Current Flexible AMOLED Technologies and Future Prospects

Hye Dong Kim (Ph. D)

2019. 11. 08

Contents

Background

- **Developed AMOLED Panels**

[55" AMOLED TV 2012]

[55" Mirrored AMOLED 2014]

[55" Transparent AMOLED 2014]

[30“ 4K Monitor 2014]

[Flexible AMOLED 2008]

[50um AMOLED 2007]

[AMOLED Card 2007]

[Foldable OLED 2007]

[3.6” AMOLED 2001]

[Both Emission AMOLED 2002]

[15.5” AMOLED 2003]

Contents

Rigid AMOLED Processes

Back Plane

Poly Si

⇩

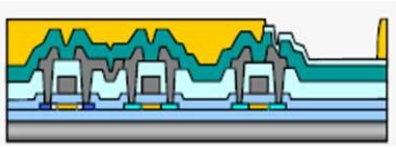
Gate

⇩

Source/Drain

⇩

Pixel



Top Gate LTPS TFT

EVEN

⇩

TFT Glass

⇩

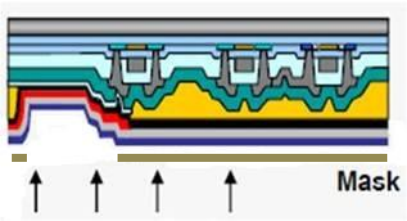
Evaporation | Encap Glass

⇩

Glass Seal

⇩

Cell Seal (laser)



FMM patterned OLED

Cell

⇩

Slim Etching

⇩

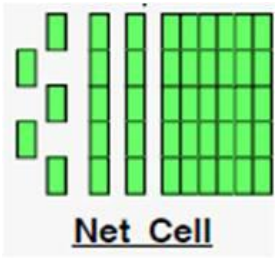
Inspection

⇩

Curing

⇩

Cell Cutting



Module

⇩

COG

⇩ chip-on-glass

Polarizer

⇩

FOG

⇩ flex-on-glass

Assembly

⇩

Shipment

EV: Evaporation, EN: Encapsulation

Reference: J. Choi, SDC Lecture (2012)

How to make flexible OLEDs?

Materials

- Substrate : Glass → Film
- TFT: Inorganic → Organic ?

Process

- Photo/Vacuum → Direct Printing ?

	Rigid	Flexible	
Material	- Semiconductor (Si, Oxide) - Insulators (SiO_2, SiN_x) - Electrodes (Metal / ITO) - OLED - Glass / Wafer	- Semiconductor (OTFT) - Insulators (Organic Insulator) - Electrodes (→ / Graphene..) - → - Flexible film	Performance Issue
Process	**Vacuum base** - Thin film Deposition - Photolithography - High temperature	**Air ambient base** - Direct Printing - Roll to Roll - Low temperature	Accuracy Issue

Hybrid Process
(Conventional + Printing)

Selected Flexible Processes for Mobile Application

Process Selections

	Rigid	Flexible (R&D)	Flexible (Product)
Substrate	Glass	Metal Foil PI coating & De-lamination	**PI coating &** **Detaching**
TFT	LTPS TFT Oxide TFT	LTPS TFT Oxide TFT Organic TFT Nano-wire TFT	**LTPS TFT**
OLED	Fine Metal Mask Patterning Laser Induced Thermal Imaging	FMM LITI WOLED Inkjet Printing Nozzle Printing	**FMM**
Encapsulation	Cell Seal	Barrier film Thin Film Encapsulation	**Thin Film Encapsulation**
Module	Glass Module	Film Module	**Film Module**

Candidates for Flexible Substrates

Requirements

- High Temperature durability - Chemical resistance - Low permeability of H_2O / O_2

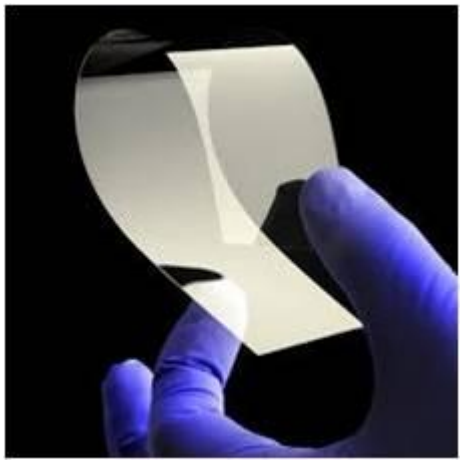
	Temp.	Available TFTs	Pros	Cons
Ultra-Thin Glass	~550°C	a-Si, Oxide, LTPS	Low moisture permeability High chemical resistance	Fragile
Metal Foil	~450°C	a-Si, Oxide, LTPS	Low moisture permeability No Gas Barrier	Rough surface Weak to chemical Opaque High CTE
Polyimide	350~400°C	a-Si, Oxide, LTPS	Chemical stability Low CTE (<7ppm/°C) (Borosilicate Glass ~3ppm/°C) High flatness	High H_2O absorption
FRP (Fiber reinforced Plastic)	~350°C	a-Si, Oxide, LTPS	High chemical resistance	Opaque Retardation
Glass –Polymer composite	~380C	a-Si, Oxide, LTPS	Low CTE High chemical resistance	Colored (Yellow) Haze

Reference: IHS, NH Investment & Securities Co. Research Center

Flexible Substrate: Thin Glass

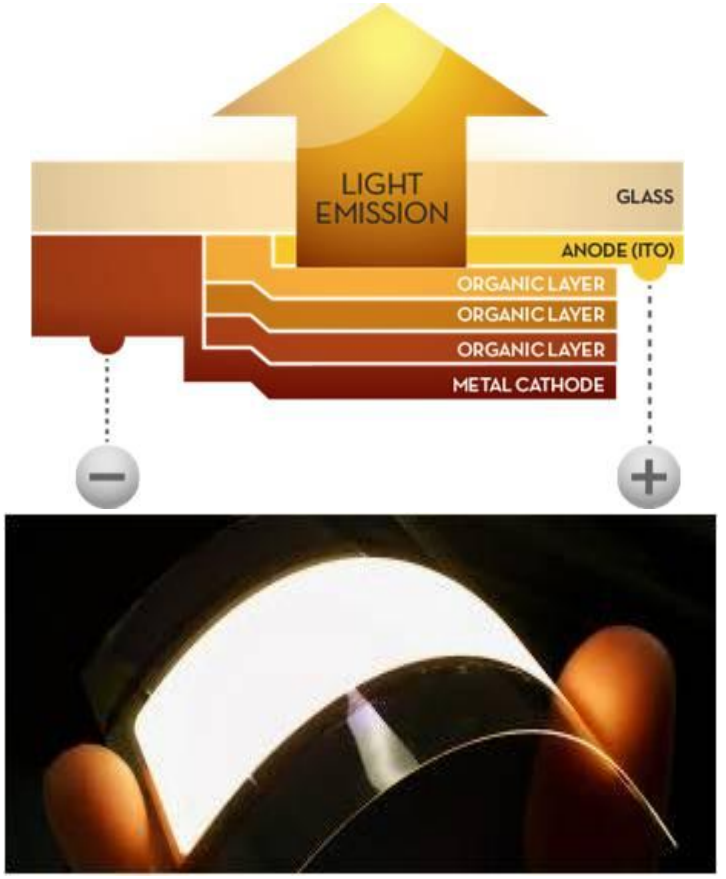
Strength

- No barrier film
- Hardness of the surface
- Transparency



Source: Corning

Source: Fraunhofer



Source: Corning , OLEDWorks

Weakness

- Accuracy of patterning
- Limitation of bending radius
- Difficult to handle in MP
- Adhesives development for high temperature

