Nutmeg Consultants

AMOLED Displays

Current Developments and Reckless Predictions

Ken Werner

Principal, Nutmeg Consultants

2 Shady Brook Lane
Norwalk, Connecticut 06854
kwerner@nutmegconsultants.com
+203/644-2156

Abstract: AMOLED Displays

The development of OLED displays has been a rocky road, with prediction after prediction running into delays and revisions. That's typical for the development of new display technologies, but the huge promise of OLED coupled with the technology's apparent simplicity made the delays particularly frustrating for OLED.

Now, Samsung Mobile Display (SMD), the primary manufacturer of active-matrix OLEDs (AMOLEDs), can't keep up with demand, and both SMD and LG Display are planning to ramp up Gen 5.5 fabs in mid-2011. These are exciting times for AMOLED, and we can expect an array of new AMOLED-based products, but the melodrama is not over.

As it turns out, although AMOLED technology appears simple, it isn't. Great advances have been made on materials and device structure, resulting in vastly improved efficiency and lifetime, but the lifetime of blue emitters is still seriously deficient for many applications.

Although the processes used for making both the OLED front planes and active-matrix backplanes are responsible for the technology's current success, they are (at least in part) about to be pressed into use for the new, much larger fabs that will soon begin production – even though they have distinct limitations even for today's generation. Process scalability is a critical issue if OLED displays are to be manufactured in larger sizes at a cost that allows them to be used in high-volume products. Therefore, it is not surprising that significant resources are being devoted to new processes that are suitable for fabs larger than Gen 5.5.

In this overview, we will look at recent developments and current issues, and make some very specific (and perhaps slightly reckless) predictions about the immediate future.

Outline

- What’s an OLED?
  - Basic structure
  - Not-so-basic structure
  - Why use an active matrix backplane?
- Basic processing
  - Front plane
  - Backplane
- What’s wrong with the processing status quo?
  - Backplane
  - Front plane

Outline (continued)

- Now for materials
  - Small-molecule (SM) vs. Polymer (RIP)
  - SM Solution Processing
  - Fluorescent vs. Phosphorescent
  - Lifetime, efficiency, and color coordinates
  - Structural work-arounds
- Where are we now?
  - One major supplier of AMOLED panels
  - Severe shortage
  - Two new Gen 5.5 fabs scheduled for mid-year start-up
  - SMD talking about Gen 8
- Predictions – short term
- Predictions – longer term

Basic structure

Not-so-basic-structure

Real-world structure

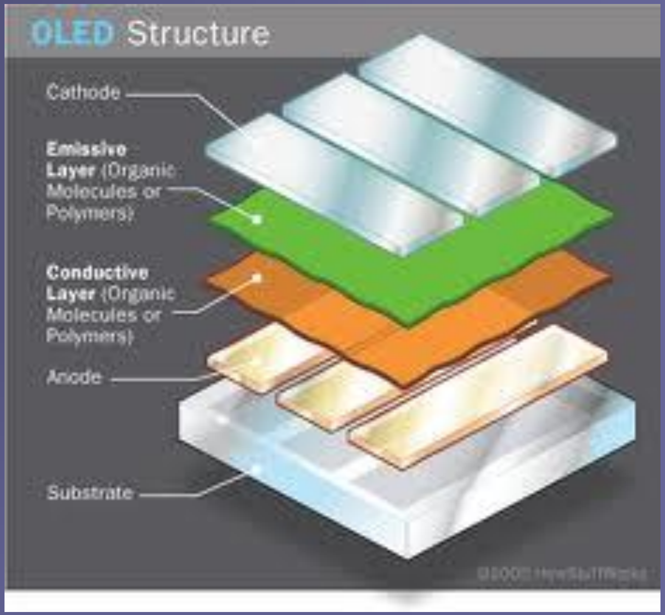
Basic operation

Why use an AM backplane?

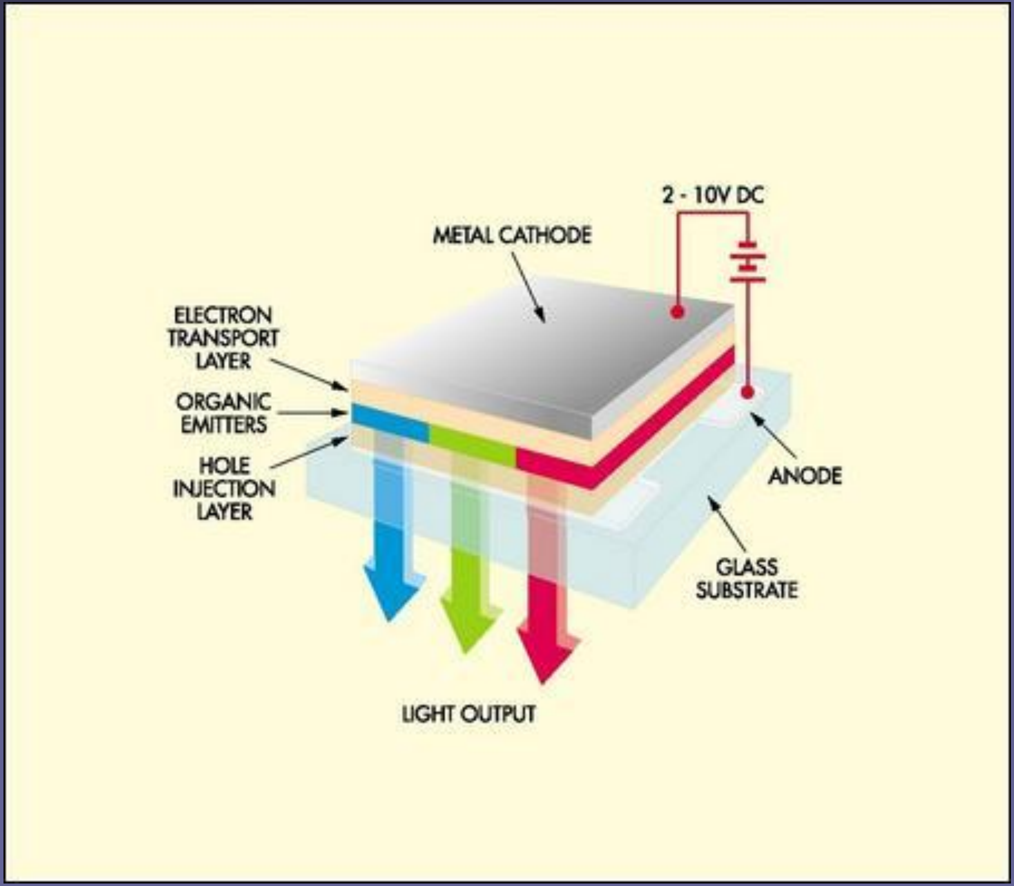
WHAT’S AN OLED?

