How to turn the promises of micro LED displays into reality?

Burkhard Slischka, Co-founder and CEO, ALLOS Semiconductors

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No need to take photos – just contact me and get a copy

bs@allos-semiconductors.com

A. Introducing ALLOS

B. Why do people look at micro LED displays?

C. Why is it so difficult?

D. Technological key decisions to take

E. Who will run the show?

ALLOS is a fabless IP licensing and technology company

Establish 150 and 200 mm GaN-on-Si technology for all applications on customers' reactors

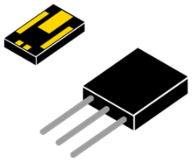
ALLOS enables customers to master GaN-on-Si epiwafer technology

We are continuously improving our technology to stay ahead

Based on 18 years track record at University Magdeburg, AZZURRO and ALLOS

GaN-on-Si matured and is now re-shaping three markets

Power semiconductors

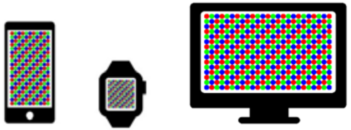


GaN-on-Si enables more energy-efficient, less complex and smaller high power electronic (HPE) devices out of silicon lines

Radio Frequency

GaN-on-Si provides higher performance and lower cost for RF devices

Micro LED displays



Only GaN-on-Si allows super-uniform, CMOS-compatible 200 mm epiwafers needed for micro LEDs

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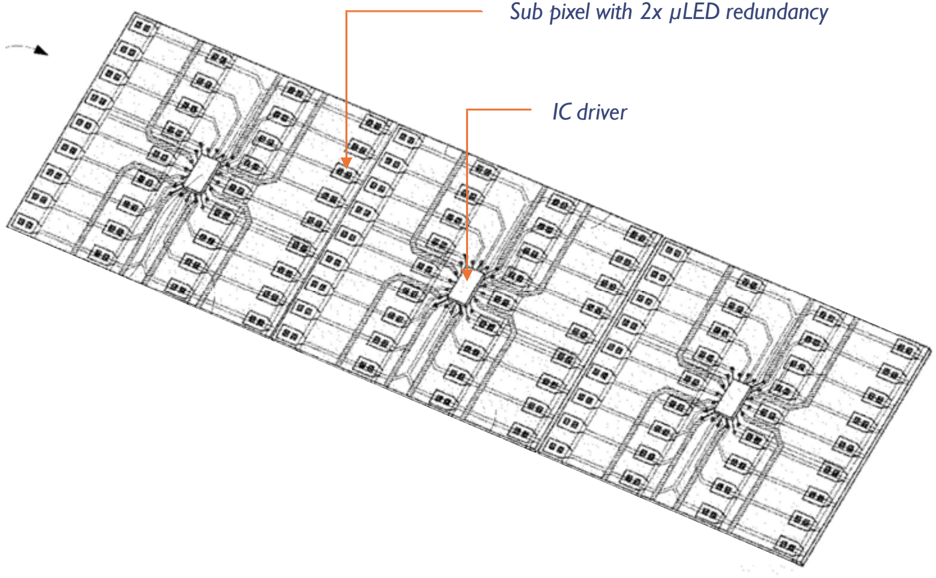
Why do people look at micro LED displays?

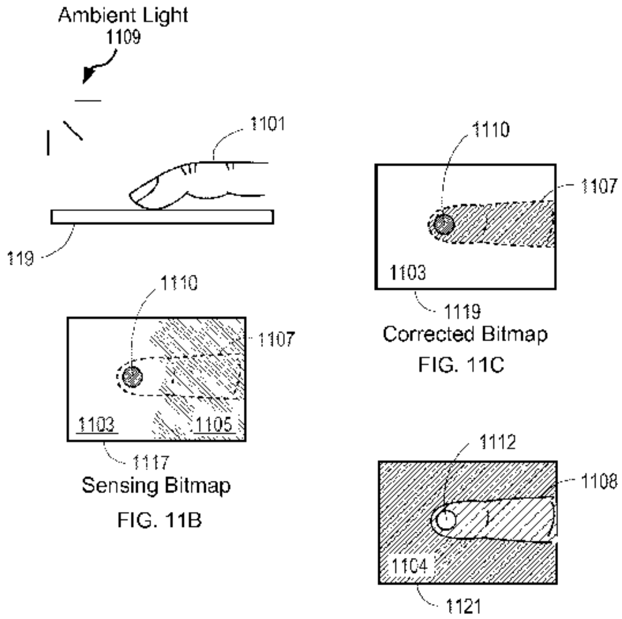
- **Low power consumption = longer battery runtime**
- Perfect black + high brightness = contrast
- **Displays readable even in sunlight**
- High resolution and pixel density
- More accurate and vivid colors
- Fast refresh rates
- Wide viewing angles
- Curved and flexible backplanes
- Long lifetime, environmental stability
- **Integration of sensors within display**

Source: YOLE Développement

Integration of sensors or solar cells between micro LEDs



A µLED display where discrete ICs positioned on the front face can drive groups of 36 subpixels featuring a 2x redundancy.
(Source: LuxVue patent US 9,318,475)



Fingerprint sensing embedded in a µLED display
(source: LuxVue patent application US 20150348504A)

