Flexible Displays and Microelectronics:
Opportunities and Challenges

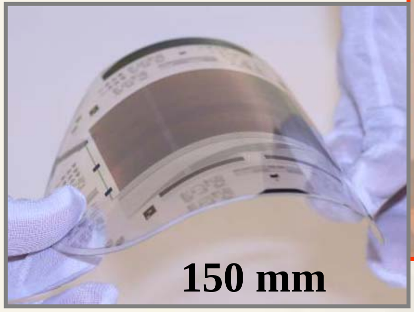
Gregory B. Raupp
Professor of Chemical Engineering
Arizona State University
Tempe, Arizona, USA

raupp@asu.edu
480-727-8752

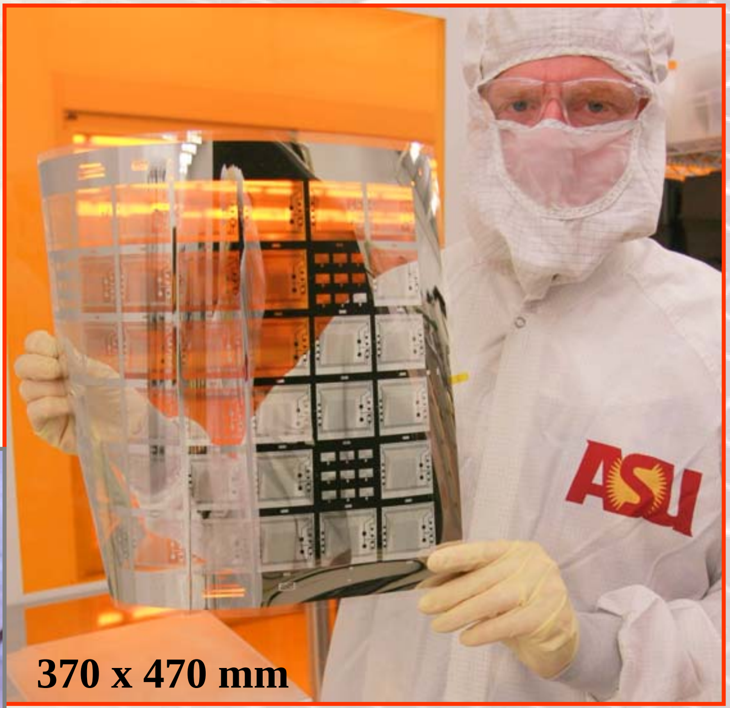
http://flexdisplay.asu.edu

Outline

- Flexible Displays and other "MacroTechnology" Opportunities
- Principal Technology Challenges
  - ➢ Manufacturing Processes
  - ➢ Device Performance
  - ➢ Materials
- Product Pull *vs.* Technology Push
- Conclusions



150 mm



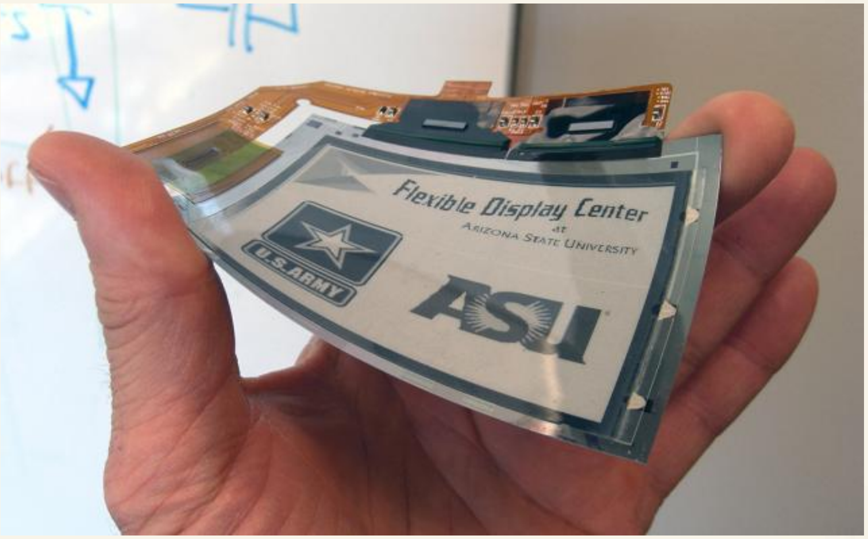
370 x 470 mm

Emerging MacroTechnology:
Flexible Displays

Reflective
Electrophoretic Displays

- Ultra-low power
- Sunlight readable
- Near-video rates

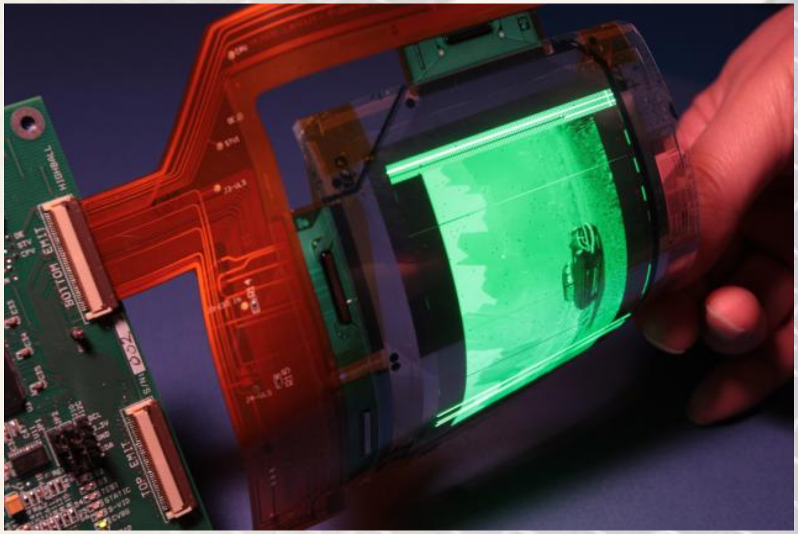
E·INK



Emissive
Organic Light Emitting Displays

- Low power
- Vibrant full color
- Full motion video

UNIVERSAL DISPLAY CORPORATION™



GENERAL DYNAMICS
Strength on Your Side™

Source: Flexible Display Center
at Arizona State University
http://flexdisplay.asu.edu

Flexible Electronics as the Enabling Platform Technology

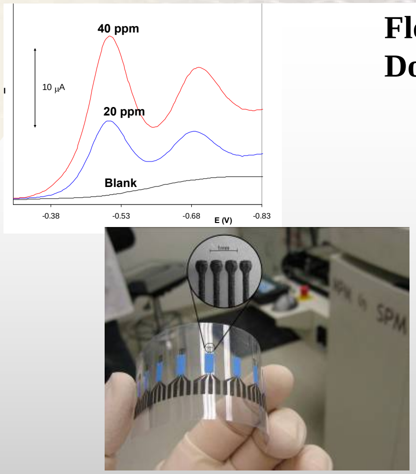
Integrate flexible TFT backplanes with frontplanes of different functionality to create new technology

Image-layer Frontplane

Flexible Displays

Sensing-layer Frontplane

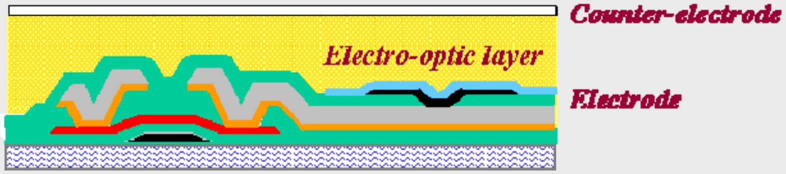
Flexible Sensor Arrays



Sensors for Environmental Threat Detection and Human Health/Performance Monitoring
Images compliments of J. Wang ASU BDI

Flexible Blast Dosimeters

Flexible Digital Radiography



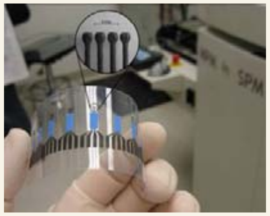
Thin Film Transistor (TFT) Pixel
Cross Section on Flexible Substrate

Transformational Positioning

Macrotechnology → does not compete / replace Si-based devices -- instead complements in applications where Si CMOS is not well-suited (new products, applications and markets)

Macrotechnology Unique Attributes:

- ***Less is not Moore!*** → not driven by transistor down-scaling (performance), instead driven by unique integrated functionality and form factor
- ***Bigger is Better!*** → large area (as well as small) applications
- ***Be Flexible!*** → compact, ultra-thin, rugged, lightweight, implantable, wearable, conformable, and (potentially) transparent



