Storage Systems
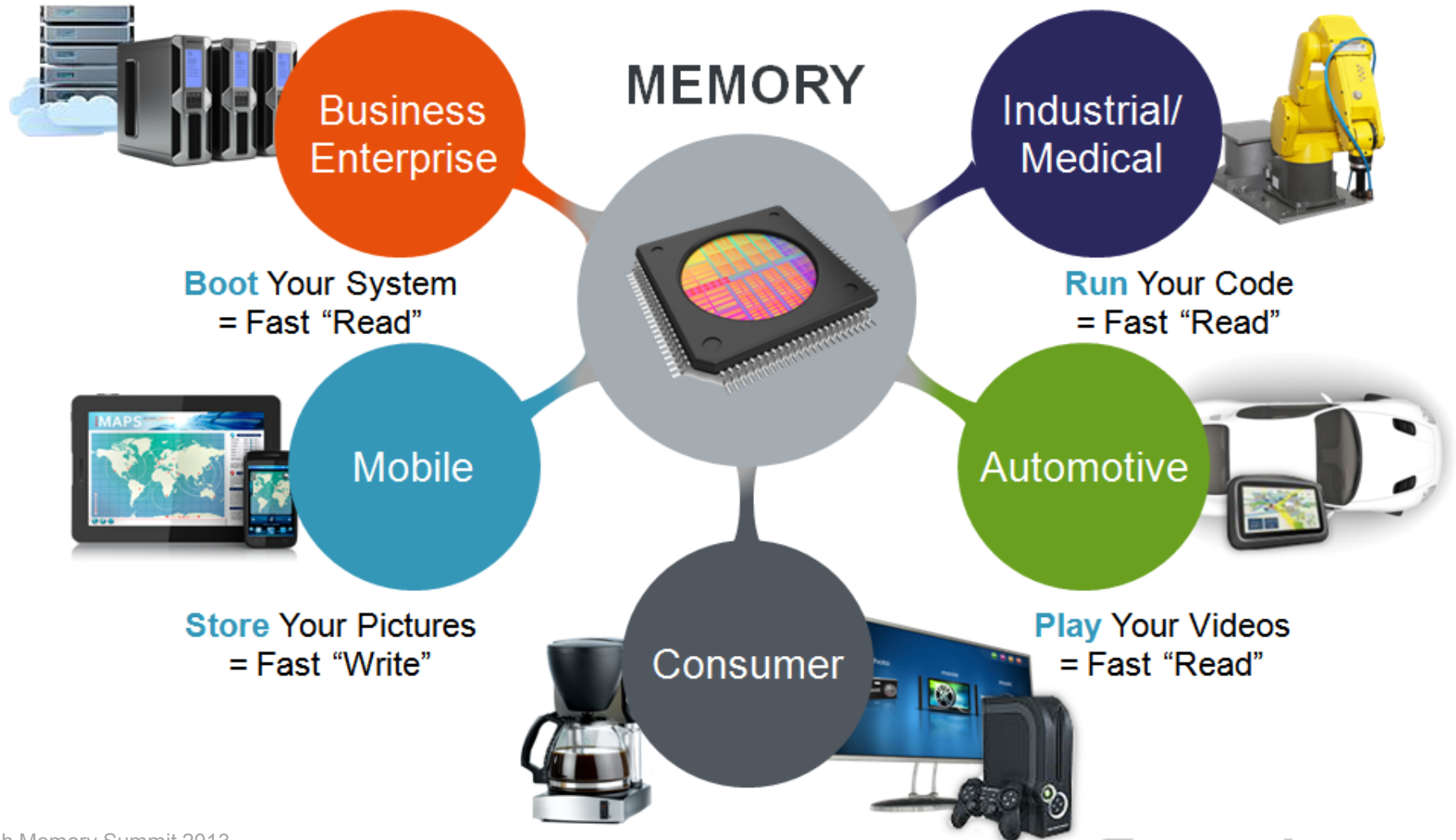# Incorporating RRAM Technology

Hagop Nazarian

Co-Founder VP Engineering, Crossbar Inc.

