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## Bimodal alteration of cognitive accuracy for spintronic artificial neural networks

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Spintronics-based artificial neural networks (ANNs) exhibiting nonvolatile, fast, and energy-efficient computing capabilities are promising neuromorphic hardware for performing complex cognitive tasks of artificial intelligence and machine learning. Early experimental efforts focused on multistate device concepts to enhance synaptic weight precisions, albeit compromising on cognitive accuracy due to their low magnetoresistance. Here, we propose a hybrid approach based on the tuning of tunnel magnetoresistance (TMR) and the number of states in the compound magnetic tunnel junctions (MTJs) to improve the cognitive performance of an all-spin ANN. A TMR variation of 33–78% is controlled by the free layer (FL) thickness wedge (1.6–2.6 nm) across the wafer. Meanwhile, the number of resistance states in the compound MTJ is manipulated by varying the number of constituent MTJ cells ( $n = 1-3$ ), generating  $n + 1$  states with a TMR difference between consecutive states of at least 21%. Using MNIST handwritten digit and fashion object databases, the test accuracy of the compound MTJ ANN is observed to increase with the number of intermediate states for a fixed FL thickness or TMR. Meanwhile, the test accuracy for a 1-cell MTJ increases linearly by 8.3% and 7.4% for handwritten digits and fashion objects, respectively, with increasing TMR. Interestingly, a multifarious TMR dependence of test accuracy is observed with the increasing synaptic complexity in the 2- and 3-cell MTJs. By leveraging on the bimodal tuning of multilevel and TMR, we establish viable paths for enhancing the cognitive performance of spintronic ANN for in-memory and neuromorphic computing.

### New concepts

Achieving high cognitive accuracy in digit recognition and pattern detection tasks is a compelling attribute for high-performance spintronics-based artificial neural networks (ANNs). While earlier experimental efforts focused on developing multistate devices to mimic spin synapses of variable synaptic weights, such device concepts are mainly based on domain wall motion and vertically stacked MTJ which suffer from low magnetoresistance readout, and hence, poor synaptic resolution and higher recognition errors. Meanwhile, improvement in recognition accuracy through magnetoresistance modulation is posited in simulation, yet plausible experimental approaches are starkly absent. In this work, we introduce a novel bimodal experimental route to improve cognitive accuracy by tuning the number of states and tunneling magnetoresistance of the ANN constructed over a CMOS-compatible design of compound spin-orbit torque magnetic tunnel junctions (SOT-MTJs). This is achieved by the concomitant implementation of a network of multiple SOT-MTJ on a shared write channel and a free layer thickness wedge. Remarkably, we show 3-cell compound MTJ with TMR between states, which is 7-fold higher than reported state-of-the-art, and enhanced recognition accuracies when coupled with optimal free layer thickness. Our bimodal design provides a path to realize enhanced cognitive performance in spintronics ANN for in-memory and neuromorphic computing.

## A. Introduction

Neuromorphic computing, based on the brain-inspired framework of hosting massive interconnected artificial neurons and

synapses as memory and processing units, can overcome the inevitable limitations of Von-Neuman architectures in performing computationally intensive tasks for artificial intelligence and big data.<sup>1-4</sup> Nonvolatile neuromorphic concepts built upon resistive,<sup>5,6</sup> phase change,<sup>7</sup> and ferroelectric<sup>8,9</sup> memristors typically require high energy (0.1–10 pJ) and long write time (10–100 ns) for switching, and display average endurance ( $10^6$ – $10^{12}$  cycles) for practical and efficient computing applications.<sup>1</sup> On the other hand, spin-based neuromorphic hardware utilizing the spin-orbit torque (SOT) mechanism for electrical switching is expected to offer energy efficiency ( $\sim 0.1$  pJ), fast write ( $< 10$  ns) and read time (30 ns), and high endurance ( $10^{15}$  cycles), enabling scalable sustainable computing.<sup>10</sup> In this light, the commercialized industry-compatible SOT-magnetic tunnel junctions (MTJs) – consisting of an insulating barrier sandwiched between the heavy metal/ferromagnetic free (FL) and reference layers, are the ideal

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building block for neurons and synapses, wherein the latter is mimicked by a multistate MTJ.<sup>11</sup>

The functional performance of such spintronic neuromorphic devices is benchmarked to vital parameters such as their learning and testing accuracies in performing cognitive tasks of digit recognition and pattern detection.<sup>11,12</sup> Numerous concepts have been proposed for accuracy improvements, including (i) the reduction of device energy barrier in enabling faster fluctuation speed for improved probabilistic behavior,<sup>13,14</sup> (ii) the enhancement of magnetoresistance values to amplify the distinction between synaptic states,<sup>15</sup> and (iii) the increase in the number of conductance states<sup>16–20</sup> to strengthen synaptic weight precision. The first option of reducing the switching energy barrier introduces undesirable thermal instability and device reliability issues, as well as a higher recognition error rate due to its sensitivity to structural defects and process-related size variation.<sup>21</sup> Notably, clubbing multistate synapses with a magnetoresistance-enhancing mechanism will be a promising means of concomitantly elevating the synaptic precision and resolution of artificial synapses for cognitive tasks. Yet, experimental efforts have largely been restricted to singly tuning the multistate functionality of synaptic devices built upon domain wall motion,<sup>22–24</sup> and vertically stacked MTJ,<sup>17–19</sup> albeit with low multistate magnetoresistance readout between two consecutive resistance states of <3%. Meanwhile, the notion of magnetoresistance modulation for enhanced accuracies is limited to simulations, without proposals of feasible routes for practical implementation. In this light, it is compelling to establish practical approaches to modulate the synaptic precision and resolution and elucidate their interplaying effects on the synaptic performance.

