Memristors and Nonequilibrium Stochastic Multistable Systems

B. Spagnolo[a,b,1], A. A. Dubkov[b], A. Carollo[a], D. Valenti[a]

[a] *Dipartimento di Fisica e Chimica "Emilio Segrè" , Group of Interdisciplinary Theoretical Physics, Università degli Studi di Palermo and CNISM, Unità di Palermo, Viale delle Scienze, Edificio 18, I-90128 Palermo, Italy*
[b] *Lobachevsky State University of Nizhny Novgorod, 23 Gagarin Ave. Nizhny Novgorod 603950 Russia*

Abstract

The main aim of this special issue is to report the recent advances and new trends in memristors and nonequilibrium stochastic multistable systems, both theoretically and experimentally, within an interdisciplinary context. In particular, memristors are multistable systems whose switching dynamics is a stochastic process, which can be controlled by internal and external noise sources, unveiling their costructive role. Furthermore, the application of memristors as memory elements in neuromorphic systems with noise-assisted persistence of memory states, chaotic dynamics, metastable chaos and chaos synchronization, new stochastic nonlinear models, noise-induced phenomena such as stochastic resonance, noise enhanced stability and phase transitions phenomena in memristors will be illustrated in the contributions of this special issue.

Keywords: resistive switching, memristor, metastability, noise-enhanced stabilization, constructive role of noise, neuromorphic systems, multistability, chaos, synchronization

*Dipartimento di Fisica e Chimica "Emilio Segrè" , Group of Interdisciplinary Theoretical Physics, Università degli Studi di Palermo and CNISM, Unità di Palermo, Viale delle Scienze, Edificio 18, I-90128 Palermo, Italy

Email address: bernardo.spagnolo@unipa.it (B. Spagnolo)

1. Introduction

Memristors are multistable systems whose switching dynamics occurs under the action of noise or a deterministic signal [1]. To use the memristors as memory elements in resistive random access memory (RRAM) and neuromorphic systems, it is necessary to significantly extend the understanding of the resistive state switching process taking into account multistability, the role of internal and external noise sources and metastable states in the transient nonlinear dynamics of such nonequilibrium systems. More generally, the presence of internal and external noise sources gives rise to interesting counterintuitive phenomena both in classical and quantum physical systems and in different models of interdisciplinary physics [2]-[13]. The internal structure of memristors and their dynamical behavior are a typical example of complex multistable systems, characterized by complex dynamic behavior, for which the theoretical techniques of nonequilibrium statistical mechanics must be applied. Moreover, the nonlinear relaxation process in multistable systems is crucial for understanding the switching mechanism in memristive nanomaterials. This special issue is devoted to considering extended versions of papers presented at the conference "New Trends in Nonequilibrium Stochastic Multistable Systems and Memristors (NES2019)", held in the Ettore Majorana Centre in Erice (Trapani, Sicily, Italy) from 18 to 21 October 2019, as well as external submissions. We have selected the best contributions, after providing a careful examination of the submissions, a desk-rejection of the papers outside the scope of the Focus Issue, and a meticulous peer-review with the help of Referees.

The aim of the meeting NES2019 was to bring together scientists interested in the challenging problems connected with the dynamics of nonequilibrium multistable systems and memristor devices from both theoretical and experimental points of view, within an interdisciplinary context. The NES2019 international event has been a discussion forum to promote new ideas in this fertile research field, and in particular to identify new trends and key technology areas such as memristors nanomaterials and technologies, development of memristors as building blocks for quantum and neuromorphic computing, new stochastic nonlinear models, phase transitions phenomena in filamentary switching in resistive random-access memory, control of memory lifetime and memcomputing.