Agenda

- Memory Applications

- Present Technology Challenges

- NAND NOR RRAM Comparison

- NAND vs. RRAM SSD System Performance

- Crossbar Technology Overview

- Conclusion

Non-Volatile Memory is Everywhere

MEMORY

Business Enterprise

Boot Your System = Fast "Read"

Industrial/ Medical

Run Your Code = Fast "Read"

Mobile

Store Your Pictures = Fast "Write"

Automotive

Play Your Videos = Fast "Read"

Consumer
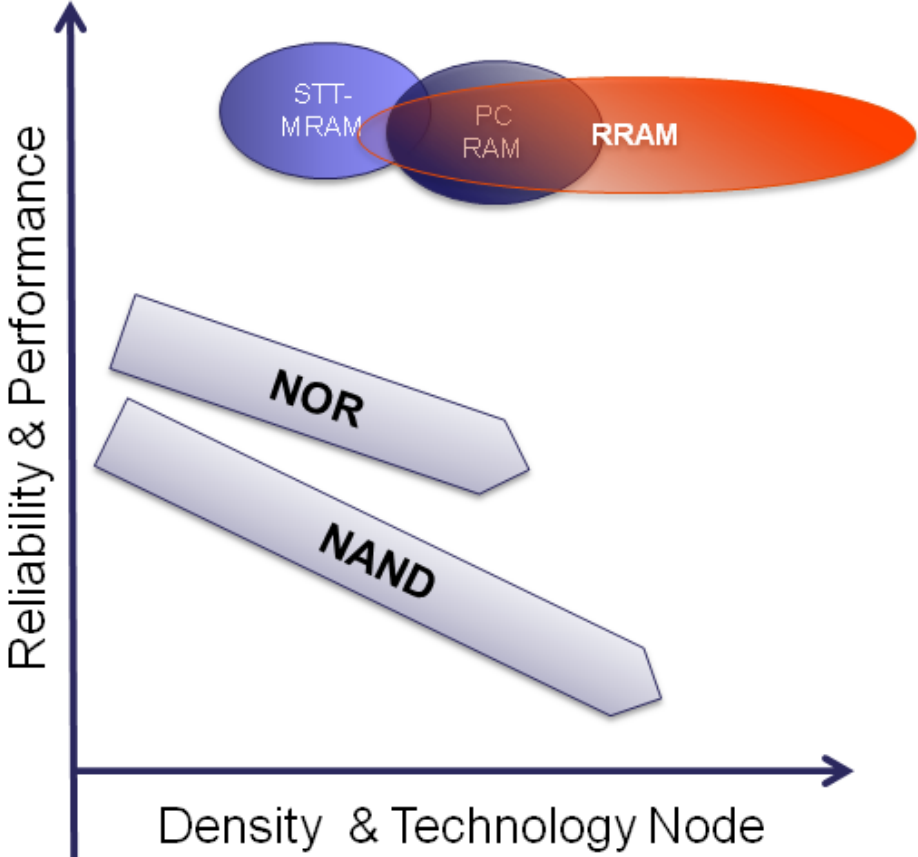
Present Challenges and Emerging Solutions

- **NAND - Scaling below 20nm challenges**
  - Reliability degradation – Bit Error Rate increase
  - Endurance decrease <50K SLC , <3K MLC
  - Floating Gate to Floating Gate Coupling
  - Program Disturb

- **NOR - Scaling below 45nm challenges**
  - Maintain low Bit Error rate
  - Maintain Endurance and Retention specs

