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Defect-engineered monolayer MoS₂ with enhanced memristive and synaptic functionality for neuromorphic computing

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Two-dimensional transition metal dichalcogenides (TMDs)-based memristors are promising candidates for realizing artificial synapses in next-generation computing. However, practical implementation faces several challenges, such as high non-linearity and asymmetry in synaptic weight updates, limited dynamic range, and cycle-to-cycle variability. Here, utilizing optimal-power argon plasma treatment, we significantly enhance the performance matrix of memristors fabricated from monolayer MoS₂. Our approach not only improves linearity and symmetry in synaptic weight updates but also increases the number of available synaptic weight updates and enhances Spike-Time Dependent Plasticity. Notably, it broadens the switching ratio by two orders, minimizes cycle-to-cycle variability, reduces non-linear factors, and achieves an energy consumption of ~30 fJ per synaptic event. Implementation of these enhancements is demonstrated through Artificial Neural Network simulations, yielding a learning accuracy of ~97% on the MNIST hand-written digits dataset. Our findings underscore the significance of defect engineering as a powerful tool in advancing the synaptic functionality of memristors.

Conventional computing, based on Von Neumann's architecture, has been the cornerstone of computing systems for several decades. This traditional computing paradigm, combined with complementary metal-oxide semiconductor (CMOS) technology, has been paramount in laying the foundation of high-performance computing and driving technological innovation across various fields. However, traditional computers encounter difficulties in processing massive amounts of data efficiently because of the physical separation between the central processing unit (CPU) and the memory unit. The constant movement of data between memory and processing units is a core issue that results in considerable latency and energy consumption, a problem commonly referred to as the Von Neumann bottleneck. In recent years, the explosive growth of data, driven by advancements in machine learning applications, artificial intelligence (AI), and various sources such as online platforms, scientific research, and the Internet of Things, has posed significant challenges for conventional computing architectures¹. The further advancement of conventional computing is also hindered by the slowing down of Moore's Law^{2,3}, which predicted the doubling of transistor counts on integrated circuits every 2 years⁴ and has been the driving force behind the exponential growth in computing. However, as transistor size approaches physical limits, sustaining the

exponential growth in computing capabilities becomes increasingly challenging^{5,6}. As a result, there is a pressing need for novel computing approaches to address the inefficiencies of conventional systems and meet the growing demands of data-intensive applications while mitigating energy consumption^{6,7}. This is where brain-inspired neuromorphic computing has gained prominence to overcome the limitations of conventional computing^{8,9}. The brain's inherent features, such as massive parallelism, in-memory computing, high integration density, and synaptic plasticity, enable it to process vast amounts of information efficiently, exhibiting remarkable abilities such as learning, recognition, decision-making, and adaptability, all while minimizing energy consumption¹⁰.

Over the years, artificial neural networks (ANNs) have been developed to overcome the Von Neumann bottleneck inherent in conventional computing architectures, leading to significant advancements in the field^{11,12}. However, challenges remain in reducing computation costs and achieving brain-like efficiency because the algorithms of ANNs and associated software are executed on conventional computers, leading to certain drawbacks. One of the main issues is the considerable power consumption of these computers when running AI applications, which far exceeds the energy efficiency of the human brain. For example, the AlphaGo system,

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which consists of 1200 CPUs and 180 image processors (GPUs), consumes several hundred thousand Watts¹³. While the human brain, with $\sim 10^{11}$ neurons and 10^{15} synapses¹⁴, consumes only 20 Watts of power, with each stimulus requiring an operation consumption of only 1–100 femto joules¹⁵. Synaptic plasticity is fundamental to the brain's computational capabilities, referring to the ability of synapses to adjust their strength based on neuronal spiking activity¹⁴, including long-term plasticity, short-term plasticity, and spike-timing-dependent plasticity (STDP), etc. In the neural system, short-term plasticity is responsible for computational functions associated with spatiotemporal information¹⁶, while long-term plasticity establishes the fundamental framework for memory and learning¹⁷, and STDP, which follows the principles of the Hebbian theory represents the learning rule and includes various forms such as asymmetric STDP, symmetric STDP, and anti-STDP^{18–20}. Emulating synaptic plasticity at the device level promises to achieve energy-efficient, higher-performance, and scalable neuromorphic computing. Different device architectures, including CMOS transistors, memristors, gate-tunable transistors, and ferroelectric transistors, have been utilized to emulate the functionality of biological synapses through electronic and optoelectronic devices.

Among these, memristors^{21–24}, initially conceptualized by Leon Chua²⁵, and later experimentally observed in HP labs, have immense potential for emulating synaptic plasticity based on their conductivity modulation from past history programming^{15,26}. These two-terminal electronic devices exhibit similar functionality to synapses and offer advantages such as excellent scalability, simple geometry, low fabrication cost, non-volatility, analog switching, low power consumption, faster switching speed, CMOS compatibility, and high integration density. Furthermore, they can be seamlessly integrated into large-scale crossbar arrays, crucial for essential vector-matrix multiplication in neuromorphic computing. A large variety of material-based memristors, including binary oxide (TiO_x ^{27–29}, SiO_x ^{30,31}, NiO_x ^{32,33}, etc.), perovskites (MAPbI_3 ^{34,35}, $(\text{C}_4\text{H}_9\text{NH}_3)_2\text{PbBr}_4$ ³⁶, MAPbBr_3 ³⁷ etc.), organic materials (organic small molecules SU-8³⁸, monochloro copper phthalocyanine (ClCuPc)³⁹, fluoropolymer⁴⁰, etc.) and 2D materials^{41–44} (graphene, hBN, 2D TMDs, etc.), have been extensively explored. Among all these, 2D TMDs emerge as exceptionally desirable materials, positioned as essential components across a broad spectrum of electronic and optoelectronic devices. This is particularly notable in the context of cutting-edge memristive and synaptic devices tailored for the advancements in Neuromorphic Computing. Due to their nearly atomic thickness and reduced screening effects, 2D TMDs offer tunable physical properties through diverse techniques, including electrostatic doping⁴⁵, defect-engineering⁴⁶, chemical intercalation⁴⁷, and strain-engineering⁴⁸. Various mechanisms, including interface electrostatic modulation, charge transfer, phase change, energy band shifts enabled by gate tunability, and defect migration, facilitate the realization of memristive behavior and synaptic plasticity in these materials. 2D TMDs-based memristors have successfully emulated crucial synapse functions, including long-term potentiation (LTP)^{32,49–51}, long-term depression (LTD)^{49–51}, and STDP^{49,51–54}. However, existing challenges persist, including non-linearity and asymmetry in synaptic weight updates, limited dynamic range, high programming current, and variability from cycle to cycle and device to device. To achieve brain-like efficiency, it is imperative to address these challenges. An ideal synaptic device should possess attributes such as a wide dynamic range, linear and symmetric synaptic weight updates, low programming current, and minimal variability both within cycles and across devices. These traits are pivotal for ensuring accurate and efficient neural network operations closely mimicking the human brain's functioning. Addressing these hurdles through physics-driven device engineering could pave the way for improved synaptic functionality.

Here, we studied the influence of on-chip Argon (Ar) plasma treatment on the memristive behavior and synaptic plasticity of chemical vapor deposition (CVD)-grown polycrystalline MoS_2 monolayer devices. Plasma treatment has arisen as a versatile method for modifying 2D materials on a large scale, providing a time-efficient and cost-effective approach^{55–57}. Ar plasma treatment has been utilized to achieve controlled atomic layer

thinning of MoS_2 flakes and induce desulfurization of MoS_2 flakes, all without the introduction of external atoms or chemical doping^{58,59–60}. Ar-plasma treatment has been used previously to improve the performance matrix, such as dynamic range and linearity of synaptic weight updates of exfoliated few-layer MoS_2 based memristor⁶¹. Here, we have shown that optimal-power Ar plasma can significantly enhance the performance matrix of CVD-grown polycrystalline monolayer MoS_2 based memristor. Our work first reveals that memristors fabricated from as-grown polycrystalline MoS_2 monolayers exhibit limitations, including a poor switching ratio (less than 10^2), non-linearity and asymmetry in synaptic weight updates, substantial cycle-to-cycle variability of switching ratio, and poor STDP behavior. Following the application of optimal-power plasma treatment, leading to a sulfur vacancy density of $\sim 3.4 \times 10^{14} \text{ cm}^{-2}$ in as-grown MoS_2 , we observed significant improvements in the performance of memristors. These improvements included a significantly expanded switching ratio (10^2 – 10^4), more linear and symmetric synaptic weight updates, a reduced non-linear factor (NLF) from 21.79 to 2.81, and enhanced STDP behavior. Furthermore, employing a three-layer ANN simulation with plasma-treated memristors shows learning accuracy of $\sim 97\%$ for recognizing hand-written MNIST digits. Our approach to enhancing resistive switching and synaptic functionality in 2D semiconductor devices opens up exciting possibilities for further research and development in the realm of synaptic devices.

Results and discussion

For the present study, polycrystalline monolayers of MoS_2 were synthesized on a SiO_2/Si substrate using the CVD technique (see Methods for details). The synthesized materials were characterized using Raman Spectroscopy, photoluminescence (PL), X-ray photoelectron spectroscopy (XPS), atomic resolution high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM), and optical microscopy. Optical micrograph and Raman spectroscopy of the as-grown polycrystalline MoS_2 monolayer are presented in Fig. 1a, b, respectively. The Raman spectrum showed two prominent peaks: the in-plane vibration mode E^{1}_{2g} at $\sim 386 \text{ cm}^{-1}$ and the out-of-plane mode A_{1g} at $\sim 404 \text{ cm}^{-1}$. In addition, a third peak at $\sim 378 \text{ cm}^{-1}$ was also observed, attributed to a disorder-induced peak⁶². The difference between the A_{1g} and E^{1}_{2g} peak positions was found to be $\sim 18.5 \text{ cm}^{-1}$, confirming the monolayer nature of the synthesized MoS_2 ⁶³. Figure 1c displays the PL with a peak observed at $\sim 1.82 \text{ eV}$ attributed to A excitons⁶⁴. Figure 1d depicts the HAADF-STEM image of MoS_2 monolayer. The image reveals that the Mo and S atoms are arranged in a hexagonal pattern, indicating the presence of a hexagonal crystal structure within the MoS_2 monolayer. Figure 1e presents the fast Fourier transform (FFT) analysis of the HAADF-STEM image. The FFT image demonstrates the hexagonal symmetry of the MoS_2 crystal, confirming the arrangement observed in Fig. 1d. Figure 1f provides additional information by indicating an inter-planar distance of 0.27 nm, corresponding to the 100 planes. Figure 1g represents the Inverse Fast Fourier Transform (IFFT) image of Fig. 1d. Figure 1h is the zoomed image of the selected area in Fig. 1g, and the inset shows the atomic model of MoS_2 . Figure 1i shows the intensity profile along the line in Fig. 1h. Additionally, XPS analysis of CVD-grown MoS_2 is detailed in Supplementary Fig. S1. We have confirmed the thickness of as-grown MoS_2 using atomic force microscopy (AFM). Supplementary Fig. S2a presents the AFM image of CVD-grown MoS_2 flake, while Supplementary Fig. S2b displays the corresponding height profile, revealing the thickness of the as-grown MoS_2 to be 0.65 nm, confirming its monolayer nature. The memristors were fabricated in a field effect geometry using the polycrystalline MoS_2 monolayer as the semiconducting channel material. Source/drain electrodes were patterned using photo-lithography, followed by Cr/Au electrode deposition through thermal vapor deposition and a subsequent lift-off process. In addition, the heavily doped Si substrate was utilized as the back gate electrode. It should be noted that we have fabricated devices on monolayer MoS_2 flakes shaped like four-point and six-point stars. Figure 1a and Supplementary Fig. S3 illustrate the various shapes of our CVD-grown MoS_2 flakes, including six-point, five-point, four-point, and three-point stars. It is well known that six-point, five-point, and