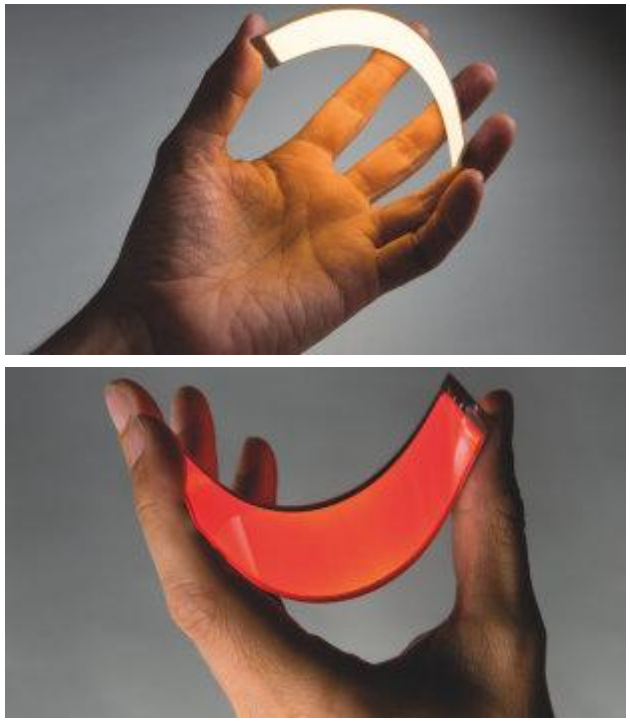
Flexible Substrate: Metal Film

Strength

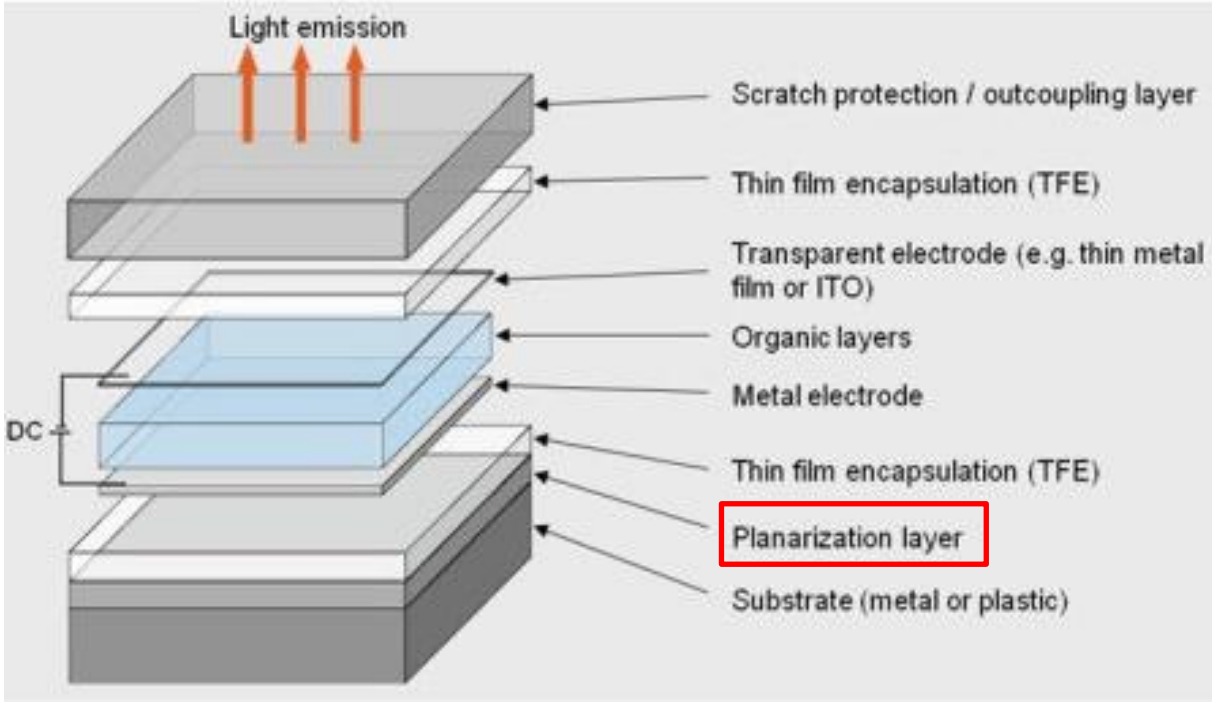
- Excellent gas barrier
- Good heat dissipation
- Shield static electricity
- Magnetic attachment

Weakness

- Limitation of bending radius
- Top-emission structure only
- CTE mismatch between metal and glass
- Surface roughness

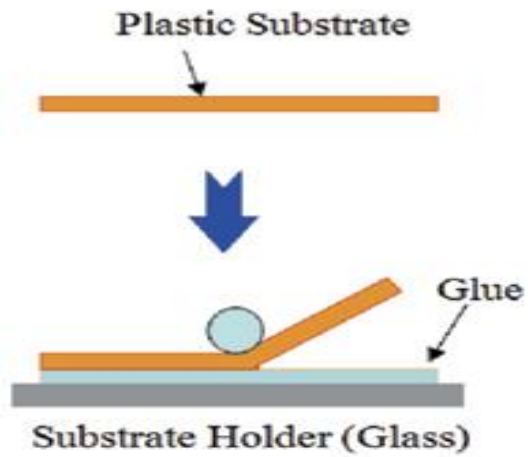


Source: Osram



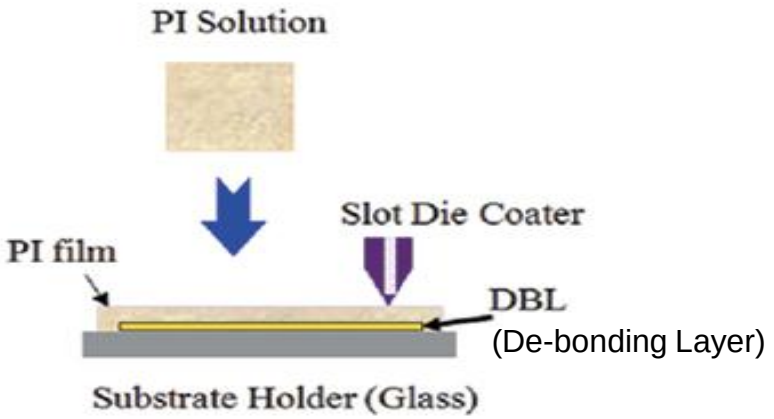
Flexible Substrate: PI film

PI film lamination



- **Lamination Issues**
  - Film flatness
  - Impurity management (Vacuum Lamination)
  - Need new adhesive

PI solution coating



Source: ITRI, SID Information Display 2011, Feb.

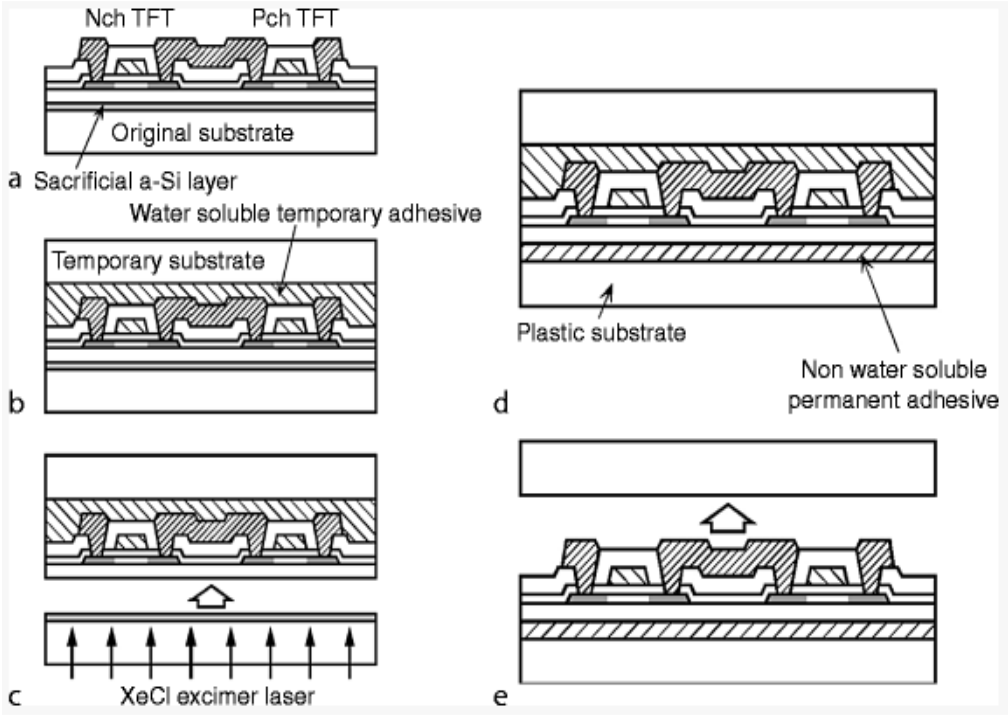
- **Strength**
  - Impurity management (no air trap)
  - Film flatness (High resolution capability)
  - No admissive
- **Weakness**
  - Unrecyclable carrier glass
  - Need barrier film

Flexible AMOLED Concepts

SDC's Flexible AMOLED Concepts

- **PI / Sacrificial a-Si layer / Oxide TFT / RGB / TFE → Laser left off**

Samsung First Flexible AMOLED
SID 2009 Best Pater Award

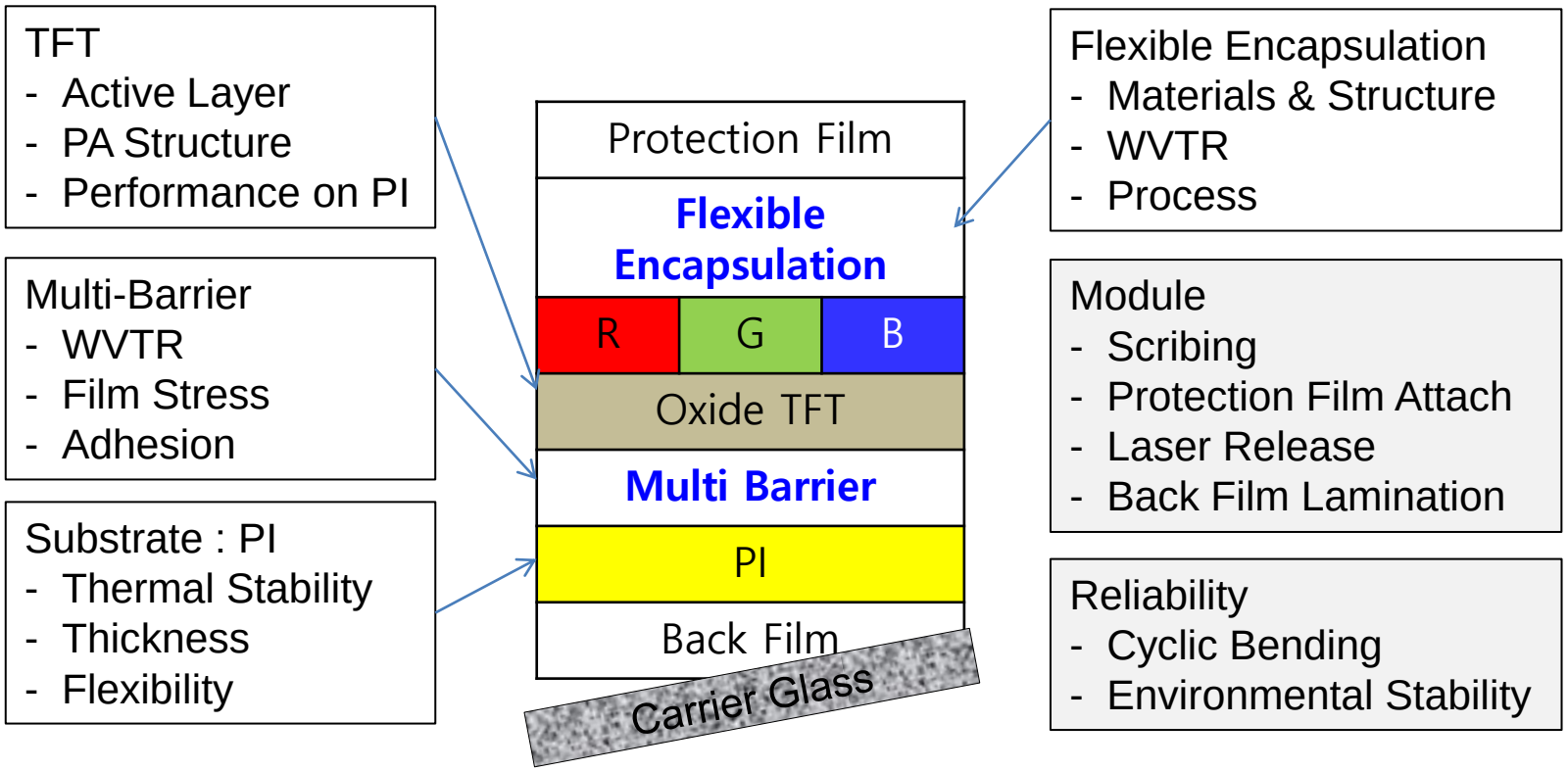


Source: Mo YG, Kim M, Kang CK, Jeong JH, Park YS, Choi CG, Kim HD, Kim SS (2010) Amorphous oxide TFT backplane for large size AMOLED TVs. SID '10 Dig 41(1):1037–1040

