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!

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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

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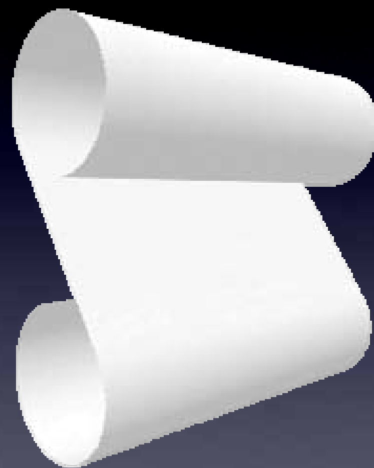
So what's the need for a flexible electronic display?



Maybe one of these examples will do...

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Multipage electronic newspaper

Sixteen flexible displays on eight A4 sheets
Networked to news content
Looks and feels like paper

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Large format, color electronic newspaper

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Electronic notepad

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Origami DVD player

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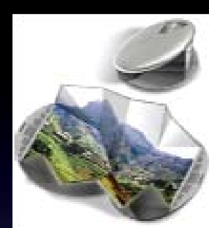
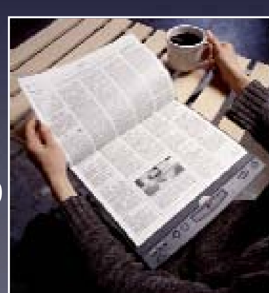
Problem - none of these are real

Minority Report, 20th Century-Fox 2002



Inventables.com 2007

IBM design concept1999



Andromeda Strain, A.S. Films 2008

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

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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).

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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

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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

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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 m^2/sec

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

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Applying existing display technology for flexible applications

"Can't I just modify what I already have?"

Plastic displays have a long history

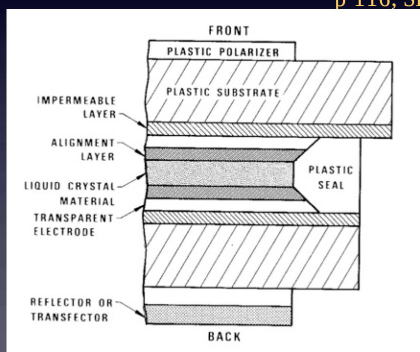
11.7/4:50 P.M.: Plastic Substrate LCD

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?

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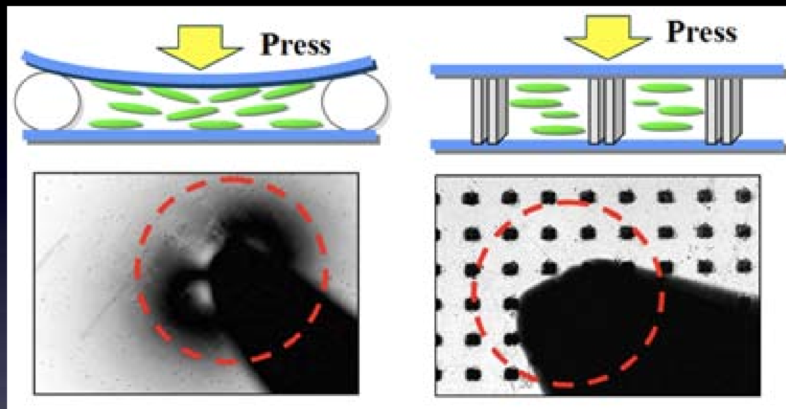
Not really



