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NEUROMORPHIC AND NEUROHYBRID SYSTEMS

20 Things You Didn't Know about Memristors

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This lecture covers the circuit-theoretic and mathematical foundation of the memristor. Numerous applications ranging from modeling of the brain to brain-like computing will be presented.

The First Steps Towards Realization of Spiking Neural Networks on Nanocomposite Memristors

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Today, the most developed artificial neural networks (ANN) are so-called formal ANN. They are being found their place in many different industrial applications. Nevertheless, the spread of formal ANN is limited by several factors. The first, they use stationary models of artificial neurons, i.e. with the fixed activation functions of various types. This excepts the possibility of simulating a real neural network dynamics and causes still unsatisfactory values of energy consumption in neuromorphic hardware in comparison with biological prototypes. The second, formal ANN are learnt mainly by different variations of error back-propagation technique which generally needs the huge marked databases, i.e. with the examples of considered task's correct solutions. Those marked Big Data can be prepared almost only by human experts, and this is a main limitation up to now for the back-propagation-learnt ANN dissemination.

But there other types of ANN exist – so-called rate-coded and temporal coding ANN, of the second and the third generation, correspondingly. They have advantages in that i) information is coded by spike trains of artificial neurons that causes more rich information representations, ii) temporal behavior of biological neural networks can be simulated in a bio-plausible way, and iii) the energy consumption of such ANN realized in neuromorphic hardware is much less than of the first generation nets.

This work is a review of recent results which were done in the area of neuromorphic systems development for all types of ANN with the use of memristors. Memristors, as the analogue resistors with memory, stay for the variable synaptic weights between artificial neurons. Also, it was shown that they can be explored as the spiking neurons, but with special stochastic spike's form. The possibility to use non-volatile multiple resistive states in some continuous range of values, and to simulate special multiplicative form of spike-time-dependent plasticity (STDP) pave the way to use different types of memristors also in the creation of the second and third generations of ANN.

Some special results got in our research group are shown. They concern the organic (polyaniline) and nanocomposite (lithium niobate with CoFe nanogranules inside it – LNO) memristive devices and neuromorphic systems based on them. The system with the one Integrate-and-Fire (IF) neuron and 4 LNO memristive weights was experimentally subjected to STDP variation under applying to its inputs the Poisson spike trains of the fixed frequency (Poisson noise). Then, in some range of threshold values for IF neuron, every memristive weight converged to its own resistive value. This fact is in correspondence with the simulation results for the similar system in [1]. So, this is the first experimental evidence for the systematic role of STDP rule and Poisson noise applied to the spiking neuron with memristive weights. To deeply understand an STDP rule meaning, including information processing on the network level, the further investigations are needed.

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Graphene Material for Neuromorphic and Neurohybrid Systems

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Graphene is a two-dimensional carbon allotrope in which the atoms are arranged in a honeycomb lattice. Graphene's very high electron mobility, high electron velocity near the Dirac points, and high thermal conductivity, make it a promising material for high-speed, low-power circuits [1]. Furthermore, this one-atom thick material has high thermal conductivity, chemical stability, flexibility and very high tensile strength [2]. Recent studies have shown that graphene is an excellent biocompatible material exhibiting astonishing stability in biological environments [3] and recordings of action potential of various cell types [4]. The combination of the above properties constitutes graphene as one of the most attractive material for bioelectronics and more specifically for electronics implanted into living tissues. Graphene can be used for the fabrication of interconnects as well as for functional electronic devices such diodes and field-effect-transistors (FETs). Of interest is that graphene can be shaped using nanolithography techniques and dry (plasma) etching.

The electronic properties of graphene can be tuned when it is patterned forming nanoribbons. Using graphene nanoribbons (GNRs), high-dense arrays of conductive interconnects and FETs can be formed allowing the fabrication of integrated neuromorphic and neurohybrid systems. Although, the application of graphene electronic devices is questionable due to the absence of energy bandgap allowing the flow of meaningful (leakage) current at Dirac point, we proposed recently [5] that using GNRs it is possible to confront successfully this obstacle [6]. Figure 1(a) presents a GNR 100nm wide and 5 µm long suitable for the realization of two or three-terminal electronic devices. Such device can be used to monitor and/or process signals from living neural cells. In addition, it can be used to generate signals to stimulate specific neural cells and thus it is plausible an all graphene neuro-interface chip to be built. Such interface chip biocompatibility is very important. We thus examined the suitability of graphene for neuronal culture adhesion. For this reason Neuro-2A mouse neuroblastoma cells were seeded on graphene slices immersed in 6 well petri dishes for 2 days at a density of 105 in DMEM medium supplemented with 10% FBS, 0.5mM glutamine and 1% penicillin and streptomycin in the absence of poly-L-lysine. As shown in Fig. 1b, Neuro-2A cells were easily grown and developed neurites, as indicated from the well-shaped cell body (soma) and the extended neurites suggesting that graphene is a suitable material for axonal sprouting of neuronal cells.

