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Seminar „Speicher- und Dateisysteme“

NVRAM

Bettina Jung

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Volatile vs. Non-Volatile

Volatile memory	Non-volatile memory
Requires a power source to retain information.	Does not require a power source to retain information.
When power source is disconnected, information is lost or deleted.	When power source is disconnected, information is not deleted.
Often used for temporary retention of data, such as with RAM, or for retention of sensitive data.	Often used for long-term retention of data, such as files and folders.

Introduction: How volatile and non-volatile memories differ.

Source:

[1] http://theydiffer.com/difference-between-volatile-and-non-volatile-memory/

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NVRAM

- **NVRAM** (Non-volatile random-access memory)
  - Retains its information when power is turned off
  - Access data at random: any storage location can be accessed directly
  - RAM needs to be addressable at the byte (not the block) level
  - Aim: combine the high speed of RAM with the low costs of Flash

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Introduction: Further describing the characteristics of NVRAM.

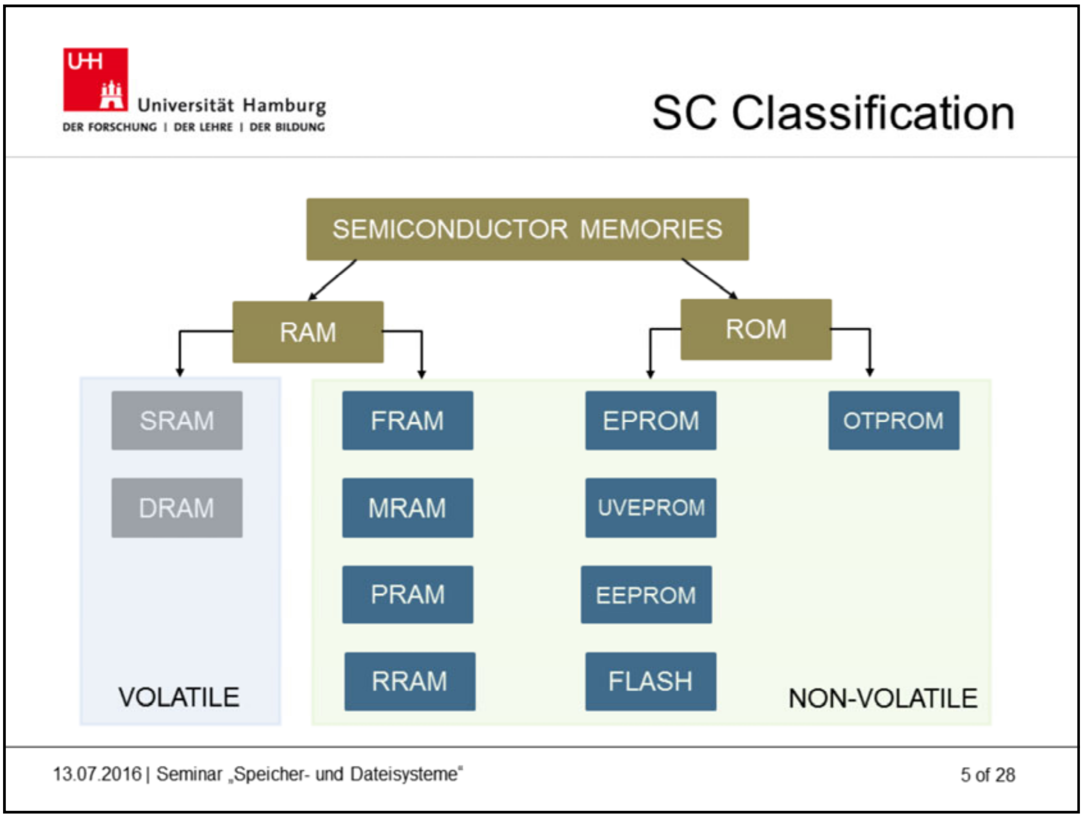
For further explanations on the characteristics of RAM the book “Server Management” from Gilbert Held notes:

“Perhaps it should have been called "nonsequential memory" because RAM access is hardly random. RAM is organized and controlled in a way that enables data to be stored and retrieved directly to specific locations.”

Sources:

[1] https://en.wikipedia.org/wiki/Non-volatile_random-access_memory

[2] http://theydiffer.com/difference-between-volatile-and-non-volatile-memory/



Classifications of Semiconductor memories:

SRAM = Static RAM

DRAM = Dynamic RAM

FRAM = Ferroelectric RAM

MRAM = Magnetoresistive RAM

PRAM = Phase Change RAM

RRAM = Resistive RAM

EPROM = Erasable Programmable ROM

UVEPROM = UV(Light) Erasable Programmable ROM

EEPROM = Electrically Erasable Programmable ROM

To describe the differences between RAM and ROM the following take-out pretty much sums it up:

“In common usage, the term *RAM* is synonymous with *main memory*. In contrast, *ROM (read-only memory)* refers to special memory used to store programs that boot the computer and perform diagnostics.

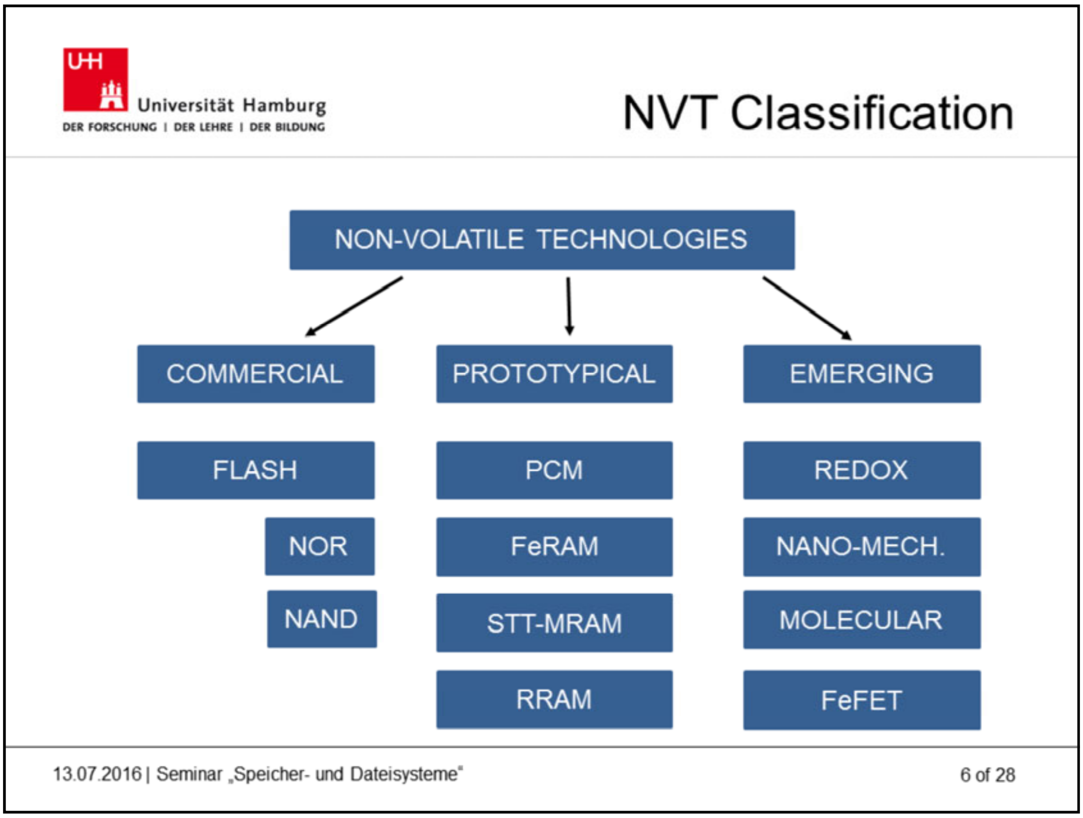
In fact, both types of memory (ROM and RAM) allow random access. To be precise, therefore, RAM should be referred to as *read/write RAM* and ROM as *read-only RAM.”* [3]

Sources:

[1] http://iopscience.iop.org/article/10.1088/0034-4885/75/7/076502

[2] Image from http://cdn.iopscience.com/images/0034-4885/75/7/076502/Full/rpp405779f01_online.jpg