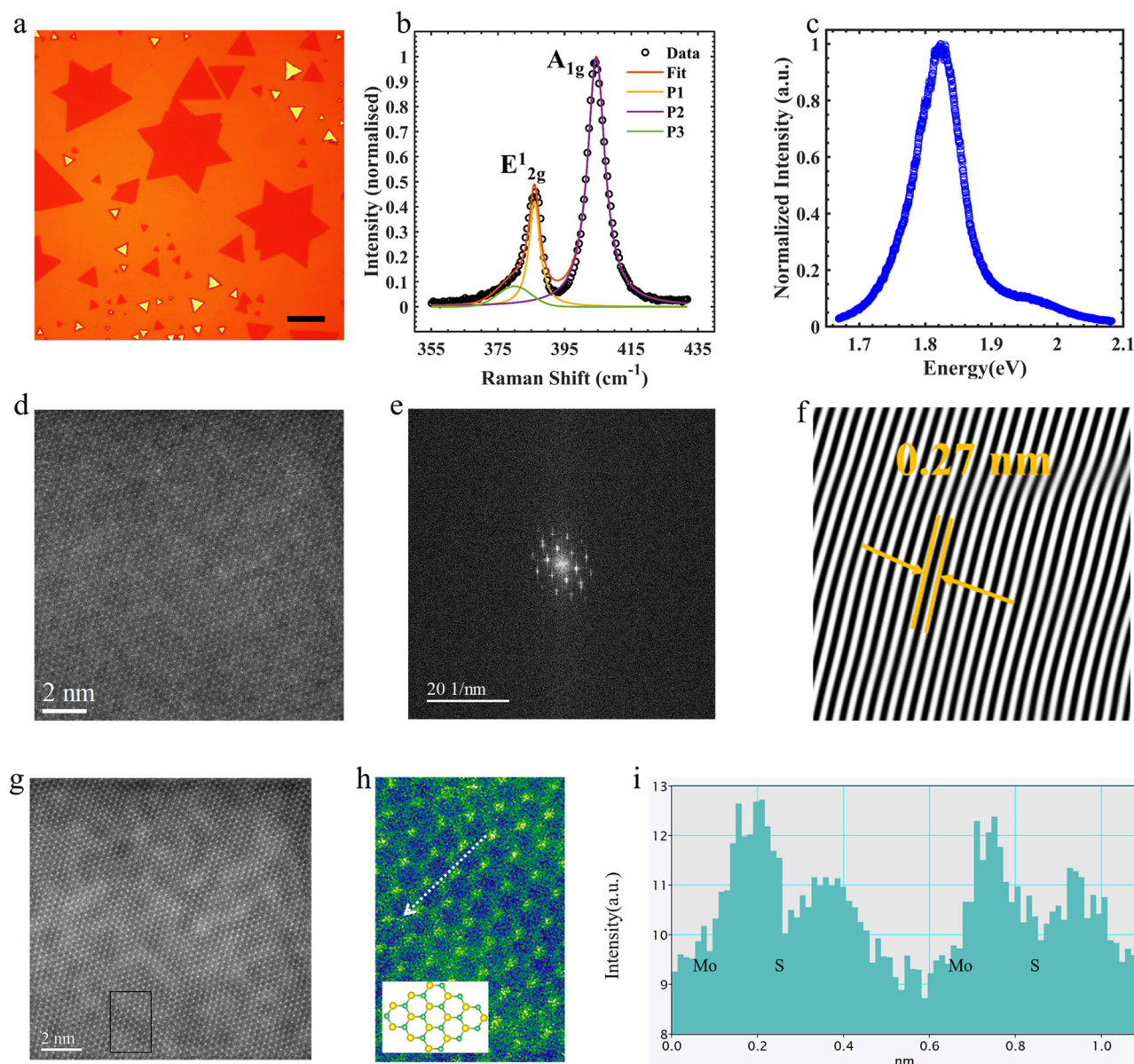


Fig. 1 | Structural characterization of CVD-grown MoS₂. **a** Optical image of CVD-grown polycrystalline MoS₂ (scale bar 20 μ m). **b** Raman and (**c**) Photoluminescence (PL) of CVD-grown MoS₂. **d** HAADF-STEM image and (**e**)

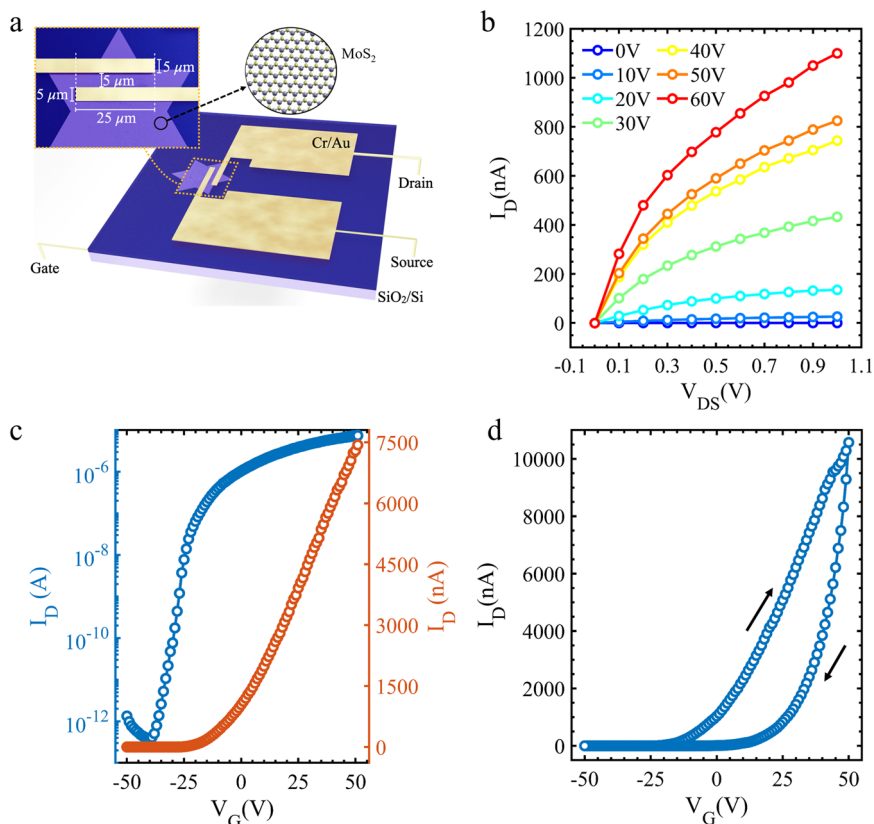
corresponding FFT pattern. **f** Interplanar spacing corresponding to 100 planes is shown. **g** IFFT of (**d**). **h** Zoomed image of selected area marked in (**g**). Inset shows the atomic model of MoS₂ (Mo: yellow, S: green). **i** Intensity profile along the line in (**h**).

four-point stars have grain boundaries (GBs)^{45,65,66}. Zheng et al. employed second harmonic generation microscopy to examine these GBs in CVD-grown MoS₂ flakes and determined that only the three-point star MoS₂ flakes are single crystals, while the other shapes are inherently polycrystalline⁶⁷. Figure 2a represent the device schematic showing the channel length 5 μ m and width 25 μ m and Supplementary Fig. S3b shows the optical image of the fabricated device. Figure 2b presents the output characteristics, i.e., the drain current (I_D) versus drain voltage (V_{DS}) for different back gate voltages (V_{GS}). It is evident that there is a good linear relationship between I_D and V_{DS} , which indicates that the field effect transistor (FET) device possesses ohmic contacts. Figure 2c displays the transfer characteristic, demonstrating the drain current (I_D) versus gate voltage (V_{GS}) in linear and logarithmic scale at $V_{DS} = 0.5$ V. It shows that the fabricated device is n-type, and the field-effect mobility is found to be ~ 16 cm²V⁻¹s⁻¹. Figure 2d exhibits the hysteresis observed in the transfer characteristics, i.e., I_D versus V_G at $V_{DS} = 0.5$ V. Several potential causes for the observed hysteresis in transfer characteristics have been identified, including electron trapping and de-trapping by adsorbed molecules on the

MoS₂ surface⁶⁸, charge trapping at the SiO₂/MoS₂ interface⁶⁹, and intrinsic defects within the MoS₂ material⁷⁰.

We first studied the switching behavior of pristine devices, as depicted in Fig. 3. Figure 3a shows the current-voltage (I - V) characteristics at 0 gate voltage. Initially, the device starts in a high resistance state (HRS) when the drain voltage (V_D) is swept from 0 to 10 V (sweep 1). As the voltage sweep progresses, the device gradually transitions to a low resistance state (LRS) and maintains this state during the sweep from 10 V back to 0 V (sweep 2). Subsequently, during the sweep from 0 V to -10 V (sweep 3), the device resets to the HRS state. Finally, the device remains in the HRS state during the sweep from -10 V to 0 V (sweep 4), the corresponding logarithmic graph is given in Supplementary Fig. S4. The observed behavior exhibits a non-linear pinched hysteresis loop in the I - V characteristics, a distinctive feature of memristive behavior^{25,26}. As shown, the hysteresis loops exhibit a counterclockwise direction in both the right and left branches. It should be noted that the MoS₂ memristor does not require an electroforming process. The underlying mechanisms of resistive switching phenomenon in lateral TMDs-based memristors are still debated, with different types of switching

Fig. 2 | Electrical characteristics of CVD-grown monolayer MoS₂. **a** Schematic of a MoS₂ memristor using a 285 nm SiO₂/Si substrate **(b)** Output characteristics (I_D versus V_D) of the device, V_G changes from 0 V to 60 V in steps of 10 V. **c** Transfer characteristics (I_D versus V_G) of the device left in logarithmic scale and right in linear scale. **d** Hysteresis in transfer characteristics, I_D versus V_G at $V_D = 0.5$ V, black arrows show the sweeping direction.



