Practical demonstration of a RRAM memory fuse

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Summary
Since its inception, the resistive random access memory (RRAM) fuse has been a good example of how small numbers of RRAM devices can be combined to obtain useful behaviors unachievable by individual devices. In this work, we link the RRAM fuse concept with that of the complementary resistive switch (CRS), exploit that link to experimentally demonstrate a practical RRAM fuse using TiO$_x$-based RRAM cells, and explain its basic operational principles. The fuse is stimulated by trains of identical pulses where successive pulse trains feature opposite polarities. In response, we observe a gradual (analog) drop in resistive state followed by a gradual recovery phase regardless of input stimulus polarity, echoing traditional, binary CRS behavior. This analog switching property opens the possibility of operating the RRAM fuse as a single-component step change detector. Moreover, we discover that the characteristics of the individual RRAM devices used to demonstrate the RRAM fuse concept in this work allow our fuse to be operated in a regime where one of the two constituent devices can be switched largely independently from the other. This property, not present in the traditional CRS, indicates that the inherently analog RRAM fuse architecture may support additional operational flexibility through, for example, allowing finer control over its resistive state.

KEYWORDS
analog memory, complementary resistive switch, memristor, RRAM, RRAM fuse

1 | INTRODUCTION

The development of a bio-inspired computation paradigm capable of demonstrating practical applications has long been a holy grail of electronics and neuroscience research. This effort has been primarily driven by the immense opportunity to be found in the powerful complementarity that exists between the fast, reliable, and precise von Neumann-based computers and the self-adaptive, massively parallel, and fault-tolerant biological systems we see in nature. However, efforts in that direction have so far been hampered by the sheer complexity involved in emulating biological processes in silico. Thus far, a number of approaches have tried to attack this problem by harnessing the power of personal computers (PCs), microprocessor units (MPUs), field-programmable gate arrays (FPGAs), and graphics processing units (GPUs) as well as bespoke systems exploiting analog complementary metal-oxide semiconductor (CMOS)
The common problem with these approaches, however, is that they all employ fundamental components and design methodologies originally conceived for von Neumann-based computation. The resulting power and area costs associated with building bio-inspired systems of any appreciable scale (e.g., see Stromatias et al.6) have prompted the evolution of alternative approaches.

One such approach exploits recent advances in the field of nanoelectronic devices that exhibit the phenomenon of resistive switching. These come in various flavours such as spin-torque transfer (STT), electrochemical metallization or the valence-change mechanism, metal-oxide-based (MOx) resistive access memory (RRAM) devices that we use and are often collectively referred to as “memristors” for historical reasons. RRAM devices boast a simple, two-terminal structure and an ability to react to external voltage/current stimuli by changing their resistive states as seen in the examples of Figure 1A,B. These properties, in turn, allow them to act both as single-component memory elements (including synapses12–15) and as computational elements,16,17 which raises the possibility of shifting much neuro-computational complexity to new components designed specifically to exhibit biological neuron- or synapse-like characteristics. These behavioral aspects, in tandem with continuous advances in the electrical and scalability characteristics of RRAM,18,19 indicate a possible route towards truly scalable bio-inspired systems. The flexibility and possibilities offered by this approach are reflected in the variety of RRAM implementations and biologically relevant applications investigated so far. These include synapse implementations (analogue synapses supporting spike timing-dependent plasticity [STDP] implemented through MOx or phase change memory-based [PCM] devices,20,21 binary stochastic synapses through STT devices22 etc.), small neural networks,23 neural activity sensors,24 and a host of others.25,26

