Flexible Display Manufacturing Development at Arizona State University

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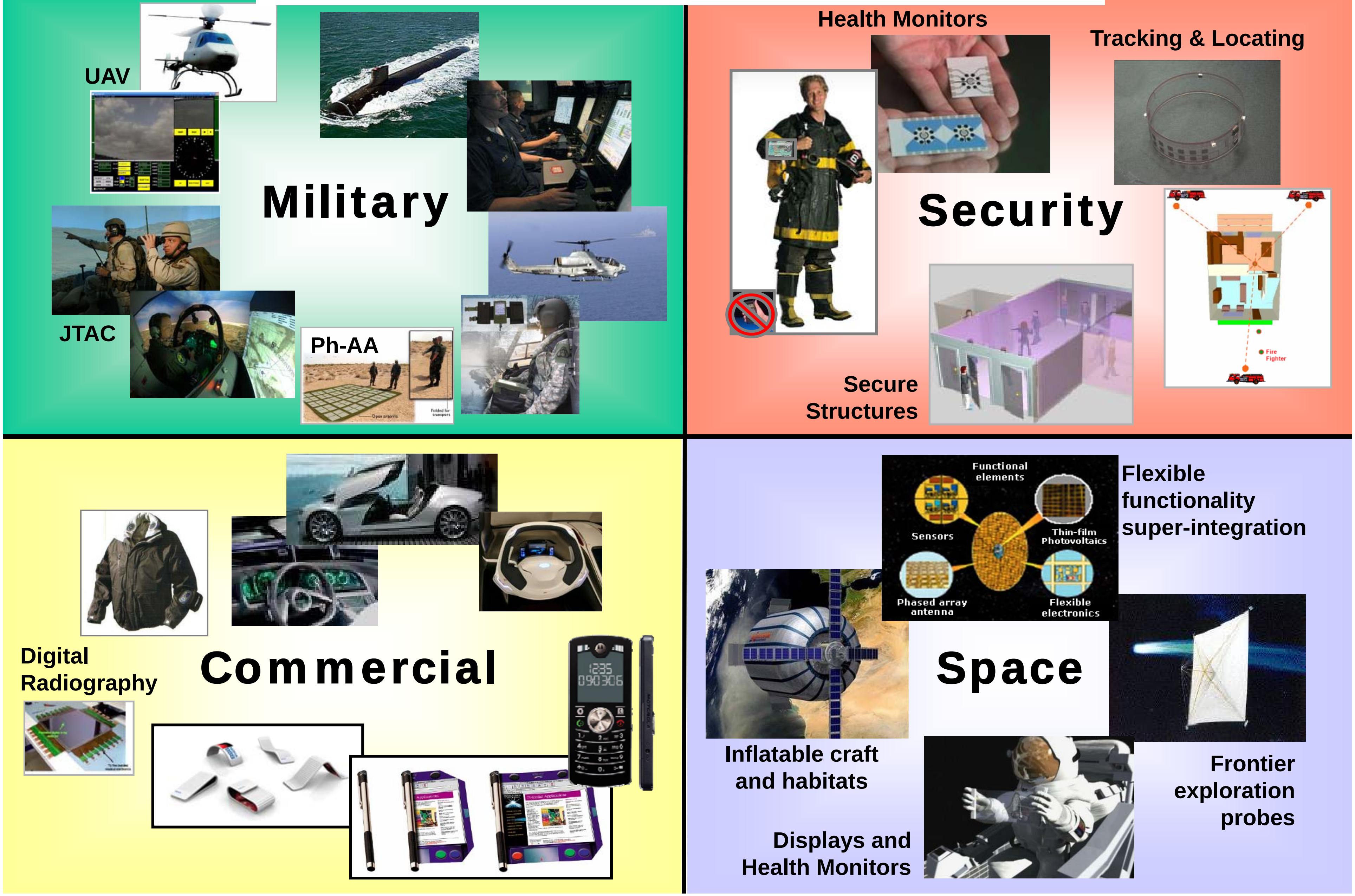
Mission: Accelerate Commercialization of Flexible Electronics Technology



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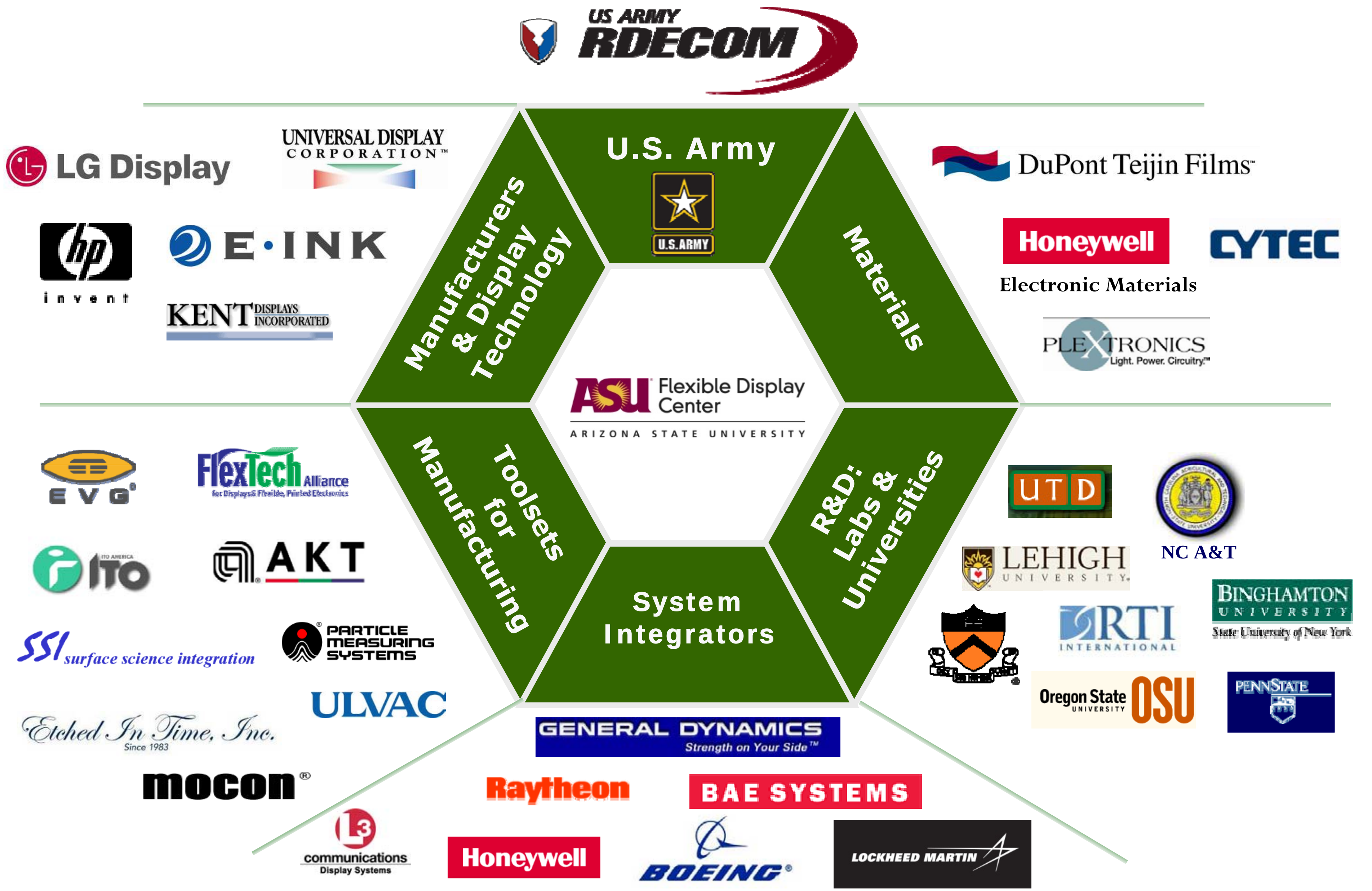
Strategic Partnership Structure