mechanisms proposed based on experimental results. One mechanism involves the dynamics of charging and discharging of trap states, which can originate from defects in the channel material, gate oxide, or semiconductor-electrode interfaces. These states can capture and release electrons or holes based on the applied voltage and, therefore, modify the electrostatic potential, free charge carrier density, and contact barriers^{71–73}. Lee et al. reported a dual-gated MoS₂ memtransistor using Al₂O₃ as the top gate and SiO₂ as the back gate, attributing the memristive loop to traps filling and emptying at the MoS₂/Al₂O₃ interface⁷⁴. Yang et al. observed memristive behavior in monocrystalline MoS₂ FETs using HfO₂ as a gate dielectric, attributing this behavior to charge trapping and de-trapping at the MoS₂/HfO₂ interface⁷⁵. When the device length is close to or shorter than 1 μm, a high drain bias increases the electric field strength, providing sufficient energy for injected carriers to overcome the channel bandgap and become trapped in the mid-gap states of Al₂O₃ or HfO₂ dielectric. In both cases, the resistive switching effects were associated with transport behaviors primarily controlled by space-charge-limited current and trap-filled limit (TFL)^{74,75}. Another mechanism involves charged point defects that are mobile enough to move when an external electric field is applied. Experiments have demonstrated that sulfur vacancies accumulate and migrate along GBs in the conducting channels of lateral monolayer MoS₂ devices, leading to changes in channel resistance and causing hysteresis in the I_D - V_D curve⁴⁵. Electrostatic force microscopy and cryogenic transport measurements revealed dynamic variations in the Schottky barrier height (SBH) in polycrystalline CVD-grown MoS₂ monolayer-based memtransistors⁴⁵. Based on these experimental results, the origin of hysteresis in the I_D - V_D curve was hypothesized that local redistribution of defects under external field, facilitated by GBs, causes the variation in the dopants density near the contact edge⁴⁵. These changes result in the dynamics variation of SBH by image-charge lowering, resulting in a pinched hysteresis loop in the I_D - V_D curve⁴⁵. Li et al. performed a systematic investigation into the switching characteristics of lateral memristors based on mechanically printed few-layer MoS₂. Their study identified two distinct DC-programmed switching modes: rectification-mediated and conductance-mediated. These modes

were associated with variations in MoS₂/Ti Schottky barriers and the redistribution of ionic vacancies within the MoS₂ channels. Their findings were supported by results from Kelvin probe force microscopy, Auger electron spectroscopy, and electronic characterization⁷⁶. While Spetzler et al. introduced a semi-classical charge transport model to study the role of defect dynamics in the switching process, the model was validated with experimental data from lateral memristive devices based on exfoliated few-layer MoS₂⁷⁶. The results based on this model the hysteresis in I - V curves is attributed to the dynamics of mobile charged vacancies which leads the formation and annihilation of a vacancy depletion region. Additionally, it has been demonstrated that the I - V curve is significantly affected by Schottky barrier lowering. However, it does not have a notable impact on the hysteresis area. This model effectively explains the I - V curve and pulse behavior, including distinct features such as different hysteresis directions, hysteresis crossing, and asymmetry observed experimentally⁷⁷. Regardless of the cause of hysteresis in MoS₂ memtransistors, this article focuses on engineering it to enhance memristive and synaptic functionality. Figure 3b shows the endurance characteristic of the MoS₂ memristor that was switched 180 times between HRS and LRS using full-sweep cycles. Notably, around the 70th cycle, we observed a sudden drop in the drain current (I_D). This phenomenon might be attributed to the release of oxide-related traps activated by the high electric field at the source electrode⁴⁵. Previous studies have linked such dip and rise patterns in endurance curves to the combined effects of gas or water molecule absorption/desorption and charge trapping and de-trapping at the semiconductor-dielectric interface⁷⁸. Considerable cycle-to-cycle variability is evident in both the HRS and LRS, and the switching ratio remains below 10^2 at $V_D = 0.5$ V. During the online training of neural networks, the utilization of devices exhibiting cycle-to-cycle variation leads to escalated training costs and significant accuracy deterioration. Because training requires a large number of writing and erasing operations, often exceeding millions of repetitions⁷⁹. Figure 3c shows the LTP-LTD characteristics of the device, which imitate the excitatory and inhibitory behavior of biological synapses. For a positive pulse (set pulse), the post-synaptic (I_D) current increases similar to the facilitation of synaptic strength

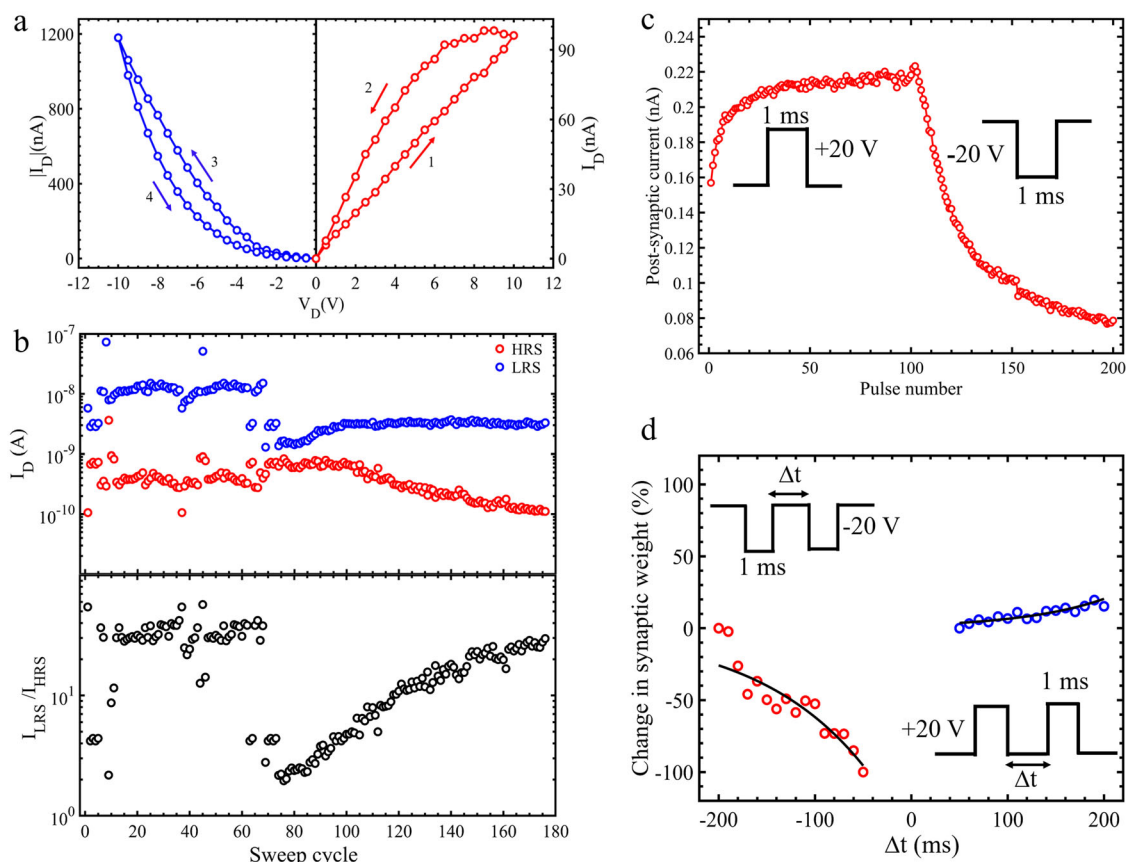


Fig. 3 | Synaptic functionality of pristine MoS₂ memristor. Switching characteristics and emulation of synaptic function in optimal-power pristine MoS₂ memristor. **a** I_D versus V_D characteristics of MoS₂ memristor at $V_G = 0$ V and scan rate 0.5 V s^{-1} **(b)** Endurance of I_{LRS} and I_{HRS} state (top) and I_{LRS}/I_{HRS} (bottom) at $V_D = 0.5$ V in the HRS (sweep 1) and the LRS (sweep 2) for 180 sweep cycles. **c** LTP and LTD characteristics, Post-Synaptic current (I_D) versus Pulse number. Here, pulses of 20 V amplitude with an on-off time of 1 ms for potentiation and pulses of

−20 V amplitude with an on-off time of 1 ms for depression have been applied, then source-drain current (I_D) was measured at read voltage (V_D) = 0.1 V. **d** The measured change in synaptic weight as a function of the time interval (Δt) between paired pulses of 20 V and −20 V, both pulses on time was 1 ms, the current was measured at each time interval after the pulse pair by applying a source-drain bias. The solid lines are exponential fits. V_G is set to 0 V for all the measurements.

of biological synapses, and for a negative pulse (reset pulse), the current decreases similar to depression of synaptic strength of the biological synapses. Here, we applied set pulses of +20 V amplitude, with an on-off time of 1 ms, reset pulses of −20 V amplitude with an on-off time of 1 ms, and measured the current after the pulses at a DC bias V_D (read voltage) of 0.1 V. Our pristine MoS₂ synaptic devices exhibited non-linearity and asymmetry in weight updates. The processes of weight increase (LTP) and weight decrease (LTD) progress differently, causing asymmetry. Initially, conductance undergoes gradual changes, but saturation takes place as the number of applied pulses increases, imposing a limit on the dynamic range and the number of attainable synaptic weight states. Dynamic range refers to the ratio of the highest to the lowest conductance in LTP-LTD characteristics. Synaptic devices with limited dynamic ranges often suffer from diminished learning accuracy in neural network applications^{80,81}. Most neuro-inspired algorithms utilize analog synaptic weight updates to learn patterns and extract features. A higher number of multilevel states (e.g., exceeding hundreds of levels) contribute to improved learning capability and enhance network robustness⁸². Linearity in weight updates signifies the linear alteration of conductance with the number of applied pulses⁸³. The non-linearity of potentiation (or depression) makes it challenging to fine-tune the conductance to the target value, resulting in poor convergence rates during training and diminished learning accuracy^{80,84}. A significant aspect of using a memristor as an artificial synapse in the latest AI technology, such as spiking neural network, is their ability to mimic STDP, which represents a temporally asymmetric manifestation of Hebbian learning, triggered by the timing correlation between spikes from pre-synaptic and post-synaptic

neurons. If the pre-synaptic spike occurs before the post-synaptic spike, the synaptic weight (or strength) increases (potentiation). Conversely, if the pre-synaptic spike occurs after the post-synaptic spike, the synaptic weight decreases (depression). The effect of correlated spiking on synaptic strength diminishes rapidly as the time interval between the spikes increases. Here, we mimicked indirect STDP (Fig. 3d) in our device by applying a pair of electrical spikes separated by a time interval Δt ^{45,85}. Specifically, a positive pair of pulses induces positive change (LTP), while a negative pair induces a negative change (LTD) in synaptic weight (conductance). We have quantified these changes by plotting the percentage change in synaptic weight, denoted as $\Delta W\%$, as a function of the time difference Δt . $\Delta W\%$ is calculated as follows

