Status and Opportunities for Phosphorescent OLED Technology

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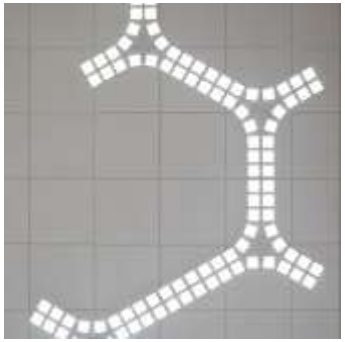
December 2016

UNIVERSAL DISPLAY CORPORATION

UDC Company Focus

IP innovator, technology developer, patent licensor and materials supplier for the rapidly growing OLED markets



OUR COMPANY

- Global University Sponsored Research Programs
- Multi-disciplinary Chemistry Organization
  - Discovery (Experimental and Computational)
  - Applied Research - synthesis & process dev.
  - Commercial Development
  - Volume Production
- Broad Physics and Engineering Organization
  - Discovery (Failure Mechanisms)
  - Device Research
  - Device Engineering
  - Processing Engineering
- Business Localization and Support
  - UDC Korea, Japan, Taiwan and China teams

In The Beginning…not very long ago

Tang & Van Slyke
Eastman Kodak
Fluorescent SMOLED

Forrest, Thompson, Baldo et al.
Princeton University, University of Southern California)
Phosphorescent OLED

1987 1988 1989 1990 1991 1994 1995 1996 1997 1998

Burroughes, Friend et al.
Cambridge University, (CDT)
Fluorescent Polymer OLED

Pioneer

1st commercial OLED display: car audio display

OLED Timeline

Source: Acuity Brands.

