ROK-EU
Semiconductor Researchers Forum

SMART
Metal

Hanwool Yeon
Research Group

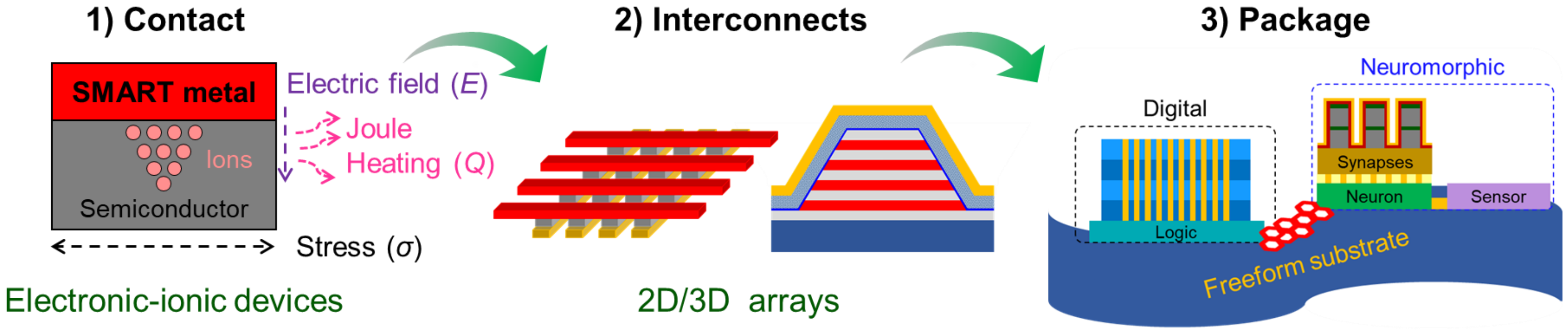
GIST

Tailoring Memristors through Metallization on Amorphous Thin Films

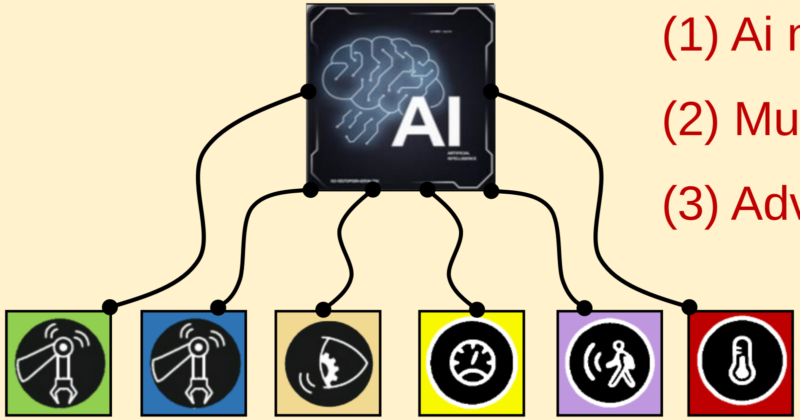
Hanwool Yeon

2024-03-26

Synergy
Mechanics
Atomic kinetics
Regulating structures
Thermodynamics



SMART Metallization Lab.



(1) Ai memory

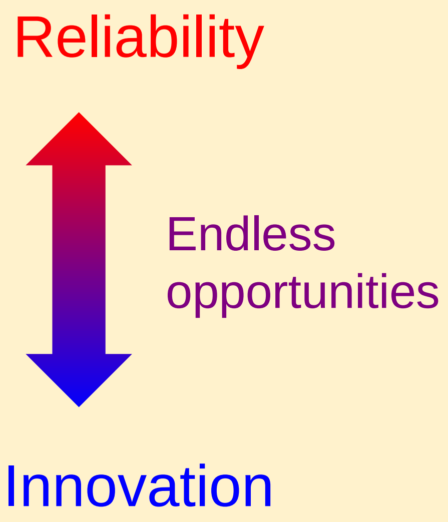
(2) Multimodal sensors

(3) Advanced packaging

Neuromorphic edge Ai
(On-device sensing & processing)

