Integrated MicroLED Assembly and QD Colour-Conversion Technologies for Microdisplays

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Eindhoven, 15.09.2026

Founding of the Fraunhofer-Gesellschaft

In Munich on March 26, 1949

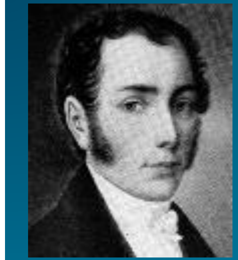
As part of Germany's reorganization and expansion of its research infrastructure, the Fraunhofer-Gesellschaft was founded in Munich on March 26, 1949.

Joseph von Fraunhofer

The new research organization named itself after Joseph von Fraunhofer (1787–1826), a Munich scholar who enjoyed equal success as a researcher, inventor and entrepreneur.

Our eponym

Joseph von Fraunhofer



Joseph von Fraunhofer

Discoverer of the Fraunhofer lines in the solar spectrum

New methods for grinding lenses

Director and partner of a glassworks

Researcher

Inventor

Entrepreneur

The Fraunhofer-Gesellschaft

Research and development contracted by industry and government

mp3 music format, white LEDs, high-resolution thermal-imaging camera

Research budget:
approx. 3 billion euros annually

Fraunhofer-Gesellschaft

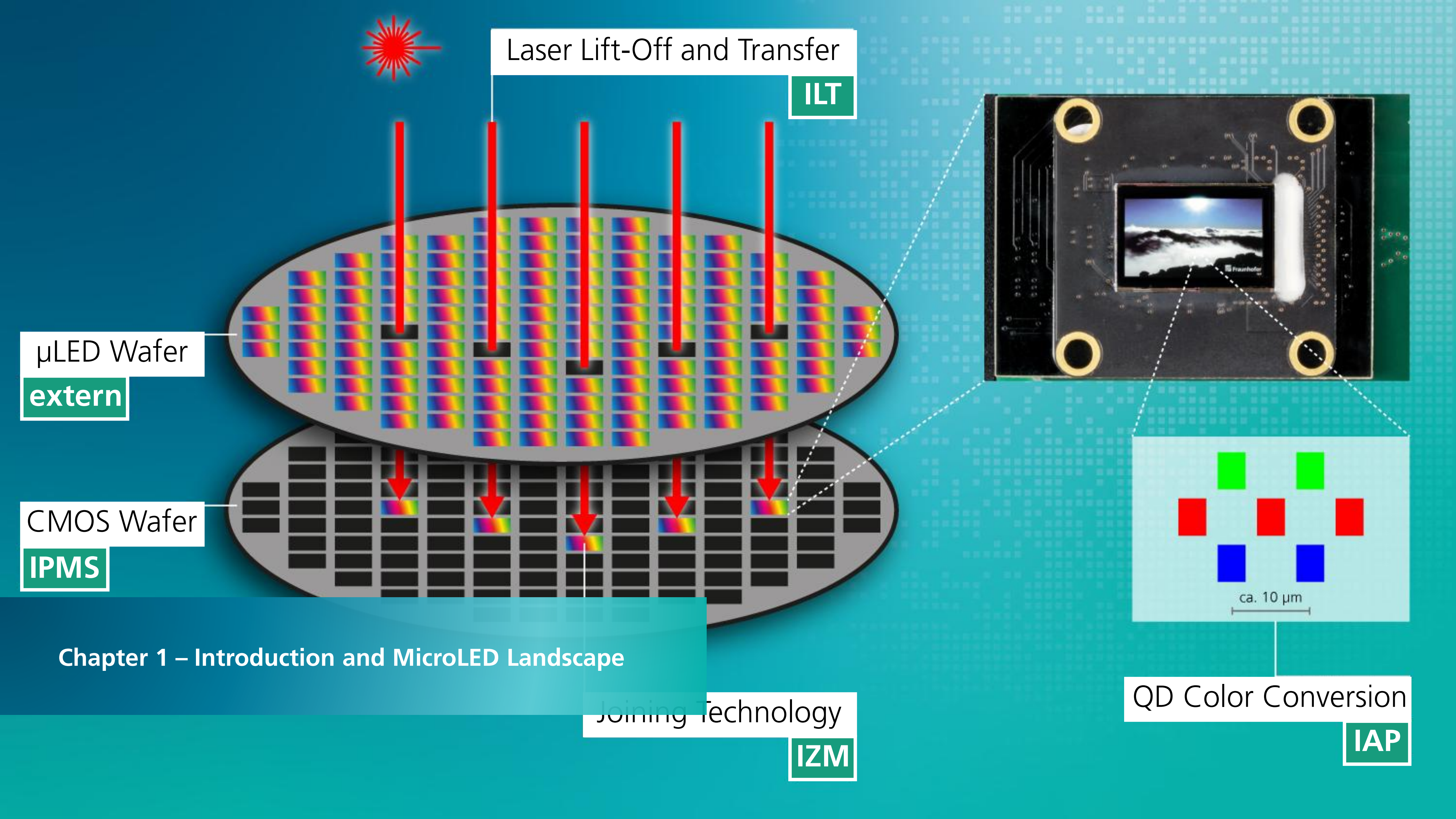
The Fraunhofer-Gesellschaft's global network

8 legally independent foreign affiliates
1 *opening soon*

Active collaboration with partners in roughly **90** countries

5 representative offices build bridges to local markets around the world

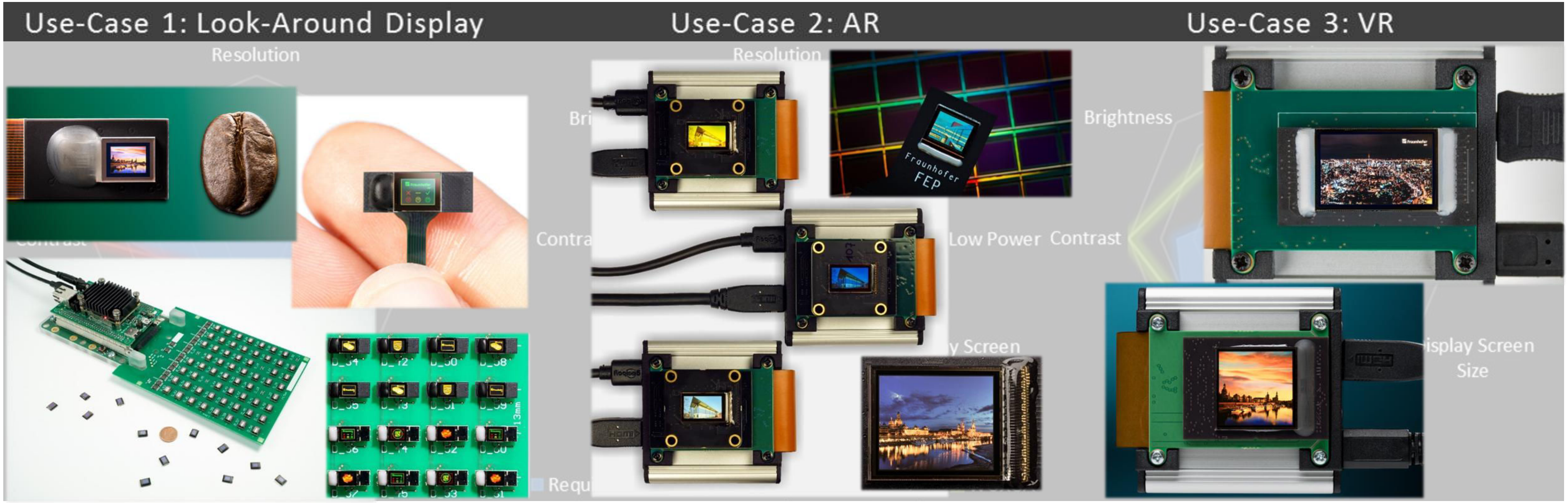
Fraunhofer



Chapter 1 – Introduction and MicroLED Landscape

Typical Micro-Display Use Cases – System Examples

Microdisplay examples by Fraunhofer IPMS



QVGA 0.18" low-power microdisplay (various colors)
0.18" 720x540 (full color)
0.18" 1440 x 1080 (high resolution mono)

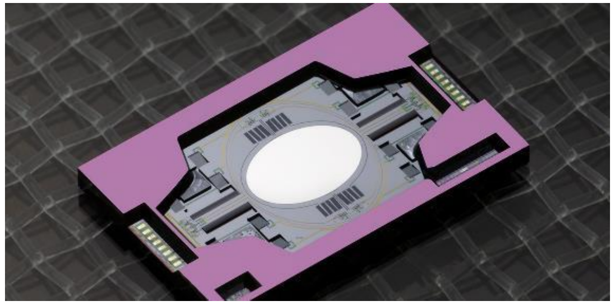
SVGA 0.61" bidirectional microdisplay
720p 0.64" microdisplay
SXGA 0.62" microdisplay (high brightness)

WUXGA 1" microdisplay
2k 1.1" microdisplay (high brightness)

Introduction Microdisplay Technologies

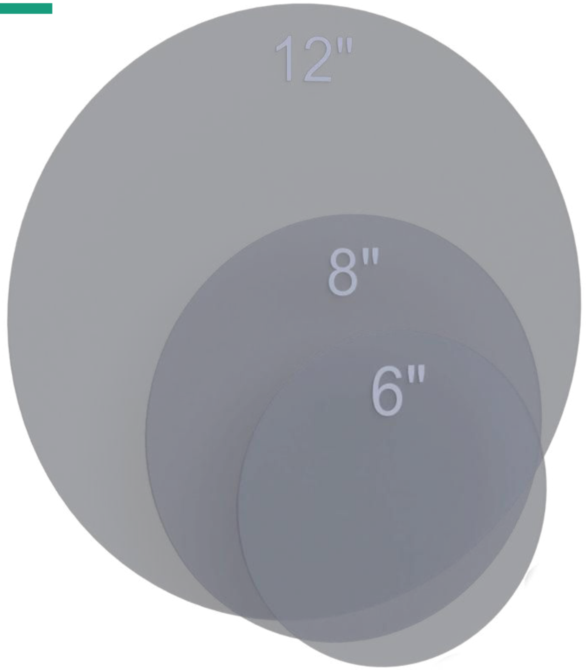
- Microdisplay Technology
  - emissive
    - OLED-on-Silicon
    - microLED-on-Silicon
  - reflective
    - LCOS
    - DMD/DLP
  - transmissive
    - LCD
  - scanning
    - MEMS scanner

this master-class



- Confidential -

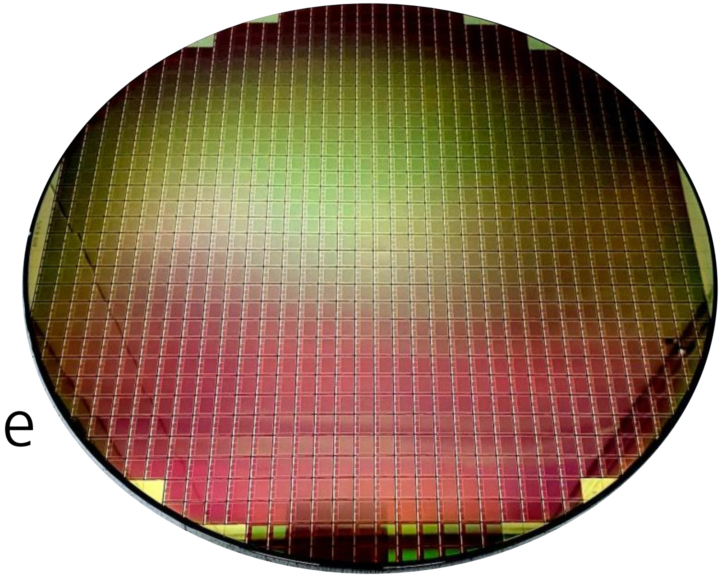
Building Blocks for a Display



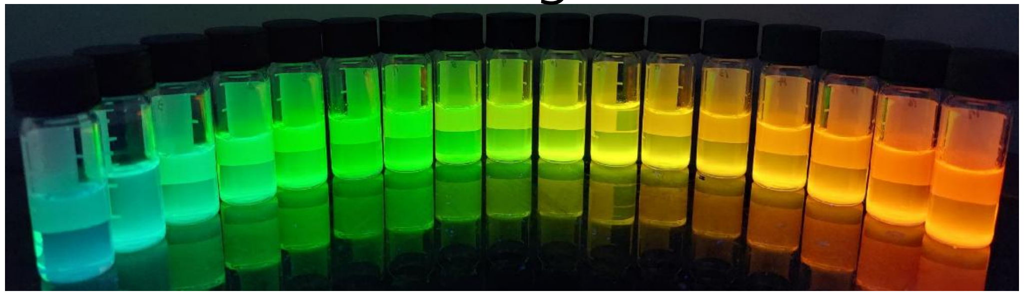
- Majority 6” and 8” GaN-on-Sapphire
- Capabilities for 12” GaN-on-Silicon

µLED Wafer

Backplane



Coloring



Fraunhofer
IPMS

Fraunhofer Institute for Photonic Microsystems IPMS

Chapter 2 – CMOS Backplane

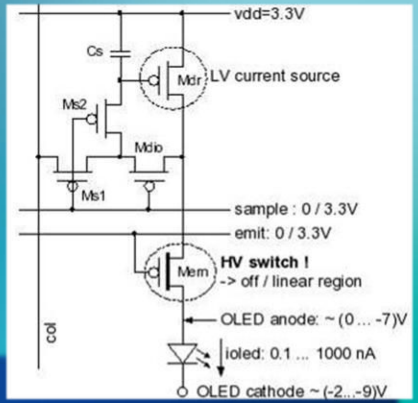
Division Microdisplays and Sensors

Dr. Uwe Vogel
Division Director Microdisplays & Sensors

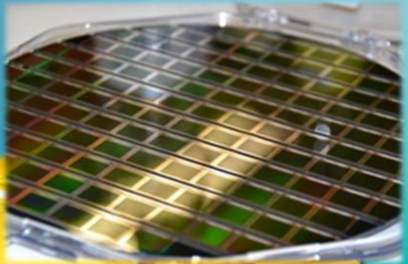
Philipp Wartenberg
Head of Department IC and System Design

Bernd Richter
Head of Department Microdisplay and Sensor Technology

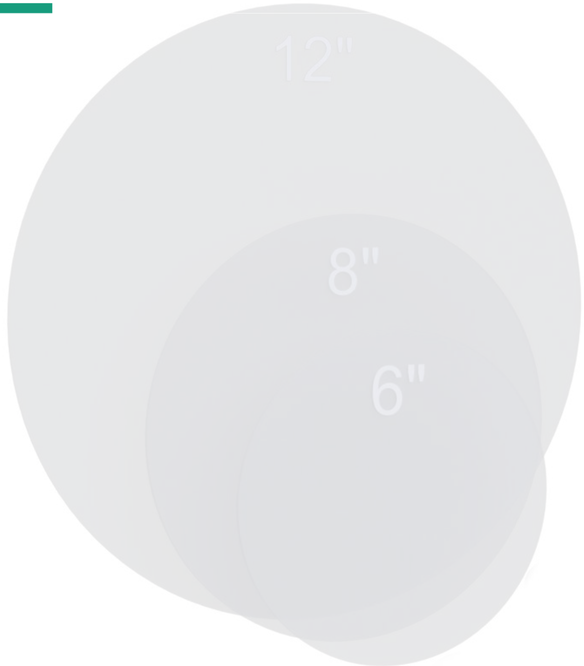
IC design
(backplane)



Optoelectronics
(frontplane)

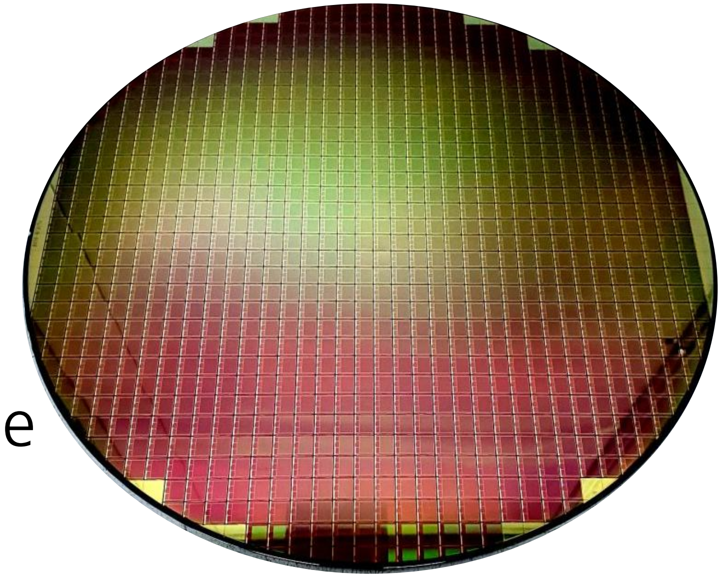


Building Blocks for a Display



µLED Wafer

Backplane



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- Capabilities for 12″ GaN-on-Silicon

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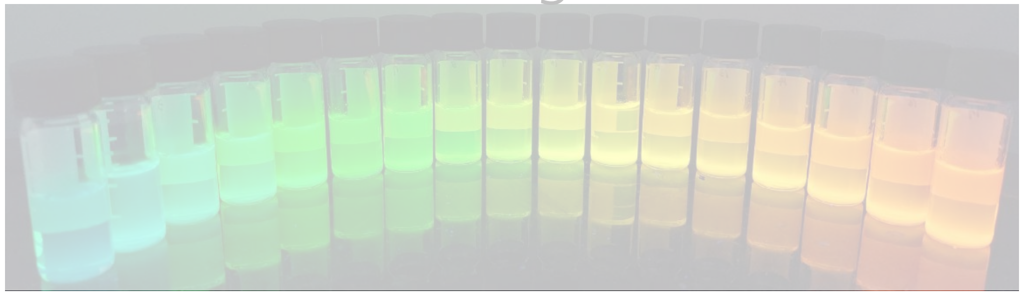
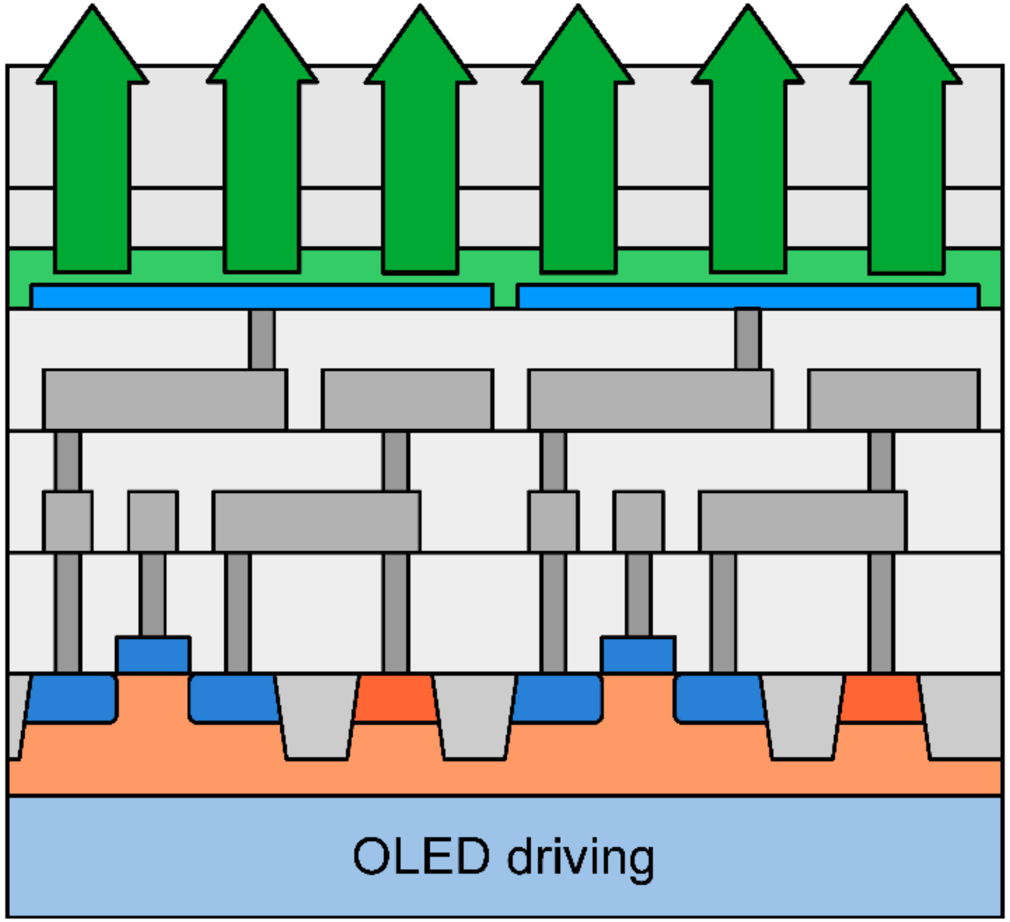


Introduction Microdisplay Technologies

- **Frontplane**
  - Monolithic integration of organic stacks or uLEDs on silicon
  - **OLED/uLED** for light emission

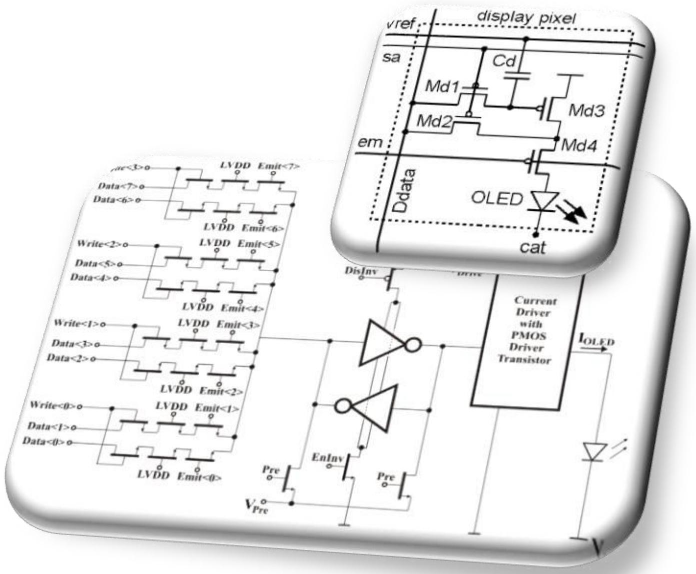
- Silicon-**Backplane**
  - State-of-the-art microelectronics
  - Small pixel size typ. <10 µm
  - High resolution, e.g. WUXGA (HD+)
  - Integration of sensors, driving electronics, processing…

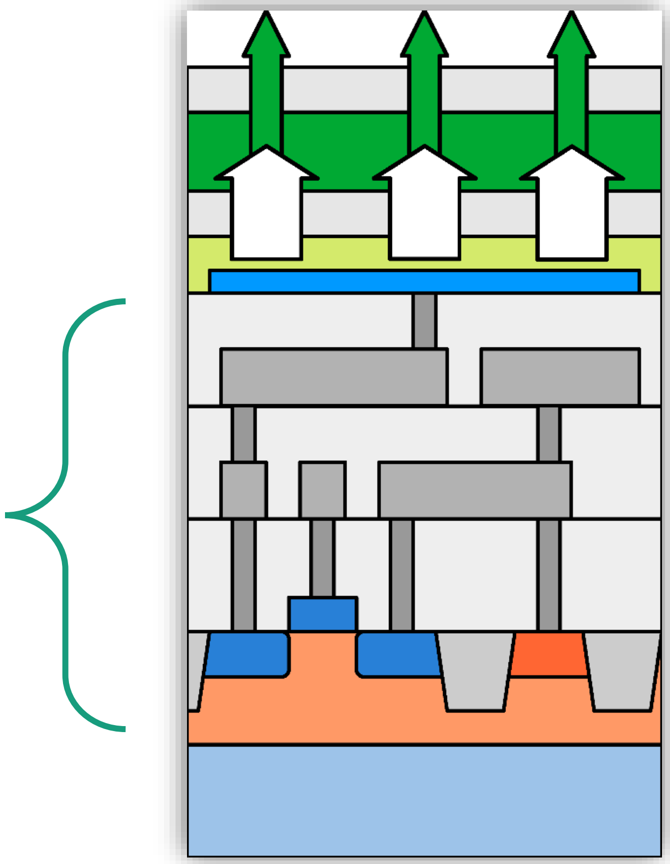


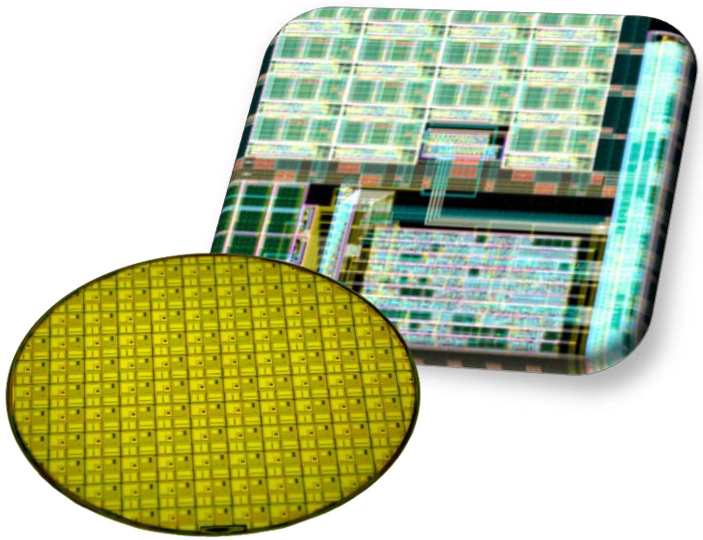
Introduction Microdisplay Technologies

Pixel Circuit

- All devices for driving and or read-out must fit under pixel electrode





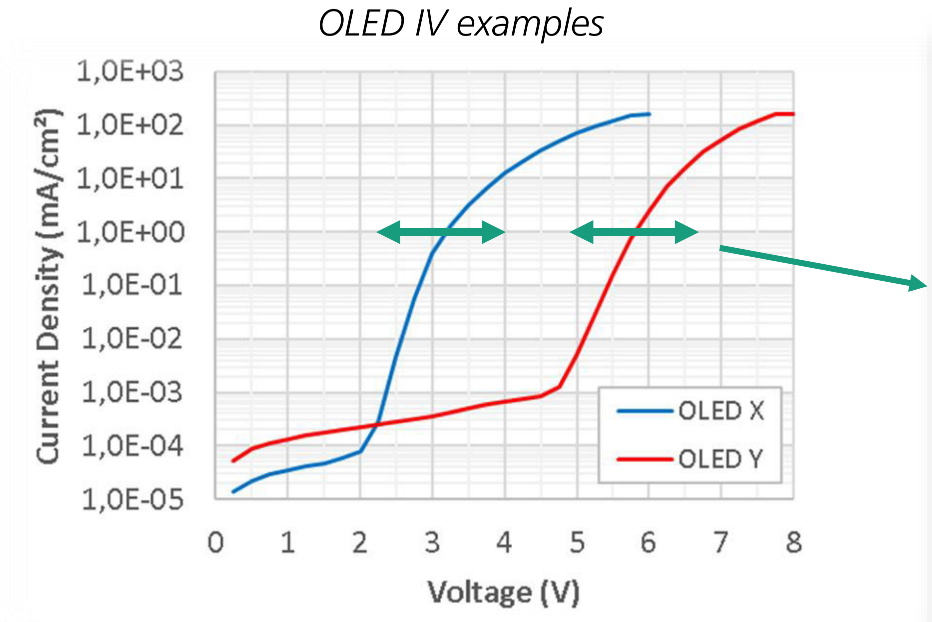


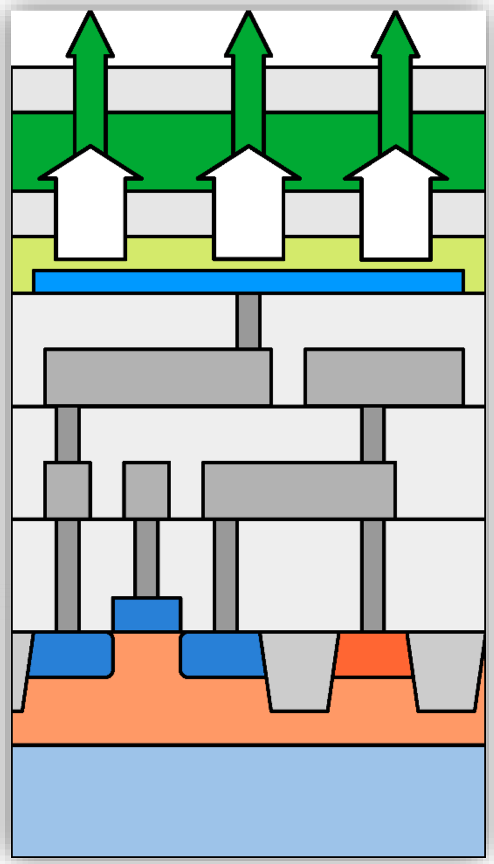
typ. 200 ... 300 mm

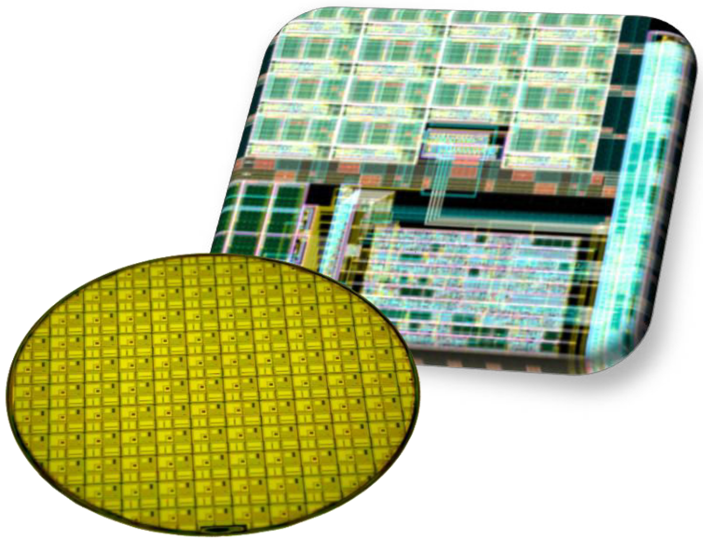
Silicon Design

- Modern CMOS technologies, typ. 180 ... 28nm
- High-res displays and imagers

Introduction Microdisplay Technologies







Pixel Circuit

- Voltage swing of CMOS transistors must match OLED/uLED-IV-characteristic

Silicon Design

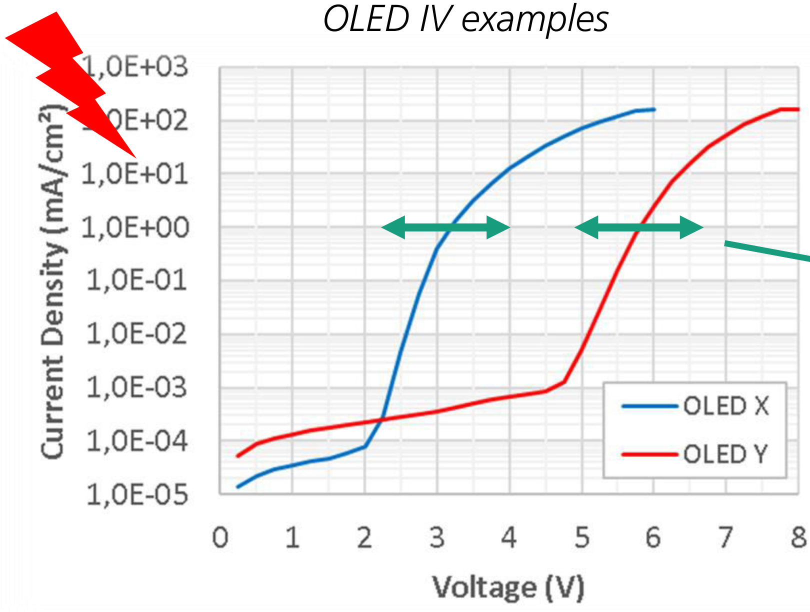
- Modern CMOS technologies, typ. 180 ... 28nm
- High-res displays and imagers

