Conductive AFM study of metal-oxide-metal nanowire arrays with resistive switching functionality

S. Brivio[1], G. Tallarida[1], D. Perego[2], S. Franz[2] and S. Spiga[1]

[1] Laboratorio MDM, IMM-CNR, via C. Olivetti 2, 20864 Agrate Brianza, Italy

[2] Dipartimento di Chimica, Materiali ed Ing. Chimica "G.Natta", Politecnico di Milano, Via Mancinelli, 20131 Milano, Italy
stefano.brivio@mdm.imm.cnr.it

Resistive switching (RS), which consists of the voltage driven resistance commutation of two terminal metal-insulator-metal structures, has been continuously attracting large attention in the field of nanoelectronics for applications in non-volatile memories [1]. Conventional top-down manufacture processes have been usually adopted to investigate and test RS even at the nanoscale, while alternative approaches, e.g. bottom-up solutions, are seldom found in literature [2].
Here we present fully bottom-up fabrication procedures of metal-oxide-metal (MOM) nanowires with engineered RS functionality. We used NiO as the functional oxide in combination with Au and Ni electrodes to tune a bipolar (i.e. opposite polarities are required to lower and increase the device resistance) and a non-polar operation (i.e. not affected by the choice of the voltage polarity). The former was achieved with an asymmetric Au/NiO/Ni/Au structure while the second with a symmetric Au/NiO/Au structure.
MOM nanowire arrays (50 nm in diameter) have been fabricated combining electrodeposition of the metallic constituents through the pores of an anodized aluminum oxide (AAO) matrix (see figure 1(0)), oxidizing thermal process and refining surface treatment. Two different fabrication procedures were followed for non-polar and bipolar RS nanowires as described in figure 1. In the process flow A, for the fabrication of symmetric Au/NiO/Au nanowires, the thermal treatment for the oxidation of the Ni segment (3) is performed at the end of the process [3]. On the contrary for the fabrication of asymmetric Au/NiO/Ni/Au nanowires (process flow B), the oxidation of the Ni segment (2') is performed after the deposition of Au and Ni (roughly filling half the pore height, see (1')). Additional Ni and Au depositions (3') complete the nanowire structure. The surface finishing produces a flat surface where the vertical nanowires are ordered with in plane hexagonal symmetry as shown in figure 2a.
For the electrical characterization of the sample, conductive atomic force microscopy (CAFM, a sketch of the setup is shown in figure 2b)) appears as the ideal technique for two reasons: it allows contacting single nanowire devices and it provides reliable electrical measurements, since the MOM structure, which contains metal electrodes within the nanowire itself, facilitates the establishment of a good electric contact [4].
We observe that both the structures are initially insulating and require a soft electroforming procedure to initiate the RS. We will show how the CAFM operation parameters impact the forming and the following RS behavior. We demonstrate to be able to test single nanowires independently from the surrounding ones.
After the forming procedure, symmetric Au/NiO/Au nanowires display a non-polar RS among different resistive states as demonstrated by the set (switch from high to low resistance) and reset (from low to high resistance) sweeps shown in figure 3a and 3b, respectively. This is usually associated to the creation of conductive filaments (set operation) and their dissolution (reset operation) by thermal re-oxidation in antifuse/fuse-like processes [5]. Indeed this is the commutation mechanism which is expected in symmetric MOM structures. The study of the threshold reset current as a function of the low resistance state value demonstrates that the reset process is thermally driven as expected for non-polar RS devices. Interestingly, this observation is confirmed even for extremely low operation power down to the nW range (i.e. reset currents of few nA) [4].
On the contrary, asymmetric Au/NiO/Ni/Au nanowires displayed bipolar RS as represented in figure 3c by a set (black, for positive voltages) and a reset (red, for negative voltages) sweeps. In the figure the current undergoes a large variation from the high resistance state, where it is below the sensitivity of the ammeter, to the low resistance state, where it is above the ammeter range. The bipolar operation is coherent with a RS model based on the migration of oxygen vacancies shorting and interrupting the electrical connection between top and bottom electrodes. Furthermore we will show that, in the bipolar operation, different low resistance states can be reached, which can show linear current-voltage characteristics, associated to metallic conduction, as well as nonlinear, which indicate energy activated conduction mechanisms.
In conclusions, this work demonstrates a fruitful application of CAFM technique to the study of single MOM nanowires that brought to the comprehension of their RS mechanisms; moreover, this work proves the potentiality of a bottom-up approach for the development of resistive switching devices,

comprehensive of both non-polar and bipolar cases, which may disclose new opportunities for device downscaling.

Acknowledgements.
This work was partially supported by Fondazione Cariplo (MORE Project no 2009–2711). The author acknowledge Prof. Christophe Muller and Dr. Damien Deleruyelle (IM2NP – CNRS - Marseille) for making their instrumentation available for part of the experiment and for the fruitful discussions.