Present Challenges and Emerging Solutions
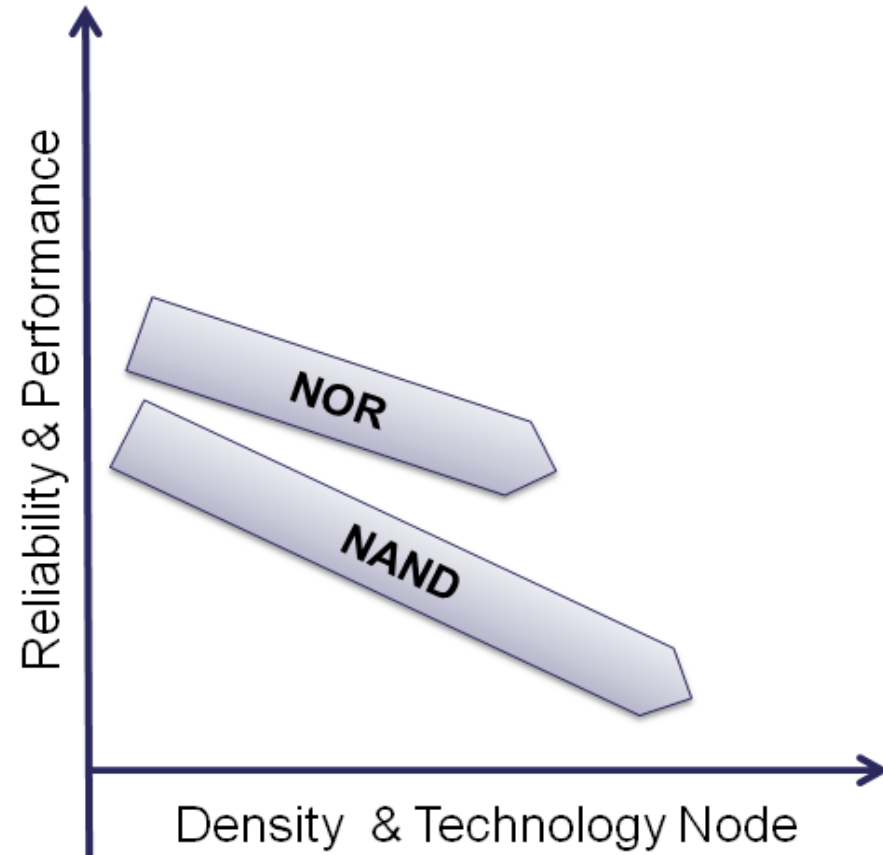
Solution

Memory with improved scalability & reliability at similar cost

- **Upgrade System Performance**
  - Reduce Latency
  - Lower Power Consumption
  - Exponentially Higher P/E Cycles

- **Cost – Same if Not Better**
  - Scalable Solution
 - Multi Level
  - Stackable

Reliability & Performance

STT-MRAM   PC RAM   **RRAM**

NOR

NAND

Density & Technology Node

Crossbar

Existing NV Memory Technology Comparison

Feature	NOR	NAND	RRAM
Non-Volatility	Yes	Yes	Yes
Random Read Time	90ns -100ns	50us	70ns - NOR **1us** - NAND
Byte Write **Page Write**	Only once Only once	Not possible Not possible	**Yes** **Yes**
Write/Program Time	700us/256B	>1000us /8KB (MLC)	64us/8KB 16us/2KB **2us/Byte**
Erase Time/Size	30ms/4KB	>2ms(Block)	Not required
Endurance	10^5	MLC 10^3	**10^8 - 10^{12}**
Cell Size **MLC/Stacking**	6-8F^2 MLC	SLC 5F^2 MLC	**SLC 4F^2** **Stacking, MLC**
Cost	Med	Low	Very Low

NAND Shortcomings in a SSD

NAND Characteristics	Implication	Remedy	Trade off
Low Retention & High BER	Reduce Lifetime	ECC & DSP	Controller Overhead and Cost, Power Consumption
Low P/E Cycles	Reduce Lifetime	Wear Leveling	Performance & Controller Overhead & Cost
No Re-Write Feature	Write Amplification	Garbage Collection	Performance & Controller Overhead & Cost
Slow Page Read	Random Read Performance & Latency	None	Performance

