Microelectronic Engineering 156 (2016) 78–81

Contents lists available at ScienceDirect

Microelectronic Engineering

journal homepage: www.elsevier.com/locate/mee

Electrical 1D tomography of nanofilaments using in-operando electrical characterization of Pt/NiO/Pt resistive memory cells during FIB milling

C. Guedj [a,*], G. Auvert [a,b], E. Martinez [a]

[a] Univ. Grenoble Alpes, F-38000 Grenoble, France, CEA, LETI, MINATEC Campus, Grenoble, F-38054, France
[b] STMicroelectronics, 850 Rue Jean Monnet, 38926 Crolles, France

ARTICLE INFO

Article history:
Received 1 July 2015
Received in revised form 14 October 2015
Accepted 28 October 2015
Available online 30 October 2015

Keywords:
Tomography
Filament
FIB
Memory
Memristor
NiO

ABSTRACT

Electrical characterization during focused ion beam (FIB) milling of an elementary Pt/NiO/Pt resistive memory cell is used to localize the conducting channels and to estimate the size and shape of the conducting nanofilament. A good agreement is found with cross sectional high resolution Transmission Electron Microscopy (HRTEM) images. This methodology is a potential tool to obtain in-operando electrical tomography of conducting paths with subnanometric spatial resolution.

1. Introduction

The measurement of complex material stacks and interfacial properties including physical and electrical properties is still among the five most difficult ITRS characterization challenges [1]. The electrical imaging of conducting filament is particularly important to help the development of resistive memory devices and to understand their operating and failure mechanisms. The nanoscale memristor device could be also used as a synapse in neuromorphic systems [2]. An interesting progress has been recently published in the 3D observation of conducting filaments by tomographic conductive atomic force microscopy [3]. In our approach, we have first performed physico-chemical and electrical characterizations in a wide range of temperatures to precisely assess the material and pristine device characteristics. In a second step, the elementary memory cell is milled at a constant speed during operation, and the evolution of electrical characteristics during milling is used to obtain the electrical shape of the conducting filament with subnanometric spatial resolution. A decanometric conical shape is obtained, in good agreement with HRTEM analysis and literature data [3]. An atomistic model involving oxygen vacancies is proposed. The possibilities and limitations of this technique are presented.

2. Experiment

The elementary memory cell is a standard Pt/NiO/Pt MIM structure previously presented [4,5]. The nickel oxide layer is obtained by thermal oxidation of sputtered Ni at 400 °C. The schematic view is represented in Fig. 1, with the corresponding view obtained in the Zeiss Nvision 40 FIB equipped with low noise micromanipulated electrical probes.

In order to obtain reproducible results, it is necessary to strictly avoid electrostatic discharge during all steps and to minimize electrical noise. First, ex-situ electrical measurements are performed under dry N_2 flow with a Cascade prober and Agilent B1500 semiconductor analyzer. A compliance of 3 mA is chosen during the SET cycles. Extensive electrical and reliability tests are performed to select the best devices. Then, the functionality of the cell is tested inside the FIB by performing several write and erase tests with a proper compliance setup. In this experiment, the cell is first put in the SET state. At room temperature, the data retention behavior shows stable characteristics for more the 10,000 s, therefore the memory state should be considered as stable during the experiment. The electrical measurements in-operando are obtained by forcing a tension of 2 mV with a HP Agilent 4156C parameter analyzer while measuring the evolution of current with sub-pA resolution during FIB milling. In this range, the behavior is ohmic at low bias when the electrical contacts are correct, therefore the total conductance can be properly measured, and the SET state should remain perfectly stable in this bias range. The setup has been optimized to reduce the impact of milling on the electrical characteristics, due to superficial amorphization, Ga^+ implantation and residual sidewalls redeposition. A

* Corresponding author at: Univ. Grenoble Alpes, F-38000 Grenoble, France.
E-mail address: cguedj@cea.fr (C. Guedj).

http://dx.doi.org/10.1016/j.mee.2015.10.020

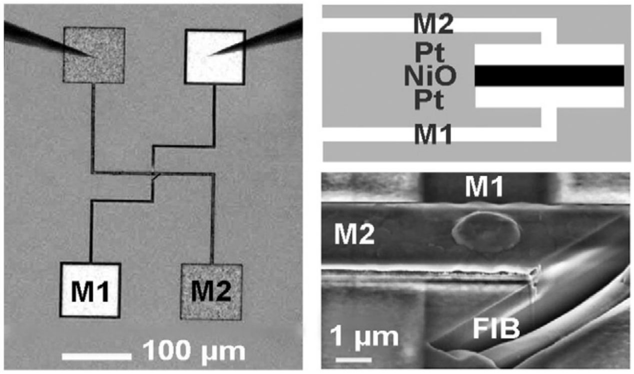

Fig. 1. Elementary resistive memory cell consisting of a standard Pt/NiO/Pt stack electrically probed (in-situ) between the top (M2) and bottom (M1) metal lines, using low noise Kleindiek electrical nanoprobes in the Zeiss Nvision 40 FIB-SEM equipment.