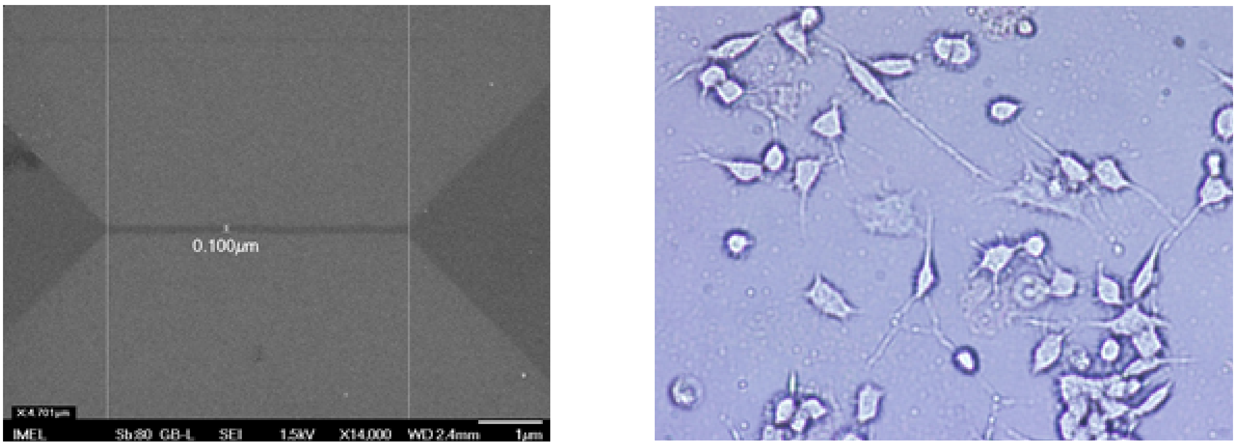

Fig.1. *(**a**) Graphene nanoribbon field effect transistor structure and (**b**) Neuro-2A cells cultured for 48 hrs on a single layer graphene template.*

In conclusion, we indicate that graphene is a suitable substrate for neuronal cell growth and proliferation by maintain ing Neuro-2A normal growth and allowing for neurite outgrowth. Various techniques and methods can be employed to fabricate the critical building blocks for the development of a graphene biocompatible neuromorphic and neurohybrid system-on-chip.

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Polyaniline Memristive Devices and Neuromorphic Networks

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Organic memristive devices [1, 2] (more particular, electrochemical polyaniline based systems) were realized for mimicking important properties of biological synapses responsible for Hebbian learning [3]. They have several features of Chua memristors [4] and Braitenberg mnemotrix [5]. It will be considered several important features of these devices.

Structure and properties

The working principle of the device is based of the strong variation of the polyaniline conductivity depending on its redox state. Therefore, the architecture of the device includes the layer of polyaniline in a contact with solid electrolyte where the reactions can occur. We will consider important features of such structures, responsible for the functional characteristics and stabilities of properties.

Oscillators

One important feature of nervous system of living beings is the possibility of working in auto-oscillation mode in fixed environmental conditions. Small variation of the organic memristive device construction allows to reach this aim. Particular architectures and obtained properties will be discussed [6].

Logic and memory

Brain mimicking information processing requires to use the same elements for memorizing and treatment of the information. This feature is responsible for learning at the hardware level. As a consequence, such systems must be very efficient in parallel processing, classification, prediction, and decision making. In this part we will consider such applications as logic with memory [7] and perceptrons [8, 9]. In the last case, features of perceptrons, based on organic memristive devices, will be compared with those, based on inorganic memristive devices [10].

Biomimicking and bioelectronics systems

This part of the presentation will be dedicated to systems, mimicking parts of the animal nervous systems, and their integration into the brain. First, we will consider a rather simple system mimicking, to some extent, a learning of the Pavlov dog [11]. Next example will show the mimicking of the part of a pond snail, responsible for its learning during feeding [12]. It is to note that in the last case we were also to reproduce not oly the properties of this system, but also its architecture, determined by direct measurements, performed with implanted microelectrodes [13]. Finally, we will consider recent results of coupling of two live neurons in the rat brain through organic memristive devices.

Stochastic networks

This part is dedicated to the most important advantage of the organic systems – the possibility to form self-organized 3D structures using appropriate molecules and methods. Realized networks have demonstrated learning capabilities, allowing some parallels with human brain learning [14].

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Memristive Devices and Systems Fabricated by LbL Technique

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Important feature of the organic memristive devices [1] is a presence of the very thin layer in the working zone, what is determined by the necessity of lithium ions diffusion in a solid state [2]. It was the reason for the fact that practically all such devices were fabricated using Langmuir-Blodgett method, allowing the thickness control at a molecular level [3]. However, there is an alternative technique allowing the same thickness resolution: polyelectrolyte self-assembling, or Layer-by-Layer (LbL) technique. Here we will consider the applicability of the method for the realization of channels of organic memristive devices.

LbL technique

The technique is based on successive electrostatic deposition of polyanione and policatione layers [4]. Special modifications of the method for the realization of polyaniline films will be underlined.

Memristive device properties

Memristive devices with active channels, babricated by LbL technique, demonstrate the presence of the rectification and hysteresis: important features for mimicking synapse properties. We will make comparison of these properties with devices, fabricated by traditional Langmuir-Blodgett method [5].

Stochastic networks

First stochastic memristive networks were realized on free standing fibers [6]. It was shown that such systems are very unstable. Thus, the strategy was to use supports with developed structures as "skeletons" to stabilize the system. This part demonstrates the possibility to form stochastic networks by LbL technique and their adaptations and learning [7].

