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Integrated Control Electronics for Adjustable X-ray Optics

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TECHNOLOGY DRIVES EXPLORATION

Non-Proprietary

Research Team

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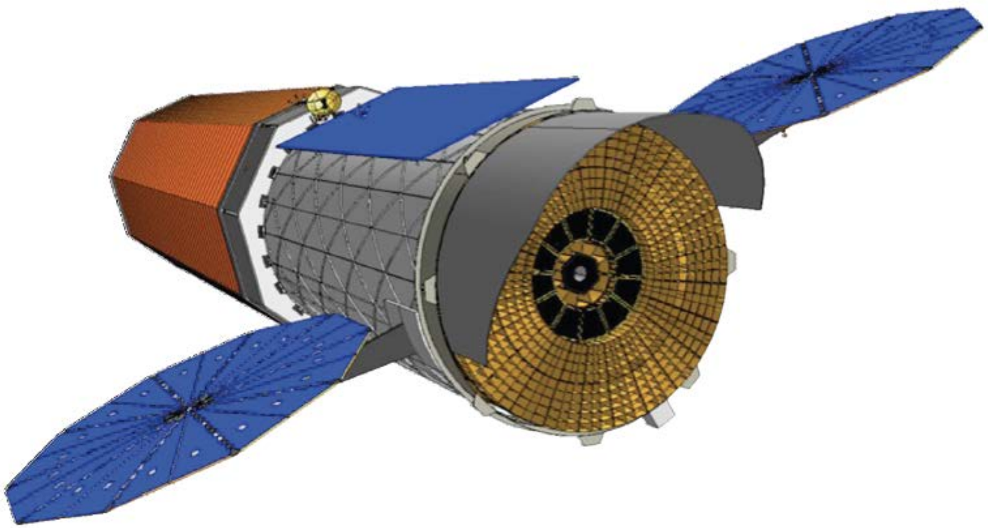
Overview of Technology

- Current technologies incapable of producing high resolution large collecting area optics
  - Chandra optics several inches thick and massive
  - XMM electroformed metal shells ~ 10 arcsec imaging performance
  - Need a new technology to produce lightweight, high resolution optics

- Thin optics, while lightweight, cannot achieve < 1 arcsec resolution on their own
  - Mirrors thin enough for large collecting area distort easily under mechanical (mounting) and thermal loads

- Adjustable X-ray optics marries two technologies, lightweight optics and adjustable/active optics, enabling control and correction of the mirror shape
  - Produces thin lightweight high resolution optics

SMART-X Mission Overview

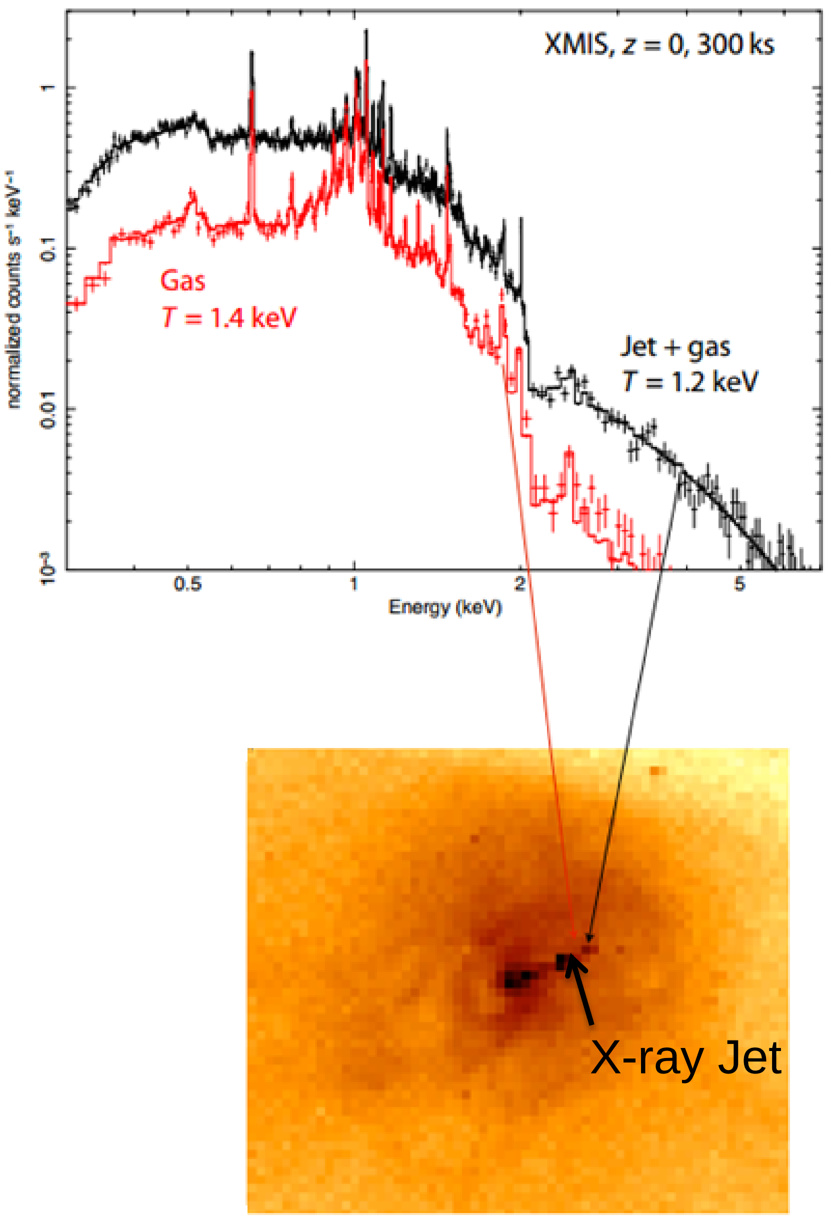


SMART-X would have imaging resolution comparable to Chandra, but with 30 times more collecting area

- Square Meter, Arcsecond Resolution X-ray Telescope
- Single telescope observatory with 10 m focal length and 3 m diameter mirrors
  - SMART-X optics will be a modular grazing incidence mirror with subarcsecond angular resolution

Science Instruments
  - X-ray microcalorimeter: 2 eV energy resolution
  - Active Pixel Sensor camera: provides large field of view, fine imaging capability (0.33” pixels)
  - Critical angle transmission gratings: high resolution spectroscopy ($\lambda/d\lambda \sim 5000$)

SMART-X Science Goals



M87, *Chandra*, 1″ pixels

- Detecting the Warm-hot intergalactic medium (WHIM)
- What happens close to a black hole?
- When and how did super massive black holes grow?
- How does large scale cosmic structure evolve?
  - Cosmic feedback
- How does matter behave at high densities?

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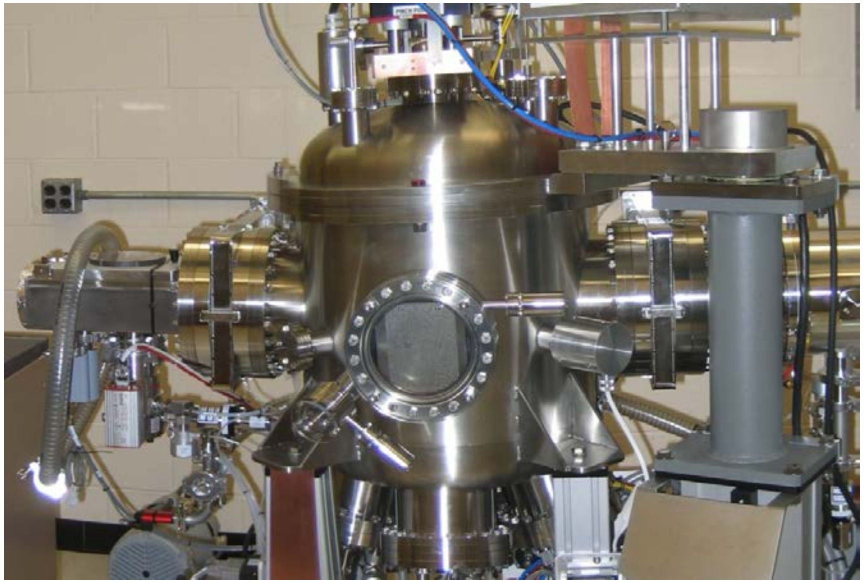
Sputter Deposition of PZT Films

- Films deposited in Kurt J. Lesker CMS-18 multi-target sputter system on Pt-coated flat or slumped glass
- Crystallized in a box furnace at 550 °C for 18 hours using 10 °C/min ramp rates
- High yields demonstrated 90 – 100%



Parameter	Value
Target Composition	$Pb_{1.1}Zr_{0.52}Ti_{0.48}O_{3.1}$ +1% Nb
RF Power Density	Target: 2.0 W/cm^2
Substrate Temperature	25 °C
Sputtering Gas	Ar
Working Pressure	2 mtorr
Deposition Time	2-4 x 12,500 s
Thickness	~1-2 μm
Annealing Conditions	18 hours @550 °C

K. Suu et al., Jpn. J. Appl. Phys. 35 (1996) 4967
Glen Fox, personal communication

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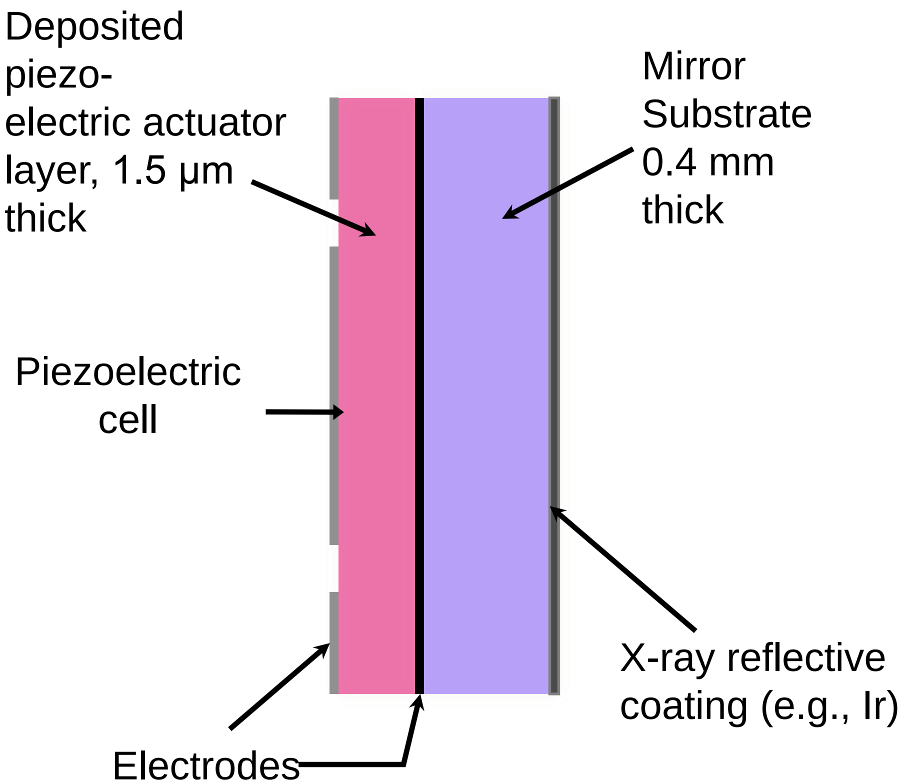
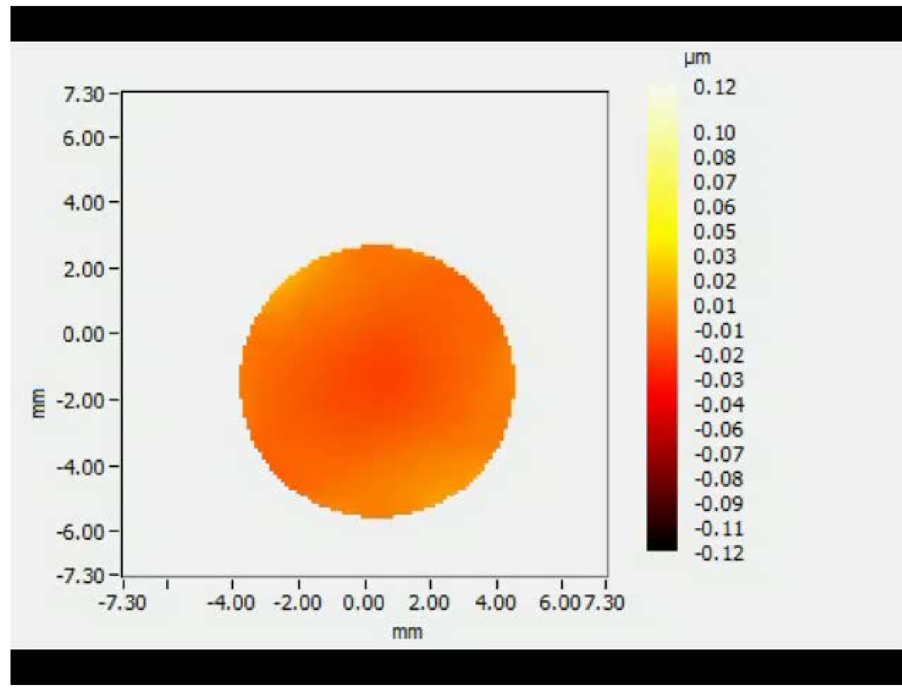
Adjustable Bimorph Mirrors

- Applying a voltage across the thickness of a piezo cell produces a strain in parallel to the mirror surface (in two orthogonal directions)



Flat test mirror (10 cm diam.): Influence functions (3 piezo cells), measured with Shack-Hartmann wavefront sensor.



- **Performance is stable and deterministic**
- **Lifetime testing of piezoelectric looks very good**
- **Lifetime testing of mirror components is underway**

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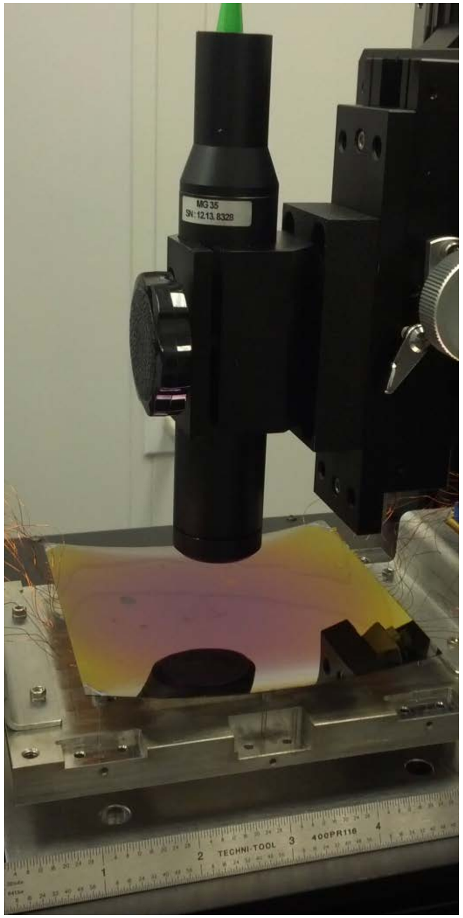
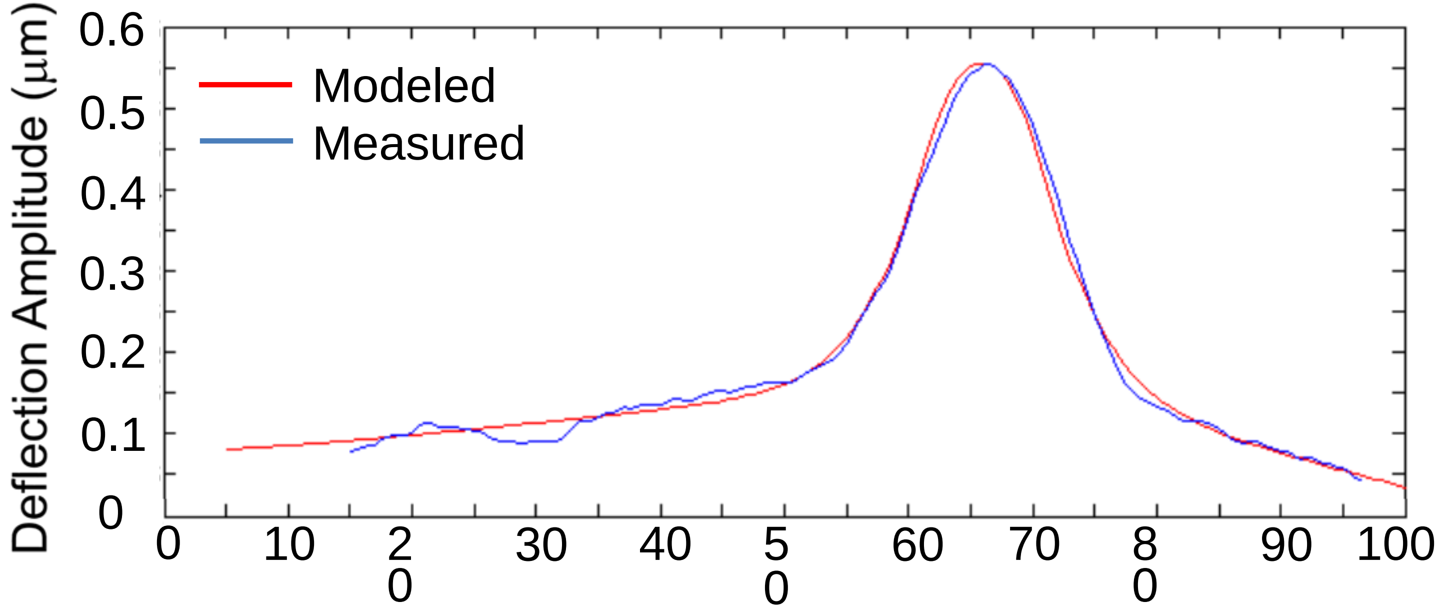
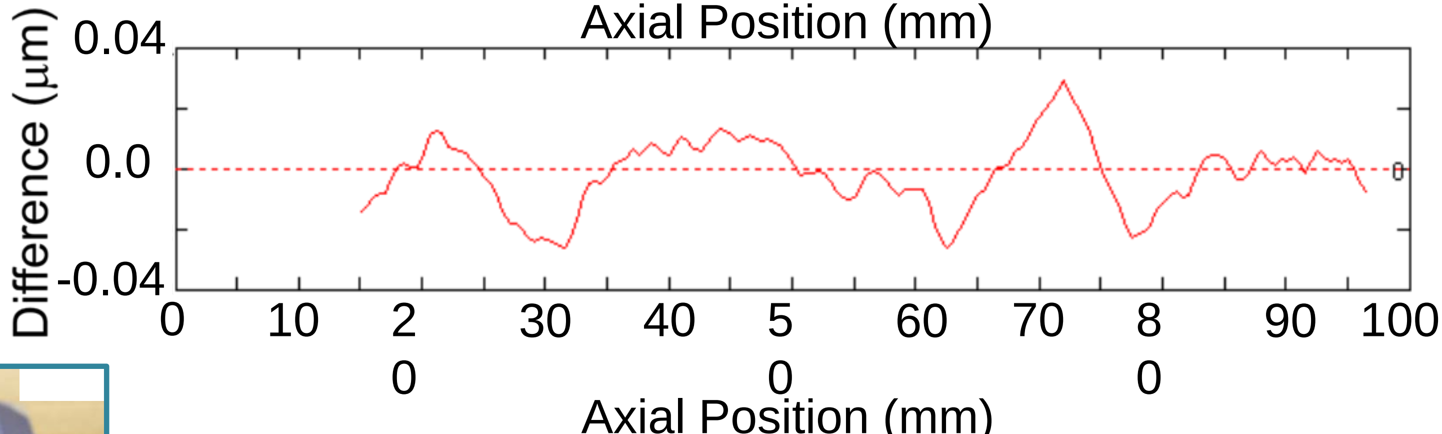
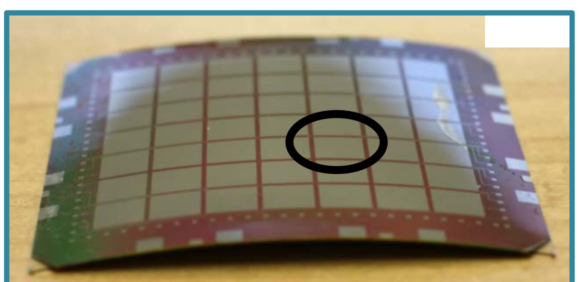
Influence Function for PZT on Slumped Glass









