

# 차세대 디스플레이를 위한 박막봉지기술 개발동향 및 이슈분석

Min Chul Suh

# Flexible Display – Applications



스마트폰



웨어러블 스마트 기기



Foldable IT 기기



Rollable IT 기기



자동차용 디스플레이



디지털 사이니지

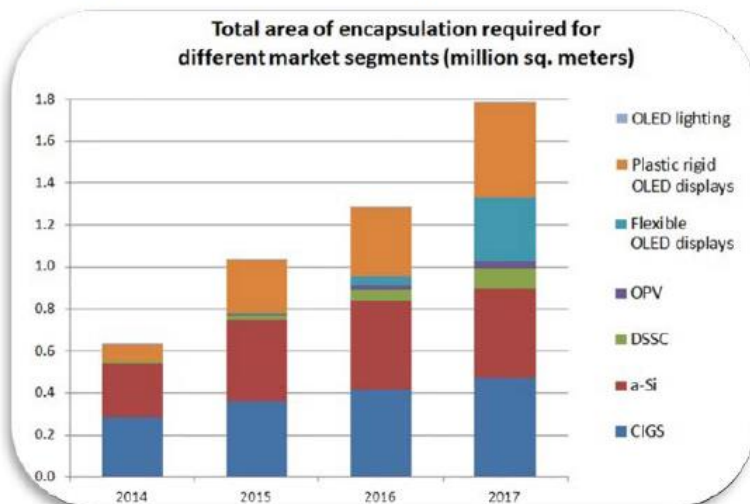
# 봉지 공정 (Encapsulation)



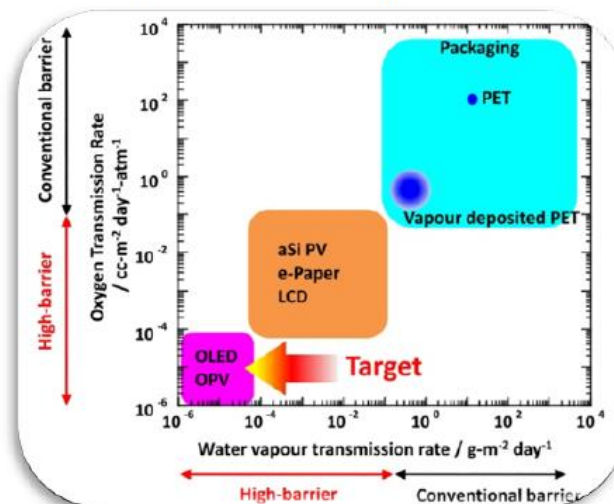
외부 환경으로부터 내부를 차단하는 것

# 봉지 공정 (Encapsulation)

## Growing Market for Encapsulation



## Encapsulation Requirement



## What is the meaning of WVTR value?



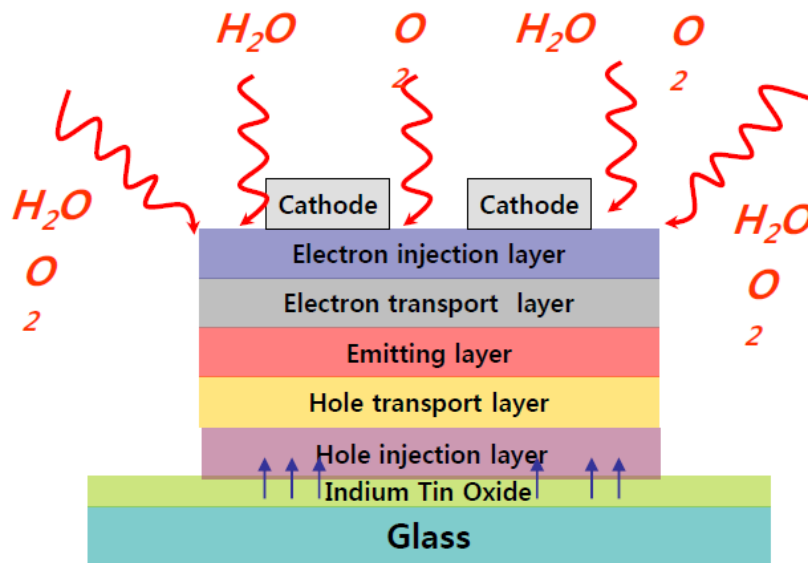
$10^{-1} \text{ g/m}^2/\text{day}$ : 1 kg of water vapor through size of a football field in 1 day

$10^{-4} \text{ g/m}^2/\text{day}$ : 1 g of water vapor

$10^{-6} \text{ g/m}^2/\text{day}$ : 0.01 g of water vapor

# Encapsulation

## ● Degradation of OLED



- Cathode 물질의 유기층으로의 확산
- Cathode의 산화 및 박리
- 전극과 유기층간의 접촉 불량
- Amorphous 유기막의 결정화
- 전기 화학적 분해
- ITO 내의 Oxygen 및 Indium 확산에 의한 유기층 산화
- 전극과 유기층간의 접촉 불량
- ITO roughness
- Energy barrier (ITO work function)

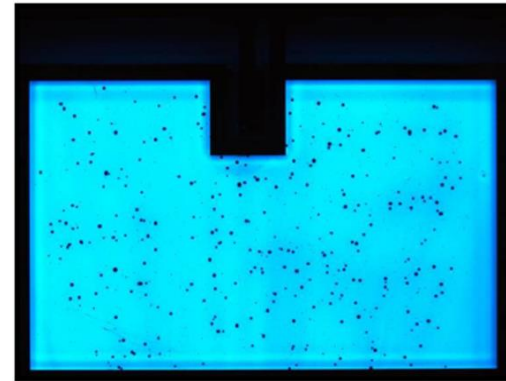
$O_2$ ,  $H_2O$  diffusion



device degradation

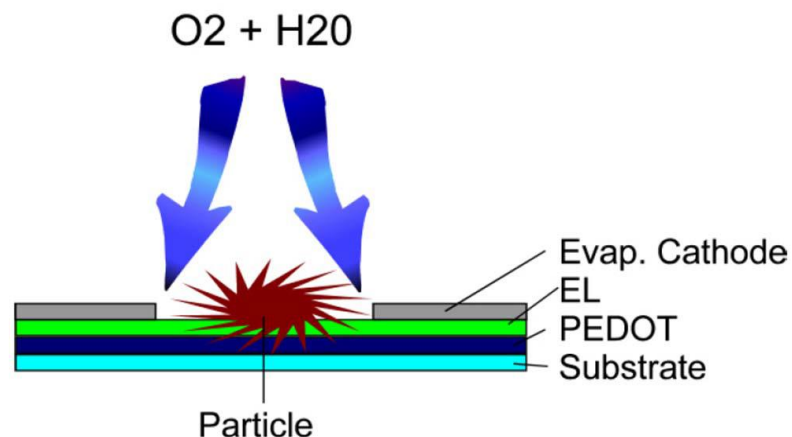
## Dark spot formation

- Particulate matter
- Pinhole defects



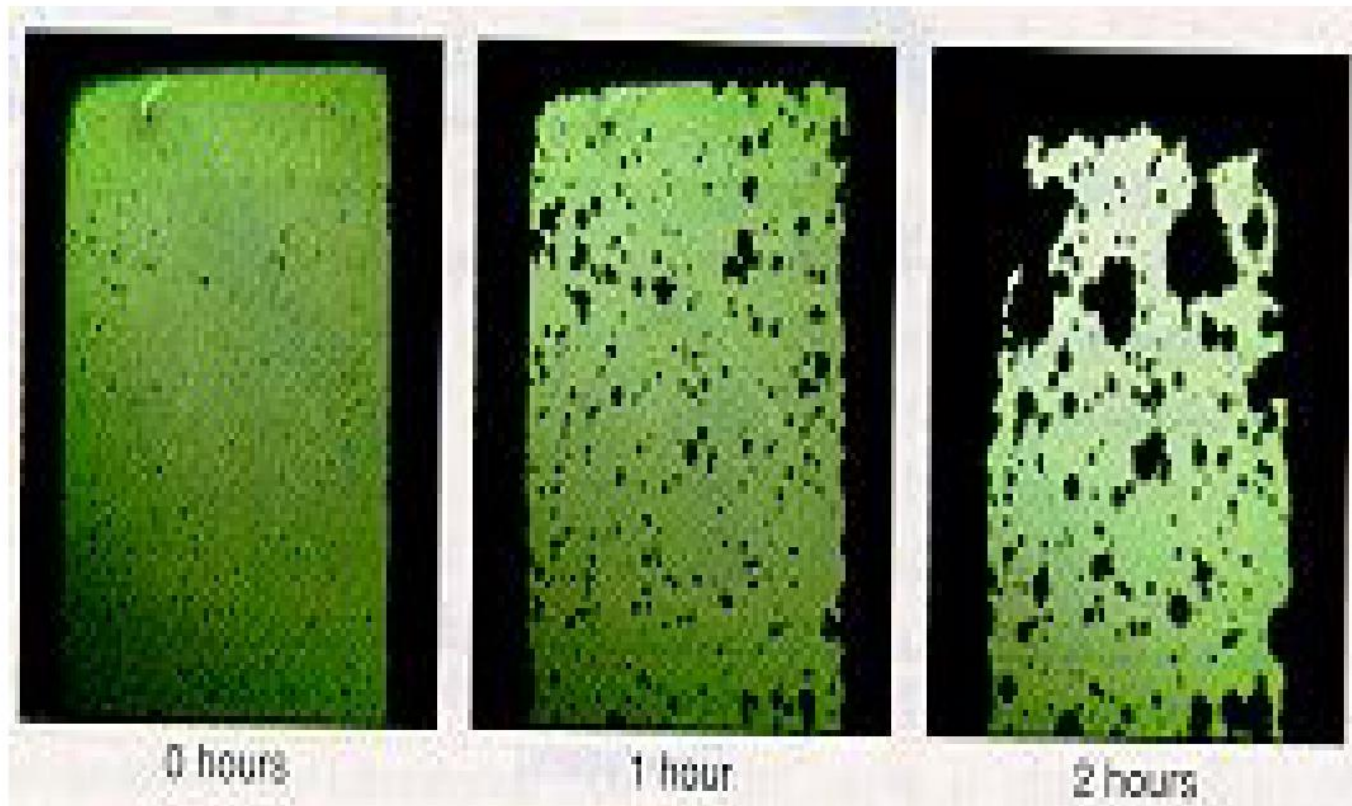
## Dark spot growth

- Primarily due to cathode delamination
- Electrochemical reaction of organic and metal cathode

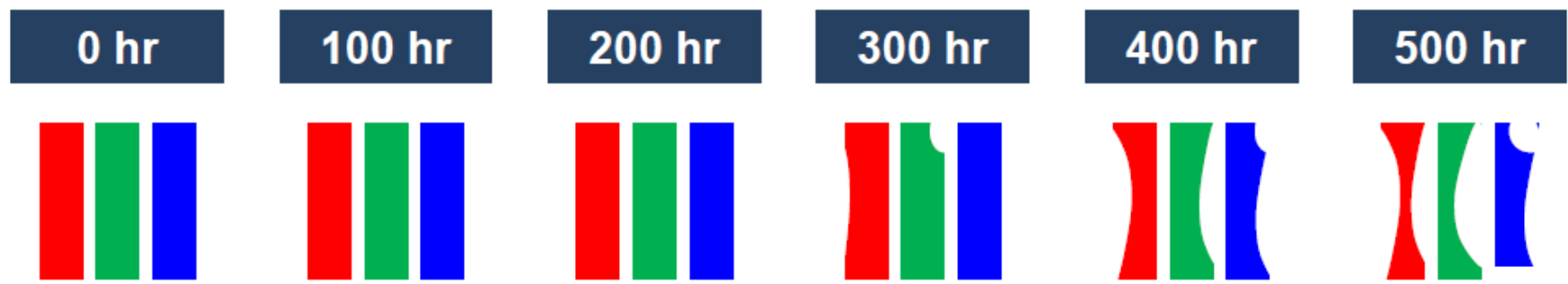
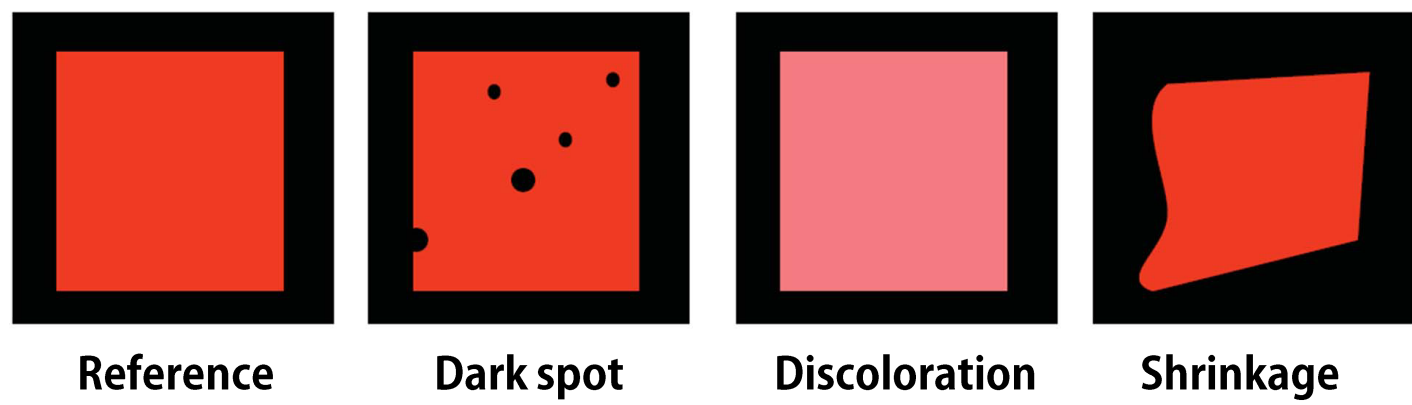


# 봉지 공정 (Encapsulation)

ITO/TPD/Alq3+Quinacridone/Mg 소자의 수분 존재(3 %) 하에서의 시간에 따른 발광 상태 변화



# Dark spots, discoloration, shrinkage of OLED pixel



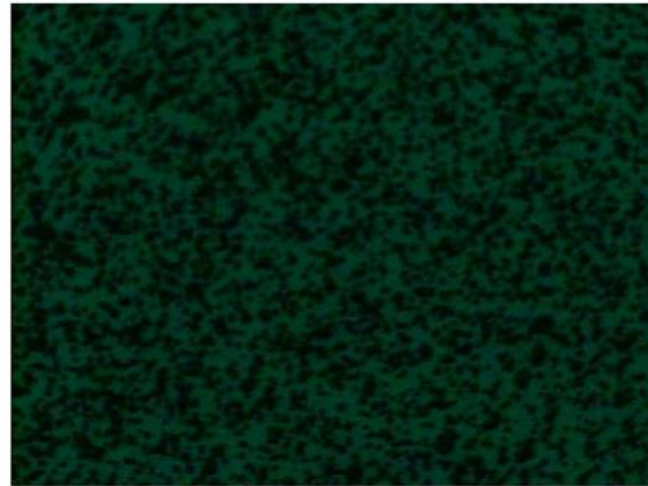
# Dark spots from poor cathode adhesion



Delaminated regions result in non-luminescent area

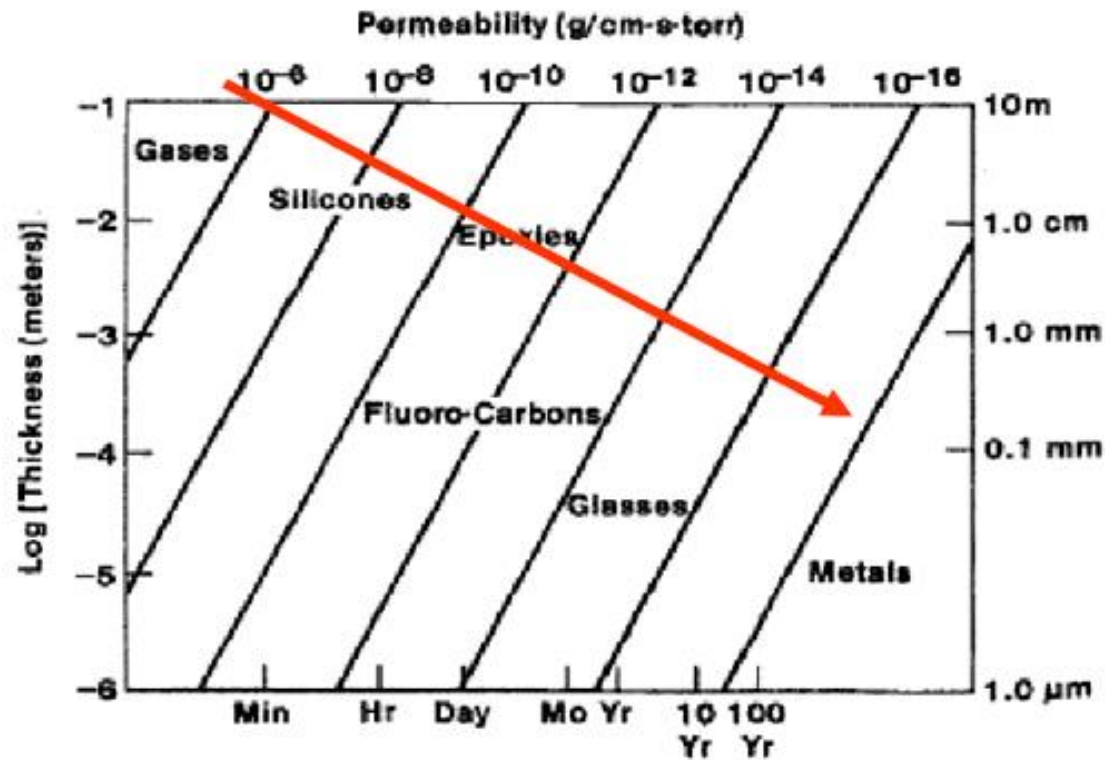


Device : OFF

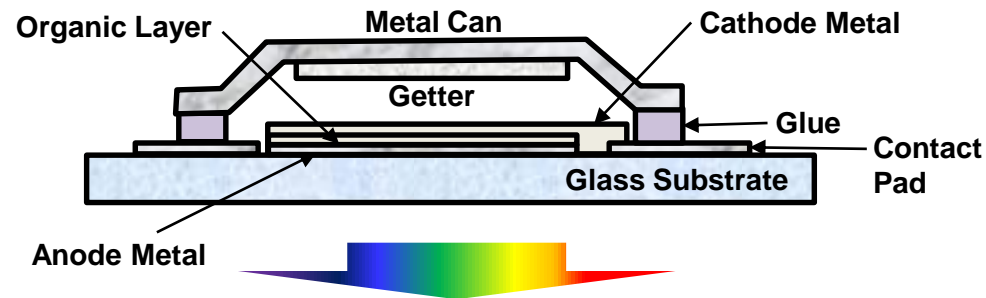


Device : ON

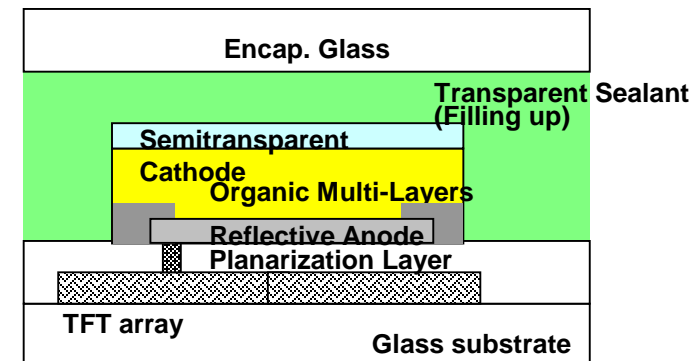
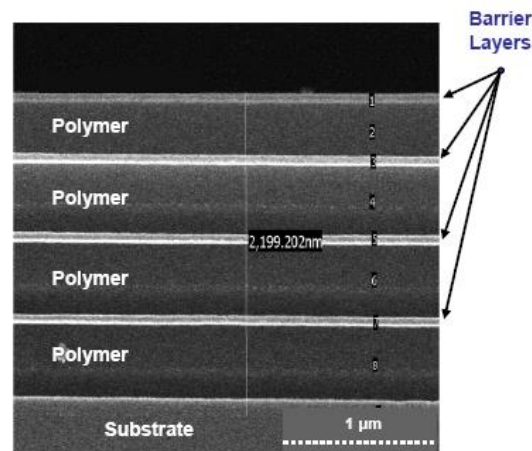
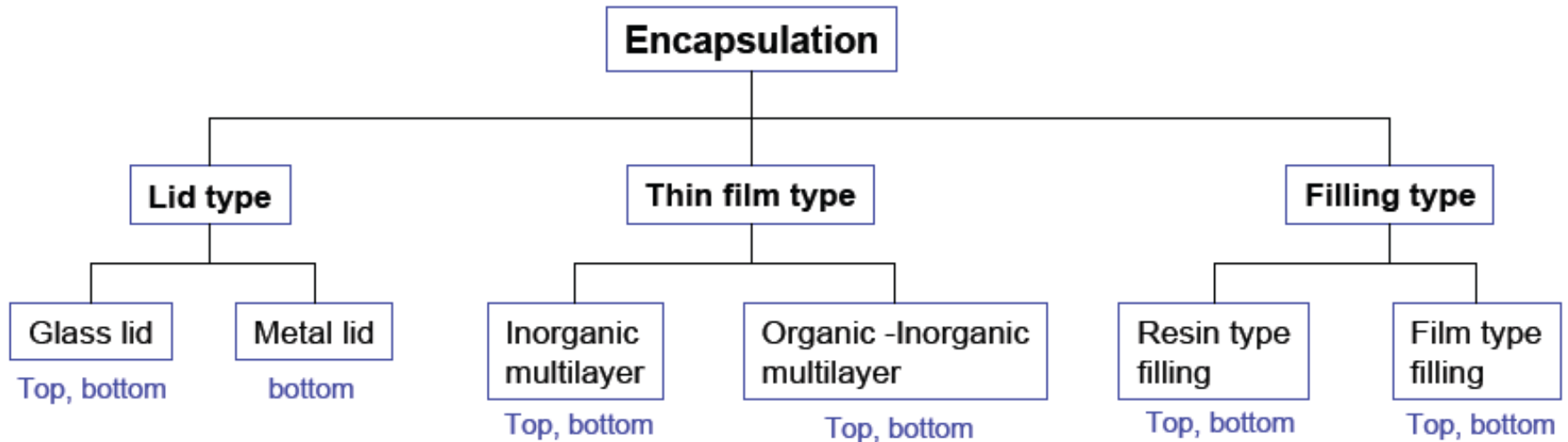
# 봉지 공정 (Encapsulation)