2. Neuromorphic systems and chaotic memristive neural networks

The NES2019 international event brought together scientists, theorists and experimentalists interested in the challenging problems associated with the switching dynamics of memristor devices and its technological applications. In this respect, neuromorphic (bio-inspired) computing based on memristive devices may offer dramatic performance improvements in solving computationally hard problems. Indeed, memristive devices, although the diffusion, stability, and switching mechanisms are not yet fully understood, remain excellent promising candidates for neuromorphic computing [14]. Among the many interesting contributions to this special issue in the research area of neuromorphic systems [15]-[32], we mention the paper [33], where the constructive role of an external noise signal, in the form of a low-rate Poisson sequence of pulses supplied to all inputs of a single-layer spiking neural network consisting of simple integrate-and-fire neurons and memristive synaptic weights, has been investigated. In particular this positive role of an external signal consists in maintaining for a long time or even recovering a memory trace of the image without its direct rewriting. In fact, the synaptic weights can be to a certain extent unreliable, due to such characteristics as the limited retention time of the resistive state or the variation of switching voltages. Nevertheless, the noise in the form of the low-rate pattern-free train of pulses can have a constructive role in the dynamical maintenance or even fine-tuning of a memory trace stored in a memristive single-layer spiking neuromorphic networks. Such a *noise-assisted persistence of memory*, on one hand, could be a prototypical mechanism in a biological nervous system and, on the other hand, brings one step closer to the possibility of building reliable spiking neural networks composed of unreliable analog elements [33].

Furthermore, concerning contributions on chaotic memristive neural networks, metastable chaos, chaos synchronization, memristor hyperchaotic system [34]-[46], we cite the paper dealing with metastable and intermittent chaos [47]. In this article, a computational model of a memristive artificial neuron taking into consideration inertia of metallic nanoparticles within the dielectric layer of the core-memristor is proposed. In particular, the underdamped mechanical motion of an Ag-cluster in a gap between two arms of a conducting bridge driven by both an electric field and a temperature gradient inside a single well potential has been considered. This model, which could successful emulate living biological neurons by neuromorphic devices, displays rich nonlinear dynamics. In fact, dynamical regimes appear in the system with variation of inertness of the Ag-nanoparticles and transitions between them. For high inertia, interesting metastable and intermittent chaos can appear in the system.

3. Resistive switching dynamics, role of noise sources and stochastic memristor models

Recently fabricated diffusive memristors have attracted a significant interest as one of the best candidates to mimic neuron activities and to implement novel computing paradigms. Such devices are capable of exhibiting a very rich dynamics consisting of a combination of chaotic and stochastic phenomena necessary for efficient neuromorphic computational systems. However, understanding of stochastic resistive switching dynamics, reset transition, dynamics of multilevel structures, phase transition phenomena and role of external and thermal noise sources in memristors is still an open problem, as we can see in the following contributions of the special issue [48]-[64]. The resistive switching (RS) effect, from a high resistance state to a low resistance state, is a bistable (or multistable) switching of resistance of a thin nanometric dielectric film sandwiched between two conductive electrodes subjected to an external voltage. The wide application of memristors is limited by insufficient stability, high variability of the resistive switching parameters during the operation, lack of understanding of drift-diffusion processes and their degradation. One of the fundamental origins of the instability of the memristor's parameters is the essentially stochastic nature of the RS process. New approaches to improve switching properties in various nonlinear multistable stochastic systems using a beneficial role of noise have recently been thoroughly investigated, as shown in the contributions [65, 67] to this special issue. Indeed, Gaussian (thermal) and non-Gaussian noise sources play a relevant role in multistable systems, as shown in the contributions [68]-[72]. Furtermore stochastic models of diffusion equations and in particular for memristor systems have been proposed in this issue [67, 66]. An archetypal model is that of an overdamped Brownian motion in multistable potential profiles [6, 67]. The beneficial or constructive role of noise usually manifests itself in a nonmonotonic dependence of the switching parameters (such as switching time, relaxation time, mean amplitude of average switching amplitude, output signal-to-noise ratio, etc.) on the noise intensity or temperature [73, 74, 75]. In other words, in nonlinear systems, the effect of noise can induce new, more ordered regimes that lead to regular structures, an increasing degree of coherence, and cause new phase transitions. Noise-induced phenomena showing the constructive role of noise in the RS process, typical of nonlinear stochastic systems, have been experimentally observed in memristors. These are the stochastic resonance (SR) [73], the stochastic resonant activation and the noise enhanced stability (NES) [74, 75]. It is worthwhile to note that the first experimental evidence of SR and NES in memristor systems has been reported in three papers of this special issue [73, 74, 75]. In particular, It was found that the memristor relaxation time depends on the temperature in a non-monotonous way with a maximum observed at the temperature close to 55 °C. This nonmonotonic behavior is a signature of the noise-enhanced stability phenomenon observed in all physical (classical and quantum), biological, chemical and ecological systems with metastable states. The stability of a metastable state can be enhanced by the noise and its average lifetime is a measure of this stability. This noise-enhanced metastability is a consequence of the interplay between the random fluctuations and nonlinearity of the complex system investigated, and it has been observed experimentally in the presence of internal (thermal) [74] and external [75] noise sources. These findings pave the way for a deeper understanding of the switching mechanism in memristor systems and at the same time for a wide range of applications where noise is used as a control parameter.

