Current and Emerging Memory Technology Landscape

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A New Era Emerging for Memory?

Convergence of many factors/pressures:

- Increasing importance of memory to user experience
  - Our lives are becoming one big shared database, with IOPs becoming more important than MIPs
- Both NAND and DRAM facing scaling challenges
  - No hard “wall,” but increasing complexity
- Explosion of “new” memory storage concepts
  - New storage physics are enabling new usage models
- Evolving memory hierarchy
  - New features, relentless cost reduction, and need for I/O performance are remaking the memory hierarchy

Memory is moving from a support role to a defining system role

Memory-Relevant Trends

Enterprise *(Servers/Storage)*

Computing *(Desktops/Laptops)*

Mobile *(Laptops/MIDs)*

Cellular *(Phones)*

Content

- Performance-driven (generally I/O limited)
- "Green" focus bringing power into foreground
- Reliability vs. cost is the trade-off

Consumption

- Ease of use
- Instant-on/off
- Power vs. "good enough" performance trade-off

Memory Scaling Challenges

Just as memory usage becomes "interesting"…

- "Planar" nonvolatile (NVM) technology scaling is becoming difficult:
  - MOS transistor-based cell; charge-storage memory effect
  - Starting to encounter physical scaling limitations
  - Manifesting first as reliability → endurance/retention
  - Increasing degree of memory management required for functionality → memory abstraction
- No scaling "brick wall," but complexity is increasing the level of management required to maintain added functionality

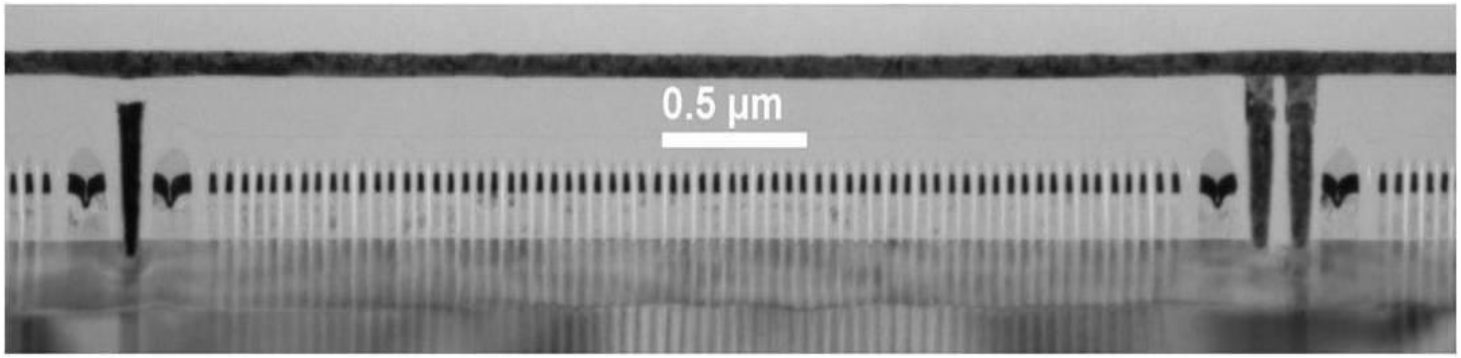
Flash Cell Scaling Challenges

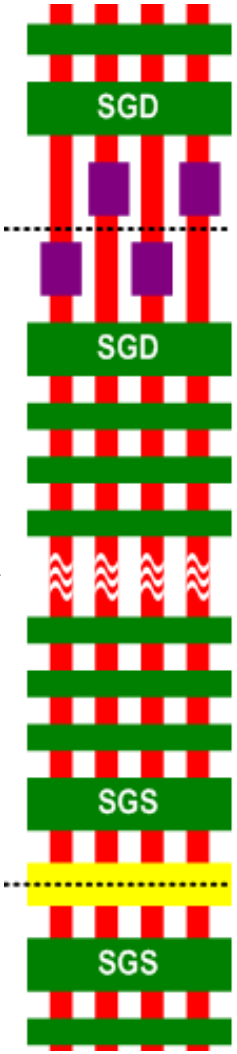
Basic NAND structure has changed little over time…

Main scaling issues:

- Few-electron problem
- Capacitance limitations
- Tunnel and interpoly charge retention
- Voltage isolation
- Parasitic charge trapping
- Read and write noise