# 봉지 공정 (Encapsulation)

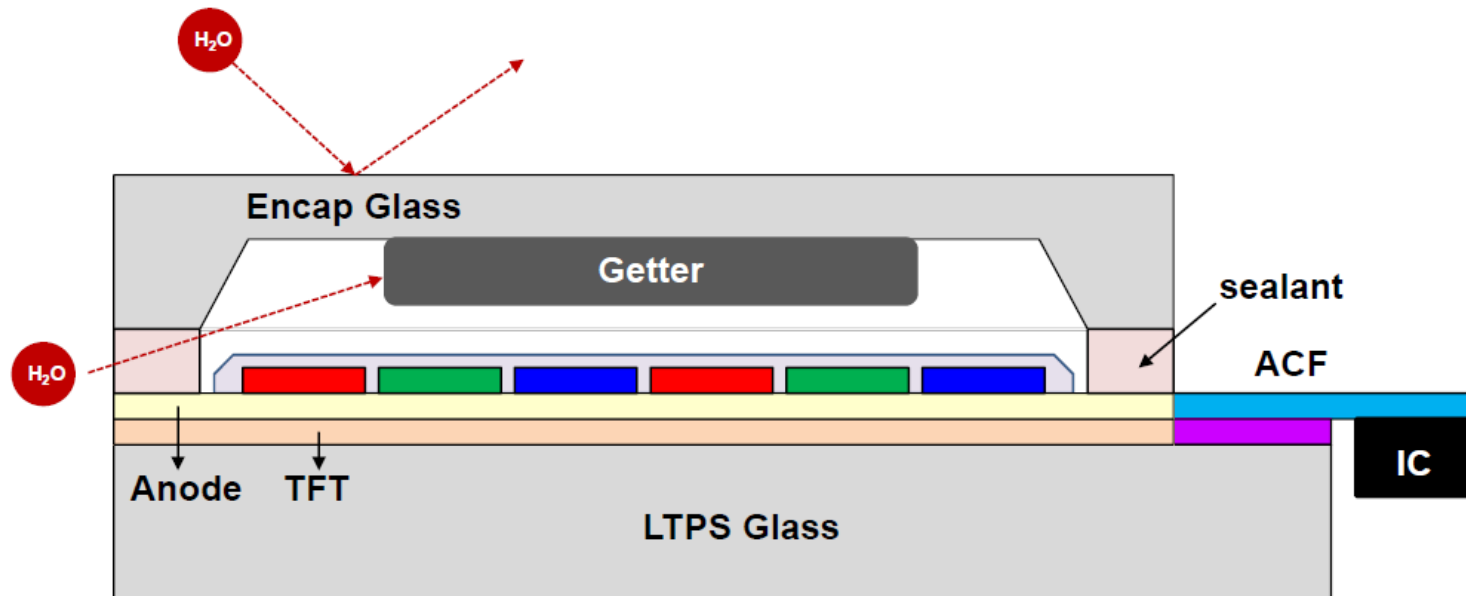


# 봉지 공정 (Encapsulation)



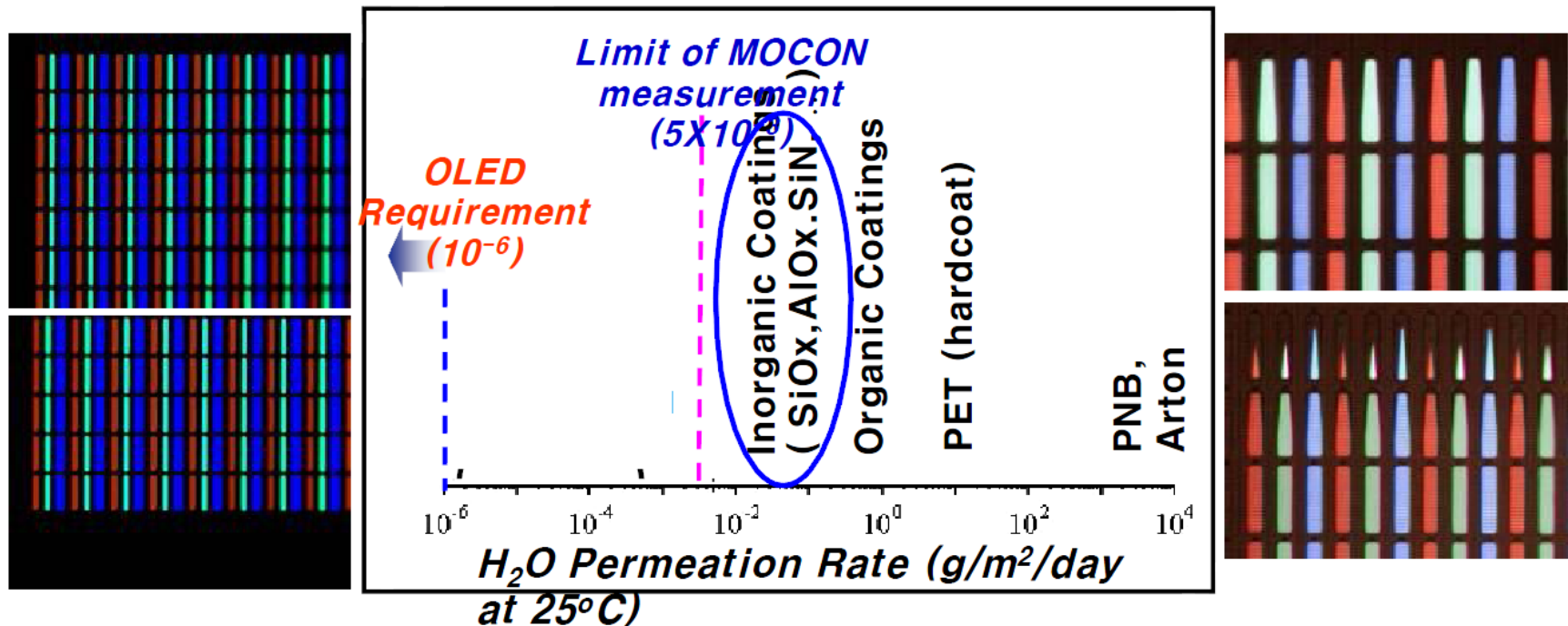
# OLED encapsulation

- Block OLED devices from water ( $\text{H}_2\text{O}$ ) and oxygen ( $\text{O}_2$ )
- Encapsulation, Encap., EN, 봉지, 封紙



# 봉지 공정 (Encapsulation)

## Barrier Properties(H<sub>2</sub>O/O<sub>2</sub>)



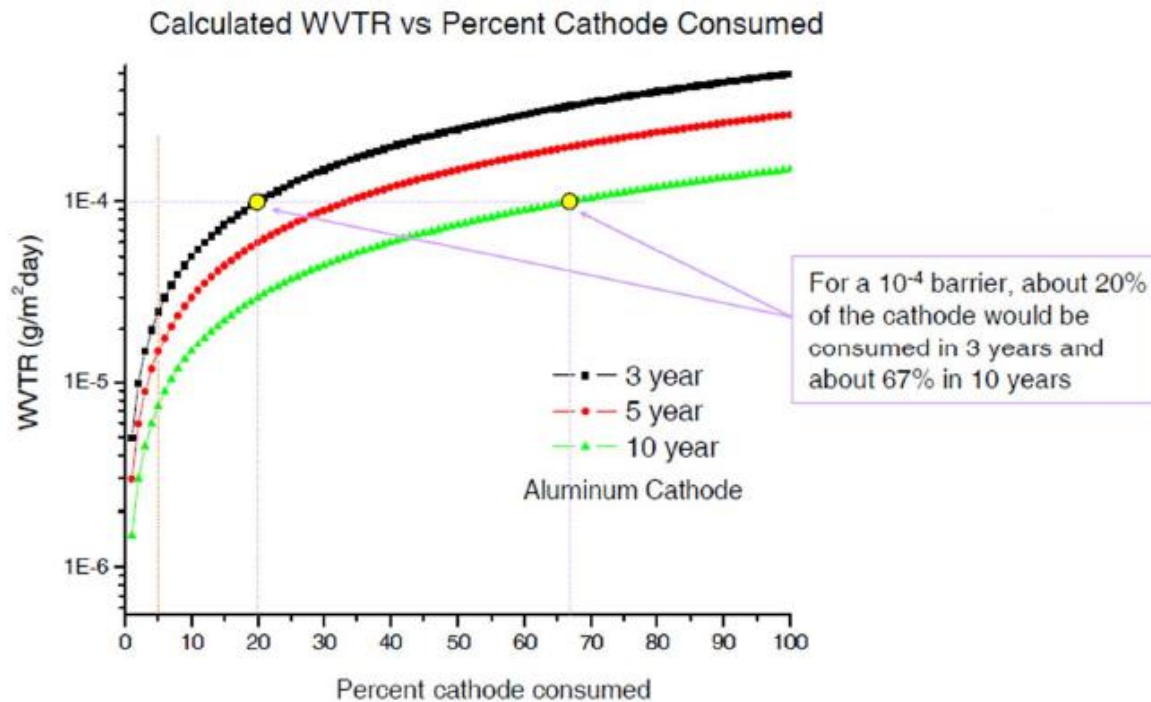
Low Barrier Properties

→ 소자 내로의 수분과 산소의 침투 원인

# 봉지 공정 (Encapsulation)

## Why $10^{-6}$ g/m<sup>2</sup>·day ?

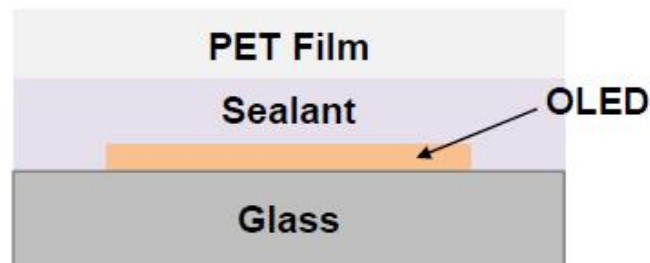
~ number based on consumption calculation for a 2,000 Å-thick aluminum cathode



# 봉지 공정 (Encapsulation)

Why  $10^{-6}$  g/m<sup>2</sup>·day ?

OLED without barrier (only PET)



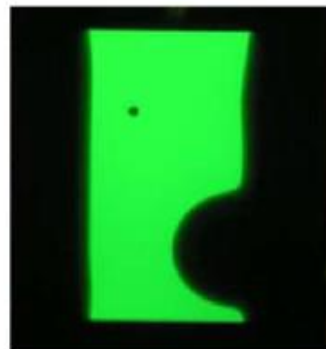
WVTR of PET: 5 g/m<sup>2</sup>/day

Lifetime: < 0.1 hr

Lifetime for general lighting: 100,000 hr



0 hr



12 hr

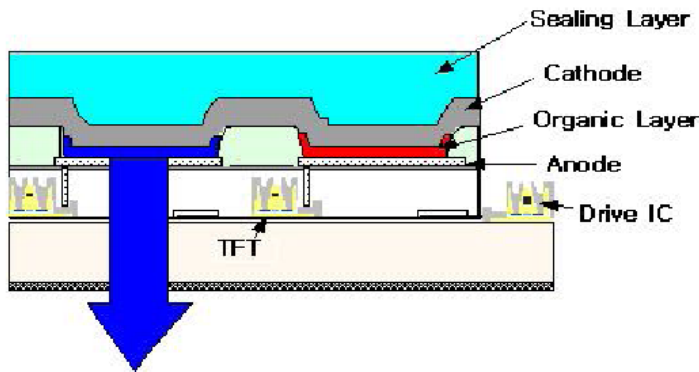


24 hr

WVTR required for general lighting ➔  $5 \times 10^{-6}$  g/m<sup>2</sup>/day

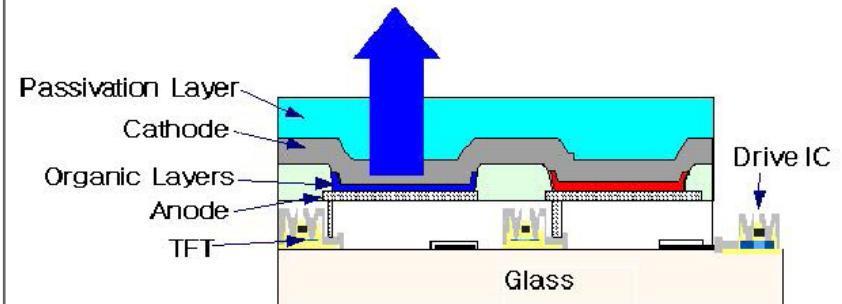
# 봉지 공정 (Encapsulation)

## 배면발광 (Bottom Emission)



- LTPS Glass 방향으로 발광됨
- Encap Glass는 뒤쪽에 존재 (소비자의 눈에 보이지 않음)
- TR에 의해 개구율 한계가 존재함 (해상도 130ppi 이하 가능)
- 저해상도의 소형 Device나 대형 Device에 유리
- 흡습제 부착 용이

## 전면발광 (Top Emission)

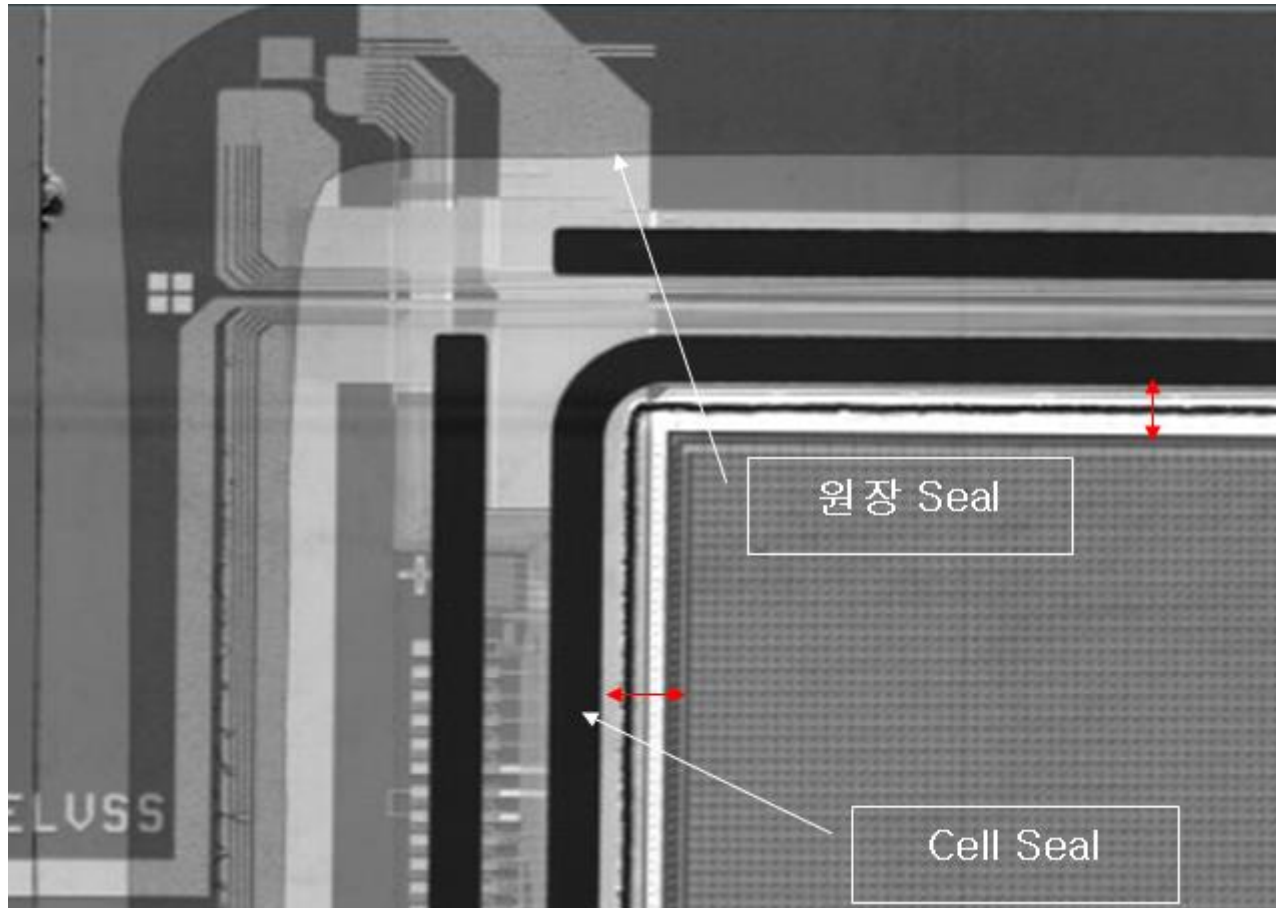


- Encap Glass 방향으로 발광됨
- Encap Glass가 앞쪽에 존재 (소비자의 눈에 직접 보이게 됨)
- TR에 의한 개구율 한계가 없음 (해상도 130ppi 이상 가능)
- 고해상도 소형 Device에 유리
- 흡습제 부착 불가 → 완전봉지

## Things to be considered for high-performance OLED encapsulation

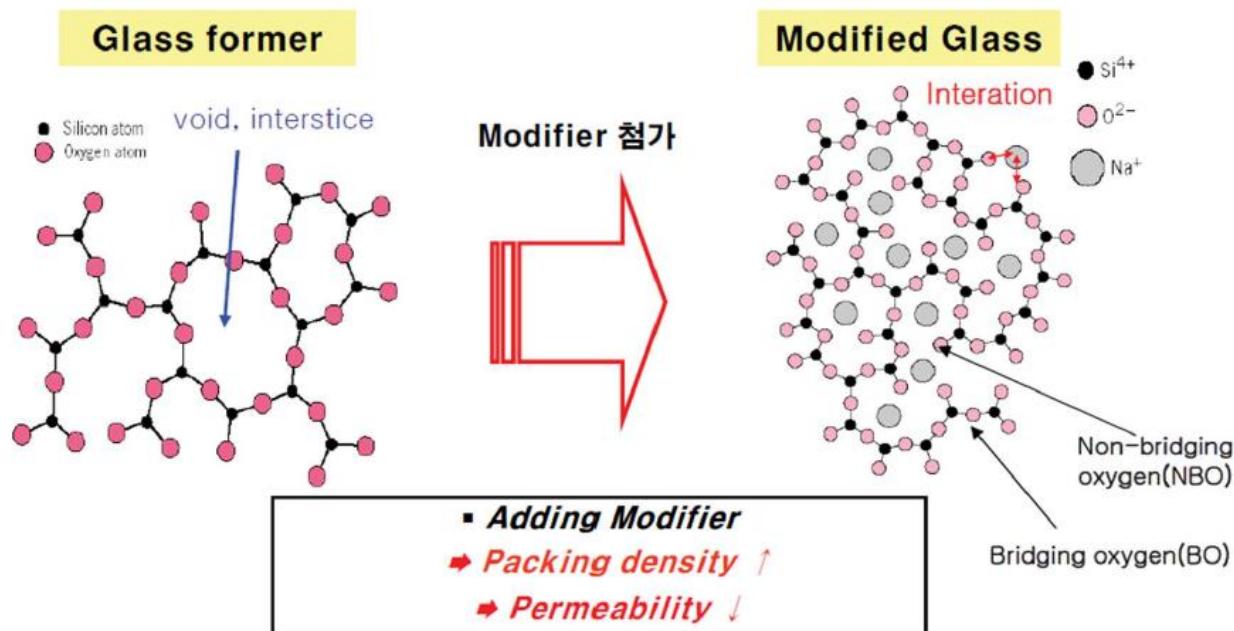
- High performance barrier: WVTR & OTR
- Flexible/Stretchable: not radius of curvature but critical strain
- Optical transparency vs UV protection
- Various form factor
- Process compatibility
- Damage to OLED during the encapsulation procedure
- Interface/adhesion
- Particles & defects
- Heat dissipation: Coefficient of Thermal Expansion (CTE)
- Chemical inertness

# 봉지 공정 – Frit Seal / Cell Seal 공정

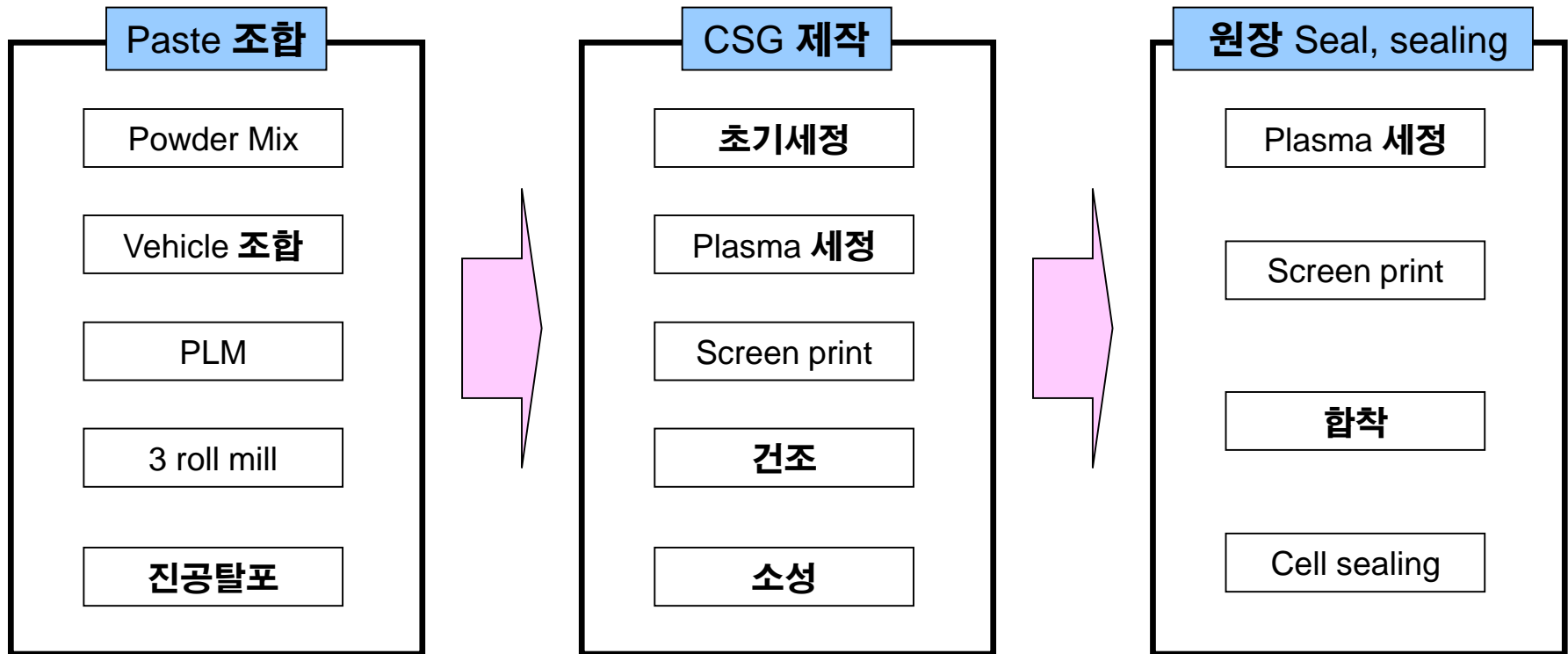


# 봉지 공정 – Frit Seal / Cell Seal 공정

- ~ Glass has a high barrier property due to a good packing density
- ~ Frit is a ceramic composition that has been fused in a special fusing oven, quenched to form a glass, and granulated. → Glass-like Material

