Thin-Film Semiconductor Technology Applied to Large Area Radiation Detectors

CIRMS Conference 2012
October 23, 2012

Bruce Gnade
UT Dallas
• **POST-DOCS/STAFF SCIENTISTS**
  – Dr. I. Mejia, Dr. Kurtis Cantley, Dr. M. Jia, Dr. I. Trachtenberg, Dr. A. Carrillo, Dr. N. Hernandez, Dr. J. Conde, Dr. Dick Chapman

• **GRADUATE STUDENTS/PROJECTS**
  – Ana Salas—PhD. – Alternate Contacts (AFOSR)
  – Duo Mao – Ph.D. – Organic Memory (ARL)
  – Mike Perez, Ph.D. – n-type flexible TFTs (NSF)
  – John Murphy Ph.D – Large Area Neutron Detectors (ARL, FUSION)
  – Martha Rivas – Pulsed Laser Deposition of Chalcogenides
  – Dewan Lutful Kabir – Reliability and Electrical Characterization
  – Lindsey Smith – Neutron converter layers (DNDO)
  – Kevin Larosa – Backplane electronics (DNDO)

• **VISITING SCHOLARS**
  – J. Ramos (UACJ), V. Martinez, (CIMAV), G. Gutierrez (CIMAV), Alfredo Luque (CNyN)

• **Collaborators**
  – Dr. David Allee (ASU), Dr. Eric Forsythe (ARL), George Kunnen (ASU)

• **FUNDING**
  – U.S. Army Research Labs, Military Tech, DOE, UT Dallas, Texas MicroPower, NSF, Texas instruments, FUSION, DNDO, AFOSR, DARPA
Agenda

• Large Area Radiation Detectors
  – Why thin-film devices
  – Large area neutron detector project
• Current state of thin-film semiconductor devices
  – Transistors
  – Memory
  – CMOS
  – Circuits
Why large area detectors?

Probability of neutron hitting 2" tube ~ 1 part in 36000
Probability of neutron hitting large area detector ~ 1 part in 3
# of TFTs per min | Area per min | Yield zero redundancies | Display \~cost/cm² | Si-CMOS ($5k/wafer) | Digital X-ray 1-up/subs | Digital x-ray 4-up/subs
---|---|---|---|---|---|---
\~10⁸/min | 4m²/min | 99.99997% | $0.05/cm² | $6.86/cm² | $29/cm² | $7/cm²

Throughput vs. Feature Size for Typical Production Processes


Future Flexible Electronics
Throughput vs cost/cm²

Thanks to Dr. Eric Forsythe – Army Research Laboratory
Large Area Sensor Arrays: The Concept with ASU

- **Neutron Detection**
- VIS / IR Imager
- Millimeter Wave
- MEMs
  - Blast
  - Acoustic
- Electronic Textiles
Three main pieces
- energy conversion layer
- sensing diode
- backplane electronics
Neutron conversion layer strategies

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Reaction</th>
<th>Thermal $\sigma$</th>
<th>Charged particles and energies (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3$He</td>
<td>$^3$He(n,p)$^3$H</td>
<td>5333</td>
<td>p: 573, 3H: 191</td>
</tr>
<tr>
<td>$^6$Li</td>
<td>$^6$Li(n,α)$^3$H</td>
<td>940</td>
<td>3H: 2727, α: 2055</td>
</tr>
<tr>
<td>$^{10}$B</td>
<td>$^{10}$B(n,α)$^7$Li</td>
<td>3835</td>
<td>α: 1472, 7Li: 480</td>
</tr>
<tr>
<td>natGd</td>
<td>natGd(n,γ)</td>
<td>49700</td>
<td>Conversion e-: 29-191</td>
</tr>
<tr>
<td>$^{157}$Gd</td>
<td>$^{157}$Gd(n,γ)</td>
<td>259000</td>
<td>Conversion e-: 29-182</td>
</tr>
<tr>
<td>$^{235}$U</td>
<td>$^{235}$U(n,f)</td>
<td>681</td>
<td>Various fission products</td>
</tr>
</tbody>
</table>

**Converter-on-diode**

- $^6$Li $^{10}$B nanoparticle composite
- Au (100nm)
- Sensing diode
- Al (100 nm)
- Flexible substrate (~1 mm)

**Converter-in-diode**

- $^6$Li nanoparticles $^{10}$B
- Au (100 nm)
- Sensing diode
- Al (100 nm)
- Flexible substrate (~1 mm)
Neutron Detector Modeling in MCNPX and MATLAB

Detector Layers simulated in MCNPX:

- Front end captures Neutron and emits charged alpha particle,
- Alpha detected with PIN diode and active pixel sensor circuit
- MCNPX used to model and optimize detector front-end layers
- Detector layers capable of being fabricated with FDC process

MATLAB model of arrayed pixel sensors with simulated alpha particle exposure (Red Boxes):

- Each cell represents an active pixel sensor
- Sensors modeled to reflect FDC process variations.
- CDS dramatically improves ability for detector to resolve alpha particle strikes
Thin-film diode optimization - MCNPX

TABLE II. Intrinsic gamma efficiencies for selected thicknesses and gamma energies. (LLD = 300keV and a 2.8 µm $^{10}$B conversion layer)

