

Flexible Displays: Market and Manufacturing Issues (and solutions)

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Outline

- Interest in flexible displays is strong
- Multiple technologies already exist
- Technical challenges are real, but are being solved
- What's the best application? Not known!



One goal for flexible displays

What makes a newspaper an attractive medium?

Large area

Flexible

Wireless

Low power

Easy to transport

Affordable

Use almost anywhere

No long boot-up time

Full of interesting content

Familiar source for information



So what's the
need for a flexible
electronic display?



Maybe one of these examples will do...

Multipage electronic newspaper

Sixteen flexible displays on
eight A4 sheets

Networked to news content

Looks and feels like paper





Large format, color electronic newspaper



Electronic notepad

Origami DVD player



Problem - none of these are real



Minority Report,
20th Century-Fox 2002



Inventables.com
2007

IBM design
concept
1999



Andromeda Strain,
A.S. Films 2008

What will it take to
develop a flexible,
paperlike, printed
electronic display?

Which technical challenges are we really discussing?

- **Flexible**
 - A mechanical aspect of displays
- **Paperlike**
 - An optical or electrical (power) aspect of displays
- **Printed**
 - An economic aspect of displays



These are multiple targets, not a single one (but often interrelated).

Possible goals for flexible displays

- **Built with polymers** – lightweight, thin, durable
- **Conformable** – able to adopt a permanent curvature
- **Fabric-like** – ability to conform to an arbitrary 3-D surface
- **Rollable** – able to be curved around a fixed radius on demand
- **Pliable** – bend it, roll it, fold it; just like paper



Possible goals for paperlike displays

- **Low power** - bistable
- **Sunlight readable** – bright light viewing
- **Scalable** – large or small areas
- **Gray scale** - intrinsic or with halftones
- **Green** – Recyclable



Possible goals for printed displays

- Cheap
- Low cost
- Inexpensive....

Something to consider

The installed capacity of all AMLCD fabs worldwide is a little less than 1 m²/sec

A single gravure printing press can run
> 10x this rate.



Applying existing display technology for flexible applications

“Can’t I just modify what I already have?”

Plastic displays have a long history

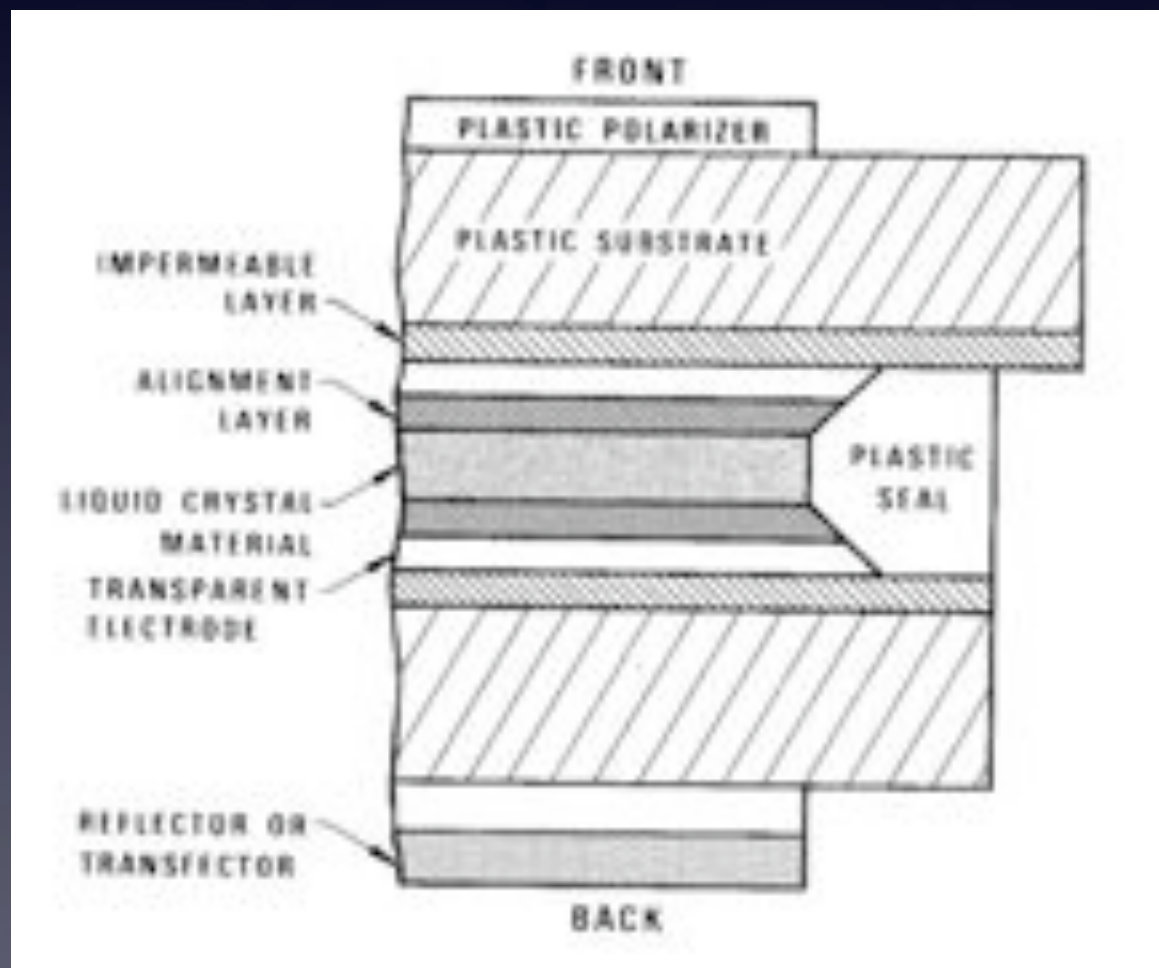
11.7/4:50 P.M.: Plastic Substrate LCD

P. Andrew Penz, Kishin Surtani, Walter Y. Wen, Milon R. Johnson, David W. Kane

Lawrence W. Sanders, Bobby G. Culley and John G. Fish

Texas Instruments, Inc., Dallas, TX

p 116, SID 1981 Digest

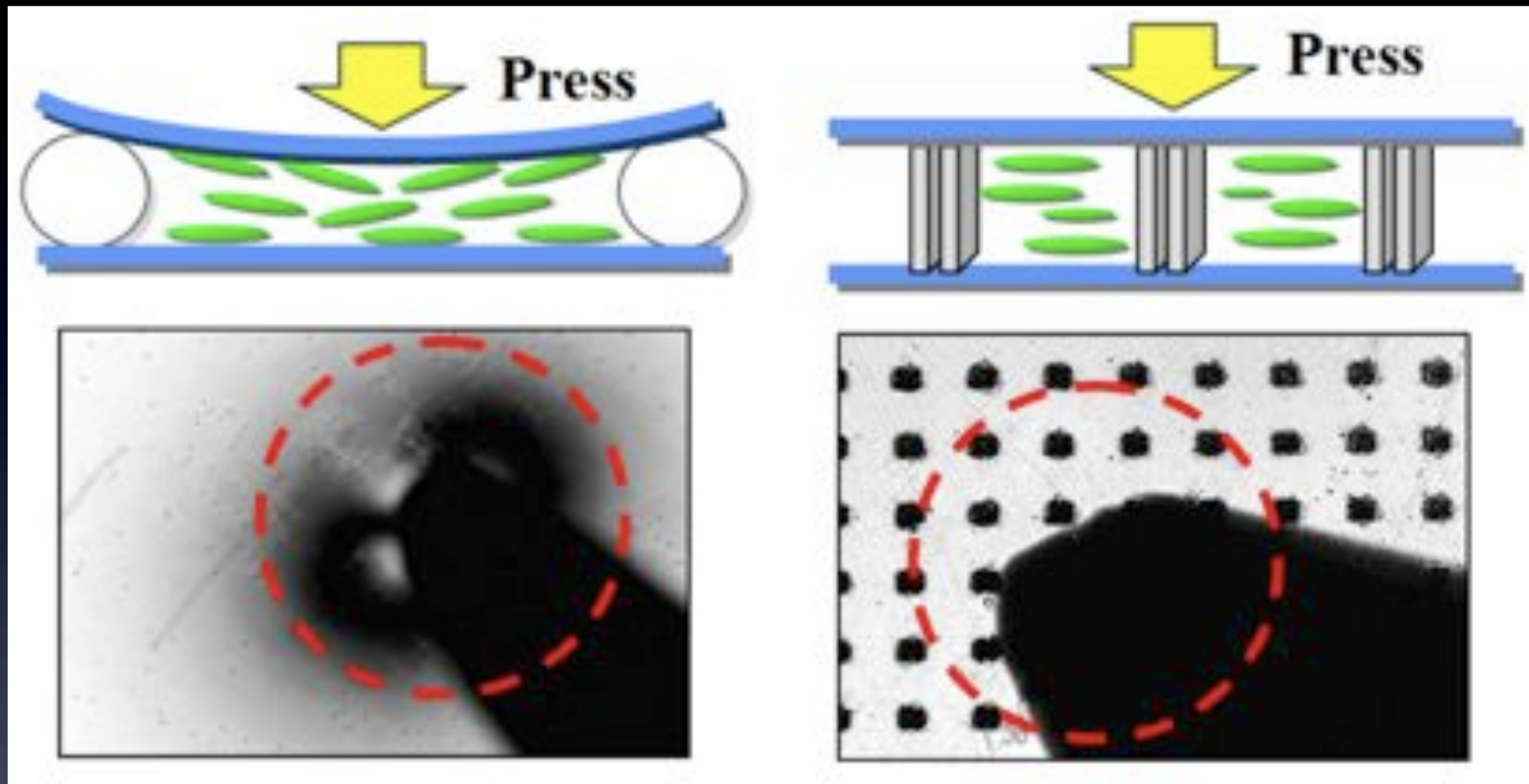


Can we adapt the LCD manufacturing infrastructure to build flexible displays?



Can these glass-based displays be made flexible?

Not really



Jin et al., IMID 2008

Conventional LCD modes are sensitive to cell gap changes

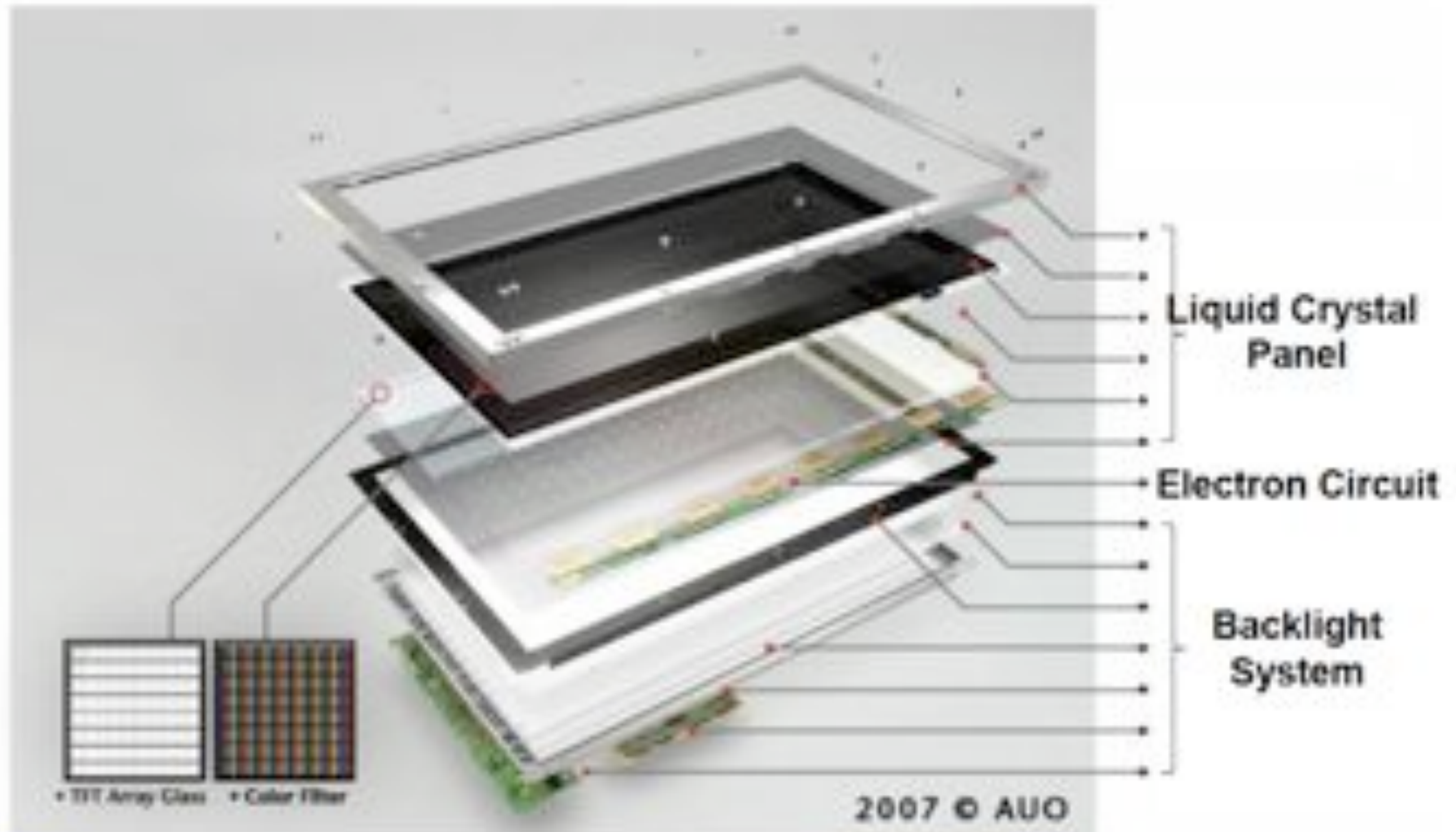
Ribs and spacers can stabilize cell...

...at the cost of degrading optics

How do you make this flexible?



Structure of LCD-TV



Stability issues in flexible displays

- Mechanical stability
 - Brittle thin film inorganic layers on top of soft organic material – will I see cracking?
- Environmental stability
 - Will my transducer or electronics be stable against oxygen and water permeating through plastic?
 - Can I build in a barrier?

Some definitions in mechanics



Stress is the internal distribution of force per unit area in reaction to an external force (load) applied to a body.

