The 20th Korea-U.S. Forum on Nanotechnology

Group II: Energy-efficient for AI & Neuromorphic System
September 14, 2026 (Monday), Mckimmon Center

Linearly programmable memristors for neuromorphic computing hardware

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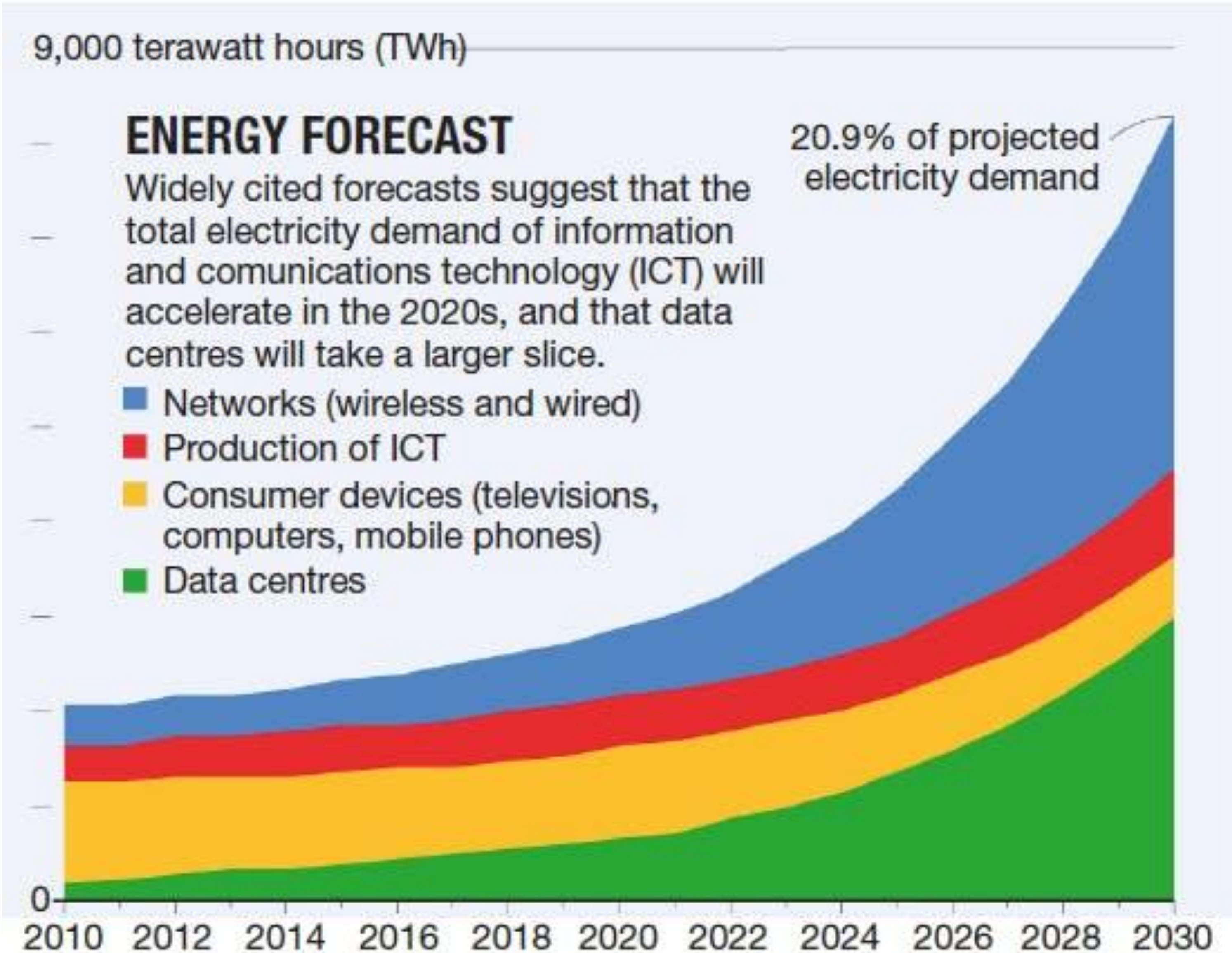
$\sqrt{\varepsilon_r \mu_r}$ $\sqrt{\varepsilon_r \mu_r}$ Vdt/dI, F/a $k\log\Omega$ mc^2, $E \times H$ PV/RT $H - PV$

Current AI hardware is not efficient energetically

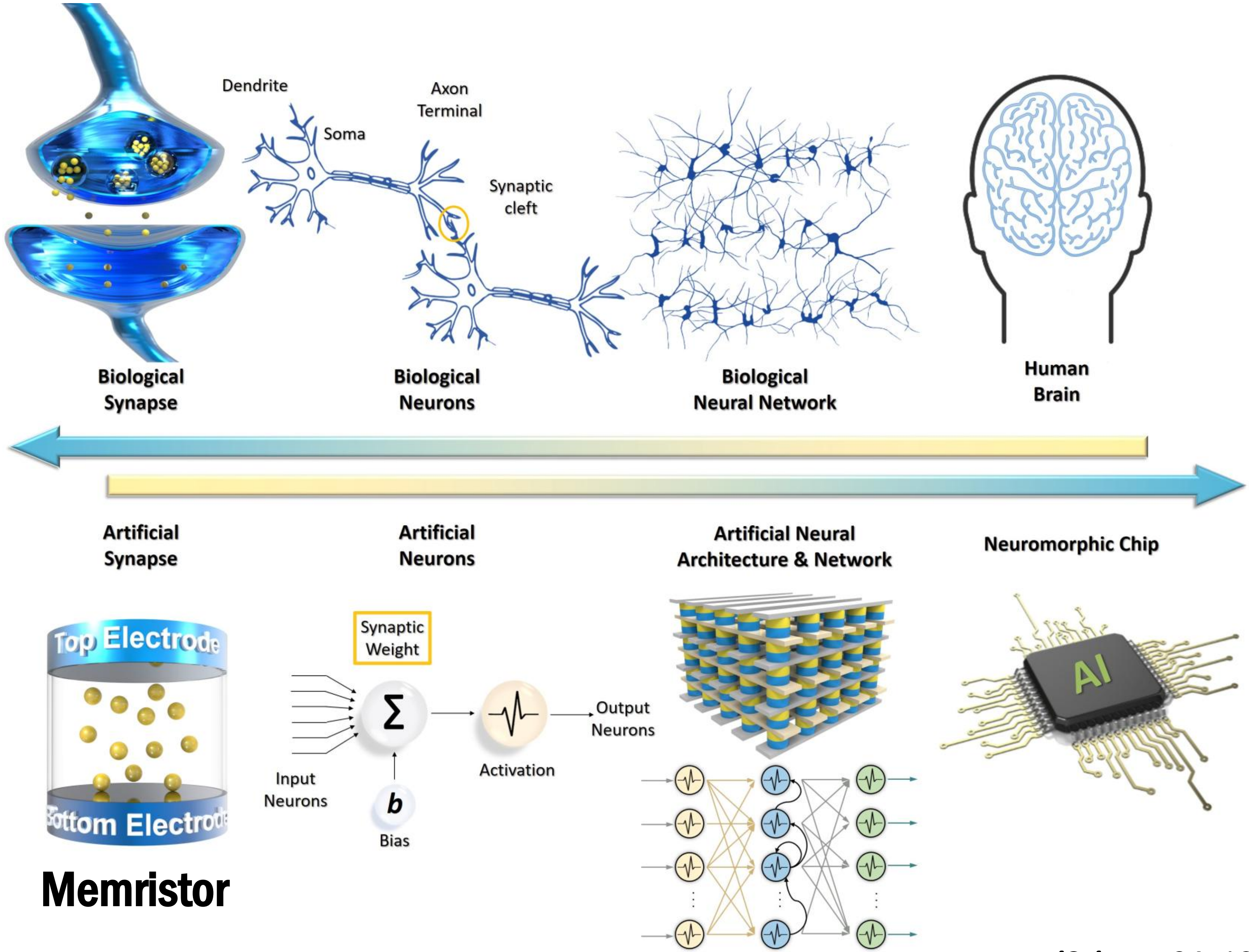
https://www.chosun.com/opinion/specialist_column/2021/11/15/MIYL74YOOFFFXA5MJJXY2T722A/

Current AI hardware is not efficient energetically



Source: *Nature* **561**, 163-166 (2018)

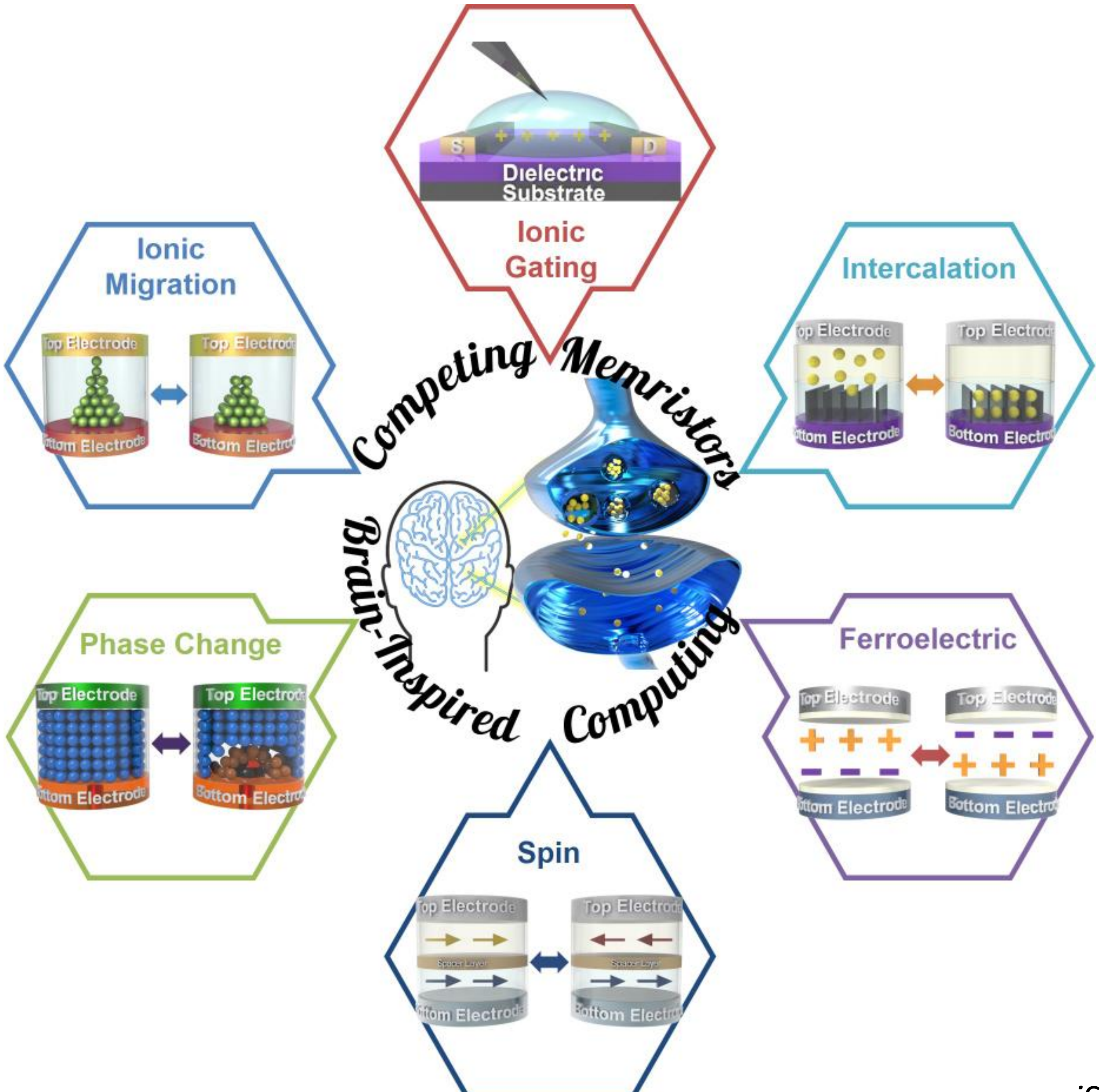
Comparing biological & artificial processor



Dr. Seung Ju Kim

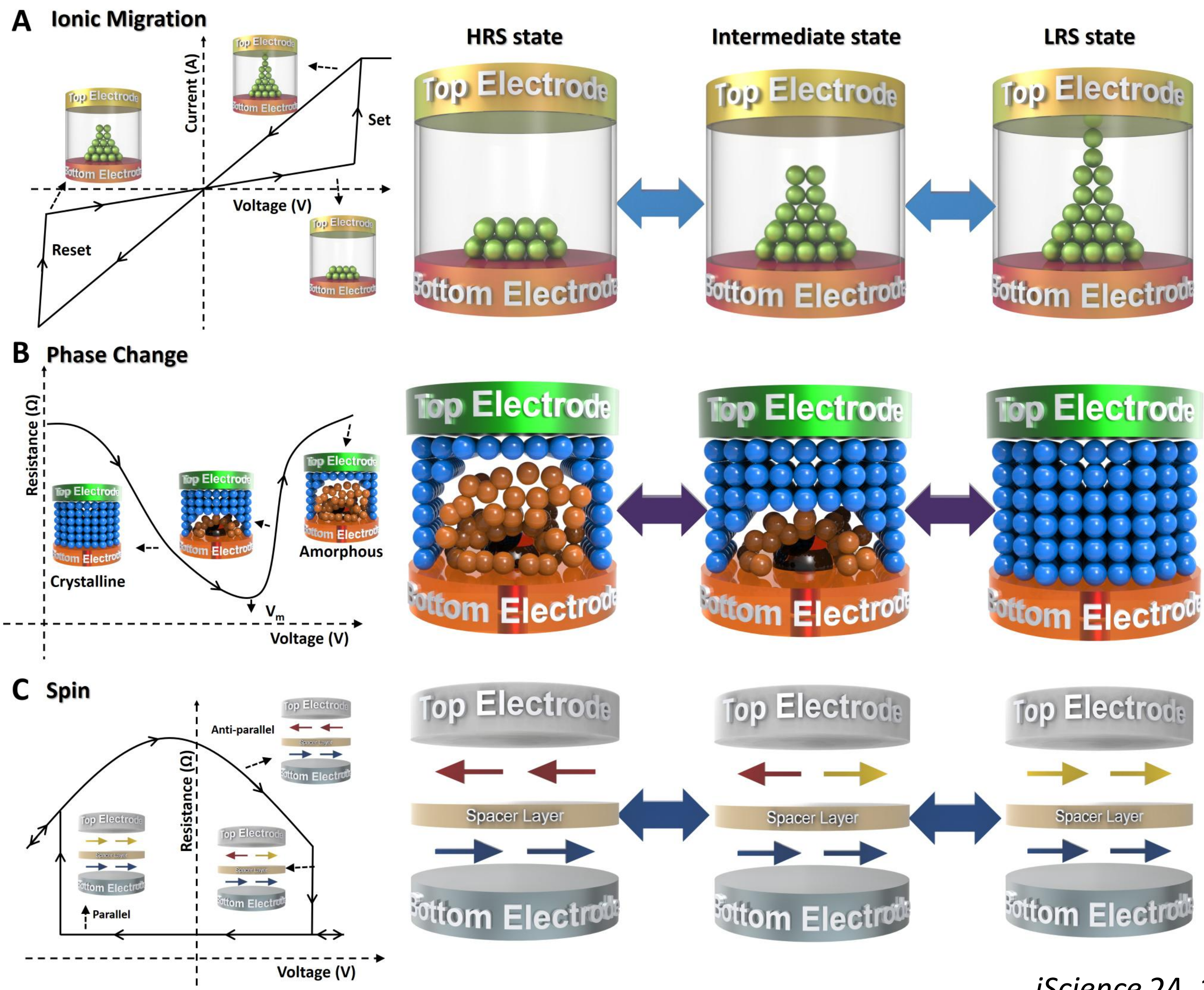
iScience 24, 101889 (2021)