Beyond their use as single-component memory/synapses, RRAM devices can also exhibit interesting properties when operated collectively in small ensembles, such as oscillators27 or chaotic attractor systems.28 One of the most well-known small device ensembles is the complementary resistive switch (CRS) configuration9 seen in Figure 2C, that is, a pair of RRAM devices supporting binary switching (i.e., between two distinct high and low resistive states [HRS and LRS]) connected antserially. In typical operation, the CRS can only be found in two distinct states: (i) an HRS whereby one of the RRAM devices is in HRS and the other in LRS and (ii) an LRS when both RRAM devices are in LRS. The CRS changes states abruptly and in a fully voltage level-dependent fashion since each RRAM device features two threshold levels of opposite polarities at which they carry out their high–low and low–high state transitions, for a total of four CRS thresholds as seen in Figure 2A. However, if the devices are allowed to exhibit analogue (gradual) switching at a voltage-dependent rate (Figure 2B), the ensemble generalizes to a “RRAM fuse” as originally described in Jiang and Shi.30 As a result, two new properties may arise: (i) the RRAM fuse becomes able to assume a large number of resistive state states, and (ii) the switching no longer occurs consistently abruptly. These properties are important because now the fuse can continuously change states in response to both stimulus duration and voltage amplitude, that is, it becomes capable of storing information on the history of the input stimulus signal in its overall resistive state (Figure 2E).

Such unconventional components that find no direct equivalent in nature may prove useful for complementing the field of bio-inspired computation (“beyond bio-inspired computation”). In this work, we experimentally demonstrate a practical RRAM fuse consisting of two metal-oxide-based solid-state RRAM devices and show how its intrinsic properties allow it to function as a rudimentary step detector. Section 2 describes the typical behavior of individual devices, presents measured electrical characterization data from solid-state devices and explains how two exemplars can be combined to result in a RRAM fuse. Section 3 shows experimental results illustrating fuse behavior while Section 4 provides a brief overview of practical fuse operation considerations including avenues for further exploration. Finally, Section 5 concludes the paper.

2 | MATERIALS AND METHODS

2.1 | Memristor device fabrication and testing

The tested RRAM devices are based on metal-insulator-metal (MIM) structure fabricated on 200-nm insulating SiO2 film, which was thermally grown on silicon wafer. The bottom and top electrodes (BE and TE) were deposited via electron beam evaporation technique, where the active layer was deposited by reactive magnetron sputtering. All layers were patterned and defined by conventional optical lithography and lift-off processes. Oxygen plasma cleaning step was carried out before each material deposition for obtaining more reliable and better quality devices. The final stack
consists of Pt/TiO\textsubscript{x}/Pt/Ti with respective thicknesses of 10/25/10/5 nm. A Ti layer was needed for adhesion purposes and the resulting TiO\textsubscript{x} film was near stoichiometric. Figure 1D,E depicts a schematic view and SEM microphotograph of a single RRAM cell, respectively.

All experiments performed towards this work employed an upgraded version of the RRAM characterization instrument reported in Berdan et al.\textsuperscript{31} All devices involved were probed directly on-wafer via a probe card as illustrated in Figure 2D. The BE was always kept grounded and all quoted voltages refer to the TE.

2.2 RRAM fuse basic operation concept

The operation of the RRAM fuse arises naturally from the resistive switching characteristics of its constituent devices and specifically the link between input voltage and degree of resistive switching under fixed-duration pulsed stimulation. The sensitivity of switching to input voltage amplitude can be assessed by applying a series of voltage pulse train ramps to each device and measuring the resistive state of the device under test (DUT) at the end of each train as seen in Figure 1B and described in detail in Serb et al.\textsuperscript{32} Subsequently, the resistive state change precipitated by each voltage level tested is assessed, and the relation between resistive state change ($\Delta R$) and applied voltage is summarized in a “voltage sensitivity” plot (or “switching” plot). Measured and fitted switching plots for pulse duration fixed at 100 $\mu$s are shown in Figure 3A for the two devices used to implement the RRAM fuse in Section 3. The fitting model used is a simple, empirical, four parameter model:

$$\Delta R(V_b) = \begin{cases} a_+ \cdot (V_b - V_{th+})^2, & V_b > V_{th+} \\ 0, & V_{th-} < V_b < V_{th+} \\ a_- \cdot (V_b - V_{th-})^2, & V_b < V_{th-} \end{cases}$$