Very Basic Passive-matrix OLED

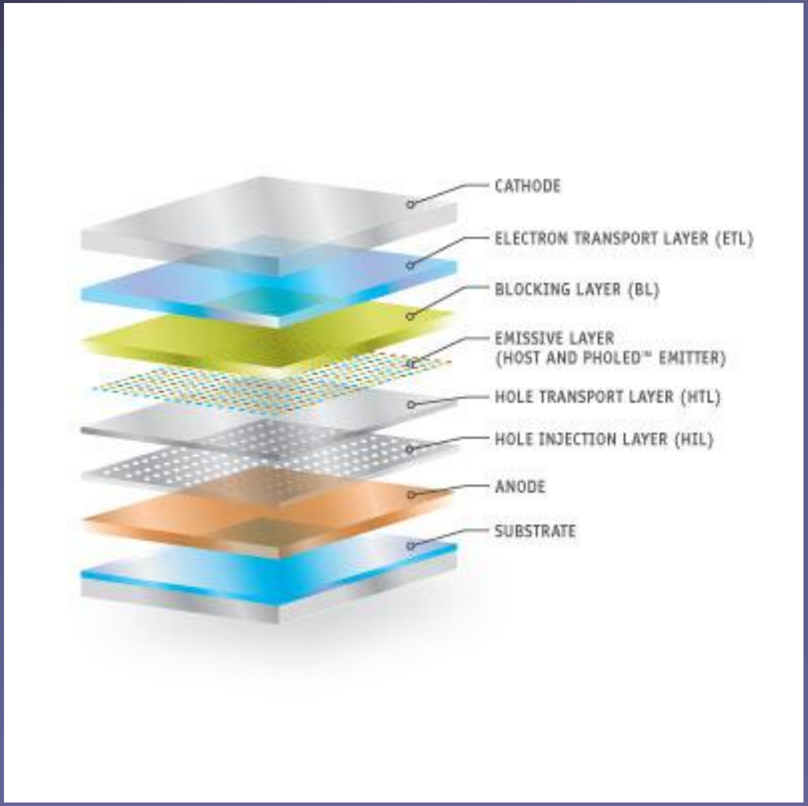
- 1963
  - Martin Pope, NYU
  - 5-nm-thick Anthracene crystal
  - Blue light at 400 volts
- 1987
  - Tang and Van Slyke, Kodak
  - Bi-layer organic structure
  - Taming the wild hole
  - 10 volts
  - IQE = 1%
  - Power conversion eff = 0.46%