Various memristors for neuromorphic computing



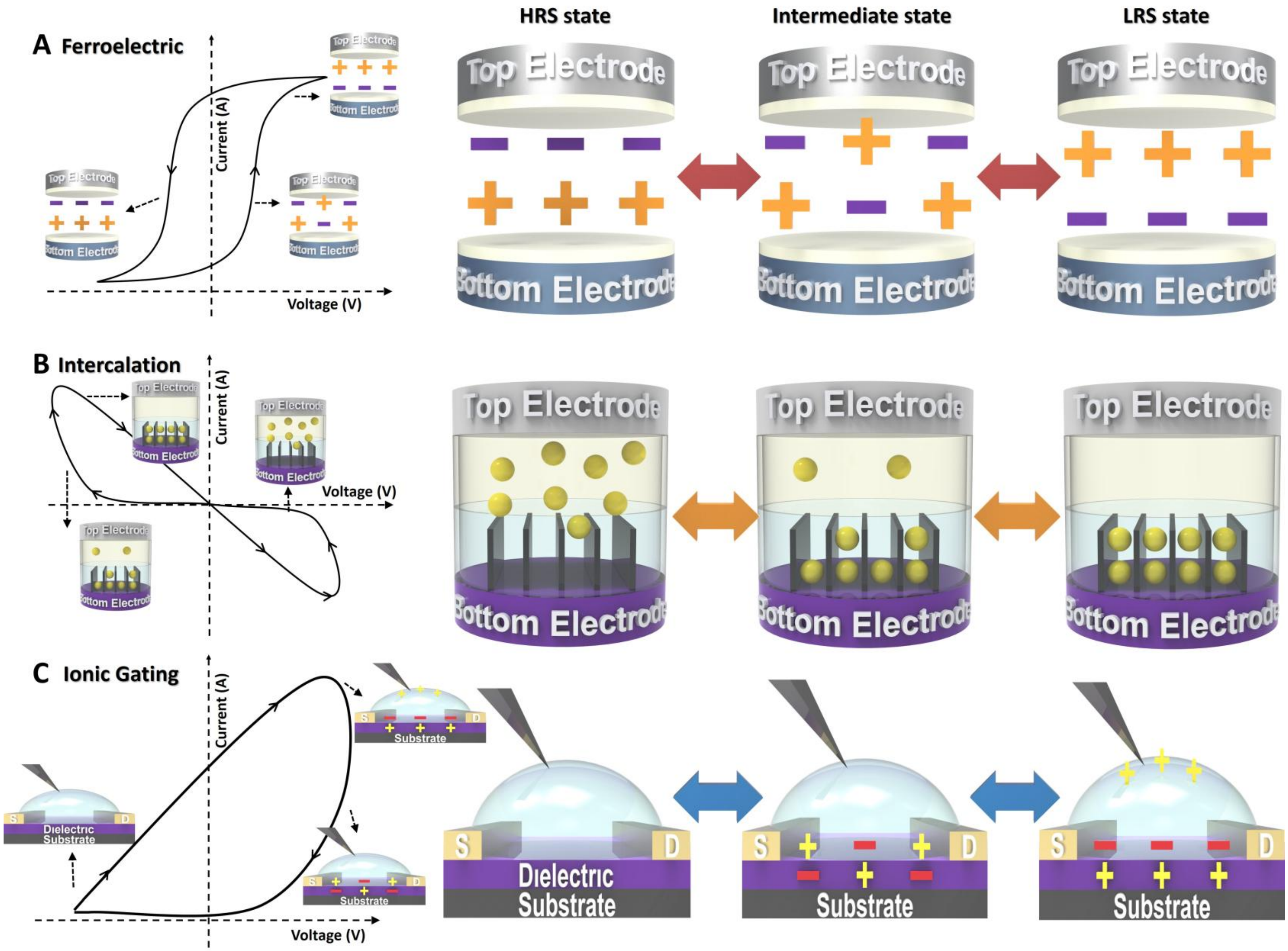
iScience 24, 101889 (2021)

Resistive switching (ionic migration), phase change, spin



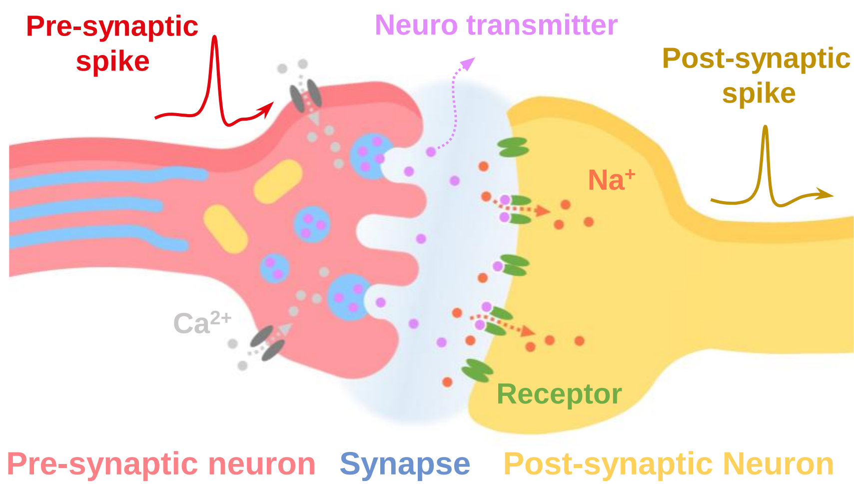
iScience 24, 101889 (2021)

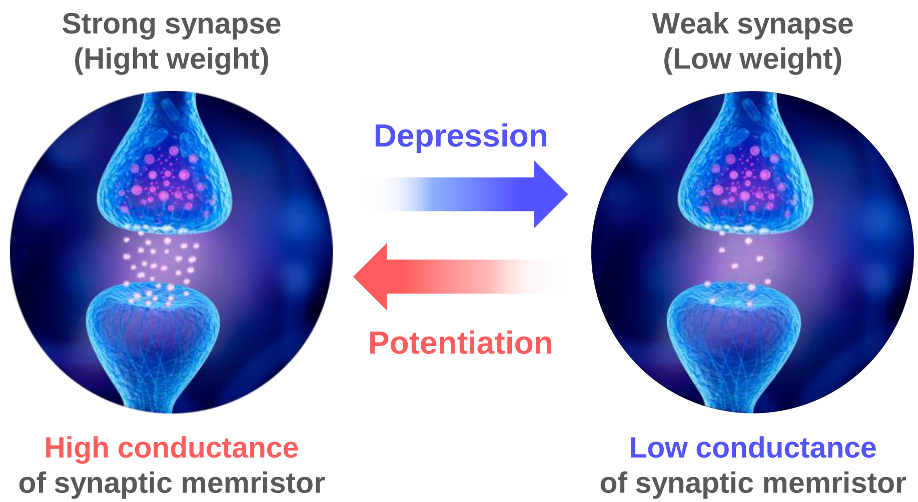
Ferroelectric, intercalation, ionic gating

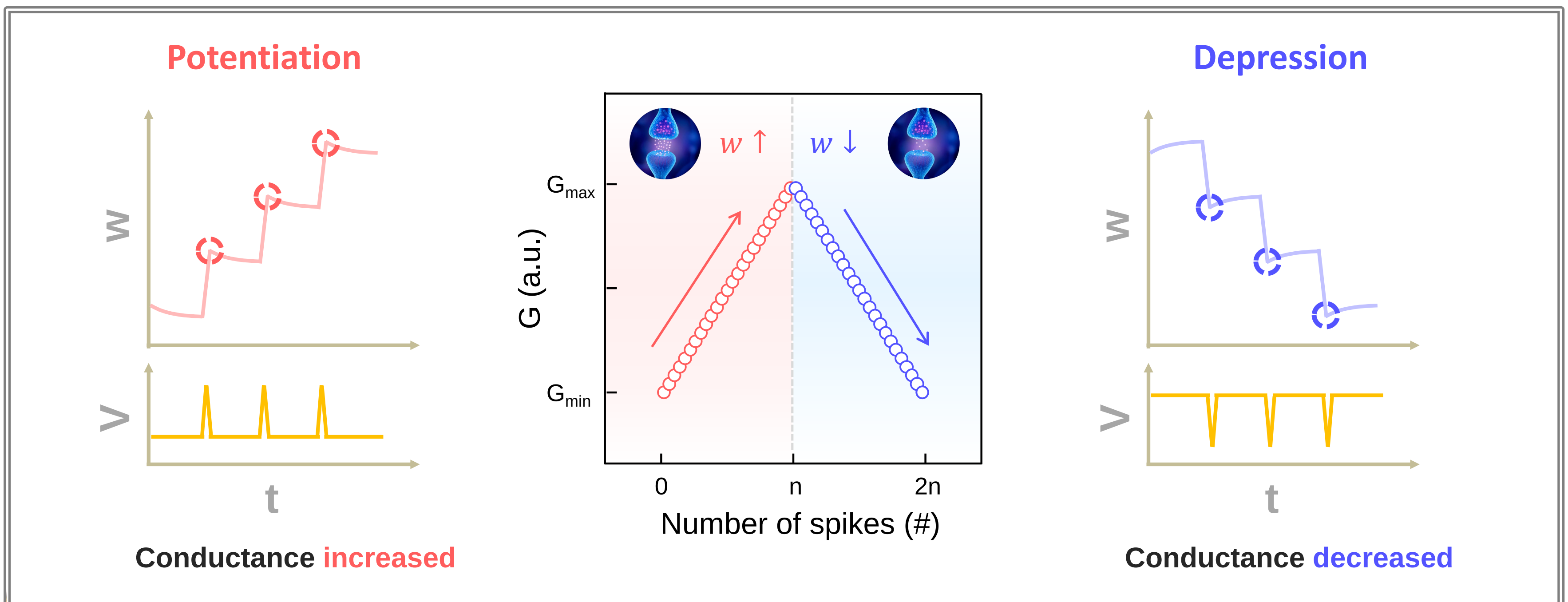


iScience 24, 101889 (2021)

Synaptic weight of artificial synapses

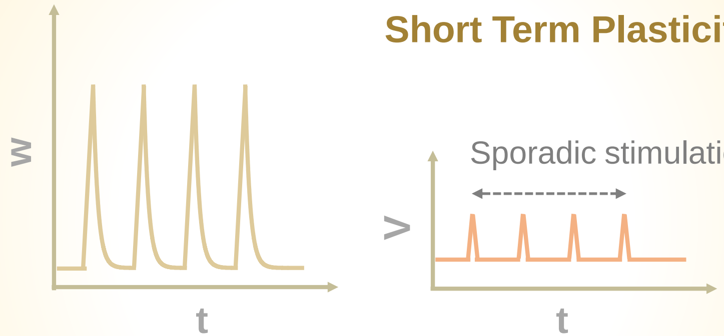






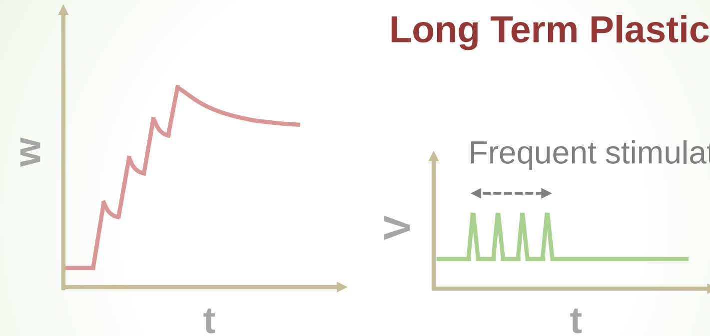
Spike-dependent weight modification

Short Term Plasticity



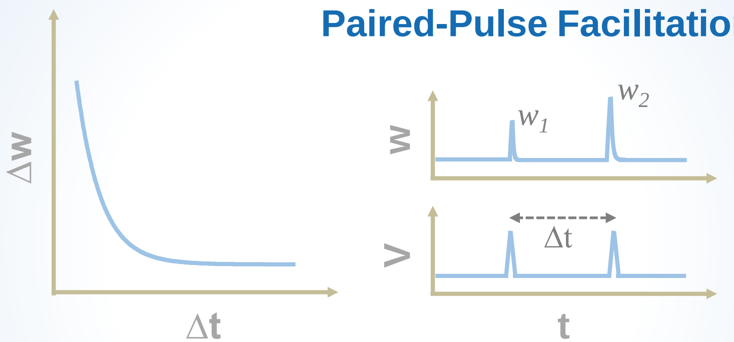
"A transient deformation in synaptic efficacy."

Long Term Plasticity



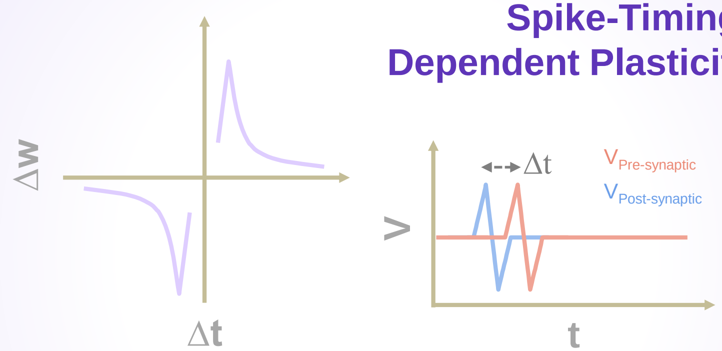
"A long-lasting change in synaptic connection."

Paired-Pulse Facilitation



"Amplification of the secondary neural signal due to the immediately preceding impulse."

Spike-Timing-Dependent Plasticity

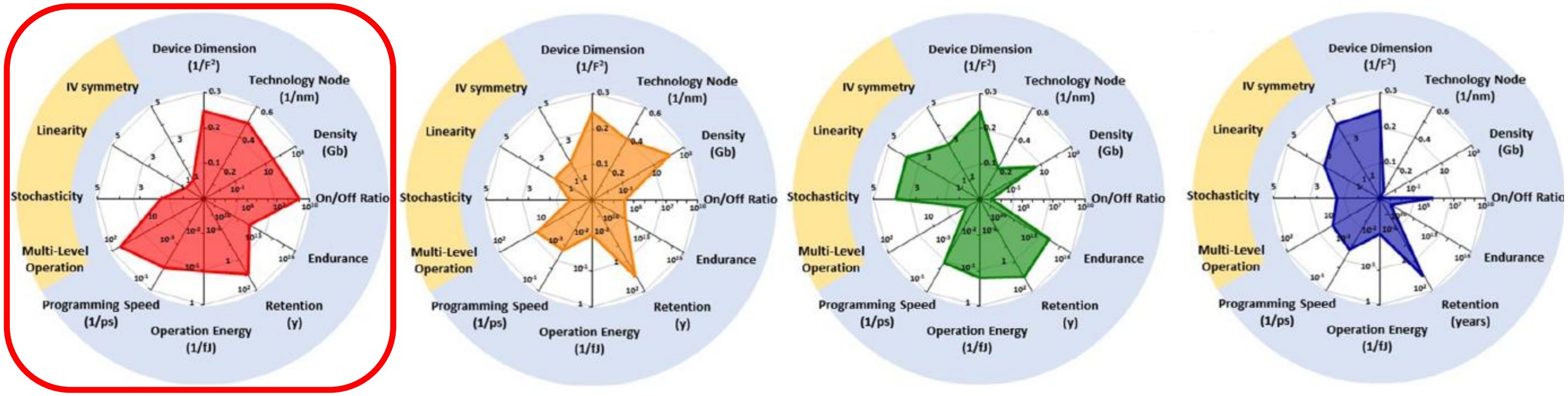


"A weight specialization based on a firing order of pre-and post-synaptic neurons."