Sensors

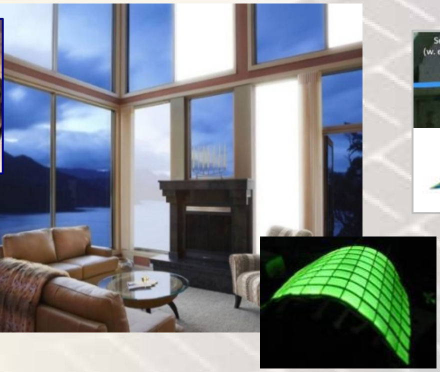
Inflatable spacecraft and extra-terrestrial habitats

Wearable Devices

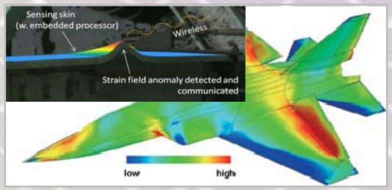
Flexible Digital Radiography

Foldable Large Area Antenna

Flexible Solar Cell



Building-integrated PV and SSL



Smart Skins for Structural Health Monitoring

Key Manufacturing Challenges

❸

Robust materials with manufacturable processes on flexible backplanes

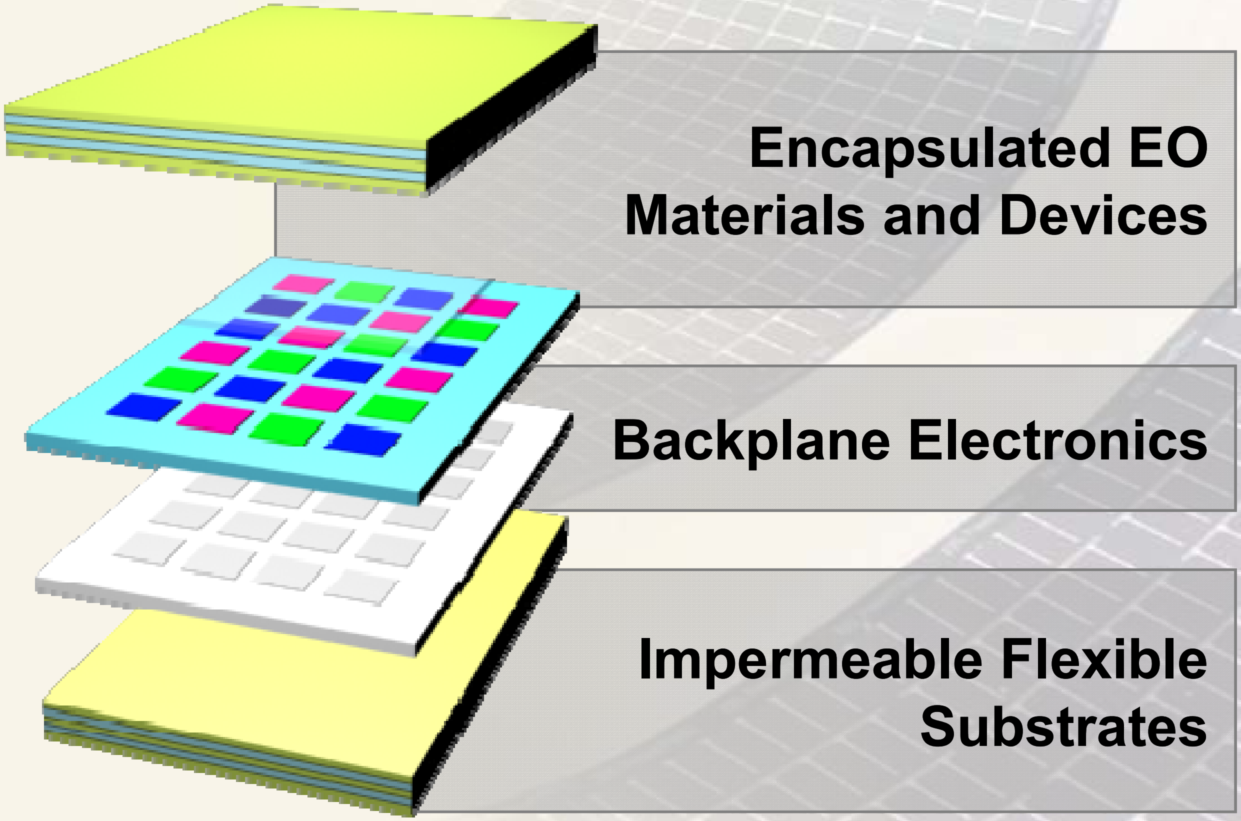
❷

Manufacturable high quality TFT materials within substrate constraints

❶

Manufacturing-ready substrates: no “drop-in” replacement for glass

Method for handling flexible substrates in display-scale automated manufacturing equipment



Encapsulated EO Materials and Devices

Backplane Electronics

Impermeable Flexible Substrates

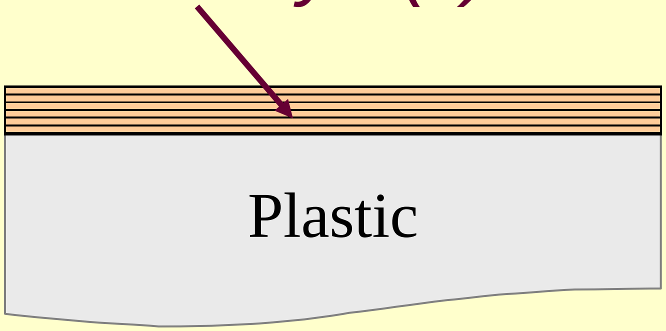
Encapsulated Electro-optic (EO) Devices **integrated with an** ***Active Matrix Backplane*** **fabricated on a** ***Flexible Substrate System***

Flexible Substrate Systems:
Down-selects and Challenges

No manufacturing-ready "drop-in" replacements for glass

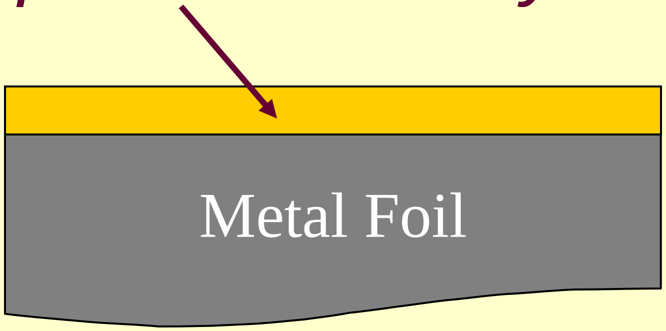
Plastic (PEN, PES, PI)

- Process T limit
- Dimensional stability
- Permeable to O_2/H_2O: *barrier layer(s)*



Metal Foil (SS)

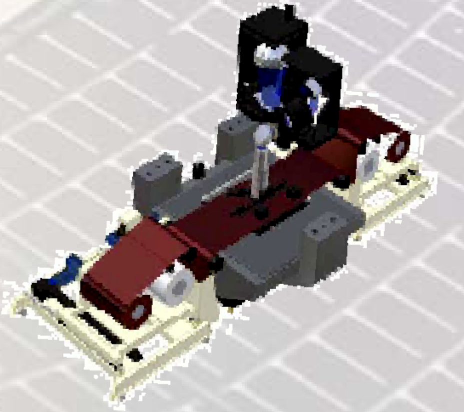
- Limited flexibility
- Stress management
- Surface passivation: *planarization layer*



Parallel Manufacturing Pathways

- **Adapt existing plate-to-plate toolset infrastructure**
  - ☒ Free-standing flexible substrates
  - ☒ Substrate fixturing / framing
  - ☒ Backside thinning: chemical etch or grind-polish
  - ☑ Substrate temporary bonding – debonding
  - ☑ Substrate coat - release
  - ☑ Layer transfer

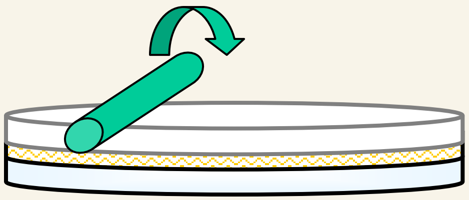
- **Adopt Roll-to-Roll manufacturing infrastructure**
  - ☒ Toolsets immature with significant issues – handling, layer alignment, resolution, reliability
  - ☒ Metrology strategy undefined
  - ☑ Take step-wise “R2R-compatible” approach focusing on critical issues