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FDC: Dual Pathway

Provide Technology Demonstrators to show capability to user community

FFW SF-PDA

FFW, PEO Soldier, PM SWAR

Mission Briefer

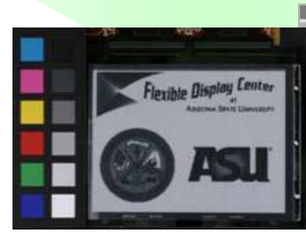
Develop the materials and manufacturing technology to enable the commercial production of flexible displays

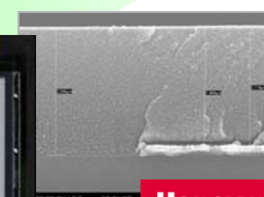
Technology Commercialized

Advanced Coater

High Performance Planarised PEN™

DuPont Teijin Films





Honeywell

PTS Thin Film Material

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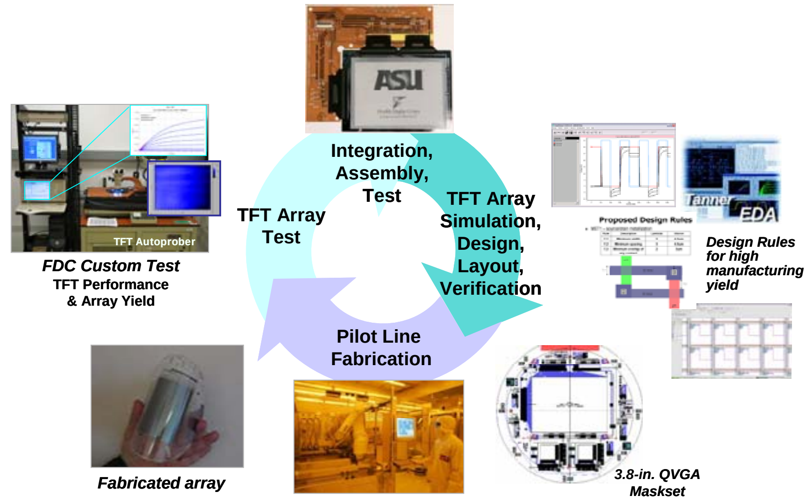
Innovation Capability Enabled by Facility, Tools, Pilot Line & Professional Staff



AZORES 5200 gT

World's First Photolithography tool with automatic flexible substrate distortion compensation

AKT 1600 PECVD / Etch

with active substrate cooling

World's First GEN II Tool Dedicated to Flexible Display Development

EVG 150XL

World's First
High performance large area nano-spray coater

EIT FPDGEN2EA Etch

World's First GEN II High Density Plasma Etcher: ashing or RIE

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FDC Technology Focus:

Transition Glass-based High Information Content Commercial Technology to Flexible Formats

Reflective

Electrophoretic Displays

- Ultra-low power
- Sunlight readable
- Near-video rates
- Maps, position data, images, text

Electrophoretic Ink

KENT DISPLAYS INCORPORATED

Cholesteric Liquid Crystal

Emissive

Organic Light Emitting Displays

- Low power
- Vibrant full color
- Full motion video
- UAVs, vehicles, command posts

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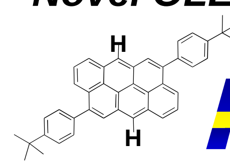
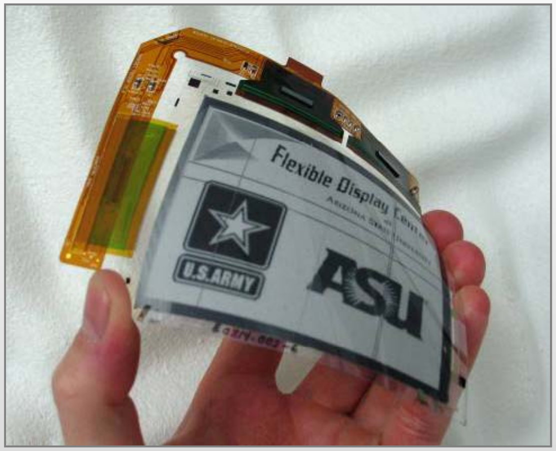
Phosphorescent OLED

Novel OLEDs



EPD Technology Demonstrators

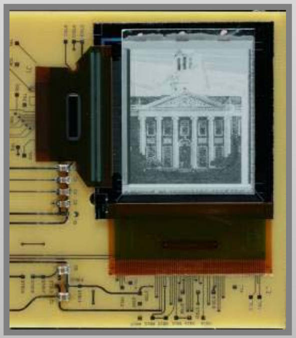
Effective Management of Plastic Substrate Challenges:
Distortion* and *Defectivity