Biological synaptic plasticity in response to different activities

Competing memristors

Ionic migration (RS) **Phase change** **Spin** **Ferroelectric**

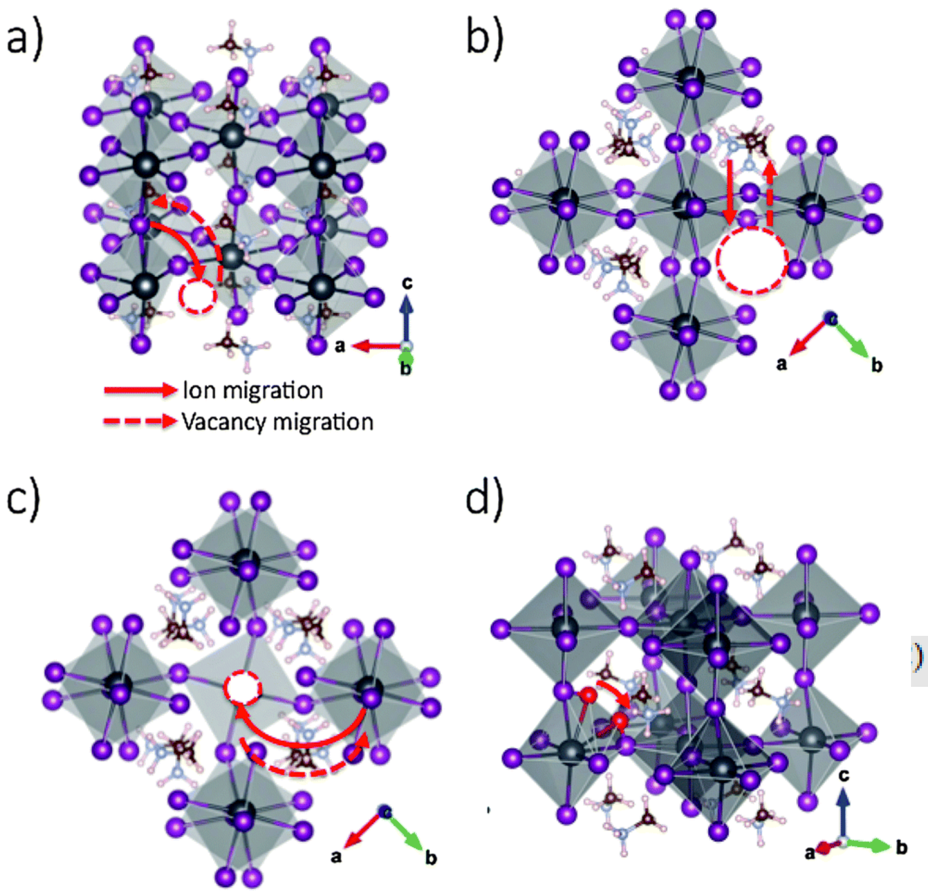


Technology	CMOS-based			Memristor-based			
	Flash	DRAM		Resistive switching	Phase change	Spintronics	Ferroelectric
Device dimension	$4F^2$	$6F^2$	Memristive computing	$4F^2$[95]	$4F^2$[126]	$4F^2$[127]	$4F^2$[128]
Feature size (F)	15 nm	17.5 nm		2 nm[95]	2.5 nm[126]	5 nm[129]	20 nm[24]
Density	512 GB	32 GB		32 GB[130]	128 GB[50]	4 GB[131]	–
On/off ratio	–	–		10^8[121]	10^3[18]	10[22]	10^4[132]
Endurance (cycles)	10^5	10^{15}		10^{12}[27]	10^{11}[133]	10^{14}[125]	10^9[134]
Retention	>10 y	64 ms		>10 y[31]	>10 y[122]	>10 y[21]	>10 y[135]
Operation energy	160 pJ	–		8 fJ[136]	100 fJ[137]	6 fJ[124]	100 fJ[138]
Programming speed	80 µs	10 ns		85 ps[139]	700 ps[122]	190 ps[140]	600 ps[141]
Multi-level operation	–	–	Neuromorphic computing	64[142]	16[143]	2[144]	10[25]
Variability	–	–		Medium	Medium	High	Low
Linearity	–	–		Low	Medium–low	High	Medium–low
Research matured	–	–		2 Mb array pattern recognition	165 k network MNIST	Single device	Single device
Pros	High density	Fast speed	–	Gradual conductance change	High density	Reliability	CMOS compatible
Cons	Individual inaccessible	Volatility	–	Nonlinearity	Conductance drift asymmetric	Less multi-state narrow dynamic range	Low density

Adv. Intell. Syst. 2000105 (2020)

Defect migration in halide perovskites

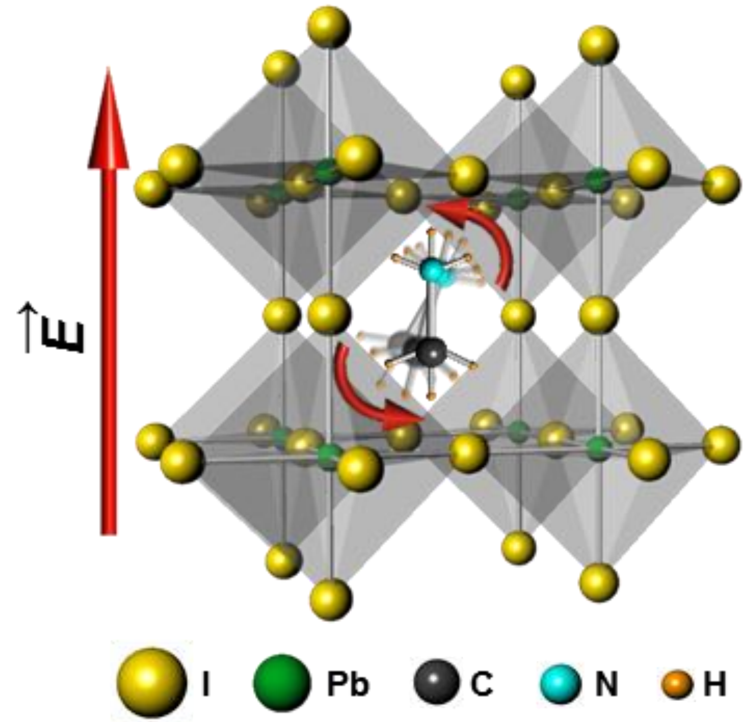
✓ **Diffusion paths for (a) V_I, (b) V_{MA}, (c)V_{Pb} and (d) I_i defects**



Azpiroz *et al*., ***Energy Environ. Sci.***, 2015, **8**, 2118-2127

✓ **Structural flexibility**

- MA cation tilted in equilibrium state (30°)
- MA cation is aligned by E-field
- Migration of ionic species easier

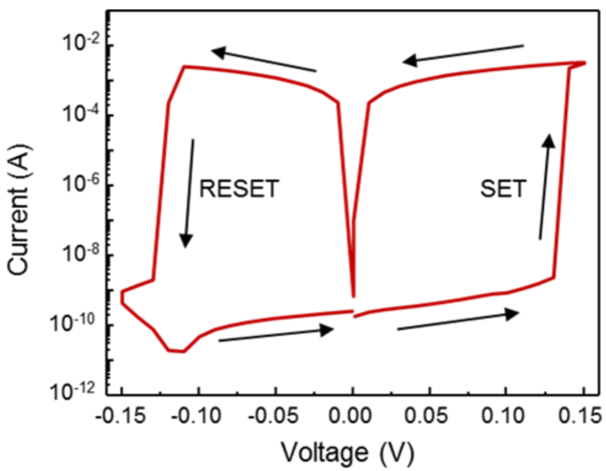


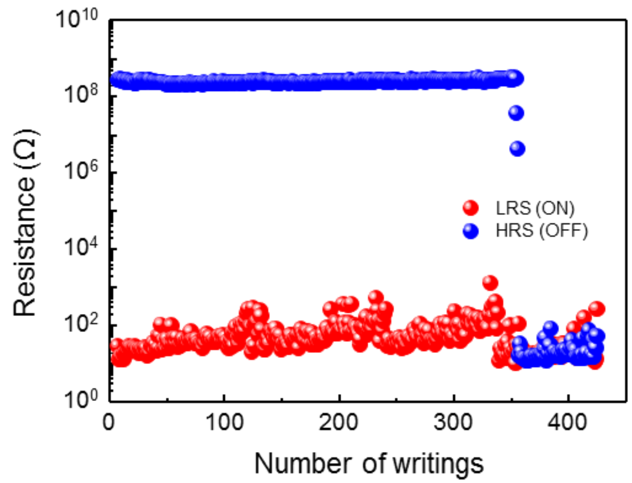
A-site molecular rotational motion in a unit cell of $CH_3NH_3PbI_3$.

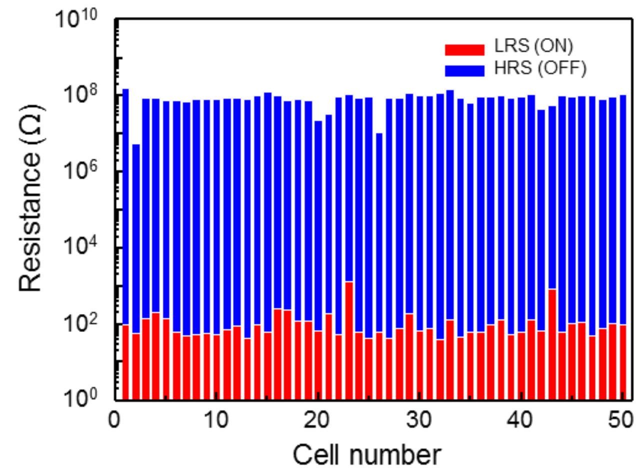
Hysteretic *I-V* characteristics
: ion migration, structural flexibility

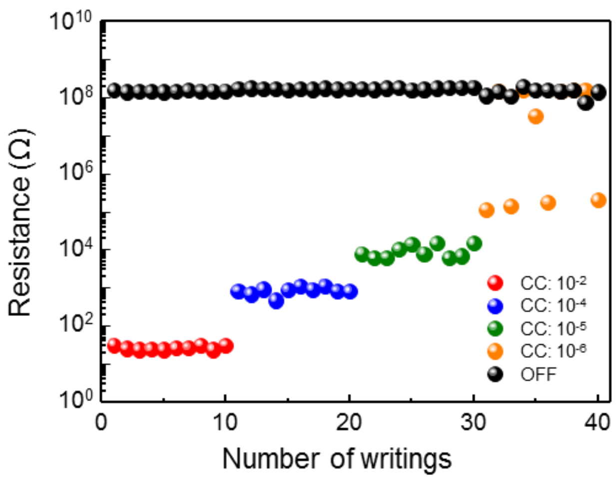
Application to microelectronics such as resistive switching memories

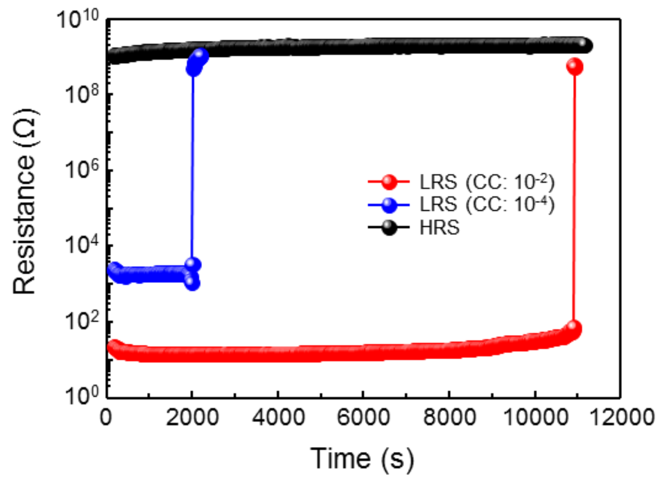
Resistive switching in $Ag/MAPI_3/Pt$











- **Ultra-low voltage resistive switching**

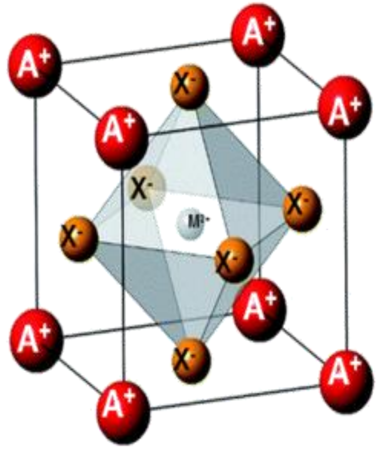
- Only ± 0.15 V of operation voltage (3.25×10^3 V/cm)
- High ON/OFF ratio (Avg. 1.12×10^6)
- Uniform resistive switching behavior
- Multi-level switching available
- 350 cycles endurance and 11000 s retention

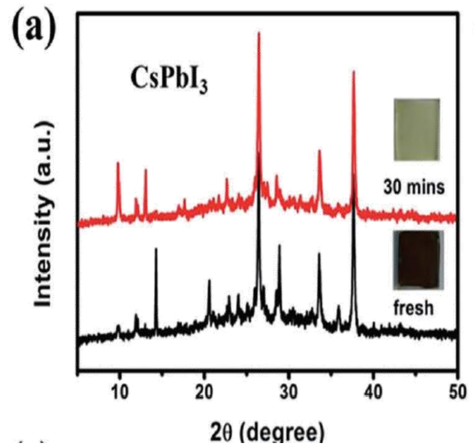
Dr. Jaeho Choi

Adv. Mater. **28**, 6562-6567 (2016)

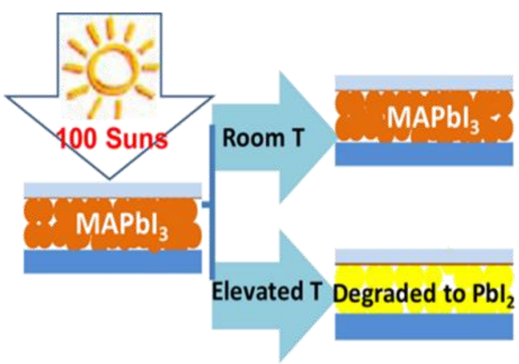
Challenges of 3D halide perovskite as artificial synapses

■ Heat & Moisture Instability of 3D Halide Perovskites





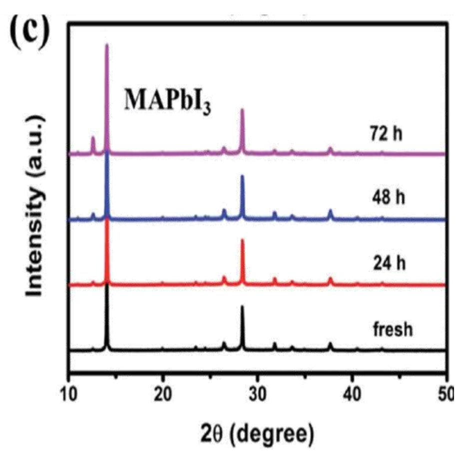
Energy Environ. Sci., 2018, 11, 234--242



ChemSusChem 2019,12,1560 –1575

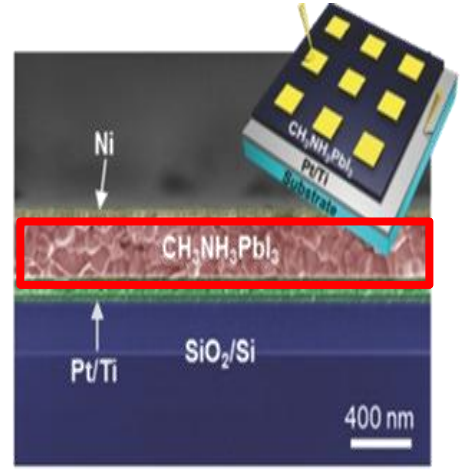
3D Organo-Halide Perovskite is an unstable phase, which is vulnerable to heat & moisture in the air, making it difficult to commercialize

3D Perovskite ($MAPbI_3$)
2~3 days in ambient air condition

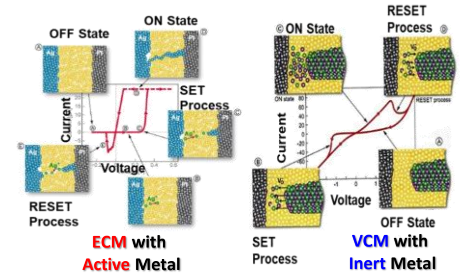


J. Phys. Chem. Lett. 2015, 6, 326–330

■ Polycrystalline nature causes non-linearity



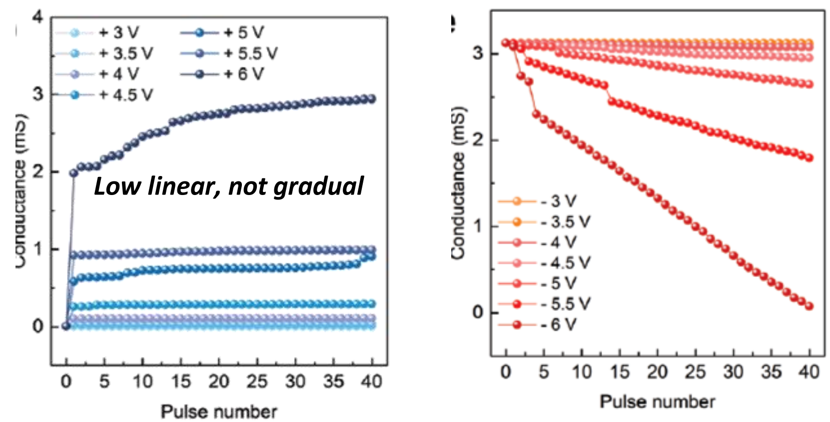
Adv. Mater. **2016,** 28, 6562–6567



R. Waser, Nanoelectronics and Information Technology 3rd edition, Wiley-VCH, (2012)

Charged ion migration controlling
is a key for the memristor.
Grain shape and size are major factors.