NEW OLED SMARTPHONES

Huawei Enjoy

Google Pixel

TCL 950

OPPO F1 Plus

Gionee M6

Asus Zenfone 3 Deluxe

One Plus 3

ZTE Axon 7

Moto Z Force

BLU Energy XL

Colawe W550

Micromax Canvas Sliver 5

MORE OLED PRODUCTS

Dell Alienware 13

Samsung Galaxy TabPro S

LG 65” 4K TV

Porsche Mission E Car

Galaxy Gear Series

ZTE Axon Watch

Apple Watch

Samsung Gear VR Innovator

Oculus Rift

LG G Flex 2

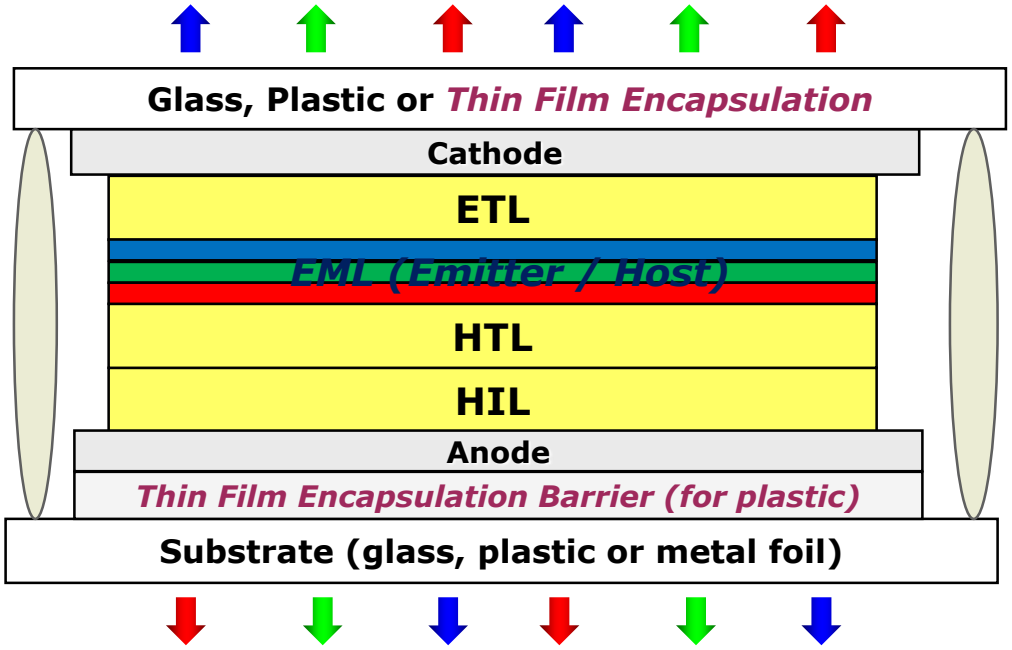
Sony PlayStation VR

LG Watch Urbane 2

Huawei Watch

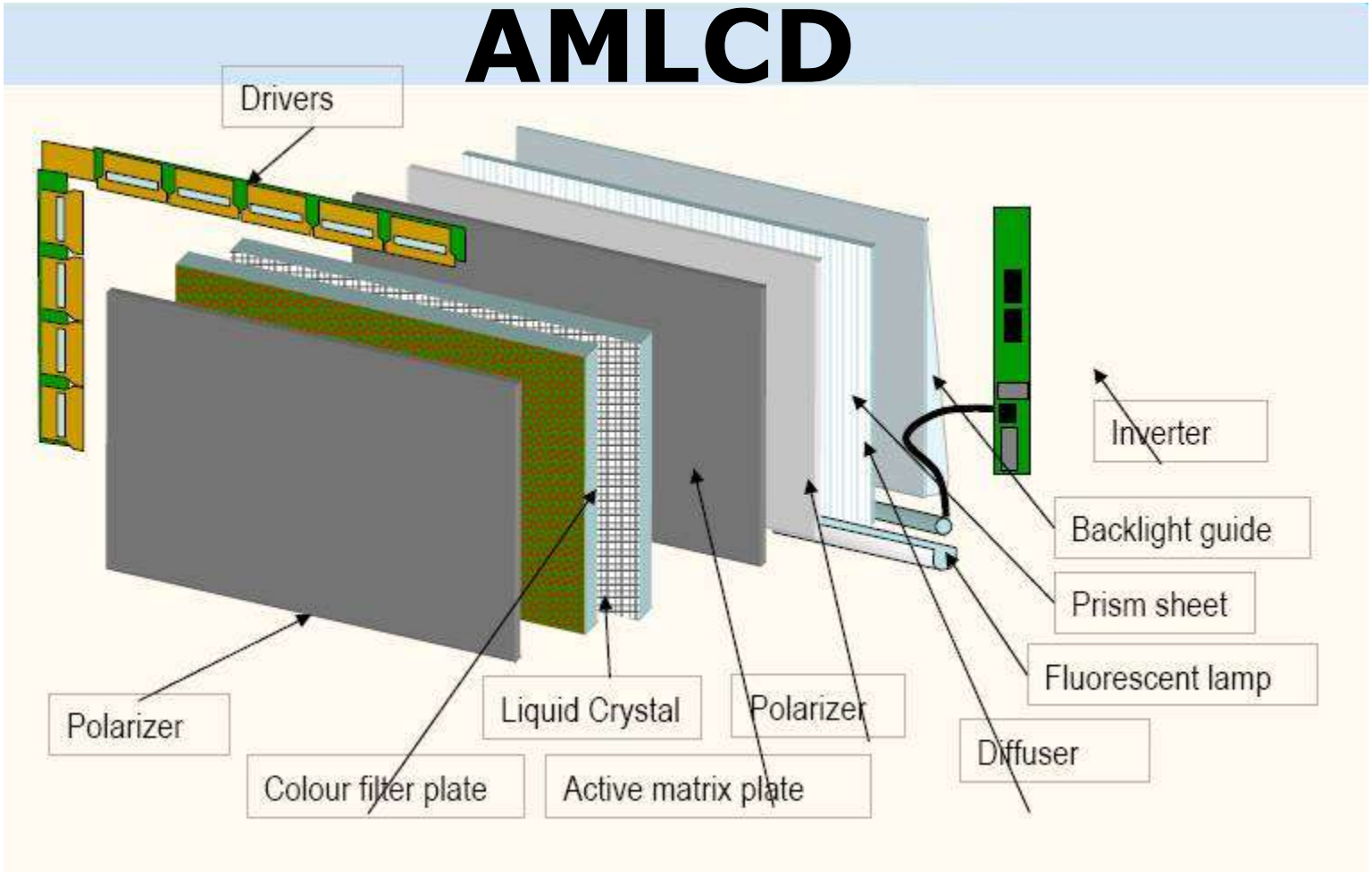
ASUS ZenWatch 3

Elegant Simplicity of an OLED

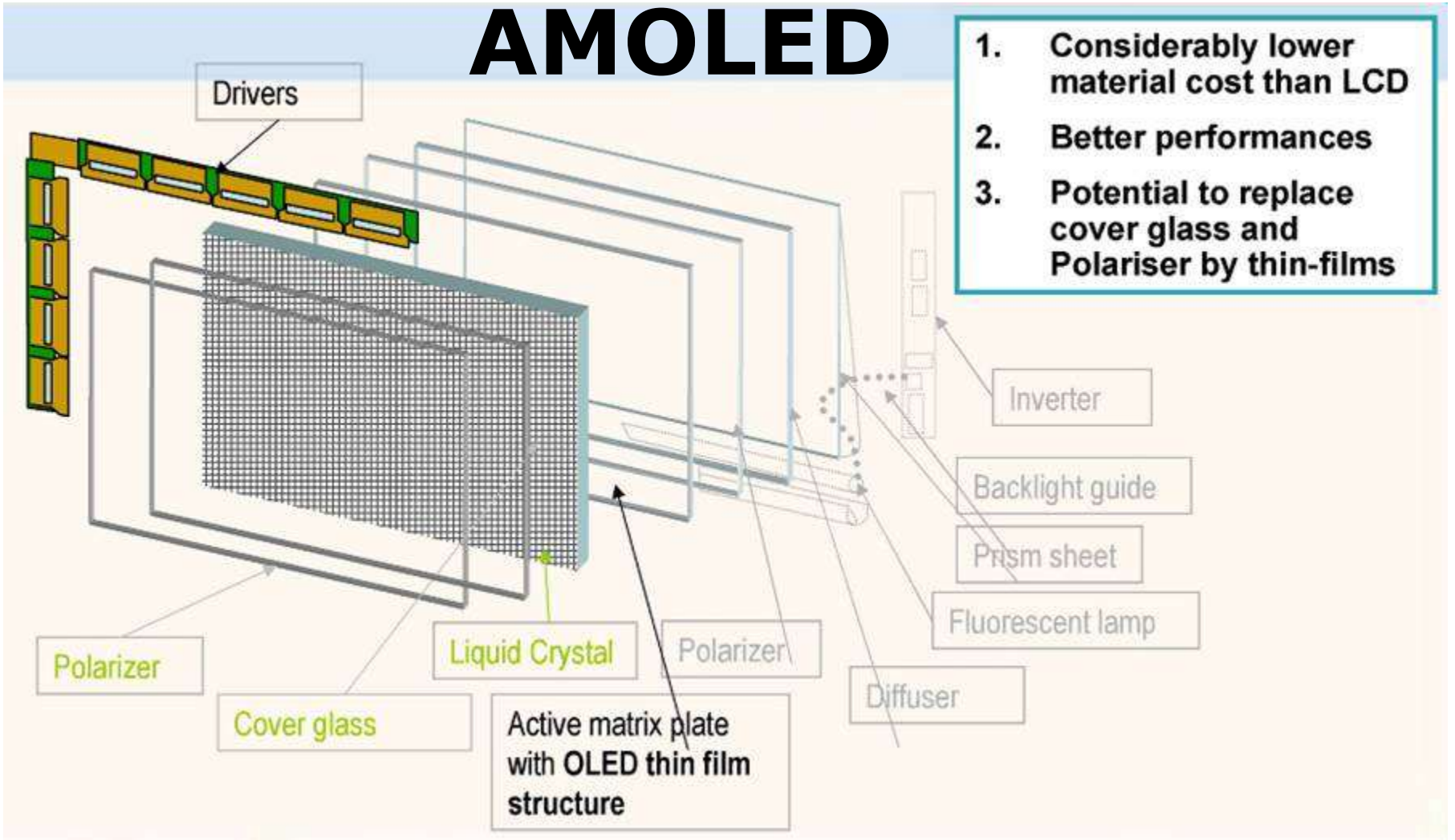


- An Organic Light Emitting Diode is a series of organic thin films between two conductors
- When electrical current is applied, bright light is emitted
- OLEDs can be used for displays and lighting
- OLEDs are not just thin and efficient - they can also be made *flexible* and *transparent*

AMOLED versus AMLCD – Display Modules



AMOLED versus AMLCD – Display Modules



LCD VS. OLED

- ✓ *Lower BOM (bill of materials)*
- ✓ *Better Performance, More Efficient*
- ✓ *Thinner and Flexible Form Factor*
- ✓ *Vivid Colors and Superior Contrast Ratio*

Image source: LG

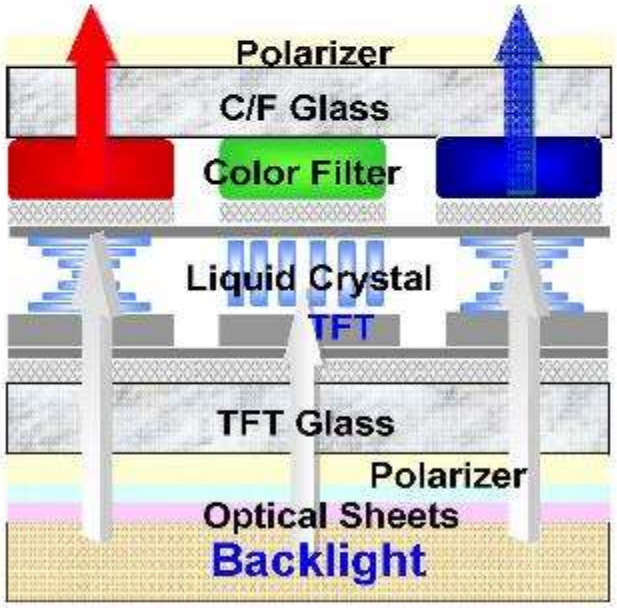
Why AMOLEDs for Mobile Devices?

SID

SS Kim, SMD, SID 2010

- **Fundamentally simpler structure than LCDs**
  - *AMOLEDs are thinner and lighter*
- **Better display performance compared to LCDs**
  - *Simply, AMOLEDs look better and are more attractive!*

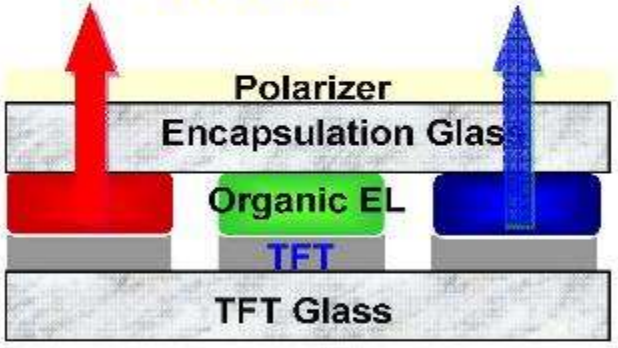
TFT-LCD



VS.