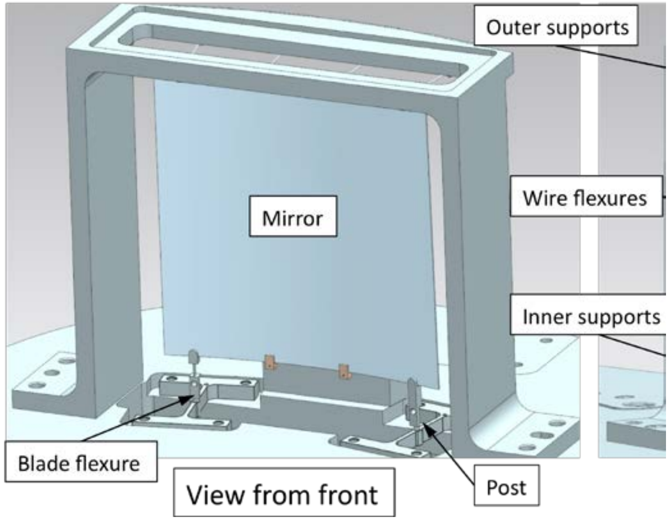
- Individual pixel activated at 4 V (=1.3 V_c)
- Show maximum displacement of ~0.45 µm with 35 nm rms error

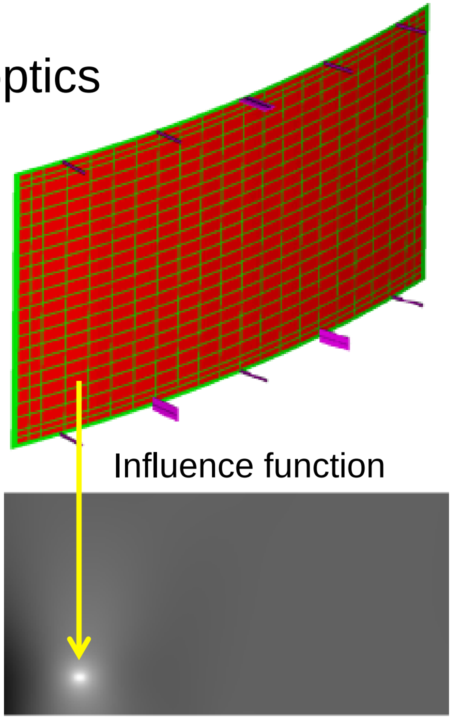
Model Used to Guide Design and Inform Simulations

Analysis of lab data, system performance predictions, and requirements are based on a detailed mathematical model that includes:

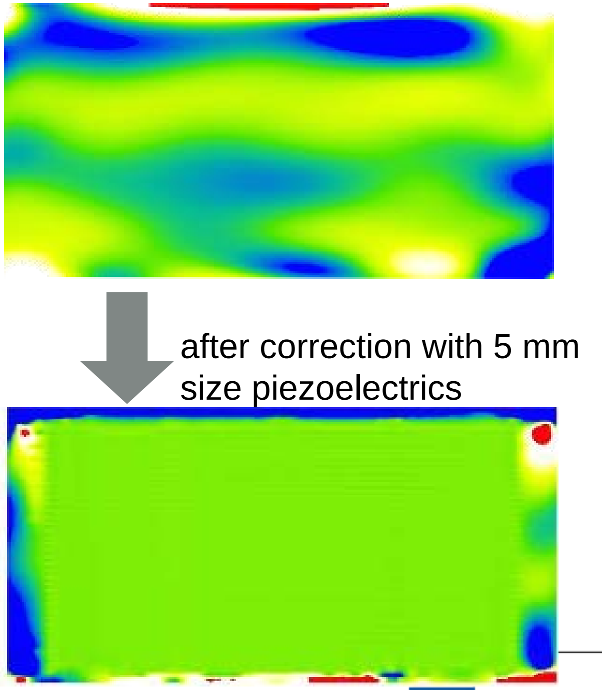
- FEM model of mount structure
- Thermal and gravity distortions of the mirror segments
- Response of the mirror segment shape to voltage applied to individual piezoelectric cells
- Solution for voltages optimizing the mirror optical performance
- Degradation of system performance due to, e.g., failure of piezoelectric cells

200 mm x 400 mm optics



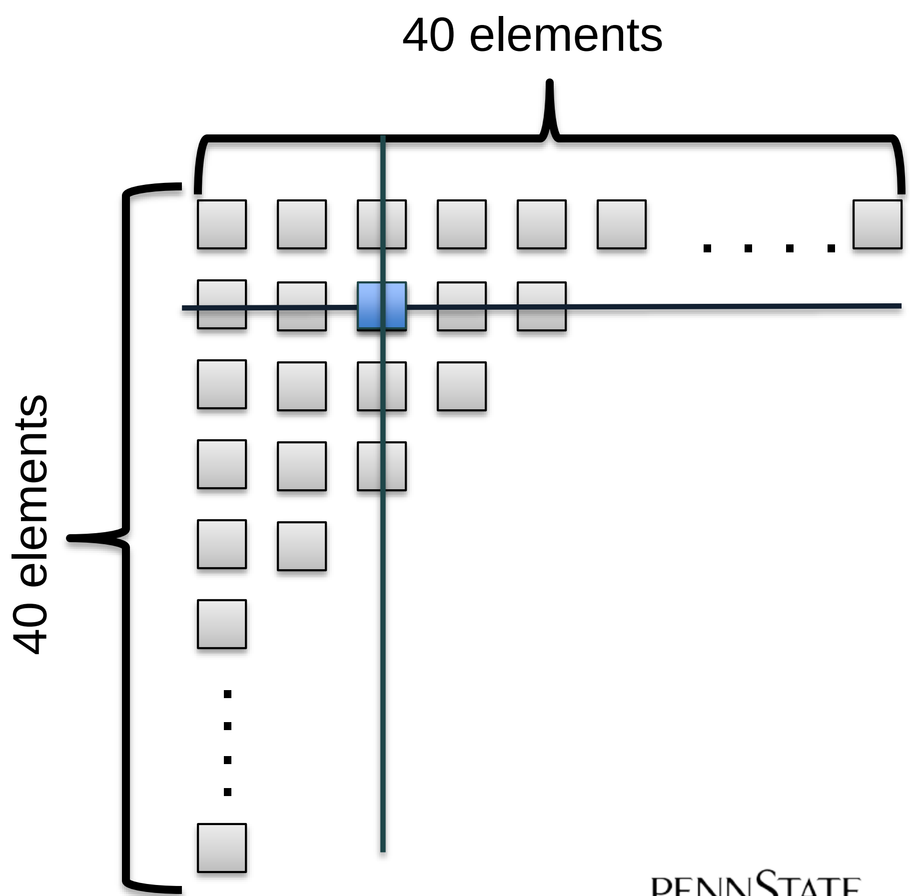


Error amplitude before correction



Integrated Electronics for X-ray Optics

- Adaptive optics systems require independent control of a large array of elements (e.g. 40 x 40)
  - Can run **1,601** contacts to each individual panel…
  - Arrays of electronics and a row-column address scheme (the same technology used in displays) **reduces the number of contacts required to 81**
  - Approach should simplify fabrication and improve reliability of X-ray telescope mirrors



Oxide Thin Film Electronics

Samsung GIZO driven AMOLED

Samsung demos 2560x1600 pixels 10" displays

2009

2010

2011

2012

Production

Primordial ooze (organic and a-SiH TFTs)

Samsung's 70-inch LCD TV using oxide semiconductor technology

Sharp's high-performance 'Retina' resolution displays based on IGZO technology

Because oxide semiconductors are fast, electrically stable, and mechanically flexible other applications beyond displays are of interest

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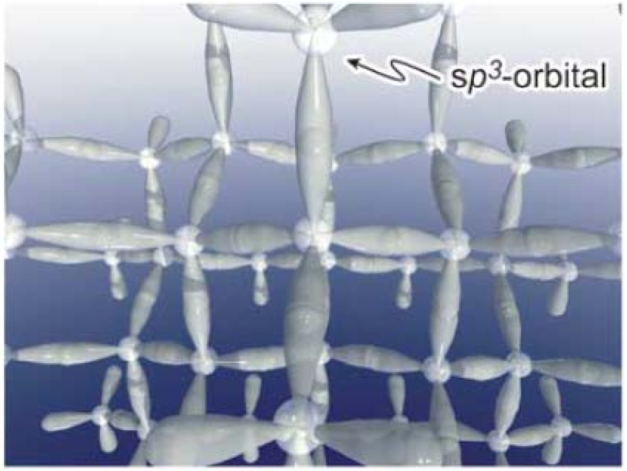
Oxide Semiconductor Bonding

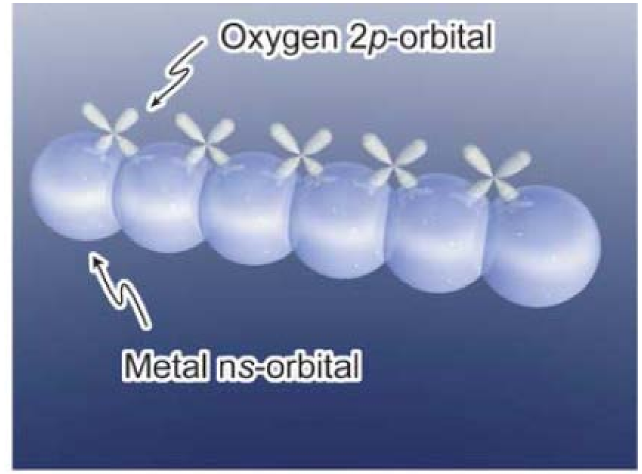
Covalent



Crystalline

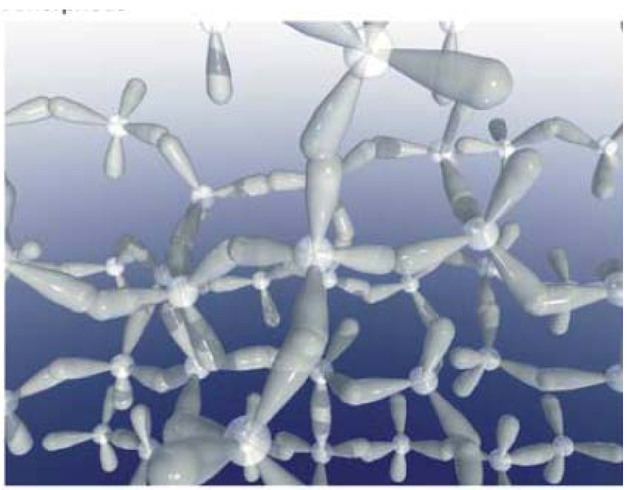
Semiconductors like Si and GaAs have sp-hybrid orbitals

Ionic



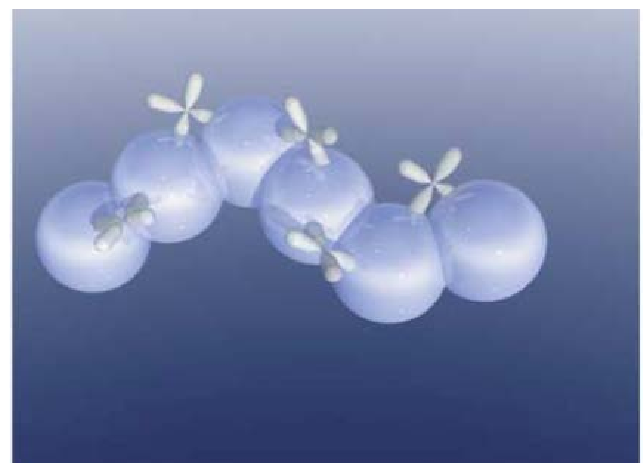
Crystalline

Oxide semiconductors (ZnO, GIZO), have conduction band formed from metal s-orbitals



Amorphous

Disorder produces large changes in carrier transport



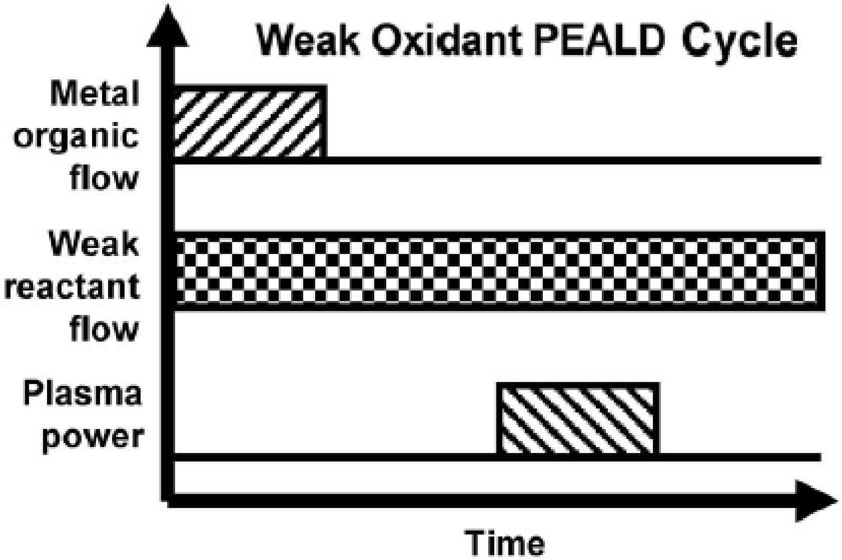
Amorphous

Disorder has small effect on transport; stable against bond rearrangement

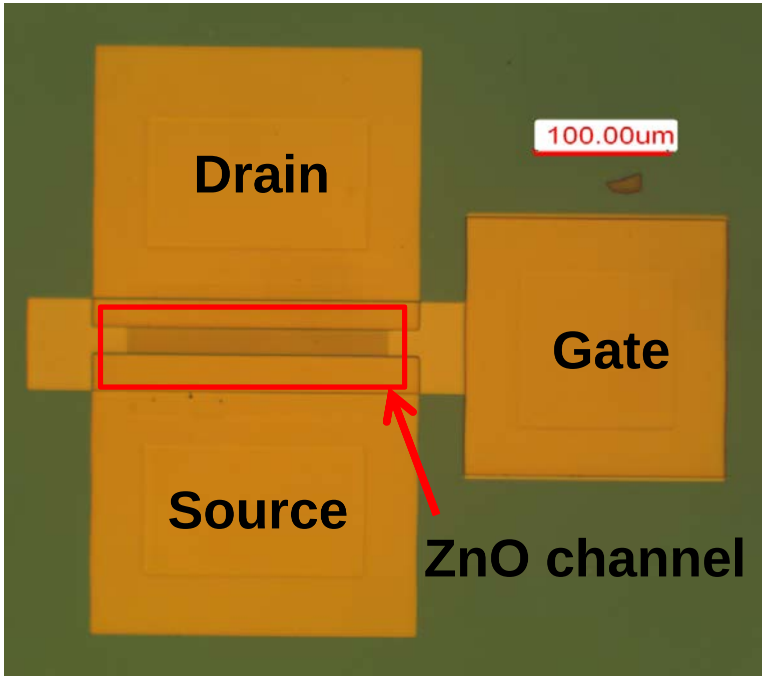
K. Nomura, et al, *Nature*, 432, pp. 488 – 492 (2004)

Deposition of ZnO Electronics (PEALD)

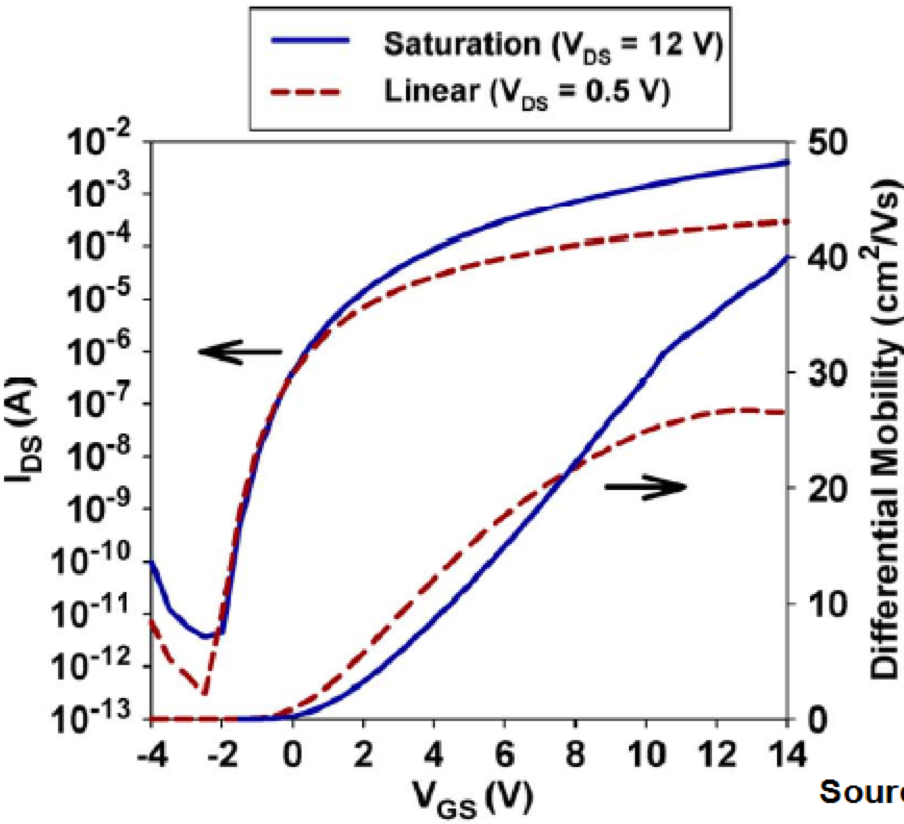
- ZnO electronics deposited via plasma enhanced atomic layer deposition (PEALD)
  - Low reactivity oxidant constantly flowing to remove excess precursors or reaction excess
  - Metal-organic precursor (Diethyl Zinc for ZnO/Trimethylaluminum for Al_2O_3) is pulsed and chemisorbs to the surface
  - RF plasma pulsed to oxidize the adsorbed precursor



Mourey, D *et al*. "Fast PEALD ZnO Thin-film Transistor Circuits." *IEEE Transactions on Electron Devices* 57.2 (2010): 531.