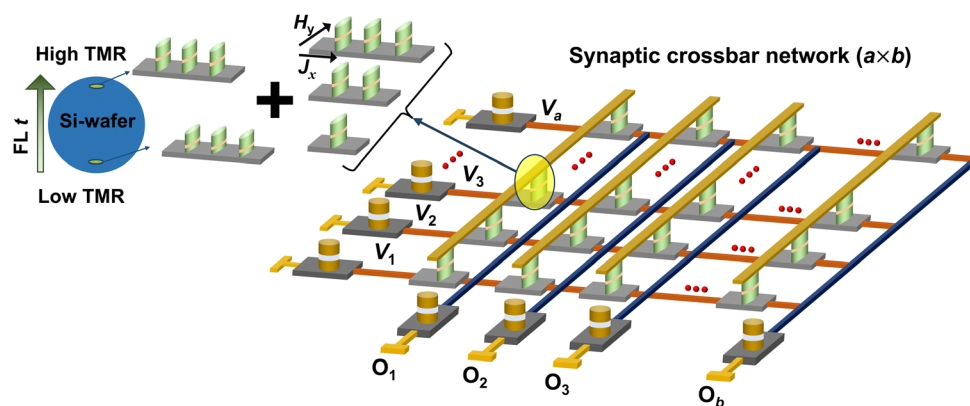
In this work, we adopt a bimodal approach of tuning multistate and magnetoresistance, by introducing compound MTJ with a varying number of SOT-MTJ cells ( $n = 1–3$ ) and free layer thickness wedge of 1.6–2.6 nm, to modulate the digit and object

recognition performance of our spintronic artificial neural network (ANN) (Fig. 1). We show that the CMOS-compatible compound MTJ design will enable thermally stable and well-distinguished multistate with large tunneling magnetoresistance (TMR) ratio between states. Further, the variation in the FL thickness enables more than 2-fold enhancement in TMR. By varying the number of states and TMR, we demonstrate enhanced test accuracies of the compound MTJ-based ANN in performing MNIST handwritten digit and fashion object recognition tasks. These results underscore that a high TMR multistate synapse is a feasible solution for enhanced performance of spin-based ANN in executing cognitive tasks.

## B. ANN design and measurement setup

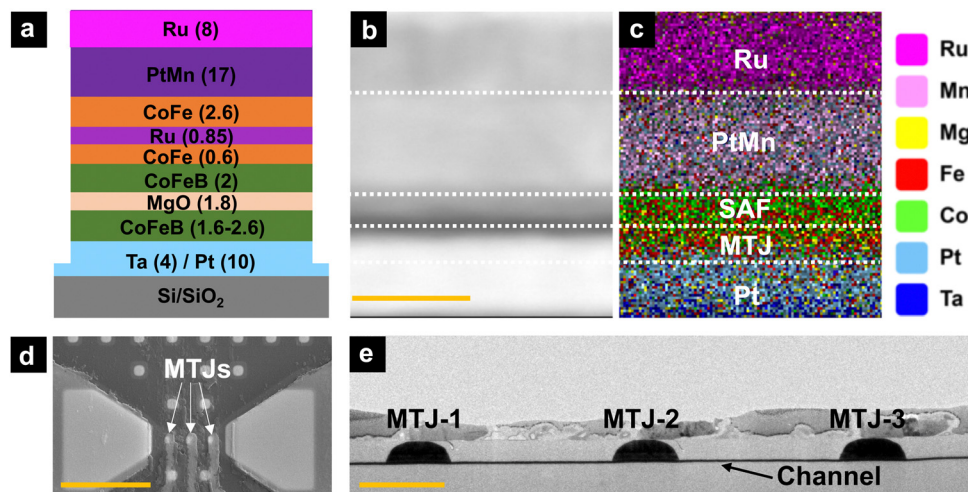
The ANN consists of interconnected synapses in a crossbar fashion with multiple presynaptic input and postsynaptic output neurons (Fig. 1). The input voltages ( $V_1, V_2, \dots, V_a$ ) are applied along the horizontal line, while the output voltages ( $O_1, O_2, \dots, O_b$ ) collected along the vertical line of the crossbar will be fed as input current spike to the postsynaptic output neurons. The intersection of the row and column of the ANN represents the bit cell, and the conductance states of these cells encode the corresponding synaptic weight ( $w$ ). The output of each postsynaptic neuron follows the vector-matrix multiplication stated as:  $O_i = \sum w_i V_i$ .<sup>4</sup>