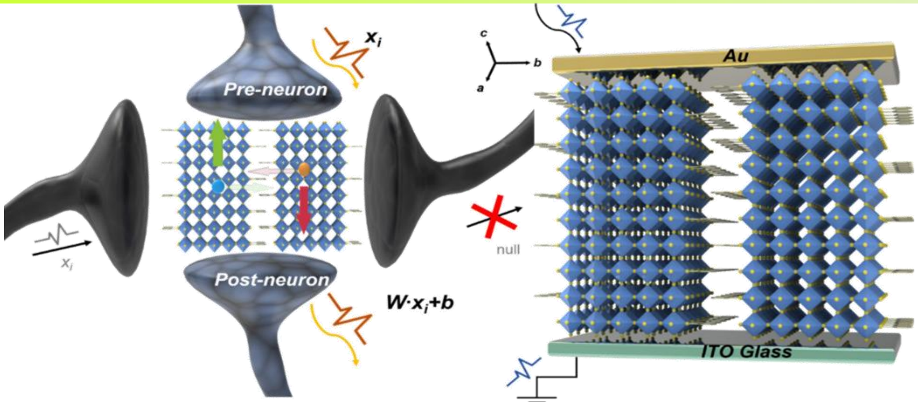
Al / POT2T / $MAPbBr_3$(3D) / PEDOT:PSS / ITO

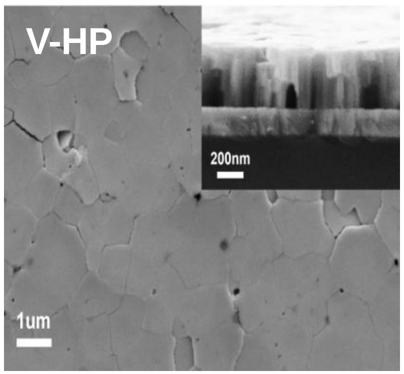


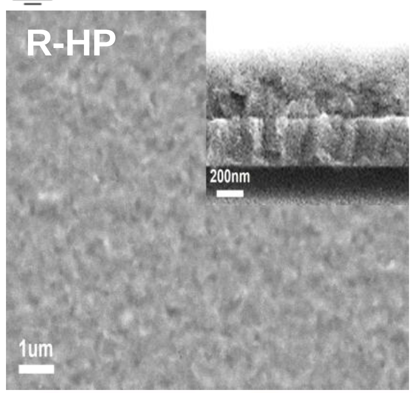
Adv. Mater. **2021**, *33*, 2007851

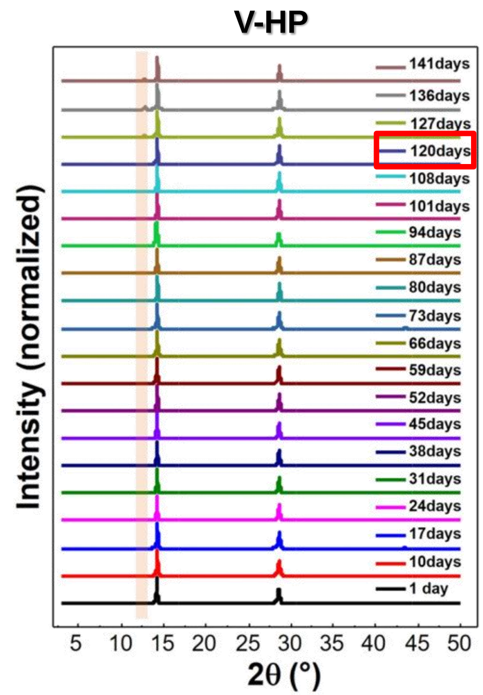
Polycrystalline nature of 3D halide perovskite hamper the reliable & controllable ionic charge migration

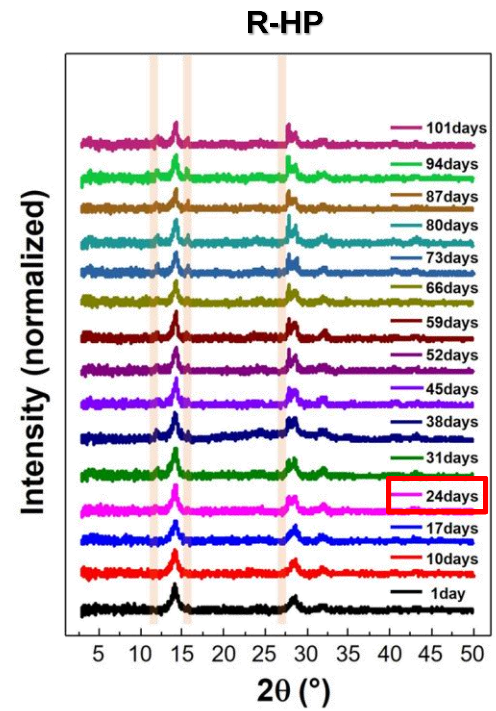
Vertically aligned two-dimensional halide perovskite on ITO

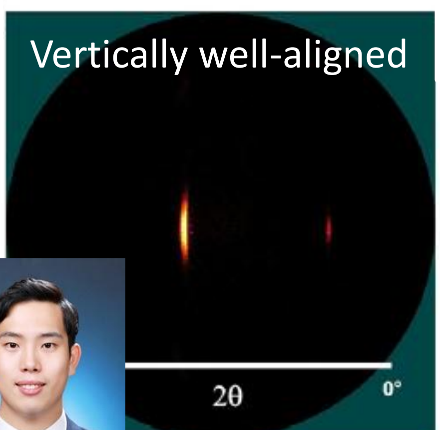


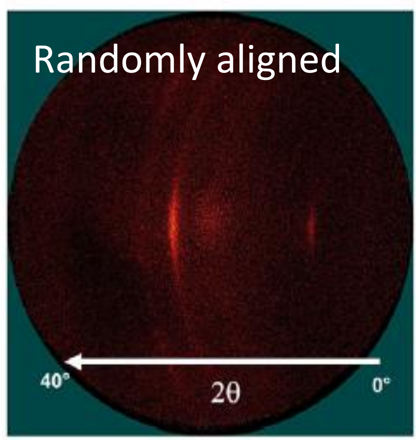


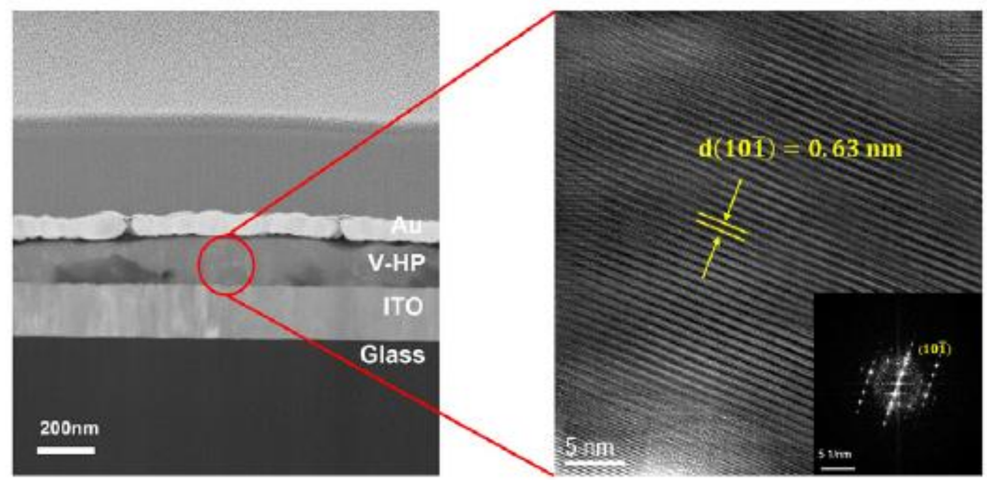




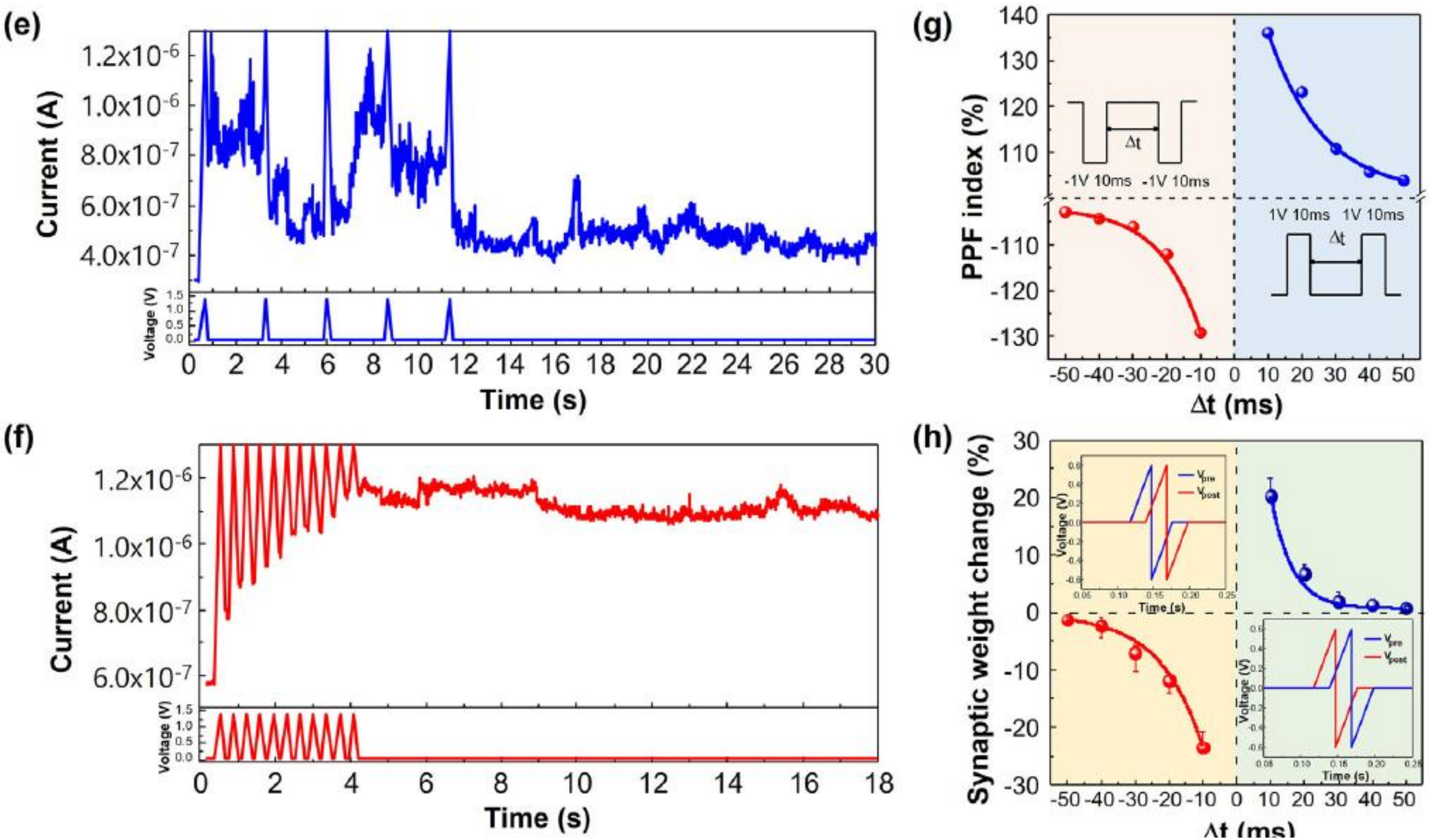








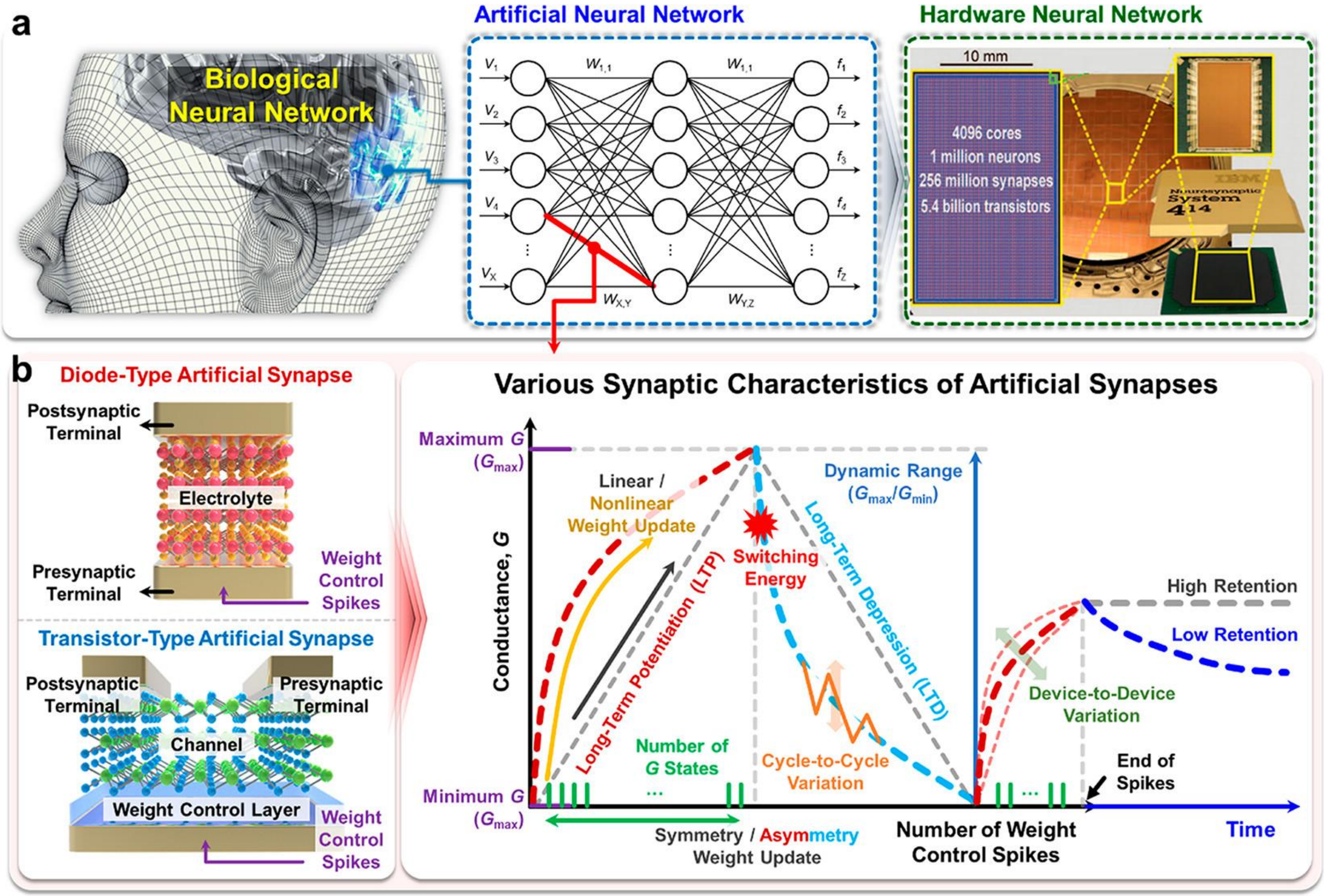
Synaptic characteristics of V-HP artificial synapse



(e) Short-term plasticity (STP), and (f) long-term plasticity (LTP).