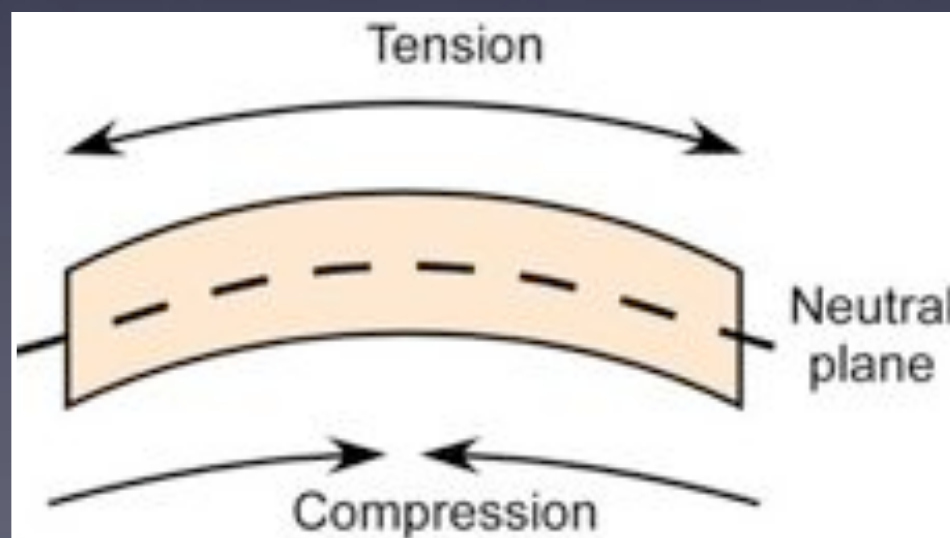
Strain is the physical deformation caused by the action of stress on a body.

Some definitions - mechanics

- **Young's modulus** is a measure of the stiffness of a given material. It is defined as the ratio, for small strains, of the rate of change of stress with strain.
- The **Coefficient of Thermal Expansion** (CTE) is the response of a physical body to a change in temperature.
- You get into trouble when materials with different Young's modulus or CTE are laminated to each other

Why are mechanics important?

- In many flexible displays, films with very different Young's modulus or CTE are layered on top of each other.
- Dramatically different strains due to stress or temperature change cause delamination or cracking.



	Young's modulus (Gpa)	CTE (ppm/K)
Polymer film	3	65
ITO	119	8

ITO on polyester is brittle!

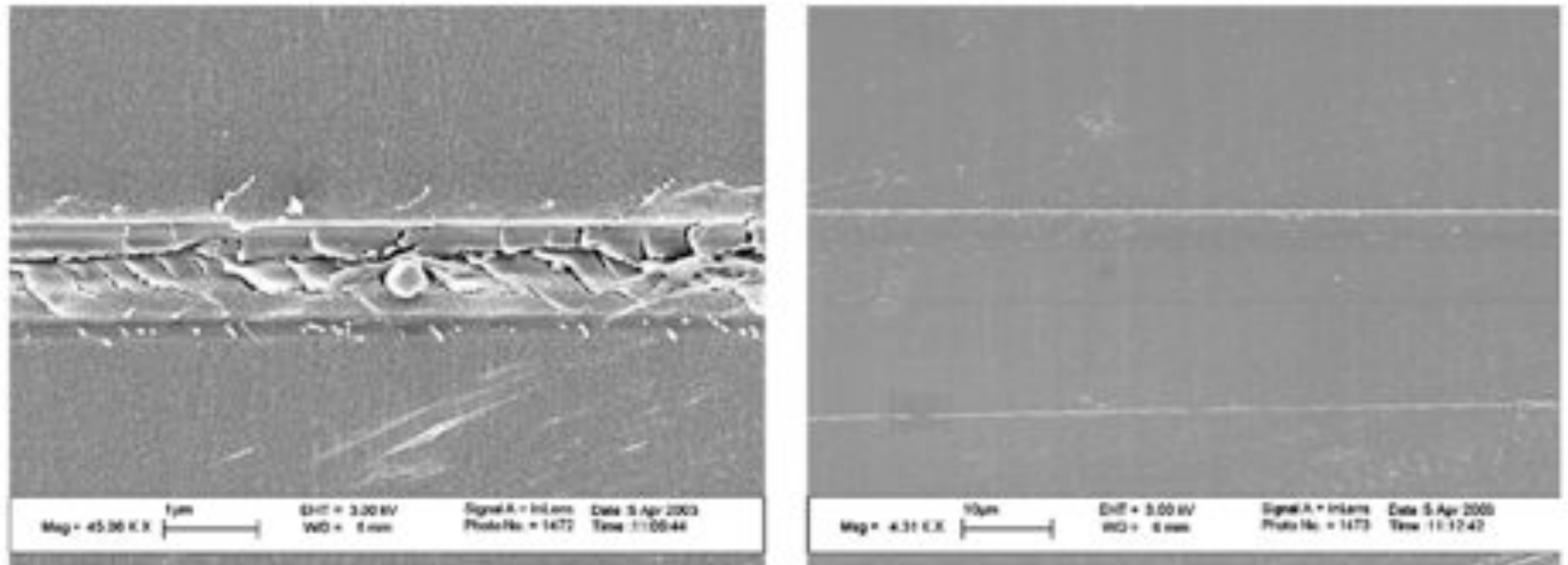
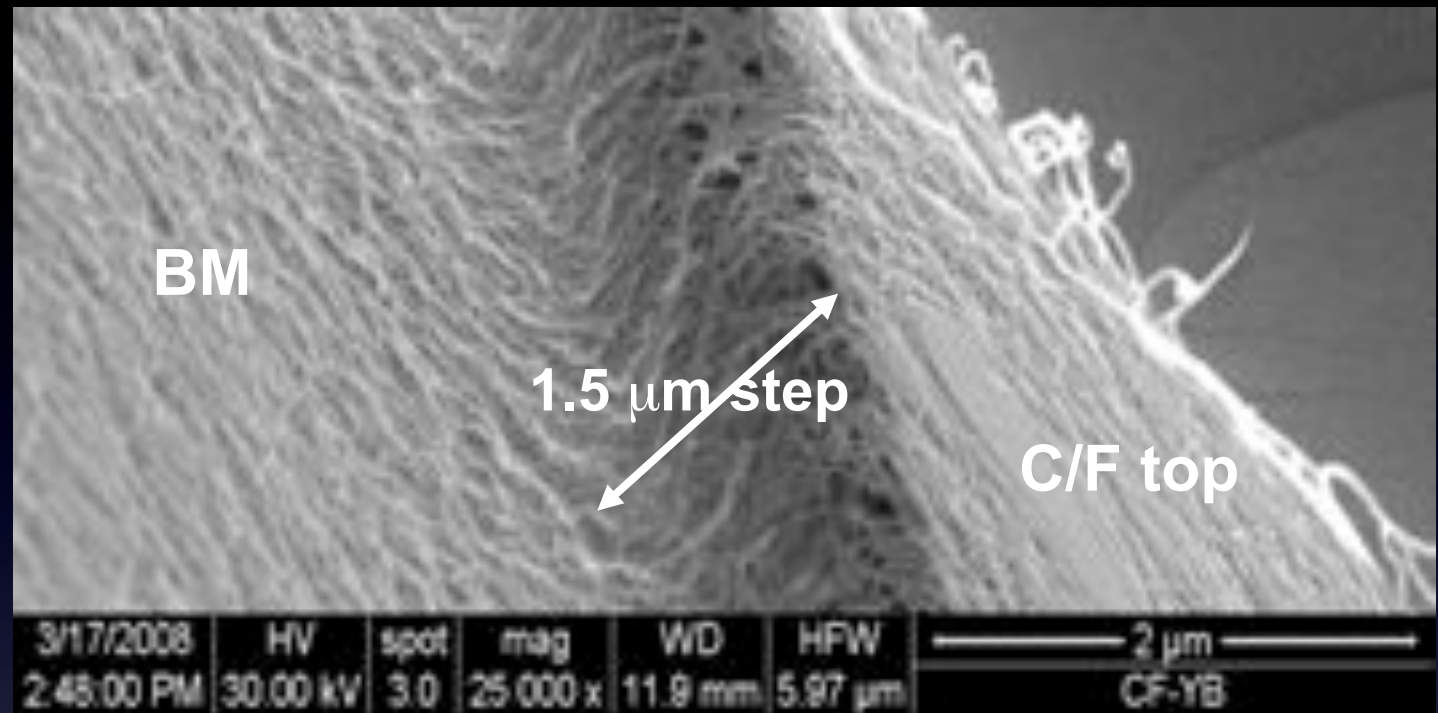


FIGURE 9 — Scanning electron micrograph of ITO-coated PET substrate showing parallel cracks created after 100K cycles of fatigue test. Resolution 1 μm (left), 10 μm (right).

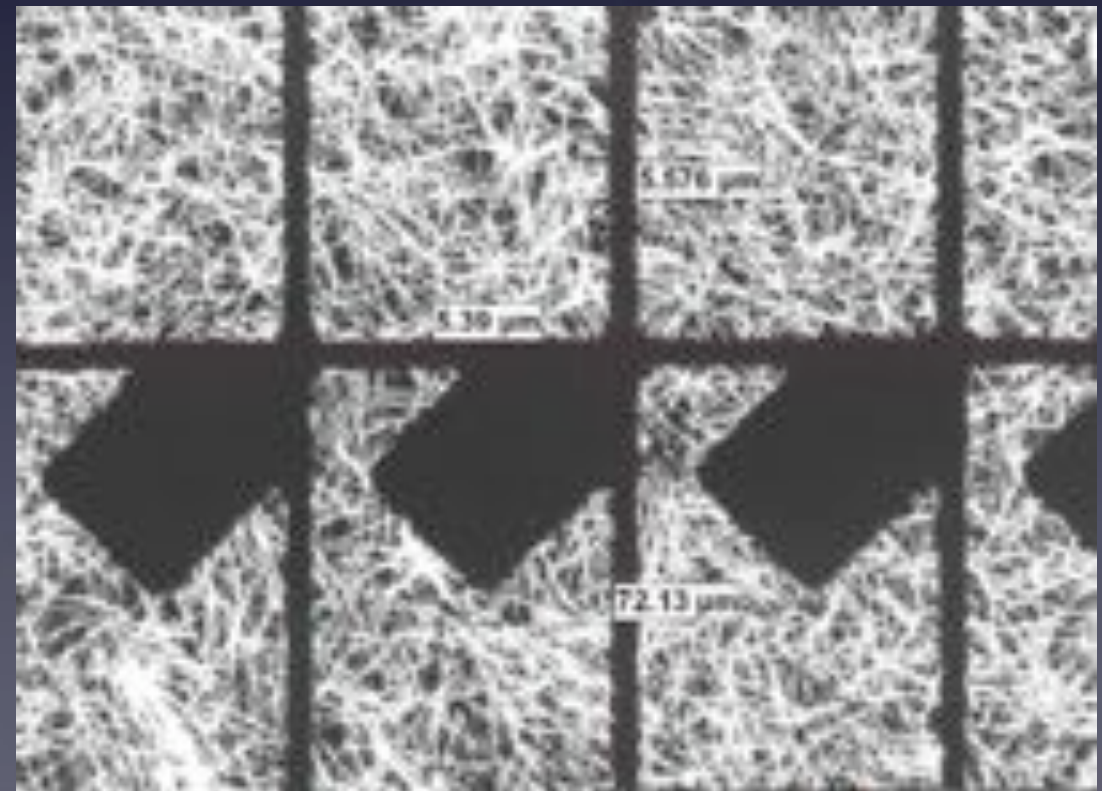
Gorkhali *et al*, J. Soc. Info. Display (2004)