OLED Structure

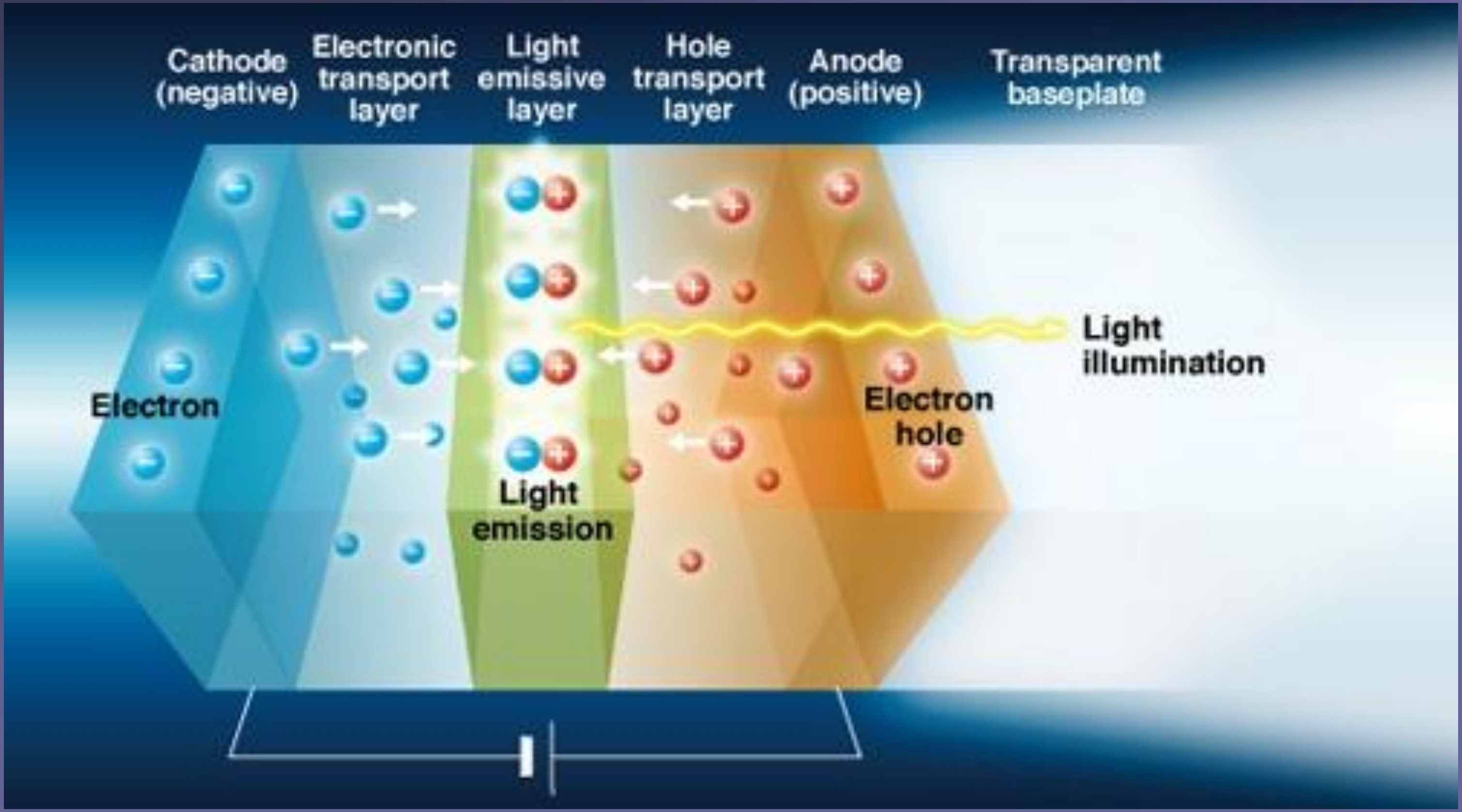


Practical OLED Structure



Source: UDC

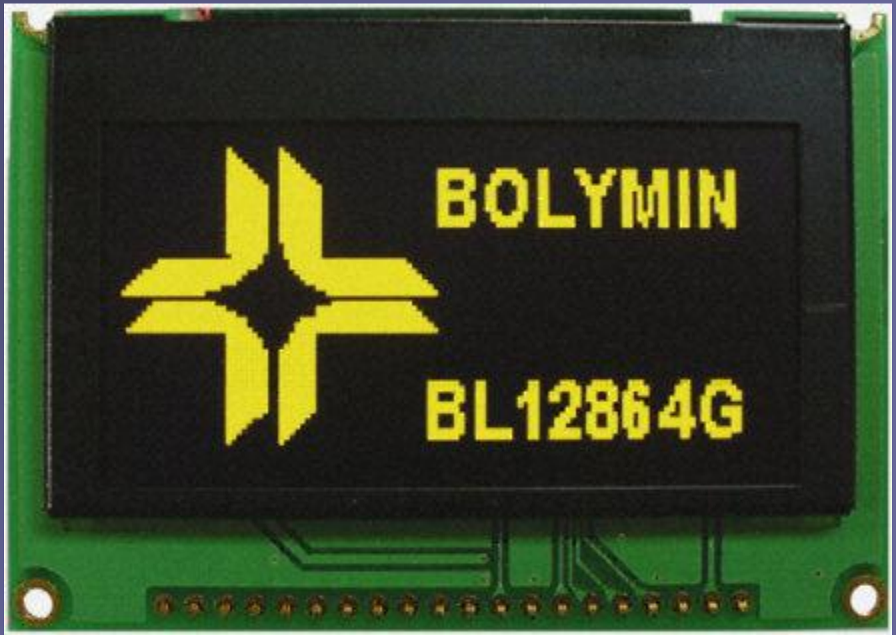
OLED Operation



(Source: Nikon)

Why Use an AM Backplane?

- Passive
  - $L = I_D \times T_D$ ($\times C_1$)
  - $T_D = 1/N \times$ frame time
  - $L = I_D/N \times$ ($\times C_2$)
  - Very high currents impact OLED efficiency and lifetime, and demand high-current power supplies
  - N = 100 is practical max
- Active
  - Pixel switch on through entire frame time
  - Moderate diode current



128 x 64 pixels, 3.3 V (Source: RS Components)