Source: Yole Développement

Display Technology	LCD	OLED	Micro LED
Mechanism	Backlight / LED	Self-emissive	Self-emissive
Contrast Ratio	5,000:1	∞	∞
Lifespan	Medium	Medium	Long
Response Time	ms	µs	ns
Operating Temperature	-40 to 100℃	-30 to 85℃	-100 to 120℃
Power Consumption	High	Medium	Low
View Angle	Low	Medium	High
Pixel per inch	Up to 800 ppi	500 ppi	>2000 ppi
Cost	Low	Medium	High

Source: LEDinside

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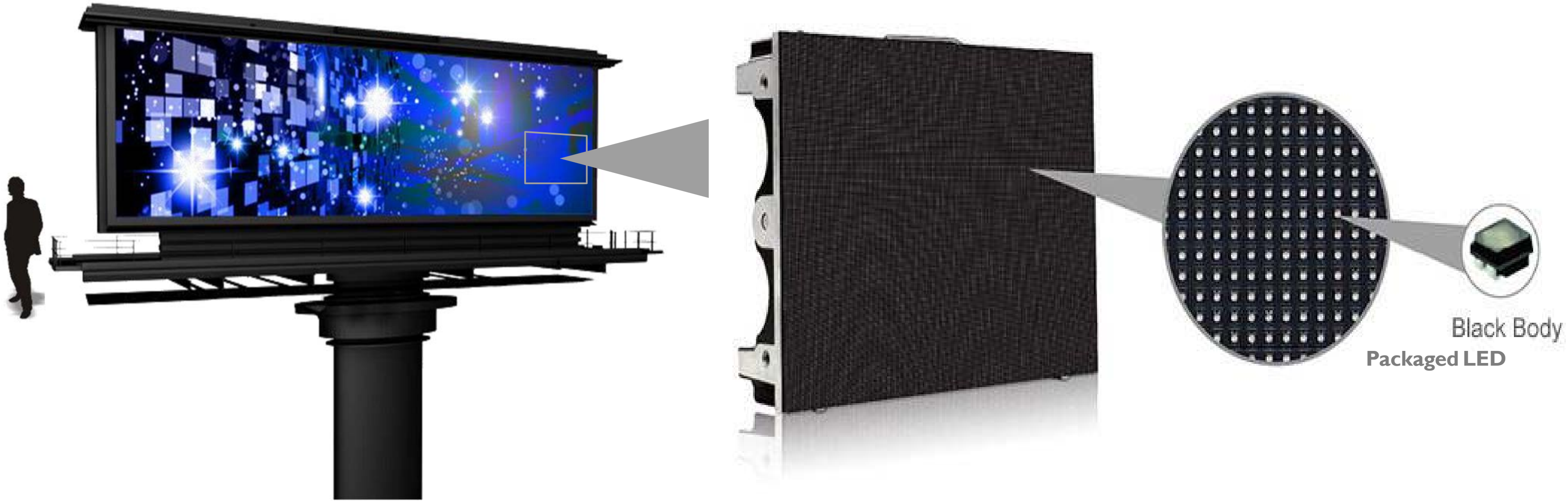
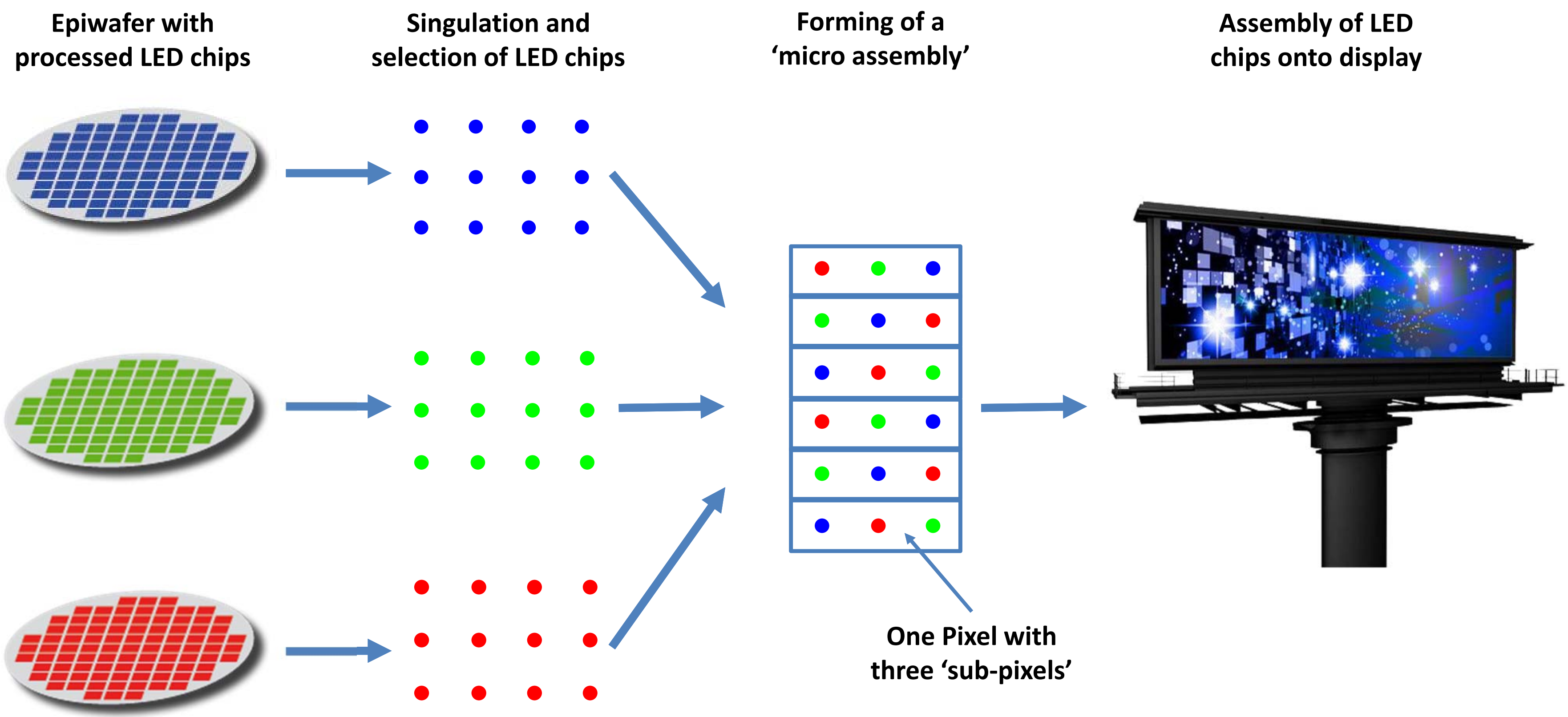
LEDs are already today used in large displays