[3] http://www.webopedia.com/TERM/R/RAM.html



PCM = Phase Change memory

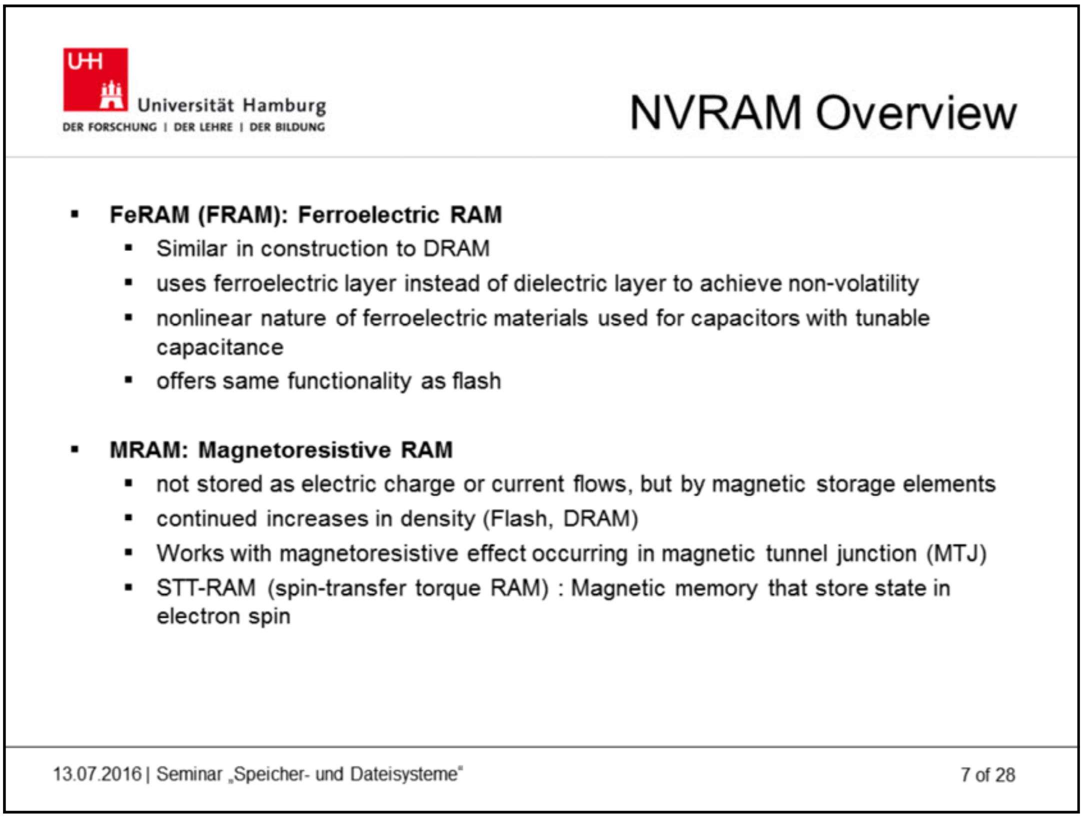
FeRAM = Ferroelectric RAM

STT-MRAM = Spin-transfer Torque Magnetoresistive RAM

RRAM = Resistive RAM

Source:

[1] Image: https://denalimemoryreport.wordpress.com/2012/03/23/isqed-who-and-what-will-win-the-universal-memory-derby/



“The prefix *ferro-* refers to iron, because permanent magnetism was first observed in a form of natural iron ore. “ [6]

“Ferromagnetism is the basic mechanism by which certain materials (such as iron) form permanent magnets, or are attracted to magnets.

In physics, several different types of magnetism are distinguished. Ferromagnetism (including ferrimagnetism)[1] is the strongest type: it is the only one that typically creates forces strong enough to be felt, and is responsible for the common phenomena of magnetism in magnets encountered in everyday life.

Ferroelectricity is a property of certain materials that have a spontaneous electric polarization that can be reversed by the application of an external electric field

Thus, the prefix *ferro*, meaning iron, was used to describe the property despite the fact that most ferroelectric materials do not contain iron.” [1]

“Spin transfer torque memory has two tiny magnets; one that's fixed and the other that spins when you apply a current; when you apply just the right current, the magnet spins to store a one or a zero.” [5]

Sources:

[1] https://en.wikipedia.org/wiki/Ferromagnetism

[2] https://en.wikipedia.org/wiki/Ferroelectricity

[3] https://en.wikipedia.org/wiki/Magnetoresistive_random-access_memory

[4] https://en.wikipedia.org/wiki/Resistive_random-access_memory

[5] http://www.techradar.com/news/computing-components/storage/how-universal-memory-will-replace-dram-flash-and-ssds-1222632

[6] https://en.wikipedia.org/wiki/Magnetism

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NVRAM Overview

- **PCM: Phase Change RAM**
  - Similar in construction to DRAM
  - PCM cells are based on a chalcogenide material
  - crystalline or amorphous states have very different resistivity properties, hence encoding binary information

- **RRAM: Resistive RAM**
  - works by changing the resistance across a dielectric solid-state material often referred to as a memristor

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Sources:

[1] https://de.wikipedia.org/wiki/Phase-change_random_access_memory

[2] https://en.wikipedia.org/wiki/Resistive_random-access_memory

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NVRAM Development Aspects

NVRAM Type	Replacement	Pros	Challenges
SST-MRAM	DRAM	High speed operation	MTJ stacking structure, high temperature, low resistence ratio
PCM	NOR	Most mature, switching time, scalability	Active power, write current & latency – power/thermal, too slow to work as main memory
RRAM	FLASH	Simple materials and structures, Fast access, moderate endurance, low power	Various and unclear switching mechanism, large cell-to-cell variability, stacking required for high density

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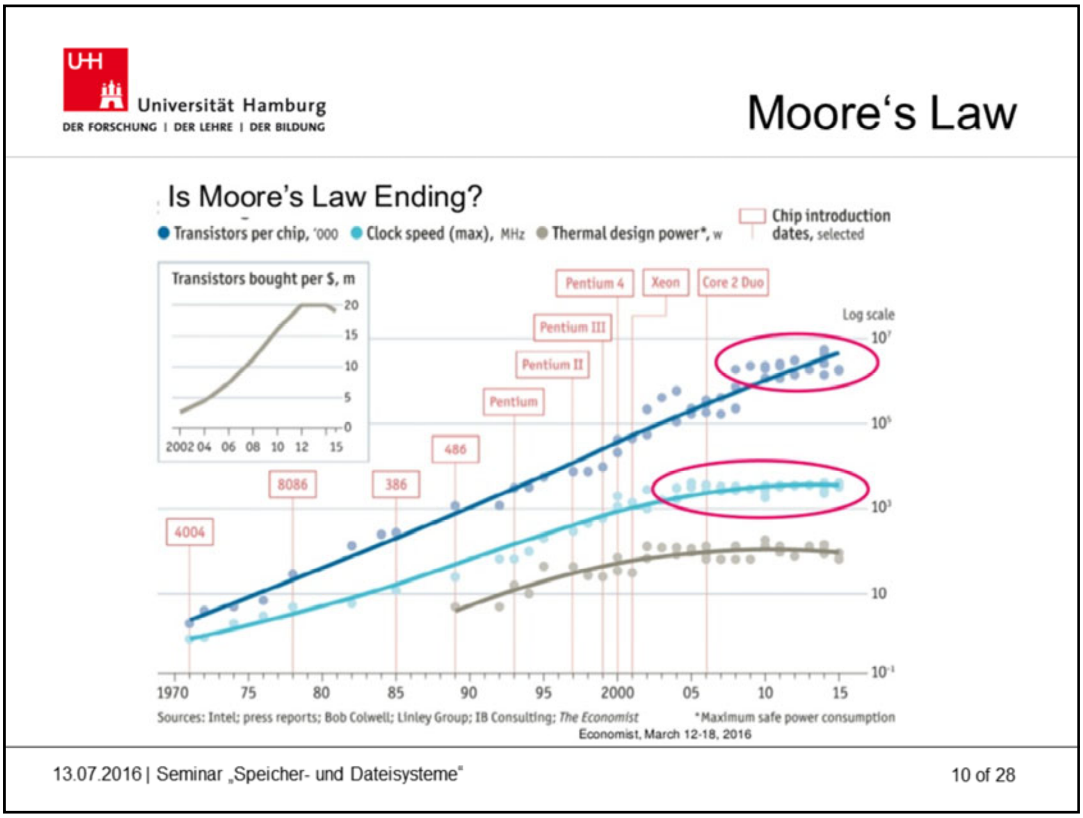
Source:

