Current and Voltage control of intermediate states in bipolar RRAM devices for neuristor applications.

H. García, O.G. Ossorio, S. Dueñas, H. Castán

Department of Electronics, University of Valladolid, Valladolid 47011, SPAIN

The control of the intermediate conductance levels in HfO2-based MIM capacitors for neuromorphic applications is presented in this work. Using voltage or current control signals shows significant differences. The potentiation levels can be controlled in a linear way using current as control signal. These levels are achieved in very short times and only depends on the current pulse amplitude magnitude. On the contrary, depression levels cannot be controlled by current but with voltage pulses. A proper control of synaptic behavior requires the combination of both types of signals.

Introduction

Nowadays, there is an increasing interest in the fabrication of neuristors in which memristors are used to create a neuron-like behavior [1]. Memristors based on resistive switching memories (RRAM) are promising candidates to implement artificial synaptic devices for their use in neuromorphic systems, due to their high number or reachable conductance levels [2].

In a previous work [3] we show that TiN/Ti/ HfO_2/W capacitors exhibit resistive switching behavior and that intermediate conductance states can be obtained by varying the voltage applied to the device (Voltage-control mode, VCM). We demonstrated that the conductance values vary near linearly when applying voltage depression pulses. During depression process, the conductance state depends on the amplitude and the duration of the voltage pulses length. Moreover, this process is accumulative: the conductance decreases when applying successive pulses of same amplitude and length. In contrast, the potentiation characteristic is not linear, as for other synaptic devices, as PRAMs: the transitions from high resistance state (HRS) to low resistance state (LRS) is very sharp and intermediate conductance state cannot be controlled. Decreasing the voltage pulse length or amplitude was not a choice. Additionally, we tried to use ramps where the voltage linearly increases and once again the characteristics remain very nonlinear. In summary, a very poor control of the potentiation state is obtained when using voltage as synapse stimulus. In this work we demonstrate that the potentiation process can be linearly controlled when using current as the synapse stimulus (Current-control mode, CCM), while the depression process is more linear when using voltage control mode (VCM).

Experimental

The devices used in this work are TiN/Ti/10-nm HfO2/W MIM capacitors. The highk dielectric was deposited by the atomic layer deposition (ALD) technique at 225 ºC using TDMAH and water as hafnium and oxygen precursors respectively. Nitrogen was used as carrier and purge gas. The bottom electrode consists of a 200 nm W layer, and the top electrode consists of a 200 nm TiN layer and a 10 nm Ti layer. Metal electrodes were deposited by magnetron sputtering.

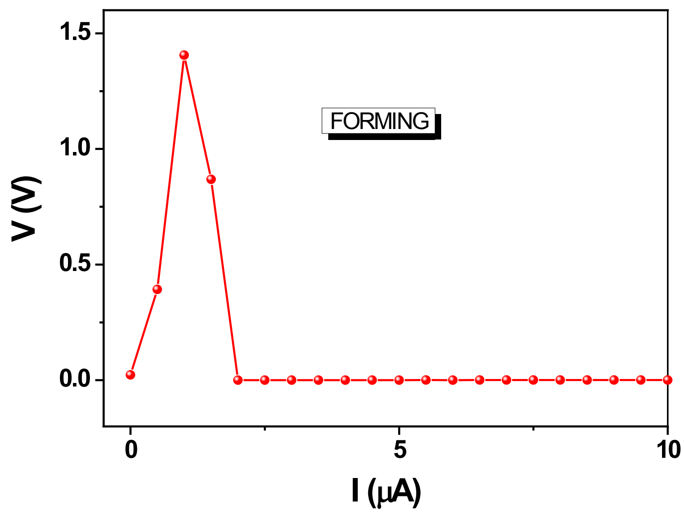

Figure 1. Electroforming in current-control mode.

An HP 4155B Semiconductor Parameter Analyzer was used to perform the voltage and the current measurements. In order to perform the pulsed measurements, we used an Agilent 33500B Series waveform generator which provides voltage pulses and ramps. The voltage waveforms are converted to mimic current waveforms using a home-made voltage to current converter. All the measurements were carried out at room temperature and the entire experimental setup was computer controlled. An HP54615B digital oscilloscope was used to record the transient signals in transient measurements.

Results and discussion

In Fig. 1 we show that the conductive path formation (electroforming) requires a very few nA current value. As the filament is formed, the devices reach the low resistance state (LRS) and the voltage falls to a very low value. Once the filament is formed, we have measured the voltage-current (V-I) characteristic instead of the more usual current-voltage (I-V) characteristic.

