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Resistively Switching Chalcogenides

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Traditional semiconductor-based electronics is based on the transfer and storage of electrons, while atomic configuration changes are detrimental to the desired device performance. The success of electronics in the past forty years has been based on a continuous decrease of the feature size ("Moore's law") and an accompanying reduction in energy consumption. However, this concept is approaching its physical limits. In striking contrast to this philosophy, a set of resistive switching phenomena exist in oxides and higher chalcogenides, in which the change of the configuration of atoms and ions represents the essential functionality.

Resistive switching describes reversible phenomena of two-terminal circuit elements which change their resistance upon electrical stimuli in a non-volatile fashion. The non-volatility guarantees that the resistance change remains for a sufficiently long retention time after the electrical stimulus has been released. Empirically, the resistance change can be described by the variation of an internal state variable of the device in response to the stimulus. In other words, the resistance values are memorized by the element, and are, therefore, also called *memristive* elements or devices. The fundamental physical principles of resistive switching based on atomic configuration changes—and, hence, the nature of the internal state variable—can be manifold, including phase transitions, ion migration and diffusion, chemical reactions, local temperature increase due to Joule heating, and many others. The scope of this Special Issue covers resistive switching phenomena from crystalline–amorphous phase change effects in higher chalcogenides to nanoionic redox effects in metal oxides, in which a filamentary valence change process causes the non-volatile resistance change.

Although the term memristive phenomena originally refers to memory applications, we will often use the same term for resistive switching devices applied in functions beyond pure memory; i.e., as a switch in integrated digital circuits, such as the field-programmable gate array (FPGA), or in other computing circuits, such as the neuromorphic systems aiming at mimicking the operation of the human brain. This Special Issue addresses the fundamental material physics and chemistry of memristive phenomena and devices based on configuration changes in oxides and higher chalcogenides. Yet, it also provides a link to technology and architecture related issues.

The first paper by E. Janod et al. reviews a relatively new and fascinating resistive switching phenomenon in narrow band-gap Mott insulators. The materials embrace the world of phase changes, as well as redox processes comprising aspects of local crystalline–crystalline phase transitions and accompanying changes in the electronic structure.

The kinetics of the switching process is comprehensively reviewed by S. Menzel et al. They elucidate the highly non-linear processes involved in phase change and redox-type valence change resistive switching, and describe new approaches to reveal the contributions of temperature and field enhancements. An essential part of the kinetics in redox-type resistive switching is the ion transport. R. DeSouza reviews the oxygen diffusion mechanism in strontium titanate—which can be regarded as a model material in the area of redox-type resistive switching—and relates the diffusion to the lattice disorder and microstructure. This work is complemented by a contributed paper by C. Lenser et al., who look at the formation and movement of cationic defects during the electroforming and resistive switching in strontium titanate thin films, using photoemission electron microscopy and hard X-ray photoelectron spectroscopy. Another related contributed paper by H. Du et al. reports on the atomic structure of antiphase nanodomains in iron doped strontium titanate films, as revealed by aberration-corrected scanning transmission electron microscopy.

A different variant of the redox-type resistive switching is touched upon by T. Tsuruoka et al. in their contributed paper. They report on redox reactions at the interface of copper and silver electrodes and tantalum oxide films in atomic switching structures, and relate the details of the observed electrochemical metallization process to the nanoporosity of the oxide.

The phase diagram of titanium oxide is quite specific because of the multitude of Magnéli phases. M. Rogala et al. contribute a paper in which they report on a conducting-tip atomic force microscopy study of thermally reduced rutile (110) single crystals, and the creation of a high density of conducting nanofilaments in tip-induced switching experiments.

Phase change materials (PCMs) are discussed in a feature article by V. Derringer et al., revealing the origin of material complexity and the resulting property portfolio. In this article,

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particular emphasis is put on elucidating the unique bonding nature of crystalline and amorphous PCMs. A different facet of certain phase change materials is discussed by H. Volker et al. in a contributed paper presenting charge transport in the crystalline PCM $GeSb_2Te_4$. The interplay of weak electron–electron interactions and pronounced disorder gives rise to electron localization, which governs the charge transport at low temperatures. In a subsequent paper, P. Jost et al. demonstrate how the interplay of disorder and electronic correlations can be tailored by stoichiometry. Phase change materials are also characterized by remarkable crystallization kinetics, which facilitate the formation and growth of nanometric nuclei on the nanosecond scale. These time and length scales enable studies of nucleation and growth by density functional theory, as presented in an article by I. Ronneberger et al.

The trailing paper is a contribution by A. Siemon et al., who have obtained Boolean logic functionality using redox-based memristive devices. This work exemplifies the great potential to reduce the number of memory accesses by alleviating the so-called von Neumann bottleneck.

The present Special Issue addresses a plethora of fascinating material properties of oxides and higher chalcogenides. These properties are related to the atomic arrangement and the materials' electronic structure. The relevant transport processes, which are either based on electrons or ions, are discussed as well. These studies provide a strong foundation to understand and utilize resistive switching in the materials discussed here. Yet, we hope that the benefit of this Special Issue extends beyond material applications in memory and storage. The close similarity of the material properties and concepts involved should also provide new input to the investigation of related materials including topological insulators, thermoelectric materials, superconductors, electrochemical gas sensors, and electrocatalysts. In this sense, we hope that this Special Issue provides important insights into a number of dynamic developments in solid-state physics, chemistry, and material science, as well as to stimulate these disciplines.

Rainer Waser received his Ph.D. degree in physical chemistry at the University of Darmstadt in 1984, and worked at the Philips Research Laboratory, Aachen. Since 1992, he is a Professor at the Faculty for Electrical Engineering and Information Technology of the RWTH Aachen University, and director at the Peter Grünberg Institute of the Forschungszentrum Jülich, Germany since 1997. His research interests target the fundamental understanding of phenomena in electronic oxides which are promising for potential memory, logic, and sensor functions.

Matthias Wuttig studied physics in Cologne and received his doctorate under guidance of Harald Ibach, working at the Jülich research center. After stays as guest scientist at Lawrence Berkeley Laboratory and AT&T Bell Labs, he joined RWTH Aachen University in 1997, where he holds the Chair for Physics of Novel Materials. His research interests include materials with unconventional electronic and optical properties.