SSD System NAND-Based
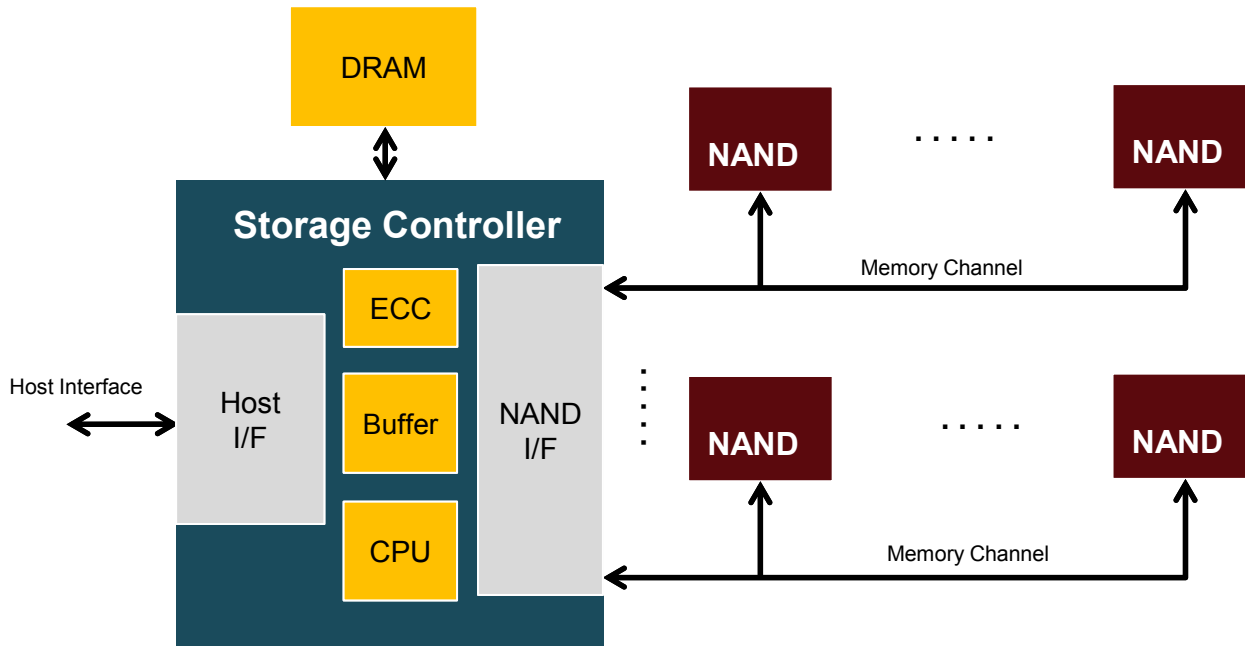
NAND Shortcomings: L2P Mapping, Garbage Collection, Wear Leveling, Bad Block Management, ECC Complexity

SSD System RRAM-Based
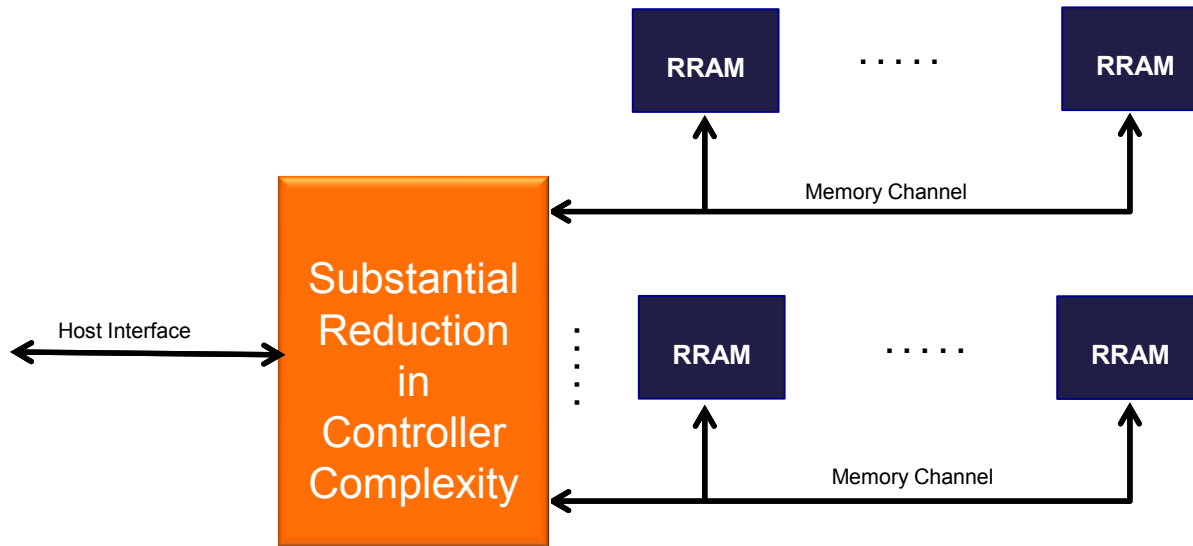
RRAM-Based SSD substantially reduces NAND shortcomings, thus significantly reducing controller complexity