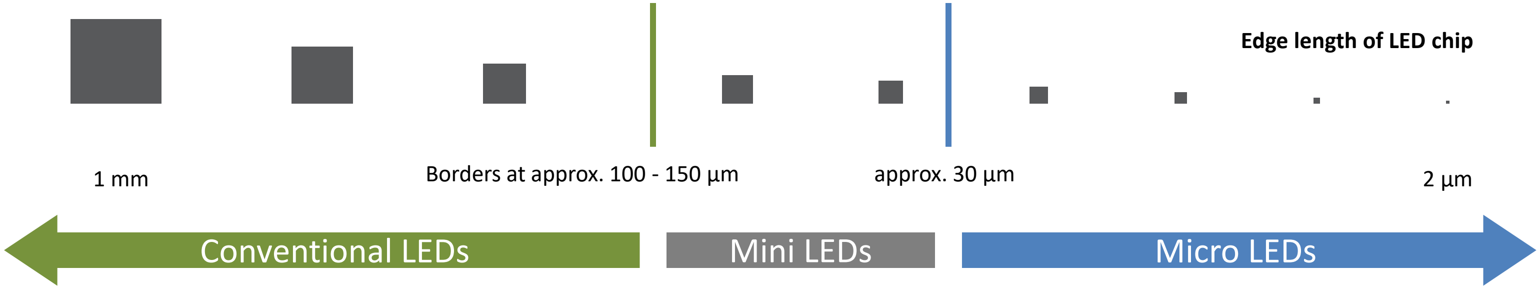
- LEDs are commonly used in large direct emissive video billboards (stadium, advertising…)
- Discrete packaged LED containing red, green and blue chips to form the individual pixels
- Pitch: 1 to 40 mm depending on display size and resolution.

Sources: YOLE Développement Absen LED

Assembling steps of an conventional LED display



What is the difficulty of working with micro LEDs?



- ➔ Micro LEDs are much smaller (and thinner) than conventional LEDs and difficult to handle
- ➔ They come in the millions for each consumer device
- ➔ Applications require that each LED works and delivers the required performance
- ➔ One 200 mm epiwafer can provide the LED chips for up to 80 HD displays

Micro LED chips are as small as atmospheric aerosol particles

Types and size distribution of atmospheric particulate matte
[in micrometres]
Source:
https://en.wikipedia.org/wiki/Particulates

Size of micro LED chips
[in micrometres]

The problem with yield for micro LEDs

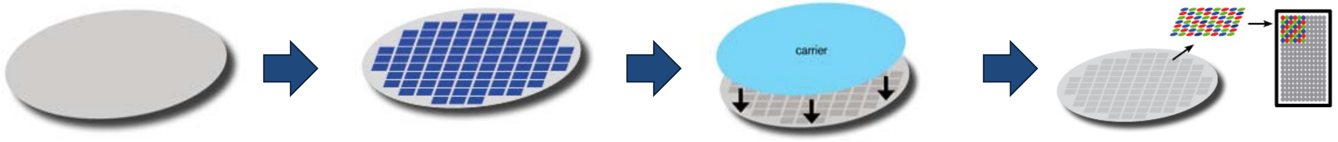
- A simple 4K UHD display has 3,840 x 2,160 pixels (= 8,294,400)
- Using RGB will require more than 24,800,000 micro LED chips

Relevant yield*	… equals amount of chips failing
90.00000 %	2,488,320.00
95.00000 %	1,244,160.00
99.00000 %	248,832.00
99.90000 %	24,883.20
99.99000 %	2,488.32
99.99900 %	248.83
99.99990 %	24.88
99.99999 %	2.49