(g) Paired-pulse facilitation and depression (PPF & PPD). (h) Spike timing-dependent plasticity (STDP)

Linearity, symmetry, dynamic range, and retention

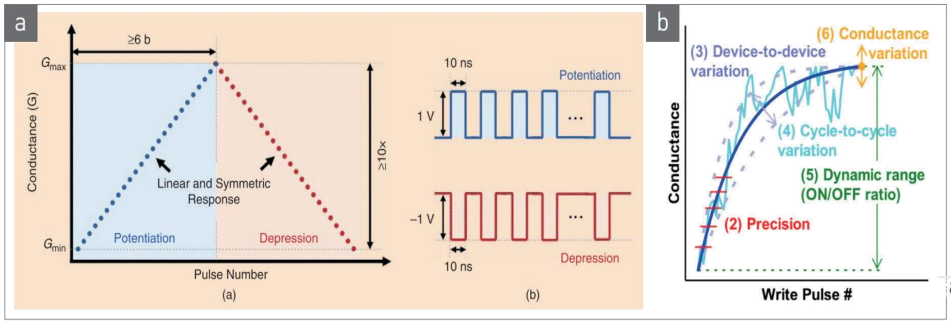


Source: *ACS Appl. Electron. Mater. 2020, 2, 2, 371–388*

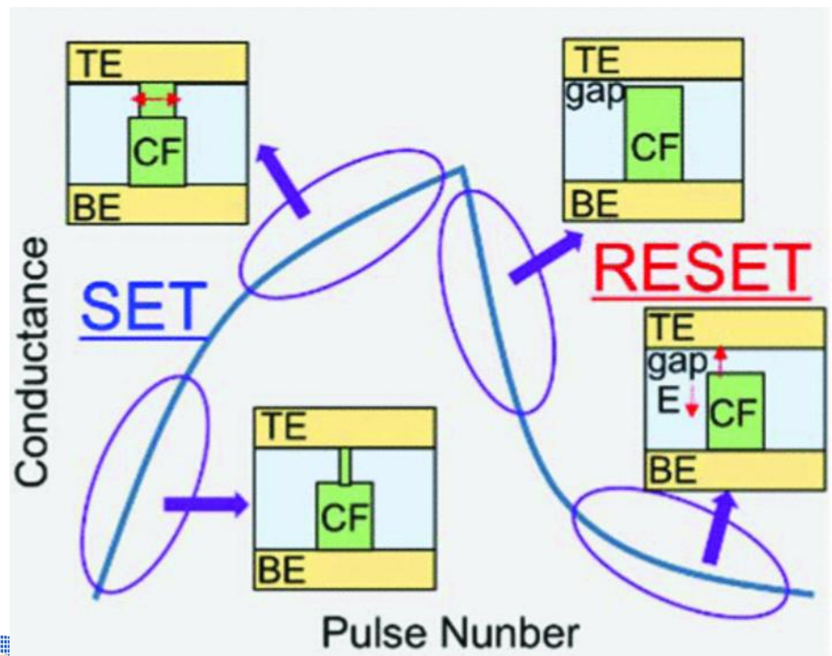
Conventional filamentary type memristors: nonlinear programming

▶ **Synaptic weight updates with memristors**

linearity & Symmetry

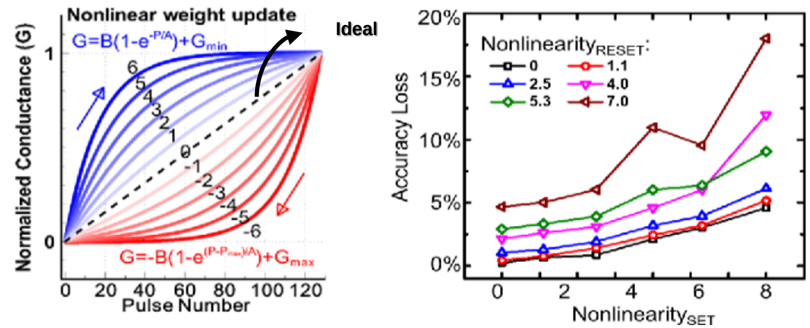


IEEE Nanotechnology magazine 12.3 (2018): 36-44.



2018 IEEE Symposium on VLSI Technology, 2018, pp. 103-104

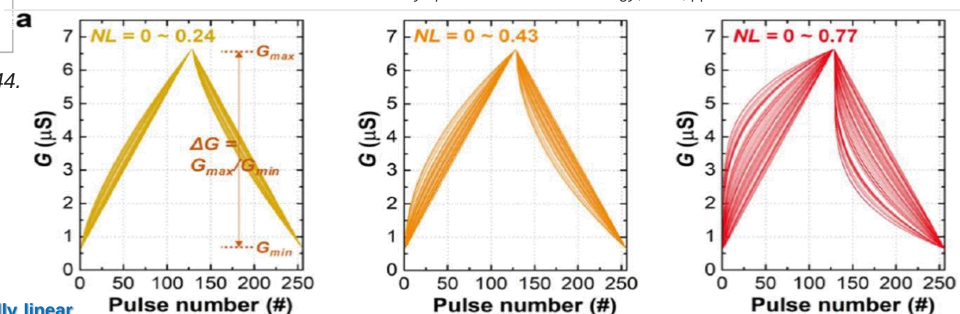
▶ **AI accuracy depending on linearity**



Non-linear : low accuracy

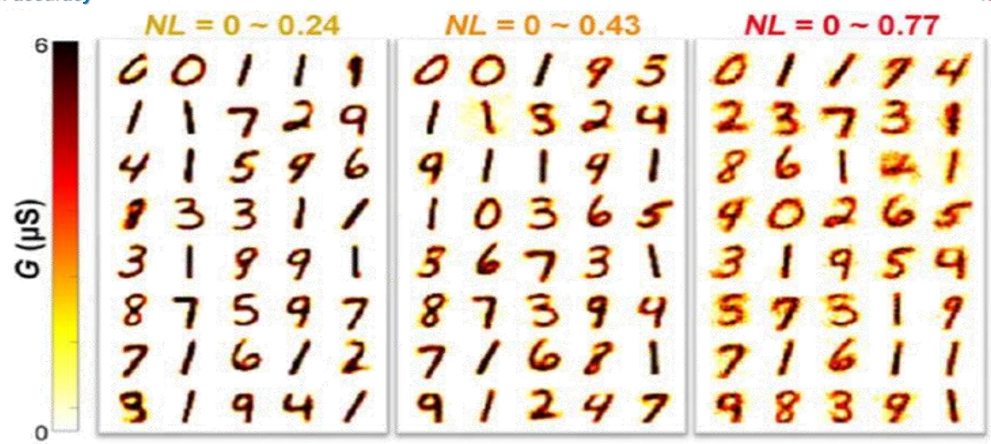
Ideally linear : high accuracy

2018 IEEE Symposium on VLSI Technology, 2018, pp. 103-104

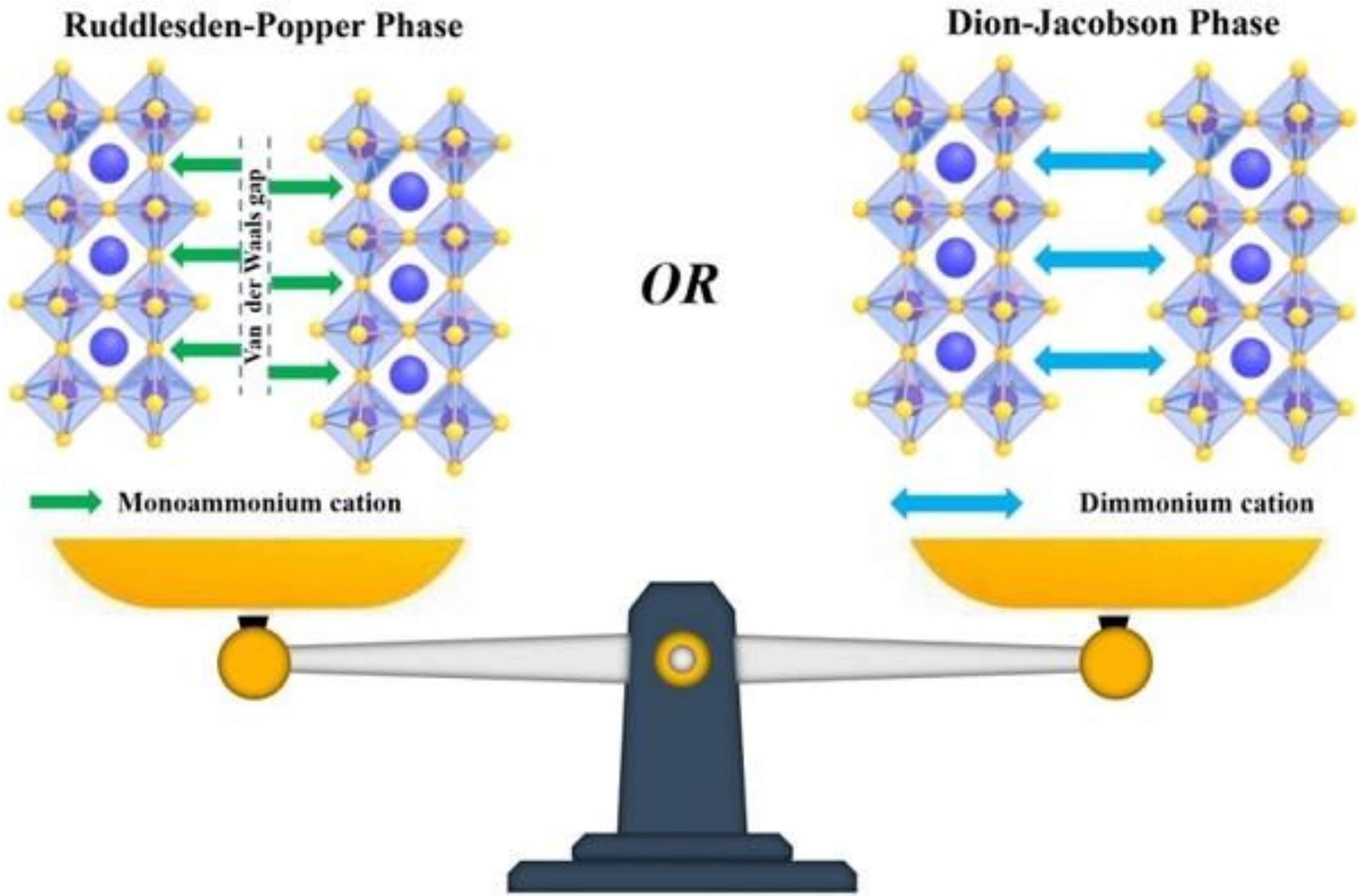


Ideally linear high accuracy

Non-linear low accuracy



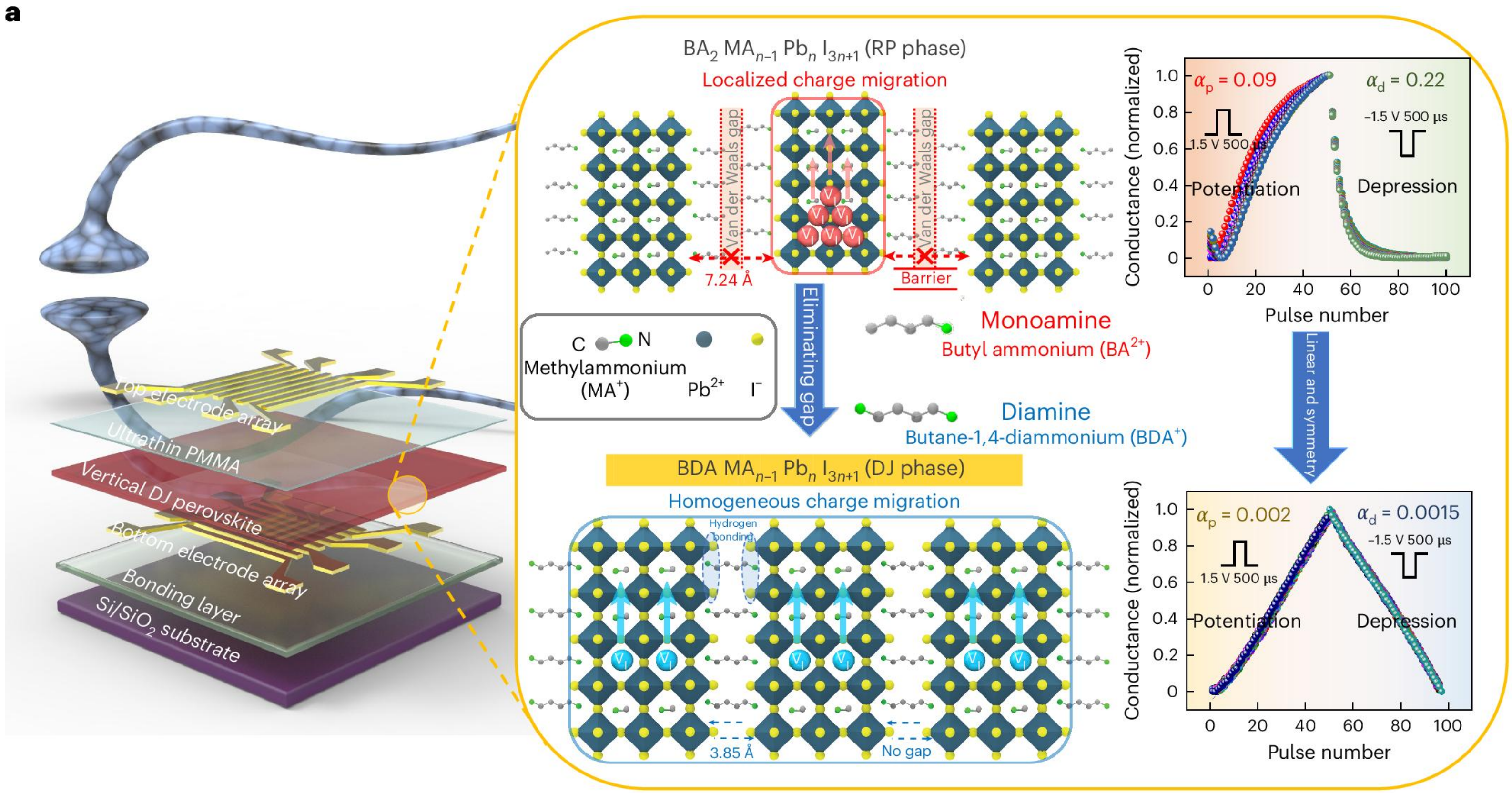
Scientific Reports **8**, 2638 (2018)



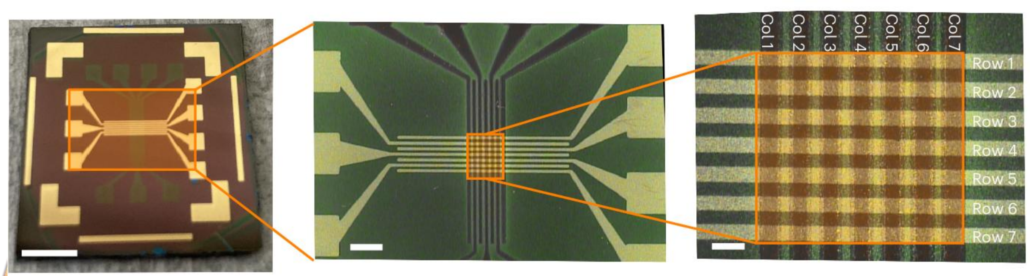
Source: ChemSusChem 2023, 16, e202300736

