| | |
|---|---|
| **Title** | Neuromorphic-inspired behaviour in core-shell nanowire networks |
| **Author(s)** | Manning, Hugh G.; Biswas, Subhajit; Kumar, Shailja; Holmes, Justin D.; Boland, John J. |
| **Publication date** | 2018-07 |
| **Original citation** | Manning, H. G., Biswas, S., Kumar, S., Holmes, J. D. and Boland, J. J. (2018) 'Neuromorphic- inspired behaviour in core-shell nanowire networks', 2018 IEEE 18th International Conference on Nanotechnology (IEEE-NANO), Cork, Ireland, 23-26 July. doi:10.1109/NANO.2018.8626353 |
| **Type of publication** | Conference item |
| **Link to publisher's version** | https://ieeexplore.ieee.org/document/8626353<br>http://dx.doi.org/10.1109/NANO.2018.8626353<br>Access to the full text of the published version may require a subscription. |
| **Rights** | **© 2018, IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.** |
| **Item downloaded from** | http://hdl.handle.net/10468/7659 |

# Neuromorphic-Inspired Behaviour in Core-Shell Nanowire Networks

Hugh G. Manning[1,2], Subhajit Biswas[2,3], Shailja Kumar[1,2,3], Justin D. Holmes[2,3] and John J. Boland[1,2]
[1]School of Chemistry, Trinity College Dublin, Ireland, email: manninh@tcd.ie
[2]CRANN & AMBER Research Center, Dublin, Ireland. [3]School of Chemistry, University College Cork, Ireland.

***Abstract*****—** Engineering smart-materials with emergent properties requires designing and characterizing systems with desirable behaviours. Neuromorphic (brain-like) architectures require plasticity, where the strength of the connections and the time with which they decay can be modulated based on the magnitude and the repetition of the applied stimuli. This functionality is emulated in our complex nanowire network material through electrical resistive switching. The formation of nano-sized filamentary connections between overlapping wires across the network facilitates a controllable transition from a high resistance state to one (or more) lower resistance states with corresponding memory retention times. We report on the neuromorphic inspired behaviors that emerge from networks of metal nanowires coated with $TiO_2$ shells.

## I. INTRODUCTION

There has been considerable interest in the use of nanomaterials for new types of nonvolatile memory technology, where the resistive switching action is controlled by the properties of both the electrodes and the dielectric materials that comprise these devices[1]. One highly desirable behaviour of neuromorphic systems is associative memory, memory that is stored and recalled by content rather than by address; such a device emulates biological memory rather than conventional digital memory and could act as inorganic synapses in brain-inspired neuromorphic hardware[2].

Recently, individual $TiO_2$ nanowires have shown memristive behaviour, where the device could retain a state of internal resistance based on the history of the applied voltage and current and could be programmed to hold multiple memory states[3]. Furthermore, single $TiO_2$ nanowires have exhibited a unique time-correlated associative learning response to heterogeneous optical and electrical stimuli[4]. To improve current response and insure switching occurs over nanoscale dimensions, a highly conductive metal nanowire was coated with a thin polycrystalline $TiO_2$ shell (40 nm) via solvothermal synthesis that yielded $Ag@TiO_2$ core-shell nanowires, as shown in the transmission electron microscope image of Fig. 1(a). Using Ag electrodes, it was found that *both* bipolar and unipolar resistive switching responses, collectively known as nonpolar resistive switching, could be selected by varying the magnitude of the current level used to activate the device. The memory retention time was intrinsically linked to the resistive switching regime, which allowed for a short-term retention time of up to $10^3$ s in the bipolar state, and long-term memory ($> 10^6$ s) formation in the unipolar regime[5]. In this work, we report on the assembly of these core-shell nanowires into randomly orientated nanowire networks (NWN) (Fig. 1(b)).