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Organic Neuromorphic Devices for Bio-inspired Information Processing

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Hardware-based implementation of neuromorphic architectures offers efficient ways of data manipulation and processing, especially in data intensive applications such as big data analysis and real time processing. In contrast to traditional von Neumann architectures, neuro-inspired devices may offer promising solutions in interacting with human sensory data and process information in real time. Therefore such kind of devices may offer in the future novel ways of data manipulation in bioelectronics. Over the past years, organic materials and devices have attracted lots of attention in bioelectronics due to their attractive characteristics for bioelectronics applications such as biocompatibility, the ability to operate in liquid electrolytes, tunability via chemical synthesis and low cost fabrication processes.

Here, various concepts of organic neuromorphic devices will be presented based on organic electrochemical transistors (OECTs), devices that are traditionally used in bioelectronics. Regarding the implementation of neuromorphic devices, the key properties of the OECT that resemble the neural environment will be presented here. These include the operation in liquid electrolyte environment, low power consumption and the ability of formation of massive interconnections through the electrolyte continuum. Showcase examples of neuromorphic functions with OECTs will also be presented, including short-, long-term plasticity and spatiotemporal or distributed information processing.

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Adaptive Behavior of Memristive Device Stimulated by Neuron-Like Signal

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The design of compact neuromorphic systems (including micro- and nanochips) capable of reproducing the information and computing functions of brain cells is a great challenge of the modern science and technology. Such systems are of interest for both fundamental research in the field of the nonlinear dynamics of complex and metastable systems and medical application in devices for monitoring and stimulating the brain activity in the framework of neuroprosthetic tasks. In this context, a memristive devices have been an object of intensive research in recent years including neuromorphic applications. It is worth noting that the construction and creation of electronic neurons and synapses (connections between neurons) based on thin-film memristive devices is one of the most rapidly developing areas of interdisciplinary research related to neuromorphic systems. Neuromorphic technologies are relevant to intellectual adaptive automatic control systems, biorobots.

We carried out experiments to investigate the behavioral plasticity of the memristive device. The signal from the electron neuron generator was sent to the memristive device and recorded by the hardware-software complex. The resistive switching from high- (1 MOm) to low-resistance (300 Om) state and back (from 300 Om to 1 MOm) with the signal amplitude increasing from 1 to 8 V was observed for the Au/ZrO_2(Y)/TiN/Ti memristive device. Such resistive switching was realized under the stimulation by the neuron-like signal with the increasing amplitude. The source signals amplitude, frequency were fixed and controlled by the hardware-software complex. Neuron-like signal was sent to memristive device during 4-5 minutes with load resistance of 1500 Om. Memristive device was in the high resistance state. It is interesting to note that nonvolatile changes in the voltage drop on the memristive device (increase on 1.5 V) are observed. This indicates the internal changes in the memristive structure and means that the resistance on the memristive device is increased or decreased accordingly. So that, the degree of resistive switching determined by the oxidation and recovery of segments of filaments can be controlled by external parameters such as pulse frequency, amplitude, action time or pulse quantity of the neuron-like signal.

In this work, we have simulated a dynamic of memristive device by using the stimulation with electric FitzHugh–Nagumo neuron-like signal imitating the signal from presynaptic neuron`s membrane to describe and predict the effects of adaptive behavior and synchronization of neurons. We investigate the stochastic nature of memristive device and describe the system parameters in real time. The results of this investigation will form the background for the design of experiment with rat brain living neurons.

We believe that due to its relative compactness and high sensitivity, the experimental implementation of such neuromorphic construction based on memristive devices will be very promising for designing a large neuron network for biorobotic and bioengineering applications.

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Neuromorphic Optoelectronic Interface for Hippocampal Neurons Stimulation

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The development of neuromorphic technologies is of great importance for neuroprosthetics and humanity. One of the neuromorphic technological solutions is the implementation of electronic devices which mimic the electrophysiological behavior of real neural networks. Neuromorphic technologies are relevant not only to medical applications, but also to non-medical tasks, such as neuromorphic information processing, intellectual adaptive automatic control systems, biorobots, etc.

In this work,we construct an optical fiber interface to connect the analog electrical FitzHugh–Nagumo neuron with living neurons. After this we studied possibilities for stimulating living neurons by transmitted from the electronic neuron optical signal and analyzed synchronization between the artificial neuron and living neurons.

The designed hybrid neural circuit consists of an analog electronic FitzHugh – Nagumo (FHN) neuron, a light-emitting diode (LED), an optical fiber, a photodiode, and an amplifier.For biologic experiments, we used the acute hippocampal brain slices (350-μm thick) obtained from a 20-28 days old C57BL/6 mouse and a Wistar rat. The signal from the electronic neuron generator is transmitted through the optic fiber communication channel to the bipolar electrode (FHC, Bowdoinham, USA) which stimulates Schaffer collaterals (axons of pyramidal neurons in the CA3 field) in the hippocampal slices. We observed EPSPs or population spikes registered in depending on the electrodes position in the CA1 area. Synchronization between the neuronal response and stimulus showed that the response is caused by the stimulation.The dependences of the neuronal response on the stimulus amplitude are shown that for small stimulus amplitudes (below 2 V) both the EPSP amplitude and the slope of EPSP change slowly as the stimulus amplitude is increased. If the amplitudes werehigher than 3V we would not be able to see the correct responses because the neurons would die under such stimulation.

