Ultralow Voltage Resistive Switching in Ultrathin Silicon Oxide

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Resistive switching phenomenon was discovered in amorphous silicon and silicon oxide more than 4 decades ago.[1] There is revived interest in using silicon based materials as the switching layer for resistive switches.[2,3,4] Although compatible with silicon technologies regarding materials and processes, recently reported silicon oxide based devices required high programing voltages (from 3.5 to 13V) that are incompatible with the state-of-the-art low-power CMOS transistors.

Here we report SiO_x based memristive devices that exhibited nonvolatile resistive switching behavior with ultralow programming voltages (<0.5 V) and ultra-high ON/OFF conductance ratio ($>10^8$). Each device consists of a heavily doped silicon bottom electrode, a ~1 nm thick SiO_x switching layer that was produced in wet chemical (Piranha cleaning with H_2SO_4 and H_2O_2) processes and a top metal electrode (Pt or Cu) (Fig. 1).

Fig. 2 shows the typical IV curves for devices with Pt and Cu top electrodes. Interestingly, the switching behavior was top electrode dependent: devices with inert metal electrodes (Pt) top electrodes exhibited nonpolar switching behavior while devices with active metal electrode (Cu) were bipolar. The turn on voltage (V_{SET}) and turn off voltage (V_{RESET}) for Pt/SiOx/Si device were -2.6 V and -0.9 V, and those for the Cu/SiO_x/Si device were +0.5 V and -1.3 V, respectively. The Cu/SiO_x/Si device also exhibited very high ON/OFF conductance ratio ($>10^8$ at 0.1 V).

The observation suggests that different mechanisms have governed the switching behavior for devices with different metal electrodes. Specifically, switching with inert metal electrodes was intrinsic within $SiO_{x,.}$ SET process involved electrochemical reduction of SiO_x to Si nanocrystal, while RESET process was dictated by the Si oxidization process caused by current generated Joule heating (Fig. 3a). Both processes were voltage polarity independent. On the other hand, resistive switching for devices with Cu top electrodes was based on cation generation and migration inside of the SiO_x. Cu ions were generated at the top electrode/oxide interface, travelled to the bottom electrode under positive bias, and were reduced to Cu metal at the bottom electrode/SiO_x interface, forming a conductive metal filament inside of the oxide. When a negative bias was applied to the top electrode, this process was reversed, corresponding to the RESET process (Fig. 3b).

Fig. 4 shows the switching curves and switching voltages of devices with Pt top electrodes during the first 115 DC sweeps. The corresponding cumulative distribution functions (CDF) are also plotted. The coefficients of variation of SET and RESET voltage are respectively 5.22%, 11.82%. The statistics data indicate that the devices had excellent cycle-to-cycle uniformity.

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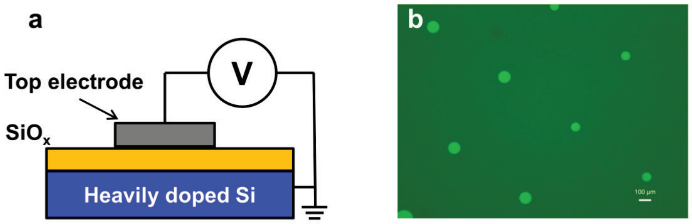

Figure 1. a) Schematic illustration of the device structure and the IV measurement scheme. During IV characterization, a voltage sweep (or pulse) is applied to the top electrode and the bottom electrode is always grounded. B) A typical optical micrograph of a sample with the fabricated SiO$_x$ devices of various sizes. Only those with a diameter of 50 µm are used for the measurement in this study.