These bit cells are represented by the multistate compound MTJ. Each constituent MTJ on the compound MTJ comprises a MgO tunnel barrier sandwiched by the bottom CoFeB free layer of varying thickness (1.6–2.6 nm) and top-pinned CoFeB reference layer (Fig. 2a, See Methods). The cross-sectional scanning transmission electron microscopy (STEM) images with



**Fig. 1** Spin-based artificial neural network (ANN). The spin-orbit torque magnetic tunnel junction (SOT-MTJ)-based crossbar array of artificial synapses connecting the two layers of neurons (input:  $a$ , output:  $b$ ). An experimental bimodal approach of tuning free layer (FL) thickness ( $t$ ) and the number of MTJ cells (circled, left inset) is utilized to improve the ANN cognitive performance. The FL thickness is controlled by the wedge ( $t$ : 1.6–2.6 nm) along the whole wafer, while  $t$  is uniform for all constituent MTJs across the compound MTJ. The synapses can be implemented using the compound SOT-MTJ device concept which incorporates 1, 2, and 3-cell MTJs without altering the prevailing crossbar architecture. The elliptical MTJ has a shape anisotropy (long axis) along the  $y$ -axis. The current is applied longitudinally through the SOT channel *i.e.*, along the  $x$ -axis direction while the assisted field is applied along the  $y$ -axis.





**Fig. 2** Structural characterization of MTJs. (a) Schematic of the multilayer stack structure of the fabricated MTJs (thickness of layers are in nm in parentheses). (b) Cross-sectional scanning transmission electron microscopy (STEM) image of the multilayer stack structure (scale bar: 20 nm), and (c) corresponding energy-dispersive X-ray composition mapping. (d) Top view scanning electron microscopy (scale bar: 5 μm) and (e) cross-section TEM images (scale bar: 500 nm) of the compound device showing 3 MTJs on a shared SOT channel.

elemental mapping show the distinct layers of the MTJ (Fig. 2b and c). The plan view scanning electron microscopy imaging and cross-sectional TEM images of the compound MTJ show three elliptical MTJs of size  $250 \times 500 \text{ nm}^2$  and spaced  $1.2 \mu\text{m}$  apart on a shared Pt/Ta write channel of  $0.9 \times (0.9\text{--}3.25) \mu\text{m}^2$  (Fig. 2d and e). The spin orientations of the in-plane anisotropy CoFeB layers are aligned along the long axis of the elliptical MTJs, which correspond to the easy axis due to shape anisotropy, while the top RL is additionally pinned to a fixed orientation by the synthetic antiferromagnet layer. A current injected into the heavy metal Pt/Ta channel will generate a spin current at the Pt/CoFeB FL interface due to the spin Hall effect, inducing magnetization switching of the FL at a sufficiently large current density.<sup>25,26</sup> An external magnetic field,  $H$ , is applied along with the SOT current to assist the FL switching in a preferable direction.

The resistance dependence of the applied field,  $R(H)$ , was acquired by sweeping a magnetic field ( $\pm 20 \text{ mT}$ ) along the easy axis of the MTJs and measuring the output voltage through a reference resistor ( $1 \text{ M}\Omega$ ) connected in series with the device under test. To examine the collective resistance dependence of applied voltage,  $R(V)$ , the voltage pulses (amplitude:  $0.1\text{--}2 \text{ V}$ , width:  $200 \text{ ns}$ , and delay time:  $1.5 \text{ s}$ ) are first applied across the write channel of the wire-bonded compound MTJ in the presence of an assisted  $H$  ( $\pm 6\text{--}10 \text{ mT}$ ), followed by a readout of the compound MTJ resistance by injecting a small reading voltage of  $\sim 0.1 \text{ V}$  across the MTJ.

