Supplemental

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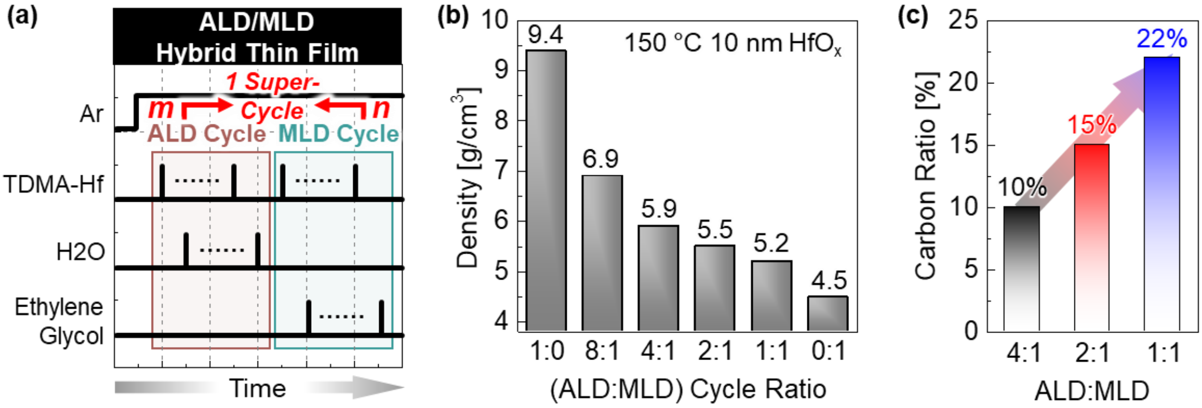

Fig. 1. (a) Conceptual figure illustrating the super-cycle approach during ALD and MLD cycles. Controllable properties include (b) film densities and (c) carbon composition by adjusting super-cycle protocols. Film densities can range from 4.5 g/cm^3 to 9.4 g/cm^3, and carbon ratio can be cotrolled up to 22% and above.

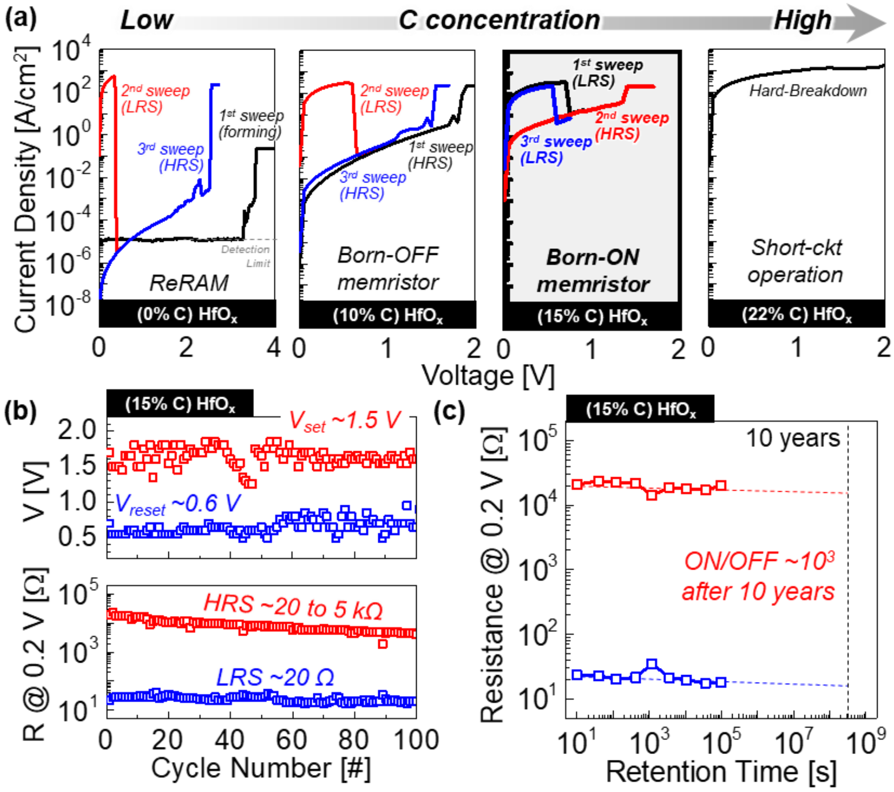

Fig. 2. (a) J–V characteristics of 10 nm-thick HfO_x memristive devices characterized by different carbon concentrations in HfO_x. The approach for doping carbon involves incorporating multiple precursors and/or reactants during the ALD process. (b) Endurance of both set/reset and low/high resistance states (LRS/HRS) for up to 100 cycles. Both V_{set} and V_{reset} exhibit excellent reproducible results of ~1.5 and ~0.6 V, respectively, regardless of the cycle numbers. While the LRS remained constant at 20 Ω, the HRS decreases from 20 kΩ to 5 kΩ. Nevertheless, the ON/OFF ratio is still above 10^2, which is comparable to other memory devices. (c) Time-dependent retention characteristic of 15% carbon doped HfO_x memristors. The ON/OFF ratio is expected to be ~10^3 after 10 years.