State of the art: 25nm NAND

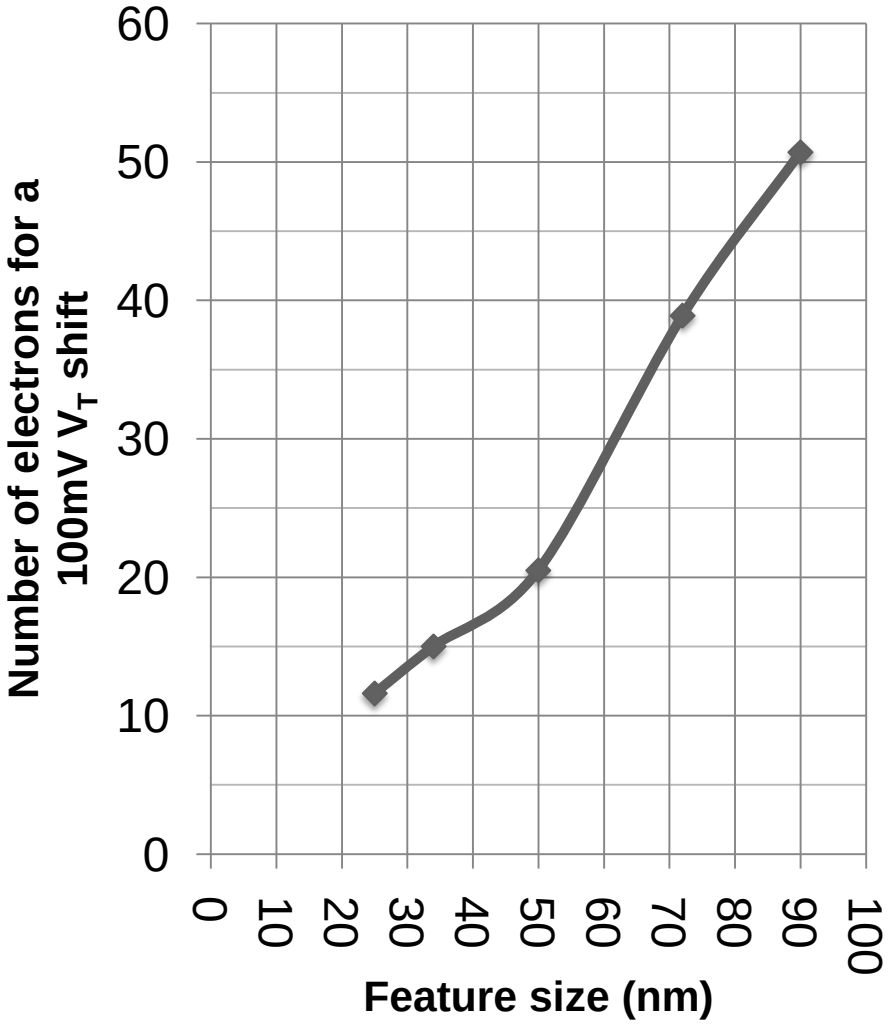




Few-Electron Effect

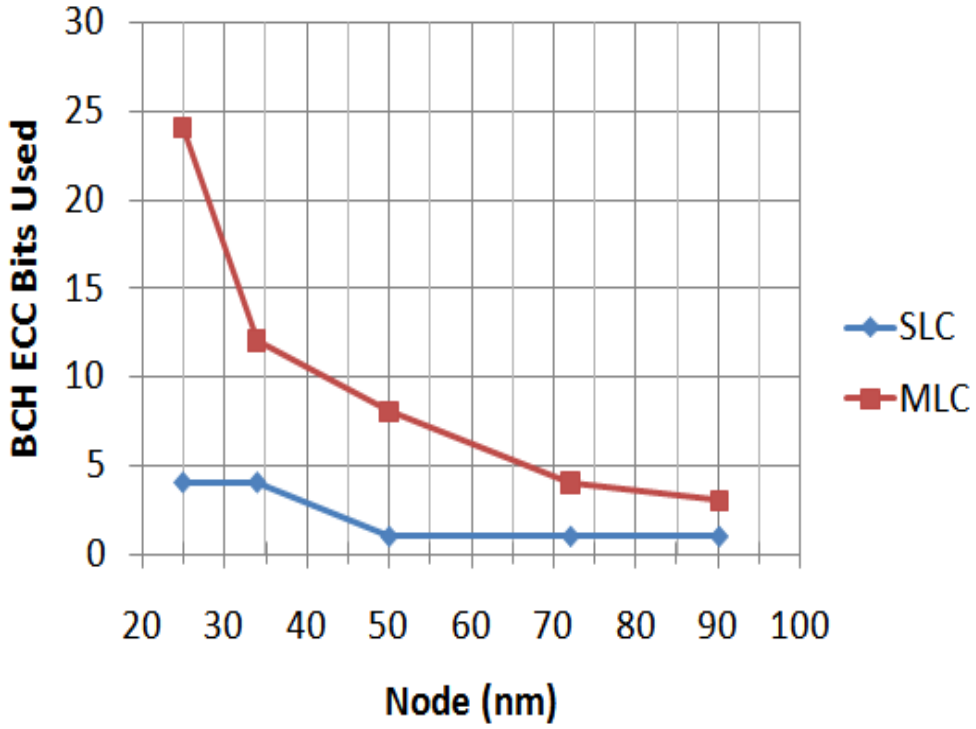
For a floating-gate cell, the number of electrons required for a V_T shift scales with the FG capacitance

At 25nm, MLC states are separated by 30–50 electrons (300–500mV)



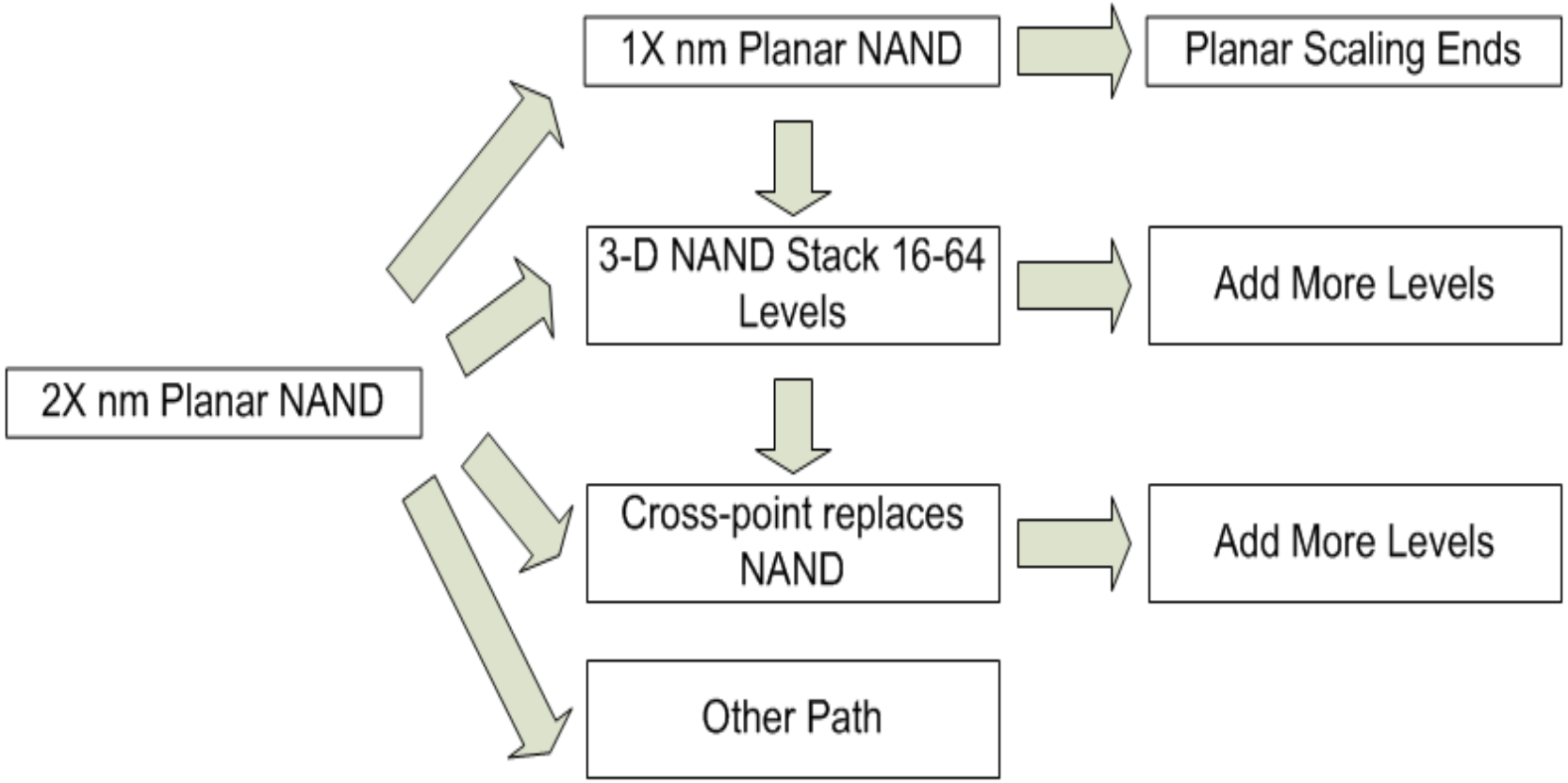
Scaling at a "System Level"