<table>
<thead>
<tr>
<th>Thickness ($\mu$m)</th>
<th>$\gamma$ Energy (keV)</th>
<th>Si</th>
<th>CdTe</th>
<th>GaAs</th>
<th>ZnO</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>511</td>
<td>0</td>
<td>9 x 10^{-14}</td>
<td>0</td>
<td>8 x 10^{-14}</td>
</tr>
<tr>
<td>10</td>
<td>511</td>
<td>0</td>
<td>6 x 10^{-13}</td>
<td>9 x 10^{-12}</td>
<td>1 x 10^{-12}</td>
</tr>
<tr>
<td>30</td>
<td>511</td>
<td>6 x 10^{-11}</td>
<td>6 x 10^{-7}</td>
<td>1 x 10^{-7}</td>
<td>3 x 10^{-7}</td>
</tr>
<tr>
<td>100</td>
<td>511</td>
<td>3 x 10^{-6}</td>
<td>4 x 10^{-4}</td>
<td>2 x 10^{-4}</td>
<td>2 x 10^{-4}</td>
</tr>
<tr>
<td>300</td>
<td>511</td>
<td>3 x 10^{-4}</td>
<td>4 x 10^{-3}</td>
<td>2 x 10^{-3}</td>
<td>2 x 10^{-3}</td>
</tr>
</tbody>
</table>
Sensing Diode Optimization: Schottky vs. MIS

Integrating over channels for peak

<table>
<thead>
<tr>
<th>Detector bias (V)</th>
<th>0V</th>
<th>5V</th>
<th>20V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles detected</td>
<td>562</td>
<td>595</td>
<td>651</td>
</tr>
<tr>
<td>Measured source strength</td>
<td>1,938</td>
<td>1,954</td>
<td>2,245</td>
</tr>
<tr>
<td>Efficiency</td>
<td>60%</td>
<td>60%</td>
<td>69%</td>
</tr>
</tbody>
</table>

Integrating over channels 100-450

<table>
<thead>
<tr>
<th>Detector bias (V)</th>
<th>0V</th>
<th>5V</th>
<th>20V</th>
<th>100V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles detected</td>
<td>785</td>
<td>772</td>
<td>752</td>
<td>869</td>
</tr>
<tr>
<td>Measured source strength</td>
<td>2,486</td>
<td>2,445</td>
<td>2,382</td>
<td>2,752</td>
</tr>
<tr>
<td>Efficiency</td>
<td>77%</td>
<td>76%</td>
<td>74%</td>
<td>85%</td>
</tr>
</tbody>
</table>
Radiation measurement setup

- Preamp
- Oscilloscope
- Amp and det bias
- MCA
- Sample chamber
The detection of two alpha particle strikes on a commercial diode and amplified with the two stage low noise thin film transistor amplifier.
Flexible CMOS

Why CMOS

- Dramatically reduced power consumption
- Analog circuitry possible
- Sensor applications

How to do F-CMOS

- Combine Processes
  - N-Type a-Si:H TFTs
  - N-Type inorganic TFTs
  - P-Type Organic TFTs
- Standard Cell Approach
Inverters

NAND Gates

NOR Gates

a-Si / pentacene CMOS Devices – with ASU
Inorganic semiconductors: $\mu \gg 100 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$

Amorphous silicon: $\mu \approx 0.01$ to $1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$

Organic semiconductors: $\mu \approx 6 \times 10^{-2}$ to $1 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$

Inorganic semiconductors: $\mu > 100 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$

### Technology Comparison

#### Chalcogenides

<table>
<thead>
<tr>
<th>Semiconductor</th>
<th>Mobility (cm²/V·s)</th>
<th>e⁻</th>
<th>h⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>CdS</td>
<td>250</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CdSe</td>
<td>650</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZnSe</td>
<td>600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SnSe₂</td>
<td>27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>InS</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SnS₂</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CuGaS₂</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CuInS₂</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZnTe</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PbS</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu₂S</td>
<td>10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Electron or Hole Concentration (cm⁻³)

- N-TYPE
- P-TYPE

Technology Comparison Chart
CBD CdS/ Evaporated Pentacene Inverters

- Optimized pentacene and CBD CdS deposition
- Inverters yield gains of about 80
Ferroelectric-based organic Memory (FeRAM) PVDF - TrFe

**MFM Capacitor – 1T-1C memory cell**
- relatively easy to fabricate
- destructive read
- complicated read / write circuitry
Fully integrated TFT used for 1T1C

1. CBD CdS as the semiconductor
2. ALD HfO₂ as the gate dielectric
3. Parylene as ILD
4. Low temperature process, maximum temperature is 100 °C
2T2C FRAM Characterization

64-bit FRAM layout
The output signal from the sensor element is a low voltage pulse with 10’s ns width, with very high impedance due to the capacitive nature of the device.

Charge amplifiers provide very high input impedance - they integrate weak charge pulses to convert them into voltage pulses with low impedance.

Potential Advantages

- Very large aperture at moderate cost based on AMLCD
- In-pixel electronics provide low capacitance for pixelated array
- Potential for high γ-ray rejection rate due to TFT array electronics
- Potential for fission neutron multiplicity measurements
- Potential for determination of directionality of the neutron source
Thank You!