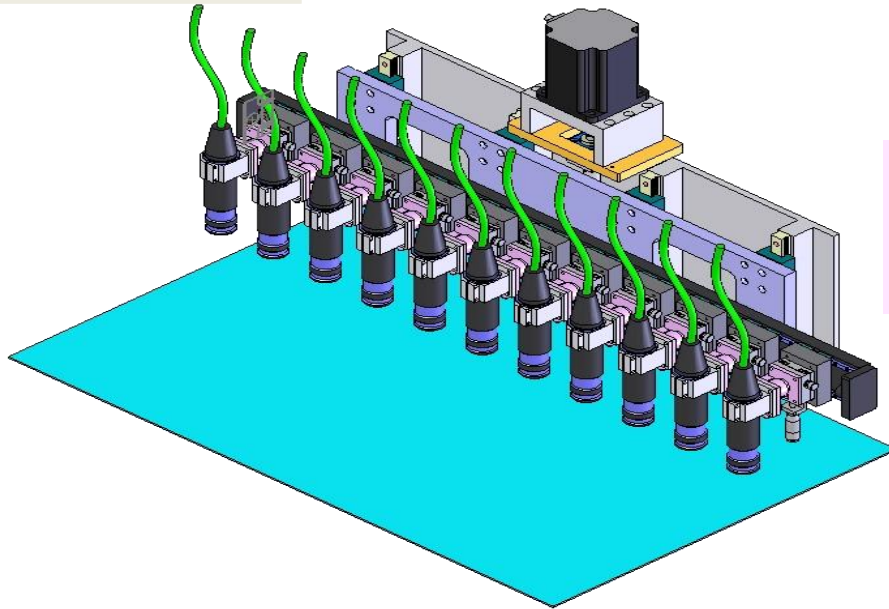


# 봉지 공정 – CSG 제작 과정

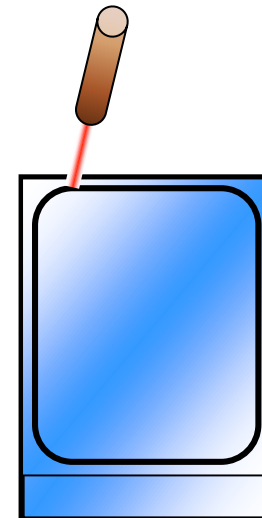
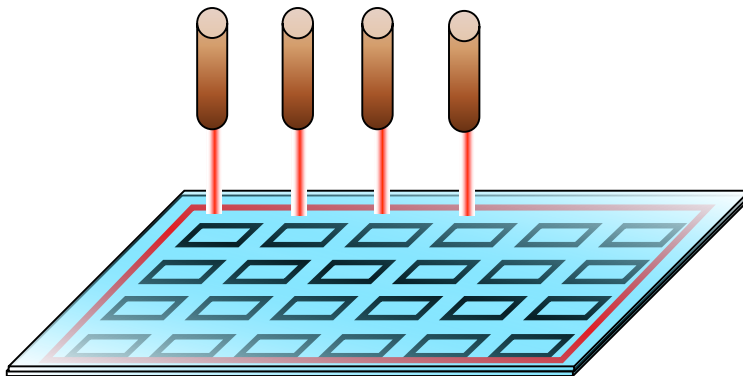


# 봉지 공정 – Cell Sealing 공정

Cell sealing









laser를 조사하여 무기 Cell seal을 순간적으로  
용융시켜 증착 기판과 봉지 기판 사이를 Cell Seal  
로 밀봉 함.



# Evolution of Flexible Display

- Flat → Conformable → Foldable → Rolled → Wall Paper
- Glass → Stainless Steel Foil → Plastic Sheet → Plastic Roll

Display	Flat	Conformable Bendable	Rolled Foldable	Wall Paper (Large Screen)
Substrate	Glass	Thin Glass/Steel	Plastic Sheet	Plastic Roll
Application	 <p>Motorola</p>		 <p>Rolled Sony</p>  <p>Foldable ITRI</p>	 <p>TV</p>  <p>Signage Displaybank</p>

# Possibility toward Flexible Display



YOUNM

# Inorganic Barriers on Plastic Film

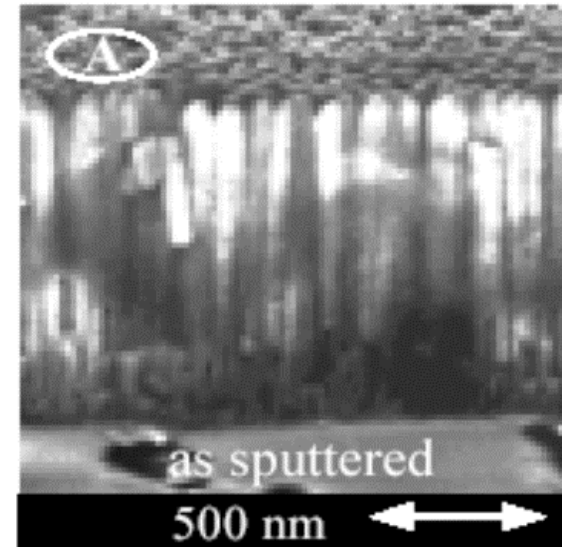
$\text{SiO}_2$ ,  $\text{SiN}$ ,  $\text{SiO}_x\text{N}_y$ : Thin film barriers show defect dominated permeation.

## Intrinsic

- poor deposition (spitting)
- columnar growth
- stress cracking
- grain boundaries
- low density (porous) films

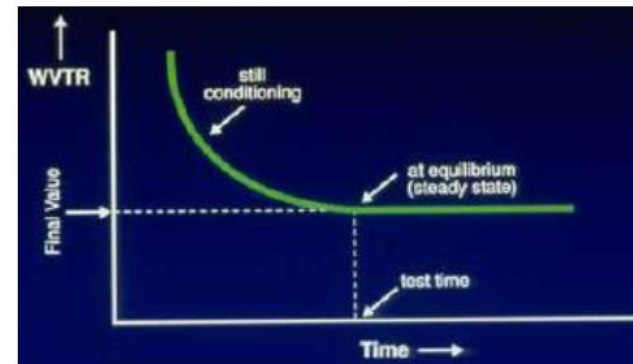
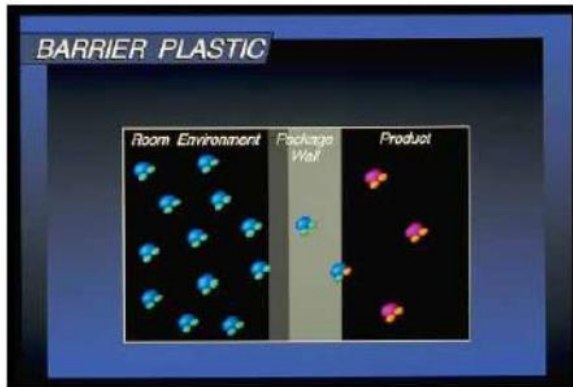
## Extrinsic

- particles / debris
- surface roughness



# Encapsulation

## ● Permeation Basics: Solution - Diffusion



- The gas absorbs at the entering face and dissolves in the materials at the high-pressure side of the materials
- Diffuses through the polymer
- Desorbs or outgases at the low-pressure side

# Demands on Barrier Film for OLED

Permeation of gases is a combination of two physical processes: dissolution and diffusion

## Principles of permeation

$$P = DS$$

$P$  : Permeation coefficient (permeability)

$D$  : Diffusion coefficient, determines how **fast** the permeant can **move** in the media

$S$  : Solubility coefficient, determines how **much** of the permeant can **be dissolved in in the film**

## Driving force

$$J = -D\left(\frac{\partial c}{\partial x}\right) \quad \text{Fick's first Law}$$

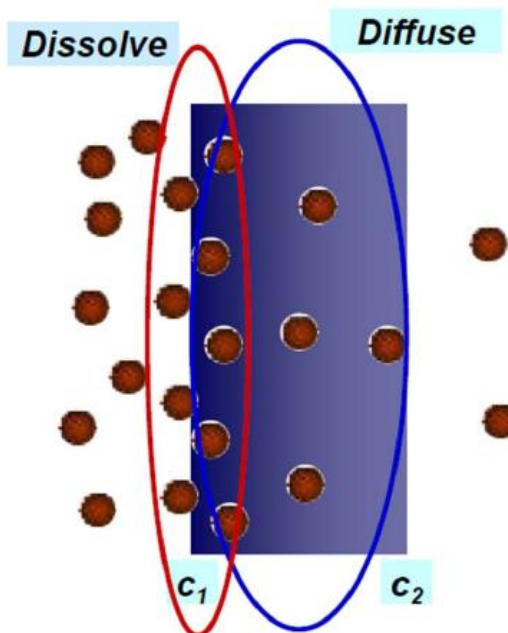
$$\rightarrow c = Sp \quad \text{Henry's Law}$$

$$J = DS \frac{\Delta p}{l}$$

$J$  : Flux of permeant

$\partial c / \partial x$  : concentration gradient

$p$  : Partial pressure of permeant



## ● Requirements of OLEDs

- Deposition process: Not damage the active layer
- WTVR  $< 10^{-6}$  g/m<sup>2</sup> day, OTR  $< 10^{-3}$  cm<sup>3</sup>/m<sup>2</sup> day
- Transparent
- Good adhesion
- Robust (Rugged)
- Similar TEC (thermal expansion coeff.) to the substrate
- Thin
- Light weight
- Flexible
- Low cost
- Solvent resistant

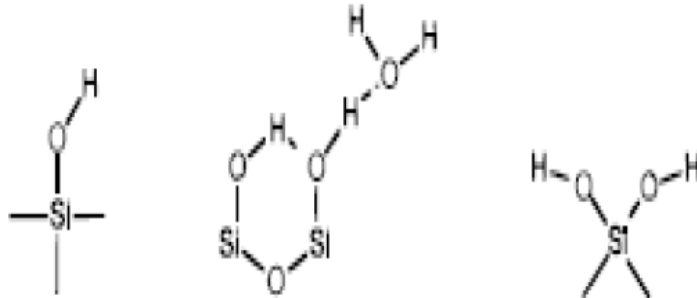
# Encapsulation

## ● Factors Affecting WVTR & OTR

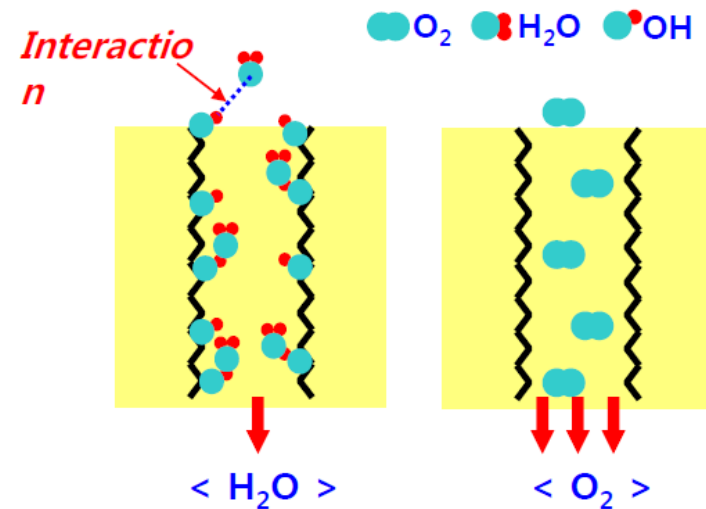
### ■ Surface Reaction at Surface of Barrier Layer

➡ OH groups formation & H<sub>2</sub>O adsorbed on surface

Ex) SiO<sub>x</sub>



Ex) O<sub>2</sub> vs. H<sub>2</sub>O



With barrier layer, WVTR & OTR



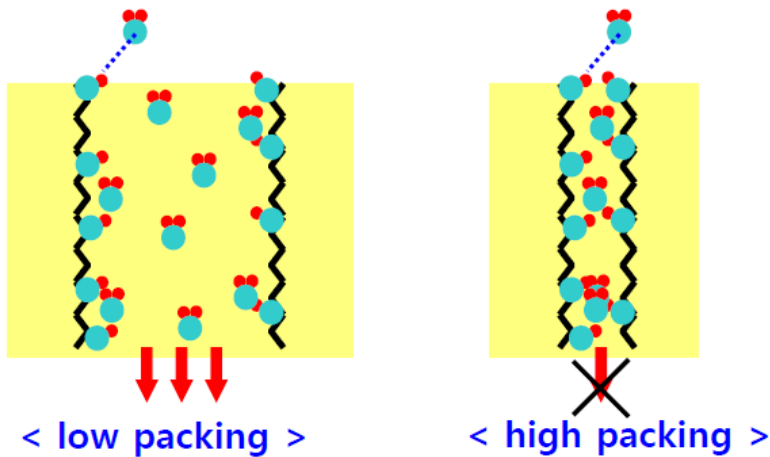
# Encapsulation

## ● Factors Affecting WVTR & OTR

### ■ Packing density

➔ Microstructure ( pore size and density )

Ex) low packing vs. high packing



Low defect density with small size

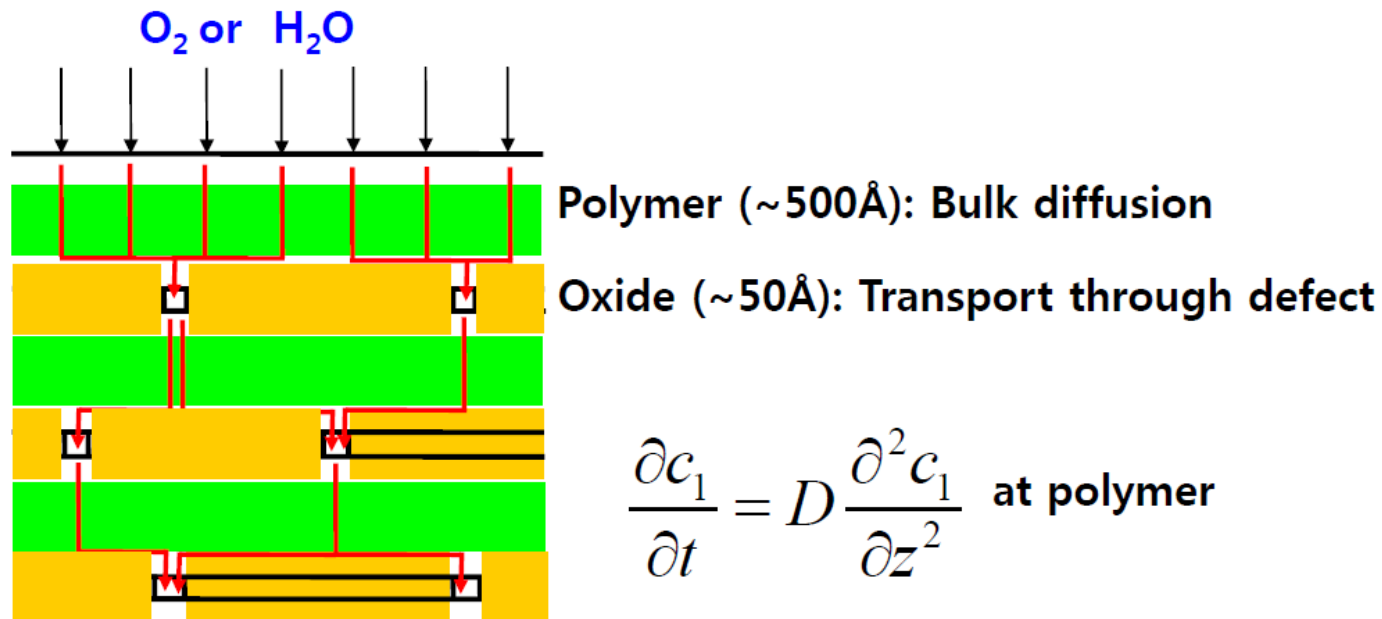
WVTR, OTR



# Encapsulation

## ● Factors Affecting WVTR & OTR

### ■ Tortuous Path (Lag Time Effect)



Longer effective path length



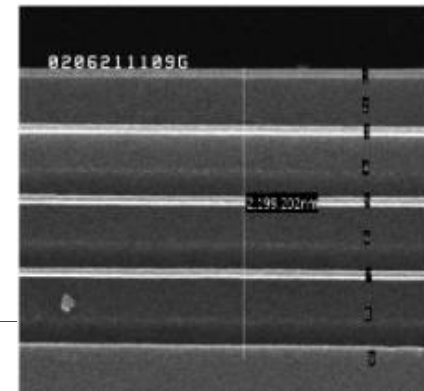
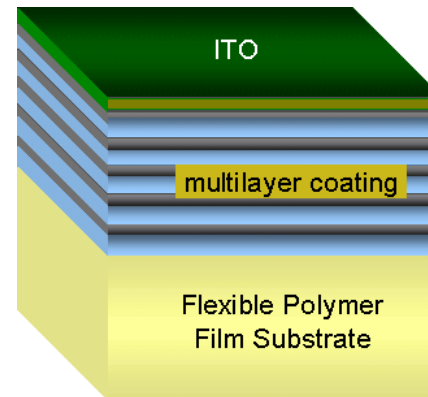
permeation rate



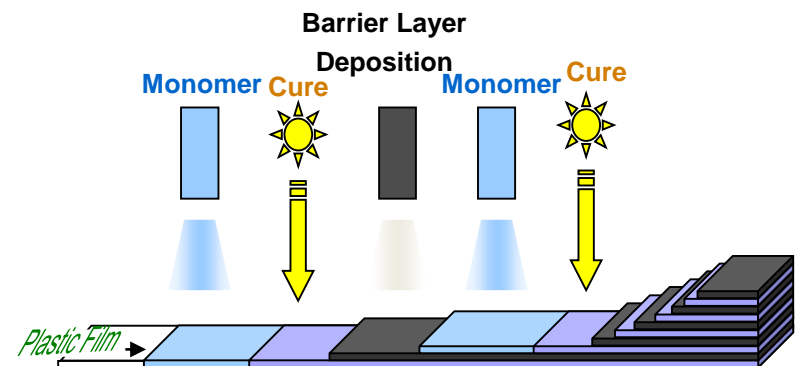
# Barrier Technology 1



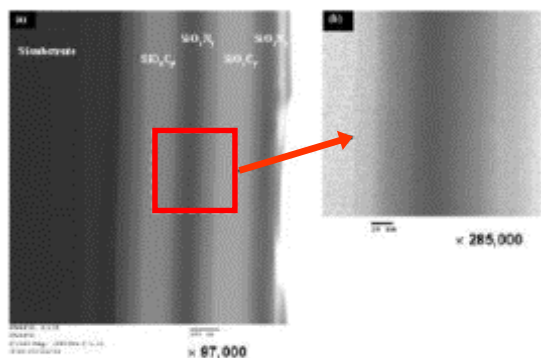
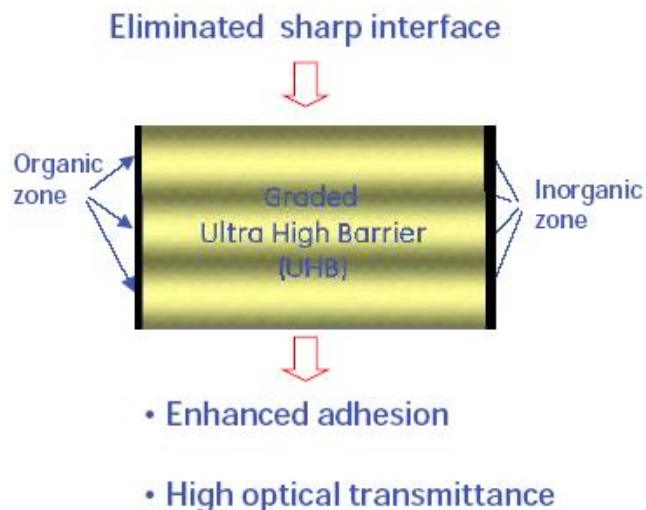
- ❑ Multiple Barrier layers
  - organic : planarization smoothing
  - inorganic : barrier to H<sub>2</sub>O, O<sub>2</sub> penetration
  - decouple defect



- ❑ Thin film barrier layer
  - Organic
    - Monomer mixture deposited in vacuum
    - Thickness 0.25~several  $\mu\text{m}$
  - Inorganic
    - Al<sub>2</sub>O<sub>3</sub> deposited by DC reactive sputter
    - Thickness 30~100nm
  - 4~5 polymer/inorganic pairs(dyads)



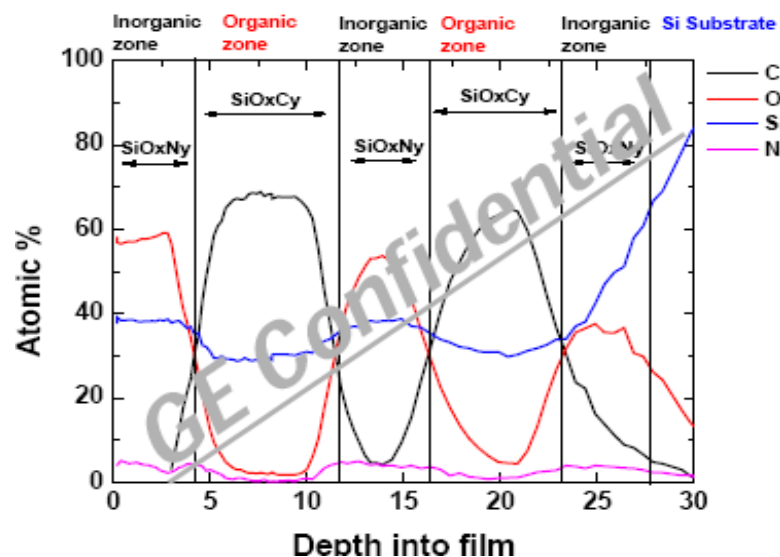
# Barrier Technology 2



## □ Multilayered structure Barrier

- Decouple defects
- Continuous Composition Transition (SiOxNy:Inorganic/SiOxCy:Organic)
- **Enhanced adhesion**
- **High optical transmittance**
- PECVD deposited inorganic layer

## XPS Spectrum of Graded UHB





## ❑ Dyad structure Barrier

- Polymer/Oxide layer
- Temperature Resistance :120°C (PEN)
- CTE 13~27 PPM
- Oxide roughness Ra=1.1nm
- substrate optical transmission 77~80%

Transparent Conductor Layer (ITO)

Oxide

Spacer polymer

Oxide

Spacer polymer

Oxide

Spacer polymer

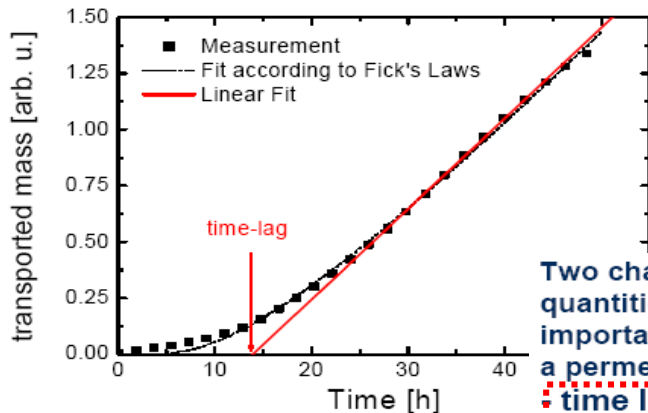
Oxide

Base polymer

SUBSTRATE

# Optimization of Barrier Layer 1

## Time evolution to permeation process



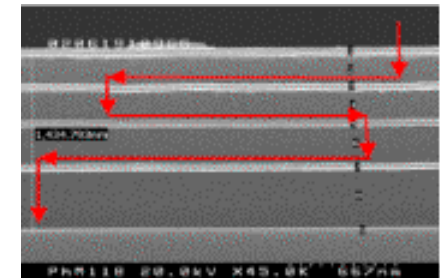
Two characteristic quantities are important to classify a permeation process:

time lag  
permeation rate

## Defect-dominant permeation process

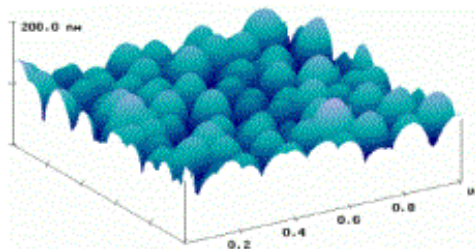


Prolonged pathway



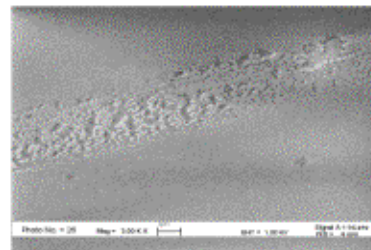
## Types of defect in organic layer

„intrinsic“ defects  
(growth related)

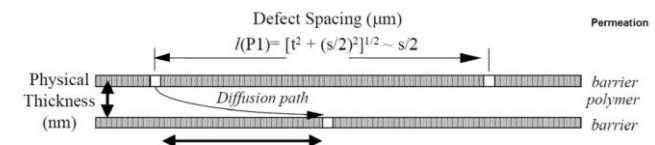


Minimized by deposition  
para and material

„external induced“ defects  
(by surface, dust-particles,...)