Acknowledgements

We acknowledge support by the Office of Naval Research Global (ONRG), through contract number N629091912135, the Government of the Russian Federation under Megagrant Program, Agreement No. 074-02-2018-330 (2), and the Italian Ministry of University and Research (MUR).

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Sun W, Gao B, Chi M, Xia Q et al. Understanding memristive switching via in situ characterization and device modeling. Nat Commun 2019;10:3453. https://doi.org/10.1038/s41467-019-11411-6

[2] Caruso A, Gargano ME, Valenti D et al. Cyclic Fluctuations, Climatic Changes and Role of Noise in Planktonic Foraminifera in The Mediterranean Sea. Fluct Noise Lett 2005;5:L349–55. https://doi.org/10.1142/S0219477505002768

[3] Guarcello C, Valenti D, Spagnolo B, Pierro V, Filatrella G. Anomalous Transport Effects on Switching Currents of Graphene-based Josephson junctions. Nanotechnology 2017;28:134001. https://doi.org/10.1088/1361-6528/aa5e75

[4] Guarcello C, Valenti D, Carollo A et al. Stabilization Effects of Dichotomous Noise on the Lifetime of the Superconducting State in a Long Josephson Junction. Entropy 2015;17:2862–75. https://doi.org/10.3390/e17052862

[5] Carollo A, Valenti D, Spagnolo B. Geometry of quantum phase transitions. Phys Rep 2020;838:1–72. https://doi.org/10.1016/j.physrep.2019.11.002

[6] Agudov NV, Safonov AV, Krichigin AV et al. Nonstationary distributions and relaxation times in a stochastic model of memristor. J Stat Mech Theory Exp 2020;2020(2):024003. https://doi.org/10.1088/1742-5468/ab684a

[7] Yakimov AV, Filatov DO, Gorshkov ON et al. Measurement of the activation energies of oxygen ion diffusion in yttria stabilized zirconia by flicker noise spectroscopy. Appl Phys Lett 2019;114(25):253506. https://doi.org/10.1063/1.5098066

[8] Ushakov YV, Dubkov AA, Spagnolo B. Spike train statistics for consonant and dissonant musical accords in a simple auditory sensory model. Phys Rev E 2010;81:041911. https://doi.org/10.1103/PhysRevE.81.041911

[9] Carollo A, Spagnolo B, Dubkov AA, Valenti D. On quantumness in multi-parameter quantum estimation. J Stat Mech Theory Exp 2019;2019:094010. https://doi.org/10.1088/1742-5468/ab3ccb

[10] Filatov DO, Vrzheshch DV, Tabakov OV et al. Noise-induced resistive switching in a memristor based on $ZrO_2(Y)/Ta_2O_5$ stack. J Stat Mech Theory Exp 2019;2019(12):124026. https://doi.org/10.1088/1742-5468/ab5704

[11] Lisowski B, Valenti D, Spagnolo B et al. Stepping molecular motor amid Lévy white noise. Phys Rev E 2015;91:042713. https://doi.org/10.1103/PhysRevE.91.042713

[12] Valenti D, Denaro G, La Cognata A et al. Picophytoplankton Dynamics in Noisy Marine Environment. Acta Phys Pol B 2012;43:1227–40. https://www.actaphys.uj.edu.pl/R/43/5/1227/pdf

[13] Guarcello C, Valenti D, Spagnolo B, Pierro V, Filatrella G. Josephson-based threshold detector for Lévy-Distributed Current Fluctuations. Phys Rev Appl 2019;11:044078. https://doi.org/10.1103/PhysRevApplied.11.044078