References

[1] International Technology Roadmap for Semiconductors-Emerging Research Devices 2011 Edition.
[2] D. Ielmini, C. Cagli, F. Nardi, Y. Zhang, J. Phys. D: Appl. Phys., **46** (2013) 074006.
[3] D. Perego, S. Franz, M. Bestetti, L. Cattaneo, S. Brivio, G. Tallarida, S. Spiga, Nanotech. **24** (2013) 045302.
[4] S. Brivio, G. Tallarida, D. Perego, S. Franz, D. Deleruyelle, C. Muller, S. Spiga, Appl. Phys. Lett., **101** (2012) 223510.
[5] R. Waser, R. Dittmann, G. Staikov, K. Szot, Adv. Mat., **21** (2009) 2632.

Figures

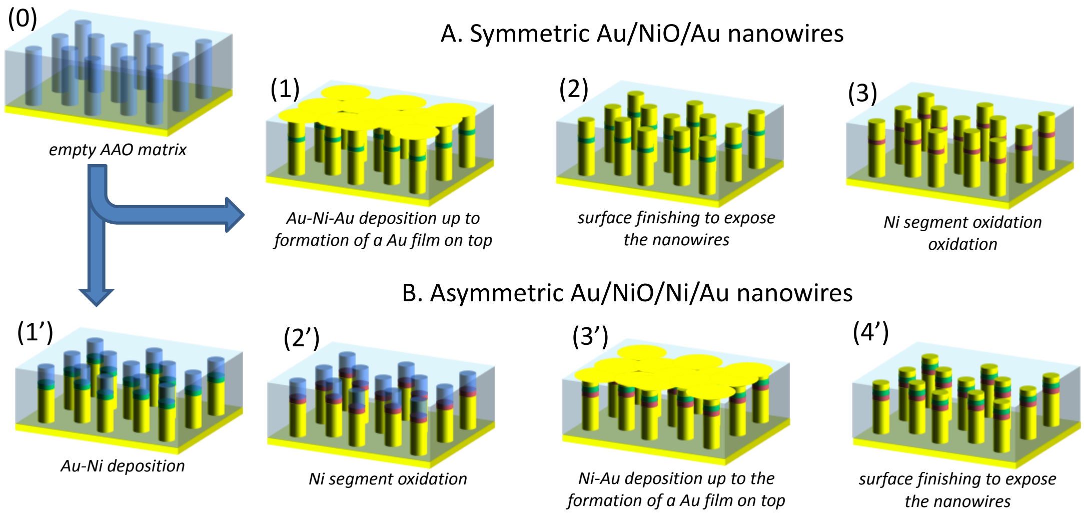

Figure 1. Process flow for the fabrication of (A) symmetric Au/NiO/Au nanowires and (B) asymmetric Au/NiO/Ni/Au nanowires. In details: (0) empty AAO array; (1) Au, Ni, Au deposition till formation of Au film; (2) polishing and soft chemical etching of the surface; (3) thermal oxidation. (1') Au-Ni deposition; (2') thermal oxidation; (3') Ni, Au deposition till formation of Au film; (4') polishing and soft chemical etching of the surface.

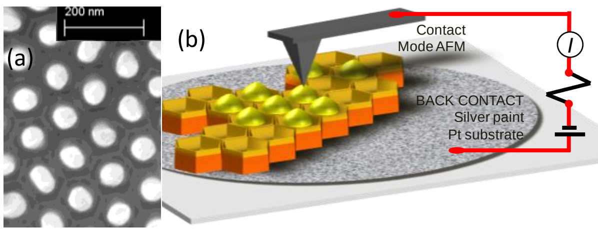

Figure 2. (a) SEM image of a nanowire array surface and (b) sketch of the CAFM setup.

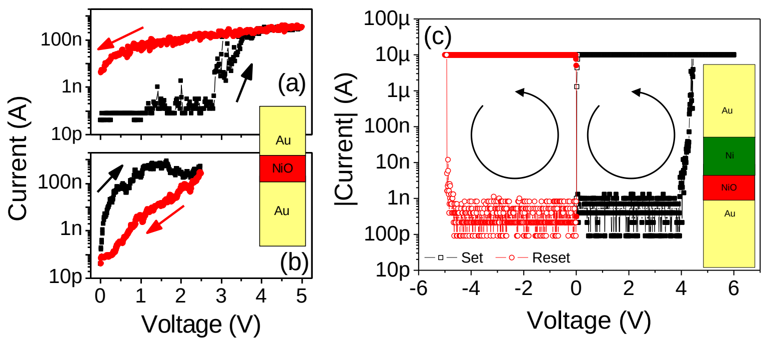

Figure 3. Set (a) and reset (b) operations of a single Au/33nm NiO/Au nanowire. Bipolar set and reset operation of a single Au/1µm Ni/160nm NiO/Au nanowire (c).