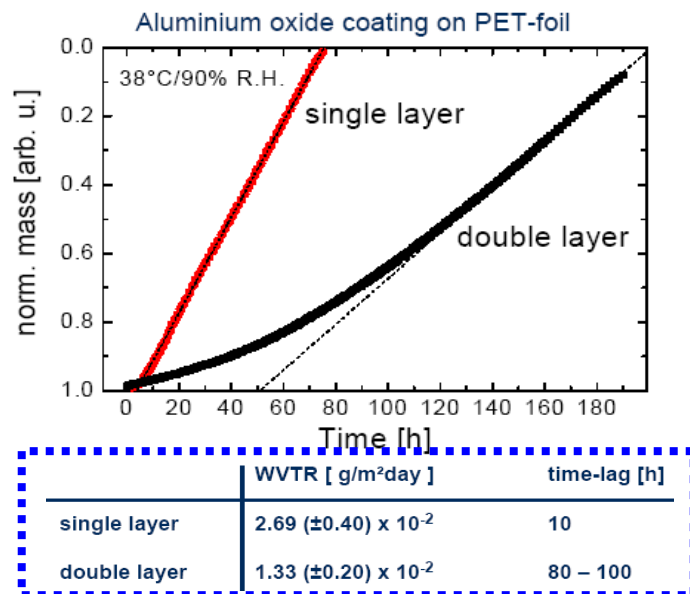


Minimized by surface roughness  
and contamination free

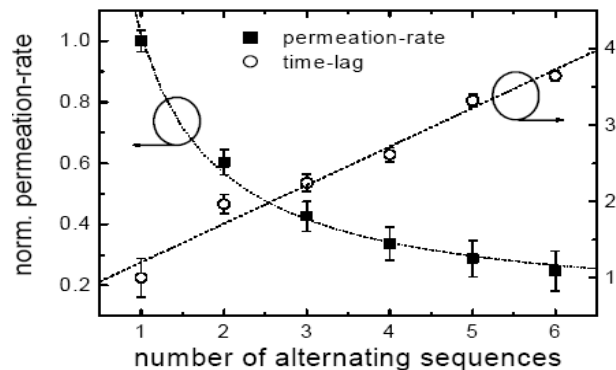


# Optimization of Barrier Layer 2

## □ Influence of alternation barrier layer

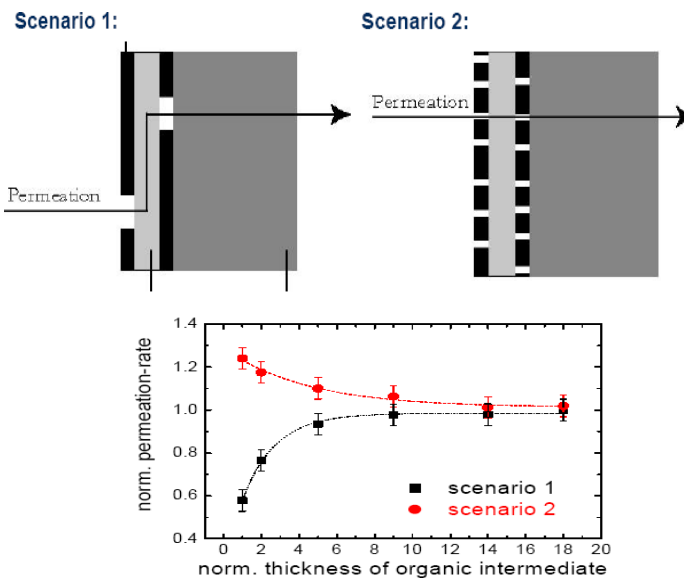


## □ Impact of large number of alternation layer



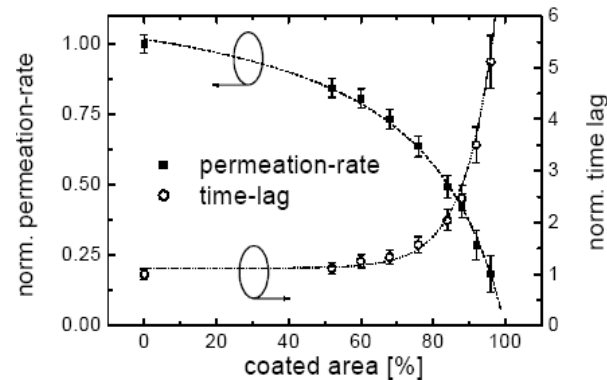
적정 layer수 결정!

## □ Impact of organic intermediate layer



organic layer의 적정두께 결정 !

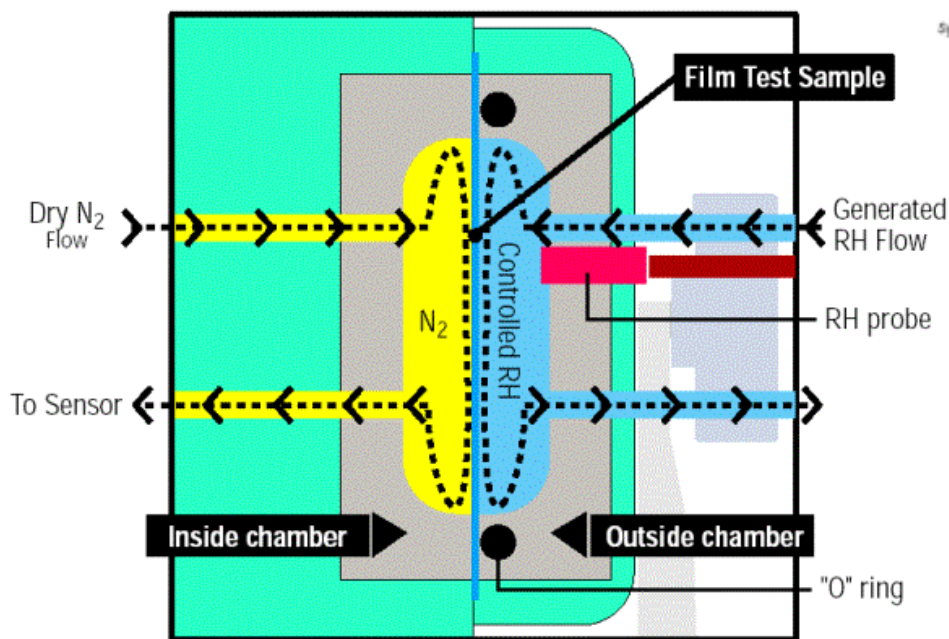
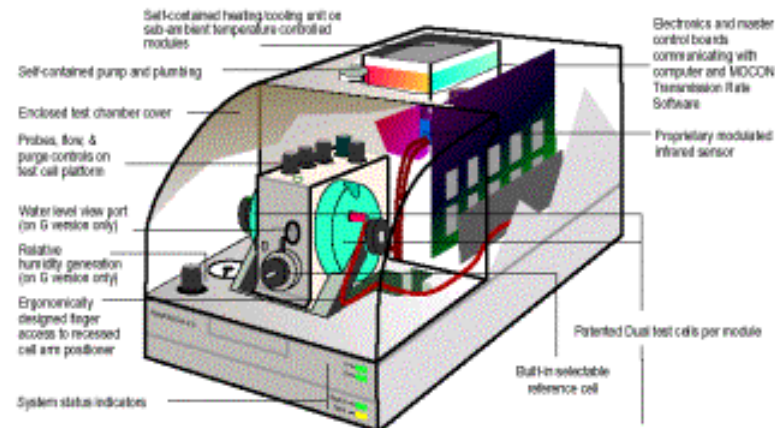
## □ Single inorganic layer effect



inorganic layer의 quality 중요!

# Test Method of WVTR (MOCON)

Detection limit :  $5 \times 10^{-3} \text{ g/m}^2 / \text{day}$



23C (75F)	90% RH
37.8C (100F)	90% RH
22C (73F)	50% RH
29.4C (85F)	80% RH

# Test Method of WVTR (Ca Test)

## Oxidized area method

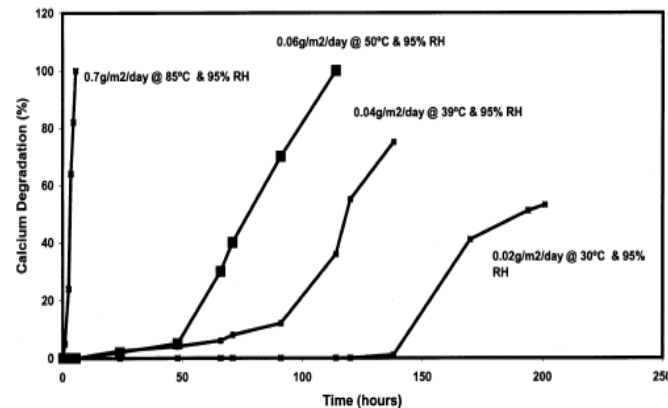
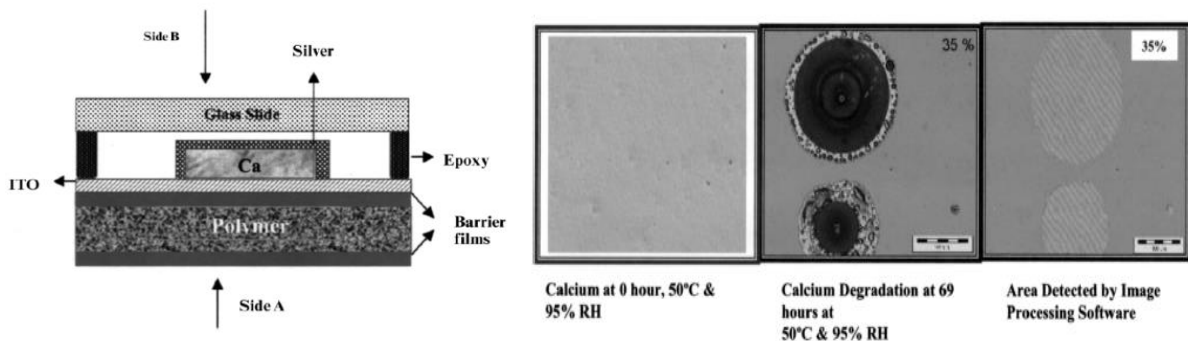


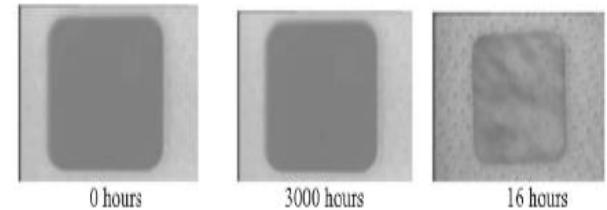
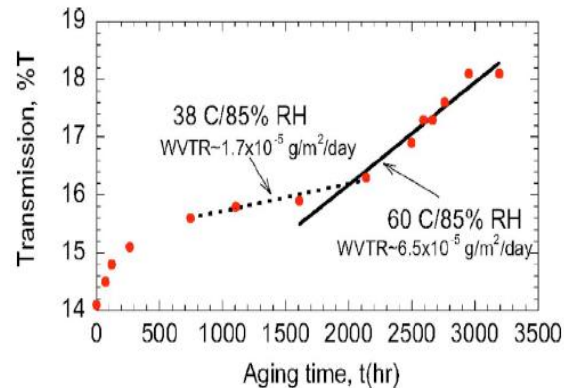
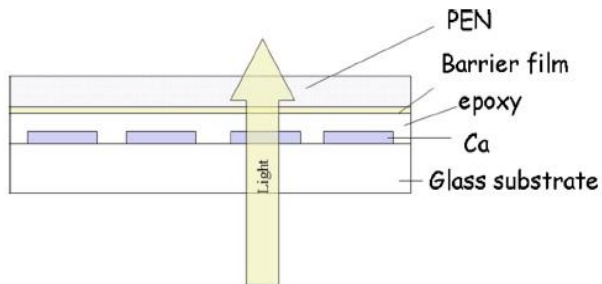
Fig. 8. Temperature dependence—sample (a).

*Thin Solid Films 417 (2002) 120–126*

- The degradation was monitored by optical microscopy and the percentage of oxidized calcium was measured
- Time taken to oxidize 100% of calciums 2.31 days  
water vapor required to oxidize 100% Calcium (for 100 nm thickness, area of 1 m<sup>2</sup> = 0.139g).  
Example : **0.06 g/m<sup>2</sup> day** at 50°C and 95% RH (**0.139 g / 2.31 days**)
- This method can provide an opportunity to study the water vapor permeation mechanism at higher temperatures

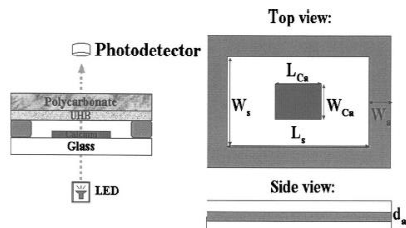
# Test Method of WVTR (Ca Test)

## Transmittance method



protected by ALD  $\text{Al}_2\text{O}_3$  barrier before and after aging for over 3000 h, and after ~16 h in ambient for a plastic lid without a barrier.

Appl. Phys. Lett. 89, 031915 (2006)



$$\text{WVTR} = -2A \frac{M[\text{H}_2\text{O}]}{M[\text{Ca}]} \rho_{\text{Ca}} \frac{L_{\text{Ca}} W_{\text{Ca}}}{L_s W_s} \frac{d(\text{OD})}{dt}$$

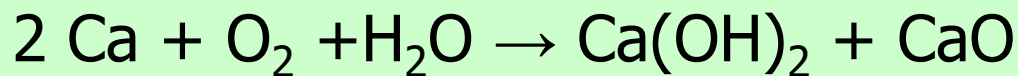
J. Vac. Sci. Technol. A, Vol. 23, No. 4, Jul/Aug 2005

$A = 1$  stoichiometric coefficient for water oxidation,  
 $M(\text{Ca}) = 40.078 \text{ g/mol}$        $M(\text{reagent}) = 18.015 \text{ g/mol}$   
 $\rho = 1.54 \text{ g/cm}^3$  the bulk density of Ca  
 $L_{\text{Ca}}, W_{\text{Ca}}$  : length and width of the deposited Ca  
 $L_s$  and  $W_s$  : length and width of the permeation area  
 $d\text{OD} / dt$  : slope of the measured optical absorbance as a function of time

- The general features for the plastic lid with an  $\text{Al}_2\text{O}_3$  ALD barrier and the glass control are the same.
- $\text{Al}_2\text{O}_3$  barrier film grown by ALD can have a WVTR  $10^{-5} \text{ g/m}^2 \text{ day}$  at room temperature

# Test Method of WVTR (Ca Test)

- Degradation of deposited Ca layer
  - Transmission increase



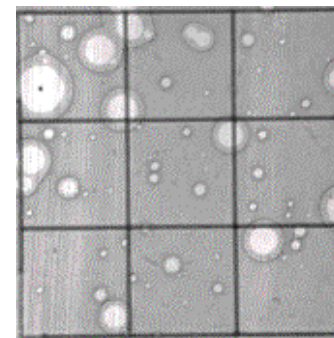
- Can be a quantitative measure of bulk WVTR
  - Transmission before / after aging
- Also used as a qualitative test for defects

Glass lid or multilayer encapsulation

Ca layer

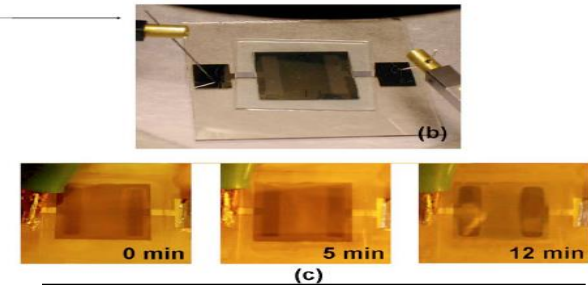
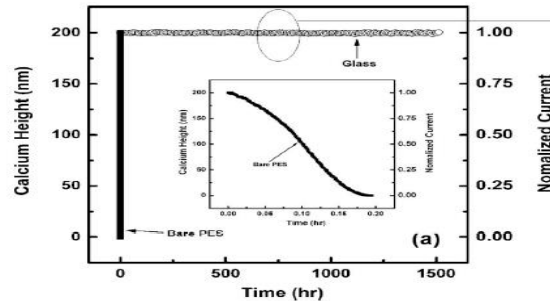
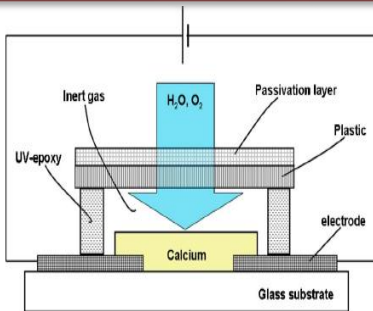
White light

barrier substrate or glass



# Test Method of WVTR (Ca Test)

## Conductivity method



Rev. Sci. Instrum. 78, 064701 (2007)

$$P = -n \frac{M(\text{reagent})}{M(\text{Ca})} \delta \rho \frac{\ell}{b} \frac{d(1/R)}{dt}$$

$\rho_{\text{Ca}}$  1.55 g/cm<sup>3</sup>

$\delta_{\text{Ca}}$  3.4 × 10<sup>-6</sup> cm Ω

$G_s = 1/R_s = (W/L) \cdot (1/R)$

L : Length of Ca  
W : Width of Ca

M(H<sub>2</sub>O) 18 amu

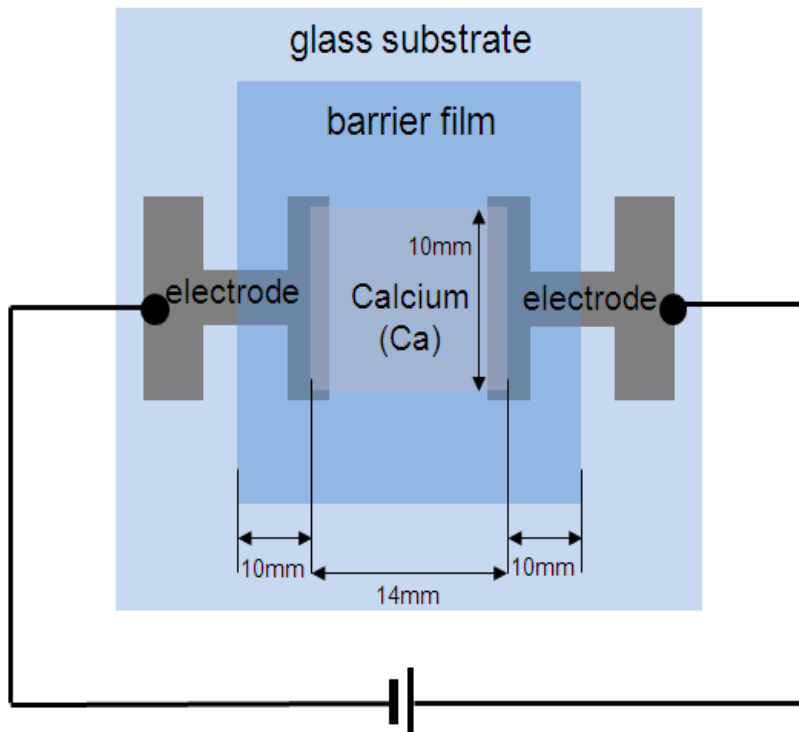
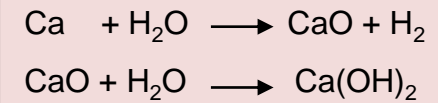
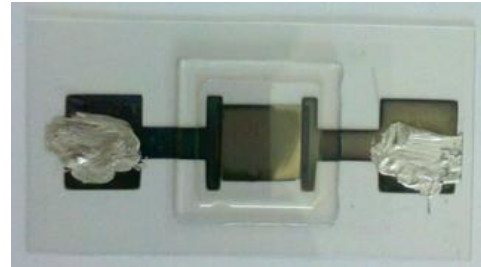
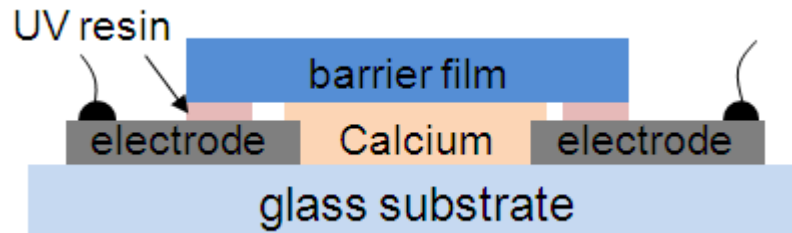
M(Ca) 40.1 amu

n = 2 stoichiometric coefficient for water oxidation,  
M(Ca) = 40.078 g/mol M(reagent) = 18.015 g/mol  
δ = 1.54 g/cm<sup>3</sup> the bulk density of Ca  
ρ = 3.4 × 10<sup>-6</sup> Ω cm is the resistivity of the Ca film.  
b = 1 cm width of the Ca film  
l = 1.4 cm separation between the Au/Cr contacts.  
1/R = measured conductance (mho).

