Semiconductor Technology from A to Z

Digital technology

Amorphous vs. Crystalline State as the Storage Principle

Phase-change memory exploits a fundamentally different physical property than the technologies covered so far: certain materials can be deliberately and reversibly switched between a disordered (amorphous) and an ordered (polycrystalline) state, whose atomic structures differ in electrical resistance by several orders of magnitude. In the amorphous state, the atoms are arranged randomly, as in a frozen liquid, which strongly impedes charge transport through scattering off the disordered structure – electrical resistance is high, and this state encodes a “0”. In the crystalline state, the atoms form a regular lattice that facilitates charge transport considerably – resistance is low, and this state encodes a “1”. The resistance ratio between the two states typically spans several orders of magnitude, enabling a very robust and error-tolerant readout method.

The Chalcogenide Material GST

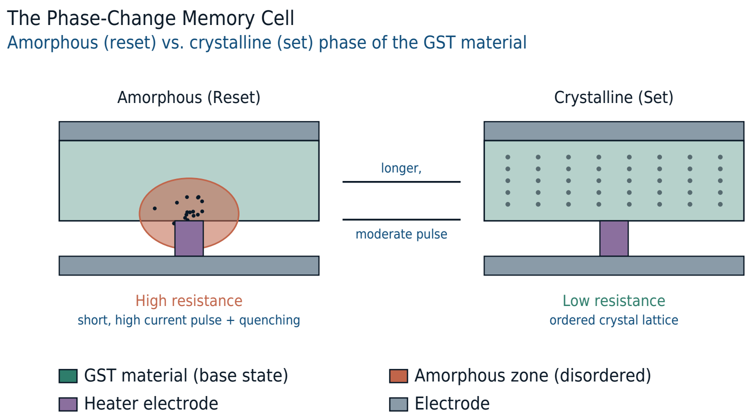
By far the most commonly used material is an alloy of germanium, antimony, and tellurium in roughly the ratio $Ge_2Sb_2Te_5$, called GST for short. GST belongs to the chalcogenide material class (compounds with group-16 elements such as sulfur, selenium, or tellurium) and has the property, crucial for memory applications, that the phase transition between amorphous and crystalline can be carried out very quickly (in the nanosecond range) and reversibly, very many times, without the material's chemical composition changing in the process – unlike, for example, the electrochemical processes in batteries, where material fatigue through chemical transformation is a central cause of aging. GST's crystallization temperature is around 150 to 200 °C, well below its melting point, allowing controlled, thermally induced switching without the cell unintentionally changing state at normal operating temperatures.

Writing by Heating and Quenching

The phase change is triggered purely thermally, usually by a small heater electrode in direct contact with the GST volume. For the amorphous state (“reset”), a short, high current pulse (in the range of a few nanoseconds) locally heats the GST above its melting point of around 600 °C and then lets it cool extremely quickly (“quenching”) – the cooling rate is on the order of several hundred million kelvin per second. This leaves the atoms no time to arrange themselves into an ordered crystal lattice, and the material solidifies in the disordered, amorphous state.

For the crystalline state (“set”), by contrast, a longer (typically a few tens to hundreds of nanoseconds) but lower-amplitude current pulse is used, which holds the material above the crystallization temperature but well below the melting point. This gives the atoms enough time to arrange into a regular crystal lattice through thermally activated diffusion. The precision of these heating and cooling profiles – exact current level, pulse duration, and edge steepness – largely determines the cell's speed, energy consumption, and reliability, and places high demands on the driver electronics.

PCM cell in the amorphous and crystalline state



Intel Optane as the Best-Known Example

The commercially best-known implementation of PCM technology was Intel Optane, based on the 3D XPoint technology developed jointly with Micron and introduced in 2015. Optane positioned itself exactly in the storage-class memory gap described at the outset: as an SSD, it was significantly faster than NAND-flash-based drives (especially for small, random write accesses and low latency), and, in a separate product variant, could even be addressed directly as an extension of working memory (Optane Persistent Memory), enabling DRAM-like access patterns while remaining non-volatile – at a lower cost per bit than DRAM and with significantly higher capacity per memory module.

Despite these unique technical characteristics, Intel discontinued the entire Optane product line in 2022 for economic reasons: manufacturing costs remained high, the market for this niche application developed more slowly than hoped, and with increasingly faster NAND flash generations (particularly through NVMe and PCIe interfaces with ever higher bandwidth), Optane's relative speed advantage over conventional SSDs diminished. A vivid example that technical superiority alone is not always enough in the market, when the competing technology advances faster than expected and the target application fails to reach a critical mass of customers.