Synergy
Mechanics
Atomic kinetics
Regulating structures
Thermodynamics

*Thanks to
Prof. Peng Lin

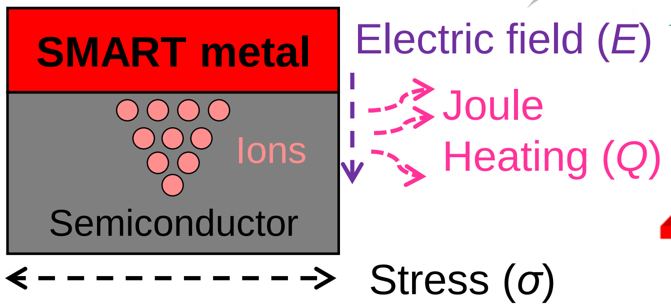


Reliability

Endless opportunities

Innovation

1) Contact

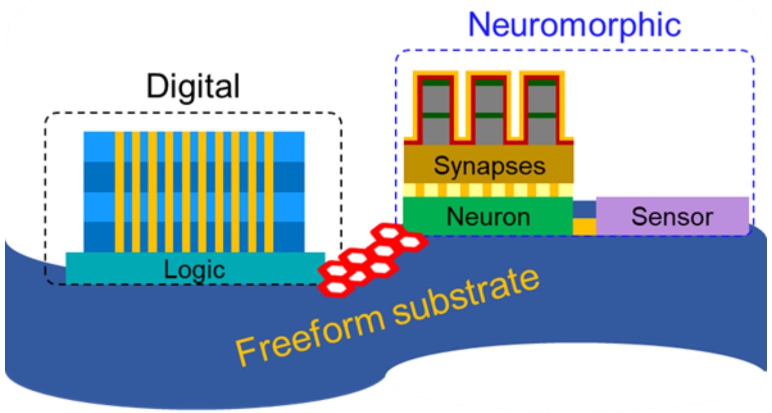


Electronic-ionic devices

2) Interconnects

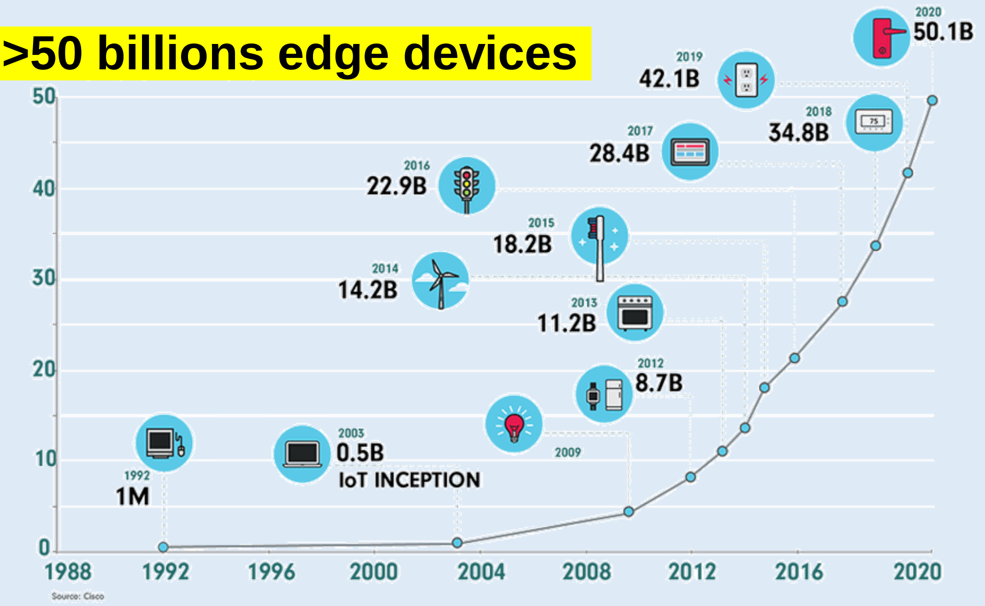
2D/3D arrays

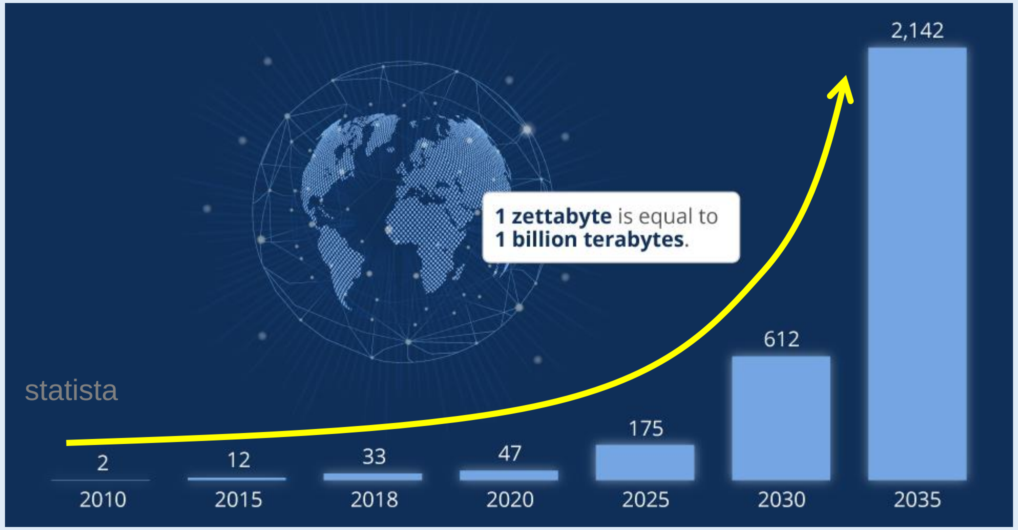
3) Integration



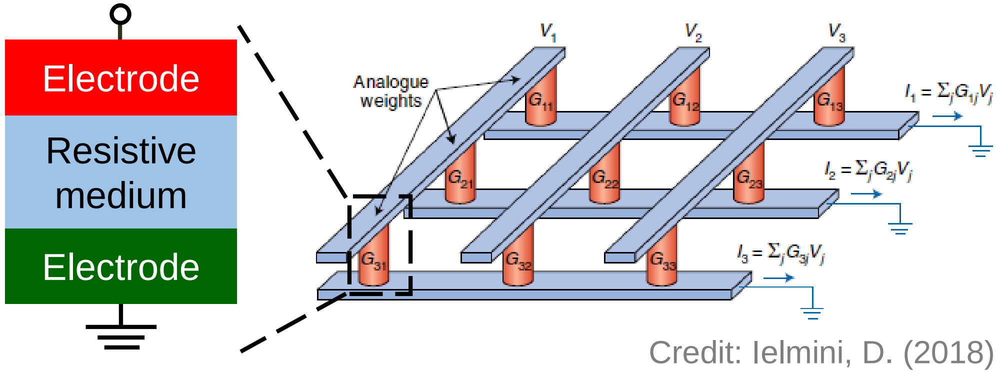
Emerging Memory Device in the Data Explosion Era

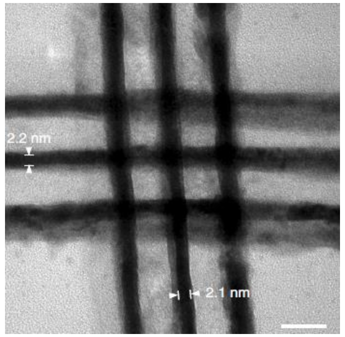
>>50 billions edge devices





Memristor (or RRAM)





Credit: Ielmini, D. (2018)

Credit: Xia, Q (2019)

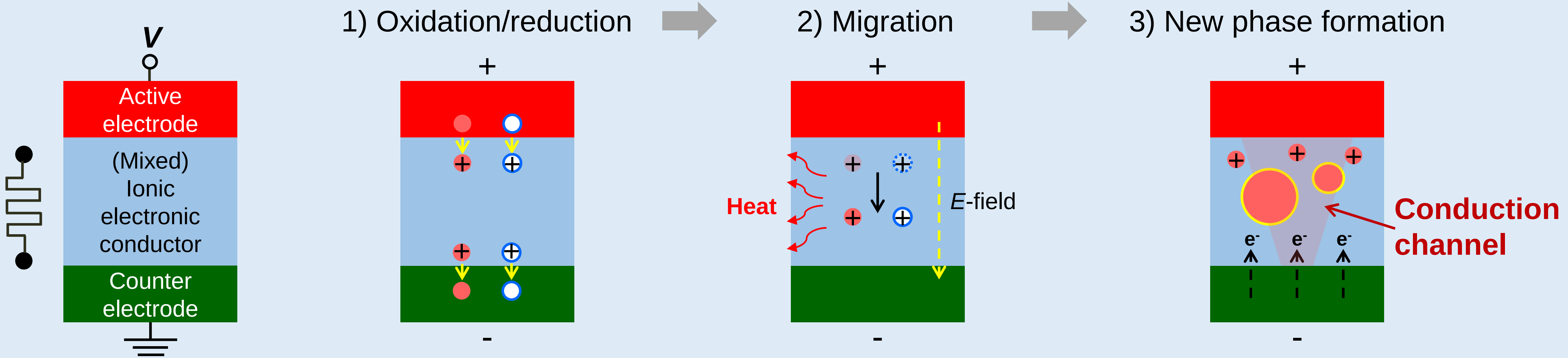
Nano-scalable, two-terminal conductance switch