### C. Free layer thickness variation

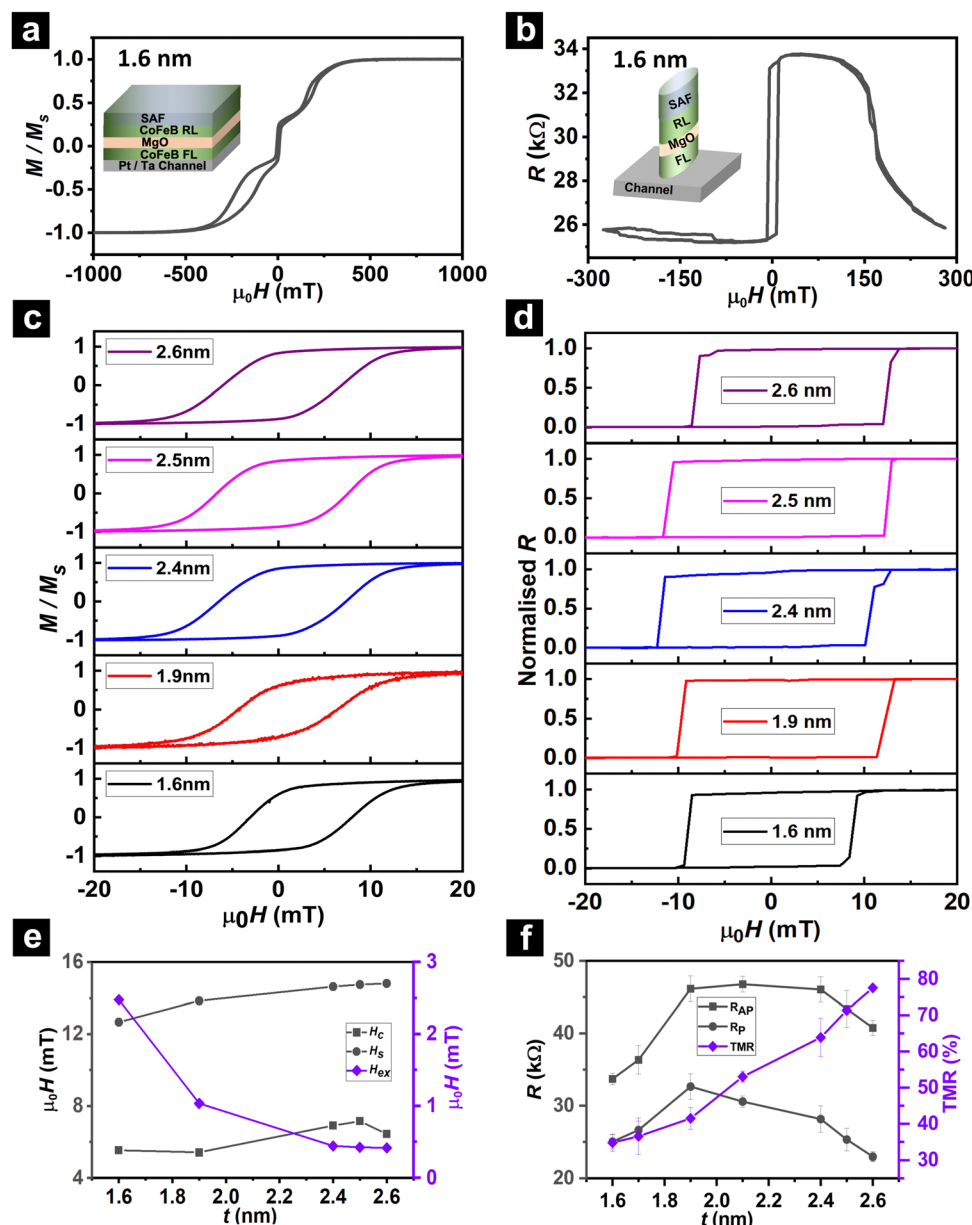
First, we examine the FL thickness dependence of magnetic and transport properties of the MTJ material stack and 1-cell devices. The major  $M(H)$  hysteresis loop of the MTJ film consisting of  $1.6 \text{ nm}$ -thick FL shows a defined step between

the FL ( $\sim \pm 5 \text{ mT}$ ) and RL switching, indicating well-decoupled switching of FL independent of RL (Fig. 3a). Meanwhile, the major  $R(H)$  loop (Fig. 3b) of the corresponding device depicts a parallel (P) aligned RL and FL at large applied  $H$  of  $+300 \text{ mT}$ . With a reduction in applied  $H$  to  $+90 \text{ mT}$ , the exchange coupling between the SAF and RL dominates over the Zeeman energy of the external magnetic field, resulting in the rotation of the RL and FL to an antiparallel (AP) configuration and an increased resistance of  $33.8 \text{ k}\Omega$ . Further reduction of  $H$  to  $-10 \text{ mT}$  results in the switching of the FL, giving rise to a P configuration with a low resistance of  $25.2 \text{ k}\Omega$ . Similar major  $M(H)$  and  $R(H)$  loops are observed across all FL thicknesses with well-decoupled switching of FL and RL, albeit with coercivity,  $H_c$ , and saturation field,  $H_s$ , variations to be discussed in the following paragraph.

Fig. 3c exhibits the minor  $M(H)$  hysteresis of the multilayer stacks for FL thickness ranging from  $1.6\text{--}2.6 \text{ nm}$ . As the FL thickness increases, the  $M(H)$  hysteresis with  $+x$  offset gradually shifts towards the left, marked by the diminishing exchange bias field,  $H_{\text{ex}}$ , from  $2.5$  to  $0.4 \text{ mT}$  (Fig. 3e, violet diamond). This is due to the reduction of stray field effect on thicker FL, which originates from the lateral magnetic flux of the SAF layer and Néel coupling originated at the CFB/MgO interface.<sup>27</sup> The increase in  $H_s$  from  $12.7$  to  $14.8 \text{ mT}$  suggests that the in-plane anisotropy along the easy-axis reduces with increasing FL thickness (Fig. 3e, black circle). Further, the coercive field,  $H_c$ , is constant to  $\sim 12\%$  across varying FL thicknesses of  $1.6\text{--}2.6 \text{ nm}$  (Fig. 3e, black square), wherein the fluctuation may be ascribed to inhomogeneity, structural defects, or localized disorder in the easy axis of the MTJ.<sup>28</sup>