[1] http://www.eetimes.com/author.asp?doc_id=1323466

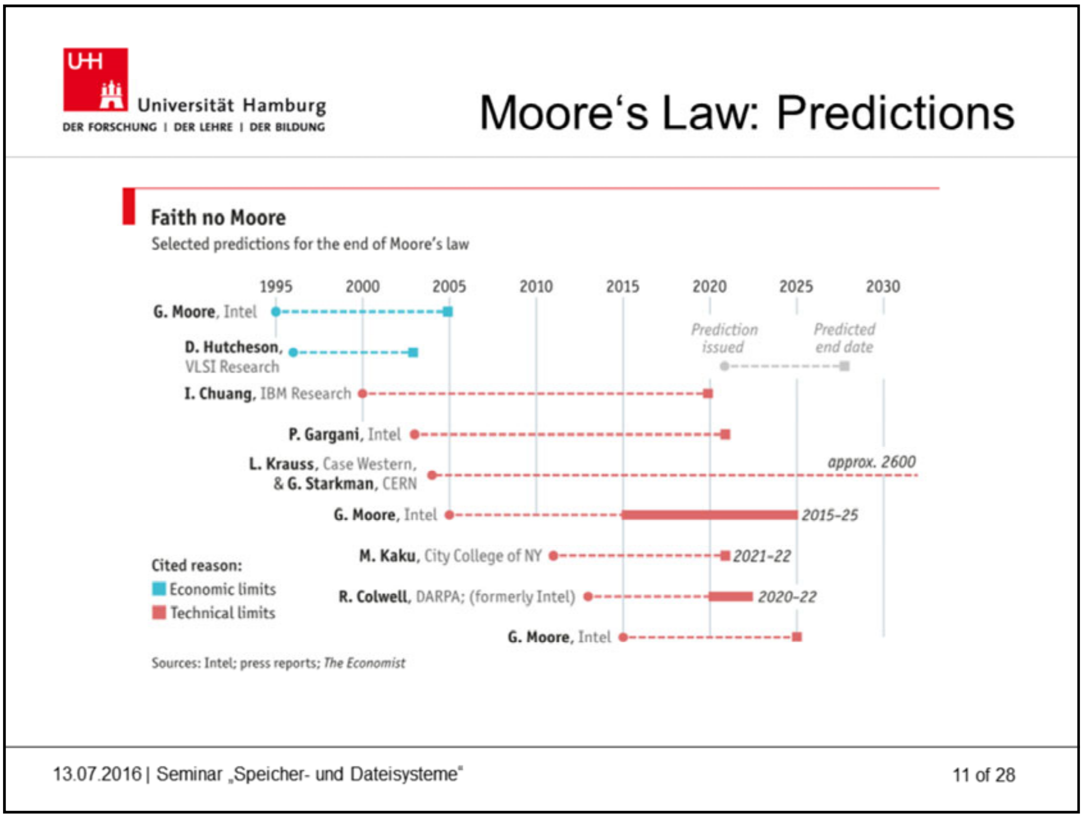


"Moore's law is the observation that the number of transistors in a dense integrated circuit doubles approximately every two years." [2]

Sources:

[1] http://www.slideshare.net/Funk98/end-of-moores-law-or-a-change-to-something-else

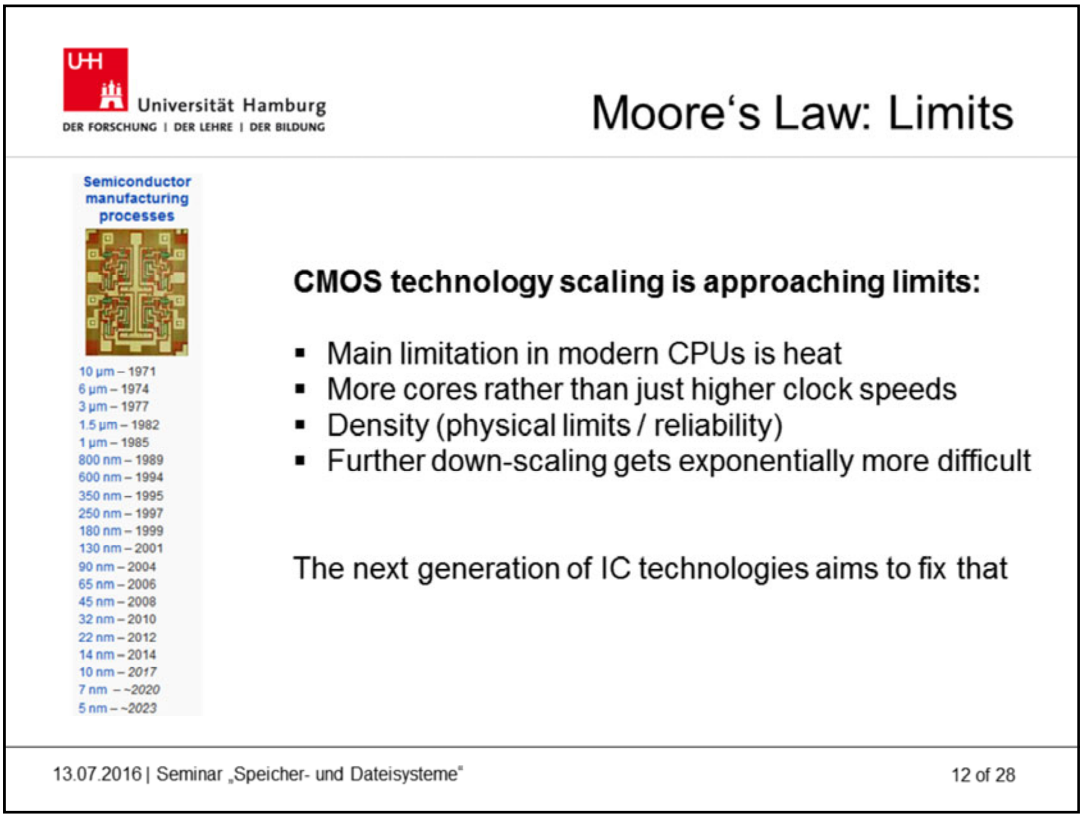
[2] https://en.wikipedia.org/wiki/Moore%27s_law



Sources:

[1] Intel; press reports; The Economist

[2] Image: http://www.slideshare.net/Funk98/end-of-moores-law-or-a-change-to-something-else



A big challenge is to get enough electrons into smaller transistors to reliably store the bits. The size-limit of transistors will reach a point where it is impossible to pack memory in any more densely.

Intel already did struggle with the release of their 14 nm semiconductor chips.

Going down to 7 nm would function but costs would explode exponentially - for that Moore's law is nigh.

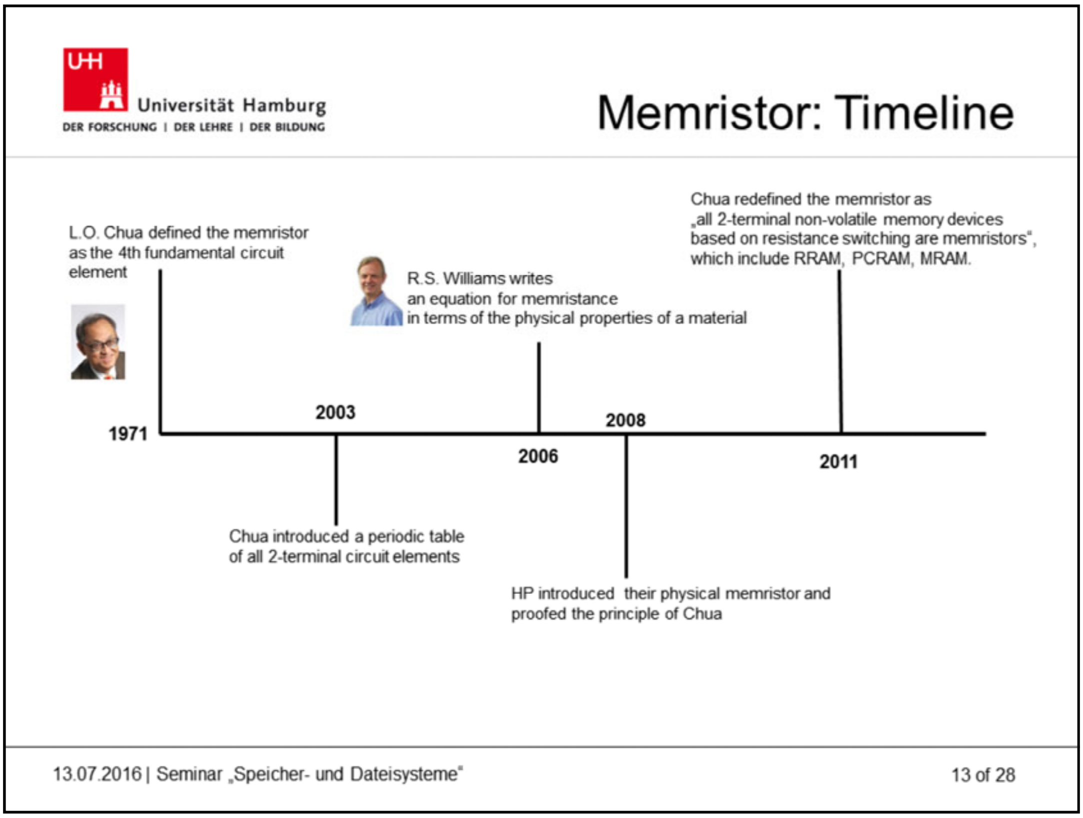
Current most viable for cheap NVRAM to replace transistors:

- PCM
- Memristor memory

Sources:

[1] http://www.techradar.com/news/computing-components/storage/how-universal-memory-will-replace-dram-flash-and-ssds-1222632

[2] Image: https://en.wikipedia.org/wiki/Semiconductor_device_fabrication



Leon O. CHUA(*June 28, 1936): professor of electrical engineering at U.C. Berkeley. He is the theoretical inventor of the memristor - described its properties.