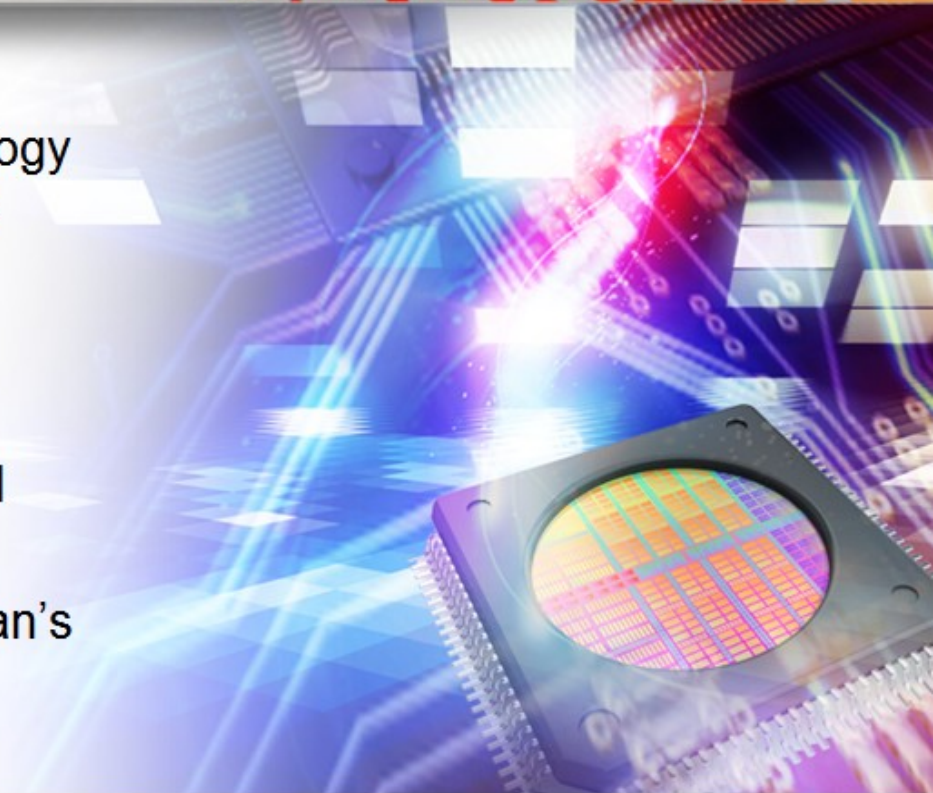| NAND Spec.	MLC	SLC	RRAM
NAND bus freq DDR (MHz)	100	100	100
Bud width (bits)	8	8	8
Page Size (KB)	16	16	4
Shift Time + Overhead (us)	100	100	25
Program Time (ms)	1.5	0.3	.032
Read Latency (us)	50	25	1
Write Amplification	3	2	1
Effective Write xfer rate (MB/s)	32	53	160
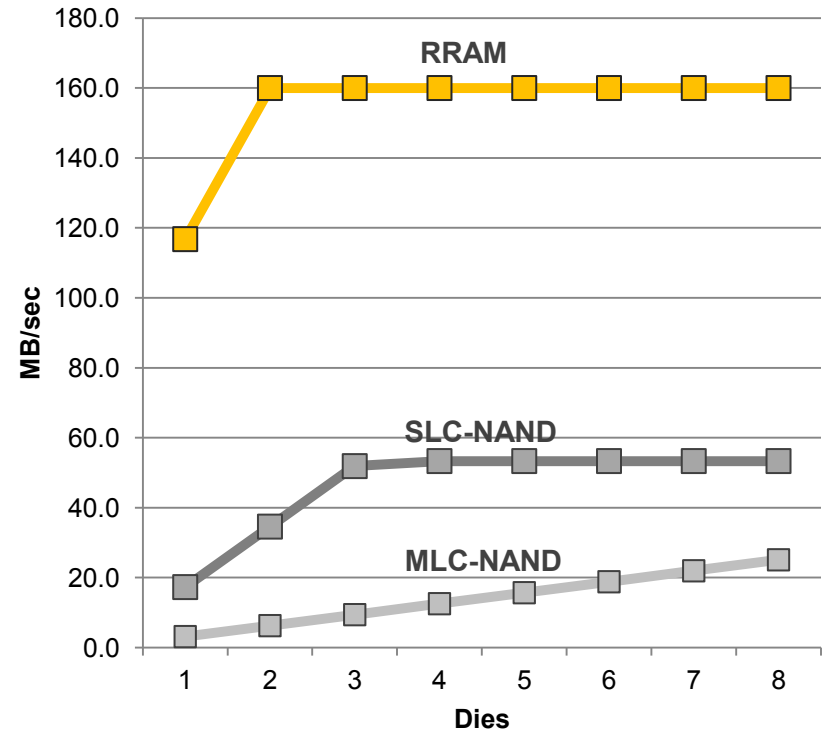
- **Maximum utilization of the channel**
- **5X performance improvement**

