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DC and low-frequency noise behavior of the conductive filament in bipolar HfO_2-based resistive random access memory

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ABSTRACT

This paper addresses the low frequency noise (LFN) properties of bipolar HfO_2-based resistive random access memory cells. It is shown that the devices exhibit a current on–off window up to 70 which is almost independent of the temperature in the range 30–180 °C. The experimental current–voltage curves in both resistance states are well reproduced by the quantum point contact model. LFN spectrum is typically characterized by $1/f$ noise in the low resistance state (LRS), while individual lorentzian components are often observed superimposed to the background $1/f$ noise in the high resistance state (HRS). Both LFN types are ascribed to defects fluctuating between a neutral and a charged state. The LFN level normalized to the square of the DC current in HRS is about two orders of magnitude higher than the corresponding value for LRS. The higher normalized LFN observed in HRS is ascribed to the smaller cross-section area of the conductive filament and to the stronger effect of the potential barrier modulation induced by a trapped electron. The normalized LFN is independent of the temperature for both resistance states as well as of the bias voltage in LRS, while it decreases with the bias in HRS, which is well correlated to the corresponding resistance decrease.

1. Introduction

Flash memories have experienced an impressive scaling trend in the last years, due to the market request of non-volatile memories with high access speed and high capacity, especially for usage in mobile devices. However this memory type is expected to face multiple difficulties in scaling below 20 nm, mainly related to physical and technological issues. Among the different solutions proposed to overcome these obstacles, memories based on a resistive switching mechanism, often referred to as resistive random access memory (ReRAM), are the most promising candidates, considering their high scalability, integration density, switching speed, simple design and compatibility with current CMOS fabrication processes [1–5].

A ReRAM cell has a simple capacitor-like structure, with a dielectric layer in between two metal electrodes. In some of the newest structures an additional metallic layer is inserted in contact with one of the electrodes in order to improve the device performance [6]. The memory effect in these devices is based on the possibility to electrically switch the cell between two well-defined resistance levels. Depending on the *I–V* characteristics, the switching behavior can be unipolar or bipolar. In unipolar resistive switching, the switching direction depends on the magnitude of the applied voltage but not on its polarity. On the contrary, in bipolar resistive switching, the change of the state can be just obtained by applying voltages of the specific polarity.

Understanding the nature of the conducting path is a central issue in the study of these types of structures. In this regard, a number of models based on different physical mechanisms have been proposed in the literature to explain the observed switching characteristics [7–12]. Even though models relying on a single or multiple conductive filaments (CF) are generally considered the most likely in transition metal oxides (TMO), no general consensus has been reached yet about the nature of the electron transport in such filamentary structures. Recent papers [13–16] suggest the quantum point contact (QPC) model as an explanation for the conduction mechanism. In this paper we investigate the DC and the low frequency noise (LFN) properties of the CF in the low (LRS) and high (HRS) resistance states of ReRAM cells with the aim of gaining further insight into the physics of filamentary conduction in HfO_2.

2. Instrumentation and sample description

The sample structure investigated in this work is depicted in Fig. 1 and consists in crossbar-patterned TiN\HfO_2(5 nm)\Hf

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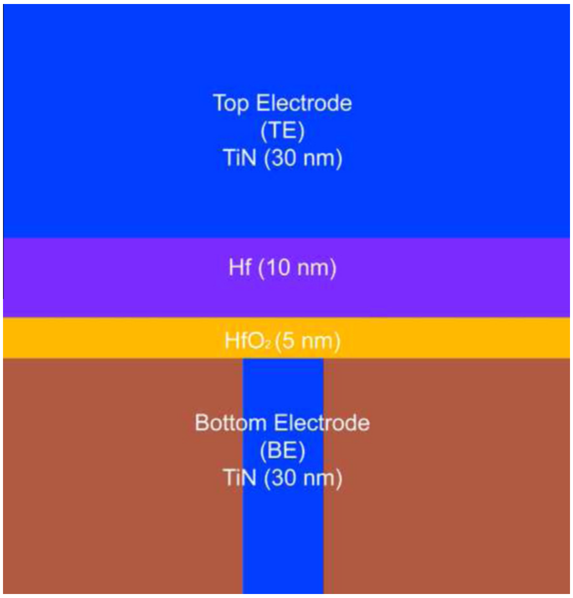

Fig. 1. Sketch of the structure of the investigated ReRAM cell.

(10 nm)\TiN(30 nm) cells. Cell area ranges from 85×85 nm^2 up to 3035×3035 nm^2. Further details about the devices can be found in [6].

