A LOOK AT THE DISPLAY INDUSTRY, CIRCA 2016

Paul Semenza
psemenza@gmail.com

Display technology and market trends

The story up to now: race to invest in TFT capacity

- May have reached the end; apps with big area demand unclear

How the balance of power is shifting in displays

- Panel making remains high capex, low margin commodity biz

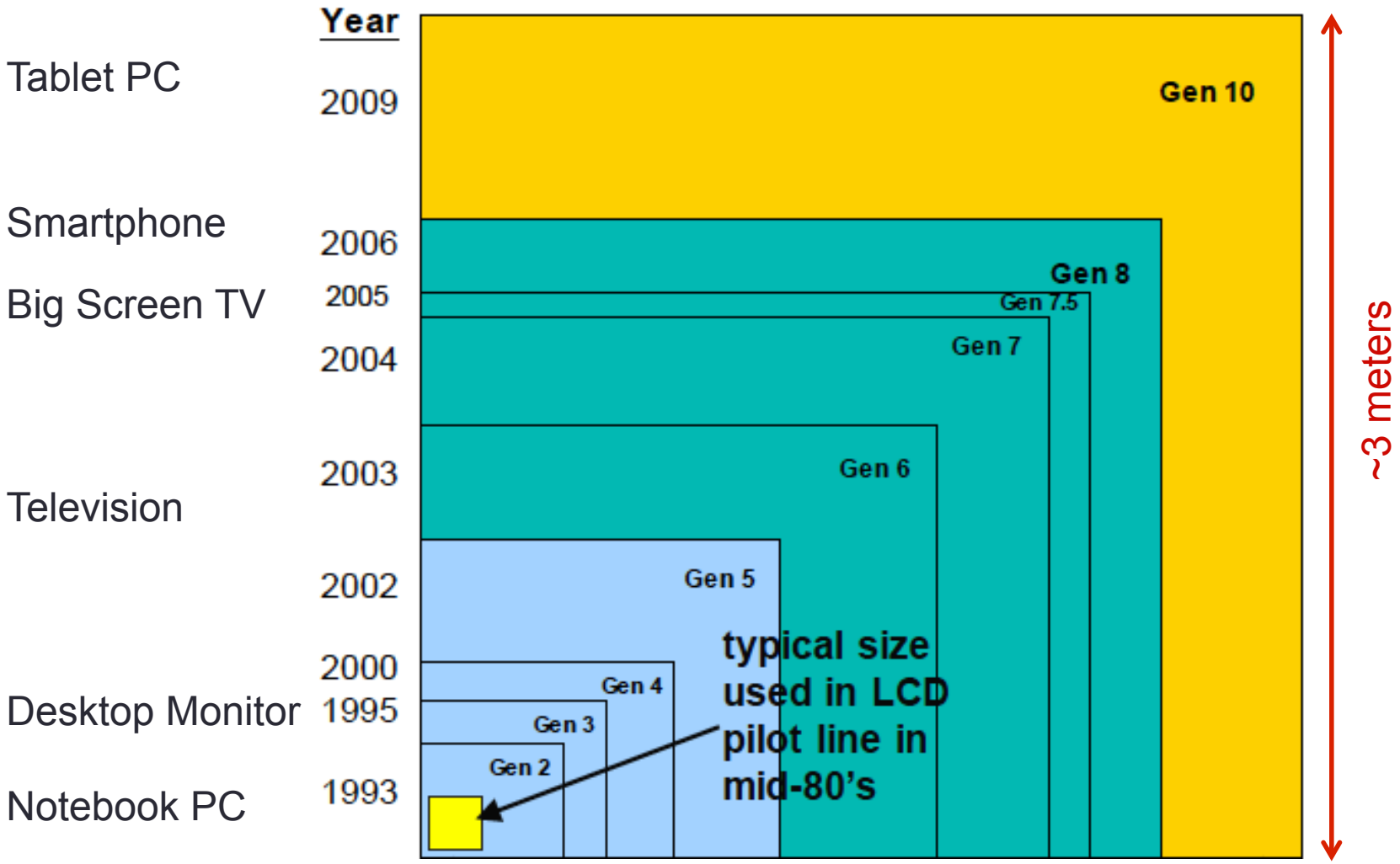
Possible ways to limit the commodity trap

- Performance, not size – but still need to fight TFT LCD

Are there other display technologies on the horizon?