The minor  $R(H)$  measurements across the MTJ devices of varying FL thickness show the sharp transition from the high resistance AP to low resistance P state for the down-field sweep, and *vice versa*, corresponding to the single domain-like characteristics expected in nanoscale  $250 \times 500 \text{ nm}^2$  device





**Fig. 3** Magnetic and transport characteristics of the MTJ film and device. (a) and (b) Major (a) film-level  $M(H)$  and (b) device-level  $R(H)$  hysteresis loop for stack structure consisting of 1.6 nm-thick FL. (c) and (d) Minor (c) film-level  $M(H)$  and (d) device-level  $R(H)$  hysteresis loops for different FL thicknesses ranging from 1.6–2.6 nm. (e) and (f) The FL thickness dependence of (e) exchange field ( $H_{ex}$ ), coercive field ( $H_c$ ), saturation field ( $H_s$ ), and (f) antiparallel resistance ( $R_{AP}$ ), parallel resistance ( $R_p$ ), and tunneling magnetoresistance (TMR) extracted from the  $R(H)$  hysteresis loops measured across at least 10 devices for each free layer thickness. Solid lines in (e) and (f) are guides for the eye.

(Fig. 3d). The device-level  $H_c$  are similar ( $\sim 10$  mT  $\pm 15\%$ ) across varying FL thicknesses, while  $2\times$  larger than the film-level  $H_c$  due to confinement effect which restricts domain motion and nucleation sites in the nanoscale MTJ.<sup>29,30</sup> Due to the fabrication process variability and small uncompensated stray field from the SAF, a small positive or negative offset in the  $R(H)$  switching hysteresis is similarly observed.

Additionally, the resistances of the P (Fig. 3f, black circle) and AP (Fig. 3f, black square) states exhibit the same dome-like dependence of FL thickness, wherein the resistance increases to a plateau at intermediate FL thicknesses before decreasing at

large FL thicknesses. This multifarious trend of resistance with increasing FL thickness is ascribed to interplaying factors of FL roughness<sup>31</sup> and resistivity,<sup>32</sup> variation in the MgO thickness,<sup>33</sup> MgO/FL interface quality,<sup>34</sup> and fabrication inhomogeneity at the circumference of the wafer. Meanwhile, the thickness dependence of TMR follows a near-exponential trend, marked by a gradual TMR increase from  $\sim 33$ –40% for FL thickness  $< 1.9$  nm and a considerable surge from  $\sim 40$  to 78% for FL thickness  $> 1.9$  nm (Fig. 3f, violet diamond). The enhancement of TMR with increasing FL thickness is ascribed to the higher concentration of tunneling electrons and increase in the spin





polarization in thicker FL,<sup>35</sup> wherein the efficiency of spin filtering across the tunnel barrier remains independent of scattering effects for FL thickness up to 3 nm.

## D. SOT switching

First, we examine the SOT-induced switching of the single-cell MTJs across different FL thicknesses of 1.6 to 2.6 nm. All the MTJs switch from the AP to P state when subjected to a negative applied  $V$  at a constant negative assisted magnetic field. Conversely, the FL switches from P to AP when a positive  $V$  is applied in the presence of a constant positive assisted magnetic field. This directional dependence of SOT mechanism is indicated by the full  $R(V)$  loop of the 1-cell MTJ of 1.7 nm free layer thickness (Fig. 4b) along with its corresponding  $R(H)$  curve (Fig. 4a). Notably, the critical switching voltage ( $V_c$ ) increases from 0.7 to 2.0 V with increasing FL thickness from 1.6 to 2.6 nm (Fig. 4c). Expectedly, the dependence of critical current for SOT-induced switching on the FL thickness follows the relationship described by the macrospin model as follows:<sup>36</sup>

$$I_c = kM_s(H_{ct} + M_s t - K_s)w_{\text{HM}}t_{\text{HM}} \quad (1)$$

where  $I_c$  is the critical SOT current,  $M_s$  is the FL saturation magnetization,  $t$  is the FL thickness,  $K_s$  is the interfacial magnetic anisotropy energy density, and  $w_{\text{HM}}$  and  $t_{\text{HM}}$  represent the SOT channel width and thickness, respectively. Further, the probability of the MTJ exhibiting field-free switching decreases sizably to zero with increasing FL thickness to

2.6 nm (Fig. 4d). The discernibly larger  $V_c$  and lower field-field switching probability suggest a possible origin of larger thermal stability factor, defined as:  $E_b/k_B T$  where  $E_b$  is the energy barrier between AP and P states at temperature  $T$ ,<sup>37</sup> in the MTJs with thicker FL. Therefore, more extensive SOT driving energy is required to overcome the energy barrier for switching transition in a thicker FL.