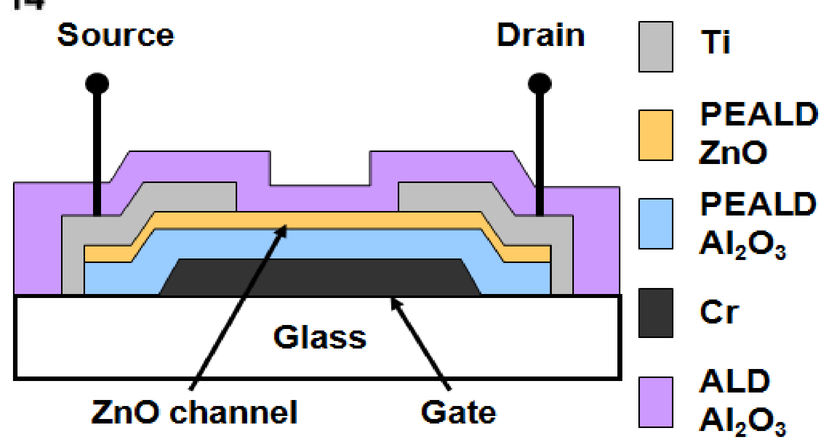


ZnO Electronics



- Oxide electronics have high performance
- Low temperature processing (<200 °C) enables flexibility of choosing substrates
- ZnO electronics are radiation hard

Mourey, D *et al*. "Fast PEALD ZnO Thin-film Transistor Circuits." *IEEE Trans. Electron Devices* 57.2 (2010): 531.



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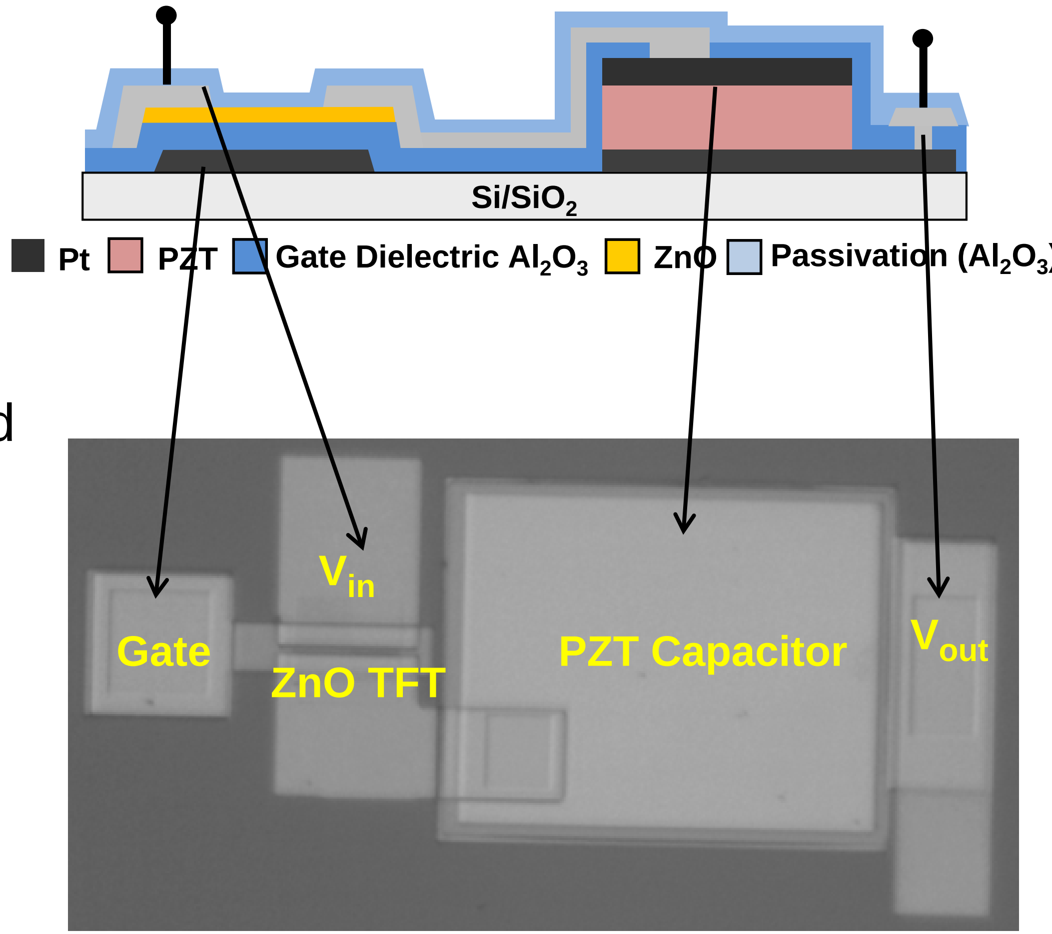
PZT Piezoelectrics Integrated with ZnO TFT

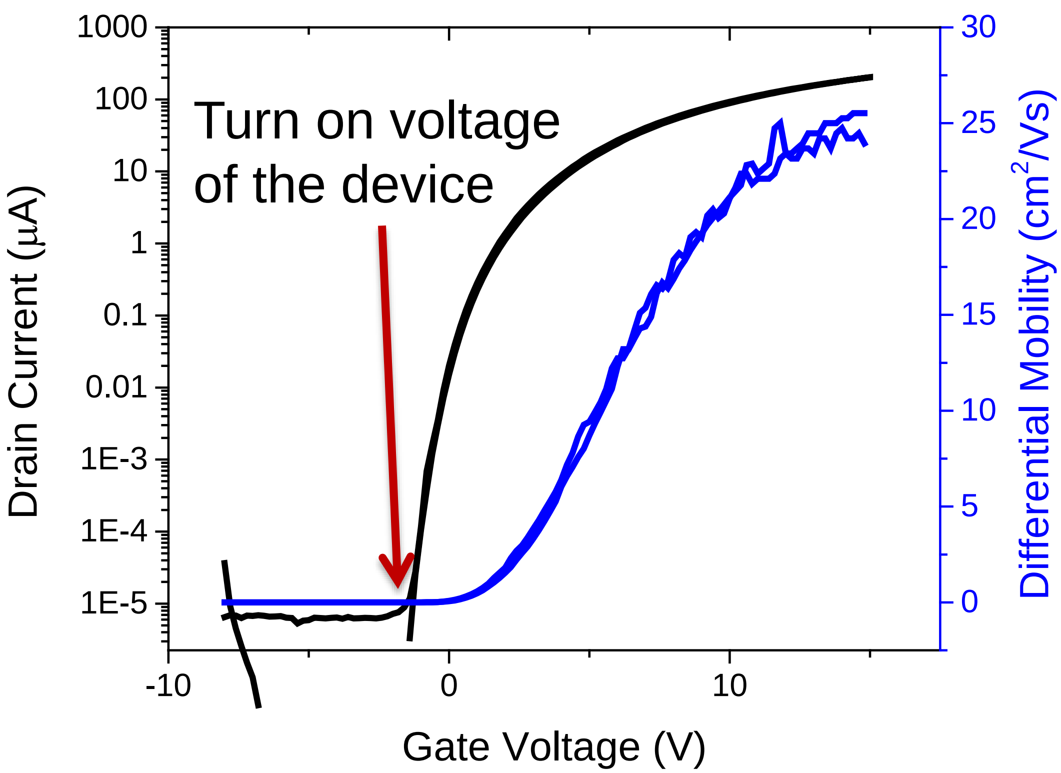
- PZT capacitor mesa (Pt/PZT) deposited and dry etched
- Top PZT contact (Pt) deposited
- PEALD Al_2O_3 (gate dielectric) and ZnO (active layer) deposited at 200 °C
- Sputtered titanium; patterned by lift off for source/drain
- 30 nm ALD Al_2O_3 passivation layer deposited at 200 °C



Process integration of ZnO TFTs and PZT capacitors was done without degrading electrical and mechanical characteristics

Co-processing ZnO electronics and PZT

- For measurements in the linear region (V_{DS} = 0.5 V) on transistors with a W/L ratio of 200/20, a differential mobility of >24 cm^2/Vs was obtained. This is comparable to transistors on glass
- No measurable changes in ε_r, $\tan\delta$, P_r, E_C, or aging rates of PZT



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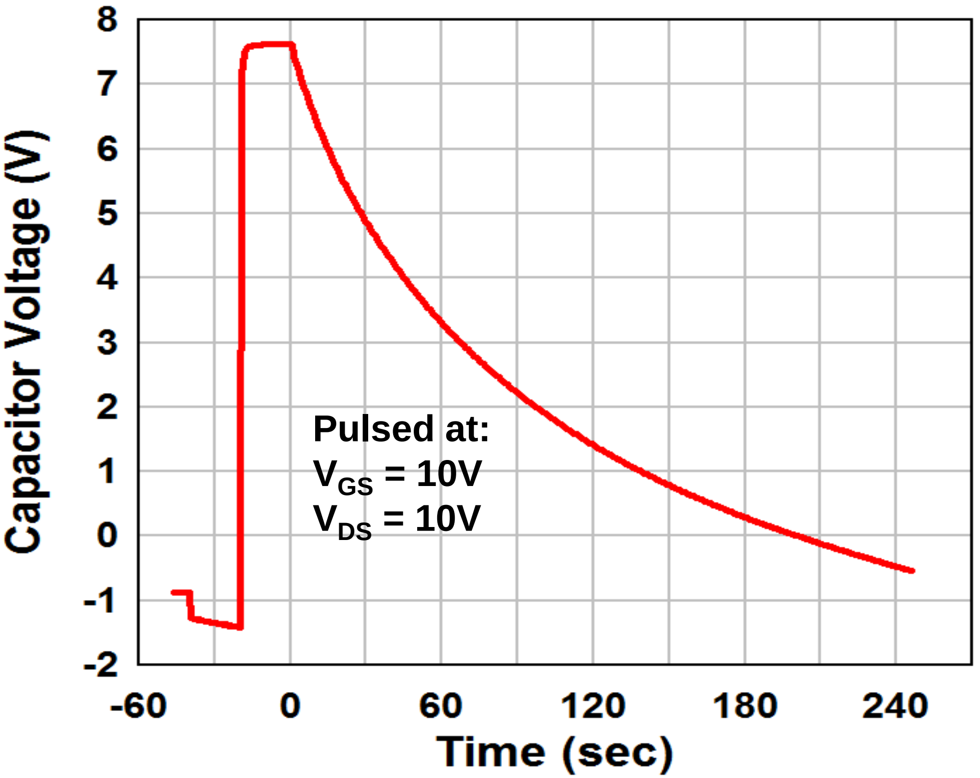
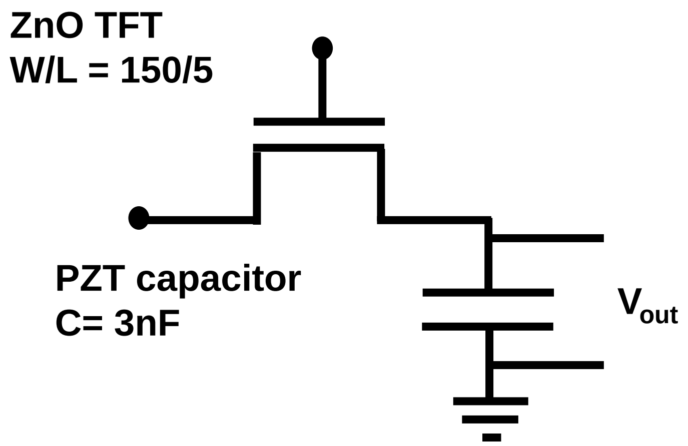
Low Leakage ZnO TFT Electronics Enable Holding Voltage on PZT Cells





PZT self-discharge time comparable to the self-discharge time seen in integrated PZT-ZnO

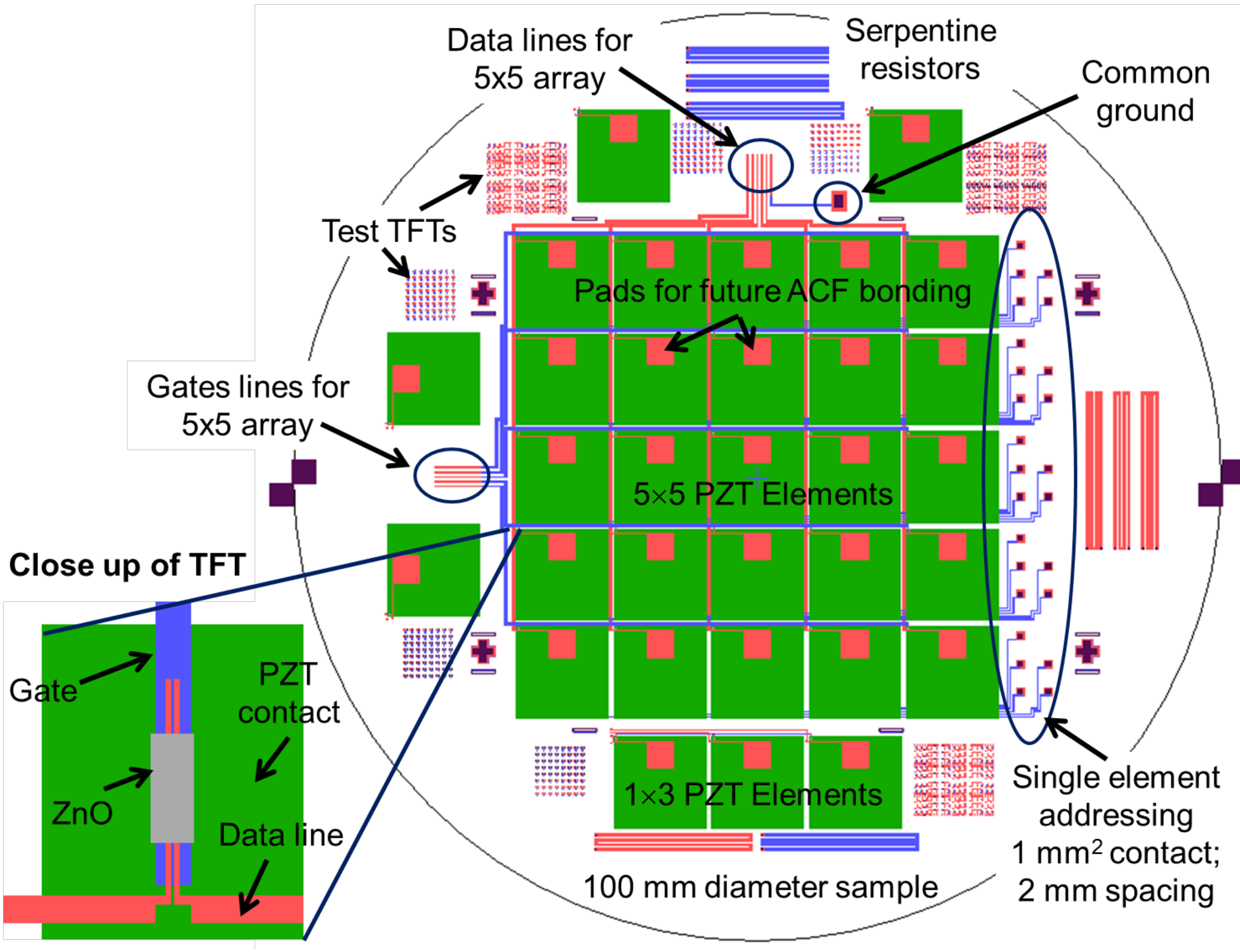
When TFT ON (V_{GS} = 10 V) a charge time constant of <3 msec was found

When TFT OFF (V_{GS} = -10 V) a discharge time constant of ~70 sec was seen

For reasonable refresh rates, V changes should be < 1 %

Row-column addressing should be possible

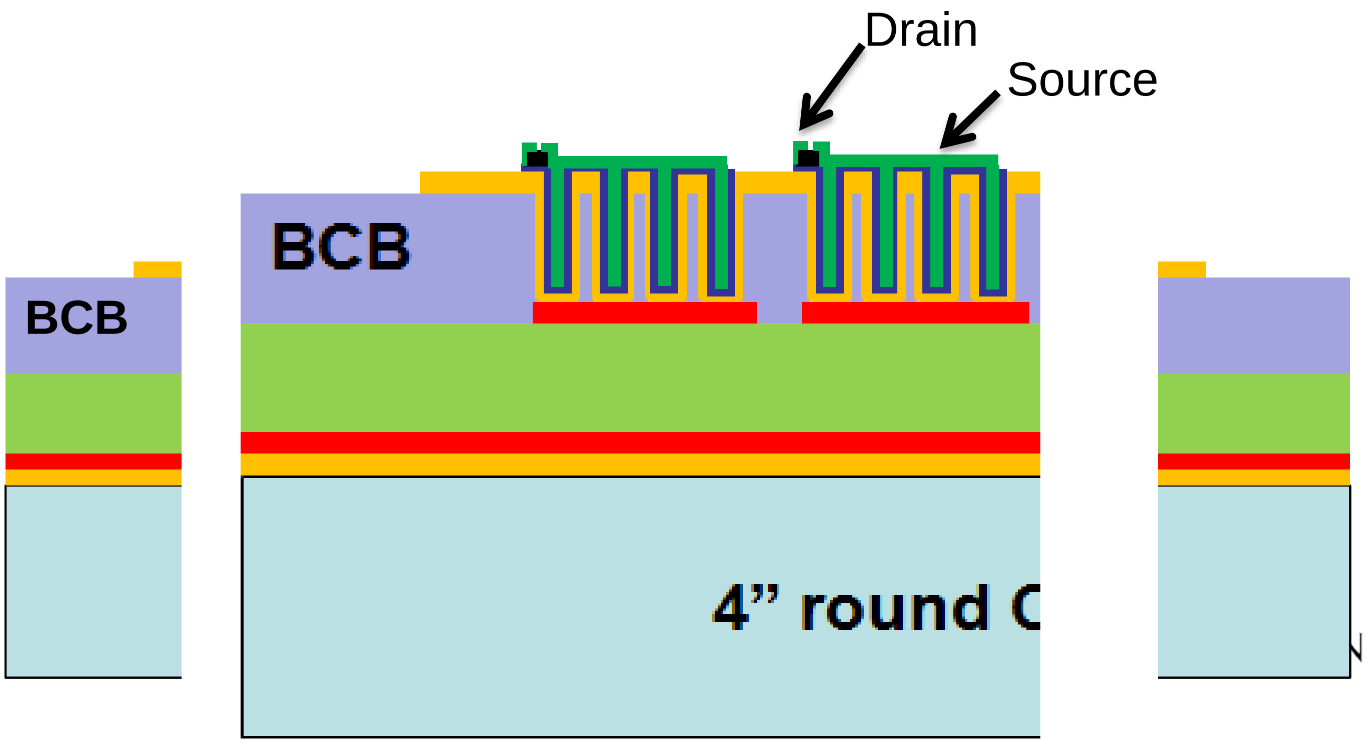
Layout for X-Ray Mirror Segment with Integrated Electronics



