Exploring the Limits of Phase Change Memories

Matthias Wuttig
Physics of Novel Materials
RWTH Aachen University of Technology
Aachen, Germany

Abstract— **Phase change materials are among the most promising compounds in information technology. They can be very rapidly switched between the amorphous and the crystalline state, indicative for peculiar crystallization behaviour. Phase change materials are already employed in rewriteable optical data storage, where the pronounced difference of optical properties between the amorphous and crystalline state is used. This unconventional class of materials is also the basis of a storage concept to replace flash memory. This talk will discuss the unique material properties which characterize phase change materials. In particular, it will be shown that the crystalline state of phase change materials is characterized by the occurrence of resonant bonding, a particular flavour of covalent bonding. This insight is employed to predict systematic property trends and to develop non-volatile memories with DRAM-like switching speeds potentially paving the road towards a universal memory. Phase change materials do not only provide exciting opportunities for applications including 'greener' storage devices, but also form a unique quantum state of matter as will be demonstrated by transport measurements. In this talk, potential limits of phase change memories in terms of switching speed, scalability and power consumption will be discussed.**

Keywords—Phase change materials, non-volatile memory

In the on-going investigation of higher chalcogenides, i.e. compounds containing sulphur, selenium or tellurium remarkable material characteristics were discovered. Some of these chalcogenides can be rapidly and reversibly switched between the amorphous and crystalline state (phase change materials) [1]. Crystallization is accompanied by a pronounced change of electronic properties such as electrical resistivity as well as optical reflectance. Especially this latter finding is highly unusual. Recently we could demonstrate that the change in optical properties is related to a change of bonding upon crystallization. While amorphous phase change materials are characterized by ordinary covalent bonding, crystalline phase change materials utilize resonant bonding [2]. This bonding mechanism is only possible in solids which employ their p-electrons for bonding and are neither too ionic nor show a strong hybridization of the s- and p-electron valence states. This insight has enabled the first 'treasure' map for phase change materials, which is depicted in Figure 1 [3,4]. Phase change materials, denoted by green dots, are found as expected for those chalcogenides, which possess a low ionicity and small s-p hybridization. Nearby compounds are found with other exciting transport properties, such as superconductors, thermoelectrics and even topological insulators [5]. The close vicinity of several classes of materials with remarkable transport properties for both electrons and phonons is due to the extraordinary bonding in these compounds. This leads to a number of characteristic and unique material properties such as high static and optical dielectric constants causing very weak electron-electron correlations [6], strong electron – phonon coupling important for superconductivity [4] and special electronic band structures enabling topological insulators [5]. Hence, these chalcogenides clearly demonstrate very interesting transport properties, which are crucial for a number of existing and emerging applications of these materials. These properties are very important regarding the application potential in non-volatile phase change memories.

In this presentation, two major issues will be addressed: How can we relate the material properties to the resulting characteristics of the electronic memories? What are potential limits for electronic memories based on phase change materials? In this regard, the most important limits are related to the highest possible switching speeds, the smallest possible cell sizes and the lowest powers required to write, erase and read information.

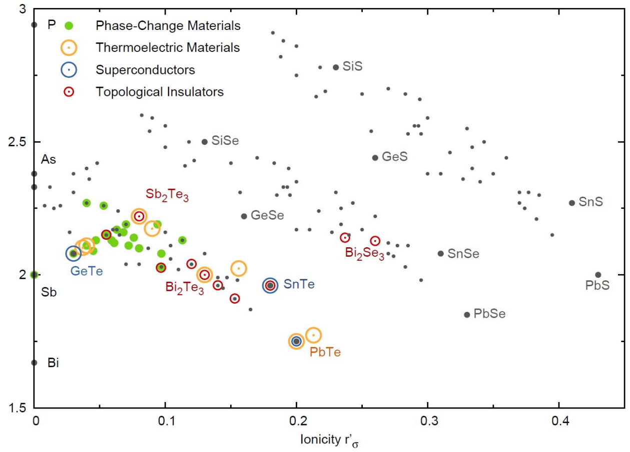

Fig. 1. Map for numerous compounds with an average number of 3 p-electrons per site. A wide variety of chalcogenides is shown which differ in their tendency towards hybridization ('covalency') and ionicity. Bands of sulphides, selenides and tellurides are clearly discernible. Phase-change materials, marked by green circles, are all localized in the lower left corner of the map. In their close vicinity, other classes with interesting properties are found, which include Thermoelectric Materials (orange), Superconductors (blue) and Topological Insulators (red circles). This is evidence that tellurides possess very interesting and technologically important electronic properties (from [4]).