Next, we study the SOT-induced switching of a multi-cell compound MTJ. Fig. 4e and f show the  $R(H)$  and  $R(V)$  loops for the 3-cell device comprising 1.7 nm-thick free layer, respectively. The 3-cell compound MTJ follows the resistor in-parallel relation, i.e.,  $\frac{1}{R_{\text{compound}}} = \frac{1}{R_{\text{MTJ-1}}} + \frac{1}{R_{\text{MTJ-2}}} + \frac{1}{R_{\text{MTJ-3}}}$ , and shows 4 resistance states corresponding to the switching of each constituent MTJ cell. For the same assisted magnetic field of  $-6$  mT, the  $V$  required for fully switching the 3-cell compound MTJ from their AP to P states is  $\sim 20$ – $30\%$  higher than the single cell-MTJ for the same FL thickness (Fig. 4g). In fact, a larger assisted magnetic field, e.g.  $-8.5$  mT, is required to completely switch the thicker FL, e.g. 2.6 nm, without encountering the breakdown of the MTJ device. This is ascribed to the larger voltage drop across the more resistive ( $\sim 600 \Omega$ ) longer write channel of the 3-cell MTJ, compared to the single-cell MTJ channel of lower resistance ( $\sim 300 \Omega$ ).

Meanwhile, the trend of higher switching  $V$  for the devices with thicker FL is also similarly observed for the 3-cell MTJs (Fig. 4g). On one hand, as the FL thickness increases, the improvement in the TMR involves a compromise of energy efficiency. On the other

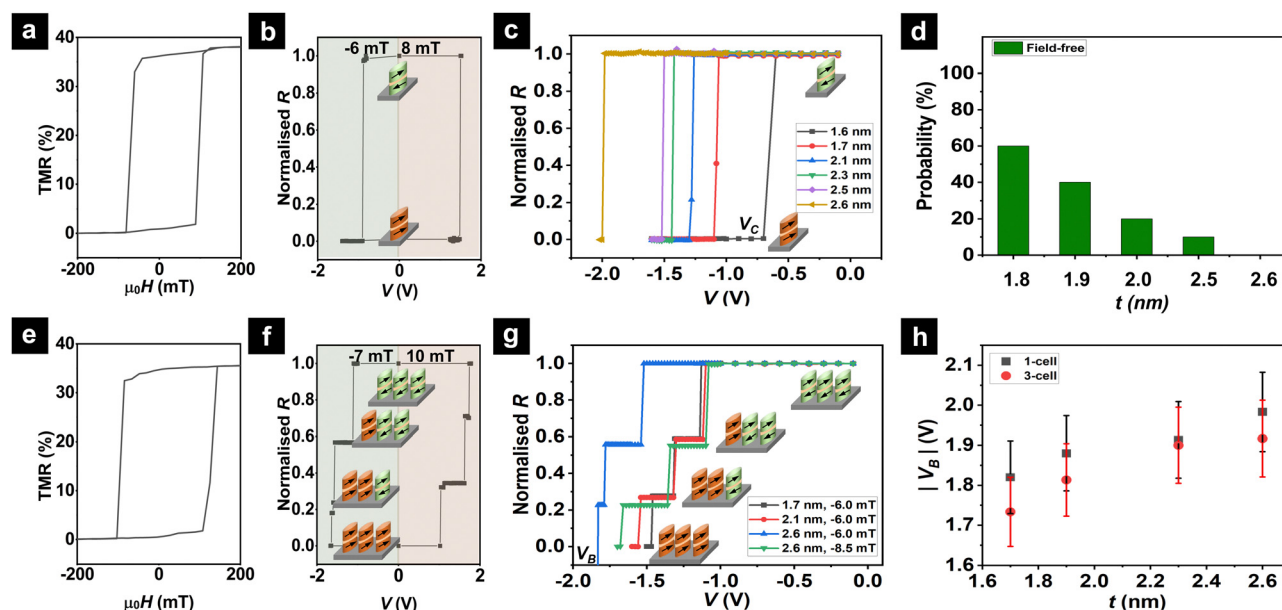
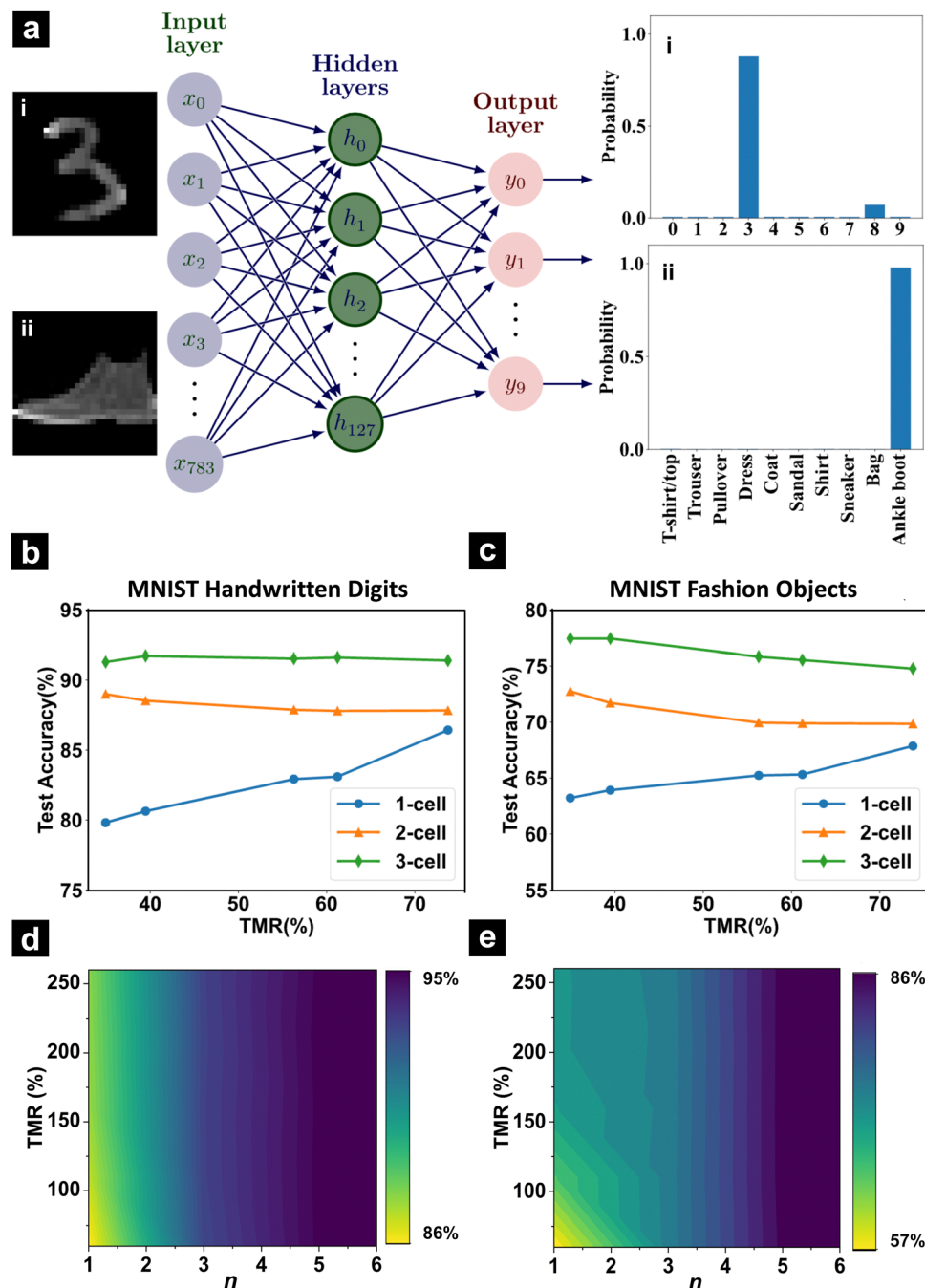