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

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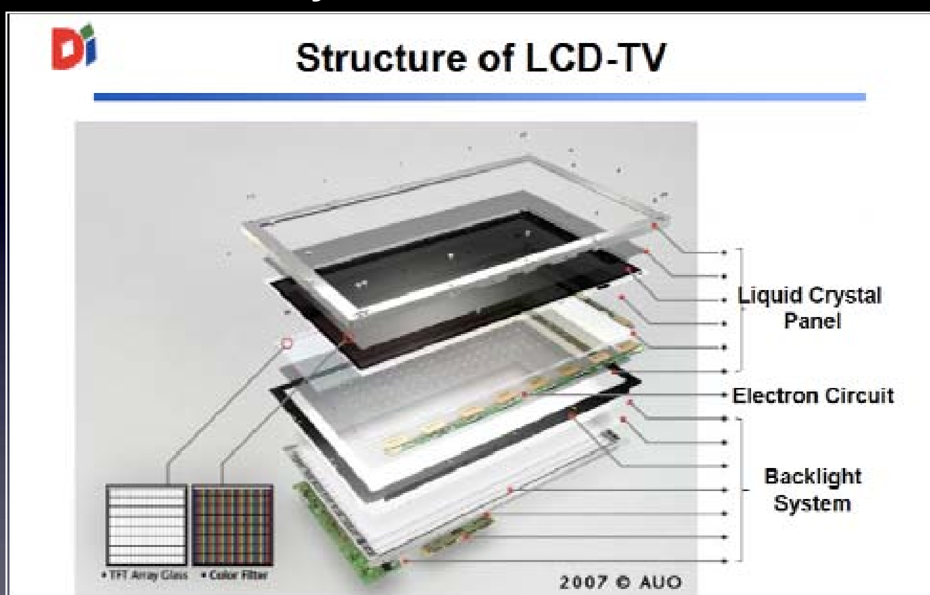
How do you make this flexible?



Y.-P. Huang, IDRC 2008

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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?

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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.

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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

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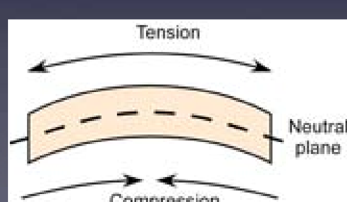
Why are mechanics important?

- 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

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ITO on polyester is brittle!

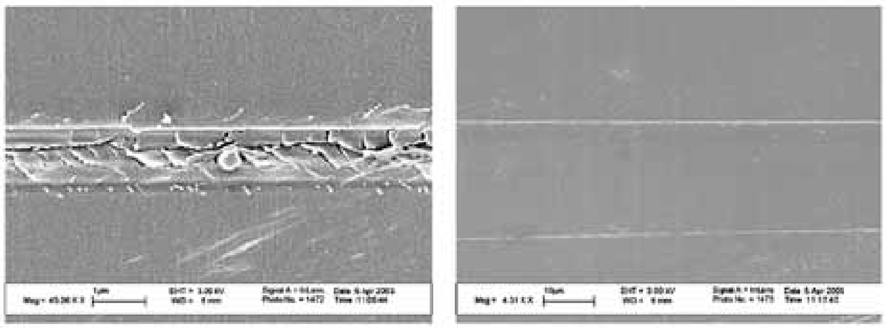

FIGURE 9 — Scanning electron micrograph of ITO-coated PET substrate showing parallel cracks created after 100K cycles of fatigue test. Resolution 1 µm (left), 10 µm (right).

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

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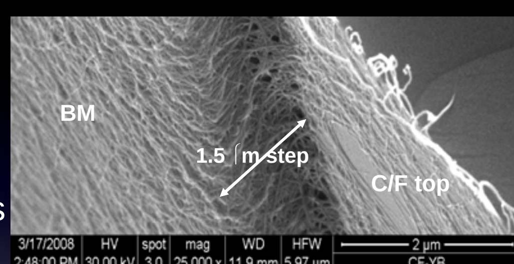
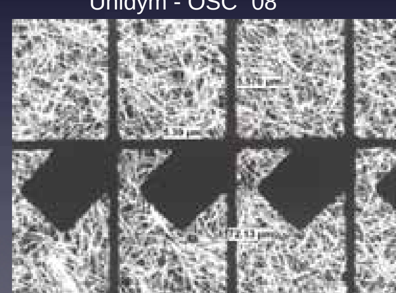
Flexible transparent conductors

