Inkjet Printing for Manufacturing of Flexible and Large-size OLEDs

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Outline

- **Introduction (to OLED, Kateeva, and inkjet printing)**
- **OLED application #1: Thin film encapsulation**
- **OLED application #2: RGB pixel printing**
- **Summary**

There is an ongoing display revolution

History of Digital Displays – the beginning of our new wave

CRT

1921 - Electronic Visual Big Bang
Limited size (< 40”)
Too heavy

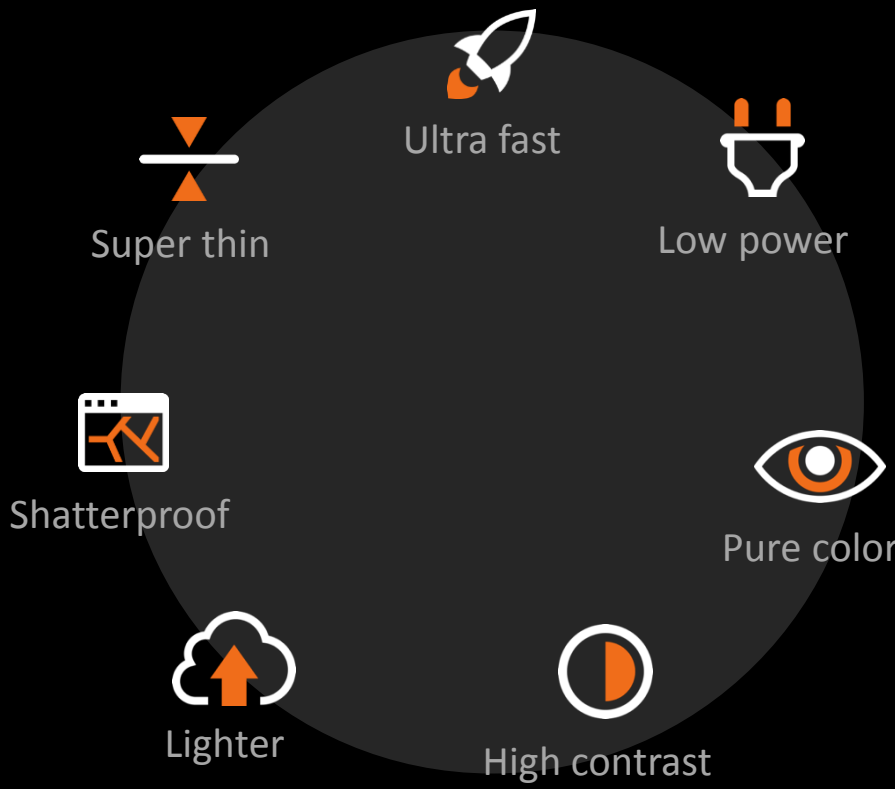
LCD

1986 - Flat and large - Up to 110” - Started the Era of Mobility
Flat and Fragile glass
Difficult to move