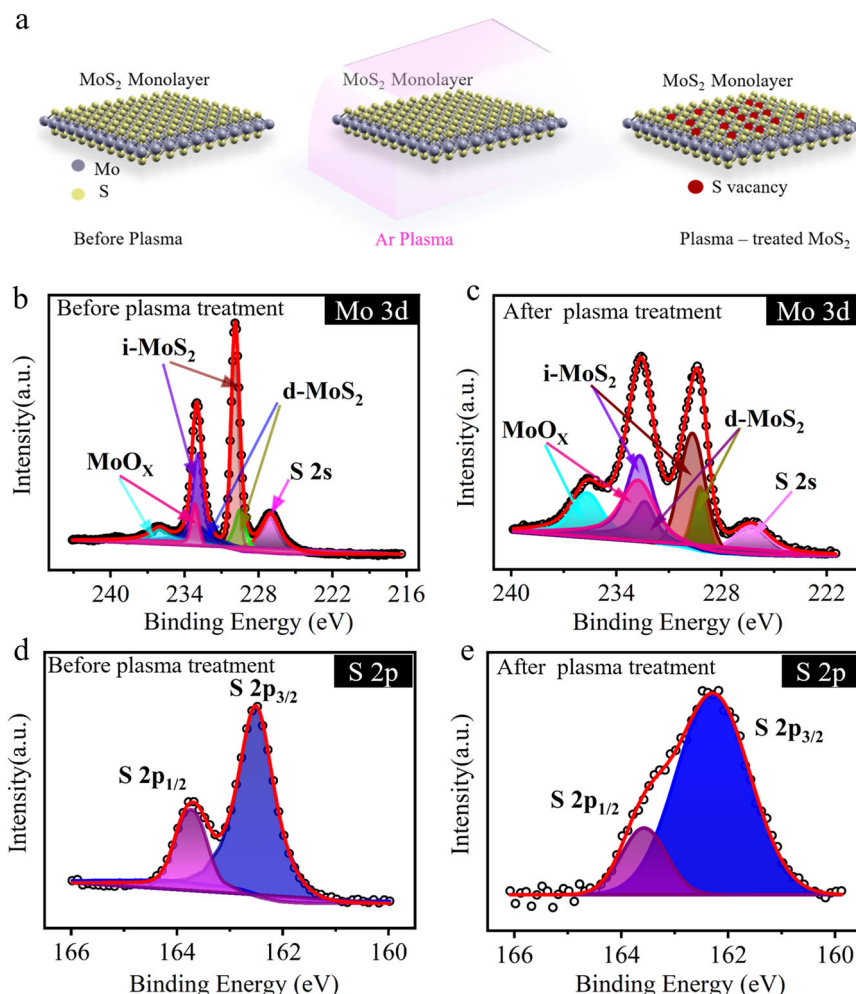
$$\Delta W\% = \frac{W_{\text{final}} - W_{\text{initial}}}{W_{\text{initial}}} \times 100 \quad (1)$$

Where W_{initial} and W_{final} are the channel conductance before applying pulses and after applying pulses, respectively. To determine the time constants for potentiation and depression, we fitted the STDP data from Fig. 3d (represented by black solid lines) using the following mathematical model⁸⁶.

$$\Delta W \propto \begin{cases} \exp\left(-\frac{\Delta t}{\tau_+}\right), & \text{if } \Delta t > 0 \\ -\exp\left(\frac{\Delta t}{\tau_-}\right), & \text{if } \Delta t < 0 \end{cases} \quad (2)$$

Fig. 4 | Defect-engineering of CVD-grown MoS₂.

a A visual representation of Ar plasma treatment. **b** XPS of Mo 3d core level of pristine MoS₂ (c) XPS of Mo 3d core level of optimal-power plasma-treated MoS₂. **d** XPS of S 2p core level of pristine MoS₂ (e) XPS of S 2p core level of optimal-power plasma-treated MoS₂.



Here, τ^+ and τ^- are the characteristic time between spikes for which there is a significant change in synaptic weight. We found these values to be 17 ms and 20 ms for potentiation and depression, respectively. Positive pulses pair show $\approx 30\%$ change in synaptic weight while negative change shows around 100%. Typically, in the emulation of brain-like STDP, synaptic weight change is more pronounced when the time interval between spikes is less. As time progresses, this change should eventually saturate. However, in pristine MoS₂, the weight change for positive spike pairs does not adhere to this pattern. Further, to address the limitations observed, such as low switching ratio, nonlinearity, and asymmetry of synaptic weight updates in the pristine device memristor, we explored a promising avenue for enhancement: on-chip optimal-power Ar plasma treatment. Determining the power of Ar plasma is crucial for creating sulfur vacancies in the MoS₂. We observed that low-power Ar plasma does not generate sulfur vacancies, while high-power can potentially damage the sample. More details are given in the Supplementary information. S atoms and Ar⁺ ions have comparable masses, and Ar⁺ ions present within the moderate power plasma generally possess sufficient energy, which is insufficient for knocking off Mo atoms and enough to remove sulfur atoms⁵⁹. Consequently, this process selectively sputters S atoms and creates sulfur vacancies, leaving Mo atoms unaffected. Figure 4a illustrates the schematic of the Ar plasma treatment process. Raman, PL, and XPS spectroscopy were performed to examine the effect of Ar Plasma at different power levels. Following low-power Ar plasma treatment, no obvious change was observed in Raman (Supplementary Fig. S5a), PL (Supplementary Fig. S5b), and XPS spectra (Supplementary Fig. S6), even after 60 s of plasma treatment. These observations conclusively confirm that low-power plasma does not induce

sulfur vacancies in the channel. However, significant changes were observed in Raman, PL, and XPS spectroscopy after optimal-power plasma treatment. Figure 4b, c show the XPS spectra of Mo 3d core level before and after optimal-power plasma treatment, respectively. The dual peaks arising from Mo⁴⁺ 3d_{3/2} and 3d_{5/2} were deconvoluted into two peaks to enhance the fitting process, employing Gaussian-Lorentzian (GL) mixing and Shirley backgrounds. Before plasma treatment (Fig. 4b), higher binding energy peaks at 229.9 and 232.8 eV signify the stoichiometric intrinsic MoS₂ (i-MoS₂), and lower binding energies peaks at 229.2 and 232.3 eV, corresponds to defective or sub-stoichiometric MoS₂ (d-MoS₂) featuring sulfur vacancies⁸⁷. Additionally, the third peak, situated below the Mo⁴⁺ 3d_{3/2} doublet at around ~ 233 eV, and the broader peak at ~ 236.0 eV, represent the Mo⁶⁺ 3d_{5/2} and 3d_{3/2} doublets of MoO₃ or sub-oxides of MoO_x, respectively. After optimal-power plasma treatment, observable modifications are apparent in the XPS spectra (Fig. 4c). The doublet peaks of Mo⁴⁺ 3d_{5/2} and 3d_{3/2} shift towards lower binding energies (Fig. 4c and Supplementary Fig. S7). The observed shift to lower binding energies in the Mo 3d peaks signifies a change in the electrostatic environment surrounding the Mo atoms. This change is a consequence of the reduction of neighboring S atoms, to which the Mo atoms were initially bonded⁸⁸. This behavior aligns with previous findings where sulfur was selectively sputtered from MoS₂^{59,88}. Also, there is a reduction in the contribution of i-MoS₂, accompanied by an increase in the contribution of defective components (d-MoS₂), confirming the introduction of more sulfur vacancies than the pristine sample⁸⁷. Additionally, the diminished integrated area of the S 2s peak relative to the Mo 3d peaks suggests a decrease in the overall sulfur content compared to the pristine sample. Figure 4d, e represent the XPS spectra of S 2s core level

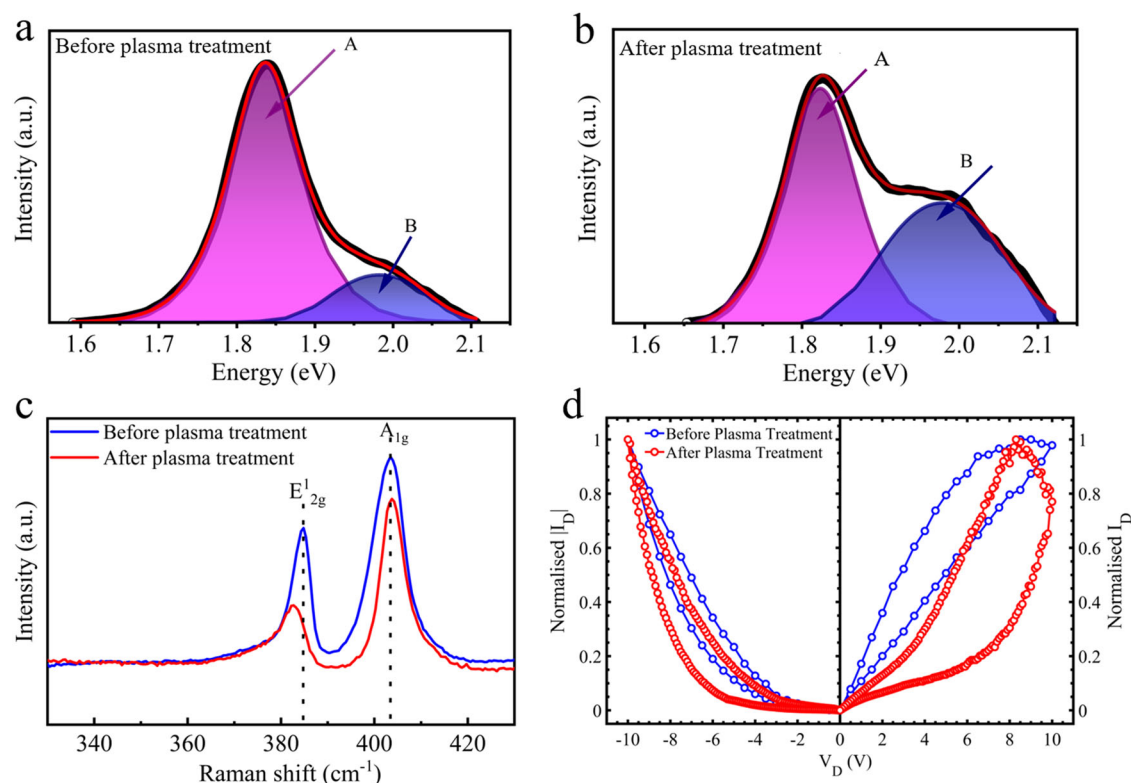


Fig. 5 | Optical and electrical characterization after plasma treatment. **a** PL spectra of pristine MoS₂ **(b)** PL spectra of optimal-power plasma treated MoS₂ **(c)** Raman spectra of MoS₂ before and after optimal-power plasma treatment **(d)** I_D - V_D

loop comparison before and after optimal-power plasma treatment at $V_G = 0$ V and scan rate 0.5 V s^{-1} .

before and after optimal-power plasma treatment, respectively. Moreover, the expanded FWHM of all peaks after plasma treatment indicates the introduction of disorder in the system⁸⁷. We also found that contribution of the MoO₃/MoO_x peak becomes larger in the plasma-treated sample, reflecting the oxidation of MoS₂ flakes⁸⁷, which is inevitable during the microfabrication process. However, Oxygen elements can not migrate into the MoS₂ channel under an external field⁶⁰. Figure 5a, b display the PL spectra before and after optimal-power plasma treatment, respectively. Both the A-exciton and B-exciton peaks were fitted with a Voigt function. The ratio of the A and B-emission intensities can qualitatively indicate non-radiative recombination; a lower B/A ratio reflects fewer defects and better sample quality⁶⁴. After optimal-power plasma treatment, the B/A ratio increases compared to the pristine sample, suggesting introducing defects in the plasma-treated sample. Additionally, Raman spectra following optimal-power plasma treatment reveal a red shift in the E_{12g} peak and a smaller blue shift in the A_{1g} peak, along with a broader full width at half maximum (FWHM) for both peaks (Fig. 5c), indicating the presence of sulfur vacancies^{60,89}. Also, Supplementary Fig. S8 shows the fitted Raman spectra after optimal-power plasma treatment, showing two defect-induced peaks at $\sim 377 \text{ cm}^{-1}$ and $\sim 411 \text{ cm}^{-1}$ ¹⁶². Supplementary Figs. S9 and S10 present the optical and HAADF-STEM images of MoS₂ following optimal-power plasma treatment. After high-power plasma treatment, no Raman and PL signals were observed, as depicted in Supplementary Fig. S11a, b. The optical image (Supplementary Fig. S12) after the high-power plasma treatment reveals a noticeable etching of MoS₂. While Supplementary Fig. S13 shows the comparison of transfer characteristics before and after optimal-power plasma treatment which reveals that optimal-power plasma does not damage the sample. Therefore, optimal-power Ar plasma was utilized to introduce sulfur vacancies deliberately. The defect concentration in both pristine and optimal-power plasma treated MoS₂ is obtained by performing stoichiometry calculations using the core level spectra of S 2s and Mo 3d.