	Metric	DRAM	Flash	Memristor
1	**Programming speed** (s)	1.00E-08	1.00E-04	8.50E-11
2	**Programming energy** (J)	5.00E-15	2.00E-17	1.15E-13
3	**Standby power** (W GB^{-1})	1.00E-01	1.00E-03	1.00E-03
4	**Endurance** (cycles)	> 1E16	1.00E+04	1.00E+12
5	**Retention** (@ RT)	64 ms	10 years	1000 years
6	**Memory states**	2	≥2	≥64

Yang, J. J. *Nature Nanotechnology* 8, 13 (2012), *Nature Rev. Mater.* 5, 173 (2020)

1) massive data storage, 2) high-density memory & 3) in-memory computing

Key Principles of Memristors

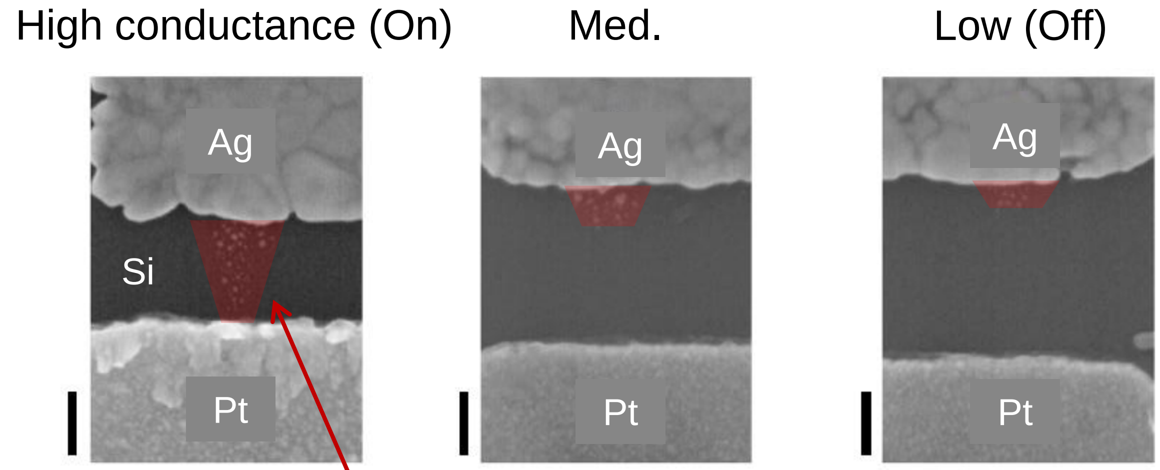


● *Extrinsic* cation (M^{n+})

⊕ *Intrinsic* cation (e.g., O vacancy)

Joule heating-accelerated ion migration

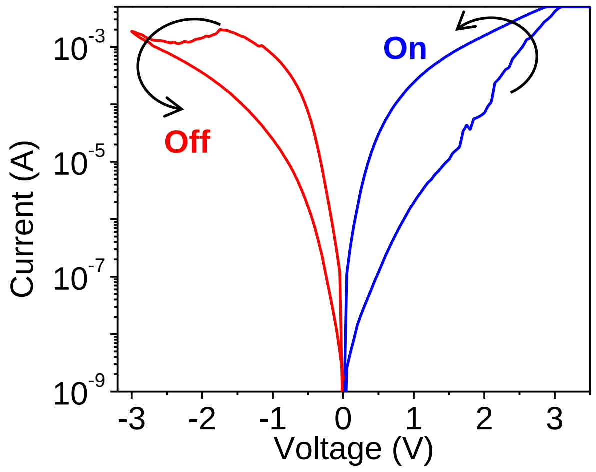
Heterogeneous nucleation & growth



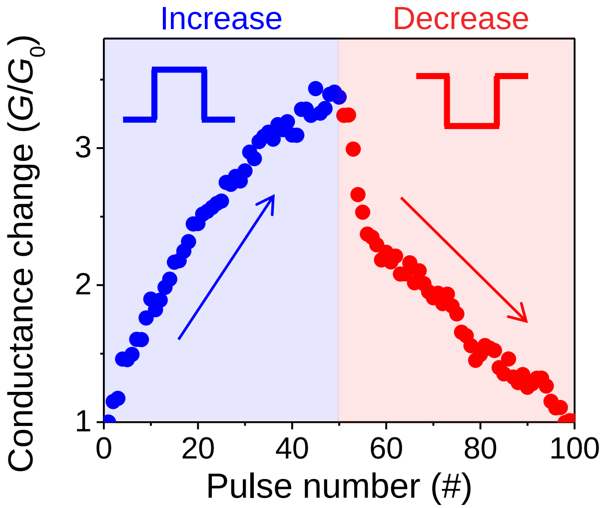
100 nm

Conduction channel

Image credit: Wei Lu group (2012)



DC switching



Pulse switching

Memristors for Diverse Applications

	Requirements	Best result	Storage	Memory	Inference	Training
1	**Spatiotemporal variation**	1%	Low	Low	Low	Not critical
1	**Conductance states**	64	2 - 16	2	2 - 32	64 - 512
2	**Analog switching linearity/symmetricity**	0.1	Not critical	Not critical	<1	<1
3	**on/off ratio**	64	>10	>50	>10	>500
4	**Off-state conductance**	0.01 μS	<1 μS	<10 μS	<0.01 μS	<0.01 μS
5	**Switching speed**	85 ps	< 10 μs	< 1 ns		Not critical
6	**Min. programming energy**	0.12 pJ	<1 pJ	<5 fJ	<10 pJ	Not critical
1	**Endurance**	1.0E+12	> 1E4	>1E16	Not critical	>1E11
2	**Retention** (@ RT)	1000 years @ RT	>10 years	> minutes	> 10 years	Not critical