OLED

2009 – Displays Everywhere
“Perfect Display”
Flexible - Conformal

OLED for display: The Perfect Display – Free from Glass



Cheaper

Flexible
Freedom from Glass

The OLED Revolution

high brightness

low power

ultra fast

ultra high contrast

large scale rollable

ultrathin

curved and flexible

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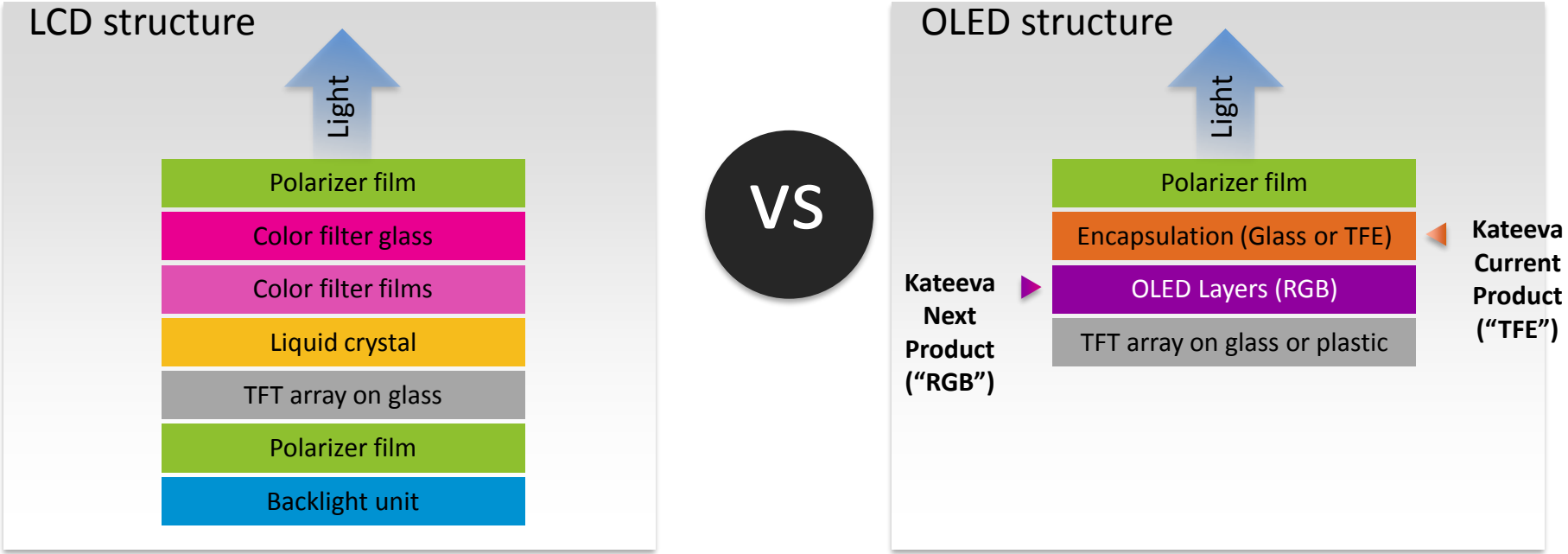
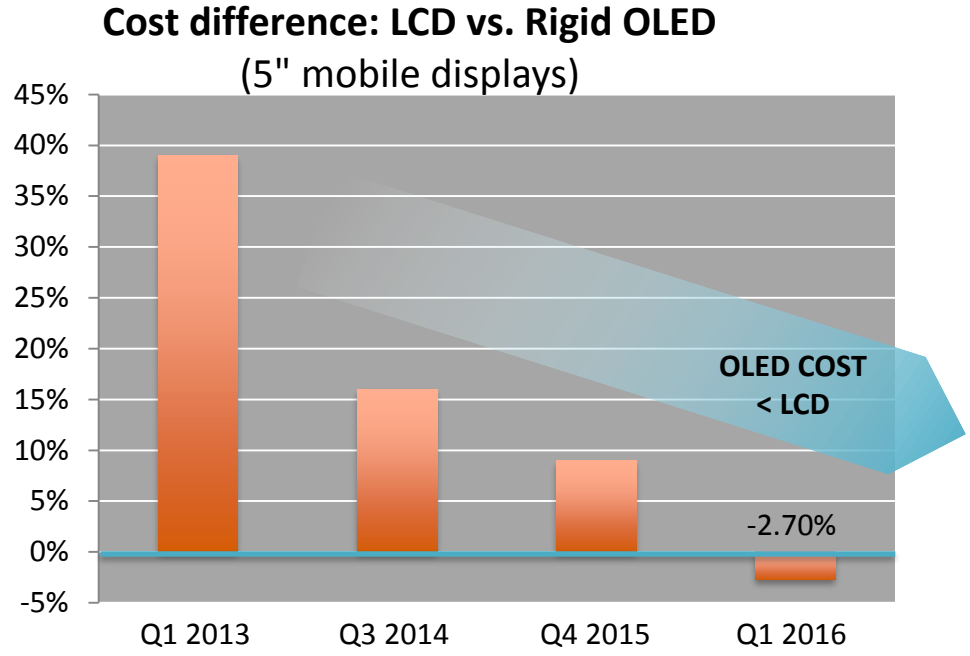
OLED is a simpler structure than LCD



OLED has the potential to be 20% to 30% cheaper than LCD with the right manufacturing technology

LCD cannot keep up with mobile OLED cost reduction



Source: IHS display search reports (2013-2016)

- OLED cost reduction trend is in the steep part of the curve
- Rigid OLED is already cheaper than LCD
- Flexible OLED will soon be cheaper than LCD

Inkjet printing will play a significant role in reducing manufacturing costs and increase yields

Kateeva

- **Founded in 2008**
- **Received 200M+ investment over eight years from venture capital and strategic partners**
- **Leading supplier of inkjet equipment for OLED mass production**
  - **In Mass Production**: Thin Film Encapsulation (TFE); >80% market share
  - **Next Mass Production Product**: RGB Pixel Printing
- **Rapidly growing global equipment company**
  - Newly renovated 75,000 sq. ft. headquarters in Newark, CA (Silicon Valley)
  - Rapidly growing headcount: currently ~330 staff
  - Lab Facilities: OLED device fabrication, ink formulation, and demo/engineering

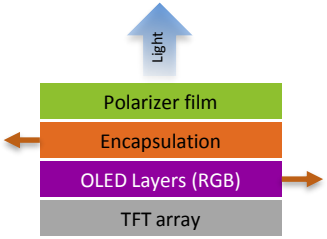
General Challenges in Bringing IJP to OLED Mass Production

- Maintaining a pure process environment (sub 1ppm O2, H2O)
  - OLED devices are extremely sensitive to trace levels of O2, H2O, and other contaminants
  - Critical for device performance and yield
- Low particles
  - Must not introduce large particles during printing
  - Even neutralize incoming particles
- Process uniformity (for display uniformity)
  - Understanding where the drops should be placed
  - The ability to accurately place the drops
- Materials
  - Optimized ink properties, optimized post-print processing, surface treatments
- Tool robustness
  - High uptime, repeatable and stable process results

Kateeva's Current and Next Mass Production Products

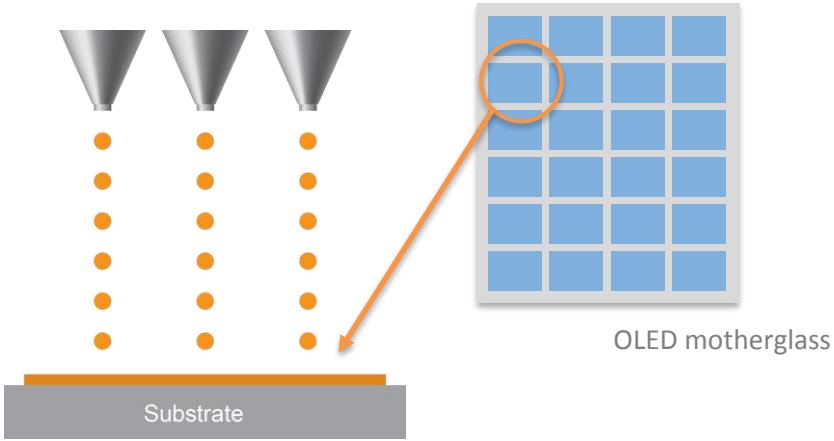
Current inkjet printing mass production product:

Thin Film Encapsulation (TFE) for mobile OLED

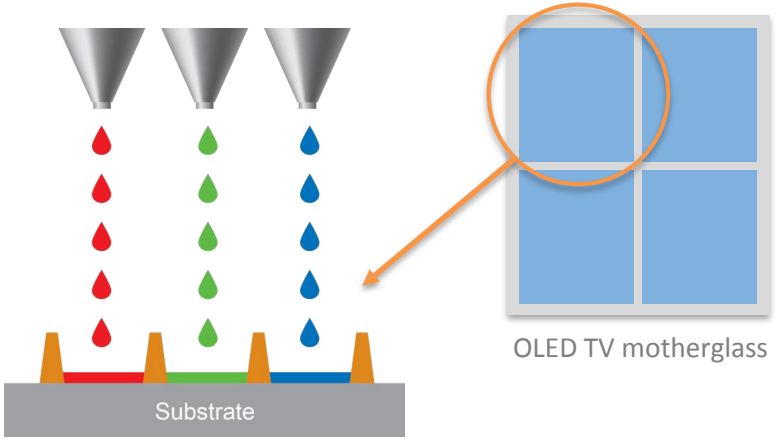


Next mass production inkjet printing product:

Red/Green/Blue (RGB) pixel printing for TV



OLED motherglass



OLED TV motherglass

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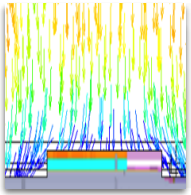
YIELDjet™ Platform: Highly differentiated technology

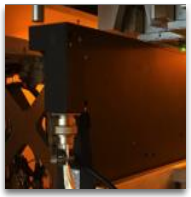


N2 printer integration

Superior film quality, low particles, easy maintenance, & reasonable cost

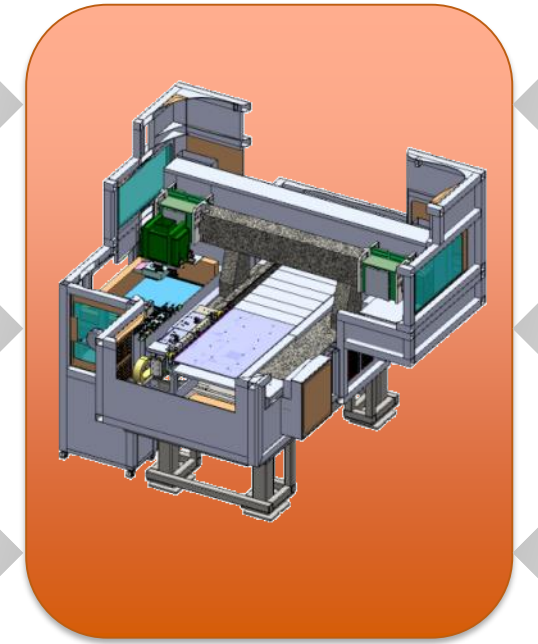
Floating stage

Ultra high accuracy, superior scalability, low particles, & enhanced film uniformity



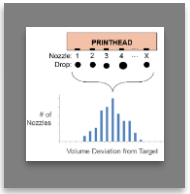
Inkjet metrology and process control

Ultrafast printhead monitoring, real time calibration, minimal downtime, enhanced yield



Printing algorithms and process control

High film quality, high film uniformity, & enhanced yield

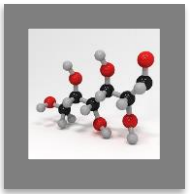


Flexible SW for Custom Patterns

Flexible SW supporting any panel design or shape

Optimized inks

Tuning of inks (in-house or with partners) for optimal printing on Kateeva systems: better performance, reliability, & yield



- YIELDjet™ platform designed from the ground up for OLED mass production
- Same platform for TFE and RGB pixel printing

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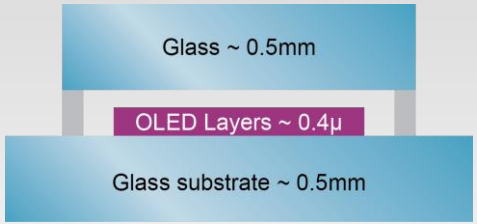
Kateeva

- Introduction (to OLED, Kateeva, and inkjet printing)
- **OLED application #1: Thin film encapsulation**
- OLED application #2: RGB pixel printing
- Summary

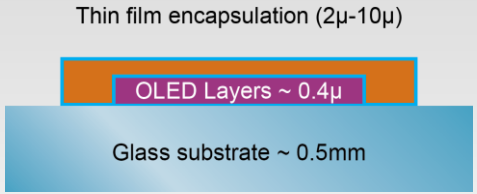
Industry Evolution to Thin Film Encapsulation (TFE)

Encapsulation addresses OLED sensitivity to O_2 and H_2O



Standard rigid

Thin Film Encapsulation replaces glass supporting thinner, less expensive, and even flexible OLED products.