3.8-in. QVGA EPD on PEN
World's Highest Temperature a-Si:H directly fabricated on polyester substrates

Effective Management of SS Substrate Challenges:
Roughness* and *Stress

3.8-in. QVGA EPD on SS
Zero-defectivity



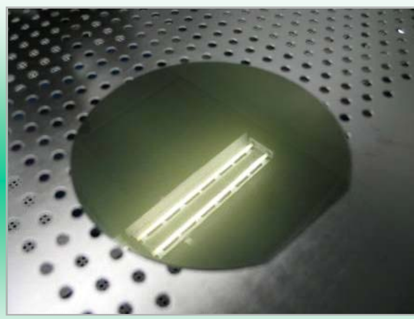
210 ppi EPD on SS
High Pixel Density
enables VGA resolution at 3.8-in diagonal

E·INK DuPont Teijin Films FlexTech Alliance for Displays & Flexible, Printed Electronics Honeywell National Starch & Chemical A member of the ICI Group

Critical Enabler:
Substrate Temporary Bonding

4 U.S. Patent Applications covering processes and materials

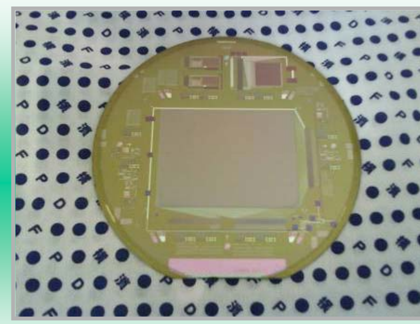
Semi-automated de-bond tool



Bonded substrate

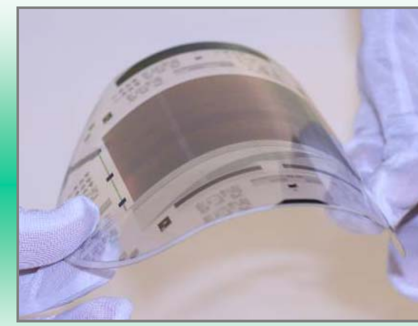
Semiconductor-grade Adhesive

Custom Solutions



After TFT Fab

Perfect bond integrity through entire fab



Debonded substrate

<u>Triggered</u> Release

No TFT degradation

No residue

No carrier damage

Plastic Substrates

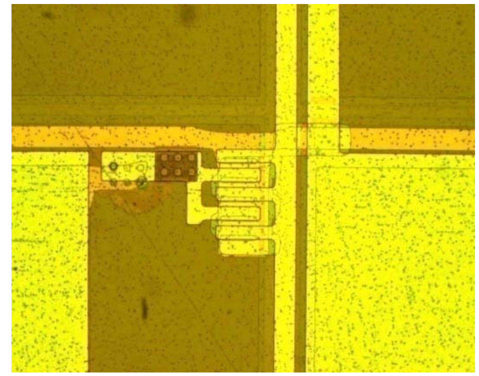
Challenges

No "drop-in" Replacement for Glass

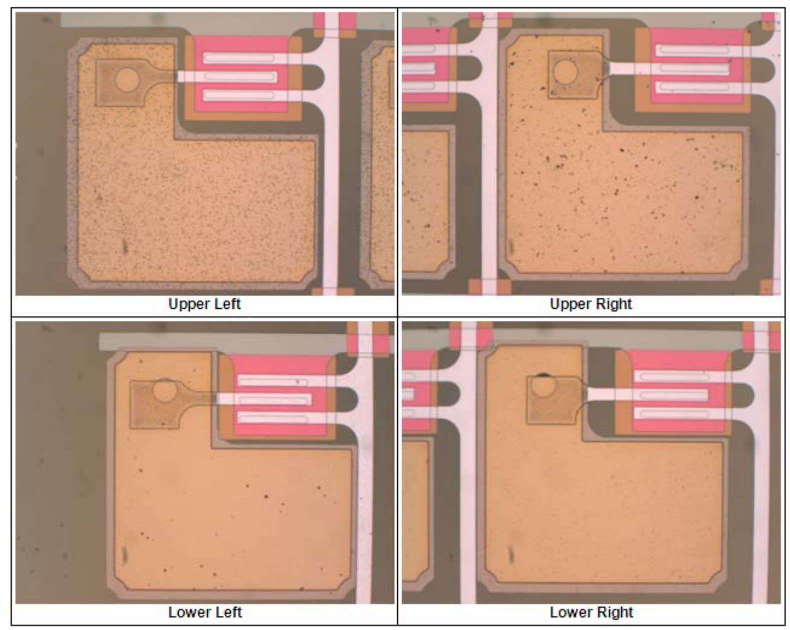
HS-PEN

- ➢ Process T Limit
- ➢ Oligomer Crystallites & Scratches
- ➢ Permeable to H_2O/O_2

- ➢ Dimensional Stability
  - Thermal cycles ➔ material run-in
    - ➢ Heat Stabilize
  - Elastic strain under deposited film stress ➔ material run-out ➔
    - ➢ forgiving design rules
    - ➢ modified lower stress processes
    - ➢ modified substrate material system