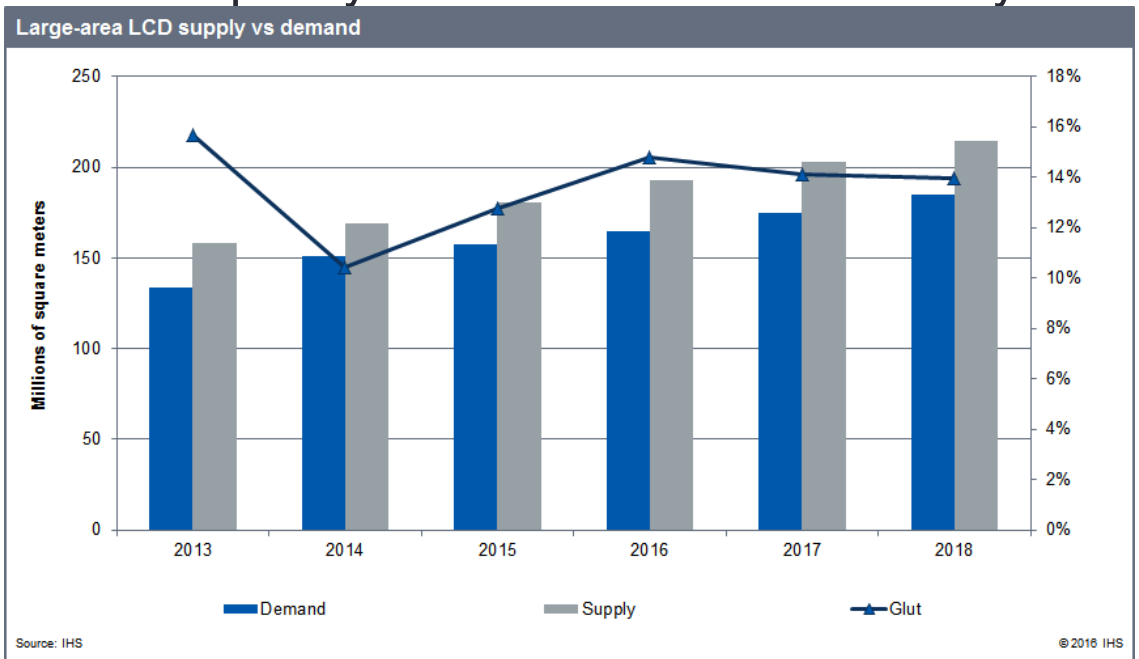
- History indicates it will take a long time

Two decades of investment competition



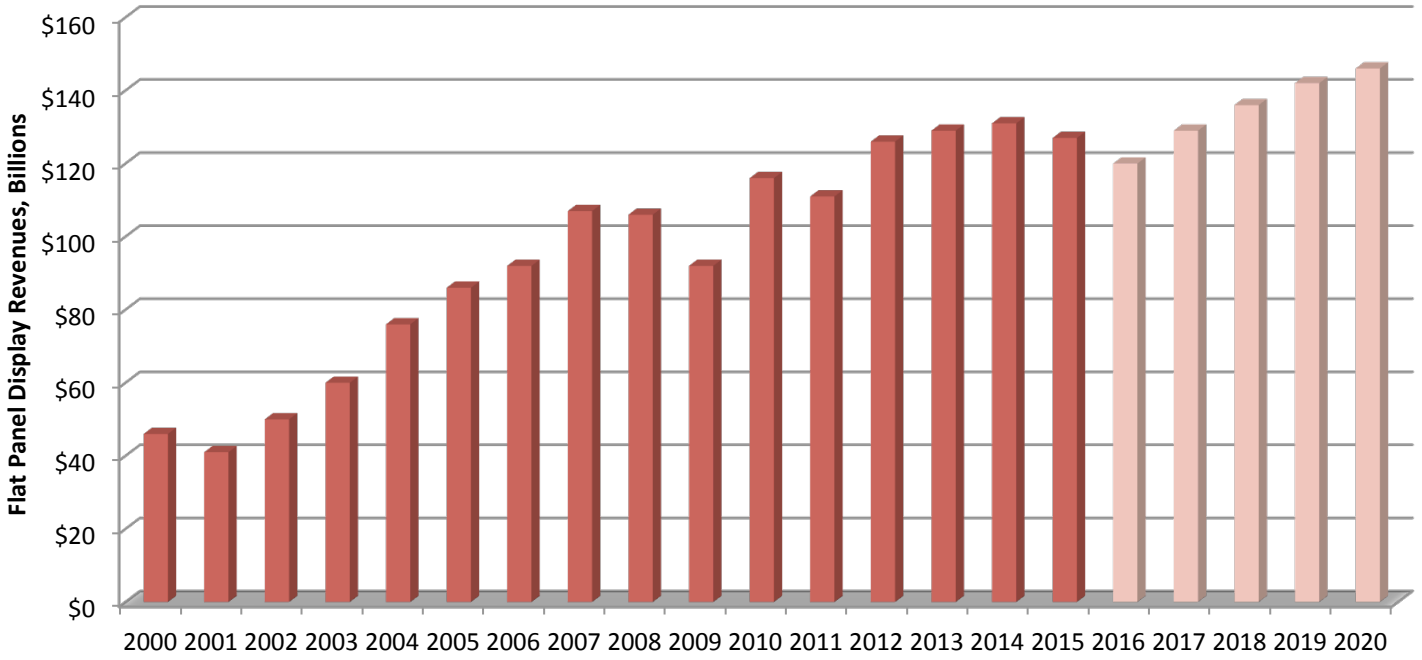
Production investments creates markets

- Fab investments enabled TFT LCD and AMOLED to broaden markets
  - Early 1990s – notebook PC – replaced EL, STN-LCD, CRT
  - Late 1990s – desktop monitor – replaced CRT
  - Early 2000s – TV – replaced CRT
  - Late 2000s – 40+" TVs – replaced PDP, RPTV
  - Late 2000s – smartphones – replaced lower resolution LCD
  - Early 2010s – tablet PC – no previous display technology
- But race to build capacity means that there is usually oversupply