![Flash Memory Summit logo]

Crossbar

- Providing non-volatile 3D RRAM technology with breakthrough cost and performance characteristics

- CMOS compatible, simple structure, superior performance

- Venture-backed, inventors of new RRAM technology

- Exclusive license to University of Michigan's RRAM inventions
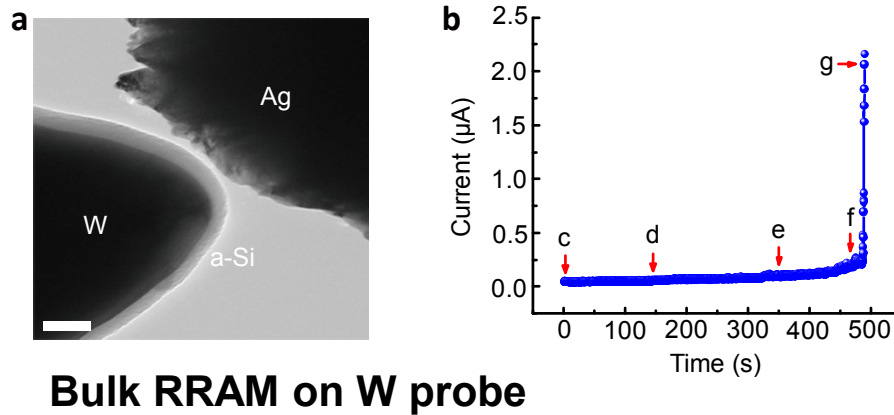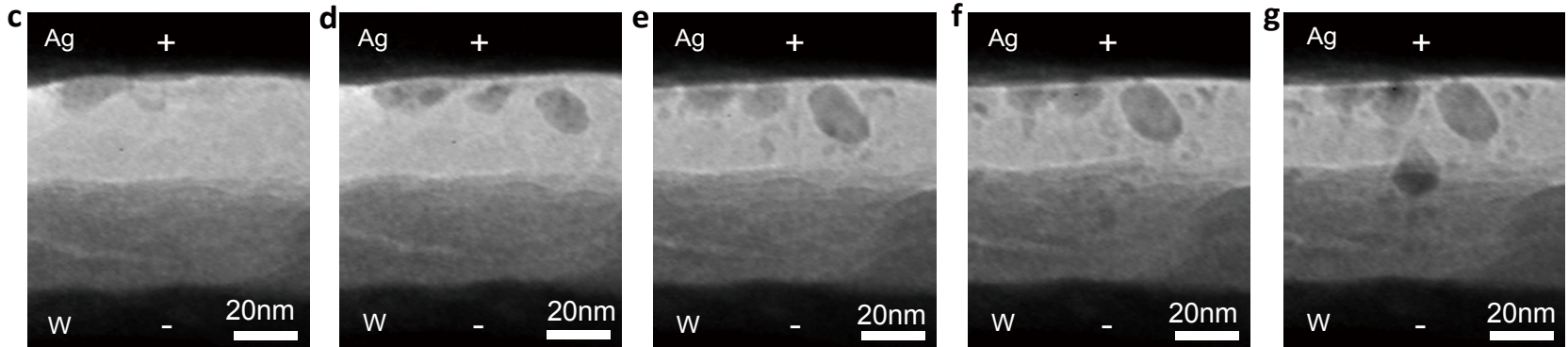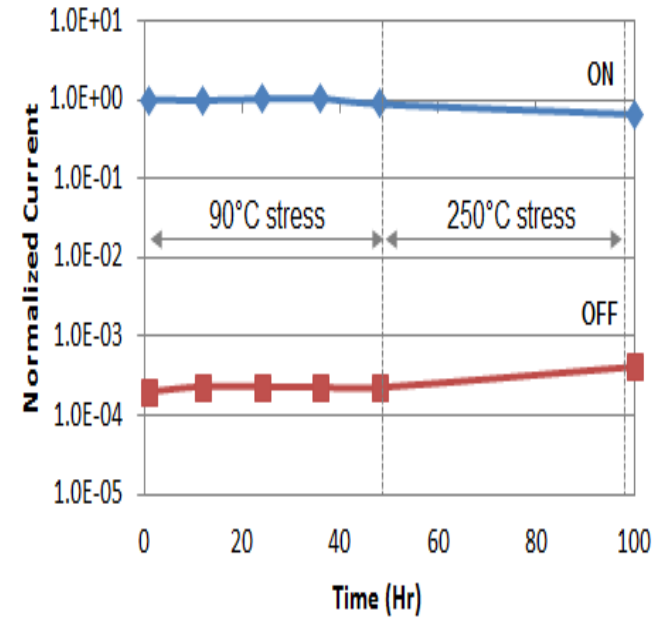
Crossbar 3D RRAM CELL