Outtake of R.S.Williams' essay on explaining memristors :

"On 20 August 2006, I solved the two most important equations of my career—one equation detailing the relationship between current and voltage for this equivalent circuit, and another equation describing how the application of the voltage causes the vacancies to move—thereby writing down, for the first time, an equation for memristance in terms of the physical properties of a material. This provided a unique insight. Memristance arises in a semiconductor when both electrons and charged dopants are forced to move simultaneously by applying a voltage to the system. The memristance did not actually involve magnetism in this case; the integral over the voltage reflected how far the dopants had moved and thus how much the resistance of the device had changed.

The resistance of these devices stayed constant whether we turned off the voltage or just read their states (interrogating them with a voltage so small it left the resistance unchanged). The oxygen vacancies didn’t roam around; they remained absolutely immobile until we again applied a positive or negative voltage. That’s memristance: the devices remembered their current history. We had coaxed Chua’s mythical memristor off the page and into being.” [3]

The following resistance switching devices are memristors:

RRAM, PCRAM, MRAM, MIM: Metal-Insulator-Metal memory cell.

Chua even goes further and defines the memristor as „if its pinched, it‘s a memristor.“ [4]

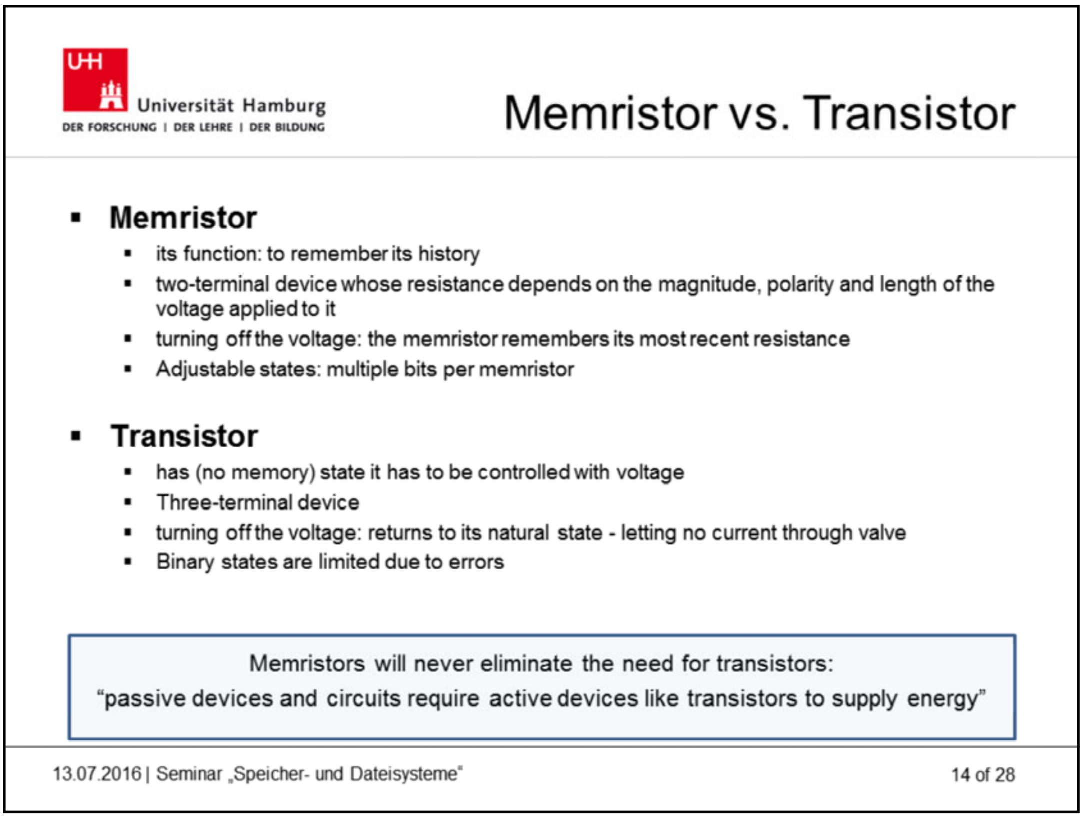
Sources:

[1] https://en.wikipedia.org/wiki/Leon_O._Chua

[2] http://people.eecs.berkeley.edu/~chua/

[3] http://spectrum.ieee.org/semiconductors/processors/how-we-found-the-missing-memristor

[4] http://sti.epfl.ch/files/content/sites/sti/files/shared/sel/pdf/Abstract_Prof_Chua.pdf



Memristor: contraction of the word memory and resistor.

Memristors are passive two-terminal circuit elements whose resistance is a function of the history of current that flowed through the device.

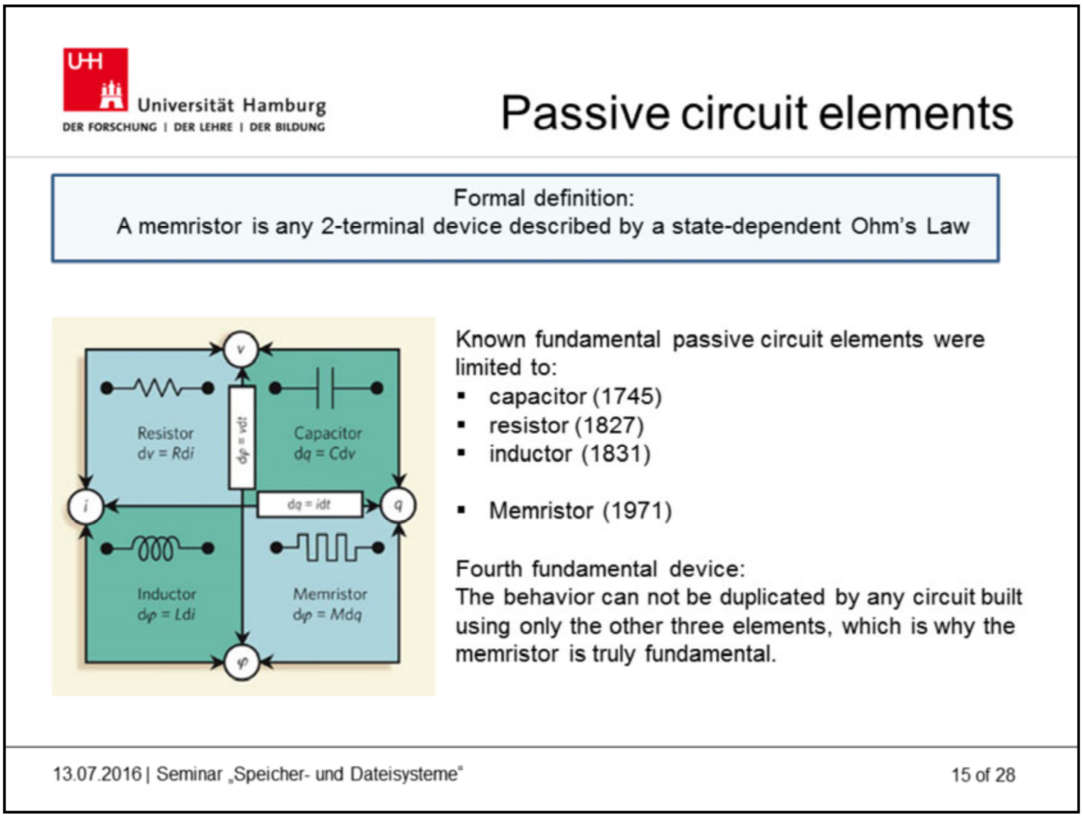
The assumption that the transistor would count as a distinct circuit element is false. The transistor actually consists of doped semiconductor resistors.