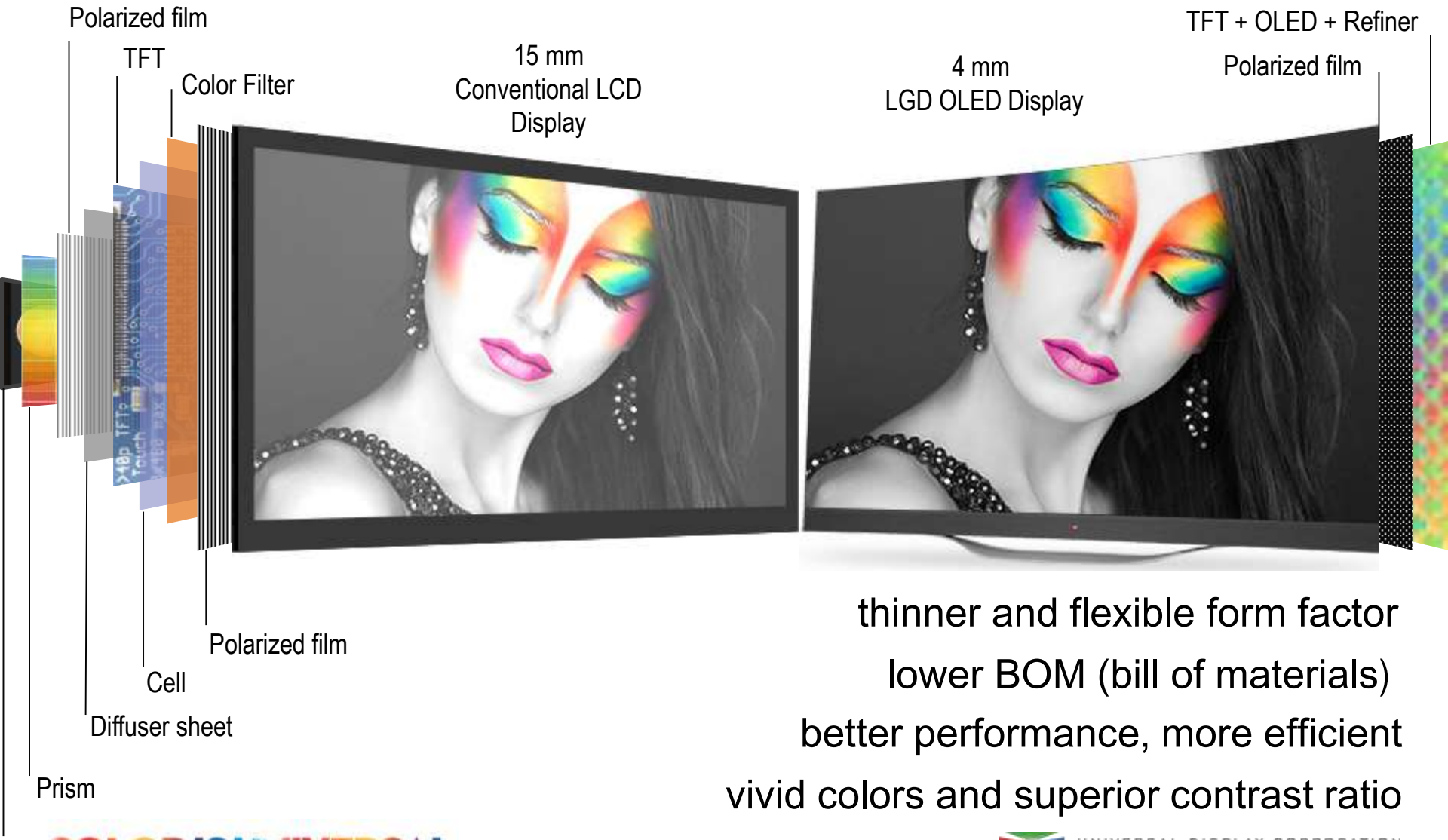
AMOLED

- *Self-Emissive*
- *Vivid Color*



- *No Color Filter*
- *No Backlight*
- *Thin & Light*

Why OLED TVs



thinner and flexible form factor

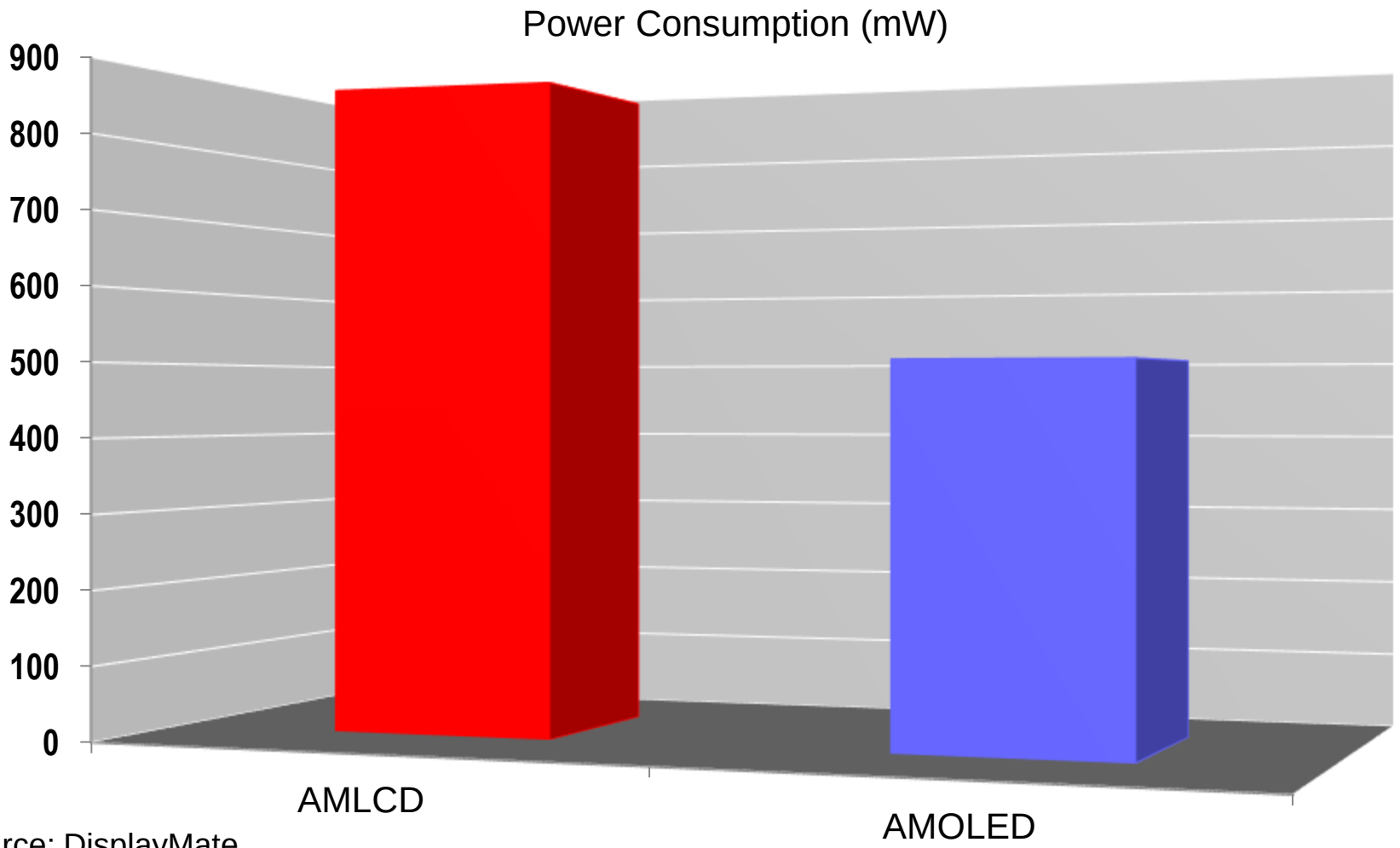
lower BOM (bill of materials)

better performance, more efficient

vivid colors and superior contrast ratio

image source: LG

AMOLED Display Power Efficiency



Source: DisplayMate

Chart comparing power consumption (mW) for Galaxy S7 versus leading AMLCD display for equivalent 5” displays operating at 400 cd/m^2. OLED is operated with 50% pixels on.