High linearity and symmetry in weight update using DJ phase

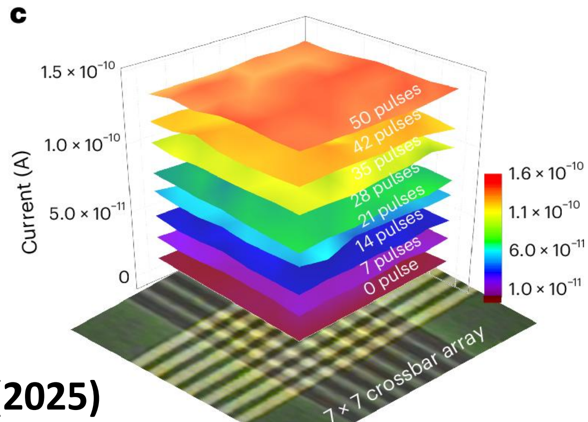
a



b

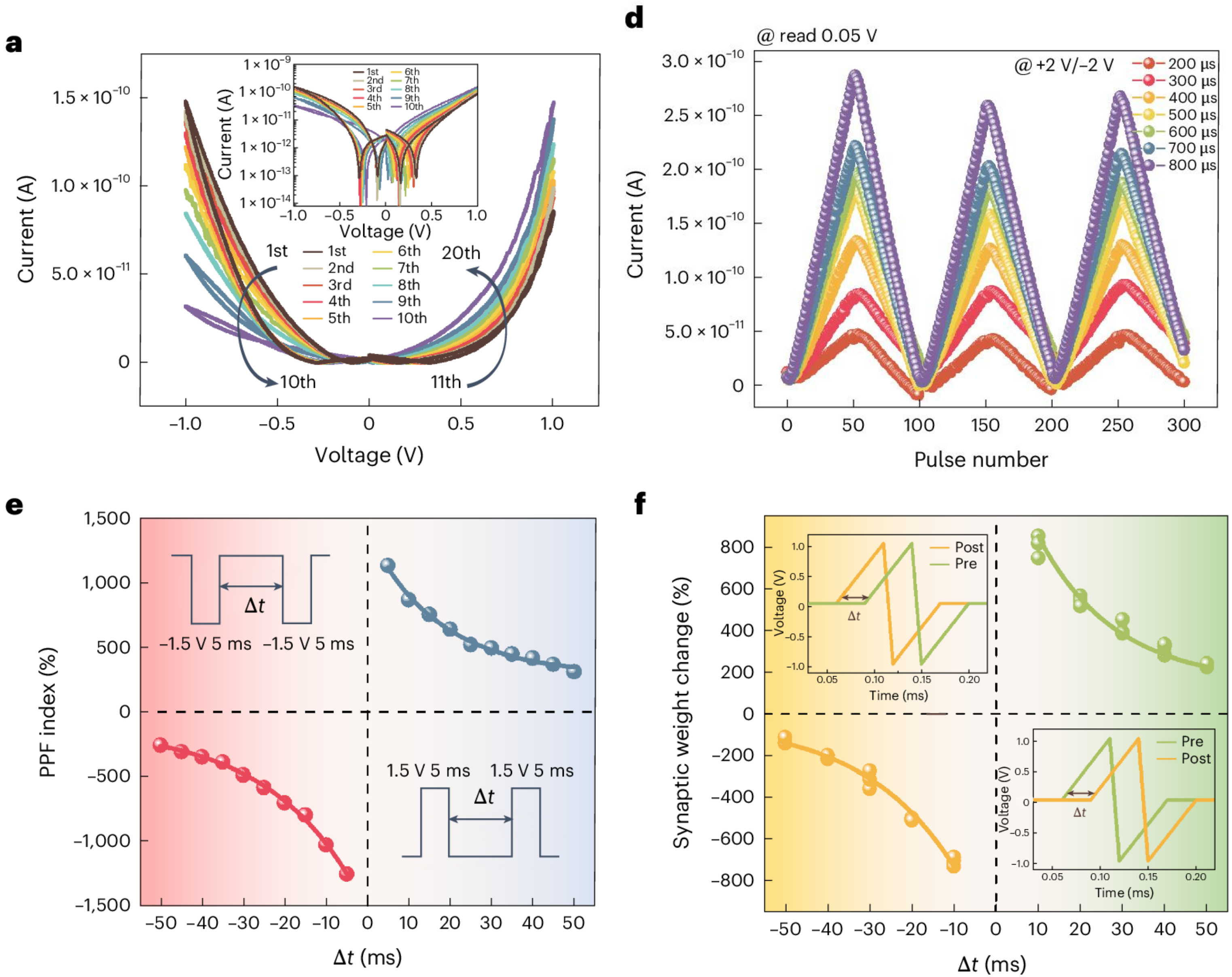


c

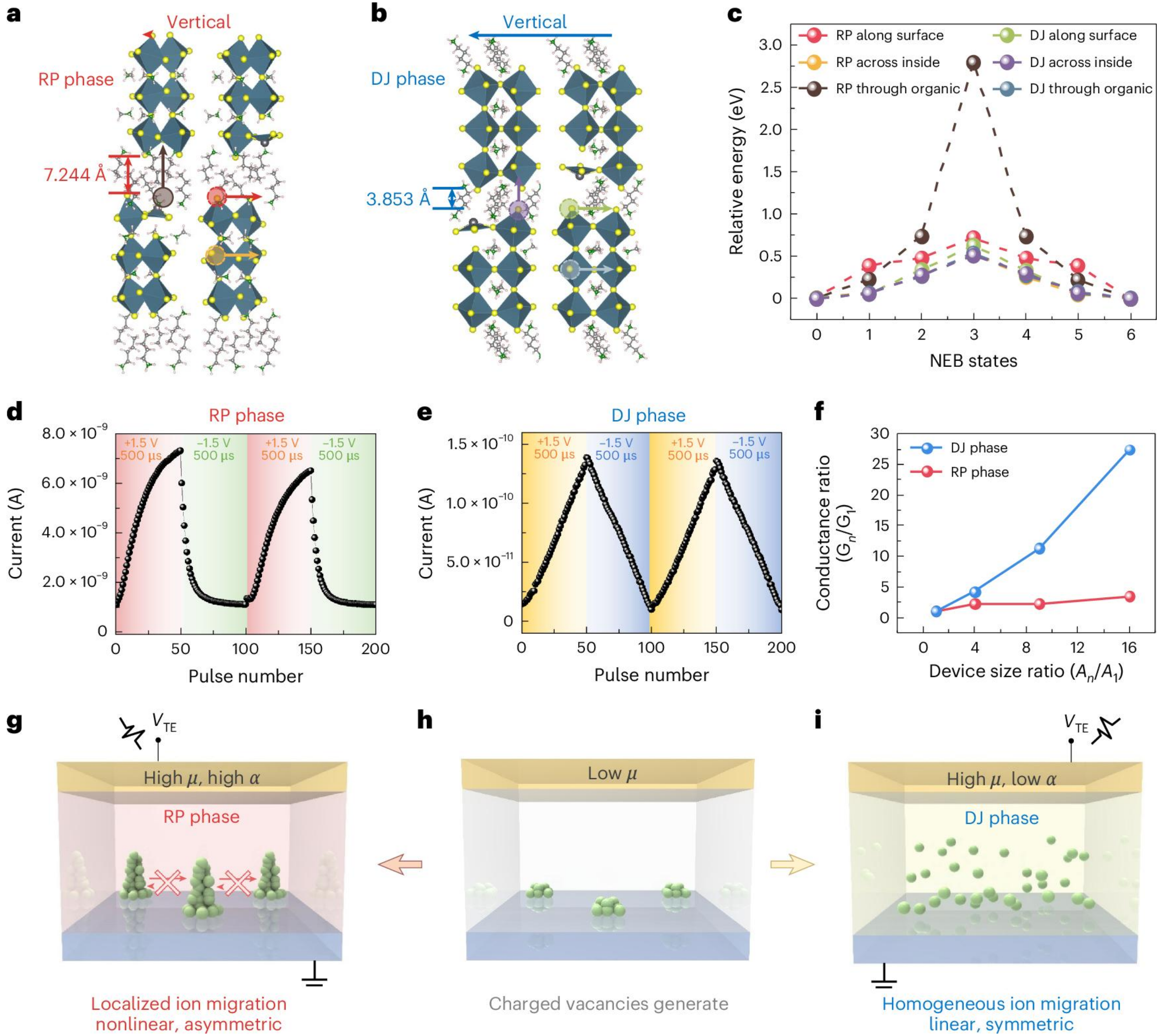


Nat. Nanotechnol. (2025)

Synaptic plasticity of DJ-V-HP artificial synapses

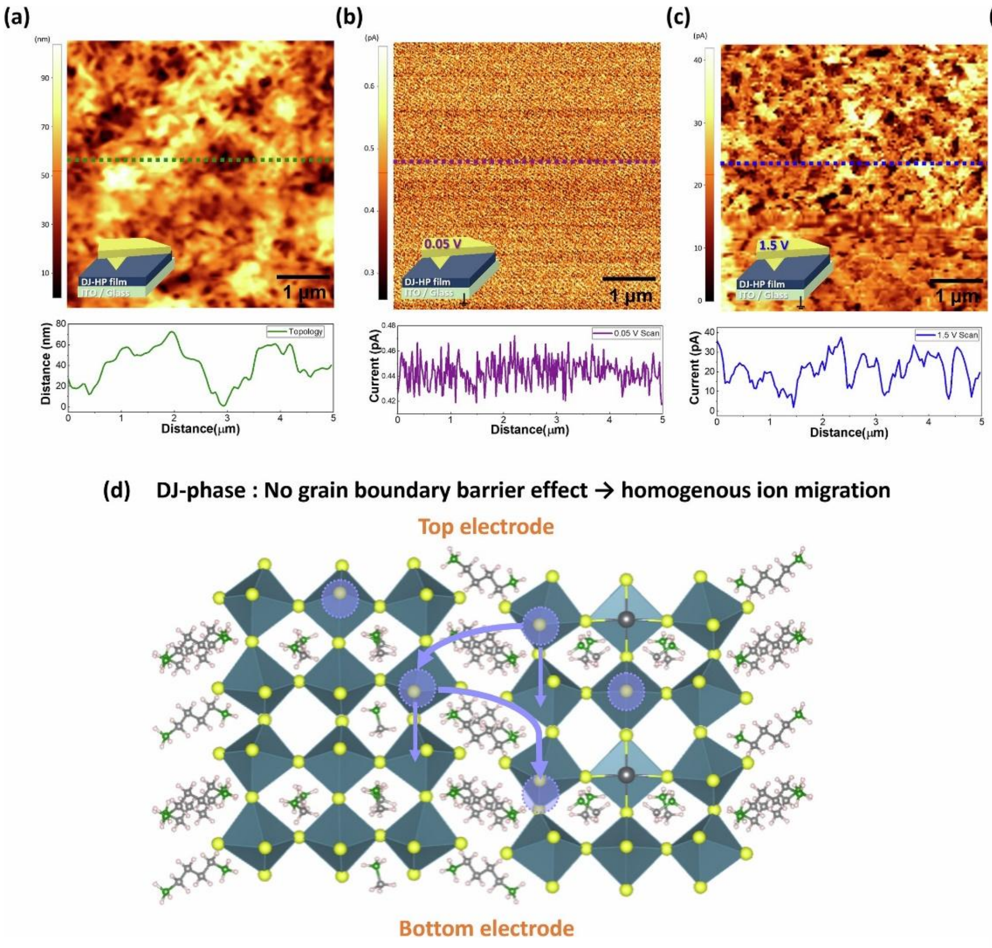


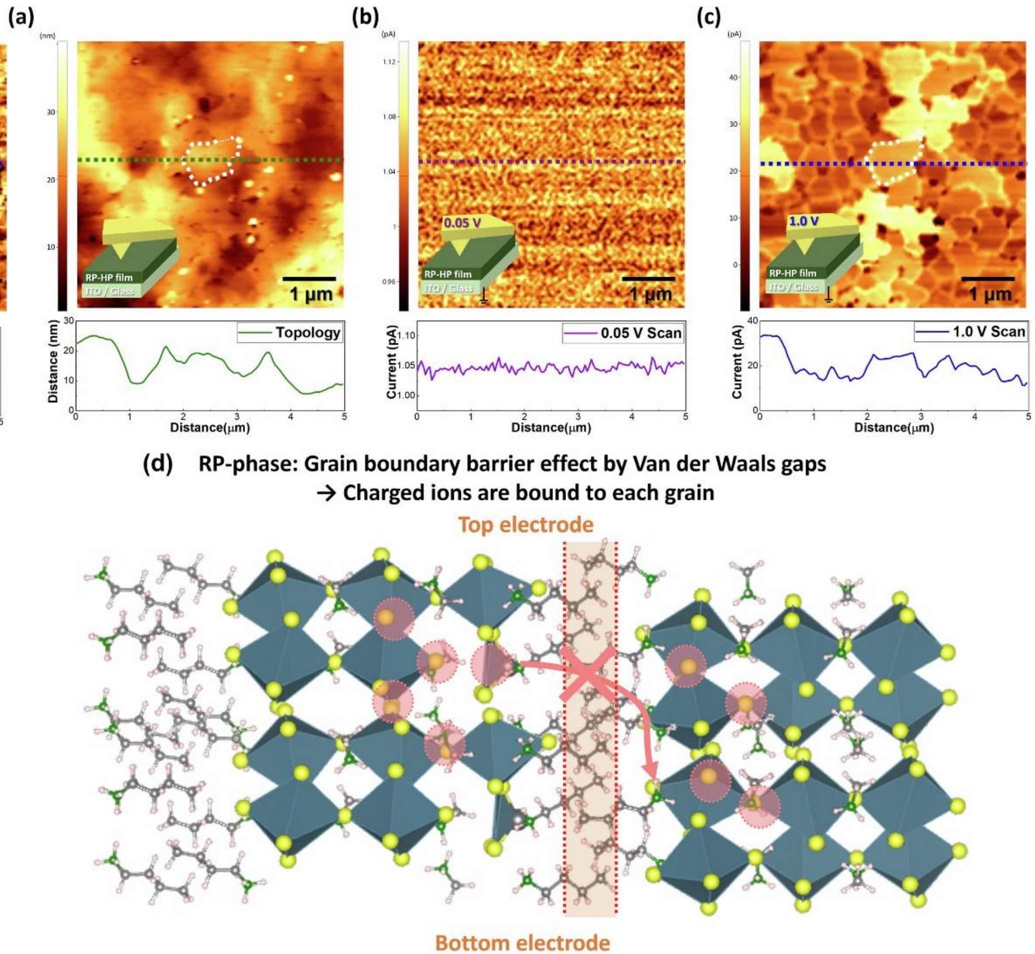
Disclosing resistive switching mechanisms in DJ- and RP-phase HPs



Prof. Donghwa Lee (POSTECH)