We performed DC measurements with a Keithley 4200-SCS parameter analyzer and LFN measurements by using the dedicated measurement system illustrated in Fig. 2 [17]. The core of the system is the low-noise section, which has been enclosed in a metal box placed close to the contact probes and is battery operated. The low noise section consists in a bias stage, a transimpedance amplifier and a cascaded AC coupled voltage amplifier. The bias stage has been implemented using a 10 µF polyester capacitor, which can be pre-charged at the desired voltage level, followed by a low-input-bias-current (1 pA) low-noise operational amplifier (TLC071) connected as a unity-gain buffer. The value of the resistance in the transimpedance amplifier R_F has been set so as to maintain the right gain-bandwidth product for both resistance states. The amplification section is divided into two cascaded stages in order to obtain high total gain maintaining a wide enough bandwidth and to avoid the saturation of the amplifier. The system enables the synchronous acquisition of the DC component at the output of the transimpedance amplifier and the AC component at the output of the voltage amplifier. The evaluation of the spectrum of the AC component is performed by means of a PC-based spectrum analyzer.

3. Results and discussion

3.1. DC characterization

The forming process was carried out by applying a positive voltage on the top electrode (TE) with a current compliance of 150 µA. As shown in Fig. 3, the forming voltage increases by decreasing the cell area, which is consistent with the stochastic nature of the breakdown event. After the forming process, the cell exhibits a bipolar switching mechanism between LRS and HRS, as reported in Fig. 4. Typical *I–V* curves for our ReRAM cell are shown in Fig. 5. LRS exhibits a linear behavior in the measured bias voltage range, while the HRS curve shows linear behavior at low biases and super-linear behavior at higher voltages. Both behaviors are well reproduced by the QPC model [13–16] (see Fig. 5), which considers a narrow constriction across the dielectric as the limiting factor for the electron conduction. Within the narrow constriction, a potential barrier whose maximum energy depends on the size of the cross sectional area determines whether the system is in the HRS or LRS mode (see Fig. 6). This potential barrier is not material-related but represents the first quantized sub-band which arises as a consequence of the electron wavefunction lateral confinement.

According to the QPC model, the current I that flows through a quantum-sized constriction is given by the expression:

$$I = \frac{2e}{h}\left\{e(V - IR_s) + \frac{1}{\alpha}\ln\left[\frac{1+\exp\left\{\alpha\left[\Phi - \frac{e(V-IRs)}{2}\right]\right\}}{1+\exp\left\{\alpha\left[\Phi + \frac{e(V-IRs)}{2}\right]\right\}}\right]\right\} \quad (1)$$

where V is the applied voltage, Φ is the potential barrier height measured from the equilibrium Fermi level, α is the shape parameter related to the thickness of the barrier t_B, e is the electron charge and h is the Planck's constant [13,14]. R_S is a series resistance external to the constriction that takes into account the non-idealities of the structure under investigation as well as other assumptions in the model [13,14]. For HRS, (1) is basically associated with a tunneling mechanism through the first sub-band. In this

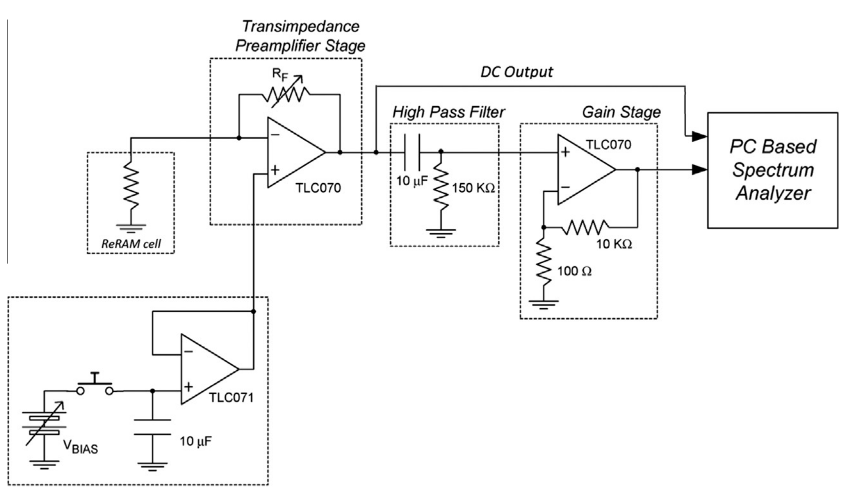

Fig. 2. Schematic set-up of the low noise amplifier stage used for the noise measurements. The value of the resistance in the transimpedance amplifier R_F has been adjusted in order to maintain the right gain-bandwidth product for both resistance states.