NAND media scaling issues are being addressed through system-level management tools such as error correction, wear leveling, and block retirement—
but **straightforward options are being exhausted**



NAND Scaling Roadmap

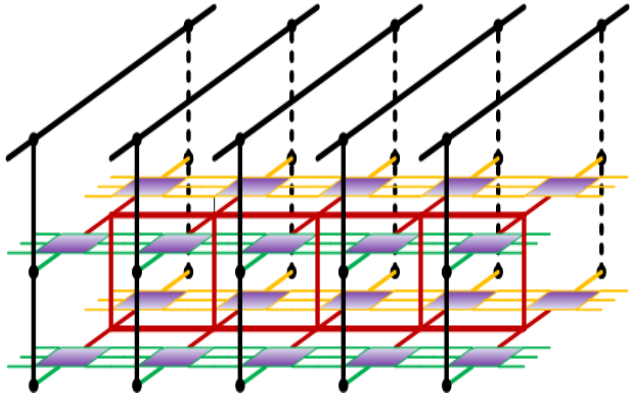
Several possible scenarios…



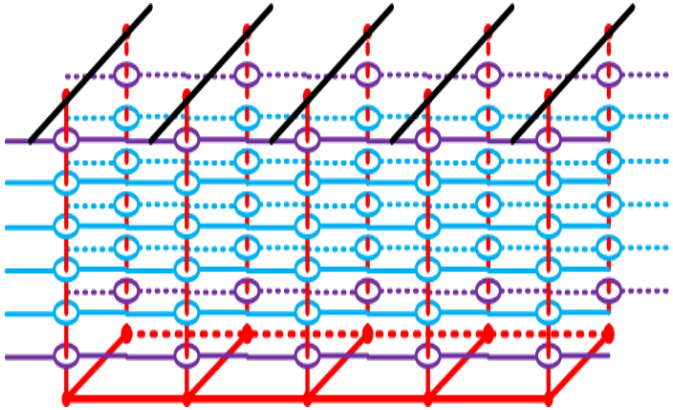
Going 3-D → Three Major Options

- **Deck-by-deck NAND** – SOI for upper decks
- **Vertical NAND** – Vertical cells arranged in vertical strings
- **Cross-point** – RRAM (resistive RAM) cells