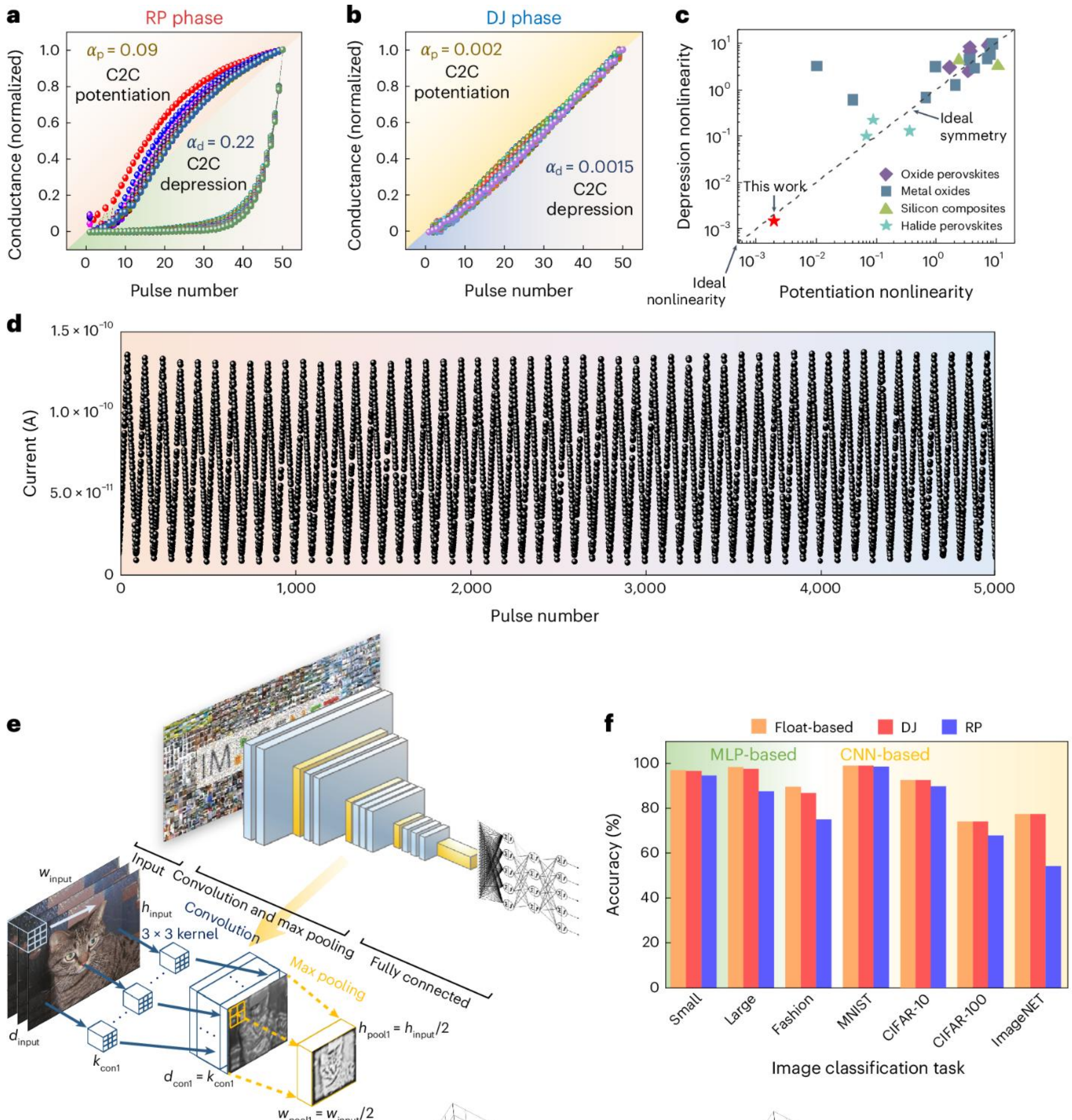
Sharp contrast in C-AFM images





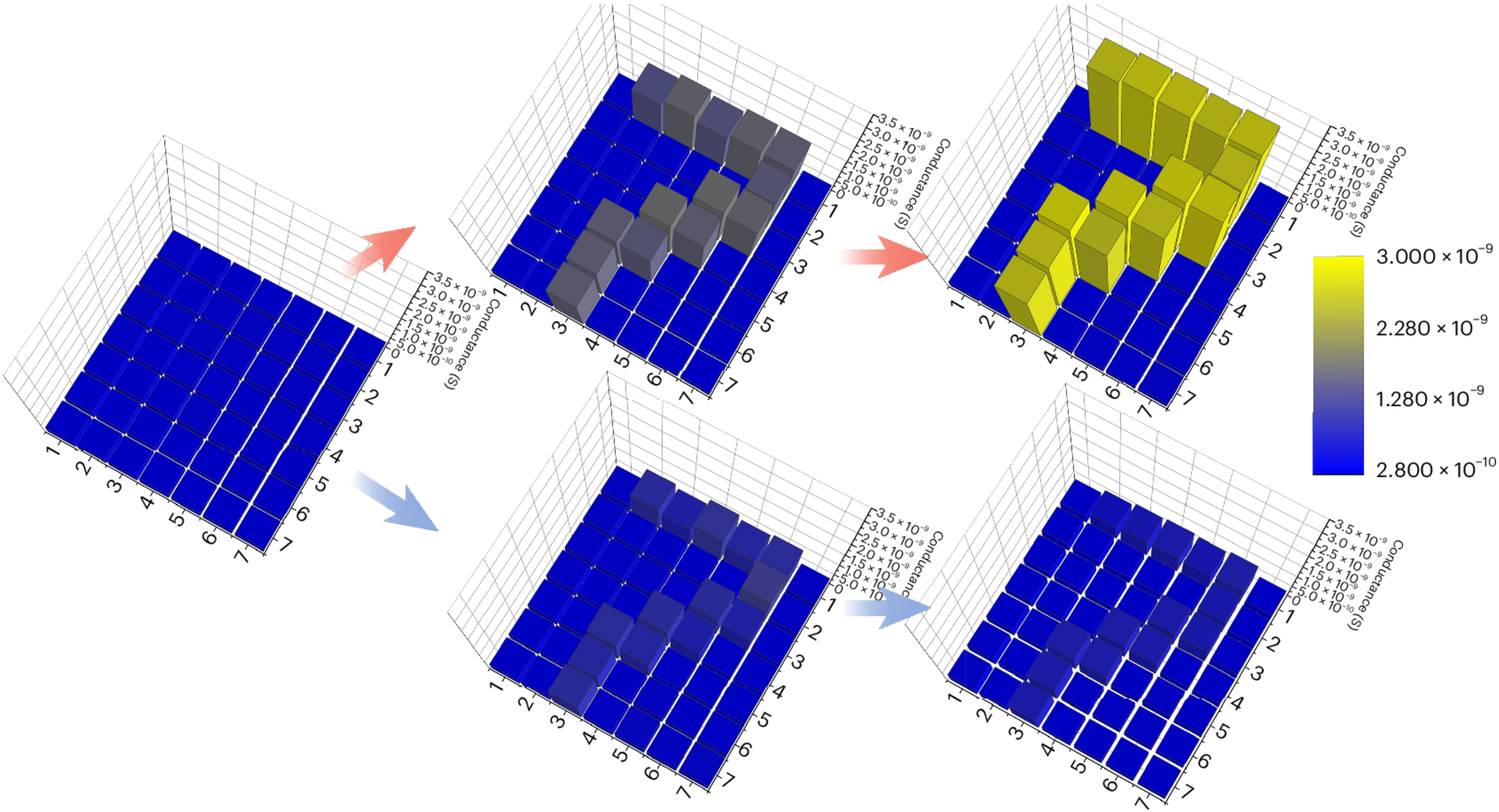
To further investigate the grain boundary barrier effect of charged ion migration, we performed conductive atomic force microscopy (C-AFM). The ion migration properties near the grain boundaries are a major determinant of whether homogeneous or localized ion migration is enabled

Neuromorphic crossbar array for AI acceleration



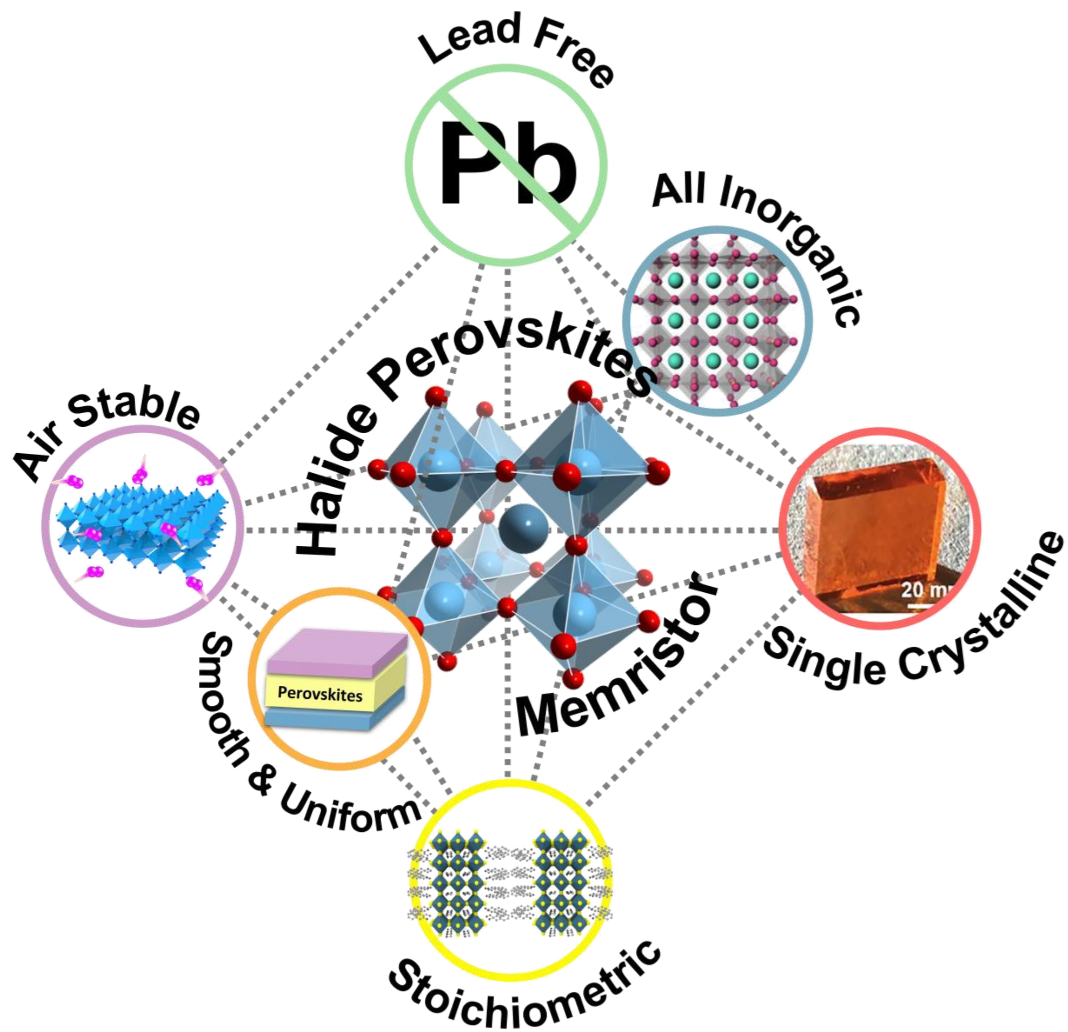
Prof. J. Joshua Yang (USC)

Programming 7 × 7-pixel hand-written images



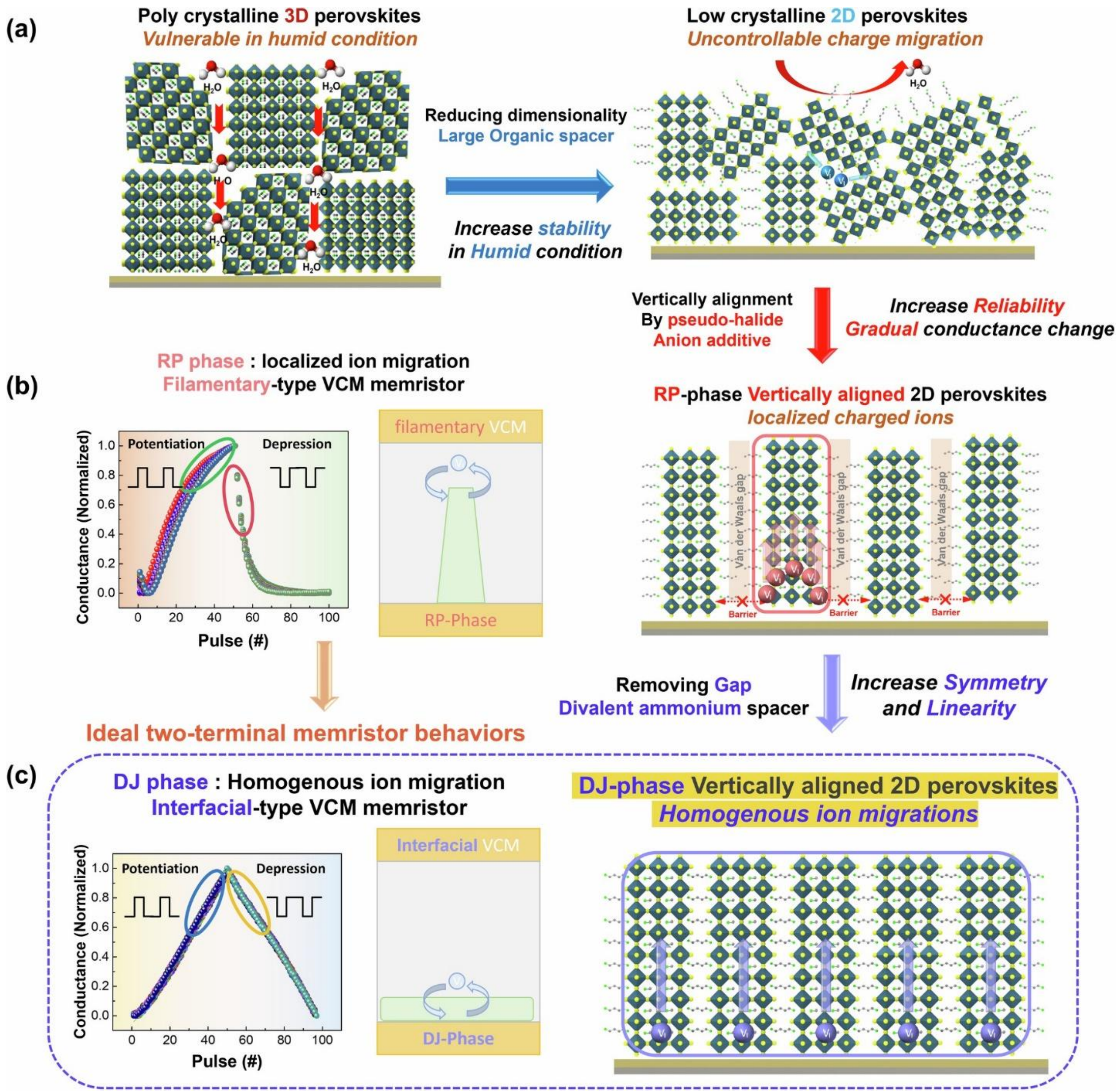
To demonstrate the synaptic weight storing capability, a 7 × 7 hand-written image was programmed into our DJ-V-HP crossbar array. We used long-term plasticity (LTP) and short-term plasticity (STP) characteristics to program the image into the crossbar