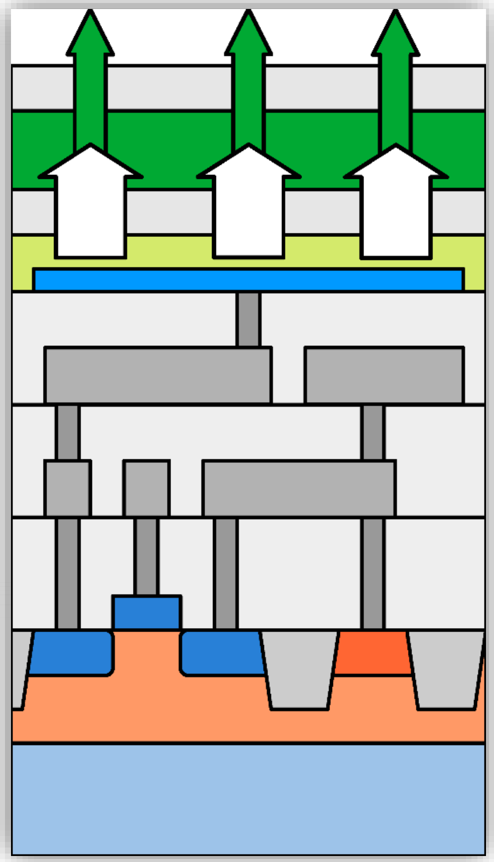
Fraunhofer IPMS

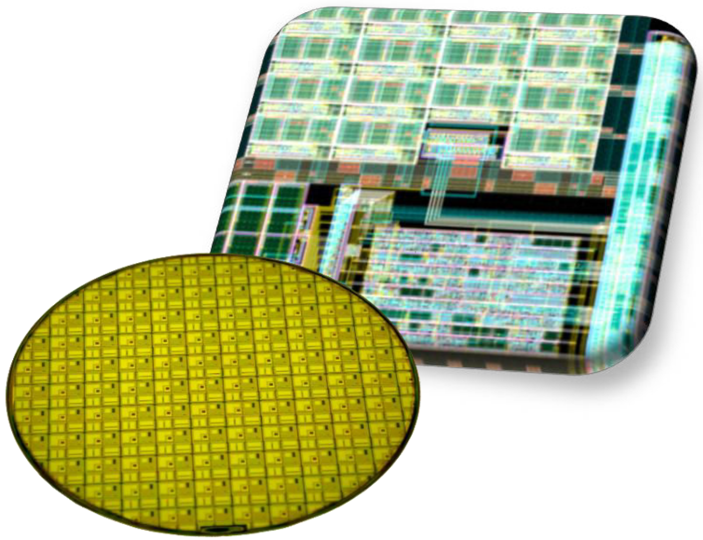
Introduction Microdisplay Technologies

uLED requires lower voltages, BUT much higher current densities beyond 10A/cm²

OLED IV examples







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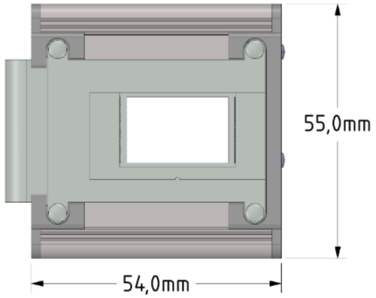
Fraunhofer IPMS

WUXGA OLED Backplane – Key Facts

Display-Parameter	JU*1010
Resolution	1920 x 1200 (WUXGA)
Screen Size	1”
Chip Size	24.68 mm x 15.2 mm
Frame Rate	60Hz, 75Hz, 90Hz, 120Hz
Contrast Ratio	>100.000:1
Pixel Setup	RGBW or monochrome
Pixel Pitch (RGBW)	11 µm x 11 µm
Pixel Pitch (subpixel)	5.5 µm x 5.5 µm
Color Depth	24-bit
Display Interface	48-bit RGB digital
Display Brightness	300 cd/m² (typ.)
Temperature Range	-40°C … + 65°C

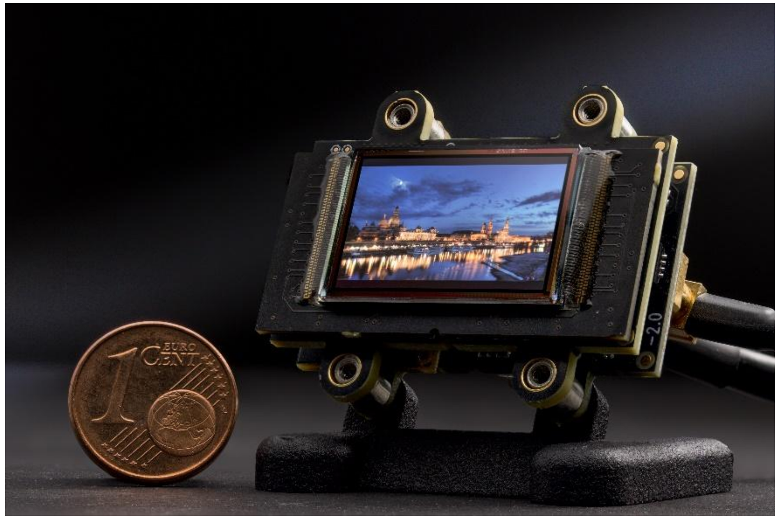


EvalKit-Parameter	Value
Interface	HDMI
Power	USB
Display Package	COB
Chip Configuration	Graphical User Interface (Win)
Operation Mode	Connects as screen

Backplane Challenges Modification

Challenges

- Limited space by given sub-pixel size of 5.5x5.5um²
- High-current typically means bigger driver / more area



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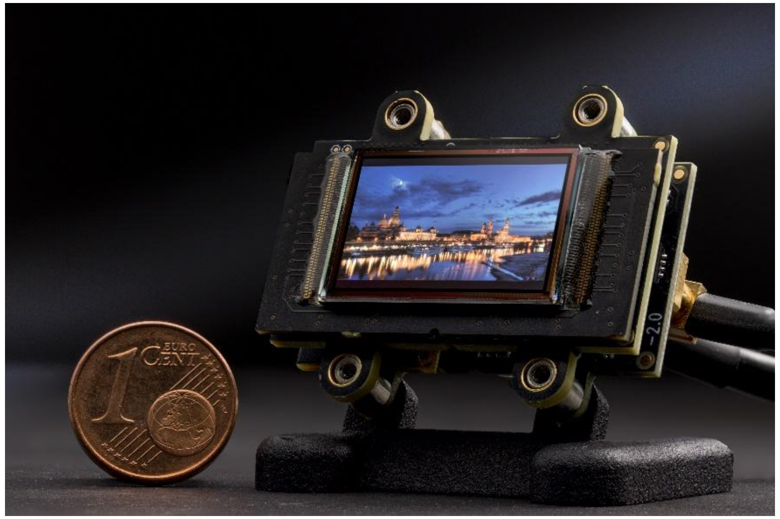

Solutions

- Introduction of new low-Vth transistor pixel architecture
- Modification of driver architecture

Backplane Challenges Modification

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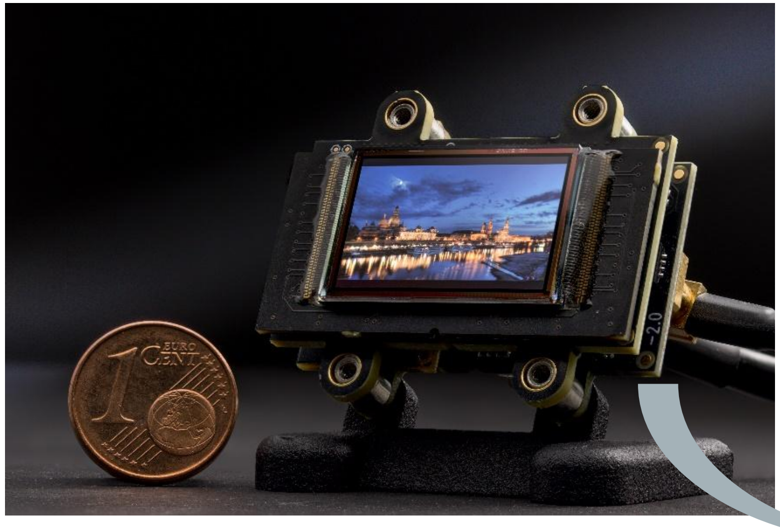

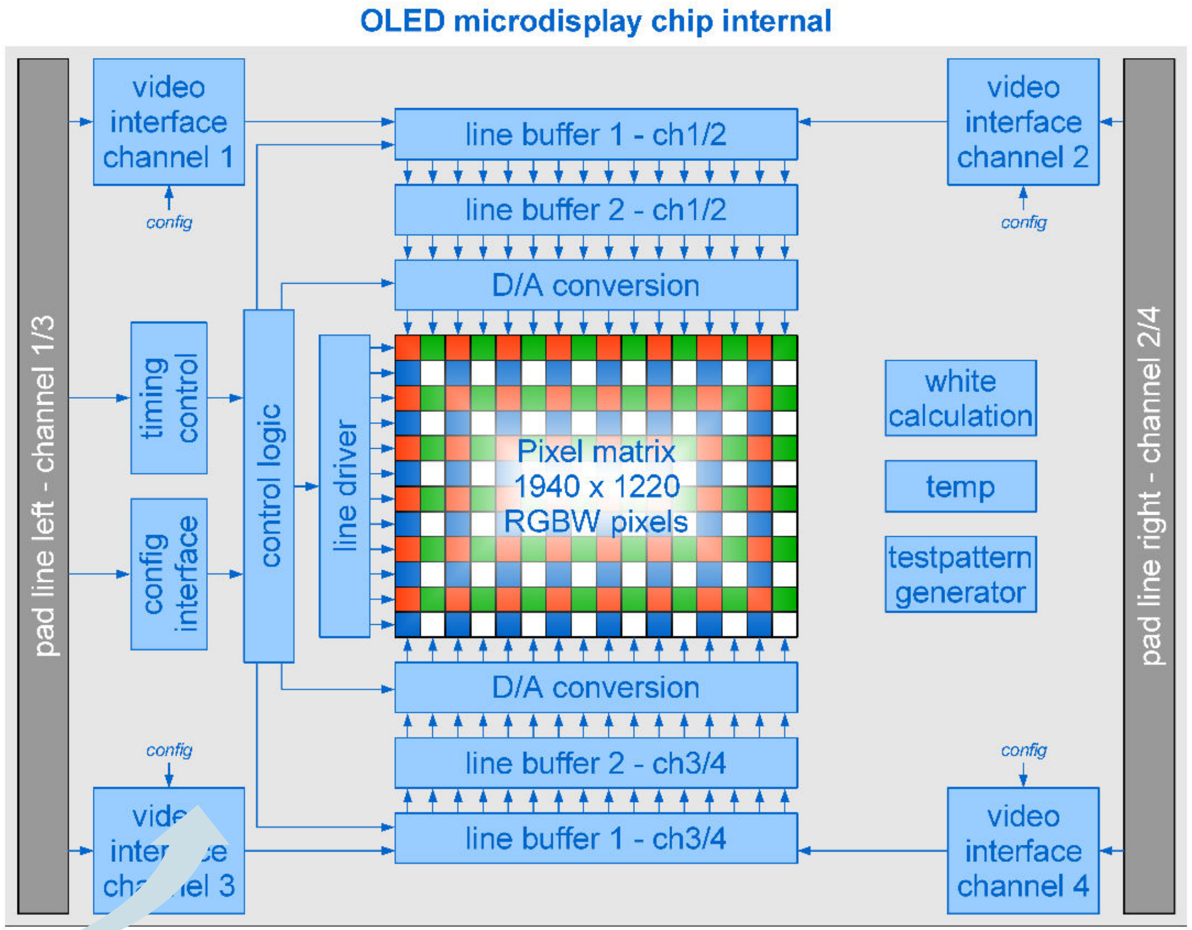

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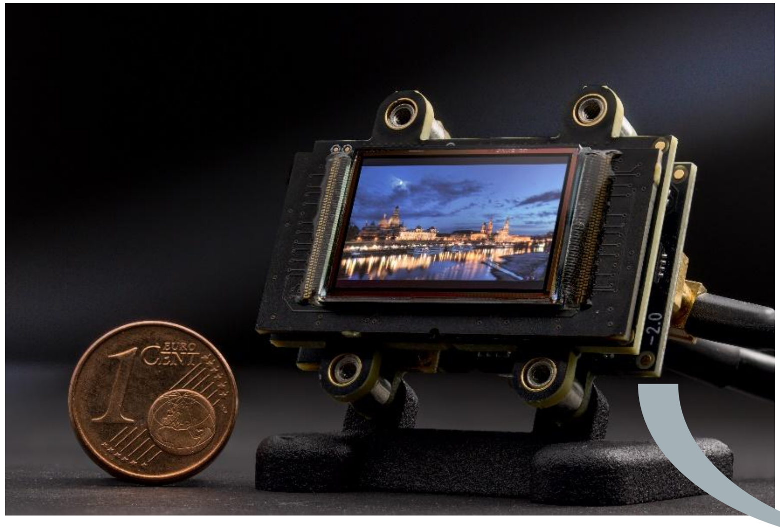
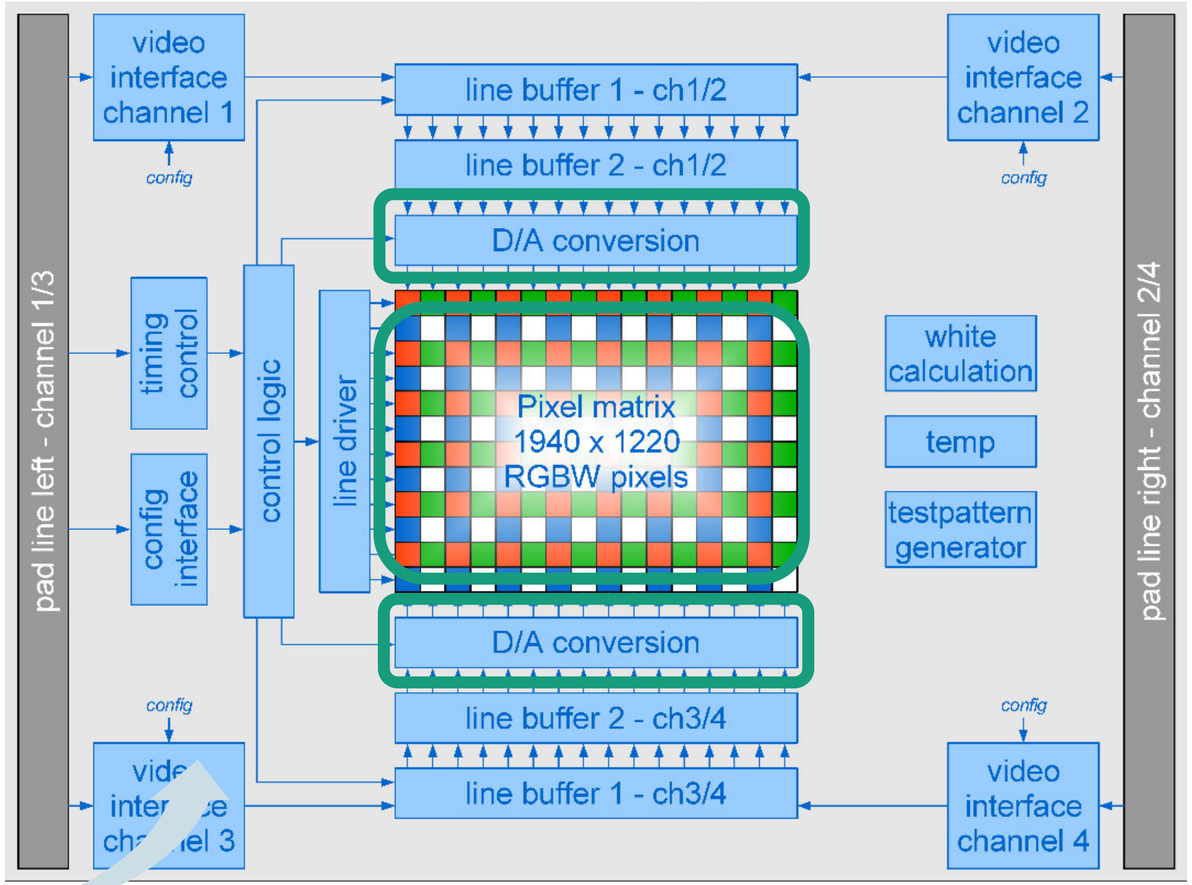


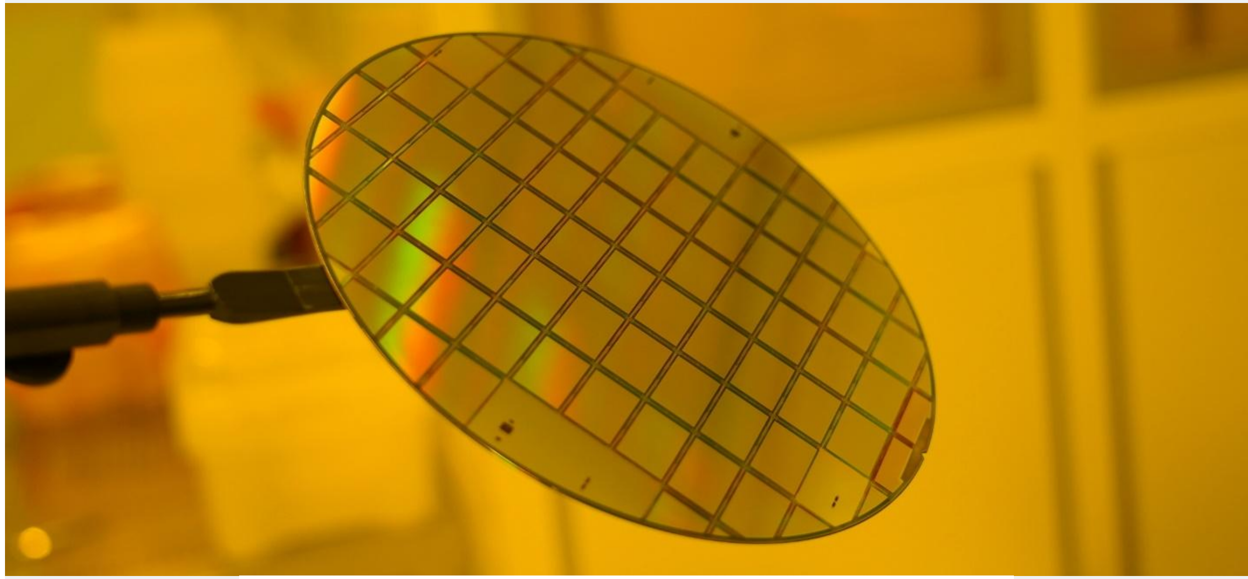
OLED microdisplay chip internal

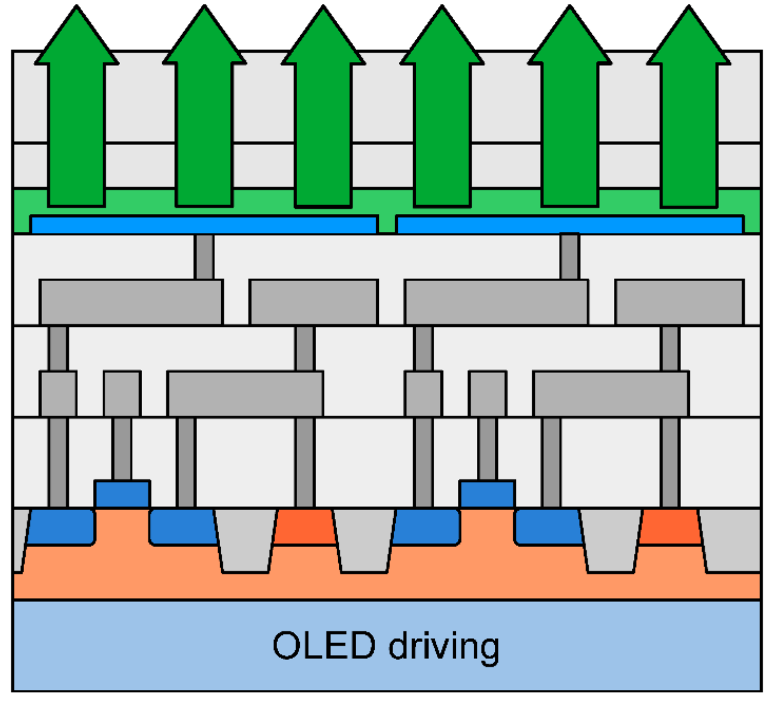


Processing

Wafer manufacturing

- **Backplane:** commercial CMOS foundry 180nm in customized variant
- **Frontplane:** initial tests with OLED frontplane

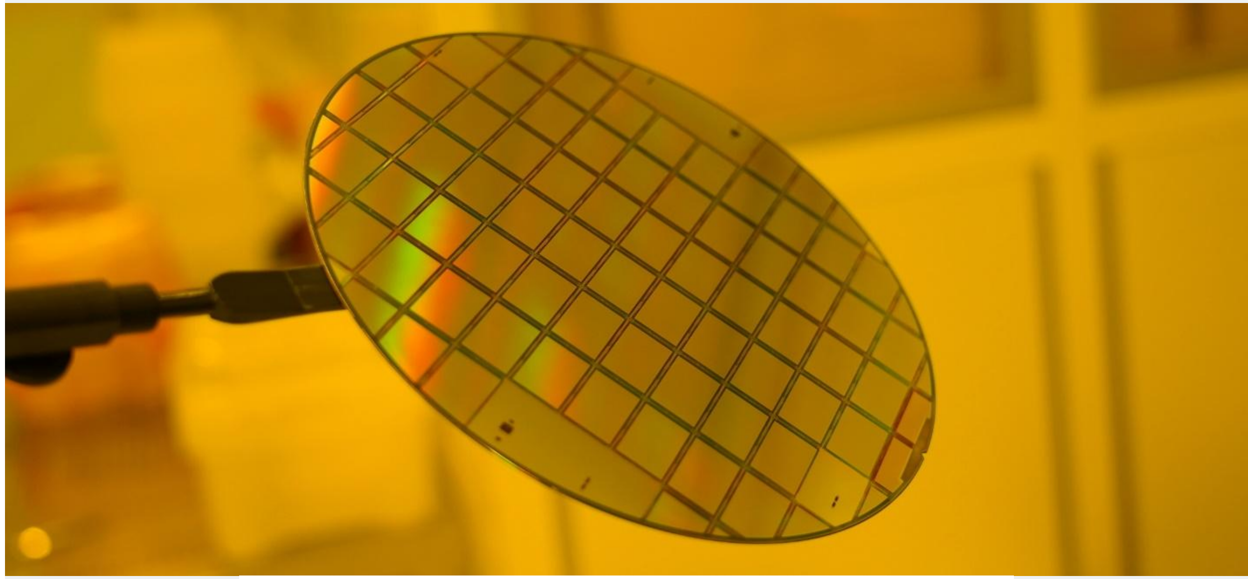


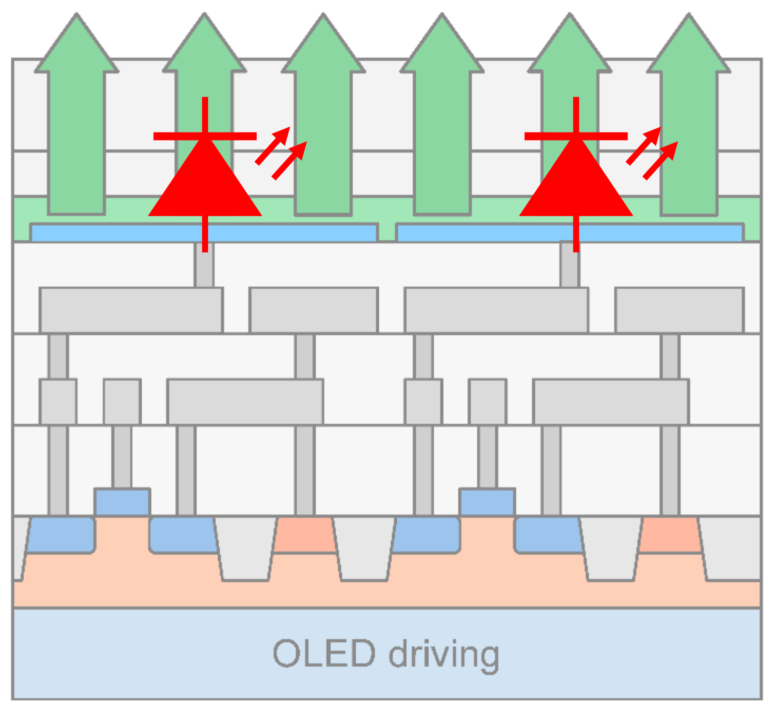


Processing

Wafer manufacturing

- **Backplane:** commercial CMOS foundry 180nm in customized variant
- **Frontplane:** initial tests with OLED frontplane
  - **Version1:** stable red OLED

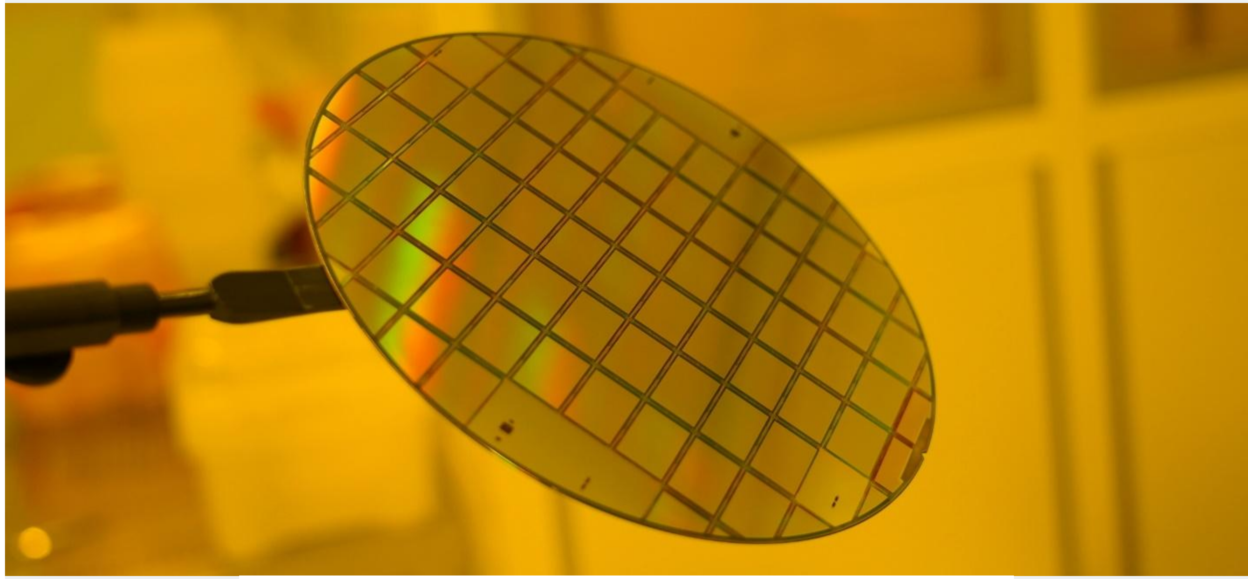


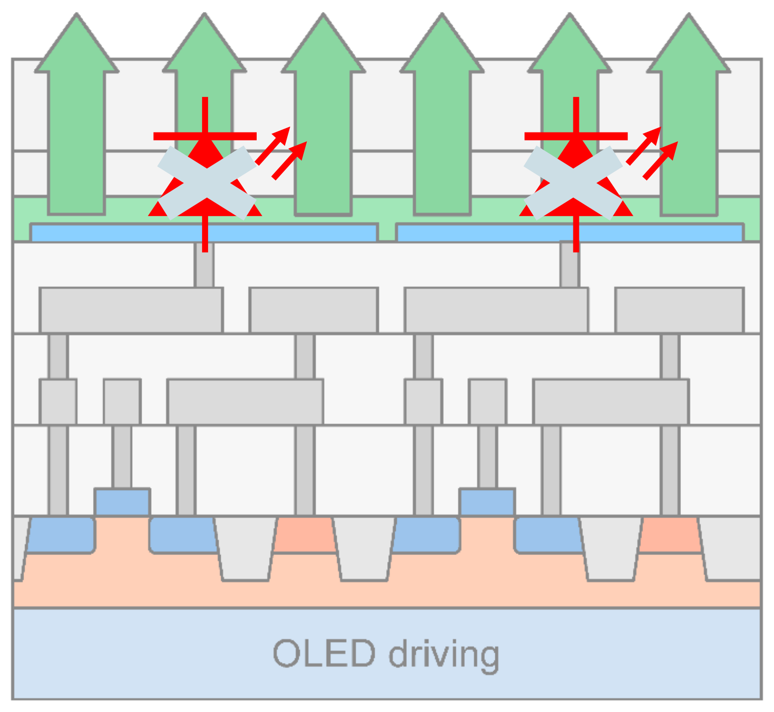


Processing

Wafer manufacturing

- **Backplane:** commercial CMOS foundry 180nm in customized variant
- **Frontplane:** initial tests with OLED frontplane
  - **Version1:** stable red OLED
  - **Version2:** “cathode-only” device for electrical characterization

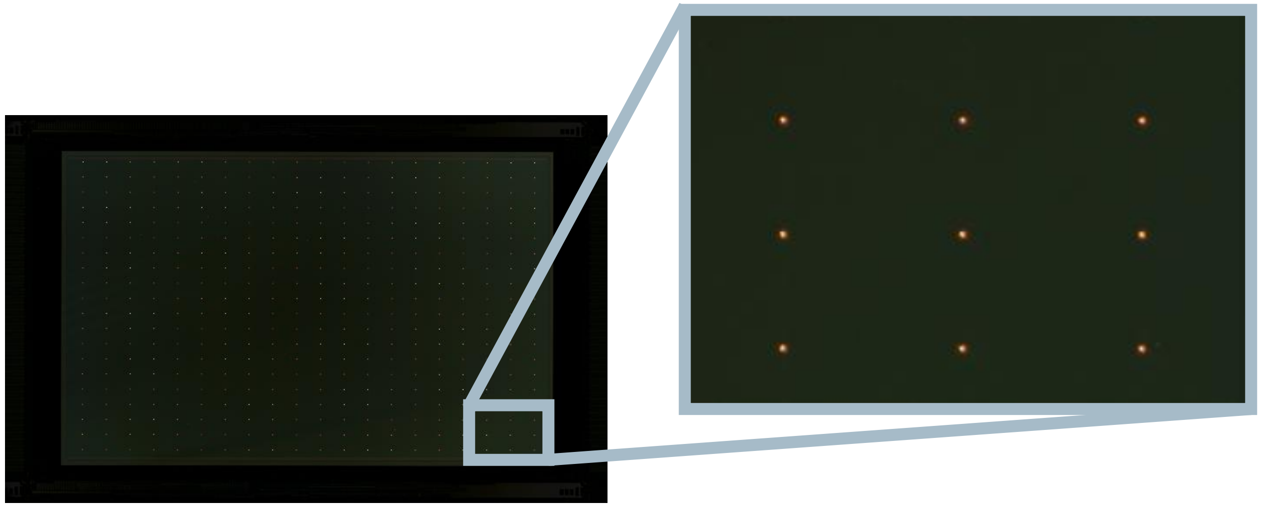




Characterization Setup

Electro-optical wafer level characterization

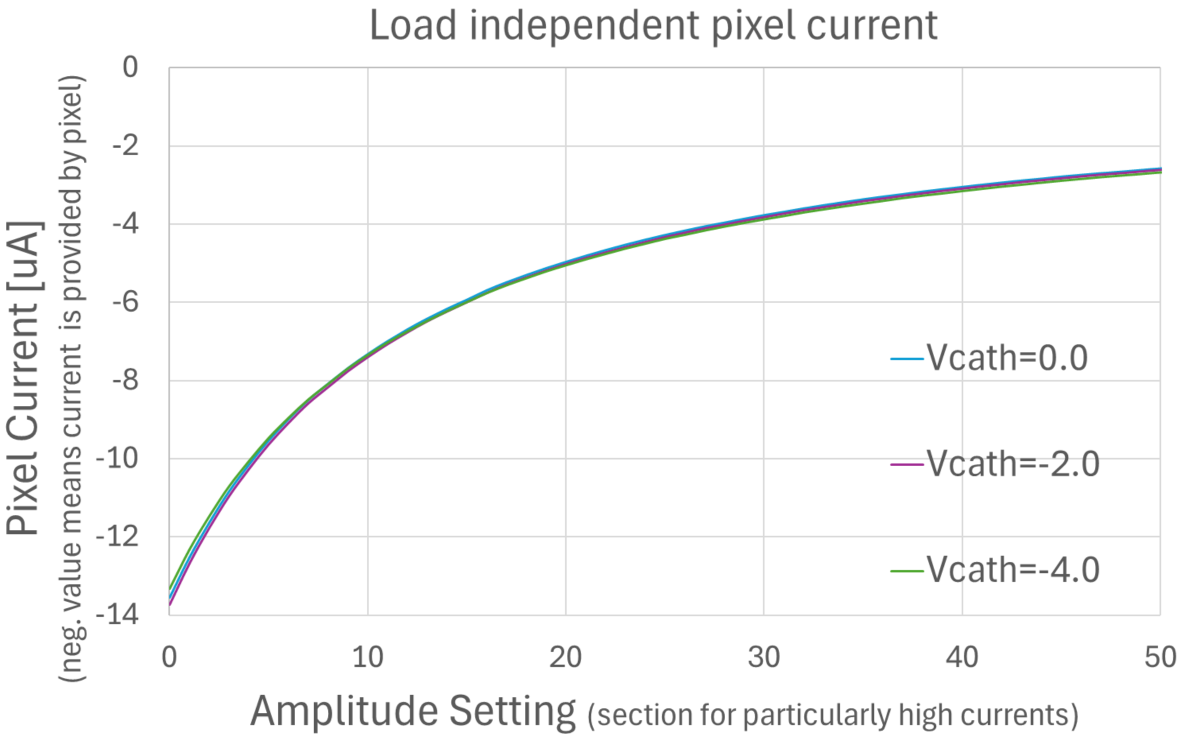
- Image characterization using red OLED
  - initial validation of data processing and driver modifications
  - 20 x 20 pixel pattern spread across the entire screen
  - Use same pattern for both devices



Characterization Setup

Electro-optical wafer level characterization

- Electrical characterization using "cathode-only"
- Temperature characterization -40°C…85°C



