Advanced Inkjet Printing: Enabling the OLED Revolution

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Outline

- **Introduction**
- **Advanced inkjet printing for mobile applications**
- **Advanced inkjet printing for TV**

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- **Founded in 2008**
- **Received multiple rounds of investment from VC firms and strategic partners**
- **Leading supplier of inkjet deposition 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**
  - Headquarters in Newark, CA; 150,000 sq. ft.
  - Rapidly growing headcount: currently >350 staff
  - International presence in Korea, China, Japan, and Taiwan
  - OLED device process lab and ink formulation lab

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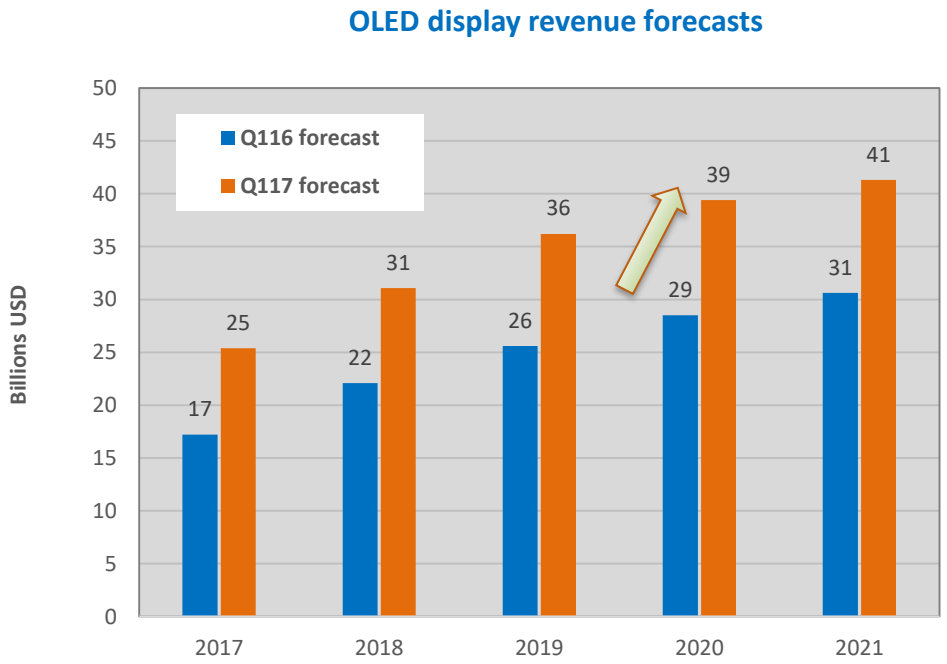
Forecasted OLED revenue and equipment spending up



Source: IHS, Q116 and Q117 Display market tracker

- OLED display market forecast has increased by > 30% from 2016 to 2017
- Increase due mostly to increase in mobile market and higher mix of flexible
- OLED equipment spending from 2017-2021 is forecasted to be ~ $80B (UBI, 2017)

(reference point: Semconductori WFE ~ $200B)

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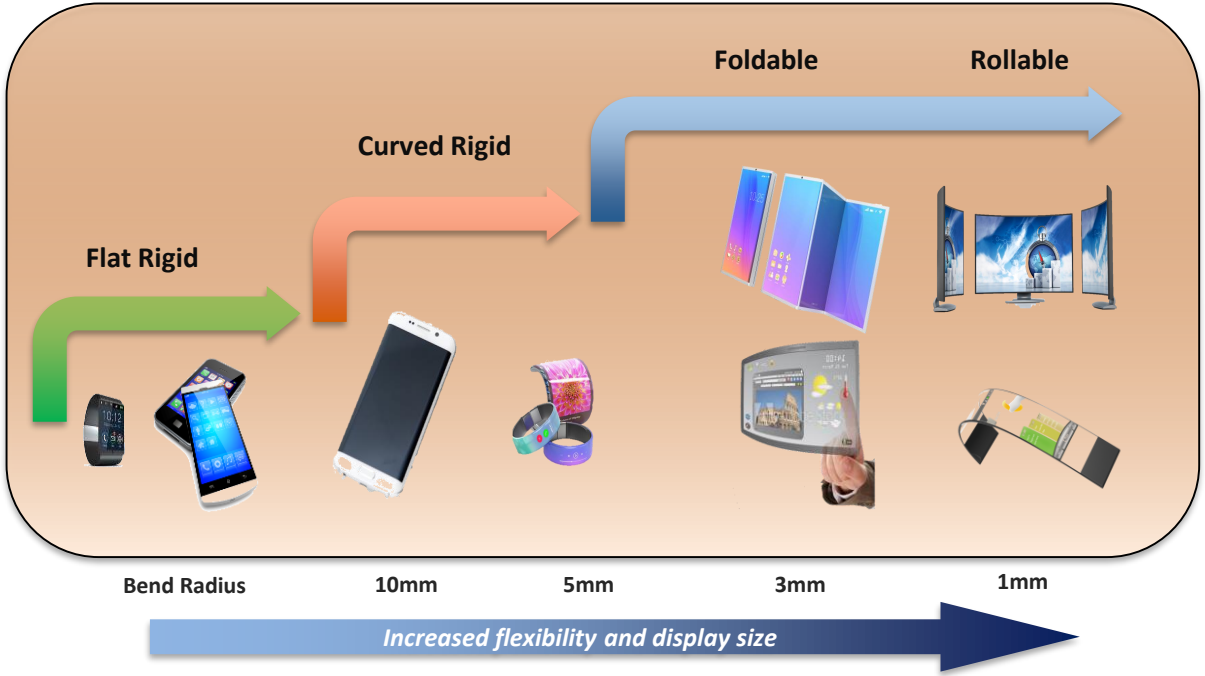
OLED Display Technology Roadmap