Flexible transparent conductors

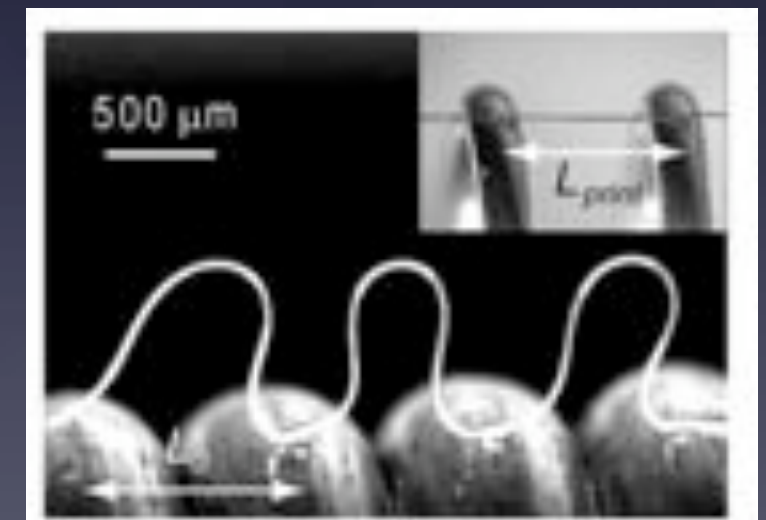
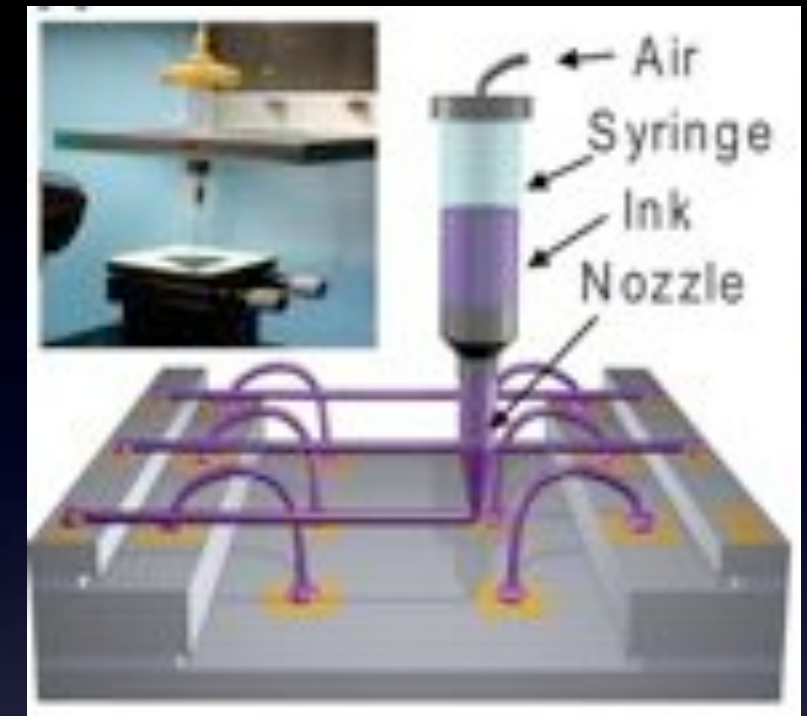
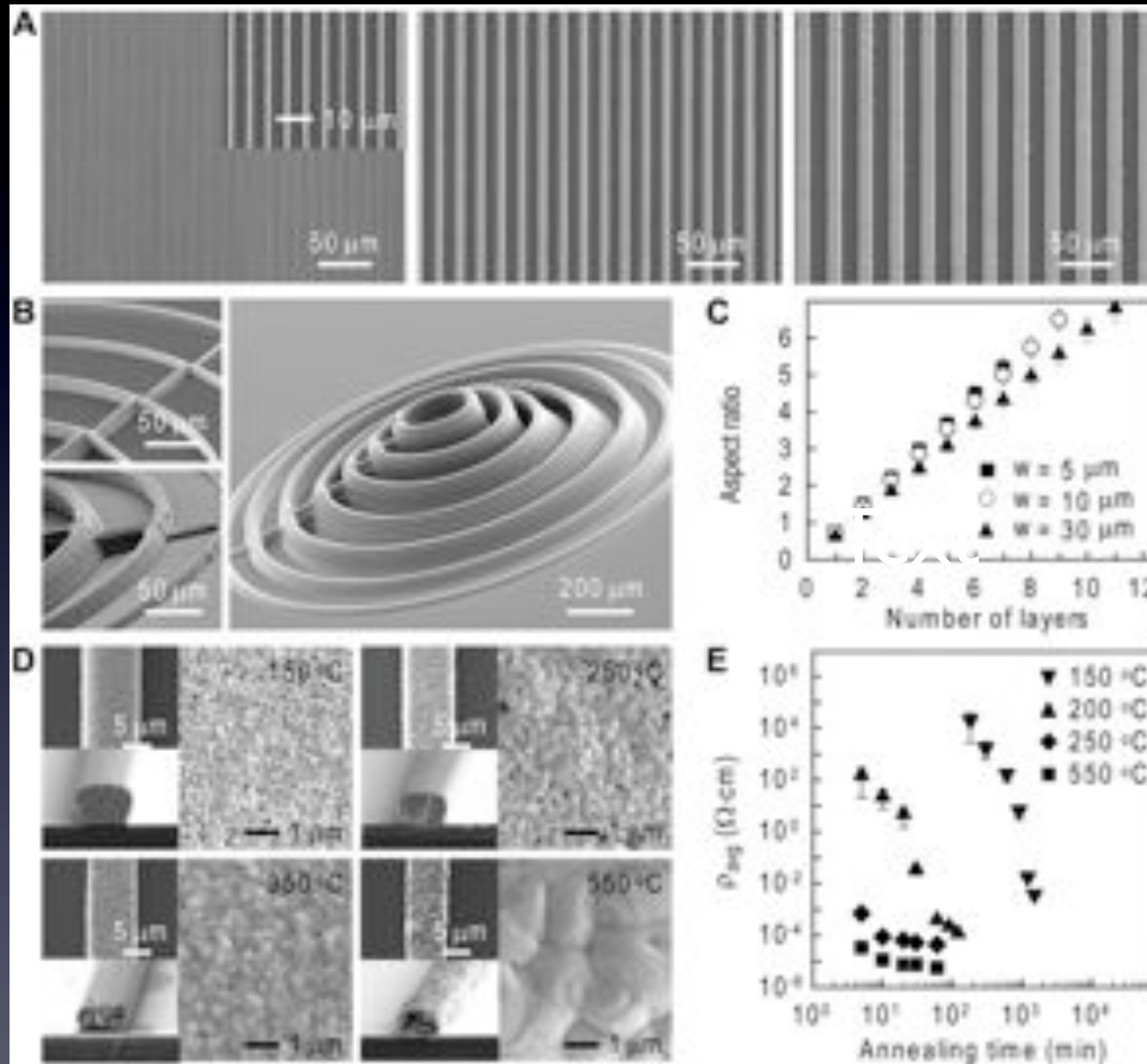
- Many types under development
 - PEDOT-PSS
 - Carbon nanotubes
 - Silver nanowires
- Status
 - **Superior flexibility** to transparent conductive oxides
 - **Inferior conductivity and stability** to best transparent conductive oxides



Unidym - OSC '08



Direct-write fabrication of flexible 3D microstructures



SEM images of planar arrays of silver microelectrodes patterned with micrometer nozzles

Published by AAAS

B. Y. Ahn et al., Science 323, 1590 -1593 (2009)

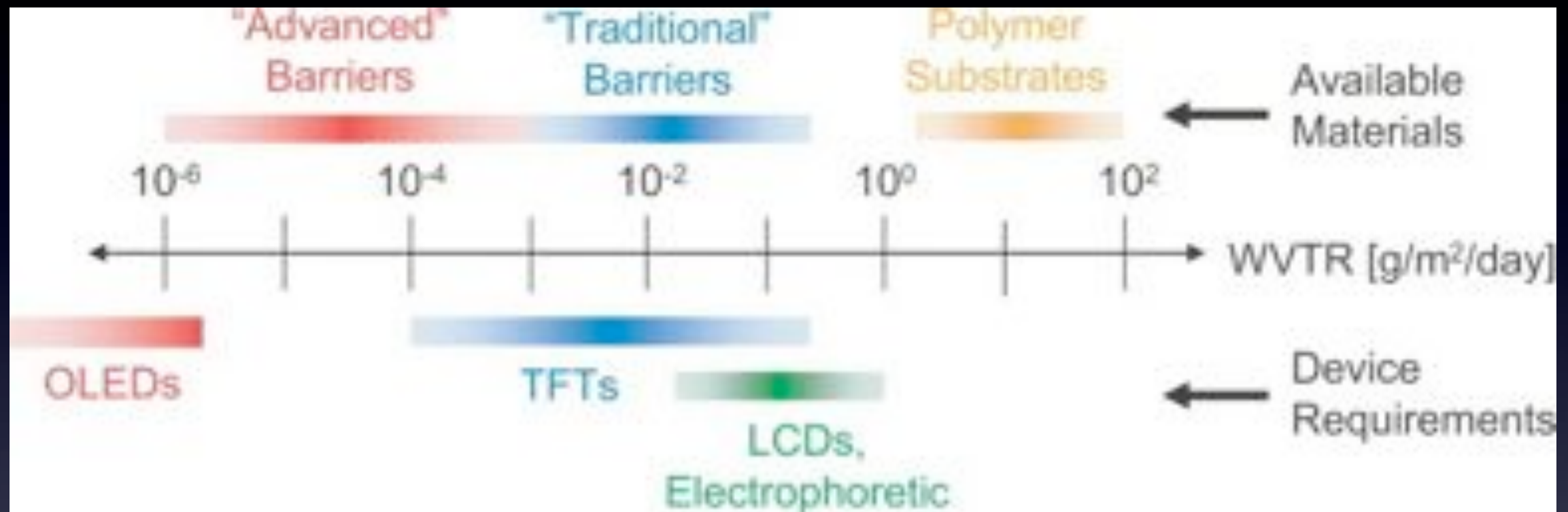
Permeability

- Polymer substrates are poor barriers to water and oxygen
- A variety of transparent thin film barriers are under active development
 - Most rely on inorganic thin films, sometimes coupled with organic layers
 - Pinholes are often the dominant factor in allowing water and oxygen to permeate
- How much protection is needed? It depends!





Permeability requirements



J. Lewis, *Mat.Today*, **9**, 38 (2006)

WVTR – Water Vapor
Transmission Rate

- Different technologies require different levels of barrier function

Barriers for OLEDs

- To oxidize 1 nm of metal no faster than 10,000 hours, permeation rate of water must be less than 5×10^{-6} g/m²-day
 - Simple single layers of metal or ceramic on plastic permit permeation of 5×10^{-2} g/m²-day
 - How to get 10,000x better?
- Types of barriers
 - Single layer
 - Can you eliminate defects?
 - Multilayer
 - Alternating organic/inorganic stacks
 - Tortuous path between pinholes in adjacent layers minimizes effects of defects

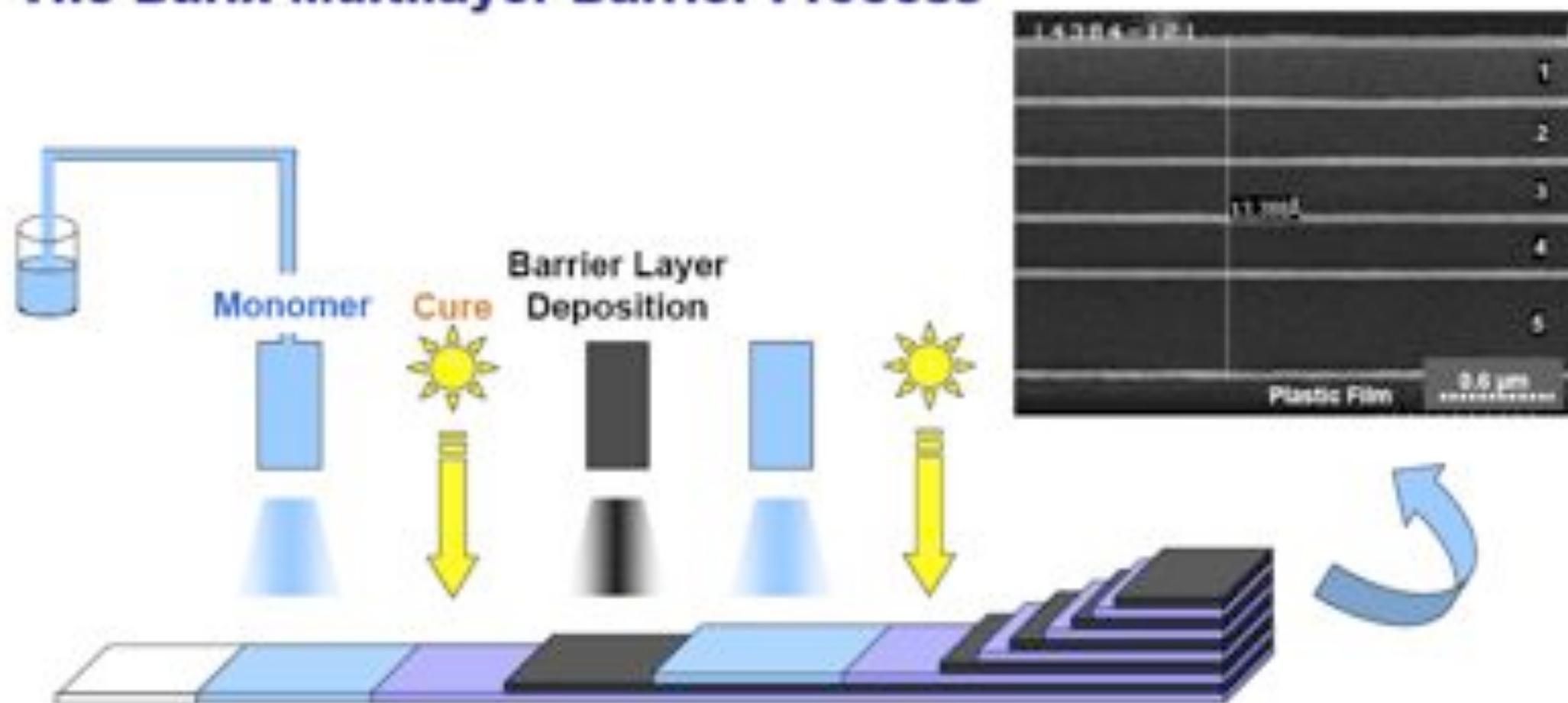
Single layer coatings

- Si:C (Dow Corning)
 - Water vapor permeation $< 10^{-4}$ g/m²-day
- Reactive atomic layer deposition of Al₂O₃ (DuPont)
 - Water vapor permeation $< 10^{-5}$ g/m²-day

Source: 2006 USDC
flexible displays conference



The Barix Multilayer Barrier Process

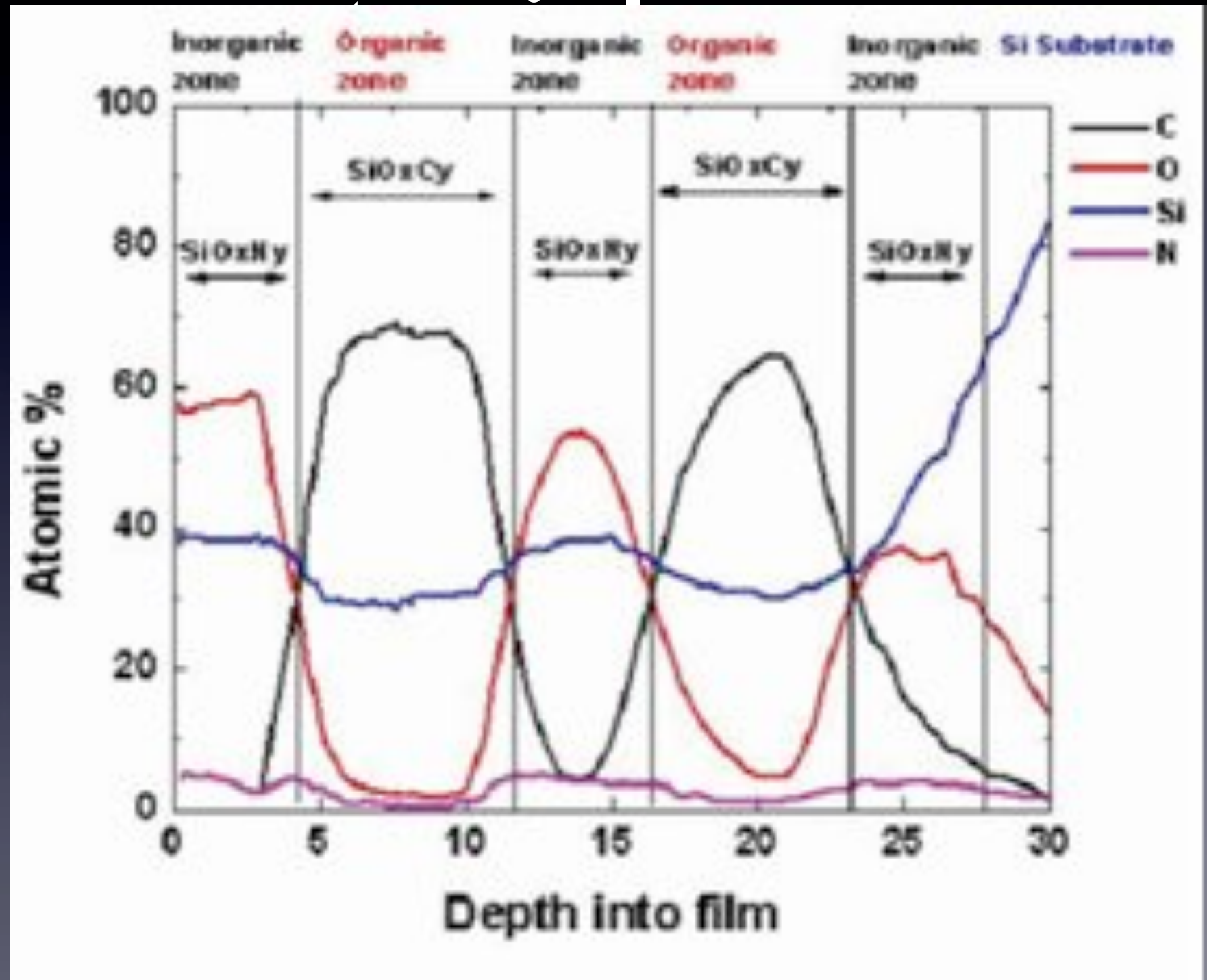


The Barix process is the deposition of inorganic barrier and organic smoothing layers whose design protects against moisture permeation. The barrier is tunable depending on the application.

