

## PHASE-CHANGE MEMORY

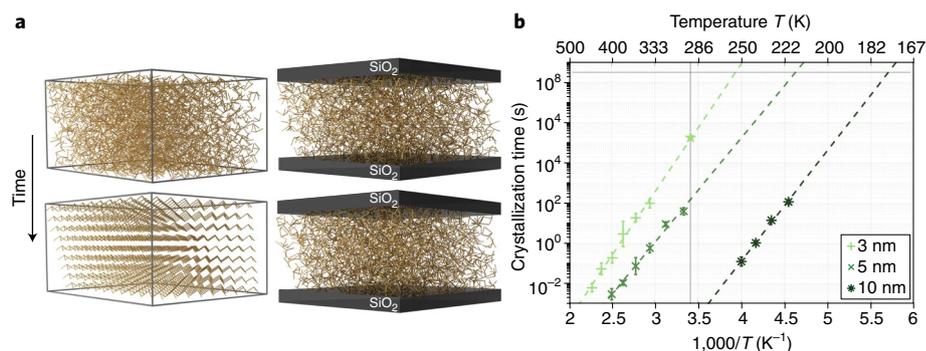
## Single-element glass to record data

Monatomic glassy antimony can now be achieved via melt-quenching in a nanoconfined volume in a device setting. In contrast to alloys currently used in phase-change memories, deviation from optimized composition is no longer an issue in this simple material.

Wei Zhang and Evan Ma

Mobile electronics, the Internet, artificial intelligence, big data and high-performance computing are changing our lives rapidly and profoundly. They also pose, however, a major challenge on data storage and processing: the volume of digital information across the globe doubles every two years, set to reach 44 zettabytes ( $4.4 \times 10^{10}$  terabytes) by 2020<sup>1</sup>. A new generation of non-volatile memories that preserve data in the absence of power supply (much like hard disk drives), and at the same time are as fast as dynamic random access memories (DRAMs), is currently being pursued to meet this challenge<sup>2</sup>. Among the competing candidates, phase-change memories (PCMs) are the most mature technology, and already start to serve as storage-class memories<sup>3</sup> to boost the computing efficiency. Writing in *Nature Materials*, Martin Salinga and co-workers now<sup>4</sup> report a new design of PCM with aggressively miniaturized memory cell volume down to only 3 nm along the vertical direction, towards increased storage density and reduced power consumption per operation. Importantly, they are able to simplify the core material from the conventional multicomponent alloys to just one single element — antimony (Sb). This eliminates the risks of compositional partitioning that could develop in alloys, degrading the PCM performance after millions of write-erase cycles<sup>4</sup>.

A PCM exploits the large electrical resistance contrast between the ordered crystalline phase ('1') and the disordered amorphous phase ('0') of chalcogenide phase-change materials to store digital information<sup>5</sup>, with the switching speed depending on the times required by the reversible crystallization/amorphization processes<sup>5</sup>. A typical commercial product employs the ternary compound  $\text{Ge}_2\text{Sb}_2\text{Te}_3$  in the memory units, and each operation takes  $\sim 100$  ns, which is approximately 1,000 times faster than solid state hard drives but ten times slower than DRAMs. The operation speed is mainly limited by



**Fig. 1 | Amorphous Sb in PCM device. a**, At room temperature, the Sb film that normally crystallizes instantly (left panel) can stay amorphous for  $10^2$ – $10^5$  seconds, when it is only a few nanometres thick and confined between  $\text{SiO}_2$  layers (right panel). Brown lines represent bonds between Sb atoms in the film. **b**, The lifetime of amorphous Sb before crystallization sets in increases with decreasing film thickness, reaching 50.8 hours at 20 °C (vertical line) for the 3 nm case. Panel **b** adapted from ref. <sup>4</sup>, Macmillan Publishers Ltd.

the write process — crystallization. Recent efforts have accelerated nucleation, by rapidly generating crystalline seeds inside the amorphous region, through either the pre-programming of the electric pulse<sup>6</sup> or a judicious alloy design leading to a new composition  $\text{Sc}_{0.2}\text{Sb}_2\text{Te}_3$  (ref. <sup>7</sup>), successfully bringing the write time down to sub-nanosecond level even in conventional memory cells (150-nm thick)<sup>7</sup>. This enables direct competition of PCMs with DRAMs and even static random access memories (SRAMs) in terms of operation speed.

Current PCM chips can also support the storage of several hundred gigabytes of data, which is several orders of magnitude higher than SRAMs, while the cost per gigabyte is 100 times cheaper<sup>3</sup>. By scaling down the cell size of memory units, the storage density of PCMs can be increased further. The endurance and thermal stability can be optimized even more, with improved confinement materials and design. However, the smaller the device, the higher its propensity for and sensitivity to local compositional variations, which may

make the memory units deviate from their intended behaviour.