Next inflections for OLED displays: 1) Foldable mobile and 2) RGB TV

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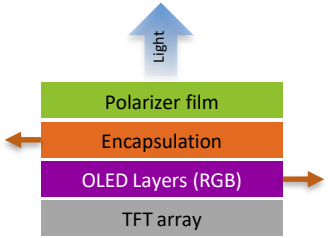
Kateeva's Current and Next Mass Production Products

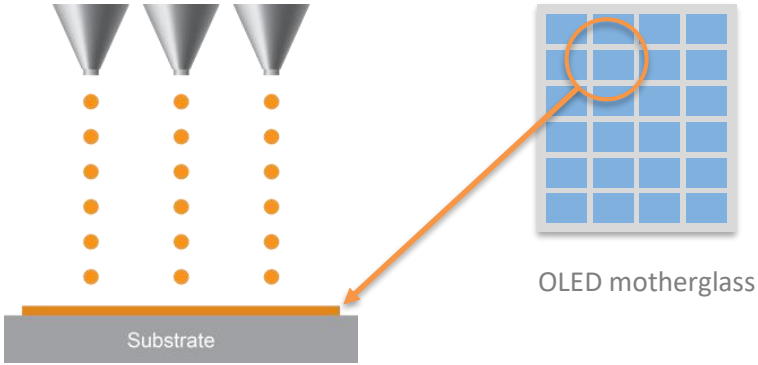
Current mass production product:

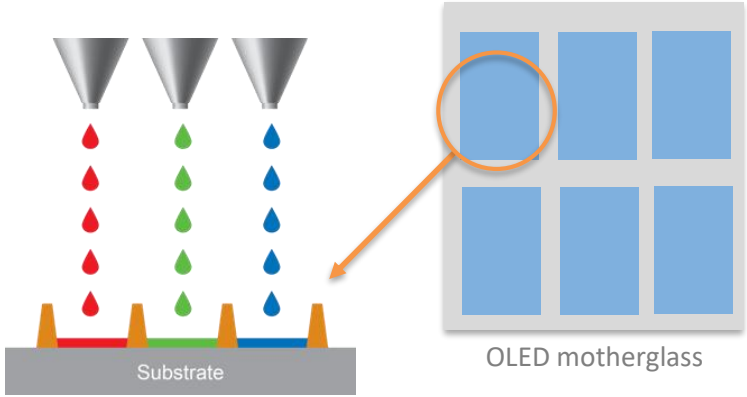
Thin Film Encapsulation (TFE) for Mobile OLED
(and later Mid-Size and TV)



Next mass production product:

Red/Green/Blue (RGB) pixel printing for TV and Mid-Size OLED





- Both product lines based on YIELDjet™ printing platform
- TFE and RGB products extend to future applications requiring contiguous films and pixel printing

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Historical challenges of using IJP for OLED mass production

Challenge	Issue	Requirement
Pure process environment	OLED lifetime degradation from of O_2, H_2O, ozone contamination	N2 environment, <1ppm O_2, H_2O)
Particle Contamination	Large particles can kill yield	• Zero large particles • Planarizing organic film to neutralize smaller particles (TFE)
Film uniformity	Non-uniform luminance in finished display	No print-mura visible (finished display)
Tool robustness	• Low uptime → reduces productivity • Process drift → reduces yield	High uptime, stable process results

Impact to Customer
Device performance
Yield
Productivity
Manufacturing costs
Production schedule

$$$

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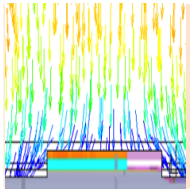
YIELDjet™ Platform: Most Advanced Inkjet Printing Solution

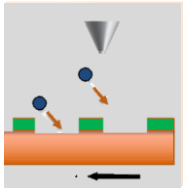


N2 printer integration

Superior film quality and device performance, low particles, easy maintenance, & reasonable cost

High-accuracy floating stage

High accuracy, superior scalability, low particles, & enhanced film uniformity

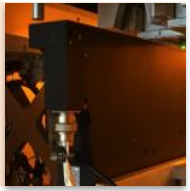


Drop placement error compensation (pixel printing)

Comprehensive algorithms correcting for sources of error

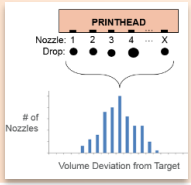
Inkjet metrology and process control

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



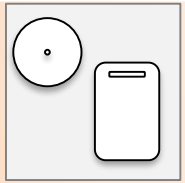
Smart Mixing™ software and process control

High film quality, high film uniformity, & enhanced yield



Flexible SW for custom patterns (blanket coatings)

