Who is Crossbar?
INNOVATORS OF NEW RRAM TECHNOLOGY

About Us

- Privately held, fabless semiconductor company founded in 2010
- Headquartered in Santa Clara, CA with presence in US, Asia and Europe
- Over 40 employees with strong expertise in memory design, manufacturing and system integration
- Raised 50M$ to date
- Partnership with large-scale manufacturing foundry
- Ready for technology licensing and product commercialization
- Backed by Artiman Ventures, Kleiner Perkins Caufield & Byers, Northern Light, SAIF partners, CBC-Capital, KIP, Tao Invest, University of Michigan

Non-Volatile 3D RRAM

- **100X** lower latency than Flash
- **20X** faster write, small pages & block erase free
- Up to a **1TB** on a single chip
- **20X** lower power per bit
- Simple implementation for a low cost manufacturing
- **Fully CMOS compatible** with standard manufacturing process
- **Highly-scalable** Resistive Random Access Memory (RRAM) technology
- **Patented**: 180 filed, 82 issued by Crossbar, Inc. + exclusive license to University of Michigan’s RRAM inventions
The Data Storage Opportunity

<table>
<thead>
<tr>
<th>2010</th>
<th>2015</th>
<th>2020</th>
</tr>
</thead>
<tbody>
<tr>
<td>People</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.8 Billion</td>
<td>7.2 Billion</td>
<td>7.6 Billion</td>
</tr>
<tr>
<td>Connected Devices</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.5 Billion</td>
<td>25 Billion</td>
<td>50 Billion</td>
</tr>
</tbody>
</table>

### Digital Universe

- 1.2 ZettaBytes (Billion TeraBytes)
- 8 ZettaBytes (Billion TeraBytes)
- 44 ZettaBytes (Billion TeraBytes)

### Physical Universe

#### People
- 6.8 Billion
- 7.2 Billion
- 7.6 Billion

#### Connected Devices
- 12.5 Billion
- 25 Billion
- 50 Billion

### Massive Data Storage, Servers and Connectivity

- Uploads on social media (mobile)
- Low latency data access
- Web and physical footprint history log
- Data mining for correlation and analytics
- Environmental and health monitoring (IoT & wearables)
- Enhanced decision making
- Create Value from Data

**Business, Government, Organizations and Individuals**

People and connected devices generating more data

Business and organizations extracting more value from data
Flash Technology is Running Out of Steam
3D NAND Replacing 2D by 2016, 3D NAND Facing Scalability Challenges

The current storage medium, planar NAND, is seeing challenges as it reaches the lower lithographies, pushing against physical and engineering limits.

"The investment in a 100k wpm 32 layer 3D NAND fab is 80-100% or more than a similar sized 16nm 2D NAND fab."

~ Michael Yang

3D Flash Manufacturing Challenges

~ Forward Insights
Crossbar’s RRAM Technology

Crossbar RRAM Cell

- 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

CMOS Integration

- Standard semiconductor manufacturing equipment
- Low temperature Back-End-Of-Line standard CMOS integration
- RRAM layer(s) on top of CMOS logic wafers. RRAM cell between two metal lines

Program

Reading a programmed cell

Erase

Reading an erased cell
Crossbar RRAM Scalable to Small Nodes

FLASH

Flash memory performance degrades in advanced tech nodes (sub 45nm)
A few electron loss causes a reliability issue
Retention and cycling become a challenge

Crossbar RRAM operation is based on the storage of a few metal atoms (atomic filament) compared to the electron storage in Flash

Crossbar RRAM

Crossbar RRAM scaling does not impact the device performance and has potential for sub-10nm scaling

Scaling ➔ less electrons ➔ performance degrades

Scaling ➔ same metallic filament ➔ same physics
No degradation & better performance
Promising Results on Sub-10nm RRAM Cells

Scaling the Crossbar RRAM cell actually increases memory effect (ON/OFF ratio)
- ON current is the current flowing thru the metallic filament \( \Rightarrow \) ON current stays similar
- OFF current is the leakage current of the cell, i.e. function of the area of the cell \( \Rightarrow \) OFF current drops

Crossbar Memory
Characteristics improve as the device size scales down

Increasing memory effect enables multiple scaling options
- More read margins \( \Rightarrow \) enabling MLC/TLC
- Keep operation voltage \( \Rightarrow \) increased memory effect (>1E4)
- Keep memory effect \( \Rightarrow \) reduced operation voltage (~1V) or faster switching
A completely New Class of RRAM products: 1T1R and 1TnR arrays