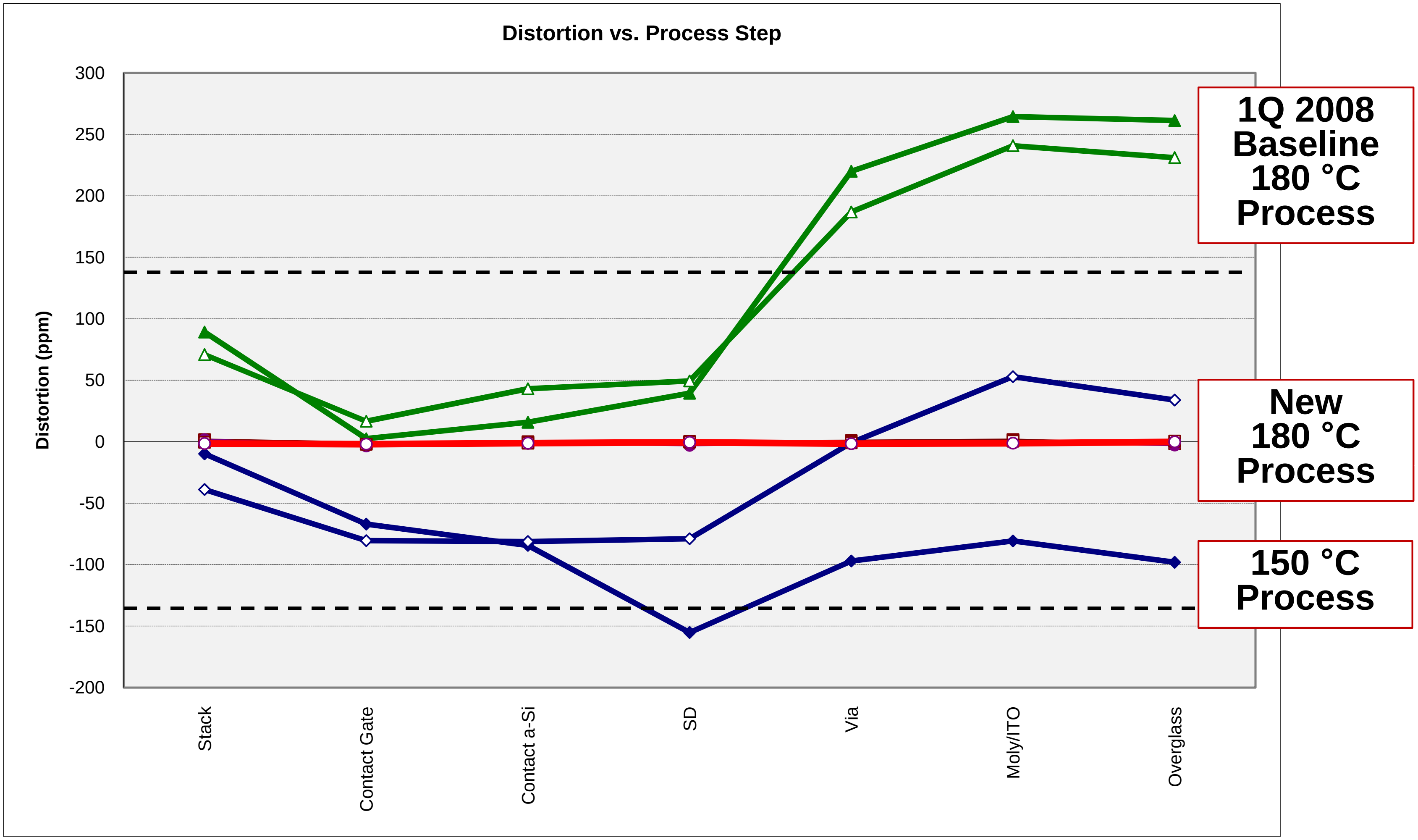
Oligomer Defectivity



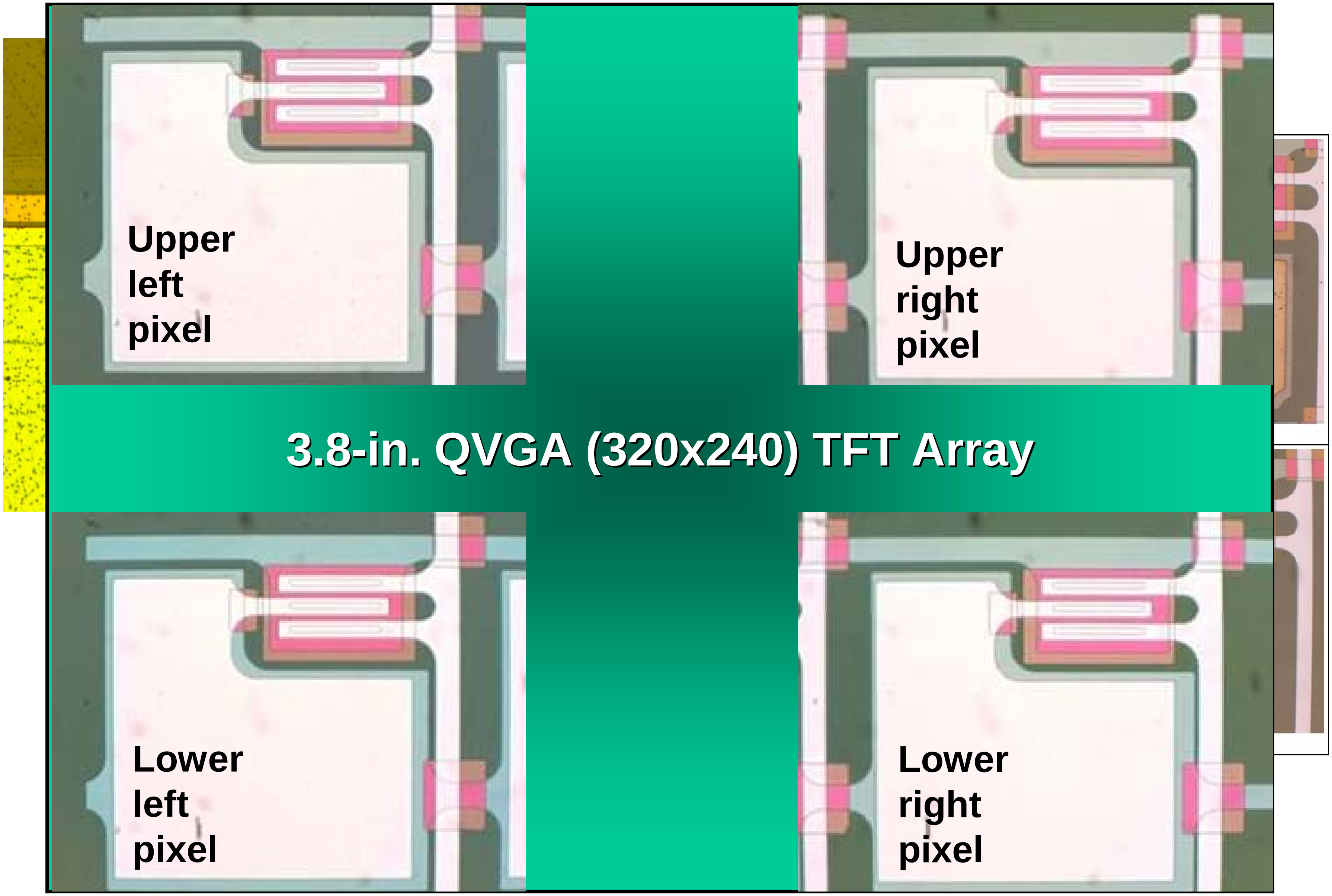
Optical Micrographs Showing TFT Alignment at Corner Pixels