The proposed optoelectronic system (hybrid neural circuit) is very effective for stimulating electrophysiological living neurons in the hippocampus and can be used in restoring brain activity/individual regions or replacing individual parts of the brain (neuroprosthetics) which were damaged due to trauma or neurodegenerative diseases.

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Charge Transport Mechanism and Trap Nature in Memristors Based on High-K Dielectrics

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The review of charge transport mechanisms and trap nature in memristors based on high-k dielectrics is presented. The charge transport mechanism in HfO_x, ZrO_x, TaO_x, SiN_x is experimentally studied and quantitatively analyzed with four theoretical models: Frenkel model of Coulomb traps ionization, Hill-Adachi model of overlapping Coulomb traps, Makram-Ebeid and Lannoo model of multiphonon isolated traps ionization, Nasyrov-Gritsenko model of phonon-assisted electron tunneling between nearby traps.

It is shown that the charge transport in Si_3N_4 and SiN_x is qualitatively described by Frenkel effect, but Frenkel effect predicts an enormously low attempt to escape factor value. The charge transport in Si_3N_4 and SiN_x is quantitatively described by the multiphoton neutral isolated trap ionization and phonon assisted tunneling between traps respectively. The thermal trap energy in Si_3N_4 and SiN_x is equal to $W_t = 1.5\pm0.1$ eV. The photoluminescence experiments and quantum-chemical simulation indicate that neutral Si-Si bonds are responsible for electron and hole localization, and charge transport in Si_3N_4 and SiN_x [1].

The charge transport in HfO_x and ZrO_x is governed by phonon-assisted electron tunneling between nearby traps. The thermal trap energy in HfO_x, ZrO_x is equal to Wt = 1.25 eV. With XPS, photoluminescence experiments and quantum-chemical simulation, it was shown that the oxygen vacancies in HfO_x, ZrO_x are electron traps [2].

The charge transport in TaO_x is limited by phonon-assisted electron tunneling between nearby traps. The thermal trap energy in TaO_x is equal to $W_t = 0.85$ eV. With XPS, photoluminescence experiments and quantum-chemical simulation, it was shown that the oxygen vacancies in TaO_x are electron traps [3].

The current leakage in HfO_x and TaO_x is equal to the current leakage in the memristor high resistive state. Hence, non-stoichiometric films can be used for the realization of memristors without forming [4].

With XPS, spectroellipsometry and quantum-chemical simulation the model of nanoscale potential fluctuations in SiN_x, HfO_x, ZrO_x, TaO_x was established [2,5]. It was obtained, that charge transport in TiN-HfO_x-Ni memristors in the low resistive state is governed by the Shklovsky electron percolation in HfO_x [5].

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Metal-Oxide Memristive Devices for Neuromorphic and Neurohybrid Systems

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The current development of science and technology is taking place against the backdrop of serious paradigmatic changes affecting various fields of knowledge and leading to the creation on the basis of a convergent approach of new artificial nature-like systems that can be organically built into natural systems. A vivid example of a new paradigm is a complex of scientific representations and technological approaches leading to the creation of unique bio-like (neuromorphic) systems based on simple organic or inorganic materials (elements) constructed with the help of nanotechnologies. One of such elements is the memristor, which, on the one hand, is a very simple two-terminal element of electrical circuits (resistance with memory effect), and on the other hand, it is a nonlinear dynamical system [1], which can reproduce the functions of biological synapses and neurons due to internal stochastic phenomena. Such properties will allow not only implementing hardware large-scale neural networks [2], but also making a qualitative breakthrough on the way to the integration of artificial electronic systems and living neuronal cultures or brain [3].

This report provides an overview of the recent results of a comprehensive investigation and modeling of the memristive effect in metal-oxide nanostructures based on zirconium and silicon oxides that have been technologically adapted and used in the development of both traditional neuron networks (such as a multilayer perceptron [4]) and spiking neural architectures based on coupling and synchronization of neuron-like oscillators [5]. The most intriguing result is the dynamic response of memristive devices to complex and noisy pulse signals, including bioelectric activity signals of living neuronal cultures, which can be analyzed at a system level using the latest statistical analysis methods.

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Redox Processes in Neuromorphic Memristive Systems Based on Graphene

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The relevance of studying electronic memristive systems is determined by the need to create a new more efficient computing architecture for processing large volumes of information, in which processing and storage of data occur in parallel, as processes in biological neural networks with synaptic connections. Memristive heterostructures based on graphene (G) and graphene oxide (GO) have demonstrated unique electrophysical properties that can be used to obtain ultrahigh density of memory and logic elements[1-4]. The effect of resistance switching in such structures is associated with reversible oxidation-reduction processes.
In this work, we demonstrated a number of methods for the well controlled formation of nanoscale G/GO heterojunctions with resistive switching like the synapses in a neural network. The 'green' photocatalytic oxidation of graphene[2,3] as well as its atomic oxygen treatment[4] were used to create self-assembled G/GO memristive heterostructures on a SiO_2/Si substrate. Electron beam irradiation is allowed to form and control the memristive G/GO heterojunctions (Fig. 1) with high spatial resolution.