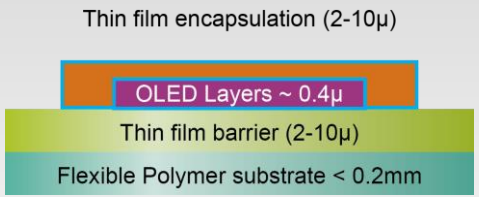


Thin rigid

Unbreakable

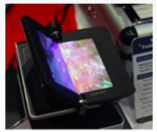
Bendable

Ø ≥ 2 cm



Thin flexible

Foldable

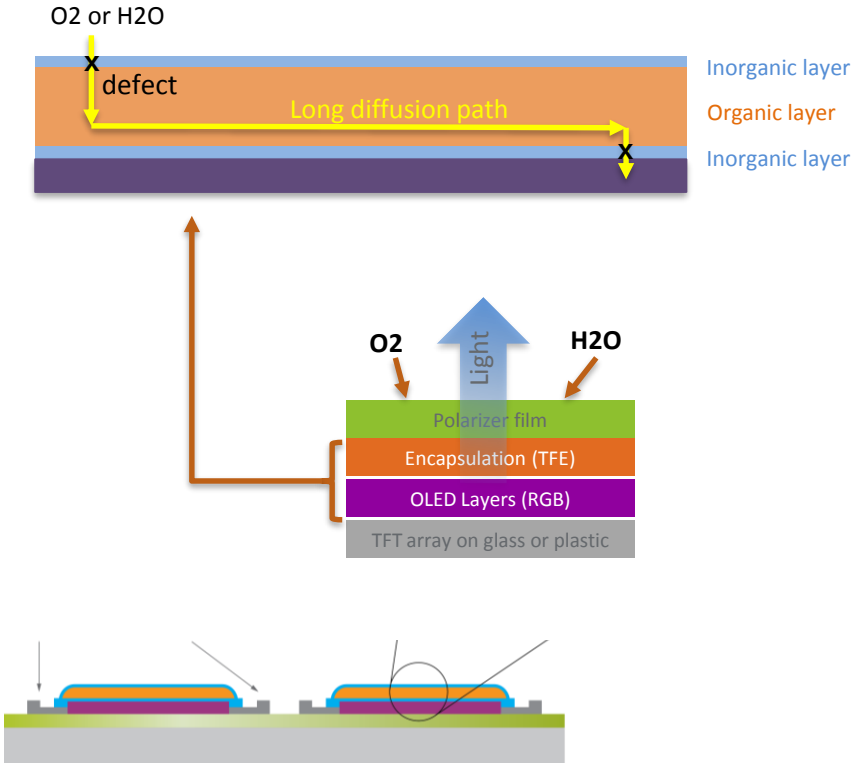


Rollable

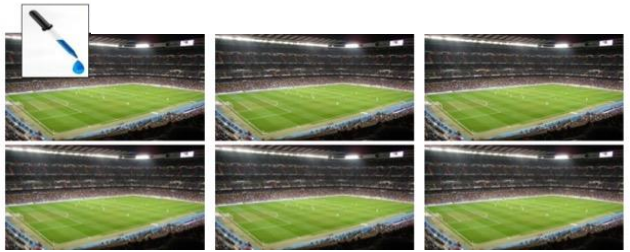
Ø ≤ 0.5 cm Ø ≈ 1 cm

X times

Layer structure of thin film encapsulation



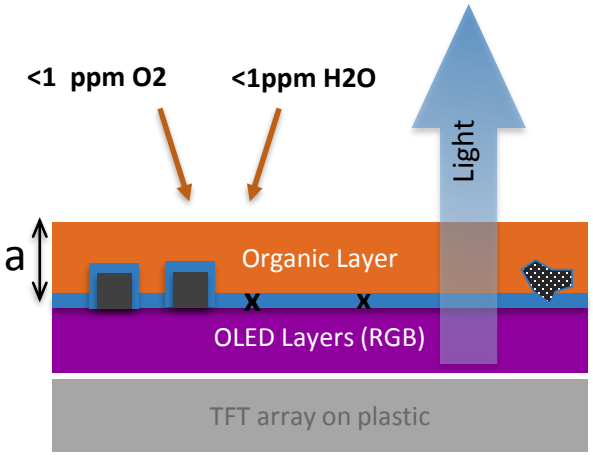
Required WVTR for OLED ~ 10^{-6} g/m^2/day
(equivalent of 1 drop across six football fields)



The organic layer plays several critical roles in the TFE stack:

- Decouples defects in the inorganic layer, creating an effective seal to H2O and O2
- Enables flexibility (flexible organic layer, inorganic layers can be thinner)
- Planarizes the top layer (improving second inorganic layer quality)

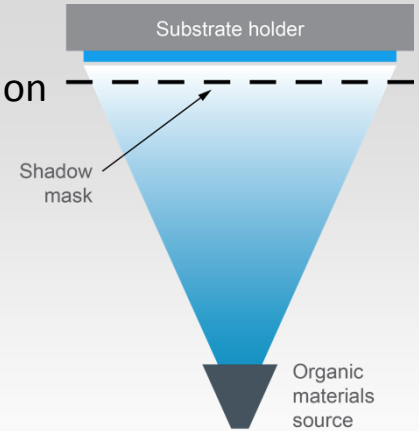
Some Requirements for TFE Organic Interlayer



- Continuous film, good adhesion to inorganic layer – no pinholes
- Highly uniform and transparent film
  - Emitted light will pass through the organic layer, so non-uniformities will cause non-uniform display to the eye – so called “mura”
  - Repeatable patterns are especially easy to pick up by the eye
- Printing and post print processing must be in a very low H2O and O2 environment (sub 1ppm O2 and N2)
- Few particles added by the printing process and rest of system
- Planarizes the top surface after printing (improving second inorganic layer quality)

Why Kateeva inkjet for TFE organic layer?