But sustainable growth is a challenge

- Market creation ultimately involved cannibalization
  - Notebook PCs cannibalized desktops, tablet PCs cannibalized notebooks
  - Smartphones cannibalized other mobile devices (DSC, GPS, MP3...)
- Replacement markets quickly saturated due to limited “slots”
  - Monitors, TVs
- A decade of little growth



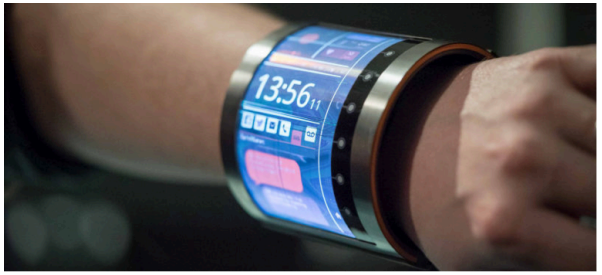
Source: IHS

Future applications: limited area demand

- Automotive
  - Opportunity for flexible, custom shapes and designs
  - Higher performance requirements than IT or CE applications
  - Much longer design cycles and operating lifetimes
  - Increasing automation of vehicles is both opportunity and challenge
    - More emphasis on information display, entertainment, communication
    - Fewer cars?

Tesla

- Body-Worn
  - Smart watch extensions: bracelets, clothing
    - Flexible, light weight
  - Near-eye
    - Always in the future?



Flex Enable

Sony

Display technology and market trends

The story up to now: race to invest in TFT capacity

- May have reached the end; apps with big area demand unclear

How the balance of power is shifting in displays

- Panel making remains high capex, low margin commodity biz

Possible ways to limit the commodity trap

- Performance, not size – but still need to fight TFT LCD

Are there other display technologies on the horizon?

- History indicates it will take a long time

Ongoing Power Shift in Display Industry

TFT LCD remains a capital intensive yet low margin assembly business

Panel Makers

Japan

- Nearly out of the large panel business
- LTPS, OLED consolidation ongoing
- Future of supply chain unclear

Korea

- Samsung, LG leaders in vertical integration
- Supply chain still dependent on Japan, U.S.
- Constant issue of investment in China

Taiwan

- AUO, Innolux continue to struggle financially
- All future investment in China

China

- Is very close to catching up – then what?

Key Value Chain Players

Apple: upstream vertical integration

- Continued investment in display R&D (organic and acquisition)
- Steps toward production (consignment of supplier lines, Taiwan fab)

Hon Hai/Foxconn: investment in critical component

Global technology suppliers: Corning, Merck, AMAT

- Continue to make significantly better margins than panel makers

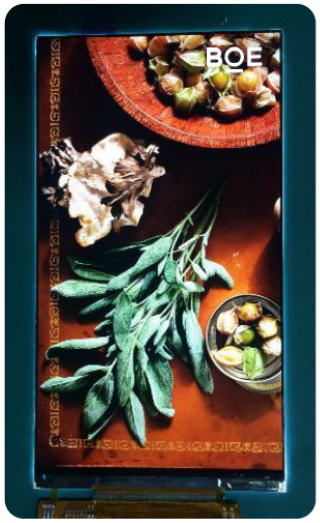
Key is defensible IP/production processes, brands, access to markets

Chinese panel makers catching up

110” 8K4K

4.7 UHD LTPS 941 ppi

5.5 UHD LTPS 800+ ppi



5.5 FHD 100% NTSC

BOE talking about avoiding commoditization by moving up performance curve, not down price curve

Display technology and market trends

The story up to now: race to invest in TFT capacity

- May have reached the end; apps with big area demand unclear

How the balance of power is shifting in displays

- Panel making remains high capex, low margin commodity biz

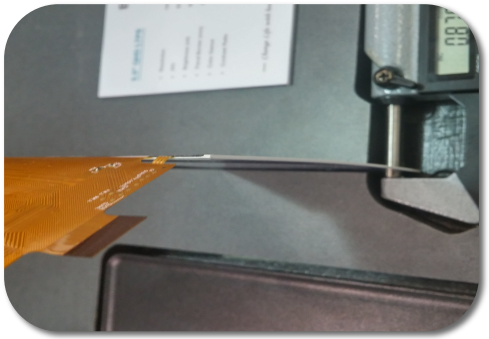
Possible ways to limit the commodity trap

- Performance, not size – but still need to fight TFT LCD

Are there other display technologies on the horizon?