- **The transmittance method requires additional work** because each layer has a different optical wavelength and the reflection values from each spot are too varied to average.
- It is particularly useful to evaluate time-dependent barrier properties because the gas permeation rate is determined by the increased resistance versus elapsed time

# Test Method of WVTR (Ca Test)

A schematic diagram of electrical Ca-test



$$P = -n \frac{M(\text{reagent})}{M(\text{Ca})} \delta \rho \frac{\ell}{b} \frac{d(1/R)}{dt}$$

$$\rho_{\text{Ca}} = 1.55 \text{ g/cm}^3$$

$$\delta_{\text{Ca}} = 3.4 \times 10^{-6} \text{ cm } \Omega$$

$$G_s = 1/R_s = (W/L) \cdot (1/R)$$

$$L : \text{Length of Ca}$$

$$W : \text{Width of Ca}$$

$$M(\text{H}_2\text{O}) = 18 \text{ amu}$$

$$M(\text{Ca}) = 40.1 \text{ amu}$$

$n = 2$  stoichiometric coefficient for water oxidation,

$M(\text{Ca}) = 40.078 \text{ g/mol}$        $M(\text{reagent}) = 18.015 \text{ g/mol}$

$\delta = 1.54 \text{ g/cm}^3$  the bulk density of Ca

$\rho = 3.4 \times 10^{-6} \Omega \text{ cm}$  is the resistivity of the Ca film.

$b = 1 \text{ cm}$  width of the Ca film

$l = 1.4 \text{ cm}$  separation between the Au/Cr contacts.

$1/R =$  measured conductance (mho).

# Commercial AMOLEDs

## ● LGD, Development of commercial flexible AMOLEDs (25.4)

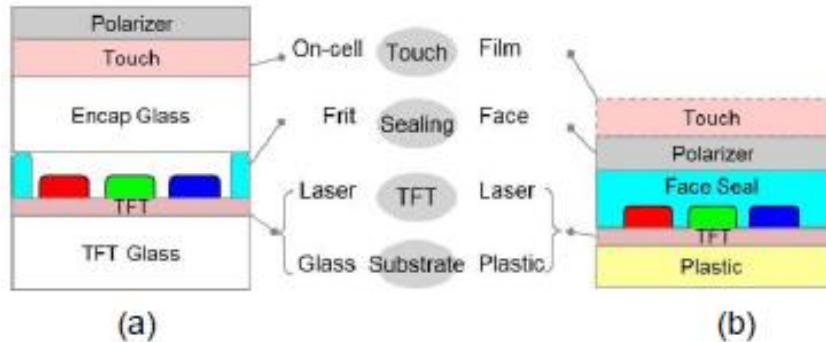


Figure 2. The structure of (a) Glass OLED and (b) Flexible OLED

→ Required to apply totally different material, design, process and equipment to commercialize flexible OLEDs

the newly-developed face-sealing encapsulation structure should have not only high transmittance but optical isotropic characteristics.

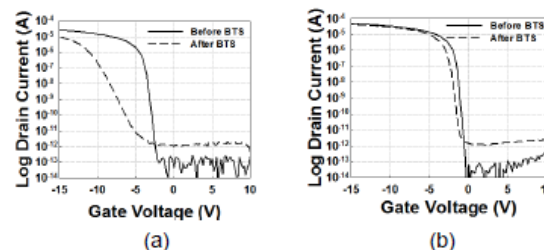
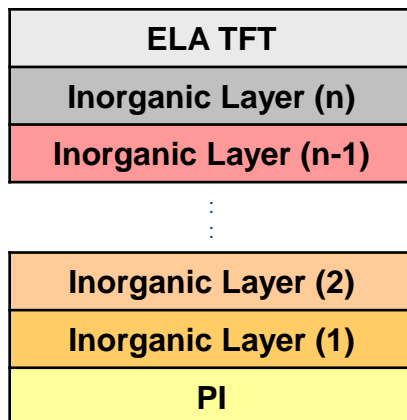


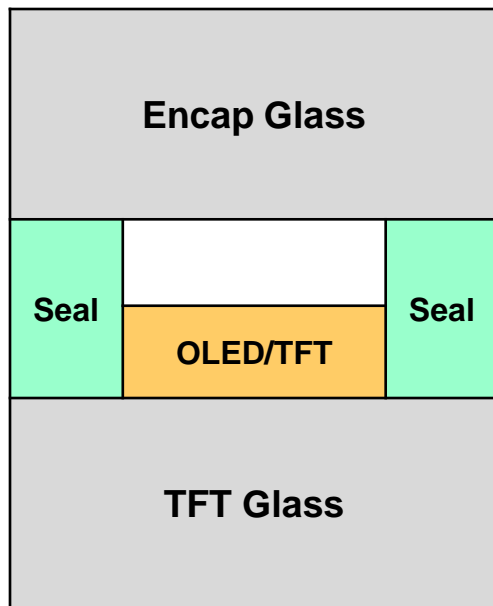
Figure 3. Development ELA-TFT on PI (a) early stage and (b) after optimization

→ Finally achieved excellent reliability characteristic by multi-layer buffer structure and process condition optimization

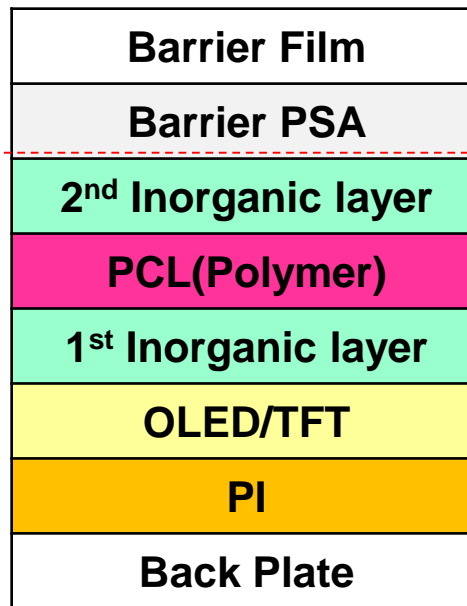
BTS condition ( $V_{gs}=0V$ ,  $V_{ds}=-20V@110^{\circ}C$ )

# Commercial AMOLEDs

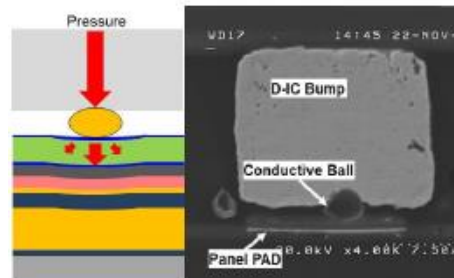
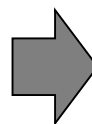
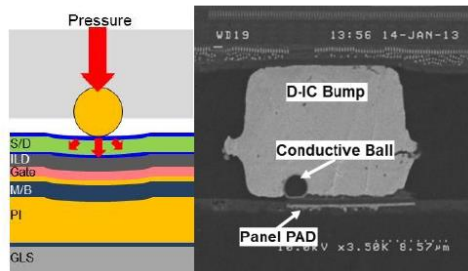
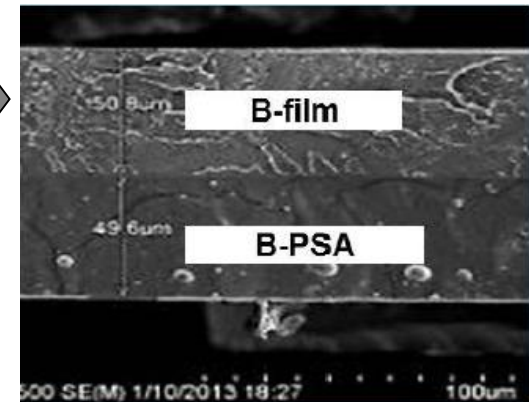
## ● LGD, Development of commercial flexible AMOLEDs (25.4)



Edge-seal Encapsulation



Face-seal Encapsulation

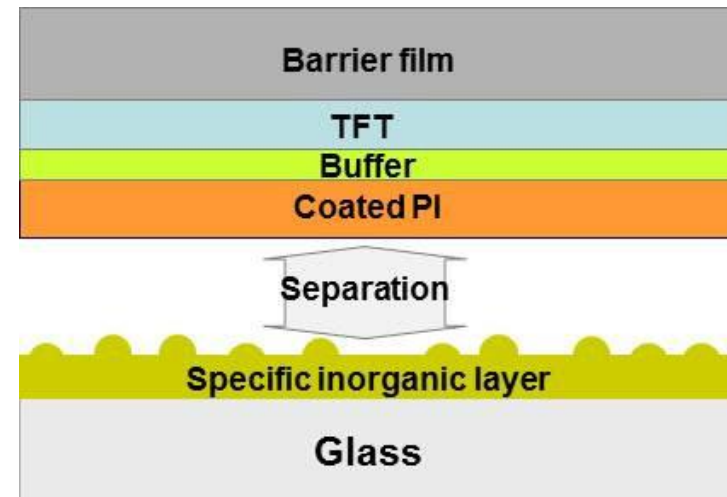
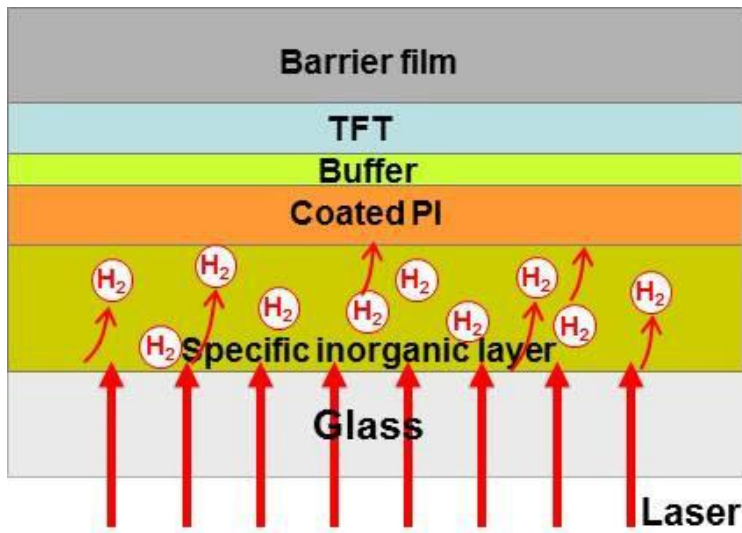
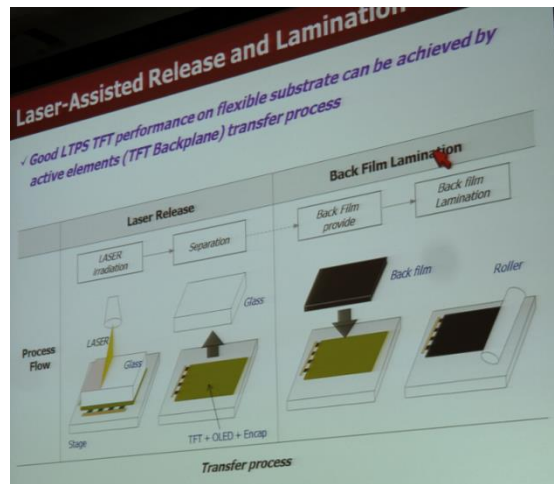


*Flexible substrate with PI under ELA-TFT has pressure absorption characteristic that induce line defects and several malfunction by COG/FOG failure*

*→ Developed conductive ball, higher hardness D-IC bump and optimized bonding pressure realized high module yield and reliability*

# Commercial AMOLEDs

## ● LGD, Development of commercial flexible AMOLEDs (25.4)



# Commercial AMOLEDs

## ● LGD, Development of commercial flexible AMOLEDs (25.4)

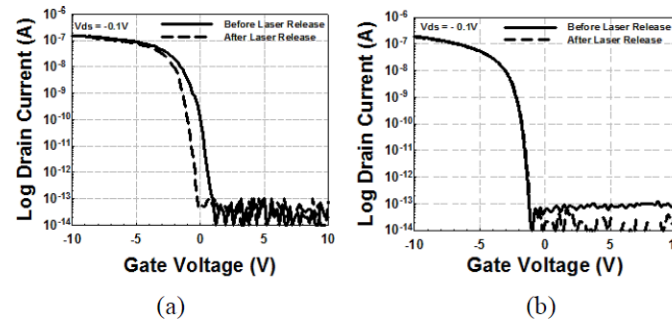
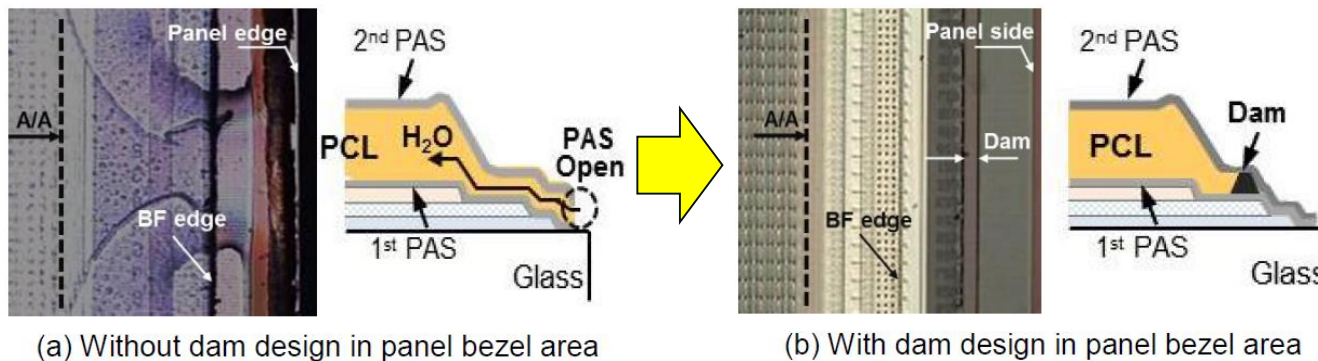


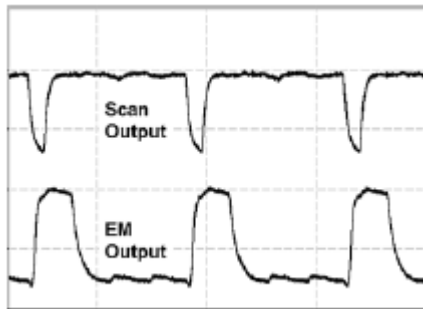
Figure 7. TFT on PI Characteristics (a) early stage and (b) after process optimization

**→ Optimization of laser irradiation process realized good TFT on PI characteristic w/o any performance change after process**

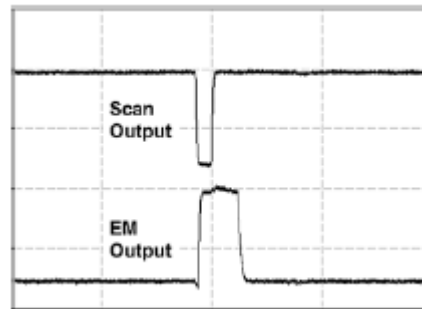
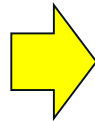


# Commercial AMOLEDs

## ● LGD, Development of commercial flexible AMOLEDs (25.4)



Abnormal gate driver output



Normal gate driver output

→ *Electrical reliability was achieved by optimized integrated gate driver circuit design*



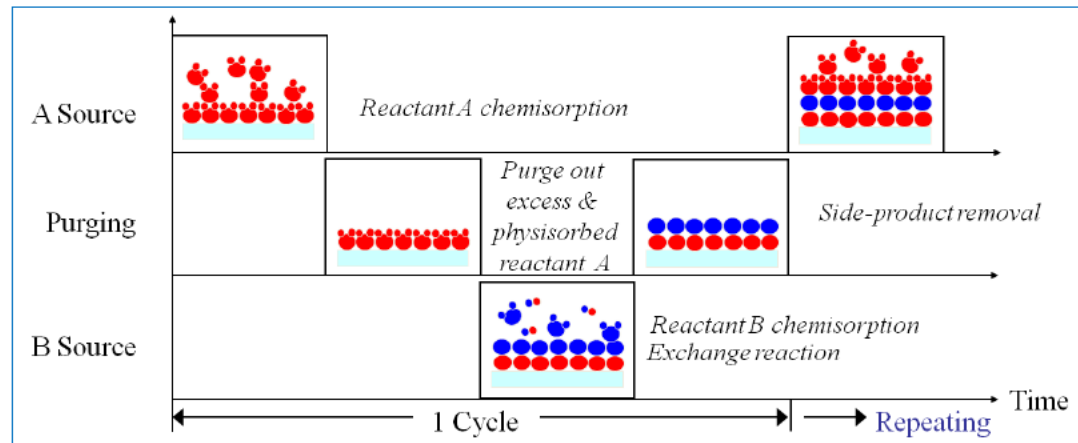
Figure 10. Photography of the 5.98-inch Flexible OLED

Item	Content	Unit
Panel size	5.98	Inch
Back-plane	ELA TFT on PI	-
Radius	700	mm
Bendable	~ 15	mm
Thickness	0.44	mm
Weight	7.12	g

# Atomic Layer Deposition

## ALD: Atomic Layer Deposition

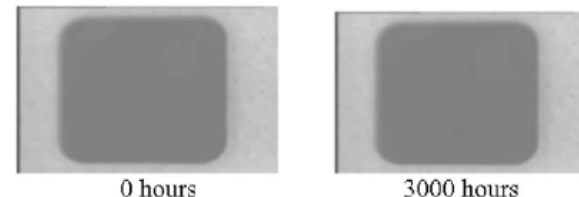
- Surface Limited Reaction; saturation growth mechanism
- Complementary Reaction
- Excellent conformality, Pin-hole and particle free, Low temperature process
- Low throughput, Large area equipment



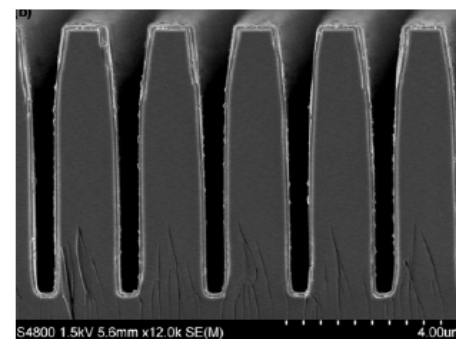
# Stretchable Encapsulation?