Fraunhofer IPMS

Characterization Setup

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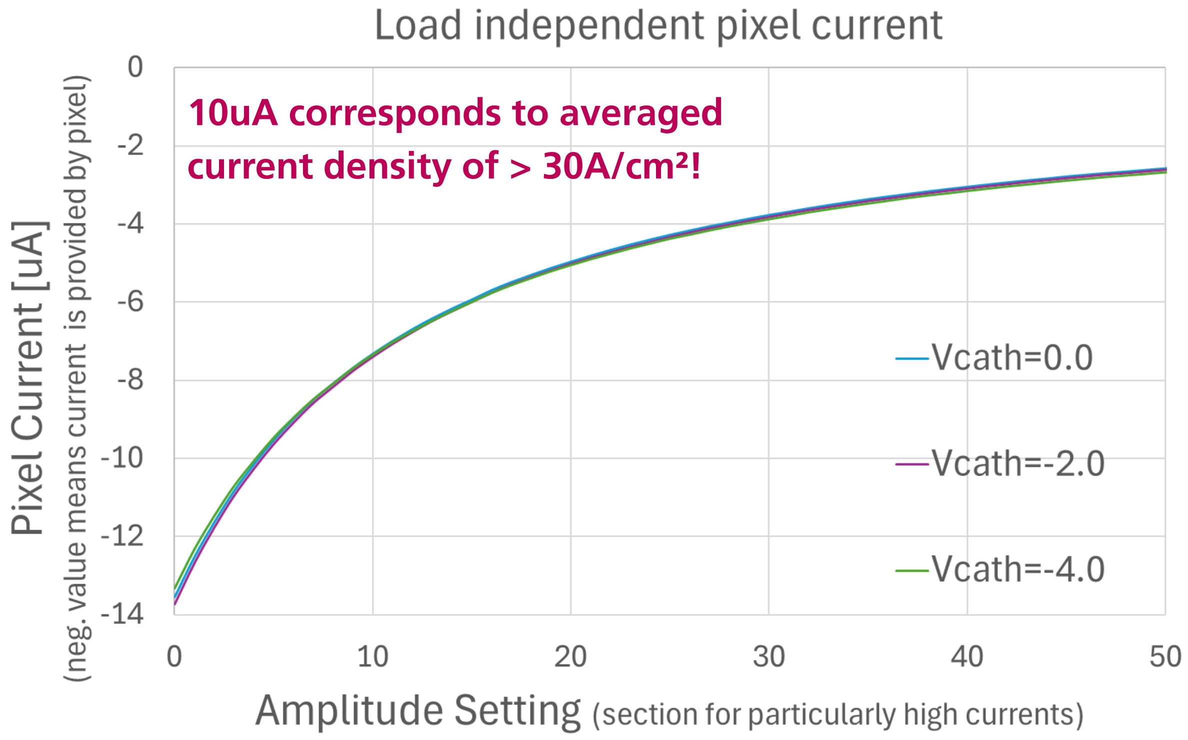
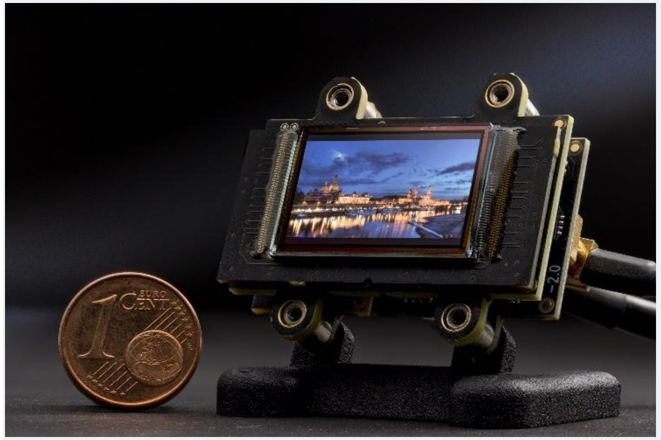


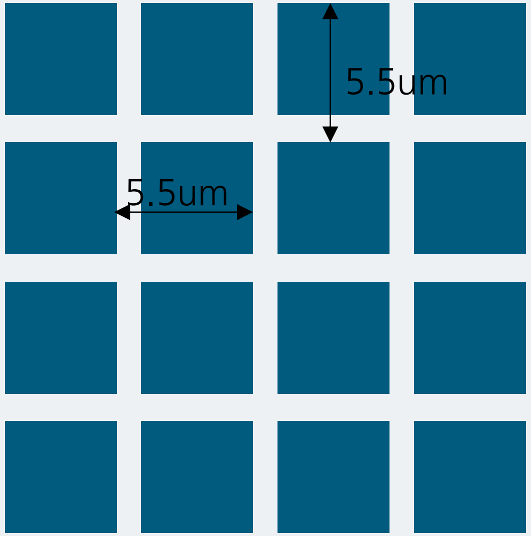
Fraunhofer IPMS

Development Plattform

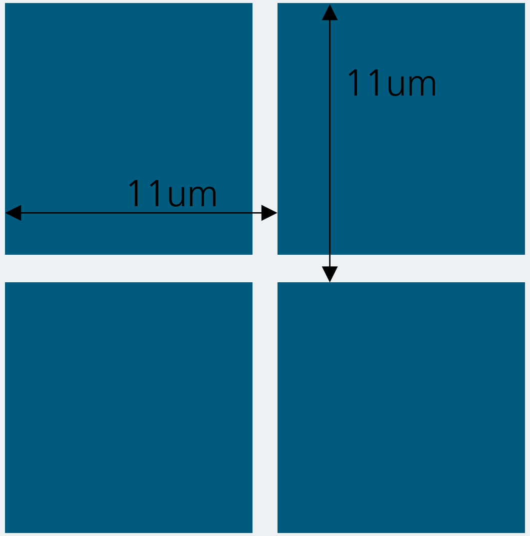
Design modification

- Design modifications enables integration of **different sized uLEDs** and assembly techniques (backplanes with **5.5um/11um/22um pitch**)
- Even higher current densities in uLED
  - Values presented so far are based on a theoretical 100% fill factor, i.e. real peak current density is **defined by uLED design**
- Established **driver platforms** accelerates customer specific developments
  - HDMI, LVDS, MIPI, SDI available
- Extensive **infrastructure and tools available** for further developments (200mm/300mm clean room)





Pixel binning including driver binning



Fraunhofer IPMS

uLED Frontplane Integration (1)

Initial successful green uLED integration

VUZIX®

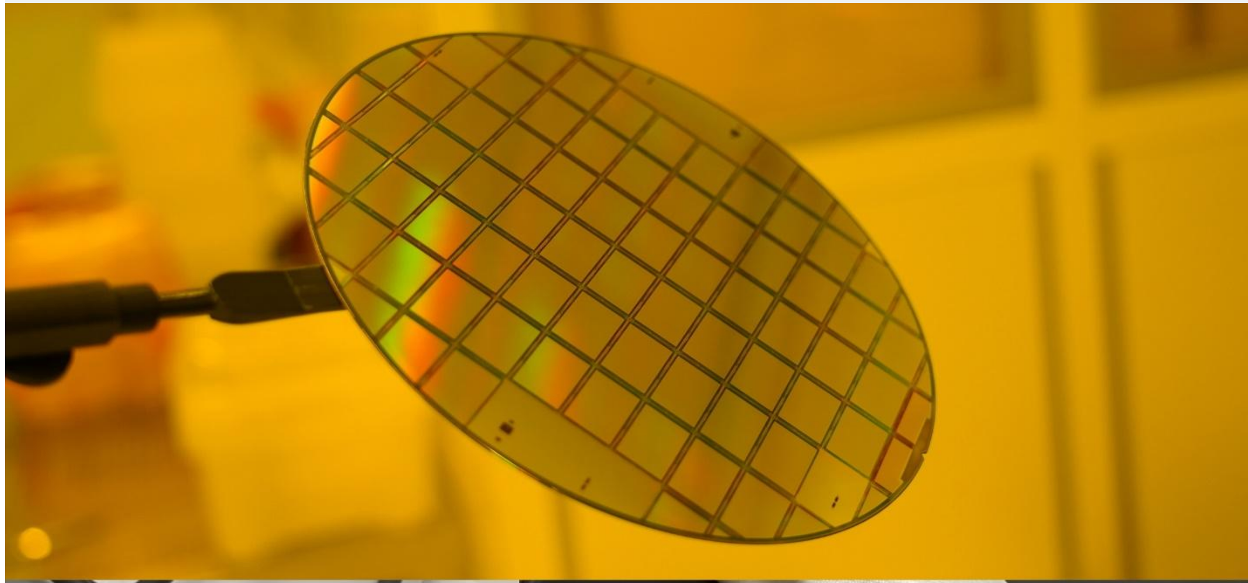
Fraunhofer IPMS

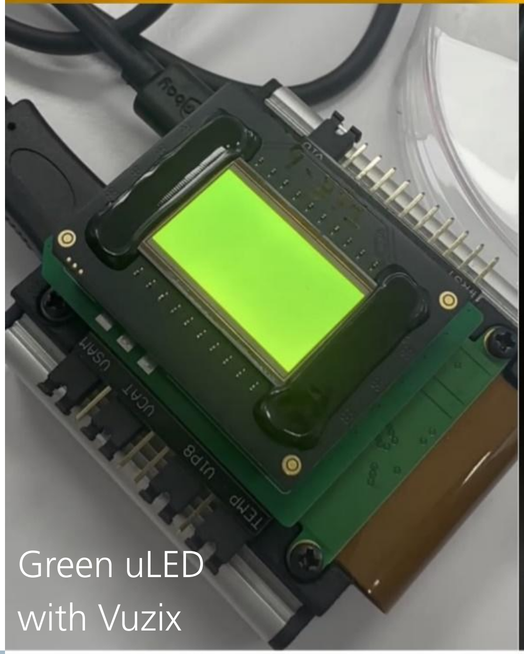
Also see: https://www.ipms.fraunhofer.de/en/press-media/press/2025/Custom-MicroLED-Backplane.html

→ **Monochrome**

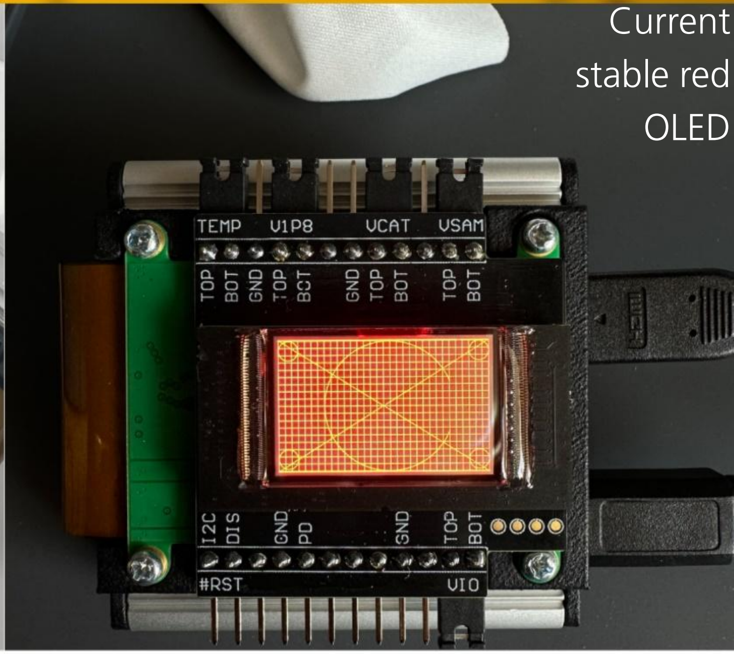
→ **QDs required for full-color**

Fraunhofer IAP





Green uLED with Vuzix



Current stable red OLED

uLED Frontplane Integration (2)

Recent successful uLED integration

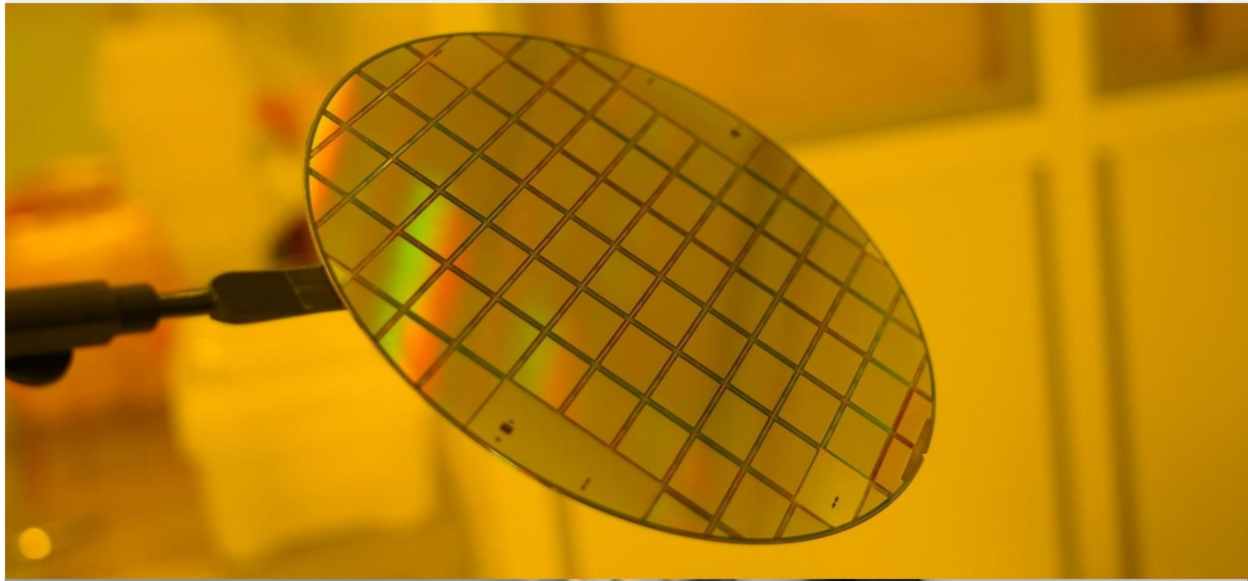
QubeDot

Fraunhofer
IPMS

Also see: https://www.linkedin.com/posts/fraunhofer-ipms_ipmsevent-microledconnect2026-microled-activity-7504139253443092481-X0Z8?utm_source=share&utm_medium=member_desktop&rcm=ACoAAFzjHGEBQHv-8paD0HGgNUzd7blzA1yOZs8

→ **Still monochrome**

→ **QDs required for full-color** Fraunhofer IAP



Green uLED
with QubeDot

Fraunhofer Institute for Laser Technology ILT

Chapter 3 – Laser-Enabled Transfer

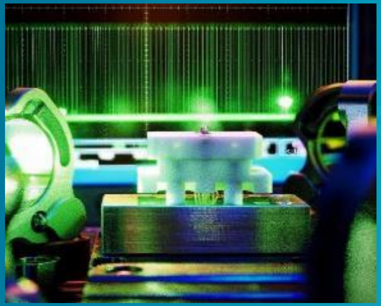
Fraunhofer Institute for Laser Technology ILT
Partner for innovations

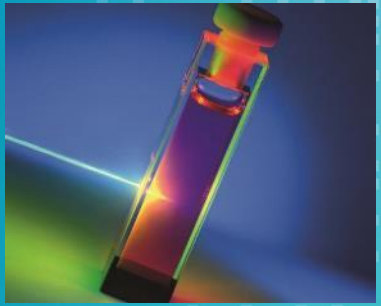
Fraunhofer
ILT

Operating Budget	43M €
Employees	~350
Student assistants	~200


LASER


OPTICAL SYSTEMS


QUANTUM TECHNOLOGY


LASER MEASURE-MENT TECHNOLOGY

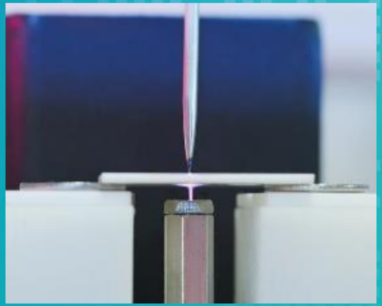

ADDITIVE MANUFACTURING


SURFACE TECHNOLOGY


JOINING


CUTTING


DIGITALIZATION


EUV & PLASMA TECHNOLOGY


MEDICAL TECHNOLOGY

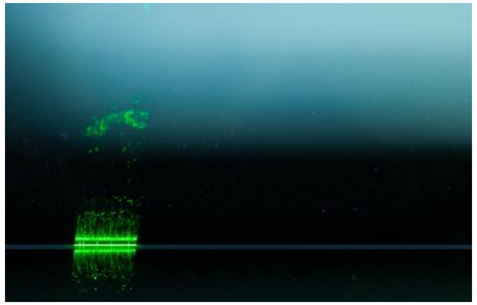
Micro & Nano Structuring | In-Volume Structuring & Lithography

Team structure

3D-Structuring

- Structuring of embossing tools
- High-Power-USP-Materialsprocessing
- Ablation of compound materials
- Fast deflection systems

Surface Structuring

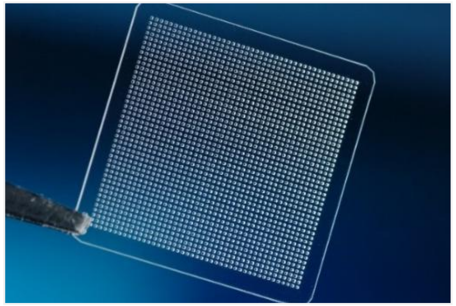


- Selective thin film ablation
- Interference patterning
- Surfacestructuring and functionalization

Drilling

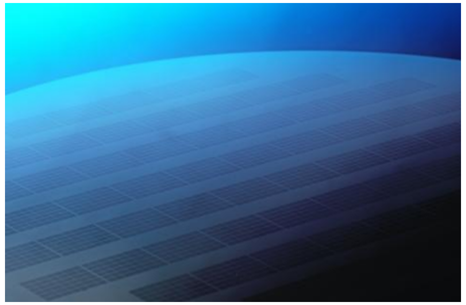
- Cooling holes for turbomachinery
- Drilling of embossing tools
- CFRP-Preforms
- Precision drilling

Transparent Materials



- USP-Processing of transparent materials
- Pump&Probe-Analysis
- Integrated optics
- SLE
- Beamshaping

Semiconductor

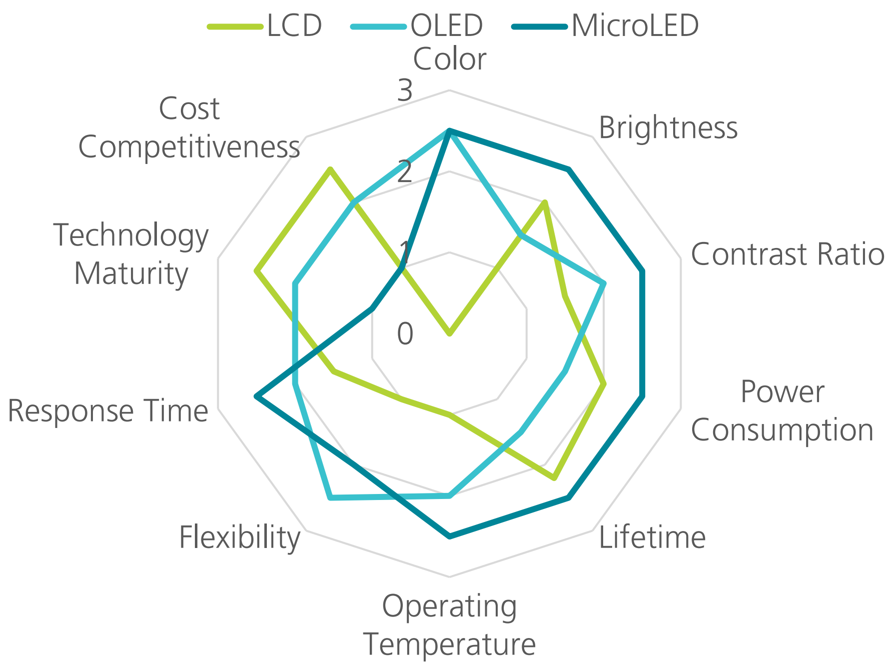


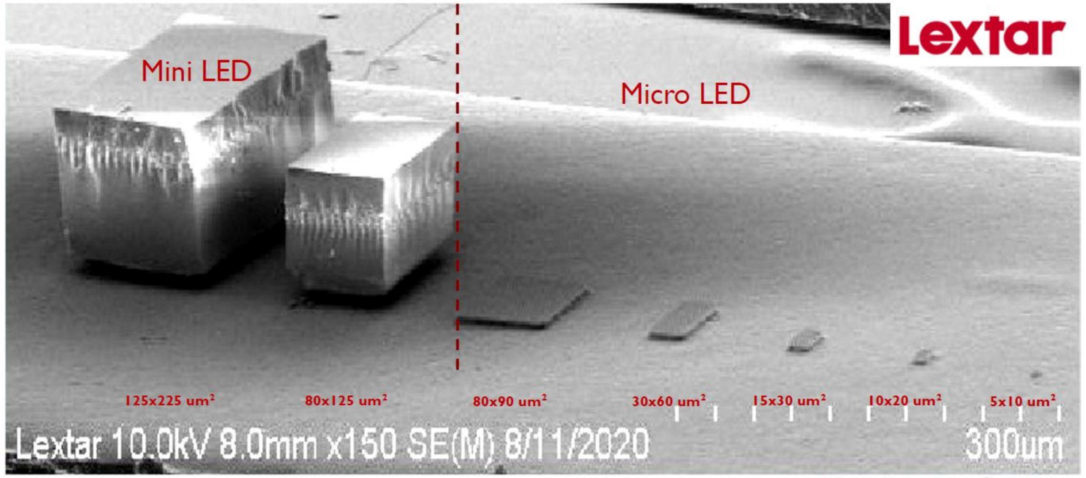
- 3D-Lithography
- Laser Direct Structuring
- Laser Lift-Off
- Laser Induced Forward Transfer
- Dicing
- Trenching
- EUV/DUV Processing

Motivation

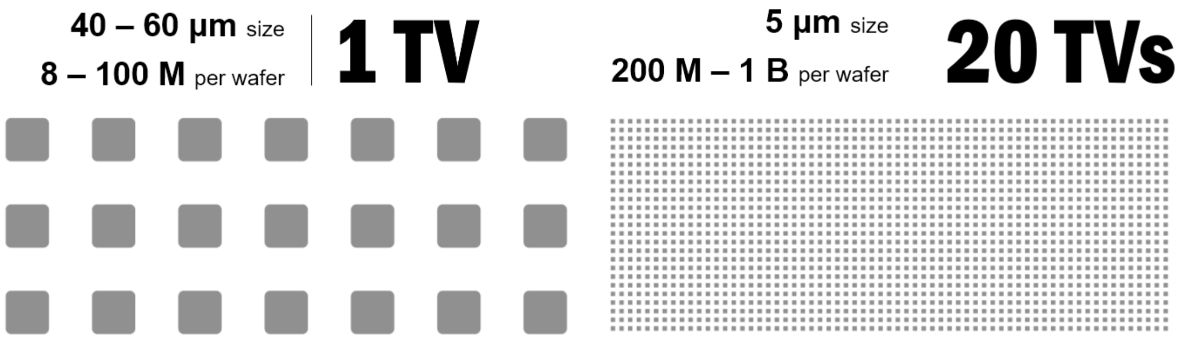
Why µLEDs?

- Benefits of µLEDs:
  - Self-emissive (Contrast, True Black, Power Consumption)
  - Fast response time
  - Brightness (inorganic materials handles higher electrical currents)
  - Lifetime (no degradation of organic materials)
  - Smaller form factor

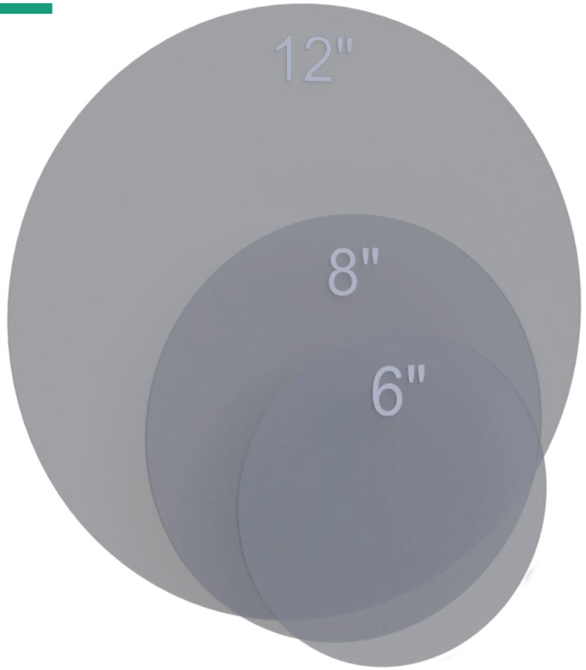




Picture is courtesy from Lextar

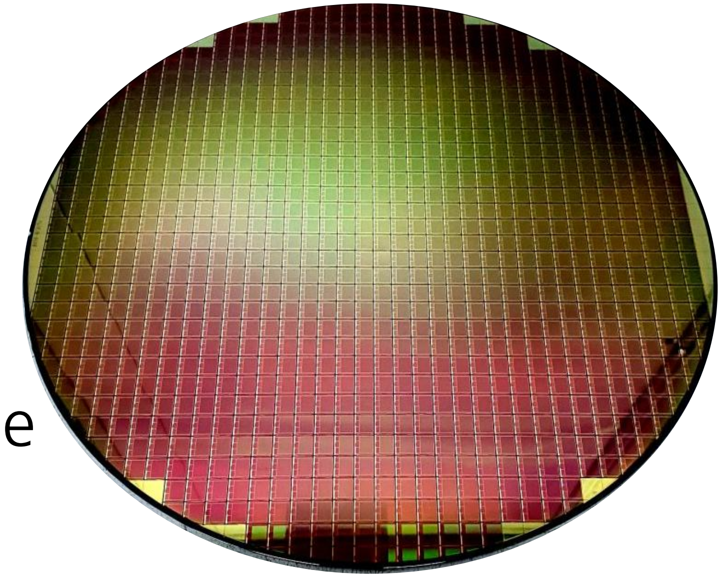


Building Blocks for a Display

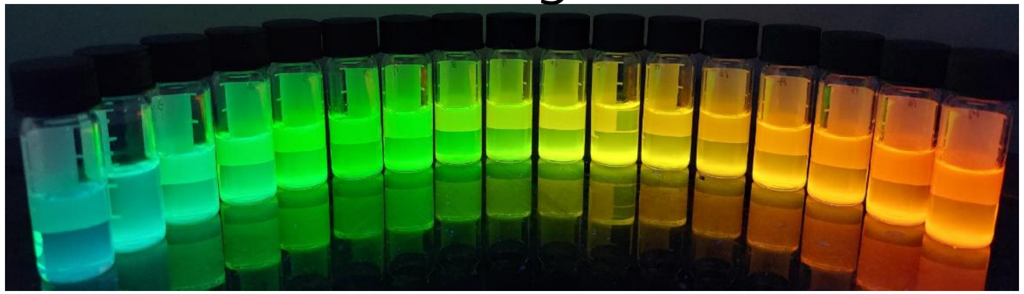


µLED Wafer

Backplane



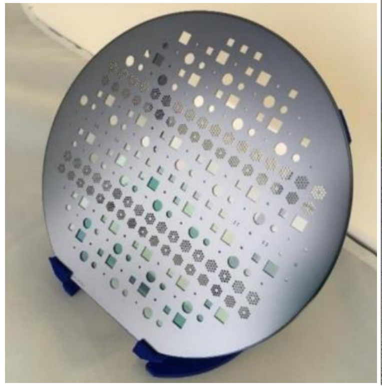
Coloring



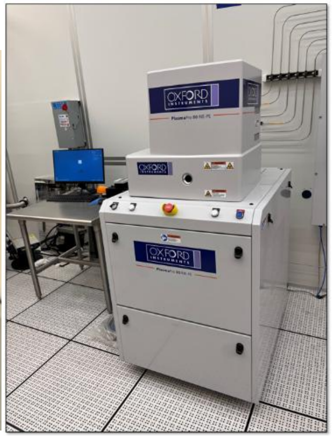
- Majority 6” and 8” GaN-on-Sapphire
- Capabilities for 12” GaN-on-Silicon

Removal of growth substrate

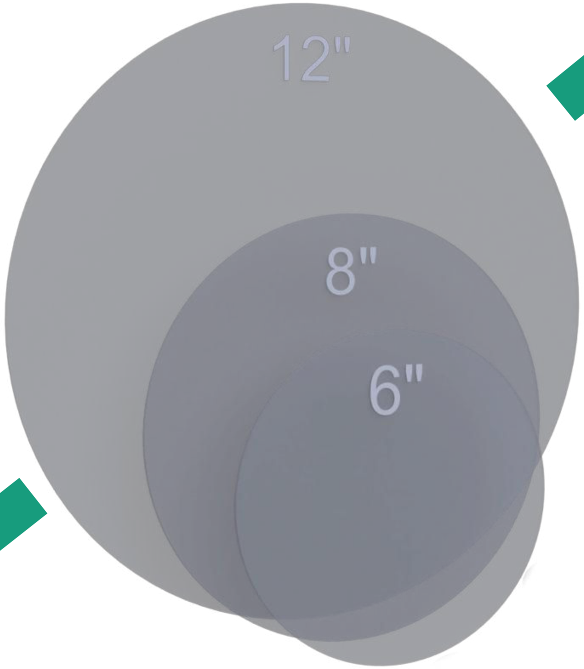
Transfer to Carrier

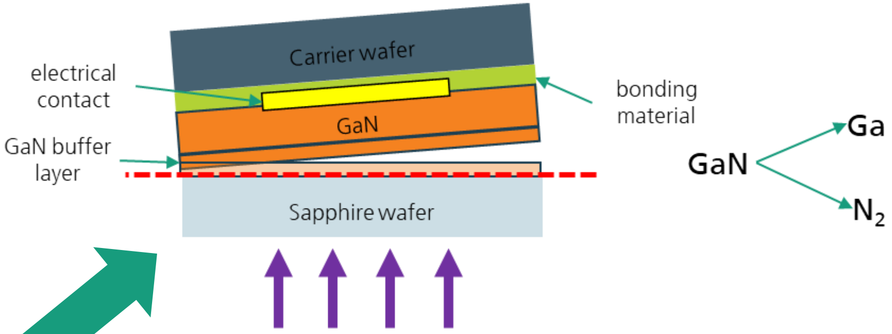


Local substrate removal

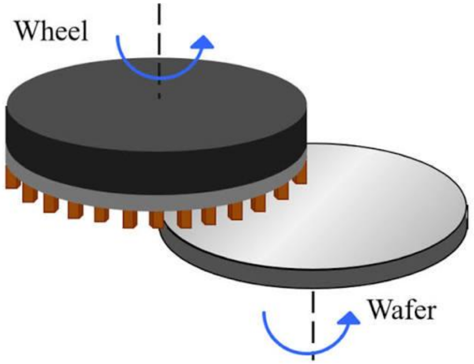


Chemical dry etching

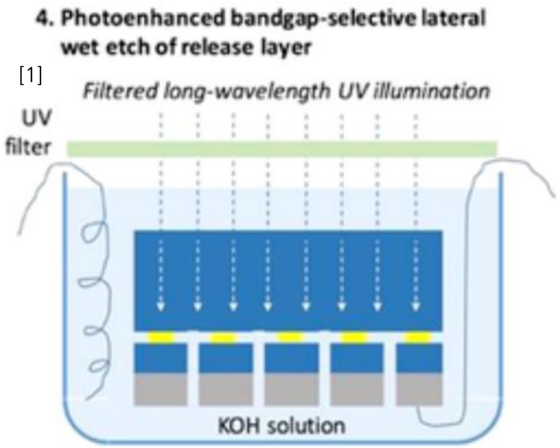




Laser Lift-Off (LLO)



Wafer thinning / backside grinding



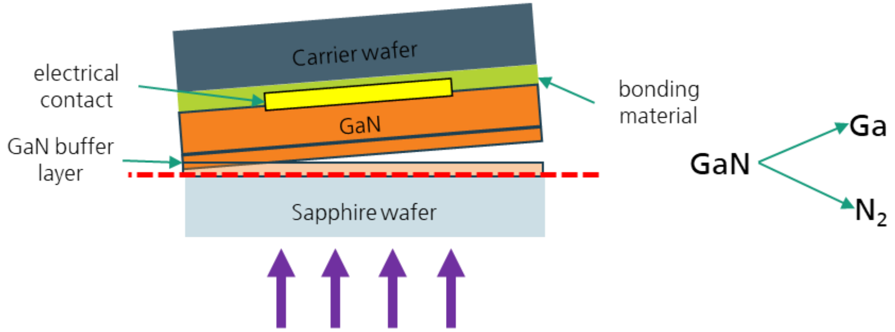
Photoenhanced wet etching

  [1] DOI: 10.1002/pssb.201600774 Public

UV CENTER OF EXCELLENCE Fraunhofer ILT

Laser Lift-Off - Transfer to Carrier

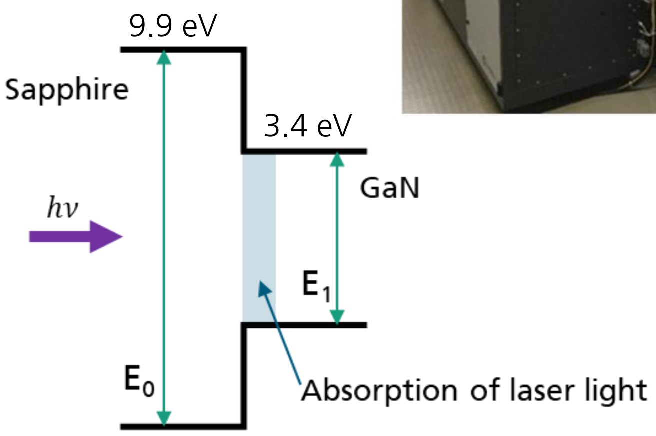
Motivation – Usage of ultrashort pulsed laser



