Crossbar Resistive RAM (RRAM): The Future Technology for Data Storage

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Strategic Marketing & Business Development

www.crossbar-inc.com
From Data Storage Servers to Memory Chips

Server

Rack

Modules (SSD, DIMM)

Memory Part

~8 stacked memory chips per package

~16 memory packages per SSD

12~24 modules per rack units

>64,000 memory chips per server cabinet
Solid-State Storage Solutions for Enterprise

- NAND Flash based solid state storage solutions outperform hard disk drives
- Combined with state-of-the-art Flash controller, NAND Flash based storage provides acceptable data integrity and reliability
- Multi-Level Cell (MLC) NAND Flash at most advanced process nodes (<20nm) breaks the cost barrier and enables affordable total cost of ownership.

Today, NAND Flash is great! But…
NAND Flash is Reaching its Scaling Limits

**Lower Endurance:**
Decreasing number of read/write cycles before failure

**Lower Reliability:**
Increasing number of Bit Error Rate as technology scales

**Increasing Array Area Overhead:**
Increasing complexity of ECC algorithms

**Deteriorating Performance:**
Increasing latencies due to error correction and wear-leveling algorithms. Degradation of performance as NAND Flash ages
Pushing the limits further

- Rely on further innovations from Flash controller companies
  - Impact on latency, ECC area overhead, power

- Rely on 3D NAND Flash using less advanced process nodes (50/30nm)
  - Same scaling challenges will come back in 1~2 generations

- Rely on emerging memory technologies beyond Flash
  - This is the time to engage and develop next gen storage infrastructure
Crossbar’s RRAM-based Technology
RRAM Memory Cell

• Information is stored in the form of metallic nano-filament in a non-conductive layer
  - Filament-based switching by electric field

• Simple, 3 layer memory cell
  - Metallic top electrode
  - Resistive switching medium
  - Non-metallic bottom electrode

• CMOS compatible beyond 10nm
  - Fab friendly materials and process
  - Standard semiconductor manufacturing equipment
  - Back-End-Of-Line standard CMOS integration
  - RRAM layer(s) on top of CMOS logic wafers

Proven Patented Technology: 125 filed, 50 issued patents
Crossbar’s RRAM-based Technology
A Completely New Class of RRAM products

• **Crossbar super-dense** memory array
  - Crossbar array (4F² memory cell)
  - 3D stackable architecture
    - Multiple RRAM layers on top of CMOS logic wafers
  - MLC (Multi-Level Cell) memory cell

• **Crossbar super-scalable** memory array
  - ON/OFF ratio improves as device size decreases
  - Increasing memory effect (ON/OFF ratio) enables multiple scaling options
  - Keep operation voltage → increased memory effect (> 1E4)
  - Keep memory effect → reduced operation voltage (expect to reach ~1V) or faster switching
  - Combination of increased memory effect and reduced operation voltage
Long-term Scalability Path vs. Flash

- Information storage in Flash is based on charge density (C/cm²)
- At 20nm, ~100 electrons are stored in the FG (ΔVt = 1V)
- Losing a few electrons can cause severe reliability issues
- **Scaling causes exponentially increasing BER, reduced data retention and cycling**

- Information is stored in the form of metallic nano-filament in a non-conducting layer
- Below 10nm, on/off current ratio exceeds 10,000x
- Increasing on/off ratio enables reliable scaling path options: increasing memory effect with reduced operating voltage and faster switching
- **Scaling improves increased on/off ratio therefore improved reliability**
Crossbar RRAM Targeted Applications

**DENSE ARRAY**
- **CUSTOMER SPECIFIC DEV**
  - (28nm and below)
  - Wearable / Mobile Computing
  - Imaging / Video
  - 512MB - 2GB

**SMALL LATENCY ARRAY**
- **READY**
  - (110nm/55nm/40nm)
  - Smartcard / NFC
  - Internet of Things
  - 256KB - 8MB

**EMBEDDED**
- **UNDER DEVELOPMENT**
  - (28nm)
  - Social Web
  - SSD / Storage / Cold Archive in Consumer & Data Centers
  - 4GB - Terabit