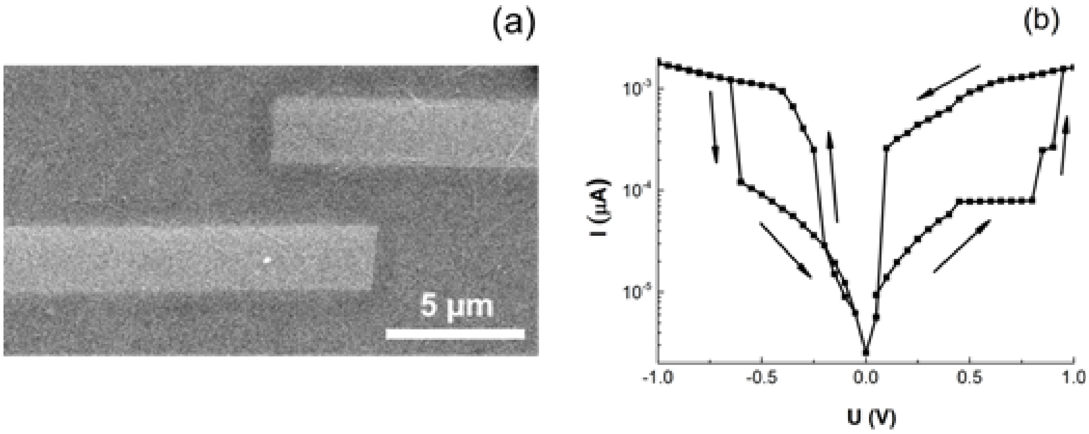

Fig. 1. *SEM-image of the lateral G/GO heterostructure produced by direct electron-beam "writing" (a) and resistance switching of G/GO memristor. It is switched at a low voltage of Set / Reset 0.8 / -0.9 V (b). Stripes of a brighter contrast in the secondary electron emission mode (a) are regions of GO, reduced using electron beam irradiation.*

Raman spectroscopy, photoemission microscopy in combination with HRSEM and electrical measurements were used to study the micromorphology of memristive systems. The G/GO memristive systems showed nonlinear behavior and resistive switching, demonstrating a high potential for storing and processing big data and for neuromorphic computations.

Acknowledgements

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Designing Memristor-Based Neural Networks with Specified Fault Tolerance

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The theory of artificial neural networks (NN) contains several important sections which are used while the solution of difficult practical tasks in various fields of science and technology. One of these sections is dependability of NN [1]. Dependability in technical science is a property of an object to keep ability to perform the required functions during the given operating time, in the specified modes and application conditions, maintenance, storage and transportation [2].

Dependability is an integrated property of a technical object that includes attributes such as reliability, maintainability, recoverability and some other or their combinations. Object parameters and their changes while the process of functioning influence dependability measure because of elements defects and degradation or some others threats (internal and external destabilizing factors).

Among the ways of increasing a system's dependability a specific place is held by insure of fault tolerance (FT) – the property that enables a system to continue operating properly in the event of the failure some of its components [3].

Based on numerical values of FT measure it is possible to create the scheme of dependability of a technical object and to calculate attributes values according to the classical theory and to perform its optimization. In the theory of NN the task of development of FT measure is unresolved [1].

The purpose of this research is to develop FT measure and methods for engineering design of memristor-based artificial neural networks (MNN) with specified FT.

The authors of the research proposed a general approach to the development of methods and algorithms for determining and ensuring the FT of MNN as single physical-information objects made as hardware-software devices which can be taught [4,5]. Most known approaches take into account only physical phenomena and processes being information carriers in the MNN with a different structure, purpose and variants of creation. The proposed approach is based on the theory of system analysis and simulation.

In accordance with the proposed approach, the definition of the term "fault tolerance of neural networks and neurocomputers" is formulated as "the property that enables to ensure specified values of operation quality (accuracy) within specified limits under the influence of any variations in the parameters of elements, structures, input information and software or any internal and external information and physical destabilizing factors of application conditions.

This report presents a variant of the quantitative criterion of MNN fault tolerance, methods and algorithms for calculating it values (based on general approach), and a practical example of FT ensuring of MNN made for industrial use.

The implementations of these methods were programmed with the help of MATLAB and a few modules were programmed with Python.

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OM&P

Self-Organizing Maps of Forearm Muscles Myographic Patterns Generated by Wrist Movements

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Self-organized maps (SOM) of the Kohonen type are a class of artificial neural networks whose learning is based on a competitive algorithm, relevant for self-organization observed in biological neural networks. The main property of SOM is the ability to represent data in an output layer, while preserving the topological features of the original input space. Such a mapping is inherent in the primary somatosensory cortex (the so-called homunculus of somatosensory cortex), the hippocampus, and it is the principle of retinotopia and tonotopia. The practical significance of this property lies in the possibility of reducing the dimensionality of the input data. In addition, SOM can be successfully used as an intermediate stage in the data classification system.

The task of teaching such a neural network by feeding real signals recorded in the nervous system is of special interest. The accumulated experience in this field can turn out to be an auxiliary base in the task of training spiking neural networks, and, not only model, but also biological cultures in vitro.