Vacuum Thermal Evaporation

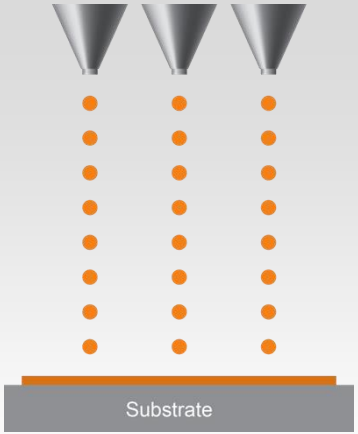


High cost/ low yield

Slow; poor planarization; many particle defects; low material utilization; difficult maintenance

VS

Precise and efficient material delivery

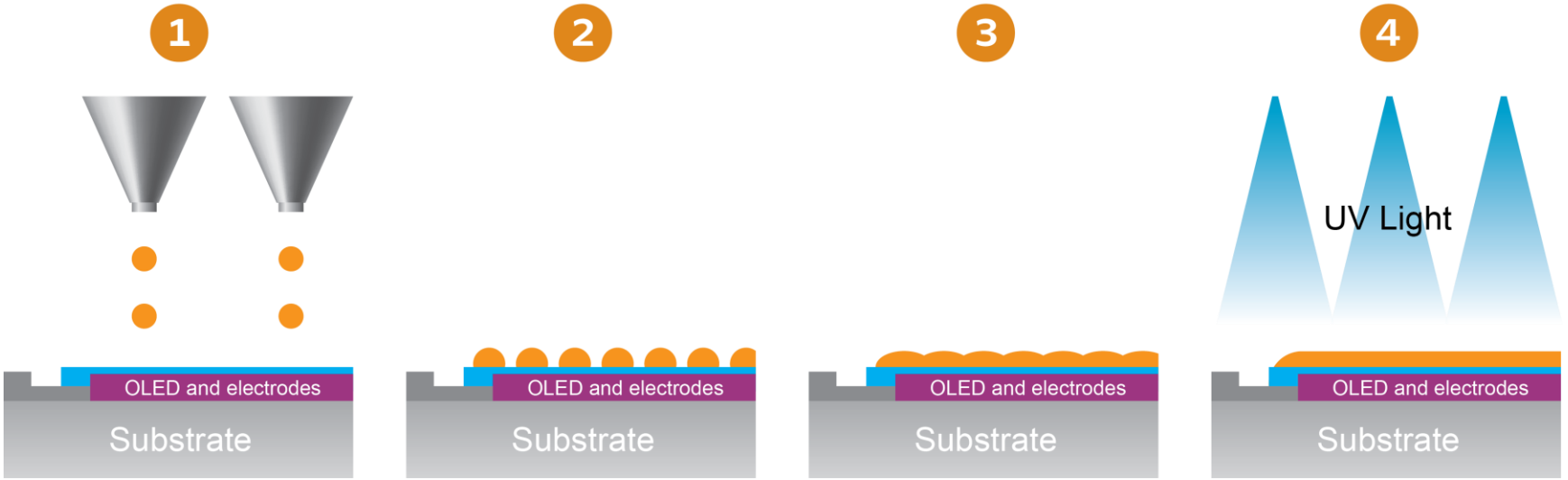


Low cost/ high yield

Fast; good planarization; few particle defects; high material utilization; easy maintenance

- Many solutions were tried, but Kateeva's inkjet printing was the solution that enabled cost-effective encapsulation for mobile flexible OLED displays in mass production

TFE application high level overview



Mobile OLED panel (~5”)

Initial drop placement by inkjet

Ink drops spread and merge

film levelling and UV curing

YIELDjet™ FLEX: Kateeva's Mass Production System for OLED TFE

- YIELDjet™ FLEX system entered mass production several years ago. Today, multiple tools are in MP
- Systems have printed millions of mura-free panels
- Systems offer very high uptime, ease of maintenance, excellent yield
- Kateeva has >80% IJP market share in TFE

TFE Mura-free Printing Results

TFE film printed on silicon (to enhance contrast)

Conventional printing

Print-Mura on finished panel

Kateeva Uniformity Technology

No Visible Print-Mura on finished panel

- A regular grid of ink drop patterns will lead to print-mura (conventional)
- Kateeva achieves mura-free films by using proprietary TFE Smart Mixing™ software
  - Generate optimized drop patterns with correct nozzle mixing
  - Supported by ultra-fast, real-time drop metrology
- Our approach is very robust, automatically compensating for:
  - Printhead non-uniformity
  - Nozzle drift
  - Out-of-spec nozzles

Ultrafast drop metrology + TFE Smart Mixing Algorithms = Mura-free printing in mass production