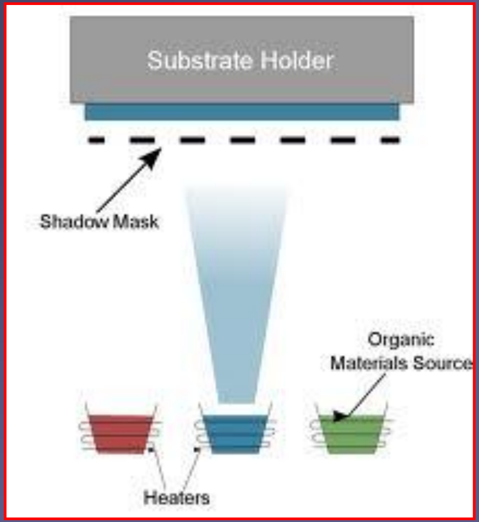
Front plane

Backplane

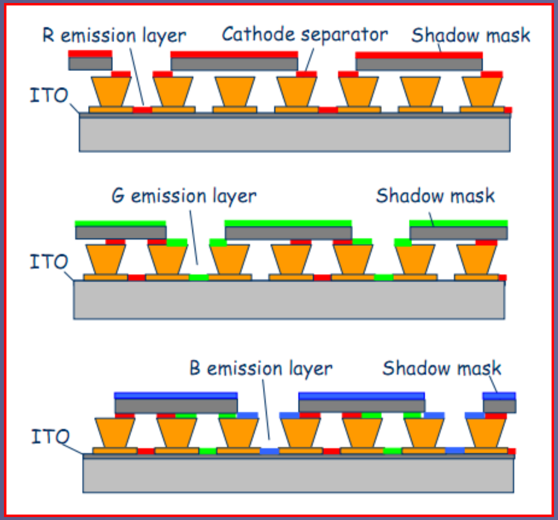
BASIC PROCESSING

Basic Front Plane Processing

- Vacuum thermal evaporation (VTE)
  - Point source
  - Material evaporated through shadow mask (FMM)



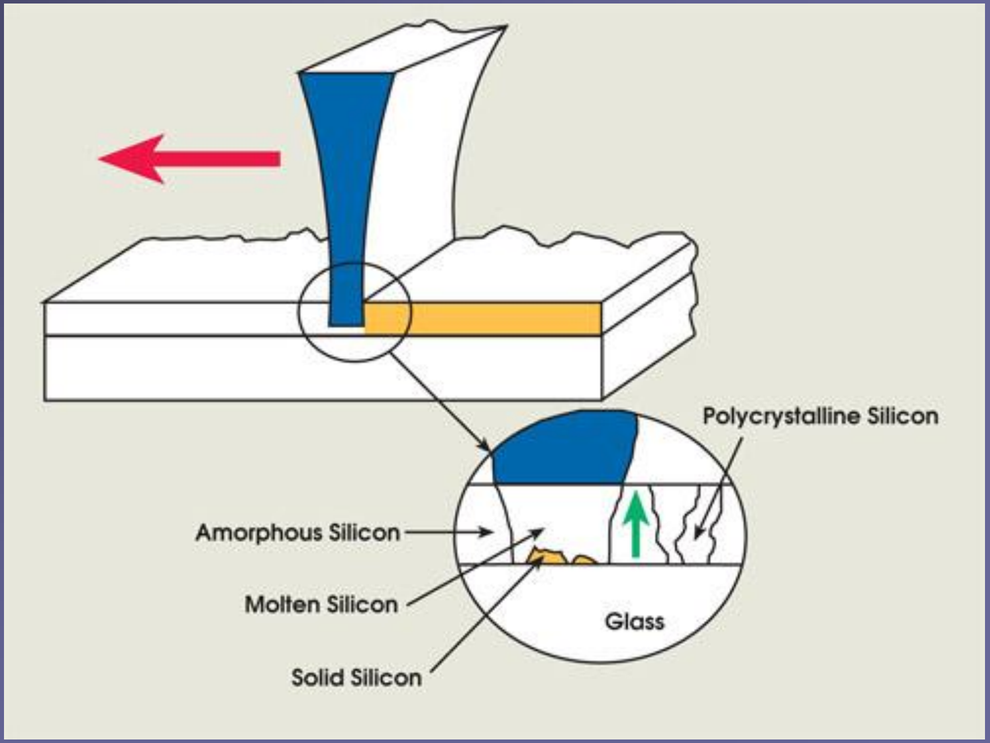
Source: J. P. Handrigan, Open Clip Art Library



Source: H. Antoniadis, OSRAM

Basic Backplane Processing

- Excimer laser annealing (ELA)
  - To convert a-Si to LTPS
  - Line (2006)
    - 465 x 0.4mm
    - 20 pulses/location



Source: Coherent

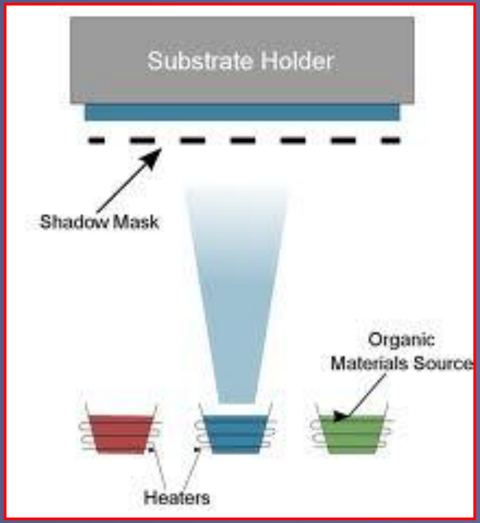
Backplane

Front plane

WHAT'S WRONG WITH THE PROCESSING STATUS QUO?