Flexible SW supporting any panel design or shape



- YIELDjet™ platform was developed from the "ground up" for OLED mass production

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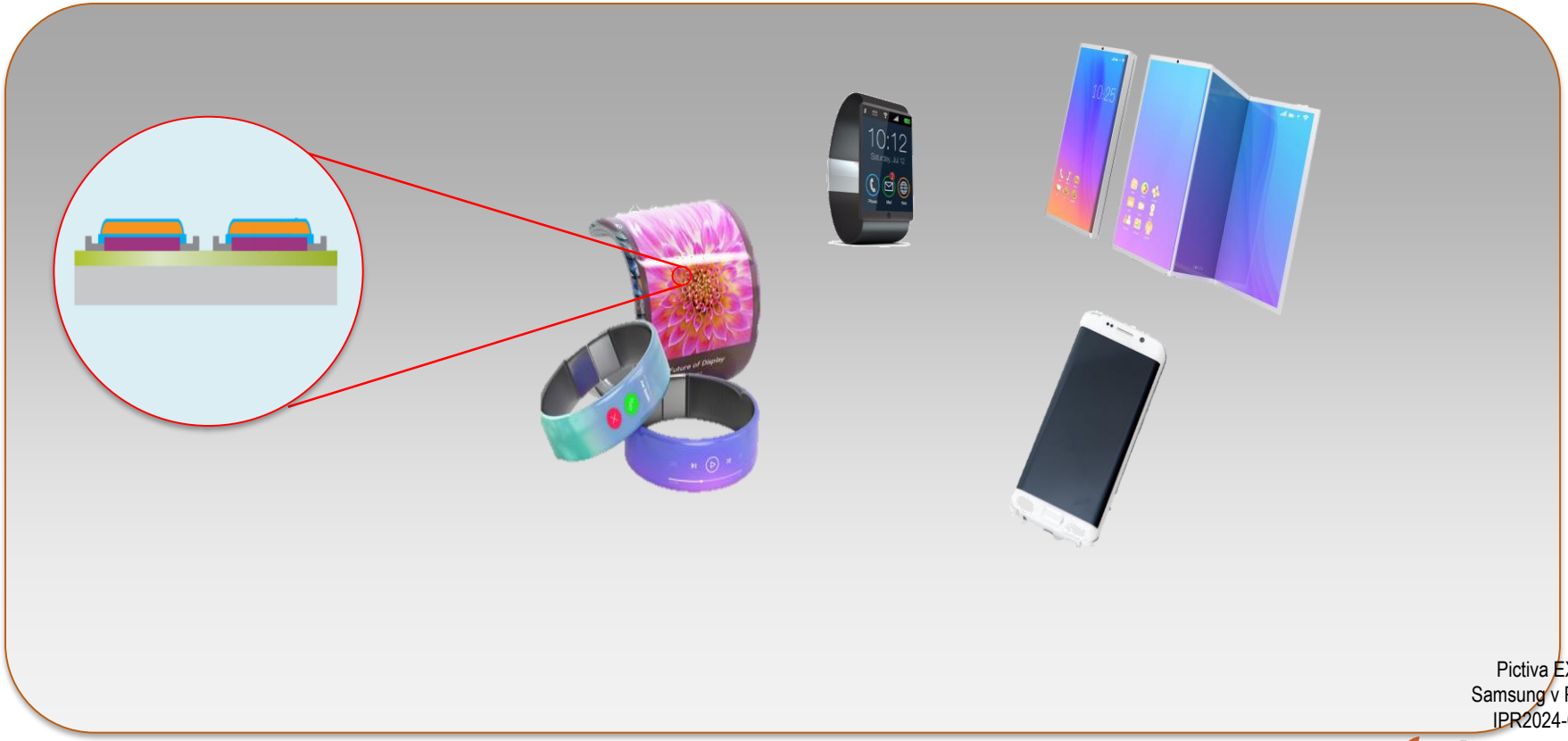
Inkjet for Mobile Products



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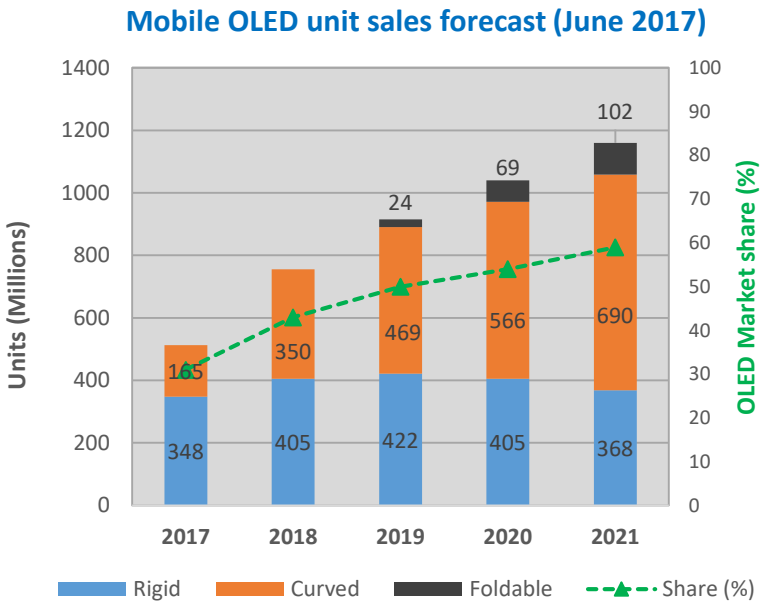
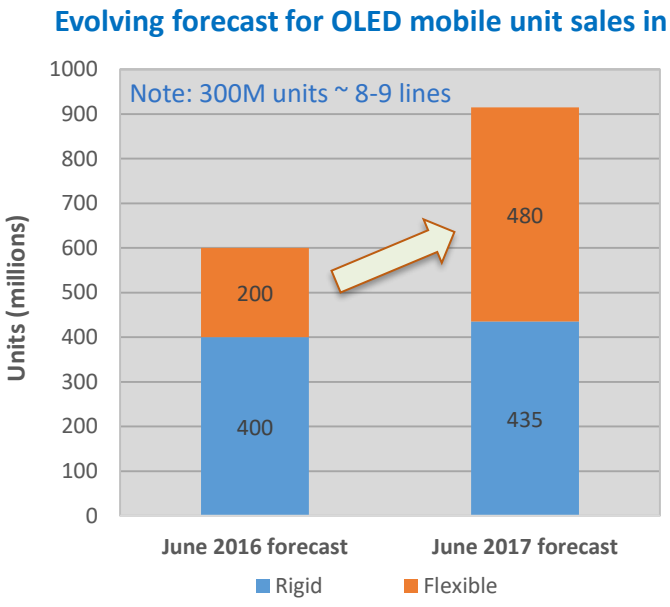
Flexible OLED for Mobile: Gaining Momentum





- OLED mobile forecast is much more bullish than 1 year ago → flexible forecast increased 2X
- All flexible mobile displays need TFE