where $\Delta R(V_b)$ is the change in resistive state, $a_+, -$ fitted scaling parameters, $V_{th+}, -$ the fit-estimated thresholds of the RRAM device, and $V_b$ the bias voltage applied across it. RRAM device resistive state read-out operations are in all cases carried out at a standardized read-out voltage of $+0.2 \text{ V}$, and resistive state is formally defined as static resistance at that voltage level. This is necessary in order to provide a comparable means of assessing resistive state for devices that may feature nonlinear $I$–$V$ characteristics.\textsuperscript{33}
**FIGURE 2** Generalising the complementary resistive switch (CRS) concept: (A) Conceptual CRS behavior summary under voltage sweep stimulation. As the voltage is continuously ramped up and down the system transitions abruptly between two distinct resistive states (blue arrows and red dashed lines, respectively). (B) Expected conceptual behavior of a RRAM fuse under voltage sweeping stimulation. (C) Both the CRS and the RRAM fuse are implemented as an ensemble of two devices connected antiserially. (D) Microphotograph of array of RRAM devices in contact with a probe card showing possible connection scheme for linking encircled devices into a fuse configuration. (E) Mapping the integral of a transformation of input voltage $V_b$ (through the “switching function,” see Figure 3A) on an analogue RRAM fuse resistive state. Saturation occurs when the RRAM fuse reaches its operational resistive state ceiling [Colour figure can be viewed at wileyonlinelibrary.com]

**FIGURE 3** RRAM fuse implementation: (A) Switching function for the two devices used to construct the RRAM fuse and fittings to model in Equation (1). Associated fitting parameters are in Table 1. Convention for forward and reverse bias regions (pale blue and red, respectively) of RRAM operation also shown. (B) Connectivity of test devices for RRAM fuse experiments in this work. (C) Example of a “switching load line” for the two devices from (A) connected as indicated in (B) and with pulse bias voltage $V_b$ slightly lower than 3 V [Colour figure can be viewed at wileyonlinelibrary.com]
Because of the antiserial connection, the switching load line consists of the positive marked in Figure 3C. Notably, the precise trajectory of resistive state. For appropriate initial values of $a_0$ "stabilising the RRAM fuse at a relatively high resistive state, similar to the HRS state in the traditional, binary CRS.

The proposed RRAM fuse topology was tested experimentally using the devices from Figure 3A connected antiserially as illustrated in Figure 2. Results are shown in Figure 4. Following initialization to a saturated state the RRAM fuse reacts to two trains of pulses with opposite polarities and suitably chosen amplitudes in a qualitatively similar manner: exhibiting a sharp, initial “dip” followed by a slower “recovery” phase as projected.

We notice that the two “dip and recovery” responses are subtly different. With negative stimulus polarity, the dip is sharper and the recovery slower than in the positive stimulus case. Closer inspection suggests this may be linked to the balance between the sensitivities of each device to voltage and the resistive state ratio of the devices affecting the precise distribution of voltage within the divider. M2 is slightly more sensitive to voltage than M1, as shown in Figure 3A while at the same time it operates at a higher resistive state than M1 and hence should capture more of the voltage applied across the RRAM fuse provided the IV curves of the devices involved, but the effects are always the same: (a) the balance of voltage distribution between the two devices in the divider shifts from one device to the other, and (b) eventually, M2 will saturate at its operational resistive state ceiling (“reset” process) and M1 will saturate at its resistive state floor (“set” process) therefore stabilising the RRAM fuse at a relatively high resistive state, similar to the HRS state in the traditional, binary CRS.

We begin by noting that pulsing the RRAM fuse at $V_b$ will always cause M1 and M2 to experience an decrease/increase in their resistive states respectively and hence their potential divider voltage ($V_d$) increases with each applied pulse, as marked in Figure 3C. Notably, the precise trajectory of $V_d$ will depend on both the shape of the switching plot and the precise shape of the $I-V$ curves of the devices involved, but the effects are always the same: (a) the balance of voltage distribution between the two devices in the divider shifts from one device to the other, and (b) eventually, M2 will saturate at its operational resistive state ceiling (“reset” process) and M1 will saturate at its resistive state floor (“set” process) therefore stabilising the RRAM fuse at a relatively high resistive state, similar to the HRS state in the traditional, binary CRS.