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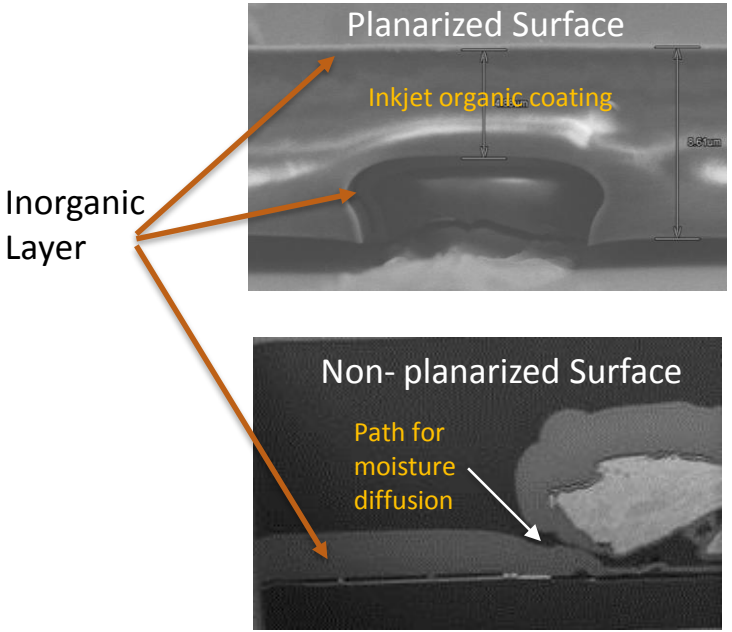
Key Organic Layer Requirement: Surface Planarization



- OLED panels prior to organic coating have significant surface topology (from particles and panel features)
- The TFE barrier quality is dramatically improved when coating over a perfectly planarized surface when compared to a non-planar surface
- Kateeva inkjet organic coating uses a liquid ink that offers excellent inherent planarization capability

Planarization is a key requirement for good TFE results.

Kateeva

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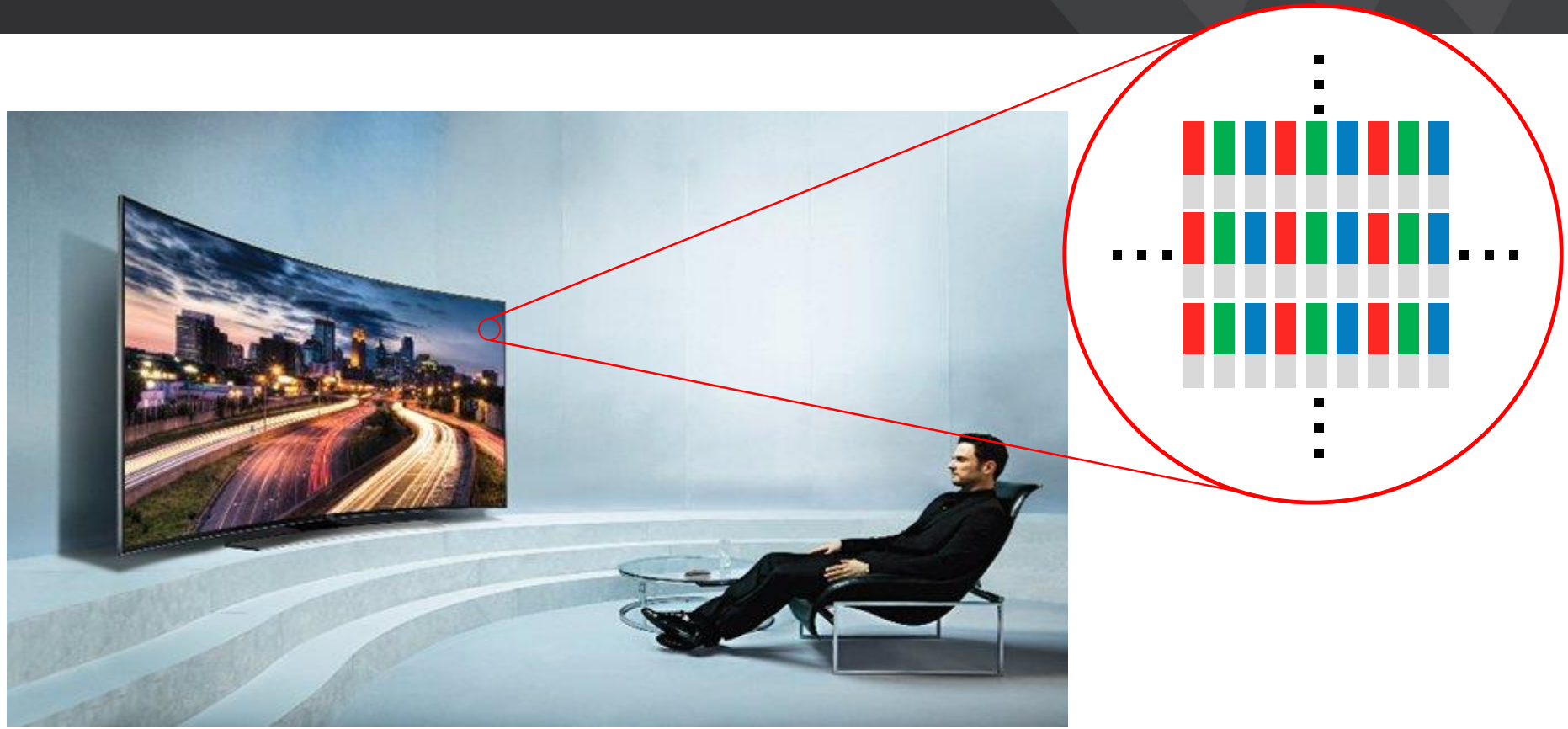
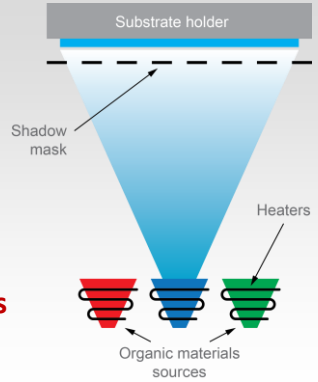
OLED “Red Green Blue” (RGB) Layer