**STAND-ALONE**
- **UNDER DEFINITION**
  - Industrial
  - Automotive
  - Consumer
  - Storage Class Memory
  - 16MB - 128MB
# Crossbar RRAM Proven Advantages vs. NAND Flash

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>NAND</th>
<th>Crossbar RRAM</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Cell Size (SLC)</td>
<td>5.44F²</td>
<td>4.28F²</td>
<td>RRAM provides better array efficiency and smaller die size</td>
</tr>
<tr>
<td>Technology Scalability</td>
<td>Severe limitations below 2xnmos</td>
<td>Scales &lt;10nm</td>
<td>Scales since it is filament based memory</td>
</tr>
<tr>
<td>Page Size</td>
<td>8~32KBytes</td>
<td>2KBytes</td>
<td>Smaller page sizes improves system performance</td>
</tr>
<tr>
<td>Read Latency</td>
<td>50~75us</td>
<td>20ns Embedded 5us Mass Storage</td>
<td>RRAM supports code execution</td>
</tr>
<tr>
<td>Page Program</td>
<td>2.2ms per 16KBytes</td>
<td>16us per 2KBytes 128us per 16KBytes</td>
<td>RRAM has faster performance</td>
</tr>
<tr>
<td>Erase Block</td>
<td>10ms</td>
<td>Not Applicable</td>
<td>RRAM Improves system performance</td>
</tr>
<tr>
<td>Byte Program</td>
<td>Not Available</td>
<td>Available</td>
<td>RRAM Improves system performance</td>
</tr>
<tr>
<td>RBER</td>
<td>1E-03 ~ 1E-02</td>
<td>&lt; 1E-06</td>
<td>RRAM scales without performance degradation</td>
</tr>
<tr>
<td>Data Retention</td>
<td>1 year</td>
<td>10 years</td>
<td>RRAM has significant advantages in retention</td>
</tr>
<tr>
<td>Endurance</td>
<td>&lt;3K ~ &lt;1K cycles</td>
<td>10K cycles</td>
<td>RRAM has significant advantages in endurance cycles</td>
</tr>
<tr>
<td>Process Complexity</td>
<td>Complex FEOL. Periphery High Voltage transistors do not scale</td>
<td>Simpler BEOL Compatible with CMOS tech scaling</td>
<td>RRAM is stacked on standard CMOS technology Easier to integrated and scale</td>
</tr>
</tbody>
</table>
# NAND Characteristics, Impact, Remedies and Trade Offs

<table>
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<tr>
<th>NAND Characteristics</th>
<th>Impact to Storage System</th>
<th>Improved by</th>
<th>Trade off</th>
</tr>
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<tbody>
<tr>
<td>Low Retention &amp; high BER</td>
<td>Reduces lifetime</td>
<td>ECC (BCH, LDPC)</td>
<td>Controller Overhead &amp; Cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Power consumption</td>
</tr>
<tr>
<td>Low P/E Cycles</td>
<td>Reduces lifetime</td>
<td>Wear Leveling</td>
<td>Performance &amp; Controller Overhead &amp; Cost</td>
</tr>
<tr>
<td>No ReWrite feature</td>
<td>Write amplification</td>
<td>Garbage Collection</td>
<td>Performance &amp; Controller Overhead &amp; Cost</td>
</tr>
<tr>
<td>No page alterable</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No Page erase</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slow page read</td>
<td>Random Read Performance &amp; Latency</td>
<td>None</td>
<td>Performance</td>
</tr>
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NAND vs. RRAM based Solid-State Drive

- Requires powerful controller to manage the shortcomings of NAND
  - ECC (due to high BER)
  - Garbage collection (NAND has no re-write feature)
  - Bad Block management (due to high BER)
  - Wear-leveling (due to low PE cycles)
  - P2L mapping