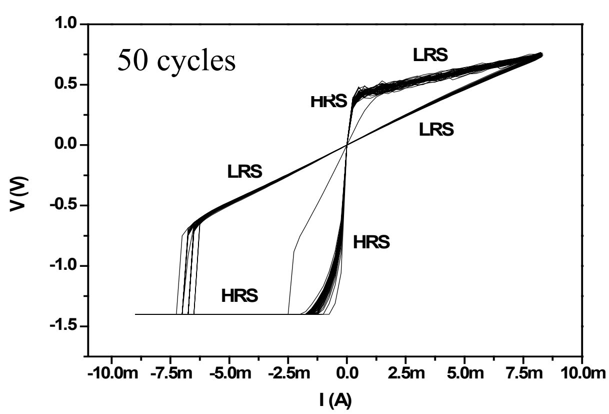

Figure 2. Voltage-current loops in current-control mode: A voltage compliance of -1.5 V was used to prevent from irreversible breakdown

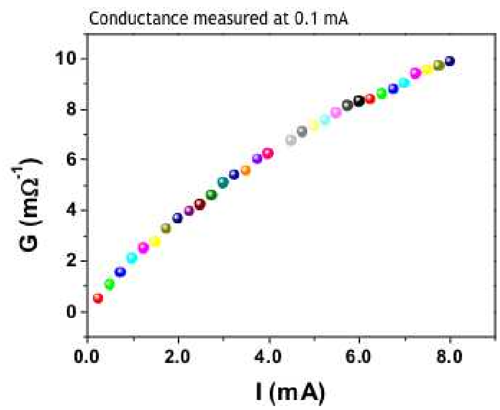

Figure 3. Conductance state measured at 0.1 mA after applying potentation current pulses of increasing amplitude.

Figure 2 shows 50 consecutive bipolar switching V-I loops. It is important to point that in the CCM mode, a voltage compliance in the reset transition must be used. Otherwise, irreversible oxide breakdown takes place due to the huge increase of the structure dissipated power. Departing from the HRS state we have applied current pulses of increasing amplitude.

In Fig. 3 we plot the conductance of the device measured at 0.1 mA as a function of the amplitude of the current pulse previously applied. We see that the synaptic potentiation linearly depends on the pulse amplitude in the CCM mode. In Figure 4 we demonstrate that potentiation occurs at the very first current pulse. Successive pulses do not modify the conductance value. In summary, the potentiation process in CCM mode is very fast, non-accumulative and nearly linear. To confirm that this process is very fast we have obtained current transients in the VCM mode which confirms that when a positive voltage is applied the current increases occurs at very short times.

In contrast, the depression process is better controlled by applying voltage pulses (VCM mode) as described in ref. 3. Moreover, the depression process is slower and accumulative. That can be observed in Fig. 5 in which a train of -0.8 V voltage pulses is applied. The conductance decreases from pulse to pulse and show very long-time rates (tens of ms for the showed voltage).

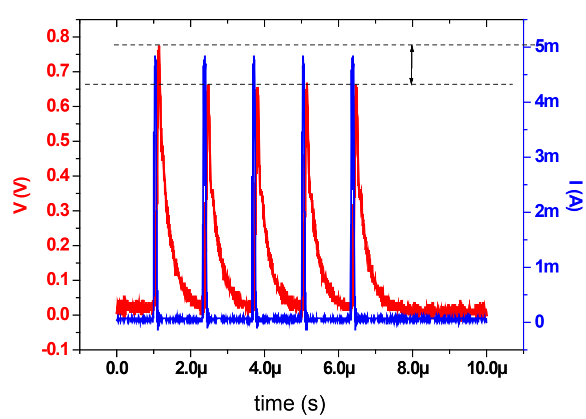

Figure 4. Instantaneous voltage decrease during a pulsed-current potentiation process.

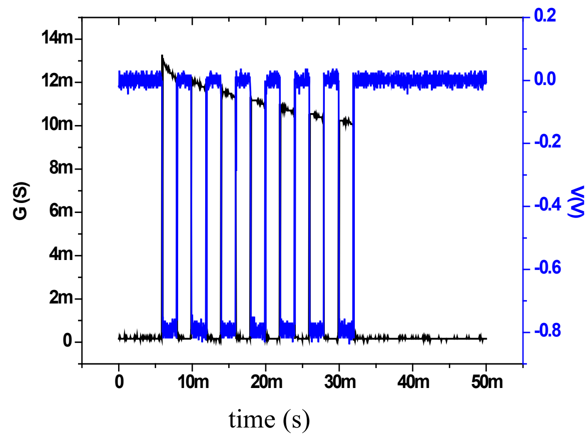

Fig.5. Cumulative conductance decline during a pulsed-voltage depression process.

The different time response between the CCM mode potentiation process and the VCM depression process can be explained as follows: During potentiation the supplied current reinforces the filament resulting a conductance increase and, consequently, a reduction of the voltage as plotted in Figure 4. Conversely, during the depression process, the filament weakens and the conductance decreases. In CCM a positive feedback process would appear that results in a dramatic destruction of the filament: decreased conductance results in a voltage increase which in turn results in a further decrease in conductivity and so on. In contrast, in VCM mode, when the conductance decreases the current decreases as well, so the process slows down, and it is necessary to maintain the voltage longer times.

Conclusions

The use of current control mode (CCM) during the potentiation processes in HfO2 RRAM synaptic devices provides a much more linear response than the more conventional voltage control mode (VCM). On the contrary, during depression the CCM cannot be used to control the intermediate synaptic levels. However, since linear depression characteristics can be achieved applying voltage pulses, a good control of the synaptic weight could bo obtained by using both kind of electrical signals.

Acknowledgments

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