- 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



Cambrios - OSC ´08

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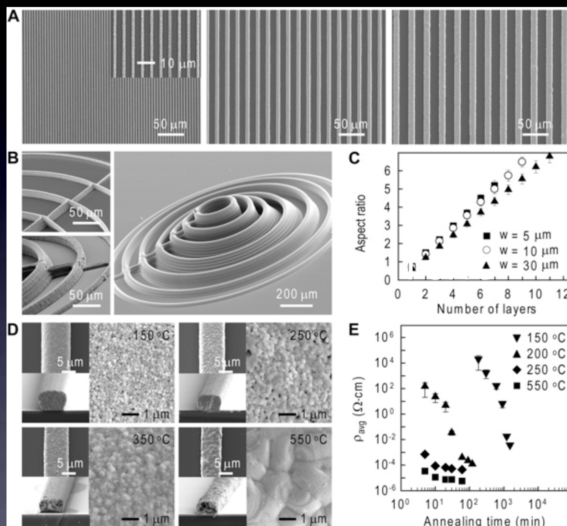
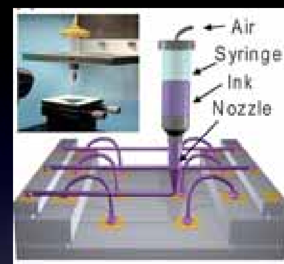
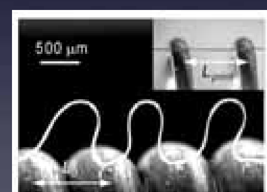
Direct-write fabrication of flexible 3D microstructures







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)

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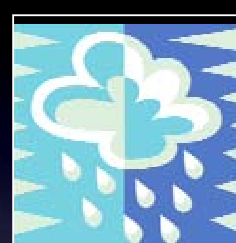
Permeability



- 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!

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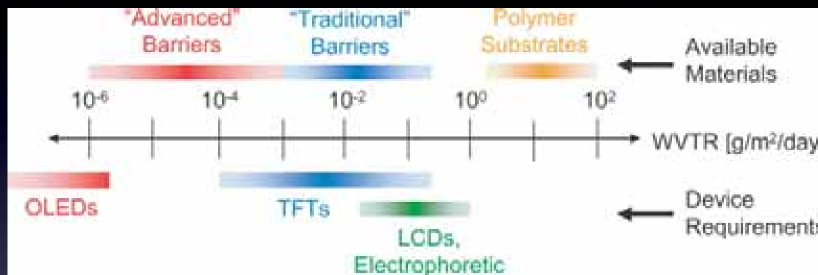
Permeability requirements



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

WVTR – Water Vapor Transmission Rate

- Different technologies require different levels of barrier function

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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/m^2-day
  - Simple single layers of metal or ceramic on plastic permit permeation of 5×10^{-2} g/m^2-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

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Single layer coatings

- Si:C (Dow Corning)
  - Water vapor permeation < 10^{-4} g/m^2-day
- Reactive atomic layer deposition of Al_2O_3 (DuPont)
  - Water vapor permeation < 10^{-5} g/m^2-day

Source: 2006 USDC
flexible displays conference

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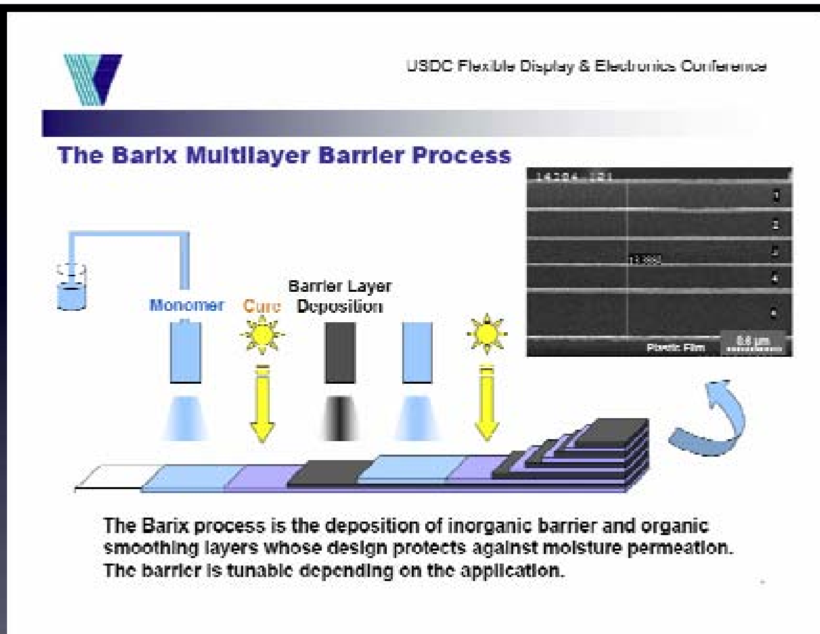