Flexible AMOLED Concepts

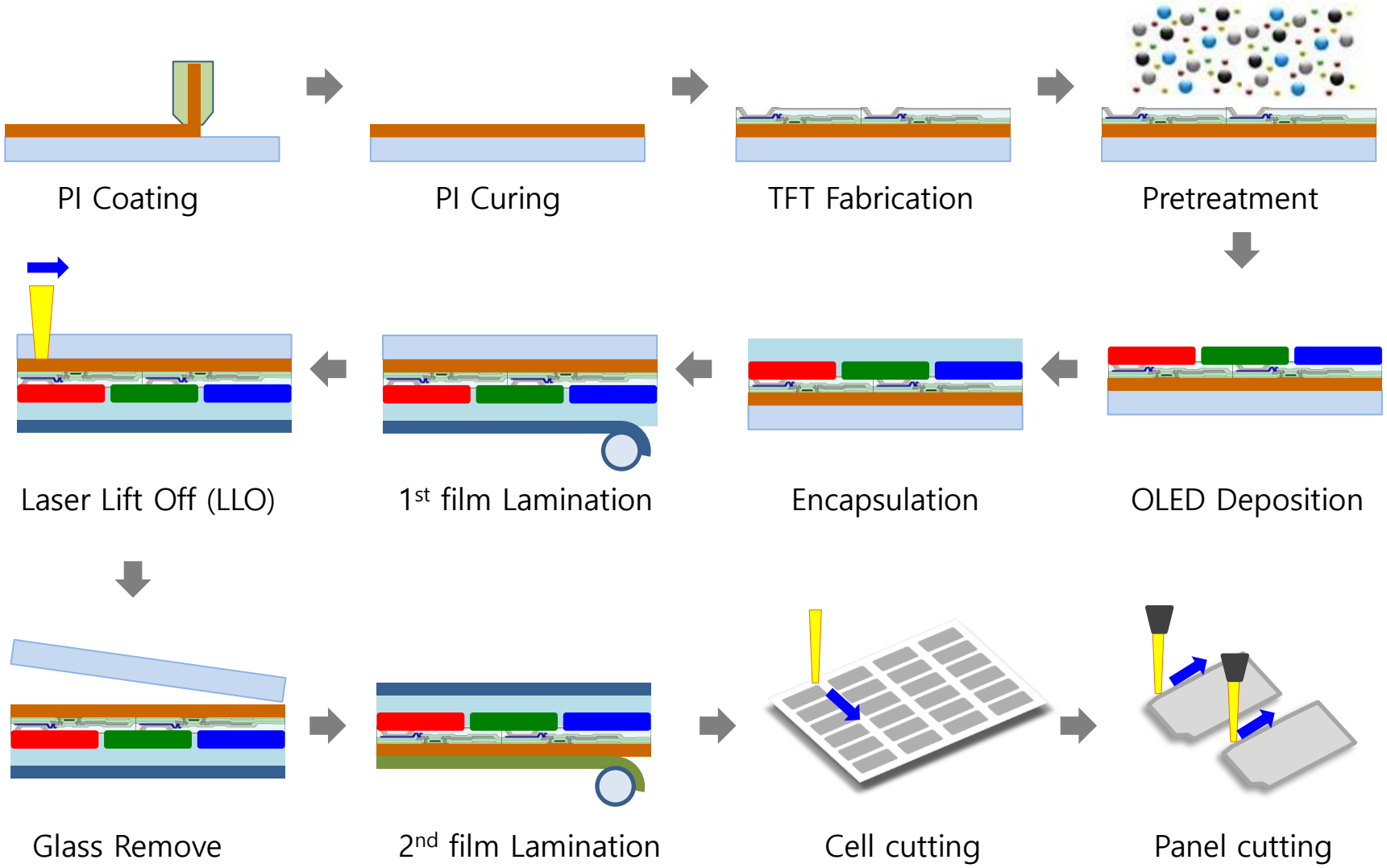
LGD's Flexible AMOLED Concepts & Issues

- **PI / Oxide TFT / WOLED / CF / Flexible encapsulation → Laser left off**



Source: LG Display, IMID 2015

Flexible AMOLED Panel __ Process Sequence

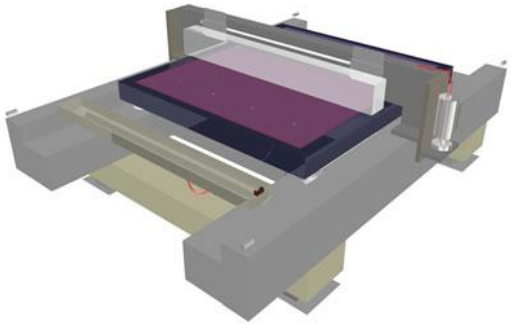


Source: Philoptics IR

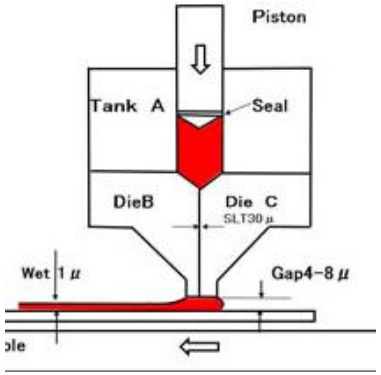
Flexible AMOLED Process __ PI Substrate

PI Slit Coating

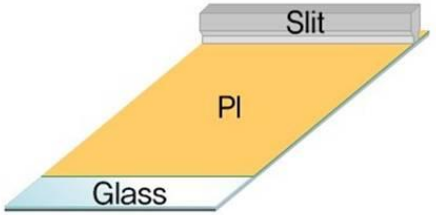
- High viscosity → Uniformity
- Process Impurities → Big Defect



Source: Toray



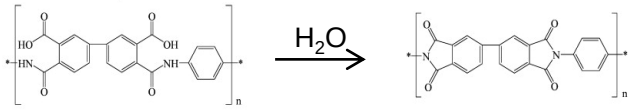
Source: Die-Gate Co



Source: LGD, http://lgdnewsroom.com

PI Curing

- Thermal imidization over 400°C (t: 10~20um)



- Remove the solvent (out gas)
- Curing temperature profile

Source: TERA Curing

Flexible AMOLED Process __ PI barrier coating

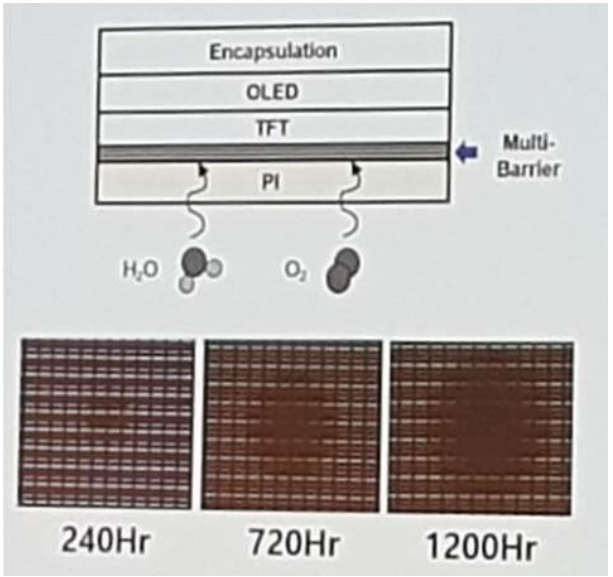
Barrier Film Coating

- Required WVTR* & OTR for OLED
  - H_20: $<10^{-6}$ g/m^2 /day, O_2: $<10^{-3}$ cc/m^2 /day
- Inorganic Barriers are coated by CVD or ALD
- Adhesion
- Stress control

*WVTR: Water Vapor Transmission Rate
OTR: Oxygen Transmission Rate

POLYMER	WVTR[a] (g/m^2/day) (37.8-40°C)	OTR[c] (cm^3 (STP)/m^2/day) (20-23°C)
Polyethylene	1.2-5.9	70-550
Polypropylene (PP)	1.5-5.9	93-300
Polystyrene (PS)	7.9-40	200-540
Poly(ethylene terephthalate) (PET)	3.9-17	1.8-7.7
Poly(ethersulfone) (PES)	14[b]	0.04[b]
PEN	7.3[b]	3.0[b]
Polyimide	0.4-21	0.04-17
15nm Al/ PET	0.18	0.2-2.9
SiO_x/PET		0.007-0.03
ORMOCER/PET		0.07