Challenges

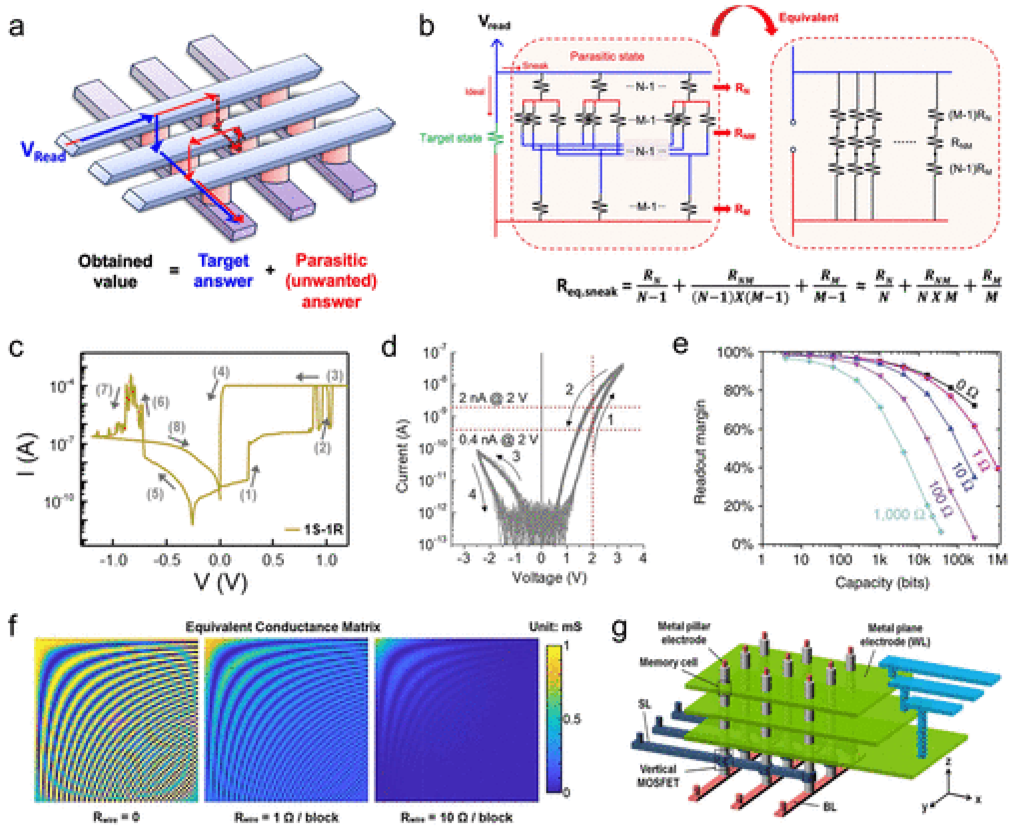


J. Phys. Chem. Lett. 2021, 12, 37, 8999–9010

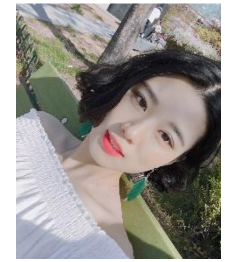
Short summary



Issue in memristor array integration



Youngmin

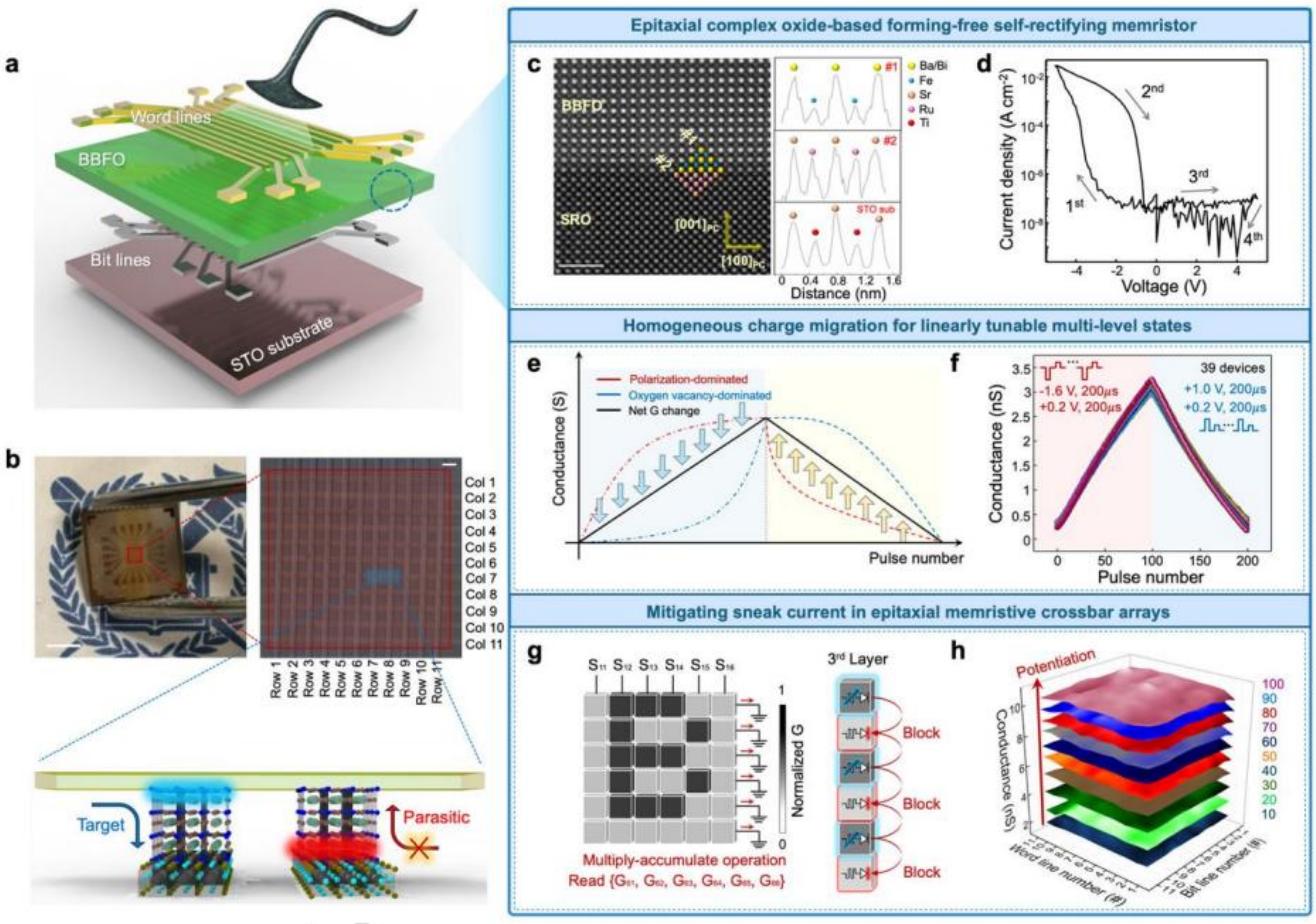


Dr. Ji Hyun Baek

Dr. In Hyuk Im

Figure 11. Issues in memristor array integration. (a) Schematic of the crossbar array with sneak current pathway during reading operation. (b) Equivalent transformed circuit diagram of the all current components during the operation of $M \times N$ crossbar array. Each sneak path is composed of serially connected $(M-1)R_N$, R_{MN}, and $(N-1)R_M$. (c) I–V characteristic of 1S-1R integrated component. (d) I–V characteristic of self-rectifying memristor. Reproduced with permission under a Creative Commons CC BY License from ref 244. Copyright 2021 Springer Nature. (e) The normalized readout margin according to the wire resistance, which is calculated by the circuit used in the SPICE simulation. Estimated crossbar array scale decreases with high wire resistance. Reproduced with permission under a Creative Commons CC BY License from ref 247. Copyright 2017 Springer Nature. (f) The color maps illustrating the effective conductance matrix in the memristor crossbar array with varying parasitic wire resistances. The left and upper sides of the map represent the conductance of the devices closer to the voltage source and bias ground, respectively. With increase in wire resistance, the device at the edge far from the source and ground receives reduced bias. Reproduced with permission under a Creative Commons Attribution License from ref 288. Copyright 2021 Wiley-VCH. (g) Illustration of the 3D crosspoint architecture based on the vertical memristor devices with the intersections of each pillar electrode and each plane electrode. Reproduced with permission from ref 289. Copyright 2013 American Chemical Society.

Programmable ferroelectric rectifier



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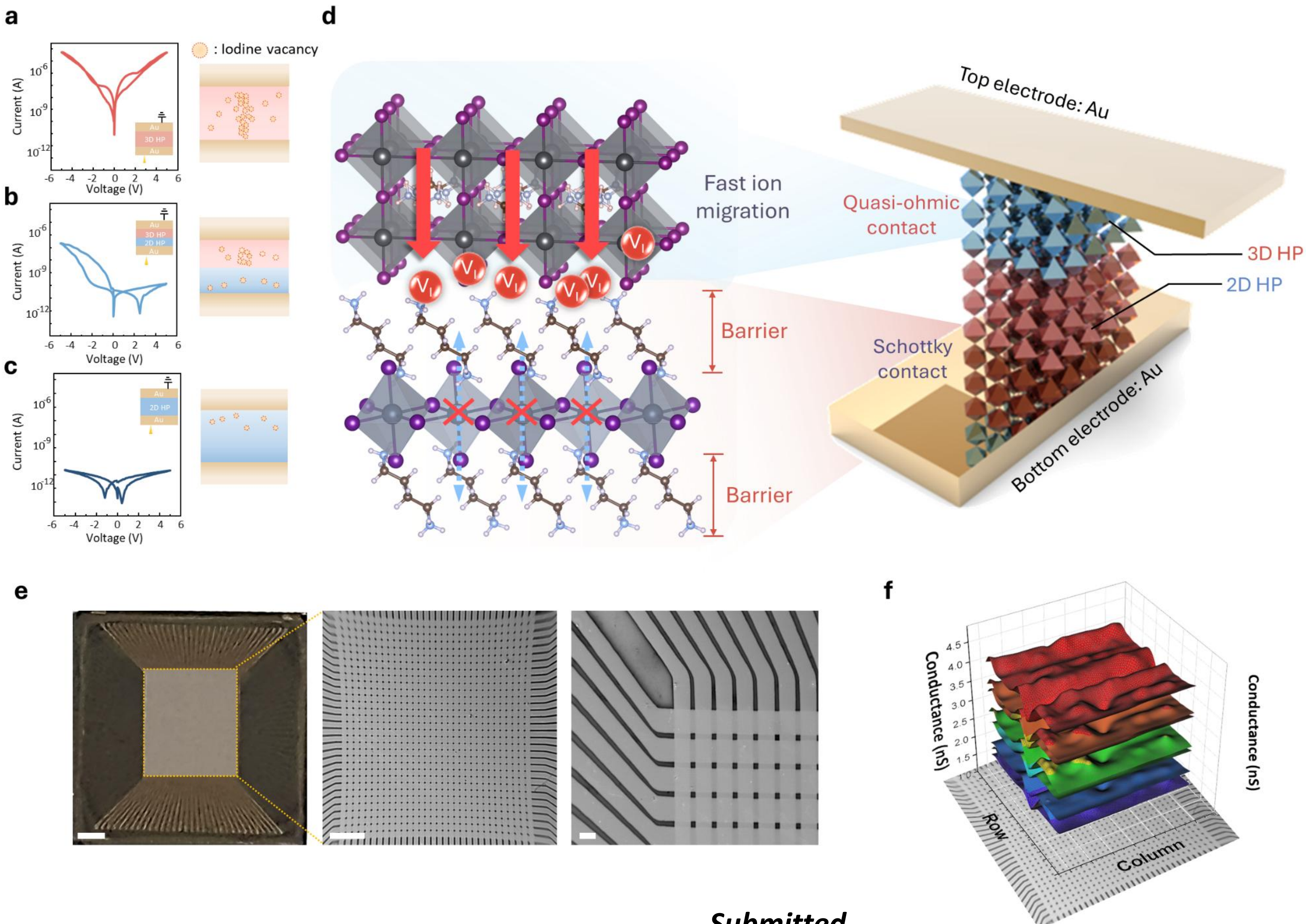
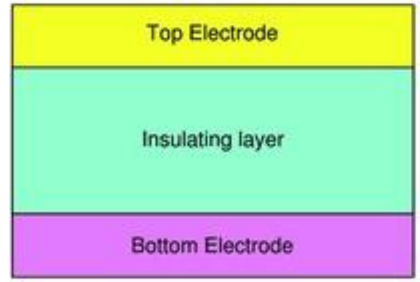
Self-rectifying 3D/2D HP memristors for crossbar array



Submitted

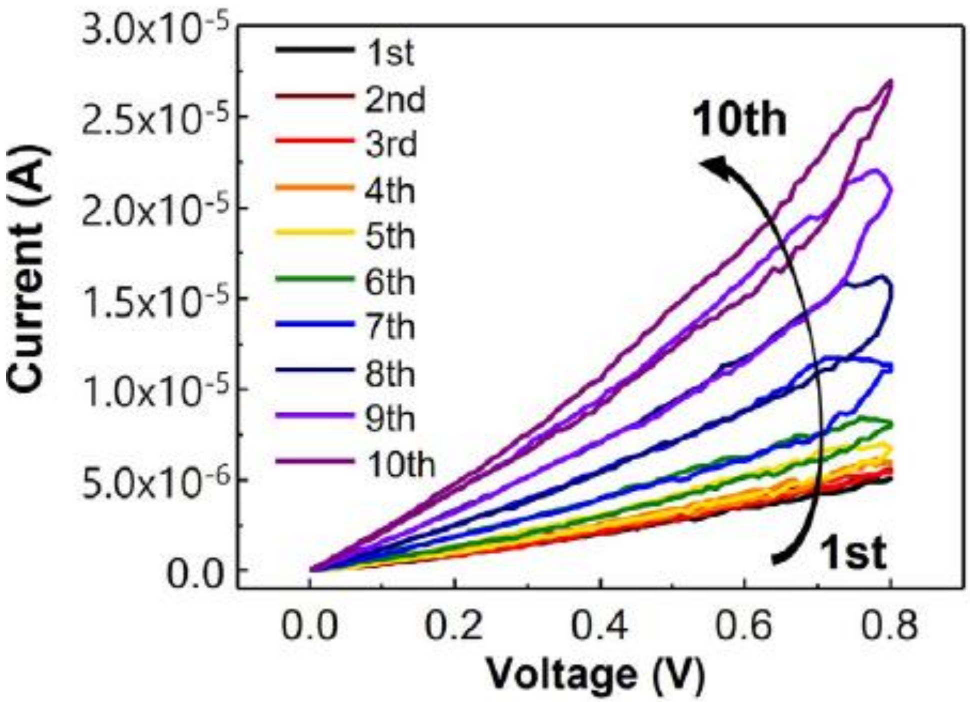
Short but clear remark

10^7 cm/s: electron in Si MOSFET
10^2 cm/s: action potential in neuron

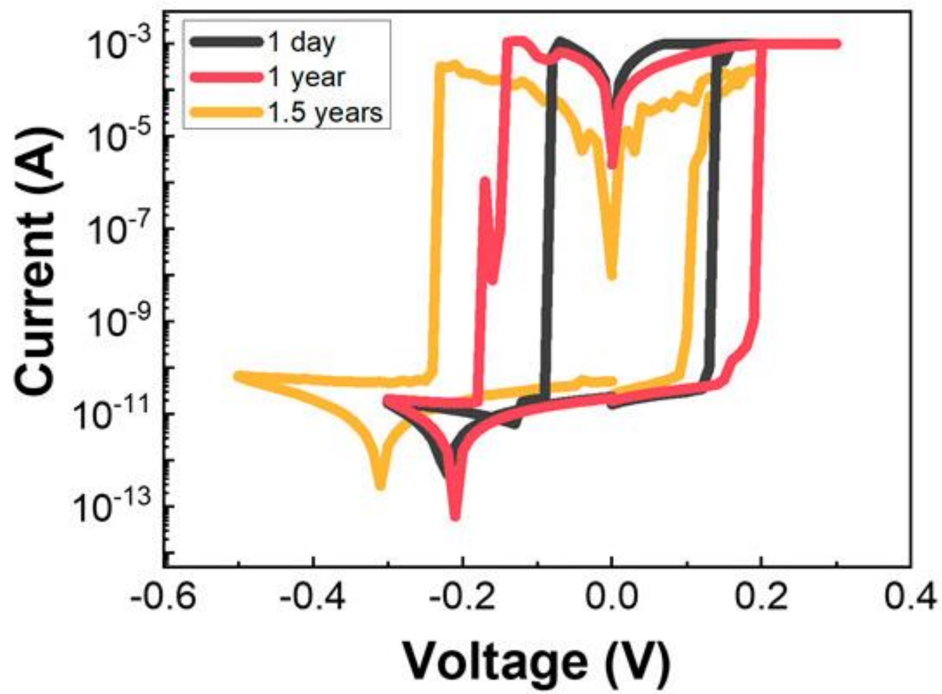


Slow and low-voltage sweep without filament formation

Fast and high voltage sweep after filament formation



Analog resistive switching
→ Neuromorphic computing



Digital resistive switching
→ Nonvolatile memory

Dr. Seung Ju Kim (SNU & USC)

Prof. J. Joshua Yang (USC)

Prof. Donghwa Lee (POSTECH)

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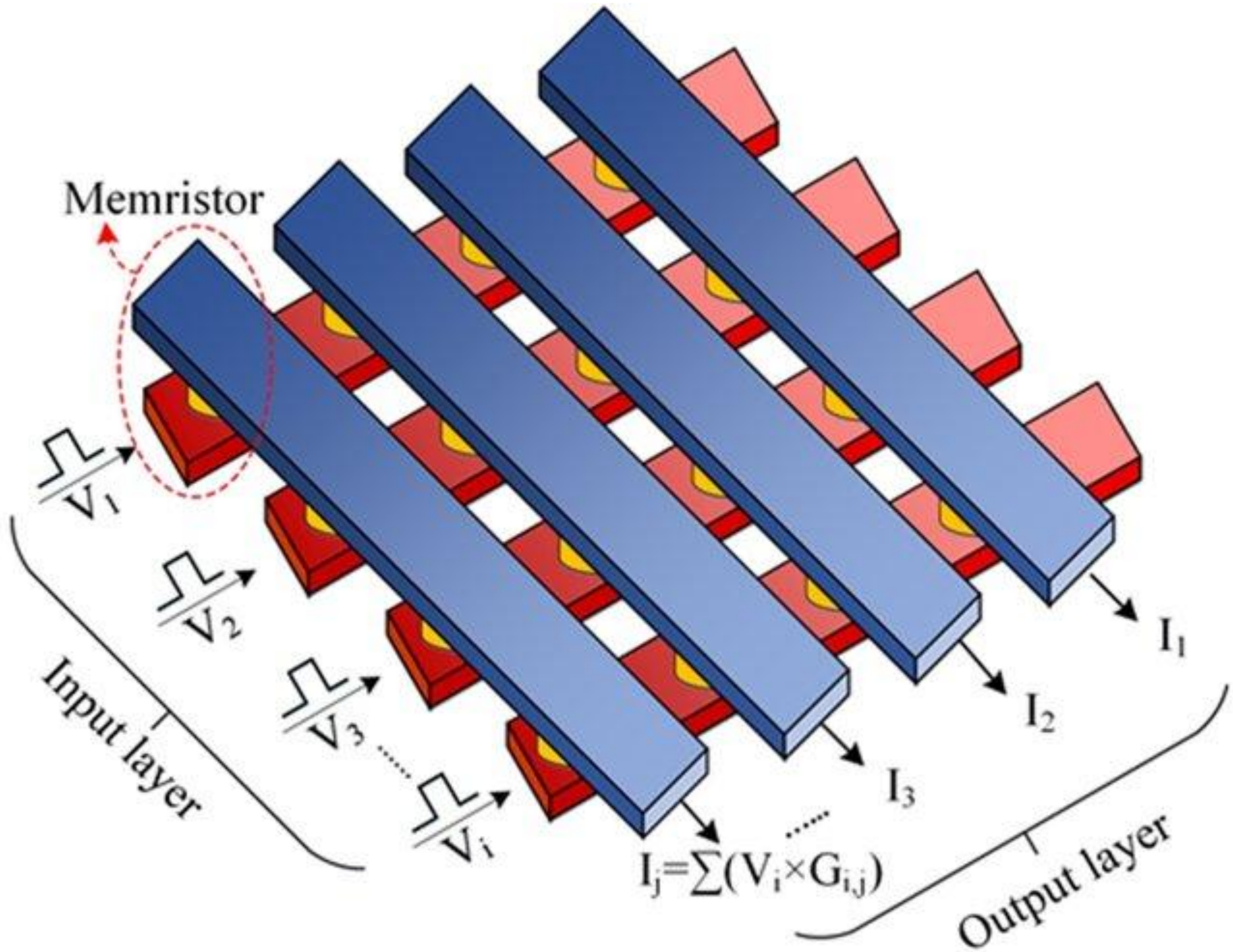
Thank you for your attention.

Q & A



Memristor
V_1
V_2
V_3
V_i
Input layer
I_1
I_2
I_3
$I_j=\sum(V_i \times G_{i,j})$
Output layer