Water vapor permeation < 10^{-5} g/m^2-day

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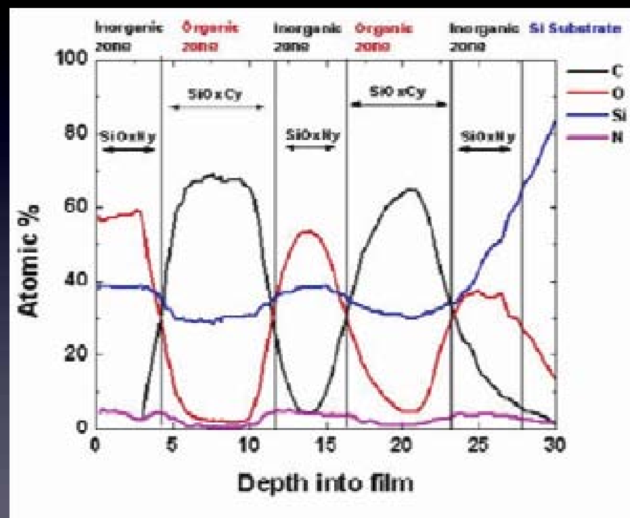
GE Graded barrier material

- PECVD
- Continuous coating
- Water vapor permeation at or below 10^{-5} g/m^2-day



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

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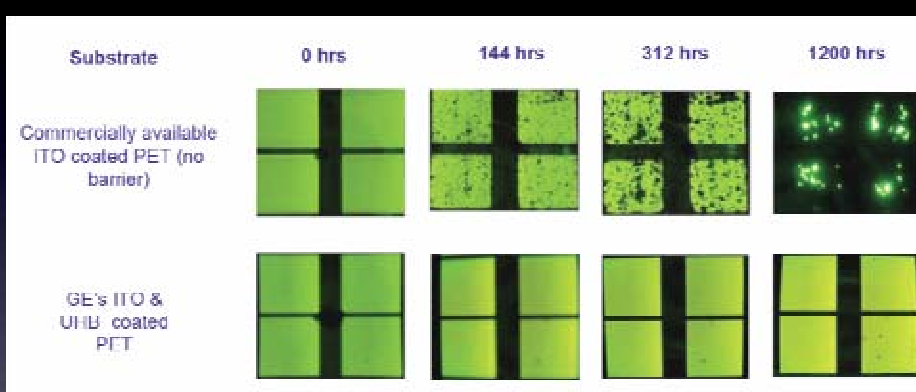
Performance of graded barrier



23 C, 40% RH stability

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

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What about the effect of flexibility on cell gap?

