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Phase-Change Memories: Materials Science, Technological Applications and Perspectives

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Editorial

Phase-Change Memories: Materials Science, Technological Applications and Perspectives

Guest Editors

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It is our pleasure to introduce this special issue in which are summarised recent progresses in the rapidly developing field of phase-change memories (PCM or PRAM), from fundamental understanding and scientific knowledge of their unique properties toward their straightforward applications, as well as some of their most promising novel perspectives. We hope that this issue will provide a snapshot of the latest developments for scientific and technological advances of the PCMs, so as to provide an exhaustive overview of the state-of-the-art and future trends. Indeed, the history of phase-change memories, which offer a unique set of features (multi-level storage, fast read/write latency, nonvolatility, good cycling endurance, and good scalability even when downscaling beyond lithographic limits), is reviewed here from their discovery more than 50 years ago toward its current leading position among emerging memory technologies, to fill the performance gap between volatile DRAM and non-volatile Flash memories. This has led PCM to play today a major role in the storage class memory arena and also for the emerging neuromorphic and in-memory computing applications, as reviewed by Fantini [1]. PCM are currently the most mature among the various kinds of emerging memories, as demonstrated in high density standalone memories. The latter meet the requirements of embedded Non-Volatile Memories (eNVM), as fulfilled by the ePCM (embedded PCM) technology that is described in the paper from Capelletti *et al.* [2]. It is demonstrated that the potential for ePCM will become the mainstream eNVM technology, at CMOS 28nm node and below, for automotive applications.

All these technological successes rely first on the working principle of PCM devices and their physics, as detailed in the work from Le Gallo *et al.* [3], in which are also raised the most challenging aspects for their future development, such as the increase of the storage capacity per cell and the reduction of power consumption. Indeed, despite previous successful achievements of PCM, many issues are still pending, such as scaling effects.

The constant downscaling of PCM cells leads to a more and more paramount role of interfaces and the finite-size effects on their unique portfolio of properties. In that context, Wang *et al.* explored, by means of atomistic simulations, a way to design novel nanoscale PCM materials based on the interface effects [4]. In a similar but experimental approach, Mio *et al.* investigated the effect of the interfaces on the disordering processes of GeSb₂Te₄ by using Ar⁺ ion irradiation [5]. Their findings, that sound essential for the interfacial PCM devices, suggest that, by a proper interface engineering, the stability of the crystalline phases can be either reduced or enhanced, both in ordering and disordering processes, the latter being the key parameters governing the switching process in PCM devices. In a close study, by means of *in situ* analysis by transmission electron microscopy (TEM) D'Arrigo *et al.* evidenced also that recrystallization of irradiation-formed amorphous nanoregions (20–100 nm in diameter) embedded in a textured epitaxial Ge₂Sb₂Te₅ (GST) film is only governed by rearrangement of the atoms at the amorphous-crystalline boundary [6]. This result tends to demonstrate that recrystallization is here a growth-dominated mechanism that is opposite to the commonly observed nucleation-dominated mechanism expected so far for

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amorphous domes surrounded by the poly-crystals of the metastable cubic phase of GST films used in conventional PCM devices. Hagen Bryja *et al.* experimentally studied the underlying mechanisms in amorphous chalcogenide-based resistive switching devices to provide guidelines for electrode material selection, as well as showed the crucial impact of interfacial interactions on device reliability [7].

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Besides, while the more and more successful growth of phase-change materials nanostructures, such as the ordered Sb–Te and In–Ge–Te nanostructures by metal–organic chemical vapour deposition (MOCVD) reported in the work from Cecchini *et al.*, [8], opens huge perspectives, it also asks for a fundamental understanding of the evolution of properties at ultimate scales. Bosoni *et al.* started to pave the way to theoretically reveal the complex change of properties induced by downscaling effects when showing the decrease of GeTe thermal conductivity between bulk material toward nanowire structure; they used state-of-the-art advanced calculation methods based on non-equilibrium molecular dynamics simulations and employed a machine learning interatomic potential [9]. Thanks again to the ongoing progress of computing approaches, Mocanu *et al.* performed molecular-dynamics simulations of the canonical GST225 material, made by using a new, linear-scaling, machine-learned interatomic (GAP) potential, to explore the effects of model size (up to 24 300 atoms!), and a quench rate down to 10^{12} K s^{-1} [10]. The promising outcome of this approach is to theoretically give an estimate for the critical minimum quench rate from the liquid, below which this phase-change material cannot be vitrified.

