NCCAVS Talk

Material Innovation for Non-Volatile Memory Selectors

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Outline

• IMI: Technical Value Proposition
• NVM Selector Key Performance Indicators
• IMI selector screening methodology
• Case study
• Summary
IMI: Technical Value Proposition
Growing Complexity & Cost of Material Development

- Advanced materials are key to Semiconductor roadmap and leadership
- Critical attributes for material discovery process
  - Enables fast screening
  - Handles complex and toxic material system
  - Minimizes fab exposure to contamination

**Process Technology Development Costs By Node**

- Advanced materials are key to Semiconductor roadmap and leadership.
- Critical attributes for material discovery process:
  - Enables fast screening.
  - Handles complex and toxic material system.
  - Minimizes fab exposure to contamination.

Source: Common Platform & All Partners Analysis

Source: Intel
IMI Offers Unique Development Platform

High Throughput Experimentation accelerates and de-risks materials innovation

Accelerated Experimentation

IMI Processing Systems
- Wet: Clean, Etch, Deposition
- Dry: (PE)ALD, (PE)CVD, PVD

Analytics Excellence

Metrology
- XRF, XRR, XRD
- Ellipsometry, UV-Vis, FTIR
- Optical microscopy
- SEM, AFM, contact angle,
- Particles (SP1)
- TEM, XPS, Auger, SIMS, TXRF, ICPMS (External Vendors)

Electrical Characterizations

Electrical Characterization & E-test
- Fully automated probers with heated and/or cooled chucks
- Device: C-V, I-V & parameter extraction (EOT, EWF)
- Parametric: Leakage, line resistance, contact resistance, capacitance
- Reliability: V_{bd}, TDDB
- Pulsed switching: I_{on}, I_{off}, retention (eg. Non-volatile memory)

DC-V Bip

Voltage

Current Density

Deep Material and Device Innovation

Application knowledge + Understanding of integration issues
Extensive Materials Capability

Deposition and characterization of multinary materials:

- Metal Oxides
- Metal Nitrides
- Metals
- Alloys
- Chalcogenides

PVD Physical Vapor Deposition
ALD Atomic Layer Deposition
Screening of Non-Volatile Memory Selectors
Non-volatile Memory Selector
- Key Performance Indicators

New Selector required to eliminate sneak current for cross-point memory

“Sneak path” solved with selector device

Selector: Key Parameters

- No forming
- Threshold Voltage ($V_{th}$)
- On current ($I_{on}$) and density ($J_{on}$)
- Off current ($I_{off}$) and density ($J_{off}$)
- Selectivity (On/Off ratio)
- Thermal stability
- Switching speed
- Endurance (AC, DC)

• Selector devices are critical to eliminating sneak current paths
• Disruptive selectors needed to address performance, density and reliability

* Ref: An Chen 2014 AVS TFUG Seminar
# New NVM Selector Device Comparison

<table>
<thead>
<tr>
<th>Choice of selector determined by trade-off between performance, reliability and ease of integration</th>
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</table>

<table>
<thead>
<tr>
<th>Feature</th>
<th>Selector Req’s</th>
<th>MSM</th>
<th>Oxide-PN</th>
<th>MIEC</th>
<th>Metal-Oxide Schottky</th>
<th>MIIM Bi-directional Varistor</th>
<th>Chal OTS</th>
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</thead>
<tbody>
<tr>
<td>Max Forward Current Density/F</td>
<td>$10^{6-7}$ A/cm²</td>
<td>$10^{6-7}$ A/cm²</td>
<td>$5 \times 10^4$ A/cm²@2V 0.5x 0.5um</td>
<td>$10^{5-6}$ A/cm²@1V ~80nm bot</td>
<td>$3 \times 10^5$ A/cm²@2V 2x2um</td>
<td>$3 \times 10^7$ A/cm²@2.5V 250nm hole</td>
<td>Feasibility shown for 90nm PCM</td>
</tr>
<tr>
<td>Feature Size</td>
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<tr>
<td>$J_{FE}/J_{RB}$ Ratio &amp;</td>
<td>$&gt; 10^5$</td>
<td>$&gt; 10^3$</td>
<td>~ 10³</td>
<td>$&gt; 10^4$</td>
<td>2.4$ \times 10^6$ $\sim 10^3$</td>
<td>$\sim 10^4$</td>
<td>Met PCM Req</td>
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<tr>
<td>$J_{\nu5}/J_{\nu5/2}$ Ratio</td>
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<tr>
<td>Directionality</td>
<td>Uni or Bipolar</td>
<td>Bipolar</td>
<td>Unipolar</td>
<td>Bipolar</td>
<td>Unipolar</td>
<td>Bipolar</td>
<td>Bipolar</td>
</tr>
<tr>
<td>Switching Time/Endurance</td>
<td>$&lt; 10ns$ / $&gt; 10^8$</td>
<td>$&lt; 10ns$ / $&gt; 10^7$</td>
<td>$10-100ns$ / ?</td>
<td>~ 1us / $&gt; 10^6$</td>
<td>$&lt; 1ns$ / ?</td>
<td>$&lt; 1ns$ / $&gt; 10^10$</td>
<td>Feasibility shown for 90nm PCM</td>
</tr>
<tr>
<td>Thermal Stability</td>
<td>$&lt; 400C$ / $&gt; 400C$</td>
<td>$&lt; 400C$ / $&gt; 400C$</td>
<td>$&lt; 400C$ / ?</td>
<td>200C / $&gt; 400C$</td>
<td>250C / ?</td>
<td>300C / ?</td>
<td>$&lt; 400C$ / Issue</td>
</tr>
<tr>
<td>Deposition Temp/</td>
<td>Fab Friendly</td>
<td>Semiconductors</td>
<td>CuO/IZO</td>
<td>NiO/IZO</td>
<td>Cu in Solid Electrolyte</td>
<td>Pt/TiO₂ /TiO₂ /Pt</td>
<td>As, Ge, Si, S, Se, Te, N</td>
</tr>
<tr>
<td>Stacks Used</td>
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<tr>
<td>I - V Curves</td>
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High Throughput Experimentation Methodology