Top Electrode

Switching Medium

Bottom Electrode

Top Electrode

Switching Medium

Bottom Electrode
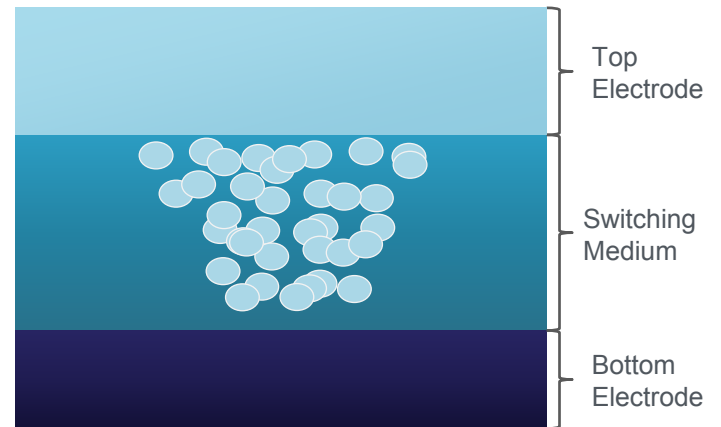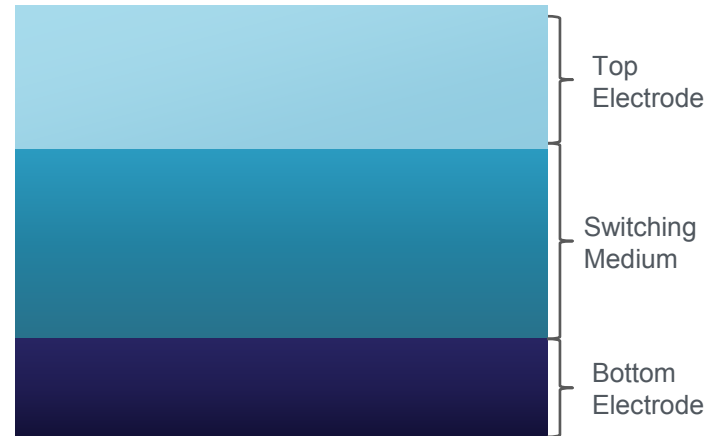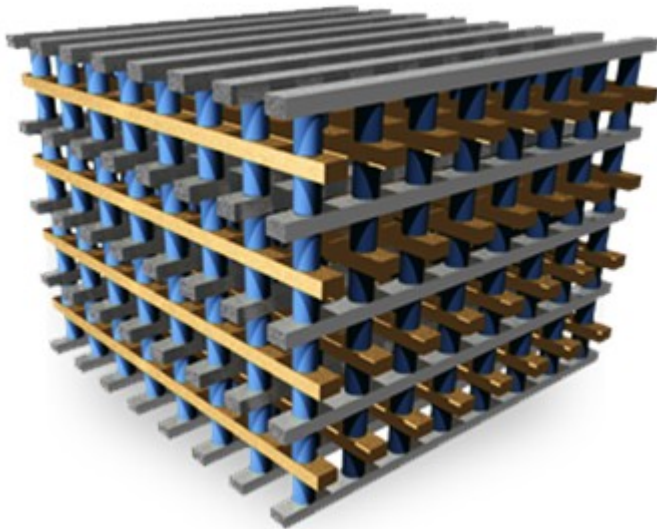
Simple Material & CMOS Compatible