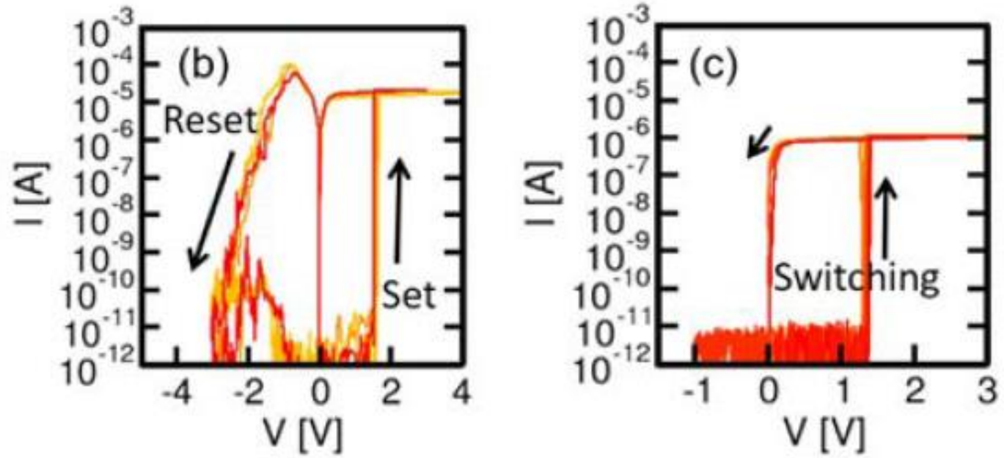
References: Yang, J. J. *Nature Nanotechnology* 8, 13 (2012), *Nature Rev. Mater.* 5, 173 (2020), Hwang, H. group, IEDM15-91 (2015)
Xiong, F. group. *Adv. Mater. Technol.* 4, 1900037 (2019), Wu, H. group, *Nature Electronics* 3, 371 (2020)

Amazing potential to meet the demands of each application.

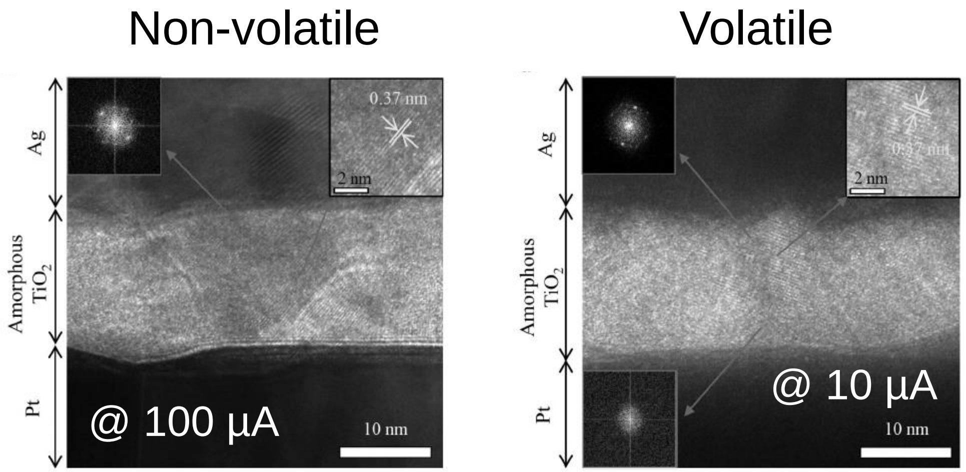
Grand Issue: Performance Dilemmas

No memristors have fulfilled all the favorable properties simultaneously

1) Programming current vs. non-volatility



Ielmini, D. group, IEDM16-87 (2016)



Hwang, H. group. *Adv. Mater.* 29, 1701752 (2017)

Less energy consumption, but poor retention

The less volume, the less stable

$$* \; Compression \propto \frac{Interfacial\ energy}{channel\ size}$$

2) Endurance vs. switching stability (variation & retention)

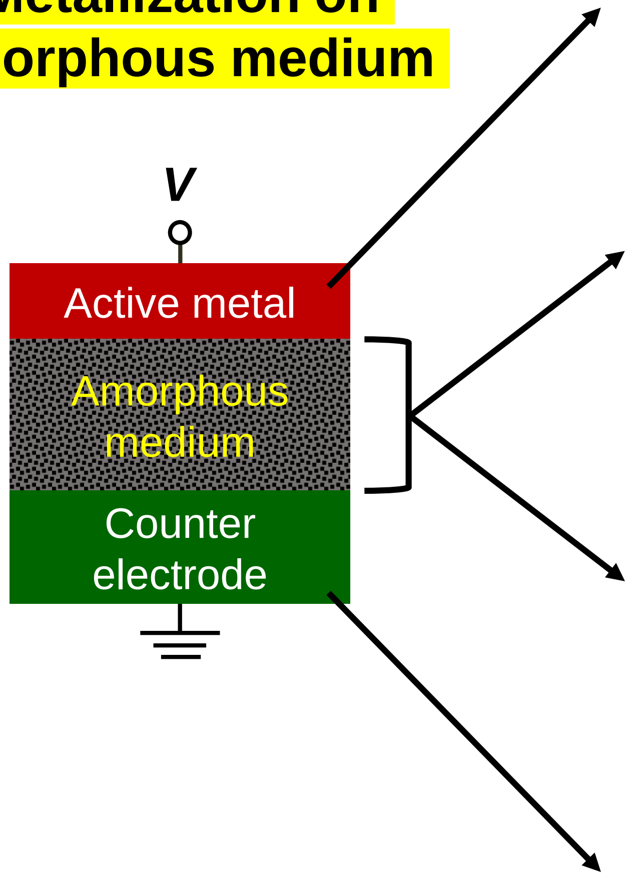
3) Digital switching vs. analog switching

⋮

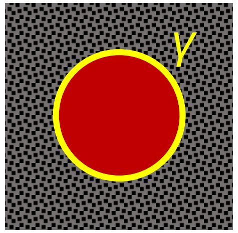
Material solutions enabling mitigation of the dilemmas are needed.

Our Material Strategies to Address the Dilemmas

Metallization on amorphous medium



1) Alloy

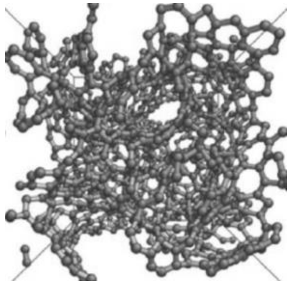


Concentration, interfacial energy, etc.