**Process**
- PVD Co-sputter

**Physical Characterization**
- Composition
- Crystallinity
- Resistivity
- Thermal Stability

**Test Vehicle**
- Dep & Test
  - Re-insertion (Dep & Send)

**Device Characterization**
- Device Types
- Leakage
- DC IV
- Pulse IV
- Endurance

Fast material screening for selector innovation:
- Metal Chalcogenide: 2500+ experiments
- MIEC: 2000+ experiments
- Transition Metal Oxide: 1000+ experiments
Process and Physical Characterizations

Site-isolated PVD Deposition

- Each spot is an experiment
- Each layer can be deposited by 1 to 5 sputter sources
- Multilayer stack capability
- Shutters for aperture and targets prevent cross-contamination

Physical Characterizations

- Thickness
- Composition
- Crystallinity
- Resistivity
- $n$ & $k$
- Thermal stability

Thermal Stability & Resistivity

Composition

Pre-filter non-viable compositions

Response Surface:
- $T_c$, Crystallization Temp

Pre-filter non-performing
Electrical Characterizations - Overview

Available E-Test Modules

<table>
<thead>
<tr>
<th>CATEGORY</th>
<th>NAME</th>
<th>DESCRIPTION</th>
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<tbody>
<tr>
<td>Imaging</td>
<td>Camera Box</td>
<td>Low magnification image</td>
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<tr>
<td></td>
<td>E-Vision</td>
<td>High magnification image</td>
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<tr>
<td>DC-V</td>
<td>DC-V Uni</td>
<td>Single voltage sweep w/wo return</td>
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<tr>
<td></td>
<td>DC-V Bip</td>
<td>Double voltage sweep w/wo return</td>
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<tr>
<td></td>
<td>V-Cyc</td>
<td>Endurance uni/bip w/wo return</td>
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<td></td>
<td>Leak</td>
<td>Leakage checks</td>
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<tr>
<td>DC-V</td>
<td>CVf</td>
<td>Capacitance vs. voltage and/or frequency</td>
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<td></td>
<td>V-t</td>
<td>Voltage stress vs. time</td>
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<td></td>
<td>V-arb</td>
<td>Arbitrary voltage sweep</td>
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<td>Rho</td>
<td>Sheet Resistance (w/wo T sweep)</td>
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<tr>
<td>DC-I</td>
<td>DC-I Uni</td>
<td>Single current sweep w/wo return</td>
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<td>Pulse</td>
<td>P-IV Uni</td>
<td>Single sweep w/wo return/op-amp</td>
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<td></td>
<td>P-IV Bip</td>
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<td></td>
<td>P-Cyc</td>
<td>Endurance w/wo return/op-amp</td>
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<tr>
<td></td>
<td>P-End</td>
<td>Burst/Endurance w/wo op-amp</td>
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<td></td>
<td>P-Verify</td>
<td>Program Verify</td>
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<td>Tran</td>
<td>Transient Waveforms</td>
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Selector Candidates Screening Stages

Increasingly advanced electrical characterization to realize promising selector candidates

- **DCIV**
  - Level 1 screening
  - All splits

- **Pulsed IV**
  - Level 2 screening
  - Selected splits

- **Endurance**
  - Level 3 screening
  - Champion splits
Summary

• New selector innovation needed to eliminate sneak current for cross-point memory architecture

• High-Throughput-Experimentation methodology accelerates and de-risk new selector material screening and device innovation

• IMI has successfully collaborated with customers to realize novel selector devices using HTE methodology

• Acknowledgments: J Watanabe and Customer+IMI collaboration teams