Water vapor permeation $< 10^{-5}$ g/m²-day

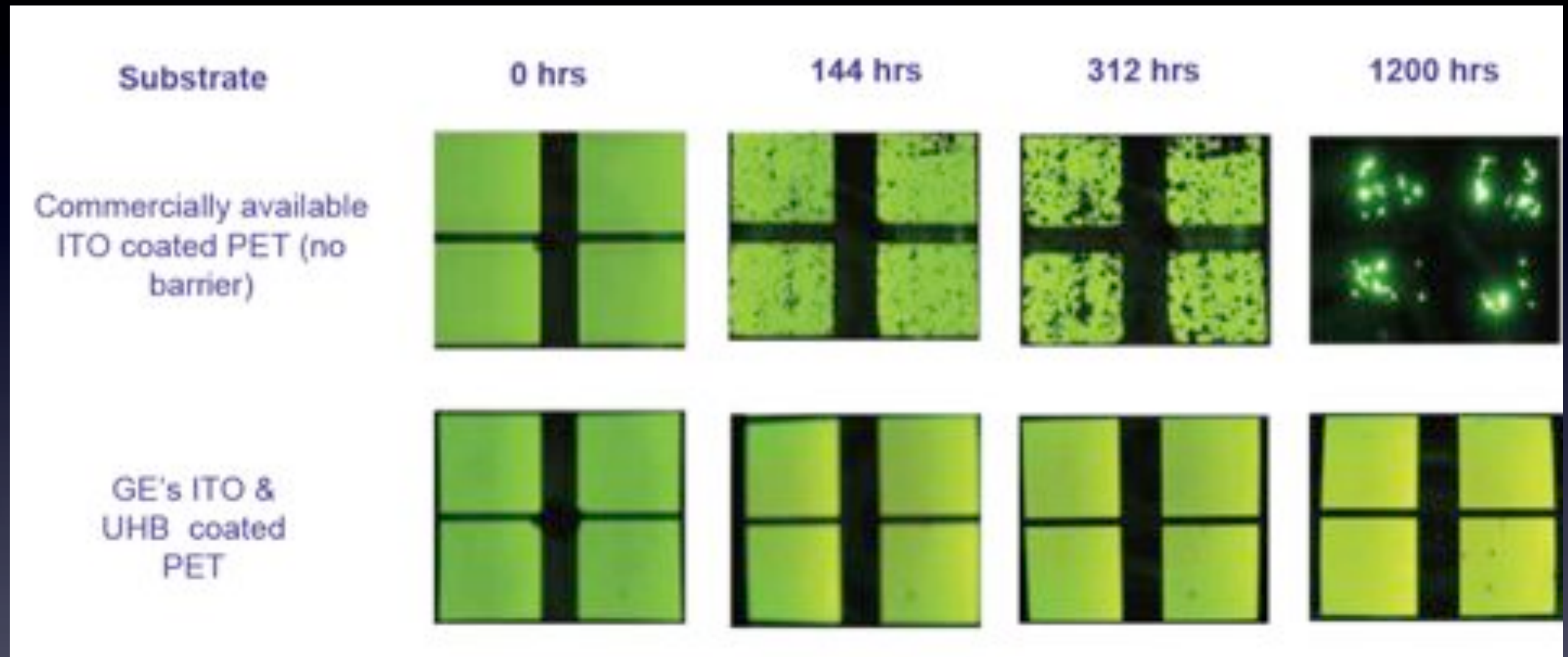
GE Graded barrier

- PECVD
- Continuous coating
- Water vapor permeation at or below 10^{-5} g/m²-day



Source: Yan et al, USDC flex electronics conference, 2006

Performance of graded barrier



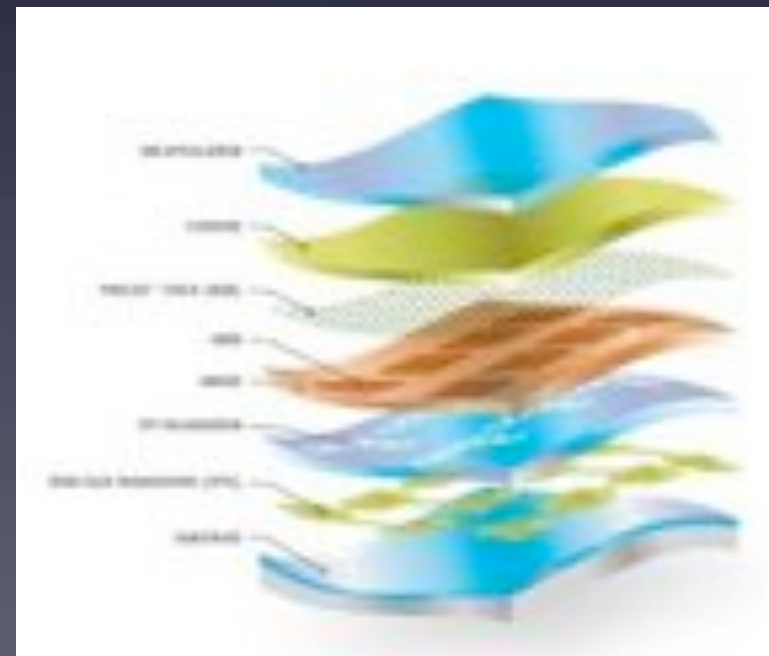
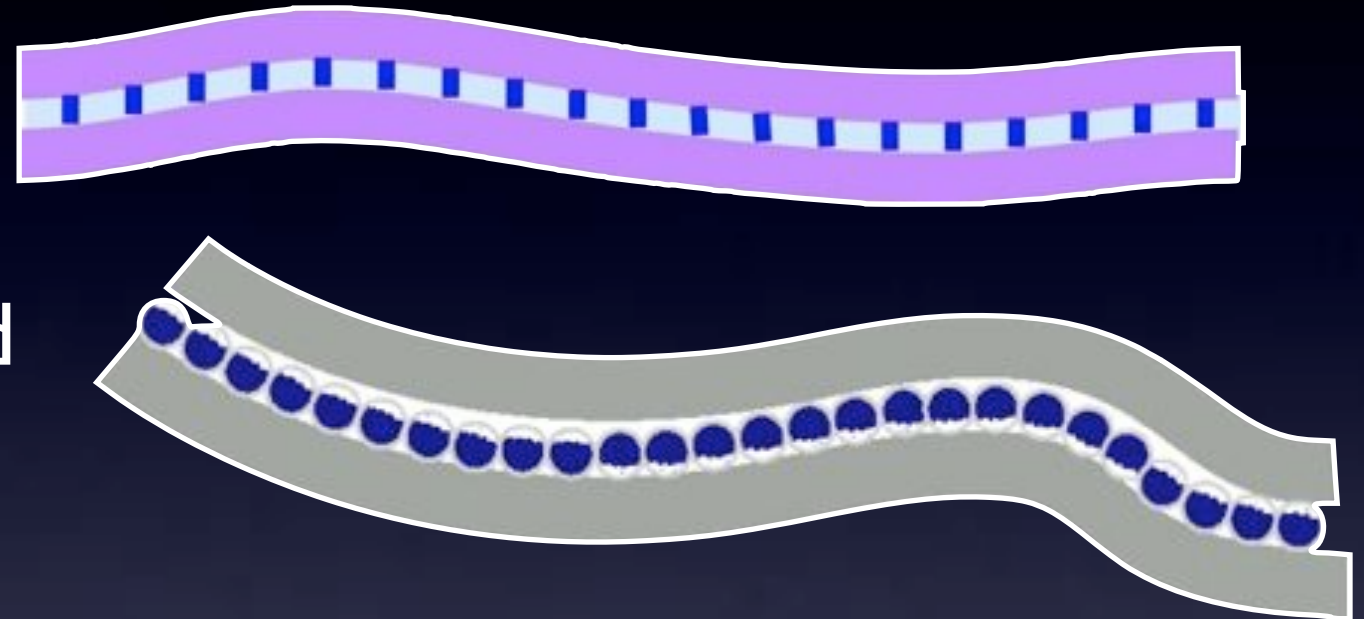
23 C, 40% RH stability

Source: Yan et al, USDC flex electronics conference, 2006

What about the effect
of flexibility on cell gap?

Strategies to maintain constant cell gap

- Use adhesive structures to enforce local cell gap
 - Spacer balls, fibers
 - Ribs
- Make the cell gap mostly solid
 - Microencapsulated display media
- Don't use a fluid electro-optical effect
 - Organic light emitting diodes

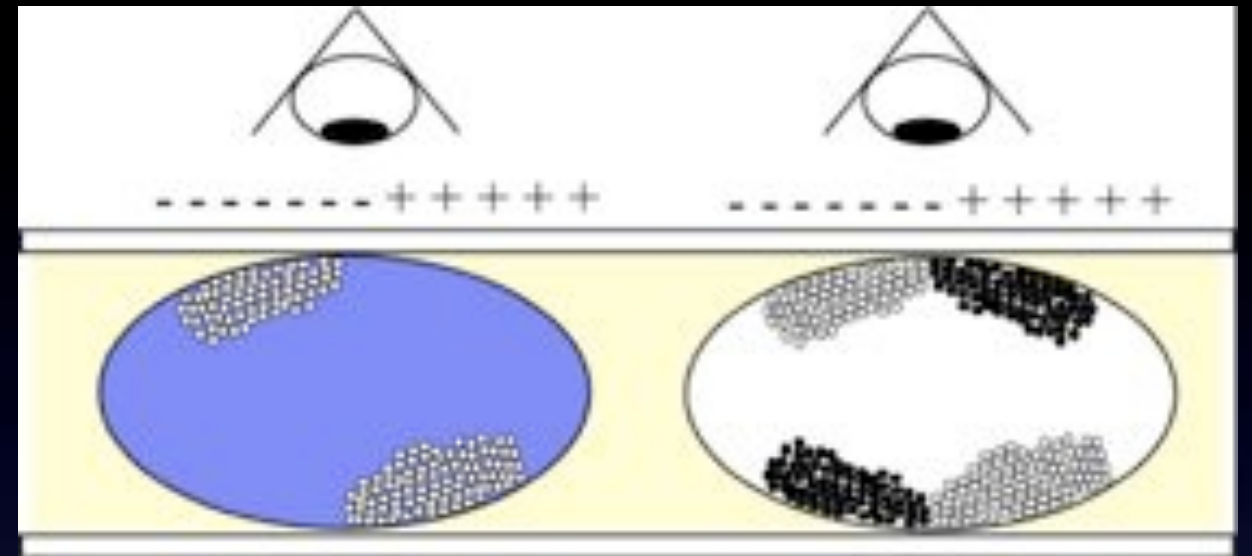


Source: UDC

Electronic paper

Encapsulated electrophoretic display

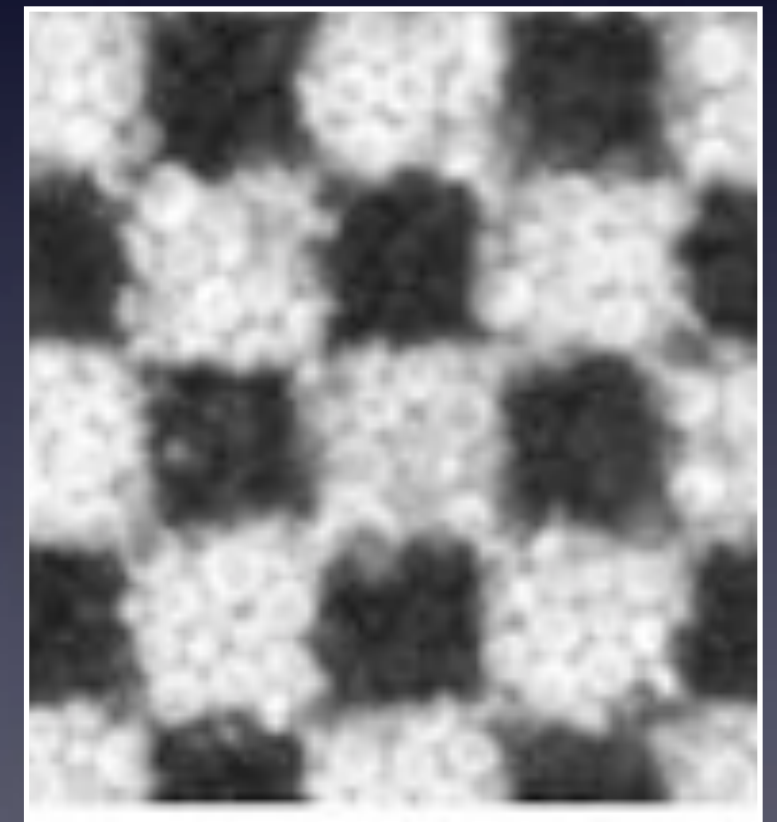
- Moving particles across a cell gap
- E Ink - microcapsules
- SiPix - embossed wells
- Flexible, grayscale, high resolution