Even a **Six Sigma = **99.99 % defect-free process will require 2,488 chips to be repaired on a 4K UHD display

- Today consumers do not accept pixel errors
- Even with *extremely high yield* a repair strategy is unavoidable

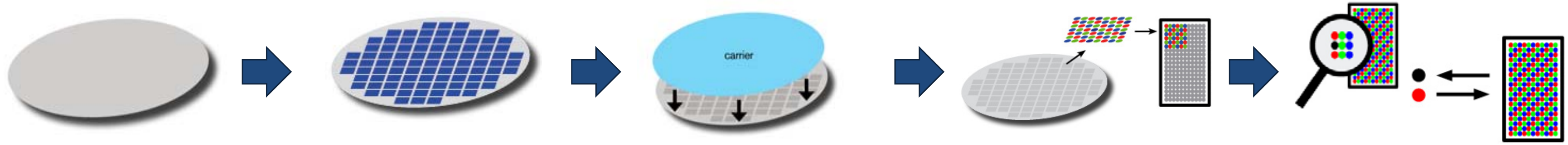
The relevant yield results from all process steps



Good area x Good LEDs on wafer x Good LEDs after bonding and substrate removal x Transfer yield

$$= \frac{\text{Good LEDs on display}^{*}}{\text{LEDs transferred to display}}$$

Simplified micro LED display manufacturing process



GaN epiwafer*

- Epi stack mostly similar to conventional LEDs
- Following production steps require very high quality and uniformity
- On sapphire or on silicon?

LED chip processing

- Existing cleanrooms in the LED industry are by far too dirty
- Existing equipment only for 2“ – 150 mm and with insufficient resolution
- Sharp decrease in cost with large diameter wafers and usage of existing CMOS lines

Thin-film (flip-chip) process

- Very thin devices needed because of aspect ratio
- Laser lift-off from sapphire, respectively grinding / etching away of silicon substrate

Mass transfer

- LED industry relies on sorting + binning
- Sheer number of LEDs requires „1 bin“
- Picking and placing of LEDs for 4K display would take 1,000 hours (42 days)
- Various mass transfer approaches
- Accuracy challenge

Inspection and repair

- Technological challenges for both detection and repair of bad (sub-)pixel
- Cost efficient repair will be possible only for a very tiny number of pixels
- Built-in redundancies as a solution?

*GaN for blue and green, while genuine red LEDs are not GaN but AlGaAs, GaAsP, AlGaInP or GaP based

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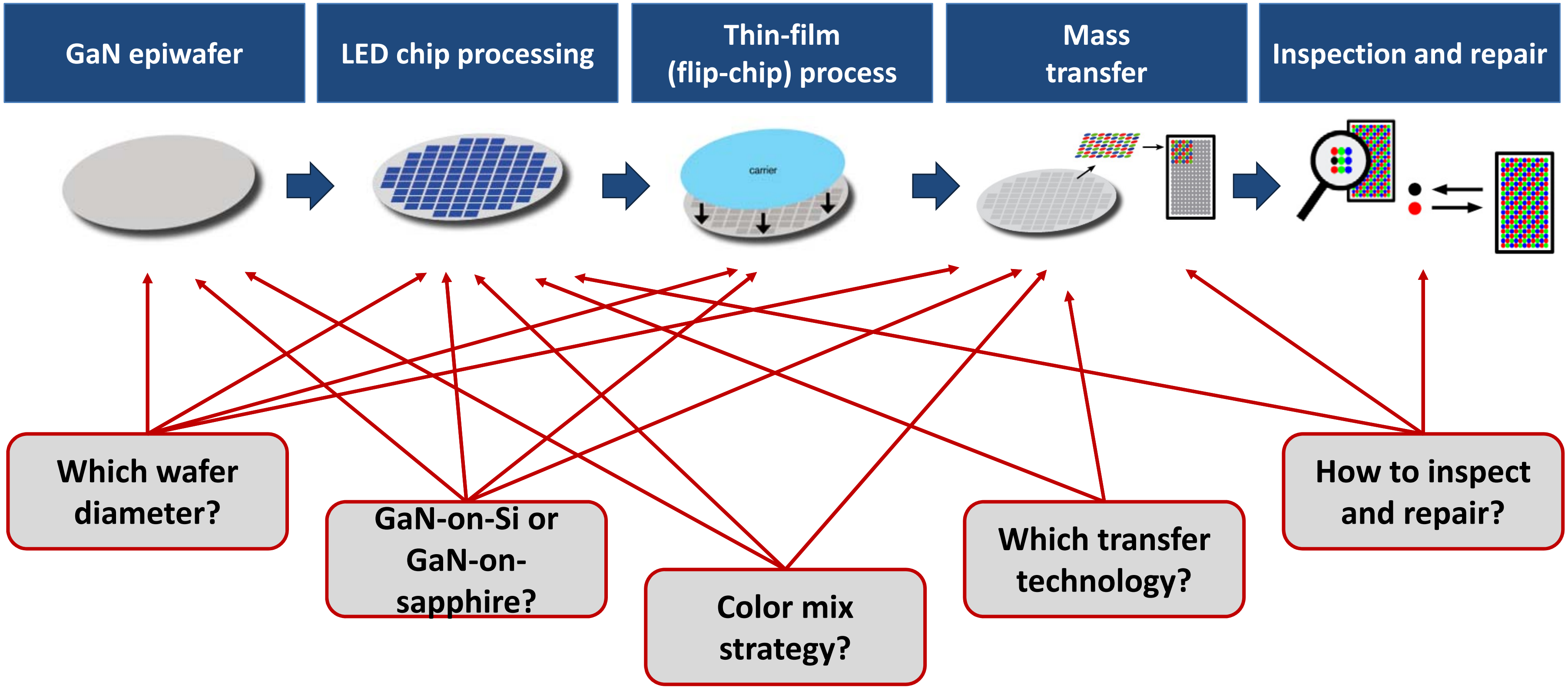
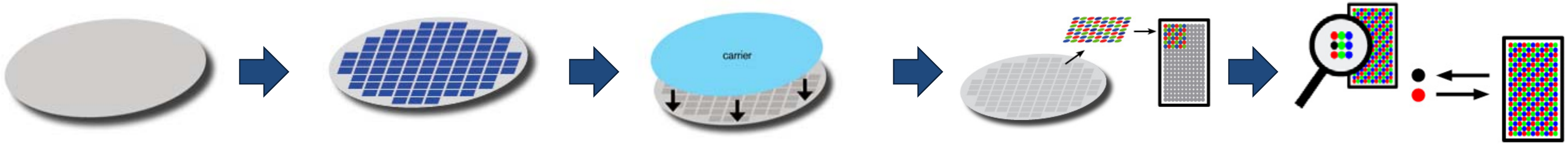
Technological key decisions for advancing into production