Source: DSCC, SID 2017

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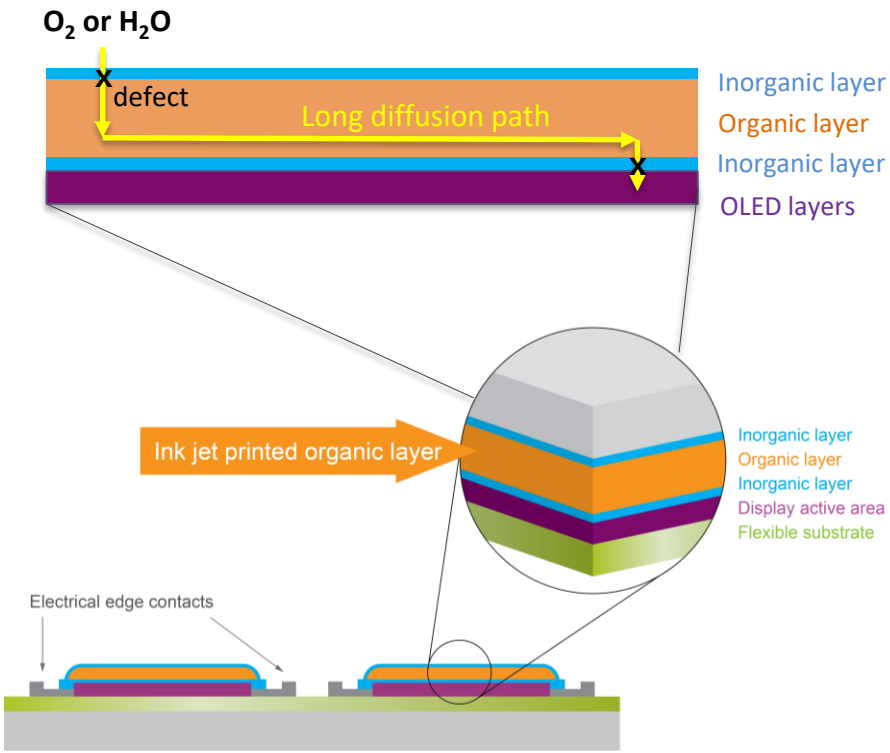
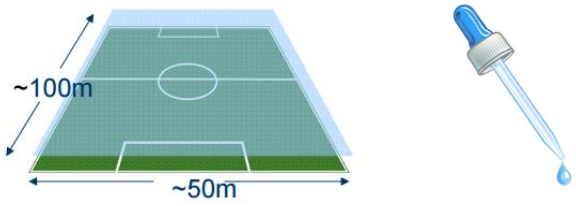
Layer Structure of Thin Film Encapsulation



Required WVTR for OLED ~ 10^{-6} g/m^2/day
(equivalent of 1 drop per month on a football fields*)



*Source: M. Weigand, Cleanzone 14 (2014)

Role of organic layer in TFE stack:

- Decouples defects in the inorganic layers, creating an effective seal to H_2O and O_2
- Enables flexibility
- Planarizes the top layer

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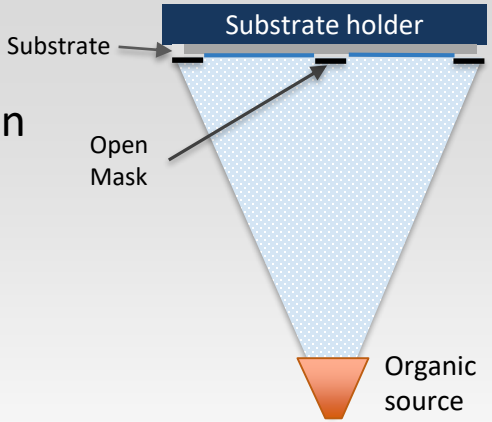
Evaporation vs. Inkjet Printing for TFE Organic Layer

Vacuum Thermal Evaporation

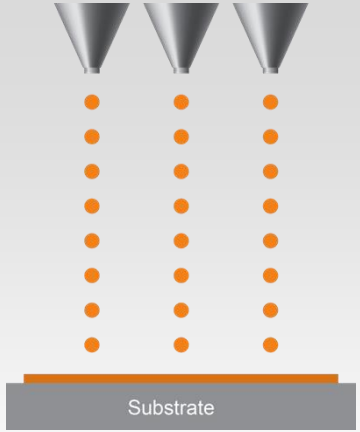


High cost/ low yield

Many particle defects; high CoO due to low material utilization and frequent PM; difficult maintenance

VS

Precise and efficient material delivery



Low cost/ high yield

Fast; good planarization; very low particle defects; lower CoO due to high material utilization and high uptime; easy maintenance

Inkjet printing is the approach of choice for OLED mass production today

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

- YIELDjet™ FLEX system entered mass production (MP) several years ago. Multiple tools are now in MP.
- Systems have printed millions of mura-free displays
- Systems offer high uptime, ease of maintenance, and "near-zero" defect rate
- Kateeva has >80% IJP market share in TFE

YIELDjet™ platform demonstrated in mass production for thin film encapsulation

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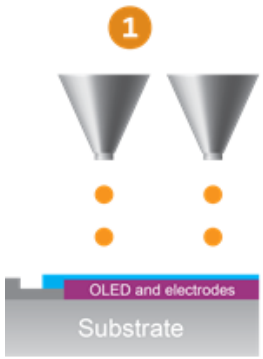
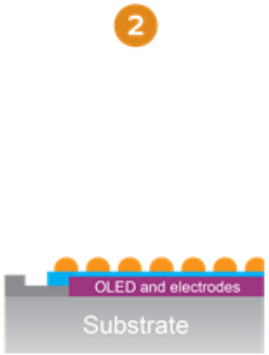
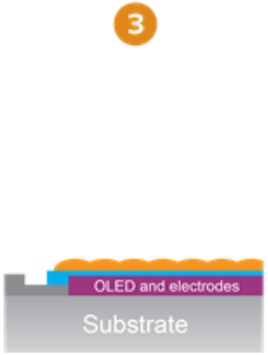
TFE Application High-Level Overview