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OLED Displays vs OLED lighting

	Displays	Lighting
Maturity	Many small sized commercial products, tablets, notebooks and 55” -77” TV available	Early entry commercial products
TFT Backplane	Challenging – major yield limitation and high capital cost for manufacturing plant	TFTs are not needed
Full color patterning	Issue for large size substrates	N/A
Blue requirement	Need high performance, deep saturated blue	Warm whites require less deep blue than displays
Cost	BOM costs soon to be lower than AMLCD	Major challenge, but $25 per klumen now possible in 2018
New Form Factors	Thin, lightweight, rugged, transparent,	Thin, lightweight, rugged, transparent, arbitrary shapes

Strong OLED Display Market Drivers

Lower Power Usage

- **RED** Phosphorescence reduces power consumption by 25%
- **Add GREEN**: 45% cumulative reduction
- **Add BLUE**: 74% cumulative reduction
- Enabled by PHOLEDs

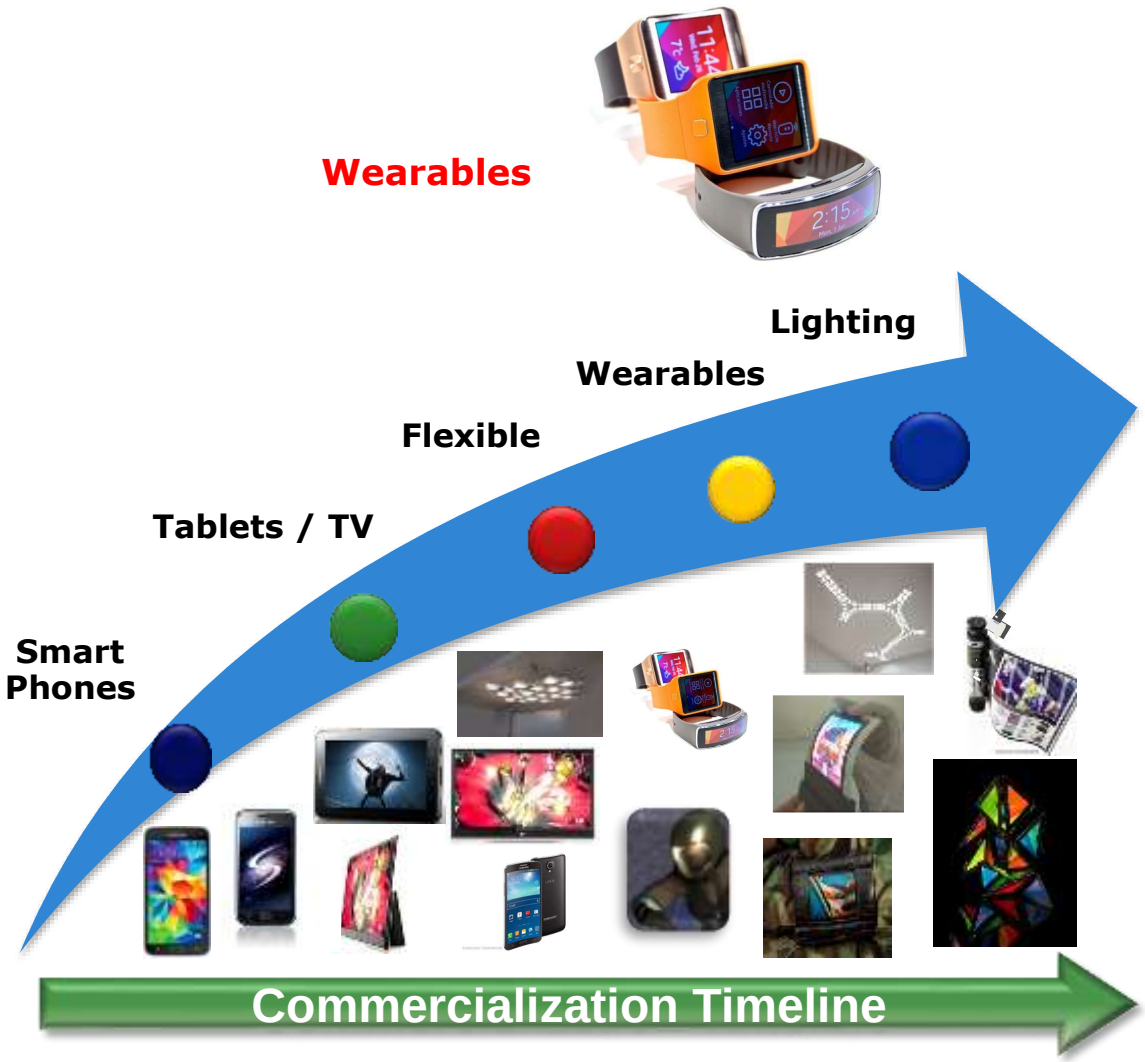
Superior Aesthetics

- Improved image quality
- Thinner form factor
- 180 degree viewing angle
- 1,000,000 : 1 contrast ratio – TRUE BLACK
- Real-time video speeds – excellent for 3D
- Self-emissive display
- On cell touch without sacrificing fill factor
- Low UV output
- **Flexible**

More Cost Effective

- Fewer manufacturing process steps
- Low cost bill-of-materials
  - No backlight required
  - No color filter required
  - No liquid crystal required
  - Reduced driver IC costs
- Enables non-glass substrates

OLED Market Expansion



Power consumption

PHOLED

Materials integration

Device and panel architecture

Lifetime

Materials integration

Device and panel architecture

Encapsulation

Manufacturability

Low Cost

Vacuum thermal evaporation

Solution and vapor printing

Form factor

Flexible

Unbreakable

Thin film barrier

How Will Flexible Lighting and Displays Develop?

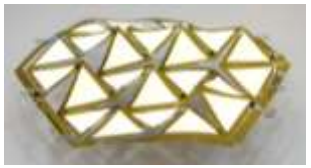
Low Power
- Thin and light
- Low power

Rugged
- Light and slim
- Unbreakable

Bendable
- Light and slim
- Wearable

Rollable
- Compact
- Low power

Free Form
- Total flexibility
- Paper-like



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Challenges of Plastic AMOLED

Key Challenges:

1) TFT Same as On-Glass

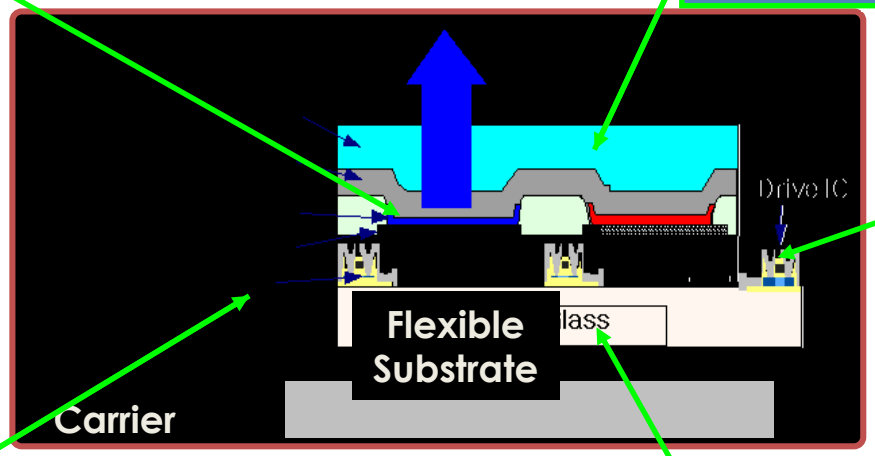
2) Low Cost Thin Film Encapsulation

3) Compatible with Existing Fab

Courtesy: HK Chung

Flexible OLED
- Flexible Anode & Cathode

Thin Film Encapsulation
- Processing Time
- Cost of Ownership



Flexible Module
- Reliability
- Bendability
- Thin Polarizer/Touch

TFT Process Architecture
- Low Temp. TFT Process
- TFT with High Reliability

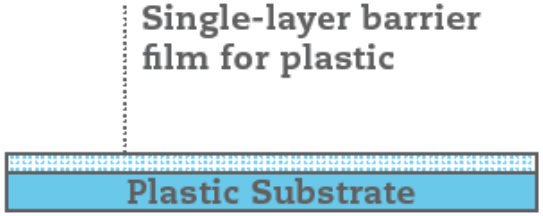
Plastic Substrate
- Moisture Barrier
- Delamination After Completion