2) Dangling bonds

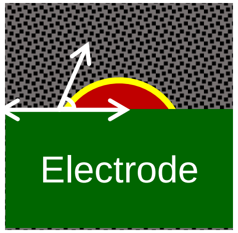
Ion mobility, nucleation barrier, etc.

3) Porosity



Ion mobility, nucleation barrier, etc.

4) Electrode surface



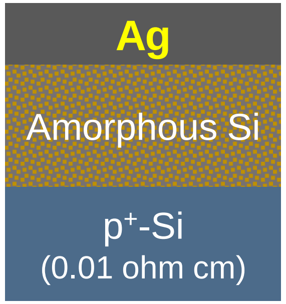
Nucleation barrier, etc.

Controlling thermodynamic and kinetic factors between metals and amorphous materials

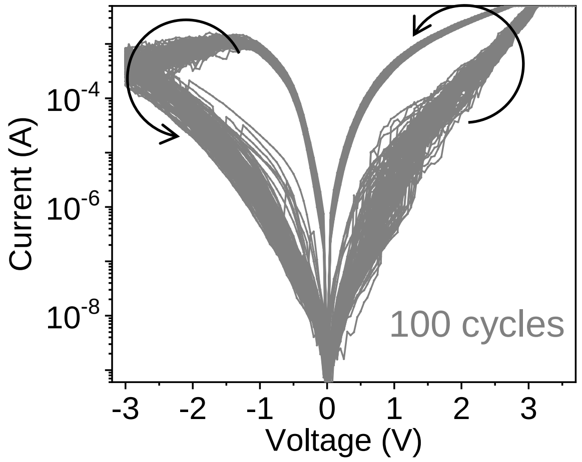
Strategy 1) Metal Alloy Design

Yeon, H. et al., *Nature Nanotechnology* 15, 574 (2020)

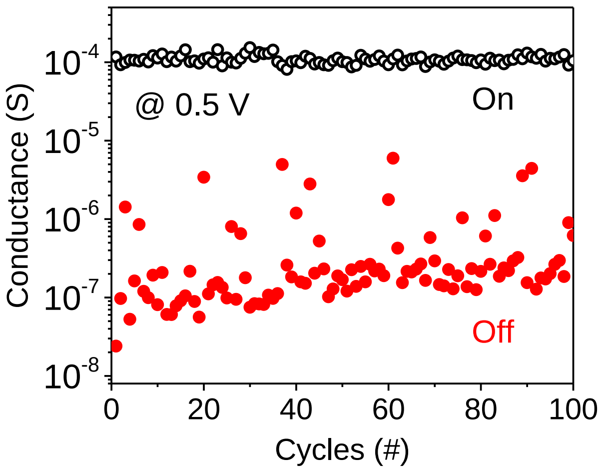
endurance vs. switching stability (variation & retention)



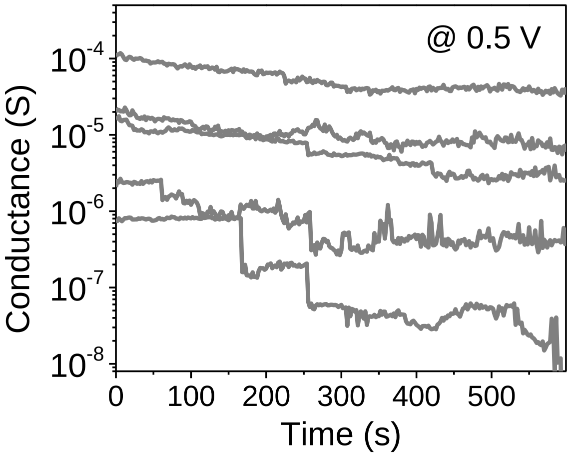
Reversible switching

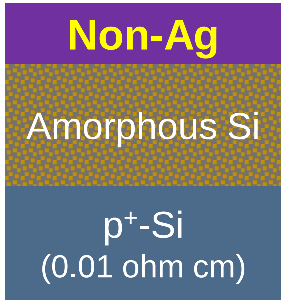


Non-uniform

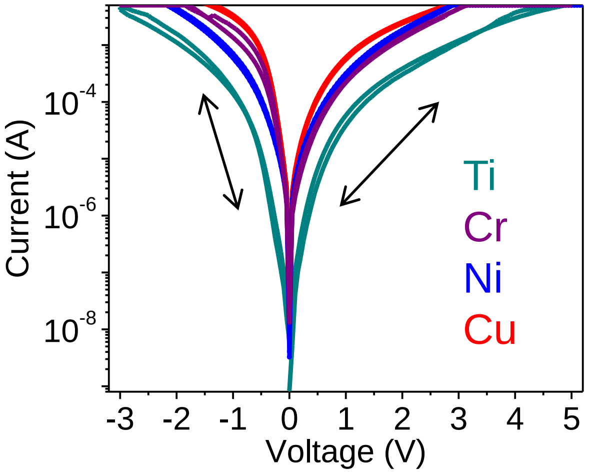


Poor retention





Irreversible switching



Active metal	migration path in Si	Thermodynamic interaction with Si
Ti	Interstitial sites	Silcidable metals Miscible (favorable)
Cr		
Ni		
Cu		
Ag		Immiscible (Unfavorable)