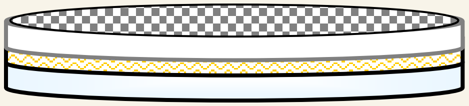
Manufacturing Protocol Options

Bond - Debond

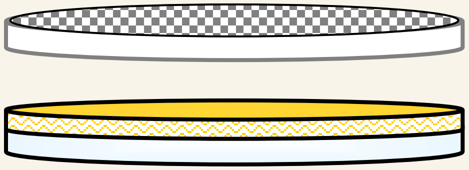
FDC SEC LG-D ITRI PV



Substrate bonded with Temporary Adhesive to Carrier



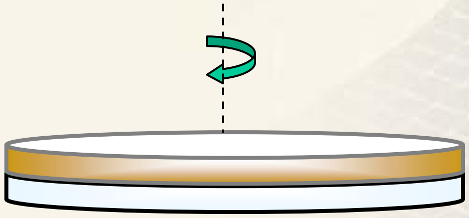
TFT Fabrication 130 – 180 °C



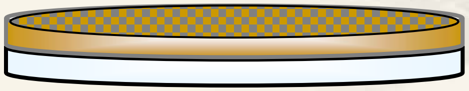
Triggered Debond:
Thermal
Solvent
Light
Mechanical

Coat – Laser Release

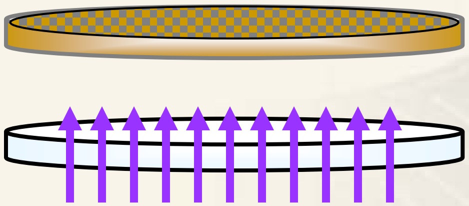
IBM Philips (EPLAR) PVI



Spin-coated Polyimide on Carrier



TFT Fabrication 280 - 300 °C



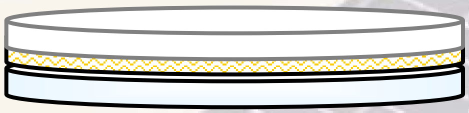
Laser Release:
Interfacial Melting

Layer Transfer

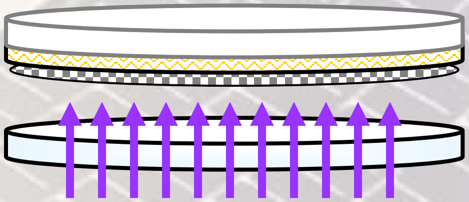
Seiko-Epson (SUFTLA)

Sacrificial poly-Si on Carrier

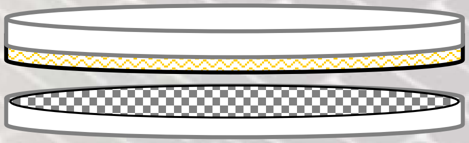
TFT Fabrication 300 – 380 °C



Temporary Substrate bonded with Water-soluble Adhesive



Laser Release: Ablation



Bond to Flex then release

Capability/Limitation Comparison

Capability/Limitation	Temp Bonding	EPLaR	SUFTLA
Flexible Substrate	**<u>High surface quality</u> polymer or metal foil**	**Solution-castable polymers (PI, BCB)**	**Any**
TFT Process Temperature Limit	**Substrate-dependent (180 °C for HS-PEN)**	**Polymer-dependent (280 °C for PI)**	**Typical glass-based TFT limits**
Flexible Substrate Distortion	**Can be significant – *but can be controlled to <u>negligible</u> level !***	**Negligible**	**Not applicable**
Release Process	**Rapid automated dry**	**Laser interfacial melting**	**Laser ablation**
Scale-ability	**?**	**?**	**?**

Temporary Bonding – Debonding:

Manufacturing Challenges

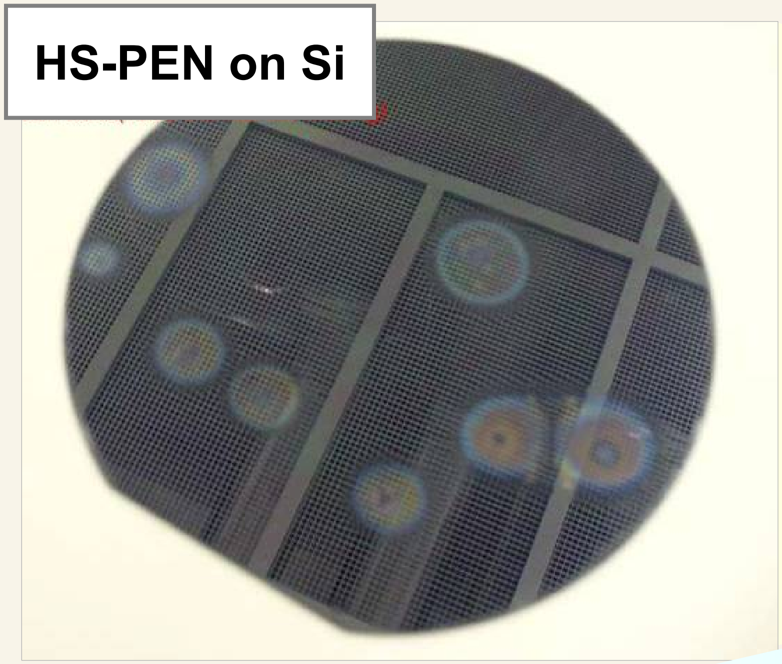
- Temporary bonding **with semiconductor-grade adhesive** (developed by Henkel with FTA funding and FDC pilot line development)
  - ✓ Compatible with Si-based TFTs
  - ✓ Low total thickness variation (TTV)
  - ✓ Defect (particle/bubble) free
  - ✓ TFT and EO process flow and toolset compatible

- Automated de-bonding
  - ✓ Triggered release (thermal, radiation, chemical, mechanical)
  - ✓ Residue-free
  - ✓ TFT array and substrate (and carrier) damage-free

Complexity of component interactions requires system-level substrate/barrier/adhesive/carrier/toolset solution