Salinga and collaborators bypassed this problem by using a single-element material, and realized the switching between the amorphous and crystalline states in pure Sb films with thickness ranging between 3 and 10 nm confined inside 40–200 nm  $\text{SiO}_2$  layers that serve as thermal and electric insulation. Sb is known to have the capability of rapid crystal growth, and it is thus very challenging to acquire and retain elemental Sb in its amorphous state at room temperature. To this end, very high cooling rates<sup>8</sup> and suitable confinements at the nanoscale<sup>9</sup> are possible solutions. Along this path, Salinga and colleagues managed to reach a fast cooling rate of nearly  $10^{10}$  kelvin per second in a nanoconfined real device setting<sup>4</sup>. The outcome is an amorphous Sb that survived up to 50.8 hours at 20 °C (Fig. 1).

Analysis of the amorphous phase reveals further interesting behaviour. On ageing at  $-173$  °C, the electrical resistance of amorphous Sb increased slowly but steadily with time<sup>4</sup>, deviating further from

the crystalline counterpart. Remarkably, the resistance drift coefficient at such a low temperature is similar to that of amorphous  $\text{Ge}_2\text{Sb}_2\text{Te}_5$  at room temperature<sup>10</sup>. Relaxation in glasses normally corresponds to a complex structural rearrangement in short-to-medium range order, including reinforced Peierls distortion<sup>11</sup> in the PCM case, towards the ideal- or ultrastable-glass<sup>12</sup> state. If and how these mechanisms play out in glassy Sb remains to be clarified. The crystallization and ageing paths are different, leading to opposite trends of resistance change. The two processes are expected to cross over in a very narrow temperature window. It will also be very interesting to assess the thermal energy required for, and the lower temperature limit of, the ageing process in amorphous Sb. Akin to monatomic tantalum (or vanadium) metallic glasses<sup>8</sup> recently obtained also by ultrafast quenching from the melt, amorphous Sb is simple in chemical composition but complex in the temperature dependence of liquid dynamics. These poor glass formers are intriguing to our understanding of glass formation and relaxation, in contrast to the normal multicomponent compositions where confusion reigns to make them easier glass formers.

Looking at the immediate potential for applications, the new PCM does

face challenging issues. The amorphous state of this pure element only showed a lifetime of  $\sim 100$  seconds<sup>4</sup> at 60–70 °C, the likely temperature window for practical use inside electronic devices. Although this lifetime is already sufficiently long for some quasi-non-volatile applications, including memory-mapped storage class memory, in-memory computing and brain-inspired neuromorphic computing, it needs to be drastically extended for truly non-volatile applications. This may be achieved, for instance, by further reducing the Sb film thickness, confining Sb in all three dimensions, and designing better confinement materials. The voltage pulse (currently 50 ns) required for amorphization needs to be shortened to become competitive with DRAMs and SRAMs. Also importantly, the crystallization speed, endurance in switching cycles and power consumption all remain to be determined quantitatively, to systematically compare with the mature PCMs that already perform remarkably well in all these aspects. What has been achieved by Salinga and colleagues is nevertheless unprecedented and eye-opening, in terms of the perspective that monatomic PCMs are indeed feasible, and that an elemental glass, usually considered impractical due to its poor glass-forming

ability, may be rendered useful in memory devices. □

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## INTRACELLULAR DIFFUSION

# A tale about square dancers and maze runners

Single-particle tracking of nanoparticles dispersed in the cytoplasm of living cells shows that non-specific interactions with the intracellular environment are the major contributors for the anomalous diffusion characteristics of intracellular motion.

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Cells are complex, multiscale textured entities of matter with singular material properties. Their interior is compartmentalized on multiple length scales by a variety of membrane-enclosed organelles with diameters from 10  $\mu\text{m}$  down to 50 nm, intermingled in an aqueous phase that is crowded with  $\sim 10,000$  macromolecule species at a total concentration of 100–400  $\text{mg ml}^{-1}$  (ref. 1). It is not surprising that transport in such a crowded environment deviates significantly from simple Brownian motion in dilute fluids<sup>2,3</sup>. Yet, despite its frequent utilization and easy-to-grasp meaning, the terminus

‘crowding’ is only loosely defined and basically integrates excluded-volume effects on all scales as well as interactions with neighbouring structures. Dissecting these two facets of crowding in cells and quantifying their differential impact on (diffusional) transport is therefore a topical problem. Now, writing in *Nature Materials*, Fred Etoc and colleagues<sup>4</sup> reveal that nanoparticles exhibit an anomalous diffusion in living cells due to non-specific interactions with intracellular components and not because of motion restriction by inaccessible sub-volumes of the crowded environment. Metaphorically

speaking, anomalous diffusion is seen for ‘square dancers’ (nanoparticles with significant non-specific interactions) that are slowed down by their dancing chorus, but not for ‘lonesome maze runners’ (inert nanoparticles) that explore the intracellular labyrinth just by themselves.

Starting with Einstein’s seminal paper on diffusion<sup>5</sup>, the erratic, thermally driven motion of small particles in fluids has been studied extensively. Modern textbooks teach students that diffusing particles perform a random walk, reminiscent of a drunkard’s locomotion after a pub crawl. Fixing few basic properties of the