NES2019

NEW TRENDS IN NONEQUILIBRIUM STOCHASTIC MULTISTABLE SYSTEMS AND MEMRISTORS

OCTOBER · 18 - 21 · 2019

ERICE (ITALY)

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Office of Naval Research
Science & Technology

18/10	19/10	20/10	21/10
Arrival Day	09:00 Savel'ev	09:00 Di Ventra	Departure Day
	09:50 Tetzlaff	09:50 Dimitrakis	
	10:20 **Coffee Break**		
	PMM Session 10:50 Mikhaylov	10:50 Erokhin	
	11:20 Filatov	11:20 Koveshnikov	
	11:50 Agudov	11:50 Panin	
	12:20 Demin	12:20 Battistoni	
	12:40 Ascoli	12:40 Korolev	
	13:00 **Lunch**		
14:00 Registration			
	15:00 Pershin	15:00 Shchanikov	
		15:20 Gismatulin	
		15:40 Guseinov	
	15:50 Brivio		
		16:00 Petrenyov	
	16:20 **Coffee Break**		
	16:50 Sanz	16:50 Filatrella	
		17:10 Guarcello	
	17:20 Tselikov		
		17:30 Carollo	
	17:50 Poster Session Oral	17:50 Leonforte	
18:00 Informal get-together at San Rocco's Cloister			
		18:10 Ben Khalifa	
	18:30 Poster Session Discussion	18:30 Round Table Project Multistability and Memristor (**PMM**)	
		19:30 Closing Remarks Free Discussion	
20:00 **Dinner**	20:00 **Social Dinner**	20:00 **Dinner**	
22:00 Almonds Sweets and Marsala at Marsala room			

Saturday 19/10

	Speaker	Talk
09:00 – 09:50	**Savel'ev**	*Comparing biological and artificial memristive neurons*
09:50 – 10:20	**Tetzlaff**	*Real-time computing by Memristor Cellular Nonlinear Networks (M-CNN)*
10:20 – 10:50		**Coffee Break**
10:50 – 11:20	**Mikhaylov**	*Towards implementation of collective dynamics of stochastic memristor-coupled artificial neurons*
11:20 – 11:50	**Filatov**	*Noise-induced resistive switching studied by Conductive Atomic Force Microscopy*
11:50 – 12:20	**Agudov**	*Nonequilibrium distributions and relaxation times in a stochastic model of memristor*
12:20 – 12:40	**Demin**	*From formal neural networks to memristor-based spiking neuromorphic systems: perspectives and open issues*
12:40 – 13:00	**Ascoli**	*A novel system-theoretic technique to analyze and design mem-computing M-CNNs*
13:00 – 15:00		**Lunch**
15:00 – 15:50	**Pershin**	*Dynamical aspects of resistance switching: Attractors, bifurcations, and ideal behavior*
15:50 – 16:20	**Brivio**	*Noise and Variability in Oxide-based Filamentary Resistance Switching Devices*
16:20 – 16:50		**Coffee Break**
16:50 – 17:20	**Sanz**	*Quantum Memristors and Quantum Neurons*
17:20 – 17:50	**Tselikov**	*Synthesis of metal oxide-based hybrid nanomaterials and their prospective in neuromorphic applications*
17:50 – 18:30		**Poster Session - Oral**
18:30 – 20:00		**Poster Session - Discussion**

Sunday 20/10

	Speaker	Talk
09:00 – 09:50	**Di Ventra**	*Memcomputing: leveraging memory and physics to compute efficiently*
09:50 – 10:20	**Dimitrakis**	*Emerging ReRAM devices and lithography manufacturing issues*
10:20 – 10:50		**Coffee Break**
10:50 – 11:20	**Erokhin**	*Organic Memristive Devices for Neuromorphic Applications*
11:20 – 11:50	**Koveshnikov**	*Resistive multi-level NVM devices for high capacity storage and neuromorphic system applications*
11:50 – 12:20	**Panin**	*Optoelectronic dynamic memristor systems based on two-dimensional crystals*
12:20 – 12:40	**Battistoni**	*Organic Memristive Devices and Organic Electrochemical Transistors: close friends in neuromorphic computations*
12:40 – 13:00	**Korolev**	*Formation of the new elements for the nonvolatile optical memory based on waveguides with switchable transparency of PCM materials*
13:00 – 15:00		**Lunch**
15:00 – 15:20	**Shchanikov**	*Memristor-based components for a bidirectional adaptive neural interface coupled with neuronal biocultures*
15:20 – 15:40	**Gismatulin**	*Charge transport mechanism of forming less $SiO_{1.09}$-based memristor in various states*
15:40 – 16:00	**Guseinov**	*Atomistic and dynamical stochastic models of metal-oxide memristive devices*
16:00 – 16:20	**Petrenyov**	*Conduction Mechanisms in Zr/ZrO_2-NT/Au Memristor Structures before and after Electroforming*
16:20 – 16:50		**Coffee Break**
16:50 – 17:10	**Filatrella**	*Josephson junctions switching current analysis for signal detection*
17:10 – 17:30	**Guarcello**	*Thermal noise effects on a memory element based on an anomalous Josephson junction*
17:30 – 17:50	**Carollo**	*Equilibrium and non-equilibrium phase transitions: a measure of quantumness*
17:50 – 18:10	**Leonforte**	*Finite-temperature topological phase transitions in two-dimensional systems*
18:10 – 18:30	**Ben Khalifa**	*Screening of the synthesis route on the structural, magnetic and magnetocaloric properties of $La_{0.6}Ca_{0.2}Ba_{0.2}Mn_{O3}$ manganite: comparison between solid-solid state process and combination polyol process and Spark Plasma Sintering*
18:30 – 20:00		**Round Table – Project Multistability and Memristor (PMM)**
		Closing Remarks and Free Discussion

Poster Session

Posters will be exposed in Saturday from 09:00 to 20:00 in the hall.

Poster discussion will be held in Saturday from 18:30 to 20:00.

Poster discussion will be preceded by a brief oral presentation session, 3 slides in 3 minutes, in which each participant will briefly show the focus and main results of the poster, inviting listeners to view it.

Boutasta	*Structural, electronic and optical propreties of Perovskite $BiFeO_3$ Nanoparticles*
Dubkov	*Stationary probabilistic characteristics of memristor in circuit with capacitor and colored Gaussian voltage source*
Gismatulin	*Charge transport mechanism of SiN_x-based memristor in various states*
Gorshkov	*Flicker noise spectroscopy as a tool for the measurement of activation energies of oxygen ion diffusion in memristor systems at fixed temperature*
Kharcheva	*Multistability in nonlinear dynamical systems induced by influence of colored noises*
Koriazhkina	*Statistical analysis of $ZrO_2(Y)/Ta_2O_5$-based memristor response to white Gaussian noise*
Korolev	*Effect of irradiation with Si+ ions on resistive switching in memristive structures based on yttria-stabilized zirconia and silicon dioxide*
Krichigin	*Memristive switching dynamics for symmetric three-stable profile based on the linear response theory*
Orlov	*Research of features bipolar resistive switching characteristics in Si_3N_4 based structure*
Rubtsov	*UNN interdisciplinary laboratory of stochastic multistable systems*
Shchanikov	*On the fault-tolerant tuning of multilayer perceptron networks based on memristor*
Si Abdelkader	*A Computational Study of $Al/La_{1-x}Sr_xFeO_3$ interface for Resistance Random Access Memory Applications*
Smirnov	*Investigation of forming-free TiO_2 memristor structures formed by local anodic oxidation nanolithography*
Vokhmintsev	*Unipolar and bipolar resistive switching in nanotubular titanium and zirconium oxide layers*

Table of contents

Nonequilibrium distributions and relaxation times in a stochastic model of memristor

Nikolai Agudov * [1], Alexey Safonov [1], Alexey Krichigin [1], Anna Kharcheva [1], Alexander Dubkov [1], Davide Valenti [1], Alexey Mikhailov [1], Bernardo Spagnolo [1]

[1] Laboratory for Stochastic Multistable Systems, Lobachevsky State University (StoLab) – Russia

Invited Talk - PMM Session

We construct a stochastic model of a memristive system based on generalization of known approaches and experimental results. For this model we obtain the analytic expressions for stationary and nonstationary solutions. It allows to analyze the equilibrium and non-equilibrium steady state distributions of internal state variable of memristive system and investigate the influence of fluctuations and other parameters on the distribution parameters including transition time to the steady state. The proposed model allows analysis based on the exact analytical results. The relaxation time is shown to have monotonic and non-monotonic dependence on intensity of fluctuations for a different set of external parameters.

The work is supported by the Government of the Russian Federation (Agreement No. 074-02-2018-330 (2))

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*Speaker

Memristive switching dynamics for symmetric three-stable profile based on the linear response theory

Aleksei Krichigin [1], Nikolay Agudov *† [1], Aleksey Safonov [1], Alexander Dubkov [2], Angelo Carollo [3,4], Bernardo Spagnolo [3,4]

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[2] Lobachevsky State University of Nizhni Novgorod (UNN) – Gagarin avenue, 23, Russia
[3] Department of Physics and Chemistry, Group of Interdisciplinary Theoretical Physics and CNISM, University of Palermo – Italy
[4] Radiophysics Department, Lobachevsky State University of Nizhni Novgorod – Russia

Poster

We investigate the influence of fluctuations on transient dynamics of memristive systems which are of great interest for resistive switching memory (RRAM). The simple analysis which can be helpful for understanding of RRAM switching kinetics under action of fluctuations is shown. The memristive filament transformation through the nucleation and growth stages is assumed. The newly nucleated phases may not be immediately stable. We consider a possibility that they initially appear to be metastable, having to undergo further transformations towards stability. The correlation properties of the filament (correlation function, correlation time, spectrum ets.) for symmetric three-stable profile of the free energy are investigated based on the linear response theory (the amplitude of periodic input perturbations is small) and high potential barriers approximation. Signal-to-noise ratio of the first harmonic demonstrates the nonmonotonic behavior and reaches a maximum. This phenomenon is known as Stochastic Resonance.

