Supplemental

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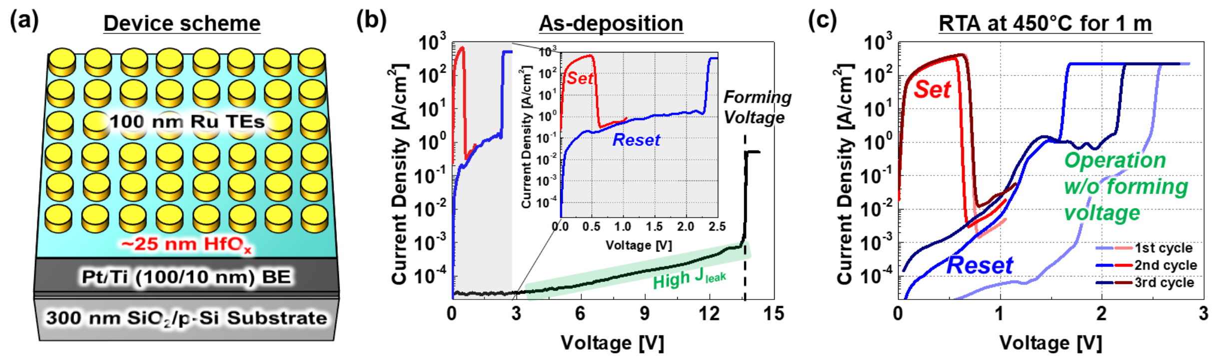

Figure 1. (a) Schematics of the memristive Ru/HfO_x/Pt devices deposited by e-beam evaopartor (Pt), ALD at 250 °C (HfO_x), and DC sputtering (Ru). Especially, for the HfO_x deposition, we used the carbonated H_2O_2 as an oxygen precursor for achieving the carbon composited films. (b) Current density–voltage (J–V) characteristics of the demonstrated devices without any annealing process. After the high voltage-based formation of HfO_x film, the devices exhibit the memristive behavior, *i.e.*, ReRAM operation. Unlike the carbon-less HfO_2 operation, the high leakage current was observed in the films. (c) J–V characteristics of the demonstrated devices with RTA at 450 °C for 1 m under N_2. After annealing, the forming voltage-free could be demonstrated, which is different from the forming behavior in ReRAM devices with respect to the magnitude of switching voltage and current level.

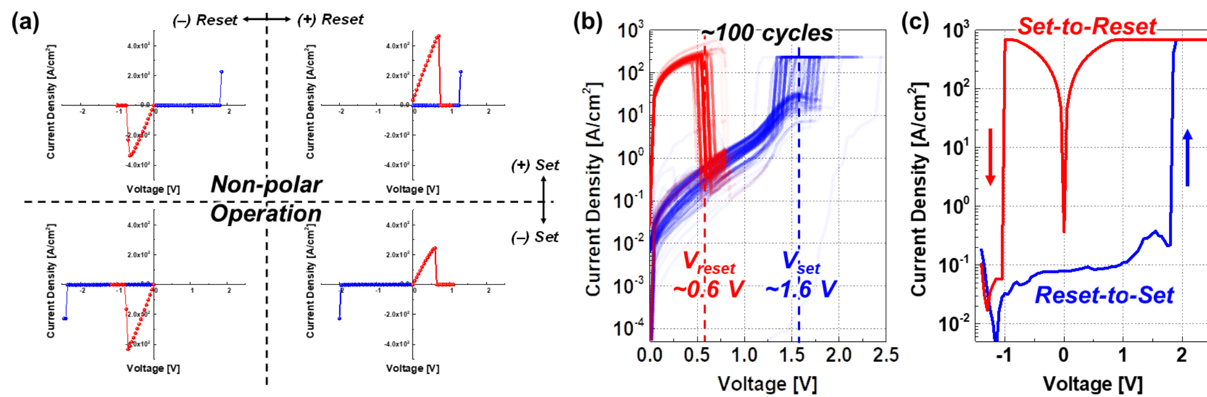

Figure 2. (a) Non-polarization switching behavior of the demonstrated devices, investigated by applying same/opposite polarities of operating voltage. (b) Cycle-to-cycle variation of the unipolar operation in the devices without applying forming voltage. The set and reset voltage (V_{set} and V_{reset}) is ~1.6 and ~0.6 V during the cycles. (c) Bipolar operation of the devices, highlighting the great merits of non-polarization switching behavior.