The stoichiometry of MoS₂ is determined from the following calculations⁹⁰.

$$\frac{S(\text{at.}\%) }{Mo(\text{at.}\%)} = \frac{\left(\frac{I_{S2s}}{\sigma_{S2s}} \right)}{\left(\frac{I_{Mo3d5/2}}{\sigma_{Mo3d5/2}} \right)} \quad (3)$$

here, $S(\text{at.}\%)$ and $Mo(\text{at.}\%)$ represent the atomic per cent (at.%) of sulfur (S) and molybdenum (Mo), respectively. I_{S2s} and $I_{Mo3d5/2}$ denotes the integrated intensity of the S 2s peak and the Mo 3d_{5/2} peak, respectively. Additionally, σ_{S2s} and $\sigma_{Mo3d5/2}$ represent the photoionization cross-sections at a photon energy of 1.5 keV, modeled by Scofield, where $\sigma_{S2s} = 1.9066$ and $\sigma_{Mo3d5/2} = 7.4630$ ⁹¹. In the case of pristine MoS₂, the calculated stoichiometry is determined to be MoS_{1.98}, resulting in a defect density of 1%. In the ideal superstructure of 1H MoS₂, the sulfur-sulfur distance is 3.162 \AA ⁹², leading to a density of sulfur atoms in monolayer MoS₂ of $\sim 2.3 \times 10^{15} \text{ cm}^{-2}$. With a defect concentration of 1%, the defect density is estimated to be $\sim 2.3 \times 10^{13} \text{ cm}^{-2}$, which aligns with values reported for pristine samples⁹³. For the optimal-power plasma-treated MoS₂, stoichiometry is MoS_{1.7} with a defect concentration of $\sim 15\%$, corresponding to a sulfur vacancy density of $3.4 \times 10^{14} \text{ cm}^{-2}$.

Next, we explored the switching characteristics and synaptic plasticity of the device after optimal plasma treatment. We compared the memristive loops of the pristine device and the plasma-treated device under identical conditions, including the V_D range and sweep rate. It is important to mention that the comparison of switching characteristics and synaptic functionality was conducted on the same device before and after plasma treatment. A significant opening of hysteresis in I_D - V_D curve has been observed after the plasma treatment (Fig. 5d). We have discussed above that optimal-power Ar plasma treatment introduces more sulfur vacancies in the MoS₂ channel, which can be attributed to the pronounced opening of hysteresis in the I_D - V_D curve after the plasma treatment. The memristive

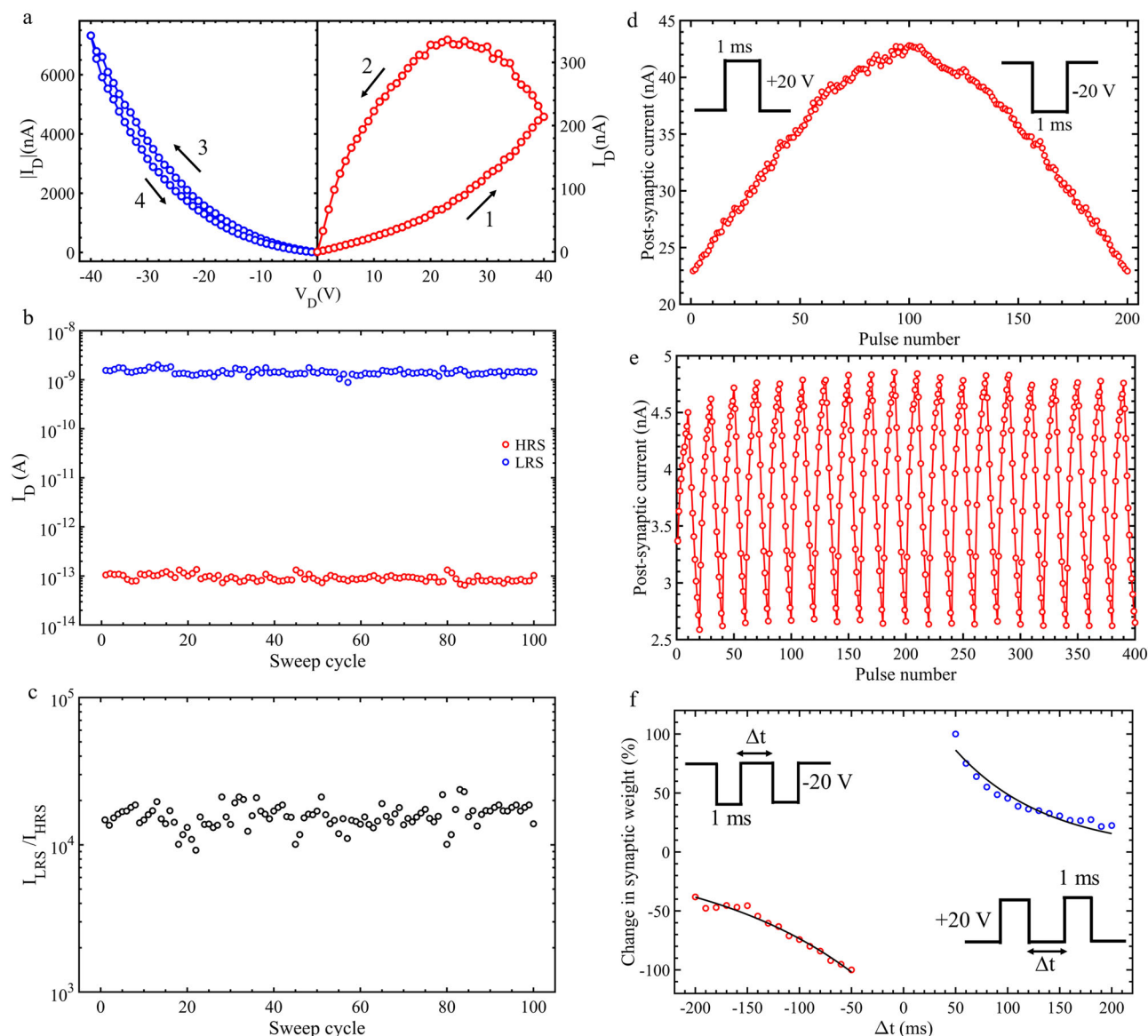


Fig. 6 | Synaptic functionality of plasma-treated MoS₂ memristor. Switching characteristics and emulation of synaptic function in optimal-power plasma-treated MoS₂ memristor. **a** I_D versus V_D characteristics of optimal-power plasma-treated MoS₂ memristor at $V_G = 0$ V, arrows show the sweep direction, scan rate was kept 2 Vs^{-1} . **b** Endurance of HRS (sweep 1) and LRS (sweep 2) state at $V_D = 0.5$ V over 100 cycles. **c** Endurance of switching ratio (I_{LRS}/I_{HRS}) $V_D = 0.5$ V over 100 cycles. **d** Post-synaptic current (I_D) versus pulse number, showing long-term potentiation and depression, set pulse amplitude was +20 V with an on-off time of 1 ms, and reset pulse amplitude was

−20 V with an on-off time of 1 ms; and current was measured at source-drain bias V_D at 0.1 V. **e** Post-synaptic current versus pulse number, set pulse amplitude was +20 V with an on-off time of 1 ms, and reset pulse amplitude was −20 V with an on-off time of 1 ms; the current was measured at source-drain bias V_D at 0.01 V for 20 switching cycles. **f** The measured change in synaptic weight as a function of the time interval (Δt) between paired pulses of 20 V and −20 V with on time 1 ms, blue data points are for positive pulse pair and red data points are for negative pulse pair and the solid lines are exponential fits. $V_G = 0$ V for all measurements.

loop shown in Fig. 6a for V_D scan ± 40 V exhibits broad hysteresis characteristics, and the corresponding logarithmic scale graph is given in Supplementary Fig. S14. Notably, Fig. 6b demonstrates a substantial enhancement in the endurance of the HRS state (sweep 1) and the LRS state (sweep 2) at 0.5 V. Following plasma treatment, a significant reduction in I_{HRS} is observed. At 0.5 V read voltage, I_{HRS} is found to be around 1 pA (Fig. 6b) after plasma treatment, while before plasma treatment, it was nearly 1 nA (Fig. 3b). If the memristor is used as a selector device, then standby power consumption is given by the following equation⁹⁴

$$P_{\text{standby}} = I_{\text{HRS}} \times V_{\text{read}} \quad (4)$$

After plasma treatment, the standby power consumption decreased significantly from ~ 0.5 nW to 0.5 pW. This reduction in off-state current

contributes to enhanced energy efficiency. Additionally, a low off-current minimizes parasitic power consumption in large crossbar arrays³¹. Moreover, the switching ratio (Fig. 6c) has been increased significantly from 10^2 to 10^4 , with minimal cycle-to-cycle variability. Figure 6d shows the LTP and LTD curves for 100 number of identical pulses. The pulse parameter and read voltage were kept the same as for the pristine devices. The observed variation in current with the number of pulses indicates a larger number of available synaptic weight states and increased dynamic range compared to the pristine device. LTP and LTD curves follow the same trajectory. Also, linearity and symmetry, the two most crucial attributes for evaluating synaptic devices, have been significantly improved. Floating gate-type synaptic devices have already been explored to enhance linearity and symmetry^{95–98}. However, these devices require the incorporation of a charged store layer and a blocking oxide, adding complexity to the

Table 1 | Comparison of different memristive devices based on MoS₂

Ref	Material (thickness, growth)	Device Geometry	Channel Length (μm)	Channel Width (μm)	Switching Ratio	Switching Voltage Range (V)
45	Monolayer MoS ₂ , CVD	planar	5	100	10 ²	±80 V
31	Monolayer MoS ₂ , CVD	planar	0.9	0.7	10 ³	±30 V
108	Monolayer MoS ₂ , CVD	planar	8.5	6	10	±20 V
76	few layer MoS ₂ , Exfoliated	planar	2	5	10	±20 V
109	multi-layer MoS ₂ , mechanically Exfoliated	Planar	NA	NA	10 ¹	−0.5 to 2 V
75	Monolayer MoS ₂ , CVD	planar	0.6	2	10 ⁵	±5 V
Our work	Monolayer MoS ₂ , CVD	planar	5	25	10 ⁴	±10 V