The work is supported by the Government of the Russian Federation (Agreement No. 074-02-2018-330 (2))

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A novel system-theoretic technique to analyze and design mem-computing M-CNNs

Alon Ascoli * [1], Ronald Tetzlaff [1], Ioannis Messaris [1], Steve Kang [2], Leon Chua [3]

[1] Technische Universitat Dresden – Germany
[2] University of California, Santa Cruz – United States
[3] University of California, Berkeley – United States

Talk

In the memristive equivalent of a standard Cellular Nonlinear Network (CNN) [1]-[2], where a single resistance-switching memory, experiencing abrupt transitions between two possible resistance states only, is placed in parallel to the capacitor in each cell, the processing elements may be approximated at any given time as first-order dynamical systems, once the respective memristors are assumed to act as resistors of either the lowest or the largest resistance. Under this assumption, the classical Dynamic Route Map (DRM) technique [3], a graphical tool applicable only to dynamical systems with one degree of freedom, and adopted to analyze and synthesize the first-order cells of standard CNNs [4], may be adopted to investigate the operating principles of the class of Memristor CNNs (M-CNNs) under study [5]. However, the DRM analysis methodology is no longer pertinent to gain insight into the data processing capabilities of M-CNNs with second-order cells, as is the case when at least some memristors experience smooth conductance changes as the bio-inspired array executes a given mem-computing task. A novel system-theoretic graphical tool, inspired by the Phase Portrait concept [6] from the theory of nonlinear dynamics, and called Second-Order Dynamic Route Map (DRM2), recently introduced [5] as extension of the classical DRM analysis technique to dynamical systems with two degrees of freedom, may provide a deep insight into the dynamical phenomena emerging in the memristive cellular arrays under these circumstances. In this presentation the DRM2 methodology is applied to draw a comprehensive picture on the way M-CNNs with second-order memristive cells store and process information locally, implementing a truly non-Von Neumann mem-computing paradigm. Gaining a deep understanding of the nonlinear dynamics of these second-order cells allows to develop a systematic procedure, centered around the DRM2 graphical tool, for a conscious design of bio-inspired cellular arrays accomplishing predefined data processing tasks through states' dynamical evolution toward prescribed equilibria [7].

[1] L.O. Chua and L. Yang, "Cellular Neural Networks: Theory", IEEE Trans. on Circuits and Systems–I, vol. 35, no. 10, pp. 1257–1272, 1988
[2] L.O. Chua and L. Yang, "Cellular Neural Networks: Applications", IEEE Trans. on Circuits and Systems–I, vol. 35, no. 10, pp. 1273–1290, 1988
[3] L.O. Chua, "5 Non-Volatile Memristor Enigmas Solved", Applied Physics A, vol. 124, 563(43pp.), 2018
[4] L. Chua, and T. Roska, "Cellular Neural Networks and Visual Computing: Foundations and Applications," 1st edition, Cambridge University Press, 2002

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*Speaker

[5] R. Tetzlaff, A. Ascoli, I. Messaris, and L.O. Chua, "Theoretical Foundations of Memristor Cellular Nonlinear Networks: Memcomputing with Bistable-like Memristors," IEEE Trans. on Circuits and Systems–I: Regular Papers, 2019, in press
[6] S.H. Strogatz, "Nonlinear dynamics and chaos: with applications to physics, biology chemistry and engineering," Addison Wesley, 1994, ISBN: 0-201-54344-3
[7] A. Ascoli, R. Tetzlaff, S. Kang, and L.O. Chua, "Theoretical Foundations of Memristor Cellular Nonlinear Networks: A DRM2-based Method to Design Memcomputers with Dynamic Memristors," IEEE Trans. on Circuits and Systems–I: Regular Papers, 2019, under review

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Structural, electronic and optical propreties of Perovskite BiFeO$_3$ Nanoparticles

Amel Boutasta * [1], Abdelhakim Benosmane

[1] Laboratoire de physique théorique, département de physique, faculté des sciences, Université de Tlemcen – Algeria

Poster

The B3LYP density function was used with the 6-31G (d,p) basis set to perform relaxed energetic contour maps of the charged form of Perovskite BiFeO by simulating the presence of water as solvent using the Onsager model.

In addition, the molecular orbital calculations such as Natural Bond Orbitals (NBOs), HOMO-LUMO energy gap and Mapped molecular Electrostatic Potential (MEP) surfaces were also performed with the same level of DFT. Electronic stability of the compound arising from hyper conjugative interactions and charge delocalization were also investigated based on the natural bond orbital (NBO) analysis.

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*Speaker

Organic Memristive Devices and Organic Electrochemical Transistors: close friends in neuromorphic computations

Silvia Battistoni * [1]

[1] Istituto dei Materiali per l'Elettronica ed il Magnetismo, Parco Area delle Scienze 37/A, Parma, Italy
(CNR-IMEM) – Italy

Talk

Organic electronic devices are considered attractive options for neuromorphic systems being able to combine a relatively inexpensive fabrication with low-energy switching and excellent properties' tunability[1]. Depending on the specific application, it is possible to adapt devices' geometry, configuration and fabrication to develop a specific distinction. Another important feature of this class of devices (at least in the case of organic memristive devices-OMDs) is the possibility of enabling a continuous resistance tuning, which correspond to a wider number of programmable states. It has been recently reported[2] that OMDs emulate cellular mechanisms such as long-term plasticity (LTP) effects that are biologic function connected to learning and memory. The emulation is not limited to the replication of synaptic potentiation or depression effect but it's also taken to the level of emulating the entire biological behaviour including the use of stimuli with frequency variations[2]. In their turn, Organic Electrochemical Transistors (OECTs) have demonstrated to emulate Short-term plasticity (STP)[3], a crucial function for a variety of computational functionality in the brain.

Regardless their original neuromorphic properties, it to be noted that both OMDs and OECTs can be adapted to the specific application that is targeted. Here we present the developing of temporary synaptic weight plasticity in OMDs that naturally evolves in permanent plasticity[2], totally in agreement with the human memorization process, and the realization of neuromorphic synaptic function with a standard OECT gated with a graphene electrode[4].

[1] van De Burgt, Y., *et al.*, *Organic electronics for neuromorphic computing.* Nature Electronics, 2018: p. 1.

[2] Battistoni, S., V. Erokhin, and S. Iannotta, *Frequency driven organic memristive devices for neuromorphic short term and long term plasticity.* Organic Electronics, 2019. **65**: p. 434-438.

[3] Gkoupidenis, P., *et al.*, *Neuromorphic functions in PEDOT: PSS organic electrochemical transistors.* Advanced Materials, 2015. **27**(44): p. 7176-7180.

[4] Battistoni, S., C. Peruzzi, *et al.*, *Synaptic response in Organic Electrochemical Transistor gated by a graphene electrode* (under submission).

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*Speaker

Screening of the synthesis route on the structural, magnetic and magnetocaloric properties of $La_{0.6}Ca_{0.2}Ba_{0.2}MnO_3$ manganite: A comparison between solid-solid state process and a combination polyol process and Spark Plasma Sintering

Haithem Ben Khalifa * [1], Firas Ayadi [2], Wissem Cheikhrouhou [1], Guy Schmerber [3]

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[2] Physics/ITODYS, Université Paris Diderot, Sorbonne Paris Cité CNRS UMR 7086, 15 Rue Jean Antoine de Baaf, 75205, Paris, France – Tunisia
[3] Physics/IPCMS, UMR 7504 CNRS-UDS, 23 Rue du Loess, B.P. 43, 67034, Strasbourg Cedex 2, France – French Guiana

Talk

$La_{0.6}Ca_{0.2}Ba_{0.2}MnO_3$ ceramics are prepared by an original route, combining soft chemistry and Spark Plasma Sintering, within a few minutes at 700°C and by the solid-state reaction at high temperatureswith an annealing temperature of 1200°C. We have studied the leverage of the powder synthesismethod on the structural, morphological, magnetic and magnetocaloric properties of the samples. X-ray diffraction analysis using Rietveld refinement revealed that our materials crystallize in the rhombohedral system with R3-c space group for the sample prepared by the Polyol-Spark Plasma Sintering method and in the orthorhombic structure with Pbnm space group for the sample synthesized by the solid-state reaction. Magnetization measurements versus temperature under magnetic applied field of 0.05 T show a paramagnetic-ferromagnetic phase transition for both samples. The Arrott plots reveal that ours materials undergo a second-order phase transition. The maximum values of the magnetic entropy change (-ΔSmaxM) under the magnetic field change of 5 T are 2.4 and 4.7 J/kg K for $La_{0.6}Ca_{0.2}Ba_{0.2}MnO_3$ synthesized by using solid-state reaction and Polyol-Spark Plasma Sintering methods respectively. The highest value of the relative cooling power RCP is found to be 244 J/kg for the Polyol-Spark Plasma Sintering sample under 5 T. These results are interesting enough and suggest that the Polyol-Spark Plasma Sintering synthesis method is a feasible route to prepare high quality perovskite material for magnetic cooling application.

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*Speaker

Noise and Variability in Oxide-based Filamentary Resistance Switching Devices

Stefano Brivio * [1], Sabina Spiga [1]

[1] National Research Council of Italy, Institute for Microelectronics and Microsystems, Unit of Agrate Brianza (CNR - IMM, Unit of Agrate Brianza) – via C. Olivetti 2, 20864, Agrate Brianza (MB), Italy

Invited Talk

Noise and variability are among the most fascinating and problematic aspects of resistive switching memories (or memristive devices). In particular, a highly stochastic behaviour is often observed in those devices whose resistance change is driven by accumulation and spread out of electrically active defects into or from nanometric filamentary regions, named conductive filaments. [1] The recent shift of the target application of memristive devices from conventional memory to more exotic scopes requires a revision or an update of the roles of their noise and variability features.