Let’s look on the wafer-related key decisions

GaN epiwafer	LED chip processing	Thin-film (flip-chip) process	Mass transfer	Inspection and repair



1. Which wafer diameter?

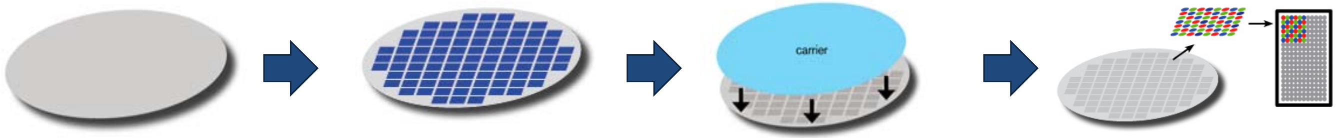
2. GaN-on-Si or GaN-on-sapphire?

3. Color mix strategy?

Large wafer will allow big leaps forward in cost and yield

1.

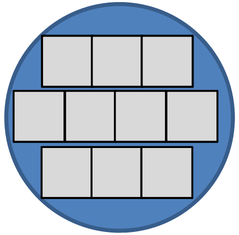
GaN epiwafer	LED chip processing	Thin-film (flip-chip) process	Mass transfer
Better uniformity and process control on single-wafer reactors	Cost per chip is reduced by larger wafers (and usage of 200 mm CMOS lines)	Lower cost per chip with larger diameter	More usable area for any given stamp size with larger wafers



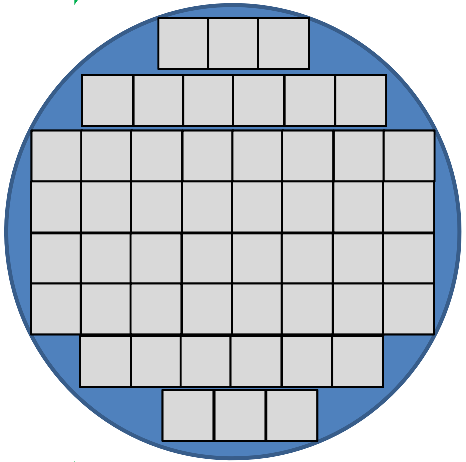
Useable area is much higher for given transfer stamp size

1.

100 mm → Total area is 4x larger → 200 mm



The larger wafer yields <u>25 % more usable chips</u> for the same cost!



10 stamps → Usable area is 5x larger* → 50 stamps

- Efficient micro LED manufacturing requires usage of a transfer stamp
- Higher transfer efficiency with larger transfer stamp
- Useable area for given stamp size is better with bigger wafers

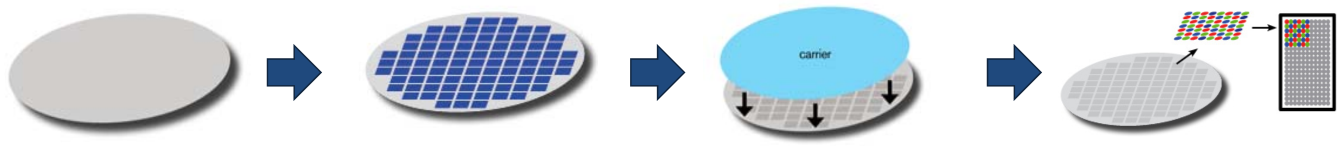
= Transfer stamp size (example)*

* Drawings not to scale and different stamp sizes give different levels of advantage

Large wafer will allow big leaps forward in cost and yield

1.