New Plastic TFT Process

Allows for glass TFT design rules on Plastic Substrates



Plastic Substrate System Solution



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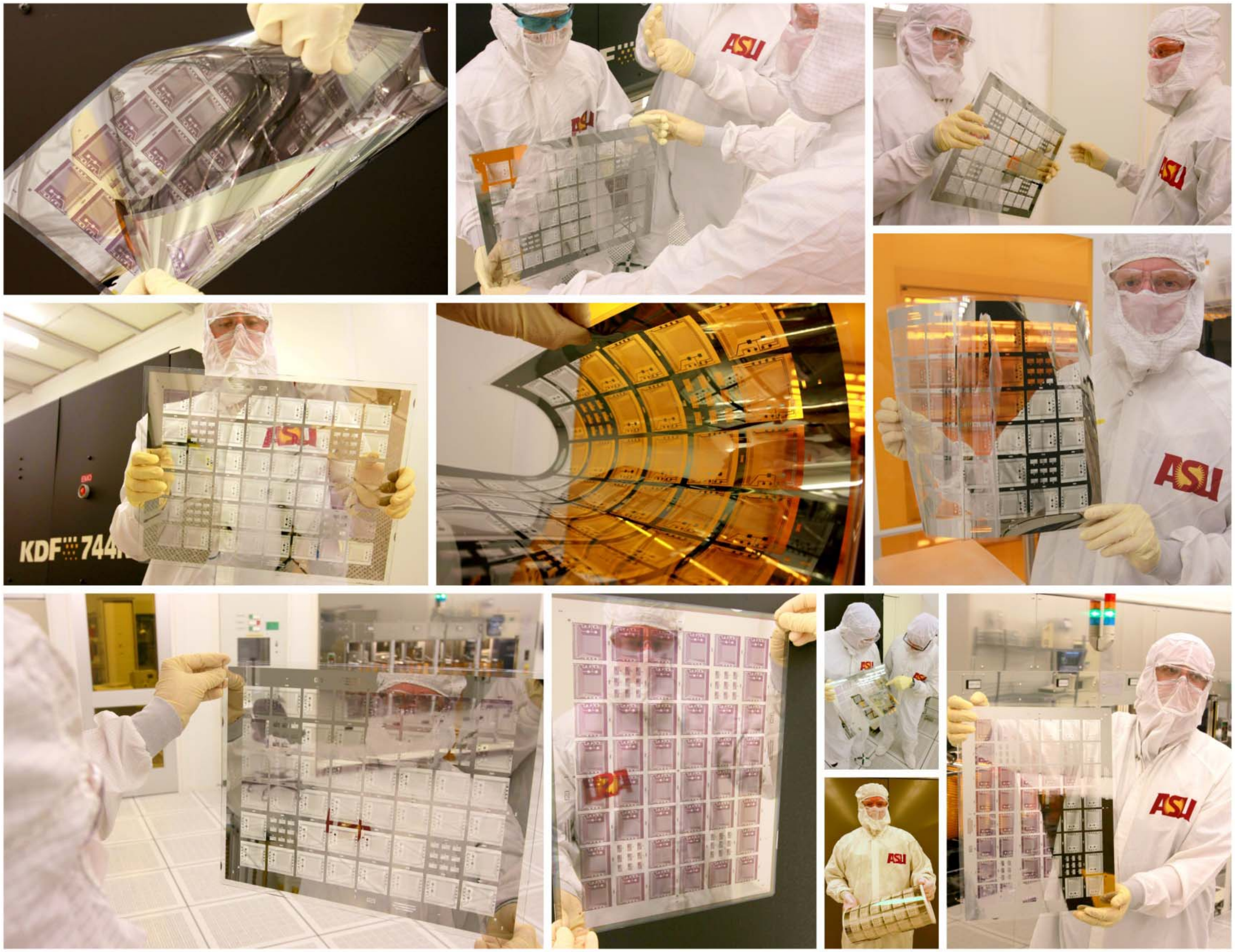
Scale-up to Gen II



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

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Glass-based TFTs

300-350 °C. Process Temperatures

→

TFTs on Flex

175-180 °C. Process Temperatures

→

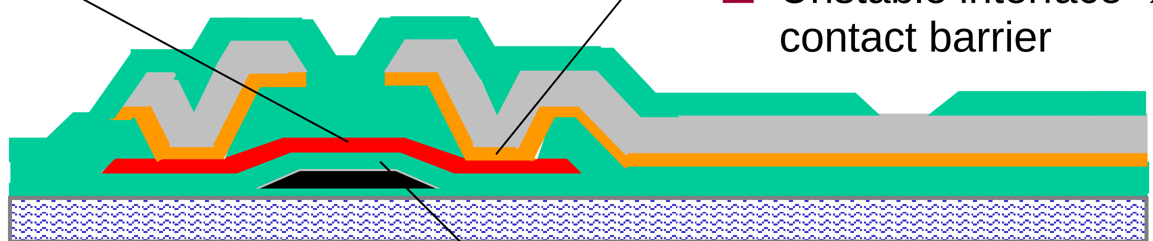
Identified New Process Windows: Achieved equivalent or better performance