Therefore, in the first part of my talk, I will give an overview of the types and the physical sources of variability and noise in filamentary devices; I will analyse the limitations and problems they raise for conventional memory applications and some solutions to mitigate their effects. In this context, I will present our investigation of the role of Al doping of the HfO2 switching layer, which introduces immobile defect sites and influences the magnitude and the nature of the variability and noise of the related devices. [2,3,4]

In the second half of my talk, I will roughly present the way in which the role of noise and variability can be revised for memristive neuromorphic applications, i.e. one of the most researched fields outside the conventional memory world. In particular, I will discuss to which extent noise and variability can be either an issue or an opportunity for different kinds of neuromorphic computation. Furthermore, I will present our latest results about the possibility of intentionally stimulate telegraphic resistance variations in filamentary HfO2-based resistance switching devices. In this study, we show that trains of identical pulses can be used to generate random and zero-average resistance variations (see supplementary figure 1) in filamentary devices due to the instating of a dynamic equilibrium condition between the processes of drift and diffusion of ionic defects at the edges of the conductive filament responsible for the switching. [5]

[1] Chen *et al.*, ECS Trans. 39, 21 (2017).
[2] Frascaroli *et al.*, Microelectron. Engin. 147, 104 (2015).
[3] Frascaroli *et al.*, ACS Nano 9, 2518 (2015).
[4] Brivio *et al.*, Nanotech. 28, 395202 (2017).
[5] Brivio *et al.*, Scie. Rep. 9, 6310 (2019) .

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[*] Speaker

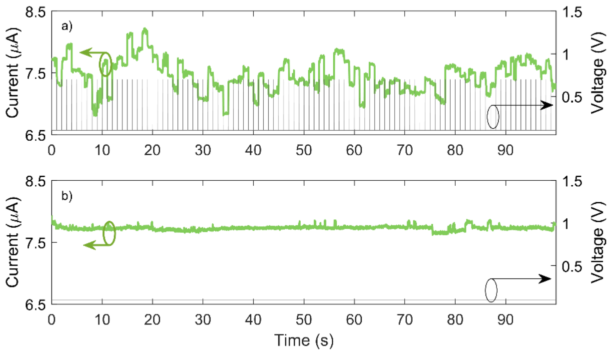

Figure 1: a) Current (green thick line, left axis) as a function of time in an experiment in which 100 pulses are delivered to the memristive device every 1 s. Pulses are 0.7 V high and 100 μs long and the current is acquired applying 0.1 V with a sampling time of 0.01 s. The applied voltage is reported as a grey thin line (right axis). Current jumps are ascribed to an effect of stimulated ionic noise. b) Current (green thick line, left axis) read at a constant voltage of 0.1 V (gray thin line, right axis).

Equilibrium and non-equilibrium phase transitions: a mesure of quantumness

Angelo Carollo * [1,2]

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[2] Radiophysics Department, National Research Lobachevsky State University of Nizhni Novgorod – 23 Gagarin Avenue, Nizhni Novgorod 603950, Russia

Talk

We derive a measure of quantum-ness in quantum multi-parameter estimation problems. We can show that the ratio between the mean Uhlmann Curvature and the Fisher Information provides a figure of merit which estimates the amount of incompatibility arising from the quantum nature of the underlying physical system. This ratio accounts for the discrepancy between the attainable precision in the simultaneous estimation of multiple parameters and the precision predicted by the Cramér-Rao bound. We apply this measure to quantitatively assess the quantum character of phase transition phenomena in peculiar quantum critical models. We consider a paradigmatic class of lattice fermion systems, which shows standard closed quantum phase transition and dissipative non-equilibrium steady-state phase transitions.

The work is supported by the Government of the Russian Federation (Agreement No. 074-02-2018-330 (2))

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*Speaker

From formal neural networks to memristor-based spiking neuromorphic systems: perspectives and open issues

Vyacheslav Demin * [1], Andrey Emelyanov [1,2], Kristina Nikiruy [1], Igor Surazhevsky [1], Anton Minnekhanov [1], Vladimir Rylkov [1], Alexander Sitnikov [1,3], Alexey Mikhaylov [4], Bernardo Spagnolo [4], Pavel Kashkarov [1,2,5], Mikhail Kovalchuk [1,2,5]

[1] National Research Center “Kurchatov Institute” – Russia
[2] MIPT – Russia
[3] Voronezh State Technical University – Russia
[4] National Research Lobachevsky State University – Russia
[5] Lomonosov Moscow State University – Russia

Talk - PMM Session

Today, there is a high and growing interest in the development and commercial use of artificial intelligence algorithms with a neural network architecture. Algorithms based on the so-called formal neural networks (FNNs), in which the activation function of a neuron is a static nonlinear transformation, are widely used. At the same time, two key limitations prevent the truly wide spread of the FNNs: 1) training of almost any algorithms based on the FNNs requires large datasets labeled by human experts, 2) the lack of massively available specialized neuromorphic computing systems dictates the need for the implementation of FNNs on sufficiently large and expensive IT network servers, which constrains the use of intelligent algorithms in mobile devices, causes significant energy costs for processing, storage and transmission of information, and also limits the potential performance of FNN-based algorithms.

Implementation of spiking neural networks (SNNs) based on memristors as analogues of synaptic contacts between artificial spiking neurons provide an opportunity to overcome both of these developmental constraints. In this paper, we demonstrate how local learning rules using information only about neighboring (connected) neurons reduce the dependence on the volume of training data samples, how some plausible local rules for SNN learning of STDP-type, can be implemented in different kinds of memristors (based on inorganic and polymeric materials). It is also shown how a simple multiplicative transformation of input and output pulses provides the possibility of implementing biologically inspired learning rules with dopamine-like reinforcement, which in the future allows creating more complex SNNs with architecture, dynamics and learning methods close to biological prototypes and having the ability to adapt network interactions during real-time information processing.

Finally, we discuss the parameters values of synaptic plasticity window in which the convergence of classic Hebbian learning is observed. Also, the possible role of an input noise signal with Poisson distribution of the moments of spikes is considered in the learning SNN, with the weights initialized during unfinished Hebbian training. Results of the work indicate the principal possibility and high prospects of constructing memristor-based SNNs having a rather complex, including recurrent, architecture and capable of partially unsupervised learning. These

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[*] Speaker

properties of hardware implemented SNNs can contribute to overcoming the above-mentioned development constraints and, accordingly, to the mass spread of neural network algorithms in all spheres of human activity.

This work was supported by grants: RFBR No. 18-29-23041, in part of investigating the local learning rules of spiking neurons with nanocomposite-based memristor weights; RFBR– 18-37-20014, in the implementation of dynamic plasticity on the basis of polymer memristors; RFBR–19-29-03022, in the production and characterization of nanocomposite memristors; and the Ministry of education and science grant No. 074-02-2018-330 (2), in examination of the influence of input noise signal on SNN training. The work was carried out on the equipment of resource centers of NRC "Kurchatov Institute".

Memcomputing: leveraging memory and physics to compute efficiently

Massimiliano Di Ventra *† 1

1 Department of Physics, University of California San Diego – United States

Keynote Talk

It is well known that physical phenomena may be of great help in computing some difficult problems efficiently. A typical example is prime factorization that may be solved in polynomial time by exploiting quantum entanglement on a quantum computer. There are, however, other types of (non-quantum) physical properties that one may leverage to compute efficiently a wide range of hard problems. In this talk, I will discuss how to employ one such property, memory (time non-locality), in a novel physics-based approach to computation: Memcomputing [1, 2, 3]. As examples, I will show the efficient solution of prime factorization, the search version of the subset-sum problem [4], approximations to the Max-SAT [5], and the ground state of Ising spin glasses [6], using self-organizing logic gates, namely gates that self-organize to satisfy their logical proposition [4]. I will also show that these machines take advantage of the long-range order that develops during their transient dynamics in order to tackle the above problems, and are robust against noise and disorder [7]. The digital memcomputing machines we propose can be efficiently simulated, are scalable and can be easily realized with available nanotechnology components. Work supported in part by MemComputing, Inc. (http://memcpu.com/) and CMRR.

[1] M. Di Ventra and Y.V. Pershin, Computing: the Parallel Approach, Nature Physics 9, 200 (2013).
[2] F. L. Traversa and M. Di Ventra, Universal Memcomputing Machines, IEEE Transactions on Neural Networks and Learning Systems 26, 2702 (2015).
[3] M. Di Ventra and F.L. Traversa, Memcomputing: leveraging memory and physics to compute efficiently, J. Appl. Phys. 123, 180901 (2018).
[4] F. L. Traversa and M. Di Ventra, Polynomial-time solution of prime factorization and NP-complete problems with digital memcomputing machines, Chaos: An Interdisciplinary Journal of Nonlinear Science 27, 023107 (2017).
[5] F. L. Traversa, P. Cicotti, F. Sheldon, and M. Di Ventra, Evidence of an exponential speed-up in the solution of hard optimization problems, Complexity 2018, 7982851 (2018).
[6] F. Sheldon, F.L. Traversa, and M. Di Ventra, Taming a non-convex landscape with dynamical long-range order: memcomputing the Ising spin-glass, arXiv:1810.03712 (2018).
[7] M. Di Ventra, F. L. Traversa and I.V. Ovchinnikov, Topological field theory and computing with instantons, Annalen der Physik 529,1700123 (2017).