OLED TV Challenge: Fabricating RGB pixels on large-size glass

Existing mobile technology: Pattern pixels with shadow mask evaporation

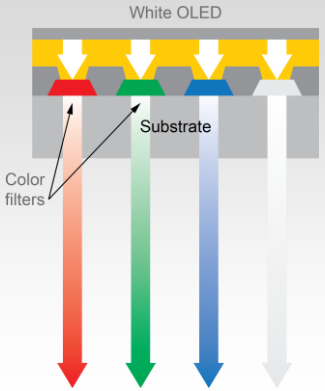
Unable to scale up to large glass required for TV



OLED manufacturers have been unable to successfully apply this technology to large-size displays

WOLED TV technology: White OLED (no pixel pattern) with RGB color filter

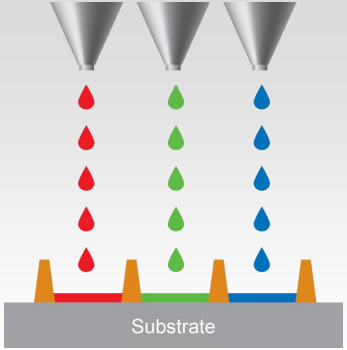
In production today, superior to LCD, but cost is high



Still uses evaporation (without shadow masks), but requires many layers, driving up cost

True OLED TV technology: Inkjet printing for RGB pixel printing

Potential for highest brightness and lowest cost TV



Most efficient use of RGB materials, no color filter or shadow mask

Inkjet printing enables cost-effective true OLED TV

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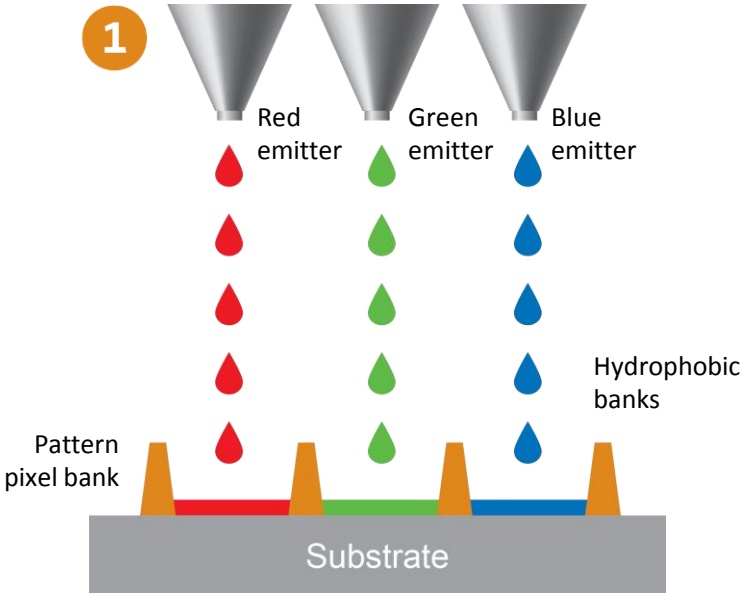
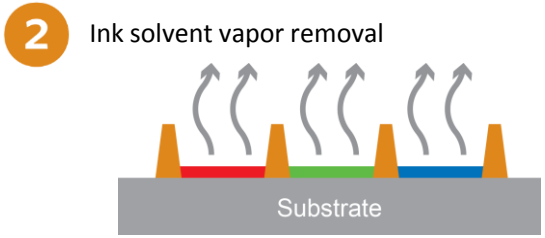
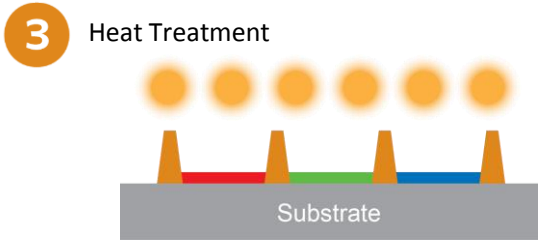
Inkjet for TV RGB Patterning



Large-size OLED panel (~55 inch)