Despite their wide dissemination for years in PCM and other devices, a basic understanding of some of the peculiar behaviour of phase-change materials having an outmost impact on devices performance is still under the scope of science. This quest of understanding is perfectly well-illustrated by the long-standing debate and the search for an explanation of the unique contrast of electronic properties occurring between the amorphous and crystalline phases of phase-change material compounds. Herein, Raty and Wuttig revisited bonding in the popular crystalline GeTe, a simple binary phase-change material alloy, by using an *ab initio* approach that goes beyond the usual one-electron description obtained with density functional theory [11]. GeTe is shown to be among a class of materials for which a peculiar set of properties prevails and previously ascribed to resonant bonding. However, the corresponding materials have been coined 'incipient metals' and their bonding 'metavalent bonding' (MVB), that significantly differs from the covalent materials or resonantly bonded materials, such as graphene or benzene. Besides, the well-known drift of resistivity of the amorphous phase of phase-change materials upon aging, that is the main process that hindered up-to-now the development of efficient multilevel storage with PCM, is still highly debated without any real consensus, yet. Within that frame, Elliott proposed a novel scenario for the resistance drift phenomenon based on an intrinsic electronic mechanism in relation to the phenomenon of persistent photoconductivity that is commonly observed in a wide range of disordered semiconductors [12]. The proposed mechanism, that involves slow charge-carrier detrapping and subsequent recombination following electron-hole injection during the RESET pulse, is governed by the energy widths of the band-tail and electronic density of states of the phase-change material, thus ruling out structural (atomistic) aging effects of most of all previous proposed drift models.

Finally, nano- and atomic-scale design of the phase-change material opens also a bright future for PCM, as for instance the significant performance

improvement when using epitaxial GeTe/Sb₂Te₃ super-lattices (SLs) instead of the conventional Ge-Sb-Te poly-crystalline alloy. Even if such kind of SLs has demonstrated very promising switching performances, the underlying mechanism at its basis is still not yet understood. This mainly results from the lack of a robust structural description of the local order around Ge atoms within the SL, which has been proposed to play a major role in the switching process. In the context of such an ongoing debate on whether pure Ge or intermixed Ge/Sb planes exist in the SL, D'Acapito *et al.* demonstrated unambiguously for the first time, by means of X-ray Absorption Spectroscopy, that the GeTe/Sb₂Te₃ layers intermixing, to form Ge/Sb mixed planes separated by pure Te planes upon growth at high temperature, is inherent to the SLs' structure, being therefore not avoidable [13]. Intermixing does not result from the lack of control of the (GeTe)₂ layer thickness and SL stacking sequence or composition, nor sample preparation, nor artifact induced by characterization method, as e.g. previously suggested by some authors to explain conflicting results between proposed models and experimental observations. The elaboration of these SLs based on a growth of highly-oriented Sb₂Te₃ layers by using a method similar to van der Waals epitaxy of 2D materials opens also numerous opportunities in a wide frame of applications. Therefore, mastering the growth of high-quality and very well-oriented Sb₂Te₃ films on various substrates is mandatory. Despite, it has been previously suggested that such a "van der Waals" epitaxy of highly-oriented Sb₂Te₃ films cannot occur on every material, due to surface chemical selectivity, Hippert *et al.* revealed here that successful growth of highly out-of-plane oriented Sb₂Te₃ layers on various materials is possible even in an industrial equipment by using standard sputtering technique. This novel growth mechanism relies on a proper substrate surface preparation involving Te saturation of the surface prior to or at the first stage of growth [14]. By unknowingly using in part the same mechanism, Saito *et al.* were able to grow high-quality layered chalcogenides and pnictides including Sb₂Te₃, Bi₂Te₃, GeTe, (Bi_xSb_{1-x})₂Te₃, and Bi_xSb_{1-x} on a variety of substrate types [15], opening new and promising fields of applications based on same or similar materials to those that were behind the success of PCM.

To conclude, we as guest editors, hope that you will appreciate this special issue on Phase-Change Memory as we did, for the high quality of this collection of state-of-the-art articles based on the high expertise of all outstanding contributors, who we consider as main leaders in the field of PCM.

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