- History indicates it will take a long time

Less about size, more on performance



Thinner

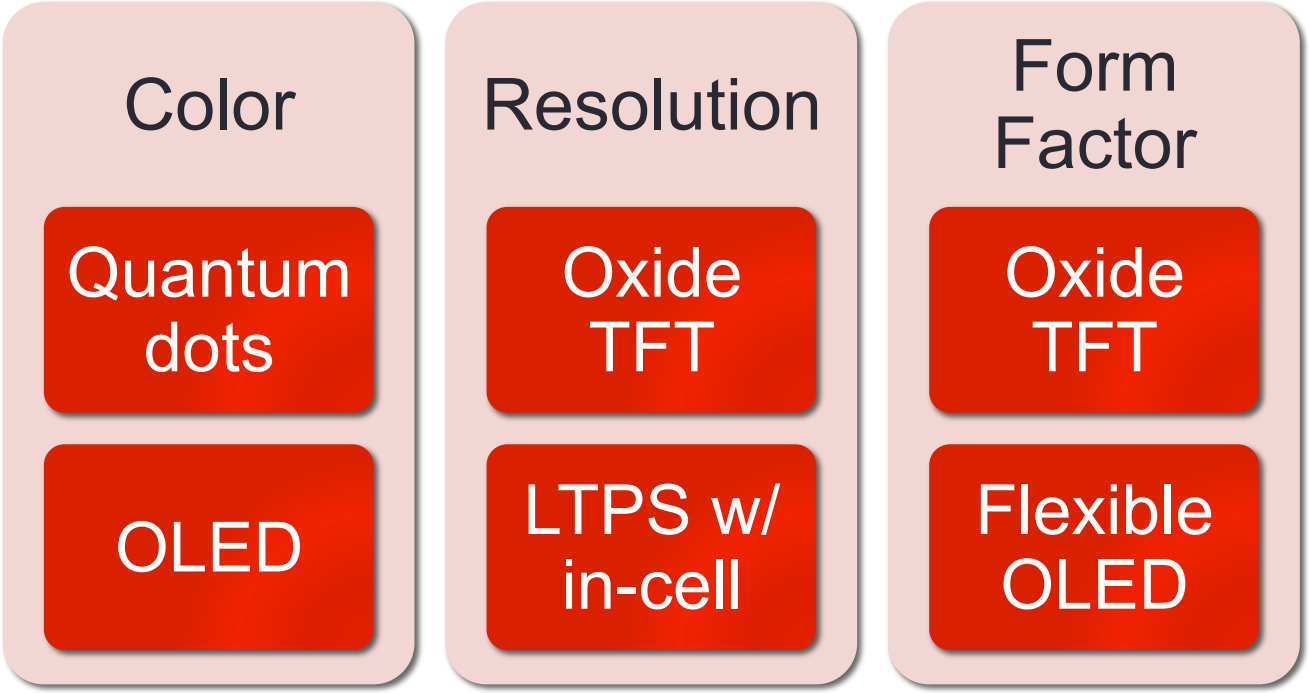
Flexible

Non-rectangular

Wider Color Gamut

Higher Resolution

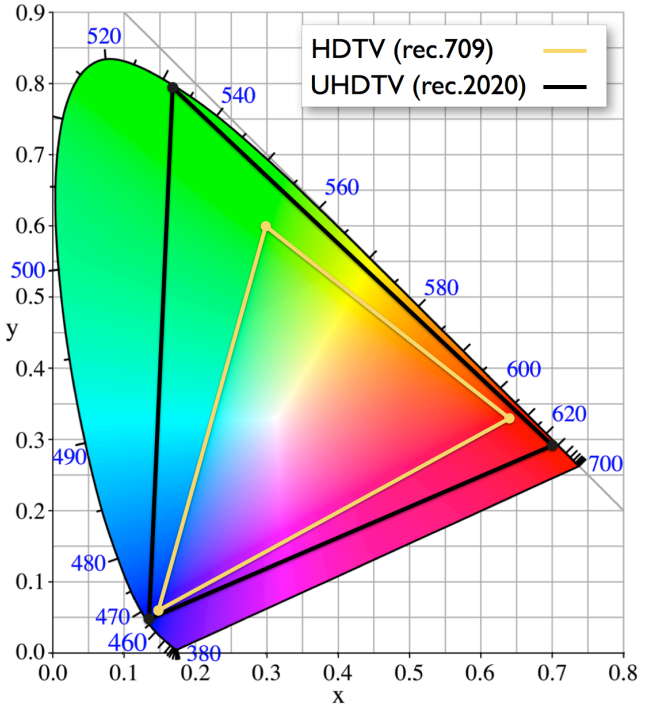
Ways to get to better performance



High levels of activity (papers, demos) around QD and oxide

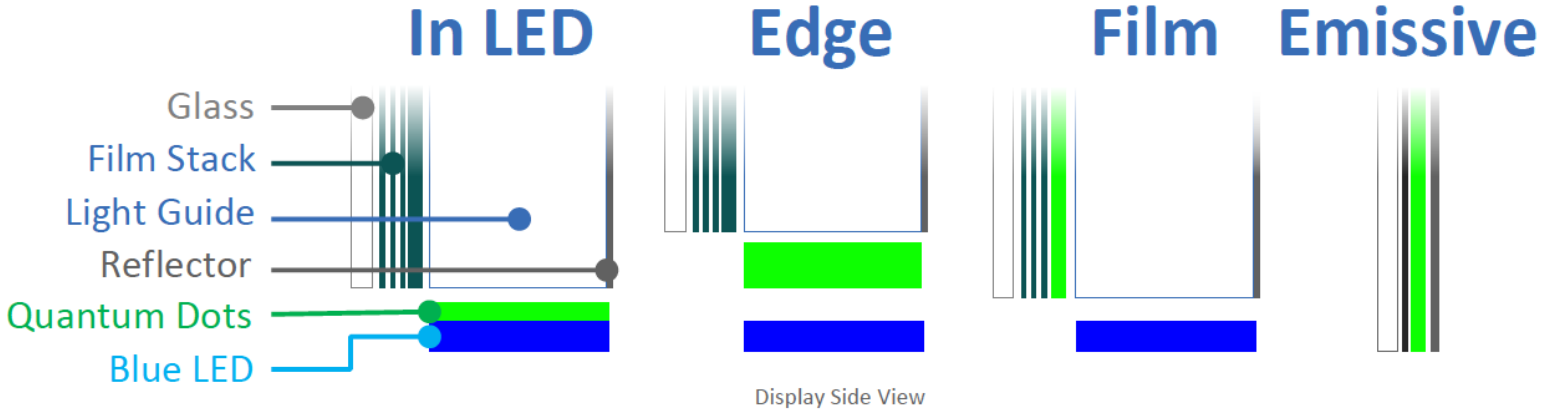
Quantum dots

Rec. 2020 represents an expansion in color gamut, which quantum dots are well-positioned to make happen – soon!



UHDTV vs HDTV Color Gamuts

Multiple ways QDs can impact the LCD stack



Jason Hartlove, Nanosys, SID 2015 Investors Conference

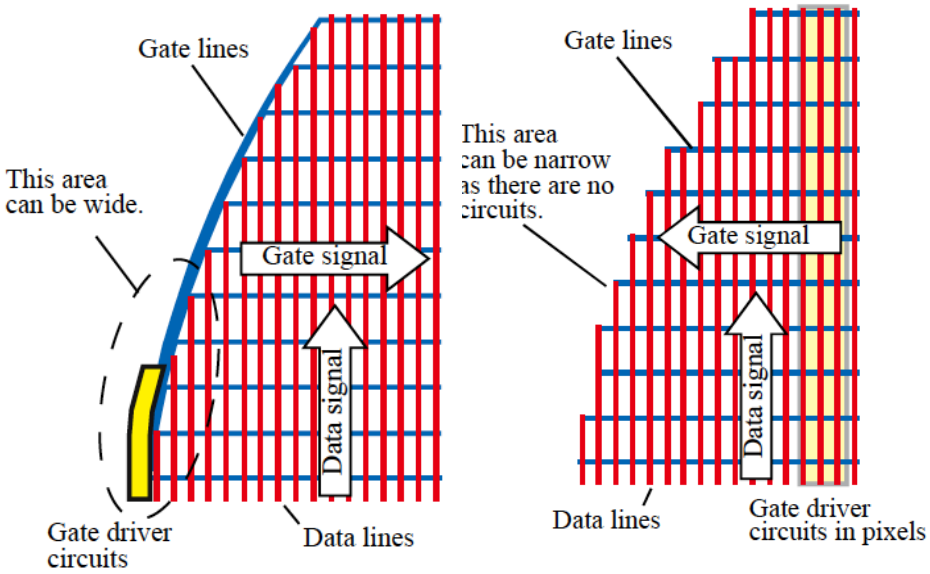
Why oxide

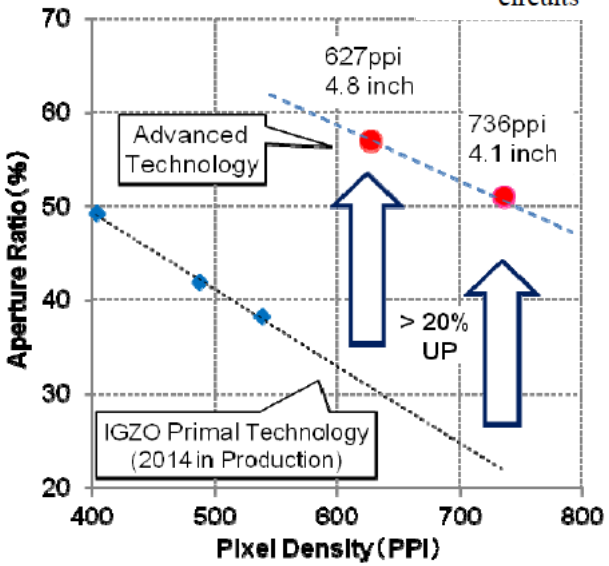
TFT characteristics	a-Si	oxide	LTPS
Mobility ($cm^2/V\text{-}s$)	<1	1-30	30-100
Uniformity	good	good	ok
Reliability	poor	good	good
V_{th} shift	>30	<1	<0.5
Mask steps	4 - 6 (7 for OLED)	4 - 6	5 - 9
Pixel circuit (OLED)	4T + 2C	2T + 1C	5T + 2C
Process temp (°C)	150 - 350	450	250 - 550
Generation	>10	8.5	6.5 - 8.5
Cost/Yield	low/high	low/high	high/low

Adapted from Toshio Kamiya, Short Course S-3, SID 2015

Why oxide

High mobility enables integration of gate drivers, eliminating bezel





Good aperture ratio at very high resolution, enabled by high transparency

Sharp, SID 2015 (59.1, 63.1)

OLED + oxide

18 inch WXGA AMOLED (IGZO)
0.18 mm thick; bend radius: 30 mm

LGD SID 2015 (65.1)