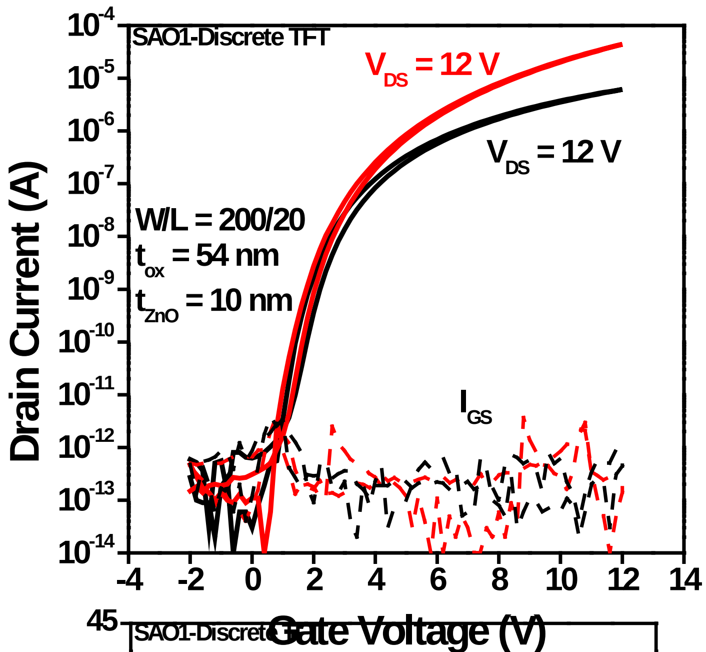
Processing

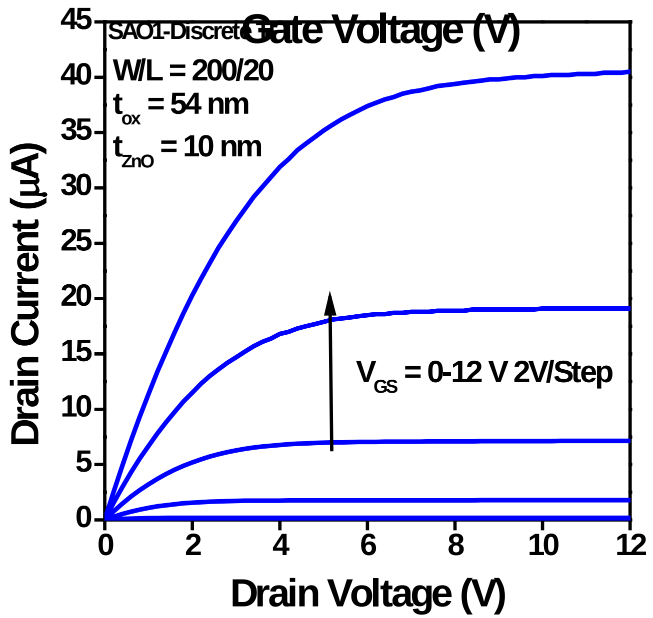
1) Deposit Ti/Pt bottom electrode
2) Sputter PZT and lift off Pt top electrodes
3) Spin coat BCB, develop and cure (225 °C) overnight

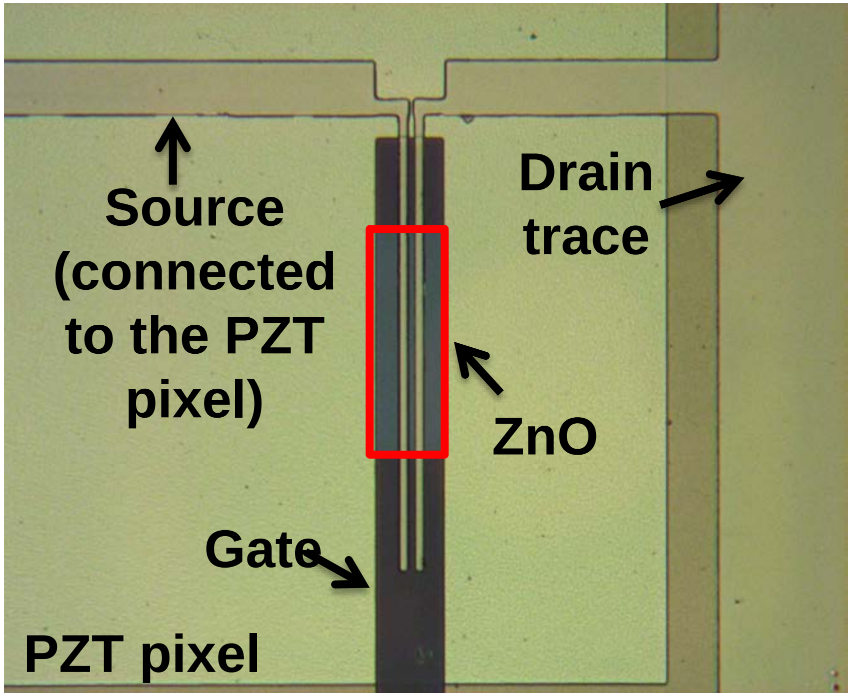
1) Lift off Ti gate
2) PEALD deposition of Al_2O_3 and ZnO
3) Pattern Al_2O_3 vias and ZnO
4) Lift off Ti drains and sources
5) Passivate with ALD Al_2O_3



PZT / ZnO Array

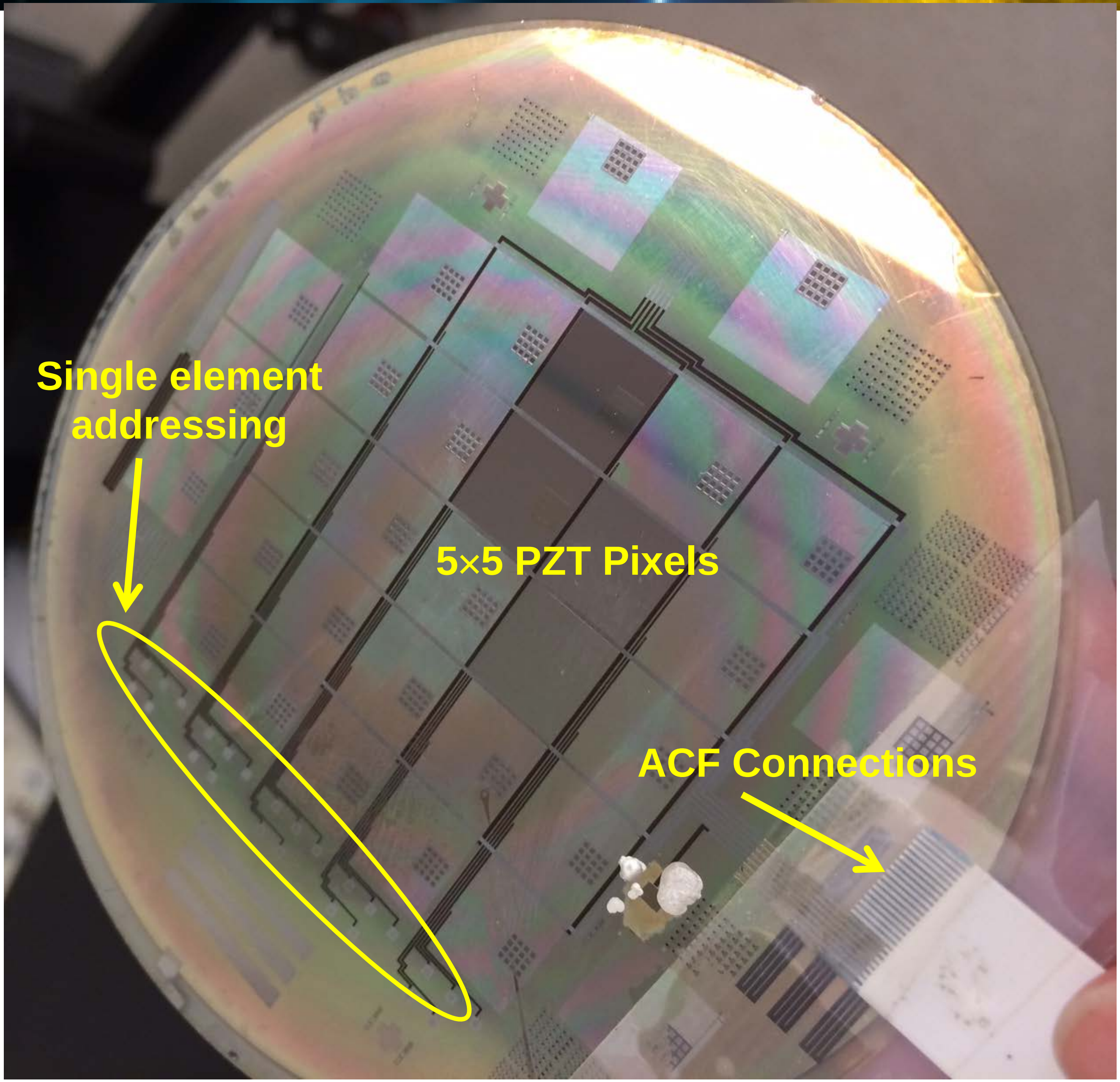






Functional transistor properties and functional PZT

ACF Bonded PZT Pixel Sample



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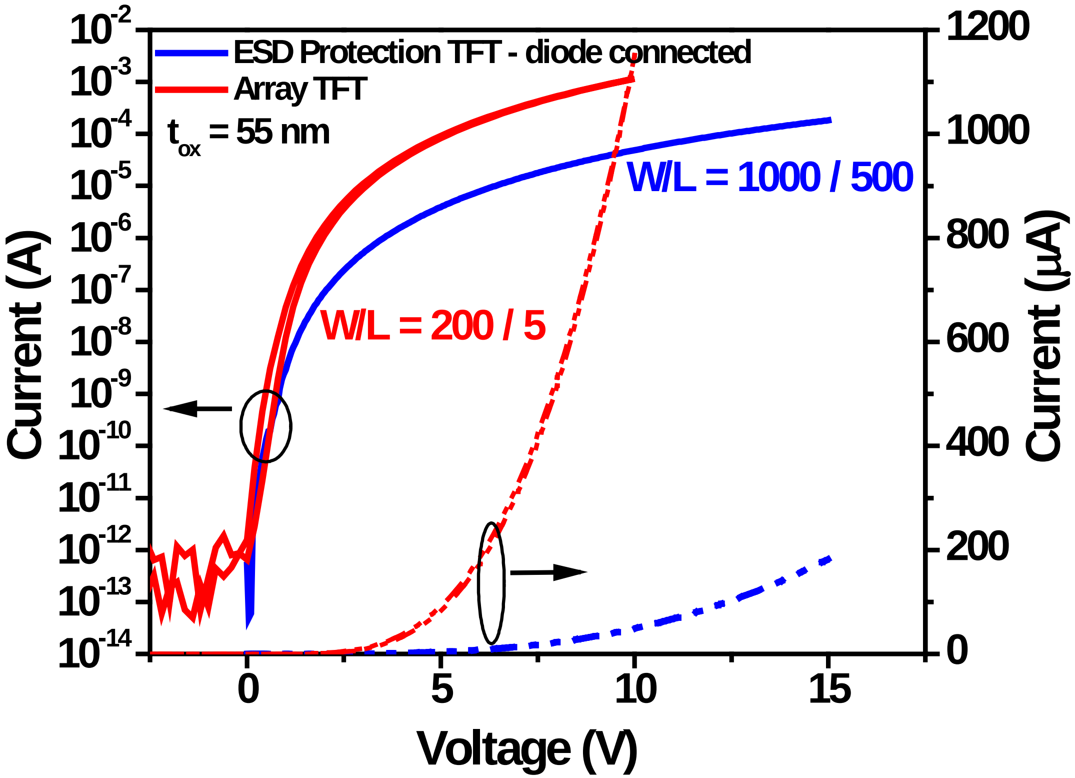
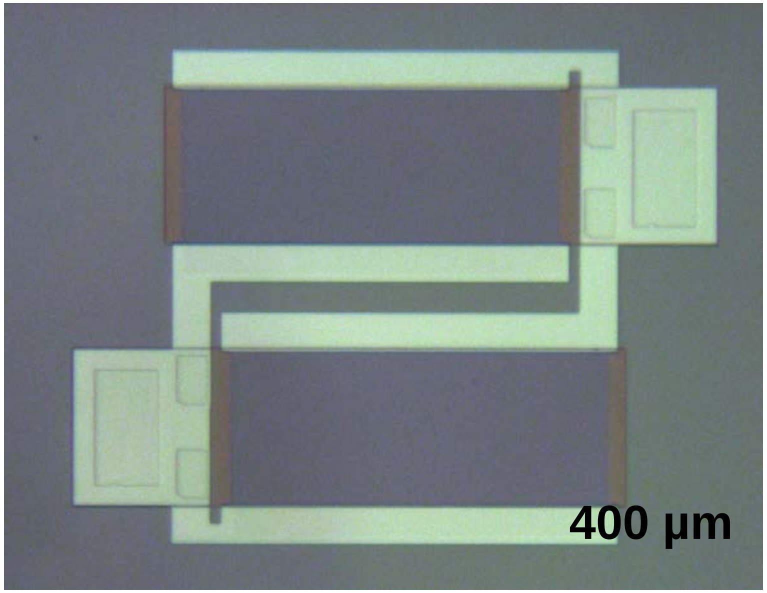
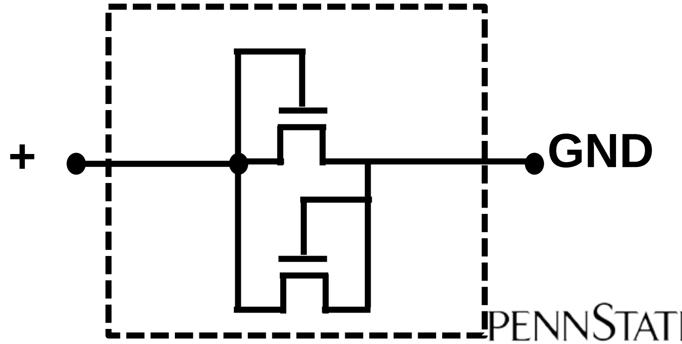
PZT-ZnO Array for Electrostatic Discharge Protection





Device under test



During normal operation of array
@ V_{DD} = 10 V ESD TFTs leak ~50µA
$R_{ON\_ESD\ TFT}$ ~200 KΩ
R_{ON_Array} TFT ~6 K Ω

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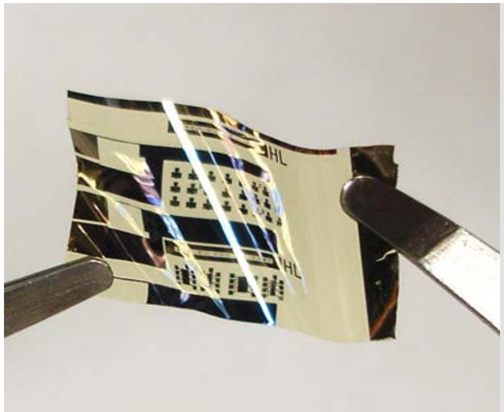
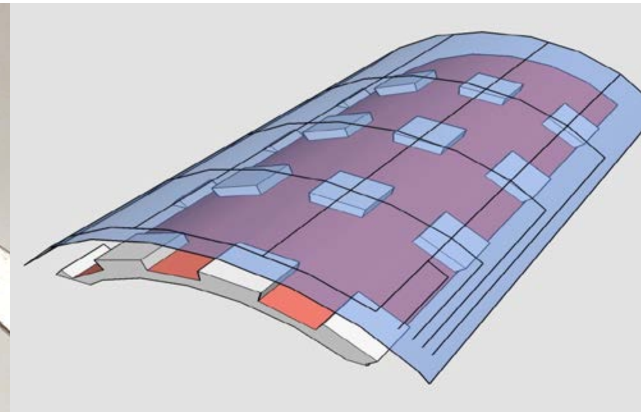
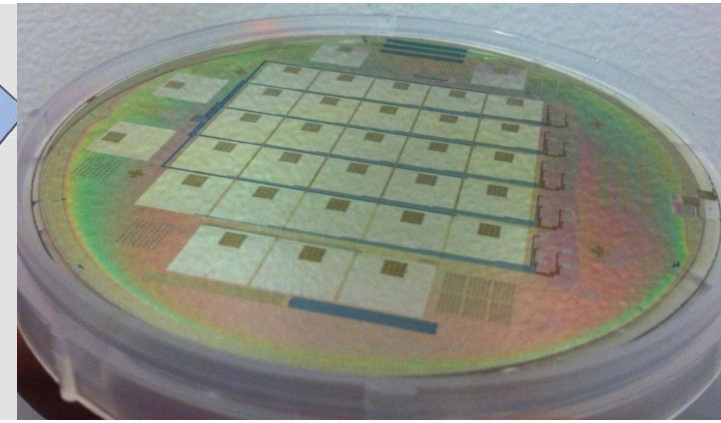
Current Development Status and Applications of Technology







- PZT films with integrated ZnO TFT enables adjustable optics for next generation X-ray space telescope
- Advancing technology would require several million $
- Integration of low level control electronics is enabling for:
  - Adaptive optics in X-ray, visible, infrared…
  - Simplification of wiring schemes in sensor or actuator arrays
  - Active rectification for self-powered mechanical energy harvesters
  - Many other possibilities…

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Summary of Key Points

1. Successfully deposited piezoelectric films on thin glass optics
    - High yield on flats and conical parts
    - Able to pattern electrodes and integrate on-cell electronics
    - Significant progress by SAO/PSU funded by NASA SMD, STMD, Moore, and Smithsonian
2. Piezoelectric thin films can correct optical distortions in thin, lightweight glass mirrors.
3. Approach is deterministic: demonstrated good agreement between modeled and measured influence functions.
4. Approach can achieve half-arcsec imaging: simulations show correction of ‘old’ (*ca. 2008*) IXO mounted mirror pair to SMART-X requirements of < 0.5” HPD.
5. Currently, we are at TRL 3. Our technology development plan leads to TRL 4 in FY16 and TRL 6 in 2018 prior to 2020 Decadal Survey.