Temporary Bonding Pitfalls

HS-PEN on Si



Blisters form at defect (bubble, particles) sites

Exacerbated by adhesive out-gassing at temperature and in vacuum

SS on Si

"Teacup" failure due to CTE mismatch between substrate and carrier

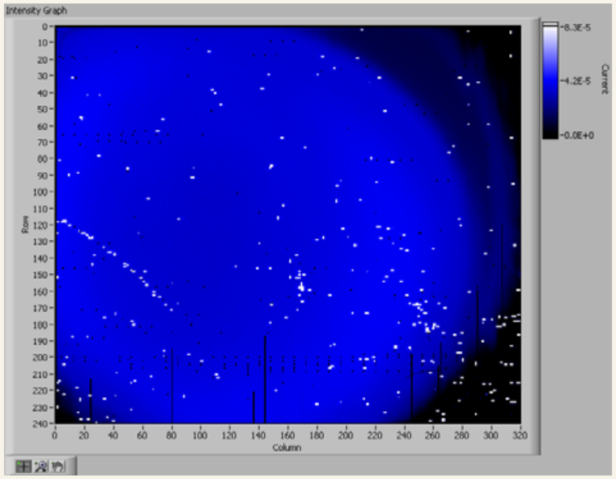
Adhesive visco-elasticity also crucial

Effect of Bow on TFT Array Quality

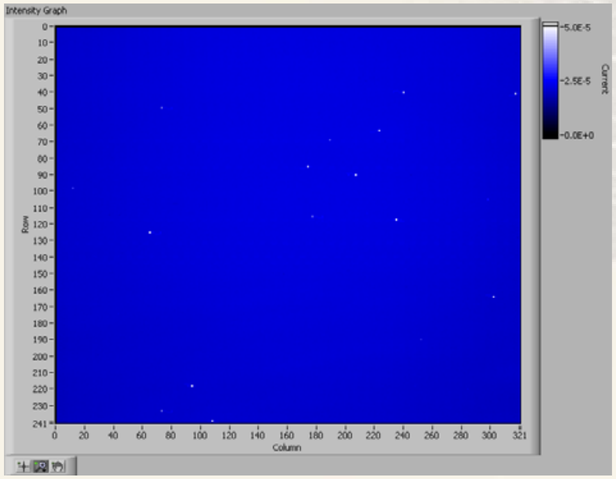
SS Substrates

TFT Drive Current Array Maps

3.8-in. QVGA EPD Display Module



Original Materials and Process



New Materials and Process

Low (Pilot Line) defectivity

<0.01% point defects

0-3 line defects

Low Temperature a-Si:H TFT Process Challenges and Approach

Glass-based TFTs

300-350 °C. Process Temperatures

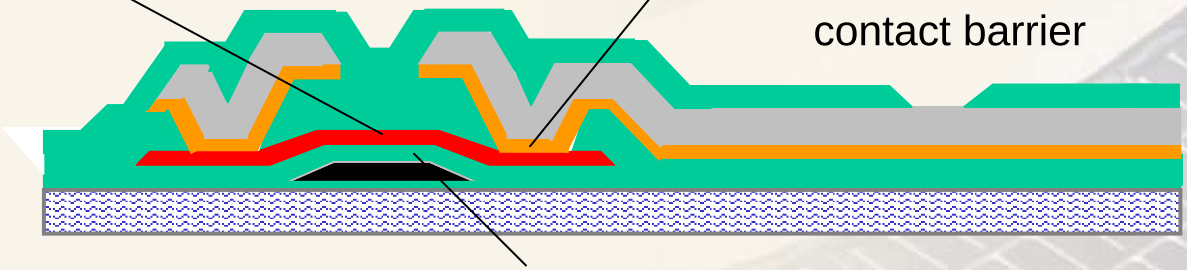
→

TFTs on Flex

180 °C. Process Temperature

→

Lower quality active device materials



a-Si:H

☒ higher SiH_2/SiH ratio → higher V_t and lower μ_{sat}

n^+ a-Si:H contacts

☒ unactivated dopants → higher ρ

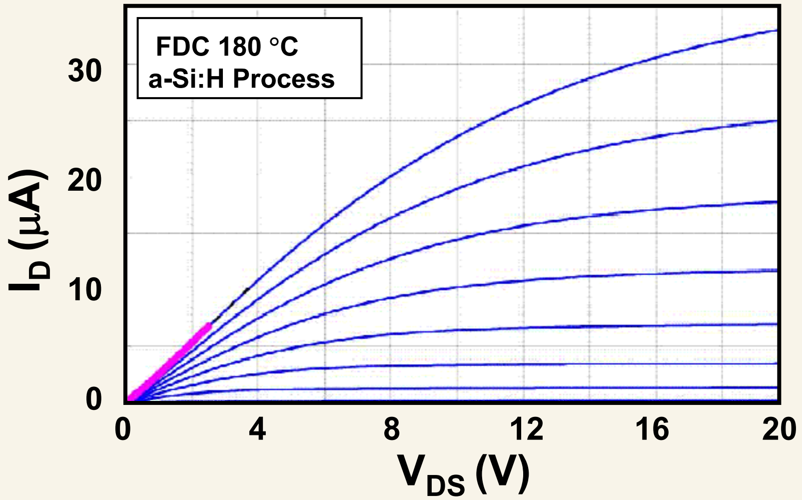
☒ Unstable interface → contact barrier

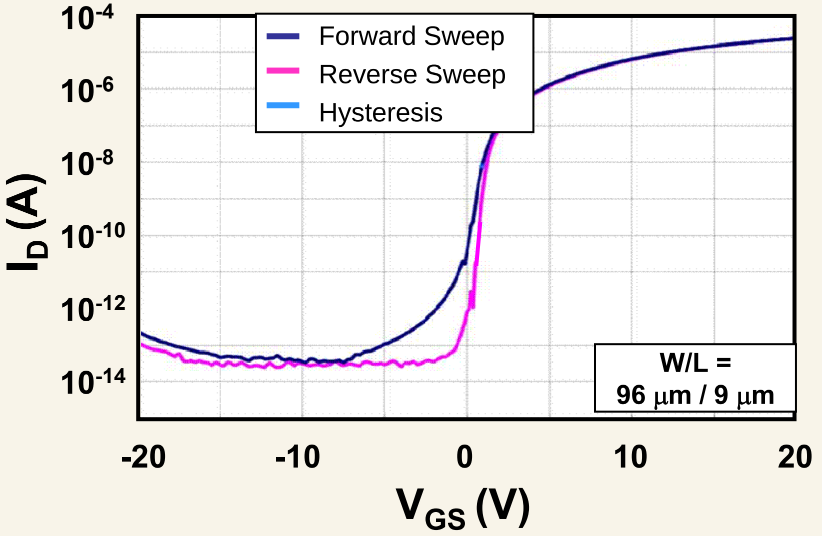
$a\text{-}SiN_x$:H gate dielectric

☒ higher charge trap density → greater ΔV_t (stability degradation) and greater hysteresis

Identify new process windows to achieve equivalent or better performance

FDC 180 °C a-Si:H TFT Performance





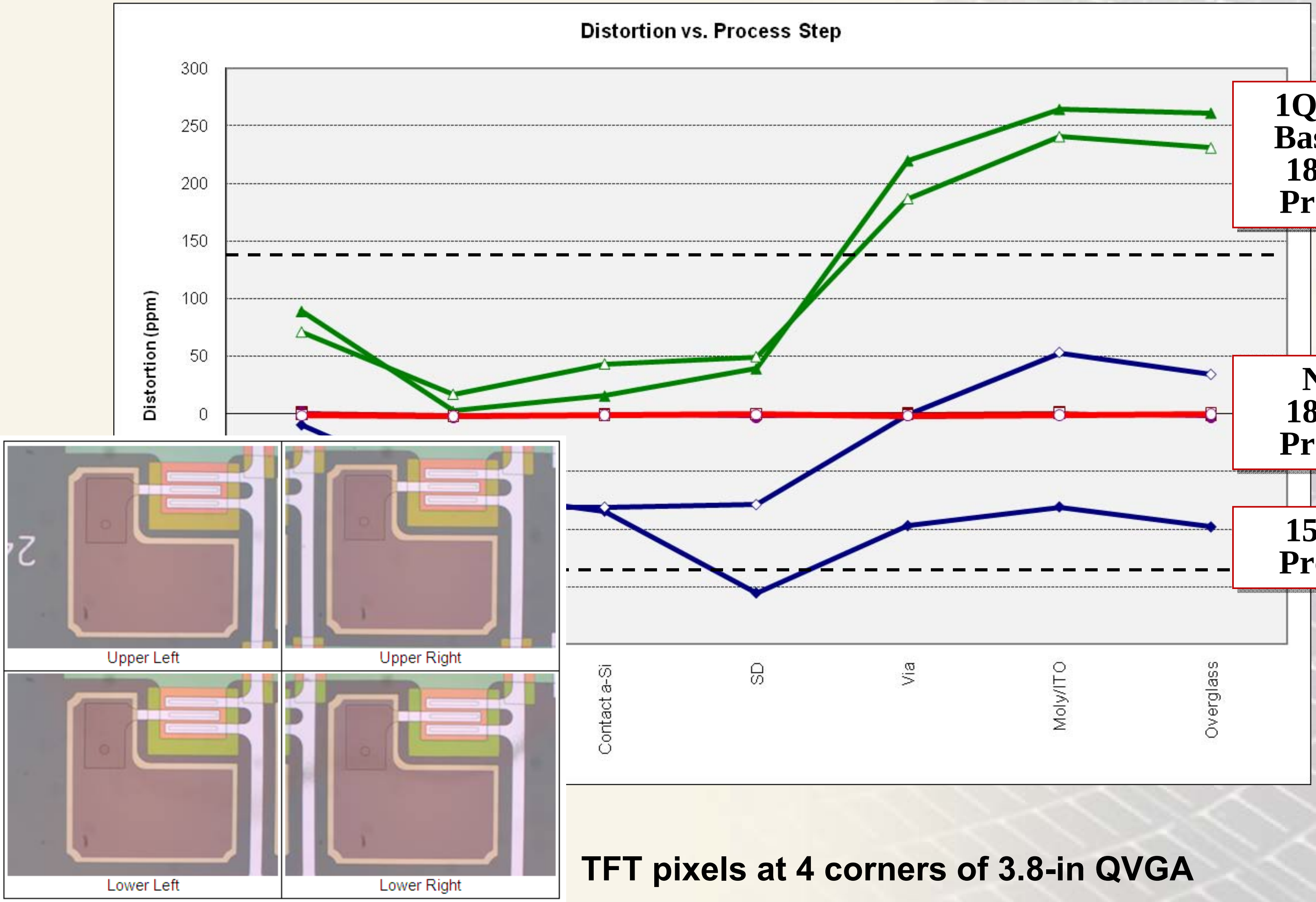
Parameter	FDC	SEC[1]	
Max. Process Temperature	180 °C (flex)	130 °C (flex)	370 °C (glass)
Saturation Mobility (cm^2/V-s)	0.8	0.5	0.5
ON/OFF Ratio	2×10^9	1×10^8	4×10^7
Drive Current (μA)	30	1.2	4.0
Threshold Voltage (V)	1.0	4.5	0.7

---

[1] P. Shin, USDC Flexible Displays Conference (2007)

Plastic Processing Breakthrough:

Zero-distortion Process



1Q 2008 Baseline 180 °C Process

New 180 °C Process

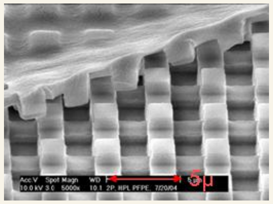
150 °C Process

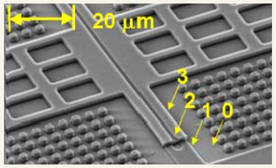
TFT pixels at 4 corners of 3.8-in QVGA

HP Self-Aligned Imprint Lithography

Circumvents Distortion Issue
Large Area Nano-device Scaleable?