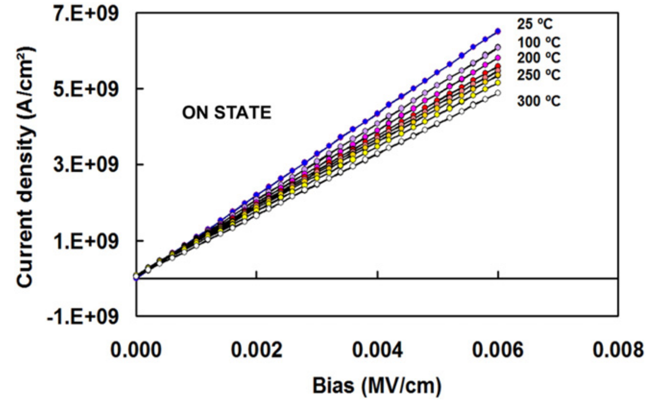

Fig. 3. Thermal evolution of electrical characteristics in the ON state. A metallic behavior is obtained.

low beam energy (5 keV) and current (80 pA) for both FIB and SEM is used to reduce the milling speed and damage. The milling box is slowly moving at a constant speed to ensure a subnanometric spatial resolution. The milling speed is precisely calibrated using a well-known feature like a reference via. After optimizing this setup, the experiment has been successfully reproduced 5 times with similar results. The results are averaged over each milling slice to obtain a simple 1D profile, although a 2D or even a 3D electrical nanotomography is also possible in principle, at the cost of time and complexity.

3. Material and device characteristics

X-Ray Photoemission Spectroscopy (XPS) and Hard X-Ray Photoelectron Spectroscopy (HAXPES) extensive experiments have been performed in the conducting (ON) and insulating (OFF) states [6]. The O/Ni ratio measured by XPS is close to 1.1. In the ON state, an increase in Ni^{3+} ions is measured [7] near the anode, and a barrier height value of 3.6 eV at the Pt/NiO interface is obtained by assuming a Pt work function of 5.2 eV.

The device after integration is displayed in Fig. 2.

The NiO layer is not perfectly flat, and the leakage paths are expected to appear at the thinnest areas, where the electrical field between the Pt electrodes is the highest. In terms of electrical performance, the device displays a non-polar behavior in agreement with previous papers [8] and appears to be surprisingly robust, since it can withstand temperatures up to 573 K. The data retention behavior shows that the ON and OFF states can be maintained during 3500 s at 573 K. Cycles of set/rest have also been measured down to 5 K, but the resistance strongly increases, and the ON/OFF conductance ratio decreases when the temperature is lowered. At higher temperatures, the thermal evolutions of I(V) curves in the ON (resp. OFF) states are displayed in Fig. 3 (resp. Fig. 4).

After the forming stage and few SET/RESET cycles to obtain stable electrical characteristics, the I(V) curves show a linear behavior at low fields. The decrease of leakage current with temperature is perfectly fitted by a metallic conduction mechanism. The situation is reversed in the OFF state, where the conduction can be described by a polaron-assisted hopping conduction mechanism possibly involving oxygen vacancies, in agreement with literature [9]. The value of the activation energy is 195 meV, not too far from the value of 350 meV originally estimated by Austin and Mott [10], and close to the value of 150 meV found by Jung et al. [11].

The electrical and reliability analysis is the necessary preliminary baseline for in-operando electrical measurements inside the FIB. These results provide an idea of the electrical impact of the FIB circuitry and damage during in-operando device milling.

4. Electrical 1D tomography inside FIB

The evolution of current and simultaneous scanning electron microscopy (SEM) sequential imaging (Fig. 5) is used to localize and identify the areas of conductance fluctuations. When a filament is milled before the end of the via, then a rapid drop of current is obtained, and the cell is put in the OFF state since the conducting channel is no longer present. The resistance evolution (from few kΩ to few MΩ) is close to the expected one for the removal of a single nanofilament, therefore the milling is not modifying significantly the electrical characteristics of the system during our improved milling setup. If no filament is milled

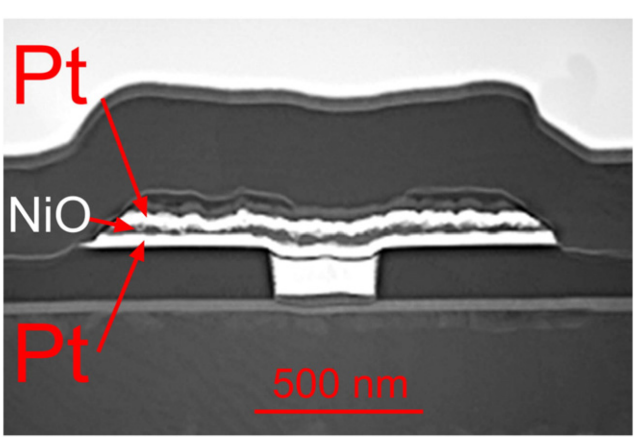

Fig. 2. Pt/Ni/Pt resistive memory cell after basic dual metal level CMOS integration on 200 mm Si wafer.

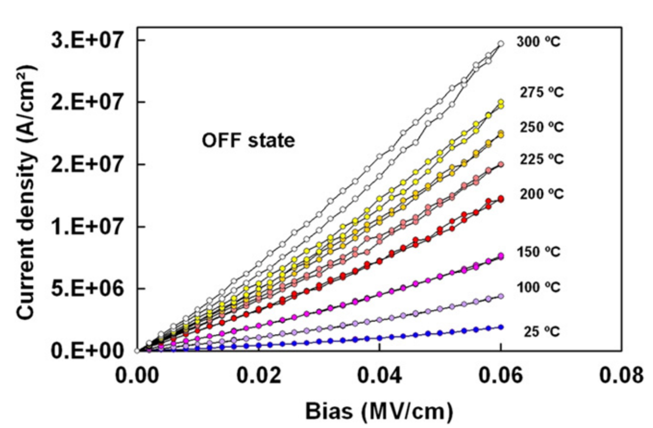

Fig. 4. Thermal evolution of electrical characteristics in the OFF state. A polaron assisted hopping behavior is obtained, with an activation energy of 195 meV.