- **Technology:** Complete detachment of the GaN layers from the substrate in a Laser Lift-Off (LLO) process

- **Conventional Method:** Usage of an ultraviolet (UV) excimer laser with ns pulse duration.
  - Thermal dissociation of GaN
  - Thermal gradient could cause damage to the backside surface

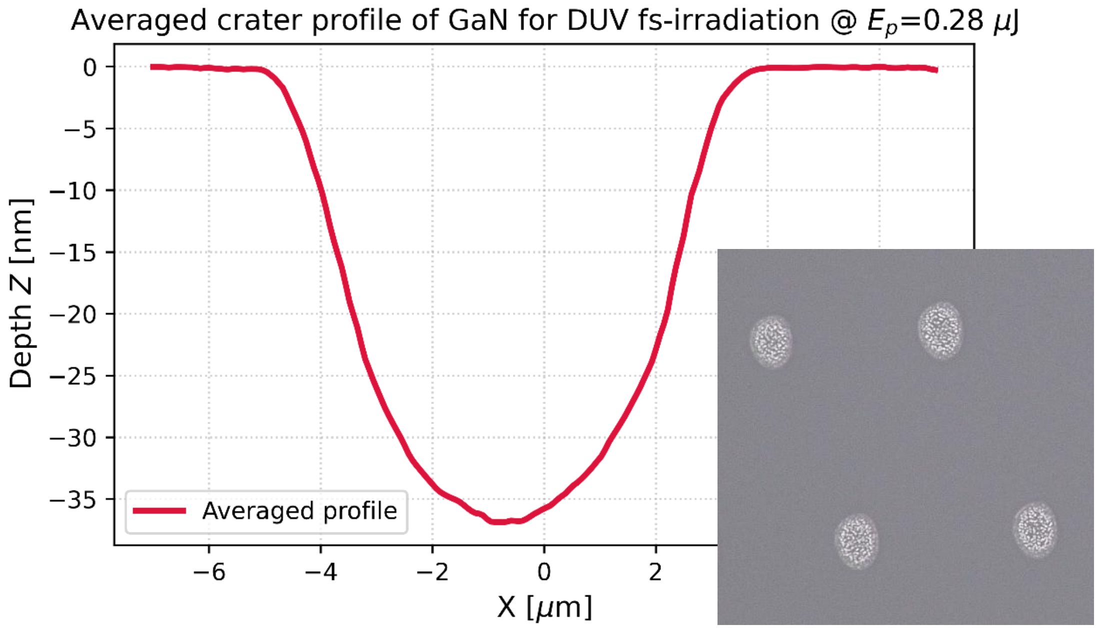
- **New approach:** Usage of UV/DUV ultrashort pulsed laser
  - **Minimize backside surface damage**
  - **Potential for processing thinner buffer layers**

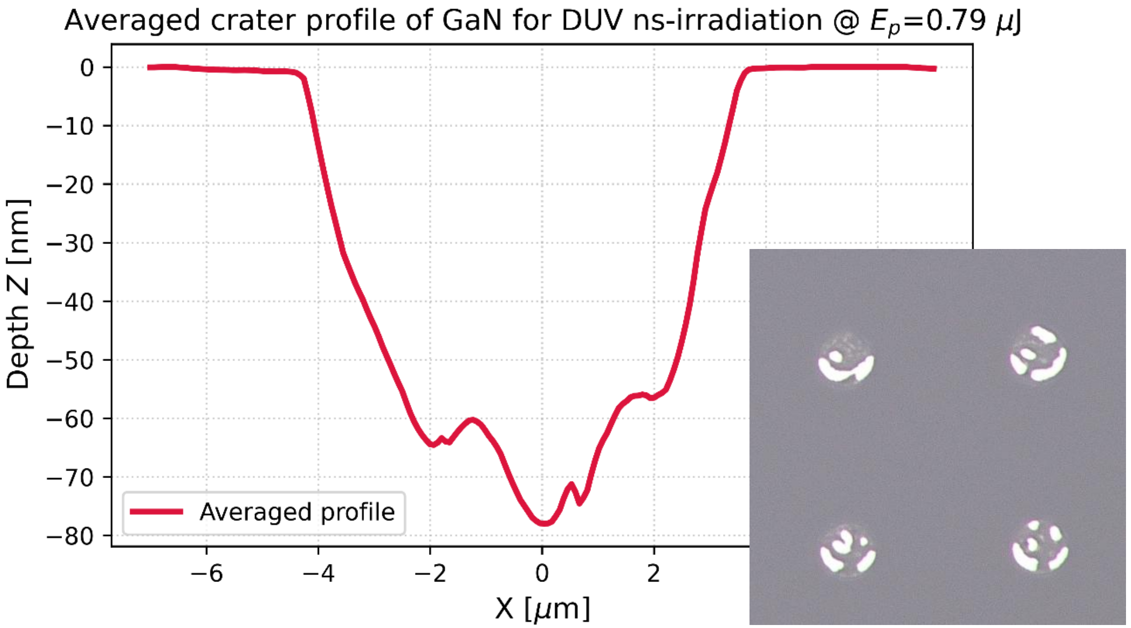


$$E_1 < h\nu < E_0$$

Comparison of penetration depth and threshold fluence

Excimer process and ultrashort pulsed process





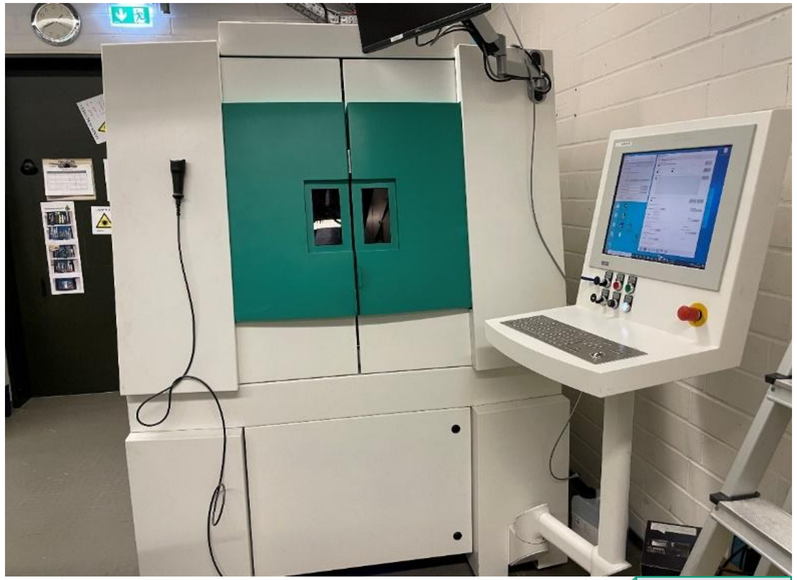
- Significant difference in threshold fluence between ultrashort-pulsed and nanosecond-pulsed exposure

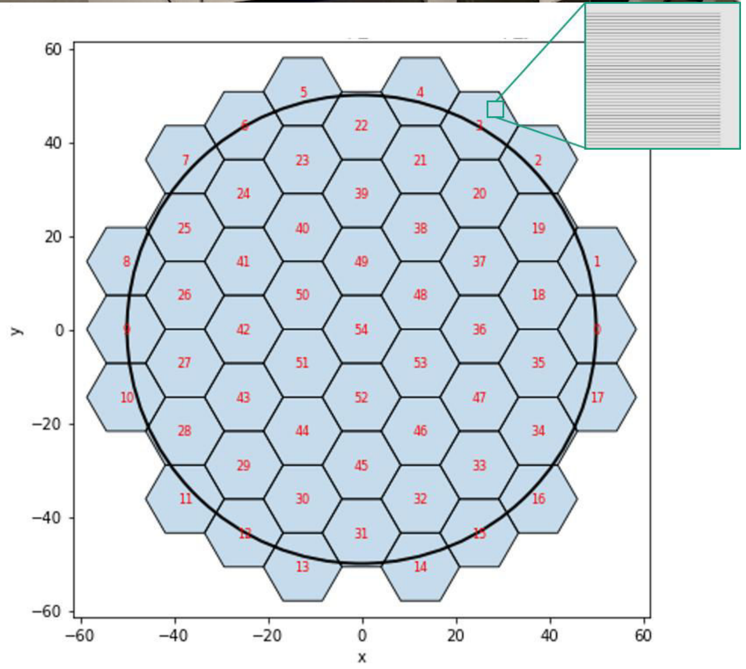
Laser Source	Formation threshold $[^{J}/_{cm^2}]$	Beam diameter $[\mu m]$
$\lambda = 248\ nm\ ; \tau = 32\ ns$	0.677 ± 0.021	5.19 ± 0.05
$\lambda = 266\ nm\ ; \tau = 8\ ps$	0.201 ± 0.004	5.51 ± 0.14
$\lambda = 345\ nm\ ; \tau = 300\ fs$	0.371 ± 0.009	6.54 ± 0.16

Processing tool for USP LLO

DUV ps-pulsed laser system

- **Laser: HyperRapid NXT 266 from Coherent**
  - λ=266 nm, P=10 W, M^2=1.22, repetition rate = 800 kHZ–4 MHz, pulse duration ~8 ps, 4 mm beam diameter
- **Scanner and F-Theta**
  - Scanner: Scanlab excelliSCAN 14 with RTC6, Scan Speed: 4 m/s (with f=160mm)
  - F-Theta: Jenoptik f=103 mm, Scanfield=50x50 mm
- **Positioning system:**
  - Aerotech positioners (XYZ), accuracy=±1 µm, Travel: x=400 mm, y=100 mm, z=100 mm



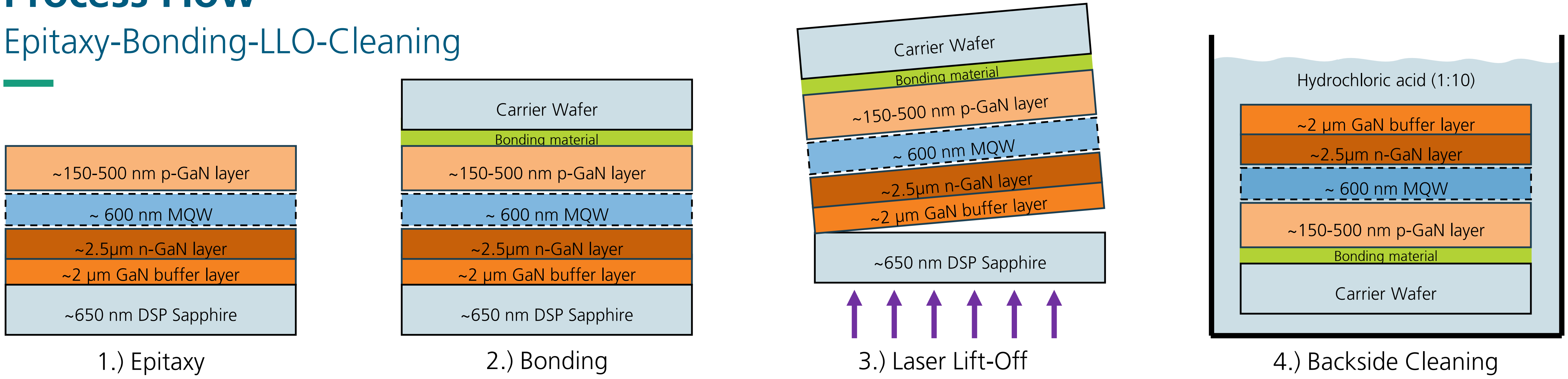


- **Process strategy:**
  - Full 4" wafer bigger than one scan field → splitting in multiple hexagons
  - Hexagons are suitable to withstand higher N_2 pressure than squares
  - $\mathcal{F}_{Peak} = 0.32\ J/cm^2$
  - Runtime ~30 minutes @ 1 MHz

  Public

Process Flow

Epitaxy-Bonding-LLO-Cleaning



- Double side polished Sapphire as epitaxial Wafer necessary to reduce laser light scattering
- Carrier Wafer often also Sapphire-Wafer to reduce stress which releases during LLO and could cause cracks
- Backside cleaning is necessary to remove metallic Gallium → improves light outcoupling
  - 5 minutes HCl (1:10)
  - 5 minutes O_2 plasma cleaning

  Public

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Mass transfer

MicroLED MASS TRANSFER TECHNOLOGIES - OVERVIEW

Most Mature Processes

- Stamp based
  - MEMS, PDMS, etc.

- Pro´s
  - Mature technology for LED´s
  - Contact process, bonding could be included
- Con´s
  - Versatility low
  - Complex mixing/sorting
  - Limitation in small size LED
  - Throughput limited especially for larger pitch

Fast Rising

- Laser based Processes
  - Excimer mask, DPSSL Scanner

- Pro´s
  - High throughput and scalable process
  - Capable for small microLED´s
  - 1 step transfer process possible
- Con´s
  - Needs microLED release
  - Needs capture material/glue

Emerging

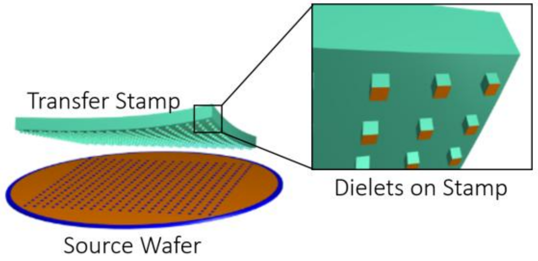
- Self-assembly & others
  - Fluidic, magnetic, etc.

- Pro´s
  - Throughput?
  - Tool Costs?
- Con´s
  - Versatility low
  - Not commercially available
  - MicroLED size limited
  - Placement accuracy

- Stamp is very good at moving large numbers of dies from donor to backplane or carrier
- Laser is very good at selectively detaching them, but die capture is an issue
- Self-assembly remains a compelling concept worth keeping an eye on, even if less mature

COMPETING TRANSFER TECHNOLOGIES – STAMP, NEEDLE, LASER NEEDLE

Stamp



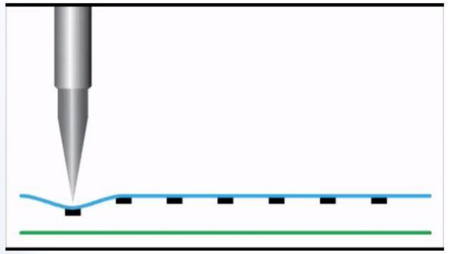
Parallel pick and place

- PDMS Stamp for transfer
- 20-40 sec cycle time, ~2k units/sec
- Placement accuracy ± 1.5μm 3σ

\+ Mature Technology
\- Slow for larger pitches (TV)

e.g. X-Celeprint

Needle



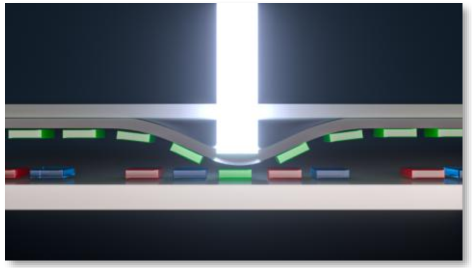
Serial single stick

- Needle and DRL for transfer
- 100 units/sec
- Placement accuracy ± 10μm 3σ

\+ Used for miniLED transfer
\- Slow and insufficient placement accuracy

e.g. K&S/Rohinni

Laser Needle



Serial single laser pulse

- Laser and DRL for transfer
- 1000 units/sec
- Placement accuracy ± 4μm 3σ

\+ Used for miniLED transfer
\- Slow and not capable for small microLEDs

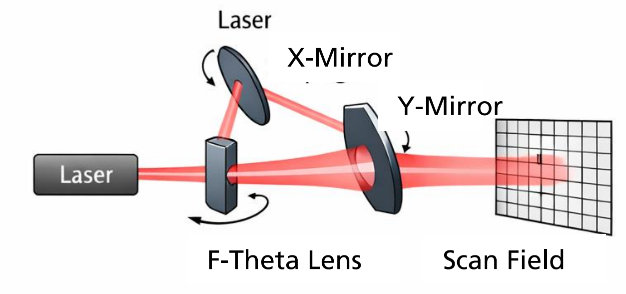
e.g. K&S/Uniqarta

DRL = Dynamic Release Layer

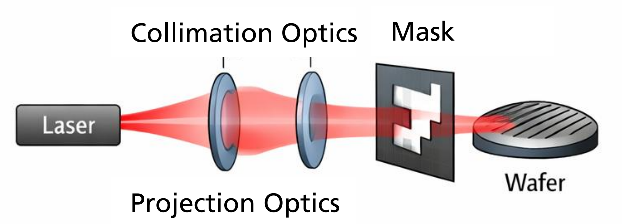
LASER BEAM DELIVERY SYSTEMS – ARCHITECTURES

Advantages:

- Flexibility in patterning
- No mask required
- High throughput for less complex patterns



Galvo Scanner



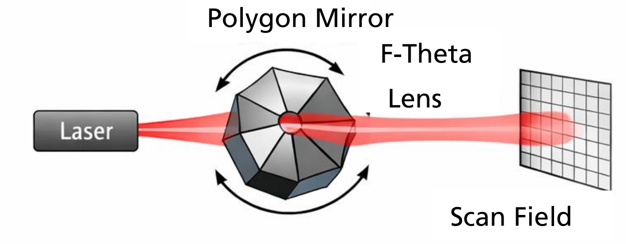
Mask Imaging

Advantages:

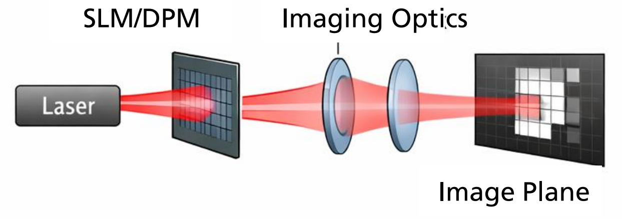
- Pattern placement accuracy, and consistency (submicron)
- High throughput for complex patterns
- High patterning precision

Advantages:

- Fastest Beam Deflection
- Large area scanning
- Used with standard F-Theta lenses



Polygon Scanner



Spatial Light Modulator

Displacement Phase Modulator

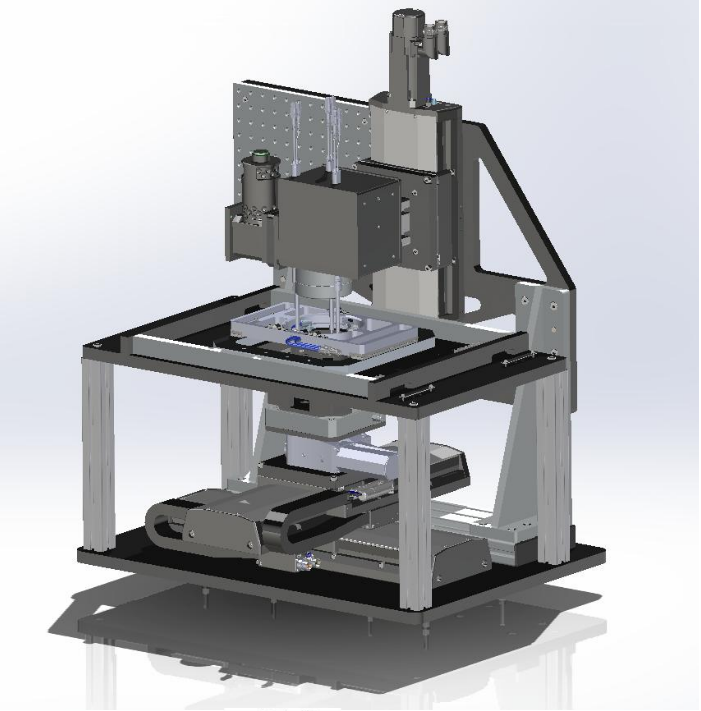
Advantages:

- Fast Imaging
- Flexible pattern on imaging plane
- Available in IR, green, and UV

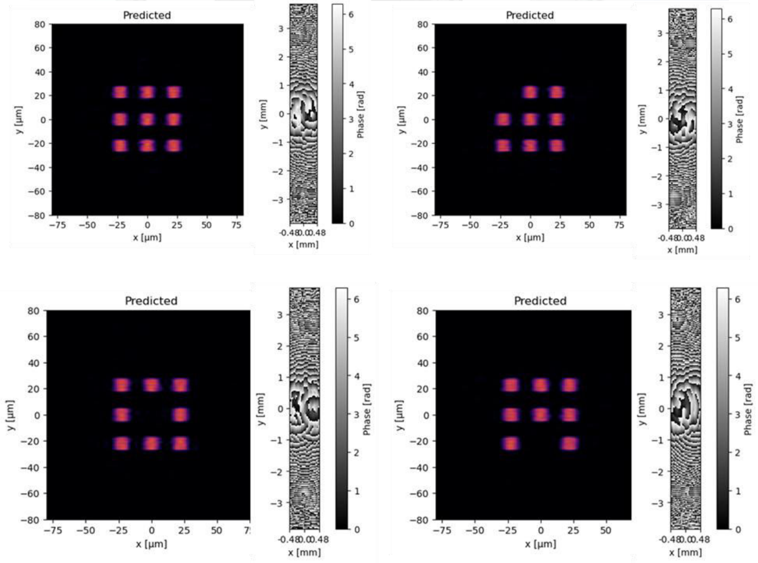
LIFT with Spatial Light Modulator

Prototype system: Design and specifications

- Galvanometric scanner with 15x15 mm scan field and optics for <3 µm optical resolution
- 11 controllable stages and a 100 kHz phase modulator
  - X & Y position of donor Wafer
  - Z position of focusing lens
  - X,Y & Z position of backplane Wafer
  - Tip and Tilt axis of backplane to ensure parallelism
  - Rotational axis of backplane
  - X & Y position of laser beam
- 3x3 multibeam with up to 11 µm Pitch
- Backplane wafer positioning ±100 nm
- Overlay-control: sub-1 µm
- Interferometric air gap control accuracy <1 µm
- Full 200 mm backplane addressable

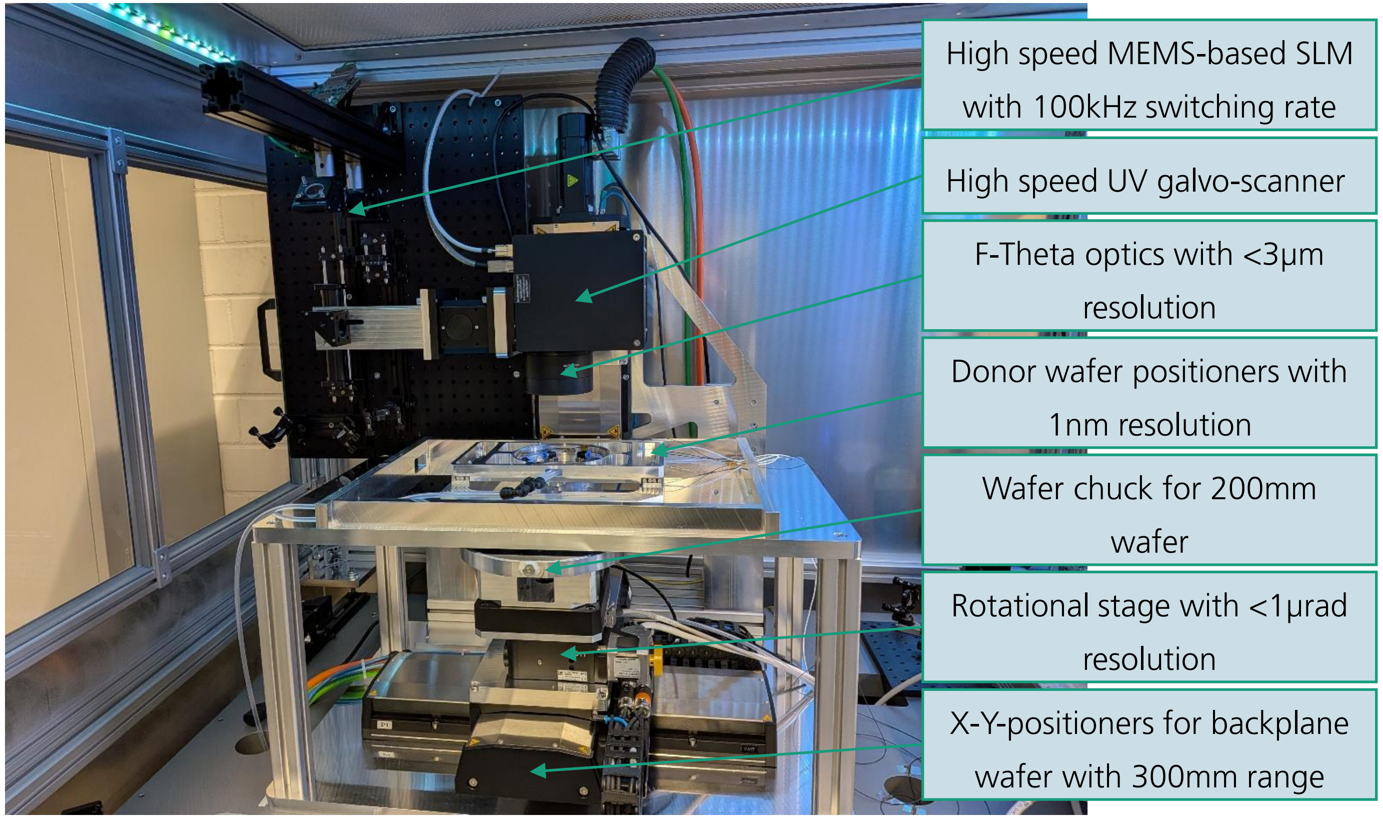


SILICON LIGHT MACHINES



LIFT with Spatial Light Modulator

µLED LIFT prototype system

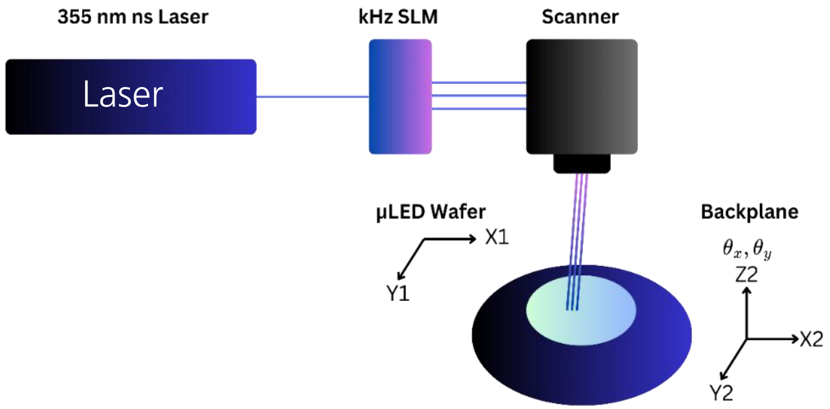


LIFT with Spatial Light Modulator

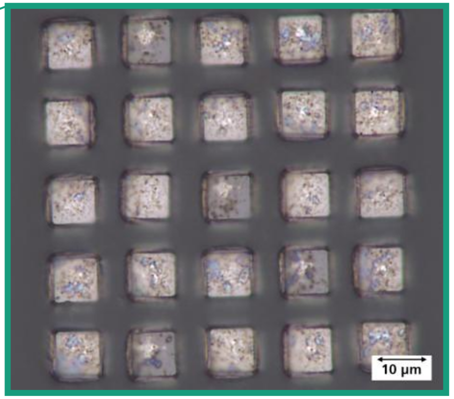
Examples and throughput considerations

- Successfully transferred µLED-Array with 15 µm pitch and 10 µm LED size
- Transfer of macroscopic patterns without any wafer movement (~10 mm-range)

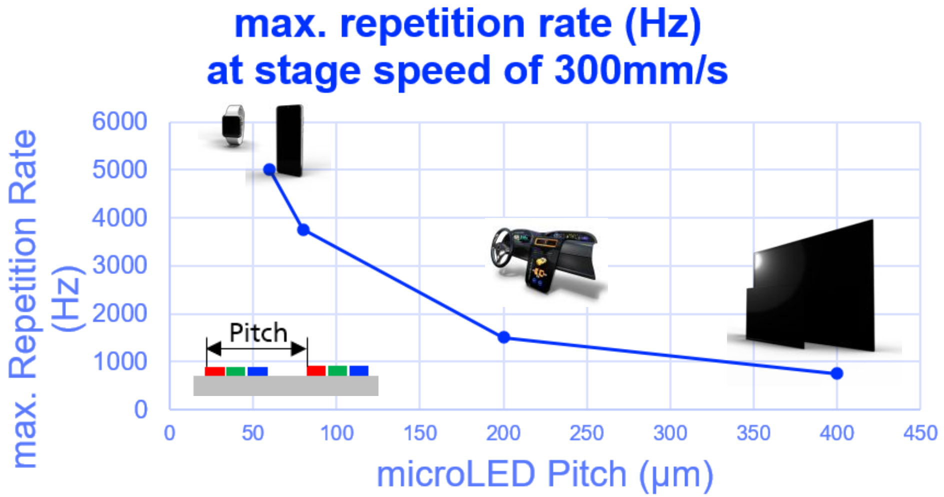
- The usage of a SLM allows for a flexible multibeam approach
- Allows to skip faulty pixels by changing the pattern on a pulse-to-pulse basis
- Increases throughput by transferring multiple devices with one shot



DIC image of transferred µLED-Array showing the "Fraunhofer ILT" lettering

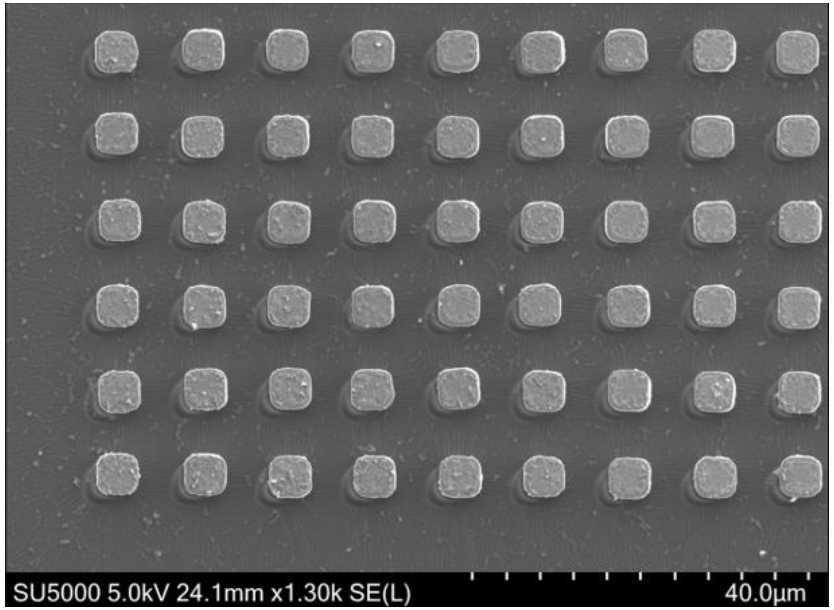


Zoom-in of transferred µLED-Array



UV LASERS ARE THE KEY TO MASS TRANSFER

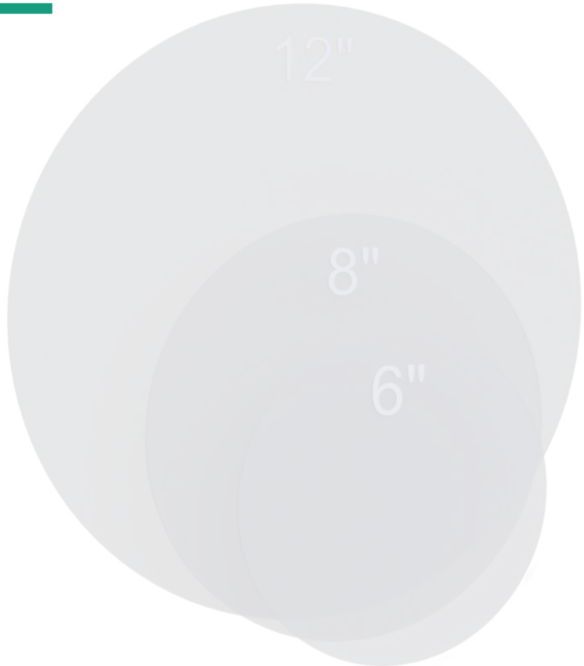
- Mandatory for Gallium Nitride microLED's
- Suitable for small(est) microLED's
- Highest Precision
- Scalability due to high power UV and DUV