What's Wrong: Front Plane

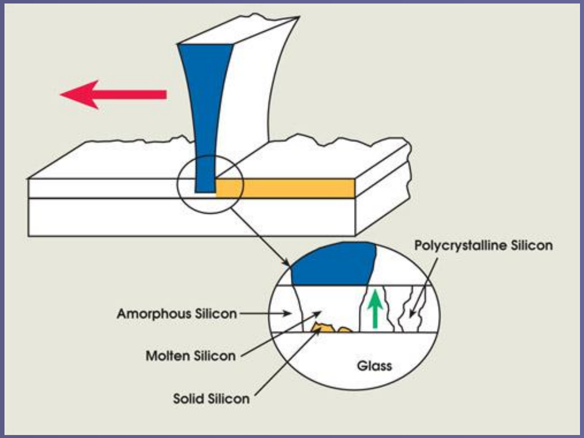
- VTE
  - Point source
  - Limited scalability
    - To about Gen 4 (680 x 880mm)
  - Wastes material
  - FMM in contact with substrate
- Alternatives
  - Linear Source (Seoul Univ.)
  - LITI (Sony)
  - OVPD (UDC, Steve Forrest, Aixtron)
  - Gas-carrier (Kodak)
  - Solution processing
    - Spin coat
    - Ink-jet printing
    - Spray (DuPont, Dainippon Screen Mfg. Co.)



Source: J. P. Handrigan, Open Clip Art Library

What's Wrong: Backplane

- Excimer laser annealing (ELA)
  - Sensitive process
  - Uniformity issues
  - Lasers age; require replacement
  - Throughput
- Alternatives
  - Variety of enhanced ELA processes
  - Sequential lateral solidification (SLS)
    - Wider process window; better mobility
  - Oven annealing (nickel enabled)
  - Just use a-Si
    - UDC doing that in flexible wrist-mounted flexible prototypes delivered to U.S. Army



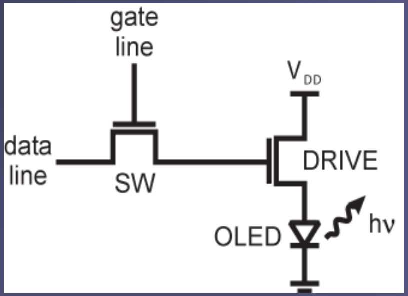
Source: Coherent

AMOLED Backplane Technologies

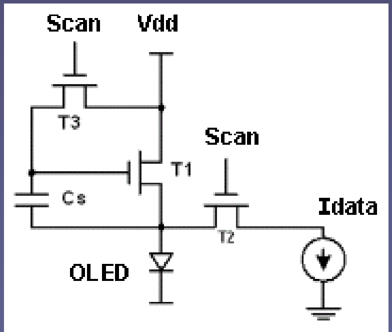
Attribute	a-Si:H	Poly-Si
Drive capacity (type)	-Low mobility -large W/L (nMOS)	-High mobility -small W/L (nMOS/pMOS)
Manufacturability and accessibility	Mature and accessible	New and not yet accessible
V_{th} uniformity across array	Good	Poor
ΔV_{th}	Poor	Good
Fabrication plants	Gen 7 (1850 x 2100 mm^2)	Gen 3.5 (600 x 720 mm^2)
Drop-in solution to existing infrastructure?	Yes	No
Normalized array-to-array cost for small displays	60%	100%

Source: Corbin Church, Ignis Innovations

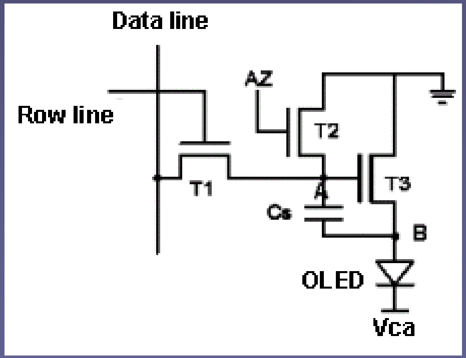
a-Si Pixel Switch Circuits for AMOLEDs



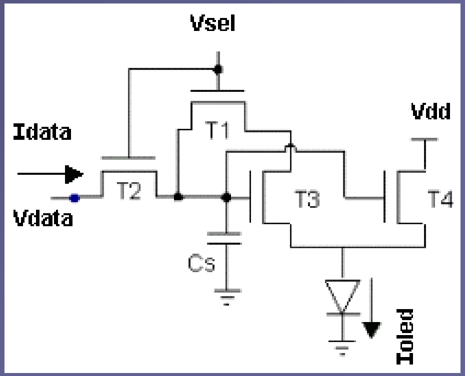
Classic 2T Solution



Casio



IBM



IGNIS

Source: Corbin Church, Ignis Innovations

An a-Si OLED

Samsung 40-inch AMOLED
“Color by White”

(prototype)

Small-molecule (SM) vs. Polymer

SM solution processing

Fluorescent vs. phosphorescent

Lifetime, efficiency, and color coordinates

Structural work-arounds

NOW FOR MATERIALS

Small Molecule vs. Polymer

- SM
  - Well developed
  - Easy to work with
- Polymer
  - Initial benefits
    - Solution processable; CDT focused on IJP
    - Possible higher luminous efficiency
  - But…
    - IJP turned out to be very difficult for OLED materials
    - Solution processes were developed for SM
    - Phosphorescent SM materials shifted luminous efficiency in SM's favor
    - Polymers difficult to work with in manufacturing environment
- Conclusion
  - All major development and manufacturing programs are now SM
    - Sumitomo Chemical/CDT presumably still developing polymer but low profile

SM Solution Processing

- Put SM materials in liquid carrier
  - Can then be spin coated, ink-jetted, or sprayed
- Materials development
  - Attain similar performance with solution processed material as with evaporated
  - Attain similar performance with ink-jetting as with spin coating
  - Different materials need different solvents and need to be optimized differently.