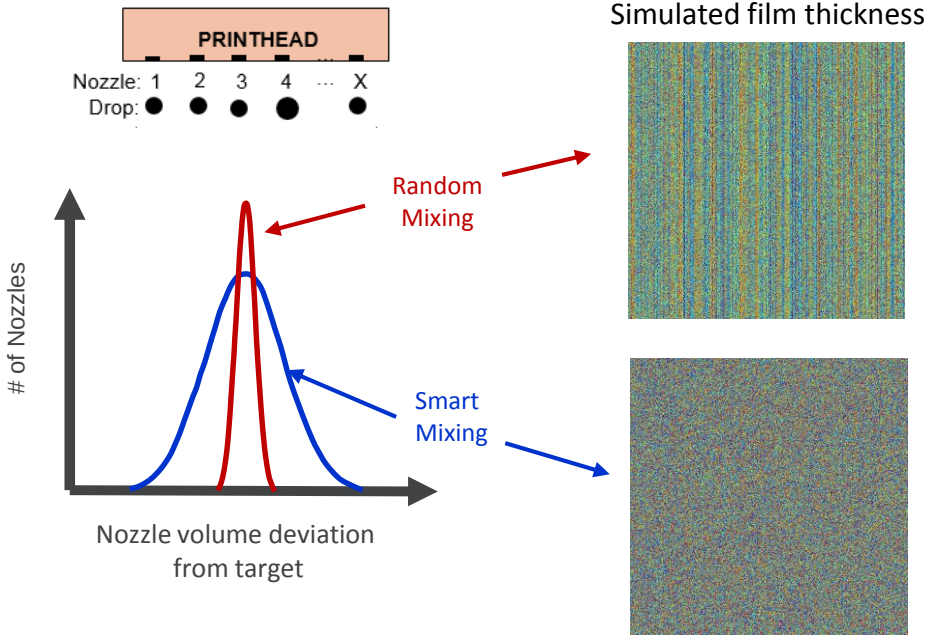
Dry out solvent in vacuum chamber



Bake panel to set the OLED film

Kateeva is now deploying beta systems for field qualification

Kateeva Proprietary Printing Algorithm: RGB Smart Mixing



Source of Print-Mura

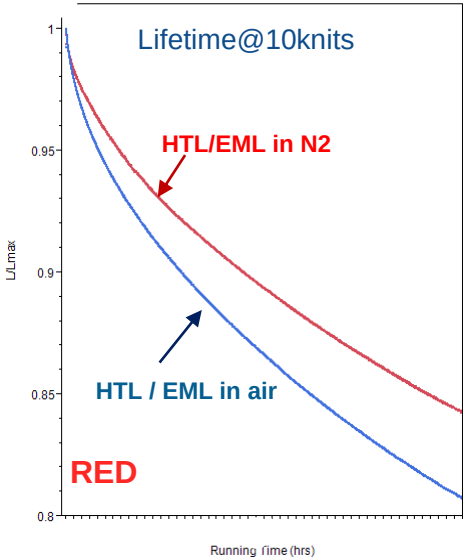
- Print-mura is fundamentally caused by nozzle-to-nozzle variations in the print heads
- Conventional approach to eliminating print mura is “random mixing” (statistical approach)
- Kateeva uses RGB Smart Mixing™ software to overcome this issue

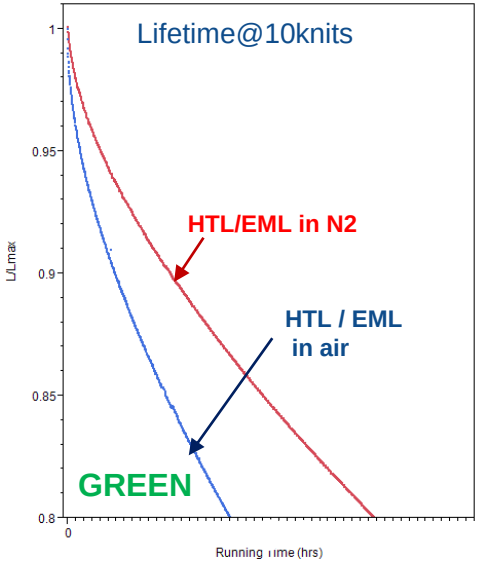
RGB Smart Mixing™

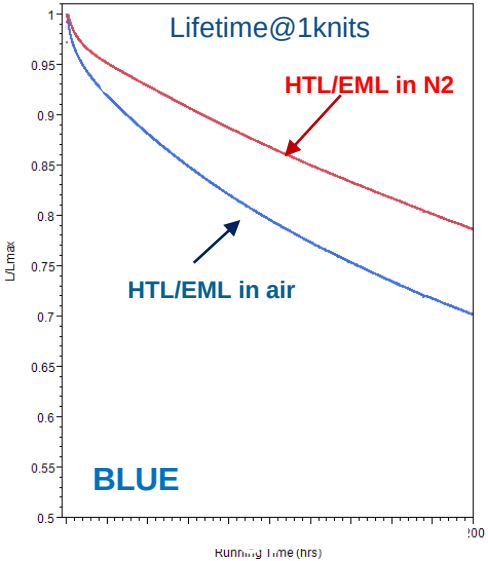
- Ultrafast drop metrology measures the print head in real time
- This information is fed into the Smart Mixing™ software. The specific nozzle mixing combinations are calculated to enable mura-free printing. No statistical uncertainty.

RGB Smart Mixing, enables mura-free printing with a much wider window of nozzle variation (almost no printhead tuning, no productivity hit, stable in MP)

Inkjet Printing in Air vs. N2







- Printing in N2 improves lifetime by 2-3X (T95) compared to printing in air
- Efficiency is typically 5-10% higher for devices processed in N2 compared to air

Kateeva

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Summary

- Kateeva's YIELDjet™ FLEX system is currently enabling cost-effective mass production of OLED displays for the critical TFE application
  - Many technological advances in inkjet printing were made to overcome historical barriers to MP
- Next YIELDjet™ tool will address cost-effective RGB pixel printing for TV. Beta systems for field qualification are already being deployed
- Inkjet printing for OLED display is just the beginning
  - Precision deposition by inkjet printing has the potential to enable many other technologies which require low cost patterned films (e.g., OLED lighting, QD applications, etc.)

Thank you