fabrication process, especially when aiming for large-scale array applications. While strategies such as encoding the input pulses have been proposed to address non-linearity and asymmetry, these methods often lead to added intricacy in on-chip implementation, time delay, and additional energy consumption^{99–101}. Our approach, on the other hand, achieves high linearity and symmetry using a straightforward two-terminal device and identical pulses. This implies that the device can transition to a specific state by employing a certain number of identical pulses. Subsequent application of an equal number of similar pulses with opposite polarity can restore the original state. This feature proves advantageous for neural network training. In Fig. 6e, we have presented the cycle-to-cycle variability of potentiation and depression for 20 cycles. Each of these cycles consists of a sequence of ten identical positive pulses (+20 V, 1 ms) followed by ten negative pulses (−20 V, 1 ms). The response remains consistently linear and symmetric throughout each cycle. We compared the I_D - V_D characteristics and LTP-LTD characteristics of 10 devices before and after optimal-power plasma treatment (Supplementary Figs. S15–S24). Additionally, Supplementary Figs. S25–S37 show the I_D - V_D characteristics for another 11 devices. We observed the consistent opening of the hysteresis in the I_D - V_D curve, as well as improved linearity and symmetry in the LTP-LTD characteristics, with reduced cycle-to-cycle variability compared to the pristine devices. Figure S30a presents the I_D - V_D characteristics over 80 cycles at ±10 V, and Figure S29b shows the same for 520 cycles after optimal-power plasma treatment for the same device. Figures S31a and S31b illustrate the HRS and LRS with sweep cycles at $V_D = 1$ V. It is evident that after optimal-power plasma treatment, the switching ratio increased by two orders of magnitude with less cycle to cycle variability, and the current at the HRS decreased. However, we have observed device-to-device variability, such as hysteresis area and asymmetry of hysteresis. This variability can be attributed to various factors, such as the inhomogeneity of CVD-grown flakes⁴⁵ and defects introduced during the fabrication process. Even slight variations in the Schottky barriers (>0.04 eV) can significantly alter the I - V characteristics, affecting both the area and symmetry of the hysteresis⁷⁷. To assess the energy efficiency of our synaptic transistor, it is important to consider the energy dissipation for each pulse. This energy, denoted as E , is determined by the product of three key factors: the average current during the pulse (I_D), the duration of the pulse (t_{pulse}), and the source-drain bias voltage (V_D) of the pulse. This relationship is expressed by the following equation⁵³

$$E = I_D \times t_{\text{pulse}} \times V_D \quad (5)$$

We have observed a minimum energy dissipation of ≈30 fJ per pulse, a value that aligns closely with the energy consumption per synaptic event in biological systems, which is around ≈10 fJ¹⁰². The STDP, shown in Fig. 6f, closely resembles that of biological synapses. As for less time interval, weight change is larger, and as time interval increases, weight change decreases with an exponential decay pattern, resulting in a time constant of 20 ms for the positive pair and 18 ms for the negative pair. Furthermore, the window for weight updates has been extended compared to the pristine sample. The alteration in synaptic weight is ≈100%, signifying improvement of spike

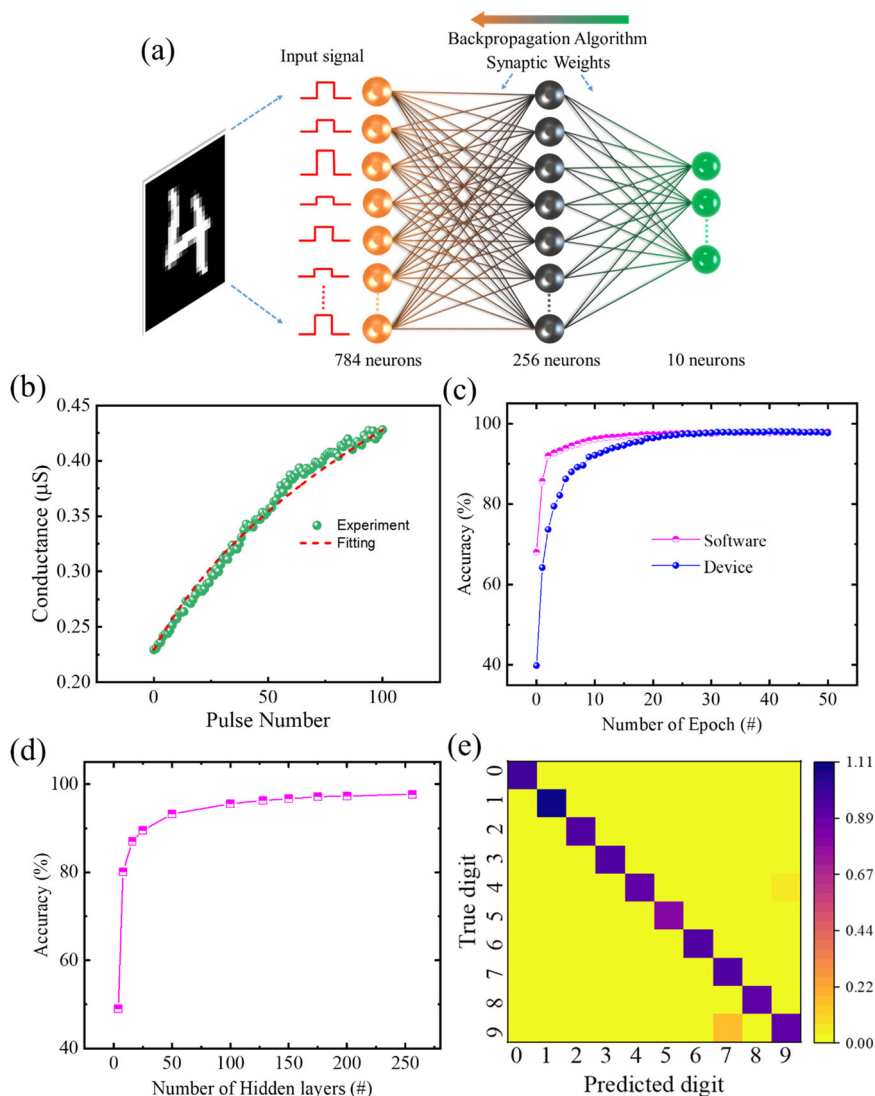
time-dependent learning. Enhanced conductance variations enable well-defined states and enhance the temporal sensitivity of the STDP behavior⁵³. Thus, a plasma-treated device shows better STDP emulation than the pristine device. Table 1 provides an overview of recent advancements in MoS₂-based memristors, comparing our work with others in terms of switching ratio and switching voltage range. While our results are competitive, future improvements could explore scaling down the channel length to achieve lower operating voltages and leveraging gate tunability for enhanced performance.

The plasma treatment provides an upper hand in realizing linear analog memory states in MoS₂-based memristors, which can further be utilized to recognize images or patterns accurately. Towards this study, finally, we demonstrate an ANN network for hand-written digit classification of Modified National Institute of Standards and Technology (MNIST) datasets¹⁰³ simulated using the open-source PyTorch package¹⁰⁴. As shown in Fig. 7a, a three-layer fully connected ANN network with 784 input, 256 hidden, and 10 output nodes is conceived in an off-chip training procedure. The input signals from the 60,000 MNIST images of 28 × 28 pixels are employed to 784 input neurons, whereas the 10 output neurons correspond to the output classes of MNIST digits ranging from 0 to 9. The normalized conductance values extracted from the LTP/LTD curves can be treated as the synaptic weights in the ANN module. The non-linear parameters from the LTP curves are extracted using the following memristive switching model,¹⁰⁵ as shown in Fig. 7b.

$$G = \begin{cases} ((G_{\text{Max}}^m - G_{\text{Min}}^m) \times \omega + G_{\text{Min}}^m)^{\frac{1}{m}}, & \text{if } m \neq 0 \\ G_{\text{Min}}^m \times \left(\frac{G_{\text{Max}}}{G_{\text{Min}}}\right)^{\omega}, & \text{if } m = 0 \end{cases} \quad (6)$$

Where G_{Max} and G_{Min} are maximum and minimum conductance in our LTP characteristics, ω is a variable and m is the non-linearity coefficient of the potentiation curve, whose value is 1 for the ideal device case. The value of m from the fitted equation for 100 pulses is extracted to be 21.79 before plasma treatment, and after plasma treatment, it has been improved to 2.81. NLF for LTD characteristics 2.79 (Supplementary Fig. S38a), indicating that LTP-LTD characteristics are highly symmetric. These coefficients, along with other parameters such as asymmetric ratio and dynamic range, play a crucial role in the high-accuracy training of such devices, as recently reported^{105–107}. To simulate the network, we use a backpropagation algorithm with cross-entropy loss as the cost function employing a nonlinear rectified linear unit activation function for the propagation of information. Figure 7c shows the recognition accuracy of the plasma-treated MoS₂ devices over 50 epochs. Interestingly, a high training accuracy of ≈97% is realized in our devices, which is also comparable to the software-based calculations. Additionally, simulations incorporating the LTD curve (Supplementary Fig. S38b) also show high training accuracy, ≈97%. This demonstrates the efficacy of the proposed devices towards the ANN implementations using future crossbar architectures. Furthermore, we have repeated the above simulations for various hidden nodes starting from 4 to 256 to study the dependence of classification accuracy of our ANN module

Fig. 7 | Demonstration of a three-layer ANN model and performance metrics. **a** Demonstration of a three-layer ANN model with 784 input, 256 hidden, and 10 output neurons using 28×28 pixel MNIST datasets as input signals. **b** The extracted non-linearity factors from the fitted potentiation curves post-plasma treatment. **c** The digit recognition training accuracy of our device compared with software values. **d** Variation of training accuracy with the increasing number of hidden neurons. **e** Confusion matrix of handwritten digits from 0 to 9 where the diagonal represents high-accuracy classification.



based on MoS_2 memristors. The variation of accuracy with the increasing number of hidden layers is represented in Fig. 7d, which is consistent with previous reports¹⁰⁵. The confusion matrix is calculated as an additional step to enhance the validation of our supervised learning process and assess our ANN model's effectiveness in distinguishing output classes, as depicted in Fig. 7e. The values along the diagonal represent the normalized predictions made by the ANN model, which correspond to the true labels found in the test data. The prominently high values along the diagonal and the correspondingly low values off the diagonal unmistakably demonstrate the strong class separation capabilities inherent in our device-based ANN implementation.

Conclusion

In summary, we have successfully introduced an experimental approach to enhance the performance matrix of CVD-grown MoS_2 memristors for neuromorphic applications. The main advantages of employing plasma treatment include its high material selectivity for sputtering material, large-scale modifications, postmetallization alteration, and a feasible technique. Plasma-treated devices substantially show improved resistive switching, endurance, and energy efficiency. These enhancements include an expanded switching ratio (from 10^2 to 10^4), significantly reduced cycle-to-cycle variability, improved STDP behavior, and linear and symmetric weight updates. NLF has been improved from 21.8 to 2.81. ANN simulations based on plasma-treated devices reveal learning accuracy of $\sim 97\%$ on the MNIST

handwritten digits dataset. Furthermore, our observations of STDP behavior suggest a promising increase in learning potential. This research significantly advances the utilization of 2D semiconductors in future neuromorphic devices.

Methods

Growth of polycrystalline monolayer MoS_2

We synthesized polycrystalline MoS_2 monolayer on $285 \text{ nm SiO}_2/\text{Si}$ substrates using the atmospheric pressure chemical vapor deposition (APCVD) technique in a single zone CVD setup. Sulfur and molybdenum trioxide (99.98% trace metal) powder, both purchased from Sigma-Aldrich, were used as precursors. The SiO_2/Si substrates underwent a 10-min bath sonication in acetone and another 10-min sonication in isopropyl alcohol. Subsequently, they were cleaned under O_2 plasma at $\sim 400 \text{ mTorr}$ for 5 min with 40 W power applied to the radio frequency coil. For the synthesis process, in a 3.5-cm-diameter quartz tube furnace, 400 mg of sulfur powder was placed in an alumina boat $\sim 18 \text{ cm}$ upstream from the MoO_3 boat (outside the furnace). The sulfur powder was heated independently using a heating belt. The substrates were placed upstream on a different alumina boat positioned on the other side of the MoO_3 boat $\sim 5 \text{ cm}$ away. The tube furnace underwent purging with ultrahigh-purity Ar gas at 400 standard cubic centimetres per minute (sccm) for 15 min, followed by a flow rate adjustment to 20 sccm. The furnace temperature was then raised to 750°C (heating rate 5°C min^{-1}), and the reaction continued for 5 min.