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[*] Speaker

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Emerging ReRAM devices and lithography manufacturing issues

Panagiotis Dimitrakis * [1]

[1] Institute of Nanoscience and Naotechnology, NCSR ”Demokritos” – Greece

Invited Talk

RRAMs are considered as the most promising devices for NVM and storage class memory applications at technology nodes below 20nm. In addition, due to their memristive properties pave the way for the realization of neuromorphic prototype circuits. The majority of these devices are two-terminal MIM structures and use as insulator (active material) metal oxides in combination with proper metals. The present models assuming the oxide and metal physical and chemical properties seem that can explain the observed resistive phenomena. Nevertheless, the effect of humidity seems to play a crucial role in the reliability of RRAMs.
In this context, nitride-based insulators are of special importance because of their immunity in humidity and oxygen related parasitic effects. The present contribution reports on the preliminary results related to our research on MIM devices where LPCVD Si3N4is used as insulating material, sputtered Cu as active (top) electrode and heavily doped Si (¡0.003 Ω.cm) bottom electrode (BE)1-3. Both conductivity types of Si n and p have been tested. The nitride interfaces modified by the insertion of a thin thermal oxide and plasma oxynitride layers. The devices have been characterized in terms of static I-V, resistance variability, impedance spectroscopy (IS) as well XPS and TEM. According to our results the MIM diodes with p+Si as BE present higher variability in VSETand VRESETcompare to those diodes with n+Si BE. IS measurements are in progress to investigate the mechanism for resistance switching. Preliminary results reveal that the resistance switching mechanism is related to a diffusion and/or injection mechanism of electrons to native bulk nitride traps (Si dangling bonds due to nitrogen deficiency). According to the mechanisms revealed by the experimental investigations, a model for I-V interpretation has been constructed.
In addition, we investigate the effects of Line Edge Roughness (LER) of electrode lines on the uniformity of ReRAM device areas in cross-point architectures. To this end, a modeling approach is implemented based on the generation of 2D cross-point patterns with predefined and controlled LER and pattern parameters. The aim is to evaluate the significance of LER in the variability of device areas and their performances and to pinpoint the most critical parameters and conditions. It is found that conventional LER parameters may induce ¿10% area variability depending on pattern dimensions and cross edge/line correlations. Increased edge correlations in lines such those appeared in Double Patterning and Directed Self-assembly Lithography techniques lead to reduced area variability. Finally, a theoretical formula is derived to explain the numerical dependencies of the modeling method.

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*Speaker

Stationary probabilistic characteristics of memristor in circuit with capacitor and colored Gaussian voltage source

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Poster

Using unified colored noise approximation (UCNA) proposed in the paper P. Jung and P. Hanggi, Phys. Rev. A V.35, 4464 (1987) we generalize the results obtained in V.A. Slipko *et al*, Phys. Rev. E V.87, 042103 (2013) for the case of an electric circuit with a memristor, capacitor and stochastic voltage source in the form of colored Gaussian noise with exponential correlation function (Orstein-Uhlenbeck process). Namely, for the model of charge-controlled ideal memristor with special dependence of the memristance on charge, we find an approximate forms of the steady-state probability distributions of resistor and charge and check these results by numerical simulations. We draw the plots of stationary probability density functions for different values of noise parameters: variance and correlation time. As shown, the average value of the charge on the capacitor in the stationary state is not zero unlike the case of white Gaussian noise perturbation. We analyze the conditions of UCNA applicability for our system, comparing the analytical results with numerics.

The work is supported by the Government of the Russian Federation (Agreement No. 074-02-2018-330 (2))

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*Speaker

Organic Memristive Devices for Neuromorphic Applications

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Invited Talk

Working principle of organic memristive device is based on the significant difference of polyaniline (PANI) conductivity in oxidized and reduced state [1]. These reversible transitions occur in the active zone, where PANI is in a contact with solid electrolyte.

The device mimics some properties of synapses what allows to use it for neuromorphic applications. In particular, several circuits, mimicking learning of living beings, were reproduced with organic memristive devices [2], including the possibility of unsupervised learning according STDP (Spike Timing Dependent Plasticity) mechanism [3].

Direct demonstration of synapse mimicking properties was done through connecting two nervous cells of the rat cortex through memristive device. It was demonstrated that firing of the second cell by the first one occurred when the conductivity of the memristive device was higher that a certain threshold level. Time delay between spikes of the cells was decreased with the increase of the connection strength [4].

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*Speaker

Noise-induced resistive switching studied by Conductive Atomic Force Microscopy

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Invited Talk - PMM Session

The local resistive switching (RS) in the contact of a conductive atomic force microscope (CAFM) probe to a nanometer-thick yttria stabilized zirconia (YSZ) film on a conductive substrate under a random noise voltage applied between the probe and the substrate has been studied experimentally. The diameter of a metal-coated CAFM probe contact to the YSZ film surface is typically ¡ 10 nm at reasonable force of the probe-to-sample interaction (∼ 1 nN) used in experiment [1]. So far, the CAFM probe contact to the YSZ film (together composing a nanometer-sized virtual memristor device) is a convenient model system allowing studying the RS at nanometer scale, particularly, studying the electron transport via single filaments [2, 3]. The 4-5 nm thick YSZ films (12 % mol. Y) were deposited by radio-frequency magnetron sputtering. The CAFM experiments were carried out in ultra high vacuum (UHV) using Omicron UHV AFM/STM LF1 in contact mode. The artificial white Gaussian noise signal applied between the CAFM probe and the sample was generated by the digital-to-analog converter (DAC) of Lcard E502 DAC/ADC unit used as an external computer-controlled programmable voltage source. The maximum DAC bitrate was 1 MHz.

The cyclic current-voltage curves of the CAFM probe-to-sample contact demonstrated well expressed butterfly-type hysteresis typical for the bipolar RS. Under the white Gaussian noise signal with certain parameters, the virtual memristor was found to switch between the low resistance state (LRS) and the high resistance state (HRS) chaotically randomly in the random telegraph signal (RTS) regime. Correspondingly, the probability density function (pdf) of the virtual memristor resistance demonstrated two peaks corresponding to HRS and LRS. The effective potential profile of the virtual memristor calculated from its response to the white Gaussian noise signal by standard technique [4, 5] manifested two local minima corresponding to the number of resistance levels. The observed effect manifests the fundamental intrinsic properties of the memristor as a bistable nonlinear system. Also, the time dynamics of the effective potential profiles of the virtual memristor reflecting its degradation has been studied.

The work was supported by the Government of the Russian Federation through Agreement No. 074-02-2018-330 (2).

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*Speaker

Josephson junctions switching current analysis for signal detection

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Talk

Josephson junction electrical behavior is governed by a quantum variable, the gauge invariant phase difference between the macroscopic phases of the two superconductors forming the junction. The quantum phase dynamics is accessible, albeit with indirect electrical measurements, essentially the current through, and the voltage across, the device. In particular, it is possible to retrieve the current at which the system switches from the zero voltage (superconducting) state to a finite voltage (normal) state. Repeating the measurements, because of thermal noise or quantum tunneling, the passage to the finite voltage occurs at slightly different current levels, thus producing a distribution of switching currents. If a signal, for instance a sinusoidal drive, is applied to the junction, the deviations from the expected distribution can be used as a clue on the features of the signal embedded in the noise. Two features of Josephson junctions make them very attractive for signal detection: a) as Josephson junctions can be miniaturized, the energy scale can be made very small; b) being superconducting elements, they can operate at the lowest temperatures; therefore thermal noise can be reduced as much as refrigeration permits. It has for instance been recently proposed to exploit Josephson junctions features for the detection of galactic axion. Such detection is quite demanding, inasmuch it calls for a device sensitive to a single microwave photon, whose energy is of the order of 10-24J, and therefore operating at temperatures around few tens of mK. Also, the rate of quantum tunneling out of the superconducting state, that is sizable at this energy scale, should be tamed. It is, therefore, of paramount importance to model the stochastic and quantum dynamical evolution of Josephson junctions with great accuracy, to identify the appropriated device fabrication parameters and the operation point. Finally, the nonlinear analysis of the escape distributions is essential for the sucess of the detection scheme, for the signal-to-noise ratio is expected to be relatively low. The choice of the most appropriated techniques of signal analysis is therefore essential to exploit the accessible information, and interweaved with the device dynamics.

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*Speaker

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Charge transport mechanism of SiN_x-based memristor in various states

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Poster

Nonstoichiometric silicon nitride SiN_x is a promising material for developing a new generation of high-speed, reliable flash memory based on the resistive effect. It is necessary to understand the charge transport mechanism in all resistive states in SiN_x to develop a resistive memory element. At present, it is generally accepted that the charge transport in the RRAM is described by the Frenkel effect. In our work, the charge transport in RRAM based on SiN_x is analyzed with five volume-limited charge transport models. It is established that the Frenkel model of Coulomb traps ionization, Hill-Adachi model of overlapping Coulomb potentials, Makram-Ebeid and Lannoo model of multiphonon isolated traps ionization and the Nasyrov-Gritsenko model of phonon-assisted tunneling between traps, quantitatively, do not describe the charge transport in the RRAM based on SiN_x. The Shklovskii-Efros percolation model gives a consistent explanation of the charge transport in all resistive states in the RRAM based on SiN_x at temperatures above room temperature.

Charge transport mechanism of forming less $SiO_{1.09}$-based memristor in various states

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Talk

The forming less $SiO_{1.09}$-based memristor was fabricated and its properties retention and endurance were measured. It was shown that retention and endurance of the forming less $SiO_{1.09}$-based memristor not less than four orders. The charge transport mechanism of the $SiO_{1.09}$-based memristor was studied in the virgin state (VS), high-resistive state (HRS), low-resistive state (LRS) and intermediate state (IS). It was shown that the charge transport mechanism of a SiO_x-based memristor in all resistive states is described by the space-charge-limited current (SCLC).

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*Speaker

Flicker noise spectroscopy as a tool for the measurement of activation energies of oxygen ion diffusion in memristor systems at fixed temperature

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Poster

The flicker noise $1/f$^g (with g=1) in the electrical current through a nanometer-sized virtual memristor (VM) is investigated at temperature T=300 K. The VM consists of a contact of a conductive atomic force microscope (CAFM) probe to an yttria stabilized zirconia (YSZ) thin film deposited on a conductive substrate [1]. We measured the electric current through a single conducting filament in the film both in low resistive state (LRS) and in the high resistive state (HRS) of the VM. It is possible due to low diameter (about 10 nm) of the CAFM probe contact to the YSZ film. Probability density functions (pdf) and spectra of the current in both LRS and HRS are measured. The noise in the HRS is found to be featured by nearly the same pdf and spectrum as the inner noise of the experimental setup. In the LRS, a considerably higher flicker noise with g=1.3 is observed in the low-frequency band (up to 8 kHz). This noise is assumed to be attributed to the motion of oxygen ions via oxygen vacancies in the conducting filament. Activation energies E of oxygen ions motion determined from the noise spectrum are distributed in the range [0.52; 0.68] eV with pdf W_E=exp [(g–1)$E/(kT)$]. This range matches satisfactory with results obtained earlier from measurements on the samples with macroscopic contacts at temperatures 300–500 K, E=0.53–0.56 eV [2]. Thus, the flicker noise spectroscopy is a promising tool for the investigation of the mechanisms of the resistive switching in the YSZ based memristor as well as for the numerical simulations of memristor devices.