Hp memristor is a nano-scale non-volatile memory device which might have the potential to replace flash memories and DRAMs in the next few years.

Sources:

[1] http://sti.epfl.ch/files/content/sites/sti/files/shared/sel/pdf/Abstract_Prof_Chua.pdf

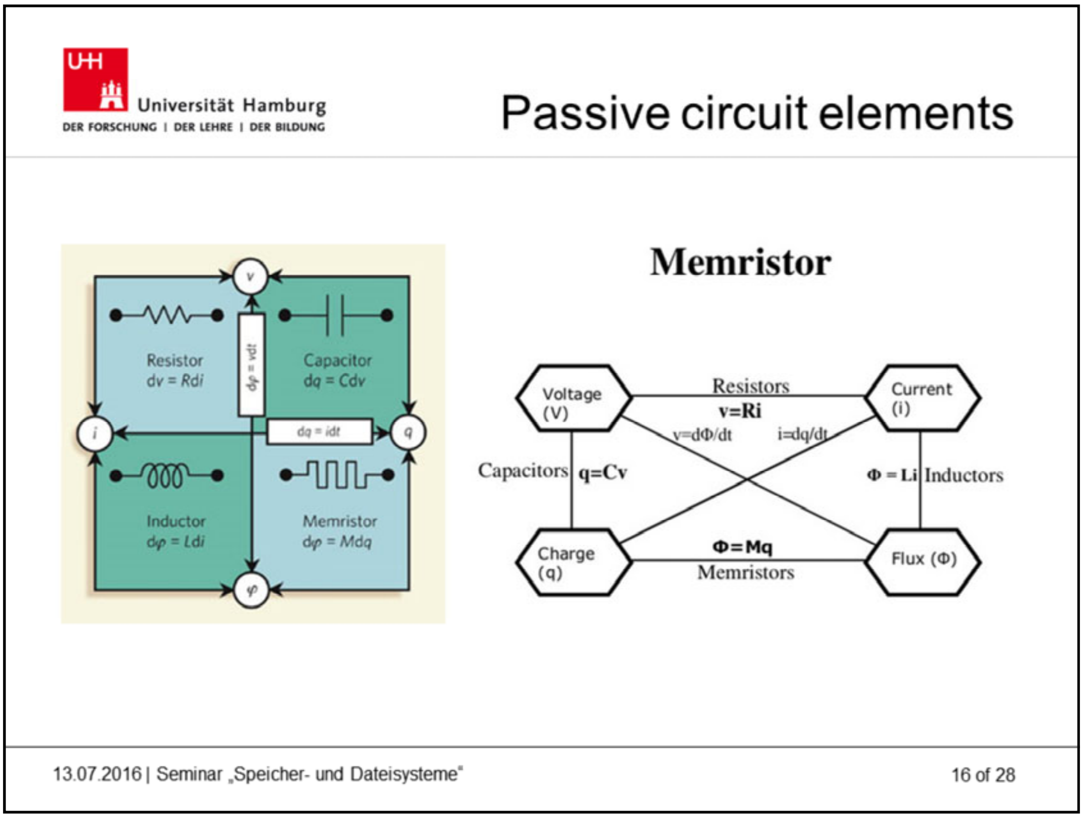
[2] http://spectrum.ieee.org/semiconductors/processors/how-we-found-the-missing-memristor



Passive circuit elements with its symbolic conventions.

Source:

[1] Image: https://regmedia.co.uk/2011/12/22/memristor.jpg



Outtake of R.S.Williams' essay describing the relationship of the circuit quantities:

"Chua discovered a missing link in the pairwise mathematical equations that relate the four circuit quantities—charge, current, voltage, and magnetic flux—to one another. These can be related in six ways. Two are connected through the basic physical laws of electricity and magnetism, and three are related by the known circuit elements: resistors connect voltage and current, inductors connect flux and current, and capacitors connect voltage and charge. But one equation is missing from this group: the relationship between charge moving through a circuit and the magnetic flux surrounded by that circuit—or more subtly, a mathematical doppelgänger defined by Faraday's Law as the time integral of the voltage across the circuit. This distinction is the crux of a raging Internet debate about the legitimacy of our memristor.

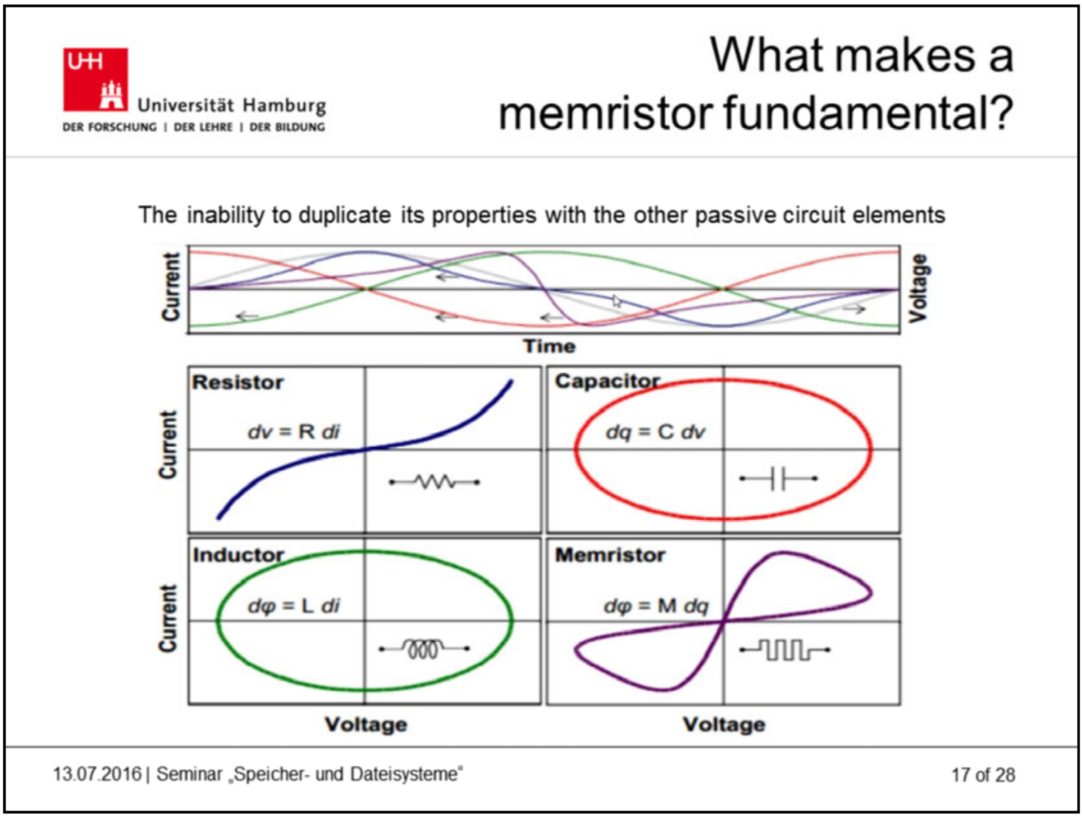
Chua demonstrated mathematically that his hypothetical device would provide a relationship between flux and charge similar to what a nonlinear resistor provides between voltage and current. In practice, that would mean the device's resistance would vary according to the amount of charge that passed through it. And it would remember that resistance value even after the current was turned off." [3]

Sources:

[1] Image: http://www.rsc.org/images/NVmemeristor-300_tcm18-118172.jpg

[2] Image: http://www.slideshare.net/mramitkumar123/memristor-ecr019

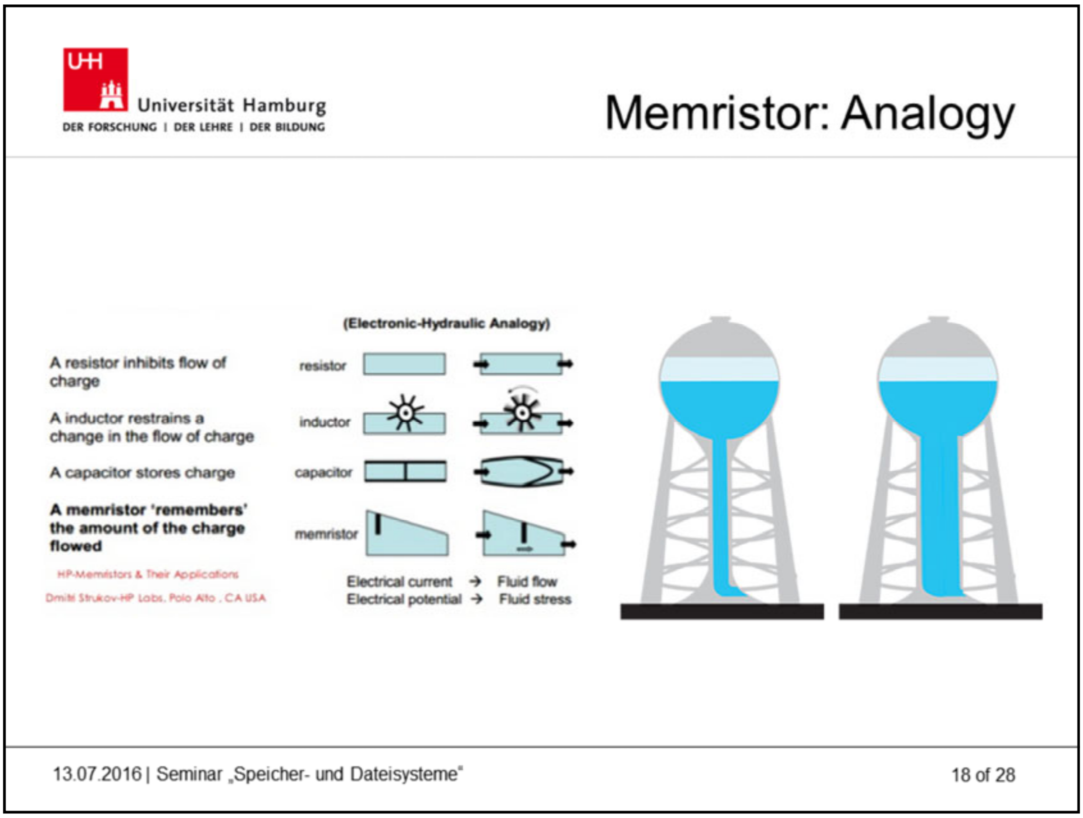
[3] http://spectrum.ieee.org/semiconductors/processors/how-we-found-the-missing-memristor



The relation between current and voltage of the memristor is charaterized by a „pinched hysteresis loop". Its current-voltage behavior is called „bow tie" by Hewlett Packard.

Source:

[1] Image: https://regmedia.co.uk/2011/12/22/memristor.jpg



Analogy of measuring the time to drain water (current) out of a tank.

Conductance = inverse measure of resistance

Increase the diameter of the pipe = Increase the conductance → more current can flow

Following Ohm's Law with Vg = I

V= Pressure (speeding due to gravity)

g=Conductance (diameter of the pipe how mnuch water can flow through it)

I = current (amount of water flowing/ amounts of electrons tha can flow per second)

What if the conductance of a conductor got bigger /smaller as it was used

A resistor is presented as a pipe through which water flows. The water represents electric charge.

"The resistor's obstruction of the flow of charge is comparable to the diameter of the pipe: the narrower the pipe, the greater the resistance. For the history of circuit design, resistors have had a fixed pipe diameter. But a memristor is a pipe that changes diameter with the amount and direction of water that flows through it. If water flows through this pipe in one direction, it expands (becoming less resistive). But send the water in the opposite direction and the pipe shrinks (becoming more resistive). Further, the memristor remembers its diameter when water last went through. Turn off the flow and the diameter of the pipe "freezes" until the water is turned back on.

That freezing property suits memristors brilliantly for computer memory. The ability to indefinitely store resistance values means that a memristor can be used as a nonvolatile memory." [3]

Sources:

[1] Image from Dmitri Strukov, HP-Memristors & Their Applications“

[2] Image modified with Photoshop: http://eu.kascomarine.com/uk/applications/deicing/tanks-and-towers/

[3] http://spectrum.ieee.org/semiconductors/processors/how-we-found-the-missing-memristor

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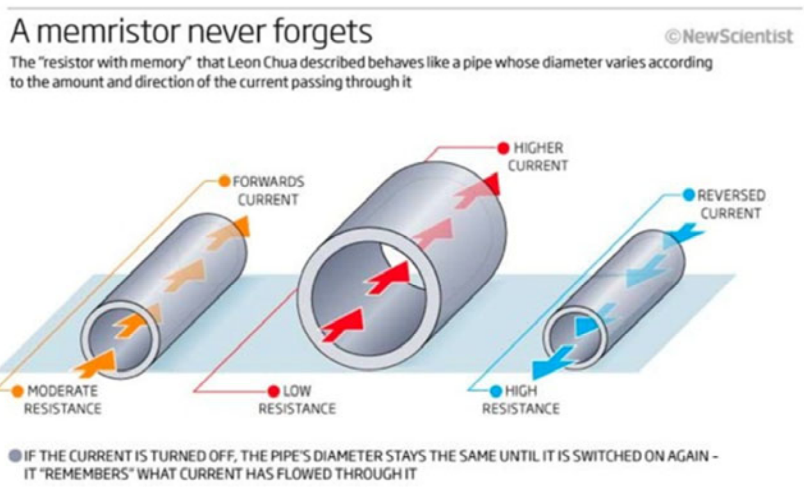
Memristor: Behavior



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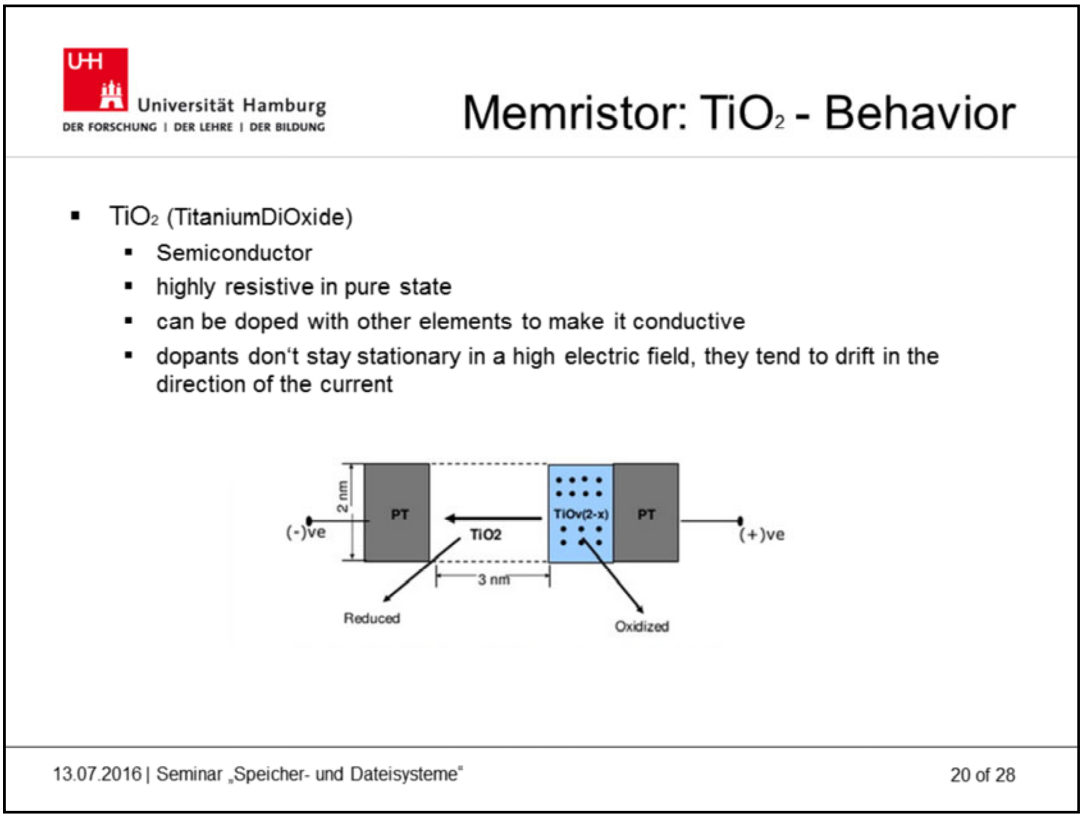
Memristance is charge-dependent resistance.

Source:

[1] Image: http://geeknizer.com/memristor-replace-transistor/



A bias voltage is put across a thin film of TiO_2 that has dopant cause them to move into pure TiO_2 , thus lowers the resistance.

Running current in the other direction will push the dopants back into place, increasing the TiO_2 's resistance.