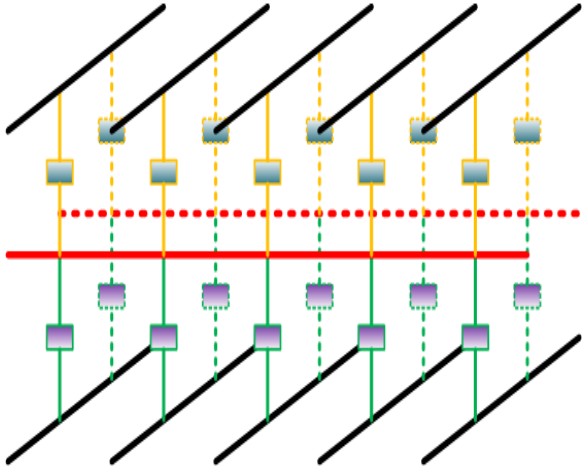
Deck-by-Deck NAND



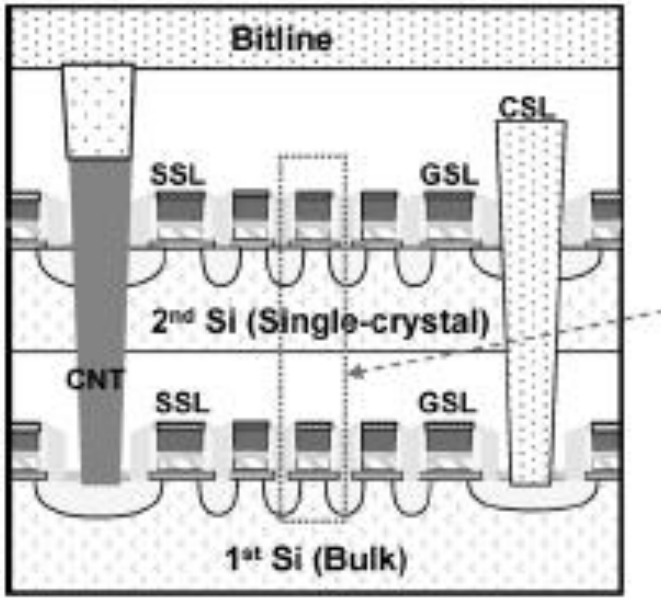
Vertical NAND



Cross-point RRAM



3-D NAND Highlights



Deck-by-Deck: Dual-Deck

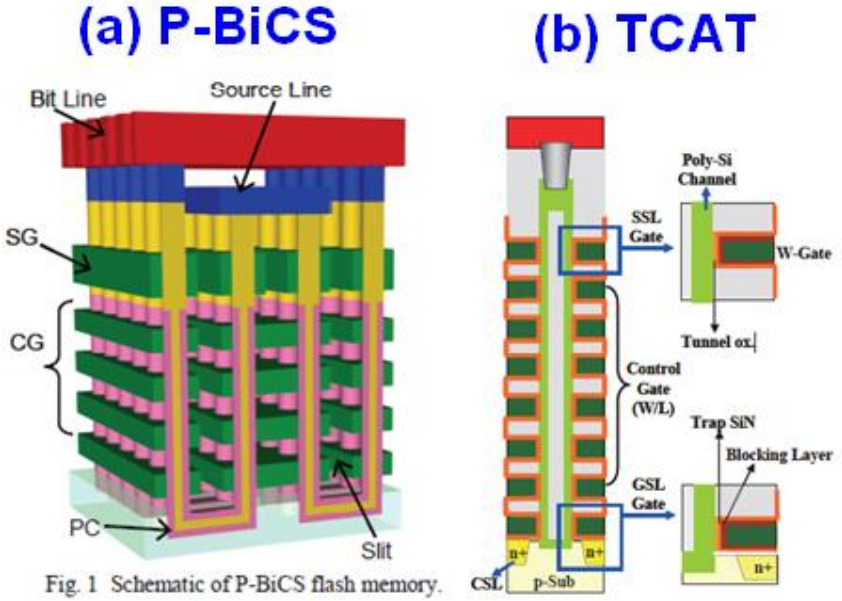


Fig. 1 Schematic of P-BiCS flash memory.

Vertical NAND

- Significant industry effort on 3-D NAND development
- Conference publications showing promising results
- Possibility to extend NAND roadmap for several generations

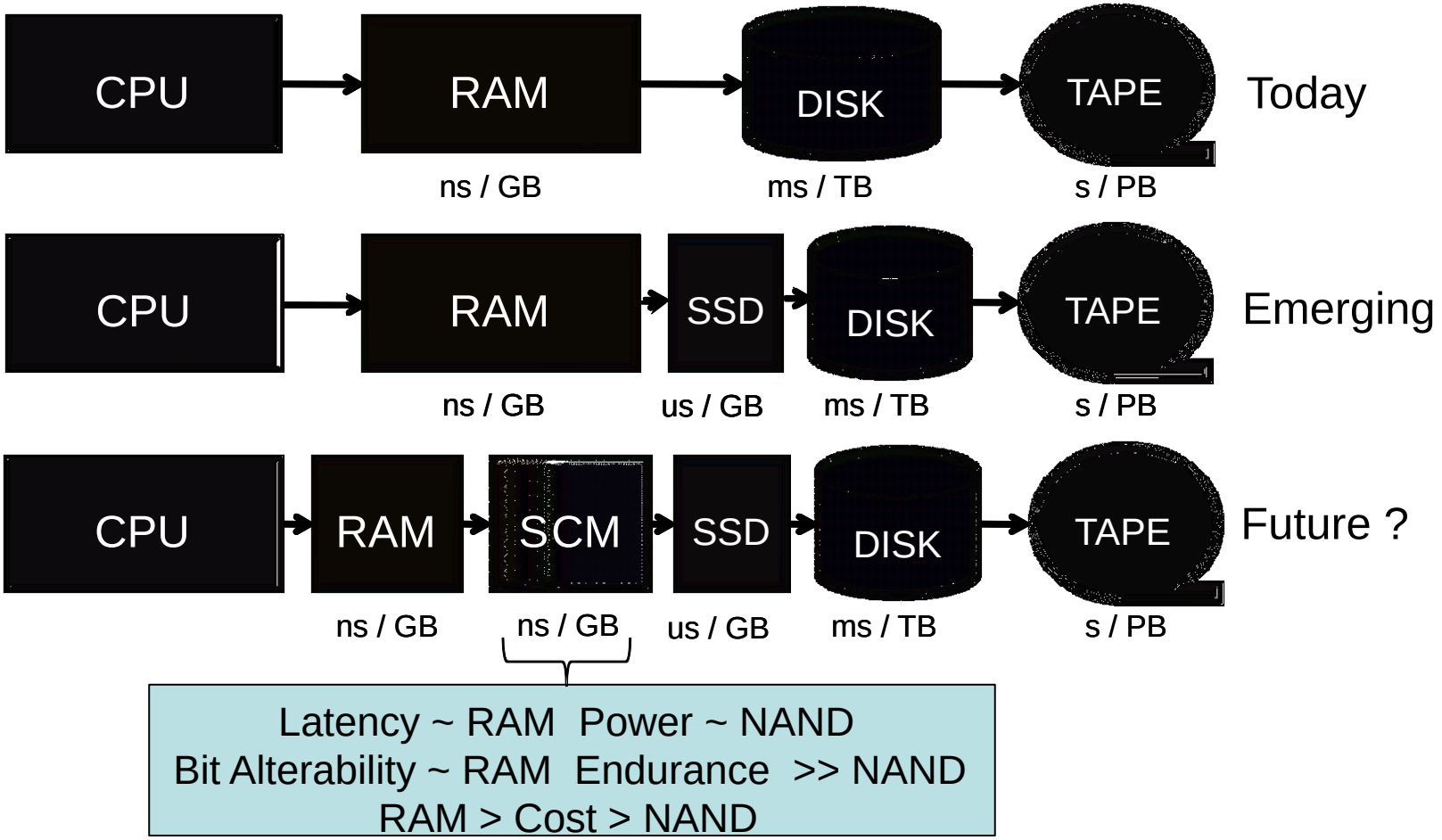
Requirements for NAND Successor

- Cost structure – beat NAND costs:
  - MLC-capable
  - 3-D-stackable
  - Simple process flow
- Scalability:
  - In x & y with lithography
  - In z with number of layers
- Reliability, performance, and power:
  - To meet emerging usage requirements
  - At component and system level

NAND Successor Not the Only Target

New Memory Hierarchy?