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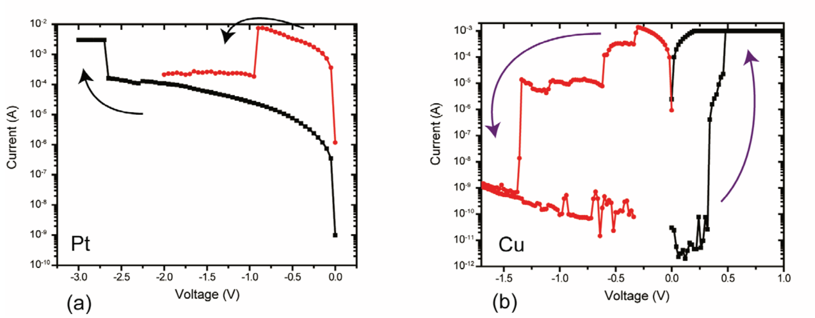

Figure 2: Typical switching curve from devices with different top electrodes. (a) Devices with Pt top electrodes exhibit nonpolar switching behavior, and (b) devices with Cu top electrodes exhibit bipolar switching behavior. The thickness of Pt and Cu electrode is 12 nm and 24 nm respectively, and the diameter of all electrode measured is 50 µm.

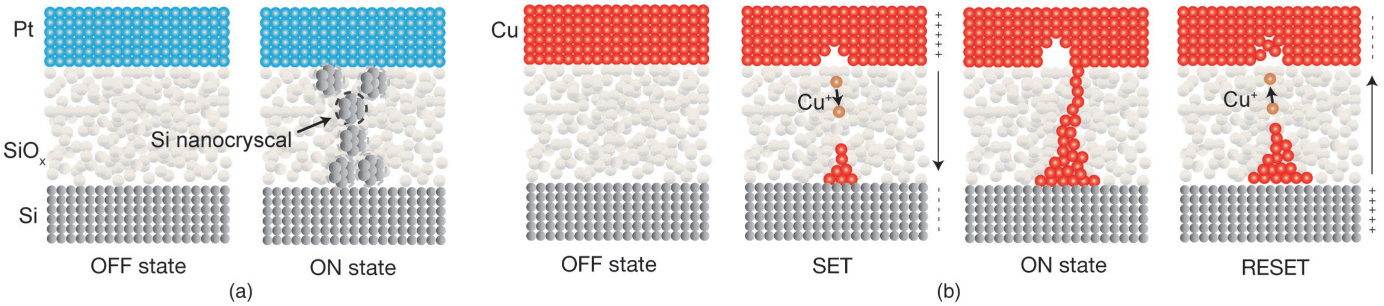

Figure 3: Schematic of the switching mechanisms for devices with different top electrodes. (a) Switching of devices with inert metal top electrode (Pt). Silicon nanocrystal conductive bridge is formed within SiO$_x$ after SET process. (b) SiO$_x$ layer with top electrode of active metal (Cu) is based on cation generation and migration inside of SiO$_x$. The Cu$^+$ ions dissolved at anode interface, travelled to the other side under applied bias, and were reduced to Cu metal, leading to the formation or rupture of a conductive metal filament depending on the polarity of applied voltage.

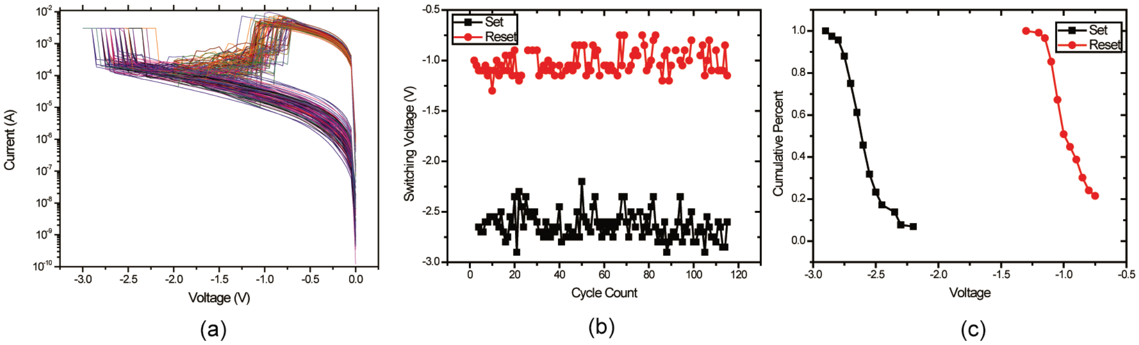

Figure 4. Uniformity of devices with Pt electrodes. (a) 115 cycles DC sweep of devices with Pt top electrode; (b) The switching voltage in each cycle of DC sweeping. The switching voltage is defined as when the current change was more than one order of magnitude after 0.02 V sweep step; (c) CDF of switching voltages.