MATERIALS SCIENCE

Toward ultimate nonvolatile resistive memories: The mechanism behind ovonic threshold switching revealed

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Fifty years after its discovery, the ovonic threshold switching (OTS) phenomenon, a unique nonlinear behavior of conductivity observed in some chalcogenide glasses, has been recently at the origin of a real technological breakthrough in the field of data storage memories. This was achieved because of the successful 3D integration of so-called OTS selector devices with innovative phase-change memories, both being based on a chalcogenide material. This paves the way to storage class memories as well as neuromorphic circuits. Here, we elucidate the mechanism behind OTS switching by new state-of-the-art materials using electrical, optical, and x-ray absorption experiments, as well as ab initio molecular dynamics simulations. The model explaining the switching mechanism occurring in the amorphous OTS materials under electric field involves metastable formation of the newly introduced metavalent bonds. This model opens the way to the design of improved OTS materials and far beyond to new fields of applications such as brain-inspired computing for the broad artificial intelligence field.

INTRODUCTION

Chalcogenide materials have attracted much attention over the years owing to their large field of applications, ranging from memories to optical or thermoelectric devices and so on. Among them, some chalcogenide compounds exhibit a unique portfolio of properties, which has led to their wide use for nonvolatile memory applications such as optical data storage or, more recently, phase-change memories (PCMs) (*1*). Besides a high infrared transparency window and large optical nonlinearities (*2*), some chalcogenide glasses (CGs) exhibit an uncommon conductivity behavior under high electric field, called the ovonic threshold switching (OTS) effect.

This OTS mechanism, discovered in the 1960s by Stanford R. Ovshinsky, consists of the reversible transition between a highly resistive state (OFF state) and a conductive state (ON state) when the voltage applied on the CG exceeds a critical threshold value, V_{th} (*3*). When the current is reduced below the holding current density, J_h, the selector recovers its high resistance state (*1*, *3*–*12*).

Some chalcogenide materials are now considered as most promising for high-density, energy-efficient, nonvolatile resistive memories owing to their successful integration in high-density three-dimensional (3D) cross-point memory (CPM) arrays (*13*, *14*). This can only be achieved by the addition of an active element, called selector, to each resistive memory cell. In the present case, the selector consists of a chalcogenide material, which allows the individual reading and programming of each memory point in the 3D memory network. This element should thus be able to provide not only a large enough current to reversibly switch the memory from the highly resistive (amorphous) RESET state to the highly conductive (and crystalline) SET state but also a very low leakage current when the memory cell is unselected to avoid any undesired programming (see Fig. 1).

OTS materials are perfectly adapted for such a use (*1*, *4*, *5*), whereas conventional transistor fails, as demonstrated in the recently developed Optane technology from Intel/Micron (*13*). However, the underlying physical mechanism of the OTS effect is still unclear, as two different models have been proposed: The first one is based on a purely electronic excitation effect by tunneling in a hopping transport framework (*6*, *7*), whereas the second one invokes a thermally assisted mechanism (*8*, *9*) with a change of local structure or electric field–assisted formation of a metastable crystalline filament (*10*, *11*) upon threshold switching.

Most known OTS materials are based on good glass formers such as Se and Se/Te CGs, all of them containing As as the network former (*12*). Originally, arsenic was introduced to improve the (meta) stability of these glasses against crystallization and external environment effects such as oxidation. However, the toxicity of As is notorious (*15*), and future technologies should thus replace it with less hazardous elements. This also creates a challenge for materials scientists and engineers.

In this work, we show how innovative As-free amorphous OTS thin films based on Se-rich GeSe glasses permit to achieve state-of-the-art OTS devices (*16*–*18*) with outstanding performance, such as well-adapted threshold voltage V_{th}, low subthreshold leakage current (I_{OFF}), and high endurance. In contrast to Ge-rich (*19*) or Sb-doped GeSe-based (*20*) OTS thin films, our Sb- and N-doped GeSe materials provide an ideal compromise between a high stability against crystallization, low V_{th}, and limited subthreshold currents that are critical for the development of higher-density and less-consuming 3D memories (*1*, *4*, *5*, *13*).

We performed electrical measurements on test OTS devices as well as spectroscopic ellipsometry and x-ray absorption spectroscopy (XAS) measurements on the OTS films. We show that Sb and N atoms modify the structure of the $Ge_{30}Se_{70}$ (GS) glass in such a way that the OTS performance is strongly enhanced. Using ab initio molecular dynamics (AIMD) simulations, we provide a model for

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Teaser: The microscopic origin of the ovonic threshold switching mechanism is unveiled here.