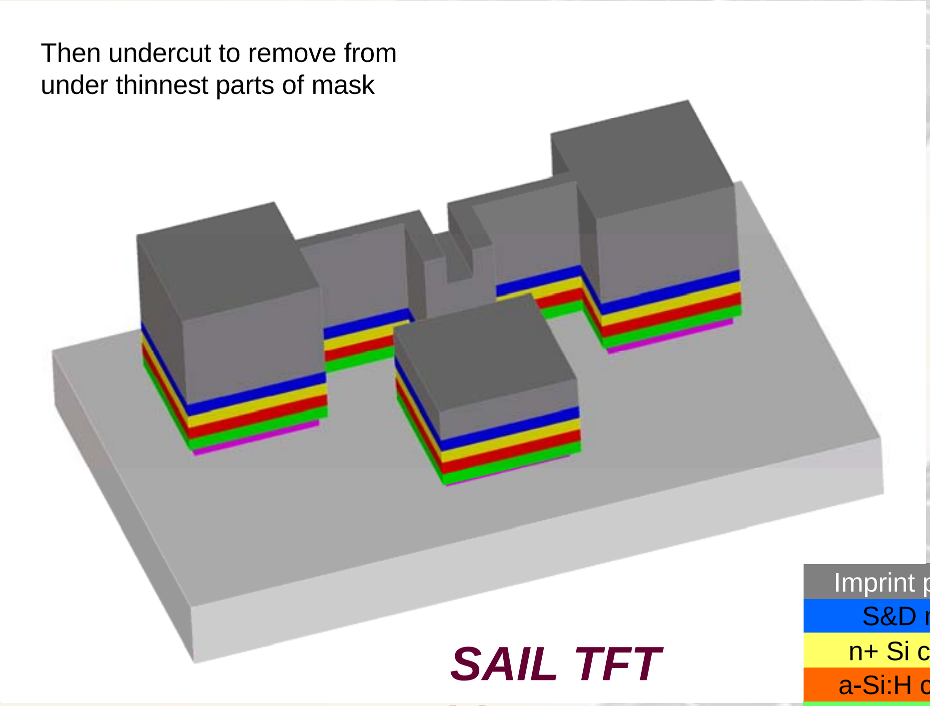
Imprint Lithography:
Photomask-free Process



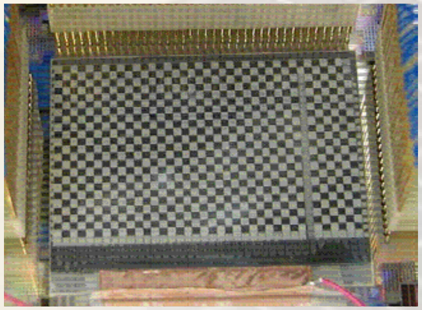


4 levels in 0.5 µm steps →
Multiple mask levels
Imprinted as single 3D structure

O. Kwon, *et al.*, IMID 2007, Daegu, ROK
Compliments of Carl Taussig


Then undercut to remove from under thinnest parts of mask

SAIL TFT
Etching Process



HP SAIL-fabricated AM-EPD
on FDC thin film stack on HS-PEN

Path to Reliable Higher Performance
Advanced TFT Technology

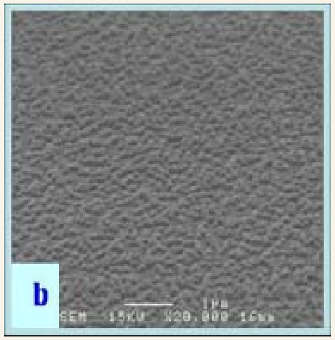
CHALLENGE:

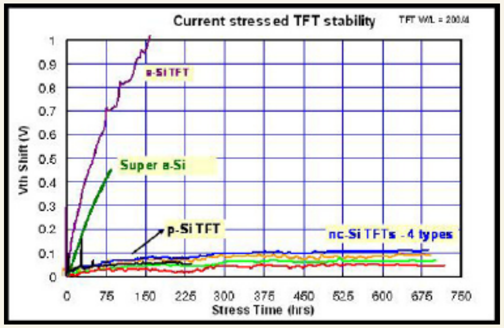
- ***a-Si:H <u>inherently unstable</u> in current-driven devices***
- ***poly-Si a <u>costly solution</u> on glass and <u>problematic on flex</u>***
- ***Organic TFTs unsuitable: <u>poor performance</u> and <u>instability</u>***
- ***CNTs a longer-range opportunity: <u>purity</u> and <u>manufacturability</u>***

APPROACH:

Seek stable high performance TFT technologies
compatible with existing a-Si:H manufacturing infrastructure

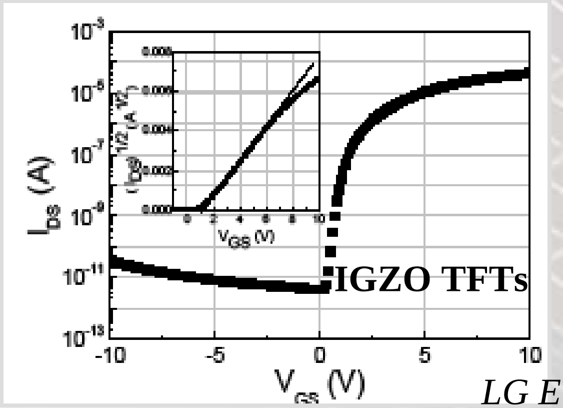
Nanocrystalline Si (nc-Si)





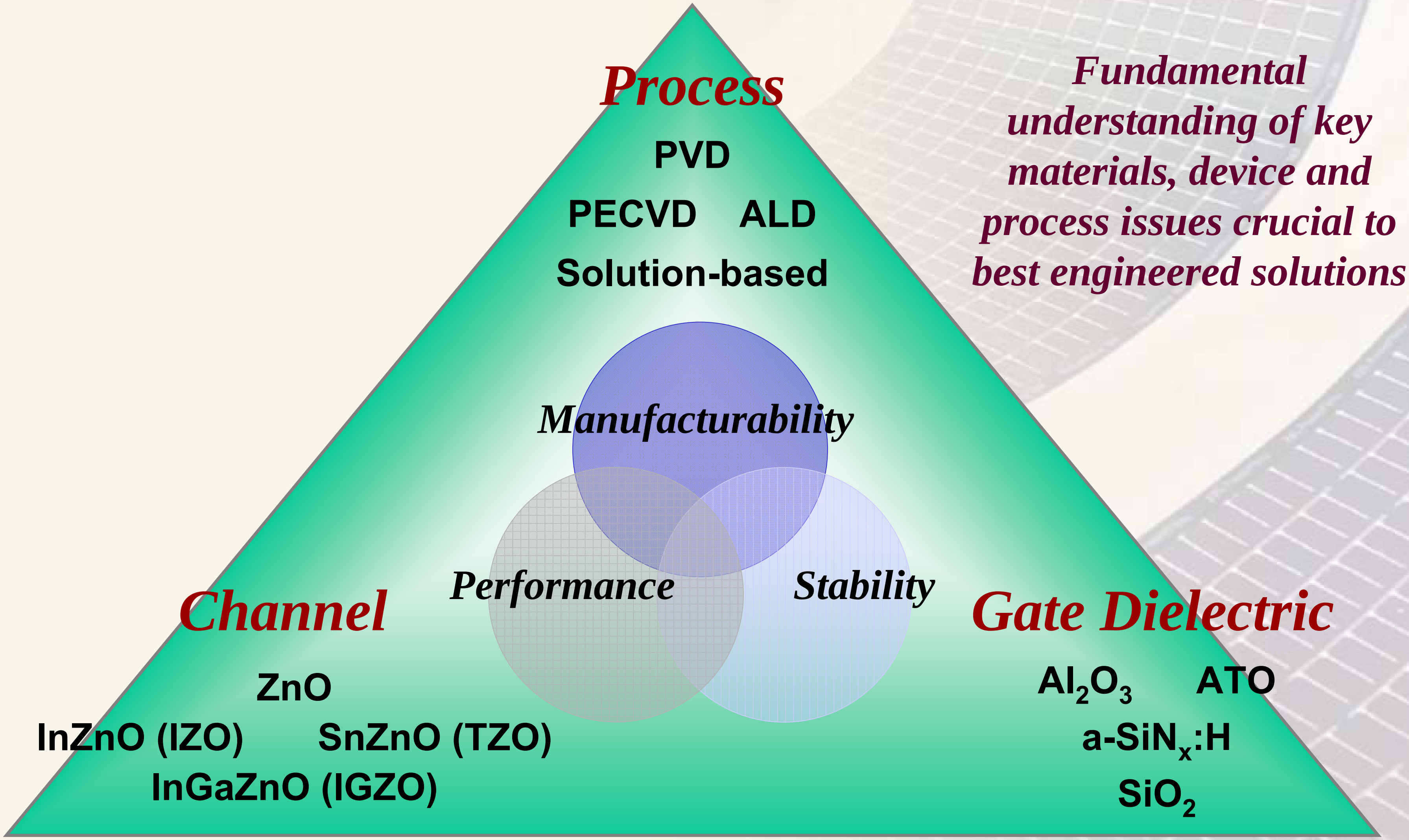
Samsung Electronics, JSID **15/2**, 113-118 (2007)