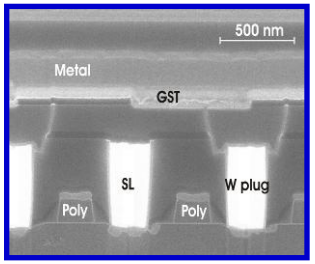
Balancing Latency, Power, Cost, and Endurance



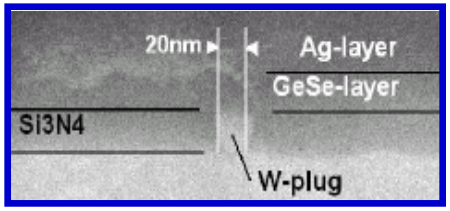
Alternative New-Memory Concepts

FERAM

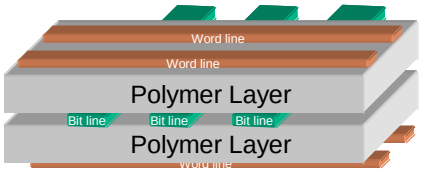
PCM



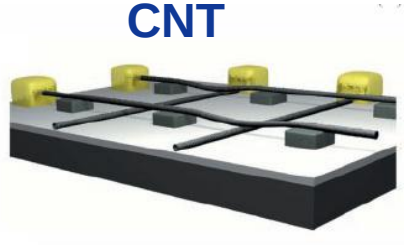
CBRAM



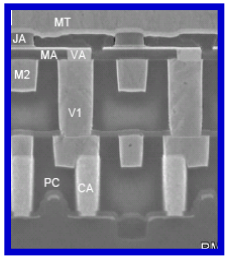
Polymer FeRAM



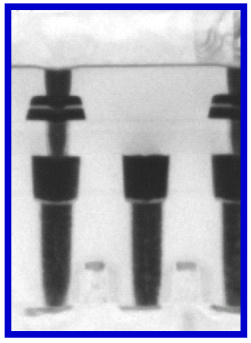
CNT



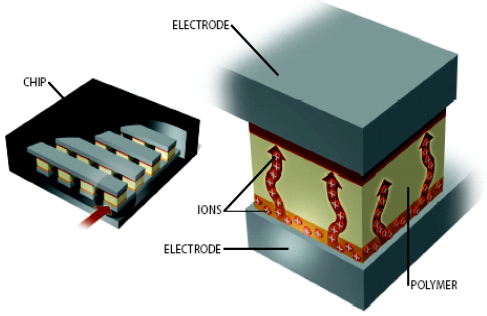
MRAM



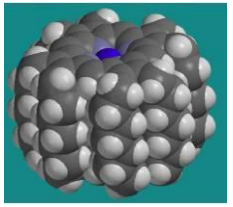
MOx-RRAM



Polymer RRAM



Molecular



Explosion of “new” memory concepts:

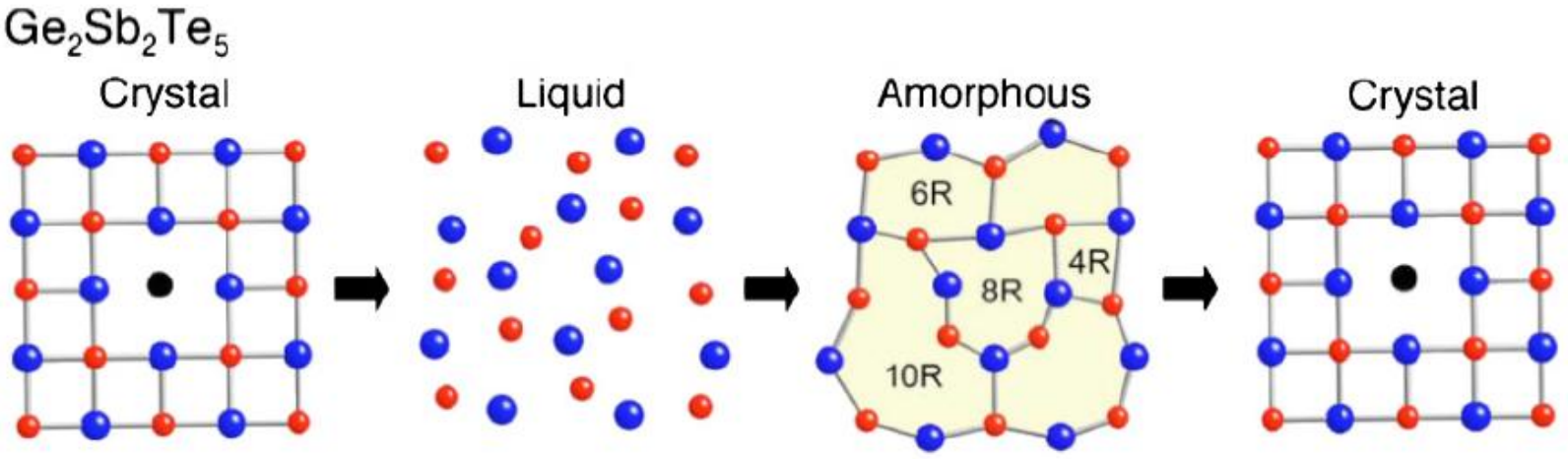
- New storage materials, new storage concepts
- Many ideas, varying functionality/cost, most unproven

Phase Change Memory Case Study

- Of the emerging RRAMs, PCM is the most mature:
  - Already in low-volume production
  - Demonstrated at Gb density vs. other EM at Mb density
  - Announced by multiple memory companies
- PCM has been heavily studied for 10+ years:
  - Widely published – lots of good-quality technical content
  - Chalcogenide-based material understanding is fairly mature
  - Many active researchers in both industry and academia
- Provides insight into other emerging-materials systems:
  - Many of the RRAMs share similar attributes with PCM

Why Phase Change Materials Are Interesting

- Amorphous and crystalline phase structures are similar
  → Easy transition between phase states
- Material contains voids and vacancies
  → Easy movement of atoms
- Volume of crystalline and amorphous phase closely matched
- Large set of materials to choose from for best performance



Terao, Japanese Journal of Applied Physics 48 (2009) 080001

Phase Change Memory Concept

Storing mechanism:

Amorphous/polycrystal phases of a chalcogenide alloy; example shown is $Ge_2Sb_2Te_5$ (GST)

Sensing mechanism:

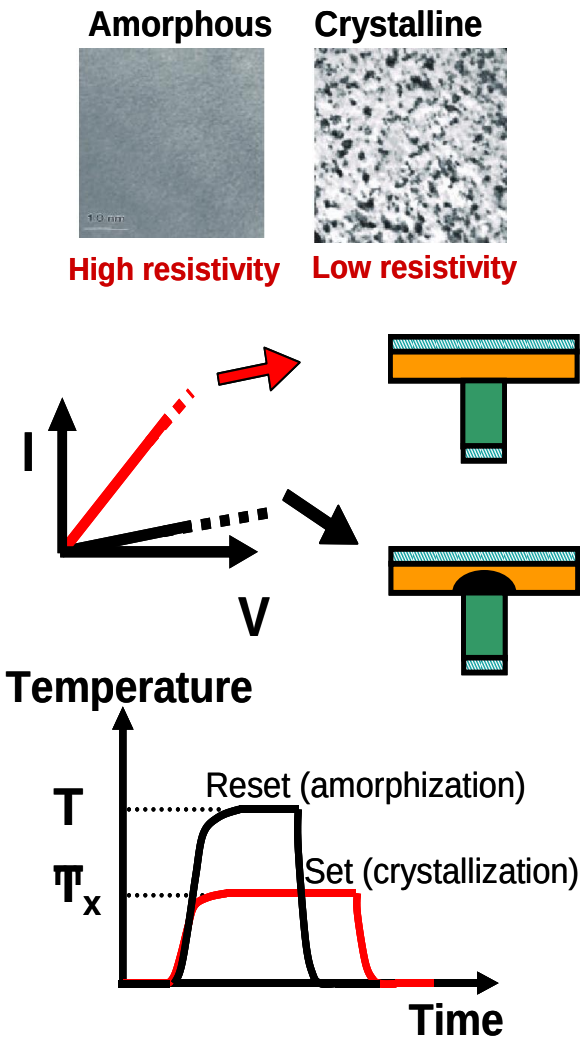
Resistance change of the GST

Writing mechanism:

Self-heating due to current flow (Joule effect)

Cell structure:

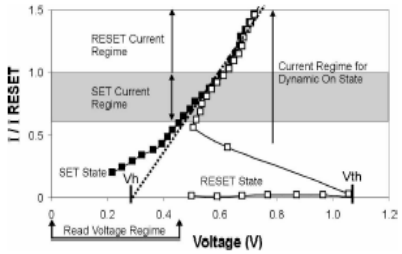
1 diode, 1 resistor (1D/1R)



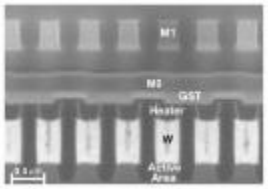
History of PCM Development

PCM cell

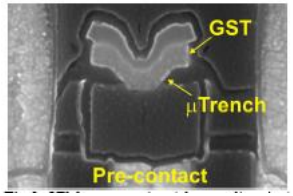
S. Lai and T. Lowrey, IEDM 2001, 180nm



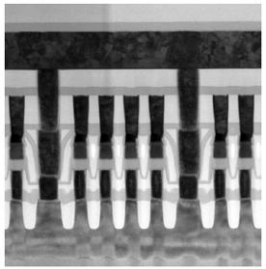
F. Pellizzer et al., VLSI 2004, 180nm



F. Pellizzer et al., VLSI 2006, 90nm

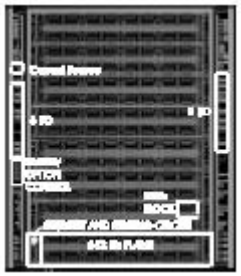


G. Servalli, IEDM 2009, 45nm

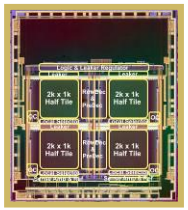


PCM array & chip

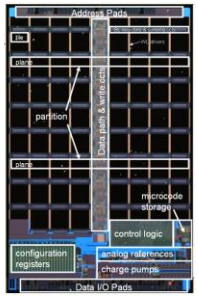
M. Gill et al., ISSCC 2002, 180nm



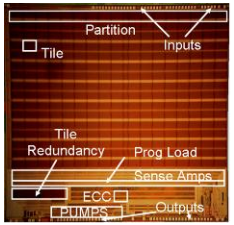
G. Casagrande et al., VLSI 2004, 180nm



Bedeschi et al., ISSCC 2008, 90nm 128Mb (256Mb MLC)



C. Villa et al., ISSCC 2010, 45nm 1Gb



2001 2003 2005 2007 2009 2011

Concept Demonstration

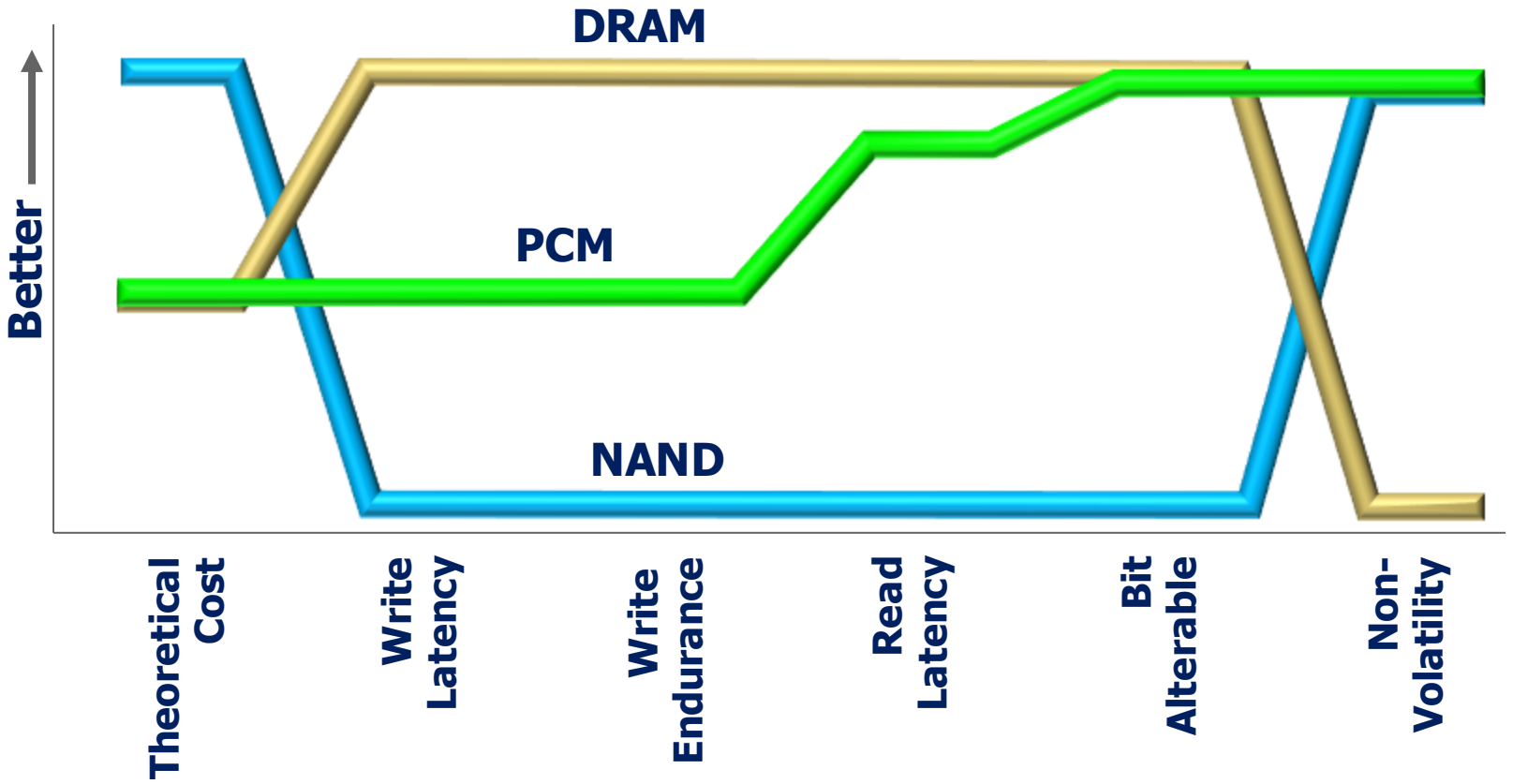
Technology Validation Product Reliability

