Semiconductor Technology from A to Z

Digital technology

MRAM – Magnetoresistive RAM 3
The Tunnel Magnetoresistance Effect (TMR) 3
Structure of the Magnetic Tunnel Junction (MTJ) 3
STT-MRAM as Today's Standard Variant 4
Properties 4

MRAM – Magnetoresistive RAM

The Tunnel Magnetoresistance Effect (TMR)

MRAM does not store information via electric charge like DRAM or flash, but via the magnetic orientation of electron spins – a fundamentally different physical storage mechanism. The basis is the tunnel magnetoresistance effect (TMR), a quantum-mechanical phenomenon: two ferromagnetic layers, separated by an insulating layer only a few atomic layers thick, allow different amounts of electric current to tunnel through depending on their relative magnetization direction. Electrons preferentially tunnel through the insulating layer when their spin orientation matches the majority spin orientation in both ferromagnetic layers.

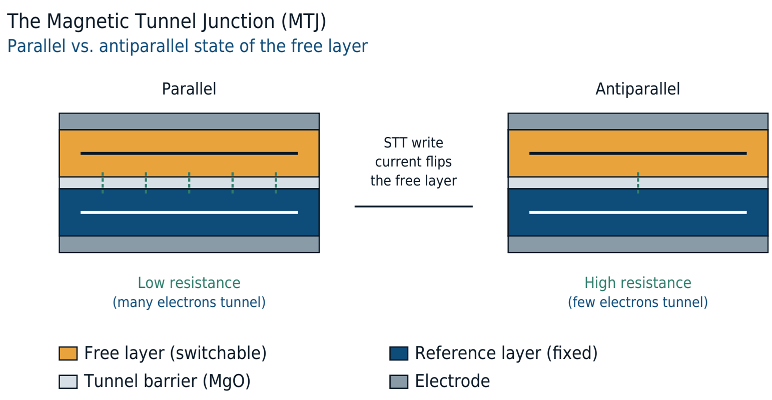
If both layers are magnetized in parallel (same orientation), most electrons find a matching state to tunnel through, and the cell's electrical resistance is low. In the antiparallel orientation (opposite magnetization), electrons must reverse their spin while tunneling, which is quantum-mechanically far less likely – resistance rises noticeably, typically by 100 to 200 percent compared to the parallel state (the so-called TMR ratio). These two clearly distinguishable resistance states encode the bits “0” and “1” and can be read out non-destructively simply by applying a small read voltage.

Structure of the Magnetic Tunnel Junction (MTJ)

The memory cell – the magnetic tunnel junction (MTJ) – consists of three central layers, typically deposited by sputtering (see the PVD chapter) in a single vacuum chamber without breaking vacuum, in order to avoid oxidation and contamination at the sensitive interfaces:

A reference layer (fixed layer or pinned layer) made of a ferromagnetic alloy, whose magnetization direction is fixed by coupling to an additional antiferromagnetic layer and stabilized against external stray fields. Above it, a wafer-thin tunnel barrier, in modern MTJs almost without exception made of crystalline magnesium oxide (MgO) only one to two nanometers thick – the crystal structure of the MgO is critical for a high TMR ratio, since it favors spin-selective tunneling probability. And finally a free layer, also ferromagnetic, whose magnetization direction can be deliberately switched for writing. Only the free layer changes state during a write operation; the reference layer serves as a stable comparison point against which resistance is measured during readout.

MTJ in the parallel and antiparallel state



STT-MRAM as Today's Standard Variant

Early MRAM generations (toggle MRAM) switched the free layer using an externally applied magnetic field, generated by current-carrying traces above and below the cell. This method required comparatively high write currents in the milliampere range and became increasingly impractical as cell size shrank, since magnetic fields cannot be arbitrarily confined to individual, closely spaced cells (crosstalk to neighboring cells).

The variant dominant today and used in all current products is STT-MRAM (spin-transfer torque MRAM): here, a spin-polarized current is passed directly through the MTJ layer stack, perpendicular to the layer planes. As the current crosses the reference layer, it becomes spin-polarized; when these spin-polarized electrons subsequently reach the free layer, they transfer their spin angular momentum to the electrons there through a quantum-mechanical effect called spin-transfer torque, exerting a torque that, given sufficient current, flips the magnetization of the free layer – entirely without an external magnetic field. Since the write current flows directly through the very cell being switched, the effect can be confined very precisely to individual cells, which makes STT-MRAM significantly more energy-efficient, less prone to interference, and above all better scalable than older field-based approaches.

Properties

MRAM combines several advantageous properties that position it uniquely among non-volatile memory technologies: it is non-volatile like flash – the magnetization direction remains stable for years without power – yet achieves write and read times in the range of a few nanoseconds, a speed comparable to

SRAM and at least approaching DRAM. Endurance exceeds 10^{12} write cycles, surpassing NAND flash by four to five orders of magnitude, since the write operation is purely magnetic and, unlike flash, causes no structural degradation of a tunnel oxide.

The current limiting factor is cell density: an MTJ cell, together with its access transistor, requires considerably more area than a comparable flash cell, and the write currents, however low compared to toggle MRAM, still limit how small and densely packed individual MTJs can practically be manufactured. For these reasons, MRAM is so far used mainly as a fast cache replacement (for example as level-3 or level-4 cache in processors), as a replacement for battery-backed SRAM in industrial and automotive controllers, and in applications with high reliability requirements – not as mass storage in the sense of an SSD.