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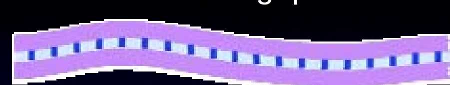
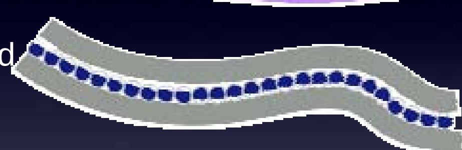
Strategies to maintain constant cell gap

- 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

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Electronic paper

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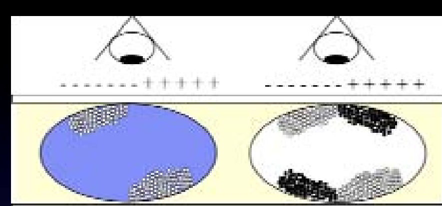
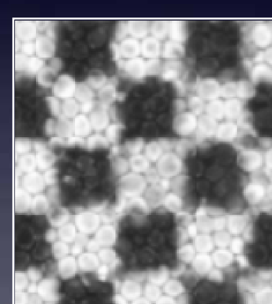
Encapsulated electrophoretic display

- 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

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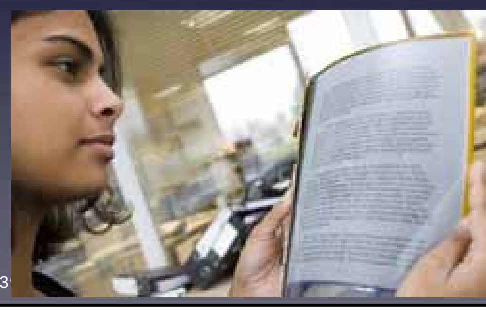
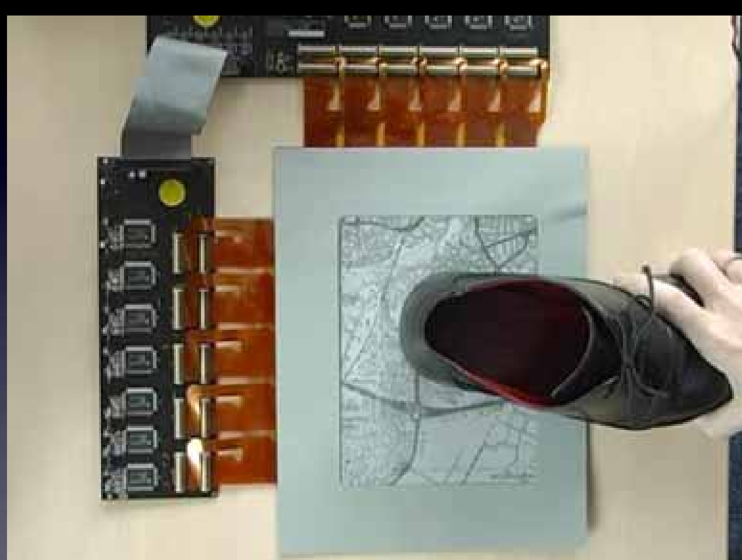
Flexible electronic paper - organic transistor backplane

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



Plastic Logic
10" 100 ppi reader
Source: Plastic Logic

Robust display



Source:
Plastic Logic

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Organic light emitting diode (OLED) displays

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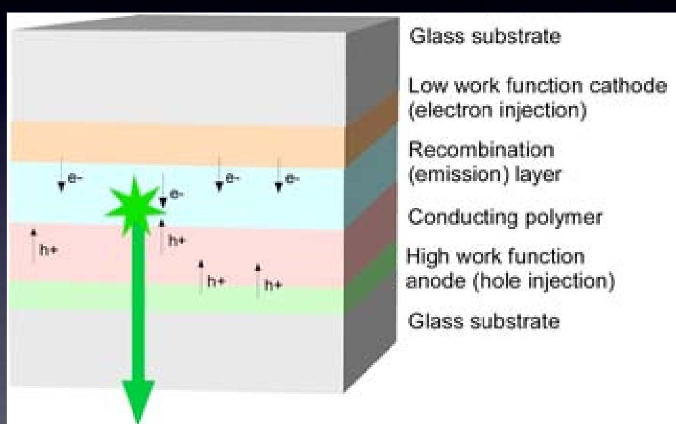
Basic bottom-emission OLED stack

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



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Ink jet printing - polymer LEDs