[14] Mikhaylov A, Pimashkin A, Pigareva Y et al. Neurohybrid Memristive CMOS-Integrated Systems for Biosensors and Neuroprosthetics. Frontiers in Neuroscience 2020;14:358. doi:10.3389/fnins.2020.00358

[15] Ryu Ji-Ho, Kim S. Artificial synaptic characteristics of TiO2/HfO2 memristor with self-rectifying switching for brain-inspired computing. Chaos, Solitons & Fractals 2020;140:110236. https://doi.org/10.1016/j.chaos.2020.110236

[16] Dowling VJ, Slipko VA, Pershin Yu V. Probabilistic memristive networks: Application of a master equation to networks of binary ReRAM cells. Chaos, Solitons & Fractals 2021;142:110385. https://doi.org/10.1016/j.chaos.2020.110385

[17] Shchanikov S, Zuev A, Bordanov I et al. Designing a bidirectional, adaptive neural interface incorporating machine learning capabilities and memristor-enhanced hardware. Chaos, Solitons & Fractals 2021;142:110504. https://doi.org/10.1016/j.chaos.2020.110504

[18] Morozov A Yu, Abgaryan K K, Reviznikov D L. Mathematical model of a neuromorphic network based on memristive elements. Chaos, Solitons & Fractals 2021;143:110548. https://doi.org/10.1016/j.chaos.2020.110548

[19] Gerasimov Y, Zykov E, Prudnikov N et al. On the organic memristive device resistive switching efficacy. Chaos, Solitons & Fractals 2021;143:110549. https://doi.org/10.1016/j.chaos.2020.110549

[20] Karamani RE, Fyrigos IA, Tsakalos KA et al. Memristive learning cellular automata for edge detection. Chaos, Solitons & Fractals 2021;145:110700. https://doi.org/10.1016/j.chaos.2021.110700

[21] Yang J, Ryu H, Kim S. Resistive and synaptic properties modulation by electroforming polarity in CMOS-compatible Cu/HfO2/Si device. Chaos, Solitons & Fractals 2021;145:110783. https://doi.org/10.1016/j.chaos.2021.110783

[22] Gerasimova SA, Lebedeva AV, Fedulina A et al. A neurohybrid memristive system for adaptive stimulation of hippocampus. Chaos, Solitons & Fractals 2021;146:110804. https://doi.org/10.1016/j.chaos.2021.110804

[23] Parit AK, Yadav MS, Gupta AK et al. Design and modeling of niobium oxide-tantalum oxide based self-selective memristor for large-scale crossbar memory. Chaos, Solitons & Fractals 2021;145:110818. https://doi.org/10.1016/j.chaos.2021.110818

[24] Wang W, Sun Y, Yuan M, Wang Z et al. Projective synchronization of memristive multidirectional associative memory neural networks via self-triggered impulsive control and its application to image protection. Chaos, Solitons & Fractals 2021;150: 111110. https://doi.org/10.1016/j.chaos.2021.111110

[25] Alsuwian T, Kousarc F, Rasheed U, Imran M et al. First principles investigation of physically conductive bridge filament formation of aluminum doped perovskite materials for neuromorphic memristive applications. Chaos, Solitons & Fractals 2021;150:111111.https://doi.org/10.1016/j.chaos.2021.111111

[26] Ryu H, Kim S. Implementation of a reservoir computing system using the short-term effects of Pt/HfO2/TaOx/TiN memristors with self-rectification. Chaos, Solitons & Fractals 2021;150:111223. https://doi.org/10.1016/j.chaos.2021.111223

[27] Mahata C, Kim S. Electrical and optical artificial synapses properties of TiN-nanoparticles incorporated HfAlO-alloy based memristor. Chaos, Solitons & Fractals 2021;153:111518. https://doi.org/10.1016/j.chaos.2021.111518

[28] Kim Dahye, Kim Sunghun, Kim Sungjun. Logic-in-memory application of CMOS compatible silicon nitride memristor. Chaos, Solitons & Fractals 2021;153:111540. https://doi.org/10.1016/j.chaos.2021.111540

