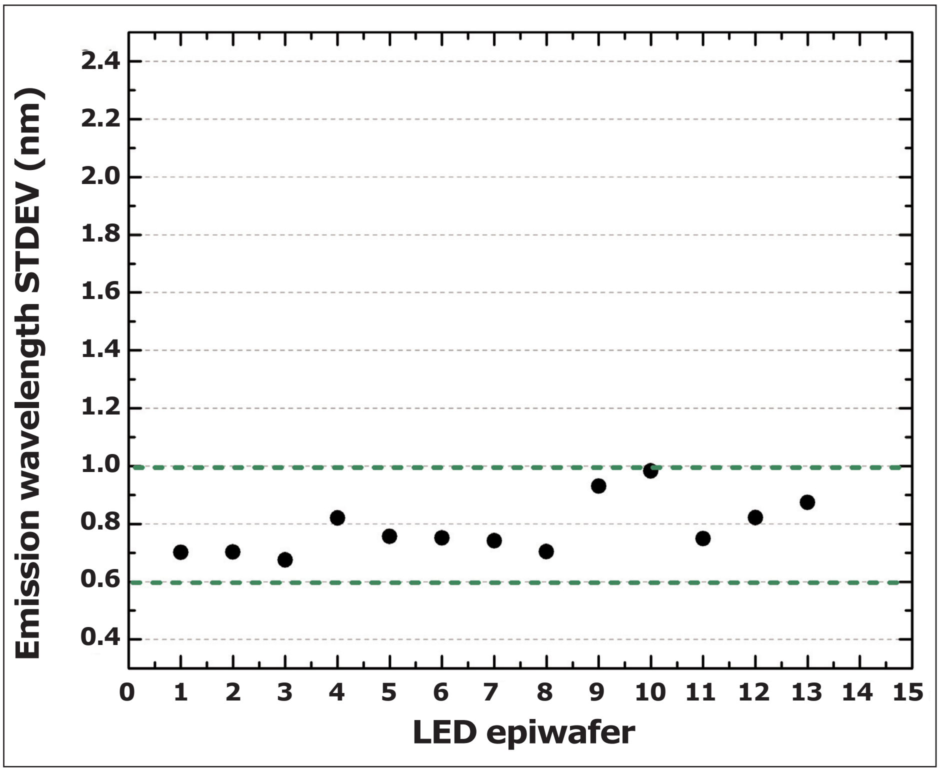

Figure 5: Wavelength STDEV for 13 consecutive production runs of 200mm GaN-on-Si LED epiwafers.

This uniformity figure is not only the best published worldwide – more importantly, this performance is reproducible, as shown by Figure 5 with data from 13 consecutive production runs of 200mm GaN-on-Si epiwafers. Thanks to ALLOS' strain engineering, the epiwafer shape during MQW growth can be kept constant so that the wavelength uniformity becomes very stable wafer-to-wafer. The average STDEV is 0.79nm and all epiwafers have values below 1nm. At the same time, all other production requirements, such as for example bow of <30μm, have been met on epiwafers with thickness of 725μm.

Summary and outlook

While the industry's prototypes are impressively demonstrating that the product features enabled by micro-LEDs provide real customer benefits, the question how high-yield and cost-competitive mass production can actually be achieved remains to be answered by the industry. For this, a breakthrough in wavelength uniformity is crucial, as otherwise low yield levels will block the path forward. However, even if that were achieved on small wafer diameters, the cost would remain prohibitive. Thus, the industry needs to move to 200mm and 300mm wafer diameters. Also, with large GaN-on-Si epiwafers the micro-LED industry can utilize the high-yield and low-cost manufacturing excellence of silicon lines.

ALLOS' 1 bin® LED epiwafer technology fulfills these essential requirements. Based on the underlying proprietary and patented strain-engineering technology, it can provide 200mm and 300mm GaN-on-Si LED epiwafers with best-in-industry wavelength uniformity values while simultaneously meeting the performance requirements — and all other manufacturing requirements.

Together with other breakthroughs — in mass transfer, for example — we see that the foundations for micro-LED mass production are becoming a reality and will deliver exciting new consumer and business applications. ■

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