- Receptor wells formed on substrate to contain drops

Source: CDT

Source: Litrex M-series jet printer

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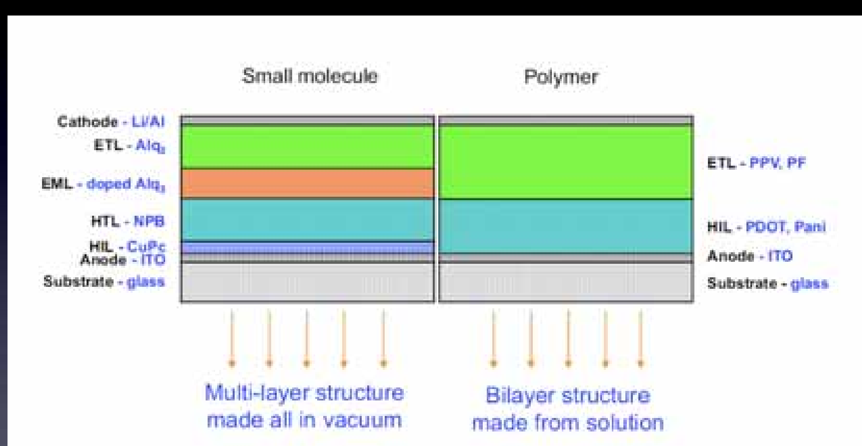
Small molecule vs. polymer OLED fabrication



Small molecule more difficult to fabricate, but higher in performance

F. So, IDRC Workshop, 2008

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Flexible OLED

- a-Si transistors on steel foil

Source: LG Philips

Organic transistors on plastic

Source: Sony

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Sony Flexible OLED – organic transistor backplane

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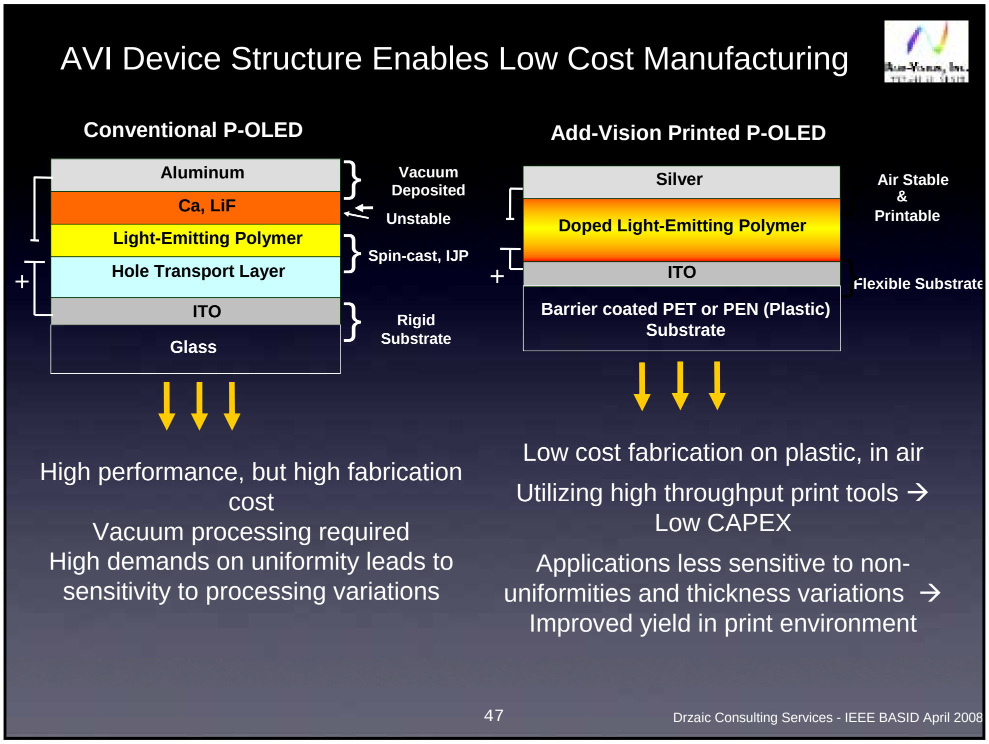
AVI Device Structure Enables Low Cost Manufacturing
Conventional P-OLED
Aluminum
Ca, LiF
Light-Emitting Polymer
Hole Transport Layer
ITO
Glass
Vacuum Deposited
Unstable
Spin-cast, IJP
Rigid Substrate
Add-Vision Printed P-OLED
Silver
Doped Light-Emitting Polymer
ITO
Barrier coated PET or PEN (Plastic) Substrate
Air Stable & Printable
Flexible Substrate
High performance, but high fabrication cost
Vacuum processing required
High demands on uniformity leads to sensitivity to processing variations
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
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Opportunities for Add-Vision's P-OLED Technology in Mobile Handsets
Icons, Indicators & Cosmetic
Backlight (Keypads)
Secondary Displays
Add-Vision P-OLED
Resident LED Backlight