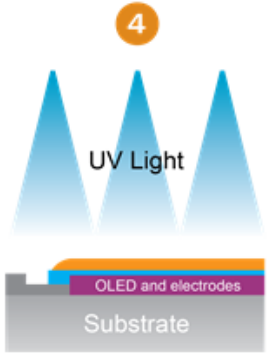
Drop jetting from printer-head



Initial drop placement by inkjet



Ink drops spread and merge



Smooth film levelling by surface tension and cross-linked with UV

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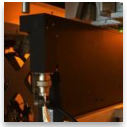
Mura-free printing with the YIELDjet™ FLEX System

Ultra-fast drop metrology



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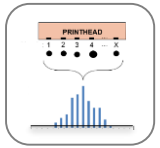
TFE Smart Mixing™ Software



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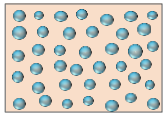
Calculate nozzle firing schedule



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Mura-free printing in mass production

TFE film printed on silicon (to enhance contrast)

Conventional printing

Print-mura on finished display

Kateeva SmartMixing™

No visible print-mura on finished display

Kateeva's uniformity technology renders final display free of print mura, which is critical for yield

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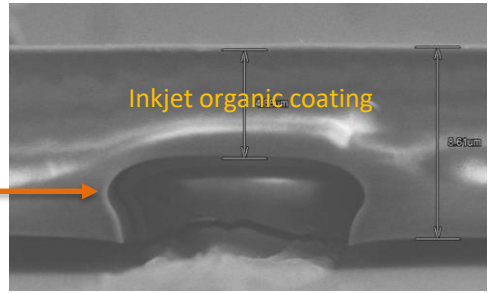
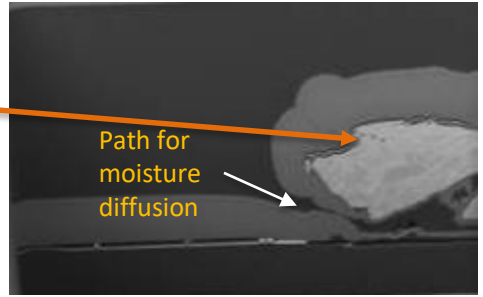
Key Organic Layer Requirement: Surface Planarization

- OLED panels prior to organic coating have significant surface topology (device features and possibly particles)
- The TFE barrier quality is dramatically improved when coating over a perfectly planarized surface when compared to a non-planar surface
  - Top inorganic layer has fewer defects if deposited on a flat surface
- Kateeva inkjet organic coating uses a liquid ink that offers excellent inherent planarization capability

IJP Organic Coating: Planarized Surface



Non- planarized Surface



Planarization is a key requirement for effective encapsulation

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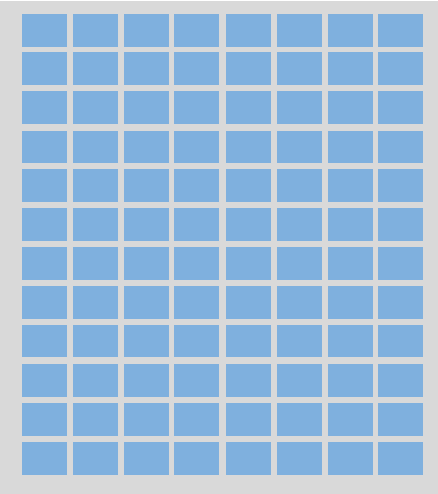
Cost of Yield Loss for Mobile OLED Displays

½ Gen 6 Line, ~30k/month



5.5” displays (100)

1% Yield Loss = $25M/year in device loss

- **The cost of 1% yield loss for one year is <u>much larger than the annual depreciation of an IJP system</u>**

- **Key assumptions:**
  - Panels with defects must be scrapped
  - 40M displays produced per year, **ASP = $70 per display**
  - 1% yield loss → 400,000 defective displays
  - Loss from scrap is assumed to be the lost revenue

YIELDjet FLEX system has a MP track record of near-zero yield loss

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Next OLED Mobile Inflection: Foldable

- Nearly all OLED display manufacturers are developing products with foldable OLED displays
- Foldable brings new challenges, many in the area of stress management
  - Film stacks must be engineered to lower stresses and/or increase yield stress;
  - Films must withstand mechanical cycling;
  - For TFE stack, this could mean new materials and thinner layers
- Kateeva is making continuous improvements in printing and ink technology to enable foldable OLED display manufacturing

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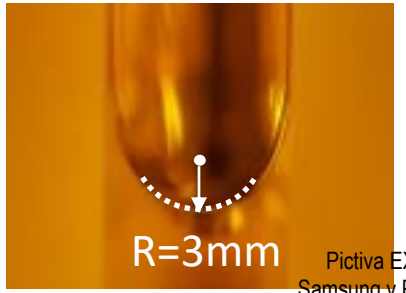
Kateeva TFE Films for Foldable Displays

Flexibility Test	Kateeva TFE Film on PEN substrate
RT Flexibility Test: 100k cycles @ 3mm radius	Passed at 8 µm
“85/85” Flexibility Test: 100k cycles @ 3mm radius	Passed at 8 µm
Minimum Thickness of Continuous, Mura-Free TFE Film	Achieved 2-3 µm continuous, smooth, and uniform film*. Work on thinner films now underway. *checked via optical profilometry and microscopy

Endurance tester

Folded substrate with organic film



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Inkjet for TV RGB Pixel Printing