Fraunhofer Institute for Applied Polymer Research IAP

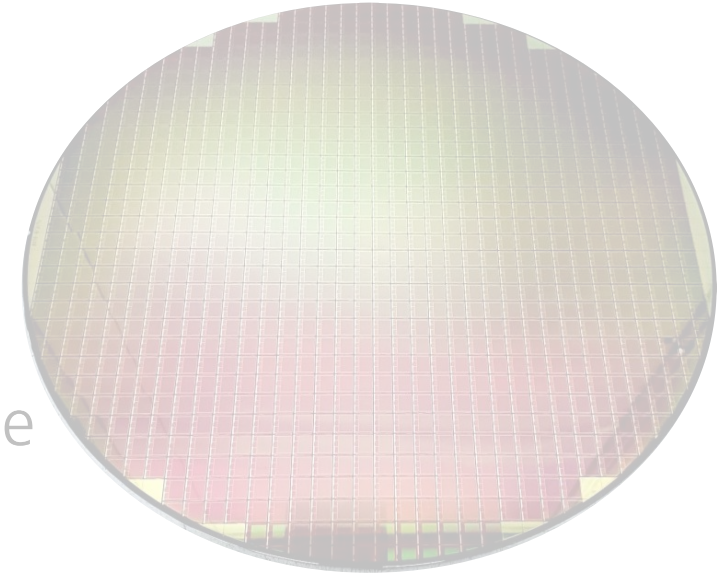
Chapter 4 – QD Color Conversion

Building Blocks for a Display

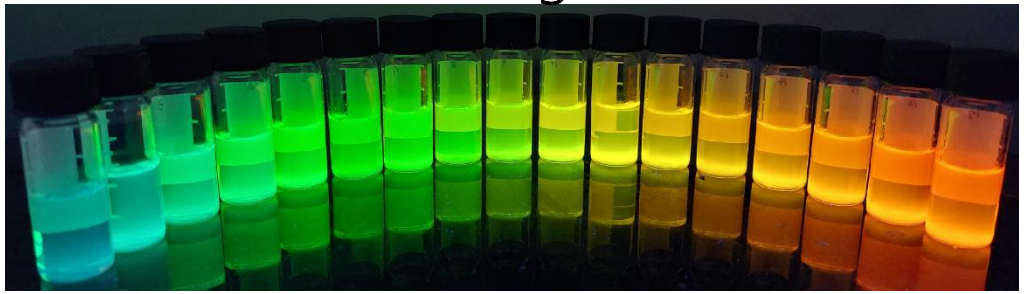


µLED Wafer

Backplane

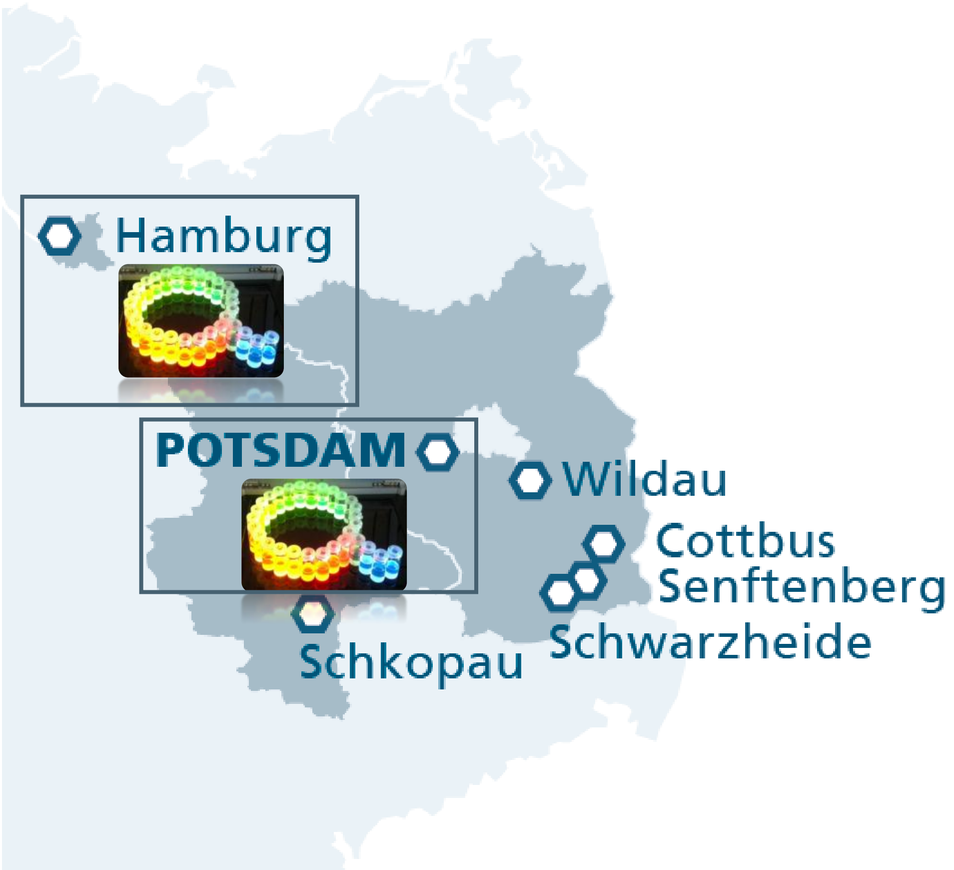


Coloring



- Majority 6” and 8” GaN-on-Sapphire
- Capabilities for 12” GaN-on-Silicon

Fraunhofer IAP at a glance



Department Functional Materials and Devices (Potsdam)

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QD Technologies and Devices

Dr. Jiyong Kim
QD Materials Head
Nanomaterials and XPS

Department Quantum Materials (Hamburg)

Dr. Jan Niehaus
Department Head

Dr. Sören Becker
Deputy Head

Color Conversion for MicroLED

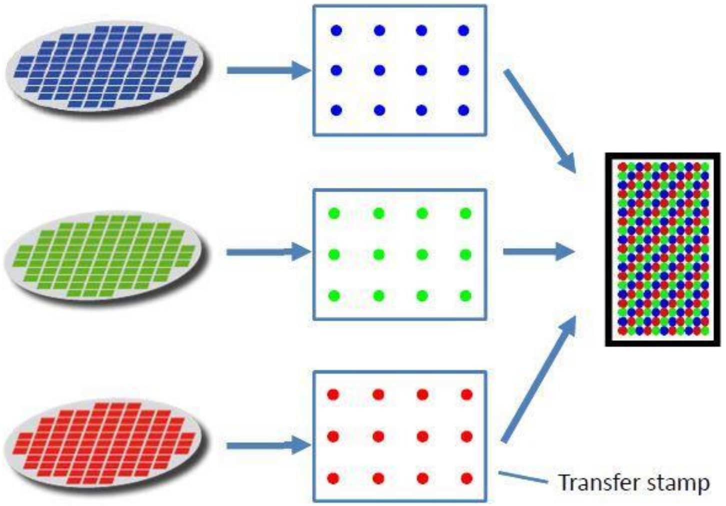
Advantages

- **Less complex µLED assembly process (compared to RBG LED)**
  - Extreme high yield for transfer process required (99.9999 % for 4K Display → 25 defect pixels)
- **Less complicated for TFT or CMOS backplane:**
  - Drive voltage mismatch: blue ~3.3 V, green ~2.2 V, red ~1.7V

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

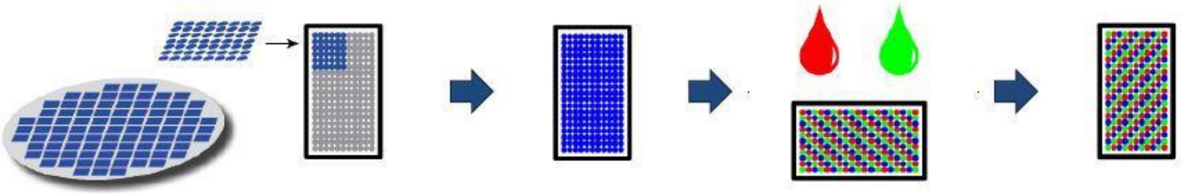
https://www.mdpi.com/2076-3417/8/9/1557

Separate Transfer and Alignment of RGB µLED LEDs



QD Color Filters on blue/UV µLED LEDs + Transfer

Transfer of blue/UV µLED LEDs + QD Color Filters

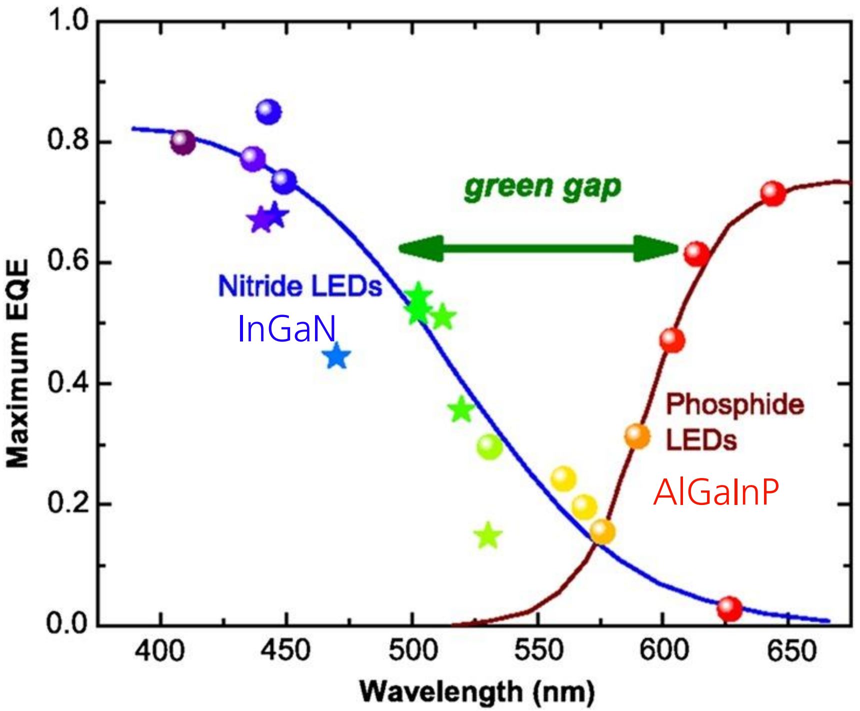


Color Conversion for MicroLED

Advantages

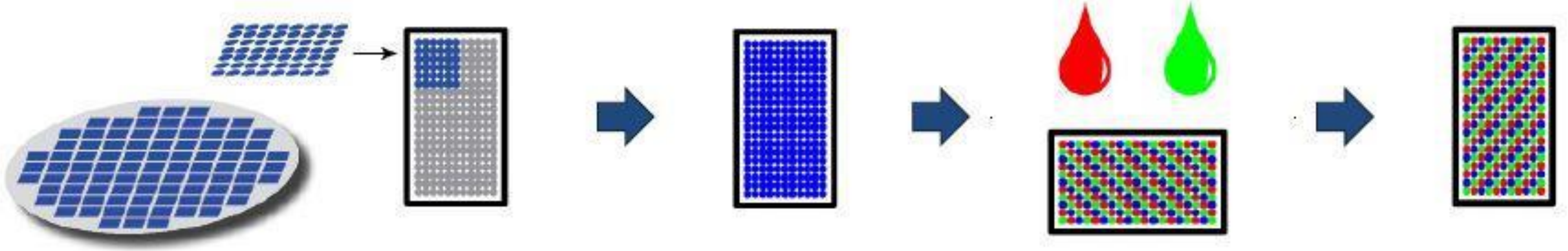
- **Less complex µLED assembly process**
- **Less complicated for TFT or CMOS backplane**
- **Mitigation route for the green gap:**
  - Lower growth temperature of green (~700°C: higher Indium content in InGaN quantum wells)
  - Less crystal quality (strain, compositional fluctuations)
  - Larger Auger recombination rate as bandgap decreases

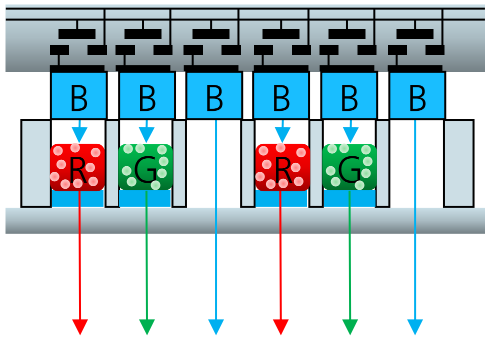
The green gap in LEDs



M. Auf der Maur et al. *Phys. Rev. Lett.* **2016**, 027401.
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.027401

Transfer of blue/UV µLED LEDs + QD Color Filters





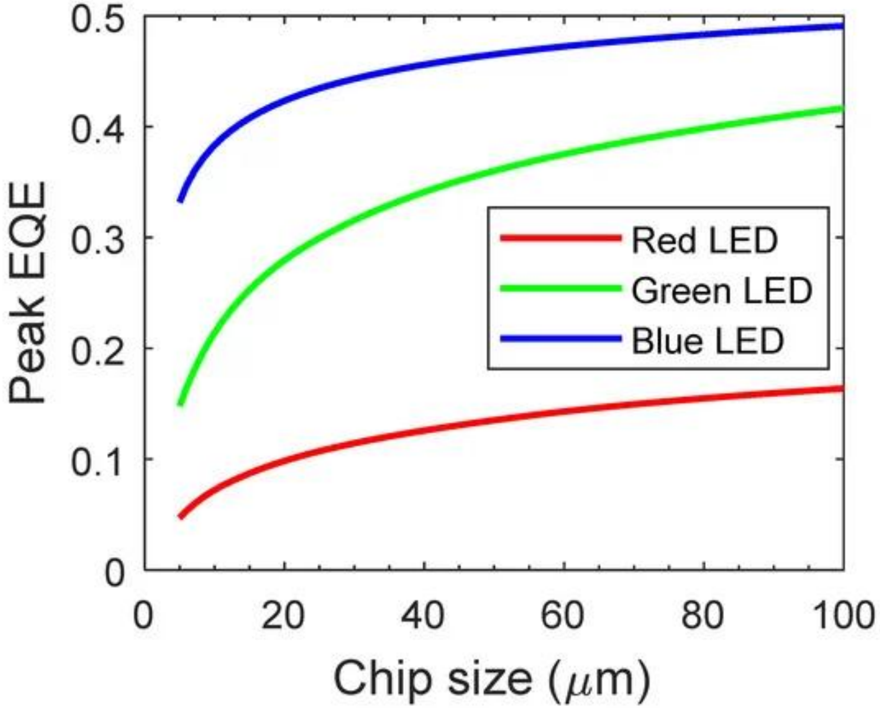
Color Conversion for MicroLED

Advantages

- **Less complex µLED assembly process**
- **Less complicated for TFT or CMOS backplane**
- **Mitigation route for the green gap**:
- **Mitigation route for the red gap**:
  - Much stronger efficiency drop for AlGaInP material for smaller LED sizes:
  - Higher thermal sensitivity (thermal management)
  - Higher defect density
  - Longer charge carrier diffusion length compared to InGaN

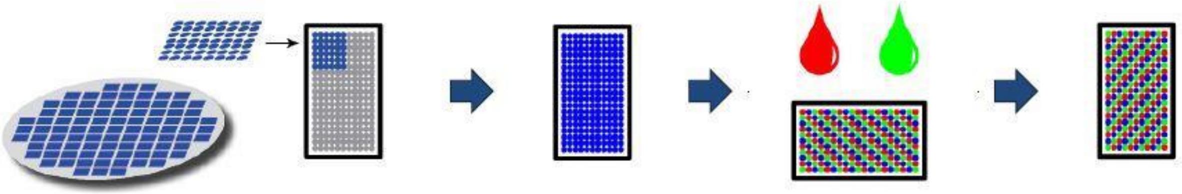
Which materials are suitable for color conversion?

The red gap in LEDs



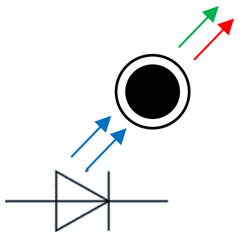
E-L Hsiang et al. *Crystals* **2020**, 10 (6).
https://www.mdpi.com/2073-4352/10/6/494

Transfer of blue/UV µLED LEDs + QD Color Filters



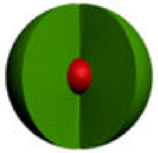
Nanomaterials for Color Conversion in MicroLED

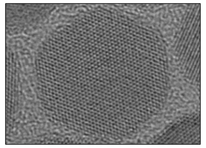
Currently 3 Promising Candidates



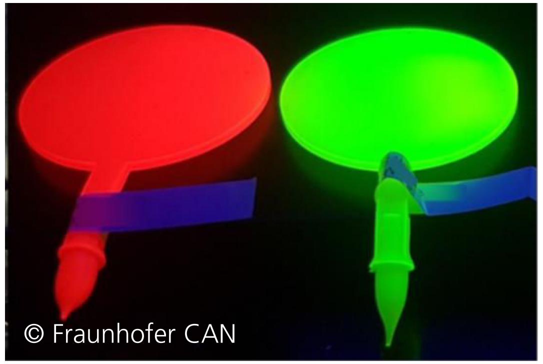
Fraunhofer IAP / CAN (Hamburg)

CdSe/CdS



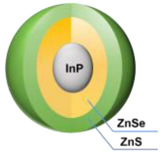


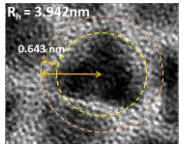
- High PLQY
- High environmental stability
- Suppressed auger recombination
- Challenges:
  - RoHS



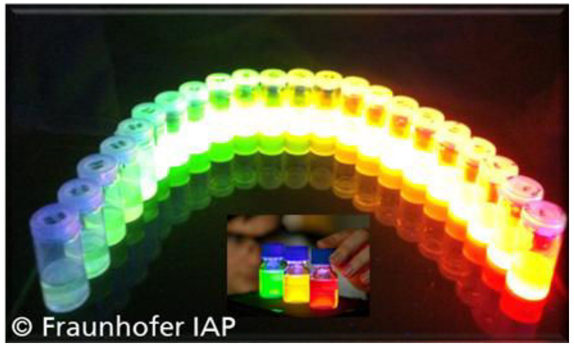
Fraunhofer IAP (Potsdam)

InP/ZnSe/ZnS

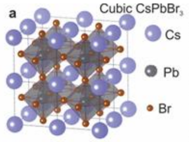


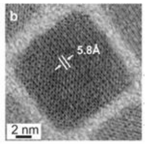


- Lower toxicity (RoHS)
- Improved photostability with ZnS outer shell
- Challenges:
  - Lower PLQY
  - Susceptive to oxidation
  - Blue challenging due to very small core

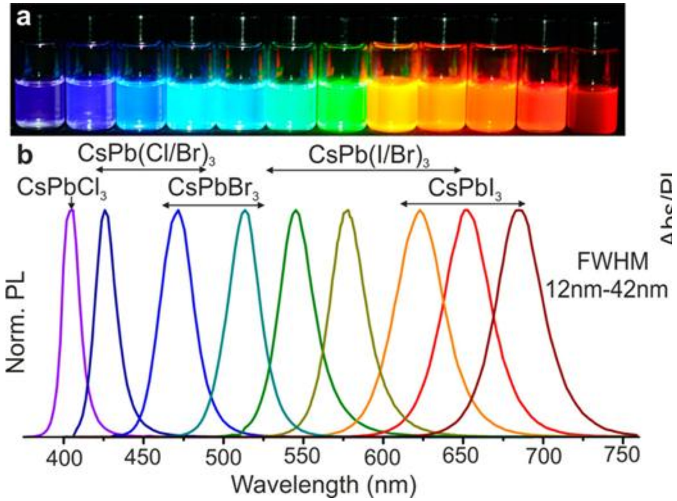


Perovskites





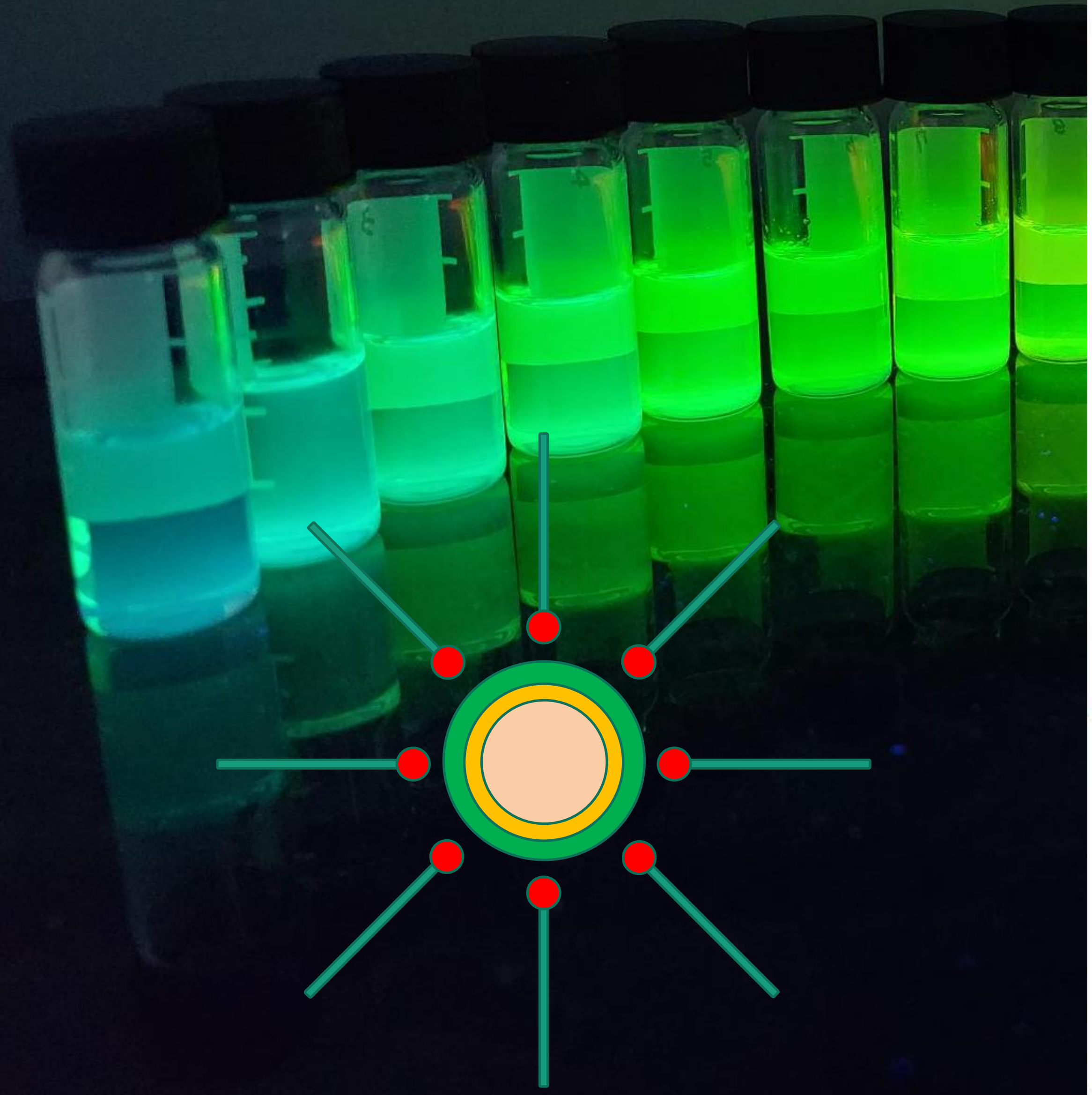
- Potentially inexpensive
- Challenges:
  - Increasing stability (shell growth)
  - Long PL decay times for some compositions

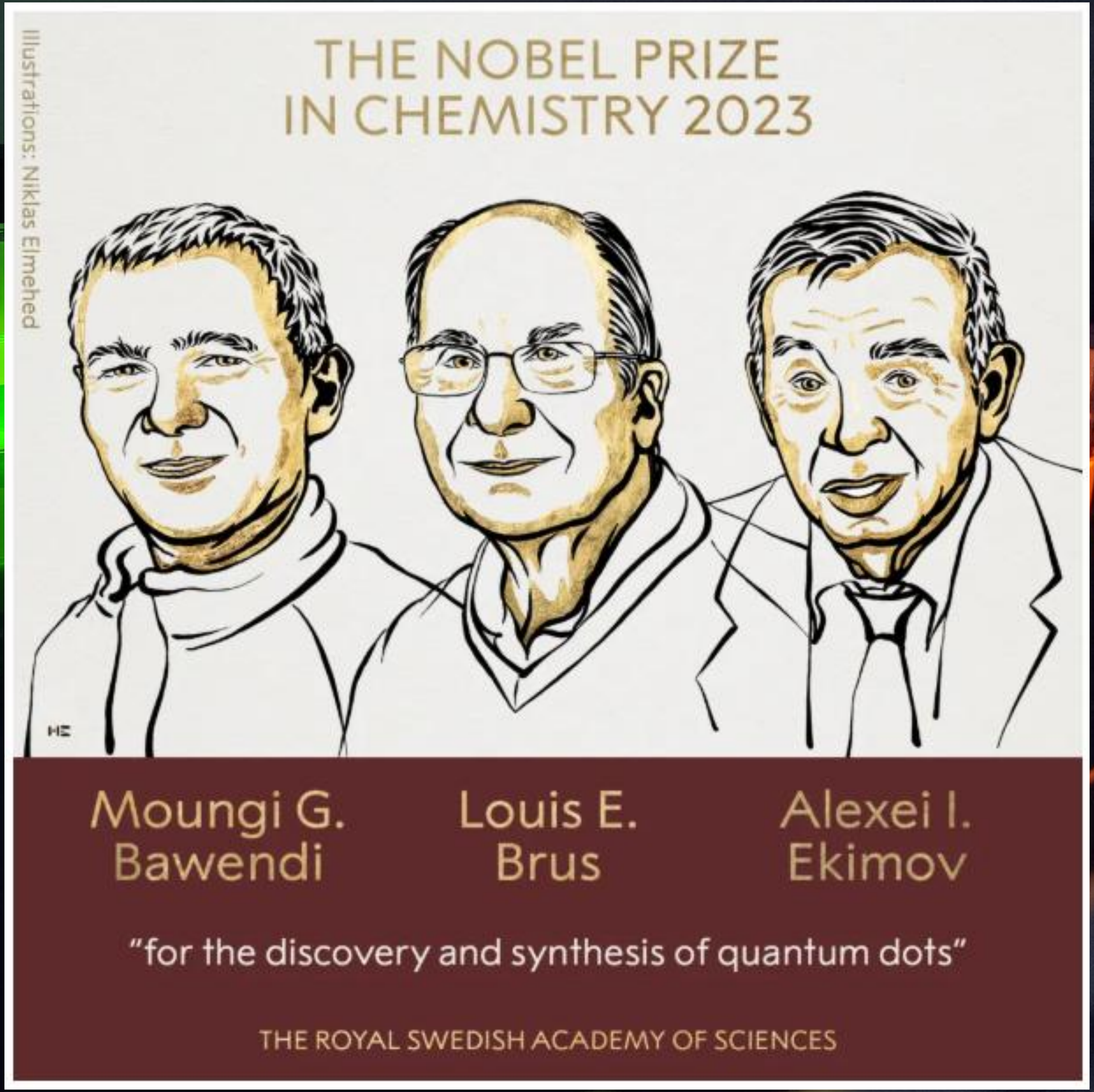


L. Protesescu et al. *Nano Lett.* **2015**, 15 (6).
https://pubs.acs.org/doi/10.1021/nl5048779

Quantum Dots

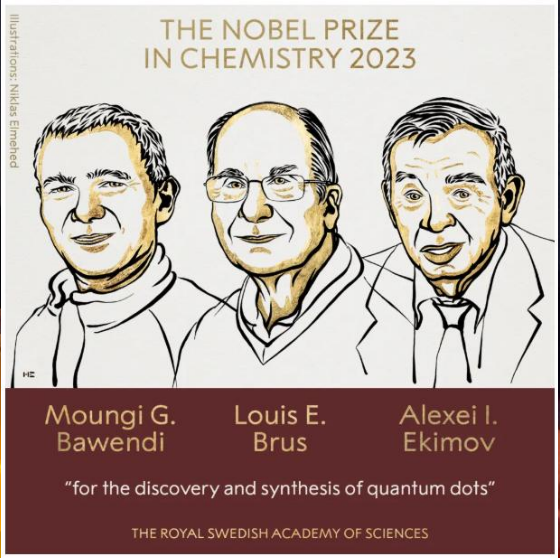
Nobel Prize 2023



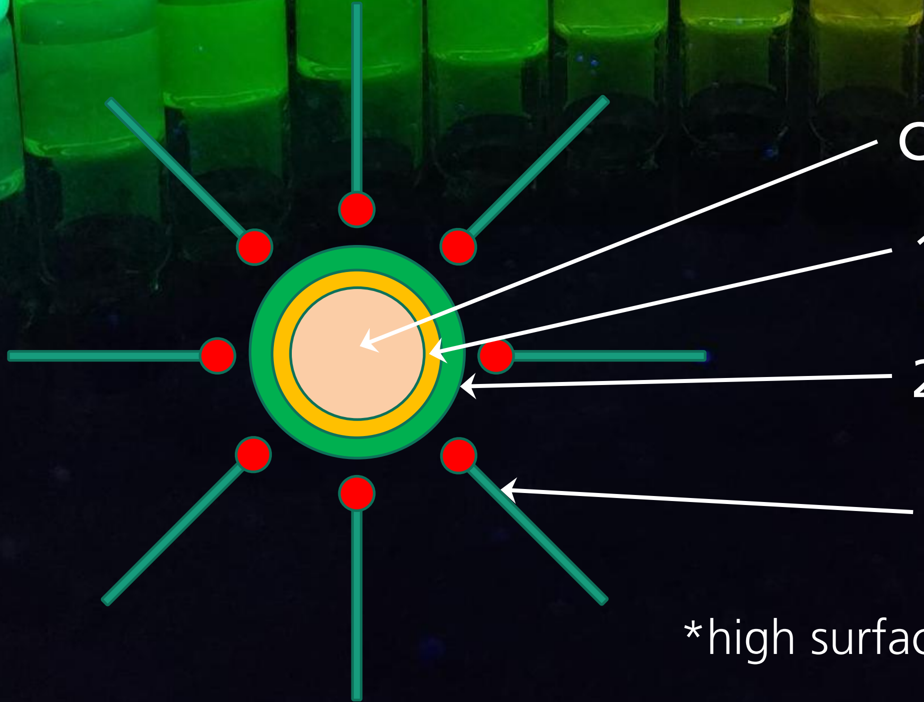


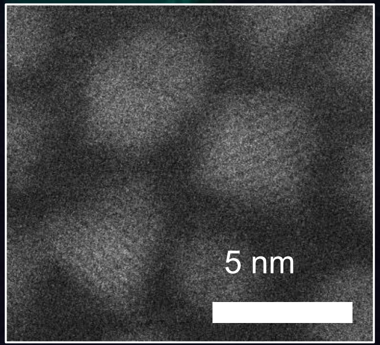
Quantum Dots

Nobel Prize 2023



Colloidal Nanocrystals

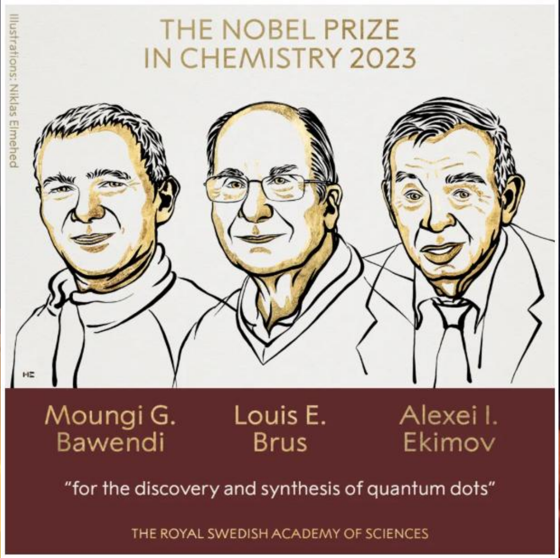




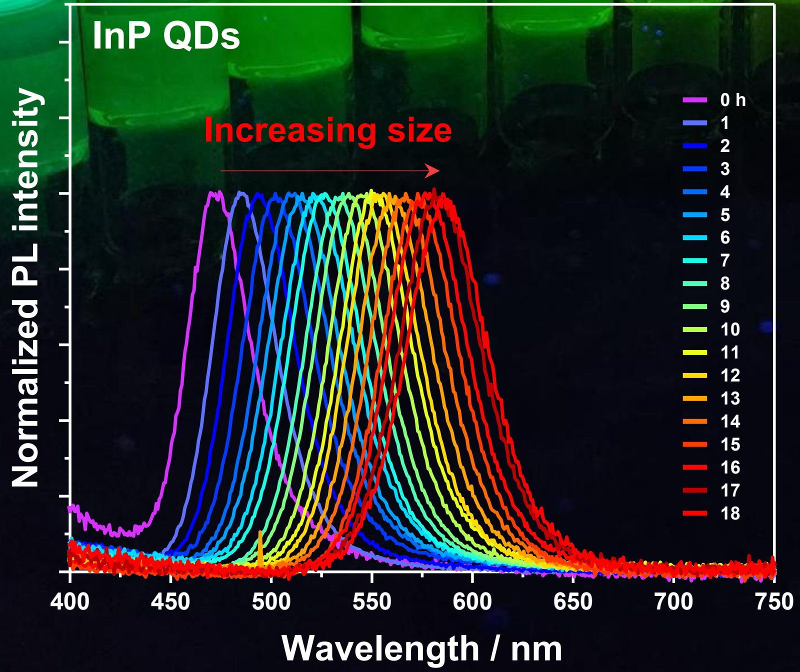
*high surface area to volume ratio

Quantum Dots

Nobel Prize 2023



Tunable color with size



Scalable Synthesis

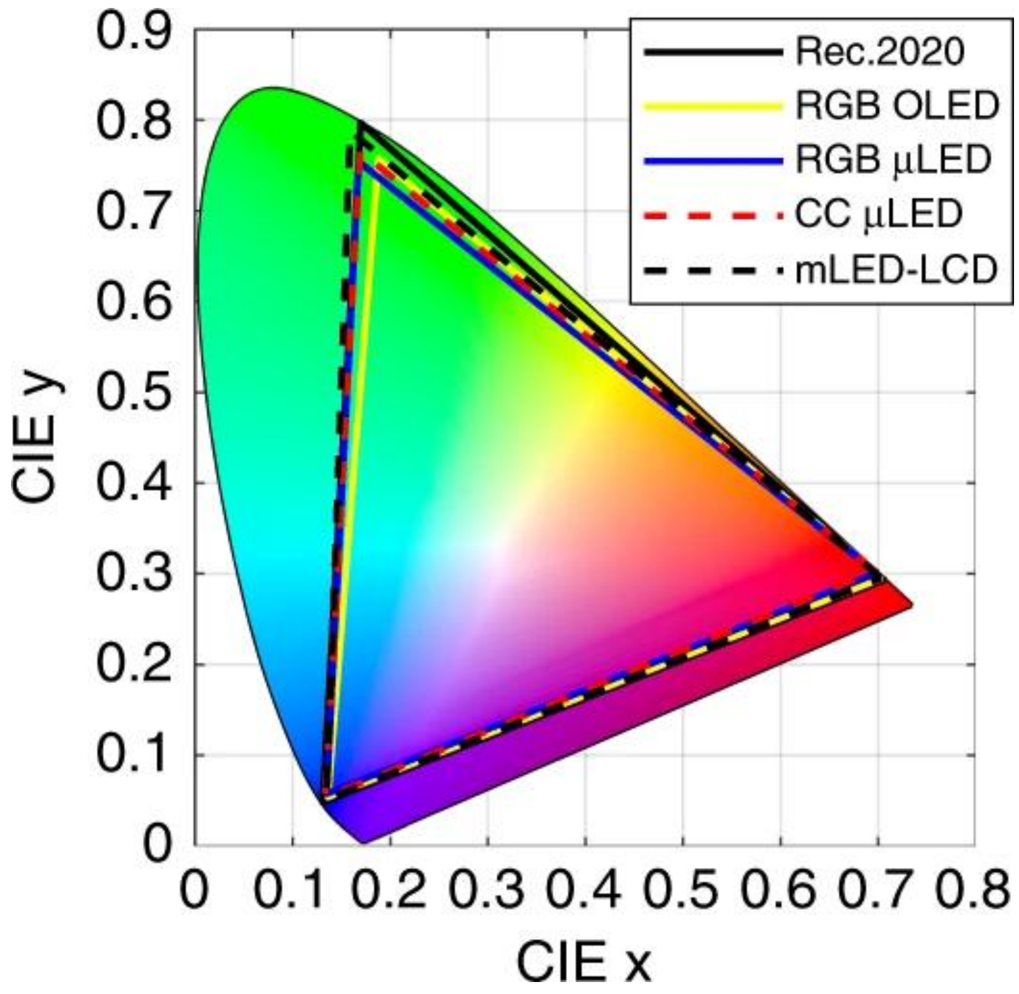
RGB vs. Blue + Color Conversion

Similarities

- **Tunable emission wavelength to achieve >100% NTSC**
- **Narrow FWHM of µLEDs and QDs (µLEDs slightly better)**
  - µLED: 18 – 30 nm linewidth (>90% of Rec.2020 color gamut)
  - QD: 20 – 30 nm linewidth (>90% of Rec.2020 color gamut)

