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Bio-inspired adaptive networks based on organic memristors

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ABSTRACT

The organic memristor is an element which varies its conductance according to its previous involvement in the signal transfer processes, i.e. it combines conductance with memory properties. The first part of the work is dedicated to the consideration of its basic principles and fundamental properties. After this, we present the architecture of the organization of model networks, demonstrating the capabilities of supervised and unsupervised learning. Finally, we discuss the possible ways, alternative to the existing lithography-based technologies, that would result in the fabrication of statistically organized networks of such elements, mimicking learning in biological systems.

1. Introduction

A fundamental difference of the brain organization with respect to the computer hardware architecture is connected to the fact that memory and processor are not separated. Both functions are performed by the same elements. Such an organization is essential for the possibility of learning, similar to that occurring in biological neurosystems. Such an architecture implies not only recording of the information but also modification of the "processor" performance for better resolving similar problems in the future.

Thus for the synthetic reproduction of such bio-inspired information processing systems new circuital elements are required. In this respect, it is useful to recall a hypothetical electronic element, the "memristor", introduced by Chua in 1970 [7]. In complete correspondence with its name, this element can be considered as a resistor with memory. During operation, it must vary its resistance according to the history of its involvement in the signal transmission process. In the most interesting case, very useful also for the realization of adaptive bio-inspired electronic networks (neuromorphic systems), the resistance of the memristor must be a function of the total charge (time integral of the current flow) passed through the device. In the case of success, such elements could be the basis of electronic circuits capable of reproducing to some extent the learning processes occurring in the brain.

In the modern neuroscience there are several models for such processes. Here we will consider mainly the synaptic type of learning that can be described by the Hebbian rule, cited below [18].

"When an axon of cell A is near enough to excite cell B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place on one or both cells so that A's efficiency as one of the cells firing B is increased".

This means that the synapses which condition the signal transfer from one neuron to another will be strengthened every time they are used, creating "Hebbian zones" which facilitate information processing. In terms of electronic circuits, it means that the resistance of the connection, transferring the signal from one nonlinear element to the other, must decrease each time when the signal is transferred through it. As the hypothetical memristor, mentioned above, must provide exactly this function, its successful realization would provide an essential step

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towards mimicking learning capabilities with artificial electronic circuits.

Recently a claim for the first realization of a memristor, a doped TiO_2 thin film, has been reported [30]. This device, however, whose attribution to the memristor hypothesised by Chua is somewhat doubtful, cannot be useful for this task. Its characteristics reveal mainly bistable electrical behavior, very useful for memory applications, but not suitable for mimicking learning. In fact, the last item requires the gradual variation of the element resistance, corresponding to the integral charge transferred by the junction.

In 2005 we have reported a polymeric electrochemical element with properties very similar to the hypothetical memristor [13]. Its working principle is based on the dramatic difference in the conductivity of conducting polymers (in particular — polyaniline (PANI)) in a reduced and oxidized states [19]. This difference can reach 8 orders of the magnitude. In a material device the transition can be triggered just by the application of the appropriate oxidation or reduction potentials, with a reduced contrast in the conductivity due to heterogeneity. At a first glance, the device seems very similar to the electrochemical field effect transistor, known since the end of 1980s [25]. However, there are significant differences in the construction and, especially, properties of the device with respect to electrochemical field effect transistors. The closest analogue of our device, reported in the literature, is a polymeric electrochemical rectifying element [6], even if there are significant differences also with this system.

For mimicking learning behavior in biosystems, the most important characteristics of our polymeric electrochemical device are the gradual increase of the conductivity when operating under positive voltage bias, and its gradual decrease when negatively biased. In addition, recently we have demonstrated that the resistance of the device is directly a function of one component of the charge (namely, ionic charge), passed through the device [2]. Therefore, the device seems to be a real organic memristor, suitable for the fabrication of adaptive material networks.

In this paper we present the basic ideas underlining the structure, properties and working principles of the single organic memristor. Thus here we do not present the details of technological processes, giving only essential requirements and referring to the published works. Then, we will illustrate the possibility to mimic learning behavior on simple examples of model circuits. Finally, we will overview the approaches that are expected to lead to the realization of complex networks capable of learning, highly parallel information processing, and decision making.

2. Materials and methods

Conducting channel of the element was realized from polyaniline (PANI). Emeraldine base PANI (Mn 100 000) was purchased from Sigma-Aldrich and used as arrived.

The channel was formed by deposition of 24–48 molecular layers with modified Langmuir–Shaefer technique [31] with the thickness of about 100–200 nm. Doping of the layer was performed by treatment with 0.1 M HCl as well as with higher molecular weight compounds [4], for example, dodecyl benzene sulfonic acid (Fluka).

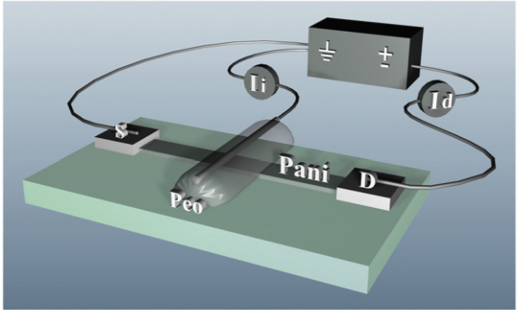

Fig. 1. Scheme of the organic memristor.

Active zone of the device represents a part of conducting polymer layer in a contact with solid electrolyte. It is formed by the cast deposition a layer of lithium salt doped polyethylene oxide (PEO), a well known solid electrolyte used for high value capacitors [15], over the PANI layer. PEO (average molecular weight 8000 000) and different lithium salts, such as $LiClO_4$, $LiCF_3SO_4$ and $LiBF_4$ [5], were purchased from Sigma-Aldrich and used without further purification.

3. Results and discussion

3.1. Organic memristor

The scheme of the organic memristor is shown in Fig. 1. The active channel is formed from PANI, deposited onto a support with two electrodes. The only requirement for the support material is its insulating nature. Initially, we have worked with glass substrates, but the last generation of the devices and deterministic networks we have fabricated on the flexible supports made from polyimide Kapton films — a highly insulating and inert material.

An important feature of the active channel is its thickness. On the one hand, it must provide a significant conductivity for reaching a high signal-to-noise ratio, but on the other hand, it must be as thin as possible, because the processes responsible for the conductivity variation are diffusion controlled (see later). Thus, thick films will require much longer time for the transformation of the whole layer thickness to reduced or oxidized state. Therefore, Langmuir–Blodgett technique was found to be the most appropriate method for the channel formation, allowing the fabrication of structures with a resolution at the level of a single monomolecular layer [24].

The next important part of the device is a medium for the redox reactions. Therefore, the central part of the channel is cast covered with a solid electrolyte in the form of a narrow (about 1 mm) stripe. PEO was chosen as the material of the electrolyte matrix, because it has demonstrated adequate properties in the case of rechargeable batteries applications [1]. Lithium salts (in particular, lithium perchlorate, but other lithium salts listed in the Materials and Methods section were also studied [5]) were used as dopants for the electrolyte formation, as lithium provides the highest mobility in