[29] Kim TH, Kim S, Hong K et al. Multilevel switching memristor by compliance current adjustment for off-chip training of neuromorphic system. Chaos, Solitons & Fractals 2021;153:111587. https://doi.org/10.1016/j.chaos.2021.111587

[30] Choi WS, Jang JT, Kim D et al. Influence of Al2O3 layer on InGaZnO memristor crossbar array for neuromorphic applications. Chaos, Solitons & Fractals 2022;156:111813. https://doi.org/10.1016/j.chaos.2022.111813

[31] Lee GH, Kim TH, Song MS et al. Effect of weight overlap region on neuromorphic system with memristive synaptic devices. Chaos, Solitons & Fractals 2022;156:111999. https://doi.org/10.1016/j.chaos.2022.111999

[32] Lee GH, Kim TH, Song MS et al. Global multistability and mechanisms of a memristive autapse-based Filippov Hindmash-Rose neuron model. Chaos, Solitons & Fractals 2022;160:112281. https://doi.org/10.1016/j.chaos.2022.112281

[33] Surazhevsky IA, Demin VA, Ilyasov AI et al. Noise-assisted persistence and recovery of memory state in a memristive spiking neuromorphic network. Chaos, Solitons & Fractals 2021;146:110890. https://doi.org/10.1016/j.chaos.2021.110890

[34] Xiu C, Zhou R, Liu Y. New chaotic memristive cellular neural network and its application in secure communication system. Chaos, Solitons & Fractals 2020;141:110316. https://doi.org/10.1016/j.chaos.2020.110316

[35] Korneeva IA, Semenov VV, Slepnev AV, Vadivasova TE. Complete synchronization of chaos in systems with nonlinear inertial coupling. Chaos, Solitons & Fractals 2021;142:110459. https://doi.org/10.1016/j.chaos.2020.110459

[36] Li JF, Jahanshahi H, Kacar et al. On the variable-order fractional memristor oscillator: Data security applications and synchronization using a type-2 fuzzy disturbance observer-based robust control. Chaos, Solitons & Fractals 2021;145:110681. https://doi.org/10.1016/j.chaos.2021.110681

[37] Guseinov DV, Matyushkin IV, Chernyaev NV et al. Capacitive effects can make memristors chaotic. Chaos, Solitons & Fractals 2021;144:110699. https://doi.org/10.1016/j.chaos.2021.110699

[38] Du C, Liu L, Zhang Z, Yu S. Double memristors oscillator with hidden stacked attractors and its multi-transient and multistability analysis. Chaos, Solitons & Fractals 2021;148:111023. https://doi.org/10.1016/j.chaos.2021.111023

[39] Setoudeh F, Sedigh AK. Nonlinear analysis and minimum L2-norm control in memcapacitor-based hyperchaotic system via online particle swarm optimization. Chaos, Solitons & Fractals 2021;151:111214. https://doi.org/10.1016/j.chaos.2021.111214

[40] Akgül A, Rajagopal K, Durdu A et al. A simple fractional-order chaotic system based on memristor and memcapacitor and its synchronization application. Chaos, Solitons & Fractals 2021;152:111306. https://doi.org/10.1016/j.chaos.2021.111306

[41] Setoudeh F, Dousti M. Analysis and implementation of a meminductor-based colpitts sinusoidal oscillator. Chaos, Solitons & Fractals 2022;156:111814. https://doi.org/10.1016/j.chaos.2022.111814

[42] Xiu C, Fang J, Liu Y. Design and circuit implementation of a novel 5D memristive CNN hyperchaotic system. Chaos, Solitons & Fractals 2022;158:112040. https://doi.org/10.1016/j.chaos.2022.112040

[43] Taheri AG, Setoudeh F, Tavakoli MB, Feizi E. Nonlinear analysis of memcapacitor-based hyperchaotic oscillator by using adaptive multi-step

differential transform method. Chaos, Solitons & Fractals 2022;159:112122. https://doi.org/10.1016/j.chaos.2022.112122

[44] Huang L, Liu J, Xiang J et al. A construction method of N-dimensional non-degenerate discrete memristive hyperchaotic map. Chaos, Solitons & Fractals 2022;160:112248. https://doi.org/10.1016/j.chaos.2022.112248