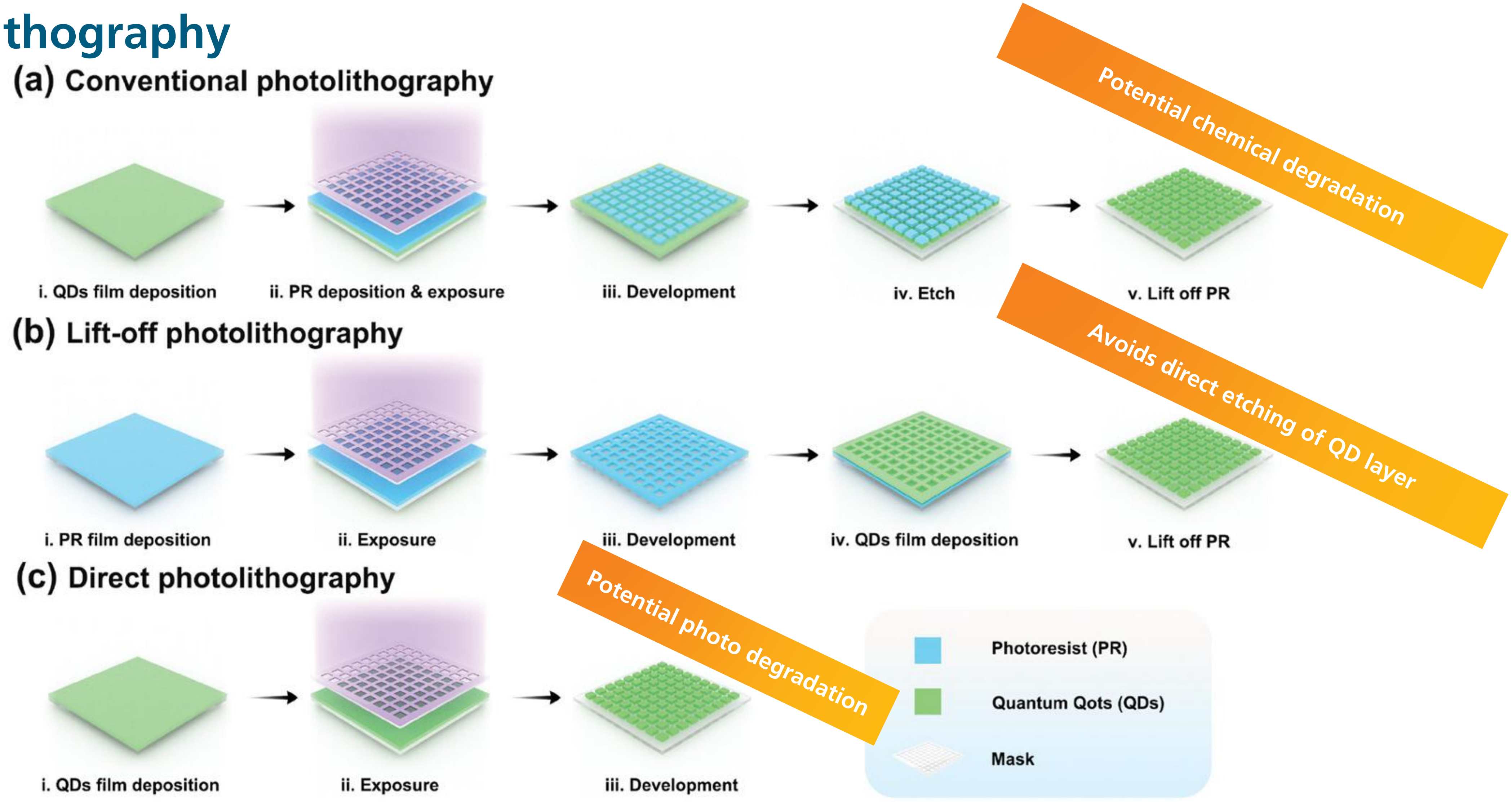
How to apply QDs for color conversion?

Cromaticity diagram of mLED/µLED/OLED displays



https://www.nature.com/articles/s41377-020-0341-9 (from 2020)

1. Photolithography



https://onlinelibrary.wiley.com/doi/10.1002/adom.202401106

2. Imprint

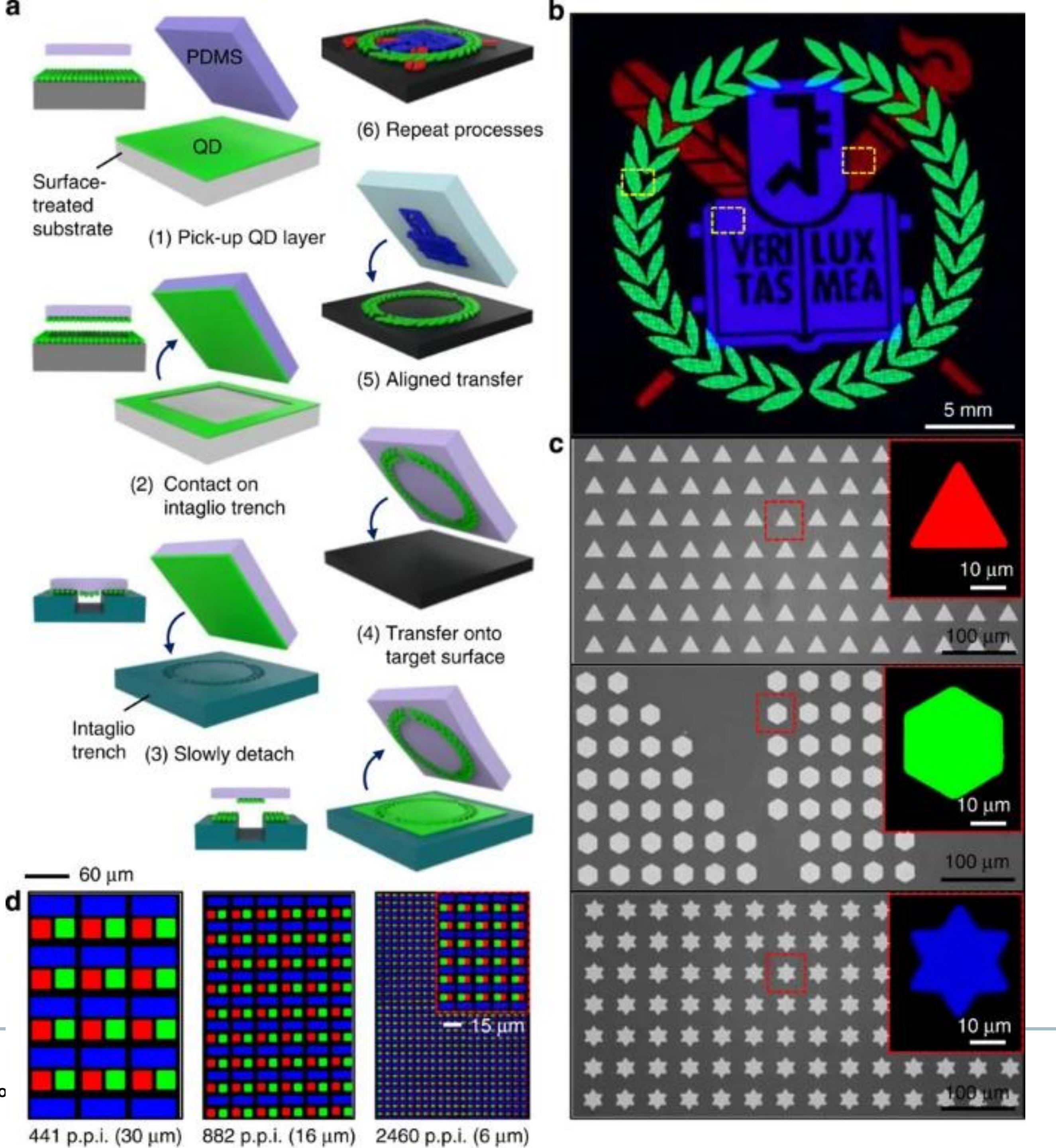
Schematic of Intaglio Transfer Printing

a) Schematic illustration of the process
b) PL image of printed patterns
c) Magnified views
d) PL images of aligned RGB pixels with
  - 30 µm (441 ppi)
  - 16 µm (882 ppi)
  - 6 µm (2460 ppi)

https://www.nature.com/articles/ncomms8149

Challenging interplay of wettabilities/adhesion

Flat substrates required



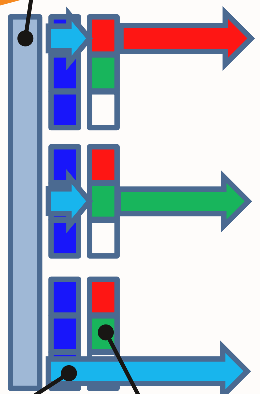
3. Ink-Jet

Still large pixel sizes

PL display

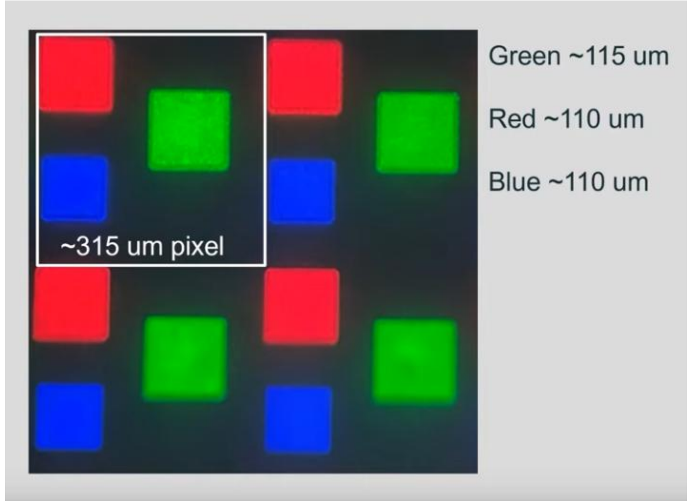
- **QDCF + Blue OLED**
- No BLU, polarizer & LC
- Low color distortion
- Thin & Flexible

QD-OLED TV



Resolution too low for MicroLED!

4K-QD-OLED made by Samsung Display



Peter Palomaki: Destroying a QD-OLED (Samsung S95B) – Part 2 (https://youtu.be/o-LbIBRuyog)

QD-OLED panel used in:
- *Samsung S95D Series*
- *Samsung S90D Series*
- *Sony A95L Series*
- *Alienware AW3423DWF Monitor*
- *Dell G3223Q Monitor*

	1st Gen	2nd Gen	3rd Gen	4th Gen	5th Gen
Pixel Layout	Diamond-Stripe	Diamond-Stripe	Square-Stripe	Square-Stripe	RGB-Stripe
Tandem OLED	-	-	-	5-Layer Tandem OLED	5-Layer Tandem OLED
EL Gen	-	Gen 2	Gen 2	Gen 3	Gen 3

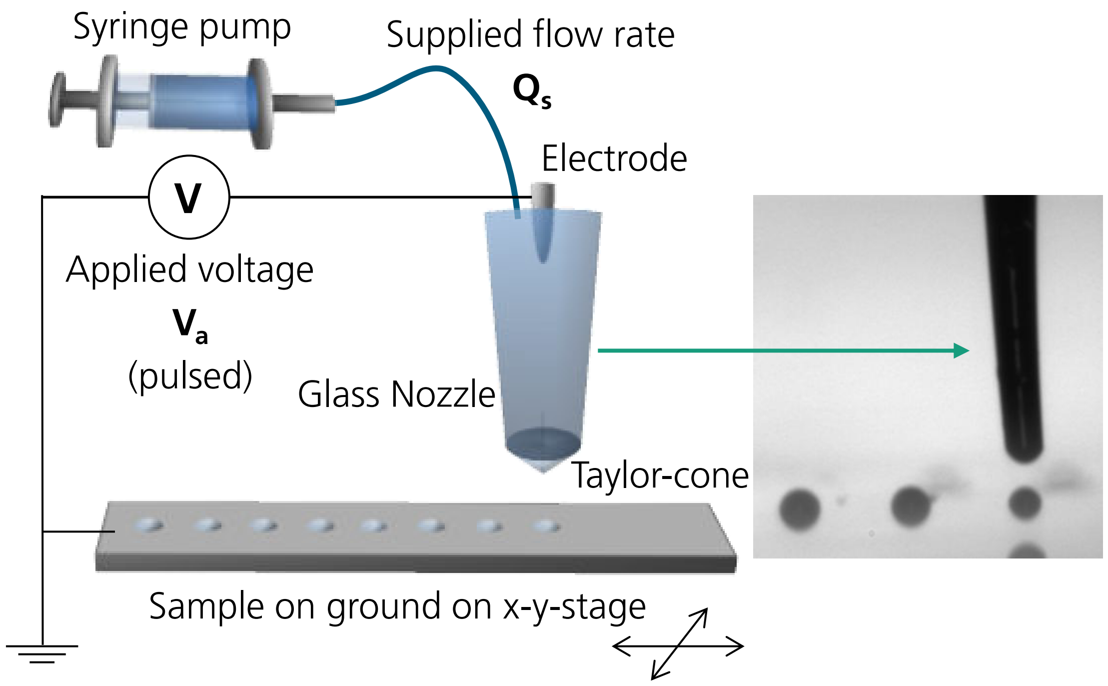
- ~140 ppi
- ~180 um pitch

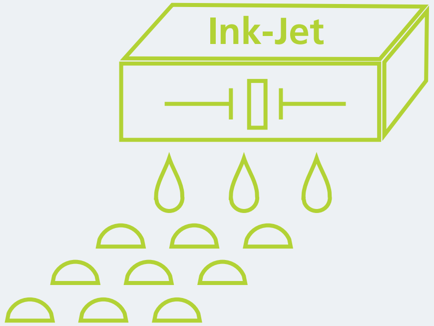
Source: MSI

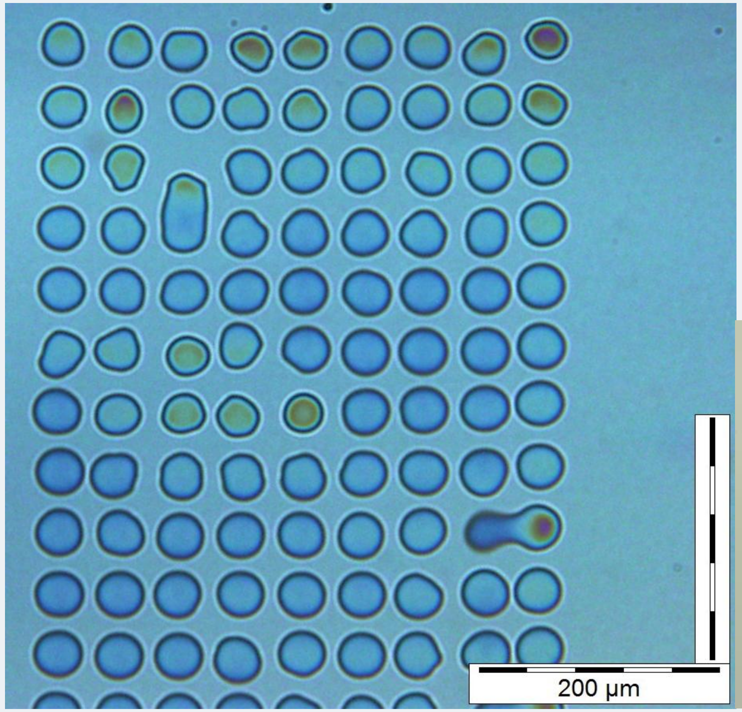
4. EHD-Jet for High-Resolution µLED

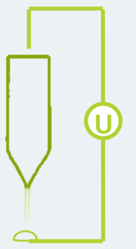
Drop-On-Demand Mode

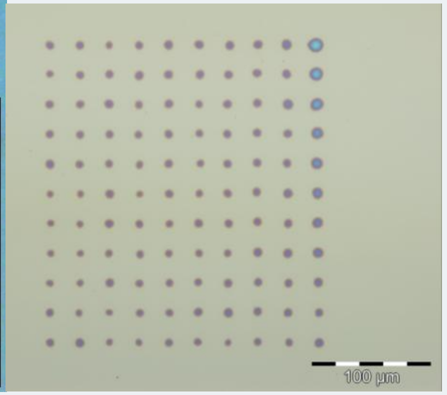
Drop ejection: pulsed electric field instead of piezo-excitation











Ink-Jet PEDOT:PSS on ITO glass (40 µm)
4 pL KM512 SHE

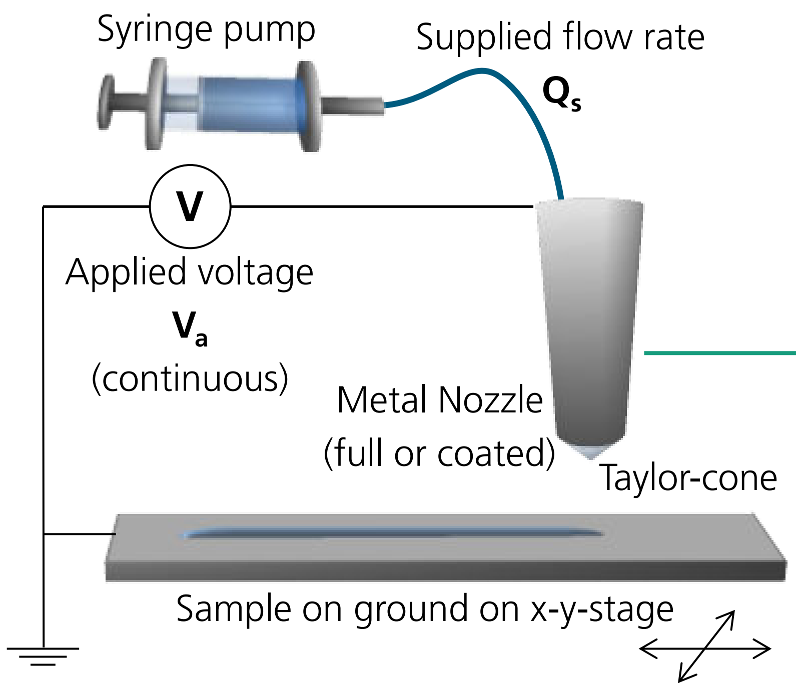
EHD-Jet (5-10 µm)
10 µm nozzle

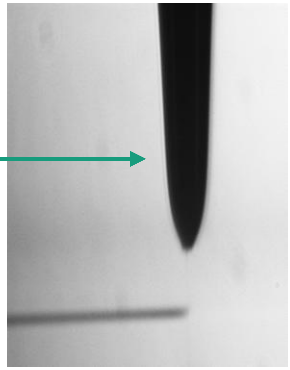
M. Gensler et al. *SID Symposium Digest* **2012**.
https://sid.onlinelibrary.wiley.com/doi/10.1002/sdtp.12115

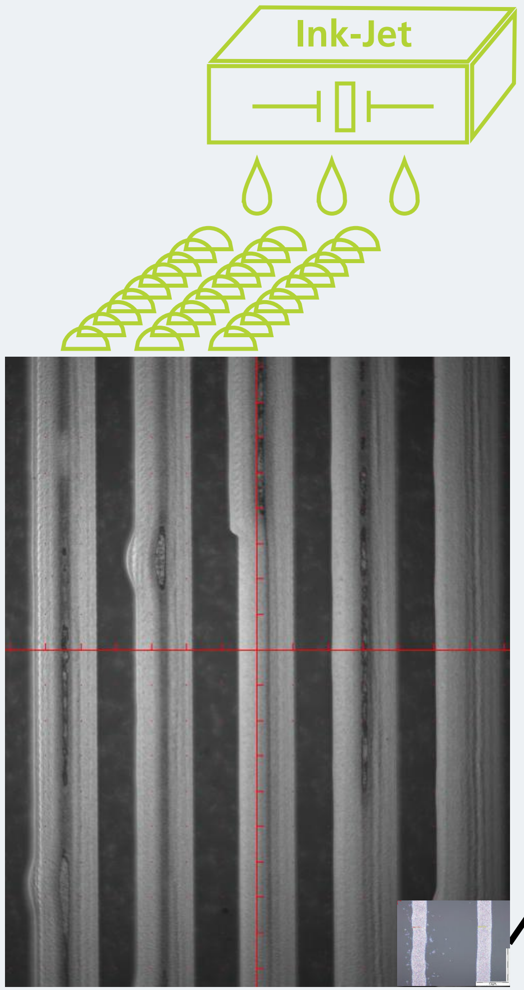
4. EHD-Jet for High-Resolution µLED

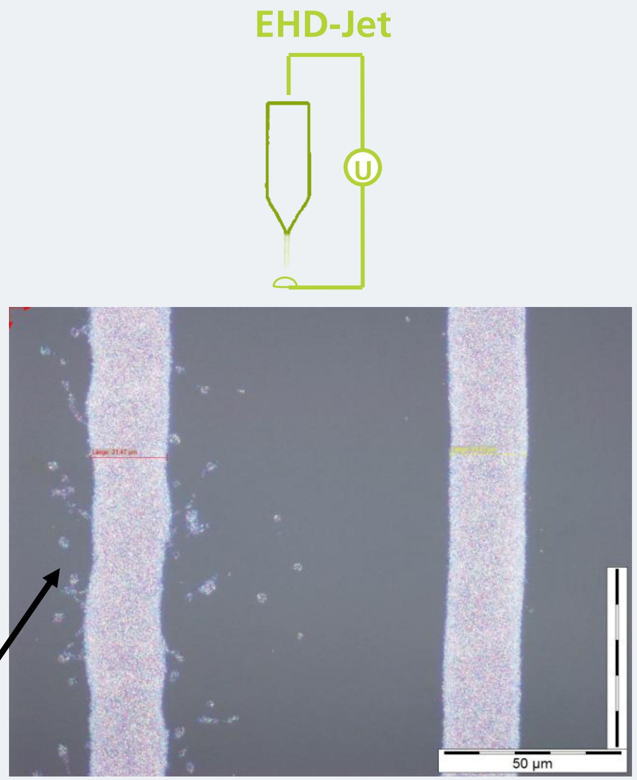
Continuous Jet Mode

Drop ejection: continuous electric field for vector printing









Ink-Jet (150 µm or 3 droplets)
6 pL KM1024i SHE

EHD-Jet (21 µm)
10 µm nozzle

Y. Kim et al. *SID Symposium Digest* **2023**. (printing of Nanohybrids)
https://sid.onlinelibrary.wiley.com/doi/epdf/10.1002/sdtp.16732

Bank Structures

Printing on the Back- or Frontplane?

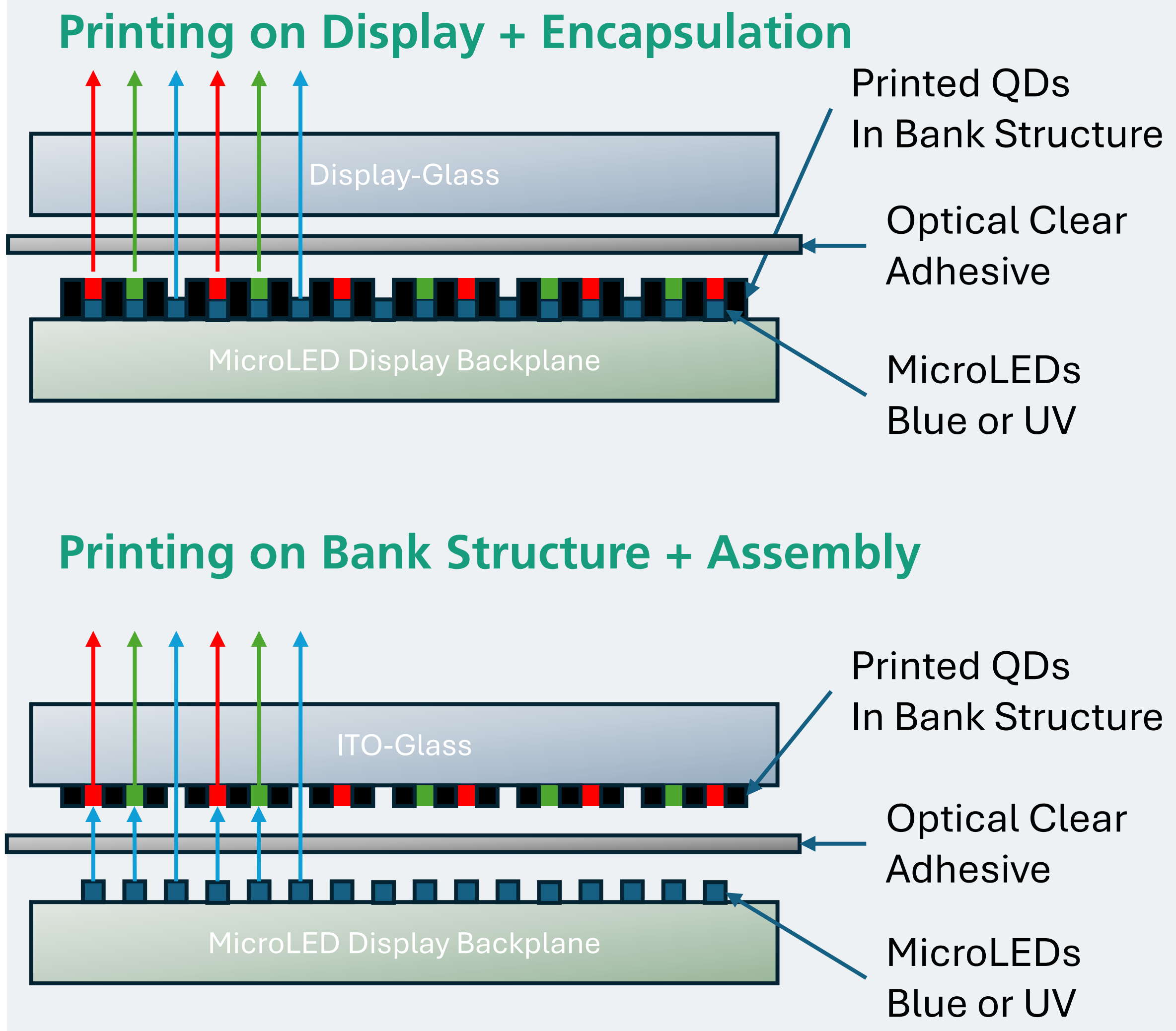
Bank Structure for Printed QDs

Disadvantages

- ITO coating required on display glass
- Gap between display and glass through OCA
- Complex alignment process

Advantages

- Improved electrical engineering for EHD (charge dissipation, substrate as ground electrode, homogeneously directed electric field)
- Bank structure processible on flat substrate instead of on complex display
- **Separation of production yields**
  - MicroLED Display + Bank + Printing



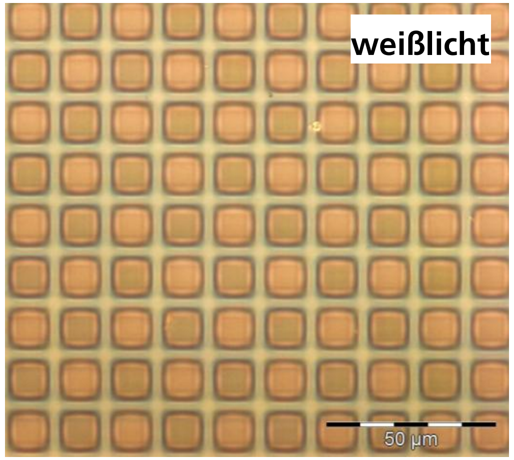
Fraunhofer

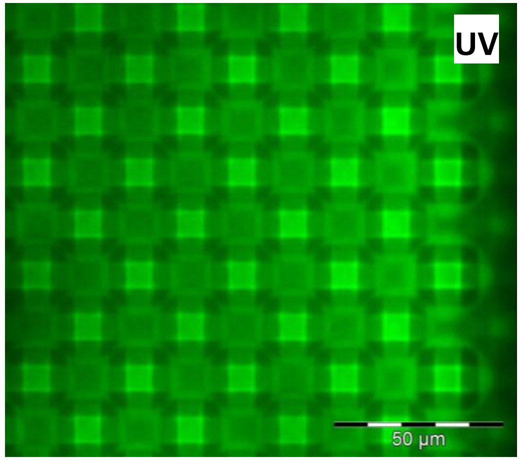
Printing into Bank Structures

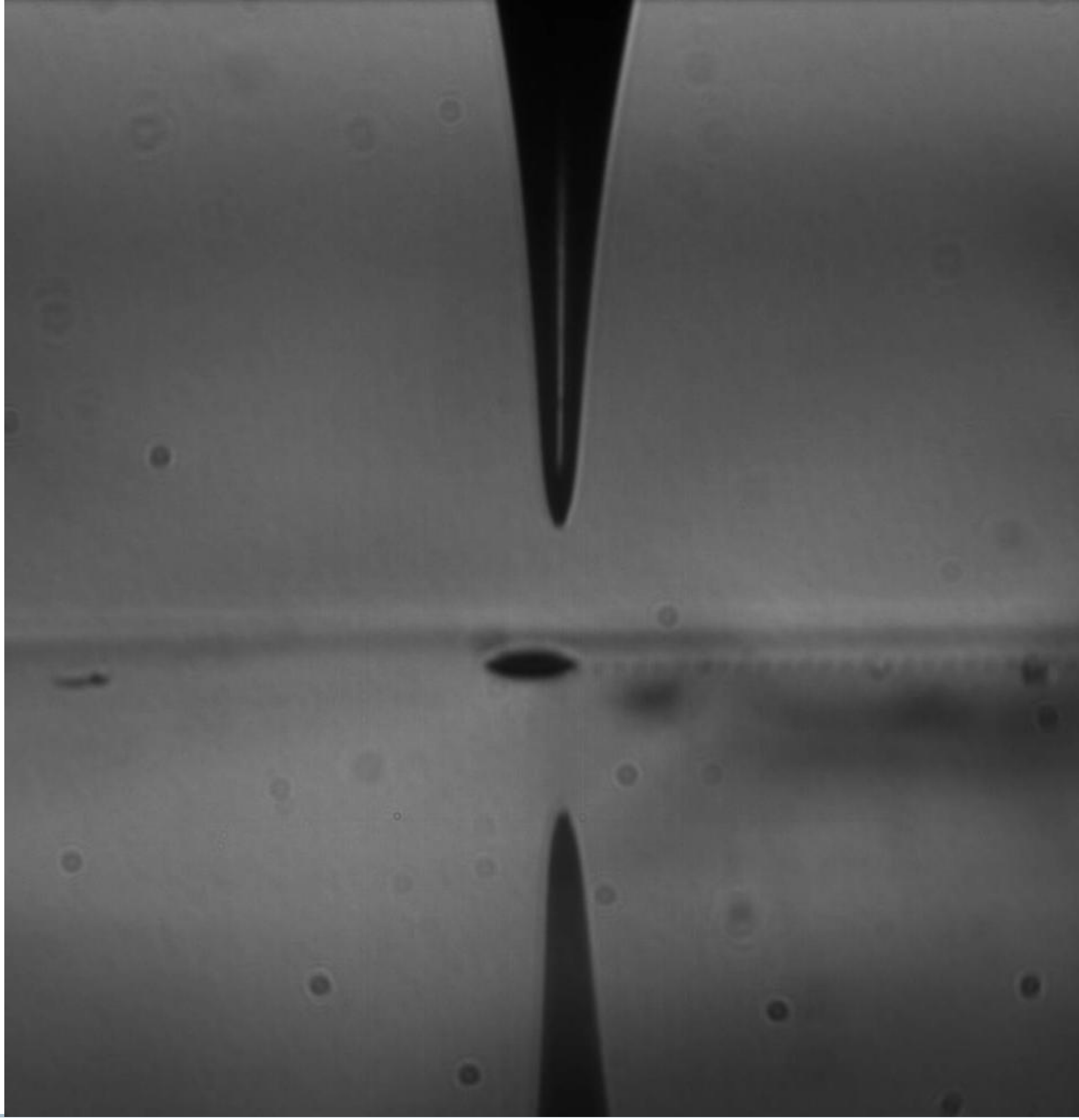
Reproducible EHD-Jet Printing of QD-Inks