Paths to Increase OLED Market – Form Factor

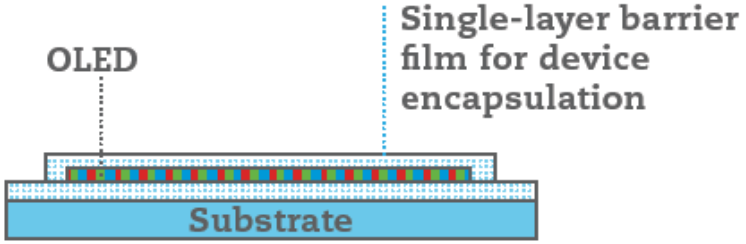
Form factor

Thin Film Barrier

Plastic Substrate System



Thin Film Encapsulation



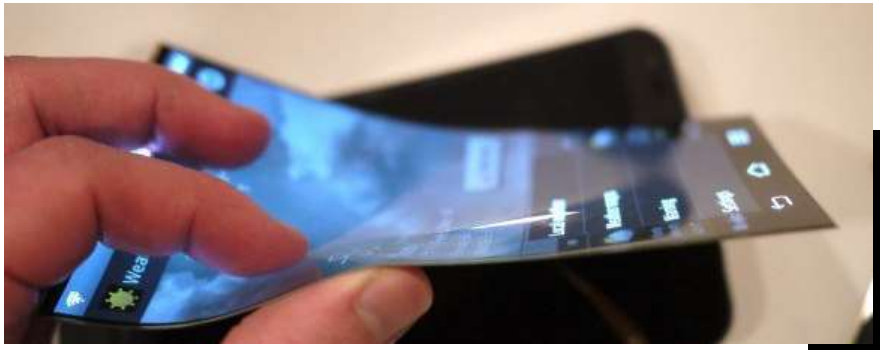
Impact:

- Lower cost – more displays per sheet and no dessicant or sealant
- Single layer enables very narrow bezel
- Enables flexible devices – game changer!!!

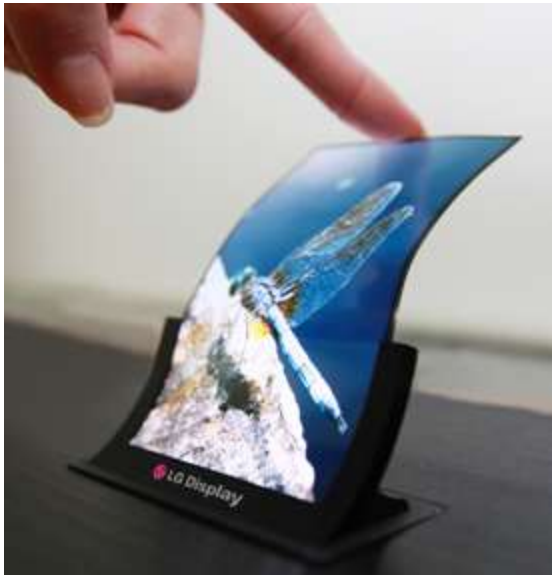
The Introduction of “Curved Phones”

LG G Flex

Future Growth: Flexible



Unbreakable



Thinner

New Form Factors

Lighter

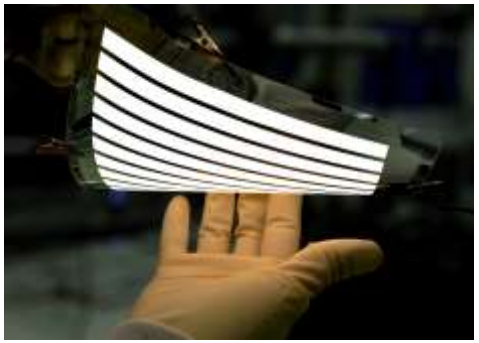
The Universal Communication Device (UCD)

Changing the way you view the world!

OLED Products for Wearable Applications

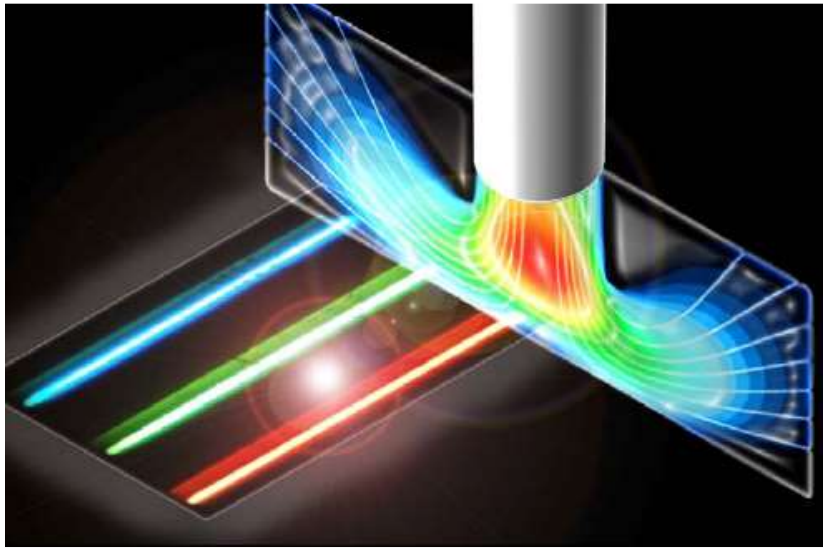
Galaxy Gear Series

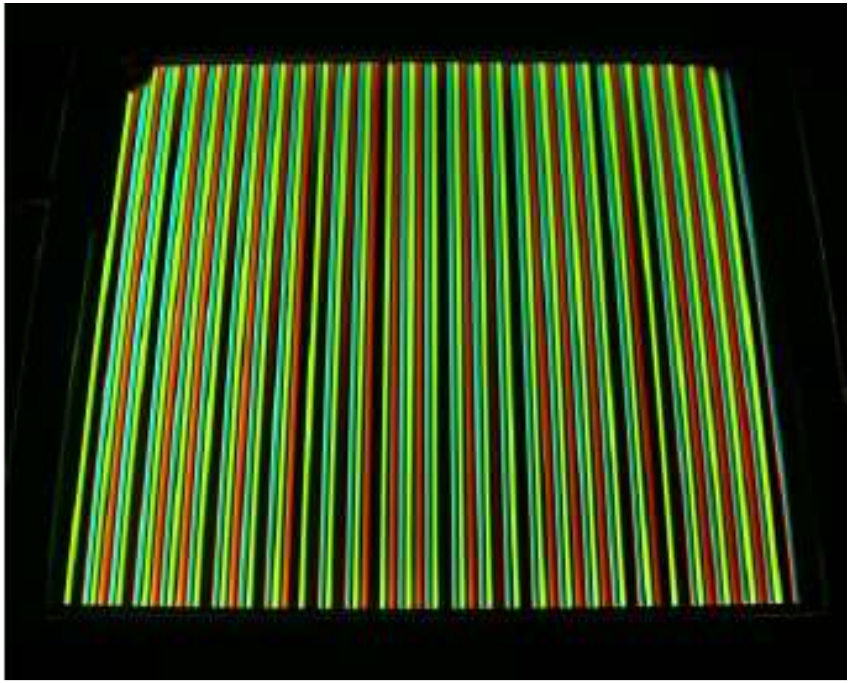
- Ideal display and lighting technology for wearable applications
- Thin, light and flexible (but needs encapsulation)
- Energy efficient – only uses power when visible
- Cool in operation – no heat sink required
- Low blue content – does not impact sleep



OVJP – Organic Vapor Jet Printing

Organic Vapor Jet Printing





OVJP: Printing with gas 'solvent'