This work is supported by the Government of the Russian Federation through Agreement No. 074-02-2018-330 (2). The CAFM measurements are carried out using the shared research facility of Research and Educational Center for Physics of Solid State Nanostructures at Lobachevsky State University of Nizhni Novgorod.

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*Speaker

Thermal noise effects on a memory element based on an anomalous Josephson junction

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Talk

Superconducting electronics is suggested as playing an important role in the search of ultra-low-power computers. One of the key challenges towards this objective is the fabrication of a reliable and scalable cryogenic memory architecture. Superconductor-ferromagnet-superconductor (SFS) Josephson junction (JJ) are promising structures suggested for such memories. In fact, interplay between the intrinsic exchange field and the induced superconductivity in the ferromagnet leads to the so-called π-junction, i.e., a JJ exhibiting an intrinsic π-phase shift in its ground state. Vertical ferromagnetic multilayer structures are being used as Josephson magnetic memories, in which Logic states usually correspond to states with different relative orientation of magnetic layers, that in turn determines whether the junction is in the 0- or π -state.

Here, we suggest an alternative cryogenic memory element based on a ferromagnetic anomalous JJ, usually called φ_0-junction. It consists of a SFS JJ with a Rashba-like spin-orbit coupling (SOC). Its ground state corresponds to a finite phase difference, $0 < \varphi_0 < \pi$, between the superconductors [2,3]. In such junctions the magnetization can be controlled by passing a current through the device [4,5]. In our proposal, the memory states are encoded in the direction of the out-of-plane magnetization of the ferromagnetic layer, which can be directly manipulated via current pulses. In order to define two sufficiently robust logic states and to establish the proper working temperature of the memory element, we investigate the current-controlled bistability of the magnetization in the presence of thermal fluctuations. In fact, we observe that the stability of the magnetization reversal phenomenon strongly depends on thermal noise, certainly affecting every storage device. In this way, we can estimate the optimal working temperature at which the magnetization reversal still persists, and how to eventually optimize the system parameters in order to improve the performances of the memory device. In particular, we take into account effects induced by a "thermal current" and a "thermal field", i.e., stochastic noise sources affecting the phase and the magnetic moment dynamics, respectively. Moreover, in a junction formed by a ferromagnet with a Rashba-Dresselhaus type SOC, a voltage gating makes it possible to decouple the Josephson and the magnetization dynamics, in order to give a concrete voltage-controlled knob for freezing the memory state, so to protect it from any external influence. If the memory can be readily write via electric current pulses, the memory reading can be performed through a feasible non-destructive readout scheme based on a dc-SQUID magnetometer.

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*Speaker

Atomistic and dynamical stochastic models of metal-oxide memristive devices

Davud Guseinov * [1], Dmitri Korolev [1], Alexey Belov [1], Evgenia Okulich [1], Viktor Okulich [1], Svetlana Gerasimova [1], David Tetelbaum [1], Alexey Mikhailov [1], Viktor Kazantsev [1]

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Talk

Stochastic plasticity is a key functionality emulated by memristive devices for perspective neuromorphic applications. Here we interpret and simulate the variation of current-voltage characteristics and stochastic memristive response experimentally observed for the ZrO2(Y)-based memristive devices. We consider several approaches to describe the stochastic response of memristors. In atomistic or microscopic approach, to model the growth and destruction of conducting channels (filaments) in thin oxide film, one should simulate the drift and diffusion of ions and/or vacancies due to the action of external and internal electric fields and temperature (Joule heating). A universal filamentary model of bipolar resistive switching has been developed for the Au/ZrO2(Y)/TiN/Ti memristive devices by using kinetic Monte-Carlo simulation of the migration of oxygen vacancies at the stages of electroforming, SET and RESET processes which reproduces well the variation of experimental switching hysteresis [1]. Statistics of the electroforming and switching voltages is collected and used to simulate the current-voltage characteristics basing on a simplified multi-filament model. As a result, it can be concluded that the intrinsic stochastic nature of atomistic processes leads to randomness of current-voltage characteristics. Another approach is macroscopic and based on a description of memristor by a system of differential equations for internal state variables [2]. It is shown that the incorporation of noise in such a system leads to an adequate representation of experimental data. Moreover, the dynamics of memristors and their networks driven by periodic alternating-polarity pulses may converge to fixed-point attractors (stable states) [3]. We find such stable states for our physics-based model of memristor calibrated to the experimental data and study the effect of fluctuations of microscopic parameters on the existence and properties of attractors. The results obtained are important for the development and testing of new approaches to the construction of biologically plausible neuromorphic systems.

We gratefully acknowledge the support of the Government of the Russian Federation (contract No. 074-02-2018-330 (2)) and partially the Russian Foundation of Basic Research (grant No. 18-29-23001).

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*Speaker

Multistability in nonlinear dynamical systems induced by influence of colored noises

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Poster

On the one hand, using the unified-colored noise approximation (UCNA) [1], it was demonstrated in [2] that the Ornstein–Uhlenbeck noise can produce bimodal stationary states in the quartic potentials. On the other hand, for the parabolic potential the stationary state is always unimodal, i.e. it is given by the normal density. In the above studies we verify and extend numerically some results of [2]. In particular, we explore the mechanism responsible for emergence of bimodal stationary states in general fixed single-well potentials.

Further, we assume that the potential is no longer fixed but it stochastically changes over time due to action of the symmetric Markovian dichotomous noise. We consider both 1D and 2D random potentials. Following the line of investigation initiated in [3] and extended in [4] we verify if the addition of the Markovian dichotomous noise can induce stationary states with more than two modal values. Indeed, additional action of symmetric Markovian dichotomous noises can induce dynamic multimodality. In particular, one observes bimodal, trimodal and four modal stationary states. It is also possible to produce a unimodal stationary state.

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[*] Speaker

Statistical analysis of $ZrO_2(Y)/Ta_2O_5$-based memristor response to white Gaussian noise

Mariia Koriazhkina *† [2,1], Dmitry Filatov [2], Dariya Vrzheshch [2], Oleg Tabakov [2], Alexey Novikov [2], Anna Kharcheva [2], Alexey Belov [2], Ivan Antonov [2], Valery Sharkov [2], Alexey Mikhaylov [2], Oleg Gorshkov [2], Alexander Dubkov [2], Davide Valenti [1], Bernardo Spagnolo [1,2]

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Poster

The development of a new type of computer non-volatile memory (Resistive Random-Access Memory – RRAM) and its key elements - memristors - is one of the most actual scientific and technological problems of modern information technologies. The memristor can be considered as a multistable nonlinear system whose behavior is described by using the methods of statistical physics. The impact of noise on such systems can lead to the occurrence of stochastic resonance, where noise plays a constructive role [1]. Some phenomena inherent to the stochastic multistable systems have been observed experimentally in memristors indeed (for example, [2]). In the present work, we have investigated experimentally the response of a memristor based on $ZrO_2(Y)/Ta_2O_5$ stack to a white Gaussian noise. A chaotic switching of the memristor between resistance states in the random telegraph signal mode has been observed. Such a behavior is inherent to the multistable systems subjected to an external noise. The experimental results obtained in the present work show the applicability of the methods of statistical physics for the description of the impact of noise on the nonlinear multistable systems. The evolution of the effective potential profile of memristor under the white Gaussian noise signal has been studied. It was found that the effective potential profile of memristor change abruptly that indicates the sudden changes of the memristor properties under the impact of noise. The impact of noise on the memristor electrical properties was attributed to the burning out of active filaments and the wakeup of next potential filaments. The results of the present work indicate that the memristors is more complex dynamic system than a system with a simple two-well fixed potential.

The study was supported by the Government of the Russian Federation (Agreement No. 074-02-2018-330 (2)) and the Ministry of Education, University and Research of Italian Government.

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[*] Speaker

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Formation of the new elements for the nonvolatile optical memory based on waveguides with switchable transparency of PCM materials

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Talk

Replacing electronic components of integrated systems with their optical functional counterparts is an important task. In particular, an integrated non-volatile memory with optical control is being developed as the next generation of non-volatile electronic memory devices with improved performance. Such a memory uses a change in the transparency of an optical waveguide under the influence of an optical signal instead of a change in the resistance of a thin dielectric layer under the application of an electric field. A promising candidate for such structures is phase-change materials (PCM) with its ability to change the transparency by the application of energetic pulse. As an active material, GeSbTe (GST) compound can be used, which, depending on stoichiometry, has variable transition parameters between crystalline and amorphous states with different transparency. For the development of non-volatile optical memory based on the effect of switchable transparency, an important task is an engineering of the structure of the optical memory cell and the development of a topology for the arrangement of elements in the circuit. In this work, we consider different variants for creating such a memory cells based on single-mode optical fibers in the upper layer of SOI wafers with a film or diffraction grating for optical control of the transparency of the GST material, and, accordingly, the transmission of light in the waveguide layer. This work was supported by the Russian Foundation for Basic Research, project no. 19-29-03040.

The work is supported by the Government of the Russian Federation (Agreement No. 074-02-2018-330 (2))

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*Speaker

Effect of irradiation with Si+ ions on resistive switching in memristive structures based on yttria-stabilized zirconia and silicon dioxide

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Poster

The development of elemental basis for a new type of nonvolatile memory (Resistive Random Access Memory) attracted much attention due to its possible application in non-von-Neumann computer systems. Memristive nanodevices with an effect of resistive switching (RS) are the most promising element for this purpose. The practical implementation of memristive structures is substantially restricted by insufficient stability of the parameters of RS [1], one of the main reason of which is the stochastic nature of formation and rupture of conducting filaments in the functional layer [2].

