UNIVERSITÀ
DEGLI STUDI DI TRIESTE

dipartimento
di ingegneria
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MRAM (Magnetoresistive RAM)

A.Carini – Digital Integrated Circuits

MRAM (Magnetoresistive RAM)

Magnetoresistive Random Access Memory (MRAM) is different from conventional types of memory like SRAM, DRAM, and Flash, where electric charge is used to store information. Instead of exploiting the charge of an electron, MRAM uses its **spin** to store data. This type of electronics is known as “**spintronics**.”

At the heart of MRAM’s spintronic nature is the **magnetic tunnel junction (MTJ)**, a thin-film structure comprised of many ferromagnetic and nonmagnetic layers.

The resistance of the MTJ, and therefore bit state of the memory element, switches purely with the change in polarization of these layers.

Since these materials can hold their polarization virtually forever when unpowered, MRAM therefore falls into the nonvolatile memory (NVM) camp, along with Flash and EEPROM.

Modern MRAMs (**Spin Torque ST-MRAM**, also called **Spin-Transfer Torque STT-RAM,** and **Spin-Orbit Torque SOT-MRAM**) promise to combine the nonvolatility of Flash, the density of DRAM, the speed of SRAM, and radiation-hardness of early MRAM.

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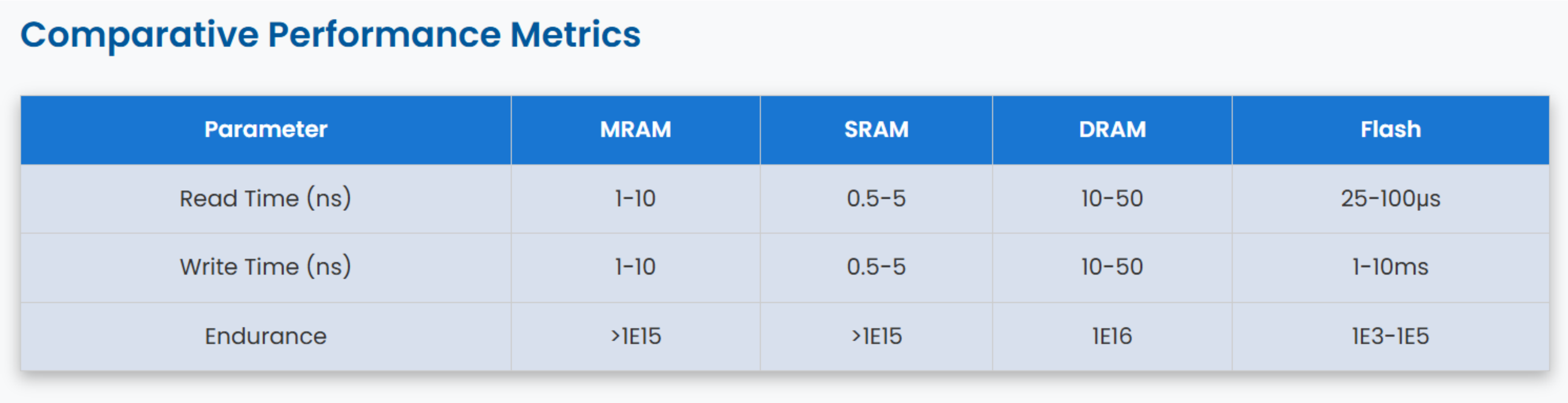
MRAM (Magnetoresistive RAM)



Comparative Performance Metrics

Parameter	MRAM	SRAM	DRAM	Flash
Read Time (ns)	1-10	0.5-5	10-50	25-100μs
Write Time (ns)	1-10	0.5-5	10-50	1-10ms
Endurance	>1E15	>1E15	1E16	1E3-1E5

From: https://www.next.gr/tutorials/digital-logic-design/

MRAM (Magnetoresistive RAM)

Performance Characteristics

State-of-the-art STT-MRAM demonstrates:

Parameter	Value
Switching Energy	< 1 pJ/bit
Access Time	5-20 ns
Endurance	> 10^{12} cycles
Retention	> 10 years @ 85°C

From: https://www.next.gr/tutorials/digital-logic-design/

Magnetic tunnel junctions

Tunnel magnetoresistance is demonstrated in structures known as **magnetic tunnel junctions (MTJs).** A basic MTJ contains a *thin tunnel layer sandwiched by two ferromagnetic layers*. The ferromagnetic material is typically some kind of iron alloy and the insulating tunnel barrier is usually aluminum oxide.

One ferromagnetic layer is **fixed** (**reference layer**) while the other ferromagnetic layer (**free layer**) **can be changed** by a driving current. The Figure shows the most basic form of an MTJ. The cell has either a parallel low resistance state or an antiparallel high resistance state.