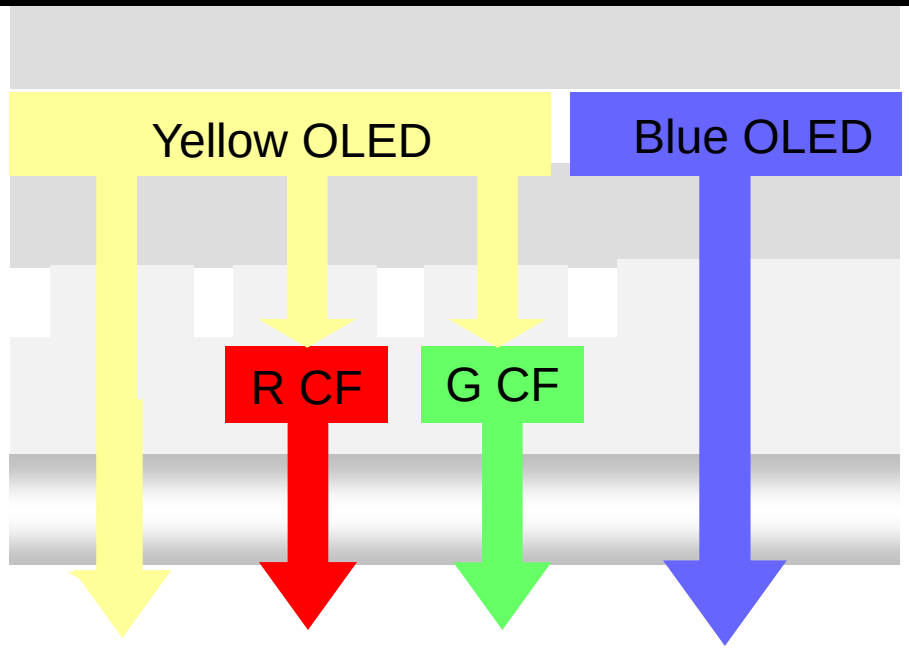
First Printed Lines at UDC Pilot Line

Moving to higher resolution: needs and considerations

- **Industry needs:**
  - Lower cost solution for pixel patterning
  - New architectures for v. high resolution and longer LT
- **Design considerations:**
  - Avoid high resolution OLED patterning
  - Improve display LT
    - maximize pixel fill-factor/maximize blue display LT
  - No power penalty
  - Can implement in bottom or top emission
  - Lower OLED manufacturing cost

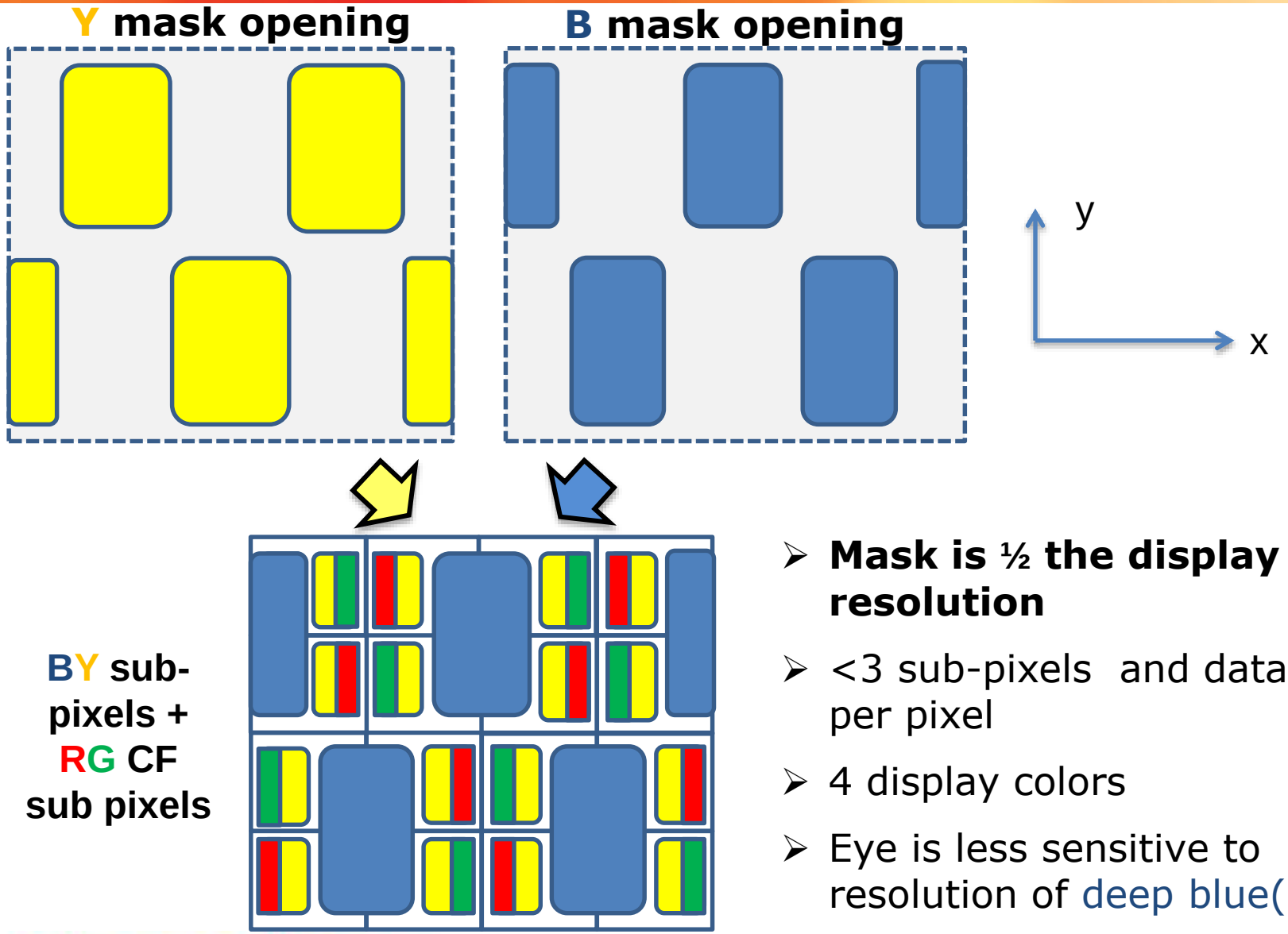
Proposed new: 'BYcolor' architecture

Novel BY Display Architecture



- Combining the best of shadow mask patterning and color filter technology
- High performance
  - Large blue (and yellow) pixels maximize display lifetime and efficiency
  - Separate color filters only for red and green
- Low cost
  - Can be used for large area substrates – mobile displays and TVs
  - Shadow mask can be sturdier – only half the resolution of the display

Applying SPR(Spatial Resolution) to BYcolor Architecture



- **Mask is ½ the display resolution**
- <3 sub-pixels and data lines per pixel
- 4 display colors
- Eye is less sensitive to resolution of deep blue(~5%)

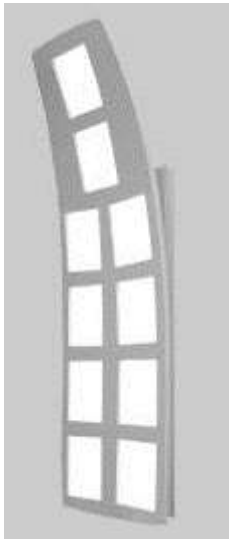
OLED Lighting

- Energy efficient – environmentally friendly
  - *Low drive voltage*
  - *Low operating temperatures, cool to touch*
  - *Long lifetime*
  - *Easy to control*
- Highly desirable color quality
  - *Wide range of CCT, high CRI possible*
  - *Color tunable*
  - *Instant "ON" , Dimmable without flicker*
  - *No glare, no noise*
  - *Low UV content*
- Novel form factor
  - *Thin and lightweight surface lighting*
  - *Transparent*
  - *Non-breakable, Flexible, Rollable…..*
- Low cost potential
  - *Scaling advantage - roll to roll process*

OLED Lighting Around the World

AcuityBrands.