In this work, we used eight-channel electromyographic (EMG) signals acquired by a Thalmic labs Myo device as an input to a 10x10 SOM. The data were collected from 37 subjects. Each subject performed different hand gestures: up, down, left, right and also diagonal movements. The raw data were preprocessed by a digital high pass Butterworth filter with a cutoff frequency of 10 Hz and root mean square (RMS) signals were evaluated in a time window of 100 ms. To quantify the functional properties of a SOM, we introduced an estimates of the quality of clustering: the intra-cluster index, which was determined by the degree of clusters scattering, and the inter-cluster index, which was determined by the degree of intersection of different clusters.

To verify the relevance of the introduced estimates, we used the standard procedure of evaluation of the quality of classification using a multilayer perceptron classifier. Thus, the classification errors were obtained used for testing our estimates. We found the correlation between the intra-cluster index and the standard error $r = 0.46$ and between the inter-cluster index and the standard error $r = 0.51$ (at the significance level $\alpha = 0.05$). A qualitative analysis of the mapping of gestures to the mapping layer showed that the SOM is able to decode the information stored in the EMG (geometrically opposite gestures are mapped into geometrically opposite clusters). The high degree of linear dependence between the standard and introduced errors indicated the possibility of effective application of SOM in tasks of biomechanics, when it is necessary to identify the correctness of a movements performance in some sports discipline by beginner or professional athletes. Further research of self-organization in formal neural networks may assist in the task of self-organization of biological neural networks in vitro.

Acknowledgements

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Photomemristors Based on Graphene/2D Crystals for Interfacing Artificial Electronic Neural Networks and Natural Neurons

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Aims

Synapse-like memristive systems are considered as a new type of electronic logic switches with extremely low power consumption and footprint that can be used to overcome the limit of current CMOS technology to create artificial intelligence components. The unique electronic and optical properties of recently discovered two-dimensional (2D) crystals, such as graphene, graphene oxide, molybdenum disulphide etc[1-8], demonstrate their enormous potential in creating ultrahigh density nano- and bio-electronics for innovative image recognition systems and information.

Methods

Memristors with a floating photogate, called photomemristors[2,3] based on biocompatible graphene and 2D crystals, are considered. The photocatalytic oxidation of graphene is proposed as an effective method of creating 2D memristive systems with photoresistive switching for synapses-like non-volatile memory of ultrahigh density. Particular attention is paid to the new concept of the formation of self-assembled nanoscale memristive elements interfacing artificial electronic neural networks and natural neurons for bioelectronics.

Results

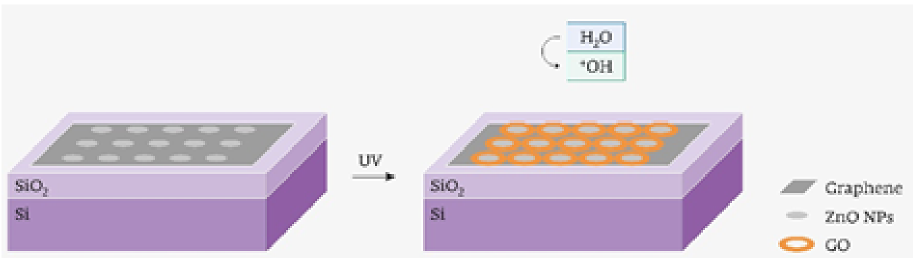

Fig. 1. *Photocatalytic oxidation scheme of graphene coated with ZnO nanoparticles (NP) under ultraviolet light to form G / GO photomemristors on a Si / SiO_2 substrate.*

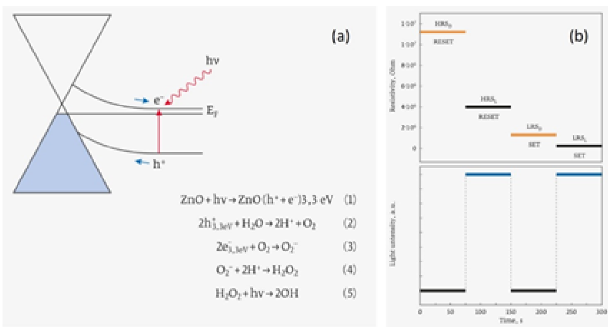

Fig. 2. *a - Schematic electronic diagram of the G / ZnO NP interface under UV irradiation. Electron-hole pairs generated in ZnO (3.3 eV) under UV irradiation (reaction 1) are separated by the built-in electric field at the G/ZnO NP interface, providing a flow of holes into the graphene; b - resistive states of the G/GO photomemistor, which are switched by a voltage of Set / Reset -3.8 / 3.3 V in the dark and -3.5 / 4 V under pulses of light and read at 2.5 V.*

Conclusions

2D biocompatible photomemristors with a floating photogate exhibit multiple states controlled in a wide range of electromagnetic radiation and can be used as neurohybrid systems for neuromorphological computations, image processing and pattern recognition necessary for creating artificial intelligence.

Acknowledgements

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Nanomaterials Based Thin Film Memristors and their Potential Application in Neuromorphic Systems

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Various electrical and structural properties of three types of thin film memristors: redox-based memristors, ferroelectric memristors and multiferroic memristors, were studied in details. Valance change redox memristors were fabricated using ink-jet printing deposition technique, while ferroelectric and multiferroic memristors were obtained using spin coating technique. For the analysis of device performance we used: current-voltage measurements, impedance spectroscopy analysis and transport parameter measurements.