## Why ALD for Inorganic Layer?

- Outstanding film quality & **barrier performance**
- **Excellent Conformal Coverage**
- **Sputtering:** porous inorganic film
  - Highly damage-prone by Argon plasma
- **PECVD:** low density of the film
  - > 200 nm for barrier stacking → low flexibility
  - SiNx 300 nm:  $\sim 10^{-3}$  g/m<sup>2</sup> day



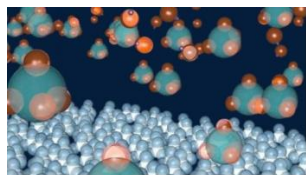
*S.M. George et.al., Appl. Phys. Lett., 89 (2006)*



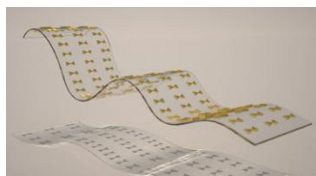
	ALD	Sputter	PECVD
Barrier Property	Excellent	Poor	Good
Optical Property	Good	Good	Good
Flexibility	OK	Poor	Poor
Surface Morphology	Extremely Flat	Relatively Rough	Very Flat
Dep. Rate	Slow	OK	OK

# Atomic Layer Deposition

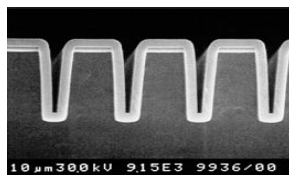
## Advantage of ALD



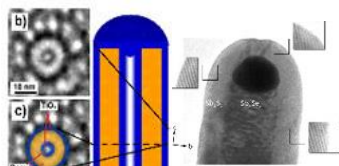
Atomic Level Control



Low Temperature



Excellent Step Coverage

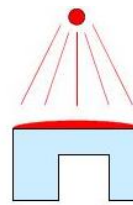


3D Structure

## Conformality



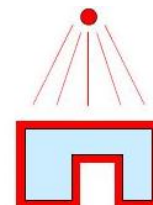
Liquid phase process  
(sol-gel)



Source controlled  
gas phase process  
(PVD)



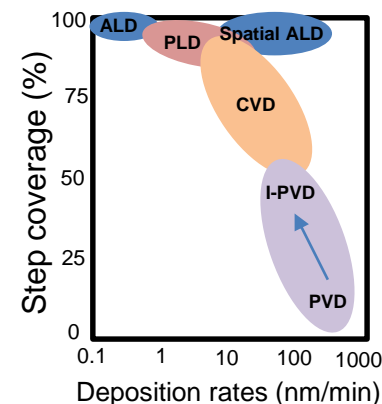
Semi-surface controlled  
gas phase process  
(CVD)



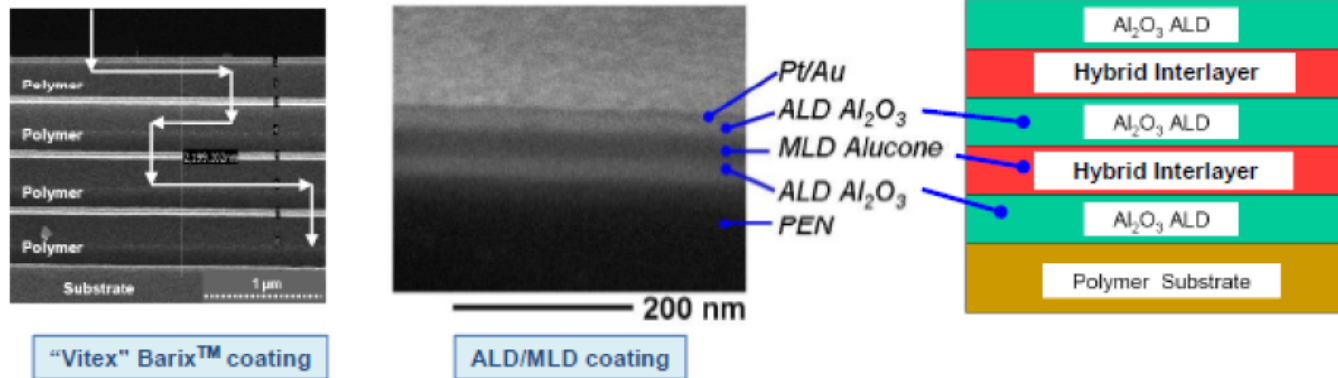
Surface controlled  
gas phase process  
(ALD)

## Comparison between ALD and other deposition method (CVD)

	CVD	ALD
Step coverage	Good (~70%)	Excellent (~95%)
Deposition temp.	< 400 °C	< 400 °C
Deposition reaction	Surface reaction + Gas phase reaction	Surface reaction
Particle	-	Good
Contamination	5 ~ 30 at% (C,O)	< 1 at%
Thickness control	Depend on gas flow rate, temp, time, etc.	Good (Depend on # of cycle)
Repeatability	OK	Good
Composition	Bad	Good



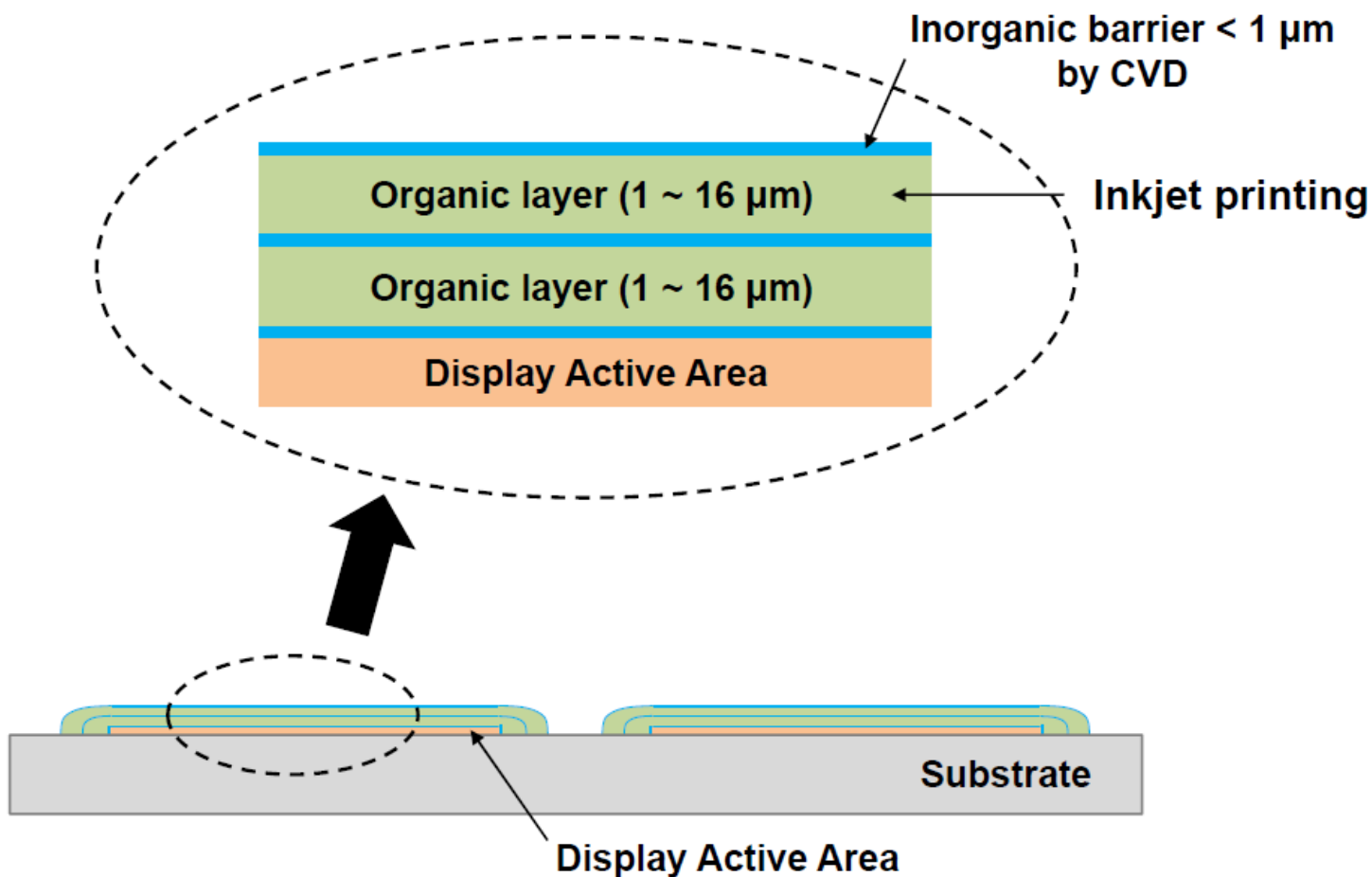
# Atomic Layer Deposition



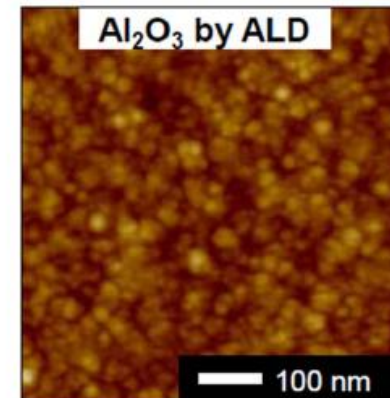
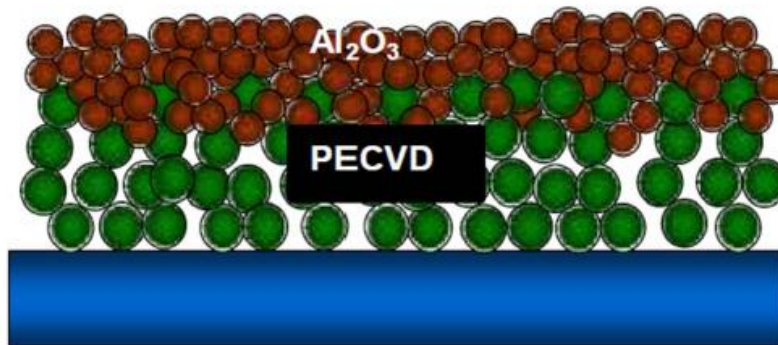
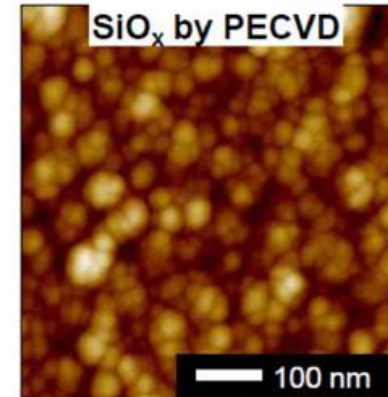
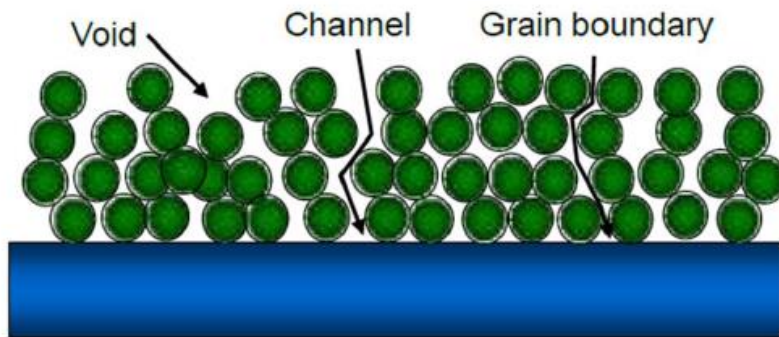
	Vitex 기술	ALD/MLD 기술	ALD/MLD 상대우위
Inorganic	Sputtering	ALD	고밀도, pin hole free, step coverage 우수
Organic	Polyacrylate	MLD	층간 화학적 결합
박막두께	> 5 μm	초박막 (< 1 μm)	박막
Throughput	매우 낮음	매우 높음	고생산성


\*MLD : Molecular Layer Deposition


# Recent Development Trend for AMOLEDs



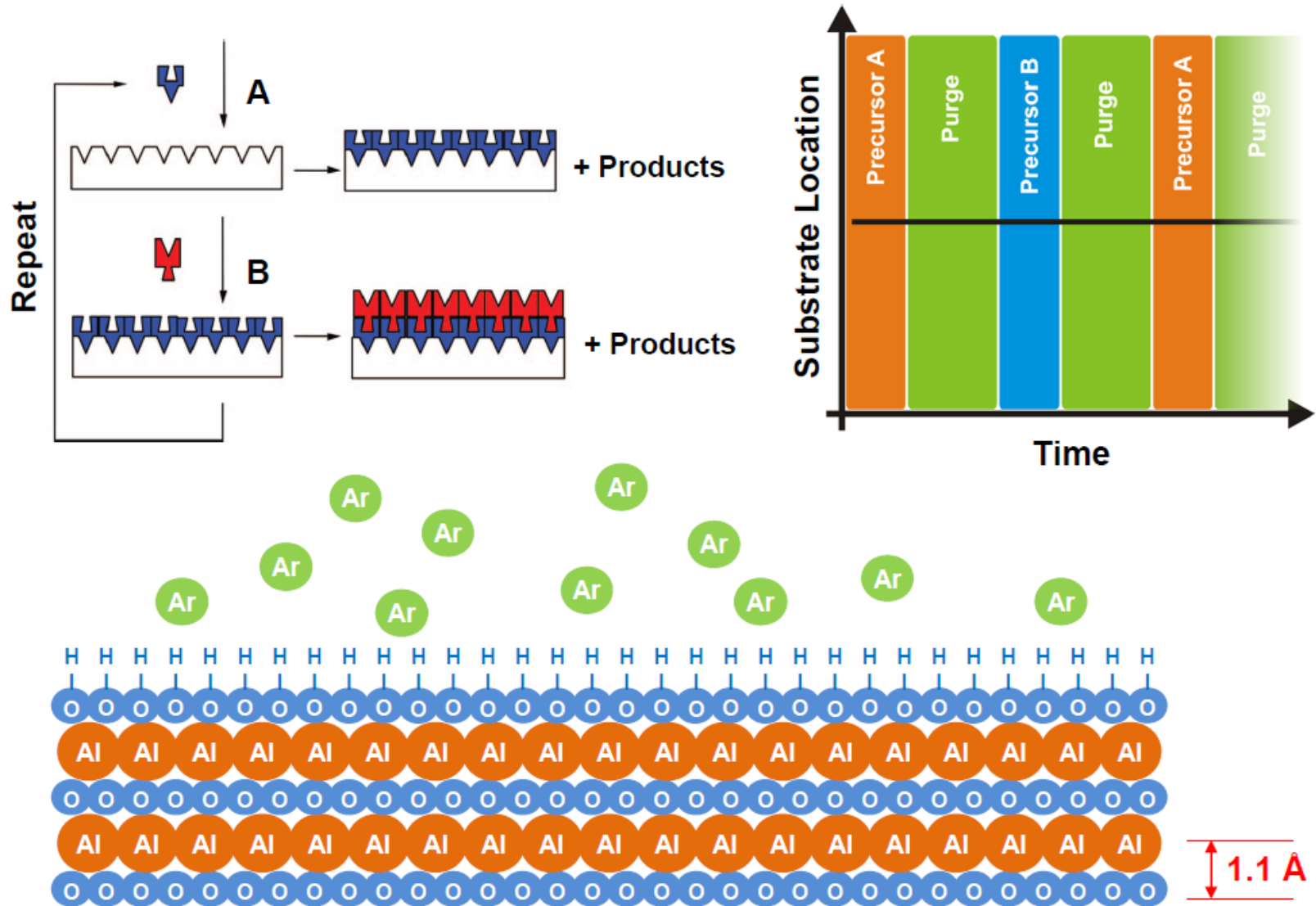
# TFE by CVD and ALD



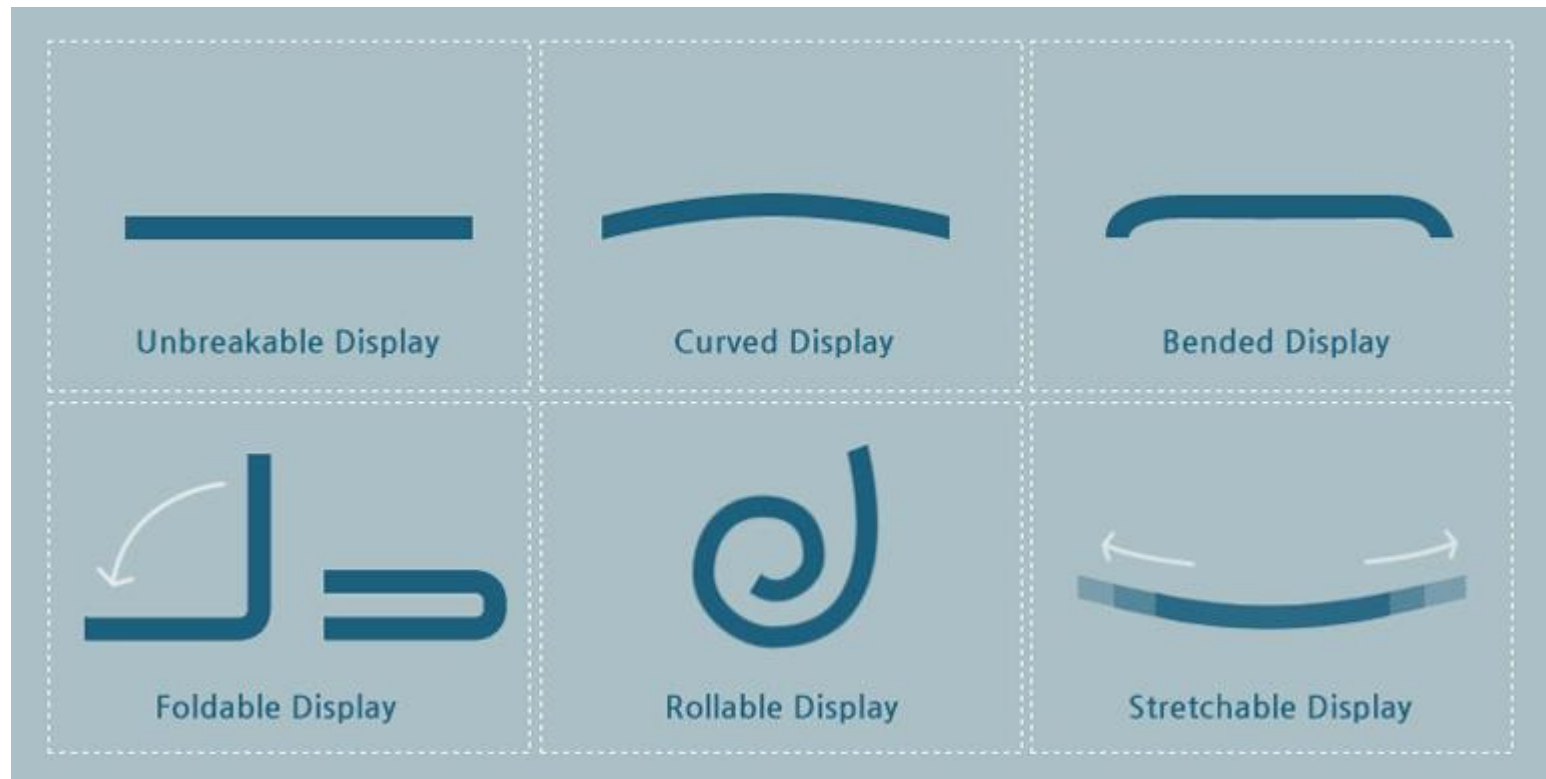
 SiO<sub>x</sub> by PECVD

 Al<sub>2</sub>O<sub>3</sub> by ALD

# ALD (Atomic Layer Deposition)



# Flexible Encapsulation?



<http://news.samsungdisplay.com>

# Flexible Encapsulation?

## 삼성디스플레이 플렉시블 OLED개발 흐름

곡률: 400R

2013년 9월  
갤럭시 라운드

플렉시블 OLED  
최초 양산



곡률: 57R

2014년 2월  
기어 핏

웨어러블용 플렉시블  
OLED 첫 양산



곡률: 7R  
곡률: 13R

2013년 8월  
갤럭시 노트 엣지

커브드 엣지 OLED  
첫 양산



곡률: 47R

2014년 9월  
기어 S

곡률 대폭 개선



곡률: 6.5R  
곡률: 12R

2015년 3월  
갤럭시 S6 엣지+

영향상부한 플렉시블  
OLED 대량양산 시대 개막



자료: 삼성디스플레이 · 키움증권

2016.4.1 전자신문 발췌

## 플렉시블 OLED 기술진화 방향

1세대	2세대	3세대	4세대
UBP	UBC	UBF	UBR
UnBreakable Plane	UnBreakable Curved	UnBreakable Foldable	UnBreakable Rollable
2013	1H15	2H16	2H17
			
			

자료: 키움증권

## 플렉시블 디스플레이 구현을 위한 핵심기술

	상세 설명
플라스틱 원도	• 평면 LCD 및 OLED의 강화유리(고릴라 글라스) 대체
터치센서	• ITO 대신 탄성이 뛰어난 대체 전극 소재 필요 예) 은나노 와이어, 메탈 메시, 폴리머 등 유연 전극
박막 봉지층	• TFE 기술 개선 - 각 층의 두께를 줄이고 적층수를 줄이는 기술개발 필요

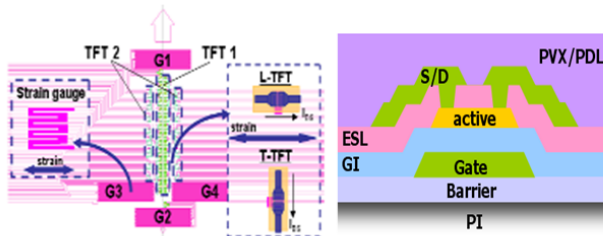
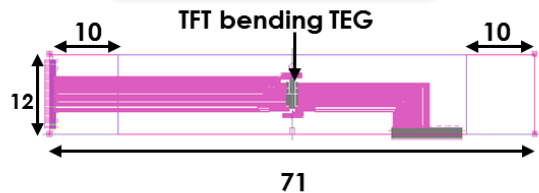
자료: 삼성전자 · 대신증권 · 산업은행

# Mechanical Issue

## Experiment

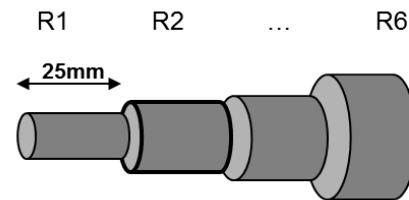
1. Bending on mandrel with Specific Radius for 1 min
2. Measurement of TFT performance in flat status after bending

## Bending TEG



\* TEG : Test Evaluation Group

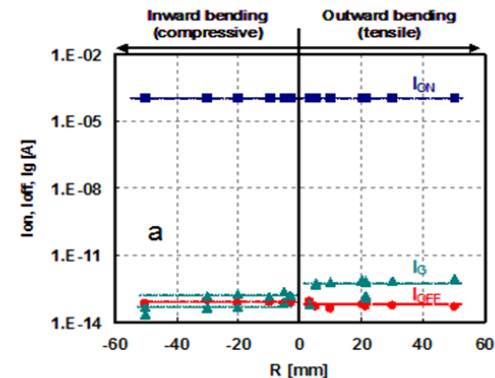
## Mandrel Set



	R1	R2	R3	R4	R5	R6
R (mm)	3	5	10	20	30	50

## Results

### Free-standing Plastic substrate



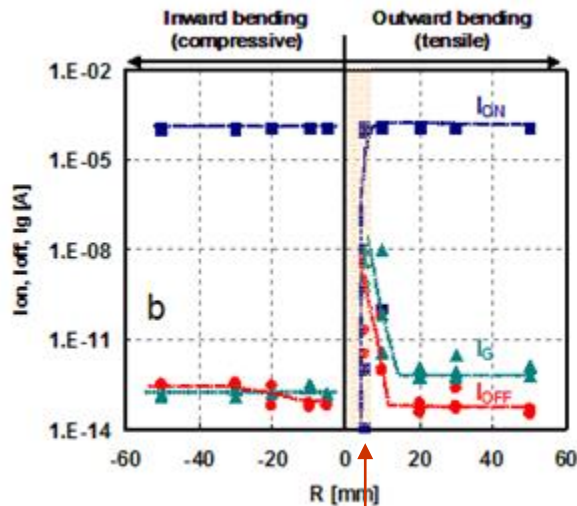
No crack  
down to  
3mm

# Mechanical Issue

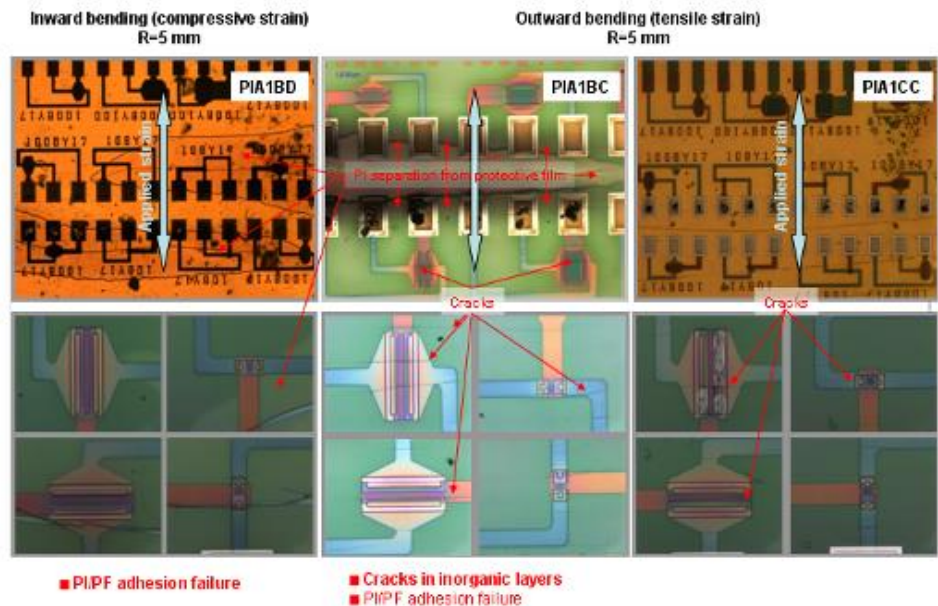
- TFT performance on free-standing plastic substrate with protective film was degraded at 10mm of bending radius  
 $\Rightarrow$  Thin substrate was required for small bending radius

## Results

### Free-standing Plastic+protective film



Crack at 10mm



# Mechanical Issue

● Transition: electrical property returns if strain eliminated

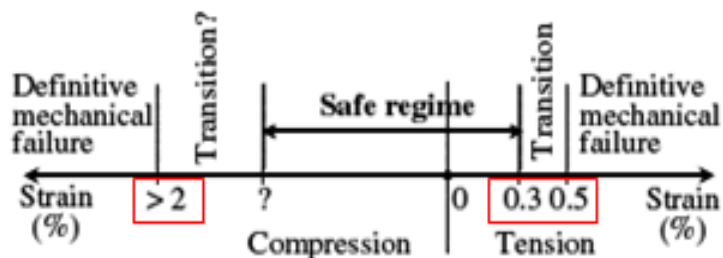


Fig. 3. Summary of the response of a-Si:H TFT on Kapton E to mechanical strain (Wagner et al., 2005).