[45] Wang Y, Li H, Guan Y, Chen M. Predefined-time chaos synchronization of memristor chaotic systems by using simplified control inputs. Chaos, Solitons & Fractals 2022;160:112282. https://doi.org/10.1016/j.chaos.2022.112282

[46] Xiu C, Fang J, Ma X. Design and circuit implementations of multimemristive hyperchaotic system. Chaos, Solitons & Fractals 2022;161:112409. https://doi.org/10.1016/j.chaos.2022.112409

[47] Wojtusiak AM, Balanov AG, Savel'ev SE. Intermittent and metastable chaos in a memristive artificial neuron with inertia. Chaos, Solitons & Fractals 2021;142:110383. https://doi.org/10.1016/j.chaos.2020.110383

[48] Maldonado D, Gonzalez MB, Campabadal F et al. Experimental evaluation of the dynamic route map in the reset transition of memristive ReRAMs. Chaos, Solitons & Fractals 2020;139:110288. https://doi.org/10.1016/j.chaos.2020.110288

[49] Goldman EI, Chucheva GV, Afanasiev MS, Kiselev DA. Changes in the structural and electrophysical properties of Ba0.8Sr0.2TiO3 films with decreasing thickness. Chaos, Solitons & Fractals 2020;141:110315. https://doi.org/10.1016/j.chaos.2020.110315

[50] Zhevnenko D, Meshchaninov F, Kozhevnikov et al. Simulation of memristor switching time series in response to spike-like signal. Chaos, Solitons & Fractals 2020;142:110382. https://doi.org/10.1016/j.chaos.2020.110382

[51] Novodvorsky O, Parshina L, Khramova O et al. Laser synthesis of thin MnxSi1-x films (x 0.5) on c- and r-Al2O3 substrates at different laser

energy densities at the target. Chaos, Solitons & Fractals 2021;142:110457. https://doi.org/10.1016/j.chaos.2020.110457

[52] Gismatulin AA, Orlov OM, Gritsenko VA, Krasnikov GYa. Charge transport mechanism in the metal–nitride–oxide–silicon forming-free memristor structure. Chaos, Solitons & Fractals 2021;142:110458. https://doi.org/10.1016/j.chaos.2020.110458

[53] Parshina L, Novodvorsky O, Khramova O et al. Laser synthesis of non-volatile memristor structures based on tantalum oxide thin films. Chaos, Solitons & Fractals 2021;142:110496. https://doi.org/10.1016/j.chaos.2020.110460

[54] Komnang AS Piedjou, Guarcello C, Barone C et al. Analysis of Josephson junctions switching time distributions for the detection of single microwave photons. Chaos, Solitons & Fractals 2021;142:110496. https://doi.org/10.1016/j.chaos.2020.110496

[55] Andreeva NV, Turalchuk PA, Chigirev DA et al. Electron impact processes in voltage-controlled phase transition in vanadium dioxide thin films. Chaos, Solitons & Fractals 2021;142:110503. https://doi.org/10.1016/j.chaos.2020.110503

[56] Panin GN. Optoelectronic dynamic memristor systems based on two-dimensional crystals. Chaos, Solitons & Fractals 2021;142:110523. https://doi.org/10.1016/j.chaos.2020.110523

[57] Zotov AV, Sirotkin VV, A.I.Il'in AI et al. Multilevel memristive structures based on bismuth selenide microcrystals. Chaos, Solitons & Fractals 2021;143:110542. https://doi.org/10.1016/j.chaos.2020.110542

[58] Yakimov AV, Filatov DO, Gorshkov ON et al. Influence of oxygen ion elementary diffusion jumps on the electron current through the conductive filament in yttria stabilized zirconia nanometer-

sized memristor. Chaos, Solitons & Fractals 2021;148:111014. https://doi.org/10.1016/j.chaos.2021.111014

[59] Kousar F, Rasheed U, Arif Khalil RM et al. First principles investigation of oxygen vacancies filaments in polymorphic Titania and their role in memristor's applications. Chaos, Solitons & Fractals 2021;148:111024. https://doi.org/10.1016/j.chaos.2021.111024