Results indicate the existence of the conduction quantization effect in valance change (titanium dioxide) memristor, as a result of space constriction inside nanosized filament, [1]. This effect in combination with conductance linearity could improve stability of multi-level cell (MLC) characteristics leading to uniform conductance distribution and enhance accuracy in neuromorphic computing, [2].

Furthermore, we present the consecutive unipolar response of ferroelectric class of memristor (Pt/$BaTiO_3$/Au), Fig. 1, which indicates the shifting of current to higher values, i.e. increased conductivity of memory element, [3]. This behavior corresponds to biological long term potentiation (LTP) effect of synapses (increased transmission of signal).

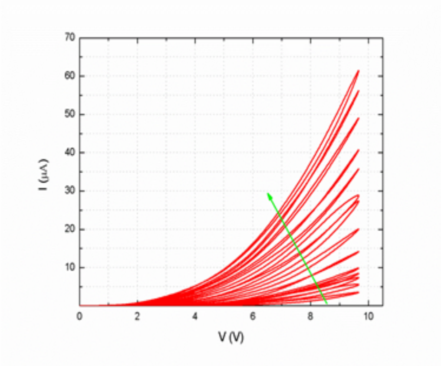

Fig.1. *Current-voltage characteristics of successive switching of the Pt/$BaTiO_3$/Au memristor, [3]*

Additionally, we report multilevel resistive switching effect in multiferroic memristors (Au/$BaTiO_3$/NiFe2O_4/$BaTiO_3$/Pt), [4] which could be improved by combining photonic and electronic excitation, [5]. Obtained results are studied and discussed considering the desired properties and requirement of memristors implemented in neuromorphic systems.

Acknowledgements

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Memristive Spinal Cord Segment Prosthesis

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I'll present main ideas and current state of the project to recreate the circuitry of the spinal cord segment. The project is organized in three main work-packages: (1) modeling and simulation and validation of the topology of the spinal cord segment; (2) design and implementation of a memristive inhibitory and nouromodulatory neuron with bio-plausible temporal dynamics of the spiking neuronal activity, eSTDP , iSTDP; (3) memristive reflex arc design, implementation and validation via biological experimental data; (4) memristive spinal cord segment design, implementation and validation using biological experimental data in vivo using rats biological models. We present intermediate results on neuromodulatory and inhibitory memristive neurons implementation and simulation of spinal cord segment.