Semicond. Sci. Technol. 26, 034001 (2011)



Source: LGD SID2018

Flexible AMOLED Process __ TFTs

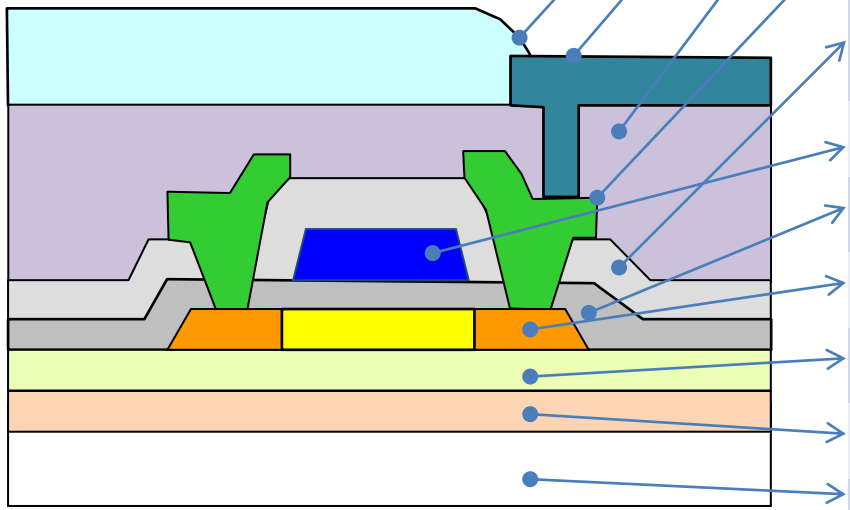
Comparison of TFTs

	a-Si TFT	LTPS TFT	Oxide TFT
Mobility (cm^2/Vs)	~1	100~150	10~60
SS (S, V/dec)	0.4~0.5	0.2~0.3	0.1~0.2
Structure	Bottom Gate	Top Gate	Top Gate
Mode	NMOS	PMOS / CMOS	NMOS
I_{off} (A)	$\sim 10^{-12}$	$\sim 10^{-11}$	$\sim 10^{-13}$
Reliability	Bad	Excellent	Good
Process Temp. (°C)	150~300	400~450	150~350
High Resolution	Bad	Excellent	Fair
Cost	Low	High	Medium
Scalability	Gen11	Gen8	Gen11
Process	Photolithography PECVD Sputter Dry Etcher	Photolithography PECVD Sputter Dry Etcher Laser Implanter Furnace	Photolithography PECVD Sputter Dry Etcher Furnace

Flexible AMOLED Process __ TFTs

Key Issues of TFT fabrication on PI

- Lower process temperature
  → Circuit design for flexible
- ELA damage on PI
  → Defect control
- PI water permeability

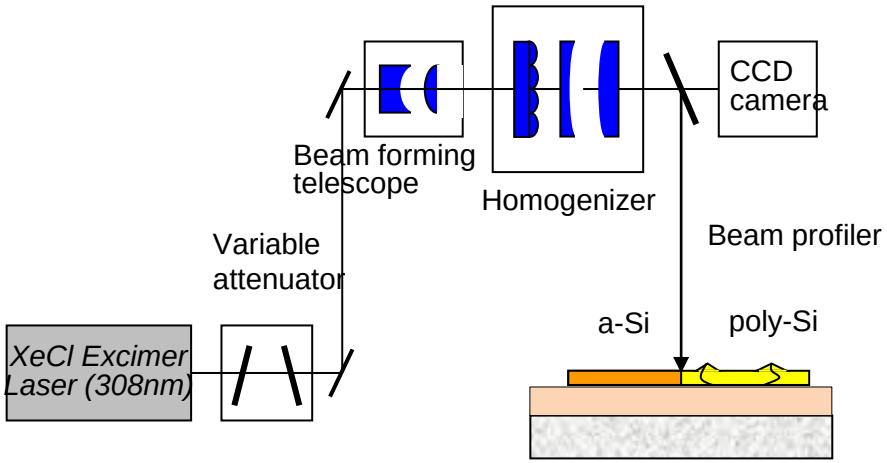


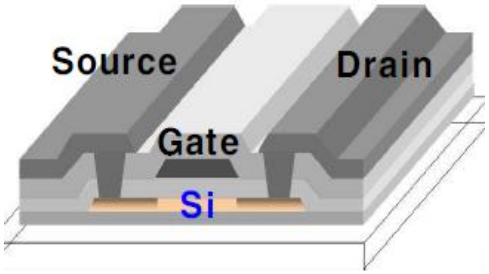
Top Gate Structure on PI

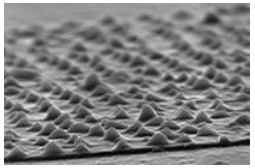
Layer	Key Issues
Pixel Define Layer	Outgas, Stability
Anode (ITO/metal)	Surface contamination
Passivation Layer (Inorganic/organic)	Uniformity, Outgas
S/D Metals (Doping & Activation)	IR drop Low activation temp.
Interlayer (dielectric)	High dielectric constant
Gate Metal	Pattern uniformity
Gate insulator	Interface control
Poly Si	ELA damage on PI
Barrier	Defects
Polymer	Defects
Glass Substrate	Cleaning

Flexible AMOLED Process ___ TFTs

Excimer Laser Annealing (ELA) based LTPS TFTs







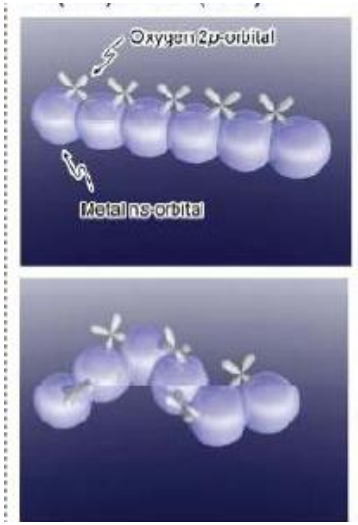
Source: SDC

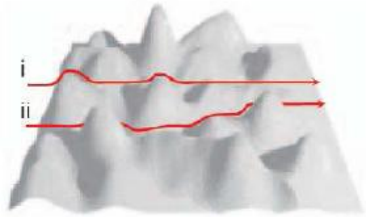
- **ELA LTPS TFTs strength**
  - High mobility (> 100 cm^2/vs)
  - CMOS availability
  - High resolution capability
  - High reliability

- **ELA process on PI film Issues**
  - Laser damage on PI film
  - ELA protrusion issue
    High I_{off}
  - Non uniformity of ELA process
  - Scalability
  - High cost (Investment & Running)

Flexible AMOLED Process __ TFTs

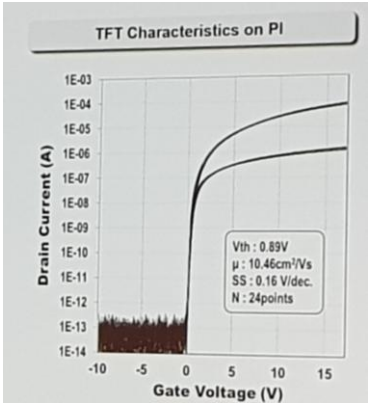
Oxide TFTs for Flexible AMOLEDs





Source: Prof. Hosono
Nature 432, 488 ((2004)

- **Pros**
  - Mobility ~10cm^2/vs
  - High uniformity
  - Scalability
  - Top Gate available
  - Low off current



Source: LGD SID2018

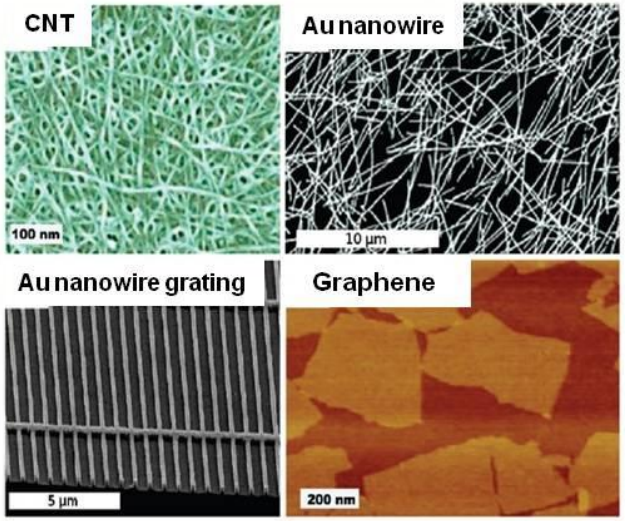
Source: SDC 19" First Oxide TFT AMOLED FPD International 2009

- **Cons**
  - High resolution limitation
  - Reliability
    (Light, bias, temp.,)
  - Sensitivity of back-channel
    (Electrostatic)

Flexible AMOLED Process __ TFTs

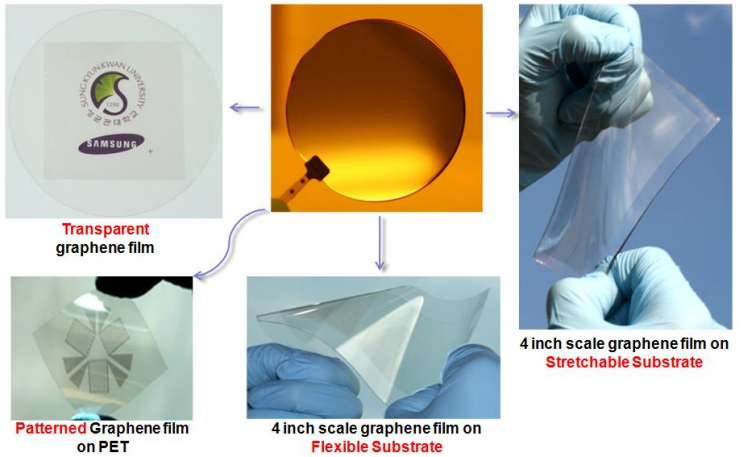
Flexible Electrodes : Connection line & Anode