978-3-9815370-2-4/DATE14/©2014 EDAA

In recent years, significant progress has been reported regarding improvements to reduce the switching time of phase change memories. Such a result is reported in figure 2, where switching in less than 6 ns is found [7]. With such switching speeds, it is possible to realize DRAM-like functionalities in a non-volatile memory, at least regarding the data transfer rates. Even shorter switching speeds have been reported, when optimized pulse shapes are utilized, where the phase change material is pre-annealed prior to the crystallization pulses. Then, even sub-ns switching becomes possible [8]. Equally impressive improvements have been reported regarding the reduction in cell size. Earlier work from IBM had demonstrated that very thin films down to a thickness of 4 nm can be successfully switched [9]. In 2010, Samsung reported working memory cells with a size of 7.5×17.5 nm [10]. This small cell size presents a significant improvement over the present state of the art for both DRAM and Flash memories and is indicative for the high scaling potential of phase change memories. Hence, both in terms of scaling and speed phase change memories can compete very well with other emerging memories and the existing memories such as Flash and DRAM. This raises the question if it will also be possible to reduce the necessary powers to read, write and erase information. Since it is necessary in phase change materials to produce an amorphous region, phase change materials have to be heated above the melting temperature. This process is rather energy consuming. Therefore, recent findings of a switching mechanism, which does not include local melting and can be realized with significantly lower powers, have created high hopes and expectations [11]. In particular, for superlattices of chalcogenides with tailored thicknesses very significant reductions in power consumption for the switching process have been reported. The implications of these findings for the future development of phase change memories will be discussed.

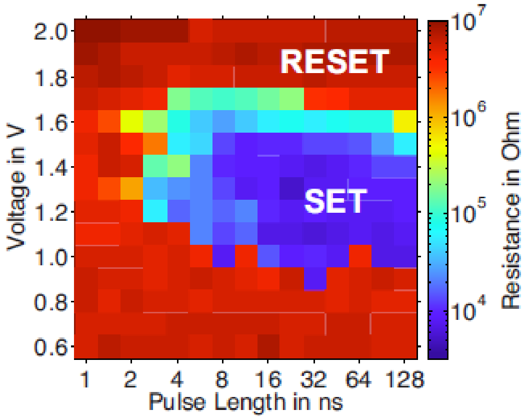

Fig. 2. Cell resistance after application of set pulses with different amplitude and length, each starting from the amorphous reset state. The color of each data point represents the cell resistance after the test pulse. For pulses longer than 4 ns a broad crystallization window opens between 1.0 and 1.5 V.

REFERENCES

[1] M. Wuttig and N. Yamada, Phase change materials for rewriteable data storage,Nature Materials 6, 824 (2007)

[2] K. Shportko, S. Kremers, M. Woda, D. Lencer, J. Robertson, M. Wuttig, Resonant bonding in crystalline phase change materials, Nature Materials 7, 653 (2008)

[3] D. Lencer, M. Salinga, B. Grabowski, T. Hickel, J. Neugebauer, M. Wuttig, A map for phase change materials, Nature Materials 7, 972 (2008)

[4] M. Wuttig, Phase Change Materials: Chalcogenides with remarkable properties due to an unconventional bonding mechanism, Physica Status Solidi B 249, 1843 (2012)

[5] M.Z. Hasan, C.L. Kane, Colloquium: Topological insulators, Reviews of Modern Physics 82, 3045 (2010).

[6] D. Lencer, M. Salinga and M. Wuttig, Design Rules for Phase-Change Materials in Data Storage Applications, Advanced Materials 23, 2030 (2011)

[7] G. Bruns, P. Merkelbach, C. Schlockermann, M. Salinga, M. Wuttig, T.D. Happ, J.B. Philipp, M. Kund, Nanosecond switching in GeTe phase change memory cells, Applied Physics Letters 95, 043108 (2009)

[8] D. Loke, T. H. Lee, W.J. Wang, L.P. Shi, R. Zhao, Y.C. Yeo, T.C. Chong, S.R. Elliott, Breaking the Speed Limits of Phase-Change Memory, Science 336, 1566-1569 (2012)

[9] H.-Y. Cheng, S. Raoux, Y.-C. Chen, The impact of film thickness and melt-quenched phase on the phase transition characteristics of Ge2Sb2Te5, Journal of Applied Physics 107, 074308 (2010)

[10] D.H. Ahn, S.L. Cho, H. Horii, D.H. Im, I.-S. Kim, G.H.Oh, S.O. Park, M.S. Kang, S.W. Nam and C.H. Chung, PRAM Technology: from Non Volatility to High Performances, E\PCOS 2010 (Milano)

[11] R. E. Simpson, P. Fons, A.V. Kolobov, T. Fukaya, M. Krbal, T. Yagi, J. Tominaga, Interfacial phase-change memory, Nature Nanotechnology 6, 501-505 (2011)