Manufacturing

PCM Characteristics

PCM offers attributes of RAM and NAND

Roughly aligned to “storage-class memory”



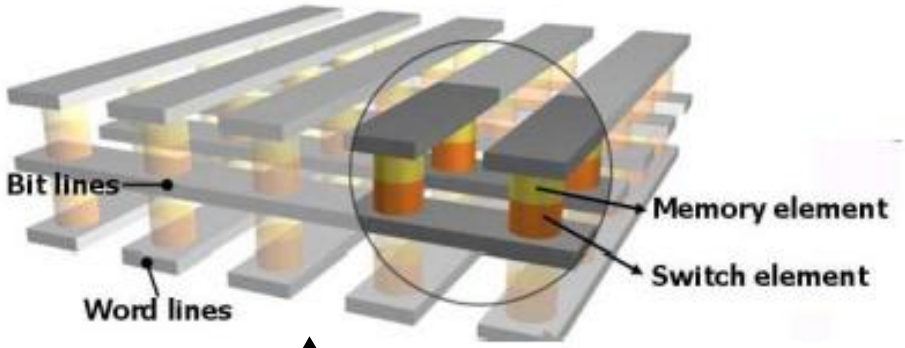
PCM Applications Opportunities

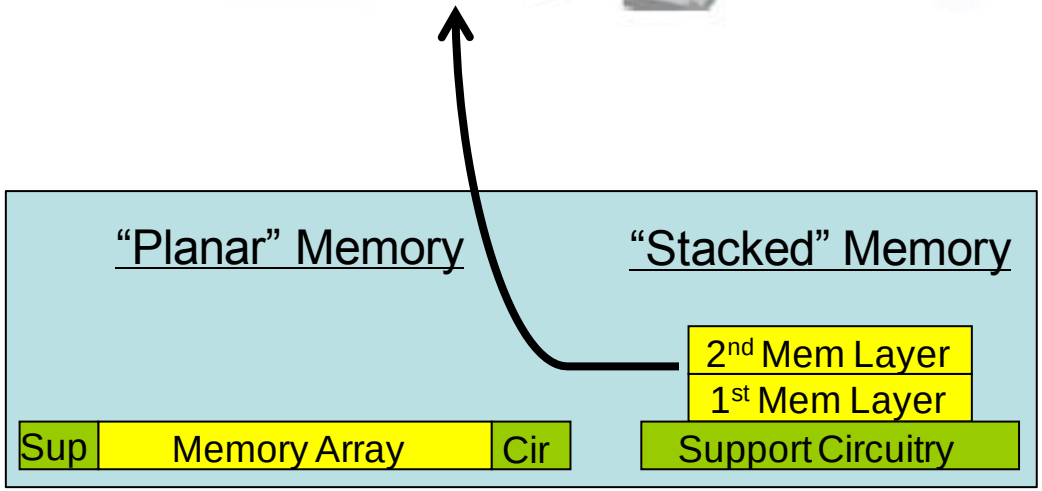
- **Wireless system** to store XiP, semi-static data
  - PCM bit alterability allows direct-write memory
- **Solid state storage subsystem** to store frequently accessed pages and elements that are easily managed when manipulated in-place
  - PCM caching to improve performance & reliability
- **Computing platforms** taking advantage of nonvolatility to reduce power
  - PCM offers endurance and write latency that are compelling for a number of novel solutions

3-D Cross-Point Memory– Best Chance to Reach NAND Cost?

Cross-point memory ***features***:

- Simple small $4F^2$ cell
  → low potential cost
- Suitable for 3-D stacking
  → cell size $(4/n)F^2$
- Array over circuitry
  → better array efficiency

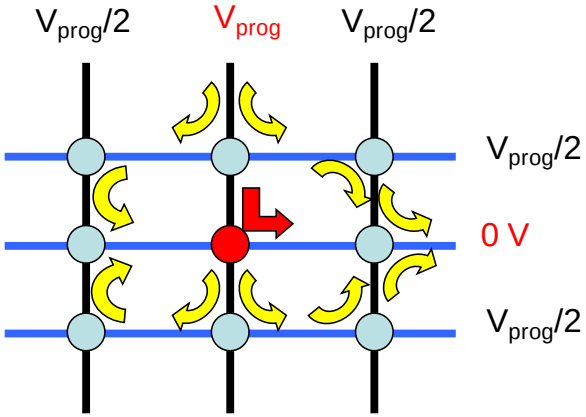


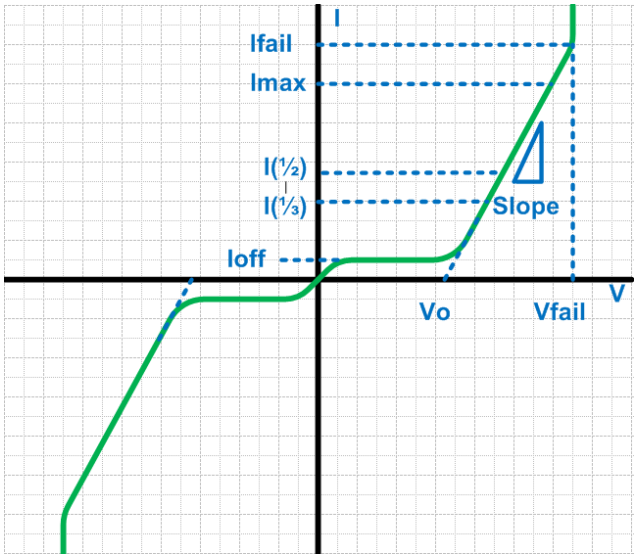


3-D Cross-Point Memory– Best Chance to Reach NAND Cost?