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

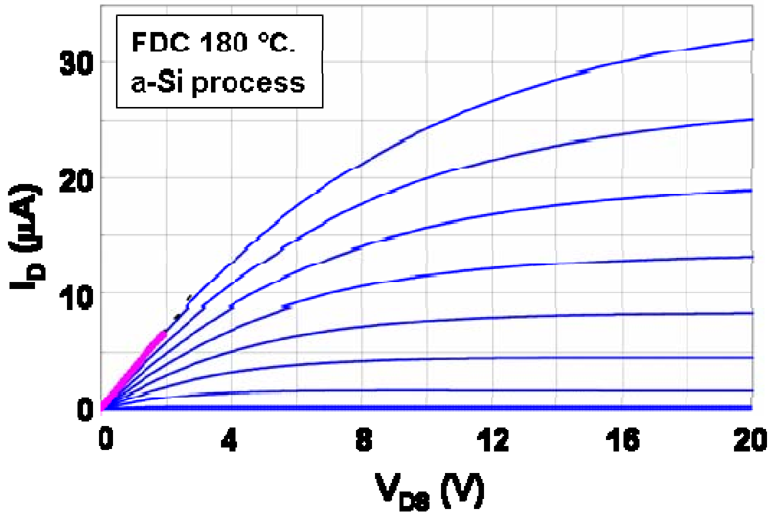


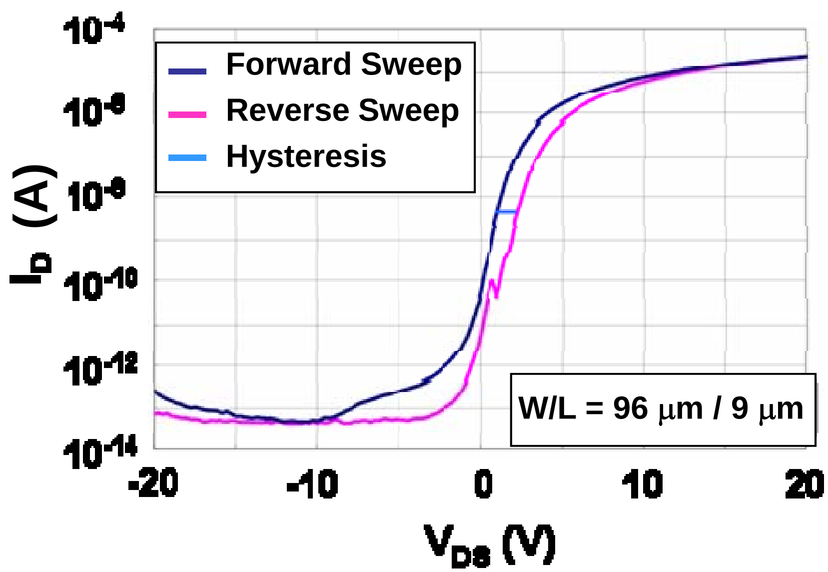
a-SiN_x:H gate dielectric

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

PENNSTATE UNT Honeywell

FDC a-Si:H TFT Performance





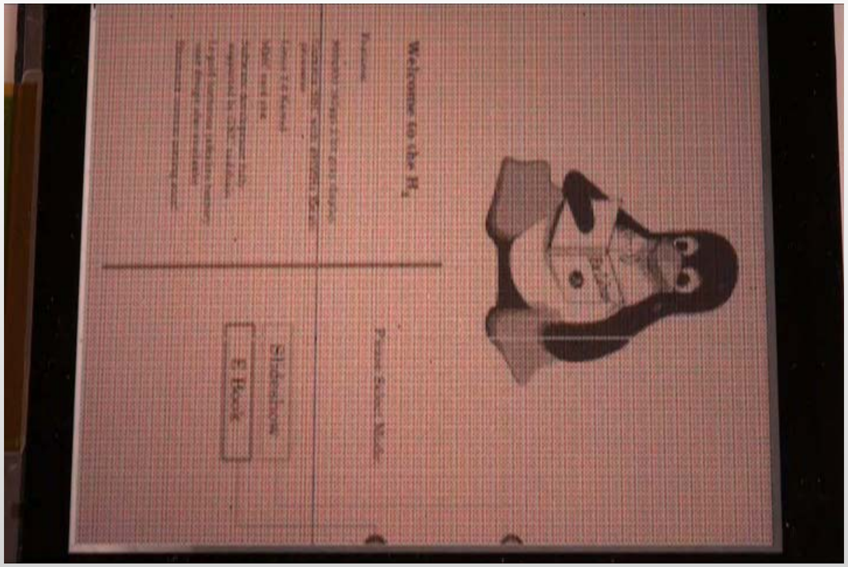
Parameter	FDC	SEC[1]	
Max. Process Temperature	180 °C flex	130 °C flex	370 °C glass
Saturation Mobility (cm^2/V-s)	0.7	0.5	0.5
ON/OFF Ratio	2 x 10^9	1 x 10^8	4 x 10^7
Drive Current (µA)	25	1.2	4.0
Threshold Voltage	1.0 V	4.5 V	0.7 V

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

Notable Low T a-Si TFT Improvements

- New Gate Dielectric
- New Channel
- New Contacts
- New Stack Etch
- New SD Etch
- New Contact Gate Etch
- Improved ILD
  - ➢ Better solvent resistance, wider process window
- Source Drain Process Optimization
  - ➢ Reduced damage from ash process
- Etch Oprtimization
  - ➢ Contact Gate, Interlayer dielectric, pixel electrode
- Update on SiN Overglass Etch
  - ➢ Optimized for OLED integration
- Improved Plastic Processing
  - ➢ Distortion and Substrate Quality
- Improved SS Planarization
- Faster Array Test
- In-Process Diagnostics

Added Functionality with E-Paper



Reflective Color

Ink-jet printed color filter array

Capacitive Touch

Enabled by Epson / E Ink Broadsheet Controller and FDC flexible display technology