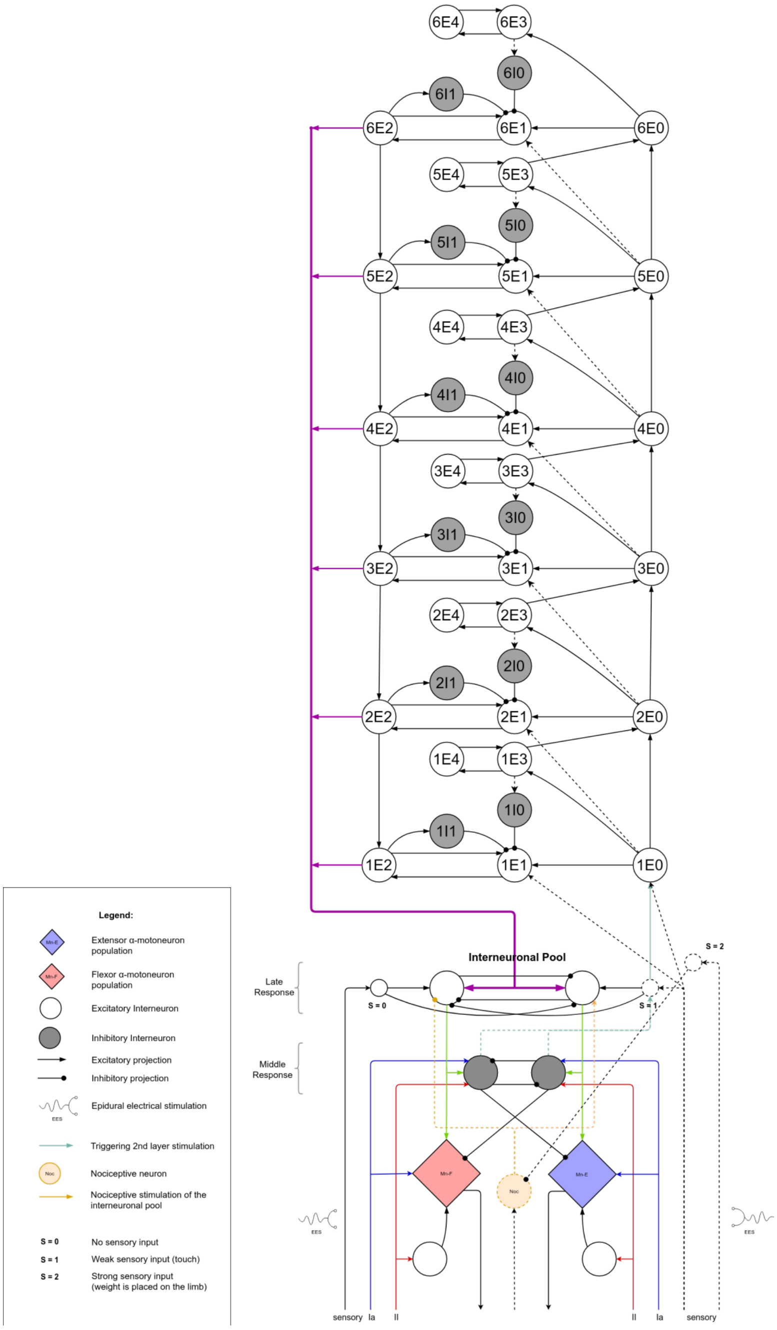

Fig.1. *Spinal cord segment schematic under validation via simulatory models.*

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Experimental Investigation of Hardware Neuron Model

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While neuroscience is one of the most dynamic branches of interdisciplinary science it still has a lot of unsolved problems in the field of information processing principles. To solve these problems a great variety of computational neuroscience methods are applied. To reproduce the principles of brain dynamics in brain-inspired information processing devices, neuroprosthetics hardware or "silicon" neurons and neural networks are used [1–2].

We investigated the dynamics of neuron-like generator based on a phase-locked loop with a specific bandpass second-order filter in the control loop.

The hardware implementation of the neuron model based on the phase-locked loop has been developed. Mathematical modelling carried out earlier has shown the presence of different self-oscillating modes [1]. Oscillations in this modes are qualitatively similar to some dynamic modes of neurons. We have observed regular spiking, regular bursting and chaotic bursting modes. The number of spikes in burst can be controlled by model parameters. Parameter space of the model has been separated into areas of different modes presence by bifurcation analysis of model dynamics.

We developed a hardware electronic prototype of the model. Oscillations in the prototype have been observed. Similar self-oscillating modes have been found in hardware as in mathematical model. We could control parameters of the model in hardware by changing values of some elements (digital potentiometers, frequency dividers) via PC user interface that lead to mode change and oscillations' parameter control (period, amplitude etc.) Hardware prototype could work both in real-time (real neuron time scale) and accelerated time. The results of experimental analysis was presented in the paper [2].

The excitability of the neuron model in response to periodic pulsed simulation has been observed both theoretically and experimentally. The neuron's responses to stimulation have been synchronized with different rational frequency ratios depending on the amplitude of stimulation.

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Self-Learning Robot Controlled by STDP-Driven Neural Network

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The most important property of the brain is the associative learning ability, which is believed to be based on neuronal plasticity. A typical example of associative learning is the classical or Pavlovian conditioning [1], which, in general, consists of associating cues (conditioned stimulus) and reward (unconditional stimulus). In turn, the neuronal plasticity is the ability of neural connections to change their effectiveness, depending on the previous history of neural activity. Earlier the mechanisms of spike timing dependent plasticity (STDP) have been sufficiently well studied both experimentally and theoretically [2]. However, the efforts have been concentrated mainly on the plasticity of single synaptic connections, whereas at the network scale many issues still remain unresolved. For example, associative learning in a network of neurons grown on a multi-electrode array (MEA) appears among unsolved problems.
Earlier in our modeling studies, we reported that STDP at the network scale can rearrange the neuronal connectivity pattern that in turn leads to unconditional learning [3,4]. However, even such simple forms of learning could be de-

stroyed by the competition of spike-conducting pathways in unstructured networks [5].
In this study, we focused on the topological property of STDT aiming at enhancing the shortest paths of excitation. This allowed us to develop a mechanism of associative learning in small neural networks. The learning consists in strengthening the connections among sensory neurons that are excited with a certain delay. An important role in establishing the association of neuronal connections is played by the competition of alternative spike-conducting pathways. The presence of competition allows replacing old, irrelevant associations by new ones in response to changes in the nature of external stimulation. The proposed algorithm allows associating sensory signals of different modalities, as demonstrated by the example of a mobile robot LEGO NXT with two touch sensors and two sonars.

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Novel Personalised Macroporous Biodegradable Conductive Hydrogel Scaffolds Via Additive Manufacturing for Nervous Regeneration

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“Smart” biomaterials for tissue reconstruction is a promising trend in regenerative medicine, potentially aiming to the development of new biointerfaces with tunable properties and on the replacement of the biomaterial with the native growing tissue.

A hybrid material should be used as a porous active medium (scaffold), necessary for the construction of newly-formed tissue, and mainly acting as a guiding and signalling function. The regenerative approach requires from modern biomaterials, first of all, acceleration of the process of the new tissue formation and supplying inherent events for nerve regeneration during rehabilitation.

Tissue engineering constructs (TEC) are used to restore biological functions of the spinal cord. The creation of TEC for the nerve regeneration is of particular importance due to a possibility for electrical stimulation specific cellular activities by controlling regeneration processes depended on electrical impulses.

The production of a tailored implant for tissue regeneration with complex and optimal architecture is inevitably linked with additive manufacturing techniques.

This work aims to discuss approaches for the additive fabrication of personalised microporous scaffolds for nerve regeneration and the significance of pore architectonics for its permeability. This issue has a distinct interdisciplinary character, being at the intersection of materials science, medicine and engineering.

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