Versatile RRAM Technology and Applications

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Co-Founder and VP of Engineering, Crossbar Inc.
Agenda

- Overview of RRAM Technology

- RRAM for
  - Embedded Memory
  - Mass Storage Memory
  - Storage Class Memory
  - FPGA Configuration, NVRAM,
    State Retainer
  - Monolithic system integration
Crossbar’s RRAM Technology

• Simple device structure using fab friendly materials and process
• Information is stored in the form of metallic nano-filament in a non-conductive layer
• Filamentary-based switching by electric field
Crossbar Technology

**Crossbar RRAM Cell**

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Normalized Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>10^{-11}</td>
</tr>
<tr>
<td>-1</td>
<td>10^{-11}</td>
</tr>
<tr>
<td>0</td>
<td>10^{-10}</td>
</tr>
<tr>
<td>1</td>
<td>10^{-9}</td>
</tr>
<tr>
<td>2</td>
<td>10^{-8}</td>
</tr>
</tbody>
</table>

Suited for low latency, high speed embedded memory

**Crossbar Selector**

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Normalized Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>-1</td>
<td>10^{-7}</td>
</tr>
<tr>
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<td>10^{-8}</td>
</tr>
<tr>
<td>1</td>
<td>10^{-9}</td>
</tr>
<tr>
<td>2</td>
<td>10^{-10}</td>
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</tbody>
</table>

**Crossbar SR Cell**

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Normalized Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>10^{-5}</td>
</tr>
<tr>
<td>-1</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>0</td>
<td>10^{-7}</td>
</tr>
<tr>
<td>1</td>
<td>10^{-8}</td>
</tr>
<tr>
<td>2</td>
<td>10^{-9}</td>
</tr>
</tbody>
</table>

Suited for high density high performance NAND or SCM memory
Scaling Improves Crossbar RRAM

- Scaling RRAM device
  - $R_{off}$ increases by $\frac{1}{\text{Cell Area}}$
  - $R_{on}$ stays nearly constant
- $R_{off}/R_{on}$ ratio improves
- Sensing window improves
- Improves BER
- Provides additional margin for MLC/TLC

<table>
<thead>
<tr>
<th>Cell Size (nm)</th>
<th>Normalized Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-1}$</td>
<td>$10^1$</td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>$10^2$</td>
</tr>
<tr>
<td>$10^{-3}$</td>
<td>$10^3$</td>
</tr>
<tr>
<td>$10^{-4}$</td>
<td>$10^4$</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>$10^5$</td>
</tr>
</tbody>
</table>

$r = 10\text{nm}$
- $I_{off} = 62\text{nA}$
- $R_{off} = 16\text{M}\Omega$

$r = 20\text{nm}$
- $I_{off} = 1\text{uA}$
- $R_{off} = 1\text{M}\Omega$

$r = 40\text{nm}$
- $I_{off} = 0.25\text{uA}$
- $R_{off} = 4\text{M}\Omega$

$r = 100\text{nm}$
- $I_{off} = 62\text{nA}$
- $R_{off} = 16\text{M}\Omega$
Benefits of Crossbar Embedded RRAM

- **CMOS + RRAM**
  - No Change to Front-end

- **CMOS + e-Flash**
  - Major changes to Front-end
  - Complex cell
  - High voltage transistors
  - Adds 6+ Masks & 40 steps
Benefits of Crossbar Embedded RRAM

- Back-end process – minimum impact
- RRAM located between metal layers
- Adds only 2 masks & 8 steps
- 32% lower cost
- Smaller die size
Advantages of RRAM for Embedded Memory

- CMOS compatible material
- Back-end process - No change in front-end
- Reduced masking steps
- Byte/Page Alterability
- Write operation – no need for block erase

Scales with advanced nodes

Reduced Manufacturing Complexity

Cost

Performance
RRAM for Mass Storage

**Performance**
- Latency reduction
- Byte/Page alterability
- Smaller page sizes
- Write - no need for block erase

**Superior endurance & retention**

**Density and Scalability**
- 3D crosspoint array stackable at advanced nodes

**Utilizes standard CMOS process**
- Mass storage available to Fabless companies
NAND and NOR Flash Based System byte alteration within 100s of ms

NAND or NOR Flash device

NAND or NOR Flash Based System byte alteration within 100s of ms

DRAM device

1) Copy to DRAM

2) Block Erase (ms)

3) Byte Alteration

4) Program to Flash ~100 of ms

CROSSBAR RRAM

Byte Alteration (μs)

CROSSBAR RRAM

RRAM Based System byte alteration within μSeconds

RRAM Device
RRAM-Based Storage Card

Services
20X
More Transactions

Responds to
Transactions
30X Faster

Performance
Increases
Substantially

- Bit-Error Rate Requirement Decreases Dramatically
- Small Buffer due to Very Fast Program and Read time
- Small CPU due to Simplicity of Managing RRAMs

Nand Memories are Replaced with RRAM

Flash Memory Summit 2015
Santa Clara, CA
Crossbar Patented IP Libraries

FPGA Configuration Bit

- Instant On
- Eliminates external non-volatile memory

Combinational Logic (MUX, LUT etc.)

NVRAM

- Stores data at power down
- Recalls at power up
- Power saving

State Retainer
**Major Advantages:**

- NV Configuration bit
- Area reduction
- Performance improvement
- Power reduction
- Instant on
  - No need for external non-volatile memory
- Embedded non-volatile memory for data/code/storage
RRAM for Monolithic Integration

- Elimination of large number of I/Os, and simplification of the external interface
  - Reduction of components
  - Power reduction due to elimination of large number of I/O

- Breakthrough performance
  - Direct wide bus connection between memory and CPU/peripheral devices

Crossbar technology = True high performance integrated system
Monolithic Integration of NVMemory with Crossbar RRAM

Crossbar RRAM Technology Enables Monolithic integration of:

- Embedded memory with 1T1R
- SCM with 1T1R or 1TnR
- Mass storage with 1TnR
- FPGA configurable logic, CPU with 1T1R

Mass Storage Memory

Code/Config/ NVRAM Memory

Periphery

M1

M2

M3

M4
Crossbar Unique RRAM Versatile Technology

- Monolithic integration of Storage, Code, Data, FPGA configuration bit memories in one silicon
- Breakthrough system performance enabled with the monolithic integration of various memory architectures
- Fabless companies access IPs for a complete memory solution (storage, code, data, and FPGA configuration) from CMOS foundries
Ready for Business

Crossbar RRAM 300mm Wafer

Crossbar RRAM Die