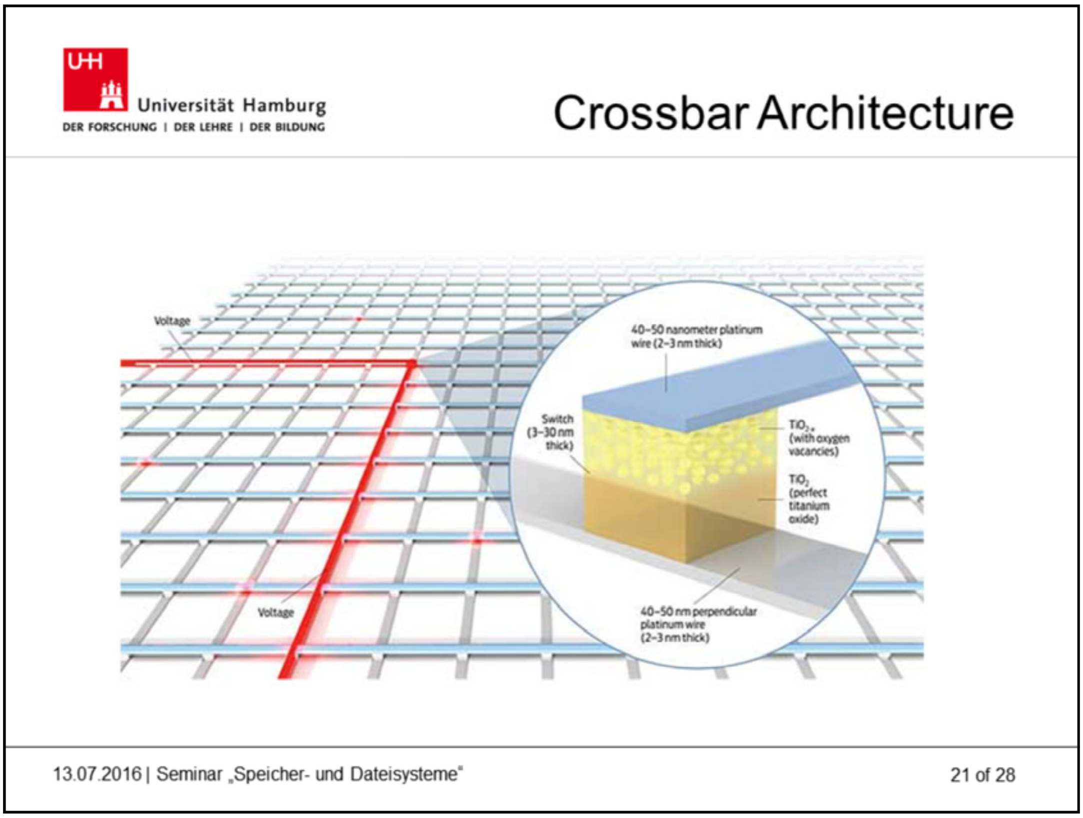
In TiO_{2-x} the vacancies (oxygen-deficient) is described in percentage by –x. The switching behavior results from the TiO_2 layer turning into TiO_{2-x} for conductivity and vice versa by applying either negative or positive voltages to it.

The memristive state comes from the voltage turned off (positive or negative). The oxygen bubbles stay where they are - the boundary between the two titanium dioxide layers is frozen. The memristor ”remembers” how much voltage was last applied.”

Sources:

[1] Image: http://www.nobeliefs.com/memristor.htm

[2] http://spectrum.ieee.org/semiconductors/processors/how-we-found-the-missing-memristor



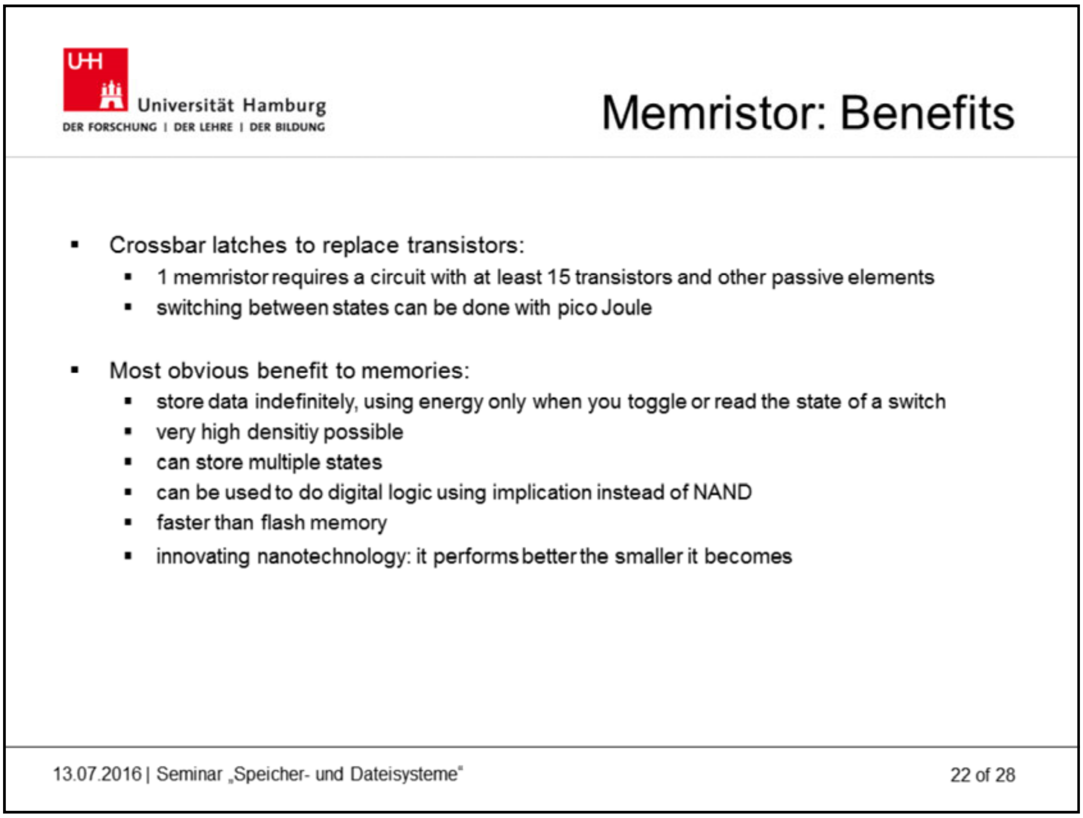
Outake from [1]:

“**THE CROSSBAR ARCHITECTURE:** The crossbar architecture is a fully connected mesh of perpendicular wires. Any two crossing wires are connected by a switch. To close the switch, a positive voltage is applied across the two wires to be connected. To open the switch, the voltage is reversed.

THE SWITCH: A switch is a 40-nanometer cube of titanium dioxide (TiO_2) in two layers: The lower TiO_2 layer has a perfect 2:1 oxygen-to-titanium ratio, making it an insulator. By contrast, the upper TiO_2 layer is missing 0.5 percent of its oxygen (TiO_{2-x}), so x is about 0.05. The vacancies make the TiO_{2-x} material metallic and conductive.”

Source:

[1] Image: http://spectrum.ieee.org/semiconductors/processors/how-we-found-the-missing-memristor



The implication:

2-terminal device of 10 nm size allow much higher /denser device integration.

How many kinds of circuits could be supercharged by replacing a handful of transistors with one single memristor?

Conventional devices use 0/1; Memristors can use any value between 0 and 1.

Faster than Flash memory.