Tailored Ink-Formulation for QD Printing

- No nozzle clogging
- Stable jet-on-demand
- Aligned printing into cavities
- **Much higher resolution than at Ink-Jet printing**
- **High and Flexible thickness achieved**







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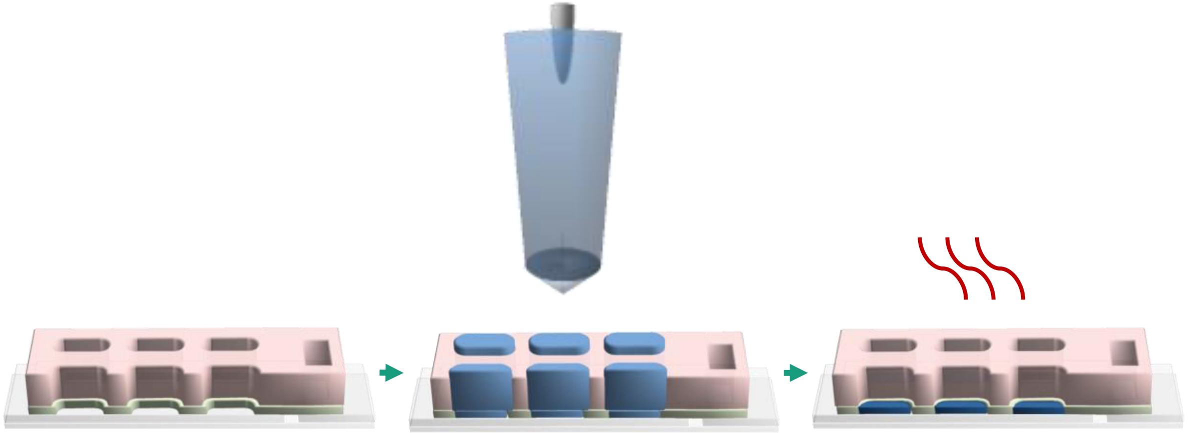
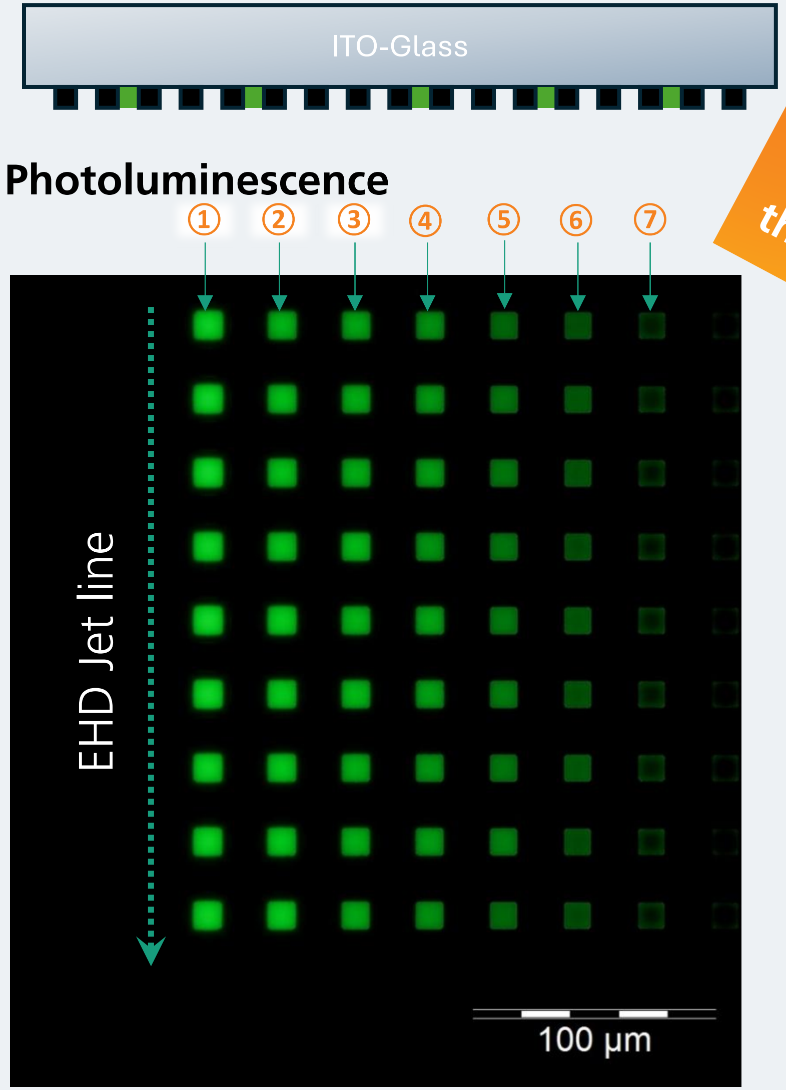


Bank Structure **Fill the Bank** **Dry the Ink**



Curing condition: 15 min at 100°C, and then 3 min at UV chamber

Flexibility in layer thickness through printing

Printing into Bank Structures

Reproducible EHD-Jet Printing of QD-Inks

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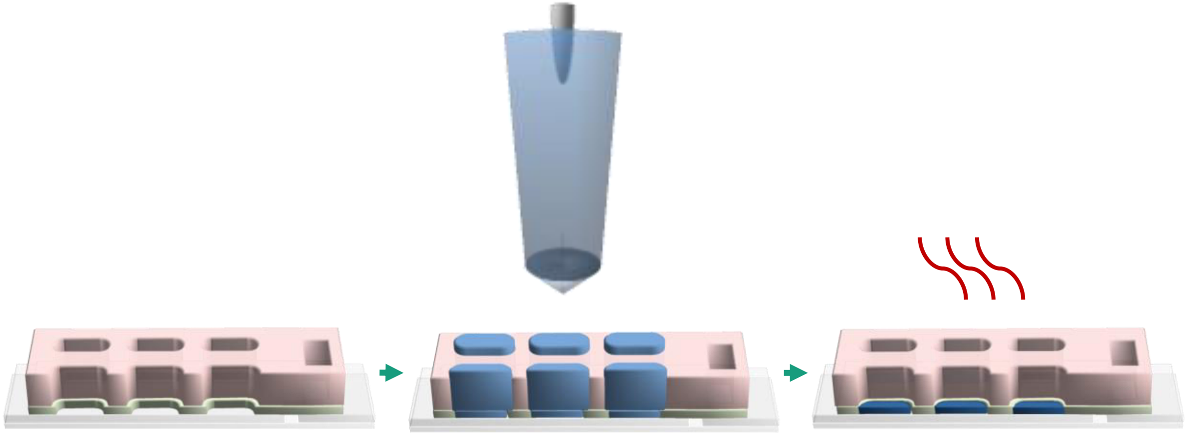
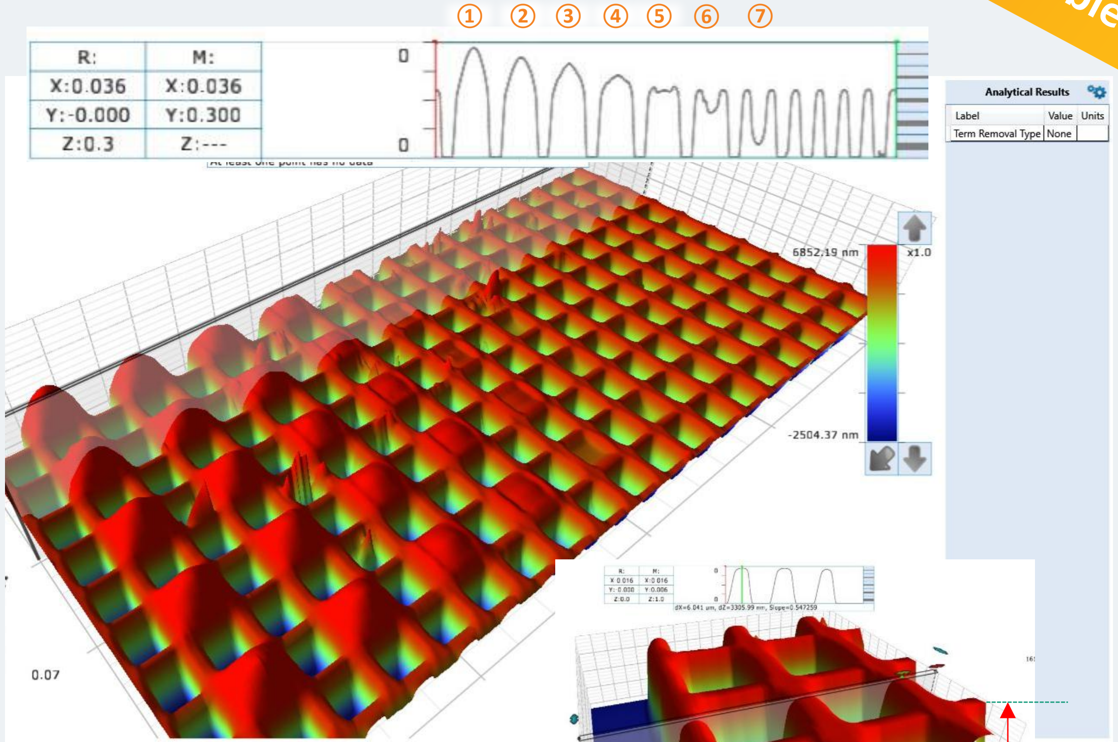


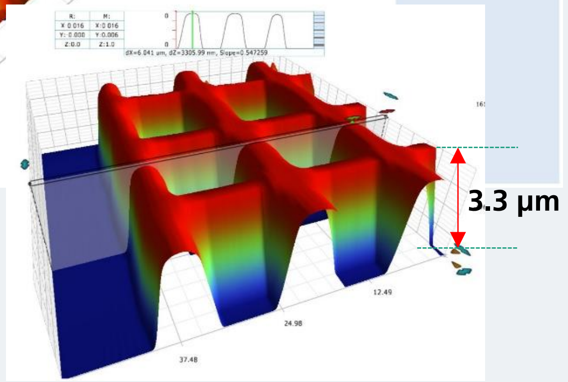
Bank Structure **Fill the Bank** **Dry the Ink**

µm thick layers possible

3D Profilometry (Dektak XT)



15 µm pitch bank structure



Curing condition: 15 min at 100°C, and then 3 min at UV chamber

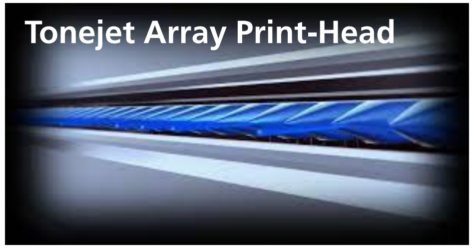
Germany-Korea Joint R&D Project
Ministry of Trade, Industry and Energy
KETI Korea Electronics Technology Institute
Hi-Accuracy GA No. 862410
Fraunhofer

From Single to Multi-Nozzle EHD-Jet

Breakthrough Potential for Industrial Applications

Emerging Technology with several companies involved

- **Electrospinning**, e.g. Nanoscience Instruments (USA)
  - **Established technology**
- Tonejet (UK): Multi-Nozzle printing of ink pigments on metal cans
  - **Technology in production since 2007, ceased in 2023**

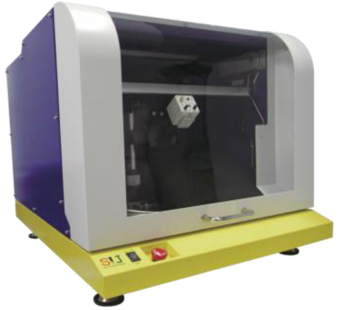


Single-Nozzle:

- Super Ink-Jet (JP): Desktop printer, international since 2012
- Tong Li Tech (CN): single-nozzle printer using glass needles
- Domicro (NL): coaxial print head based upon the LP50
- **Fraunhofer IAP (GER): Pilot printer for process and ink**

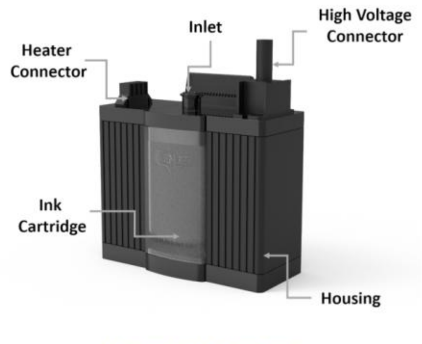
Multi-Nozzle:

- Enjet (KR): EHDison-H16 → 256 nozzles planned in 2 years
- Scrona (CH): MEMS-GEN3-128 print head → 256 nozzles planned
- **Notion Systems (GER): n.jet EHD with Scrona print head**



Super Ink-Jet Desktop Printer
Source: Printedelectronics.com

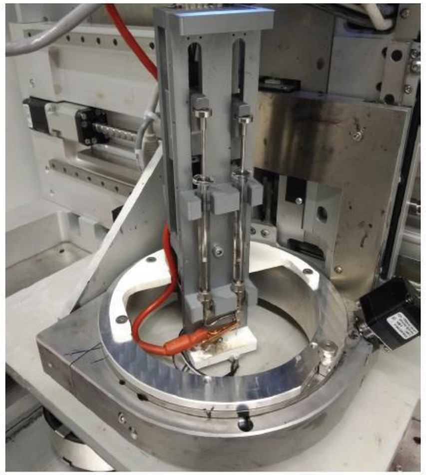
Ton Li Tech Co Limited
Source: ejetprinting.com



EHDison-H16 Printhead

Enjet EHDison-H16 (launched 2025)
Source: enjet.co.kr

From single to multi-nozzle



DoMicro DM50-ENP for LP50
Source: DoMicro.nl

Scrona Multi-Nozzle PH-128 (launched 2025)
Source: scrona.ch

n.net EHD
Source: notion-systems.com

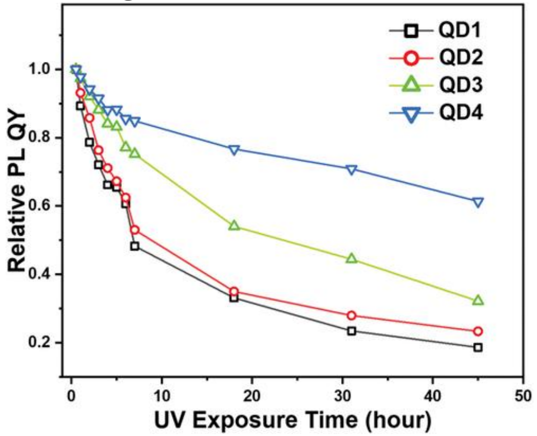
Challenges for QD Materials

Challenge 1: QD Material Stability

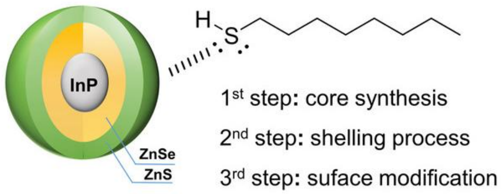
- High Radiance in MicroLEDs (Majority 1 W/cm², AR 5 W/cm²)

1. **Giant-Shell Approach**
2. **Stable-Ligand Approach**
3. **Encapsulation**

2. Stable-Ligand Approach

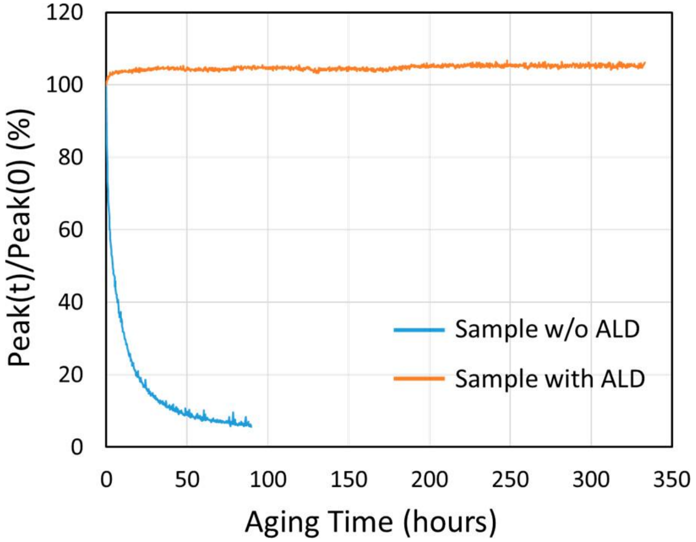


- QD1: w/o OTT
- QD2: 0.2 ml OTT
- QD3: 0.4 ml OTT
- QD4: 0.6 ml OTT

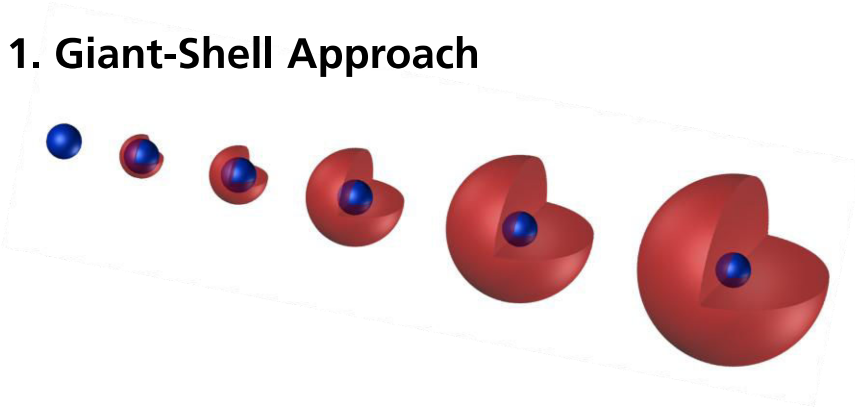


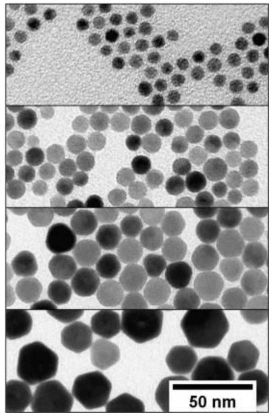
https://onlinelibrary.wiley.com/doi/10.1002/smll.202203093

3. Encapsulation



1. Giant-Shell Approach





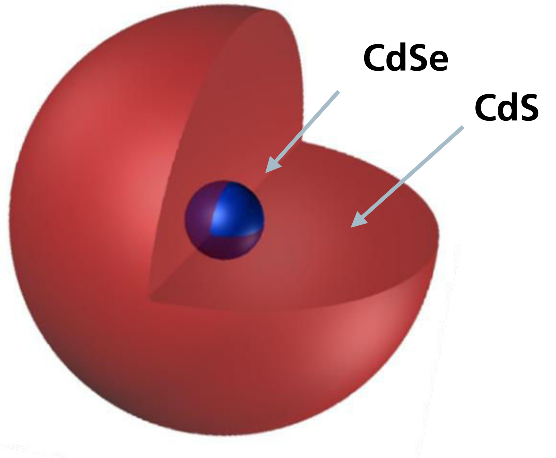
  - Confidential - Fraunhofer

Challenges for QD Materials

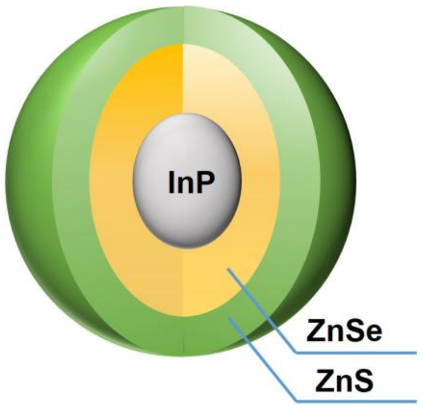
Challenge 2: High Absorbance for thin layers

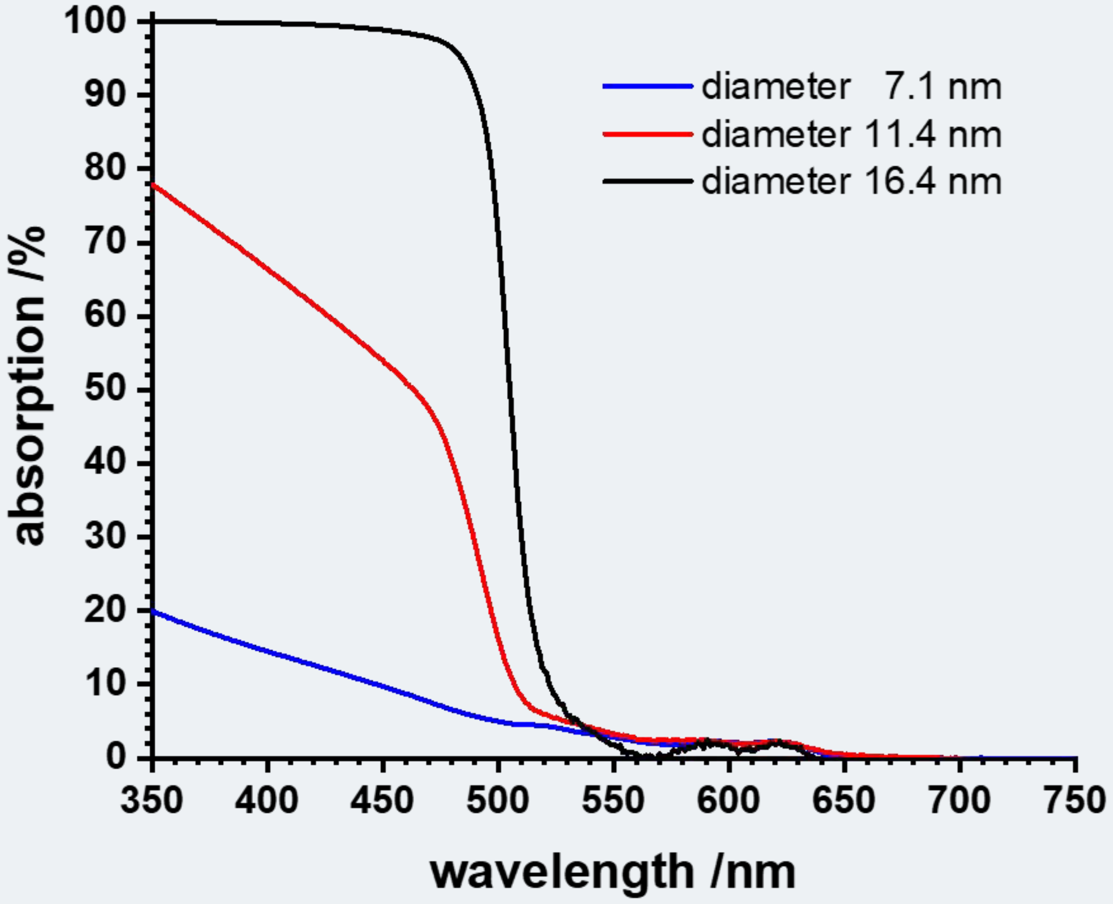
Absorption Coefficient (ε)

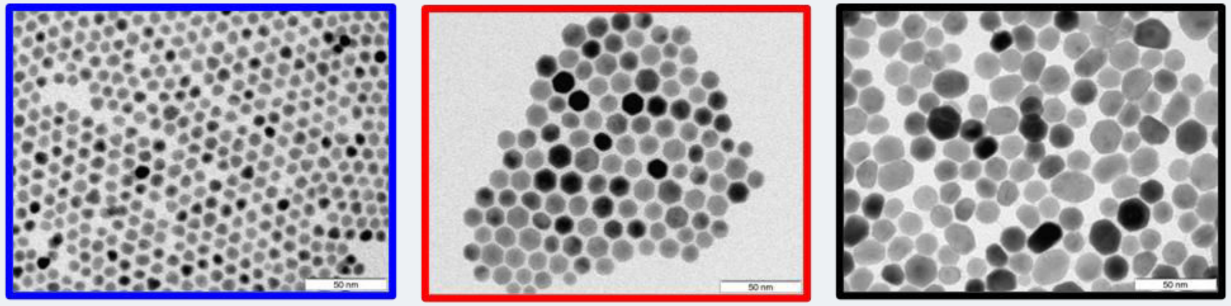
- CdSe/CdS: ~2 10^7 cm^{-1} M^{-1}
- CdSe/ZnSe/ZnSe: ~5 10^6 cm^{-1} M^{-1}
- InP/ZnSe/ZnS: ~6 10^5 cm^{-1} M^{-1}
- **→ 1 - 2 orders of magnitude smaller!**



Giant-Shell







- Confidential -
Fraunhofer

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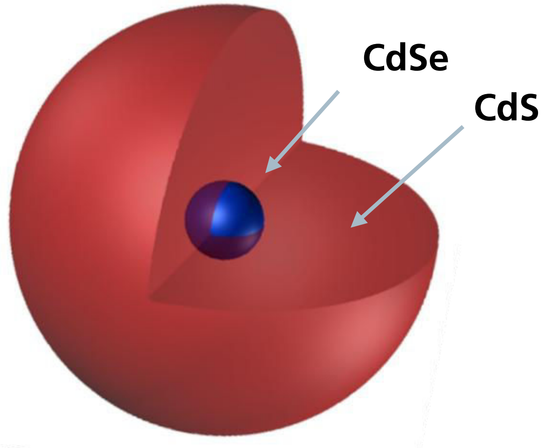
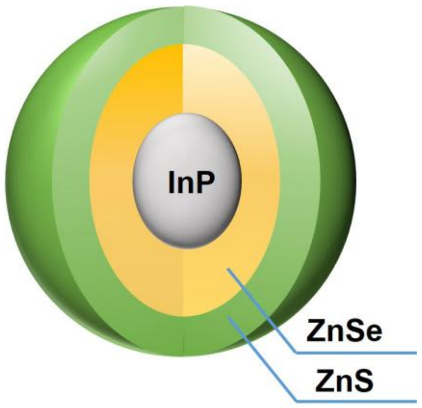
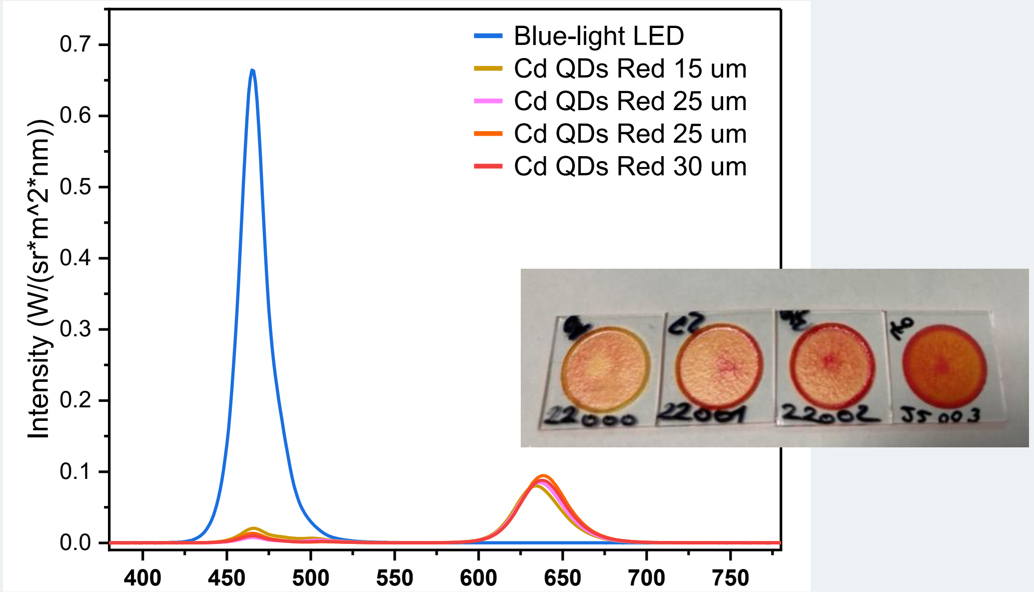
- **→ 1 - 2 orders of magnitude smaller!**

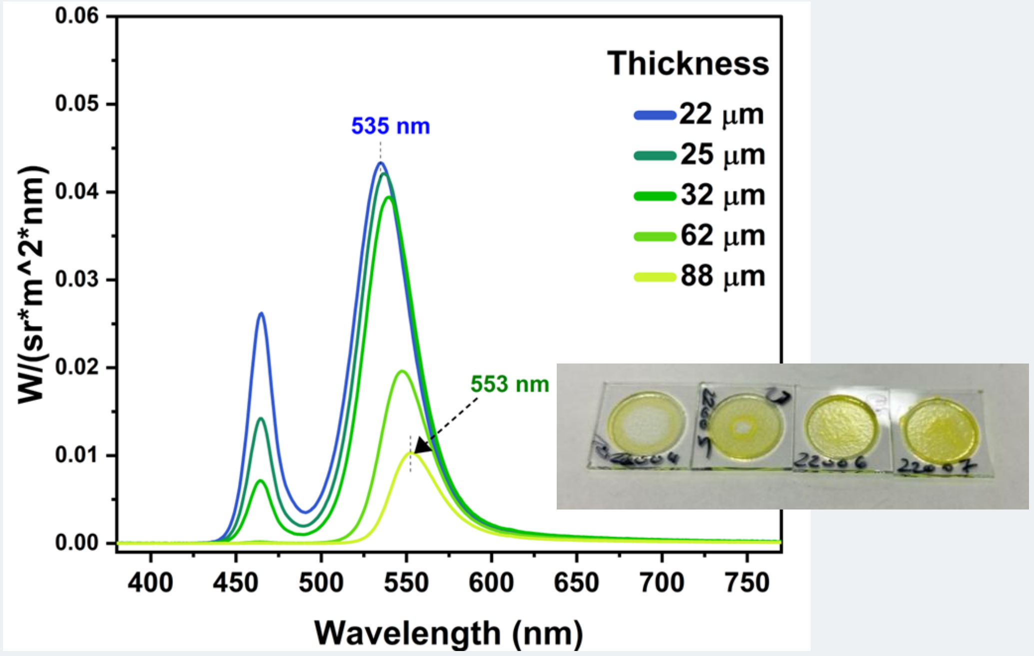
Strategies for increased optical density required



Giant-Shell







Fraunhofer

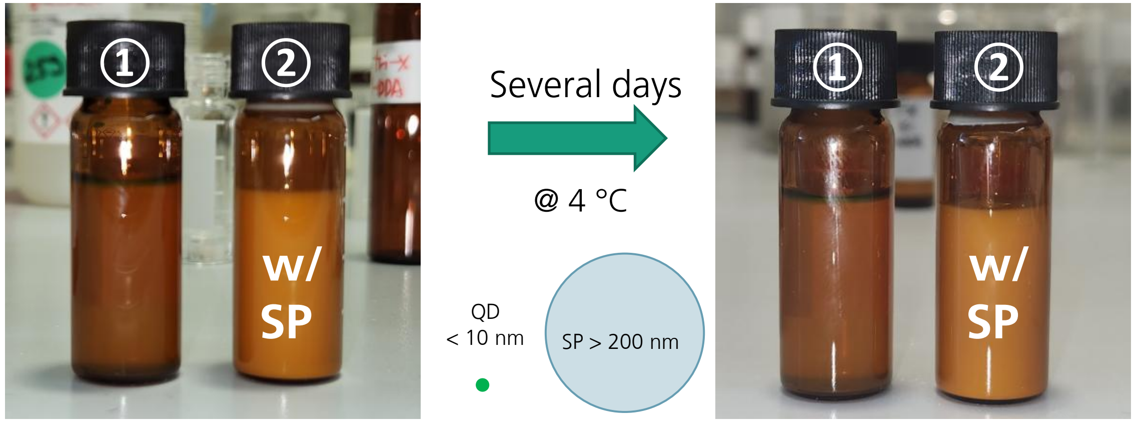
Challenges for QD Materials

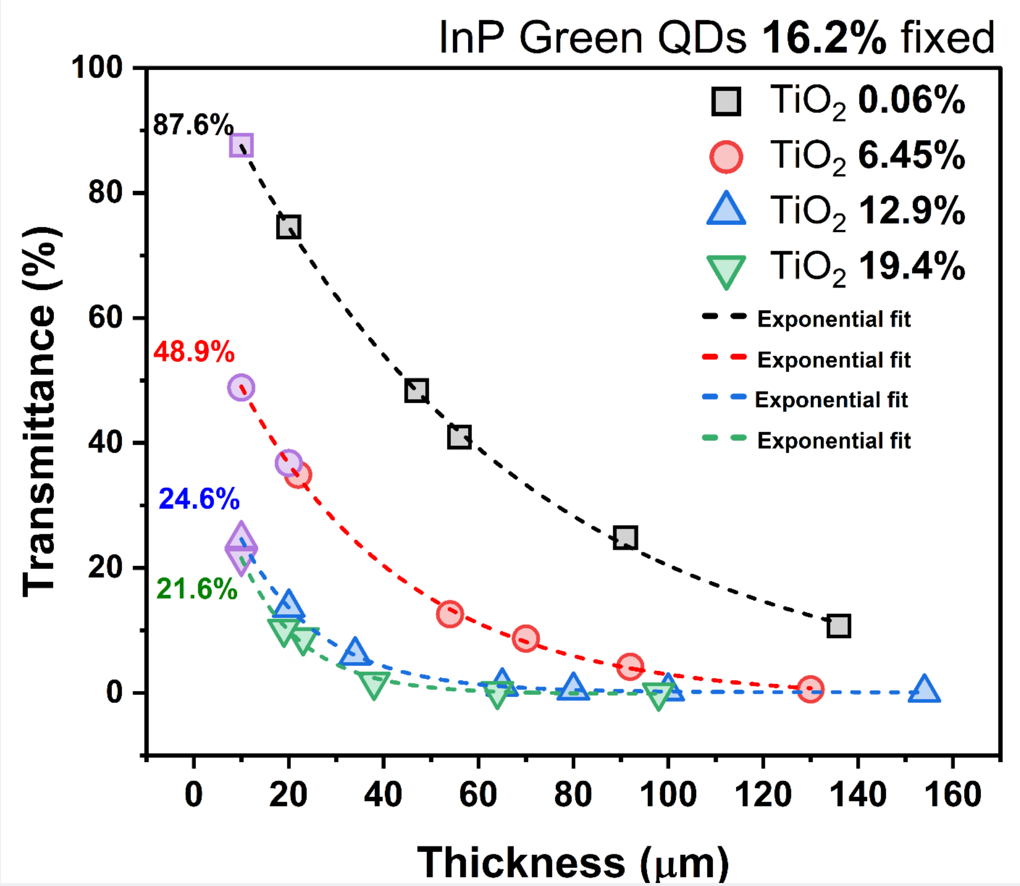
Challenge 2: High Absorbance for thin layers

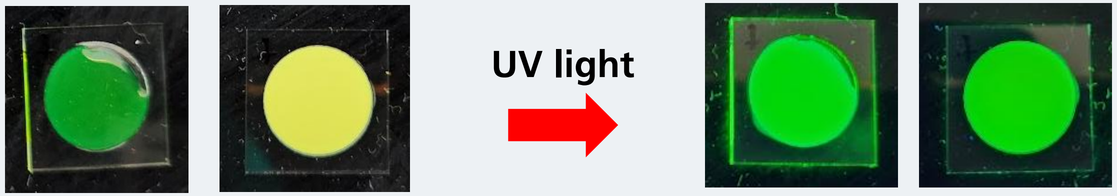
Scattering Particles for Increased Optical Density

- Optical attenuation increased (strong drop in transmittance)
- → about 1 order of magnitude

- Strongest effect on transmittance for thin layers (<40 µm)
- Saturation effect at around 13% TiO_2 content







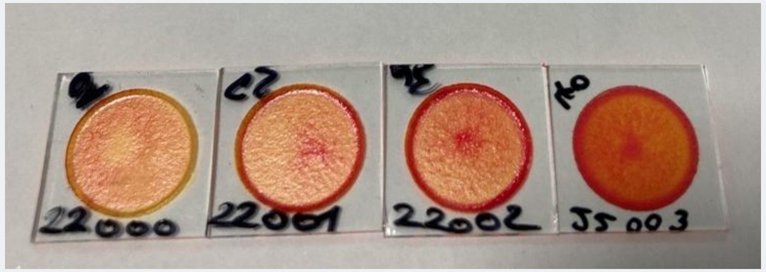
Challenges for QD Materials

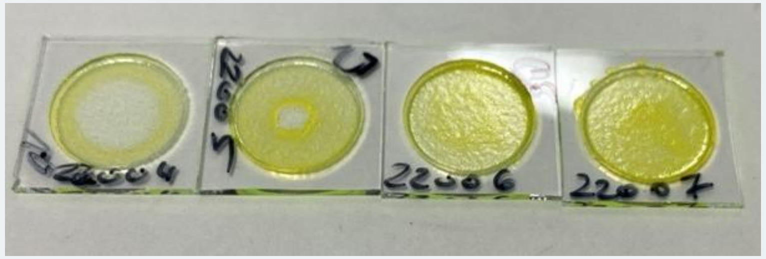
Challenge 2: High Absorbance for thin layers

Approximate Layer Thicknesses (OD ~ 2 or 99% Abs.)