Fluorescent vs. Phosphorescent

- Original SM materials fluorescent
  - Photon emission only from singlet state
    - Max 25% IQE
- UDC-developed phosphorescent materials
  - Photon emission from both triplet and singlet states
    - Max 100% IQE
    - Phosphorescent red in general use
    - Green in qualification
    - Blue lifetime needs work
- Hybrid
  - Current AMOLED displays use phosphorescent red with fluorescent green and blue

Lifetime, Efficiency, and Color Coordinates

UDC PHOLED Data

UNIVERSALPHOLED™ DATA		1931 CIE COLOR COORDINATES	LUMINOUS EFFICIENCY (cd/A)	OPERATIONAL LIFETIME TO 50% L_0 (hrs)
RED	DEEP RED	(0.68, 0.31)	15	95,000
	DEEP RED	(0.67, 0.33)	22	120,000
	NEW RED	(0.66, 0.34)	22	600,000
	RED	(0.65, 0.35)	24	300,000
	RED	(0.64, 0.36)	28	500,000
GREEN	NEW GREEN	(0.33, 0.62)	76	600,000
	GREEN	(0.33, 0.62)	65	500,000
	GREEN-YELLOW	(0.46, 0.53)	69	350,000
BLUE	NEW LIGHT BLUE	(0.18, 0.39)	46	9,000

Sample Performance Data. These results are measured at 1000 cd/m² and are for bottom-emitting structures (with no cavities). Lifetime data is based on accelerated current drive conditions at room temperature.

New light blue has 30% greater luminous efficiency and almost 100% greater operating lifetime than UDC's previous light blue PHOLED emitter. Suitable for OLED lighting (where a warm white is desirable) and displays utilizing the two-blue structure.

UDC P2OLED Materials – Previous Gen

DEVICE	CIE COLOR COORDINATES	LUMINOUS EFFICIENCY (cd/A)	OPERATIONAL LIFETIME TO 50% L. (HRS)	INITIAL LUMINANCE (cd/m²)
RED	(0.67, 0.33)	12	100,000	500
GREEN	(0.33, 0.62)	34	63,000	1,000
BLUE	(0.15, 0.22)	6	1,000	500
LIGHT BLUE	(0.18, 0.39)	19	6,000	500

Sample Performance Data. This data is for spin-coated, bottom-emission structures (with no cavities) using a full set of OLED materials developed by Universal Display. The operational lifetime data is based on accelerated current drive conditions at room temperature.

