Understanding the Role of Dopants in Transition Metal Oxide Dielectrics for Digital and Analog Resistive Switching

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Resistive Random Access Memory (ReRAM) devices have gathered significant attention recently for high-density non-volatile data storage applications. This paper discusses the role of intentional doping in transition metal oxide dielectrics, particularly HfO_2, and its implications on the device performance. In addition to the digital switching where the state of the devices changes abruptly by the application of appropriate voltages, routes to achieve a more gradual multi-state analog switching will be also discussed. The underlying mechanism of switching for both digital and analog cases will be analyzed through transport studies based on temperature dependent current-voltage (I-V) and admittance spectroscopy techniques and correlated with the materials parameters.

ReRAM devices with ultra-fast switching speeds (<10 ns), low-energy consumption ($<10^{-15}$J), and non-volatile data retention characteristics are attractive for high-density universal memory applications [1]. However, currently researched ReRAM devices have several challenges including need for one-time electroforming, variability, limited endurance, relatively high write/erase energies, and necessity for bidirectional selector diodes. In addition, the mechanism of switching and charge transport is widely debated. Though several materials have been reported to demonstrate the ReRAM switching characteristics, the dependence of device characteristics on materials parameters is not well understood. Of several materials, HfO_2 based ReRAM devices are particularly interesting because of the compatibility with the existing CMOS process technology [2-5]. In order to solve the existing challenges in HfO_2 based ReRAM devices, we have performed systematic experimental study to investigate the role of intentional dopants in HfO_2 dielectrics and correlated it with the device performance.

Two-terminal devices were fabricated with Ru/doped-HfO_2/TiN stacks. The dopants under investigation were Mg and Mn. The incorporation of dopants were achieved by the reactive co-sputtering of Mn or Mg with Hf in Ar:O_2 environment. TiN top electrodes were patterned using wet-etching. The devices with dimensions 100 µm x 100 µm were studied in this work. All electrical characterizations were performed by probing the samples in Lakeshore cryogenic probestation using Keithley 4200 Semiconductor Characterization System (SCS) and 4225 Ultra-fast Pulse Measurement Unit (PMU). The performance analysis of the devices was performed in 1 transistor 1 resistor (1T1R) configuration by connecting the external transistor. Precautions were taken to minimize the forming/set current overshoot over the compliance current due to parasitic capacitances.

The Mg-doped samples indicated excellent ReRAM bipolar digital switching characteristics. A significant reduction in the forming voltages could be achieved as the concentration of Mg was increased in HfO_2 compared to the un-doped HfO_2 samples. This indicated the possibility of achieving a forming-free operation by adding Mg-dopant in HfO_2 dielectrics. Our transport studies indicated that the introduction of Mg increases the concentration of oxygen-vacancies concentration in HfO_2 which reduces the forming voltages. In addition, the Mg-doped samples indicated significantly reduced set/reset voltages and improved uniformity in performance from one device to another. The room-temperature and high-temperature retention testing showed better performance for the Mg-doped samples over the un-doped samples. The mechanism of switching and charge transport was studied using temperature dependent I-V and switching measurements.

On contrary to Mg-doped samples, the Mn-doped samples showed analog switching characteristics where a gradual change in resistances as a function of voltage could be achieved. The mechanism of reconfiguration was dominated by the trap-assisted conduction mechanism. The devices manifested transient and steady state change in the conductance. These devices were further studied for applications as biologically inspired artificial synapses for neuromorphic computing. The transient characteristics was utilized to demonstrate short-term-plasticity (STP) and working memory responsible for cognition and decision making while steady state change in conductance was utilized to demonstrate adaptation and learning.

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