- CdSe-based QD systems: ~15 – 25 µm
- InP-based QD systems: ~ 40 – 80 µm

Further strategies for higher absorbance?





Challenges for QD Materials

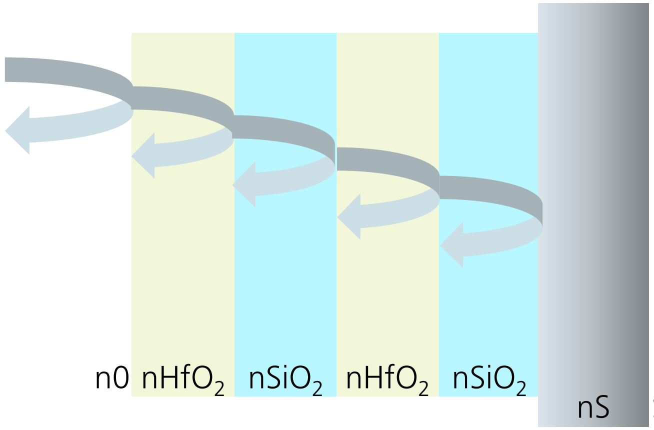
Challenge 2: High Absorbance for thin layers

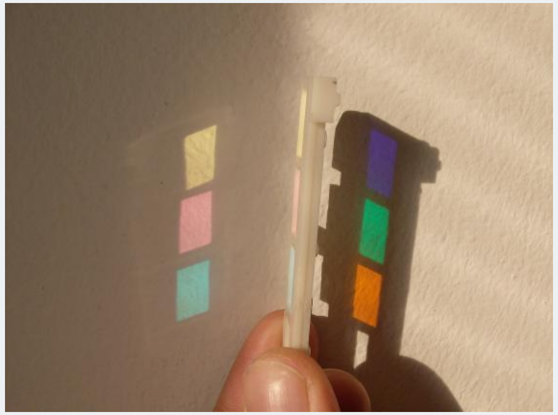
Approximate Layer Thicknesses (OD ~ 2 or 99% Abs.)

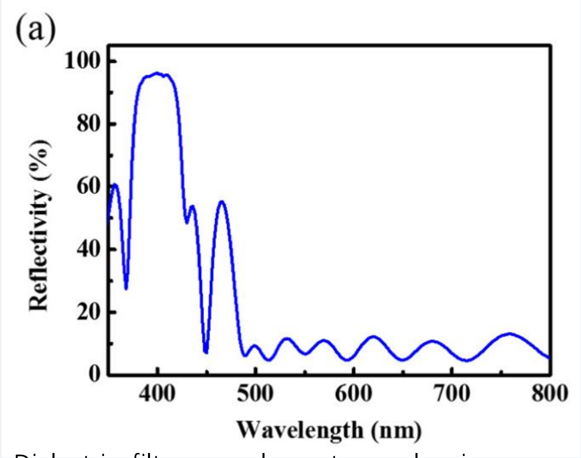
- CdSe-based QD systems: ~15 – 25 µm
- InP-based QD systems: ~ 40 – 80 µm

DBR may be used on thinner layers

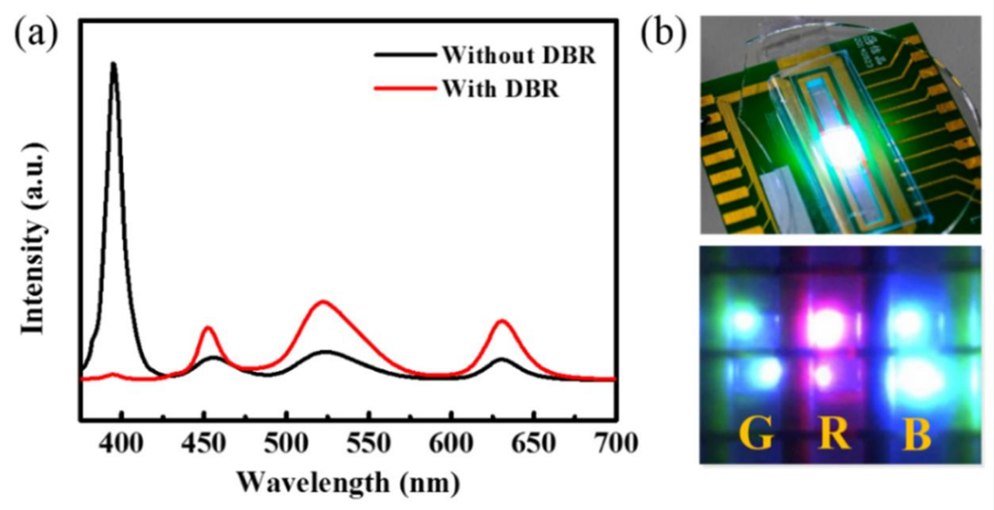
- Distributed Bragg Reflector (DBR)
- Han et al.: 17.5-pair of HfO_2/SiO_2 multiple-layer structure







Wikipedia: https://commons.wikimedia.org/wiki/File:Dielectric_filter_complementary_colors.jpg



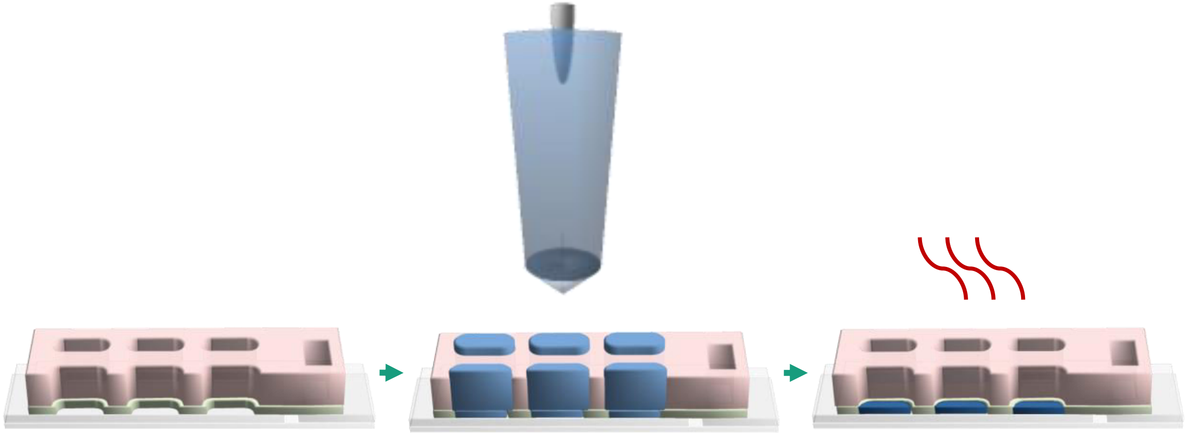
https://opg.optica.org/oe/fulltext.cfm?uri=oe-23-25-32504&id=333320

Challenges for QD Materials

Challenge 3: High layer thickness in a single print

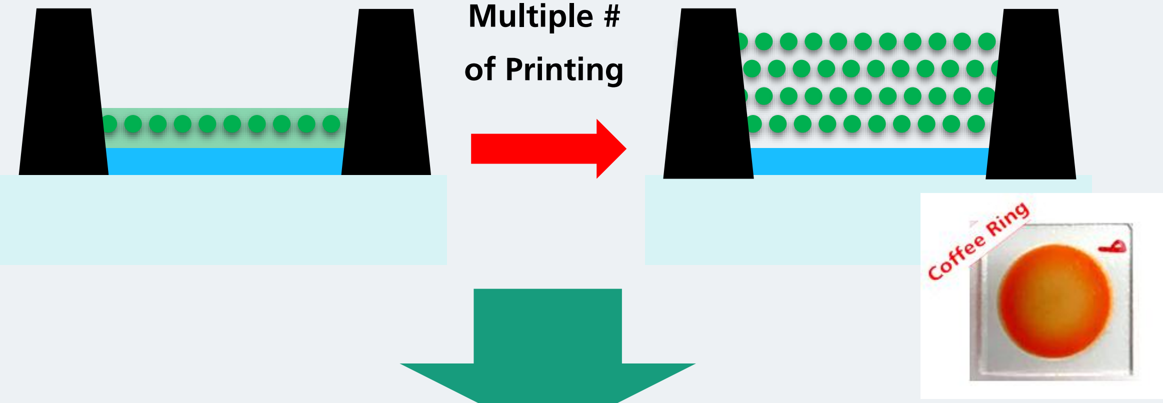
Non-Solvent Type QD-Inks

- Bank filling in a single step → Reduced processing time
- Increased layer homogeneity
- No ligand exchange required → Improved QD stability

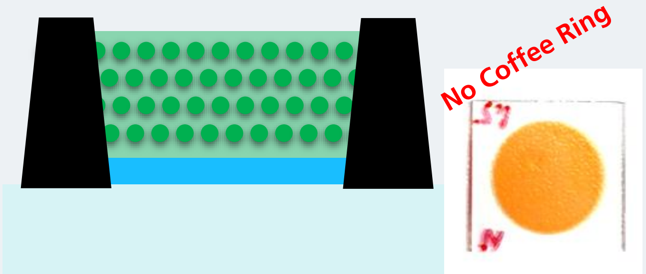


Bank Structure | Fill the Bank | Dry the Ink

Solvent based QD inks



Non-Solvent based QD inks



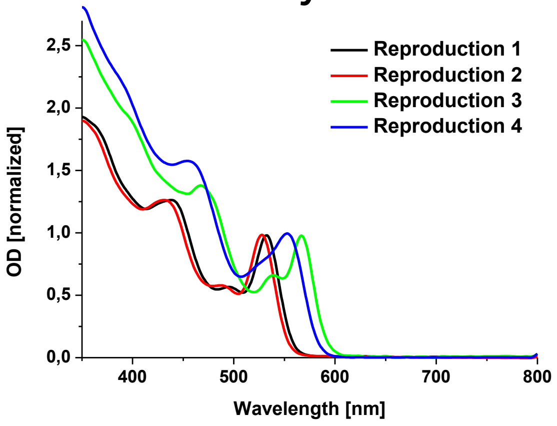
Challenges for QD Materials

Challenge 4: Reproducibility of Synthesis

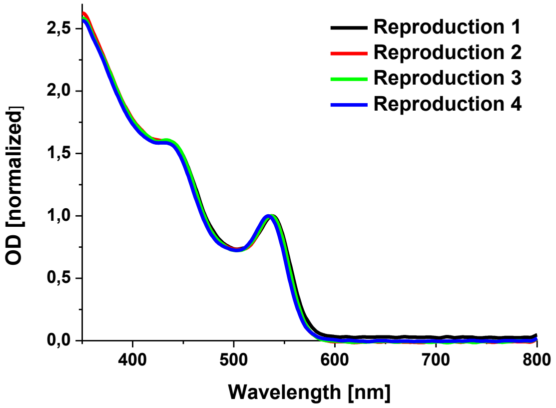
Continuous flow synthesis

- optimized for high throughput (e.g. 1 g/min for PbS)
- high reproducibility
- reduction of production costs
- increased laboratory safety
- environmentally friendly production

Batch synthesis

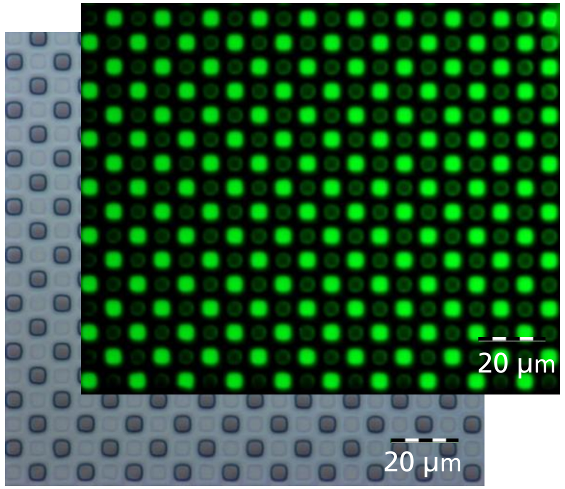


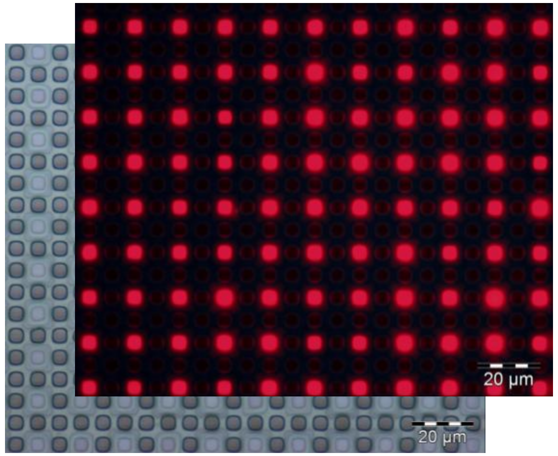
Flow synthesis

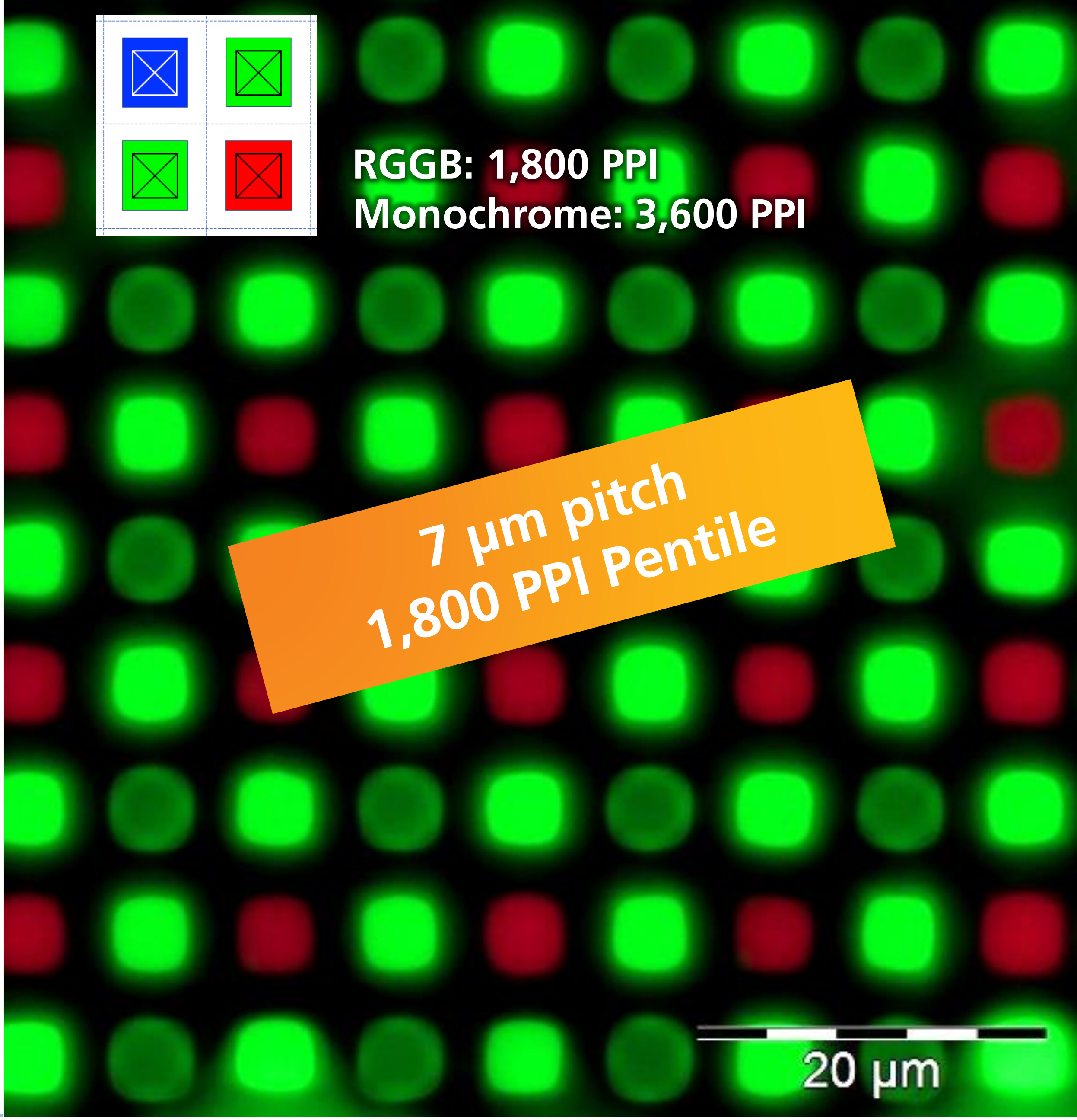


Fraunhofer IAP: QD Color Conversion

High-Resolution printed red and green QD color converters (7 µm pitch)

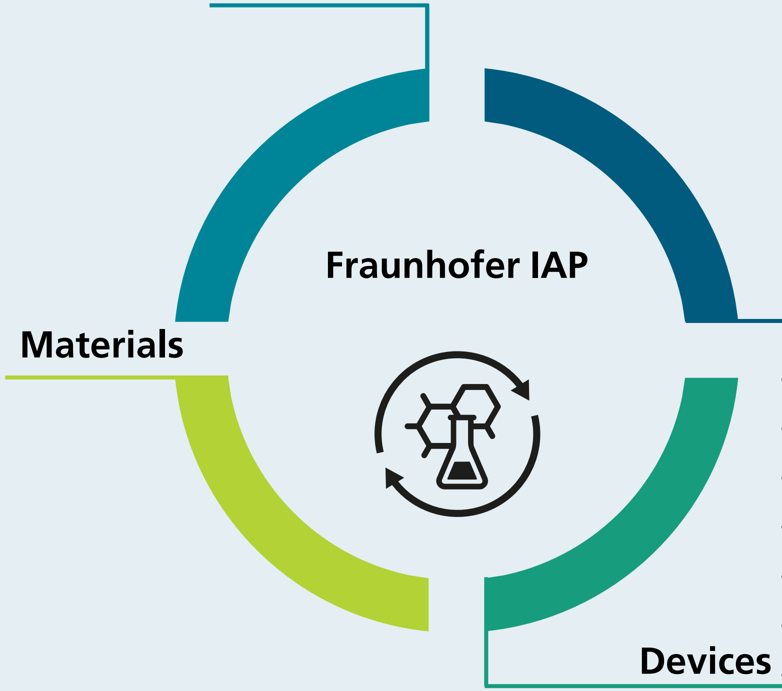


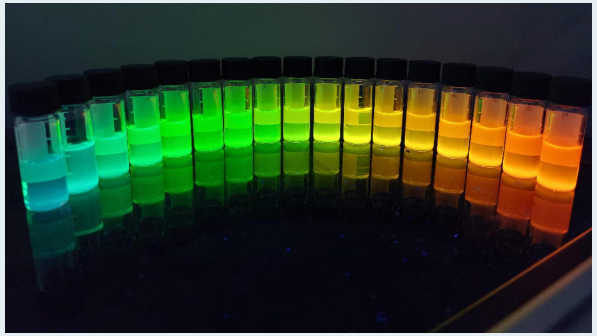




Germany-Korea Joint R&D Project
Ministry of Trade, Industry and Energy
KETI Korea Electronics Technology Institute
Hi-Accuracy GA No. 862410
Fraunhofer

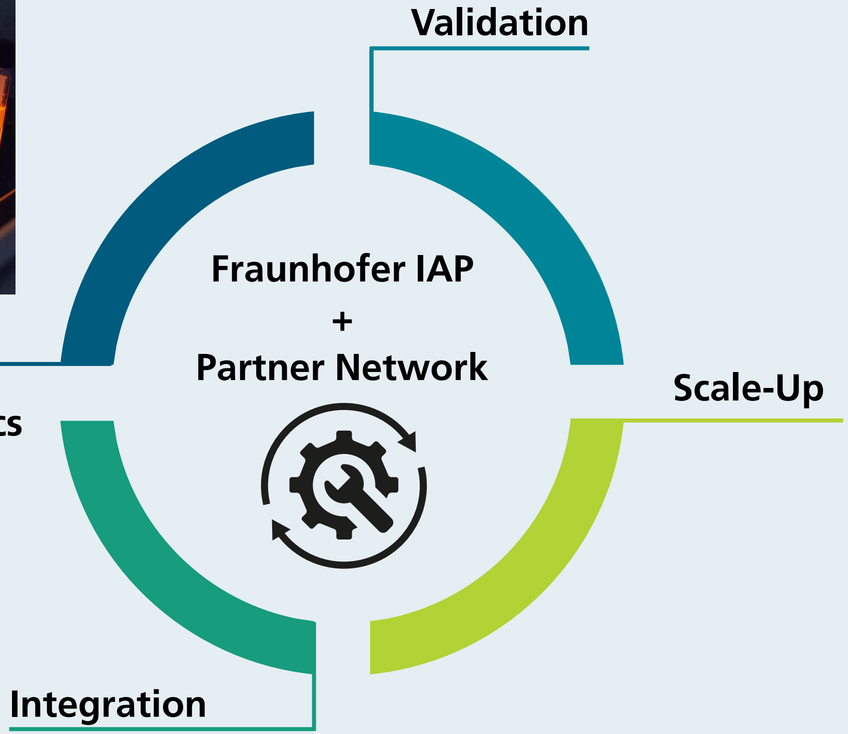
Fraunhofer IAP: Bringing Materials into Applications



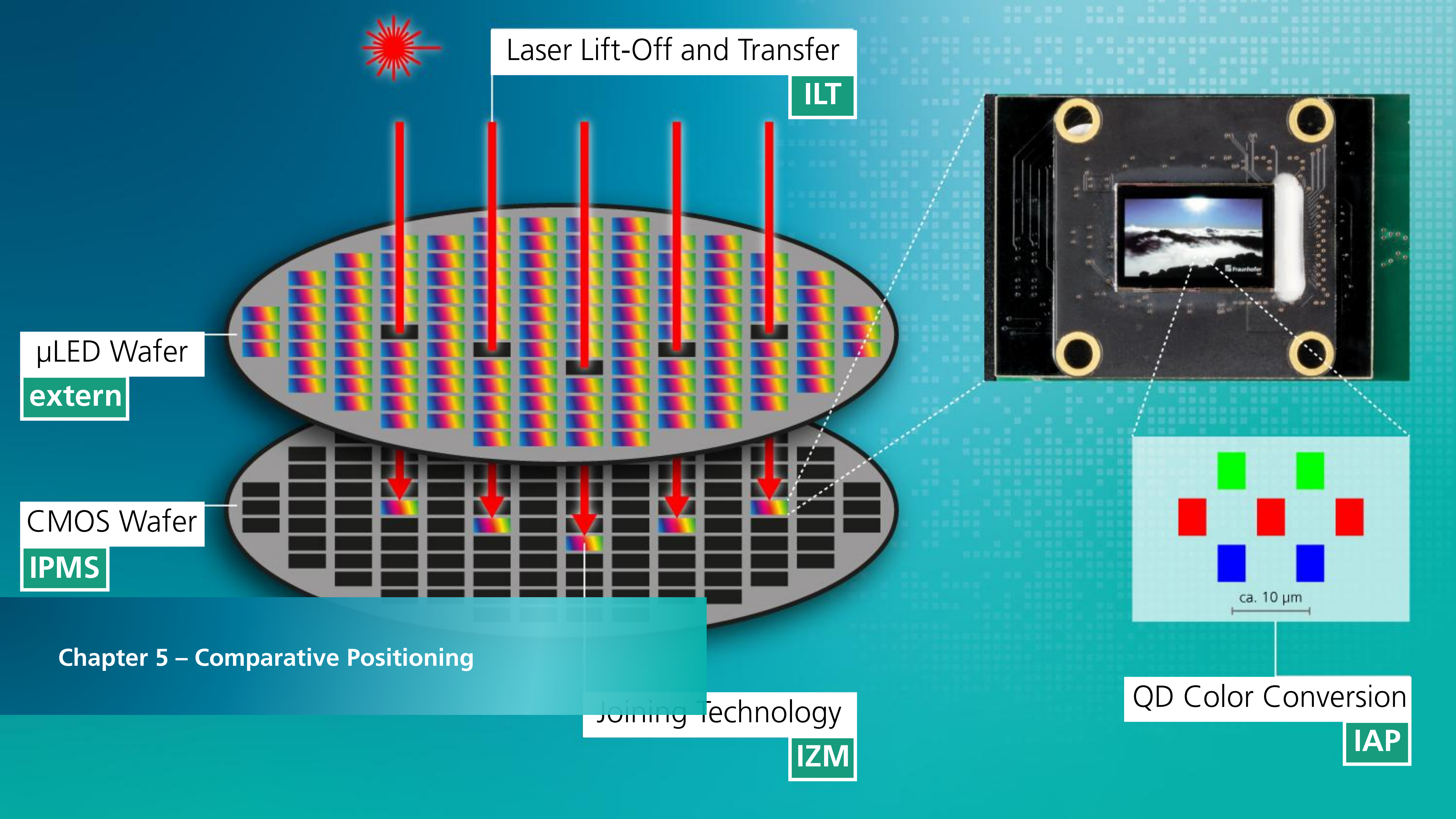


Applications

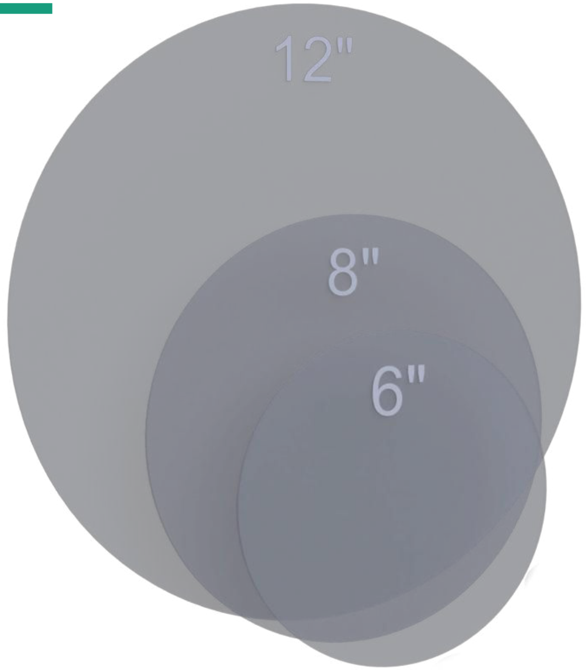
- Organic and Printed Electronics
- Display Technologies
- Nanoscale catalysts
- Medical applications
- OLED, QD-LED
- OPV
- Perowskites



Chapter 5 – Comparative Positioning

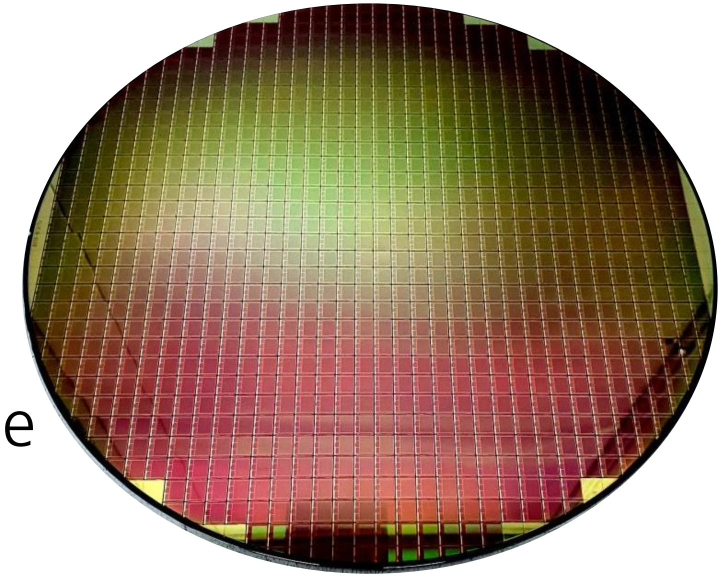


Summary

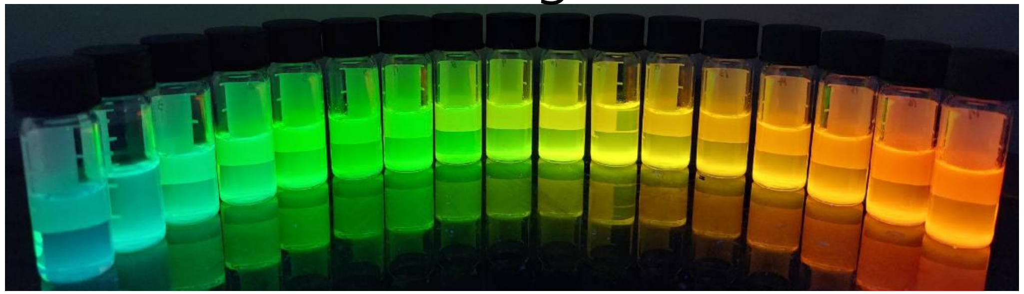


µLED Wafer

Backplane



Coloring



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