Fig. 4 Electrical manipulation of compound MTJ. (a)  $R(H)$  and (b)  $R(V)$  loop for a 1-cell device comprising 1.7 nm-thick free layer. (c) The field-free  $R(V)$  plot of the 1-cell MTJ showing increasing critical switching voltage ( $V_c$ ) for AP to P transition with increasing FL thickness. (d) Histogram plot showing the diminishing probability of field-free switching in 1-cell MTJs with increasing FL thickness. Up to 10 devices were measured for each FL thickness, of which all MTJs exhibit field-assisted switching. (e)  $R(H)$  and (f)  $R(V)$  loop for a 3-cell device comprising 1.7 nm-thick free layer. (g) The  $R(V)$  plot of the 3-cell MTJ for different FL thicknesses showing 4 resistance states in the presence of an assisted negative field of 6–8.5 mT. (h) The average breakdown voltage ( $V_B$ ) of the 1- and 3-cell MTJ for different FL thicknesses. Schematic inserts with arrows showing the free and reference layer spin orientations of each MTJ during the switching process. The MTJs in green and red represent the initial antiparallel and switched parallel configurations, respectively. The red (green) shade in (b) and (f) correspond to the P  $\rightarrow$  AP (AP  $\rightarrow$  P) transitions.



hand, the average device breakdown voltage ( $V_B$ ) window extends from 1.8–2.0 V for 1-cell and 1.7–1.9 V for 3-cell when the FL thickness increases from 1.6 to 2.6 nm, suggesting that a thicker FL can better cushion device breakdown (Fig. 4h). However, the field-free switching of the FL is largely impeded by the  $V_C > V_B$  trend observed for thicker FL, hence switching of the thicker FL

typically require an assisted field. Therefore, we posit that efforts towards the optimal performance of the MTJ-based neural network, beyond training and test accuracy, should also involve fine-tuning parameters of SOT switching efficiency and device breakdown voltage by optimizing the FL thickness, number of MTJ cells, and writing channel dimensions.