Citizen



SiPix



200 ppi image - Bouchard
et al., SID 2004

Flexible electronic paper - organic transistor backplane

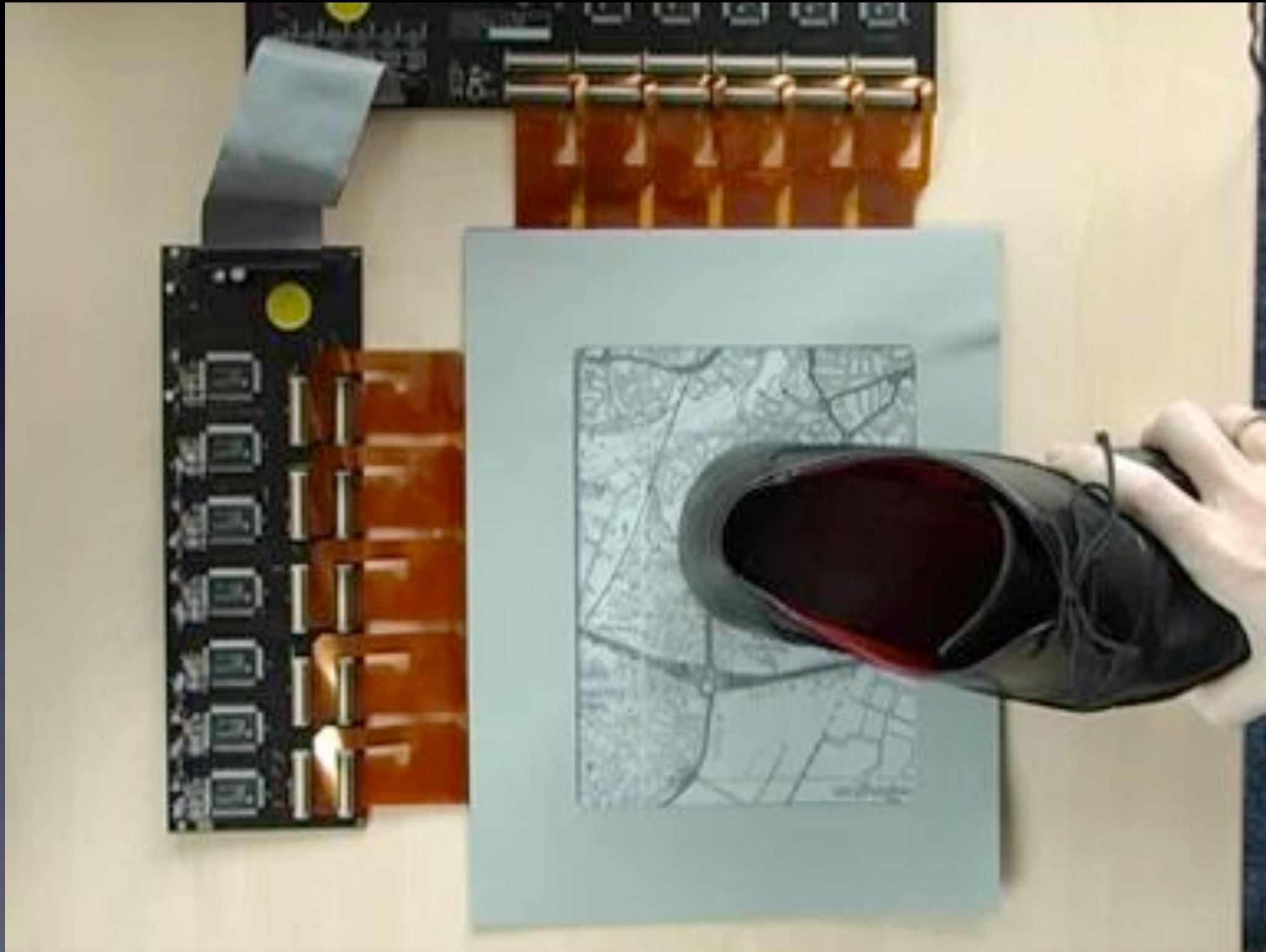


Polymer Vision reader - rollable 5", 80 ppi.
Source: Polymer Vision

Plastic Logic
10" 100 ppi reader
Source: Plastic Logic



Robust display

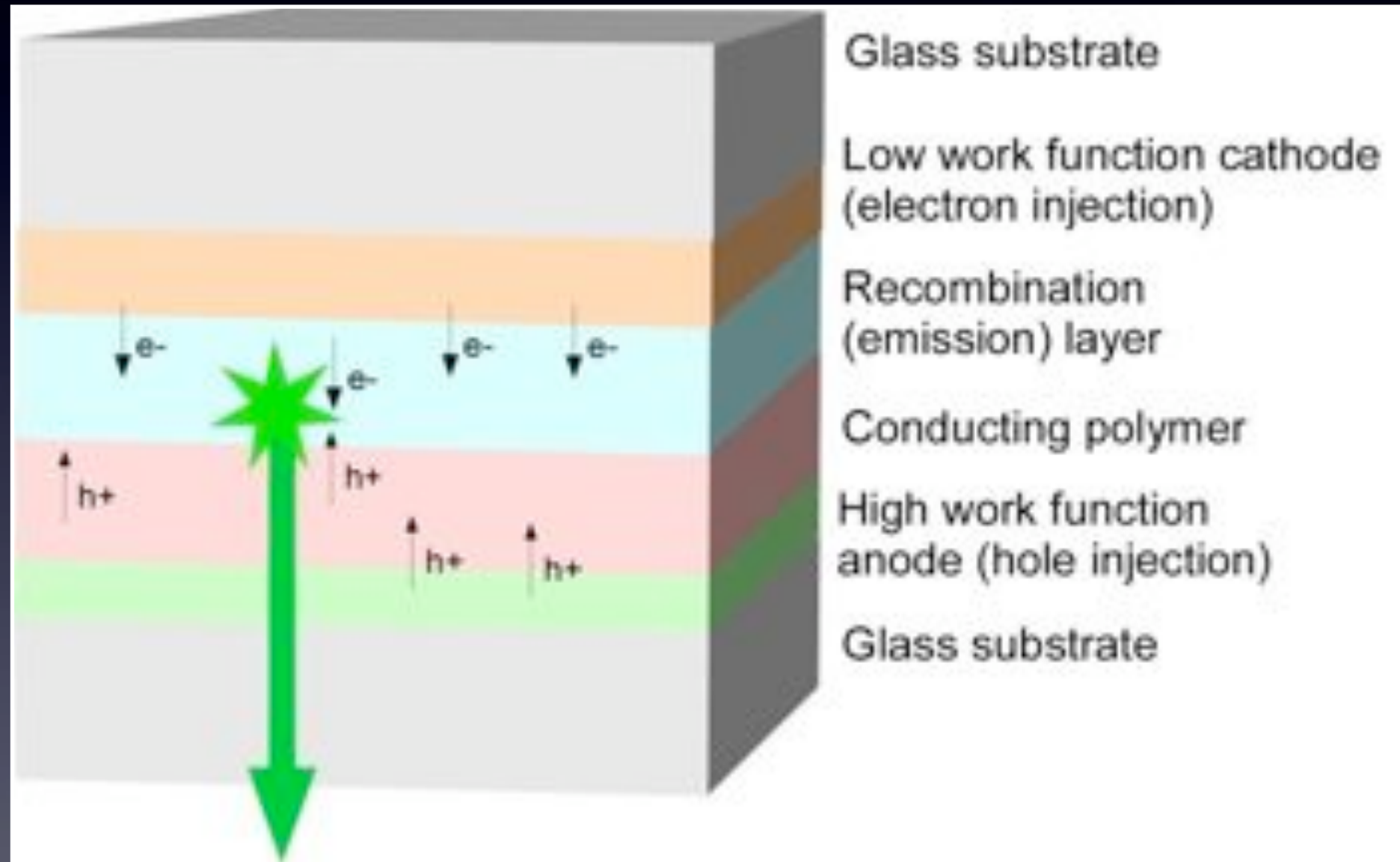


Source:
Plastic Logic

Organic light emitting diode (OLED) displays

Basic bottom-emission OLED stack

- Very thin! Entire stack between glass (or plastic) plates $< 1\ \mu\text{m}$ thick
- Output equivalent to indoor luminance ($100\ \text{cd/m}^2$) at a few volts



Ink jet printing - polymer LEDs

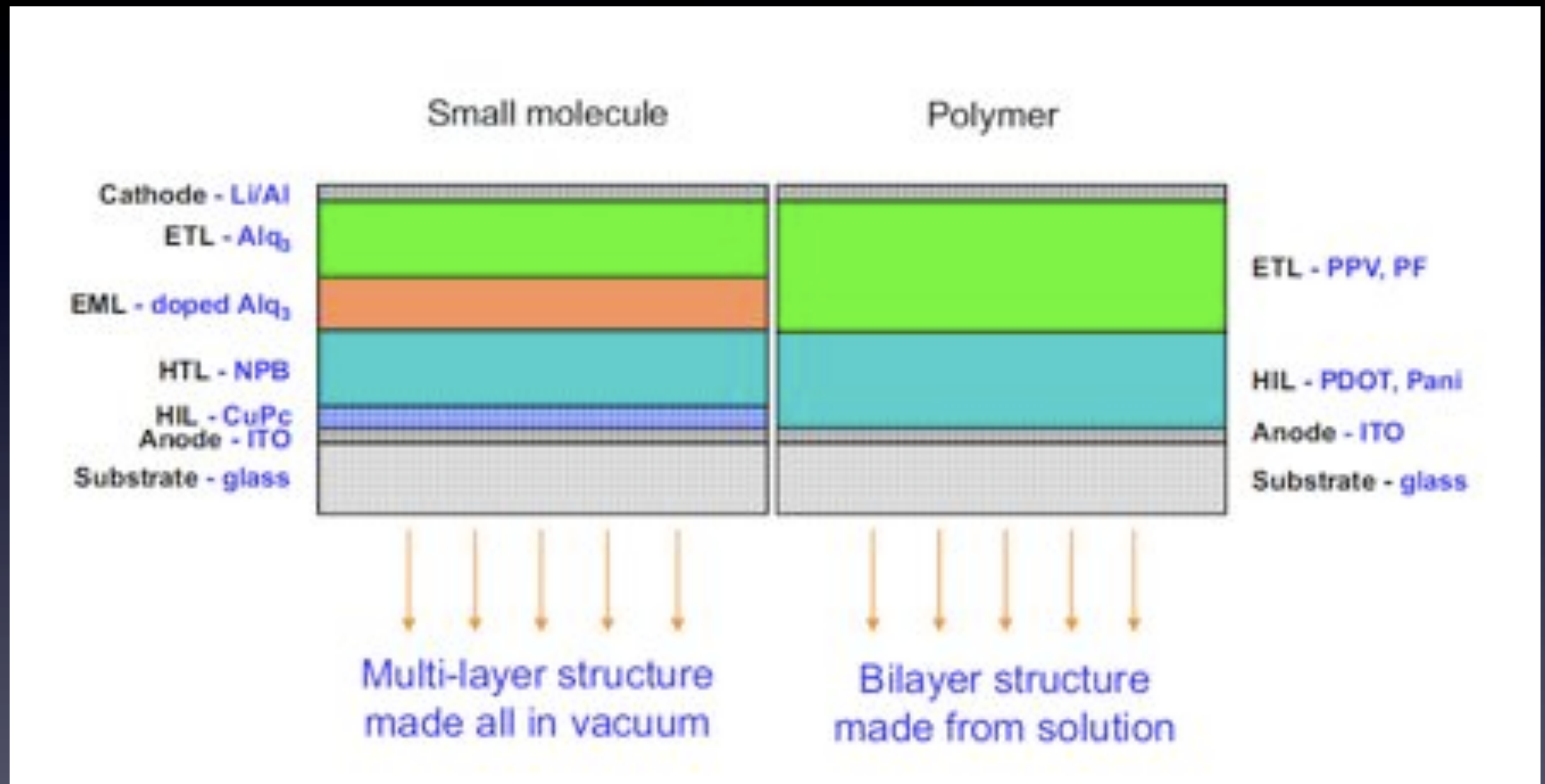
- Receptor wells formed on substrate to contain drops



Source: CDT

Source: Litrex M-series jet printer

Small molecule vs. polymer OLED fabrication



Small molecule more difficult to
fabricate, but higher in performance

F. So, IDRC Workshop, 2008

Flexible OLED



a-Si transistors on steel foil
Source: LG Philips



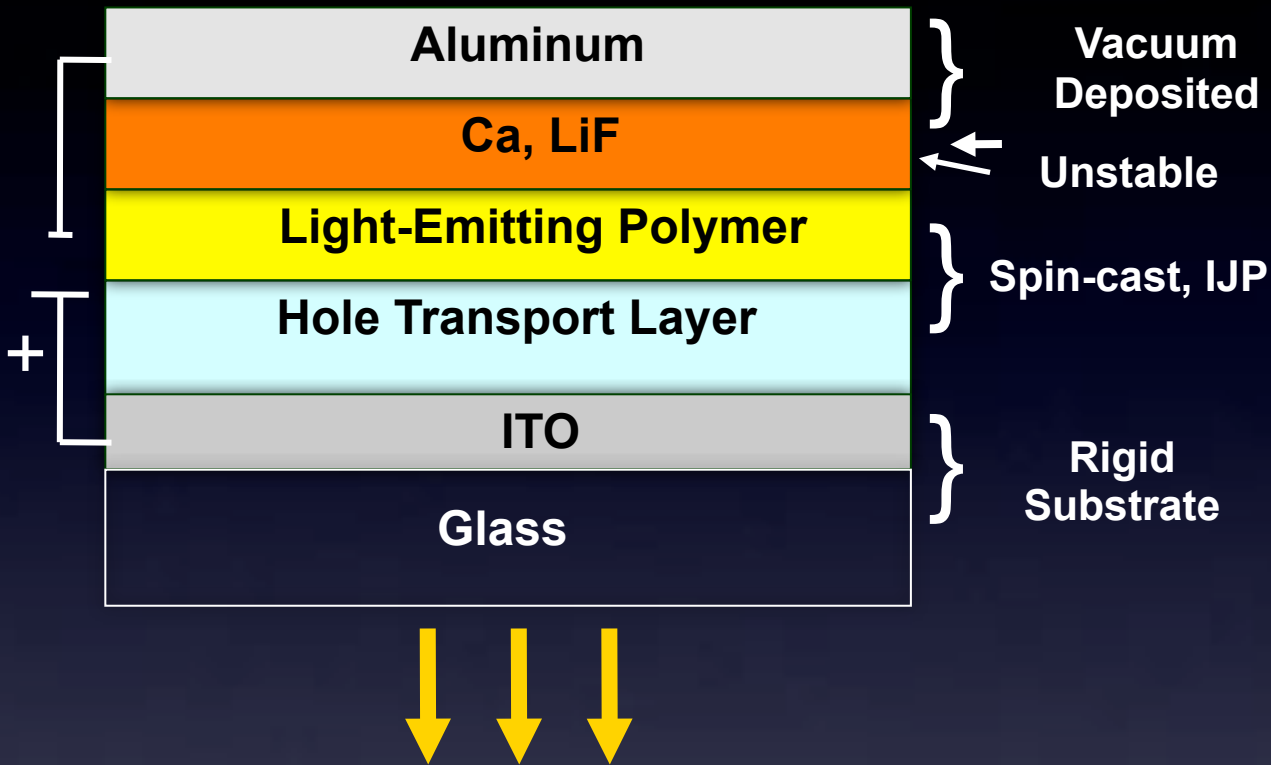
Organic transistors on
plastic
Source: Sony



Sony Flexible OLED – organic transistor backplane

AVI Device Structure Enables Low Cost Manufacturing

Conventional P-OLED



High performance, but high fabrication cost
Vacuum processing required
High demands on uniformity leads to sensitivity to processing variations