[60] Park J, Kim T-H, Kim S et al. Conduction mechanism effect on physical unclonable function using Al2O3/TiOX memristors. Chaos, Solitons & Fractals 2021;152:111388. https://doi.org/10.1016/j.chaos.2021.111388

[61] Vasileiadis N, Loukas P, Karakolis P et al. Multi-level resistance switching and random telegraph noise analysis of nitride based memristors. Chaos, Solitons & Fractals 2021;153:111533. https://doi.org/10.1016/j.chaos.2021.111533

[62] Choi WS, Kim D, Yang TJ et al. Electrode-dependent electrical switching characteristics of InGaZnO memristor. Chaos, Solitons & Fractals 2022;158:112106. https://doi.org/10.1016/j.chaos.2022.112106

[63] Parshina L, Novodvorsky O, Khramova O et al. Tuning the resistive switching in tantalum oxide-based memristors by oxygen pressure during low temperature laser synthesis. Chaos, Solitons & Fractals 2022;161:112384. https://doi.org/10.1016/j.chaos.2022.112384

[64] Kwon O, Kim S, Agudov N et al. Non-volatile memory characteristics of a Ti/HfO2/Pt synaptic device with a crossbar array structure. Chaos, Solitons & Fractals 2022;162:112480. https://doi.org/10.1016/j.chaos.2022.112480

[65] Alonso FJ, Maldonado D, Aguilera AM, Roldán JB. Memristor variability and stochastic physical properties modeling from a multivariate time series approach. Chaos, Solitons & Fractals 2021;143:110461. https://doi.org/10.1016/j.chaos.2020.110461

[66] Sweilam NH, ElSakout DM, Muttardi MM. Numerical solution for stochastic extended Fisher-Kolmogorov equation. Chaos, Solitons & Fractals 2021;151:111213. https://doi.org/10.1016/j.chaos.2021.111213

[67] Agudov NV, Dubkov AA, Safonov AV et al. Stochastic model of memristor based on the length of conductive region Chaos, Solitons & Fractals 2021;150:111131. https://doi.org/10.1016/j.chaos.2021.111131

[68] Battistoni S, Sajapin R, Erokhin V et al. Effects of noise sourcing on organic memristive devices. Chaos, Solitons & Fractals 2020;141:110319. https://doi.org/10.1016/j.chaos.2020.110319

[69] Guarcello C, Bergeret FS. Thermal noise effects on the magnetization switching of a ferromagnetic anomalous Josephson junction. Chaos, Solitons & Fractals 2020;142:110384. https://doi.org/10.1016/j.chaos.2020.110384

[70] Ushakov Y, Balanov A, Savel'ev S. Role of noise in spiking dynamics of diffusive memristor driven by heating-cooling cycles. Chaos, Solitons & Fractals 2021;145:110803. https://doi.org/10.1016/j.chaos.2021.110803

[71] Guarcello C. Thermal noise effects on the magnetization switching of a ferromagnetic anomalous Josephson junction. Chaos, Solitons & Fractals 2021;153:111531. https://doi.org/10.1016/j.chaos.2021.111531

[72] Maldonado D, Aguilera-Pedregosa C, Vinuesa G et al. An experimental and simulation study of the role of thermal effects on variability in TiN/Ti/HfO2/W resistive switching nonlinear devices. Chaos, Solitons & Fractals 2022;160:112247. https://doi.org/10.1016/j.chaos.2022.112247

[73] Mikhaylov AN, Guseinov DV, Belov AI et al. Stochastic resonance in a metal-oxide memristive device. Chaos, Solitons & Fractals 2021;144:110723. https://doi.org/10.1016/j.chaos.2021.110723

[74] Filatov DO, Koryazhkina MN, Novikov AS et al. Effect of internal noise on the relaxation time of an yttria stabilized zirconia-

based memristor. Chaos, Solitons & Fractals 2022;156:111810. https://doi.org/10.1016/j.chaos.2022.111810

[75] Koryazhkina MN, Filatov DO, Shishmakova VA et al. Resistive state relaxation time in $ZrO_2(Y)$-based memristive devices under the influence of external noise Chaos, Solitons & Fractals 2022;162:112459. https://doi.org/10.1016/j.chaos.2022.112459