Metal Oxides



LG Electronics, SID 2007

(Some) Oxide TFT Options



Process

PVD

PECVD ALD

Solution-based

Manufacturability

Performance

Stability

Channel

ZnO

InZnO (IZO) SnZnO (TZO)

InGaZnO (IGZO)

Gate Dielectric

Al_2O_3 ATO

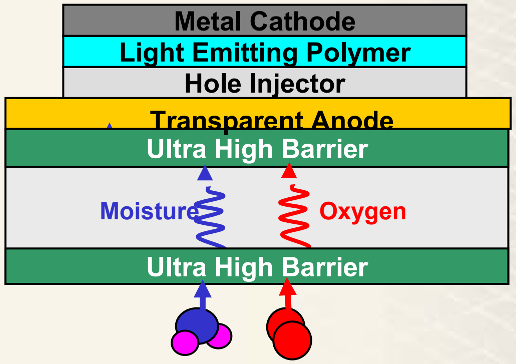
a-SiN_x:H

SiO_2

Fundamental understanding of key materials, device and process issues crucial to best engineered solutions

Barrier / Encapsulation Requirements

Moisture/Oxygen Permeability (Transmission Rate)



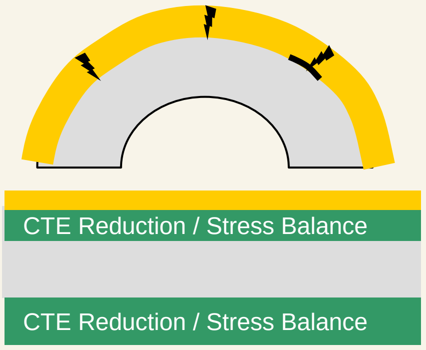
H_2O (WVTR)

low 10^{-6} g/m^2/day

O_2 (OTR)

< 10^{-3} cc/m^2/day

Thermo-mechanical stability



Shrinkage

< 20 ppm/hr @150°C

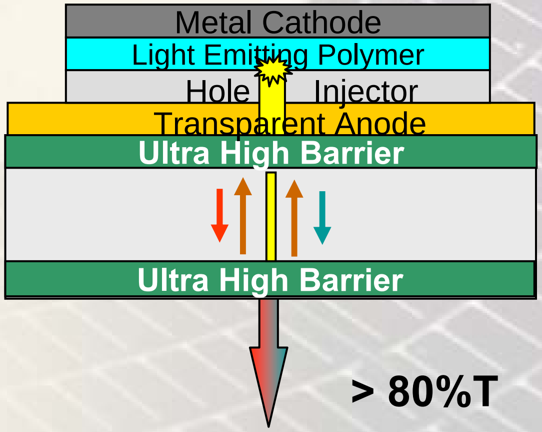
Bending

diameter ≤ 1"

Adhesion

≥ 4B

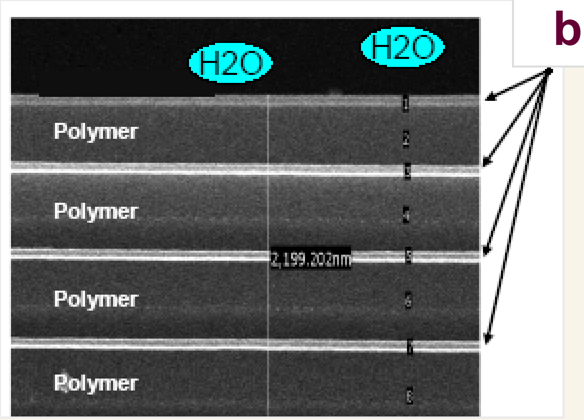
Optical Transmission



> 80%T

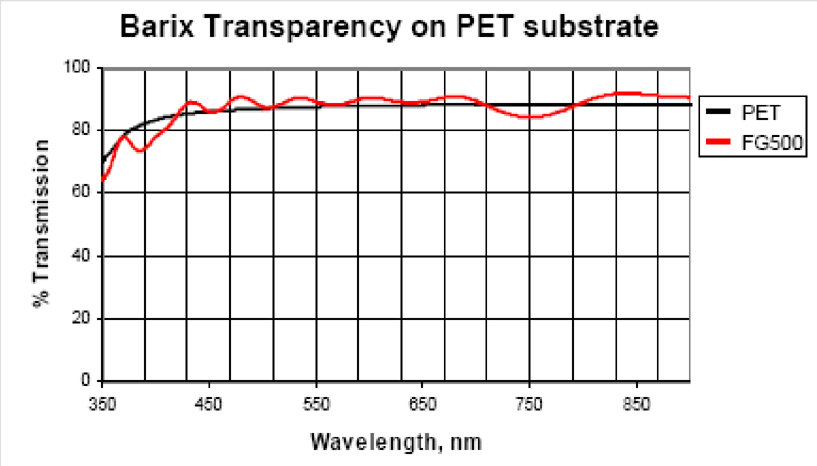
Courtesy of GE Global Research

Vitex Multilayer Barix™ Approach

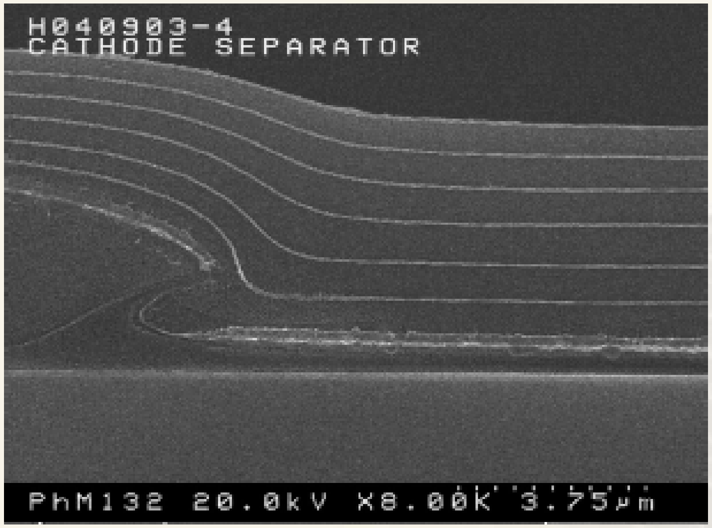


Inorganic barrier layers

3-7 diads (polymer-inorganic pairs)



Polymer layers provide planarization and conformal coverage of defects

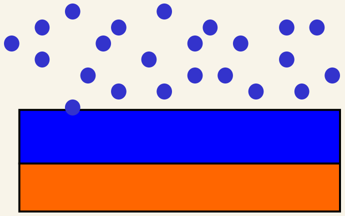


Effectiveness of multi-layer approach attributed to isolation of defects and enhanced diffusion length

Direct Observation of Water Distribution in Barrier Films

X-ray Reflectivity (XR)

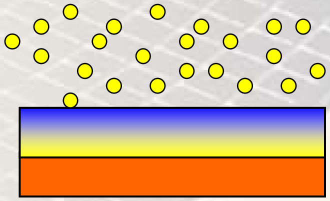
Water 'looks' like polymer
(similar density)