Materials	Process	Sheet Resistivity (ohm/sq)	Flexibility
ITO	**Anode**	**< 100**	**Not flexible**
Al, Mo, Cu	**Source/Drain**	**100~200**	**Flexible**
Nano-imprinting	Auxiliary electrode	~100	Flexible
Conductive Polymers	Anode	~10^3	Flexible
Carbon Nanotubes	Anode	~10^2	Flexible
Graphene	Anode	10^3/<100	Flexible



K. Kumar et. al. ACS Nano, 4(1),11, (2010)

- **Graphene film deposited by CVD**

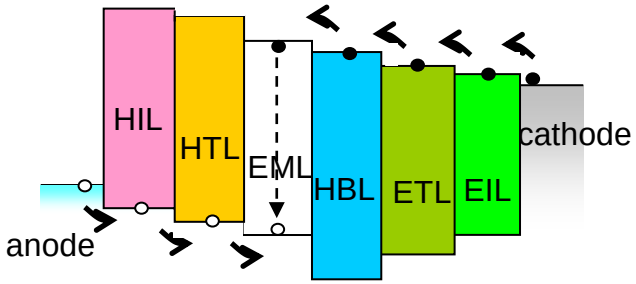


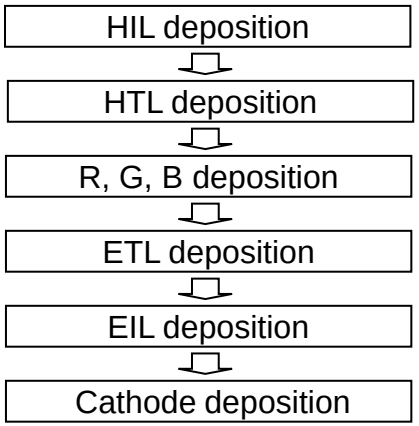
B. H. Hong & J. H. Ahn (SKKU) Nature, 457, 706-710 (2009)

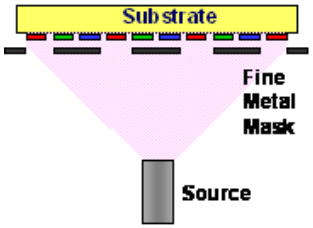
Flexible AMOLED Process __ OLEDs for Mobile

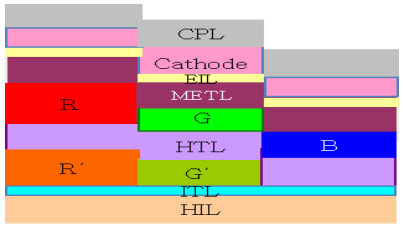
FMM patterned OLED

- **Top Emission, RGB side by side**

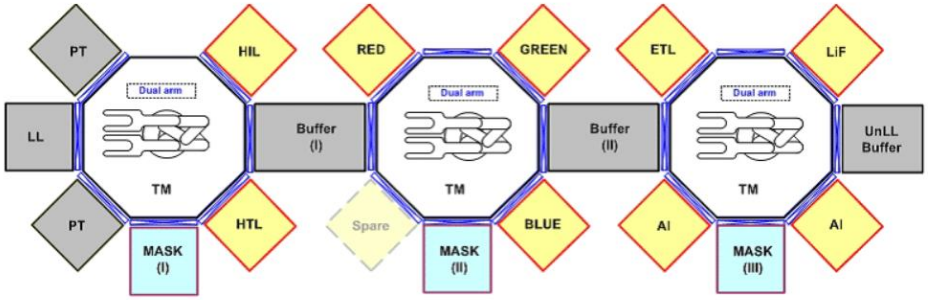








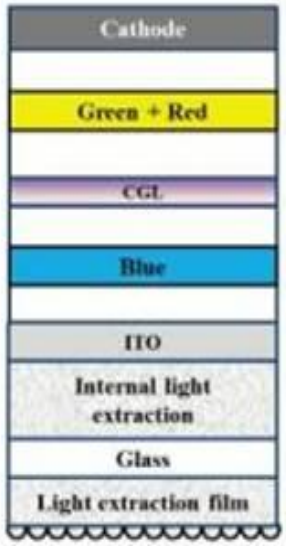
- **Strength**
  - Adaptability of top emission structure
  - Low threshold voltage (low power)
- **Issues**
  - Color viewing angle (micro cavity)
  - Scalability (Gen. 6)
  - Mask issues
- **Key technologies**
  - Precise mask fabrication
  - Undeformed mask tension
  - Mask alignment accuracy
  - Uniform source



Source: Sunic System

Flexible AMOLED Process __ OLEDs for TV

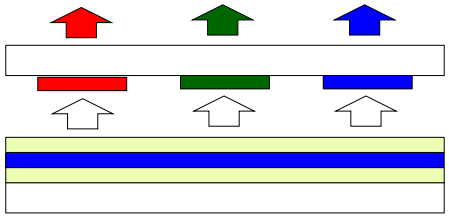
WOLED



2 Stack

3 Stack

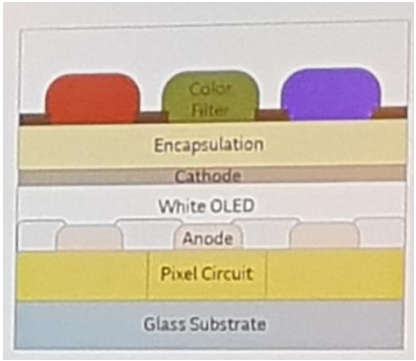
Source: OLED Info, LGD



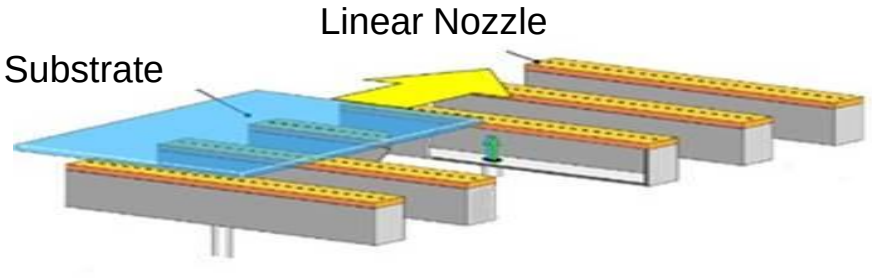
Top emission WOLED structure

- **Strength**
  - Scalability
  - High resolution
  - Multi panel

- **Issues**
  - High voltage
    - High power consumption
    - Low peak luminescence
  - Narrow color volume
  - Top emission adaptability



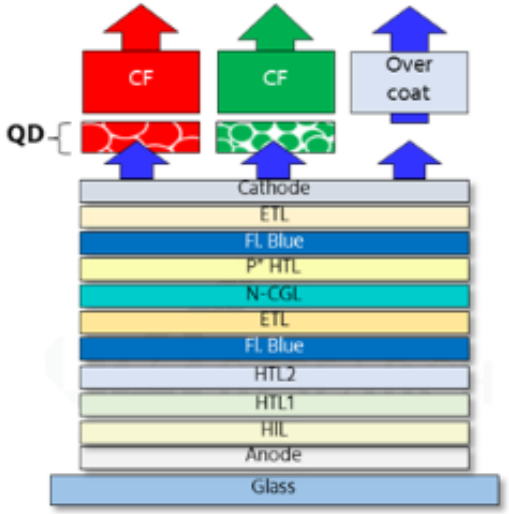
VR 3840x4800 (1443ppi)
Source: Google/LGD SID 2018



Source: Semiconductor Science and Technology Vol 30, No5, 2015

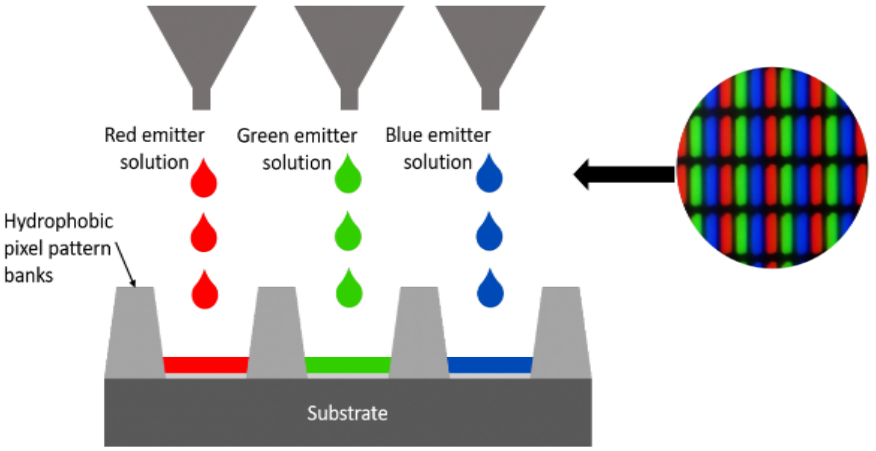
Flexible AMOLED Process __ OLEDs for TV

QD OLED



Source: UBI Reserch

Inkjet OLED



Source: RADIANT Vision System

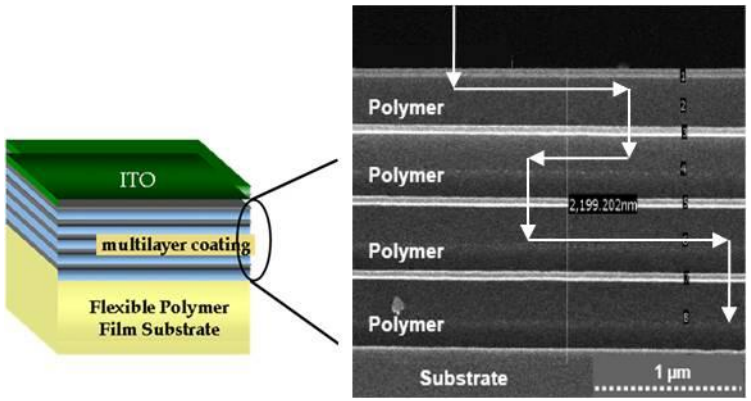
- **Strength**
  - Scalability
  - High color purity
  - High resolution
  - Multi panel
- **Issues**
  - High voltage
  - High cost
  - Short life time of blue device
  - Flexible adaptability

- **Strength**
  - RGB capability
  - High color purity
  - Low material cost
- **Issues**
  - Scalability
  - Short life time of blue device
  - High resolution

Flexible AMOLED Process __ Thin Film Encap.