GaN epiwafer	LED chip processing	Thin-film (flip-chip) process	Mass transfer



Better uniformity and process control on single-wafer reactors	Cost per chip is reduced by larger wafers (and usage of 200 mm CMOS lines)	Lower cost per chip with larger diameter	More usable area for any given stamp size with larger wafers

Yield improved by single wafer processes, which become economic with large wafers

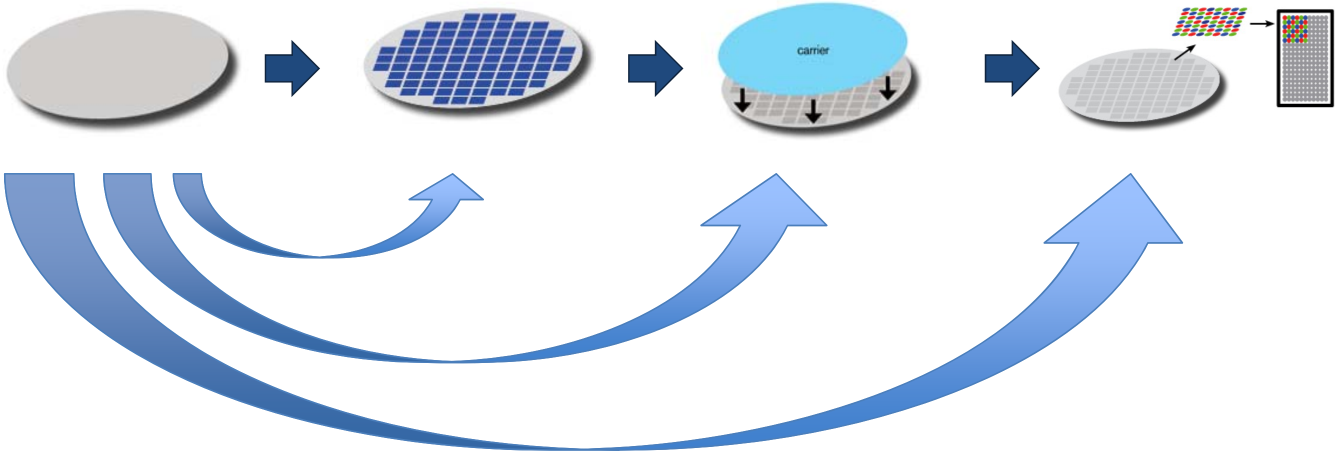
Apply silicon industry best practices to drive down cost

2.

	GaN-on-sapphire?	or	GaN-on-Si?
Diameter	Today most is still 100 mm and below, some 150 mm		200 mm available 300 mm will be possible
Cost of epiwafer	Only latest equipment is sufficient Possibly some advantage in growth time		Only latest equipment is sufficient Much cheaper substrate
Device processibility	Limited by thick substrate and strong bow		Long-standing problems like cracks, bow, strain, etc. have been solved
Thin-film (flip-chip) process	Laser lift-off and bonding are immature (problem increases with larger diameter)		Silicon substrate removal and bonding are established processes in silicon industry
Crystal quality	Has natural advantage as GaN grows nicely on sapphire		Top-layer crystal quality is now competitive with 2 x 10^{-8} TDD
Device performance	Is optimized after decades		Competitiveness of V_f and output power has been achieved
Uniformity	Challenge increases with wafer diameter		Scales with diameter if good strain engineering is applied

2.

GaN-on-sapphire? or GaN-on-Si?



More importantly, GaN-on-Si epiwafers enable yield-improvements and cost-savings in later manufacturing steps!

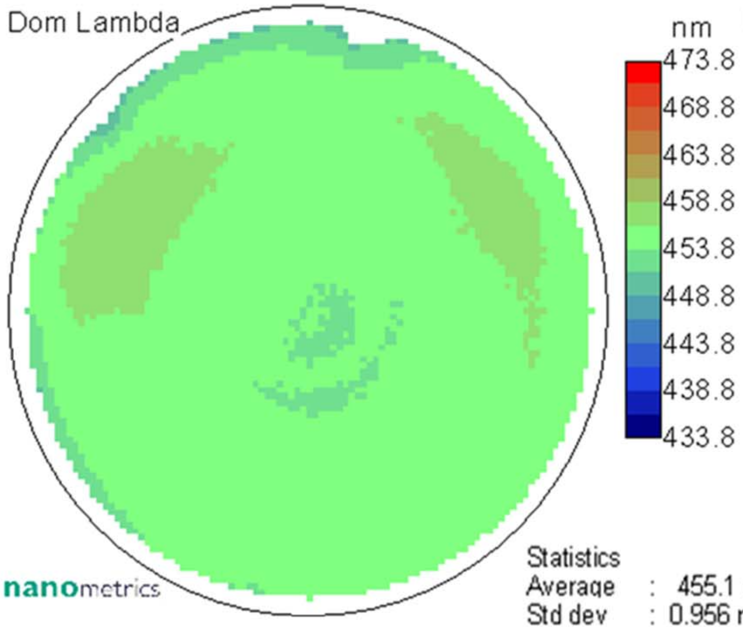
2. ALLOS‘ strain-management is successfully applied to 200 mm GaN-on-Si micro LED epiwafer