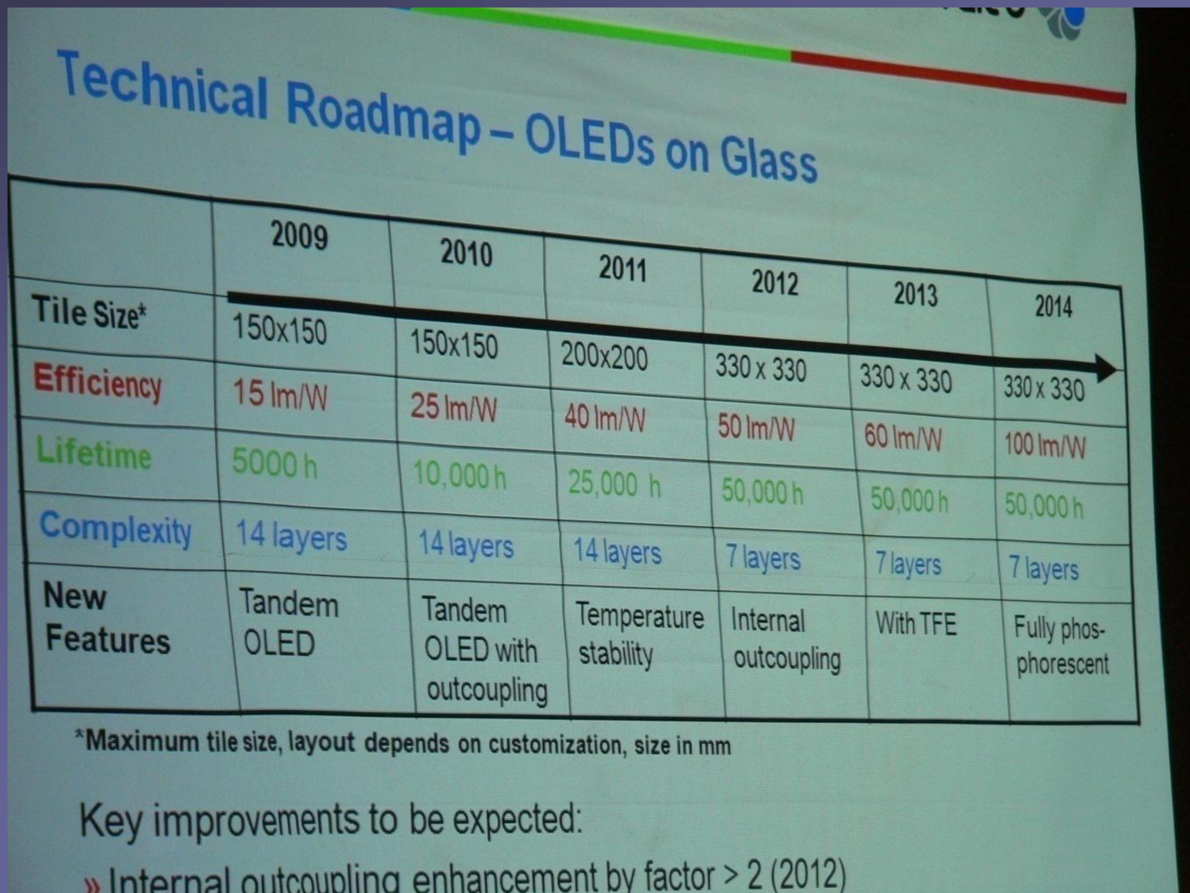
UDC P2OLED Materials – Current Gen

UNIVERSALP²OLED™ DATA	1931 CIE COLOR COORDINATES	LUMINOUS EFFICIENCY (cd/A)	OPERATIONAL LIFETIME TO 50% L_0 (hrs)
RED	(0.66, 0.34)	15	62,000
GREEN	(0.33, 0.63)	66	130,000
LIGHT BLUE	(0.18, 0.39)	18	5,300

Sample Performance Data. These results are for spin-coated, bottom-emission structures (with no cavities). The operational lifetime data is based on accelerated current drive conditions at room temperature at an initial luminance of 1,000 cd/m² and without any burn-in or other pre-aging methods.

"Through the development of optimized ink formulations, the company has also demonstrated ink-jet printed P2OLED devices with comparable performance to devices made by spin-coating. While spin coating is a technique generally only used for research purposes, ink-jet printing is one of the leading solution-processing candidates for use in large-area manufacturing settings. *(Source: UDC)*

Novaled Transparent White for Lighting



Technical Roadmap – OLEDs on Glass

	2009	2010	2011	2012	2013	2014
Tile Size*	150x150	150x150	200x200	330 x 330	330 x 330	330 x 330
Efficiency	15 lm/W	25 lm/W	40 lm/W	50 lm/W	60 lm/W	100 lm/W
Lifetime	5000 h	10,000 h	25,000 h	50,000 h	50,000 h	50,000 h
Complexity	14 layers	14 layers	14 layers	7 layers	7 layers	7 layers
New Features	Tandem OLED	Tandem OLED with outcoupling	Temperature stability	Internal outcoupling	With TFE	Fully phos-phorescent

*Maximum tile size, layout depends on customization, size in mm

Key improvements to be expected:

» Internal outcoupling enhancement by factor > 2 (2012)

15-in. RGBW panel using two-stacked white OLED and color filters for large-sized display applications

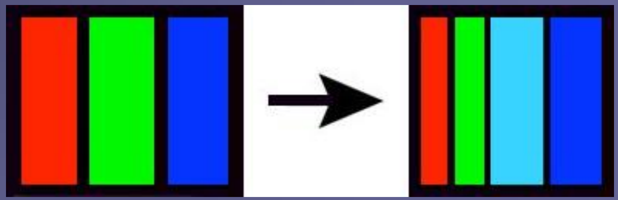
Chang-Wook Han, Yoon-Heung Tak, and Byung-Chul Ahn
LG Display Co., Ltd., OLED Technology Team, 1007 Deogeun-r, Wollong-myeon, Paju-si, Gyongki-do 413–811, Korea.

A 15-in. HD panel employing two-stacked WOLEDs and color filters for which the color gamut can be as high as 101.2% (CIE1976) and the power consumption is 5.22 W. The WOLEDs exhibit a current efficiency of 61.3 cd/A and a power efficiency of 30 lm/W at 1000 nits and their CIE coordinate is (0.340, 0.334). A 15-in. RGBW panel was investigated to verify the electrical and optical performance compared to that of a 15-in. RGB TV made by using FMM technology. The characteristics of the 15-in. RGBW panel are comparable tothose of the 15-in. RGB panel. Color filters combined with WOLEDs is a possible patterning technology for large-sized OLED TV, which surpasses the limits of fine-metal-mask technology.

Journal of the Society for Information Display -- February 2011 -- Volume 19, Issue 2, pp. 190-195

Structural Work-arounds

- White AMOLED with RGBW MCF
  - Kodak favored this approach
  - Made prototypes with Samsung
  - LG bought Kodak’s OLED business
- UDC two blue
  - Light blue for lifetime
  - Dark blue for gamut
    - Most colors can be realized with the light blue
    - Dark blue only used for colors that need it
      - So dark blue used much less than light blue
  - Blue lifetime is essentially the lifetime of the light blue phosphor



WHERE ARE WE NOW?

Suppliers

- Samsung Mobile Display (SMD)
  - Supplies 95% of all AMOLEDs today from Gen 4 fab
  - 3 million/month capacity (3-inch equiv.)
  - Severe shortage
    - Tablet displays not feasible from Gen 4
    - Several smart phones planned for AMOLED had to use AMLCD
  - Gen 5.5 scheduled for mid-year start-up
    - 30 million/month capacity (3-inch equiv.)
    - Tablet-sized displays part of mix
      - AMOLED Galaxy Tab scheduled for mid-year introduction
  - Front plane: linear source
  - Backplane: SLS LTPS

Suppliers (continued)

- LG Display
  - Gen 4.5 fab operating; prod-ready “in next few months”
  - LGD has just announced Gen 8
    - Production-ready at end of 2011
    - Ready to order equipment now (early March)
    - This is a VERY ambitious schedule
    - Will use Kodak color-by-white approach
- AUO
  - Volume production announced for H2’11
    - In part of former TMD (AFPD) Gen 4.5 LTPS plant in Singapore or Gen 3.5 LTPS plant in Taiwan
  - Start-up already delayed twice, but…

AUO to Make Additional Investment in Singapore-based AFPD

February 21, 2011 -- AUO continues to accelerate its AM-OLED LTPS production facility. According to reports AUO (AU Optronics) is expected to make additional investment of US$25 million in AFPD, a 100% wholly-own subsidiary of AUO in Singapore. The investment will be spent in acquiring and installing production equipment in support of the company’s planned move to volume production of AM-OLED displays.