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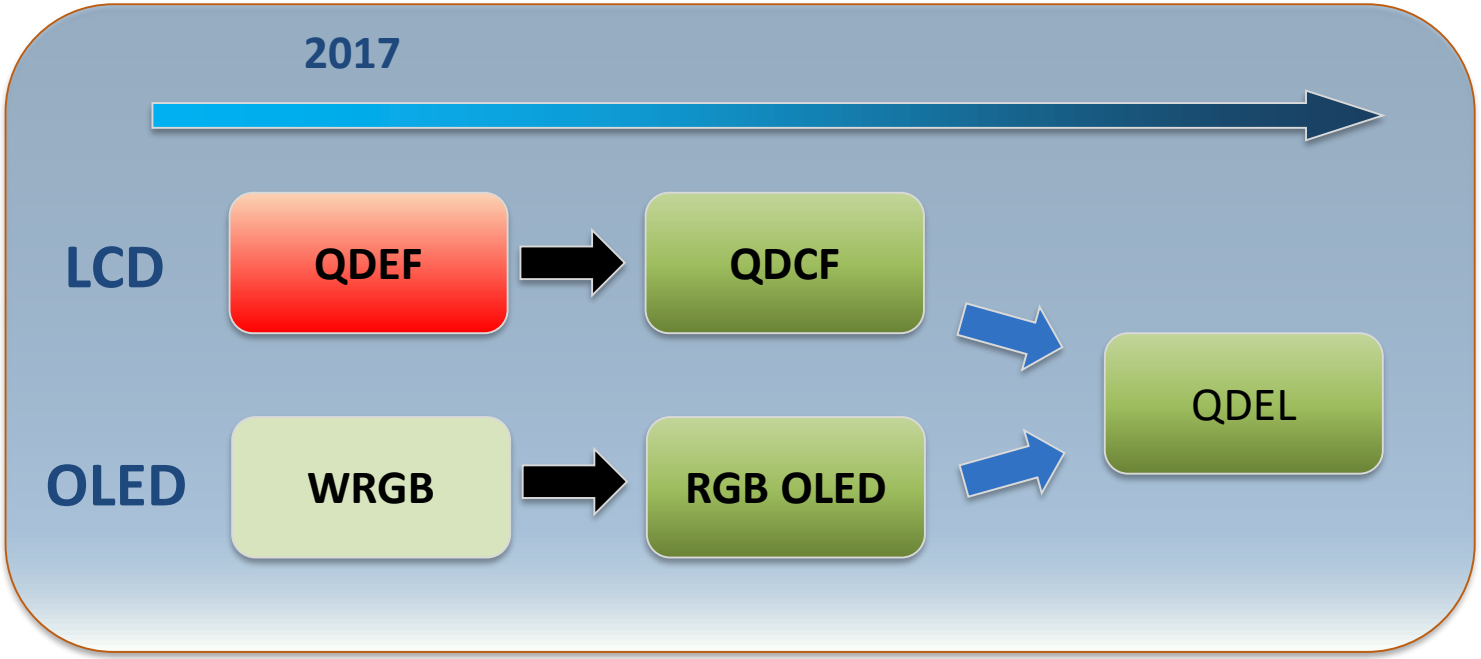
TV Technology Roadmap



Inkjet printing will play an critical role in the TV technology roadmap

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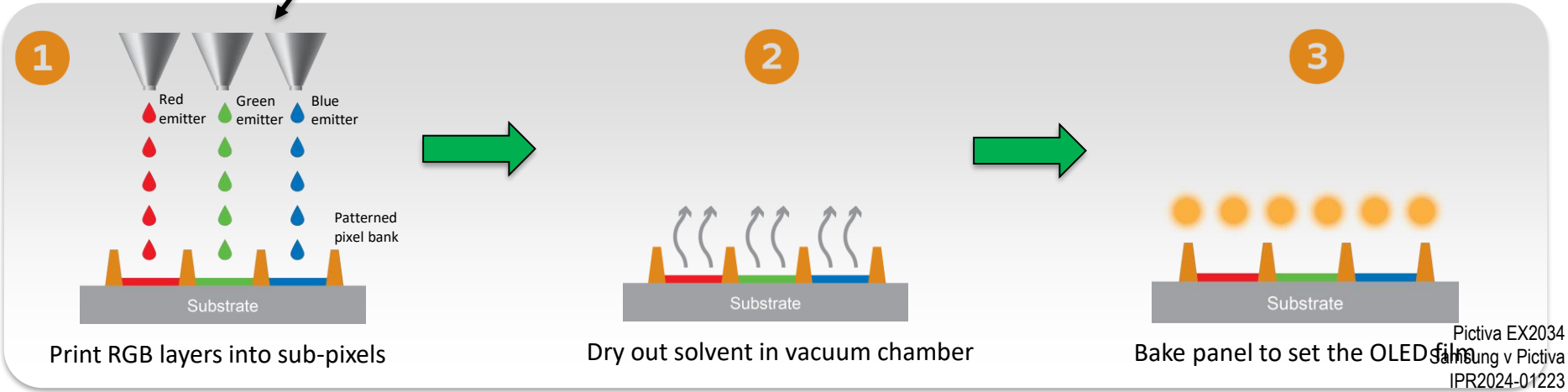
Inkjet for RGB OLED TV Pixel Printing



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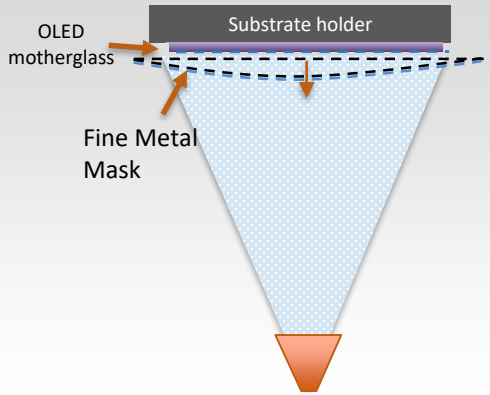
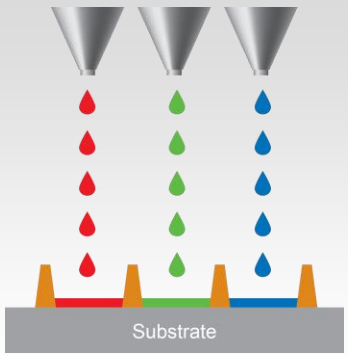
VTE vs. Inkjet Printing for RGB OLED on Large Area Substrates

Vacuum Thermal Evaporation



VS

Inkjet Printing



Although used successfully for smartphones, VTE has been unable to scale to large glass sizes due to mechanical issues with the fine metal mask