Contacts

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  - http://www.mri.psu.edu/facilities/nanofab/

Back-up charts

Current Development Status of Technology

Note: Discuss the current development status of the technology and what you perceive to be next steps to advance the technology to a "commercial ready stage"

What will it cost to advance this technology? (ROM cost)

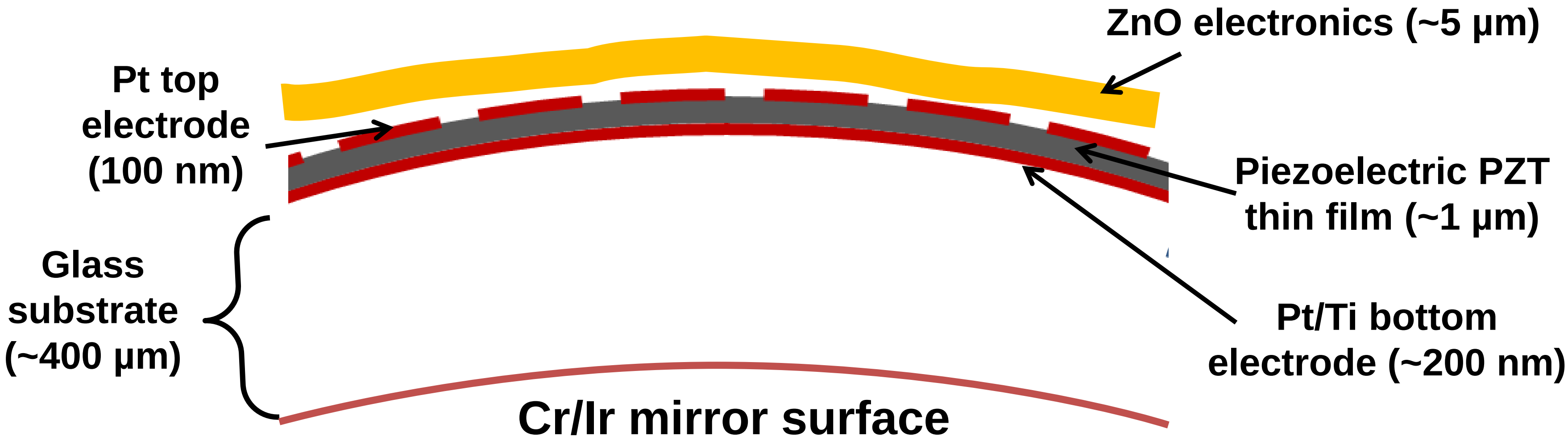
Why should NASA, Industry, and other government agencies invest in this technology?

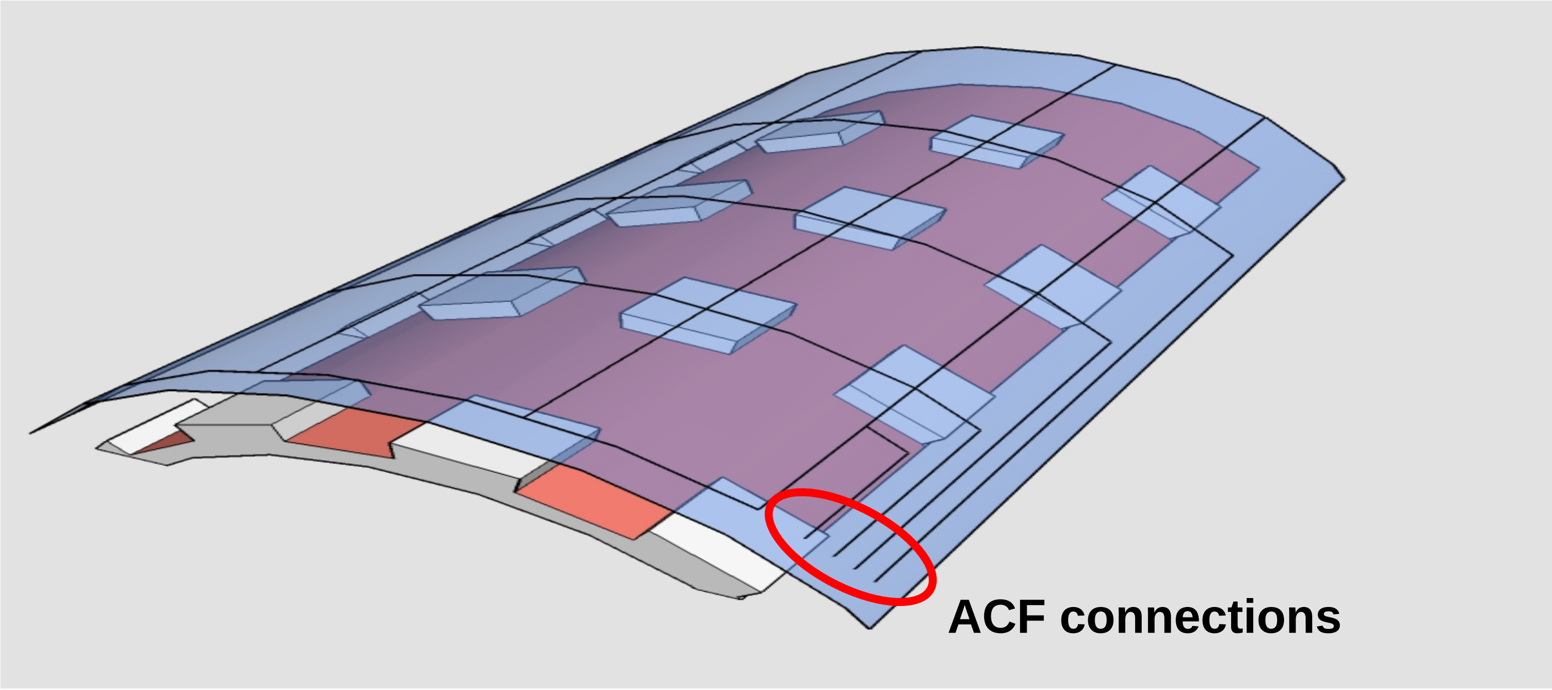
Target Technology Market Applications

The basic technology of integrating PZT PiezoMEMS with control electronics is generically interesting for

- Active surfaces
- Mechanical energy harvesting for self-powered sensors
- Ultrasound inspection arrays (medical, infrastructure) on flat or curved surfaces

ZnO TFTs on Thin Flexible Substrates





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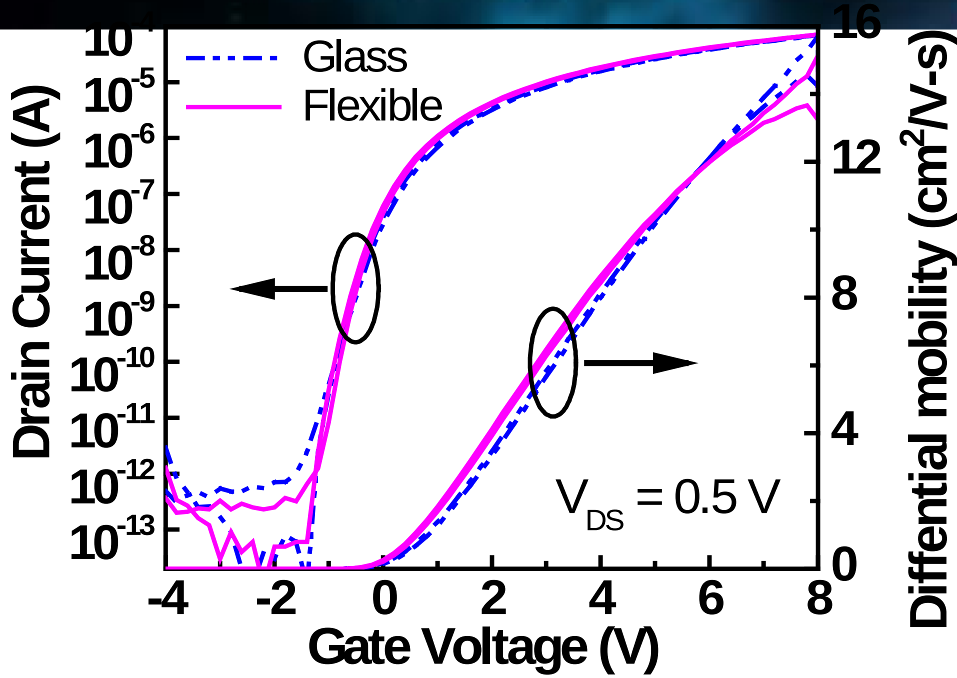
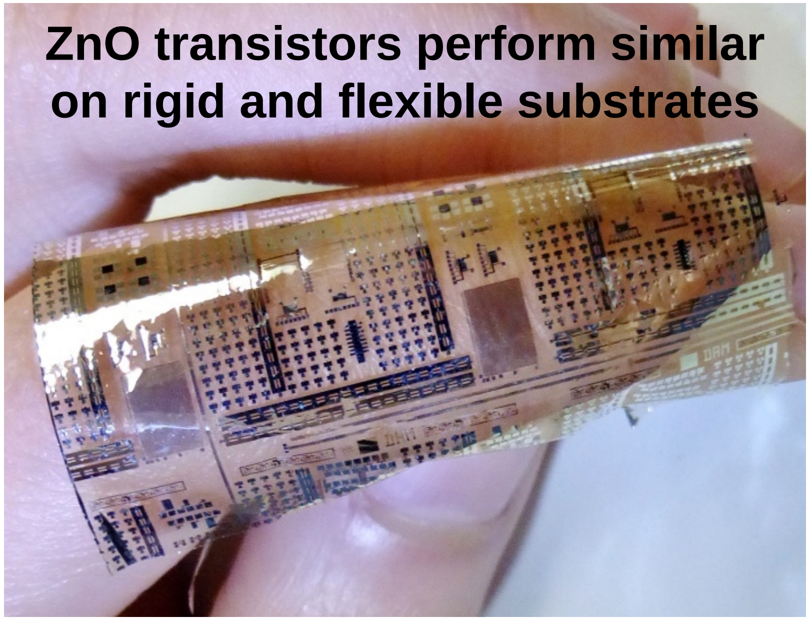
ZnO TFTs on Flexible Substrates





Simple mechanical fatigue test

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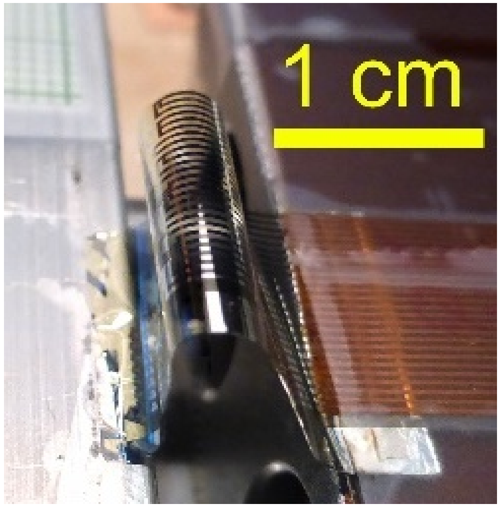
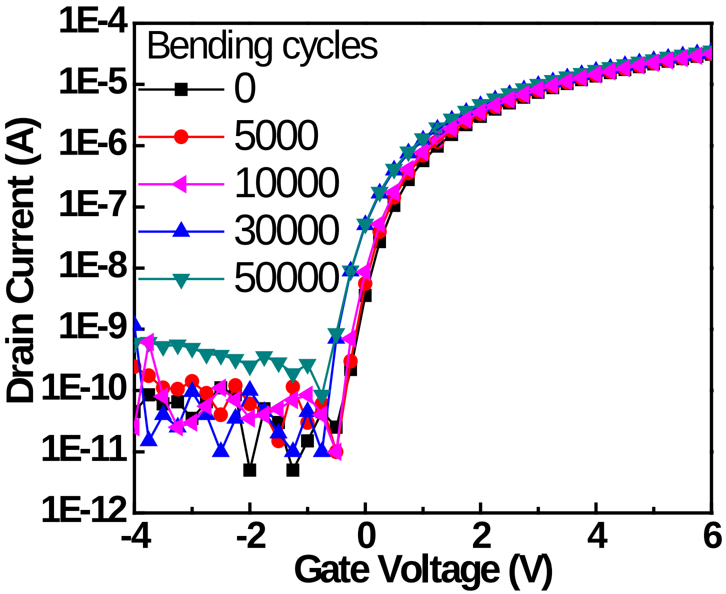
- TFTs put through repeated bending and flattening
- Bending radius ~ 3.5 mm



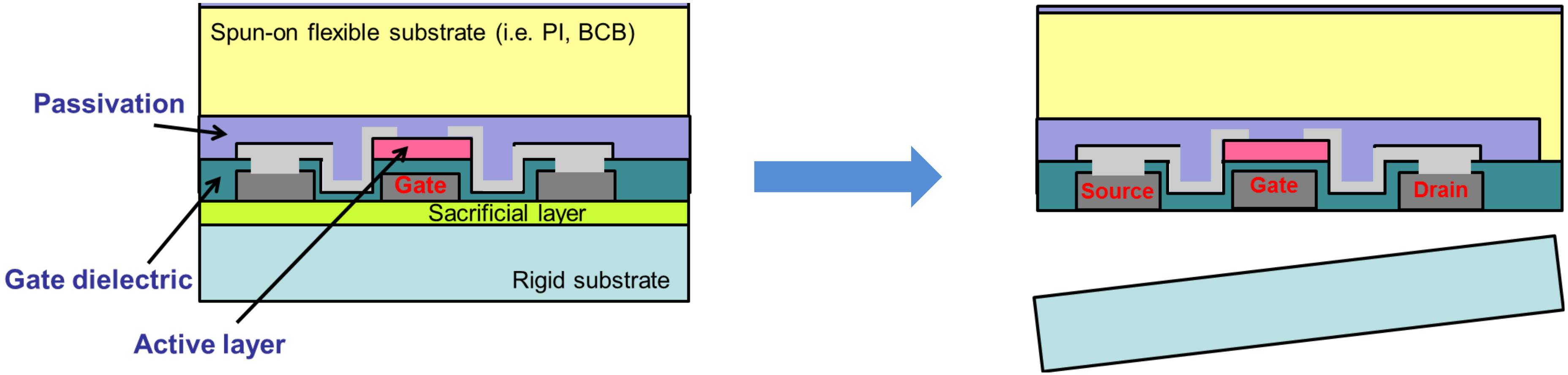


Optical Profilometry Data

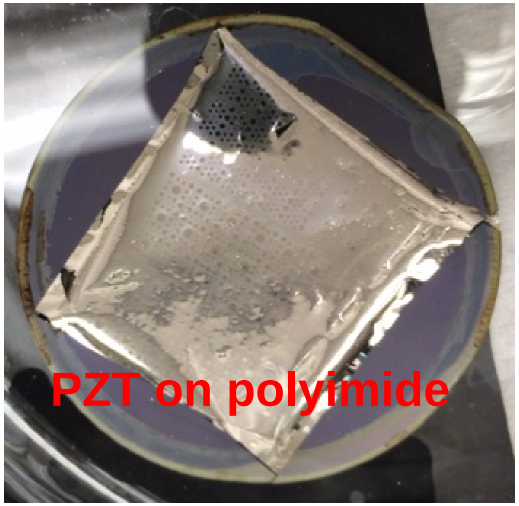
- Optical profilometry measurements made via the shorted TFTs at 0V and 10 V
  - Due to the issue with thin transparent layers, change is observed but unquantified

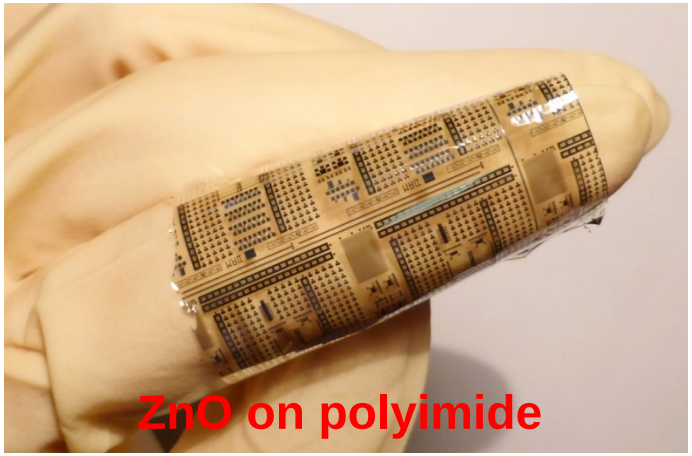
Other Options for Electronics on Curved Surfaces

Fabricate the ZnO electronics on a rigid substrate with a sacrificial layer and spin on polyimide



Using chemical wet etching we can remove the sacrificial layer and have the electronics on a flexible substrate



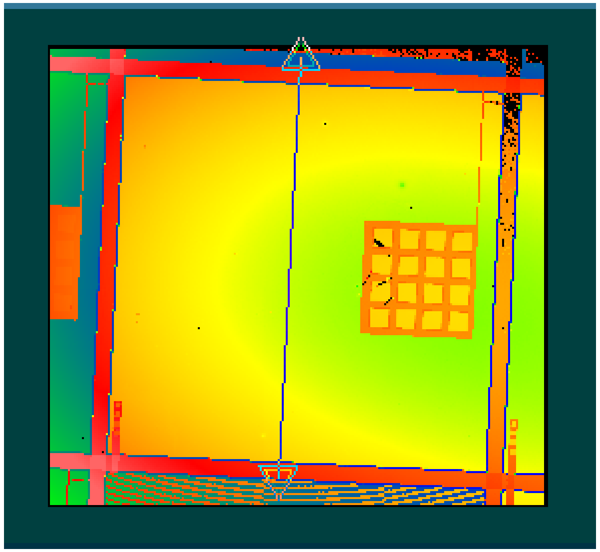


This process can also be used to have PZT on a thin flexible substrate

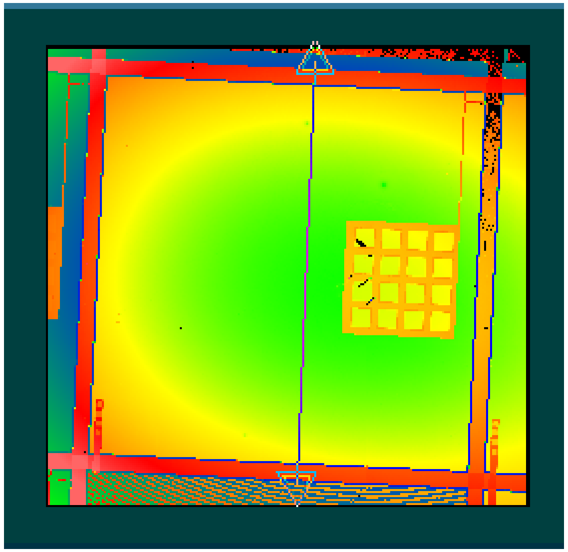
Optical Profilometry Data

- » Optical profilometry measurements made via the shorted TFTs at 0V and 10 V
  - » Due to the issue with thin transparent layers, change is observed but unquantified