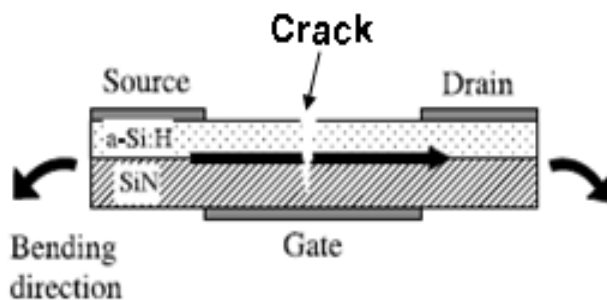


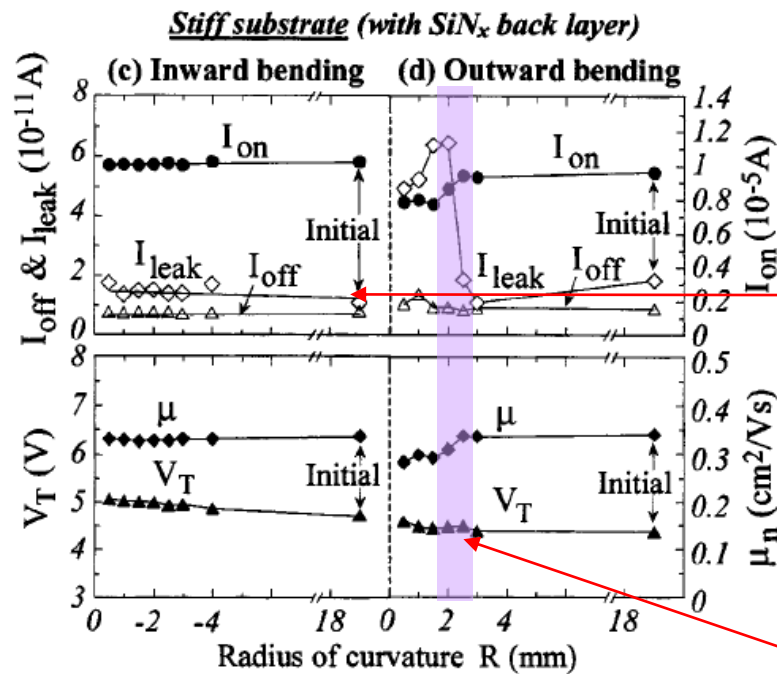
Fig. 4. Crack formation in a TFT when the strain and the source-drain current path are parallel. The arrow depicts the current path.

Stress type	Critical strain
Compressive	~2%
Tensile	~0.5%

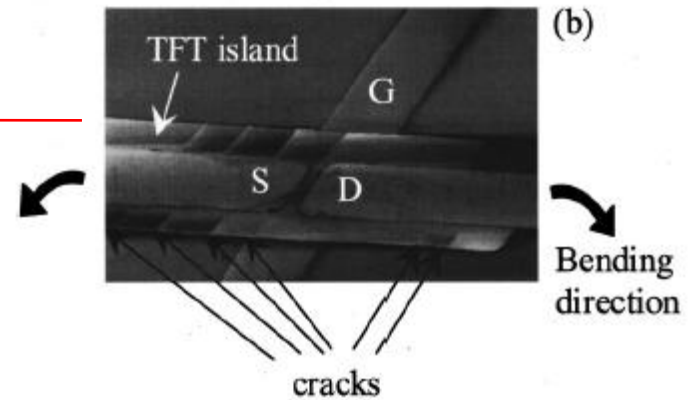
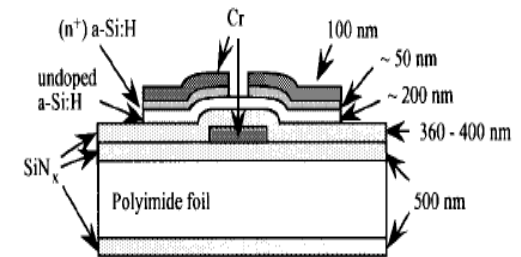
H. Gleskova et al., Solar Energy 780, p687 (2006) (PI substrate)

# Mechanical Issue

As  $\epsilon$ (tensile) increases,  $V_{th} \uparrow$ ,  $\mu \downarrow$ ,  $I_{off} \uparrow$



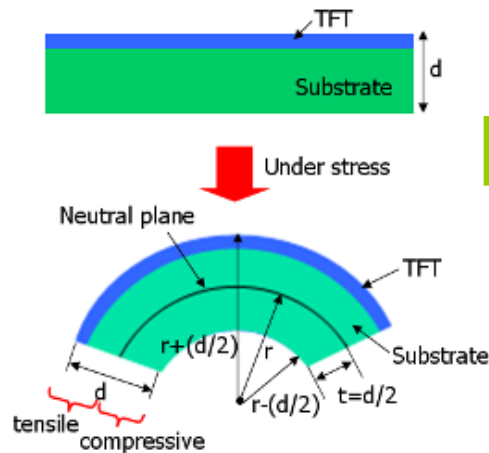
$\epsilon = 0.5\%$  ( $R = 2mm$ )



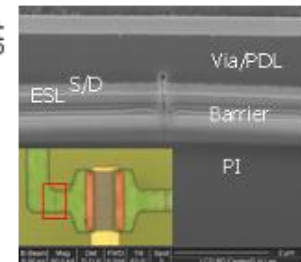
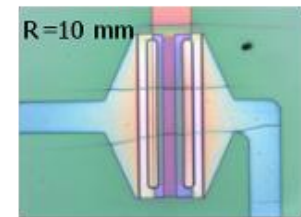
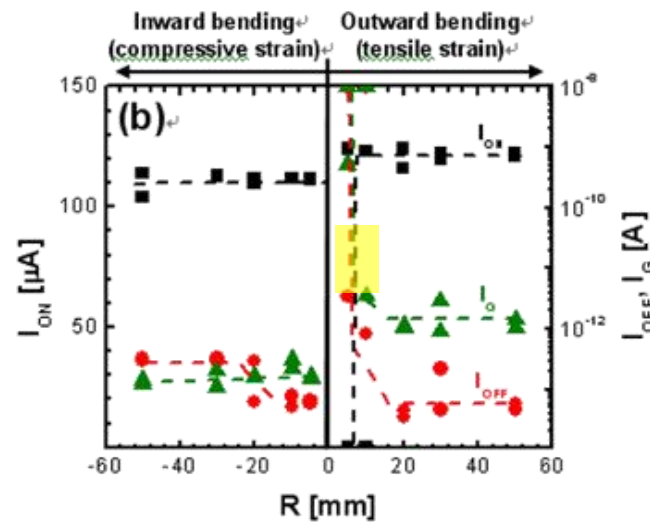
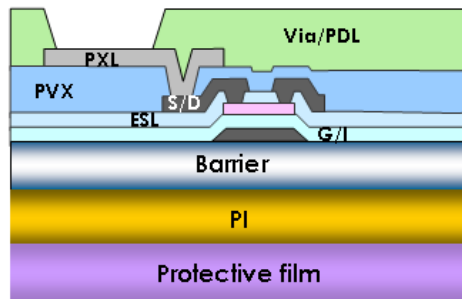
H. Gleskova (Princeton Univ.)\_APL, 75, p3011 (1999), IEEE\_EDL, 20, p473 (1999)

# Mechanical Issue

- $\epsilon \sim 0.5\%$  (tensile) @  $r=10\text{mm}$
- $\epsilon \sim 1\%$  (compressive) @  $r=5\text{mm}$

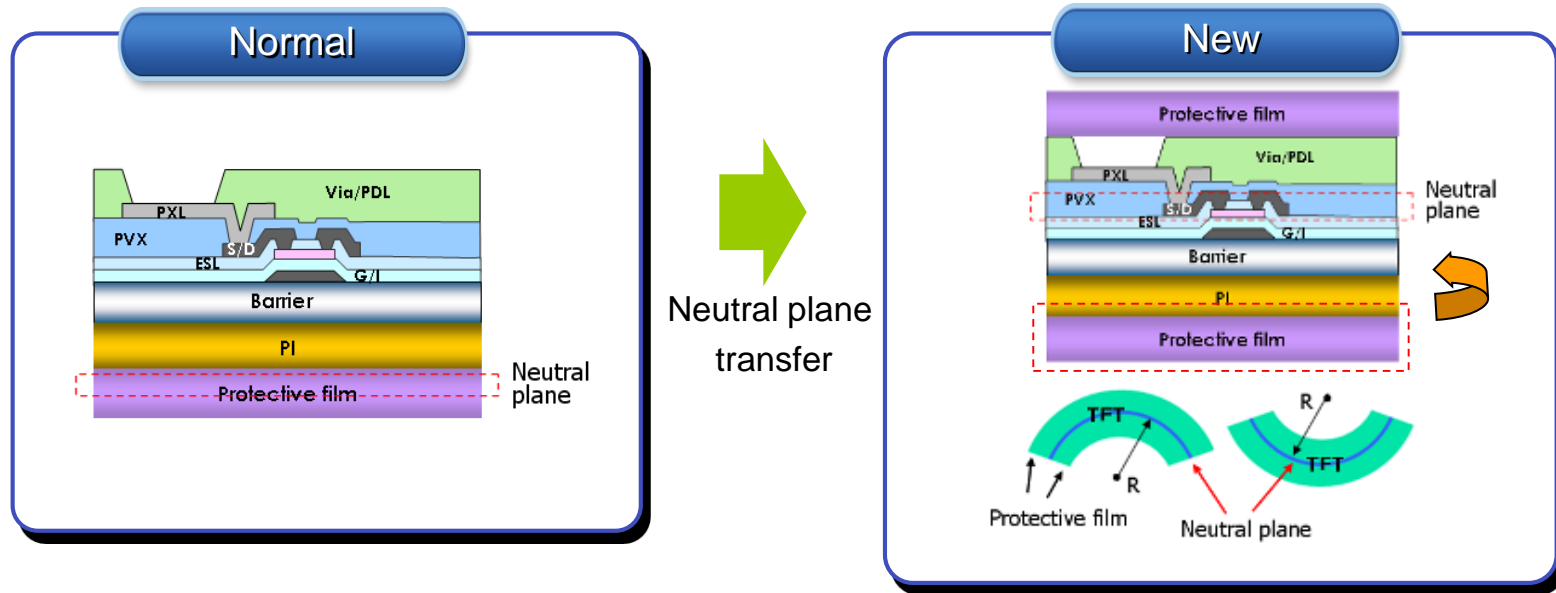


$$\epsilon_{top} = \frac{\Delta L}{L} = \frac{(r + d/2) \theta - r \theta}{r \theta} = d/2r$$



# Mechanical Issue

- Position of neutral plane is close to the middle of total thickness



$$\varepsilon_{top} = \left( \frac{d}{2r} \right) A = \left( \frac{d}{2r} \right) \frac{(1 + 2\eta + \chi\eta^2)}{(1 + \eta)(1 + \chi\eta)} \quad d = d_f + d_s$$

$$\eta = \frac{d_f}{d_d} = 0.015 \quad \chi = \frac{Y_f}{Y_s} = 23.5 \quad \rightarrow \quad A = 0.8 \approx 1$$

	d (um)	Y(Gpa)
TFT	1.5	200
PI+Protective film	103	8.5

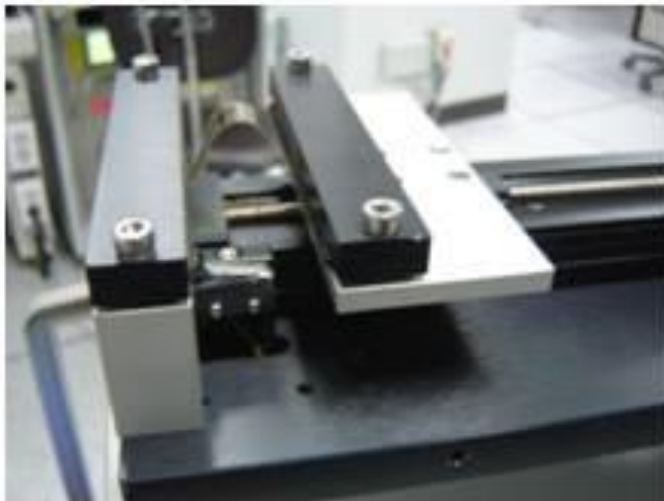
# Mechanical Issue

$R_c = 10$  mm (one time bending)

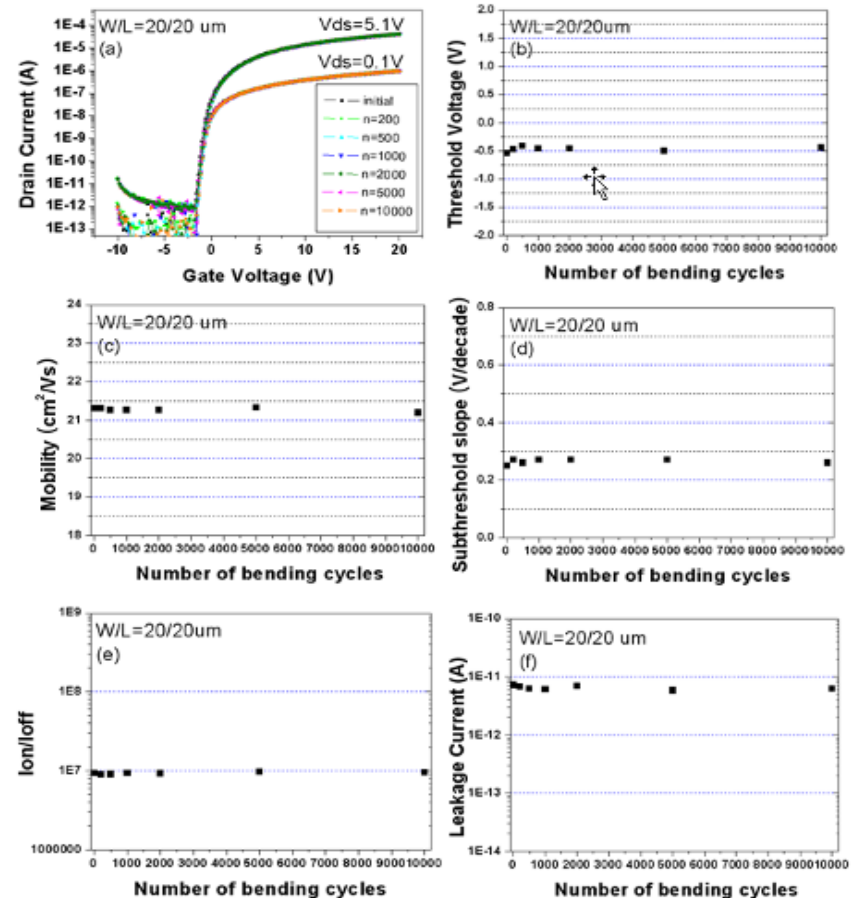


New structure

$R_c < 5$  mm (cyclic bending)

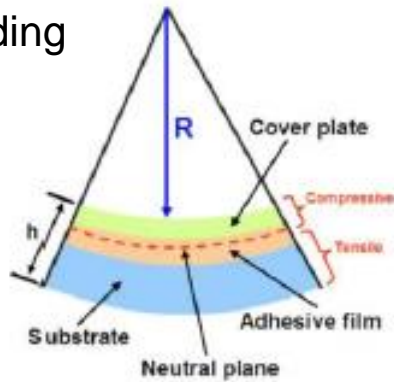


## Tensile ( $R=5$ mm)



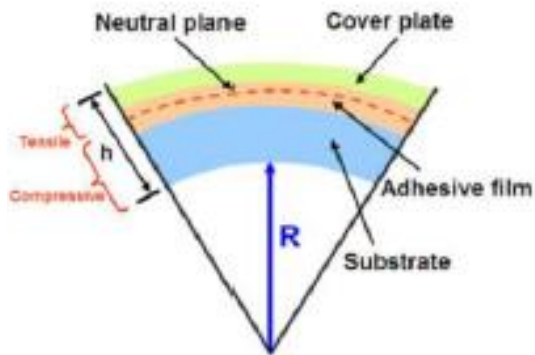
# Flexible Encapsulation?

In-Folding



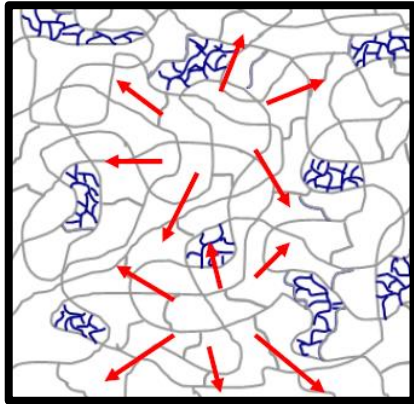
압축 응력 받음 → Buckling 피로 파괴 발생

Out-Folding



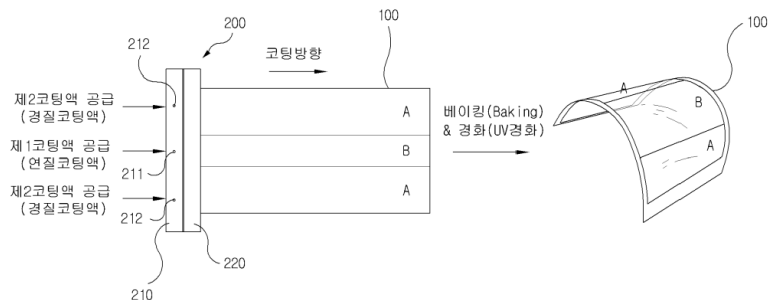
인장 응력 받음 → Crack 피로 파괴 발생

# Flexible Encapsulation?

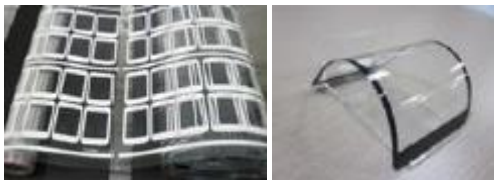


Soft organic area (저밀도 유기 가교 영역) 와  
hard inorganic network (고밀도 무기 가교  
영역) 을 가지고 있는 신소재 개발

→ 굴곡 유연성 및 고경도 표면 특성 동시 구현

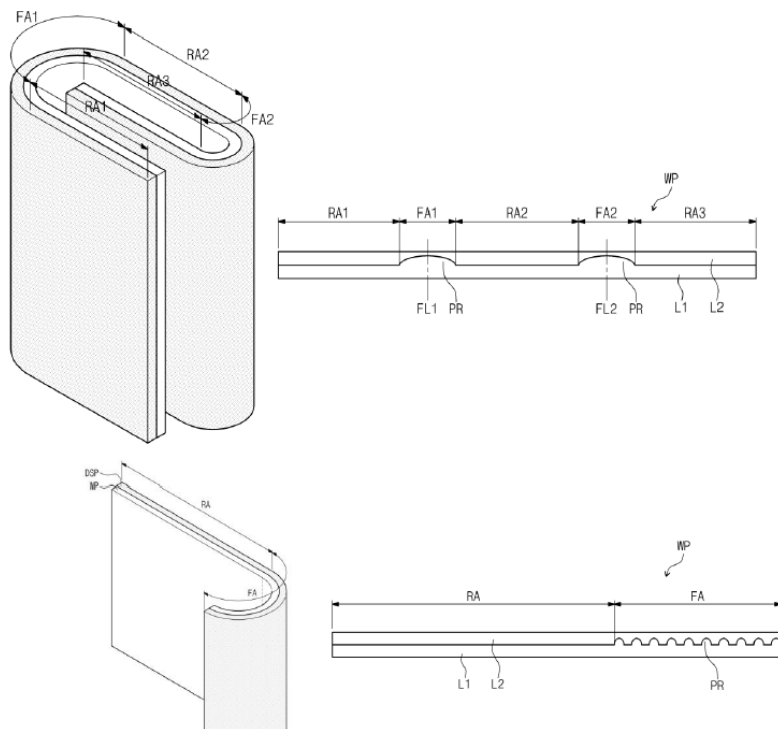


필름 + 코팅 단순 구조 또는 굴곡 / 평탄부  
복합구조 개발

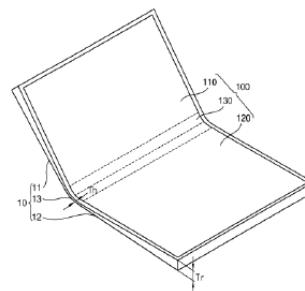


Roll-to-Roll 연속 공정 및 Curl free 공정 개발  
(Film)

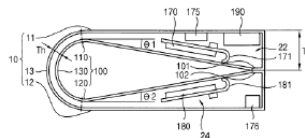
# Flexible Encapsulation?