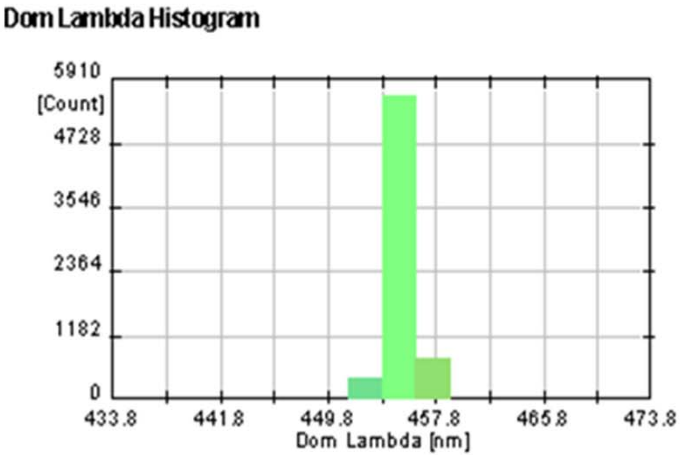

Typical 200 mm GaN-on-Si epiwafer of ALLOS for micro LED

- **Large diameter: 200 mm** ✓
- **Flat wafers: <30 µm at 725 µm thickness** ✓
- **No cracks, no residual strain** ✓
- **High crystal quality: TDD ~2 x 10^{-8}** ✓
- **Excellent emission uniformity: <1 nm sigma** ✓

Excellent emission uniformity < 1 nm is achieved on 200 mm GaN-on-Si micro LED epiwafer

2.





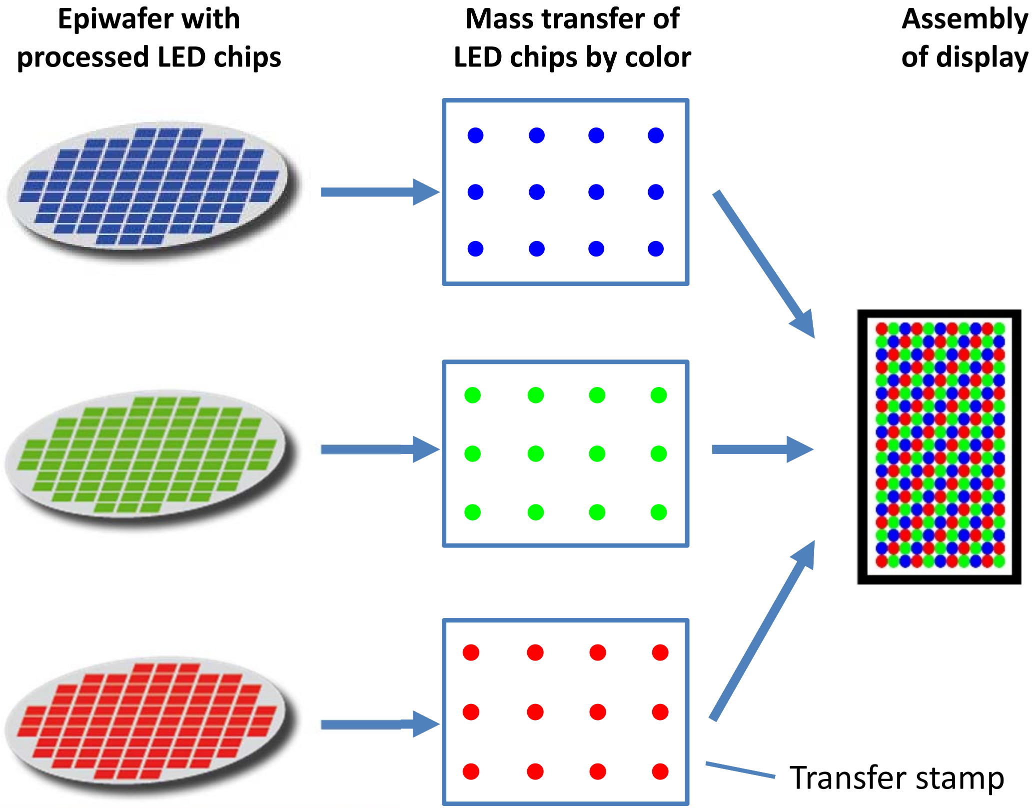
Max count : 5628 at 455.0 nm
Bin size : 2.5 nm
Mean : 455.1 nm
Median : 455.1 nm

Statistics
Average : 455.1 nm
Std dev : 0.956 nm (0.210 %)
Median : 455.1 nm
Min : 452.0 nm
Max : 457.6 nm