**Fig. 5** Bimodal tuning of cognitive accuracy for recognition tasks. (a) Schematic of the ANN constructed in a  $784 \times 128 \times 10$  configuration (middle) and illustrated with input examples of MNIST digits ((i), left) and fashion objects ((ii), left) and corresponding recognition probability ((i) and (ii), right). (b) and (c) The test accuracy for MNIST (b) handwritten digits and (c) fashion objects after training with 40 epochs for 1-, 2- and 3-cell MTJs. (d) and (e) 2D contour plots of the test accuracy for (d) handwritten digit and (e) fashion object recognition tasks as a function of TMR values and the number of MTJs of the synaptic device. The  $R_P$  is arbitrarily fixed at 10 k $\Omega$  while the  $R_{AP}$  is varied over the range of 16–36 k $\Omega$  to generate the TMR values of 60–260%. The test accuracies in detecting fashion objects are consistently poorer than recognizing digits for a particular number of cells and TMR.



To elucidate the interplaying effect of synaptic resolution and precision, we further model the ANNs built upon devices comprising an extended range of commercially viable TMR of 60–260% and 2–7 resistance states (Fig. 5d and e). Regardless of the TMR values, large cell numbers, *e.g.* 6-cell MTJs, produce consistently higher test accuracies for both digit and object

The MTJ multilayer stack consisting of SOT channel/FL/Tunnel barrier/RL/SAF/capping layer was fabricated on an 8-inch thermally oxidized Si-wafer using the Singulus Timaris<sup>TM</sup> DC magnetron sputtering at room temperature. Details of the multilayer stack composition and thicknesses (in nanometers) are as follows:

- (1) SOT channel: Ta (4)/Pt (10),
- (2) FL: CoFeB (1.6–2.6),
- (3) Tunnel barrier: MgO (1.8),
- (4) RL: CoFeB (2),
- (5) SAF: CoFe (0.6)/Ru (0.85)/CoFe (2.6)/PtMn (17),
- (6) Capping layer: Ru (8).

The wafer was subsequently annealed in the magnetic vacuum annealing oven at 573 K for 60 minutes in the presence of a 1 T in-plane magnetic field applied along the wedge direction. The spin Hall angle of the Pt/CoFeB layers is  $\sim 0.11$ .

### Device fabrication

The MTJ multilayer stack was patterned into three-terminal compound MTJ devices by optical lithography using Canon EX5<sup>TM</sup> stepper and Ar-ion beam etching using Oxford CAIBE<sup>TM</sup>. The device fabrication involved 5 key steps in creating the alignment mark, write channel, cell, open pad, and top electrode consisting of Ta (5)/Al (80)/Ru (5). The array of elliptical MTJs, of dimension  $250 \times 500 \text{ nm}^2$ , are patterned with their long axis along the wedge direction. For a particular FL thickness, a maximum of 18 dies can be segmented perpendicular to the wedge direction. The calculated device resistance-area lies in the range of 2.2–3.6 k $\Omega \mu\text{m}^2$  for the MTJ sizes of  $250 \times 500 \text{ nm}^2$ .

### Magnetic characterization

The multilayer thin film companion wafer, deposited along with the device wafer, was diced into  $0.4 \times 0.4 \text{ cm}^2$  samples along the wedge direction. Magnetometry measurements were performed using the Princeton<sup>TM</sup> alternating gradient magnetometer on the MTJ samples of varying thicknesses. The major and minor  $M(H)$  hysteresis loops of these diced multilayer thin film samples were obtained by performing a magnetic field sweep of  $\pm 1000$  and  $\pm 20 \text{ mT}$ , respectively, parallel to the inplane easy axis.

### Electrical measurements

The  $R(H)$  and  $R(V)$  measurements were performed using a custom-designed probe station equipped with AC lock-in (Zurich Instruments) in the presence of an assisted magnetic field (6 to 10 mT). To extract the FL thickness dependence of  $R_{\text{AP}}$ ,  $R_{\text{P}}$ , and TMR, the  $R(H)$  loops were measured on at least  $\sim 10$  devices for each free layer thickness. For  $R(V)$  measurements, a train of voltage pulses (0.1–2.0 V, 200 ns, delay time: 1.5 s) was applied across the SOT channel using the Agilent pulse function generator, and the output voltage was measured across a reference resistor (1 M $\Omega$ ) connected in series with the MTJ devices. The top electrodes of the constituent MTJ cells in the compound MTJ are connected to one another *via* wire bonding using the WESTBOND Inc., 7KFH, to obtain the collective response of the compound MTJs.

### Simulations

The performance evaluation of the spintronics-based ANN is conducted using TensorFlow,<sup>45</sup> employing the MNIST handwritten digit dataset and the fashion object dataset. Each test

sample ( $28 \times 28$  pixels) is normalized and converted into a column vector (784 pixels) to feed the input layer of the network. The sigmoid-like curve is considered for the activation function of the neuron while the network is trained with full precision weights employing the Adam optimizer,<sup>46</sup> with the loss computed using sparse categorical cross-entropy. Subsequently, post successful training with full precision weights, both positive and negative weights are quantized based on experimentally measured conductance states (normalized) of our fabricated multistate MTJ devices. The 2, 3, and 4 state devices represent the synaptic bit precision for the simulation.

### Data availability

The data that support the findings of this study are available within the article.

### Conflicts of interest

The authors declare no competing interests.

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