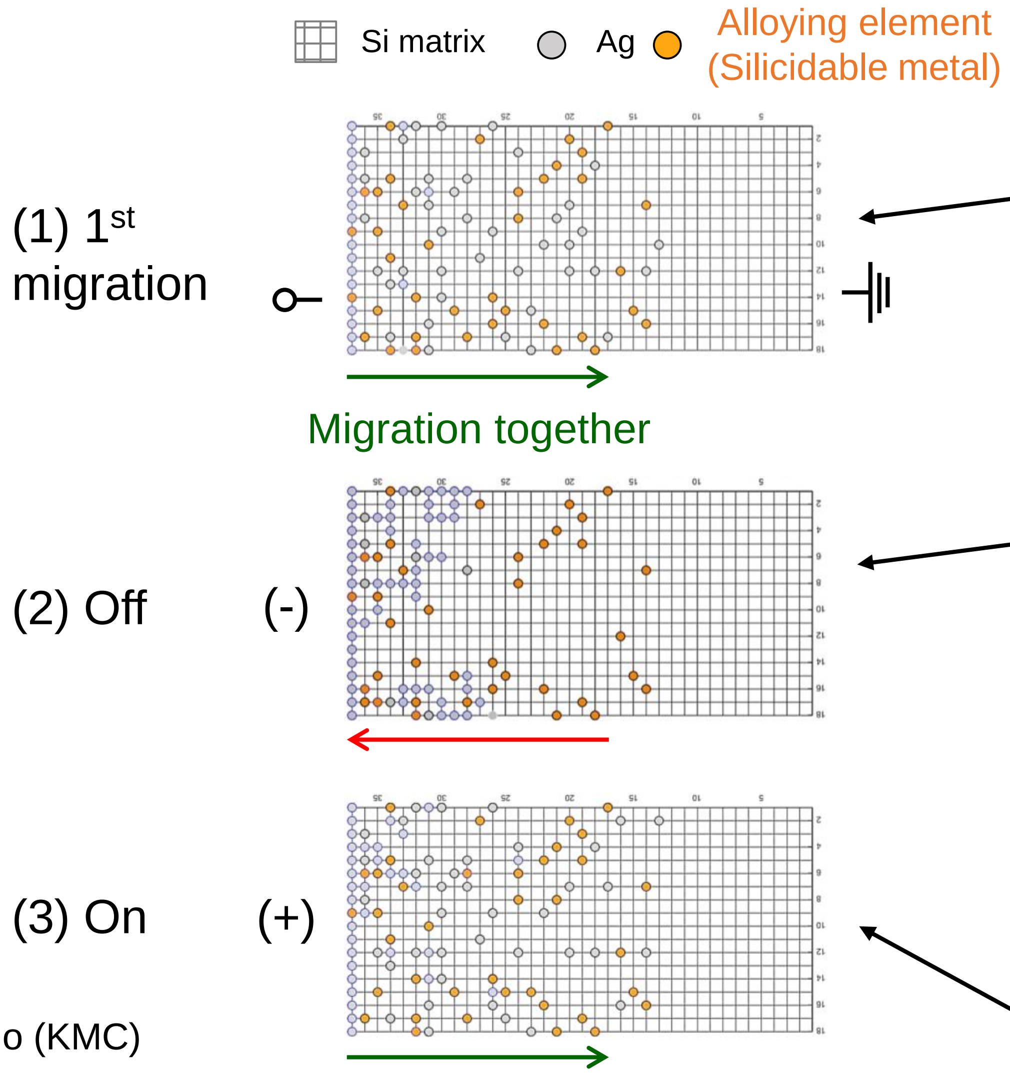
Let's make Ag alloy!

Switching stability would be strongly related to **thermodynamic stability** of metals in Si

Strategy 1) Metal Alloy Design

Yeon, H. et al., *Nature Nanotechnology* 15, 574 (2020)

Let's imagine metal movements!



(1) High mobility of alloying elements

Ag: Dominant material
Alloying elements: additives

(2) Attractive interactions with the medium

Strong bonding of alloying elements with Si
Poor backward migration
***Residual channels**

(3) Favorable thermodynamic interactions of alloying metal with Ag

Alleviation of repulsive interaction btw Ag and Si
***Backbone of channels~**
Stabilization of Ag channels

*Kinetic Monte Carlo (KMC) simulation results

Collaboration with Tsinghua Univ. & Lawrence Berkeley National Lab.

*DFT calculation: Chanyeol Choi (co-1st author)

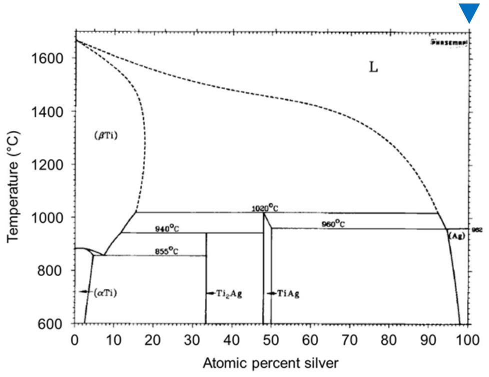
Strategy 1) Metal Alloy Design

Yeon, H. et al., *Nature Nanotechnology* 15, 574 (2020)

