

ENGINEERING

Phase-Change Materials for Electronic Memories

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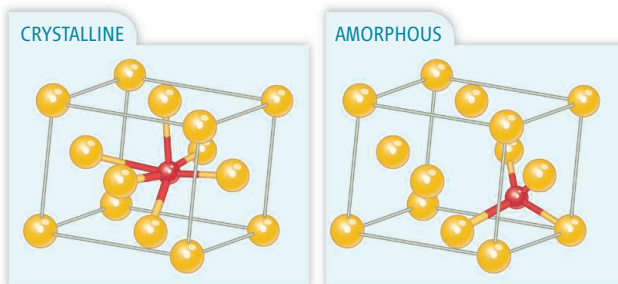
Cell phones, digital music players, and digital cameras have become pervasive and almost essential components of everyday life. The next wave of digital devices, such as ultramobile PCs and internet-connected personal assistants, promise to further influence the way we live and work. All these devices have been enabled by rapid increases in the storage density of solid-state nonvolatile memory, called flash memory, which operates by injecting and storing a charge for long periods of time in an insulated, floating gate structure. Encouraged by the success of flash, alternatives are being explored that may be faster, smaller, and offer higher levels of functionality. One approach aims to exploit the phase-change materials used today in rewritable CDs and DVDs.

Flash memory is used to store not only music, pictures, and other data on portable devices but also the operating system and application programs that enable the devices to work. Information is stored by placing or removing electrons on an electrically isolated capacitor that is integrated into a transistor. The presence or absence of electrons changes the behavior of the transistor which can be associated with a binary data bit (a “0” or a “1”). The distinctive feature value of flash versus other solid-state memory is nonvolatility. Stored data will remain even in the absence of power. A single flash memory device today can store 10’s of billions of bits of information, but as new portable device applications continue to emerge, demands are constantly being made to increase storage density. However, some of the physical limits for the storage mechanism are being approached, which has stimulated interest in the study of new storage physics.

State-of-the-art flash uses features of ~45 nm today, but serious issues begin to arise for feature sizes below about 20 nm due to retention of electrons. Of the new nonvolatile memory alternatives, phase-change memory is rapidly gaining favor as the leading candidate to succeed flash, but also because it offers the possibility of new usage models for nonvolatile memory.

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The materials used in rewritable CDs and DVDs also show promise as electronic memories systems.



Crystal versus amorphous phase. A germanium atom in the face-centered cubic structure formed by tellurium atoms. The germanium atoms occupy the octahedral and tetrahedral symmetry positions in the crystalline and amorphous states, respectively. [Adapted from (1)]

Phase-change memory uses a different storage mechanism than does flash memory. Data are stored not as charge but as a physical structural difference in the material. These materials undergo a stable, rapid, and reversible transition between an ordered crystalline and a disordered amorphous atomic structure. The two phases have different reflectivities, which have been exploited in optical memories, but also different conductivities, which can be exploited in electronic memories.

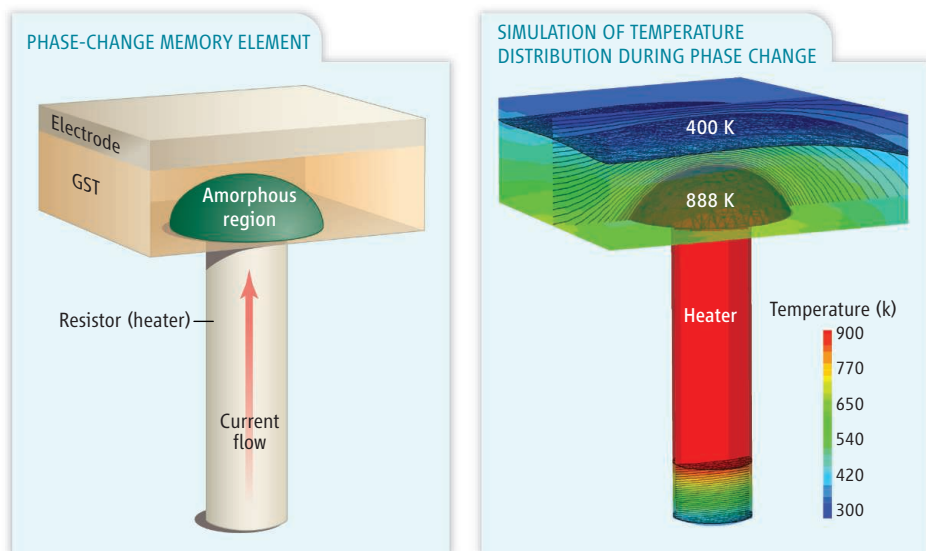
The materials are generally called chalcogenides, because they contain one of the group 6 periodic elements. One of the most

widely studied materials is GST, a glassy alloy of germanium, antimony, and tellurium.

The transition between the two phases for chalcogenides is achieved by applying heat to “melt” the material, putting it in a disordered state, and subsequently cooling it, which will “freeze” the material in the disordered phase or allow crystals to grow and result in a locally ordered

phase; the final phase is determined by the rate of cooling. The transition between these two phases for GST can be quite fast: about 1 ns to form the disordered phase and about 100 ns to form the ordered phase.

