Semiconductor Technology from A to Z

Digital technology

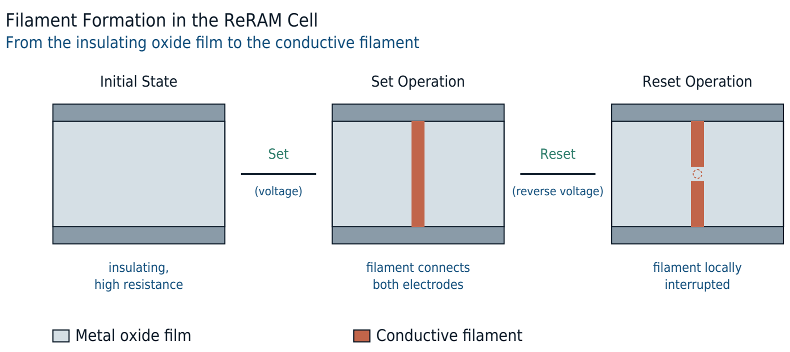
ReRAM – Resistive RAM

The Principle of Filament Formation

ReRAM stores information via the electrical resistance of a thin metal-oxide film embedded between two electrodes – a structure often referred to, due to its simplicity, as a “MIM structure” (metal-insulator-metal). In its as-fabricated initial state, this oxide film is largely insulating and homogeneous. By applying a sufficiently high voltage in the so-called forming step (performed once, at the cell's first activation), oxygen vacancies within the oxide lattice – or, in other material systems, metal ions from one of the electrodes – migrate along the electric field and arrange themselves into a thin, conductive path: a so-called filament, often only a few nanometers in diameter. This filament locally bridges the insulating layer and drastically lowers the cell's resistance at that spot, while the rest of the oxide film remains insulating.

Physically, this is an electrochemical process: the oxygen vacancies act as positively charged defects in the oxide lattice (since a negatively charged oxygen ion is missing at that lattice position) and can be moved in a targeted way by an electric field, much like ion migration in a solid-state electrolyte. This property – resistance change through ion movement rather than charge storage – fundamentally distinguishes ReRAM from flash and places it close to memristive devices.

Filament formation: initial state, set, and reset



Set and Reset Operations

Creating or strengthening the conductive filament is called the set operation and switches the cell from the high-resistance to the low-resistance state (“1”). By applying a voltage of reversed polarity, the filament can be partially dissolved again at its weakest point, as the oxygen vacancies migrate back and a thin insulating gap forms locally within the filament – the reset operation, which returns the cell to the high-resistance state (“0”). Notably, reset typically does not dissolve the entire filament but only a short section of it – an energetically more favorable and faster process than rebuilding the filament from scratch.

Since both operations, set and reset, rely purely on the movement of ions or vacancies within the solid and cause no mechanical or electrical stress on a tunnel oxide as flash does, they are in principle faster (switching times in the nanosecond range have been demonstrated in research results) and gentler on the cell than Fowler-Nordheim tunneling in flash.

Material Systems

The most common material systems for the resistive film are transition-metal oxides such as hafnium oxide (HfO_2), titanium oxide (TiO_2), and tantalum oxide (Ta_2O_5) – materials already familiar from high-k dielectric fabrication (see the compound semiconductors and high-k materials chapter) that can therefore be integrated into existing CMOS process lines comparatively easily and without exotic new precursors, typically using atomic layer deposition (see the ALD chapter) for precise, nanometer-scale thickness control. Common electrode materials include platinum, titanium nitride, or other inert or readily oxidizable metals, depending on whether one electrode is meant to serve deliberately as an oxygen reservoir.

Properties and Challenges

ReRAM cells have an extraordinarily simple structure: in the simplest case, merely a crossing point between two perpendicular traces with an oxide film in between (a so-called crossbar architecture). This makes them potentially very dense and inexpensive to manufacture – the theoretical cell size approaches the smallest possible area occupied by the crossing of two minimally wide traces ($4F^2$, where F is the minimum feature size). The simple structure also allows building multi-layer 3D stacks, where several crossbar planes are fabricated on top of one another to further multiply storage density per chip area.

The biggest challenge is variability: filament formation is a stochastic process at the atomic scale, in which the number, position, and exact geometry of the involved oxygen vacancies differ from cell to cell and even from write cycle to write cycle within the same cell. This leads to noticeable fluctuations in the resulting resistance values (cycle-to-cycle and device-to-device variability), which complicates reliable readout at high bit density and requires more elaborate read circuitry with adaptive reference values. In addition, the crosstalk problem in large crossbar arrays (sneak-path currents through neighboring, unaddressed cells) poses an architectural challenge that is often addressed with additional selector elements per cell. Both issues are subjects of active research and among the main reasons why ReRAM is so far manufactured in high volume less often than MRAM or PCM.