There are many approaches to increasing the stability of RS process parameters [3–6]. One of them is using of ion irradiation which allows to control the defect and impurity composition of active layer [7]. In present work the effect of ion irradiation on the parameters of RS in memristive structures based on yttria-stabilized zirconia and silicon dioxide films (40 nm in thickness each) exposed to Si+ ion irradiation is studied. It is established that the ion irradiation leads to increase the stability of the parameters of RS in the investigated memristive structures. This fact may be caused by the strongly localization of the nuclei of the conducting filaments which is correspond to the size of atomic displacement cascades produced by implanted atoms.

This work was supported by the Russian Foundation for Basic Research, project no. 18-37-00456.

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[*] Speaker

Resistive multi-level NVM devices for high capacity storage and neuromorphic system applications

Sergei Koveshnikov *† [1]

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Invited Talk

Resistive memory arrays with improved functionality and reliability will be of a great importance for developing new, more effective elements for neuromorphic devices, non-volatile memory of a terabit scale, energy-efficient single-chip systems and new generation of computers operating based on new physical principles.

HfOx is a mainstream oxide in the fab and is a strong candidate for RRAM. To provide RRAM feasibility, three key issues need to be resolved: (1) quantification of the *intrinsic* trade-offs between operative voltage, current and Set/Reset switching time, (2) improvement of intrinsic and extrinsic variability of switching characteristics, and (3) development of HVM compatible forming methods. In this work these issues are addressed by developing fully integrated, low parasitics ($C_{parasitics} \sim 50$ fF) 1T/1R enabling *intrinsic, real-time* Set/Reset switching and development of a HVM friendly pulsed forming. Key RRAM performance parameters including low (LRS) and high (HRS) resistance, Set/Reset voltage (Vt) and switching time (ts) were measured as a function of operative current (Icompl), voltage range, pulse speed (dV/dt_{rise}) and temperature using *real-time* AC methodology.

The report is also aimed at study of the fundamental properties of structural defects in thin dielectric films based on metal oxides that are currently used in resistive memory array structures. Switching mechanism of a resistive memory cell from its low-resistance to high-resistance state and back is the subject of discussion and intensive research. A common hypothesis is that the switching of a resistive memory cell is due to electrically and thermally driven diffusion of oxygen vacancies. The lack of a clear understanding of switching physics along with mechanism of conductive filament formation during forming and its role in the process of subsequent resistive switching is one of the unsolved fundamental problems that prevents the improvement of the resistive memory array functionality, particularly, cycle to cycle variability of the threshold switching voltages and cell resistance in its high resistance state.

To understand the switching mechanisms in the resistive memory based on hafnium oxide and other metal oxides, our recently developed approach will be based on highly controlled formation of a conducting filament and the experimental study of the electronic properties of defects in dielectrics. To controllably form a single conducting filament we have developed several unique techniques; one of them is our knowhow and is based on the localization of the electric field. Our ability to precisely position the conducting filament along with the capabilities of electron-beam lithography and fabrication of the fine structure for transmission electron microscopy make it possible to visualize the filament within the memory cell and to study its electrical properties, structural changes and chemical composition during and after resistive switching.

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Finite-temperature topological phase transitions in two-dimensional systems

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Talk

Chern insulators represent a class of 2D topological systems, which show non-trivial topological phases, characterised by the Chern number, a topological invariant taking on different values depending uniquely on the band structure of the ground-state.
The Chern number cannot be used to describe the topological phases of systems at thermal equilibrium, as for any mixed state, since it is defined only for pure states.
The Uhlmann approach allows to study topological phases and geometric properties to the case of the mixed states.
Here, by using this approach we define new tools, such as the mean Uhlmann curvature or the Uhlmann number, which permit to capture distinctive topological properties of Chern insulators at finite temperature.
We also demonstrate how these quantities do not exhibit temperature-driven phase transitions, while describing on the contrary a clear cross-over behaviour from a zero-temperature topological phase to a trivial high-temperature one.
This behaviour can be assessed by defining a crossover temperature, which depends on a universal critical scaling close to the topological phase transition.
In spite of its mathematical definition, the Uhlmann approach can be readily related to experimentally accessible quantities, such as the dynamical conductivity, or more generally, the dynamical susceptibility.
The Uhlmann number can be indeed considered as a straightforward generalisation of the Chern number, and therefore a generalised TKNN relation can be introduced, linking the Uhlmann number to the dynamical conductivity.

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*Speaker

Towards implementation of collective dynamics of stochastic memristor-coupled artificial neurons

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Invited Talk - PMM Session

One of the ways determining the development of emerging neuromorphic systems is based on the possibility of creating simple electronic analogues of neuron and synapse using thin-film memristive devices and arrays. Synaptic plasticity is the main property of memristive devices which is used for the realization of learning rules in memristive neuromorphic systems. Experimental implementation of such systems requires both engineering the memristive device structure for obtaining reproducible switching parameters and reliable demonstration of plasticity of memristive devices connecting electronic neurons in specific spiking neural architectures. In this work, the stochastic synaptic plasticity is studied for the optimized multilayer memristive devices and device models based on the yttria-stabilized zirconia (YSZ) and TaOx thin films by using different voltage and current pulse trains, simulated and experimentally generated electrical activity of FitzHugh-Nagumo and Hodgkin-Huxley artificial neurons. Different mechanisms of spike timing dependent plasticity in response to overlapping and non-overlapping pre- and postsynaptic spikes are demonstrated by using first- and second-order memristor stochastic models and compared with experimental data. Theoretical and experimental investigation of the dynamics of two electronic neurons coupled by a memristive device exhibiting the effect of short-term and long-term synaptic plasticity has revealed the conditions for synchronization of artificial neurons depending on the weight of synaptic connection. This study represents the first step towards the implementation of biologically plausible electronic cognitive systems based on self-organization in memristive neural architectures. The research is supported by Russian Foundation of Basic Research (18-29-23001).

The work is supported by the Government of the Russian Federation (Agreement No. 074-02-2018-330 (2))

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*Speaker

Research of features bipolar resistive switching characteristics in Si_3N_4 based structure

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Poster

NVM as charge trap flash (SONOS, TANOS), ReRAM and FeRAM use high-k dielectrics as HfO_x, $Hf_0.5Zr_0.5O_2$, AlO_x, SiO_x, SiN_x, AlO_x now. In Si_3N_4 of charge trap the charge transport limited by multiphonon trap ionization It is proved that the traps responsible for memory effect are the Si-Si bonds [1]. The charge transport in high-k dielectrics is determined by electron and hole traps. The charge transport in ReRAM based on HfO_2 is controlled by trap assisted tunneling between traps. $Hf_0.5Zr_0.5O_2$ is used as memory medium in ferroelectric memory FeRAM. Unlike most metal oxide based RRAM that use the movement of oxygen vacancies, the switching mechanism in SiN-based RRAM is still unclear [2].

For this purpose we have fabricated and researched Ni/Si_3N_4 /SiO2 /p+Si RRAM structures. Heavily doped p-type Si was used instead of a conventional bottom electrode (BE). 2 nm SiO_2 was formed by oxidation and 4 nm Si_3N_4 film, serving as a resistive switching layer, was then deposited using low-pressure chemical vapor deposition (LPCVD) at 700 C, with a mixture of SiH_2Cl_2 and NH_3 (in the ratio ∼1:3). Finally, the Ni (100 nm thickness) top electrode was deposited using a thermal evaporator using a shadow mask, with a device size of 200 μm. All electrical properties were characterized via the DC voltage sweep mode using Agilent B1500A semiconductor parameter analyzer and the bottom electrode (p+ Si) was grounded.

Figure 1 shows that typical bipolar resistive switching is observed in our fabricated structures. Device is set under a current compliance of 3 mA to prevent permanent dielectric breakdown and to obtain reset process. The positive bias leads to set switching, in which the devices are switched from HRS to LRS. Here, for both devices, the forming-free resistive switching makes no difference between the forming and the set voltage. Our fabricated MIS structure shows reproducible bipolar switching. The operation voltage was with 3.6∼5.0 V during set process (V set=3.6∼4.0 V, V reset= -1.6∼ -2.2 V). Memory window is at least 5 orders. It should be noted leakage current is small enough 10 -11 A at 1 V and room temperature in the initial state. Number of cycles is more than 100.

Simulation results of the I-V curves in the temperature range showed LRS is described preliminary by SLC (space-limited current) charge transport¸ HRS is work in progress.

This work was supported in part by the Russian Science Foundation (project N 19-29-03018).

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*Speaker

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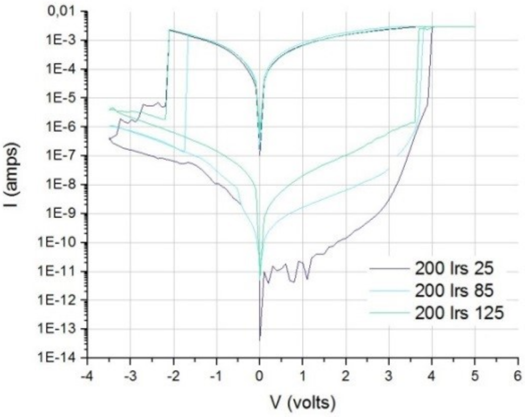

Figure 2: LRS and HRS I-V curves of Ni/4nm Si_3N_4 /2nm SiO2 /p+Si structure for temperature range 25-125°C (size=200 μm) showing bipolar resistive switching behavior

Optoelectronic dynamic memristor systems based on two-dimensional crystals

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Invited Talk

The optical modulation of the resistive switching opens the door for a new optoelectronic device, an optical memristor, which can be optically and electrically controlled with ultra-high speed and ultra-low power consumption. Optical memristive systems with memory elements switched by electromagnetic radiation can be used in optically reconfigurable and tunable neural networks for neuromorphic computing and brain-inspired artificial intelligence systems. The unique electronic and optical properties of 2D materials demonstrate huge potential in creating information-sensor systems for highly effective monitoring and processing of information in real time. [1, 2].