Furthermore, we observe that the pulse voltage amplitude has been set in such way that the switching load lines form a “bottleneck,” that is, a region in the divider voltage space whereby both devices experience relatively small changes in resistive state. For appropriate initial values of $V_x$ (as in example of Figure 3C), the net effect is that during the early stages of pulsing at constant amplitude $V_b$ the RRAM fuse will experience a drop in overall resistance driven by M1 while in later stages, it will experience a rise in overall resistance driven by M2. This intermediate stage where the fuse features relatively low resistive state is similar to the traditional CRS LRS where both devices in the complementary switch are at their resistive state floors. RRAM fuse operation is similar when the polarity of $V_b$ is reversed. We have thus created a simple, analogue circuit component that encodes the accumulation of many same polarity pulsing events as an HRS while reacting to unexpected, antipolar pulsing events by dropping its resistive state, as shown in Figure 2E.

### 3 EXPERIMENTAL RESULTS

The mismatch in the voltage sensitivity of the two devices in the RRAM fuse has a further implication: if the fuse is operated at lower voltages, it might be possible to exert an influence on the resistive state of M2 only while leaving M1 largely unaffected. Experimental results in Figure 5 show that this is indeed the case. The RRAM fuse sets and resets in a completely bipolar fashion (opposite polarity has opposite effect on resistive state) fully consistent with the voltage sensitivity plot for M2, although at higher voltages in comparison to solo operation of M2. Whether this isolation of M2

| Parameter                  | M1  | M2  | Units |
|----------------------------|-----|-----|-------|
| $V_{th^+}$                 | 1.07| 0.71| V     |
| $V_{th^-}$                 | −0.52| −0.45| V     |
| $a_+$                      | 235.2 | 439.4 | Ω/V^2 |
| $a_-$                      | −91.8 | −298.2 | Ω/V^2 |
| Base resistive state       | ≈3.3| ≈4.5| kΩ    |
| Resistive state range      | 3.0–3.6 | 4.1–4.9 | kΩ    |
can be achieved throughout the entire resistive state range of M1 and if so under what specific biasing circumstances requires further, dedicated study. The ability to selectively exert control on only one of the two devices in the RRAM fuse may allow access to far more flexible modes of fuse operation, for example, opportunities to set fuse resistive state to an “ultra-HRS” level where both constituent RRAM devices at their operational resistive state ceilings, a situation normally inaccessible in the traditional CRS topology. The precise interrelation between operating voltages and RRAM fuse operating regimes is a complex topic that merits further, dedicated study.

4 | DISCUSSION

In this work, we used a simplified description of RRAM operation in Section 2 in order to offer a basic, concept-level explanation of the observed fuse ensemble functionality. However, practical RRAM devices typically exhibit rich dynamics far beyond what our “well-behaved” switching plots can capture. Let us review our assumptions and consider the implications when they no longer hold:
“The switching plot can be modelled by a monotonic function of bias voltage”: in practice, it has been observed that devices can exhibit nonmonotonic switching plots like the example in Serb et al.32 (fig. 4(b2)) where the switching plot exhibits a curvature reminiscent of \( f(x) = a \cdot x^3 \). Such switching characteristics would imply that the switching load lines in Figure 3C might cross for appropriately selected bias voltages and thus automatically define fixed points that the RRAM fuse could be forced to converge to (attractors) if initialized within the corresponding basin of attraction (Figure 6A). Nevertheless, so long as the RRAM fuse constituent devices are operated at a voltage where the switching load lines do not cross, the fundamental behaviors seen in Section 3 are in principle preserved.