Add-Vision Printed P-OLED



Low cost fabrication on plastic, in air
Utilizing high throughput print tools → Low CAPEX

Applications less sensitive to non-uniformities and thickness variations → Improved yield in print environment

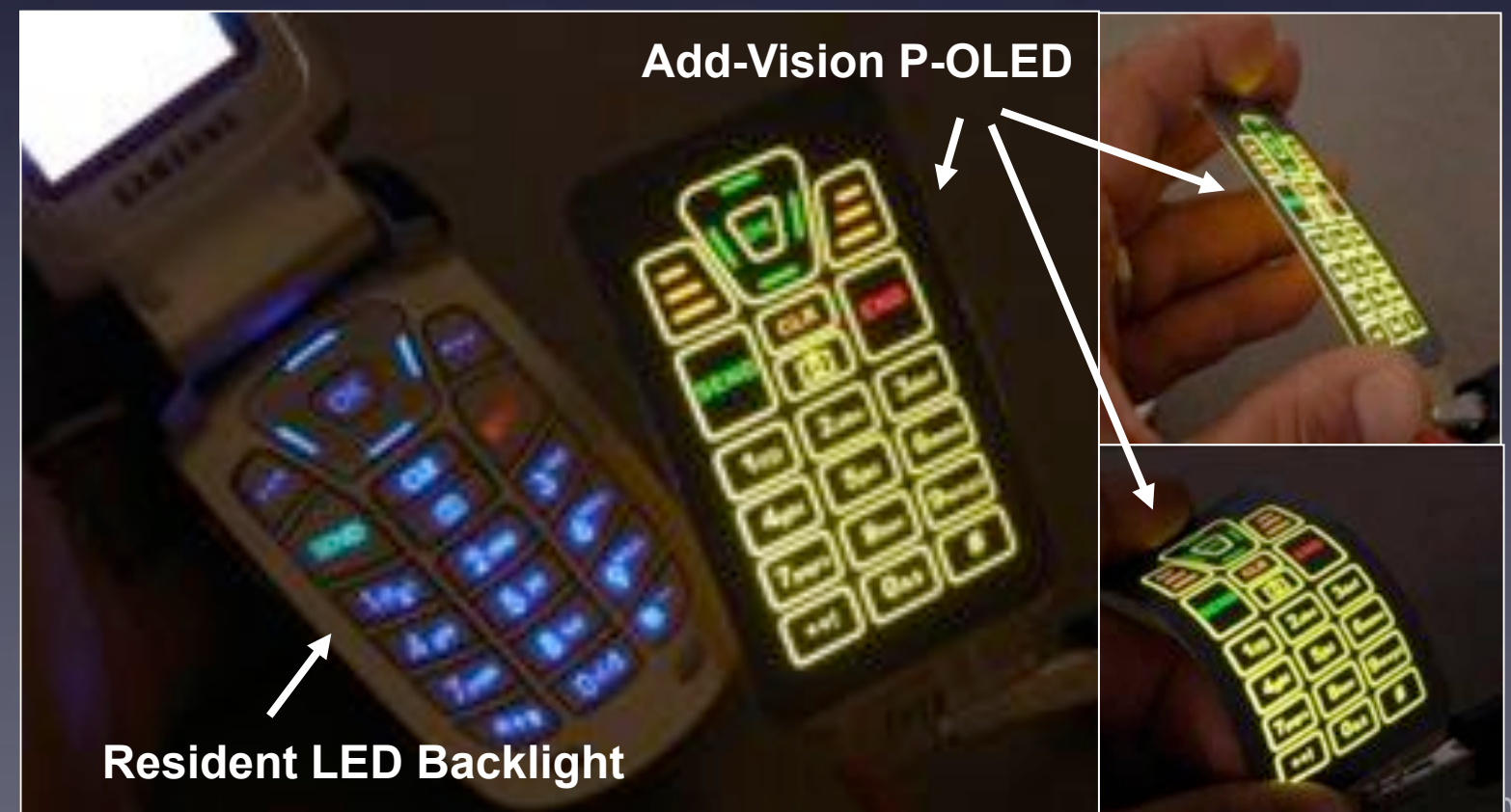
Opportunities for Add-Vision's P-OLED Technology in Mobile Handsets

Icons, Indicators & Cosmetic



Backlight (Keypads)

Secondary Displays



OLED lifetime

- In a well-sealed cell, both small molecule and polymer OLEDs have demonstrated emissive lifetimes of over 100,000 hours at luminance $> 100 \text{ cd/m}^2$ (bright room lighting).
- Plastic cells are not nearly this stable with current commercial barriers

What about flexible backplanes?

Flexible amorphous silicon displays



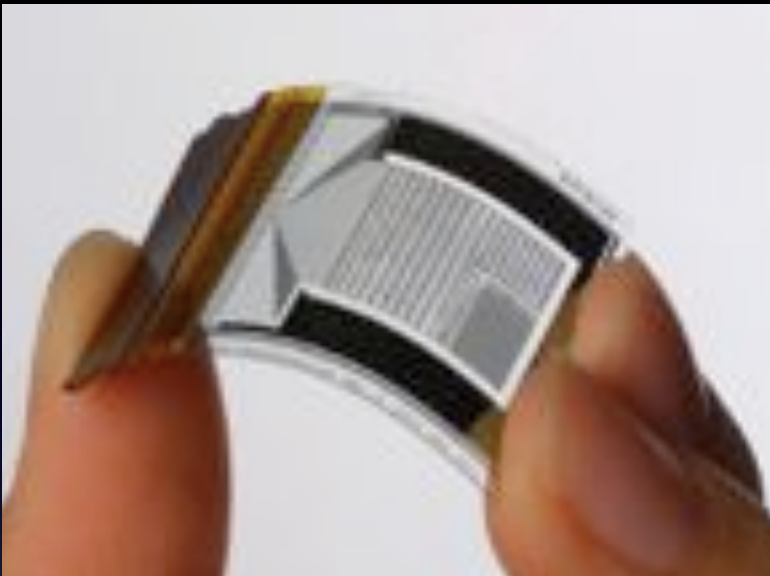
LG Philips
a-Si on steel EPD



Samsung
a-Si on plastic, 130 C process
A4 EPD

Conventional processing on
unconventional substrates

p-Si circuits on flex - SUFTLA



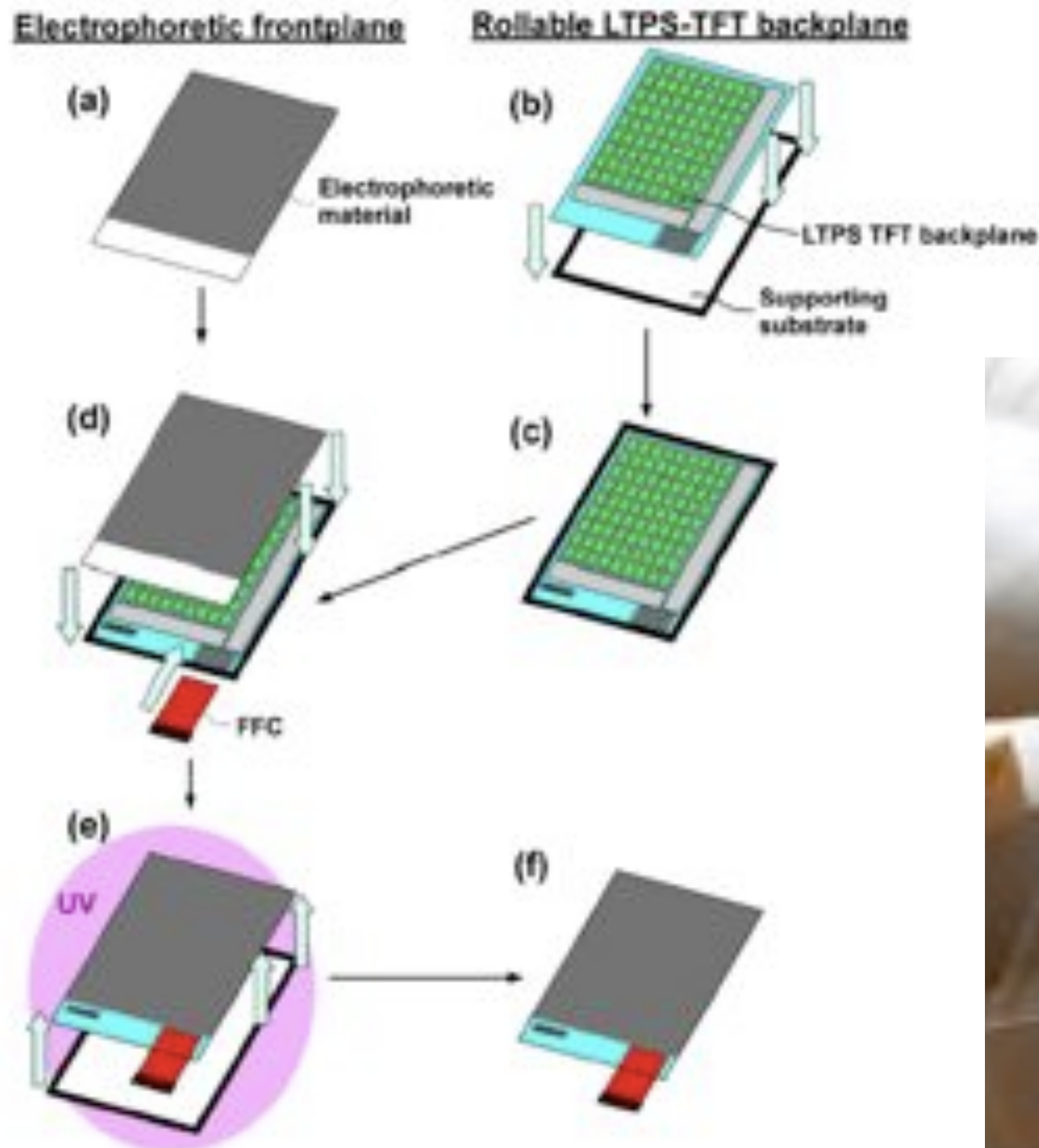
8-bit microprocessor

- Form p-Si circuits on top of sacrificial a-Si layer on glass
- Laser release, then transfer to plastic sheet



397 ppi (3 Mpixel) flex display
M Miyasaka, JSID 2007

96 μm thick flex display



Kodaira *et al*, JSID 2008



Flexible displays from EPLAR laser release

- Coat custom polyimide film on glass
- Build display cell (OLED, EPD)
- Laser release PI film from glass



18 micron thick OLED
French *et al*, SID 2007

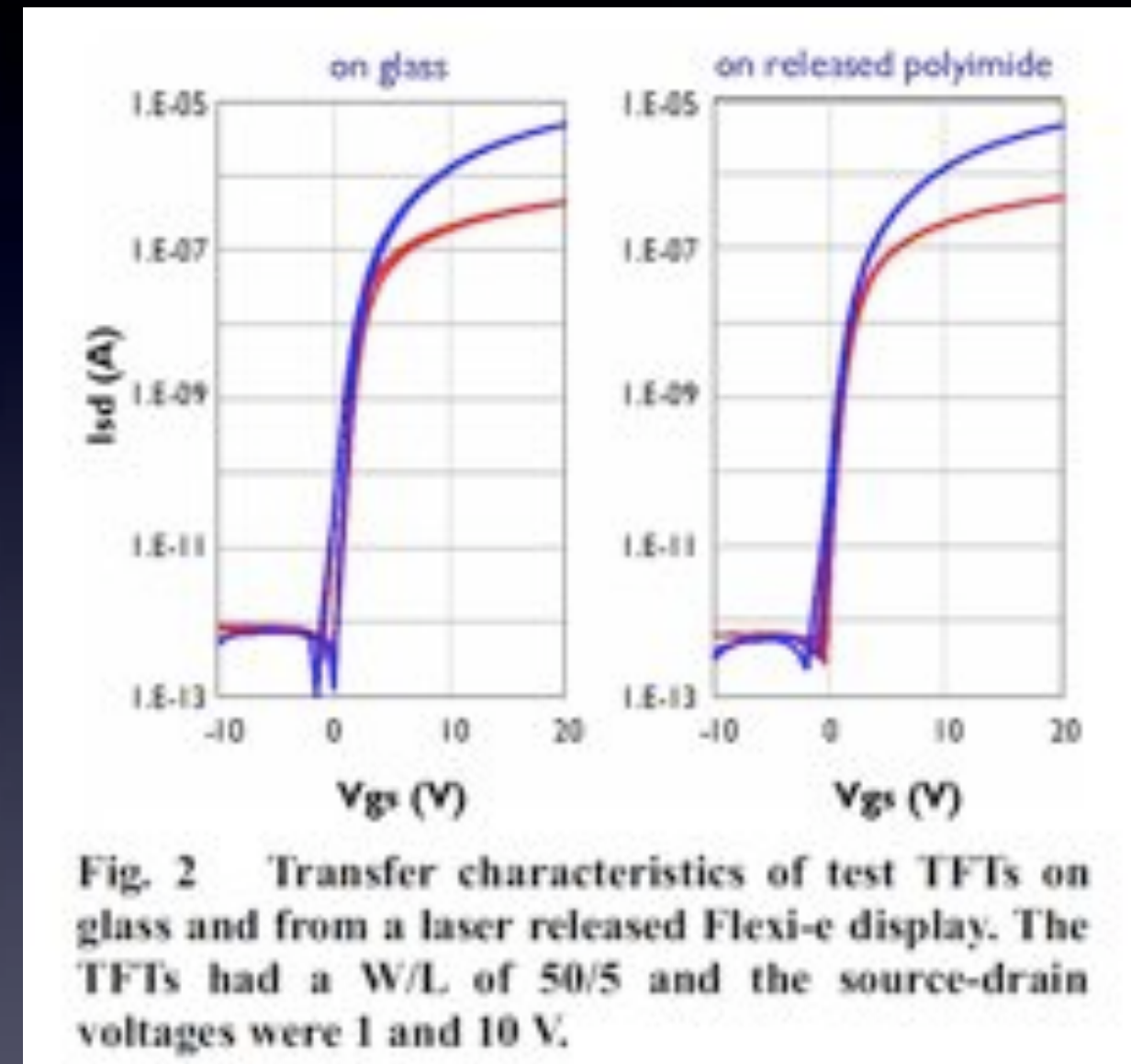
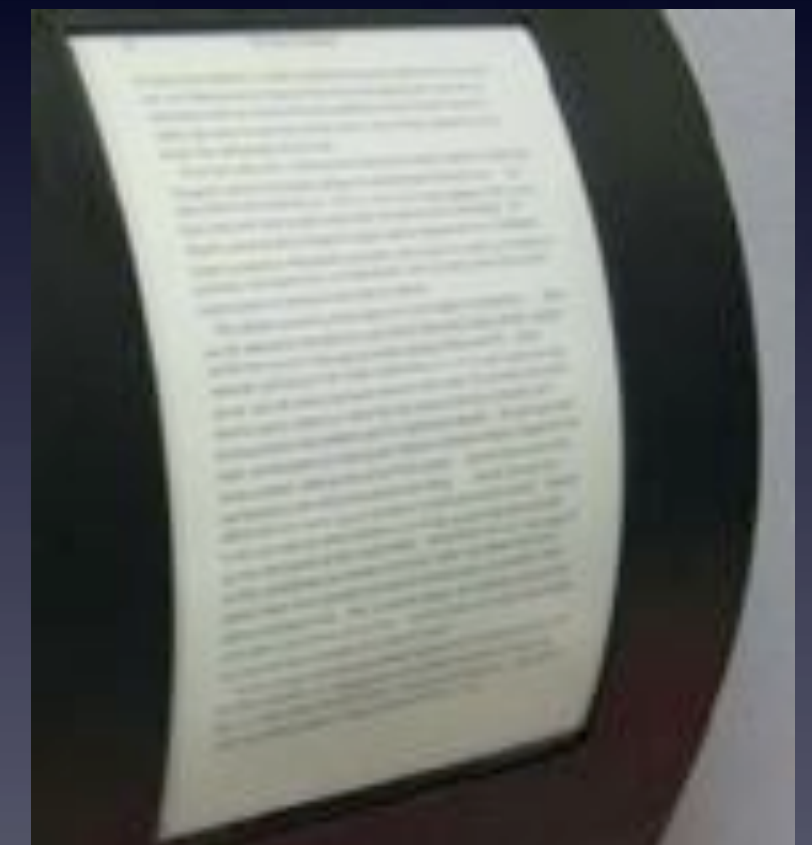


Fig. 2 Transfer characteristics of test TFTs on glass and from a laser released Flexi-e display. The TFTs had a W/L of 50/5 and the source-drain voltages were 1 and 10 V.