- Ultra-low Latency Memory
- Low Density
- Applications:
  - Code memory (Mbytes)

Flexibility to optimize density and performances

- Very High Storage Density
- High Performance
- Applications:
  - Storage Class memory (GBytes)
  - Mass-storage (TBytes)
A Completely New Class of RRAM Products  
Small Pages, Lock Erase-free Operation

NAND Flash Array

Page Program  
(8~16KBytes)

No possibility to update a page

Block Erase  
(4~8MBytes)

NAND Page Program is slow: 600~1350us
• Use DRAM as write buffer  
• Use portion of TLC NAND in SLC mode as write buffer  
⇒ Write buffer size limited in case of sequential writes (e.g. copy a movie in SSD)

NAND Block Erase is very slow: 10ms
• Use FTL techniques to delay issuing erase operations  
• Write updated data at different location and mark previous location as invalid  
• Issue block erase command when storage is idle  
⇒ When storage is filling up with data, erase become essential and might introduce large and unpredictable latencies

RRAM Array

Page Write  
(256 Bytes)

Every page can be updated

RRAM Page Write is fast: 1us per 256Bytes  
(10-20X faster)

Every page can be updated (no erase required)

Architected for Simplicity, Latencies and Power Efficiency
SSDs Accessible in 10s of Microseconds

<table>
<thead>
<tr>
<th>NAND-based SSD *</th>
<th>3D-NAND</th>
<th>TLC NAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>3ms (average)</td>
<td>17ms (max)</td>
<td>5ms (average)</td>
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<tr>
<td>1000ms (max)</td>
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<table>
<thead>
<tr>
<th>NAND</th>
<th>SLC</th>
<th>MLC</th>
<th>TLC</th>
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</thead>
<tbody>
<tr>
<td>25us</td>
<td>50us</td>
<td>75us</td>
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</table>

<table>
<thead>
<tr>
<th>RRAM (1TnR)</th>
<th>n=1</th>
<th>n=32~128</th>
<th>n=2000+</th>
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</thead>
<tbody>
<tr>
<td>25ns</td>
<td>200~300ns</td>
<td>2us</td>
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RRAM-based SSD

Enabling Extremely Faster SSDs

Crossbar

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A New Approach to Memory Class Storage

DENSITIES INCREASE

KBytes  MBytes  GBytes  TBytes

HDD  NAND SLC  NAND MLC/TLC  3D NAND MLC/TLC

NOR FLASH  1T1R RRAM  3D RRAM  3D RRAM MLC/TLC

Code Execution, Cache and Data Buffer

Hot & Cold Mass-storage Applications


Crossbar

Archive Storage Applications

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Crossbar’s Product Lines

**Embedded IP Licensing:** a low cost, low energy on-chip non-volatile memory solution to be integrated with micro-controllers, application-specific and more complex system-on-chips, at Back End Of Line of standard CMOS manufacturing process.

**Crossbar 3D RRAM:** a high-capacity, super-dense, low-latency, non-volatile 3D memory solution, fully CMOS compatible with standard manufacturing process and scalable with CMOS advanced process nodes, to be licensed as stand-alone storage products.
Crossbar RRAM Transforms the Future of Electronics

Crossbar RRAM BENEFITS

- **100X lower read latencies** vs NAND, **20X faster write** vs NAND, Small page, block erase-free storage architecture
  - RRAM-based SSD accessed in microseconds range vs milliseconds range for Flash-based SSD
  - Fast download, application launch or picture preview
    - 5G ready, 1Gbit/s direct download in NVM
    - 4K ready, 1.5 GB/s direct download in NVM
- **CMOS integration** of on-chip storage with logic
  - Simplification, low latency, lower energy
  - Logic + analog + RF + memory + storage on a single chip
- **Half the size of NAND**
  - Reducing rack space, increasing number of VMs per servers, more database transactions per sec
- **Reduced energy costs**
  - 20X lower power vs NAND
  - Drastic reduction of background memory accesses (erase-free, write amplification=1, simplified garbage collection
- **Data integrity** across **wide range of temperature** up to 125°C
  - Crossbar RRAM is based on electric phenomena. No effect on temperature
- **Reliability** coming from better margins (1000X on/off ratio)