Source:

[1] Image: http://spectrum.ieee.org/semiconductors/processors/how-we-found-the-missing-memristor

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Preliminary Benchmark

	Memristor	PCM	STT-RAM	DRAM	Flash	HD
Chip area per bit (F^2)	4	8–16	14–64	6–8	4–8	n/a
Energy per bit (pJ)[2]	0.1–3	2–100	0.1–1	2–4	10^1–10^4	10^6–10^7
Read time (ns)	<10	20–70	10–30	10–50	25,000	5–8x10^6
Write time (ns)	20–30	50–500	13–95	10–50	200,000	5–8x10^6
Retention	>10 years	<10 years	Weeks	<Second	~10 years	~10 years
Endurance (cycles)	~10^{12}	10^7–10^8	10^{15}	>10^{17}	10^5–10^6	10^{15} ?
3D capability	Yes	No	No	No	Yes	n/a

Source:

[1] Image: http://www.zdnet.com/article/the-future-of-storage-2015-and-beyond/

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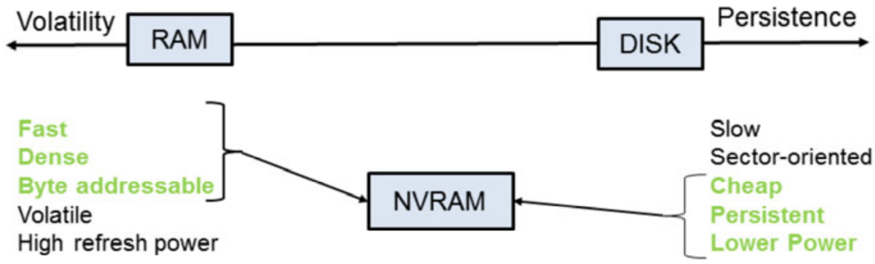
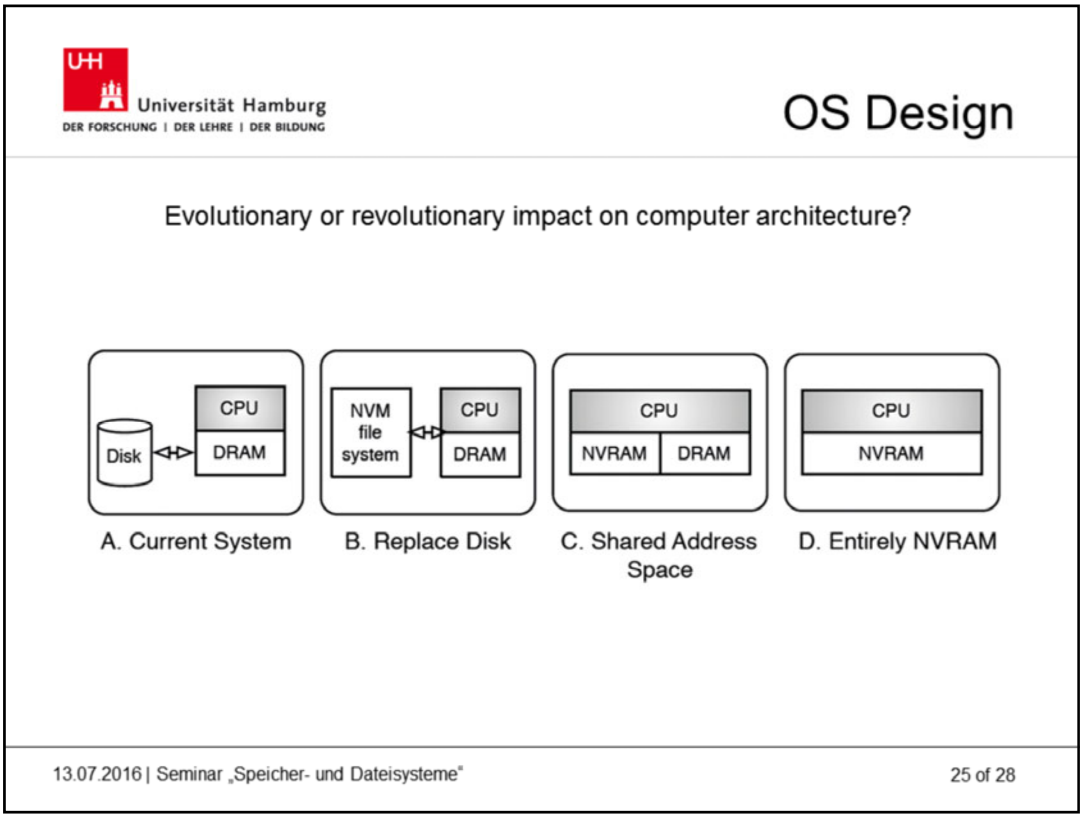
NVRAM: Universal Memory

Universal memory to replace DRAM, Flash and SSDs

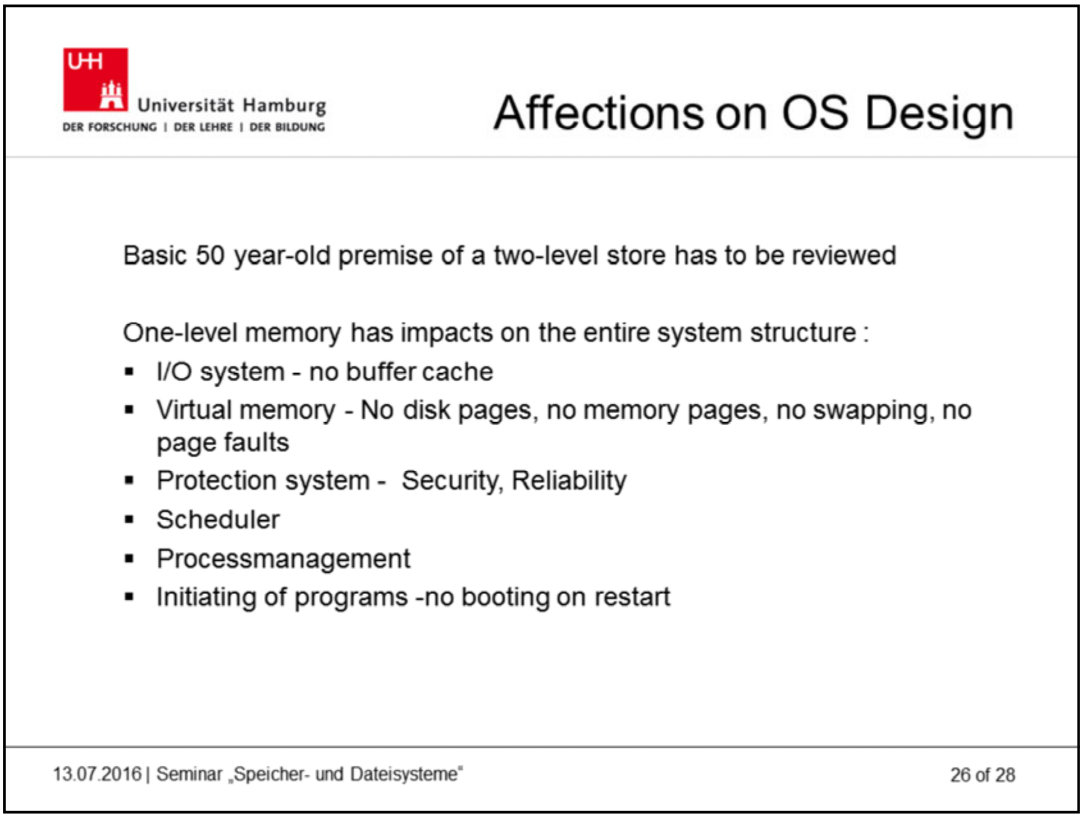




“Figure 1 shows a progression of options, from a conventional system with CPU, DRAM and disk (option A) to a system with only CPU and NVRAM (option D).” [1]

Source:

[1] https://homes.cs.washington.edu/~luisceze/publications/novos-hotos2011.pdf



Computing architecture has not changed since Von-Neumann architecture turing machines (1948).

R.S. Williams once said that the memristor is the biggest project for HP since introducing RISK 20 years ago - but doing its software is the bigger thing (3:1 work).

Source:

[1] https://homes.cs.washington.edu/~luisceze/publications/novos-hotos2011.pdf

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Opportunities and Issues

Potential issues, questions,and opportunities that NVRAM technology presents for OS design:

- How would we choose to organize the OS and persistent storage?
- How would we structure, share, and protect persistent storage?
- What parts of the OS could we simplify or remove, and what features or capabilities would be enabled by this technology?
- If memory never goes away, what does it mean to do a backup?
- How do you check data integrity when your system restarts if parts of it are always on?
- What happens if you take memory out of a server and put it in another system; do you want the information to move like a disk does or go away like memory (sensitive data) today?
- If you can't reboot to refresh a driver or get rid of a virus that's loaded into memory, how do you handle maintenance and security?

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Source:

[1] https://homes.cs.washington.edu/~luisceze/publications/novos-hotos2011.pdf

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Citations

"There have been about a dozen possible technologies [in development] and if at least one of them succeeds it will be the single largest change to computer architecture that has happened in decades."

Intel's Jim Pappas

"I'm convinced that eventually the memristor will change circuit design in the 21st century as radically as the transistor changed it in the 20th. Don't forget that the transistor was lounging around as a mainly academic curiosity for a decade until 1956, when a killer app—the hearing aid—brought it into the marketplace. My guess is that the real killer app for memristors will be invented by a curious student who is now just deciding what EE courses to take next year."

H.P. R.S.Williams

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Sources:

[1] http://www.techradar.com/news/computing-components/storage/how-universal-memory-will-replace-dram-flash-and-ssds-1222632

[2] http://spectrum.ieee.org/semiconductors/processors/how-we-found-the-missing-memristor