Kateeva's inkjet printing is scalable to large glass sizes (scanning system) and can meet the resolutions required for premium TV

Inkjet printing can enable mass production of RGB OLED TV

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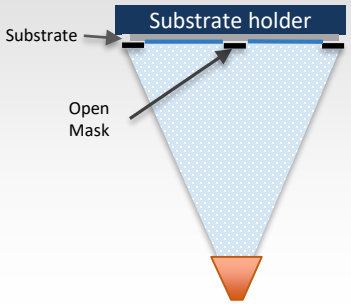
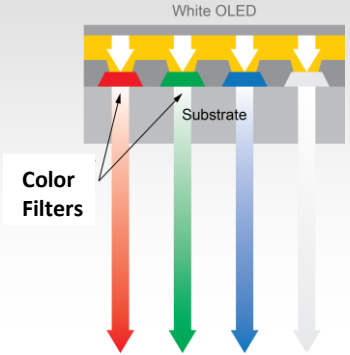
WRGB vs. RGB Technology for OLED TV

WRGB OLED TV technology

VTE with open mask for white OLED deposition



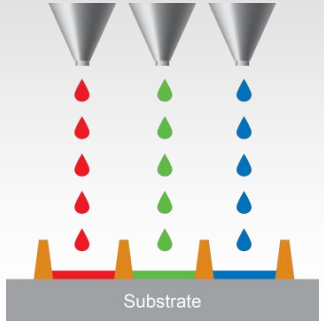
Bottom emission with color filters



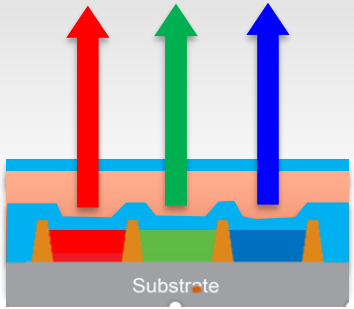
In production today; superior to LCD. inefficient use of materials, costly to manufacture.

RGB OLED TV technology

Inkjet printing for RGB pixel patterning



Top emission no color filters



Most efficient use of material; no color filters. Potential for lower cost and better visual experience.

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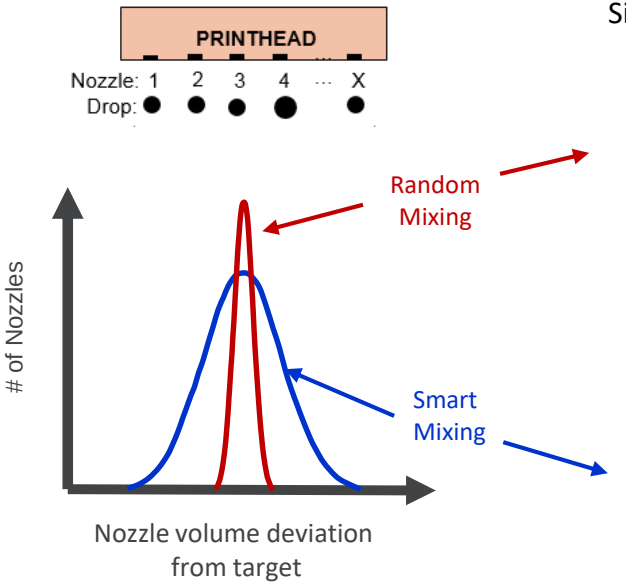
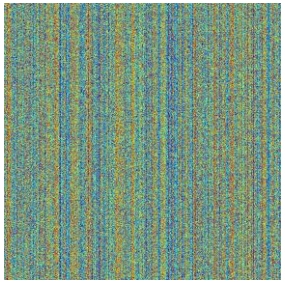
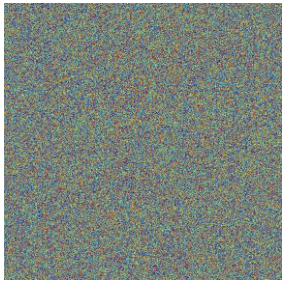
RGB Smart Mixing™ Technology



Simulated film thickness





RGB SmartMixing™ Technology

- Ultra-fast drop metrology is used to continuously measure drop characteristics of all nozzles in the print array
- This data is used to calibrate the Smart Mixing™ software. Specific nozzle combinations are calculated for each sub-pixel to render final display free of print mura

Process Window and mass production robustness

- Smart mixing: mura-free results with a wide nozzle-to-nozzle drop volume variation in the print head (~ +/-5%)
- Random mixing: requires a narrow nozzle-to-nozzle drop volume variation in the print head (~ +/-1%)

Kateeva's design philosophy: "Don't fight the print head!"
Leave the print head in its more natural state and monitor it frequently

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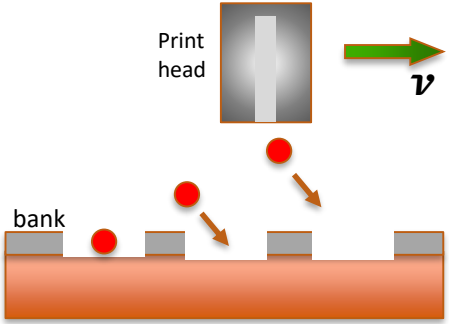
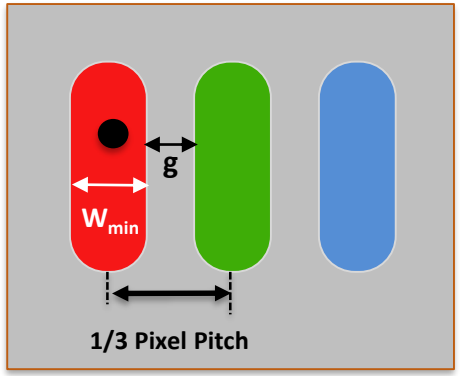
RGB Printing: Defining Maximum Printable Resolution