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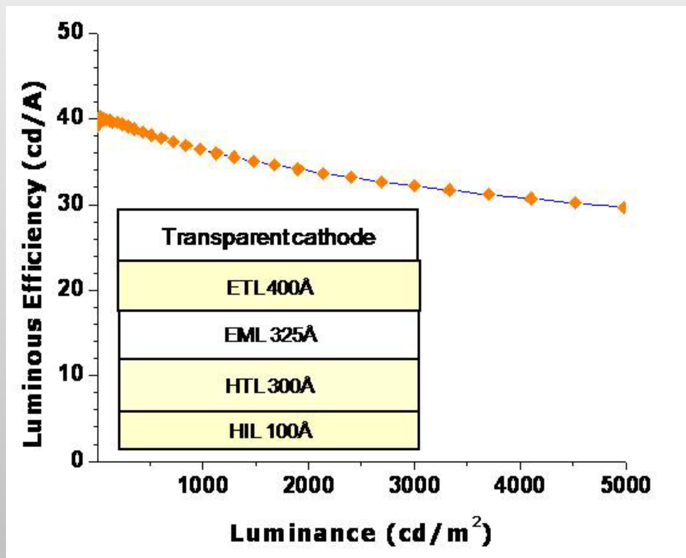
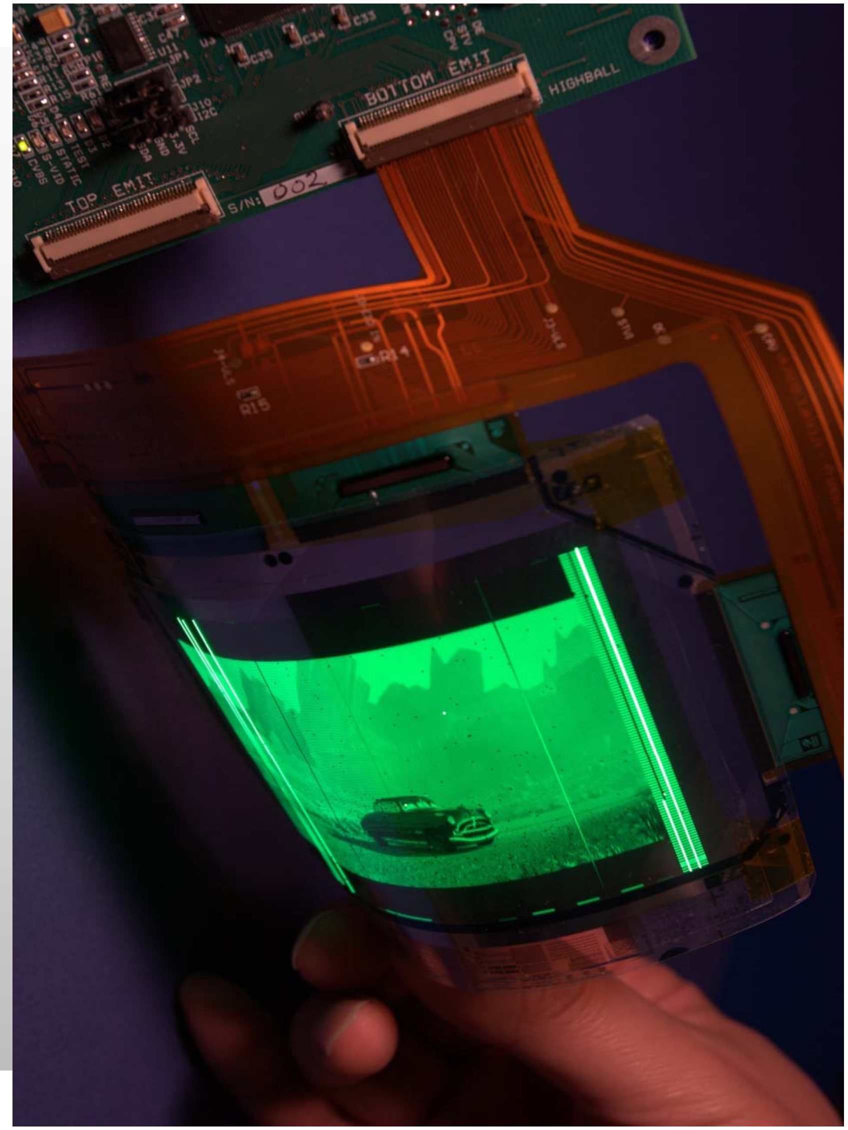
PHOLED w/ FDC low T a-Si

PEN Substrate

- **More Efficient than LCD**
- **Full Color/Video**
- **Glass-based Commercial since 1997**





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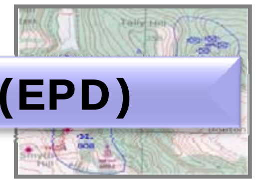
Near-Term Technology Goals

2007	2008	2009	2010

Reflective (EPD)

3.8-in. diagonal
QVGA

3.8-in. diagonal
¼QVGA
Color



3.8-in. diagonal
QVGA - Color

6-8 in. diagonal
SVGA mono
¼SVGA color

¼ QVGA	160x220
QVGA	320x240
VGA	640x480
¼ SVGA	400x300
SVGA	800x600

Emissive (OLED)

1-in. diagonal
64x64
Mono (green)

3.8-in. diagonal
QVGA
Mono (green)

~4-in. diagonal
QVGA
RGB Color

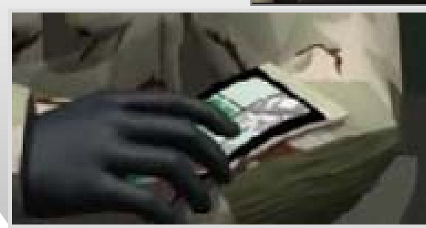
6-8 in. diagonal
VGA

2007	2008	2009	2010-11

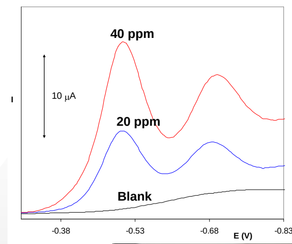
Flexible Electronics as a Core Platform Technology

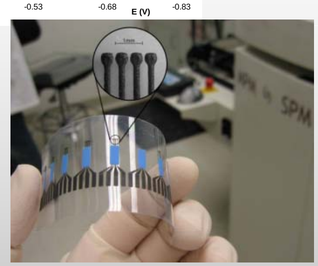
Integrate flexible TFT backplanes with frontplanes of different functionality to create new technology

Image-layer Frontplane
Flexible Displays



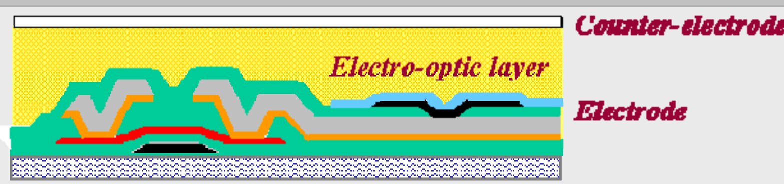
Sensing-layer Frontplane
Flexible Sensor Arrays