0 V



~10 V



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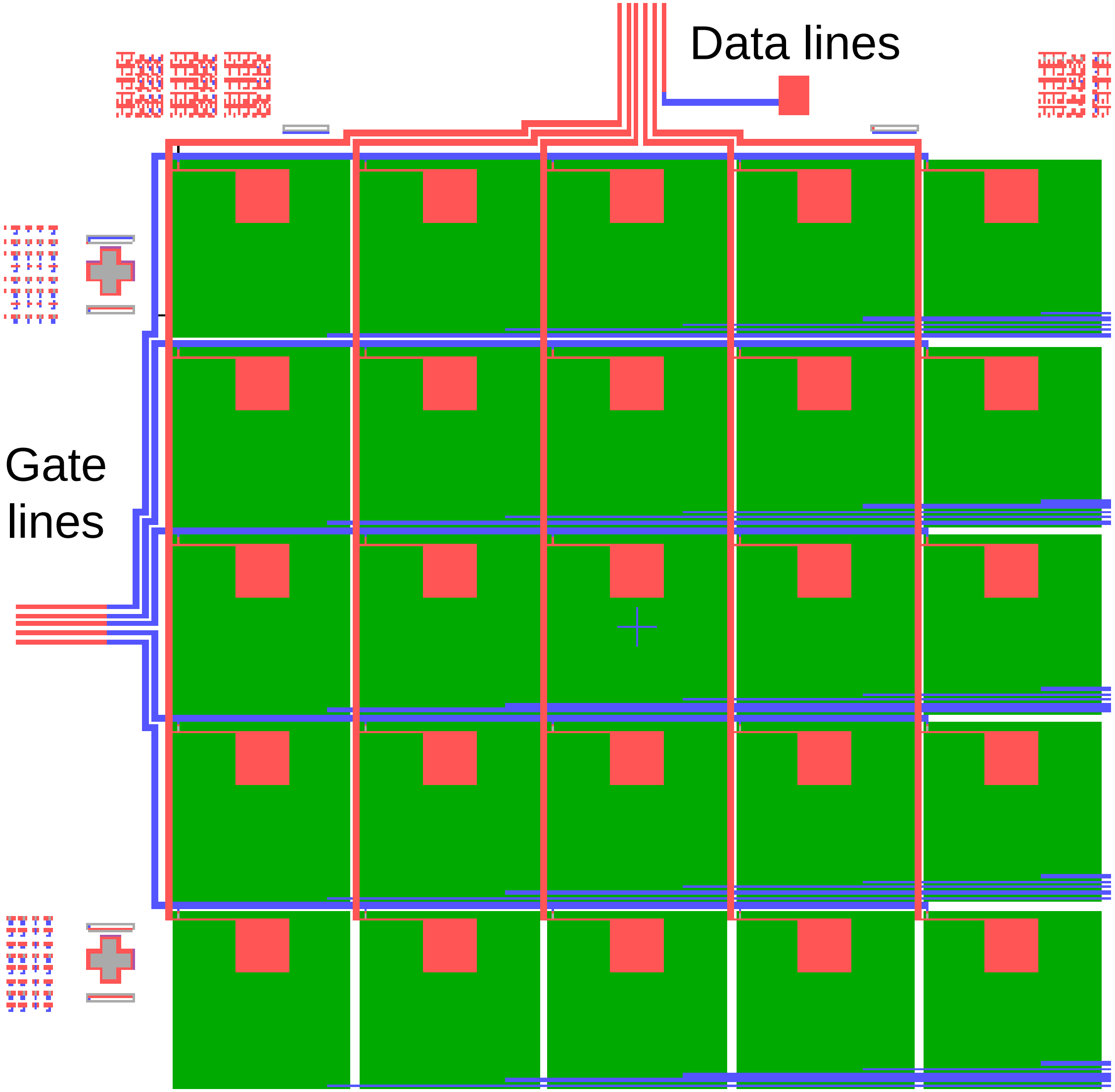
Simplifying Electrical Interconnections



Anisotropic conductive film (ACF) bonding of gate & drain leads

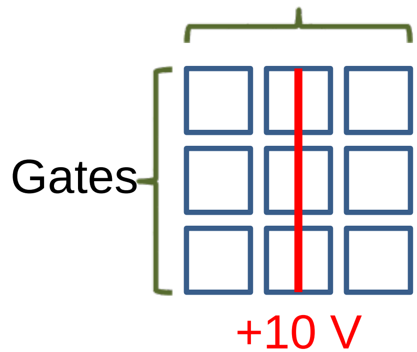
Initial demonstrations on flat glass were successful

SMART-X Mirror Control Electronics

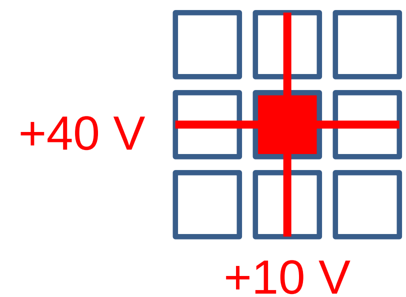
- 16 Analog out channels with a range of ±40 V
- Controlled via ethernet and LabView

- **Example Voltage Control – Addressing an Individual Pixel**

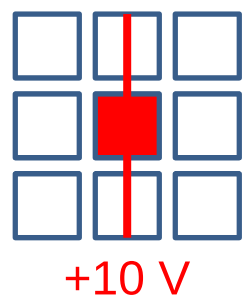
1. Set desired voltage on drain line



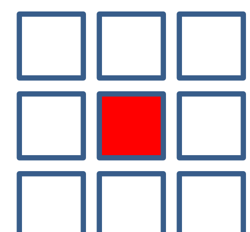
2. Open desired gate line



3. Close gate line



4. Remove drain line voltage



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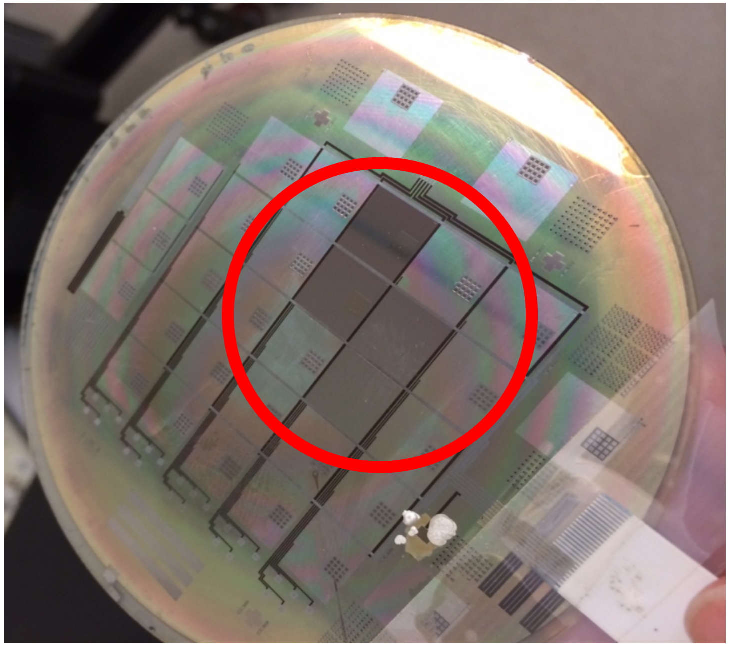
Optimizing Deposition Conditions

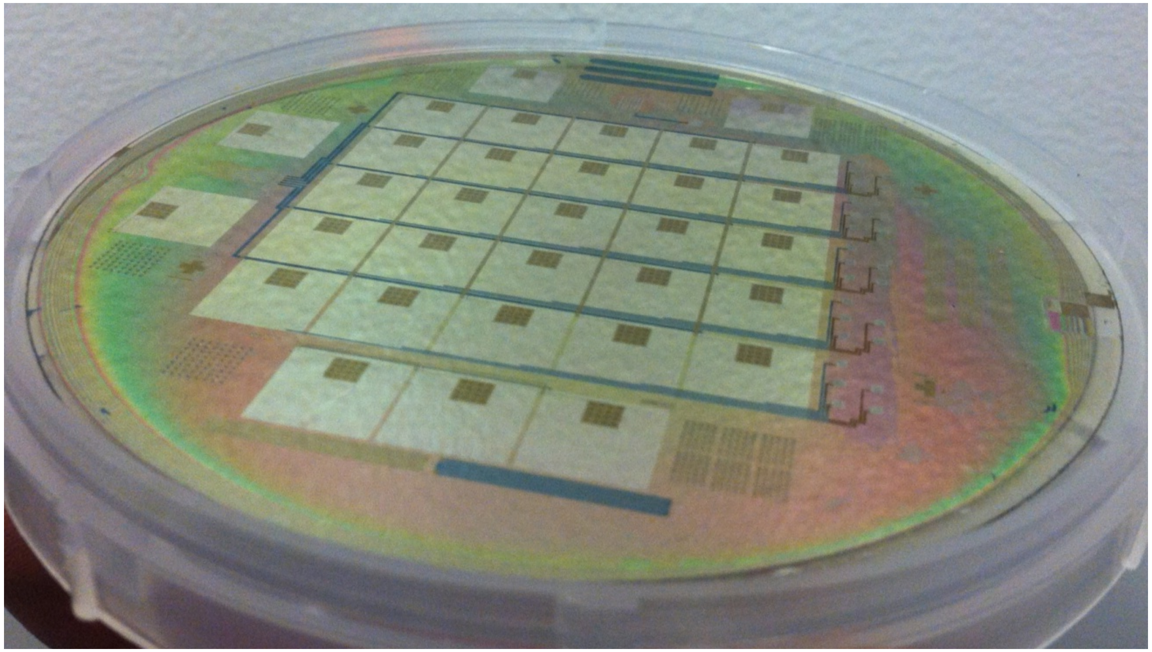
In some of the first wafers, the final lithography step for the TFTs resulted in some of the PZT pixels being lifted off as well

- This was ultimately solved by depositing the bottom electrode at a higher temperature (150 °C compared to room temperature) to increase adhesion

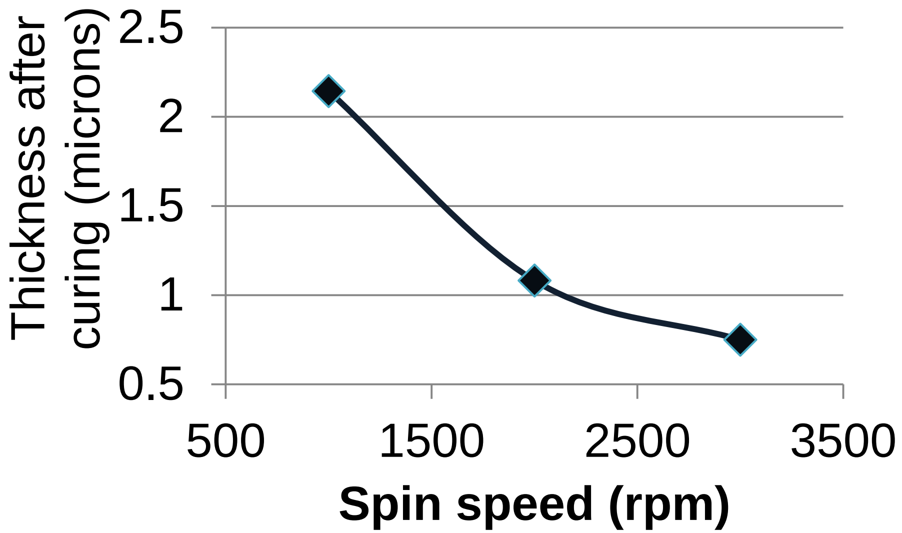
First Generation



Second Generation



Processing Developments



BCB (dielectric layer) processing optimized

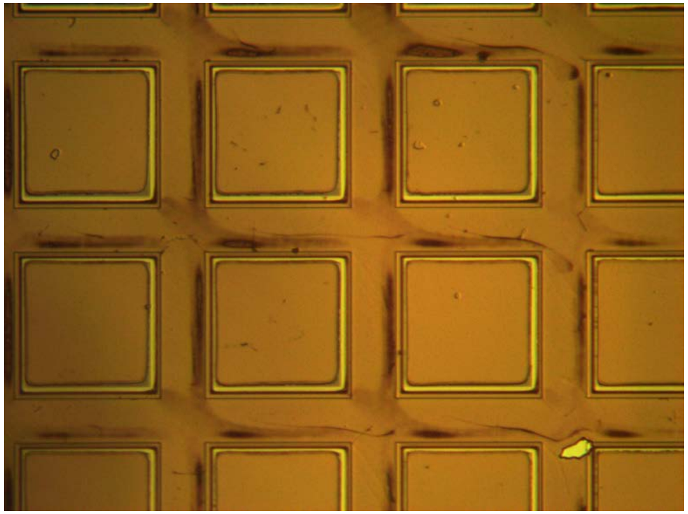
-Conditions for curing have previously be determined

-Addition of extra BCB solvent (T1100) was added to dilute down to a 1 micron thickness

TFT deposition

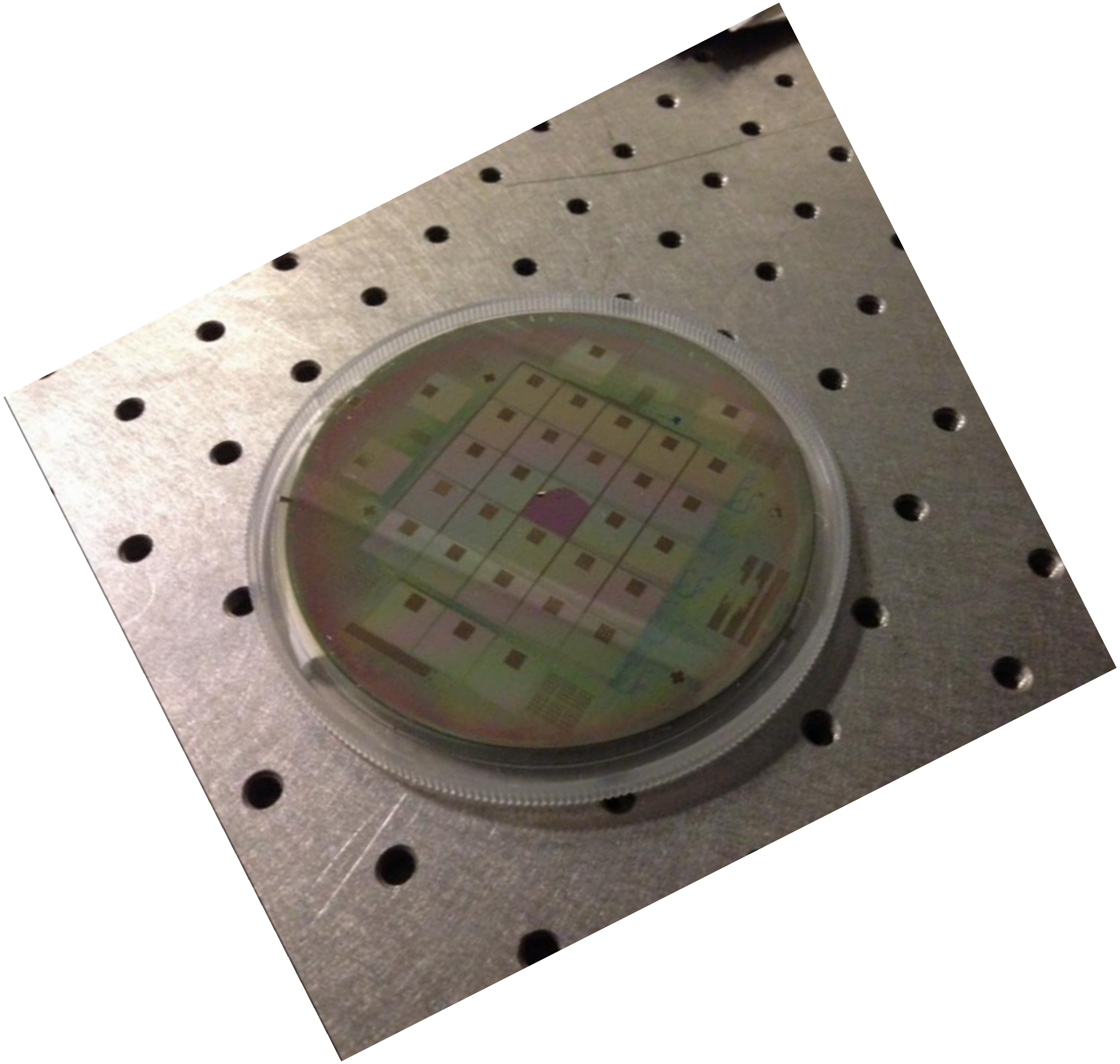
-Processing is complicated as a result of the easily etched ZnO layer

-Cr gate layer replaced with Ti as Cr on BCB was cracking due to stress

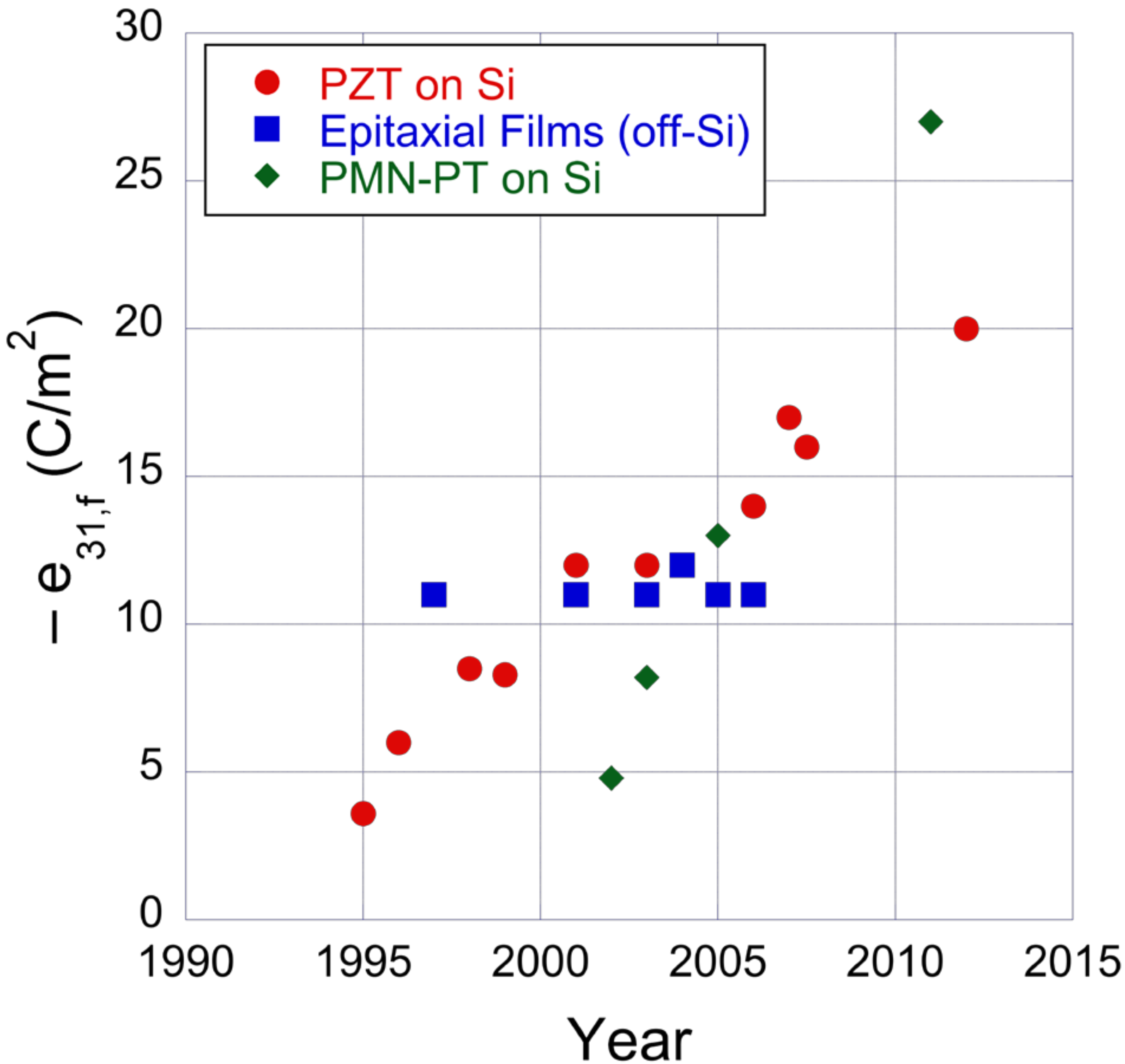


View of the BCB vias on the top electrodes demonstrating excess resist and nonuniform Ti coating on thick (>4 μm) BCB