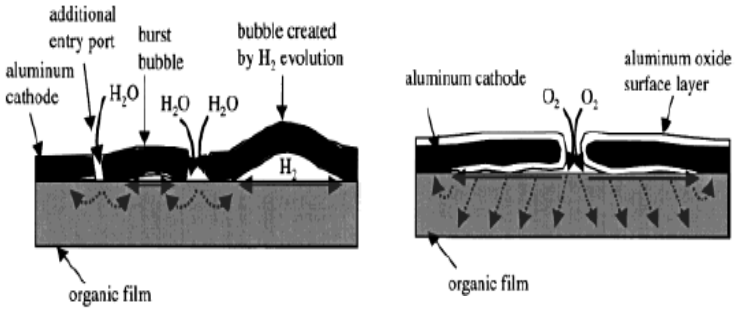
Dark Spots

Vitex TFE



Semicond. Sci. Technol. 26, 034001 (2011)

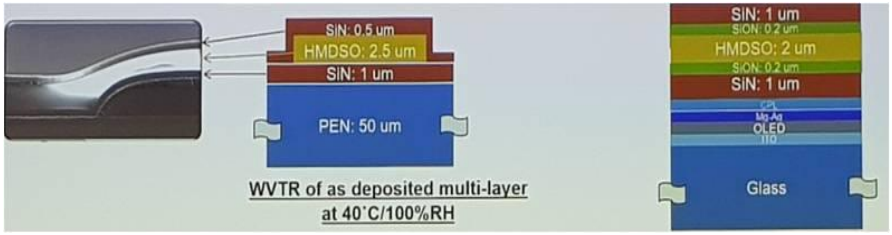
Degradation Mechanism



Adv. Funct. Mater. (2001)

AKT SiN/HMDSO

Multi layer structure on PEN Multi layer structure on OLED

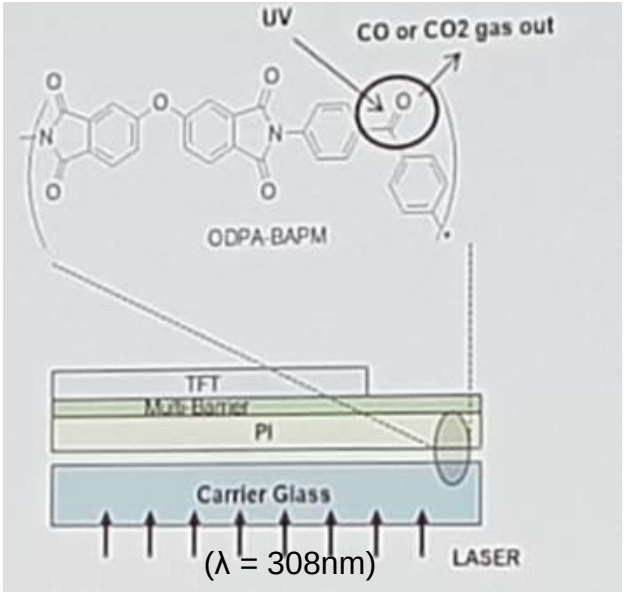


< Detection limit = $5x10^{-5}g/m^2$ day

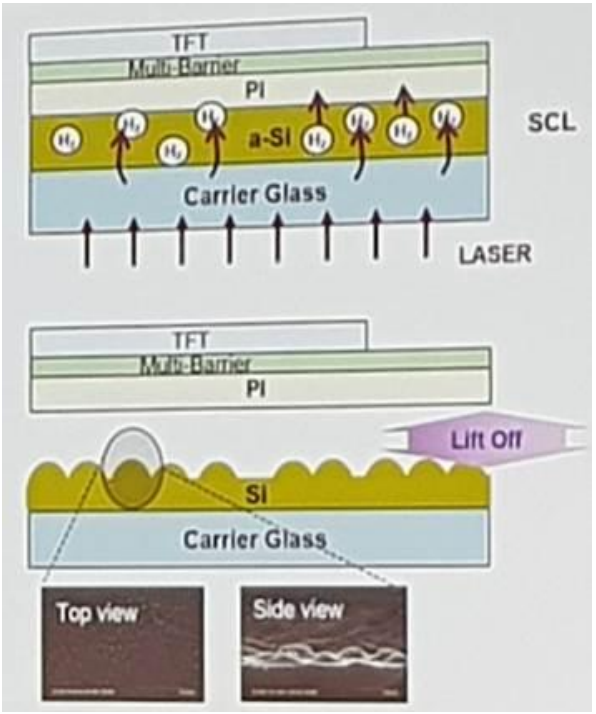
Source: AKT SID 2018

Flexible AMOLED Process __ Detach

- **Laser Lift Off (LLO) w/o SCL**

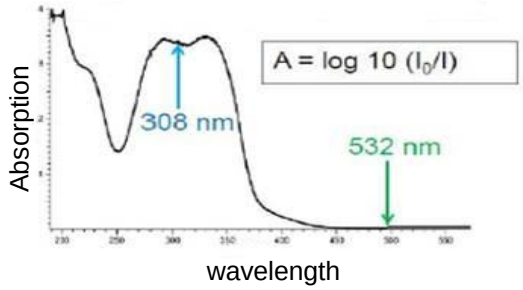


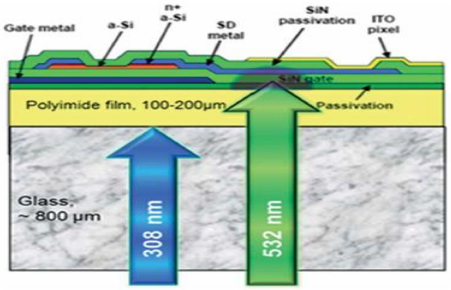
- **LLO w SCL (Sacrificing Layer)**



Source: LGD SID 2018

- PI film absorption spectrum

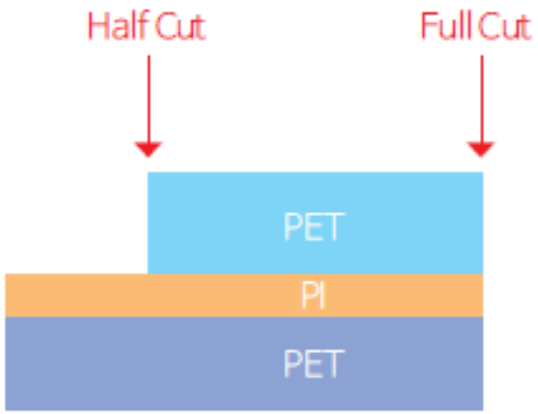




Source: Applied Surface Science 197 (2002) 745

Flexible AMOLED Process __ Cell Cutting

- **Multi Film In-situ Laser Cutting**



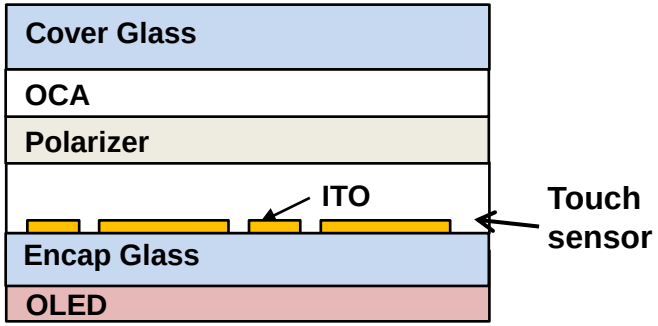
Source: Philoptics IR Report

- **Issue**
  - Selective cutting of Multi-layer
  - Edge crack prevent
  - Particle management
  - Shape flexibility
- **Laser : DPSSL*/CO_2**

*DPSSL: Diode Pumped Solid State Laser

Flexible AMOLED Process __ Touch panel

Touch Panel for Rigid

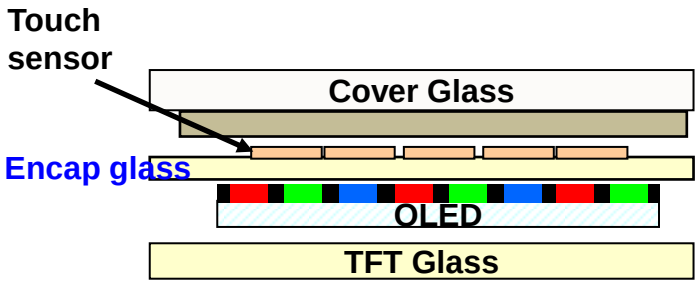


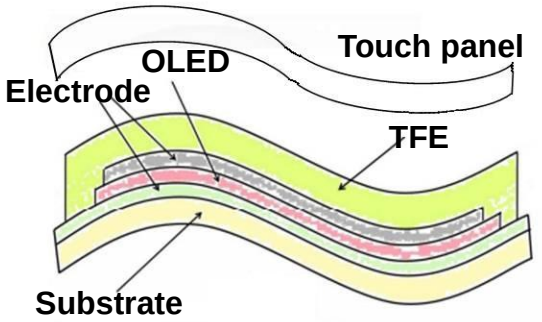
On-cell Touch

- Direct ITO pattern on Encap. glass

Touch Panel for Flexible

- **Touch Panel Options**
  - Touch panel attach to TFE layer
  - Touch panel attach to polarizer
  - Direct pattern on TFE layer
  - Direct pattern on Cover glass