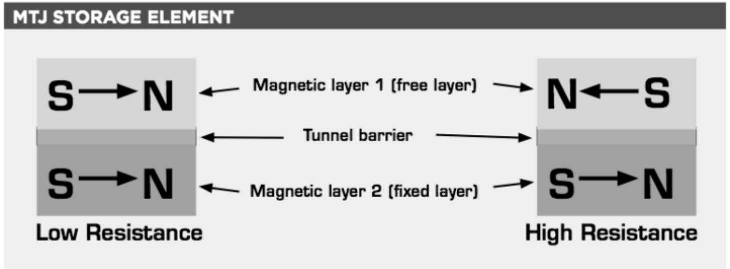


Figure 2.3-1. The MTJ has low electrical resistance when the magnetic moments of the ferromagnetic layers are parallel, and high electrical resistance when they are antiparallel [8].

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Magnetic tunnel junctions

Within a ferromagnet, the **quantum mechanical spins of the conduction electrons** are quantized into two possible vector values: the **majority of electrons** have their spins aligned **up with respect to the magnetic field**, while the **minority** population of electrons will have their **spins aligned down**.

If the conduction band electrons in the free and fixed layers are spin-aligned in the same direction, then the tunneling current across the insulator will be greater than if they are antiparallel.

Current is flowing perpendicular to the film plane (i.e., in the stack direction, from one layer to the next).

Information storage is therefore accomplished by storage of magnetic states. If the MTJ’s **magnetic layers are antiparallel** and therefore in a **high resistance** state, then under applied voltage there will be **little tunneling current** and this will be **sensed as a “0.”** The **parallel**, or **low resistance** state, **is a “1.”**

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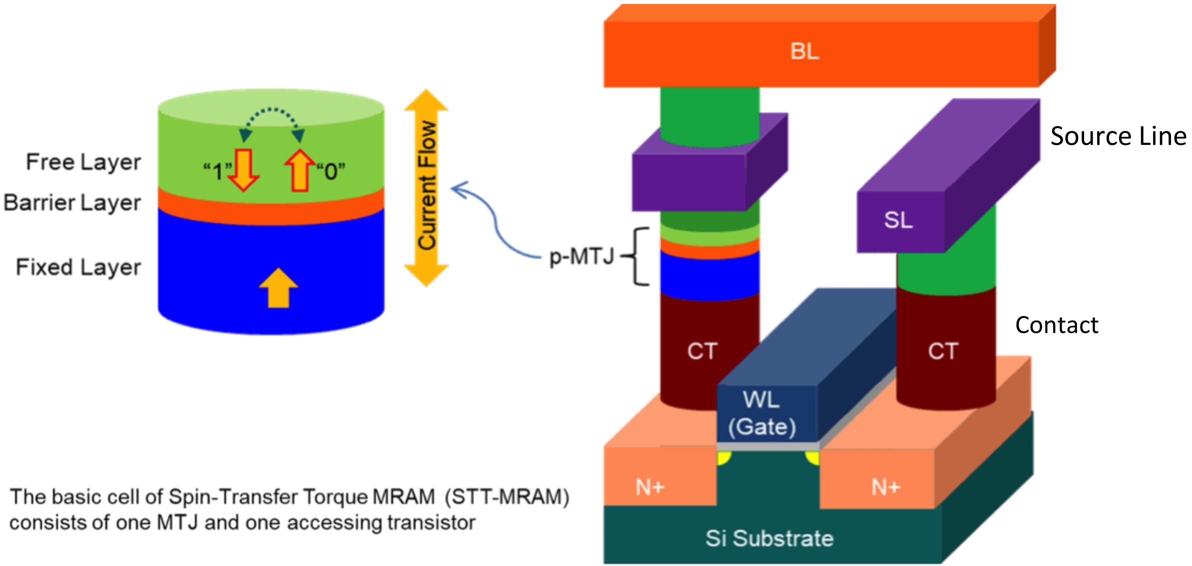
STT-MRAM