Or maybe…

AUO to offer 3.5 inch AMOLED display and plans to recruit 3,000 engineers in Taiwan

AUO is back in to the OLED business, AUO offers at their website a 3.5 inch AMOLED Display. AUOs new 3.5 Gen AMOLED production line is ready in Q2 2011. The yearly capacity of this plant will be 70 million small displays (the plant can make 20K 680x880mm substrates a month). AUO plans to recruit 3,000 engineers in Taiwan this year to expand manpower for its display and solar technology businesses, AUO said Thursday.

The additional hires will be responsible for research, manufacturing, marketing and sales of AUO's display and solar products, which supports the company's work on low-carbon display technology like OLED and electronic papers,

Suspect

<u>Display specs</u>
Size: 3.5 inch
Resolution (pixel): 360 R.G.B x 640
Active Area (mm): 43.2 x 76.8
Pixel Pitch (mm): 0.120
Luminance (cd/m²): 300
Contrast Ratio >10,000 : 1
Production:2011 Q2

Suppliers (continued again)

- CMI
  - CMEL included in merger.
  - Status has not been clear, but…
  - CMI said recently that it will resume AMOLED activities
- Selected PM OLED makers
  - Tohoku Pioneer
  - RITDisplay
  - TDK

New Generations

- Gen 5.5 AMOLED fab costs about the same as Gen 8.5 AMLCD fab ($2.5B)
- SMD will build second, improved Gen 5.5 and about Gen 8
  - Needed for competitive AMOLED TV
- LGD building Gen 4.5
- Will skip Gen 5.5 and go directly to Gen 8

PREDICTIONS – SHORT TERM

Predictions – Short Term

- Gen 5.5 ramp-up will not go smoothly
  - Processing leaps too great
  - Yields will take time to come up
  - Shortages will last longer than predicted
- Product introductions – such as AMOLED Galaxy Tab – will be delayed until late 2011
  - Samsung Electronics is basing its projections on what SMD is telling them about panel availability

Prediction – Short Term

- Flexible AMOLEDs in commercial products
  - Not this year
  - Very nice prototypes but industry will be focused on getting production of Gen 5.5 glass products rolling

SMD 4.5-inch WVGA Flexible AMOLED

PREDICTIONS – LONGER TERM

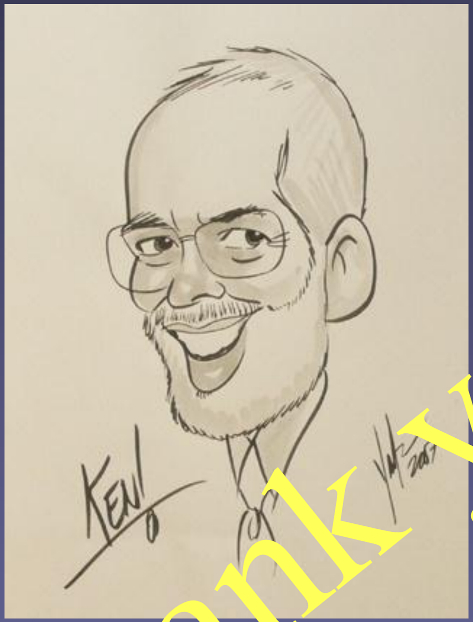
Predictions – Longer Term

- Small-screen TV at high but not ludicrous price
  - Late 2011/early 2012, probably from LG Electronics
  - Samsung OLED Galaxy Tab not far from a TV
- 32-inch TV
  - Gen 6 enabled practical 32-inch LCD-TV
  - Demonstrator late 2011 from LGE; panel from LGD Gen 5.5 plant
- Large-screen TV
  - We may see prototypes, but real products will have to wait for Gen 8
  - Need Gen 5.5 experience before building Gen 8; 18 months to build
- 600 million AMOLED cell phones by 2015
  - SS Kim (SMD) prediction at SID 2010 keynote
  - 2011: Gen 5.5 = 30M per month = 360M per year x 2 = 720M per year
  - Production will be there, market may not follow Kim's prediction

AMOLED Developers

- Principal developers
  - Samsung SMD (devices, manufacturing)
  - LG (materials, devices, manufacturing)
  - AUO (devices, manufacturing)
    - Volume production H2'11 in part of former TMD (AFPD) Gen 4.5 LTPS plant in Singapore and/or Gen 3.5 plant in Taiwan
  - Kodak (materials, process development)
    - Sold OLED business to LG December 2009
  - DuPont (materials, solution processing)
  - UDC (materials, device prototypes)
  - CDT (polymer materials, processing)
    - Sold to Sumitomo Chemical August 2007
  - CMI
    - CMEL included in merger. Status not clear.

Questions or comments?



Thank you!

Muito Obrigado!

(감사합니다)

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