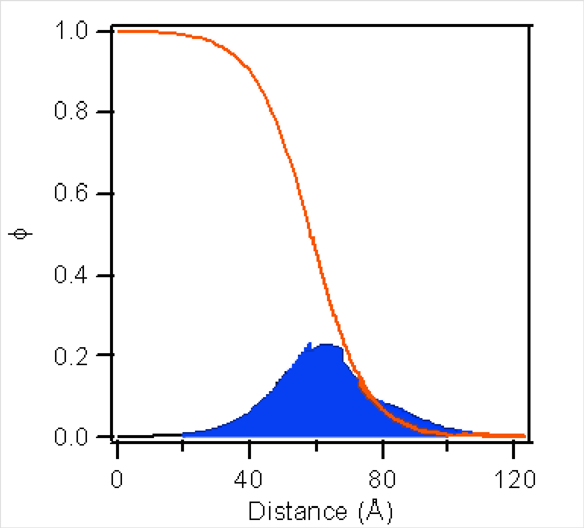
- Measure thickness change due to moisture absorption
- Mass density profile
- Estimate permeation rate

Neutron Reflectivity (NR)

Water visible
(Heavy water)



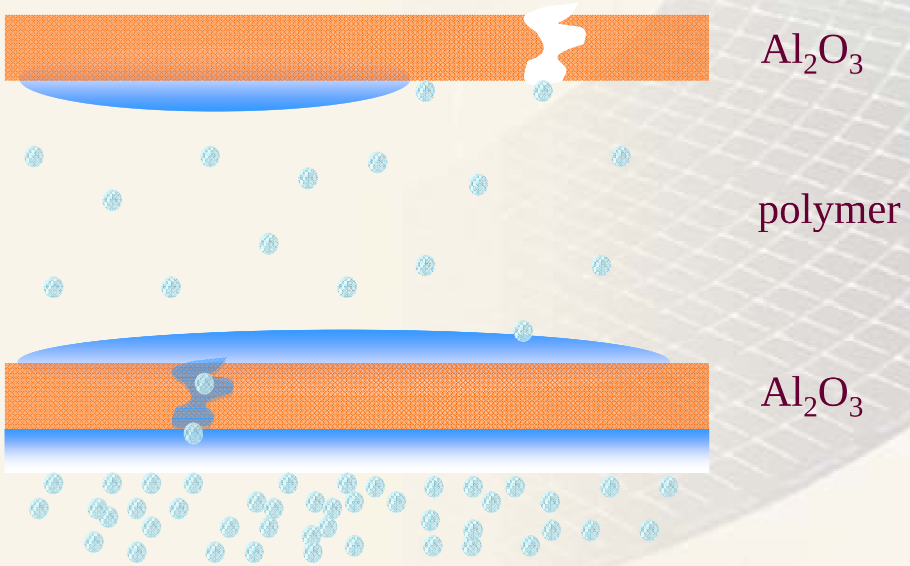
- Isotopic sensitivity (^{1}H *vs.* ^{2}H)
- Measure water distribution within film



Water concentrated at interface

Vogt *et al.*, *J. Appl. Phys.* 97, 114509 (2005)

Proposed Mechanism for H_2O Transport



- Moisture permeation is dominated by defects
- Water transport retarded by oxide/polymer interface
  - Water adsorbs at interface
  - Internal desiccant effect
- Leads to long lag times
- Equilibrium behavior not important if lag time > lifetime

- ***Potential paradigm shift in design of nanao-engineered barriers***

Vogt *et al.*, *J. Appl. Phys.* 97, 114509 (2005)

Transparent Conductors:
ITO replacement

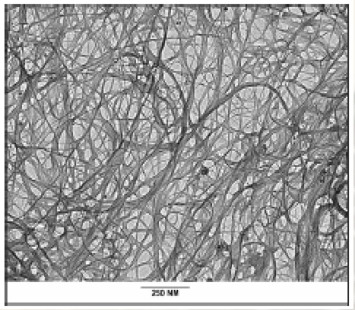
Flexibility

< 40 Ohm/ sq **Conductivity**

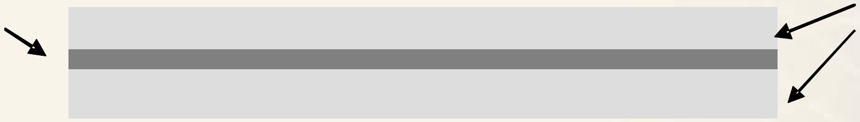
Transparency **> 90 %T**

Options

- ✓ Conductive polymers
- ✓ CNT films
- ✓ IMI composites



TEM of
CNT Film
Source: ***Eikos***



Silver

Dielectric ITO
TiO_2
Nb_2O_5 …

Product Pull *vs.* Technology Push

iNEMI Flexible Electronics Roadmap 2009 listed
"slow pace of <u>product</u> development"
as a "showstopper" !

Recent NSF and ONR co-funded
Working Group commissioned to assess the global
competition in Flexible Electronics recommended
establishment of application-driven center-level efforts
in the U.S.

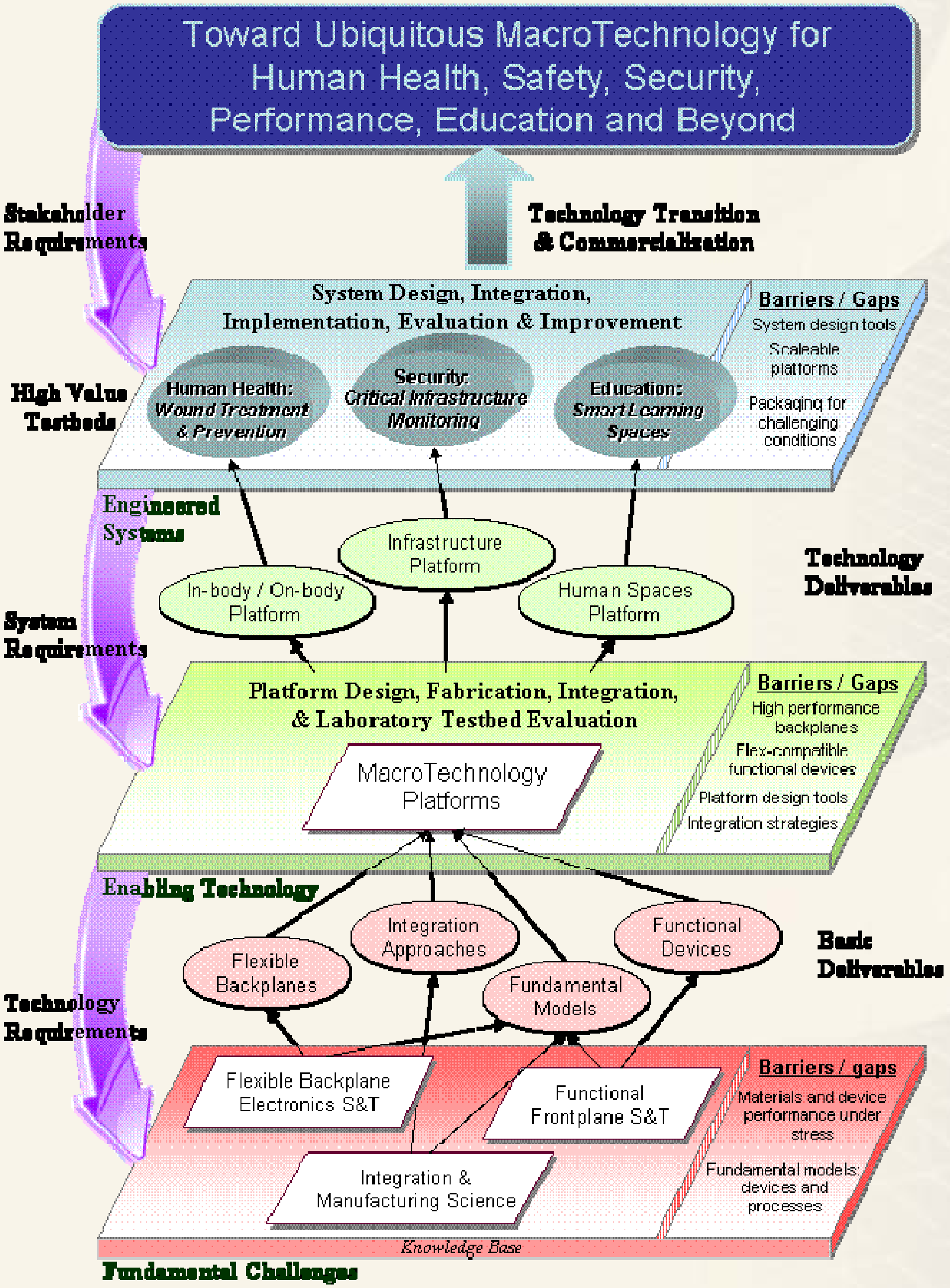
Center for Ubiquitous MacroTechnology (CUbiq-M)

An NSF Engineering
Research Center Concept

Vision

The Center for Ubiquitous MacroTechnology will demonstrate large-area flexible electronics (MacroTechnology) as a transformative tool for a broad range of new high-value applications and industries. The worldwide electronics industry has generated tremendous economic and societal impact despite severe design limitations: with few exceptions, electronic products are small, rigid, fragile, opaque and incompatible with living tissue. *CUbiq-M* proposes engineered systems-driven research to liberate electronics from these arbitrary constraints. *CUbiq-M's* vision is that a new wave of ultra-thin, lightweight, flexible, conformable, rugged, biocompatible, self-healing and transparent MacroTechnology products will provide transformative solutions for critical national problems in healthcare, safety, security, sustainability and beyond. These new products will catalyze economic growth and global competitiveness.

