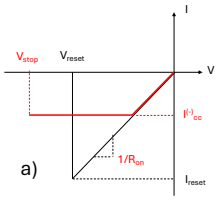
Beyond Binary Erasure: Harnessing a Constrained RESET Operation for Analog Synaptic Plasticity in ReRAM

Shehla Yasmeen, Aaron DiFilippo, Marius Orlowski

Neuromorphic computing overcomes von Neumann bottlenecks by co-locating memory and processing. Filamentary ReRAM and CBRAM are promising synaptic candidates due to compactness, non-volatility, and analog tunability, but conventional binary SET/RESET offers coarse control over conductance. This work reports a novel regime in Cu/TaO_x/Pt CBRAM—constrained RESET—where a compliance-limited RESET strengthens rather than ruptures the filament. For high-resistance filaments (R_{on} > 1 kΩ), constrained RESET reduces resistance up to tenfold, while robust filaments are unaffected, making the effect self-limiting and most useful for fragile states. The reconstruction of the Cu atom filament leads to reduced electric fields, reduced Joules heat, and reduced resistance, rendering this mechanism self-limiting. Electrostatic simulations show that a weak filament (truncated cone) concentrates electric field at its narrow tip (>1.6×10^6 V/cm) under negative bias, driving Cu^+ electromigration toward the constriction and forming a stable hourglass (double-cone) morphology. To harness this for analog weight control, we integrate the memristor with a series transistor operating in saturation, providing tunable compliance current (I_{cc}). Using pulse trains, we implement two programming techniques: (i) Incremental Step Pulse with Verify Algorithm (ISPVA), modified to stay below the rupture threshold, and (ii) Incremental Gate Voltage with Verify Algorithm (IGVVA), where gate voltage (hence I_{cc}) is incremented with fixed programming pulses. The three control parameters (ramp rate, compliance current, stop voltage) map to biological learning mechanisms, enabling precise, linear, symmetric synaptic weight updates. This work addresses three persistent challenges: instability of high-resistance states, asymmetry between potentiation/depression, and lack of linear analog control. The constrained RESET operation, implemented with transistor-based compliance control, provides stable, fine-grained weight updates. It is fully compatible with existing ReRAM stacks, adds no fabrication complexity, and improves retention and variability, accelerating commercialization for edge AI, robotics, and autonomous systems. The advantages of the new potentiation technique include: (i) Precise and stable analog resistance control for reliable synaptic weight updates, (ii) Non-destructive constrained RESET enabling symmetric and linear weight modulation, (iii) High-resistance state stabilization for improved memory retention and device reliability.



b)

R_{on} (SET) [Ω]	3,850	1,280	548	435	329	210	107
R_{on} (a-RESET) [Ω]	342	352	520	430	328	209	107
ΔR_{on} [Ω]	3,508	928	28	5	1	1	0

Fig. 1 a) conventional RESET operation resulting in rupturing of the filament, in back; constrained RESET operation, in red. b) Resistance decrease of the filament before and after the constrained RESET operation.

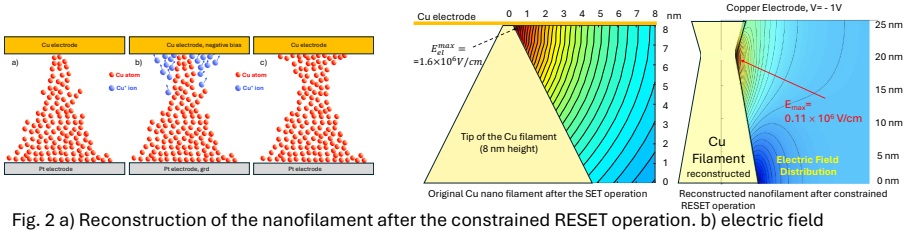


Fig. 2 a) Reconstruction of the nanofilament after the constrained RESET operation. b) electric field distribution before and after the reconstruction of the filament

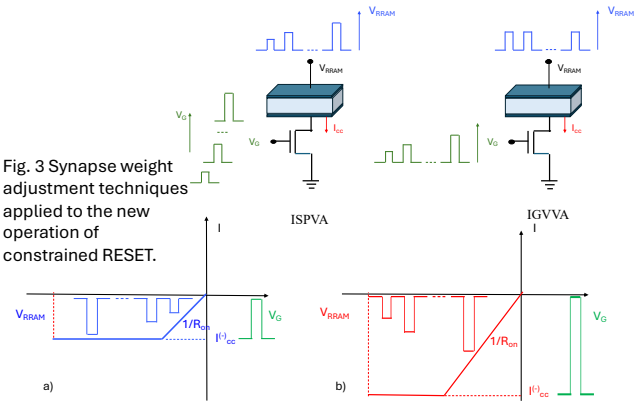


Fig. 3 Synapse weight adjustment techniques applied to the new operation of constrained RESET.