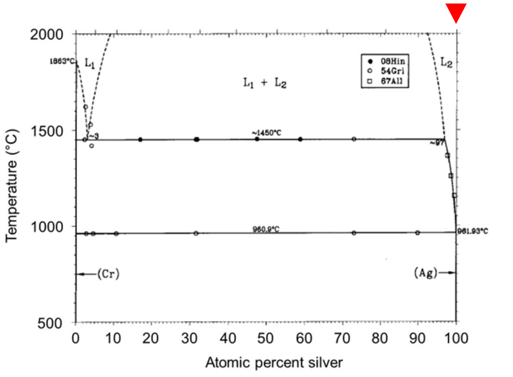
Coupling of

(1) thermodynamic interactions & (2) Kinetics

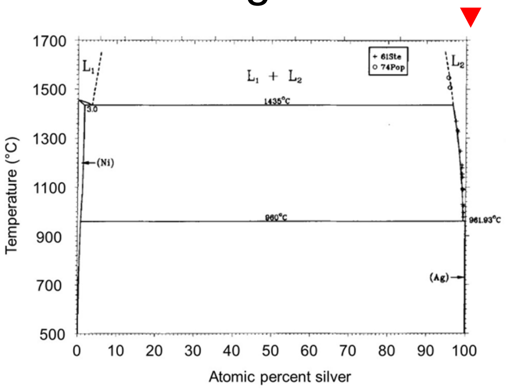
Ag-Ti



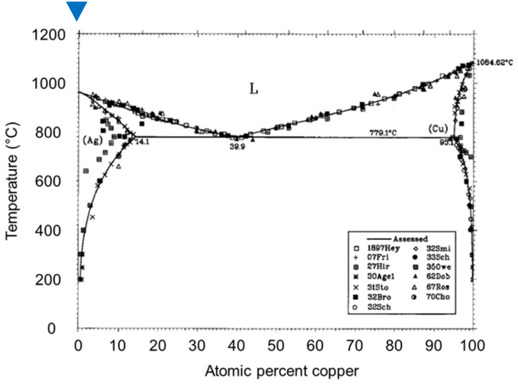
Ag-Cr

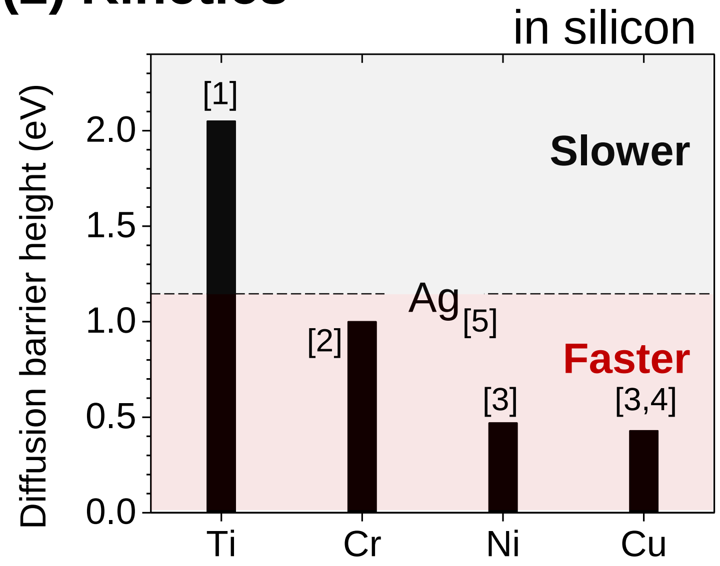


Ag-Ni



Ag-Cu





[1] *JJAP*. 30, 2659 (1991).
[2] *Mater. Res. Bull*. 9, 971 (1974).
[3] *Appl. Phys. A*. 30 1 (1983).
[4] *J. Electrochem. Soc*. 149, G2 (2002).
[5] *J. Phys. D*. 20, 1148 (1987)

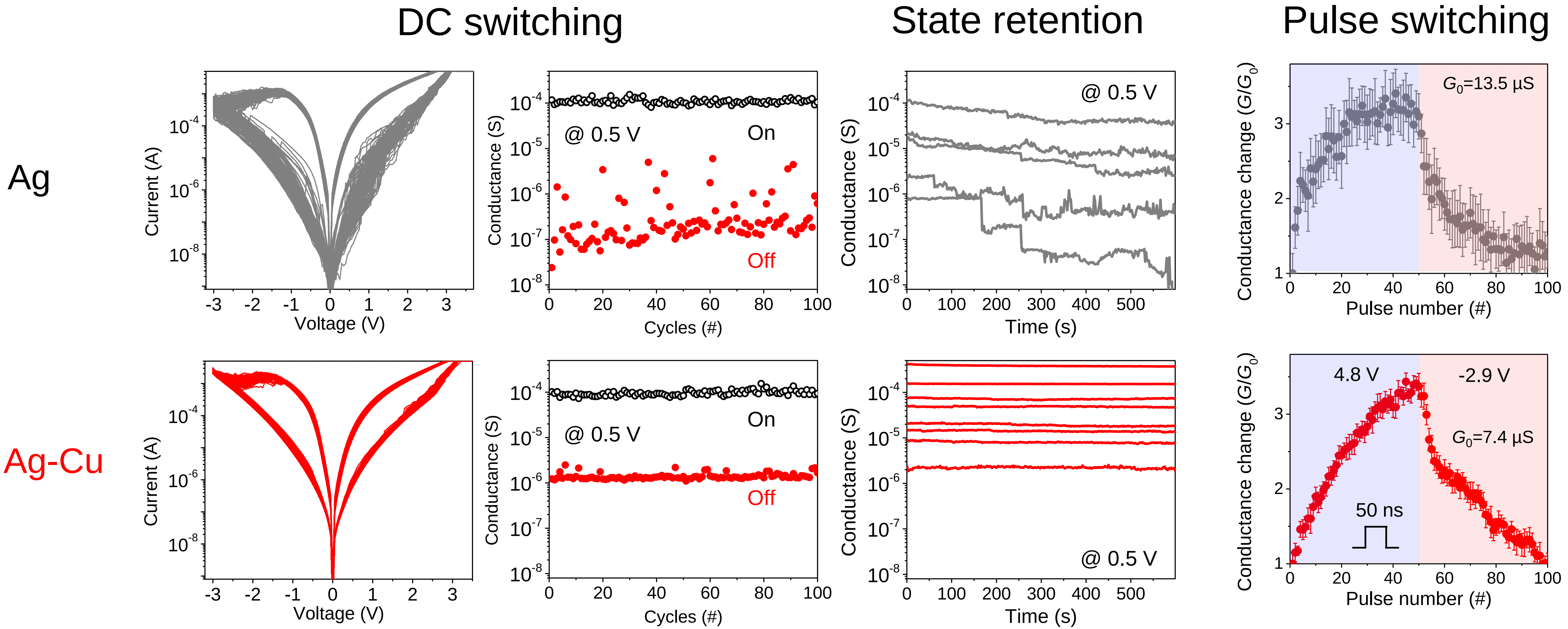
Alloying element	Thermodynamic interaction with Ag	Diffusivity (mobility)
Ti	Miscible (favorable)	Slower than Ag
Cr	Immiscible (unfavorable)	Faster
Ni	Immiscible (unfavorable)	Faster
Cu	Partially miscible	Faster

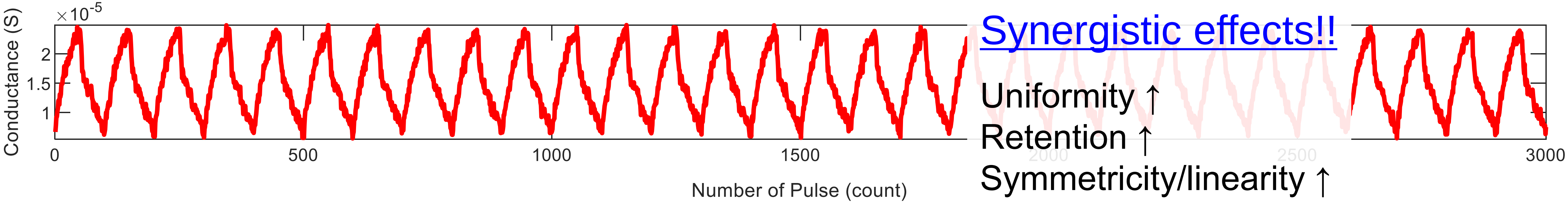
Cu, backbone of Ag channels
→ Uniform switching (stable 'off' state)

→ Stable retention properties
\+ Better analog switching performance

Strategy 1) Metal Alloy Design

Yeon, H. et al., *Nature Nanotechnology* 15, 574 (2020)





Synergistic effects!!