French and Shinn, IMID 2008



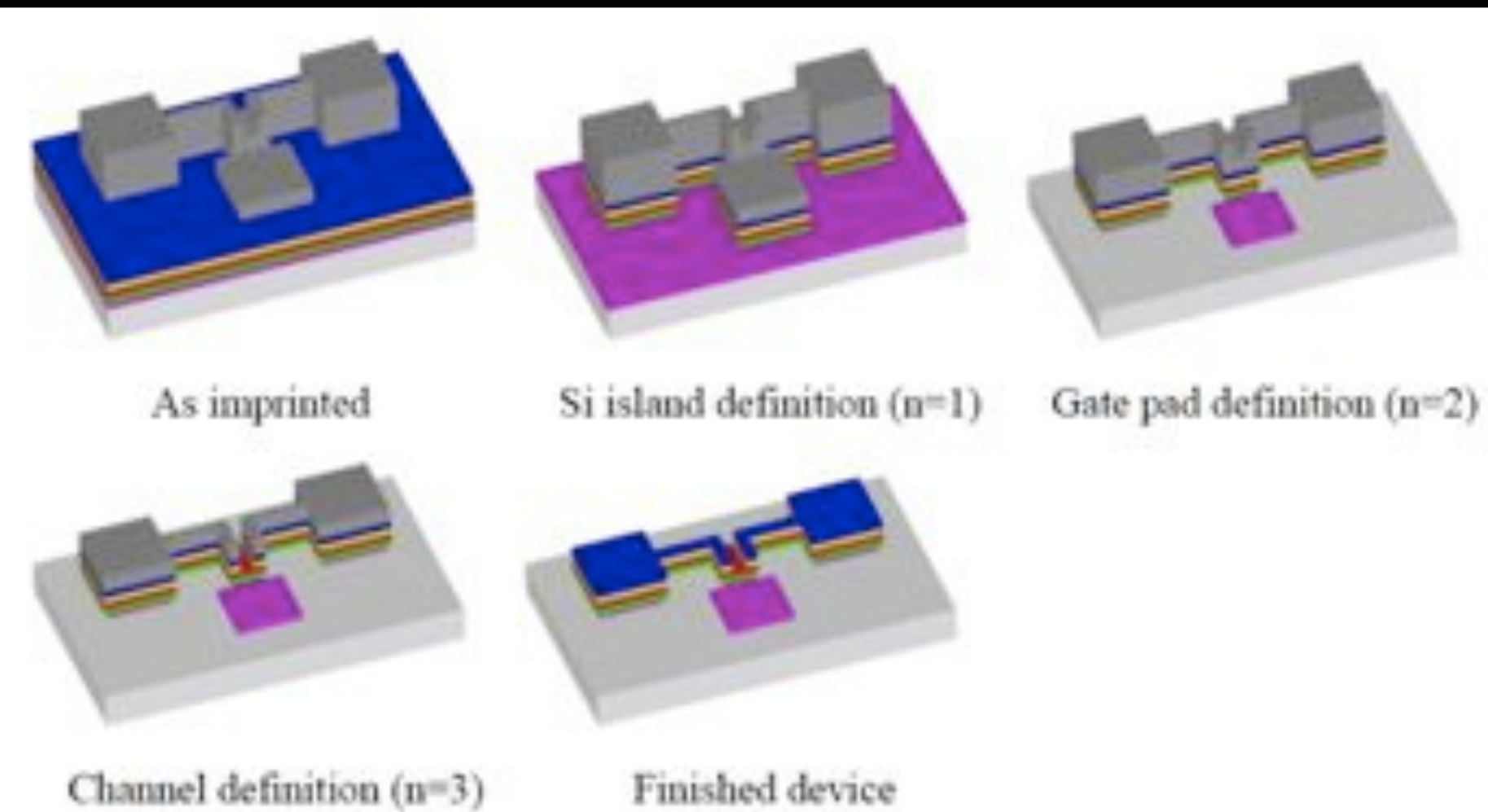
Fig. 1 Photograph of nine Flexi-e TFT arrays on a 370 x 470 mm substrate.



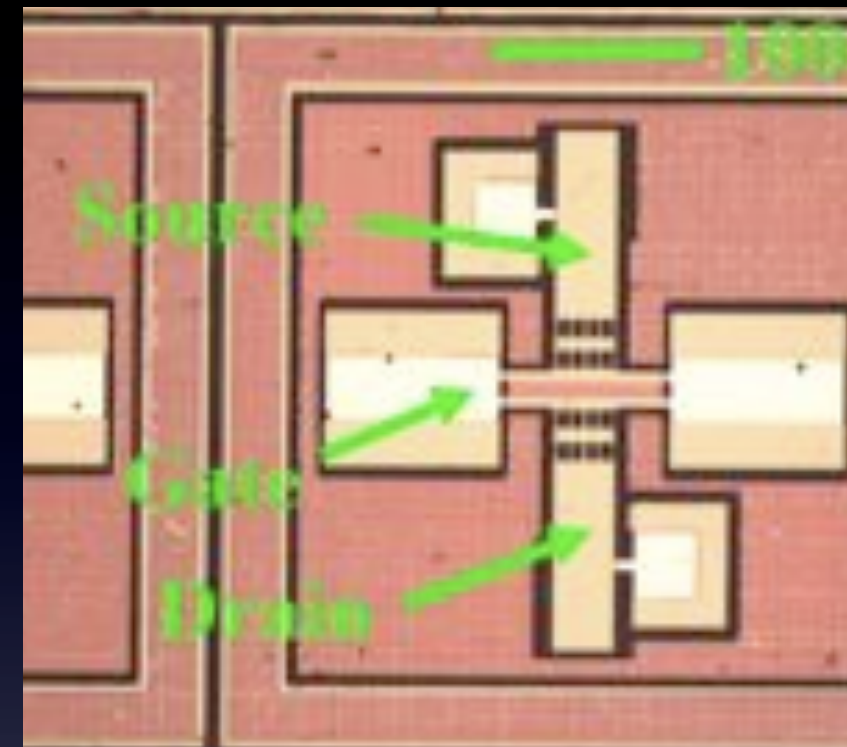
1.9" and 9.7" "Flexi-e" displays
Scheduled for introduction in 2009 by PVI

French and Shinn, IMID 2008

Self-Aligned Imprint Lithography (SAIL)



- Blanket deposition of (gate) metal, dielectric, undoped Si, n+ Si, (S/D) metal, resist
- Imprint resist to provide variable thickness
- Multiple etching steps forms transistor stack
- No registration required!
- Roll compatible



Jackson et al., SID Tech Dig (2008)

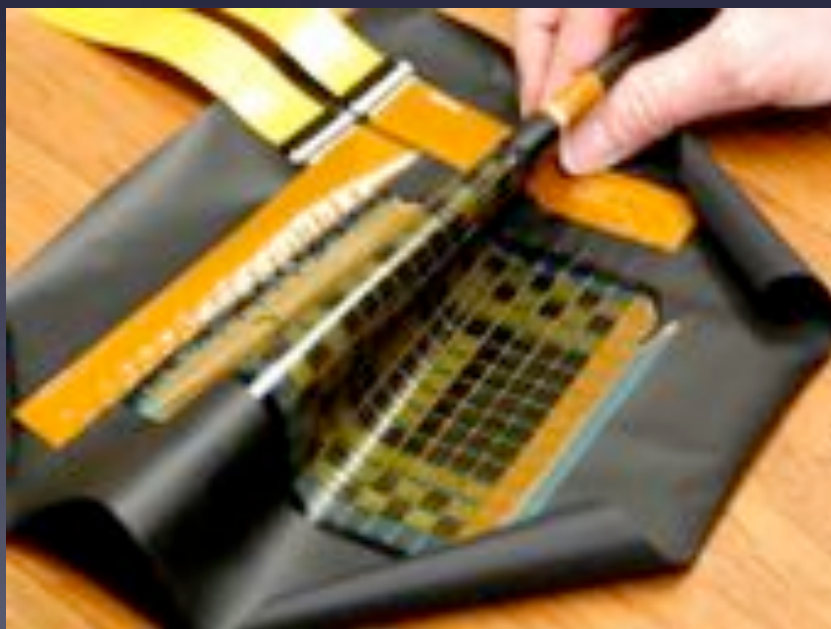
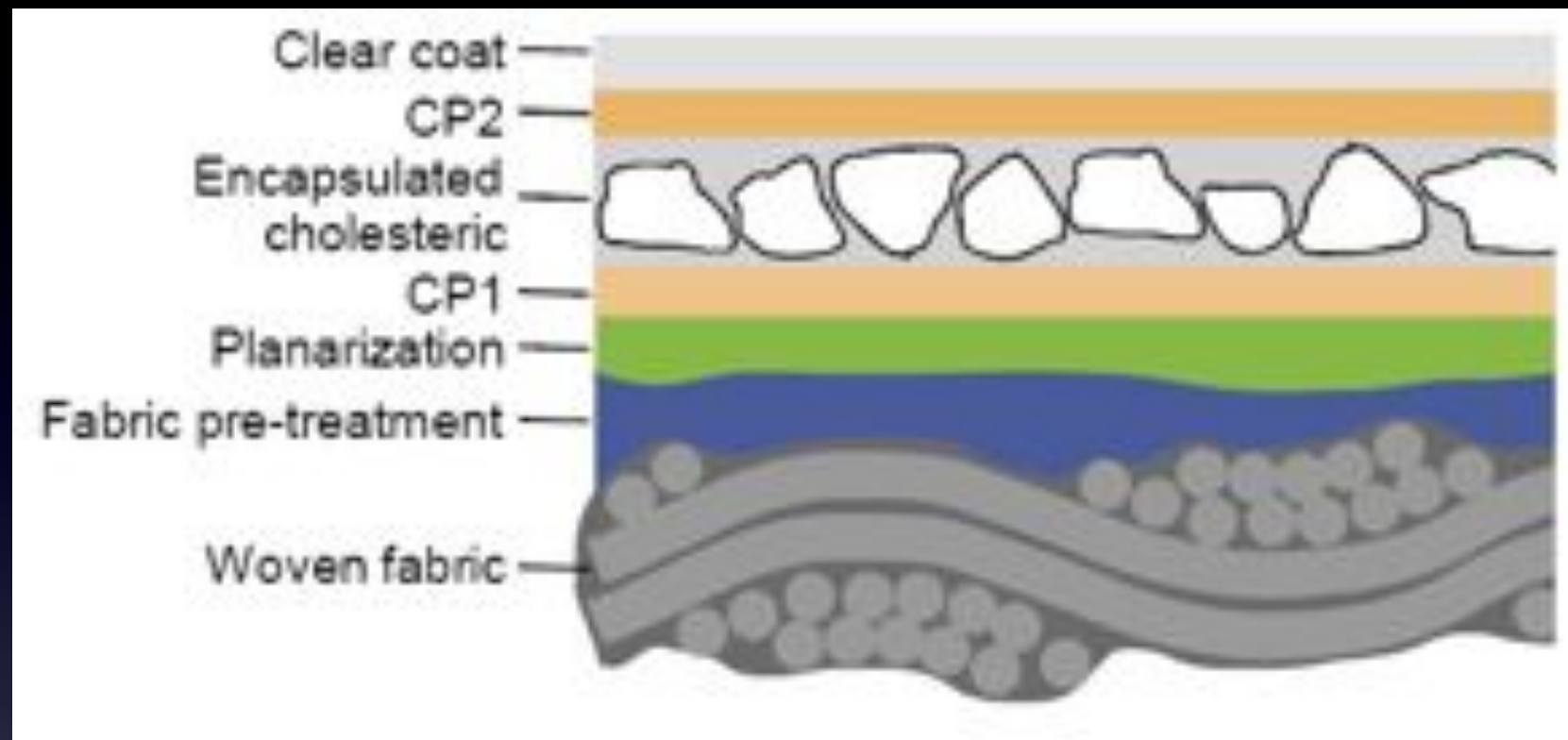
Drzaic Consulting Services - IEEE BASID April 2008