Cross-point memory ***challenges***:

- Compatible diode selector
- Must be multilevel cell capable (2–3 bits/cell)
- Must be able to stack layers of cells
- Low temperature processing
- Interconnect-intensive





Selector "diode" requirements:

- A "non-ohmic" device
- Compatible with memory element
- Stringent on/off current requirements
- Unipolar- or bipolar-depending cell

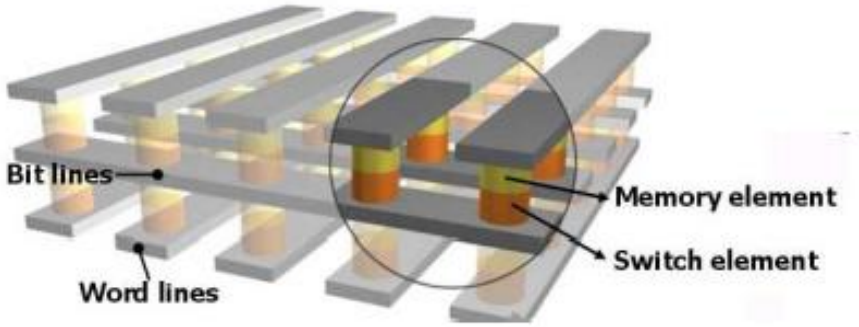
Wide Range of Cross-Point Options and Combinations

Selection Device

- Homojunctions → polySi p/n junctions
- Heterojunctions → P-CuO/n-InZnO
- Schottky diode → Ag/n-ZnO
- Chalcogenide ovonic threshold switching (OTS) materials
- Mixed ionic electronic conduction (MIEC) materials

Memory Device

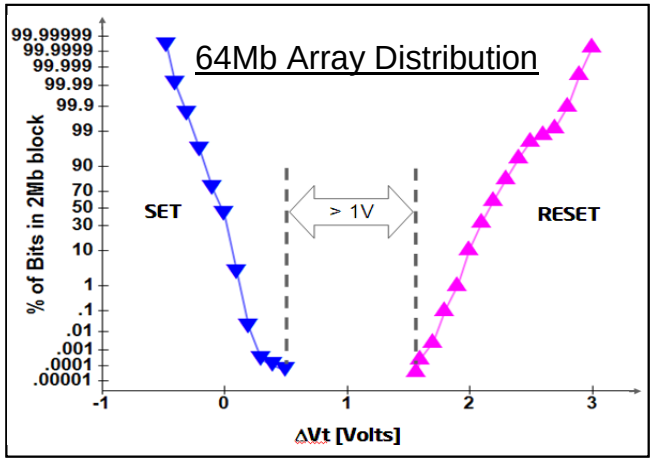
- STTRAM
- RRAM or CBRAM
- PCM

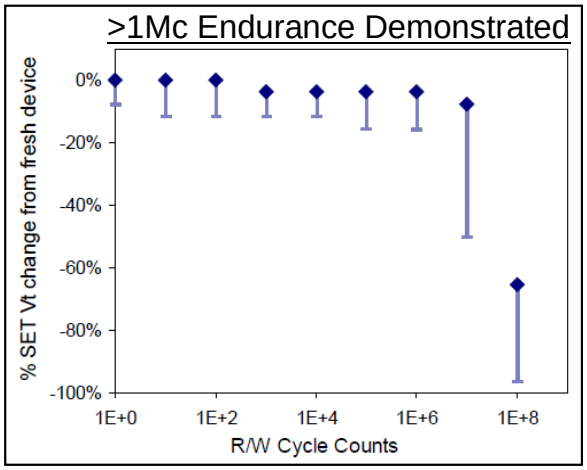


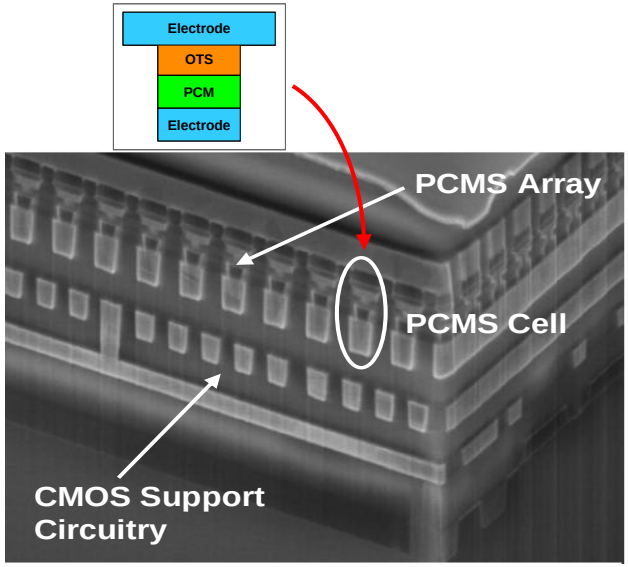
Phase Change-Based Cross-Point

Stacked phase change memory 64Mb demonstrator:

- Same PCM memory concept
- Ovonic threshold switch – OTS as selection device
- OTS is the same class of materials as PCM but “frozen” in the amorphous phase







3-d corner view of PCMS array

Summary: A New Era Emerging for Memory!

- Increasing importance of memory to user experience:
  - Our lives are becoming one big shared database
- Increasing importance of memory to system performance:
  - Server performance and power, client portability, and instant-on
- Both NAND and DRAM facing scaling challenges:
  - No hard "wall," but increasing complexity
  - New storage concepts are emerging for cost and features
- Evolving memory hierarchy around NVM capabilities:
  - Moore's Law cost treadmill → NVM becoming high-performance storage
  - New memory features → possibility of storage-class memory

Memory is moving from a support role to a defining system role

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