First Fabricated Flat Mirror



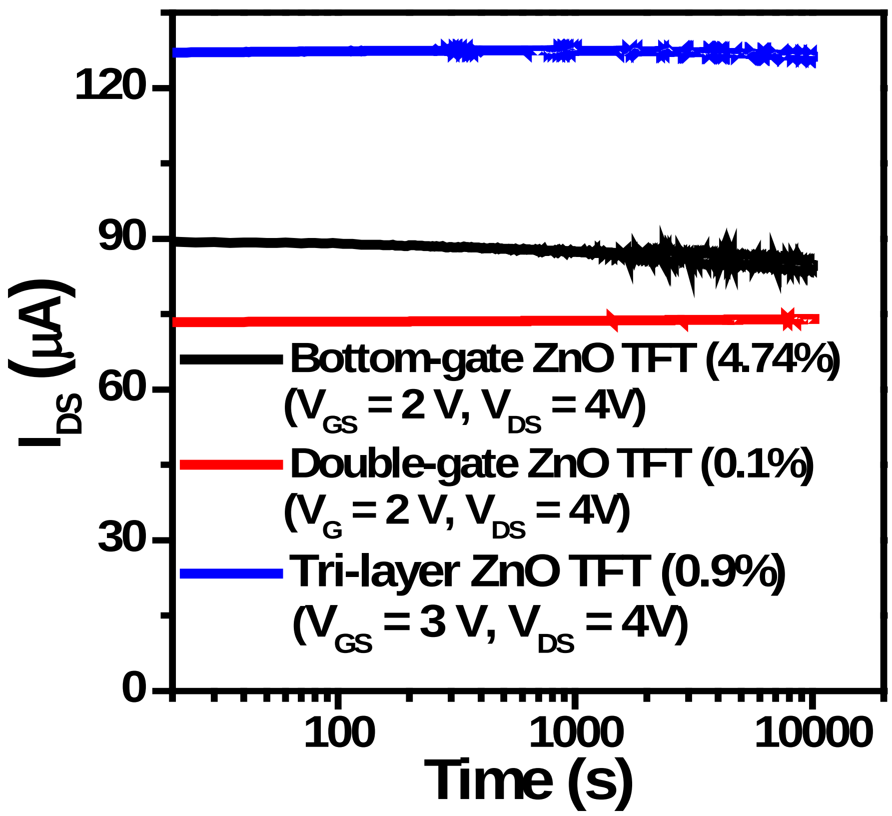
PZT Film Piezoelectric Response

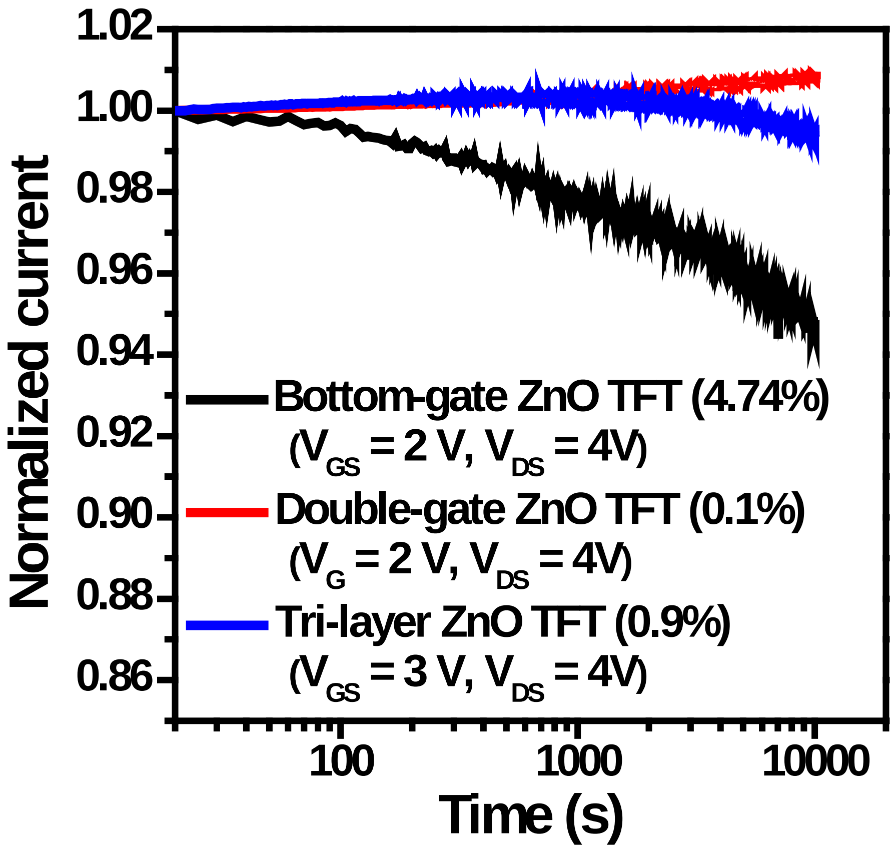


- Optimized response achieved in gradient-free, oriented PZT and PMN-PT
- Properties of epitaxial films on Si are excellent, providing large P_r is achieved

Adapted from P. Muralt

PEALD ZnO TFTs Stability





ZnO PEALD TFTs have better stability than many other oxide semiconductors, a-Si:H, and organic TFTs

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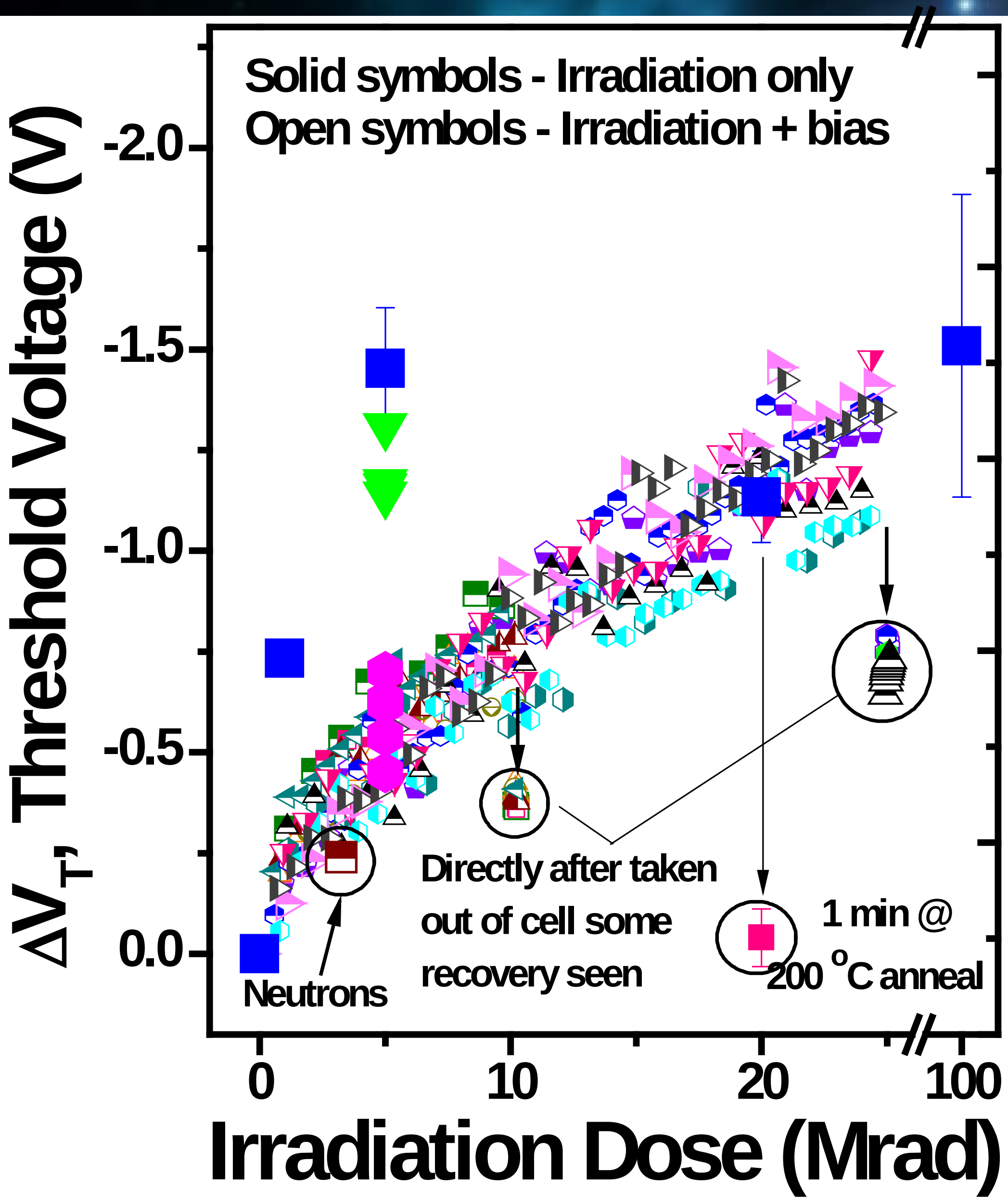
High Radiation Tolerance of ZnO TFTs



- Van Allen belt contains high fluxes of electrons (0-10 MeV) and protons (>10 MeV)
- ZnO electronics can function without a problem, for the adjustable optics system, for cumulative doses over 100 Mrad

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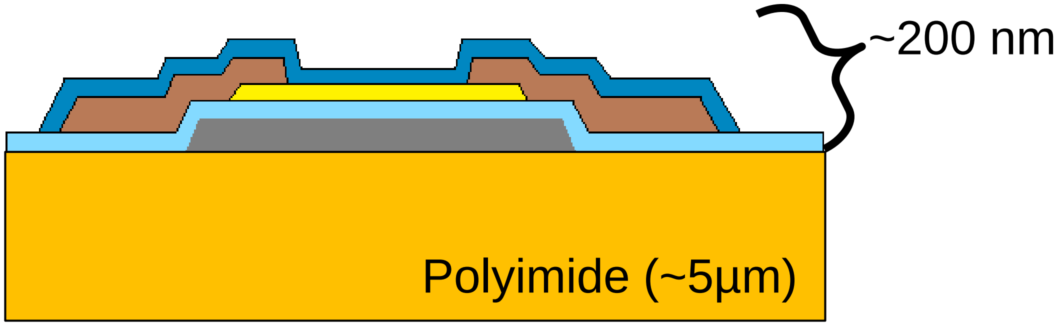
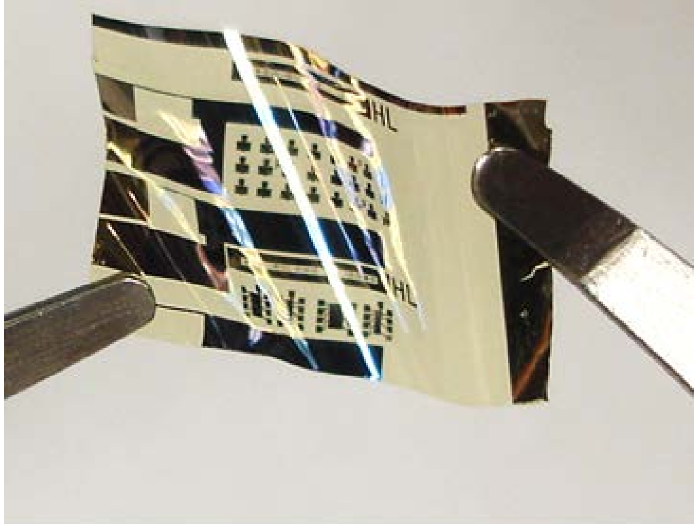
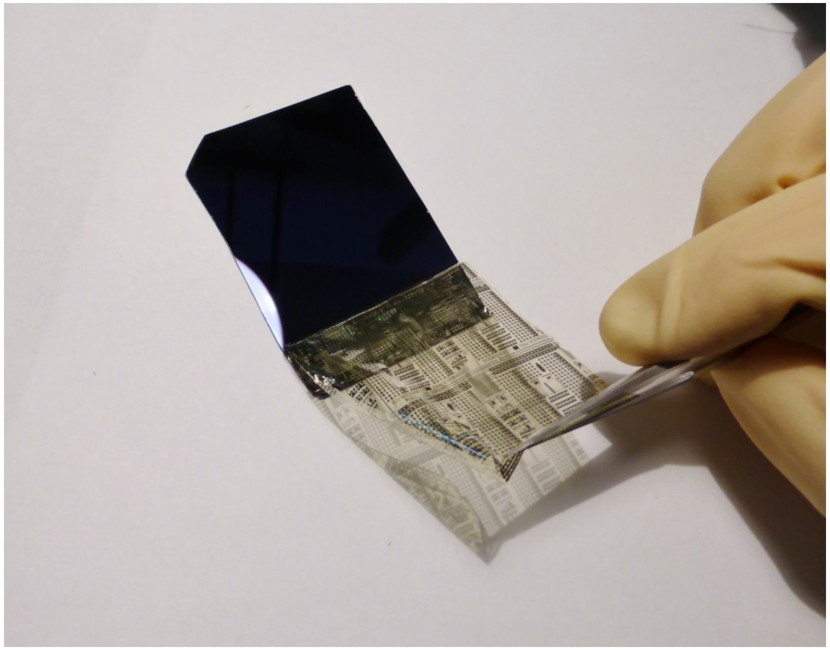
ZnO TFTs on Thin Flexible Substrates

Device fabrication on flexible substrate similar to fabrication on rigid substrate





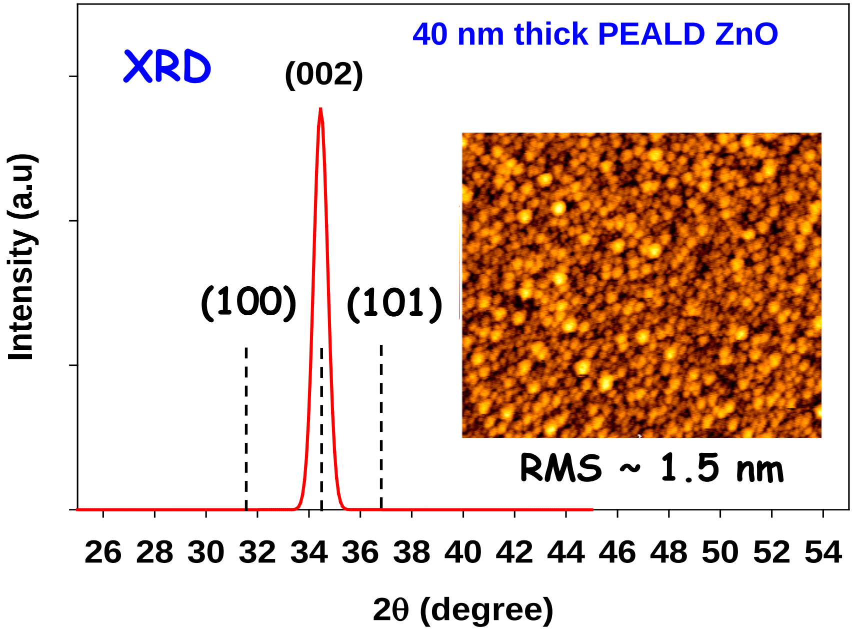
ZnO transistors on 5µm thick polyimide

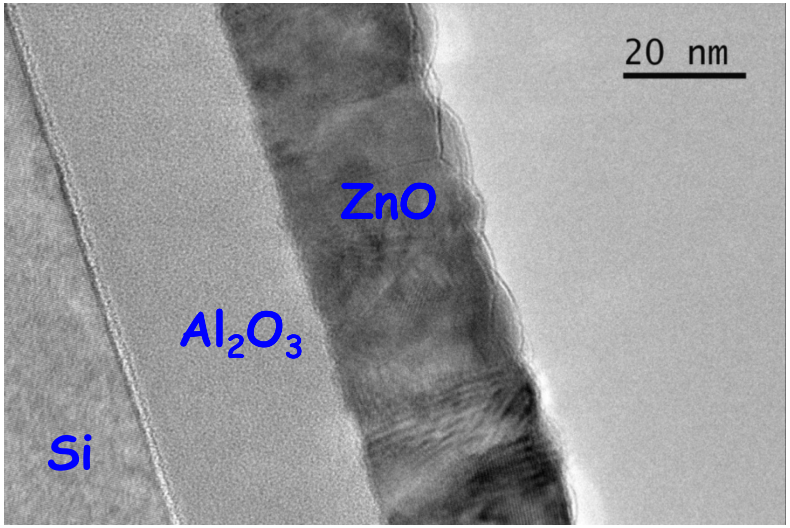


After devices completed, flexible substrate is detached by mechanical stripping

PEALD ZnO Thin Films

Highly crystalline undoped ZnO films from PEALD





Hexagonal wurtzite crystal structure

- 200 °C PEALD ZnO films show only (002) peak; ALD films at 200 °C show (100), (002), (101)
- ZnO thin film grain size estimated ~10 – 20 nm by TEM/SEM/XRD
- Even very thin films (<30 nm) show strong (002) diffraction
- Columnar grain structure
- Amorphous Al_2O_3 with smooth Al_2O_3/ZnO interface
- High resistivity ZnO films (important for enhancement mode devices), ALD ZnO film conductive

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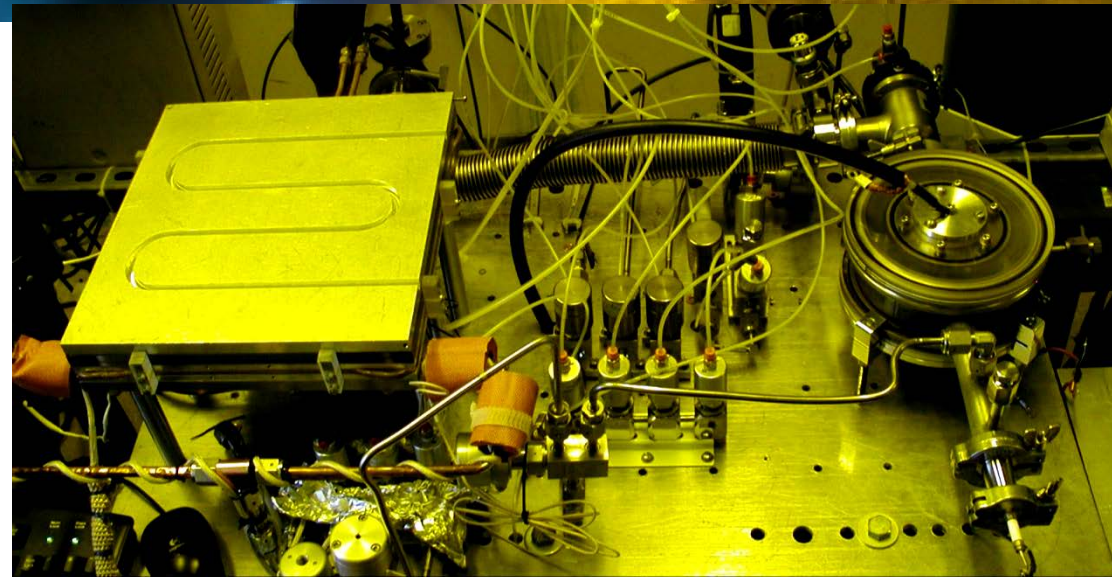
PEALD Deposition Systems