“The switching function is independent of running resistive state”: in practice, this dependence can be very complex, but in the simple case where running resistive state influences switchability in an approximately multiplicative way, we can describe the effect through a window function which “stretches” the switching function (and therefore also the switching load lines from Figure 3B) in the \( y \)-direction (Figure 6B). In that situation, the precise opening of the bottleneck region will continuously change during operation as the devices change their resistive states, but the qualitative behavior from Section 3 will still be preserved so long as the bottleneck does not completely disappear (i.e., switching load lines do not cross). The precise effects of this complexity require further, dedicated study.

“RRAM device \( I-V \) is linear”: nonlinearities and asymmetries in the \( I-V \) characteristics of the RRAM devices will affect the precise distribution of voltage between the two halves of the RRAM fuse (Figure 6C). This breaks any direct link between measured individual RRAM resistive state (carried out at a standard read-out voltage) and actual potential divider voltage under fuse pulse stimulation conditions. For the same reason, the resistive state of the entire fuse acting as a single component is different to the sum of the as-measured individual RRAM component resistive states. However, so long as a change in “as measured” \( R(M_1)/R(M_2) \) ratio translates into a shift of the potential divider voltage in the expected direction, the qualitative behavior of the RRAM fuse will be preserved. The precise conditions under which this shall occur are a subject of further study.

**FIGURE 6** Understanding the complexity of the RRAM fuse behavior. (A) If switching functions are not monotonic in \( V_x \), then the fuse can potentially react to stimuli of appropriate amplitude \( V_b \) by converging their resistive states towards/away from specific attractors/repellers. (B) The dependence of switching voltage sensitivity to the running resistive state of each constituent device of the fuse implies that as the fuse changes state the switching load line and consequently the shape of the “bottleneck” area is constantly being reshaped. (C) Nonlinearities and asymmetries in device \( I-V \) render predicting the constantly shifting divider voltage \( V_x \) for given bias voltage \( V_b \) in operando and consequently the precise degree of switching difficult [Colour figure can be viewed at wileyonlinelibrary.com]
The RRAM fuse’s intrinsic properties hint towards some interesting applications: the observed relationship between dip and recovery indicates an inherent ability of the fuse to respond quickly and strongly when a series of many pulses of the same polarity is suddenly interrupted by stimuli of the opposite polarity, that is, to detect sudden changes in input signal polarity regardless of the actual polarities of all stimuli involved. This opens up the possibility for the application of the RRAM fuse as a rudimentary, single-component step detection element for bio-inspired computation. When operated in such manner, long series of the same polarity events in the input data stream will be encoded into high fuse resistive state values while the arrival of even relatively small numbers of “novel” signals will appear as substantial drops in fuse resistive state. In biological terms, the RRAM fuse will therefore act as a “direction of change-independent” variation of the classical adaptable neuron. Notably, higher level applications exploiting this behavior have already been proposed where RRAM devices are connected in square or hexagonal pixel grids, that is, connectivity patterns similar to those observed in the outer plexiform layer of the retina, for the purpose of image edge detection.

5 | SUMMARY

Overall, in this work, we have (a) presented an analogue generalization of the well-known CRS concept, (b) provided a simple and intuitive link between basic device characteristics and expected RRAM fuse operation, (c) showed experimental evidence of fuse behavior in metal-oxide device pair ensembles, and (d) made some important observations regarding the expected influence of three key RRAM device properties on the precise fuse characteristics (voltage sensitivity of switching, resistive state-dependence of switching and $I-V$ nonlinearity). We have also concluded that while they will undoubtedly affect behavior quantitatively, the qualitative aspects of fuse behavior are expected to be conserved so long as a few simple but fundamental assumptions hold. Our discussion highlighted the emergence of a wealth of complexities as the traditional, binary CRS is generalized to a RRAM fuse, complexities that must either be mitigated to allow good single-component step detector operation or engineered to allow the RRAM fuse to fulfill entirely different functions in a single component (both currently under investigation). Finally, we have offered a glimpse into how the inherent properties of the proposed RRAM fuse may allow it to find interesting applications, exemplifying its ability to act as a simple, two-terminal, single-component step detector.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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