- Substantial reduction in controller complexity
  - Byte or small page alterability
  - Higher PE cycles
  - Reduced ECC overhead
  - Reduced DRAM usage

- Superior Performances
  - Smaller Read Latency
  - Faster Program time
  - Lower Power Consumption

- Extended lifetime
Crossbar RRAM for Data Storage

8 TBytes 2.5” SSD product concept

- 8 stacked dies of 512Gbit RRAM
- 16 Crossbar RRAM Package on a SSD
- Host Interface: standard vs. custom
Our Path to TeraBytes Data Storage

**TECHNOLOGY**

- **Scalability**
  - 8nm RRAM cell demonstrated

- **MLC**
  - 2bit-cell demonstrated on large On/Off Ratio

- **3D RRAM Layers**
  - Ease of manufacturability

- **Embedded NVM**
  - Enabling cost-efficient fast read array

**DESIGN**

- **1Mbit**
  - 110nm
  - TODAY

- **8Mbit**
  - 40nm

- **64Gbit**
  - 28nm
  - Under definition

- **512Gbit**
  - 28nm

- **TBytes**
  - 1xn
  - Under definition
From Crossbar RRAM Chips to Data Storage Servers

How will you leverage the superior characteristics of Crossbar RRAM to your specific needs?

- Higher Capacity (TeraByte on a chip)
- Scalable path (sub 10nm)
- Better Reliability
- Faster Read Latency
- Small Page granularity
- Fast Program Time
- Lower Power Consumption
- Extended Lifetime
About Crossbar

Innovators of New RRAM Technology Enabling New Classes of Enterprise, Consumer and Embedded Applications

Strong Memory Expertise

Over 30 employees with strong expertise in memory and product development

- Founded in 2010 and based in Santa Clara, CA
- Presence in US, China and Europe
- Backed by Artiman Ventures, Kleiner Perkins Caufield & Byers, Northern Light, SAIF partners, KIP and others.
- Series C funding complete: Over $50M raised to date
- Patented technology: 125 filed, 50 issued by Crossbar, Inc. + exclusive license to University of Michigan’s RRAM inventions

Non-Volatile 3D RRAM Technology

Breakthrough cost and performance
Differentiated, scalable, 3D, low-cost memory solution

- Fully CMOS compatible with standard manufacturing process
- Crossbar array enabling high-capacity data storage
- 20X faster read & write performance
- 20X lower power per bit
- Available in CMOS-based demo
- Ready for product commercialization and licensing
Additional Resources

10 Start-ups to Follow in 2014
Peter Clarke - 07 January 2014

The drive for SSDs: What’s holding back NAND flash?
Hagop Nazarian and Sylvain Dubois, Crossbar - November 26, 2013

RRAM – A New Approach To Embedded Memory
Sylvain Dubois, Crossbar - February 11, 2014

Top five solid-state flash storage news stories of 2013
Todd Erickson – December 9, 2013

Startup pits RRAM against DRAM and flash storage
Agam Shah – August 5, 2013

New Non-Volatile Memory for a New Era: Crossbar Announces their RRAMs
Bryon Moyer – September 5, 2013

RRAM – The End of NAND Flash
Babbzzz – August 18, 2013

RRAM Challenges Flash Storage
William Wong - September 17, 2013

Denser, Faster Memory Challenges Both DRAM and Flash
Tom Simonite – August 14, 2013

Overcoming Challenges in 3D Architecture Memory Production
April 9, 2014

Crossbar: Pioneering a New Type of Memory
April 8, 2014

Crossbar in CNBC’s Disruptive Technology Segment
Aug 13, 2013

Bay Area Company’s Chip Promises Big Leaps In Storage, Battery Life
Sept. 20, 2013

New Types of RAM could revolutionize your PC
January 5, 2014

Crossbar Technology – Real Time TEM Visualization of Filament Formation
August 5, 2013

CROSSBAR Resistive Memory: The Future Technology of NAND Flash