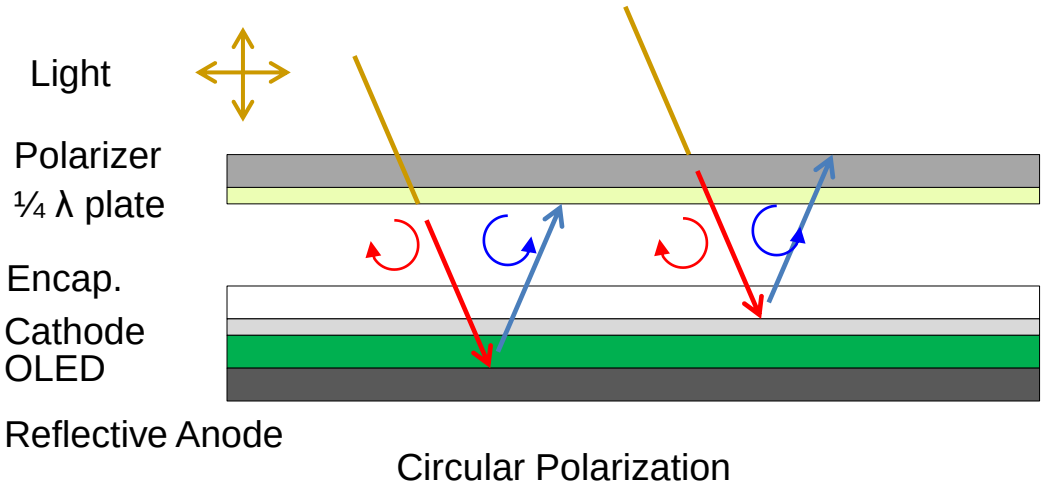


Flexible AMOLED Process __ Polarizer Attach

■ Polarizer : Enhance outdoor Visibility

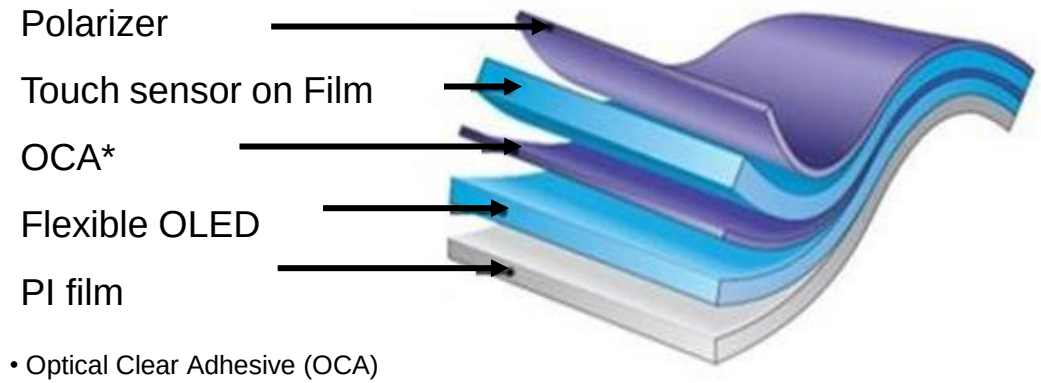
- **Reflective Anode of Top emission structure**
  → Enhance OLED efficiency
  → Degrade the panel contrast ratio

- **Use polarizer with a phase retardation plate**
  - Incident light + Reflected light → Out of phase
    → Canceled out.
  - But, reduce the OLED light over 40%

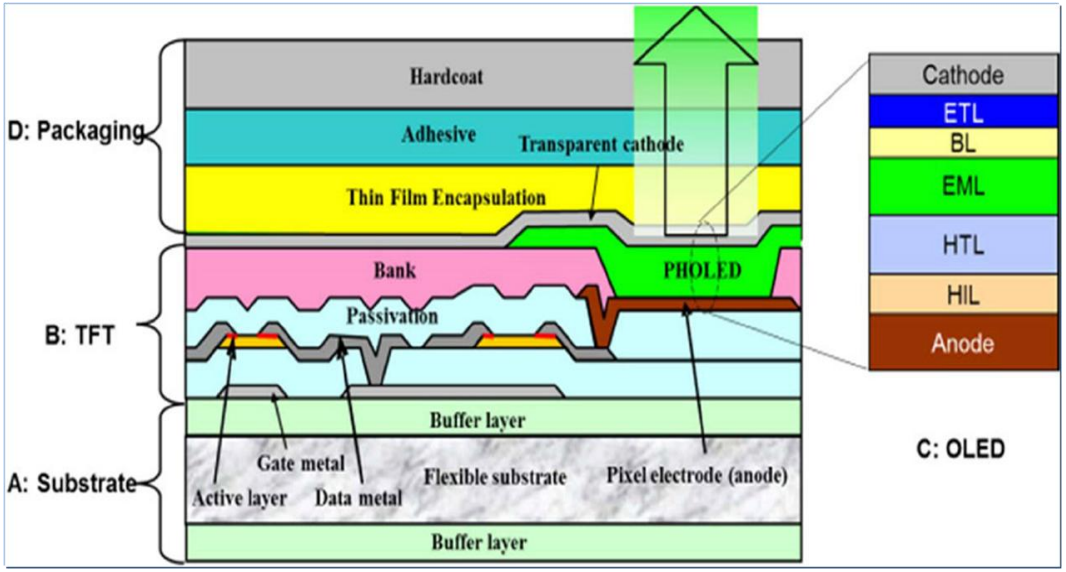


Circular Polarization

Completed Flexible AMOLED



- Optical Clear Adhesive (OCA)
- Optical Clear Resin (OCR)



Source: Lecture by Hanyang Univ .

Contents

Technology Roadmap of Flexible Display

	2013	2014	2015	2016	2017	2018	>2020
Substrate	Semi-Flexible	→	→	Flexible	→	→	→
Display Feature	Bendable	→	Curved	Foldable	Rollable Stretchable	→	Spherical
Substrate Material	Polyimide	PEN Film	Polyimide	→	→	Transparent Polyimide	T. Polyimide Elastomer
Electrode Material	ITO	CNT	ITO	Ag NW		Graphene	
Backplane	LTPS	→	→	→	LTPO Oxide	→	High μ Oxide
Emission	EPD OLED	→	→	OLED	→	OLED u-LED	→
Encapsulation	Hybrid	→	→	→	→	→	Single Layer
Touch Panel	ITO	ITO CNT	ITO	ITO Ag NW	→	ITO Graphene	Graphene Ag NW
Cover Window	Tempered Glass	→	Tempered Glass	High H Plastic			
Manufacturing Process	Gen 4.5 Gen 5.5		Gen 6	Gen 6		Gen 8	> Gen 10

Reference: NH Investment & Securities Co. Research Center

Foldable Display

- **Issues**
  - In-folding / Out-folding
  - High mechanical reliability (Folding cycle)
  - Anti-Scratch
  - Cost competitiveness

Royole 7.8” FlexPai 2019

Lenovo Foldable PC 13.3” 2019 (LG Panel)

Samsung Galaxy F Foldable 7.3” 2019

Huawei 8” Mate X 2019

Rollable Display

Rollable AMOLEDs

- **Advantages**
  - Space utilization freedom
  - Easy to carrier
- **Issue**
  - Mechanical Reliability of rolling

Source: LGD

Source: SDC

Transparent Flexible

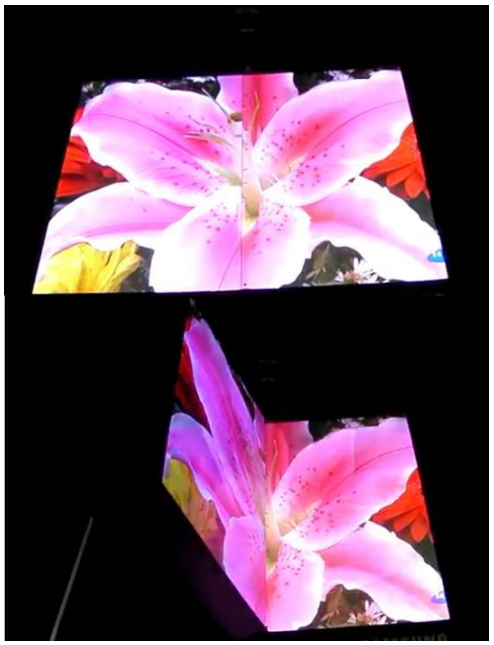
- 77” UHD
- WOLED
  (40% Transparency)
- Rollable (Radius 80mm)
- Oxide TFT/Transparent PI