In this work, optoelectronic switching structures based on graphene, graphene oxide and molybdenum disulfide are considered for dynamic signal processing. 2D optoelectronic memristor structures exhibit multiple states [3-4], which can be monitored in a wide range of optical excitations and used as sensors for recording signals in artificial vision systems, pattern recognition, and fast image processing. A new optoelectronic dynamic memristive structure with layered QDs [5–6], controlled by an ultrafast photoinduced phase transition [7], is promising for creating information systems with stochastic information processing. Phase transitions controlled by charge and temperature cause tunable periodic oscillations due to two state variables that exhibit chaotic behavior similar to that in a network of biological neurons.

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*Speaker

Dynamical aspects of resistance switching: Attractors, bifurcations, and ideal behavior

Yuriy Pershin * [1]

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Keynote Talk

Memristive devices may have quite interesting behavior from the dynamical system point of view. Summing up some recent research, I will talk about similarities and differences in the memristive dynamics depending on the type of device or, equivalently, its model. In particular, I will discuss the possibility of stable fixed points in the time-averaged dynamics of pulse-driven memristive devices, and link these to an overlooked characteristic of "pinched" hysteresis loops. An interesting finding is that the presence or absence of stable points can often be related to the type of window function used in the device model. Moreover, a bifurcation analysis shows that there is a class of memristive devices with two stable fixed points existing simultaneously. Finally, I will introduce a dynamical test that unambiguously determines whether a given physical system is a memristor or not, and discuss the results of its application to resistance-switching memories.

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[*] Speaker

Conduction Mechanisms in Zr/ZrO_2-NT/Au Memristor Structures before and after Electroforming

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Talk

Non-volatile resistive switching random-access memory (ReRAM) based on oxides of transition metals (TiO_2, ZrO_2, HfO_2, etc.) has several technical and technological advantages over the present floating-gate Flash memory. Whereby ReRAM has attracted tremendous attention for both scientific and commercial interest due to a smaller size, enhanced endurance, high operation speed and low power consumption. Nevertheless, the study of resistive switching is complicated by the fact that even the same structure and the same material can switch in both unipolar and bipolar modes, also, because of different charge conduction mechanisms in high (HRS) and low (LRS) resistance states. For instance, ZrO_2-based memristor structures after pre-electroforming showed the ohmic conduction, the Schottky emission, the Poole-Frenkel emission and space charge limited conduction mechanisms. The differences in the behavior of ZrO_2-based memristors can be caused by such factors as thickness and defectiveness of oxide layer, bandgap and configuration of energy zones, synthesis and pre-electroforming conditions, materials of metallic contacts, etc.The nanotubular array of zirconium oxide (ZrO_2-NT) with a thickness of 1.7 μm was synthesized using anodization of metallic zirconium foil (99% purity). Zr-foil with the thickness of 120 μm was previously immersed in the ultrasonic acetone bath for 10 min, treated with a solution of acids $HF:HNO_3:H_2O$ = 1:6:20, washed with distilled water and dried in air. The anodization was carried out in a two-electrode electrochemical cell at a constant voltage of 20 V and a temperature of 20°C for 15 minutes. The electrolyte was a solution of ethylene glycol containing 5 wt. % H_2O and 1 wt. % NH_4F. Au-contacts of 50 nm thick and 140 μm in diameter were deposited through the stencil mask on the ZrO_2-NT surface using magnetron sputtering Q150T ES Quorum Technologies equipment.*J-E* characteristics of fabricated structures were measured by Cascade Microtech MPS150 highly-precise probe station at room temperature. The measurement was performed applying the harmonic signal with frequency $f = 0.01$ Hz and various values of applied voltage and the bias voltage. The Zr-foil was grounded, and a signal was applied to Au-contacts.

Research of *J-E* curves demonstrated an opportunity to realize unilateral and bilateral conductivity before and after pre-electroforming, respectively; consequently, there are different conduction mechanisms for these two cases. Based on the *J-E* characteristics analysis in full cycles of harmonic voltage applying, conduction mechanisms for non-electroforming and electroforming memristors during resistive switching were studied. It was established that conduction mechanisms before electroforming are found to be Schottky emission and Poole-Frenkel emission with the dominance of the latter. On the other side, there are ohmic conduction in LRS and space charge limited conduction in HRS after electroforming that follows from the study of *J-E* curves in double-logarithmic plots.

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UNN interdisciplinary laboratory of stochastic multistable systems

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Poster

An interdisciplinary laboratory of stochastic multistable systems (StoLab) was established at the Lobachevsky University of Nizhny Novgorod (UNN) in 2018. The laboratory combines and integrates activities of research groups working in theoretical and experimental areas. Prof. B. Spagnolo provides management of the laboratory and application of modern statistical analysis methods for investigation of memristive systems. The UNN researchers provides the experimental study and, in particular, the verification of novel theoretical descriptions.

The laboratory work is coordinated by the Sector of modern methods of stochastic analysis. The activity of this Sector is aimed at the solving of fundamental problems of external and internal noises influence on the behavior of multistable memristive systems, investigation and analysis of phenomena with the constructive role of noise. The second main task of the theory sector is further improvement of fundamental methods of statistical analysis. The third task includes drafting of the methodology and detailed plan for experimental works of the other 4 laboratory Sectors involved in the research of specific complex physical systems and media.

The Sector of technology of memristive materials is engaged in the creation of various memristive nanostructures "metal-dielectric-metal" based on oxide films as laboratory samples for microstructural analysis and investigation of the nature of internal noise, as separate memristor devices for analysis the influence of external noise and as matrices of memristor elements for integration into analog-digital circuits of neural networks.

The Sector of the microscopic probe investigations of the memristive systems is engaged in the study of the properties of various memristor "metal-dielectric-metal" nanostructures based on oxide films under the influence of noise, in particular, in the experimental verification of the theoretical macroscopic models of the memristors taking in the account the effects of the external and intrinsic noise.

The work of the Sector for physics of noise is devoted to the analysis of microscopic nature of flicker and high frequency noise origin and influence on memristive nanostructures.

The Sector of neuromorphic technologies develops algorithms and verification of models of impulse (spike) neural networks based on the processes of self-organization in arrays of memristor devices.

This work is supported by the Grant of the Government of the Russian Federation (contract No. N – 074-02-2018-330(2)).

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A Computational Study of Al/La$_{1-x}$Sr$_x$FeO$_3$ interface for Resistance Random Access Memory Applications

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Poster

Resistance random access memory (ReRAM) is emerging as a next-generation nonvolatile memory. One of the most promising materials for the ReRAM application is a composite of a reactive metal and a mixed-valance manganite. One of the current hypotheses regarding the origin of the resistive switching of such systems is a voltage-controlled reversible formation of a high-resistance aluminum oxide layer at the AlLa$_{1-x}$Sr$_x$FeO$_3$ interface through oxygen migration from La$_{1-x}$Sr$_x$FeO$_3$.

In this study, an atomistic model of the resistive-switching phenomena at the Al/LSFO interface has been studied by periodic plane-wave density functional calculations using the VASP code and PAW potentials. The changes in the structure, energy, and electronic structure of these systems during the oxygen vacancy formation in LSFO, the oxygen migration through the Al/LSFO interface, and the AlOx formation were investigated.

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*Speaker

Quantum Memristors and Quantum Neurons

Mikel Sanz *† 1

1 University of the Basque Country (UPV/EHU) – Spain

Invited Talk

Technology based on memristors, resistors with memory whose resistance depends on the history charges crossing the device, has been a turning point to develop neuromorphic architectures for classical computation. However, in contrast to the known quantized models of passive circuit elements, such as inductors, capacitors or resistors, the design and realization of a quantum memristor was still missing. We introduce the concept of quantum memristor as a quantum dissipative device whose decoherence mechanism is controlled by a continuousÂ-measurement feedback scheme, which accounts for the memory. We provide numerical simulations showing that memory effects actually persist in the quantum regime. We show how to engineer the quasiparticle dynamics in Josephson junctions to construct quantum memristors in superconducting circuits and use our quantization method to design memristorÂ-type constructions in other quantum platforms, particularly photonics. We will discuss the relation between the hysteresis area and the memory. Finally, we use this building block to quantize the Hodgkin-Huxley model describing the propagation of the action potential in the axon of a neuron. Finally, we discuss the construction of quantum mem-perceptrons based on quantum memristors.

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Comparing biological and artificial memristive neurons

Sergey Saveliev *† 1

1 Department of Physics, Loughborough University (LU) – United Kingdom

Keynote Talk

A diffusive memristor [1] in parallel with a capacitor and in series with a resistor has been proven to mimic biological neurons. Such systems [2] are currently called “artificial neurons” allowing to design neuromorphic circuits [3] for artificial intelligence applications. The next step is to mimic neuron activities on external stimulus, such as frequency selectivity [4]. This requires analysing current and voltage spike dynamics in artificial neurons. Currently, these studies attract significant attention after famous publication on observation of chaos in artificial neuron [5]. In this talk I will present recent studies if spike dynamics and a possibility to control degree of chaos in the system.

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On the fault-tolerant tuning of multilayer perceptron networks based on memristors

Sergey Shchanikov * [1], Anton Zuev [1], Ilya Bordanov [1], Sergey Danilin [1]

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Poster

One of the promising memristors applications is a hardware implementation of artificial neural networks (ANN). Articles illustrated successful examples of a memristors-based multilayer perceptron network [1,2] and Hopfield network [3] have been published several times for the last years. As can be seen from these works there is an obstacle in this way caused by imperfections in memristor technology. Memristors are characterized by variations in their electrical parameters which have a significant influence on ANN performance. There are various active or passive ways to minimize negative impacts and fault-tolerant ANN tuning is one of them.

The approach to the fault-tolerant tuning of a multilayer perceptron network based on memristors is proposed and described in this report. It makes it possible to provide necessary fault tolerance by the use of various learning algorithms, initial values of synaptic weights, initial conditions, LRS and HRS values, and by changing the distribution of synaptic weight values. In order to investigate and illustrate the capabilities of the proposed approach, it has been applied to perceptrons solving different problems. Research results have been obtained during a simulation and funded by the grant of the President of the Russian Federation MK-3927.2019.9 2019.