Simultaneously, when the furnace temperature reached $\sim 725^\circ\text{C}$, the heating belt around the sulfur boat was increased to 150°C and maintained at that temperature for 25 min. After the reaction, all the heaters were turned off, and the furnace was allowed to cool to room temperature naturally.

Material characterization

Raman and photoluminescence spectroscopy. The coverage and growth quality of polycrystalline MoS_2 was characterized using an optical microscope (Nikon LV150N). Raman and PL spectra were collected using a LabRAM HR, Horbia Jovin Yvon spectrometer with a 532 nm laser.

X-ray photoelectron spectroscopy(XPS). XPS was performed to verify the chemical composition of the CVD-grown MoS_2 films using a Thermo Scientific XPS instrument, which was equipped with a monochromatic $\text{K}\alpha$ Al X-ray line as the X-ray source. The X-ray beam had an approximate diameter of 400 μm and an energy of 1486.6 eV. To counter sample charging, all spectra underwent charge correction against the C 1s adventitious carbon peak at 284.8 eV.

High-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM). Atomic resolution high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) images were acquired with Hitachi HD2700C dedicated STEM with Cs probe corrector. Other microscopes were employed with an acceleration voltage of 200 kV.

Device fabrication and electrical measurement

MoS_2 memristor was fabricated using a standard photo-lithography method followed by thermal evaporation of metal (5 nm Cr and 50 nm Au) and lift-off in acetone. All electrical, endurance, and synaptic plasticity measurements were carried out in a home-built probe station using a Keithly 2636B dual channel source meter unit controller using LabVIEW programs at ambient conditions.

Ar plasma-treatment

The Ar plasma treatment was conducted using a Diener Zepto plasma cleaner. For low-power plasma treatment, the conditions included a pressure of 0.3 mbar, a power of 5 W, and a treatment time of 60 s. optimal-power plasma treatment was carried out with a pressure of 0.3 mbar, a power of 10 W, and a treatment time of 5 s. High-power plasma treatment was performed under the following conditions: a pressure of 0.3 mbar, a power of 20 W, and a treatment time of 5 s.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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References

- Najafabadi, M. M. et al. Deep learning applications and challenges in big data analytics. *J. Big Data* **2**, 1 (2015).
- Track, E., Forbes, N. & Strawn, G. The end of moore's law. *Comput. Sci. Eng.* **19**, 4–6 (2017).
- Kish, L. B. End of moore's law: thermal (noise) death of integration in micro and nano electronics. *Phys. Lett. A* **305**, 144–149 (2002).
- Moore, G. E. Cramming more components onto integrated circuits. *Proc. IEEE* **86**, 82–85 (1998).
- Markov, I. L. Limits on fundamental limits to computation. *Nature* **512**, 147–154 (2014).
- Shalf, J. The future of computing beyond moore's law. *Philos. Trans. A Math. Phys. Eng. Sci.* **378**, 20190061 (2020).
- Shalf, J. M. & Leland, R. Computing beyond moore's law. *Computer* **48**, 14–23 (2015).
- Roy, K., Jaiswal, A. & Panda, P. Towards spike-based machine intelligence with neuromorphic computing. *Nature* **575**, 607–617 (2019).
- Monroe, D. Neuromorphic computing gets ready for the (really) big time. *Commun. ACM* **57**, 13–15 (2014).
- Kendall, J. D. & Kumar, S. The building blocks of a brain-inspired computer. *Appl. Phys. Rev.* **7**, 011305 (2020).
- LeCun, Y., Bengio, Y. & Hinton, G. Deep learning. *Nature* **521**, 436–444 (2015).
- Krizhevsky, A., Sutskever, I. & Hinton, G. E. Imagenet classification with deep convolutional neural networks. In *Advances in Neural Information Processing Systems 25* (eds Pereira, F., Burges, C. J. C., Bottou, L. & Weinberger, K. Q.) 1097–1105. <http://papers.nips.cc/paper/4824-imagenet-classification-with-deep-convolutional-neural-networks.pdf> (Curran Associates, Inc., 2012).
- Silver, D. et al. Mastering the game of go with deep neural networks and tree search. *Nature* **529**, 484–489 (2016).
- Kandel, E. R. et al. *Principles of neural science*, Vol. 4 (McGraw-hill New York, 2000).
- Jeong, D. S., Kim, K. M., Kim, S., Choi, B. J. & Hwang, C. S. Memristors for energy-efficient new computing paradigms. *Adv. Electron. Mater.* **2**, 1600090 (2016).
- Fioravante, D. & Regehr, W. G. Short-term forms of presynaptic plasticity. *Curr. Opin. Neurobiol.* **21**, 269–274 (2011).
- Ho, V. M., Lee, J.-A. & Martin, K. C. The cell biology of synaptic plasticity. *Science* **334**, 623–628 (2011).
- Attneave, F., B., M. & Hebb, D. O. The organization of behavior: a neuropsychological theory. <https://api.semanticscholar.org/CorpusID:144400005> (1949).
- Bi, G. & Poo, M. Synaptic modification by correlated activity: Hebb's postulate revisited. *Annu. Rev. Neurosci.* **24**, 139–166 (2001).
- Wang, S., Zhang, D. W. & Zhou, P. Two-dimensional materials for synaptic electronics and neuromorphic systems. *Sci. Bull.* **64**, 1056–1066 (2019).
- Türel, z, Lee, J., Ma, X. & Likharev, K. Neuromorphic architectures for nanoelectronic circuits. *Int. J. Circuit Theory Appl.* **32**, 277 – 302 (2004).
- Wang, J. et al. Handwritten-digit recognition by hybrid convolutional neural network based on hfo2 memristive spiking-neuron. *Sci. Rep.* **8**, 12546 (2018).
- Chanthbouala, A. et al. A ferroelectric memristor. *Nat. Mater.* **11**, 860–864 (2012).
- Qian, C. et al. Artificial synapses based on in-plane gate organic electrochemical transistors. *ACS Appl. Mater. interfaces* **8**, 26169–26175 (2016).
- Chua, L. Memristor-the missing circuit element. *IEEE Trans. Circuit Theory* **18**, 507–519 (1971).
- Strukov, D. B., Snider, G. S., Stewart, D. R. & Williams, R. S. The missing memristor found. *Nature* **453**, 80–83 (2008).
- Deng, T., Ye, C., Wu, J., He, P. & Wang, H. Improved performance of ito/tio2/hfo2/pt random resistive accessory memory by nitrogen annealing treatment. *Microelectron. Reliab.* **57**, 34–38 (2016).
- Banerjee, W. et al. Variability improvement of tio2/al2o3 bilayer nonvolatile resistive switching devices by interfacial band engineering with an ultrathin al2o3 dielectric material. *ACS Omega* **2**, 6888–6895 (2017).
- Zhang, R. et al. Role of oxygen vacancies at the tio2/hfo2 interface in flexible oxide-based resistive switching memory. *Adv. Electron. Mater.* **5**, 1800833 (2019).
- Choi, B. J. et al. Electrical performance and scalability of pt dispersed sio2 nanometallic resistance switch. *Nano Lett.* **13**, 3213–3217 (2013).