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 cd/m^2 (bright room lighting).
  - Plastic cells are not nearly this stable with current commercial barriers

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What about flexible backplanes?

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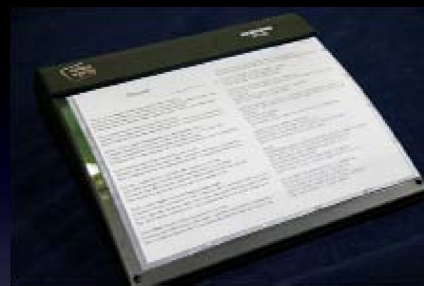
Flexible amorphous silicon displays

LG Philips
a-Si on steel EPD



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

Conventional processing on unconventional substrates

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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

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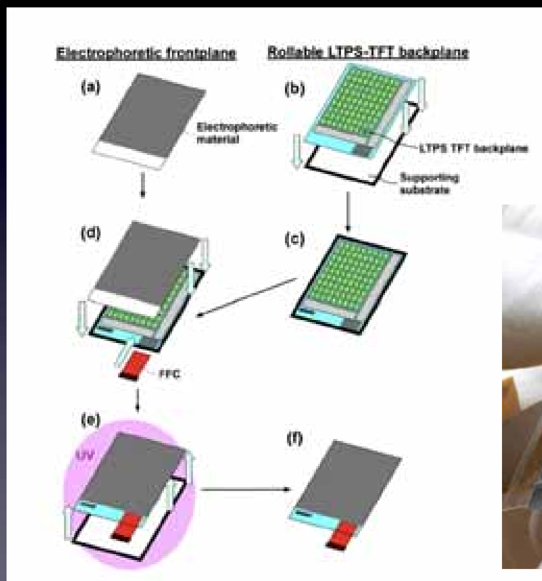
96 µm thick flex display



Kodaira *et al*, JSID 2008

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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

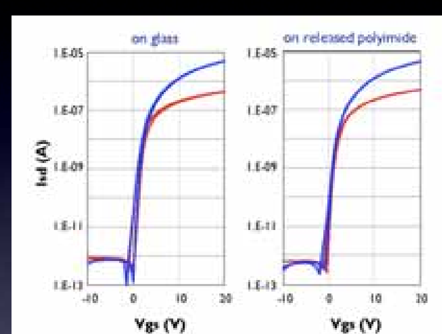

Fig. 2 Transfer characteristics of test TFTs on glass and from a laser released Flexi-e display. The TFTs had a W/L of 50/5 and the source-drain voltages were 1 and 10 V.