82.7% in 2.5 nm bin
99.0% in 5.0 nm bin

Color mix strategies I: genuine RGB technology

3-A



Pro

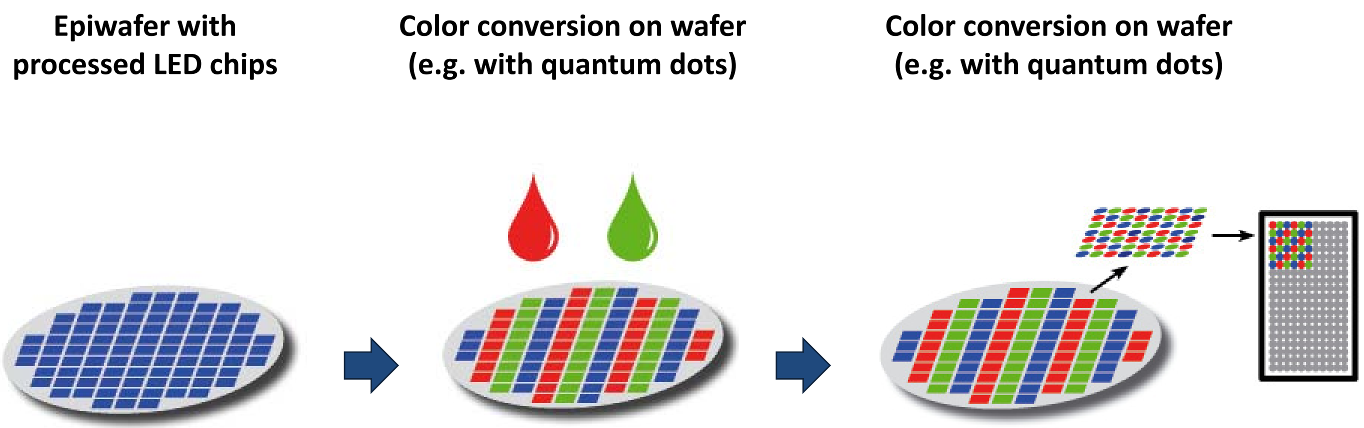
- Genuine LED chips have best possible brightness and color
- Fastest possible display response time

Con

- Requires a separate transfer step for each color
- Red only available in maximum wafer size of 150 mm

Color mix strategies II: Color conversion on wafer

3-B



Pro

- Only one transfer step for all three colors
- Color conversion in wafer processing line might be most cost-efficient

Con

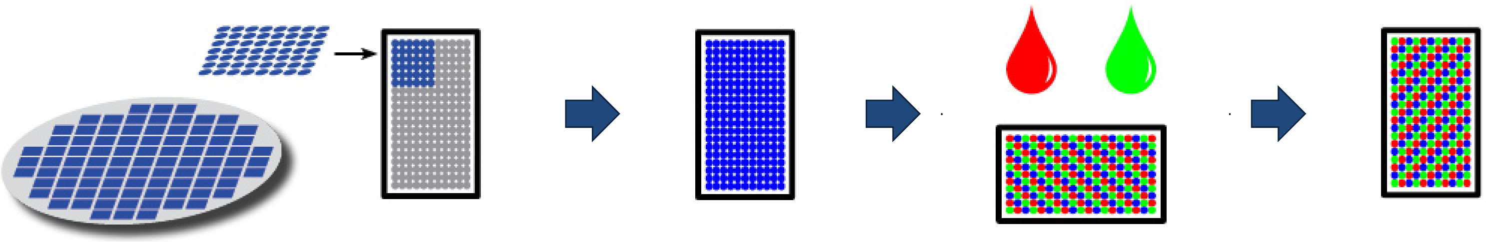
- Color conversion of such tiny chips is not yet established
- Some light is lost through color conversion
- Color conversion accuracy might require extra distance between LEDs on wafer

Color mix strategies III: Color conversion on display

3-C

Transfer three blue LED chips for each pixel to the display

Apply color conversion on display



Pro

- Only one transfer step for all three colors
- Sufficient pitch between LED chips on display allows precise color conversion
- Pitch between LED chips on wafer can be very small

Con

- Color conversion of such tiny chips is not yet established
- Some light is lost through color conversion

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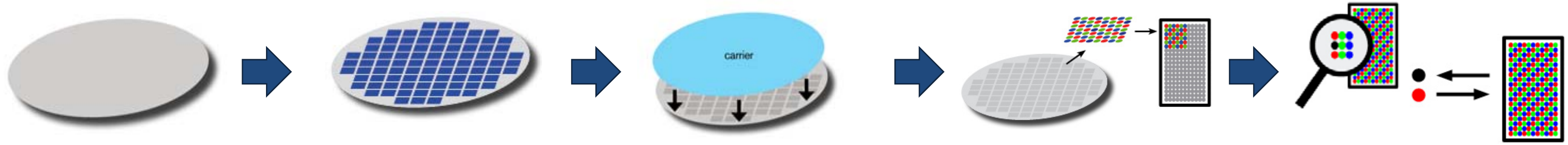
Who will bring micro LEDs into production, and how?

GaN epiwafer	LED chip processing	Thin-film (flip-chip) process	Mass transfer	Inspection and repair



Made by established LED makers?	IP and technology from LED companies, production at CMOS foundries	Display and device makers and new comers will drive technology and market from here
• Material of choice will be 200 mm GaN-on-Si • Investing in latest generation epi reactors	• Upgrade existing thin-film LED manufacturing processes and IP • Device processing at 200 mm lines at foundries • Move to single wafer processes to achieve end-to-end yield needed	• Start-ups and global technology leaders alike develop new approaches • Manage end-to-end yield • Realize consumer benefits on new devices • Lower entry-barriers then e.g. in OLED

Thank you for your attention and your feedback!

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bs@allos-semiconductors.com

ALLOS Semiconductors GmbH
Burkhard Slischka, CEO
Breitscheidstrasse 78
01237 Dresden, Germany

Office: +49-351-212 937-0
Fax: +49-351-212 937-99

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