Towards a reliable memristor for advancing biologically-inspired computing

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Abstract. This paper focuses on fundamental research in nanotechnology, specifically on studying memristors (resistors with memory) by non-invasive scanning probe microscopes. Memristors, key components of so-called neuromorphic (brain-inspired) hardware systems, form the basis of the much-needed new computing principles relevant to cognitive processing, big-data analysis, and low-power AI systems based on machine learning and the Internet of Things. Here, the focus is on the nanoscale physics of memristive systems, understanding of which will give progress to the development of better-performing neuromorphic devices with the goal of sustaining the growth of innovative data science and information technologies

The demand for more efficient ways of processing and communicating information is growing globally. Driven by this, new electronic devices based on nanotechnology are being developed. However, scaling such devices has physical limits, which calls for new non-conventional types of devices and new computing principles. One such device is called a memristor – memory resistor [1,2]. It has a simple form of a two-terminal structure, with three layers – two electrodes that send and receive electrical signals and an insulating layer between them. It is like a resistor that changes its resistance by applying an outside electrical stimulus, and it memorises its resistance states [3]. Such a device can be used to both store and process data. Besides the application for on-chip memory and storage and in-memory computing, here, the focus is on biologically inspired computing [4].

One such biological concept for computing is a neural network - a set of neurons connected by synapses that have weights. Artificial neural networks (ANNs), which are in some sense inspired by biological ones, perform superior to classical systems in processing cognitive and data-intensive tasks, even surpassing humans in complex tasks such as playing the game Go [5]. However, in ANNs, processing and memory units are physically separated, which causes the so-called Von Neumann bottleneck due to the constant information flow between memory and processing units. Co-location of logic and memory as well as parallel processing in the human brain inspired neuromorphic computing – modelled on biological neural networks. Its key advantages are energy efficiency (human brain uses 20 W), execution speed, and ability to learn. Memristive systems have become an integral unit of neuromorphic hardware and are said to emulate synaptic behaviour in the brain [6].

Methodology and progress

At the Jožef Štefan Institute, Ljubljana, we are working with a nanoparticle-based memristor [7] (see Figure 1), which has a metal-insulator-metal structure. The insulating matrix (SiO2 or TiO2) contains alloy nanoparticles of AgPt and AgAu. By applying voltage on metal electrodes, ionised silver cations are released from their reservoir nanoparticle, transported through the matrix, reaching the bottom inert electrode, where upon receiving an electron, they start forming a conducting filament growing from the bottom electrode toward the top electrode. It is a volatile device because the filament lifetime is only some microseconds. Therefore, analogue switching between high and low resistance states happens fast and is controlled by the applied voltage. Statistical variance exists in switching properties and needs to be minimised for commercial applications.

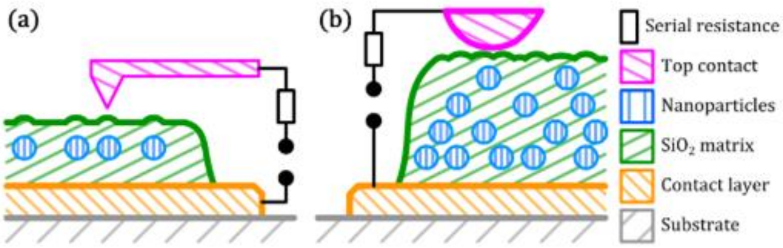

Figure 1: Sketch of a nanoparticle-based memristor. This is work by my supervisor Hassanien among others: Vahl, A. et al. , Diffusive Memristive Switching on the Nanoscale, from Individual Nanoparticles towards Scalable Nanocomposite Devices, Nature Scientific reports (2019).

As a non-invasive tool, an atomic force microscope is used to study memristive properties. Its probe has a tiny conductive tip which plays the role of the top electrode in the device [8]. The tip radius is only about 20 nanometres. Such a microscope is not only able to image nanostructures in three dimensions but also manipulate them and measure some of their properties, such as conductivity, that we are very interested in. For conductivity measurements, the physical principle of quantum-mechanical tunnelling of electrons between the tip and sample (our memristive device) is responsible for current flow. The technique is called conductive-AFM (C-AFM), where the current map of the sample surface is collected at some bias voltage applied between tip and sample, or I-V (current-voltage) spectra are taken at certain positions on the sample surface. dI/dV spectroscopy is performed to measure local density of electronic states of the sample [9].

The initial measurements have shown memristive switching behaviour of a few samples (see Figure 2). We have yet to analyse them, especially their statistical variance and consistency, given that we performed a large number of measurement cycles.

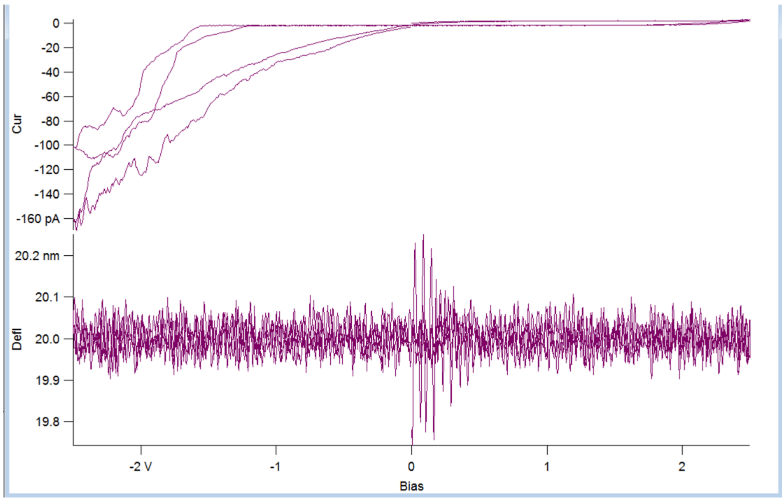

Figure 2: One of the I-V spectra of the measurements performed on the nanoparticle based memristor, clearly showing memristive switching.

Future work and outlook

In order to improve device stability and performance, one has to think of other concepts in terms of materials and device configuration, so we are currently working on growing nanoscale graphene on our gold substrate to do so.

Memristors have already secured their principal role in neuromorphic engineering as an artificial synapse, so researchers are racing to devise the optimal memristive device, which can only be done through trial and error. There is diverse research using different nanomaterials and device configurations to reach optimal conditions. Integration of a large number of nanoscale memristors in a neuromorphic network is another challenge, albeit it has been demonstrated [10]. Such a novel type of nanoelectronic device and its computing principles are poised to be a game-changing technology in the 21st century. There seems to be growing interest and investment in smarter and more efficient technologies such as this biologically inspired one, which will one day become part of our daily life.

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