The transition is rapid because only a small change in atomic structure is required to alter its phase. In GST [see the first figure and (1)], the ordered (crystalline) phase is believed to be a distorted rock salt structure, with the germanium atoms in an octahedral coordination; the disordered (amorphous) phase bonds the germanium atoms to a tetrahedral coordination. This structural change takes place locally, does not require relaxation of the complete structure,



Making resistive memories. (Left) Phase-change memory element. (Right) Simulation of temperature distribution during phase change.

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and does not require diffusion. The change in electronic state accounts for the large change in optical and electrical properties.

Exploitation of the phase-change behavior of chalcogenide materials for storage is accomplished by one of two means: optical or electrical. In the amorphous phase, the material has a low reflectance and high resistance; in the crystalline phase, it has a high reflectance and low resistance. For optical storage, the heat required to change the phase is provided by a laser, and the reading of the stored data is done using a lower-power laser. However, high-power, slow, and large rotating optical drives are not suitable for the small devices that use flash.

Recent research (2) has focused on exploiting the electrical-resistive change behavior of phase-change materials for the development of a solid-state memory device. For these devices, the heat required to invoke phase change (and hence resistance change) is provided by passing a current through a resistor, or heating element, in contact and in series with the chalcogenide material (see the second figure). The stored data is read by passing a lower current through the chalcogenide and sensing its resistance. The power required to invoke a phase change is low because the vol-

ume of melted material is small, with a cross section of about 50 nm by 5 nm, making it viable for the development of high-density, high-performance memories.

Electrical phase-change memories are interesting for two primary reasons. The first is enhanced functionality. Phase-change memory can be altered at the bit level and can be written more than 1 million times, whereas flash must be altered in large blocks of bits and can be written only tens of thousand of times. The merger of some of the properties of today's flash and dynamic random-access memory (DRAM) provides a new level of functionality that can result in not only replacing flash but also replacing some usages of DRAM, such as storing frequently used operating code and high-performance disk caching.

The second reason for interest in phase-change memory is the small size of its memory element and its scalability. The phase-change physics shows promise to be scalable to dimensions of below 5 nm (2), providing the opportunity to continue the rate of cost reduction and density increase established by flash memory well into the next decade.

The ability to store more than one bit of information in a single phase-change mem-

ory element has been demonstrated (3), opening the possibility for further density increases. Multiple-bit storage exploits the fact that the resistance can be set to one of many discrete values through the proper combination of amorphous and crystalline properties in the memory element. For example, four resistance levels in a single memory element effectively store two bits of information.

Phase-change memory is emerging as a leading contender for replacing flash memory and expanding the capabilities of nonvolatile memory into the next decade. High-density, 128 Mb, phase-change memory prototypes have been demonstrated (4) at 90 nm, showing good performance and reliability. These prototypes are initiating the first steps of this technology into the marketplace.

References

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PALEONTOLOGY

New Tricks with Old Bones

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Progress in the field of ancient-organism genomics is prying open doors into the tombs of the long-deceased relatives of humans and other mammals. Advances in high-throughput DNA sequencing have provided initial glimpses of the nuclear genomes of ancestral organisms—cave bears, mammoths, and our closest relative, Neandertals, which diverged from a common ancestor with humans approximately 700,000 years ago (1–4). New discoveries have answered longstanding questions and opened new areas of debate, particularly regarding human evolution. Despite these developments, the preciousness of ancient remains, age-associated DNA damage, and sample contamination persist as barriers to progress, and the field of ancient-organism genomics lags far behind that of

extant organisms. A series of promising new technologies and approaches for advancing the field—including novel ways to maximize DNA recovery, targeted capture of specific genomic regions, and analysis strategies for addressing the important issue of result contamination—are poised to contribute to insights into the genomes of extinct organisms.

Material for ancient DNA studies is restricted by preciousness of the specimens (particularly in the case of hominids) and the destructive processes required for the extraction of DNA from samples. Whole-genome amplification techniques begin to address this problem, but the small fragment sizes (often fewer than 100 base pairs) and damage characteristics of ancient DNA tend to result in the preferential amplification of undamaged modern and environmental contaminating DNA (5). Emulsion polymerase chain reaction (emPCR), a recently developed technique in which DNA molecules are spatially segregated and amplified in aqueous droplets in a water-

Paleogenomic researchers are finding new ways to solve the problems of sample rarity and contamination.

in-oil emulsion (6), is a promising method for increasing sample yield. Each droplet contains a single template DNA molecule, and the cycles of enzymatic reactions that replicate it occur in the isolated droplets, substantially reducing the preferential amplification of undamaged modern DNA molecules over ancient damaged ones. This approach enables an unbiased increase in the yield of authentic endogenous nuclear DNA. Recently, nanogram amounts of starting material from 50,000- to 70,000-year-old horse, wolf, and bison were amplified by a factor of 500 to 1000 to microgram quantities (7). Applied to precious ancient material, this technique should greatly increase the amount of DNA sequence obtained per unit mass, reducing the degree of sample destruction required to carry out genomic studies.

The introduction of new parallel sequencing platforms has dramatically increased the production of random genome sequence, but many studies require the sequencing of specific regions from an organism's genome.

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