A gallery of flexible display devices



PVI - flexible digitizing tablet

Conformable displays from microencapsulated cholesteric liquid crystal



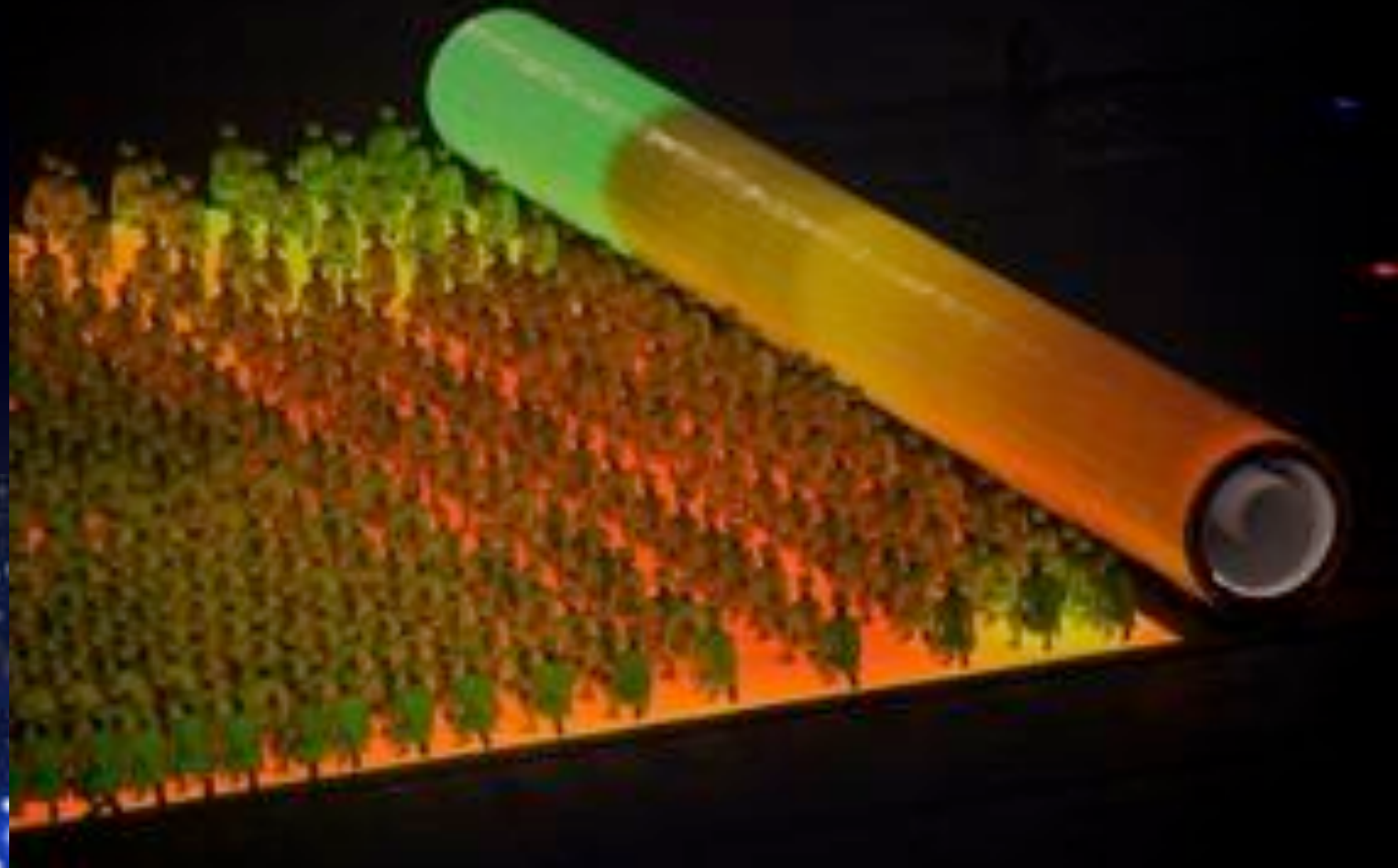
Source: Kent Displays; Kent State University

Flexible packages and fibers for LEDs

Beijing Olympics



Source: Boston.com



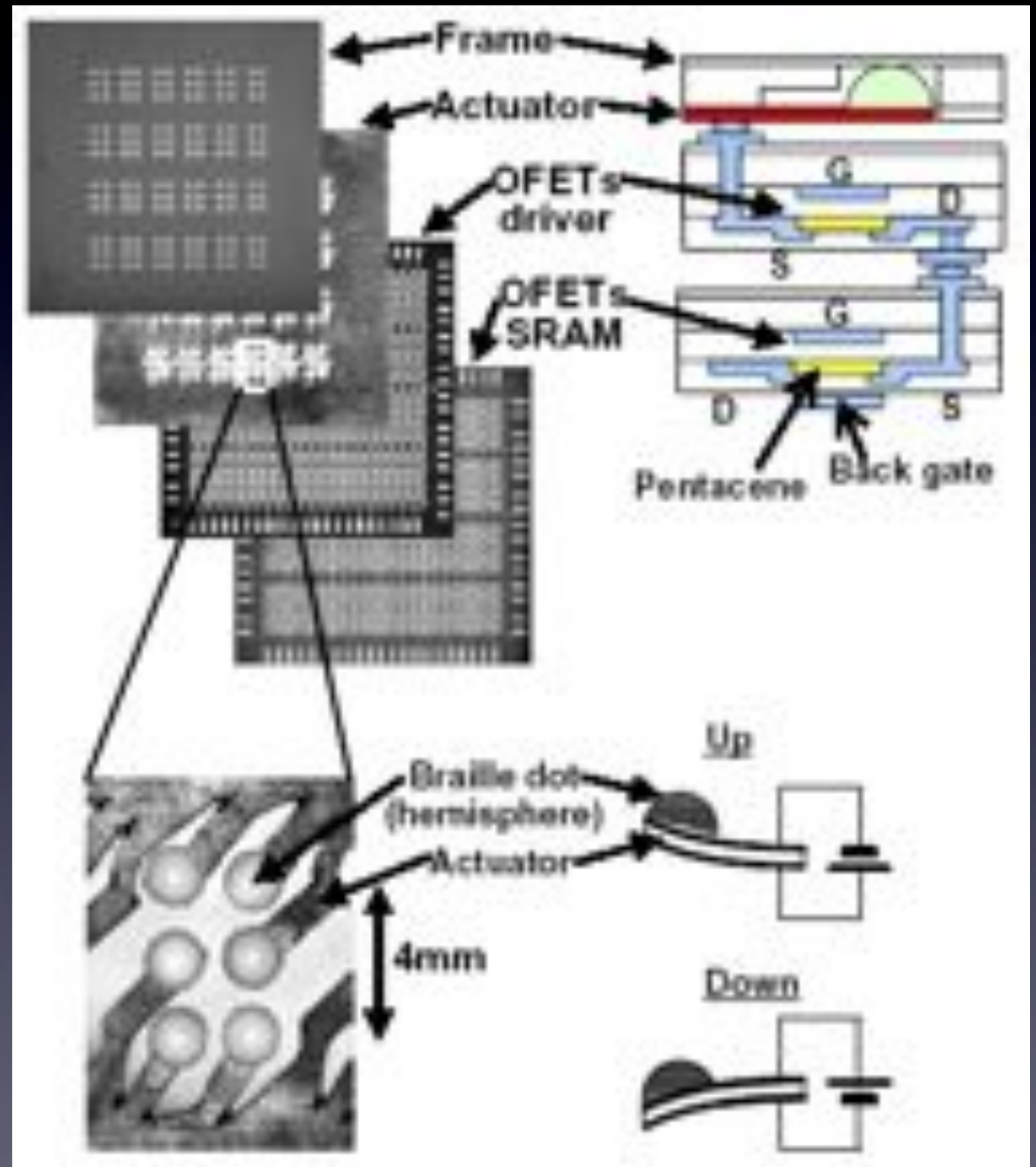
Source: eNil, flickr.com

Flexible plasma display



- Plasma contained in glass fibers
- 1 mm thick
- Shinoda Plasma Displays

Electronic Braille display



Takamiya et al.,
IDW '06, 261 (2006)

<http://www.ntech.t.u-tokyo.ac.jp>

Wearable displays



Source: www.luminex.it

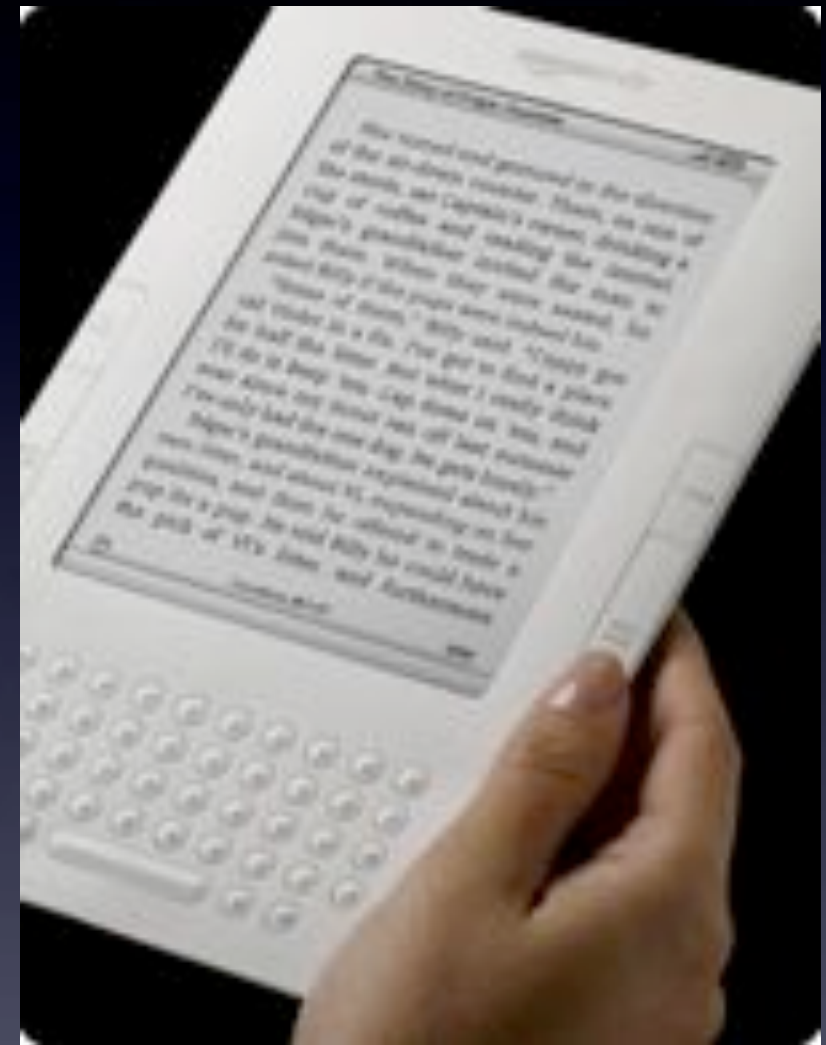


Source: www.mitchellpage.com

What about future adoption of products?

Case study – the Amazon Kindle ebook

- What's the most important property?
- Always connected to the network?
- Lots of information content available
- The paperlike screen?



Answer: all of them!

Do flexible displays uniquely solve a problem?



vs.

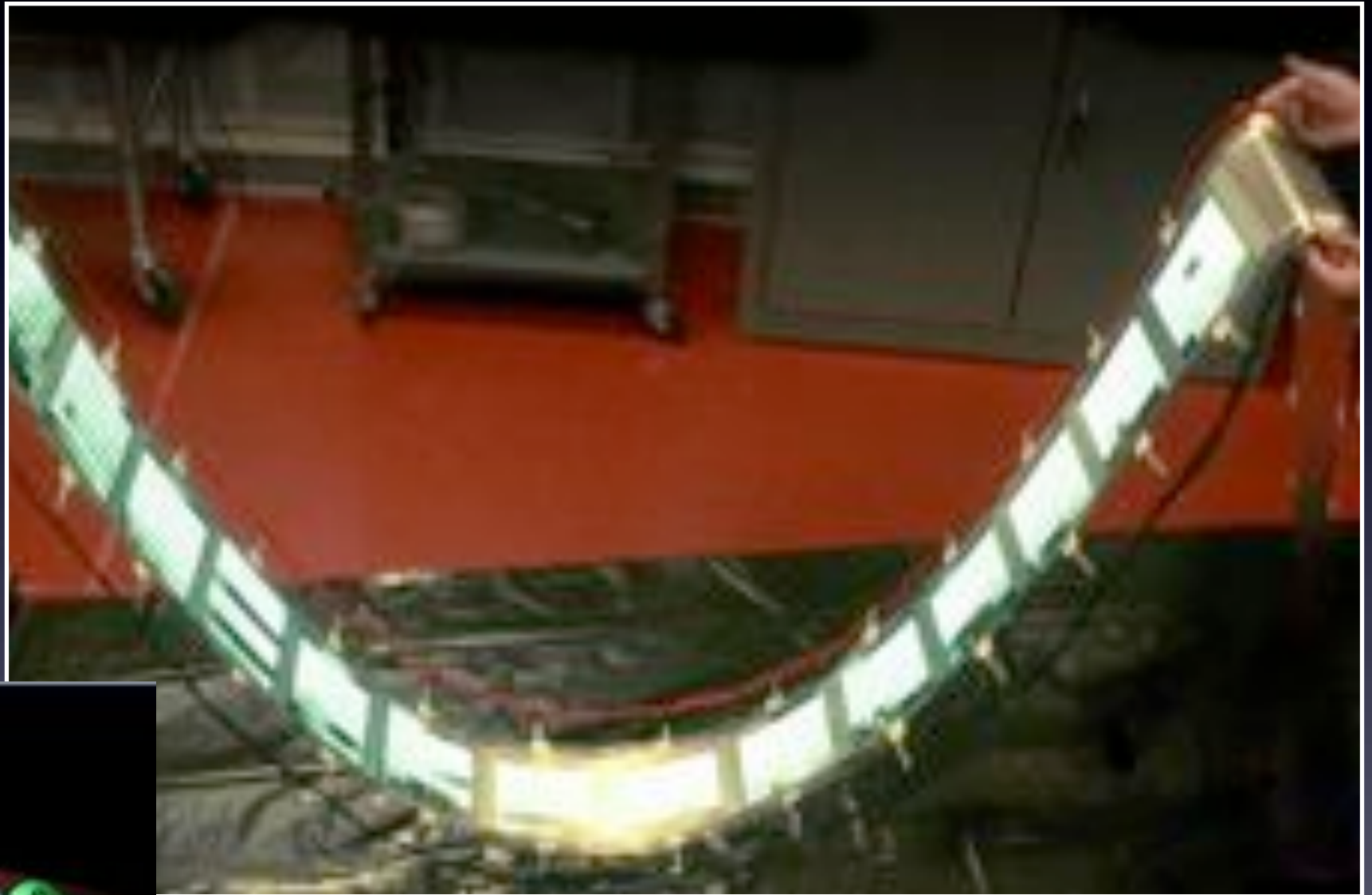


vs.



OLED solid state lighting

- Low cost and high efficiency look very attractive
- How do you screw these into a light socket?



Source: GE

How to enable a flexible display technology

- Solve the technical problems
- Have a reasonable manufacturing strategy
- Fix a problem for the customer that the competition cannot solve
- Convince the markets of the value

One concept of the Killer Application

The Nokia 888



www.yankodesign.com 2005



Nokia 888

YankoDesign, 2005