Bulk RRAM on W probe
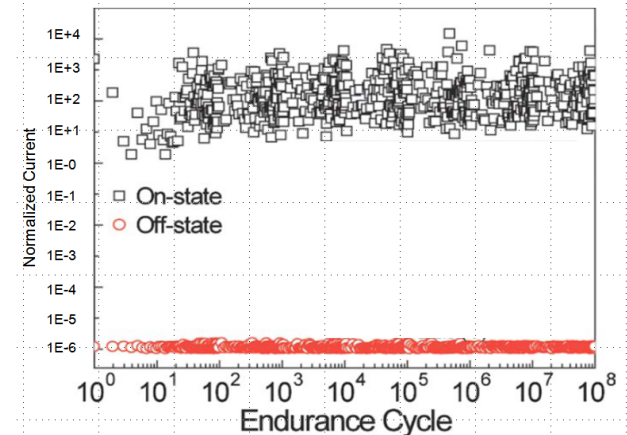
Yang, et al. Nature Communications, 3, 732, 2012.

Breakthrough Characteristics & Performance
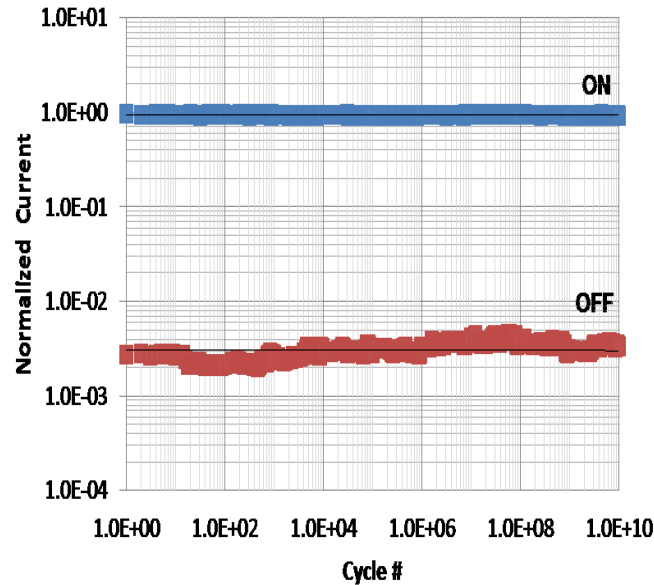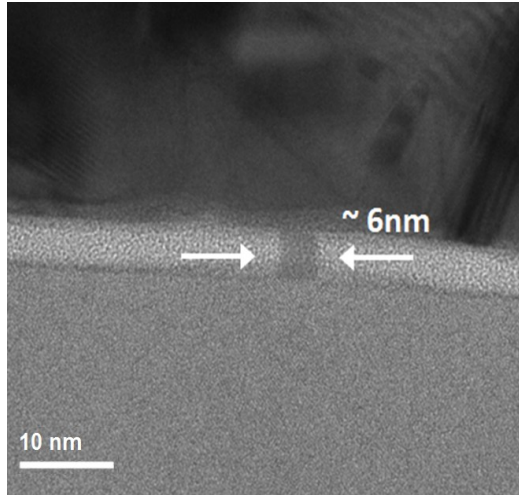
- **Sub 10nm Cell is achievable**

- **Immune to 10 Billion disturb cycles**

- **10Yr 85C Data Retention achieved**

- **100 Million Endurance Cycles Demonstrated**

Summary

- **Crossbar RRAM** feature set offers present and future SSD systems with:
    - **Superior Performance & Reliability**
    - **Scalability**
    - **At a lower cost**

- **Crossbar** has the required **technological** and **architectural** characteristics to **revitalize next generation Non Volatile memory** systems through its unique RRAM offering

Thank You!