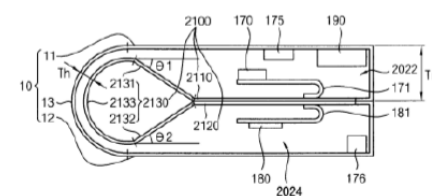
도면2



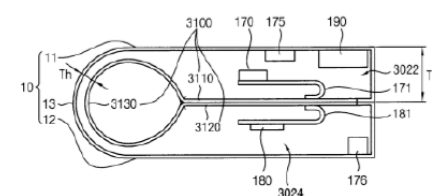
도면3



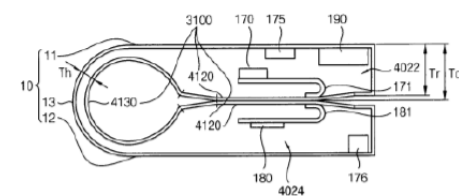
도면4



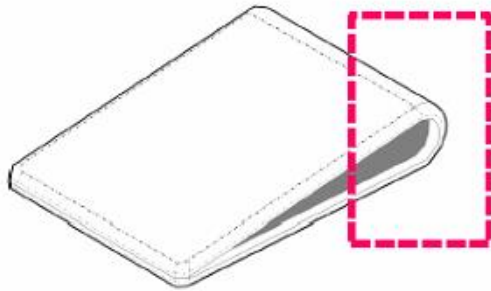
도면5

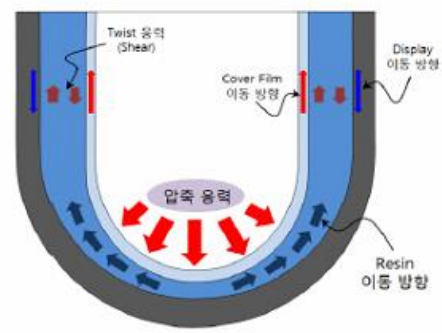
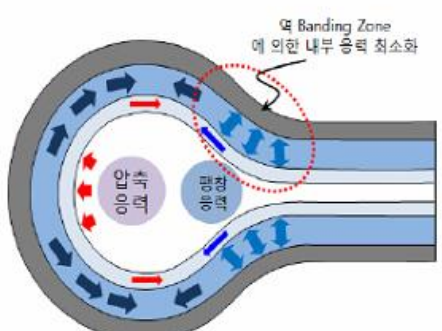


도면6

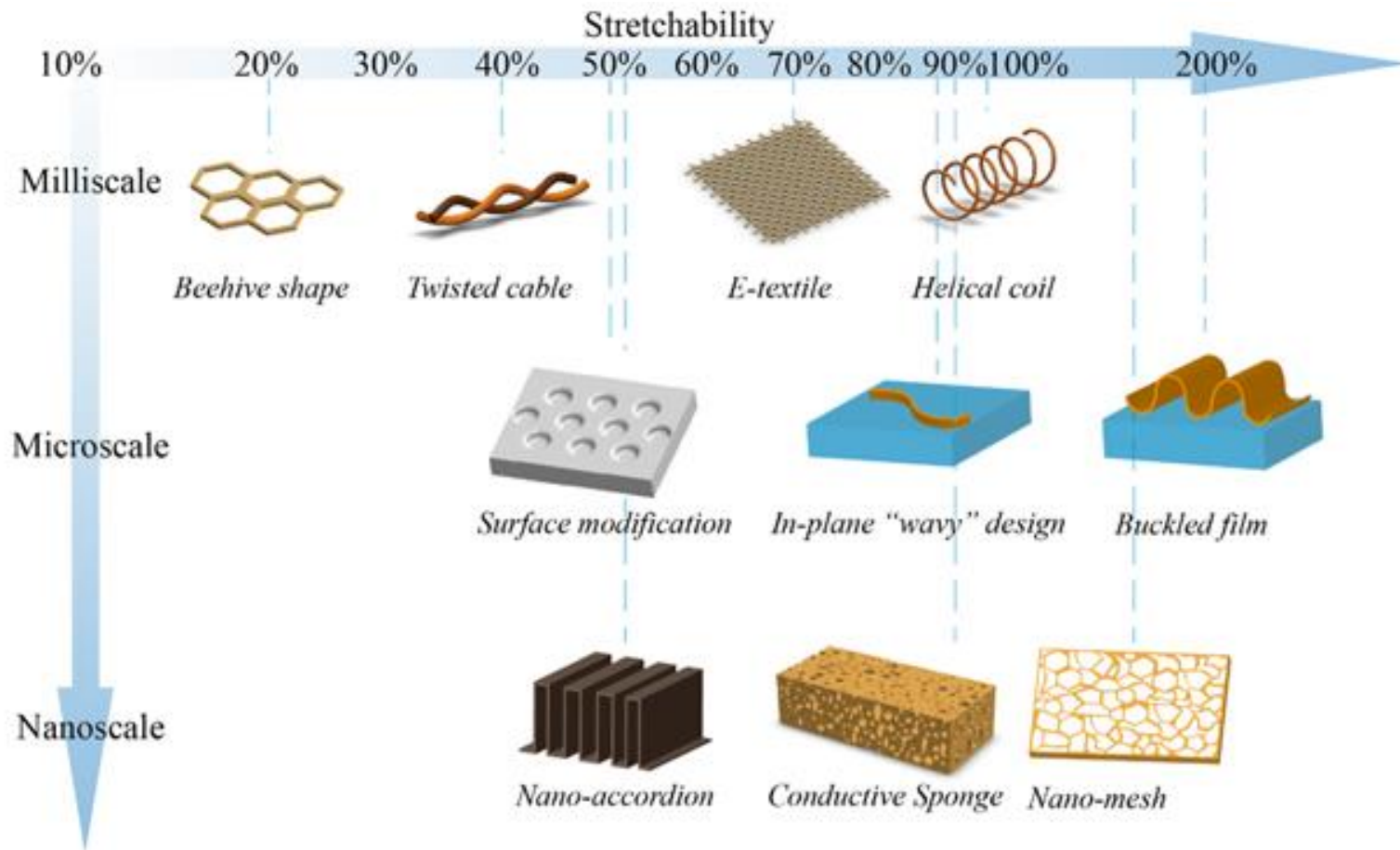


# Flexible Encapsulation?



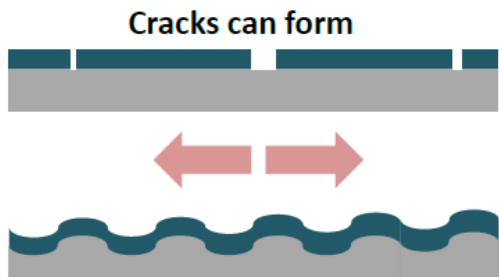
Internal Stress by Design	Key Factors
	<p>❖ Effect Factors</p> <ol style="list-style-type: none"> <li>① Radius</li> <li>② Design</li> <li>③ PI</li> </ol> <p>➡</p> <p>❖ Design Considerations</p> <ol style="list-style-type: none"> <li>① Modulus</li> <li>② Strength</li> <li>③ Hardness</li> </ol>
	<p>❖ Effect Factors</p> <ol style="list-style-type: none"> <li>① Radius</li> <li>② Hinge Design</li> <li>③ PI</li> </ol> <p>➡</p> <p>❖ Design Considerations</p> <ol style="list-style-type: none"> <li>① Modulus</li> <li>② Strength</li> <li>③ Hardness</li> </ol>

# Flexible Encapsulation?



# Flexible Encapsulation?

Strain applied to the encapsulation layer



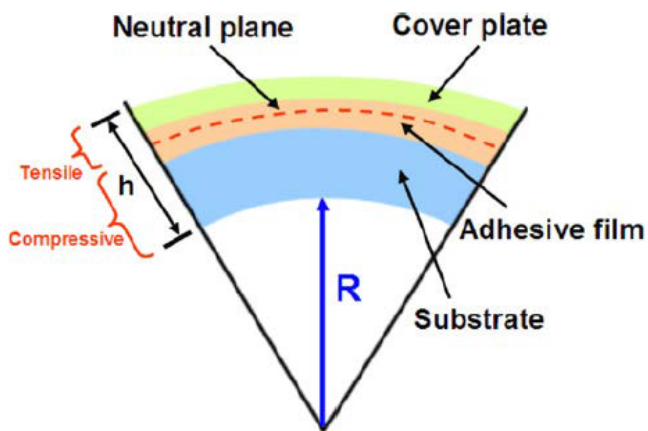
Flat substrate

Micro-strain = Macro-strain

Wavy substrate

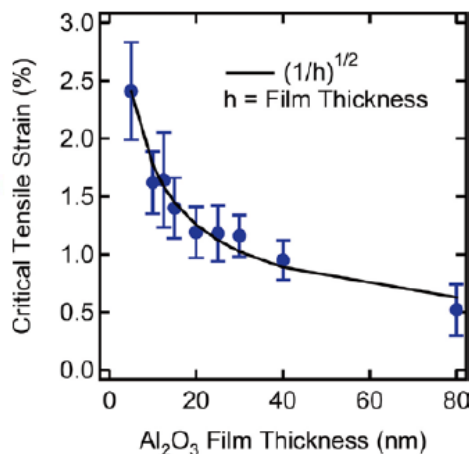
Micro-strain  $\ll$  Macro-strain

A corrugation structure must be incorporated to decrease real strain



where  $\eta = \delta_f / \delta_s$ ,  $\chi = Y_f / Y_s$ .

$\delta$  is thickness and  $Y$  is Young's modulus.



With the substrates thickness of 0.1 mm,

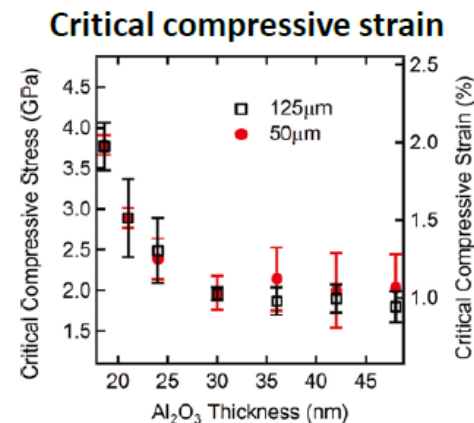
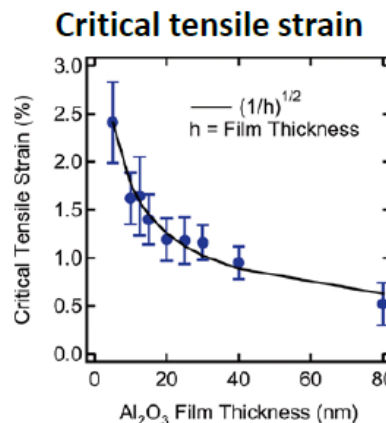
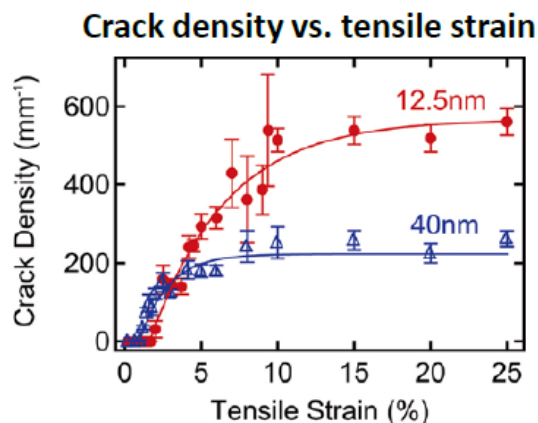
Radius of curvature 20 mm  $\sim$  0.25 % strain  
 10 mm  $\sim$  0.5 %  
 5 mm  $\sim$  1.0 %  
 2 mm  $\sim$  2.5 %

With the structure of 2 mm curvature, the inorganic layer thickness must be lower than 10 nm, at least!!

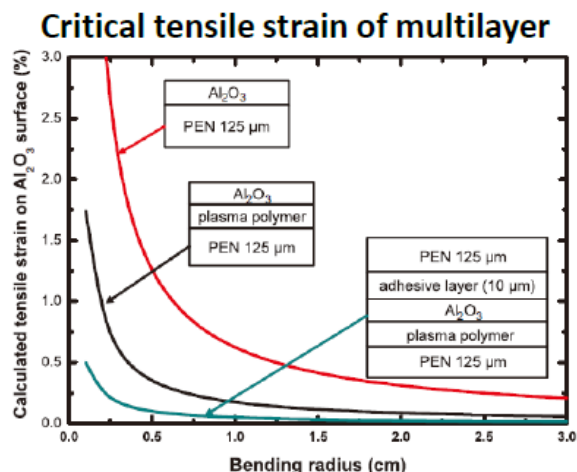
S.M. George et.al., *J. Appl. Phys.*, **109**, 084305 (2011)  
*ACS Nano* **9** (2015), 7515–7522

# Flexible Encapsulation?

## Mechanical flexibility of $\text{Al}_2\text{O}_3$ layer



S.M. George *et.al.*, *J. Appl. Phys.*, 109, 084305 (2011)



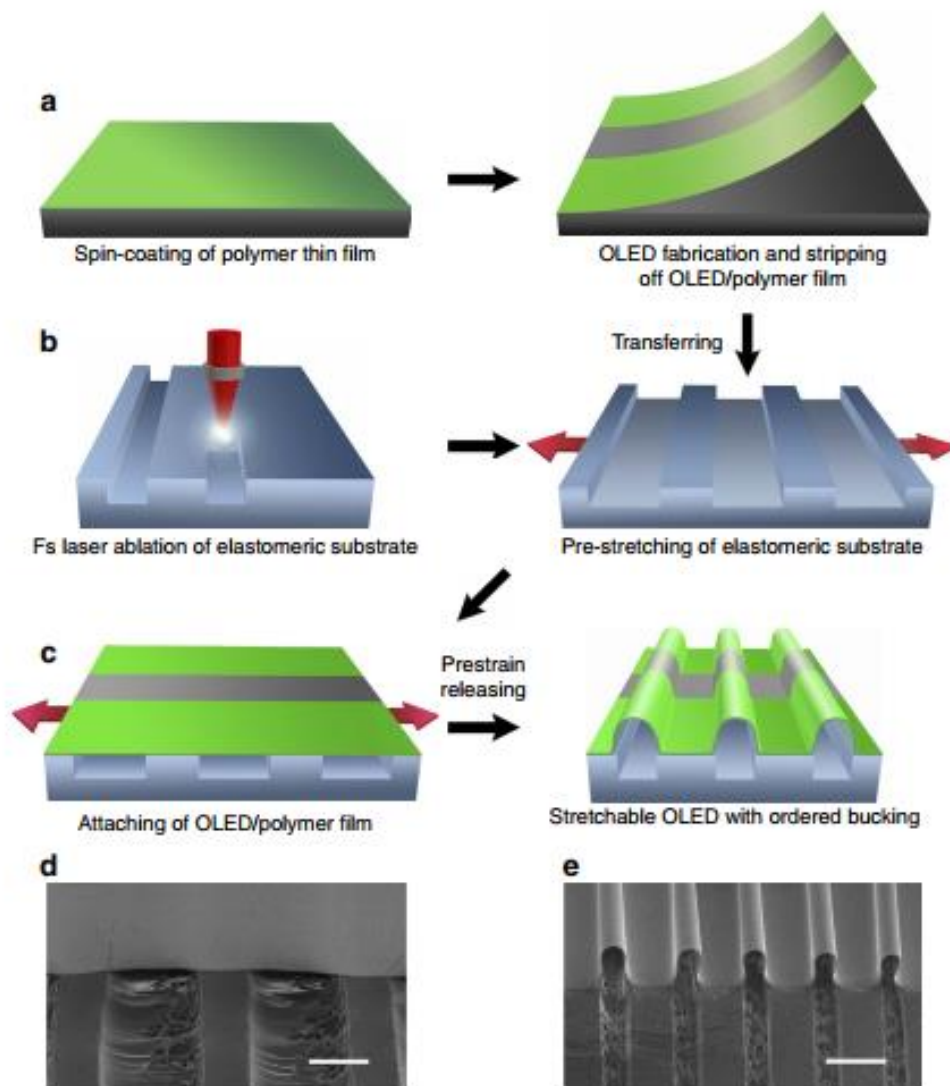
S.M. Cho *et.al.*, *J. Appl. Phys.*, 114, 143505 (2013)

**Multilayer strain:**

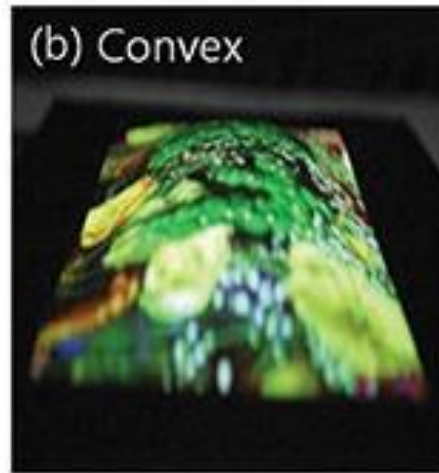
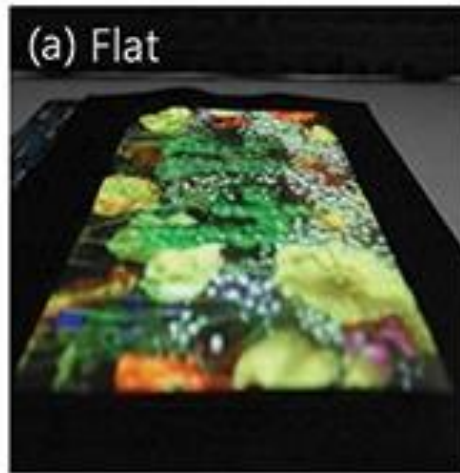
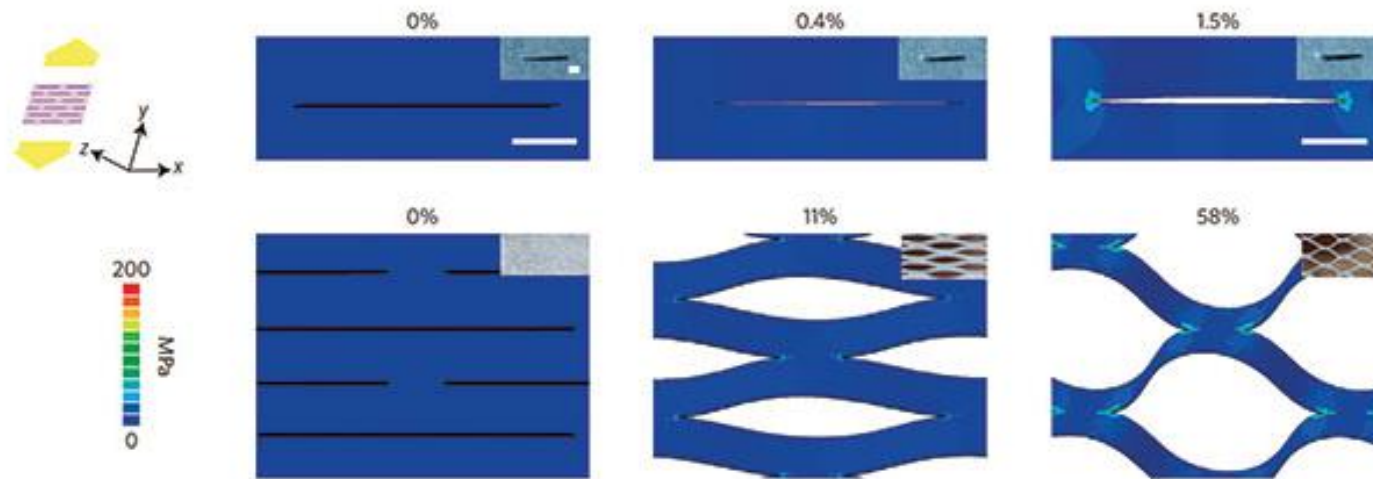
$$\varepsilon_t = \left\{ \frac{Y_o d_s}{2(1 + \nu_o)} \left[ \beta \left( \frac{2\omega^4}{\lambda^3} + \frac{\lambda}{2} \right) - \frac{2d_i \omega^4}{3\lambda^2} \right] + \frac{Y_o}{1 - \nu_o^2} \right\} \times \frac{3}{2\omega^4 h_i^2 d_o Y_i R},$$

The mechanical properties of  $\text{Al}_2\text{O}_3$  layer, and organic/inorganic multilayer is investigated in-depth to design flexing tests

# Flexible Encapsulation?



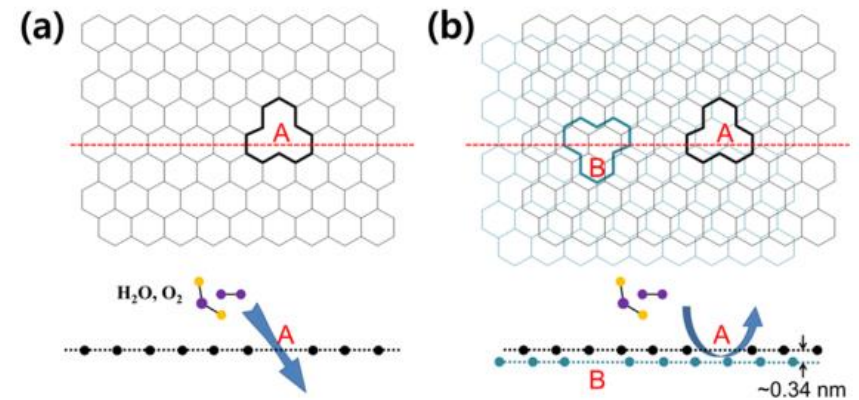
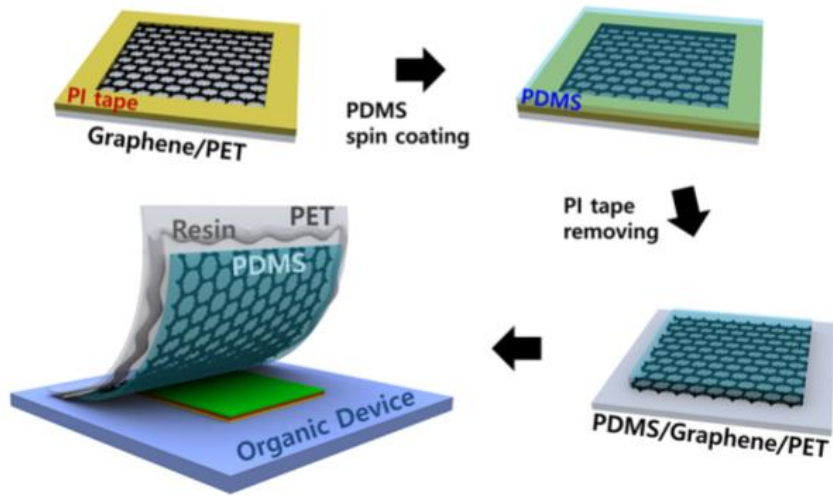
# Flexible Encapsulation?



Y. T. Hong, Information Display (2017).

# Flexible Encapsulation?

## PDMS/Graphene/PET



T.W. Lee et al. ACS Appl. Mater. Interfaces 2016, 8,14725–14731

**Thank you  
for attention**