Source: LGD SID 2018

Tile Display

Rigid Tile

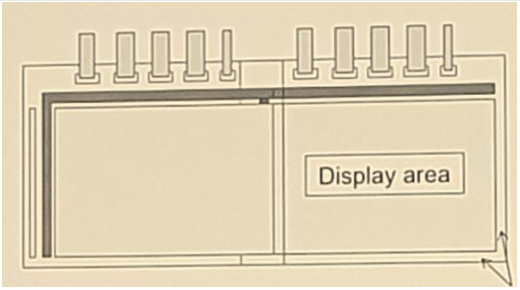
- **Issue**
  - Optical matching



Source: SDC FPD international 2008

Flexible Tile

Source: SEL SID2015



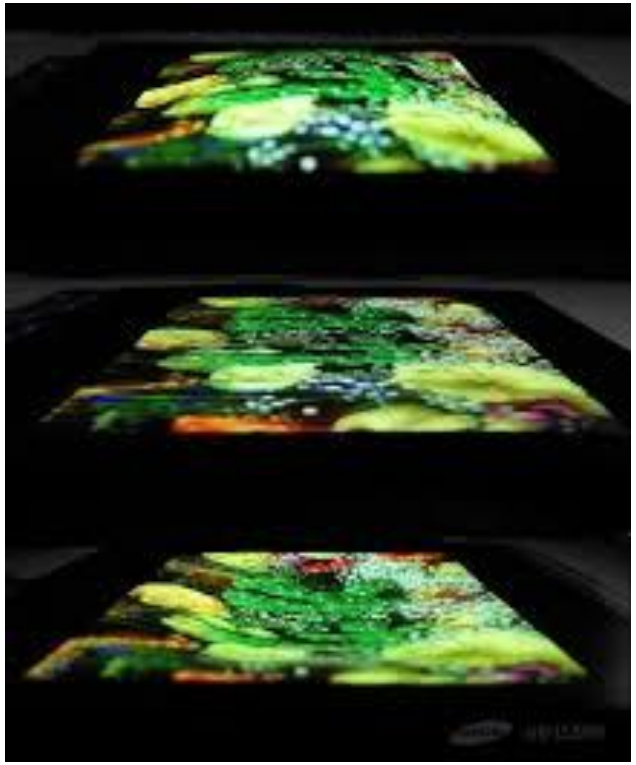
Transparent edge

Source: SEL SID2018

Stretchable Display

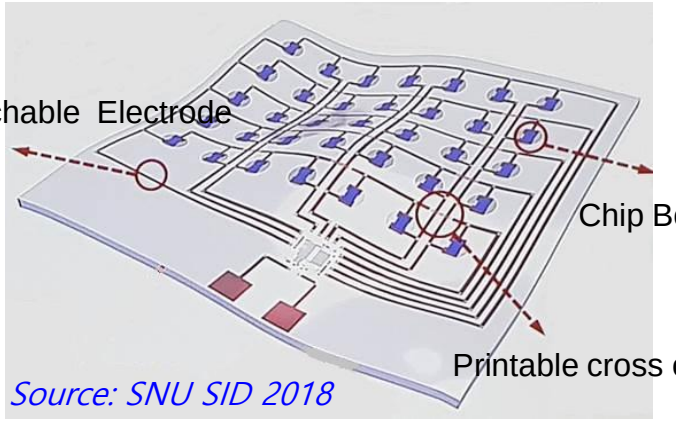
Stretchable AMOLEDs

- **Issue**
  - Pixel Island patterning
  - Stretchable electrode design
  - Stretchable substrate



Source: SDC SID 2017

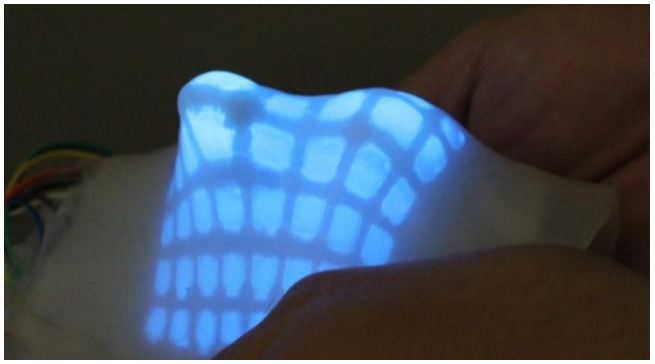
Stretchable LEDs



Source: SNU SID 2018

Stretchable Electronics

Elongation : > 635%, ZnS phosphors



Source: 2016 Science, Vol. 351, Issue 6277, pp. 1071

AMOLEDs To be

Panel

- **Stretchable / Tile display**
- **Total compensation algorithm** (Uniformity & Lifetime)
- **Carrier Recycle Flexible Process**

BP

- **Epitaxial LTPS TFT**
- **High mobility Oxide TFT**
- **Other Function integration** (Sensors)

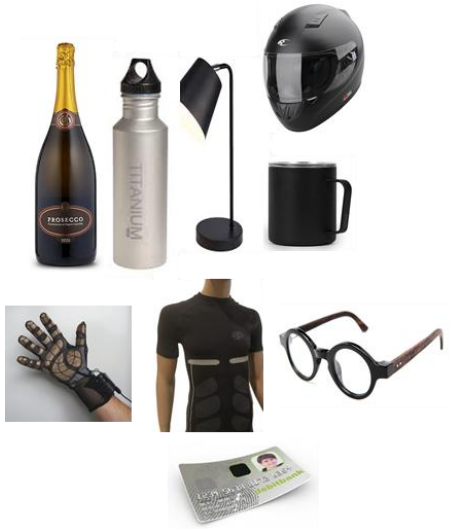
OLED

- **Top emission, RGB patterned**
- **All Ph. OLED**
- **Mask-less patterning**
  Laser deposition (AR/VR), Organic vapor jet (TVs)

Encap.

- **Single layer Encapsulation**
- **Patternable**
- **Wide color viewing angle**

The Evolution of Electronics

	Computer	Smart Phone	IoT
			
Era	**Computer**	**Smart Phone**	**IoT**
Quantity	~300 million /year	~50 billion /year	> 1 trillion /year
Cost	~$100 / IC	~$1~10 / IC	~$1~ ¢ 10 / IC

Source: Pragmatic

Why do the IOT need flexible electronics?

- Inexpensive: Wafer → Large-area processes / Direct Printing
- Seamless Attachment: Attached to a variety shape of objects
  (bottles, clothes, watch, packages, cars etc)
- Multi Functions: Easy to laminate or combine

Personal

- Electronic skins
- Wearable bio-electronics
  (watches, gloves, shoes..)
- Implantable devices
- VR, AR devices

Automobile

- Self driving sensors
- Displays
  (Flexible, transparent…)
- Conformable lights

Industry

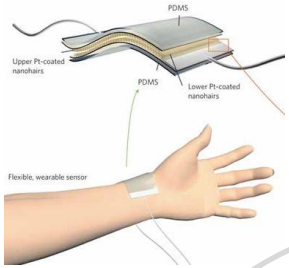
- IOTs
- Logistic sensors
- Infrastructure sensors
- Equipment sensors

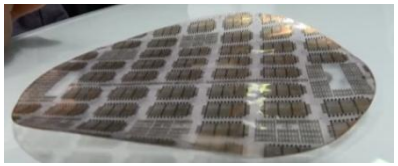
Agriculture

- Environmental sensors
  (Gas, temp. humidity..)
- Flexible lights
- Products growth sensors
- Products management

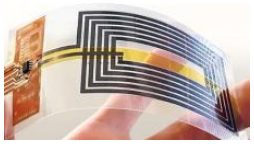
Flexible Electronics with Various Functions

Strain Sensor
Nature Materials
volume 11 (2012)

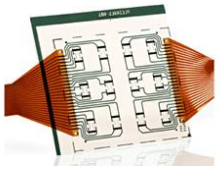




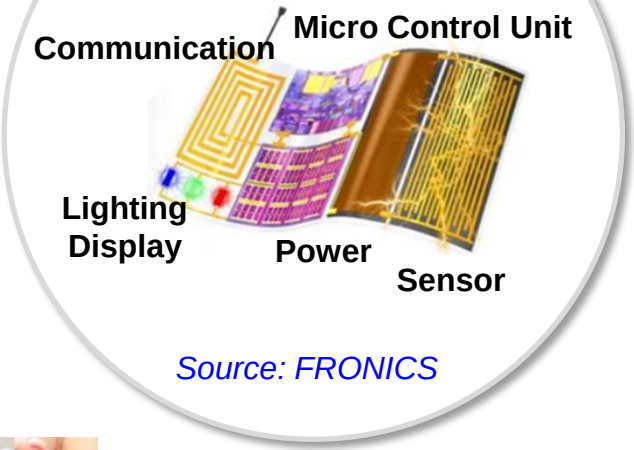
ARM Processor
by PragmatIC



Graphene RF
Materials Today
Vol. 21. Issue 3. April 2018



Temperature Sensor
by Isorg



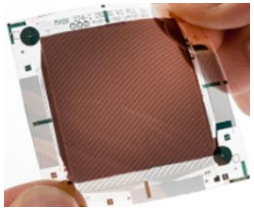


Image Sensor
By Isorg/ Plastic Logic

Flexible lighting
by LG chemical

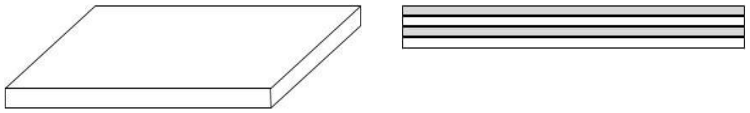
Flexible AMOLED
by Samsung Display

Flexible solar cell
by infinityPV

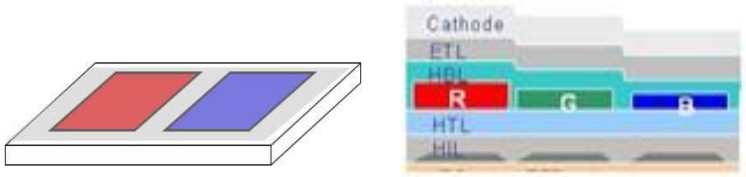
Flexible Battery
by Sekisui Chemical

What can be helpful?

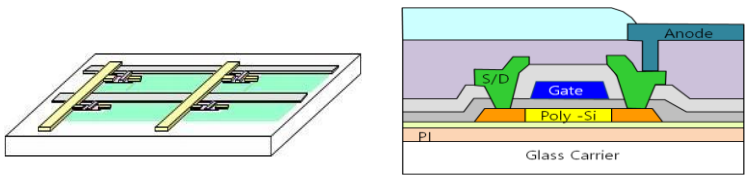
Flexible AMOLEDs



Encapsulation



OLED



LTPS TFT

Flexible Electronics

- Organic Device Reliability
  (Organic solar cell/sensors)
- Printing Process (I/J)

- Organic Device
- Material Development
- Organic Printing & Patterning

- Wafer → Glass
- High Performance TFTs on Flexible
  (Laser Crystallization)
- Flexible Substrate & Processing

Thank You !