Semiconductor Technology from A to Z

Digital technology

Comparison & Context

MRAM, ReRAM, PCM, and Flash Directly Compared

All three technologies pursue different physical principles – magnetic alignment in MRAM, filament formation via ion migration in ReRAM, structural phase transition in PCM – but in practice compete directly with one another and with established flash memory, since they target similar application areas. The key differences at a glance:

- Speed: MRAM is the fastest, achieving write and read times in the low nanosecond range, comparable to SRAM. PCM and ReRAM follow with switching times of a few tens to a few hundred nanoseconds, while NAND flash is significantly slower for write operations due to block-wise erasing, reaching into the millisecond range.
- Endurance: MRAM clearly exceeds all other technologies with over 10^{12} cycles, since the magnetic switching process causes no structural material fatigue whatsoever. ReRAM and PCM typically fall in the range of 10^6 to 10^9 cycles – for PCM limited by mechanical volume changes of the GST during repeated melting, for ReRAM by gradual structural changes in the filament region. Both nevertheless remain several orders of magnitude above NAND flash.
- Scalability and cell density: ReRAM is considered the most densely scalable, thanks to its simple crossing structure (crossbar architecture) and the possibility of multi-layer 3D stacking, followed by PCM, which also allows comparatively compact cells. MRAM is the most limited in achievable cell density due to its more complex MTJ layer structure and the additional area required for the access transistor.
- Maturity: PCM (in the form of 3D XPoint/Optane, although now discontinued) and MRAM (as embedded memory in commercial microcontrollers and SoCs) have already reached commercial production maturity and are manufactured in the millions. ReRAM is still largely in development or, so far, used only in specialized niche applications with low volumes.

Rating grid of the four technologies

Memory Technologies Compared
Qualitative ranking of MRAM, ReRAM, PCM, and NAND flash

	Speed	Endurance	Cell Density	Maturity
MRAM	●●●●●	●●●●●	●●○○○	●●●●○
ReRAM	●●●○○	●●●○○	●●●●○	●●○○○
PCM	●●●○○	●●●○○	●●●○○	●●●●○
NAND-Flash	●○○○○	●○○○○	●●●●●	●●●●●

●●●●● = very high / very mature ○○○○○ = low / early in development

Applications and Outlook

None of the three technologies will displace flash as the dominant mass-storage technology in the foreseeable future – NAND flash remains unbeatably cheap per bit thanks to decades of process optimization, extreme scaling, and enormous manufacturing volumes. Instead, MRAM, ReRAM, and PCM are increasingly establishing themselves in complementary, specialized roles: MRAM as a low-power, extremely fast, and practically unlimited-endurance cache and SRAM replacement in embedded systems, where battery-backed SRAM previously had to ensure data retention during power loss. PCM and ReRAM position themselves as potential building blocks for storage-class memory in data centers, where the gap between DRAM and SSD storage still persists.

A particularly promising field of research is so-called in-memory computing, in which compute operations – especially the matrix-vector multiplications central to neural networks – are carried out directly within the memory array, instead of first transporting data to a separate compute unit. Since resistive and phase-change memory cells encode their state as an analog resistance value, they can in principle be used directly for the weighted summation of signals (Kirchhoff's current law across a crossbar structure approximately realizes a matrix multiplication in hardware). This approach promises to bypass the so-called Von Neumann bottleneck – the fundamental limitation of classical computer architectures, in which memory and compute unit are physically separated and the data transfer between them accounts for a large share of the energy consumption of modern AI accelerators.