French and Shinn, IMID 2008

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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

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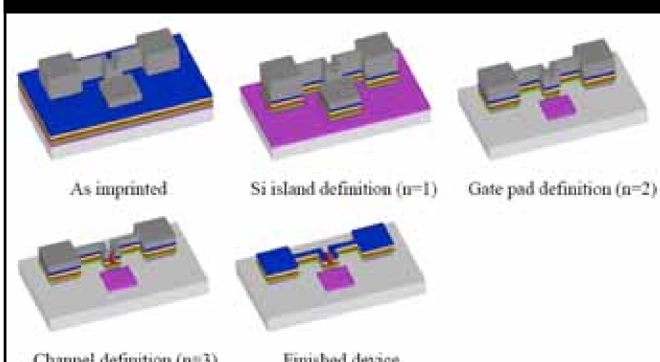
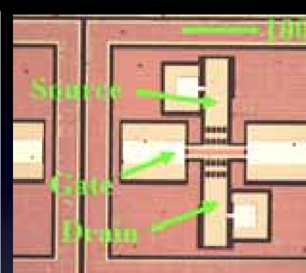
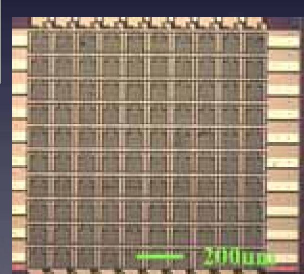
Self-Aligned Imprint Lithography (SAIL)







- 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)

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A gallery of flexible display devices

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PVI - flexible digitizing tablet

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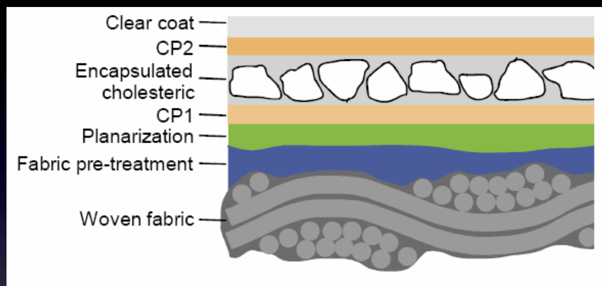
Conformable displays from microencapsulated cholesteric liquid crystal



Source: Kent Displays; Kent State University

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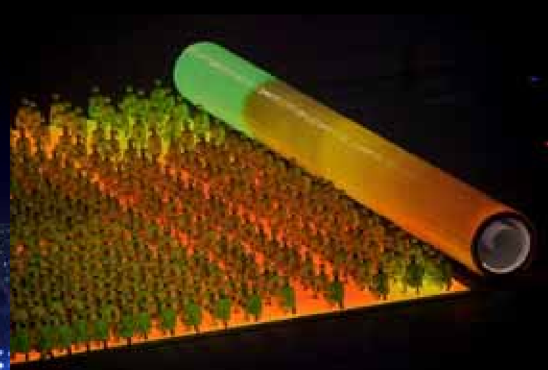
Flexible packages and fibers for LEDs

Beijing Olympics



Source: eNil, flickr.com

Source: Boston.com

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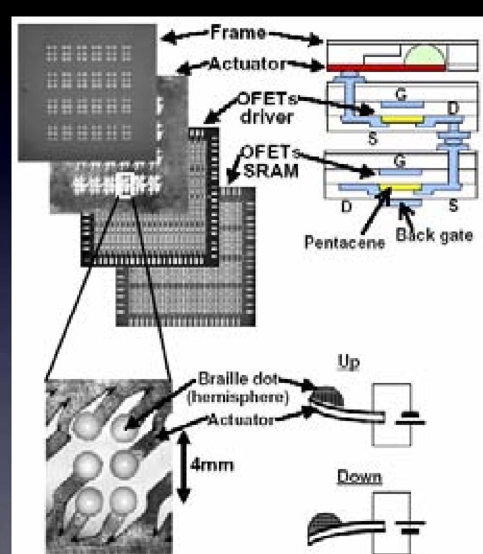
Flexible plasma display

- 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

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What about future adoption of products?

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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!

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Do flexible displays uniquely solve a problem?

vs.

vs.

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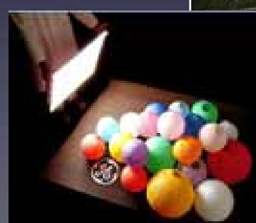
OLED solid state lighting

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



Source: GE

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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

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One concept of the Killer Application

The Nokia 888

www.yankodesign.com 2005

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