13.3 inch 8K (664 ppi) using CAAC-IGZO

Advanced Film Device/Semiconductor Energy Laboratory SID 2015 (63.3)

But a-Si, LTPS not slowing down

3.5 inch VGA a-Si AHVA LCD on plastic

AUO SID 2015 (9.3)

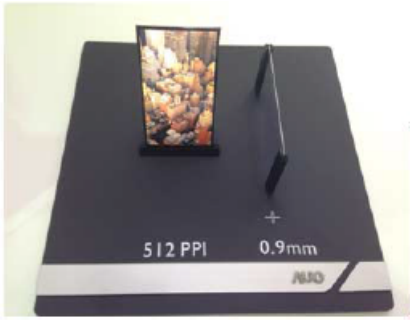
55 inch 8K (7680x4320) 120 Hz a-Si IPS

Panasonic SID 2015 (72.1)

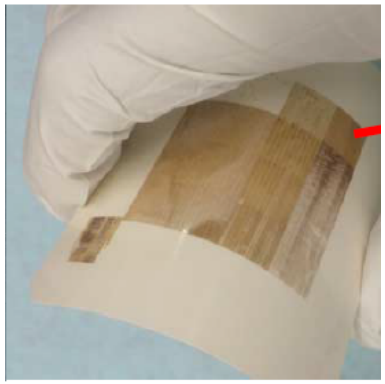
8 inch 4K, in-cell touch

JDI SID 2015 (63.2)

4.3 inch FHD LTPS, 0.9 mm thick



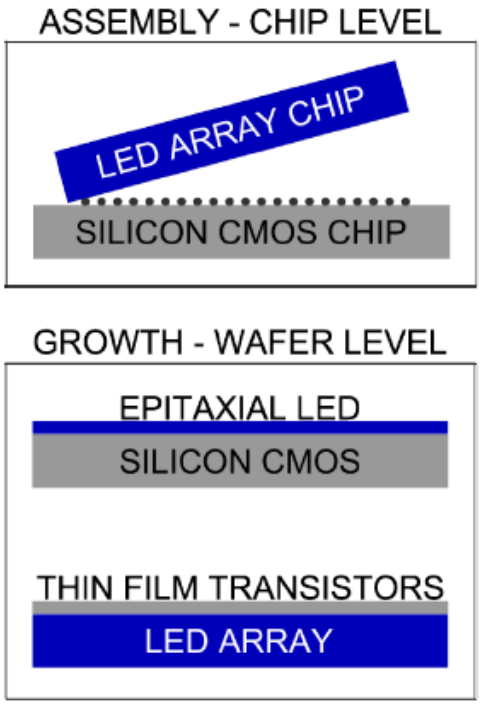
AUO SID 2015 (4.3)



Polysilicon TFTs produced at 150°C w/liquid silicon ink

Delft U of Technology, JAIST SID 2015 (29.1)

Integrating micro LEDs and TFTs

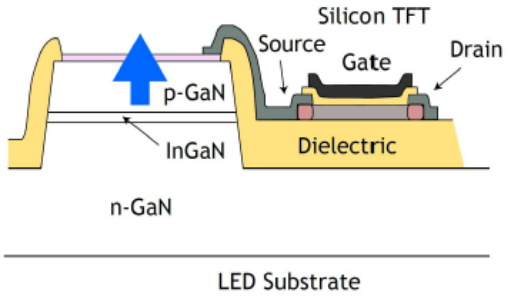


Wafer bonding/ flip-chip: limited density

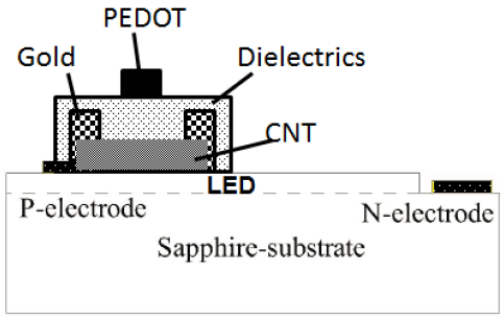
Build LED array, deposit a-Si thin film, laser crystallize to form TFTs

Print SWCNT TFT backplane on top of LED array

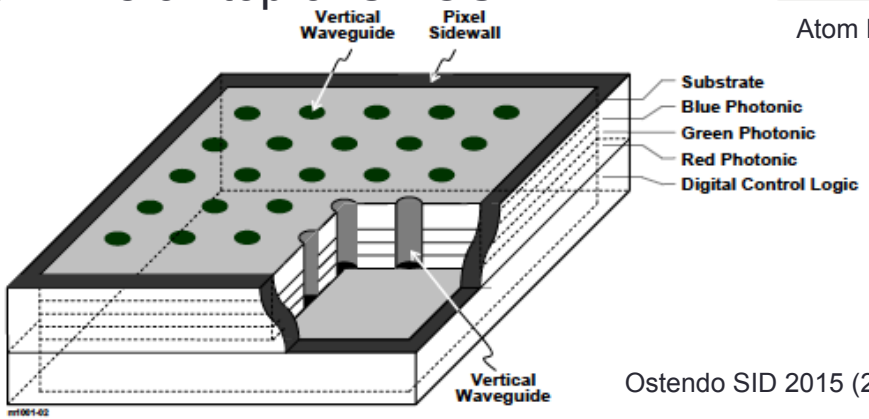
Build 3D stack of red, green, blue LEDs on top of CMOS