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*Speaker

Memristor-based components for a bidirectional adaptive neural interface coupled with neuronal biocultures

Sergey Shchanikov *† [1], Sergey Danilin [1], Anton Zuev [1], Ilya Bordanov [1], Alexey Pimashkin [2], Dmitri Korolev [2], Alexey Belov [2], Alexey Mikhaylov [2], Viktor Kazantsev [2]

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[2] Lobachevsky State University of Nizhny Novgorod – Russia

Talk

The results of designing an artificial neural network based on memristors (ANNM) have been presented in this report. The ANNM is implemented with two arrays of memristive microdevices in the original 16×16 cross-bar topology [1]. It is a component of bidirectional adaptive neural interface for automatic registration and stimulation of bioelectrical activity of a living neuronal culture used in a robotics control system. Memristive devices were fabricated on the basis of a newly engineered Au/Ta/ZrO2(Y)/Ta2O5/TiN/Ti multilayer structure, which contains self-organized interface oxide layers, nanocrystals and is specially developed to obtain robust resistive switching with low variation of parameters. Each array is mounted into a standard metal-ceramic package and can be easily integrated into the neurointerface circuit. Memristive devices demonstrate bipolar switching of anionic type between the high resistance state and low resistance state. Both states are characterized by nonlinear current-voltage characteristics. It is worth noting that such nonlinear characteristics are appropriate for the formation of passive cross-bar arrays with a highest density per chip achieved at the moment [2]. During the design stage, the ANNM model was created and the simulation of its operation was performed. The simulation makes it possible to investigate ANNM operation accuracy in the presence of destabilizing factors such as device-to-device variability, the high- and low-resistance device states ratio, a finite number of discrete resistance states, etc. For this purpose, the authors apply an algorithm for the simulation and design of ANNM synapses with the required accuracy, which is based on a general approach and described in [3]. This investigation shows promising capabilities of using metal-oxide memristive devices for the hardware implementation of ANNM and the possibilities of numerical analysis of manufacturing tolerances for the informational and physical parameters of the ANNM synapses. All the developed models and algorithms are implemented as Python-based software. The research was supported by the Russian Science Foundation (grant No. 16-19-00144) and the Government of the Russian Federation (Agreement No. 074-02-2018-330 (2)).

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Investigation of forming-free TiO_2 memristor structures formed by local anodic oxidation nanolithography

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Poster

The von Neumann architecture was the basic computer system architecture for several decades. Due to the attainment of the resolution limit of for integrated circuits (IC) manufacturing, a technological barrier has arisen to increasing the scaling of the structures of IC elements in accordance with Moore's law. This led to a slowdown in the data exchange speed between the processor and computer memory, which is especially important in applications related to large data volume processing, managing "smart houses" using the Internet of Things (IoT) technology. One of the possible solutions to this problem is the transition of computer systems to the human brain architecture, which is an array of parallel-connected low-power computing elements (neurons), interconnected via special channels (synapses). The actual method of technological implementation of this crossbar architecture is the nonvolatile resistive memory RRAM, based on memristor structures of metal oxides, interconnected by cross data buses. One of the main operations in the implementation of such structures is the post-growth treatment of the oxide (for example, electroforming). However, the electroforming method is difficult to control and has significant limitations, since it requires the application of high voltages (tens of volts), which can lead to breakdown and degradation of the oxide, and also adversely affect the stability of the memristor. Therefore, development of methods for the manufacturing of oxide nanostructures (ONS), that do not require additional forming operations (forming-free), is an important task in the technology of obtaining memristor structures.

To carry out the experimental studies, a Si/SiO_2 semi-insulating silicon substrate was used, on which a thin titanium film with a thickness of about 20 nm was formed by magnetron sputtering. Then, by local anodic oxidation using a scanning probe microscope and a cantilever with a conductive platinum coating, a titanium ONS with lateral dimensions of 2×2 μm and a height of 2.9 ± 0.2 nm was obtained. Investigation of the obtained titanium oxide nanostructures electrical characteristics were carried out using the current AFM spectroscopy, while the titanium film acted as the lower contact electrode, and the conductive platinum AFM probe served as the upper contact electrode.

Experimental studies have shown that the obtained by local anodic oxidation nanolithography structures exhibits a memristor effect without carrying out an additional electroforming operation. The analysis of the obtained characteristics showed a switching of the structure between the high (HRS) and low (LRS) resistance states when applying voltages of 2 V, while the HRS was 10.28 ± 1.84 GΩ and the LRS was 0.06 ± 0.02 GΩ.

The obtained results can be used to develop technological processes for the RRAM element formation based on oxide nanosized titanium structures formed by the local anodic oxidation.

This work was supported by RFBR according to the research projects N – 19-29-03041 mk, N – 18-37-00299 mol_a and by Grant of the President of the Russian Federation No. MK-2721.2018.8.

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[*] Speaker

Real-time computing by Memristor Cellular Nonlinear Networks (M-CNN)

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Invited Talk

The increasing complexity of heterogenous sensor-processor systems in the ubiquitous digitalization requires the development of new concepts for computing. Many efforts are devoted to the construction of neuromorphic arrays, especially to memristive memory crossbar arrays as decentralized computing structures allow the application of more power efficient information processing methods compared to those running on conventional architectures. Furthermore, it has been shown that different algebraic operations can be implemented on crossbar structures for computation of certain mathematical operations in a typical memory system. On the other hand, leakage currents, device variations, and limited calculation precision are considered as challenges in current investigations of these structures. With a local coupling structure, the concept of M-CNN is rather resilient to device variations, thus allowing the implementation of high-speed analogue multidimensional data processing algorithms on miniaturized sensor-processor realizations with digital outputs. Additionally, recent investigations have shown that by applying certain programming parameter sets, M-CNN can be applied as pure memory systems as well.

The presentation will provide an in-depth introduction to the M-CNN theory with the illustration of cellular networks-based computing problems. The recent generalization of a well-known methodology based on first-order standard CNN cells has enabled determination of cell-state equilibria, the so-called Dynamic Route Map (DRM) analysis, for the treatment of second-order M-CNN cells [1] that are based on first-order memristor models. The dynamic behaviour of these networks will be discussed for recently introduced memory operations by using a memristor model proposed by Pershin *et al.* [2].

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Synthesys of metal oxide-based hybrid nanomaterials and their prospectives in neuromorphic applications

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Invited Talk

Neuromorphic devices based on memristors (elements with a resistance varying upon the application of an external field) have provoked keen interest of researchers owing to their possible application in constructing artificial neuron networks on their basis, which can simultaneously store and process information [1]. It has been noted in the literature that memristors based on TiOx/TiO2 layers are most interesting owing to their complete compatibility with the standard process of production of complementary metal-oxide semiconductors (CMOS technology) [2-3]. However, detailed analysis of the influence of structural parameters on the memory effect and switching in such layers has not been carried out. We have investigated the effect of thickness of the TiOx and TiO2 layers on their memristor properties [4]. The distribution of the stoichiometry index over the depth of the layer has been determined.
Another prospective material for memristor applications are nanostructured ZnO thin films such as films consisting of a network of ZnO nanowires [5]. We report thin zinc oxide films manufacturing by reactive magnetron sputtering at room temperature, and examine their structural and optical properties. We show that the partial oxygen pressure in DC mode can have dramatic effect on absorption and refractive index (RI) of the films in a broad spectral range. In particular, the change of the oxygen pressure from 7% to 5% can lead to either conventional crystalline ZnO films having low absorption and characteristic descending dependence of RI from 2.4-2.7 RIU in the visible to 1.8-2 RIU in the near-infrared (1600 nm) range, or to untypical films, composed of ZnO nano-crystals embedded into amorphous matrix, exhibiting unexpectedly high absorption in the visible – infrared region and ascending dependence of RI with values varying from 1.5 RIU in the visible to 4 RIU in the IR (1600 nm) respectively [6].

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[*] Speaker

Unipolar and bipolar resistive switching in nanotubular titanium and zirconium oxide layers

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Poster

Metal/insulator/metal memristor structures based on anodized titanium (TiO2-NT) and zirconium (ZrO2-NT) oxide layers were fabricated and investigated. Using electron microscopy technique, it was shown that the synthesized TiO2-NT layers are 80 – 200 nm thick, and the ZrO2-NT layer is 1.7 μm and consists of an ordered array of nanotubes with an outer diameter of tubes (45 ± 10) nm and (55 ± 10) nm, respectively. Memristors with a diameter of 100 μm with a Ti/TiO2-NT/Au and Zr/ZrO2-NT/Au structure were made by magnetron deposition of gold through a mask.

The current-voltage characteristics of fabricated micromeristors in the unipolar and bipolar egimes are measured. Reversible resistive switching from low-resistance state (LRS) to high-resistance state (HRS) and backwards for studied memristors are observed. Switching voltages between resistive states and ranges of memristors resistance variation in HRS (RHRS) and LRS (RLRS) are estimated. The resistance ratios RHRS / RLRS >~ 10ˆ2 and 10ˆ4 for memristors based on nanotubular oxides TiO2-NT and ZrO2-NT, respectively, have been determined.

A comparative analysis with literature data for continuous layers and thin oxide films was performed. It has been found that the nanostructuring of the oxide layer by the anodizing method helps to reduce the electric field strength necessary for reversible switching of the structure between resistive states. The analysis of the current-voltage characteristics in double logarithmic coordinates was done. It was determined that the ohmic type of conductivity is registered in the LRS, and the space charge limited conduction (SCLC) dominates in the HRS. Based on the mathematical model of SCLC, the electrophysical properties of the synthesized TiO2-NT and ZrO2-NT layers were calculated. The prospects of using the structures Ti/TiO2-NT/Au and Zr/ZrO2-NT / Au as memristor memory elements are shown.

Acknowledgments: The work was supported by Act 211 Government of the Russian Federation, contract N – 02.A03.21.0006 and by Minobrnauki initiative research project N – 16.5186.2017/8.9. Contribution to the study from R.V.K. was funded by the RFBR according to the research project N – 18-33-01072.

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