31. Tsai, T. M. et al. Origin of hopping conduction in sn-doped silicon oxide rram with supercritical fluid treatment. *IEEE Electron Device Lett.* **33**, 1693–1695 (2012).
32. Li, Y. et al. Analog and digital bipolar resistive switching in solution-combustion-processed nio memristor. *ACS Appl. Mater. Interfaces* **10**, 24598–24606 (2018).
33. Le, V. Q. et al. Van der waals heteroepitaxial azo/nio/azo/muscovite (ana/muscovite) transparent flexible memristor. *Nano Energy* **56**, 322–329 (2019).
34. Yang, J. Q. et al. Leaky integrate-and-fire neurons based on perovskite memristor for spiking neural networks. *Nano Energy* **74**, 104828 (2020).
35. Xiao, Z. & Huang, J. Energy-efficient hybrid perovskite memristors and synaptic devices. *Adv. Electron. Mater.* **2**, 1600100 (2016).
36. Kumar, M. et al. Switchable two-terminal transparent optoelectronic devices based on 2d perovskite. *Adv. Electron. Mater.* **5**, 1800662 (2019).
37. John, R. A. et al. Reconfigurable halide perovskite nanocrystal memristors for neuromorphic computing. *Nat. Commun.* **13**, 2074 (2022).
38. Subramanian, A., Tiwale, N., Kisslinger, K. & Nam, C.-Y. Reduced stochastic resistive switching in organic-inorganic hybrid memristors by vapor-phase infiltration. *Adv. Electron. Mater.* **8**, 2200172 (2022).
39. Zhou, J. et al. A monochloro copper phthalocyanine memristor with high-temperature resilience for electronic synapse applications. *Adv. Mater.* **33**, 2006201 (2021).
40. Song, Y.-W., Song, M.-K., Choi, D. & Kwon, J.-Y. Encapsulation-enhanced switching stability of mos2 memristors. *J. Alloy. Compd.* **885**, 161016 (2021).
41. Liu, C. et al. Two-dimensional materials for next-generation computing technologies. *Nat. Nanotechnol.* **15**, 545–557 (2020).
42. Huh, W., Lee, D. & Lee, C.-H. Memristors based on 2d materials as an artificial synapse for neuromorphic electronics. *Adv. Mater.* **32**, 2002092 (2020).
43. Cao, G. et al. 2d material based synaptic devices for neuromorphic computing. *Adv. Funct. Mater.* **31**, 2005443 (2021).
44. Kwon, K. C., Baek, J. H., Hong, K., Kim, S. Y. & Jang, H. W. Memristive devices based on Two-Dimensional transition metal chalcogenides for neuromorphic computing. *Nanomicro Lett.* **14**, 58 (2022).
45. Sangwan, V. K. & Hersam, M. C. Electronic transport in two-dimensional materials. *Annu. Rev. Phys. Chem.* **53**, <https://doi.org/10.1146/annurev-physchem-2018> (2018).
46. Lin, Z. et al. Defect engineering of two-dimensional transition metal dichalcogenides. *2D Mater.* **3**, 022002 (2016).
47. Wan, J. et al. Tuning two-dimensional nanomaterials by intercalation: materials, properties and applications. *Chem. Soc. Rev.* **45**, 6742–6765 (2016).
48. Dai, Z., Liu, L. & Zhang, Z. Strain engineering of 2d materials: issues and opportunities at the interface. *Adv. Mater.* **31**, 1805417 (2019).
49. Sangwan, V. K. et al. Multi-terminal memtransistors from polycrystalline monolayer molybdenum disulfide. *Nature* **554**, 500–504 (2018).
50. Yan, X. et al. Robust ag/zro2/ws2/pt memristor for neuromorphic computing. *ACS Appl. Mater. Interfaces* **11**, 48029–48038 (2019).
51. Lu, X. F. et al. Exploring low power and ultrafast memristor on p-type van der waals sns. *Nano Lett.* **21**, 8800–8807 (2021).
52. Xu, R. et al. Vertical mos2 double-layer memristor with electrochemical metallization as an atomic-scale synapse with switching thresholds approaching 100 mv. *Nano Lett.* **19**, 2411–2417 (2019).
53. Paul, T., Ahmed, T., Tiwari, K. K., Thakur, C. S. & Ghosh, A. A high-performance mos2 synaptic device with floating gate engineering for neuromorphic computing. *2D Mater.* **6**, 045008 (2019).
54. Yan, X. et al. Vacancy-induced synaptic behavior in 2d ws2 nanosheet-based memristor for low-power neuromorphic computing. *Small* **15**, 1901423 (2019).
55. Nan, H., Zhou, R., Gu, X., Xiao, S. & Ostrikov, K. K. Recent advances in plasma modification of 2d transition metal dichalcogenides. *Nanoscale* **11**, 19202–19213 (2019).
56. Sovizi, S. et al. Plasma processing and treatment of 2d transition metal dichalcogenides: tuning properties and defect engineering. *Chem. Rev.* **123**, 13869–13951 (2023).
57. Jadwiszczak, J., Kelly, D. J., Guo, J., Zhou, Y. & Zhang, H. Plasma treatment of ultrathin layered semiconductors for electronic device applications. *ACS Appl. Electron. Mater.* **3**, 1505–1529 (2021).
58. Liu, Y. et al. Layer-by-layer thinning of mos2 by plasma. *ACS Nano* **7**, 4202–4209 (2013).
59. Ma, Q. et al. Controlled argon beam-induced desulfurization of monolayer molybdenum disulfide. *J. Phys. Condens. Matter* **25**, 252201 (2013).
60. Li, T. et al. Reconfigurable, non-volatile neuromorphic photovoltaics. *Nat. Nanotechnol.* **18**, 1303–1310 (2023).
61. Li, D., Ryu, B., Yoon, J., Li, Z. & Liang, X. Improvement of analogue switching characteristics of mos2 memristors through plasma treatment. *J. Phys. D: Appl. Phys.* **53**, 135305 (2020).
62. Mignuzzi, S. et al. Effect of disorder on Raman scattering of single-layer Mo S 2. *Phys. Rev. B* **91**, 195411 (2015).
63. Li, H. et al. From bulk to monolayer mos2: evolution of Raman scattering. *Adv. Funct. Mater.* **22**, 1385–1390 (2012).
64. McCreary, K. M., Hanbicki, A. T., Sivaram, S. V. & Jonker, B. T. A- and B-exciton photoluminescence intensity ratio as a measure of sample quality for transition metal dichalcogenide monolayers. *APL Mater.* **6**, 111106 (2018).
65. Sangwan, V. K. et al. Gate-tunable memristive phenomena mediated by grain boundaries in single-layer MoS2. *Nat. Nanotechnol.* **10**, 403–406 (2015).
66. Karvonen, L. et al. Rapid visualization of grain boundaries in monolayer mos2 by multiphoton microscopy. *Nat. Commun.* **8**, 15714 (2017).
67. Zheng, W. et al. Controlled growth of six-point stars mos2 by chemical vapor deposition and its shape evolution mechanism. *Nanotechnology* **28**, 395601 (2017).
68. Li, T., Du, G., Zhang, B. & Zeng, Z. Scaling behavior of hysteresis in multilayer MoS2 field effect transistors. *Appl. Phys. Lett.* **105**, 093107 (2014).
69. Park, Y., Baac, H. W., Heo, J. & Yoo, G. Thermally activated trap charges responsible for hysteresis in multilayer MoS2 field-effect transistors. *Appl. Phys. Lett.* **108**, 083102 (2016).
70. Shu, J. et al. The intrinsic origin of hysteresis in mos2 field effect transistors. *Nanoscale* **8**, 3049–3056 (2016).
71. Sup Choi, M. et al. Controlled charge trapping by molybdenum disulphide and graphene in ultrathin heterostructured memory devices. *Nat. Commun.* **4**, 1624 (2013).
72. Arnold, A. J. et al. Mimicking neurotransmitter release in chemical synapses via hysteresis engineering in mos2 transistors. *ACS Nano* **11**, 3110–3118 (2017).
73. Guo, Y. et al. Charge trapping at the MoS2-SiO2 interface and its effects on the characteristics of MoS2 metal-oxide-semiconductor field effect transistors. *Appl. Phys. Lett.* **106**, 103109 (2015).
74. Lee, H.-S. et al. Dual-gated mos2 memtransistor crossbar array. *Adv. Funct. Mater.* **30**, 2003683 (2020).

75. Yang, S.-T. et al. Submicron memtransistors made from monocrystalline molybdenum disulfide. *ACS Nano* **18**, 6936–6945 (2024).
76. Li, D. et al. Mos2 memristors exhibiting variable switching characteristics toward biorealistic synaptic emulation. *ACS Nano* **12**, 9240–9252 (2018).
77. Spetzler, B., Abdel, D., Schwier, F., Ziegler, M. & Farrell, P. The role of vacancy dynamics in two-dimensional memristive devices. *Adv. Electron. Mater.* **10**, 2300635 (2024).
78. Ding, G. et al. Reconfigurable 2d wse2-based memtransistor for mimicking homosynaptic and heterosynaptic plasticity. *Small* **17**, 2103175 (2021).
79. Burr, G. W. et al. Experimental demonstration and tolerancing of a large-scale neural network (165 000 synapses) using phase-change memory as the synaptic weight element. *IEEE Trans. Electron Devices* **62**, 3498–3507 (2015).
80. Chen, P. et al. Mitigating effects of non-ideal synaptic device characteristics for on-chip learning. In *2015 IEEE/ACM International Conference on Computer-Aided Design, ICCAD 2015* 194–199 (Institute of Electrical and Electronics Engineers Inc., 2016). Conference date: 02-11-2015 Through 06-11-2015.
81. Kim, S. et al. Pattern recognition using carbon nanotube synaptic transistors with an adjustable weight update protocol. *ACS Nano* **11**, 2814–2822 (2017).
82. Yu, S. Neuro-inspired computing with emerging nonvolatile memories. *Proc. IEEE* **106**, 260–285 (2018).
83. Chen, P.-Y., Peng, X. & Yu, S. Neurosim+: An integrated device-to-algorithm framework for benchmarking synaptic devices and array architectures. In *2017 IEEE International Electron Devices Meeting (IEDM)*, 6.1.1–6.1.4 (IEEE, 2017).
84. Zhao, M., Gao, B., Tang, J., Qian, H. & Wu, H. Reliability of analog resistive switching memory for neuromorphic computing. *Appl. Phys. Rev.* **7**, 011301 (2020).
85. Mohta, N., Mech, R. K., Sanjay, S., Muralidharan, R. & Nath, D. N. Artificial synapse based on back-gated mos2 field-effect transistor with high-k ta2o5 dielectrics. *Phys. Status Solidi (a)* **217**, 2000254 (2020).
86. Song, S., Miller, K. D. & Abbott, L. F. Competitive hebbian learning through spike-timing-dependent synaptic plasticity. *Nat. Neurosci.* **3**, 919–926 (2000).
87. Kim, I. S. et al. Influence of stoichiometry on the optical and electrical properties of chemical vapor deposition derived mos2. *ACS Nano* **8**, 10551–10558 (2014).
88. Baker, M., Gilmore, R., Lenardi, C. & Gissler, W. Xps investigation of preferential sputtering of s from mos2 and determination of mosx stoichiometry from mo and s peak positions. *Appl. Surf. Sci.* **150**, 255–262 (1999).
89. Parkin, W. M. et al. Raman shifts in electron-irradiated monolayer mos2. *ACS Nano* **10**, 4134–4142 (2016).
90. Zhu, Y. et al. Room-temperature photoluminescence mediated by sulfur vacancies in 2d molybdenum disulfide. *ACS Nano* **17**, 13545–13553 (2023).
91. Scofield, J. H. Theoretical photoionization cross sections from 1 to 1500 keV. Technical Report UCRL-51326 (Lawrence Livermore Laboratory, California University, 1973).
92. Kolobov, A. V. & Tominaga, J. *Two-Dimensional Transition-Metal Dichalcogenides* Vol. 239 (Springer, 2016).
93. Hong, J. et al. Exploring atomic defects in molybdenum disulphide monolayers. *Nat. Commun.* **6**, 6293 (2015).
94. Shi, Y. et al. Electronic synapses made of layered two-dimensional materials. *Nat. Electron.* **1**, 458–465 (2018).
95. Park, E. et al. A 2d material-based floating gate device with linear synaptic weight update. *Nanoscale* **12**, 24503–24509 (2020).
96. Seo, S. et al. The gate injection-based field-effect synapse transistor with linear conductance update for online training. *Nat. Commun.* **13**, 6431 (2022).
97. Tang, J. et al. A reliable all-2d materials artificial synapse for high energy-efficient neuromorphic computing. *Adv. Funct. Mater.* **31**, 2011083 (2021).
98. Krishnaprasad, A. et al. Graphene/mos2/siox memristive synapses for linear weight update. *npj 2D Mater. Appl.* **7**, 22 (2023).
99. Ma, W. C.-Y. et al. Demonstration of synaptic characteristics of polycrystalline-silicon ferroelectric thin-film transistor for application of neuromorphic computing. *Semicond. Sci. Technol.* **37**, 045003 (2022).
100. Jerry, M. et al. A ferroelectric field effect transistor based synaptic weight cell. *J. Phys. D Appl. Phys.* **51**, 434001 (2018).
101. Kuzum, D., Jeyasingh, R. G. D., Lee, B. & Wong, H.-S. P. Nanoelectronic programmable synapses based on phase change materials for brain-inspired computing. *Nano Lett.* **12**, 2179–2186 (2012).
102. Kuzum, D., Yu, S. & Wong, H.-S. P. Synaptic electronics: materials, devices and applications. *Nanotechnology* **24**, 382001 (2013).
103. Deng, L. The mnist database of handwritten digit images for machine learning research [best of the web]. *IEEE Signal Process. Mag.* **29**, 141–142 (2012).
104. Paszke, A. et al. Pytorch: an imperative style, high-performance deep learning library. *Proceedings of the 33rd International Conference on Neural Information Processing Systems* **721**, 8026–8037 (2019).
105. Mallik, S. K. et al. Thermally driven multilevel non-volatile memory with monolayer mos2 for brain-inspired artificial learning. *ACS Appl. Mater. Interfaces* **15**, 36527–36538 (2023).
106. Mallik, S. K. et al. Ionotronic WS2 memtransistors for 6-bit storage and neuromorphic adaptation at high temperature. *npj 2D Mater. Appl.* **7**, 63 (2023).
107. Jena, A. K. et al. Bipolar resistive switching in tio2 artificial synapse mimicking pavlov's associative learning. *ACS Appl. Mater. Interfaces* **15**, 3574–3585 (2023).
108. Jadwiszczak, J. et al. Mos2 memtransistors fabricated by localized helium ion beam irradiation. *ACS Nano* **13**, 14262–14273 (2019).
109. Huh, W. et al. Heterosynaptic mos2 memtransistors emulating biological neuromodulation for energy-efficient neuromorphic electronics. *Adv. Mater.* **35**, 2211525 (2023).

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Author contributions

M.R. and A.R. designed the experiment. M.R. synthesized the samples, performed the electrical measurements, and analyzed the data. M.R., S.K.M., S.S., G.V.P.K., and A.R. wrote the manuscript. S.K.M. and S.S. carried out the simulations. S.C. and A.S. carried out the optical measurements. S.H. helped in TEM measurement and analysis. All the authors discussed the results and contributed to finalizing the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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