Lumiode SID 2015 (26.2)



Atom Nanoelectronics SID 2015 (P-151)



Ostendo SID 2015 (26.1)

Display technology and market trends

The story up to now: race to invest in TFT capacity

- May have reached the end; apps with big area demand unclear

How the balance of power is shifting in displays

- Panel making remains high capex, low margin commodity biz

Possible ways to limit the commodity trap

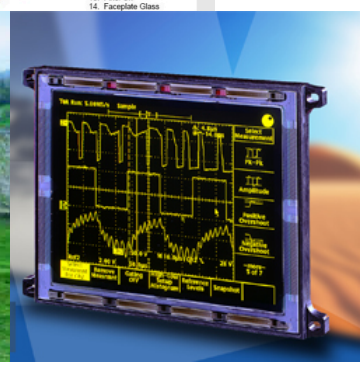
- Performance, not size – but still need to fight TFT LCD

Are there other display technologies on the horizon?

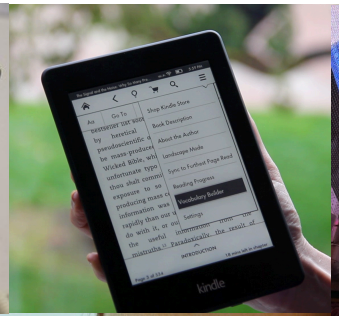
- History indicates it will take a long time

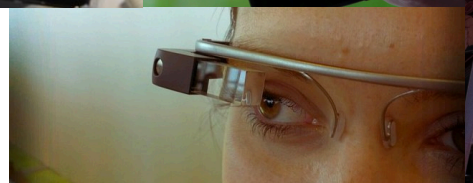
TFT: display technology monoculture?

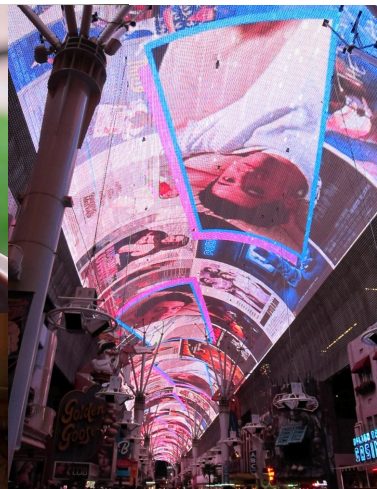
- Many technologies have been vanquished by TFT LCD:
  - MEMS (Qualcomm)
  - PDP (Panasonic, Pioneer)
  - FED (Candescent, Sony)
  - PALC (Sharp)
  - EL (Planar, Sharp)
  - CRT (many)



- While a few have figured out how to coexist with TFT LCD:
  - OLED – mobile, TV
  - EPD – readers, indicators
  - LED – public display
  - DLP – projection
  - “x” on Si – near-eye