Simple system

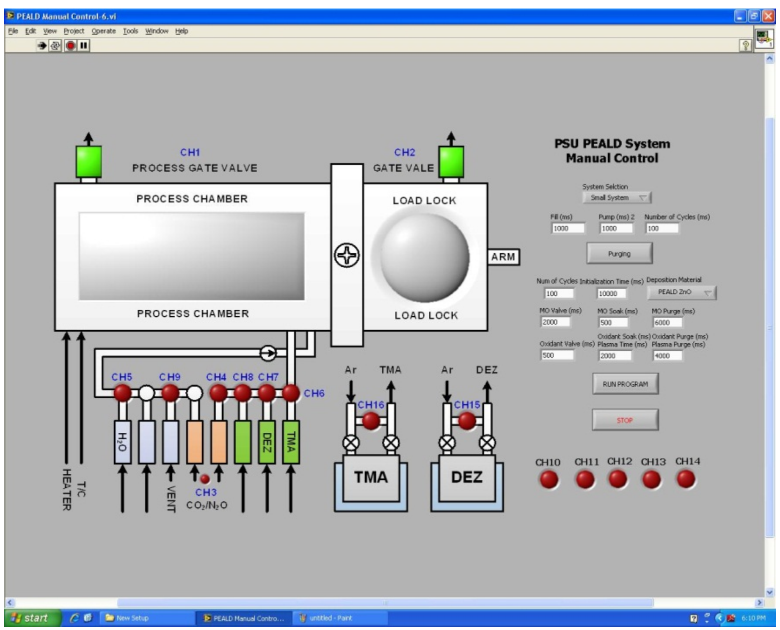
Easy to build

LabView control
300 °C max, 200 °C typ.
Low power RF (< 100W)
Sources:
- **diethyl zinc (DEZ/DMZ)**
- **trimethylaluminum (TMA)**
- **N_2O, CO_2, Ar, ozone**
- **water (for ALD)**

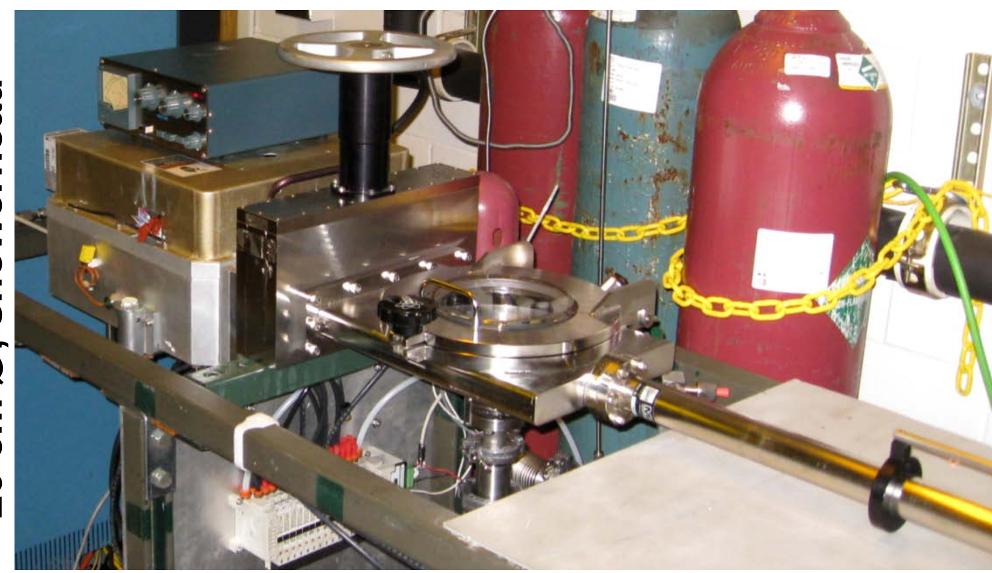


Larger system
20×20 cm, ~laminar

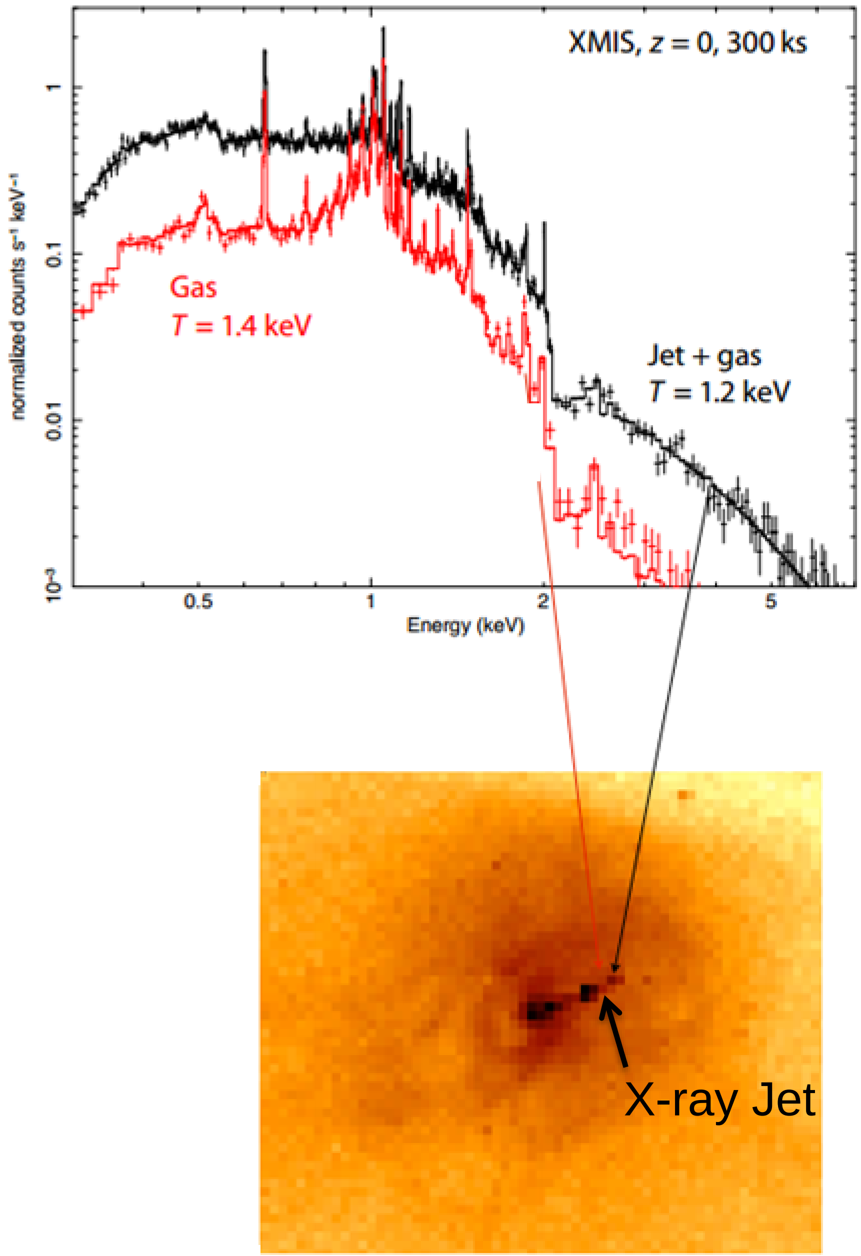
Small system
10 cm ∅, non-laminar



Load-locked system
20 cm ∅, showerhead



Galaxy Cluster Evolution with SMART-X



M87, *Chandra*, 1″ pixels

- Example of SMART-X science: galaxy cluster evolution
- Multimillion-degree gas with fine spatial structure requires subarcsecond X-ray imaging
- Complex spectrum requires high-resolution spectroscopy

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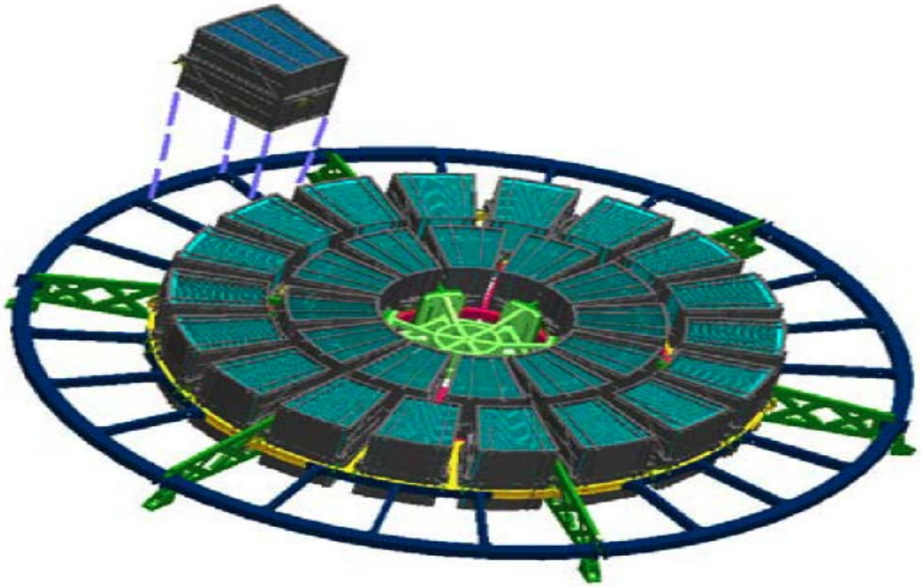
X-Ray Telescope Cylindrical Surfaces

- Telescope consists of nested hyperboloids
- Individual control of pixelated array allows for control of mirror shape
- Up to 10,000 m^2 of PZT actuators for 0.5 arcsecond resolution

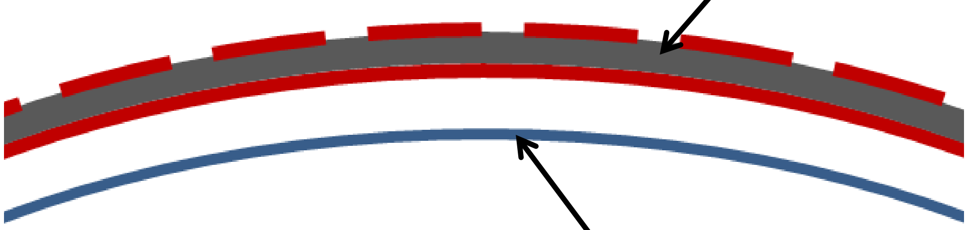


<u>Cylindrical optical requirements:</u>

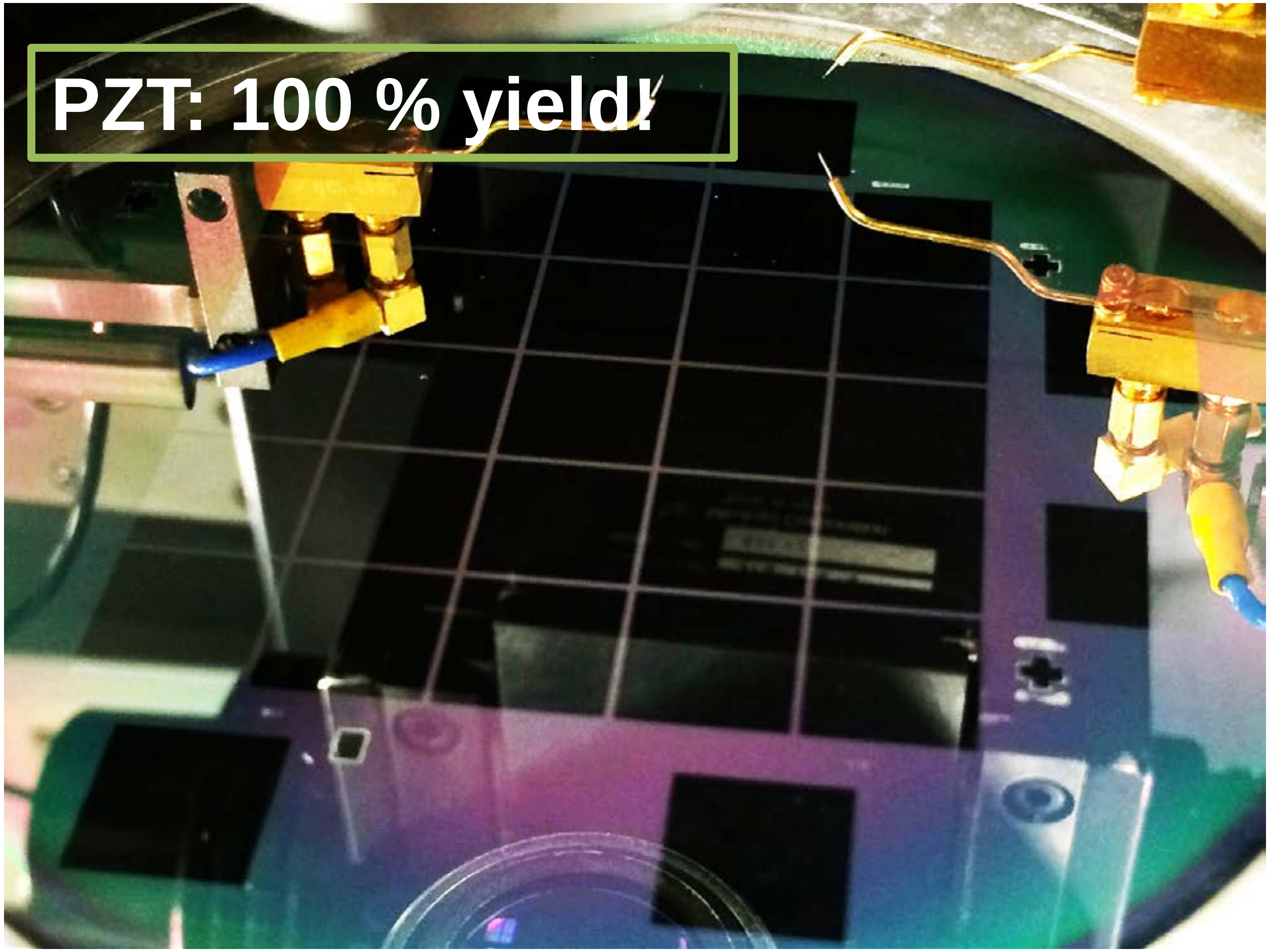
200 mm long

150-350 mm wide

150 mm – 1.5 m radius of curvature



High Yield PZT Cells on 5 x 5 Array



<u>On the 5x5 array</u>

Capacitance: 857 ±

10 nF

Dielectric loss:
0.028 ± 0.002

- Relative permittivity ~ 1450

(PZT films are typically 1000-1500)

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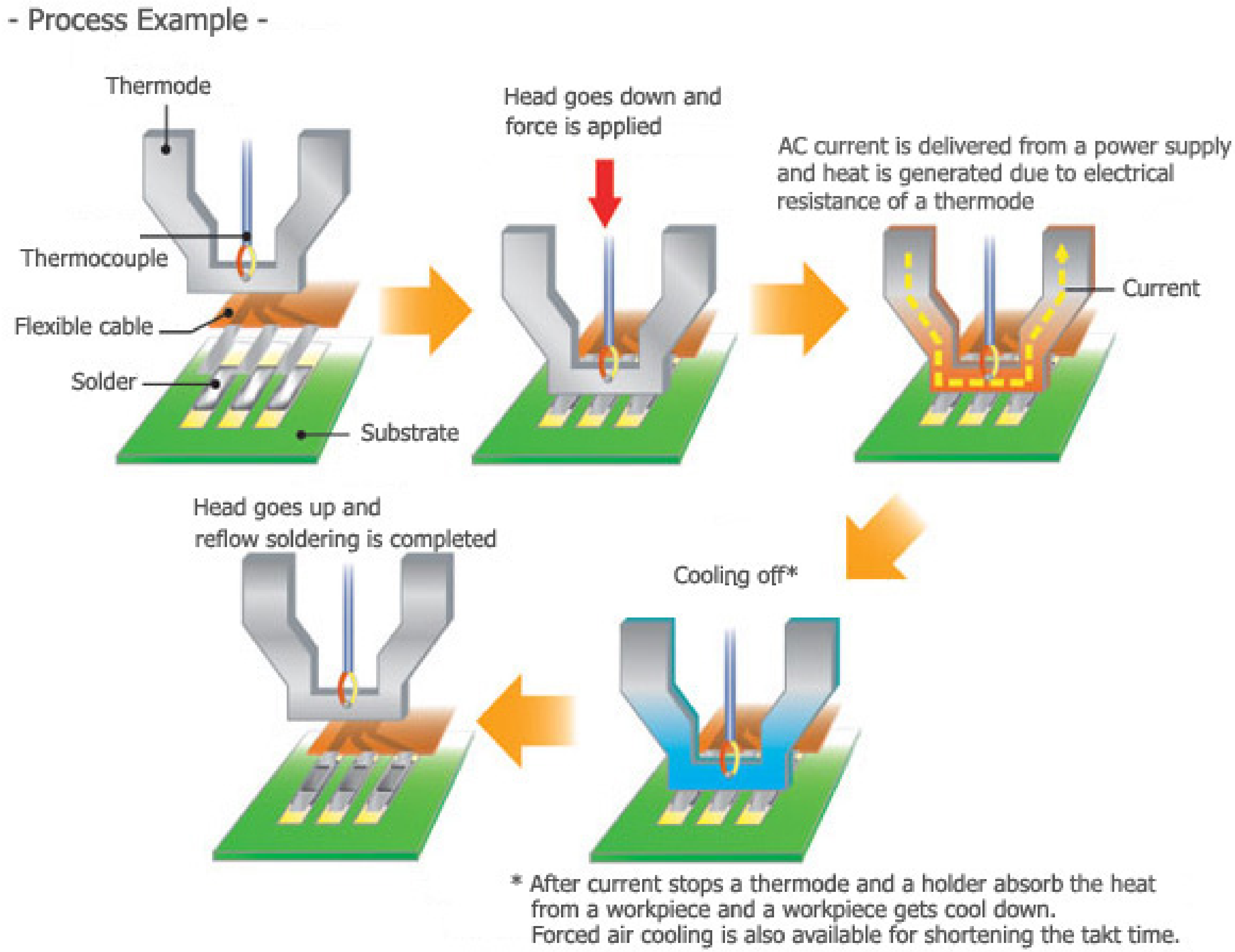
Anisotropic Conductive Film Bonding (ACF)



*Amada Miyachi MR-130A (http://miyachiindia.com)