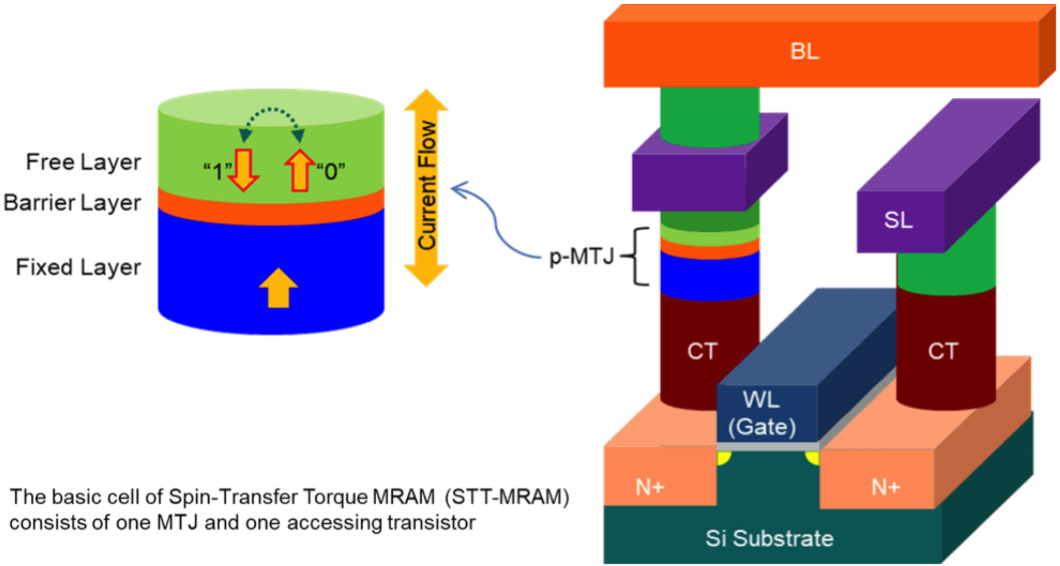


The basic cell of Spin-Transfer Torque MRAM (STT-MRAM) consists of one MTJ and one accessing transistor

Read Operations: Read operation begins when the wordline (WL) is selected and a voltage is applied between the bit-line (BL) and the source-line (SL). Current will pass through the MTJ or not depending on the state of the MTJ which can be sensed/measured.

- From: https://www.avalanche-technology.com/...

STT-MRAM



The basic cell of Spin-Transfer Torque MRAM (STT-MRAM) consists of one MTJ and one accessing transistor

Write Operations: Write operation begins when the WL is selected and a positive voltage difference is established between SL and BL for writing a "Logic 0" or a negative voltage difference is established to write a "Logic 1". The current amplitude required to ensure a successful write is related to the material of the tunnel barrier layer, the writing pulse duration, and the MTJ geometry.

- From: https://www.avalanche-technology.com/...

Writing mechanism of Spin-Transfer Torque

1 A current is applied
To write a bit, a current is driven **through the MTJ (Magnetic Tunnel Junction)**, perpendicular to its layers.
2 The current becomes spin-polarized
As electrons pass through the **fixed (pinned) layer**, they become **spin-polarized**:
Most electrons acquire the same spin orientation (aligned with the fixed layer)
3 Transfer of angular momentum
When these spin-polarized electrons enter the **free layer**:
They transfer their **angular momentum** to it
This creates a **torque** acting on the magnetization

In case the electrons pass first in the free layer, when they reach the fixed layer, if it has opposite polarity they are forced to change spin, which again creates a spin torque on the free layer that change the state.

Writing mechanism of Spin-Transfer Torque

4️⃣ **Magnetization switching**

If the current is strong enough:

The torque forces the **free layer magnetization to flip**

This results in two stable states:

- **Parallel (P)** → low resistance
- **Antiparallel (AP)** → high resistance

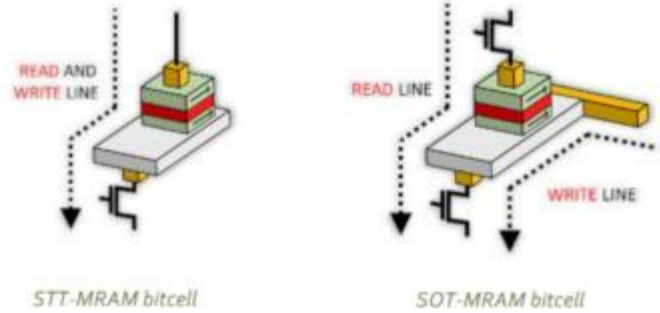
Current direction determines the bit:

- Current in one direction → sets **Parallel (P)**
- Current in the opposite direction → sets **Antiparallel (AP)**

So the **direction of current controls the stored bit**

SOT-MRAM

SOT-MRAM (spin-orbit torque MRAM) has the potential to challenge STT-MRAM, as it is a faster, denser and much more efficient memory technology.
SOT-MRAM devices feature switching of the free magnetic layer done by injecting an **in-plane current** in an adjacent SOT layer (unlike STT-MRAM where the current is injected perpendicularly into the magnetic tunnel junction and the read and write operation is performed through the same path).



- From: https://www.mram-info.com/

See:

- Jason Heidecker-MRAM Technology Status - NASA
- https://www.mram-info.com/
- https://www.next.gr/tutorials/digital-logic-design/magnetoresistive-random-access-memory-mram-tutorial
- https://www.avalanche-technology.com/key-things-to-know-about-stt-mram-what-is-it/