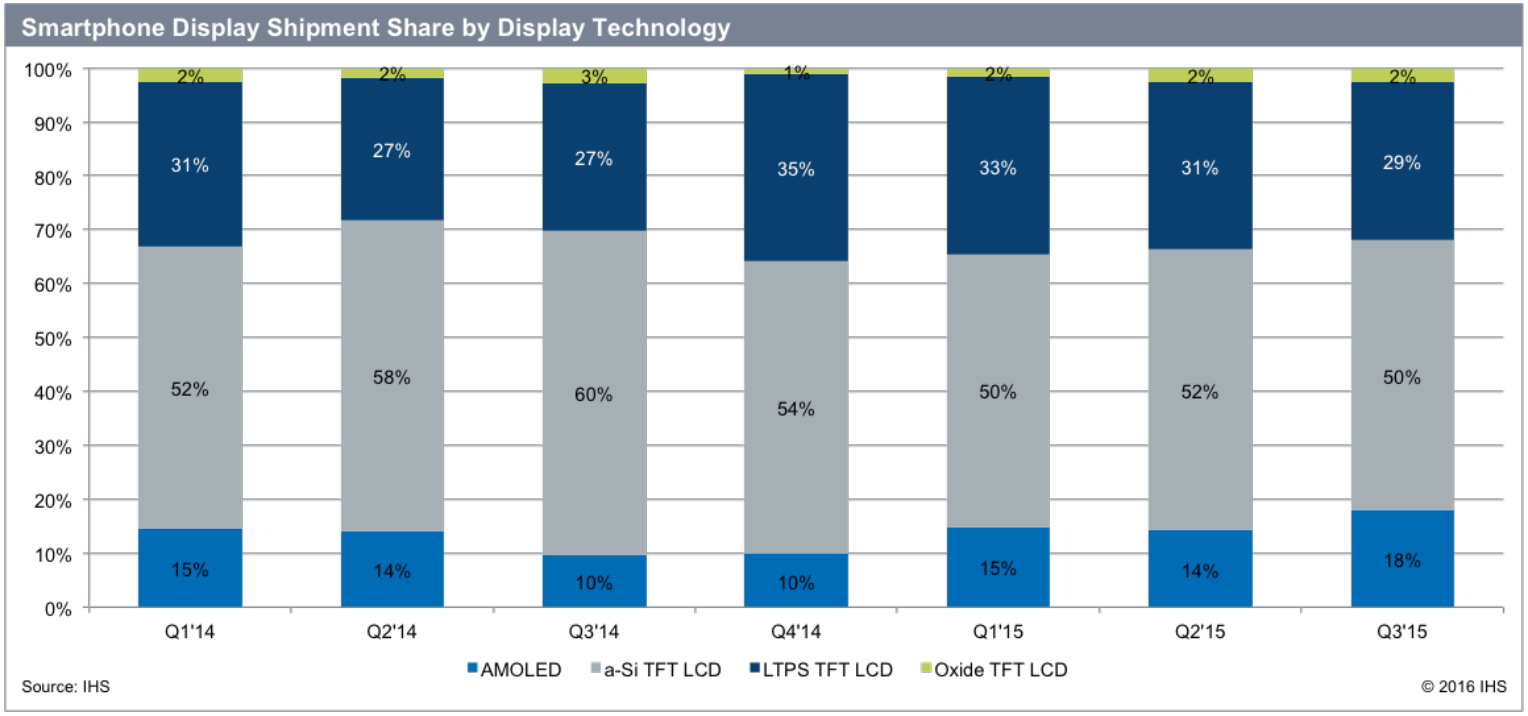






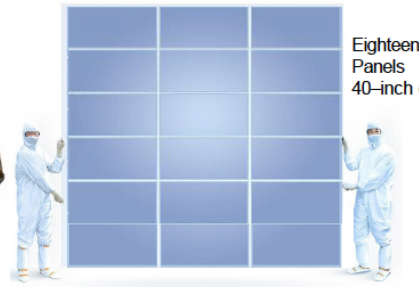
Technology diversity in smartphones

- High volumes, complex product mix
- Emphasis on performance: resolution, power consumption, thickness
- Requirement for touch integration
- All of these technologies use a combination of 3 backplanes and 2 media

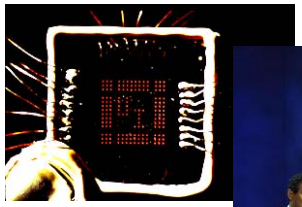


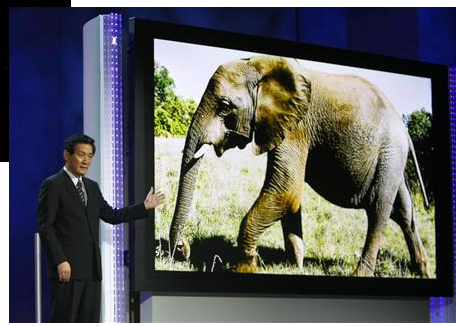
Display technologies take a long time!

- TFT-LCD
  - First working device: 1962
  - First demonstration: 1971
  - First production: 1983
  - Mass production: 1990



- Plasma
  - First demonstration: 1964
  - Mass production of large color displays: 1997
  - Peak of production: 2006





- OLED
  - Conductive organic polymers developed: 1977
  - First OLED devices: 1987
  - First production (PM): 1997
  - First full color (AM) production: 2007

E Ink rapidly commercialized technology

- Electrophoretic displays: from idea to manufacturing within a decade
  - mid 1990s inception
  - 2004: first ebook reader

- In part, this was due to focus
  - Experiment with technologies (flexible displays, OTFTs, color)… but keep focus on core technology that can use existing ecosystem (EPD film, integrated with existing TFT backplanes on glass)
  - This meant looking at what was deliverable soon (low power, high readability, light weight) vs. in the future (flexibility)

Flexible displays need ecosystem change

- Manufacturing
  - Change in materials, handling, deposition
  - Need for encapsulation for plastic, organic materials
  - Potential switch from batch to roll-to-roll processes
- Application
  - Will existing applications value lighter weight, thinner, more rugged devices?
    - Phones, smartwatches
  - Can new applications be created based on flexibility?
- Complementary technologies
  - What about the rest of the device?

Display technology and market trends

The story up to now: race to invest in TFT capacity

- May have reached the end; apps with big area demand unclear

How the balance of power is shifting in displays

- Panel making remains high capex, low margin commodity biz

Possible ways to limit the commodity trap

- Performance, not size – but still need to fight TFT LCD

Are there other display technologies on the horizon?

- History indicates it will take a long time

Summary: where the industry is today

- Display industry is in the midst of the latest down cycle, due to the lack of a new wave of application growth
- In each downturn, there is a culling of players and technologies
  - With the exit of most Japanese firms, consolidation and weakness in Taiwan, there are now a few major display suppliers – although Chinese producers are rising
  - The display technology race is now dominated by a few types of TFTs combined with LCD or OLED
- Key materials and equipment providers continue to be more profitable than panel makers
- Increasing vertical integration from a few key players

Where to look for impact

- Materials, equipment, processes
  - Sell picks and shovels – don't mine
- Develop technologies to support higher performance
  - Resolution, color, processing
- Investing in new display technologies requires patience
  - Creating an entire new ecosystem is a rare event
- But niches can develop more quickly
  - Focus on providing benefits, not technology

THANK YOU

psemenza@gmail.com