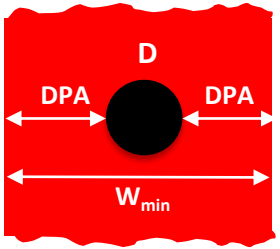


- Kateeva defines the maximum printable resolution by the minimum sub-pixel width for which the entire drop can be placed into the open area of the sub-pixel
- The minimum printable sub-pixel width is then defined by the drop diameter (*D*) and the drop placement accuracy (*DPA*) in the scan direction. These two parameters can be controlled by printer design. The gap between subpixels, *g*, is defined by the bank material and photolithography process



$W_{min} = D + 2*DPA$

Max resolution (dpi) = 1/ pixel pitch = $1/\{3*(W_{min}+g)\}$



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RGB Solution Lifetime Status

Recent Material Vendor Reported IJP Results

Color	CIE-x	CIE-y	Efficiency (cd/A)	EQE (%)	Voltage (V)	T95 (hrs)
DuPont	0.65	0.34	18.2	15.2	7.3	22,860
Merck	0.66	0.34	27	23	5.3	15,000
Sumitomo	0.66	0.34	28	NA	NA	>>10,000
DuPont	0.28	0.66	71.2	19.2	5	11,550
Merck	0.31	0.64	76	21	5.3	9,000
Sumitomo	0.33	0.62	92	NA	NA	17,000
DuPont	0.14	0.09	4.4	5.3	7	1,620
Merck	0.14	0.12	10.7	10.2	6.5	<100
Sumitomo	0.14	0.11	9.3	NA	NA	400

VTE lifetimes from 2012 (UDC)

PHOLED at 1000 nits	1931 CIE	Efficiency cd/A	T95 (hrs)
Red	0.66,0.34	29	23000
Green	0.31,0.63	85	18000
Blue	0.18,0.42	50	700

Solution lifetimes are on par with evaporated lifetimes when OLED smartphones were widely introduced to the market

- Lifetime for printed RGB TV will not be showstopper due to the combination of:
  1) Solution RGB materials progress
  2) Nitrogen-purged inkjet printing
  3) The use of advanced compensation schemes

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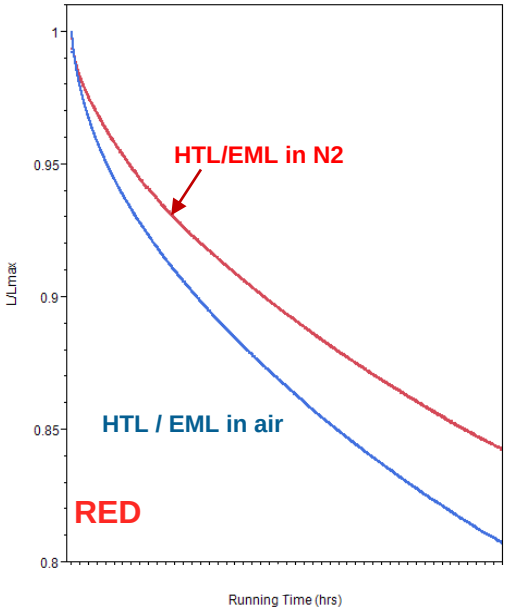
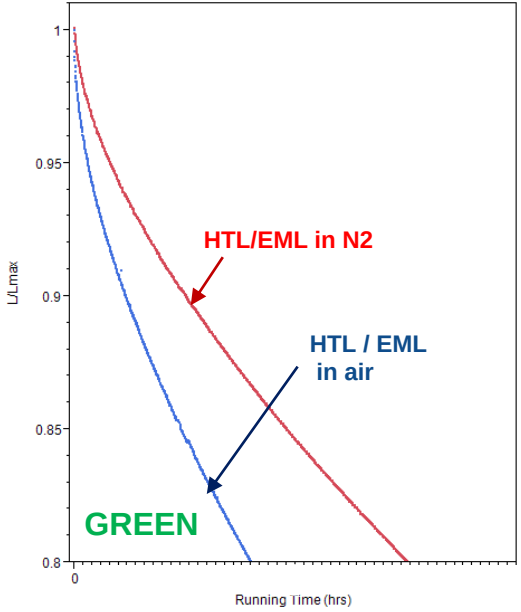
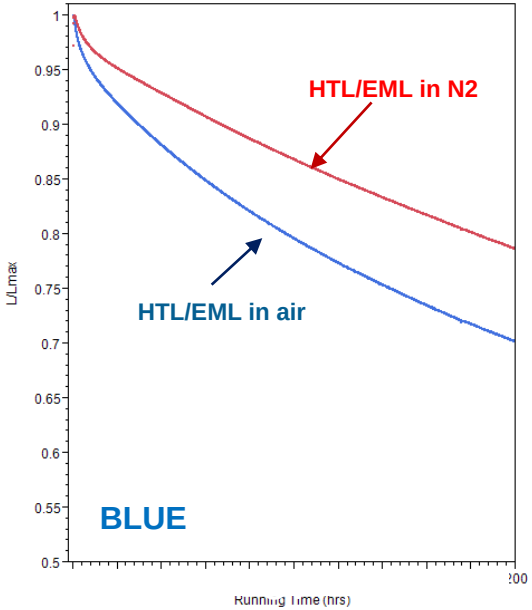
All Data from SID Symposium Digest of Technical Papers: Dupont (2016), Merck (2017), Sumitomo (2017), UDC (2012)

Inkjet Printing in Air vs. N2 – Lifetime Advantage







Printing in N2 improves lifetime by 2-3X (T95) compared to printing in air

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Kateeva: Inkjet Deposition for the OLED Revolution (and more)

	Mobile OLED	Large-size OLED	Mid-size OLED
TFE	In mass production	Technology ready today	Technology ready today
RGB	Non-IJP Technology OK	Beta Site Qualifications In Progress	Roadmap (under R&D)
	Today	2017+	2018+

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Thank you!

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