*Now available @



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2015 OLED Panel Performance Specs

Panels from LG Chem: PHOLED Technology from UDC

TODAY

CCT	3000K / 3500K / 4000K	
Color Consistency	± 2 MacAdam	
Luminance	2000-3000 cd/m^2	
L70 **3000K** **3500K / 4000K**	40K hrs @ 3000 cd/m^2; 72K hrs @2000 cd/m^2 30K hrs @ 3000 cd/m^2; 54K hrs @2000 cd/m^2	
	HIGH CRI	**STANDARD CRI**
Efficacy	55 - 60 lm/W	80 lm/W
CRI	85-90	80
R9	24-41	> 0

From Acuity Brands

Pixel Efficacy: Status & Targets

Pixel Efficacy ∝ LER x IQE x OC x EEF

- LER = Luminous Efficacy of Radiation (= Max efficacy of emission spectra)
- IQE = Internal Quantum Efficiency
- OC = Outcoupling Efficiency
- EEF = Electrical Efficiency Factor (= Optical Energy Gap – Applied Voltage)

	Target and Practical Limit
LER [lm/W]	350
IQE [%]	95%
OC [%]	60%
EEF [%]	90%
Pixel Efficacy [lm/W]	**180 (at 3,000 cd/m^2)**

- White PHOLEDs already emit with IQE ≈ 100% at low luminance. Challenge is to maintain IQE ≈ 95% at 3,000 cd/m^2.

UDC White OLED Pixel Efficacy Target = 180 lm/W

OLED and LED Lighting – Living Together

2015 DOE Roadmap for OLED Lighting

Table 6.3 Breakdown of OLED Luminaire Efficiency Projections

Metric	2014	2017	2020	Goal
Panel Efficacy[1] (lm/W)	60	125	160	190
Optical Efficiency of Luminaire	100%	100%	90%	90%
Efficiency of Driver	85%	85%	90%	95%
Total Efficiency from Device to Luminaire	85%	85%	81%	86%
Resulting Luminaire Efficacy[1] (lm/W)	51	106	130	162

Notes:

1. Efficacy projections assume CRI >80, CCT 3000 K

US Department of Energy – OLED Cost Roadmap

Manufacturing Roadmap

Solid-State Lighting Research and Development

Prepared for the U.S. Department of Energy

August 2014

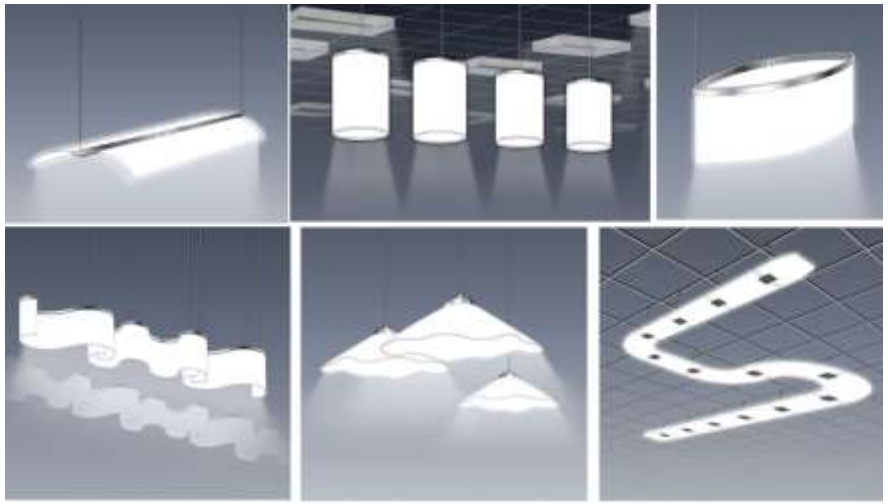
Prepared by Bardsley Consulting, Navigant Consulting, SB Consulting, and SSLS, Inc.

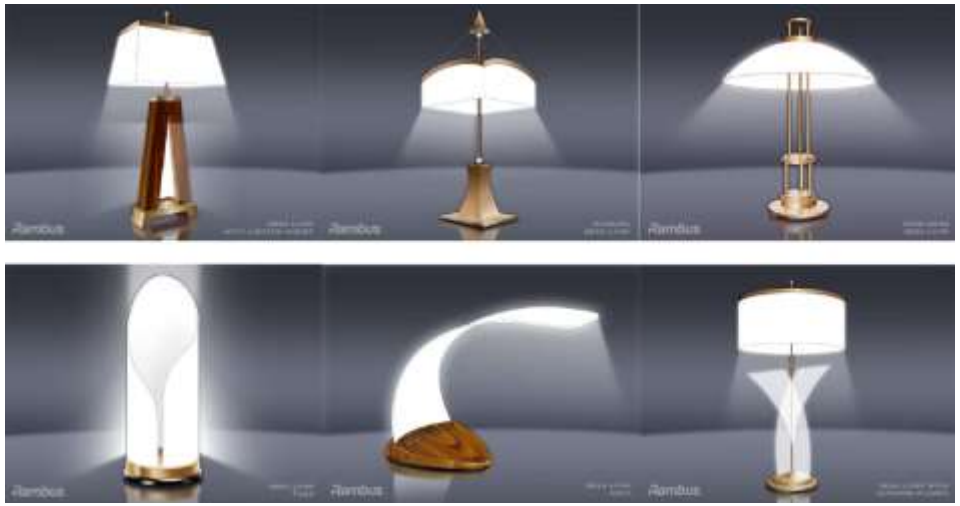
Table 1.6 OLED Panel Cost Estimated Progress ($/m^2)

	2013	2014	2016	2020	2025
Integrated Substrate	250	200	150	40	20
Organic Deposition	600	500	250	70	30
Assembly and Test	350	300	200	50	20
Overhead[d]	300	200	100	20	10
Total (unyielded)	1,500	1,200	700	180	80
Yield of Good Product (%)	25	40	70	75	80
Total Cost	6,000	3,000	1,000	240	100

Flexible OLED Lighting

Conventional Lighting





Flexible OLED Lighting

Courtesy: HK Chung

Novel Form Factor – flexible & rugged

Safety Clothing by GE (concept)

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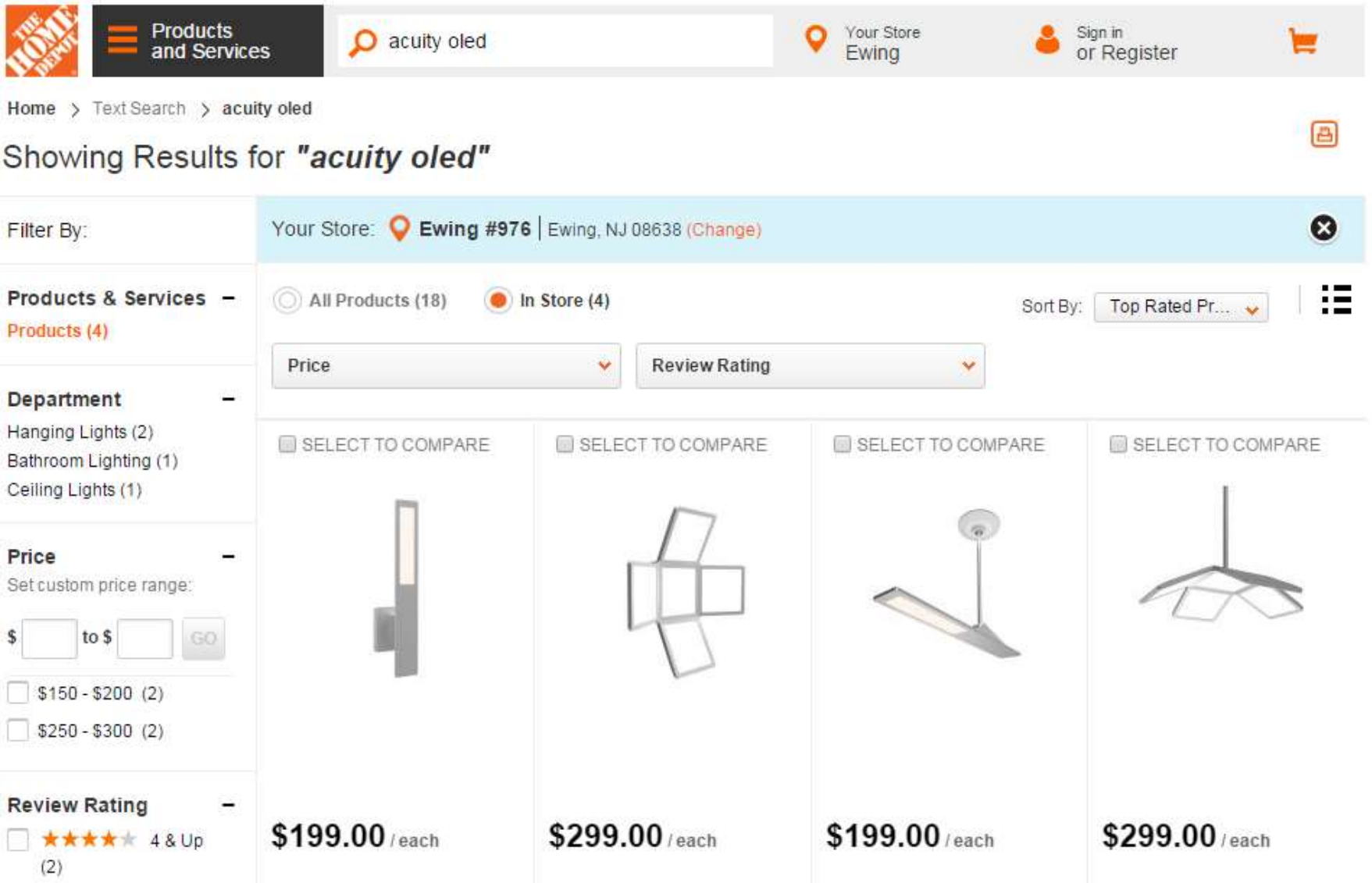
OLED Lighting – Entering the Mass market



