

# Preface

A memristor is a two-terminal device whose resistance depends on one or more internal state variables of the device. A memristor is defined by a state-dependent Ohm's law. Its resistance depends on the entire past signal waveform of the applied voltage, or current, across the memristor. Using memristors one can achieve circuit functionalities that it is not possible to establish with resistors, capacitors and inductors, therefore the memristor is of great pragmatic usefulness. Potential unique applications of memristors are in spintronic devices, ultra-dense information storage, neuromorphic circuits, and programmable electronics.

Despite explosive growth of memristor related findings there are few results on networks of memristive devices. Our book fills the gap. There are four main parts in the book yet their boundaries are eroded and their contents might sometimes overlap.

The first part deals with foundations of the memristor theory and applications. We start the book with a canonical text by Chua ("The Fourth Element"), where existence of memristor was predicted. This is followed by Williams's vivid vision of the impact the discovery of material memristors made on electronics and computer engineering ("Aftermath of Finding the Memristor"). In his chapter "Resistance Switching Memories are Memristors" Chua introduces fundamental circuit-theoretic concepts and properties of memristors, clarifying and demystifying common misconceptions on memristive devices. The ubiquitous nature of memristors is highlighted, from a historical perspective by Gandhi et al. ("The Detectors Used in the First Radios were Memristors"). They prove that first wireless radio detectors, or cat's whiskers, are amongst the first engineered memristors. The chapter "Memristor, Hodgkin-Huxley, and Edge of Chaos" by Chua demonstrates memristive properties of the Hodgkin-Huxley equation. Two critical elements of the Hodgkin-Huxley circuit model are a potassium ion channel memristor, and a sodium ion channel memristor, both of which are locally active. Adhikari and Kim help readers to differentiate between two devices, which are usually confused by non-initiated people: memristors and memristor.

The second part uncovers a rainbow of neuromorphic network architectures based on memristor assemblies. The memristor with adaptive thresholds mimic

higher-order behaviour of synapses, show Cai and Tetzlaff in “Synapse as a Memristor”. Sheridan and Wei introduce material systems, anion based memristive devices, which are used in the design of learning networks with neuromorphic architectures (“Memristors and Memristive Devices for Neuromorphic Computing”). Memristive networks showing a long-term potentiation and spike-time-dependent plasticity, and associative memory, are discussed by Thomas and Kaltschmidt in their chapter “Bio-inspired neural networks”. Chapter “Self-organization and Emergence of Dynamical Structures in Neuromorphic Atomic Switch Networks” by Stieg et al. introduces networks of atomic switches, inorganic synapse-like devices. The atomic switching networks are proved to be a uniquely scalable physical platform capable of exploring the dynamical interface of complexity, neuroscience, and engineering.

Serrano-Gotarredona et al., in “Spike-Timing-Dependent-Plasticity with Memristors” give a tutorial on the realisation of learning networks with memristors. They illustrate their approach on a visual cortex layer capable of orientation extraction. A memristor bridge synapses, based on a Wheatstone bridge-like circuit consisting of four identical memristors with specifically oriented polarities, are implemented by Kim et al. in “Memristor Bridge-based Artificial Neural Weighting Circuit”. Networks of memristor bridge synapses are employed in image processing tasks. Nano-scale cellular-nonlinear network implemented from memristors in “Cellular Nonlinear Networks with memristor synapses” by Corinto et al., and utilised in image processing and multiplication tasks. Variable memristor networks are analysed and their efficiency in robot control is evaluated by Howard et al. in “Evolving Memristive Neural Networks”. Computer experiments conclude that the variable memristor synapses bestow more behavioural degrees of freedom to the networks, allowing them to outperform the comparative synapse types.

The third part deals with dynamic behavior of memristive networks. Budhathoki et al. investigate the relationships among flux, charge and memristance of diverse composite memristors, using both linear and nonlinear memristor models, and analyze the characteristics of complex memristor circuits (“Behavior of Multiple Memristor Circuits”). In the chapter “A Memristor-Based Chaotic System with Boundary Conditions”, Hu et al. incorporate charge-controlled and flux-controlled memristors into Chen oscillator and categorise non-trivial dynamical behaviour, including chaotic attractors. Gale et al. (“Spiking in Memristor Networks”) show emergence of an oscillatory behaviour in groups of two and three memristors. Polyaniline (PANI) is an essential material of the organic memristive device. In his chapter “Organic memristive devices and neuromorphic circuits” Erokhin shows how to make organic memristors of PANI polymers and experimentally studies types of learning implementable in the networks of polymer-based organic memristors.

The fourth part is about computing with memristive networks. Kavehei et al., “Memristive in situ Computing”, overview designs and computational potential of resistive random access memories, phase change memories and spin-transfer torque magnetoresistive memories. Designs of through-silicon via on chip stackable memristor arrays and their applications in neuromorphic circuits, current and temperature sensors are discussed in the chapter “Memory Effects in Multi-Terminal solid state devices and their Applications” by Sacchetto et al. Binary arithmetic is at the

heart of all general purpose computing devices. Bickerstaff and Swartzlander, in “Memristor-Based Addition and Multiplication”, provide an overview of analog and digital implementations of binary additions and multiplications. The schemes are exemplified on a ripple carry adder and an array multiplier. Circuit designs of memristors emulators for practical laboratory experiments are presented by Biolek in “Memristor emulators”.

Vourkas and Sirakoulis, in “Modeling memristor-based circuit networks on crossbar architectures”, explore dynamics of regularly connected networks of memristors; they also model memristors using quantum-mechanical phenomenon of tunnelling and test universal logic schemes. Computing potential of two- and three-dimensional memristive networks is discussed in chapters “Computing shortest paths in 2D and 3D memristive networks” by Ye et al., and “Computing Image and Motion with 3-D Memristive Grids” by Kai et al. Both chapters provide viable architectural designs and computer models which could be used in future material implementations of massively-parallel memristive processor at nano-, micro- and meso-scales. Flak, in “Solid-State Memcapacitors and Their Applications”, introduces the concept of a memcapacitor, evaluates their physical implementations, and analyses a potential of memcapacitors for memory and logic applications. Stateful logical operations and synthesis of Boolean functions using the memristive stateful operations are outlined in chapter “Memristive Stateful Logic” by Lehtonen et al. A two-dimensional excitable medium with memristive diffusion links is imitated via Oregonator model and analysed by Asai in “Reaction-Diffusion Media with Excitable Oregonators Coupled by Memristors”. A range of spatio-temporal behavioural scenarios is discovered, including emergence of non-uniform spatial patterns of excitation determined by initial conditions and memristor polarities. Pham et al., in “Autowaves in a lattice of memristor-based cells”, study two-dimensional cellular non-linear networks, where every cell is equipped with memristors, and FPGA implementations of these networks. Generation and propagation of excitation waves is demonstrated. Iconic designs of memristive cellular automata are presented by Itoh and Chua, in “Memristor Cellular Automata and Memristor Discrete-Time Cellular Neural Networks”. Cellular non-linear networks equipped with non-linear passive memristors show non-trivial behaviour, and perform logical and image processing operations.

The book is a unique self-contained compendium of results on memristor research developed by top world experts in the field. All aspects of memristor networks are presented in detail, in a fully accessible, often tutorial-like style. Mathematics, physics, engineering and computing of memristor devices are tackled in detail. The book is an indispensable source of information and an inspiring reference text for future generations of computer scientists, mathematicians, physicists and engineers.

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