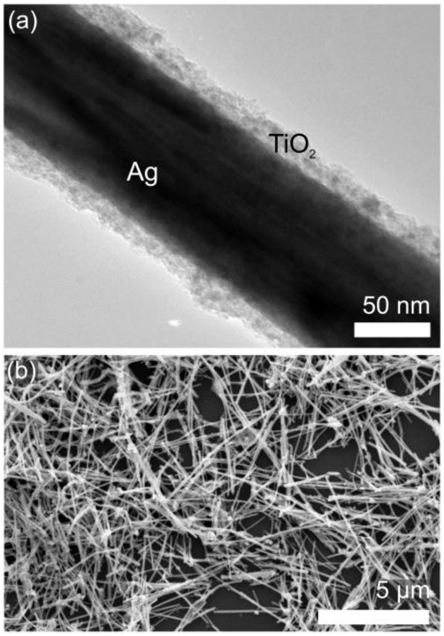

Fig. 1. (a) A high-resolution transmission electron microscope image of a $Ag@TiO_2$ core-shell nanowire. (b) A scanning electron microscope image of a core-shell nanowire network.

A NWN involves a random arrangement of nanowires on a substrate, such that its connectivity allows for at least one and in most cases multiple pathways between two opposing electrodes. NWNs are of immense technological interest due to their properties of high transparency, high porosity, flexibility, ease and low cost of fabrication[6]. The performance of any collective is controlled by the interactions between the individual components; these properties are not only defined by the material but augmented by the additional functionalities derived from the network, such as fault tolerance, self-selective pathways, and the decentralization of information [7]. We show that NWNs have the potential to become promising memristive architectures for neuromorphic applications due to their interconnectedness and the neurosynaptic-like behaviours at each of the junctions. Neuromorphic computers are expected to outperform conventional computing architectures at tasks which are natural to biological brains, such as self-learning, sensory processing, pattern recognition and motor control.

## ACKNOWLEDGMENT

The authors wish to acknowledge funding from the European Research Council under Advanced Grant 321160. This publication has emanated from research supported in part by a research grant from Science Foundation Ireland (SFI) AMBER Centre under Grant Number SFI/12/RC/2278. The facilities and staff at the Advanced Microscopy Laboratory at Trinity College Dublin are acknowledged for their support.

## REFERENCES

[1] S. Menzel, U. Böttger, M. Wimmer, and M. Salinga, "Physics of the switching kinetics in resistive memories," *Advanced functional materials,* vol. 25, pp. 6306-6325, Oct 2015.

[2] Z. Wang, L. Wang, M. Nagai, L. Xie, M. Yi, and W. Huang, "Nanoionics ‐ Enabled Memristive Devices: Strategies and Materials for Neuromorphic Applications," *Advanced Electronic Materials,* 2017.

[3] C. O’Kelly, J. A. Fairfield, and J. J. Boland, "A Single Nanoscale Junction with Programmable Multilevel Memory," *ACS Nano,* vol. 8, pp. 11724-9, Nov 25 2014.

[4] C. J. O'Kelly, J. A. Fairfield, D. McCloskey, H. G. Manning, J. F. Donegan, and J. J. Boland, "Associative Enhancement of Time Correlated Response to Heterogeneous Stimuli in a Neuromorphic Nanowire Device," *Advanced Electronic Materials,* vol. 2, Jun 2016.

[5] H. G. Manning, S. Biswas, J. D. Holmes, and J. J. Boland, "Nonpolar Resistive Switching in Ag@TiO2 Core-Shell Nanowires," *ACS Applied Materials & Interfaces,* 2017/10/13 2017.

[6] C. Gomes da Rocha, H. G. Manning, C. O'Callaghan, C. Ritter, A. T. Bellew, J. J. Boland*, et al.*, "Ultimate Conductivity Performance in Metallic Nanowire Networks," *Nanoscale,* vol. 7, pp. 13011-13016, Aug 14 2015.

[7] H. G. Manning, F. Niosi, C. Gomes da Rocha, A. T. Bellew, C. O'Callaghan, S. Biswas*, et al.*, "Emergence of Winner-takes-all Connectivity Paths in Random Nanowire Networks," *Nature Communications,* vol. (Submitted), 2018.