ERC Strategic Plan Design



Toward Ubiquitous MacroTechnology for Human Health, Safety, Security, Performance, Education and Beyond

Stakeholder Requirements

Technology Transition & Commercialization

System Design, Integration, Implementation, Evaluation & Improvement

High Value Testbeds

Human Health: *Wound Treatment & Prevention*

Security: *Critical Infrastructure Monitoring*

Education: *Smart Learning Spaces*

Barriers / Gaps
- System design tools
- Scaleable platforms
- Packaging for challenging conditions

Engineered Systems

Infrastructure Platform

In-body / On-body Platform

Human Spaces Platform

Technology Deliverables

System Requirements

Platform Design, Fabrication, Integration, & Laboratory Testbed Evaluation

MacroTechnology Platforms

Barriers / Gaps
- High performance backplanes
- Flex-compatible functional devices
- Platform design tools
- Integration strategies

Enabling Technology

Flexible Backplanes

Integration Approaches

Fundamental Models

Functional Devices

Basic Deliverables

Technology Requirements

Flexible Backplane Electronics S&T

Functional Frontplane S&T

Integration & Manufacturing Science

Barriers / gaps
- Materials and device performance under stress
- Fundamental models: devices and processes

Knowledge Base

Fundamental Challenges

Exemplary Technology Demonstrations

Wound Care / Avoidance

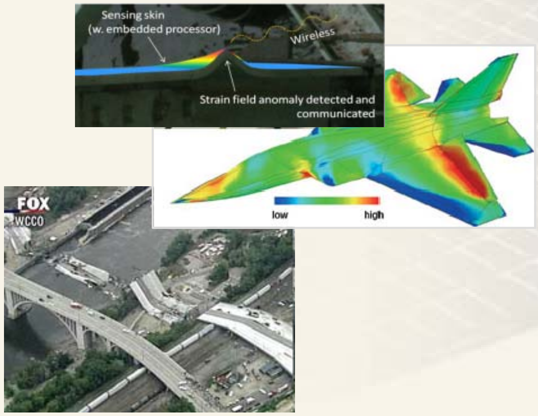
"Smart" Bandages and Implantable Films

- *Electronic stimulation*
- *Diagnostic sensors*
- *Controlled drug release*
- *Wireless interrogation*
- *Self-powered*

Critical Infrastructure Monitoring

Smart Conformable Skins

- *Strain field sensing arrays*
- *Visual read-out / indicators*
- *Wireless interrogation*
- *Internal or external surfaces*



Smart Spaces / Buildings

Enabling Technologies

- *Large area building-integrated PV/SSL*
- *Surface-embedded unobtrusive sensor net*
  - *+ human activity (security and health)*
  - *+ environmental conditions (health)*
- *Actuator-control and decision systems*
- *Surface-embedded "edge-to-edge" HCIs*

Demonstration I:
In-body/on-body for Human Health

Demonstration II:
Infrastructure-integrated for Security / Safety

Demonstration III:
Building-integrated for Human Performance

Engineered Systems

Biosensing & drug delivery
Stretchable / compliant
Biocompatible / soft
Small area

Mech sensing & actuation
Low deformation / rollable
Rugged / durable
Small to human-scale area

Sensing – human interfaces
Conformable / "seamless"
Surface-durable / stable
Small to large area

Summary

- **Flexible Displays and MacroTechnology hold great promise for new products of unique from, fit and function for military, health, security, energy and the environment, and space applications**
- **Opportunities for breakthroughs and advances**
  - ✓ **Manufacturing processes**
  - ✓ **Devices (TFT backplanes and functional frontplanes)**
  - ✓ **Materials**
- **Specific Challenges and Gaps**
  - ✓ **Scale-ability → scaling laws, limitations and tradeoffs**
  - ✓ **Stable high performance TFT technology for OLEDs and beyond**
  - ✓ **High performance low cost flexible barrier / encapsulation technology**
  - ✓ ***Product focus as the technology driver***

For Further Information

Flexible Display Center

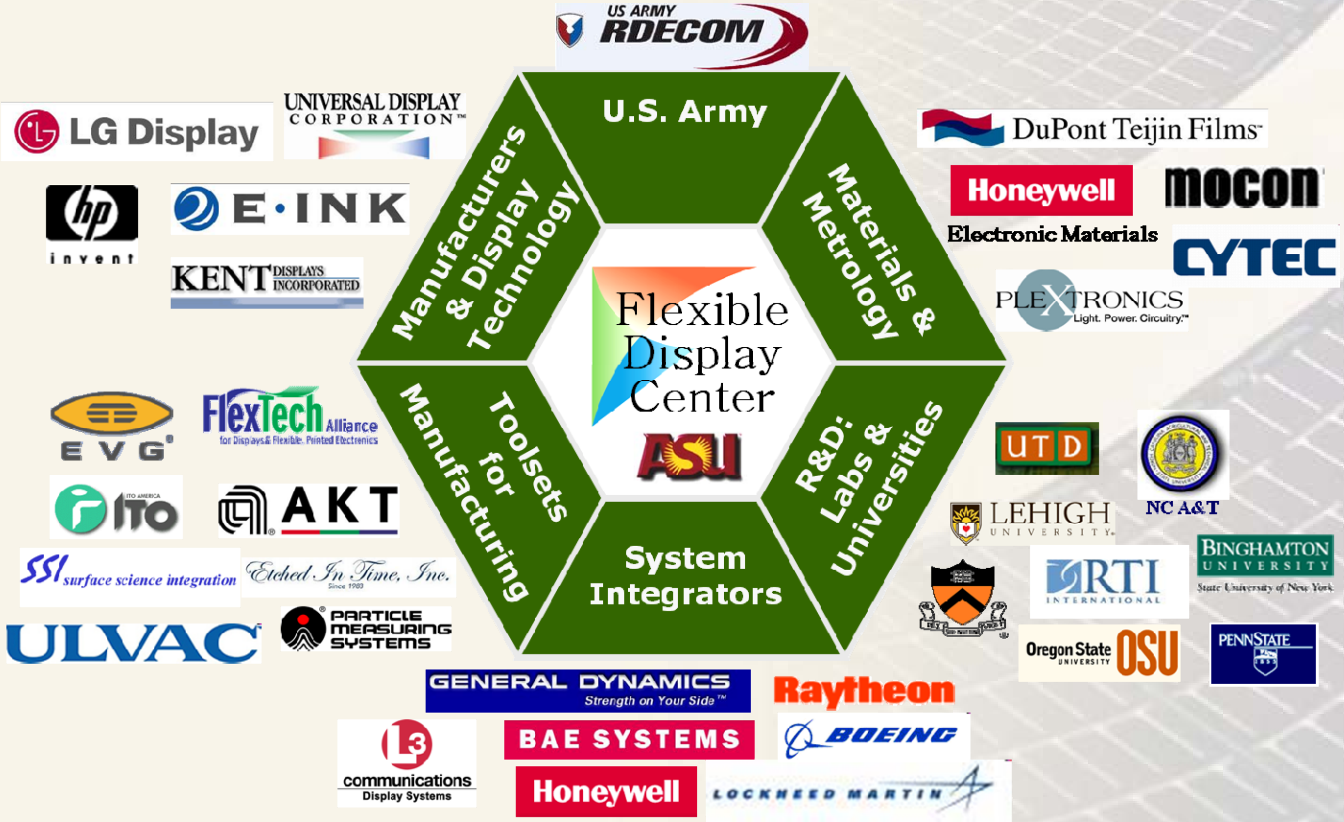
- Dr. Nick Colaneri, Director
- nick.colaneri@asu.edu
- 480-727-8971

NSF ERC Proposal effort

- Prof. Greg Raupp
- raupp@asu.edu
- 480-727-8752

Acknowledgements

- ASU gratefully acknowledges the substantial financial support of the U.S. Army through Cooperative Agreement W911NF-04-2-0005
- We also gratefully acknowledge the FDC’s Members for their technical and financial contributions to the Center



Thanks to the FDC Team

Thank You !