Uniformity ↑
Retention ↑
Symmetricity/linearity ↑

Strategy 1) Metal Alloy Design

Yeon, H. et al., *Nature Nanotechnology* 15, 574 (2020)

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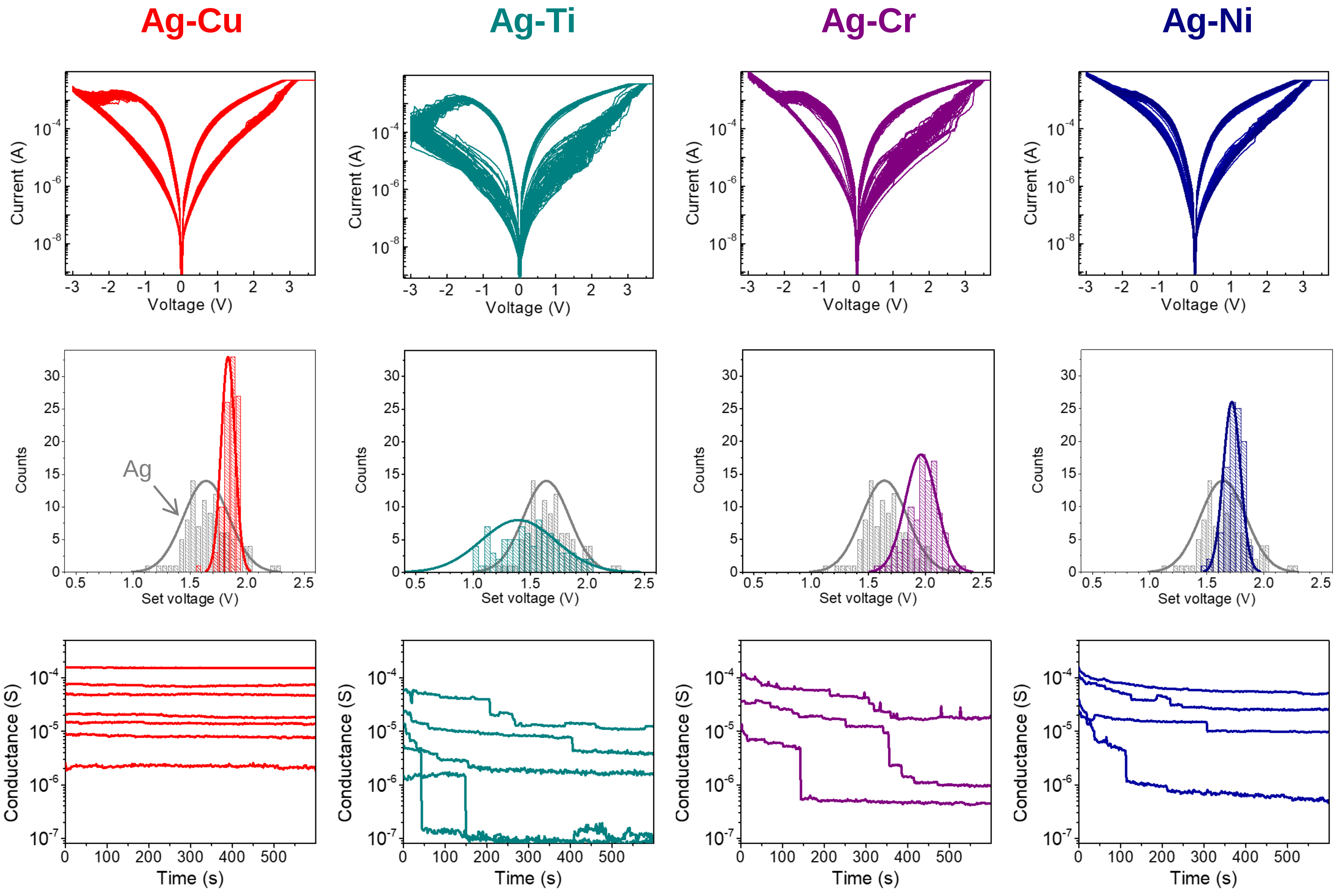


Uniformity ↑
Retention ↑

No effect
(Too slow to form backbone)

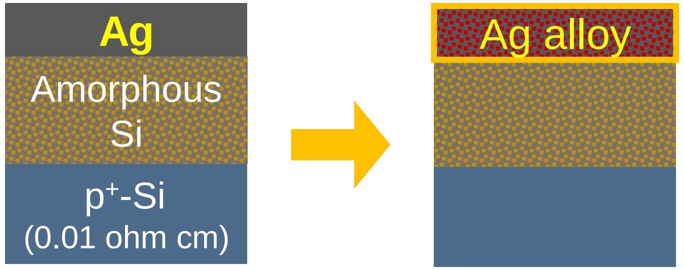
Uniformity ↑
(residual channel)
Retention –
(repulsive interaction)

Uniformity ↑
(residual channel)
Retention –
(repulsive interaction)

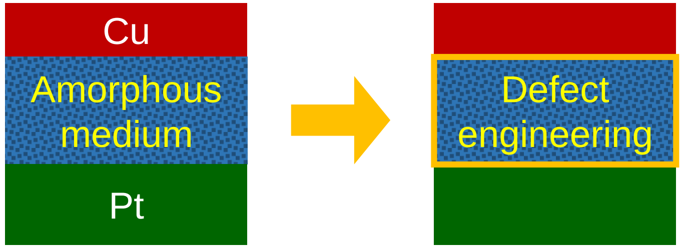
Summary

SMART metallization on amorphous thin films for resolving performance dilemmas & realization of application-tailored memristors

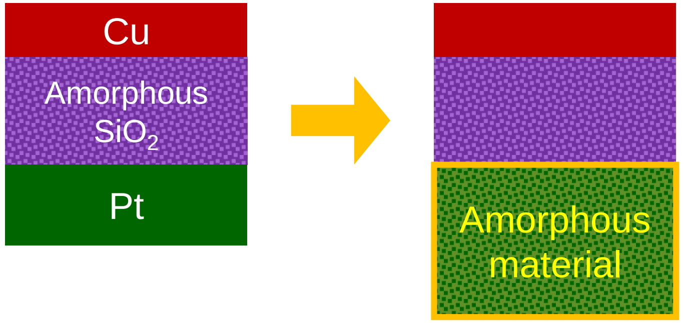
1) Endurance vs. switching stability (variation & retention)



2) Programming current vs. non-volatility



3) Digital switching vs. analog switching



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