Flexible DRG

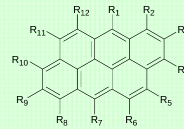
Sensors for Environmental Threat Detection and Human Health/Performance Monitoring
Images compliments of J. Wang ASU BDI



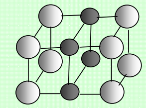
Thin Film Transistor (TFT) Pixel Cross Section on Flexible Substrate

Building Blocks

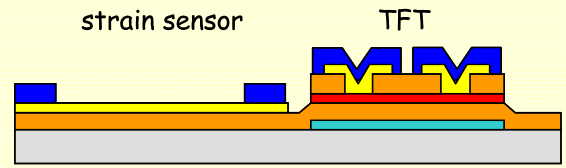
- Flexible Electronics
  - ✓ Materials
  - ✓ Digital, Analog
  - ✓ Sensors
  - ✓ Remote Communication
  - ✓ CAD Tools
- Demonstrated many of the Blocks Necessary to Build System
- Improvements in performance will increase capabilities



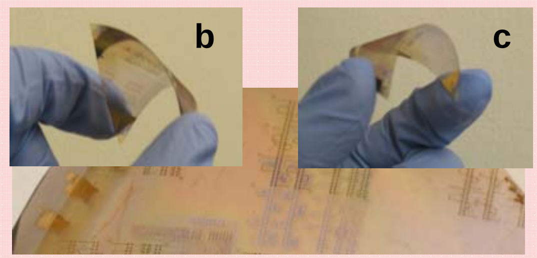
USP 7,135,243



Organic-inorganic materials



Transistors, analog circuits, sensors



Process Integration

Applications

B. Gnade, M. Quevedo (UT Dallas),
D. Allee, S. Venugopal (Arizona State Univ)
T. Jackson (Penn State Univ)
E. Forsythe (Army Research Lab)

Flexible CMOS

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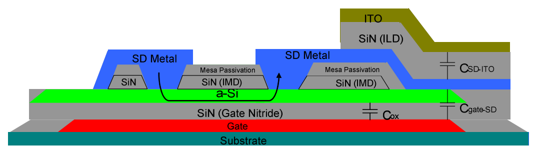
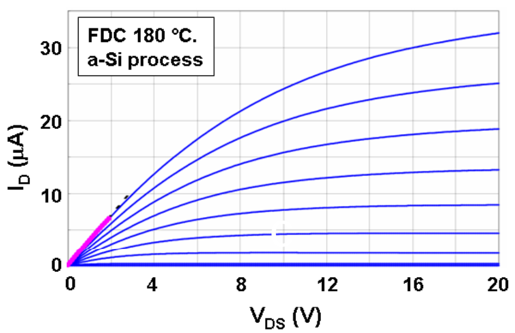
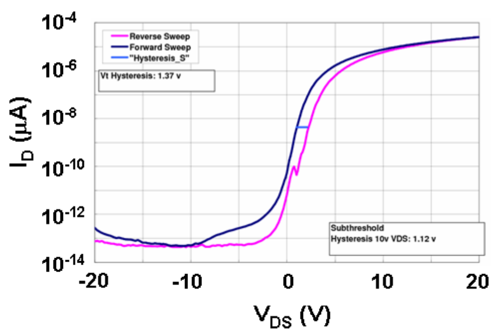
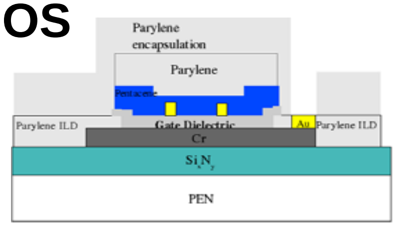
NMOS

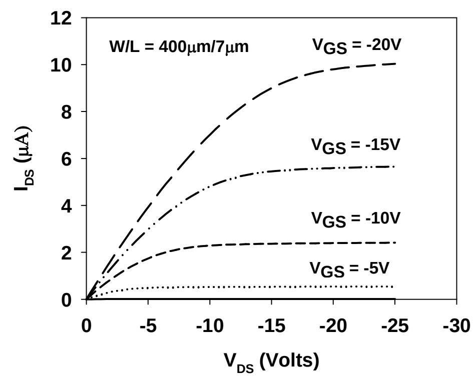


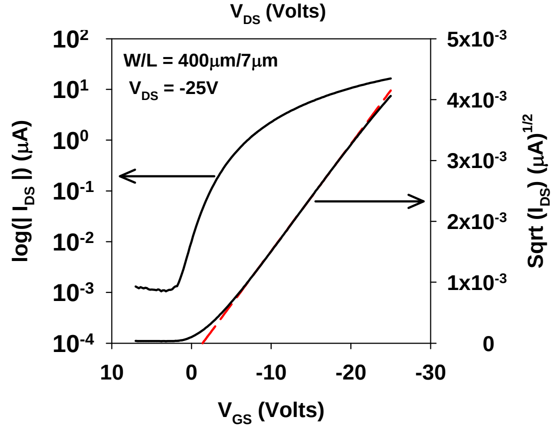




PMOS







- **Why CMOS**
  - ✓ Dramatically reduced power consumption
  - ✓ Analog circuitry possible with Sensor applications
- **How to do F-CMOS**
  - ✓ Combine Processes
    - ➢ N-Type a-Si:H TFTs
    - ➢ N-Type ZnO TFTs
    - ➢ P-Type Organic TFTs
    - ➢ OTFTs are Post-Processed on top of a-Si:H TFTs
  - ✓ Standard Cell Approach

ARL UTD PENNSTATE 1855

Conclusions

- **FDC Effective Partnership Model and Powerful Capability enabling rapid advances in Flexible Display and Manufacturing Technology Development**

- **Enabling Commercial Successes towards Manufacturing**
  - ✓ **High quality high performance plastic substrate: *DTF Planarised PEN™***
  - ✓ **Low temperature planarizing thin film material: *Honeywell PTS Materials Series***
  - ✓ **Large Area mist coater: *EVG 150XL (GEN 3.5)***

- **Critical Path Technology Advances**
  - ✓ **Materials, tools and processes for Flexible Substrate Systems**
  - ✓ **State-of-the-art low temperature 180 °C a-Si:H TFT on flex technology**
  - ✓ **Rugged / Conformal / Opaque → Bendable / Rollable / Transparent transition underway (*Plastic processing advances*)**