Application of Tunable OLED Luminaires

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Expanding the boundaries of lighting™

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Application of OLED Luminaires

OLED luminaires can be used in:

- Retail stores
- Offices
- Hospitals
- Galleries
- Supermarkets

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Application of OLED Luminaires

The luminaires can be used in:

- Retail stores
- **Offices**
- Hospitals
- Galleries
- Supermarkets

CCT=4,000K

CCT=3,500K

CCT=2,700K

Energy Savings Potential in 2020

DOE analysis compares corridor lighting scenarios

Traditional design with fluorescent troffers

OLED design with vertical and pendants

COMPARED TO TRADITIONAL LIGHTING DESIGNS, USING OLEDs IN CORRIDORS COULD SAVE . . .

73%

Energy reduction

Which equates to

163 tBtu

And saves businesses

$1.7B per yr.

In 2020

From DOE

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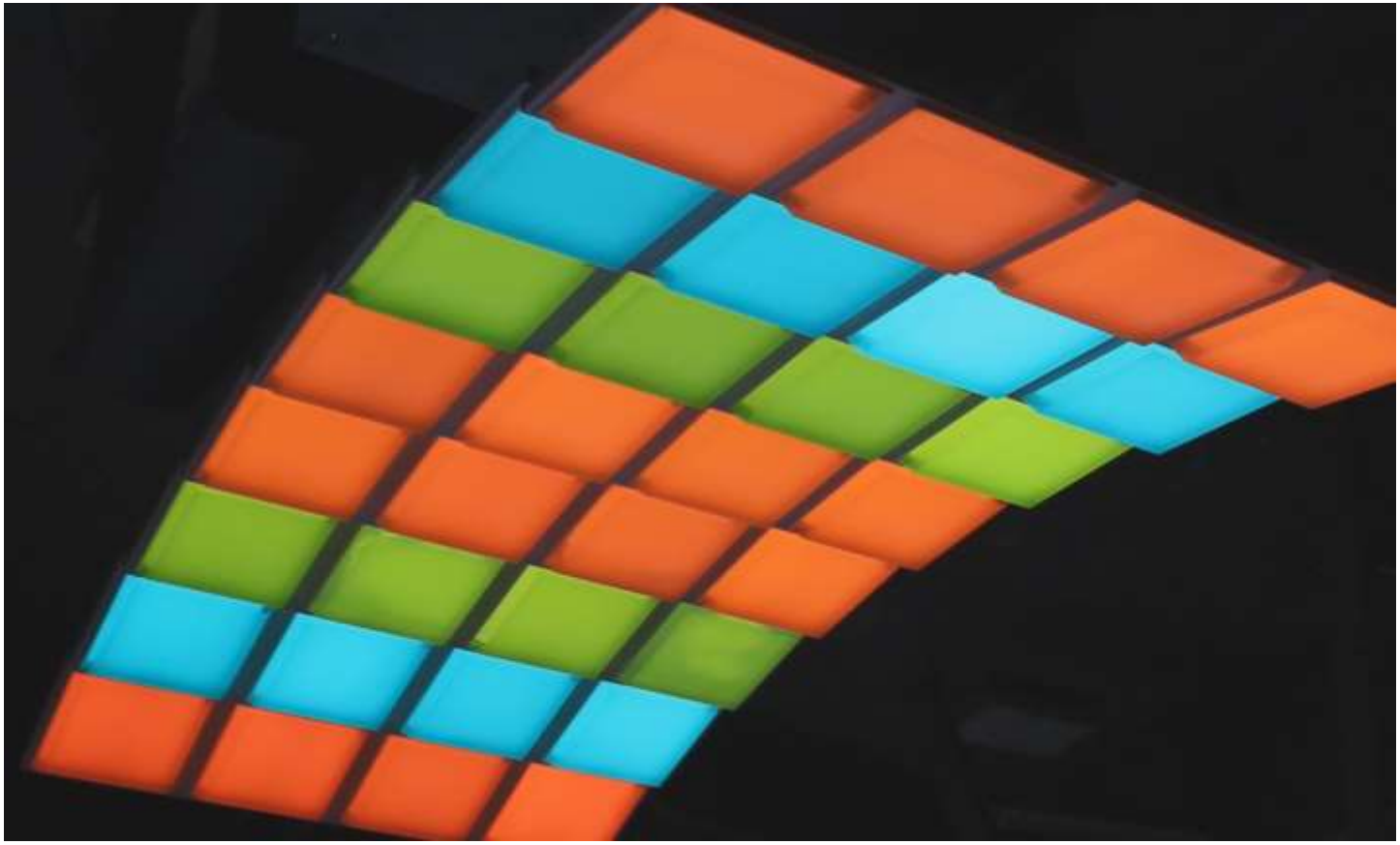
Luminaire with Color Tunable WOLED Panels



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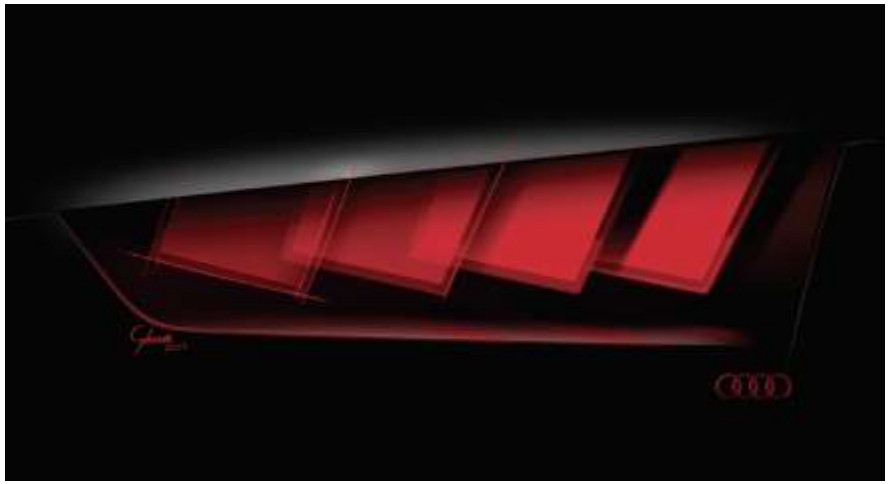
- **32x 6” x 6” panel PHOLED Luminaire**

Automobile Applications for OLED Lighting

Source: BMW



Audi

- OLEDs offer the ability to create shapes of any size
- OLEDs provide extremely uniform light

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Thank you.