UNIVERSITY OF Southampton

Memristive Technologies: Data Storage & Beyond

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Theme Lead – Rad-hard Electronics

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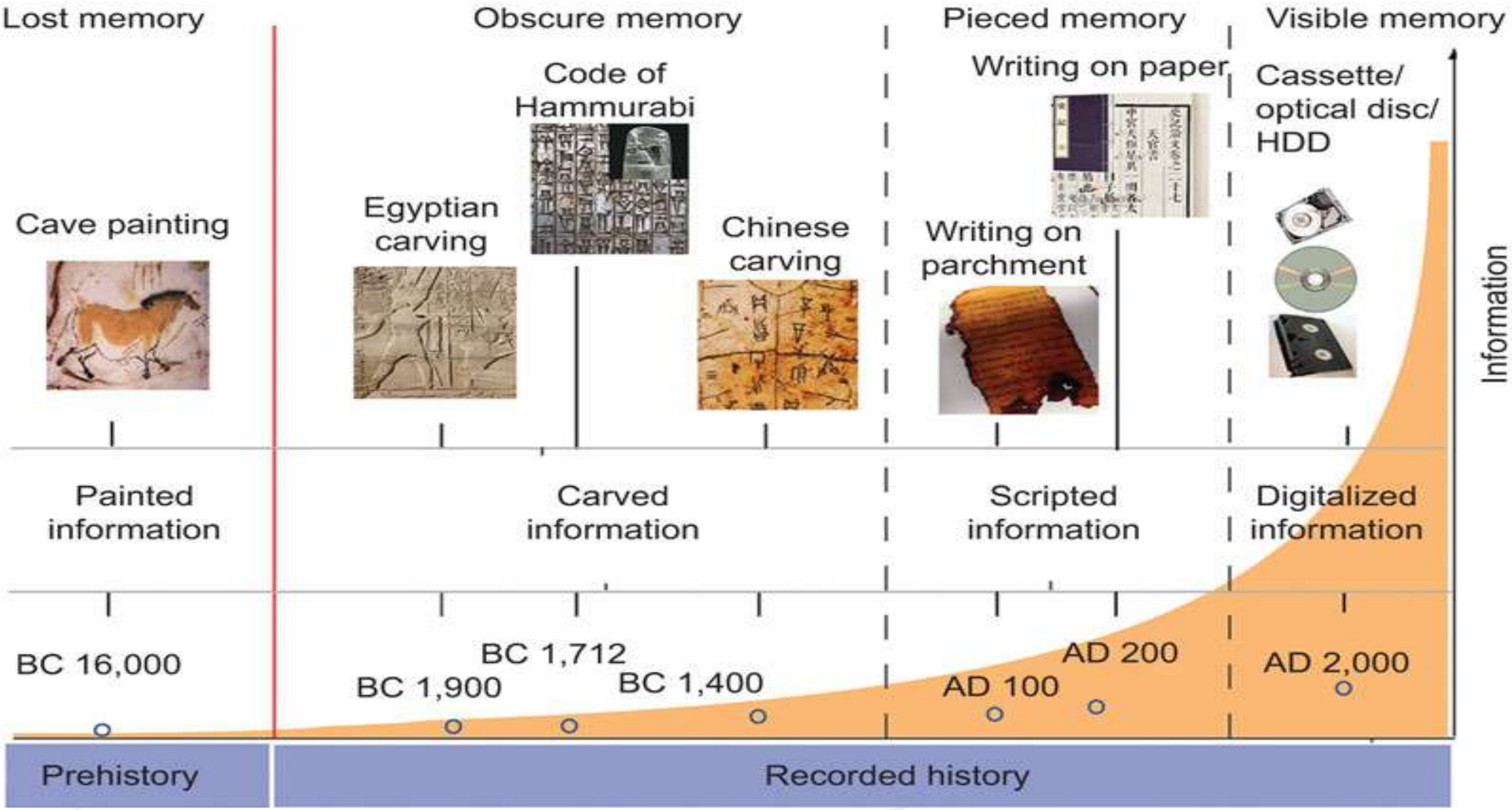
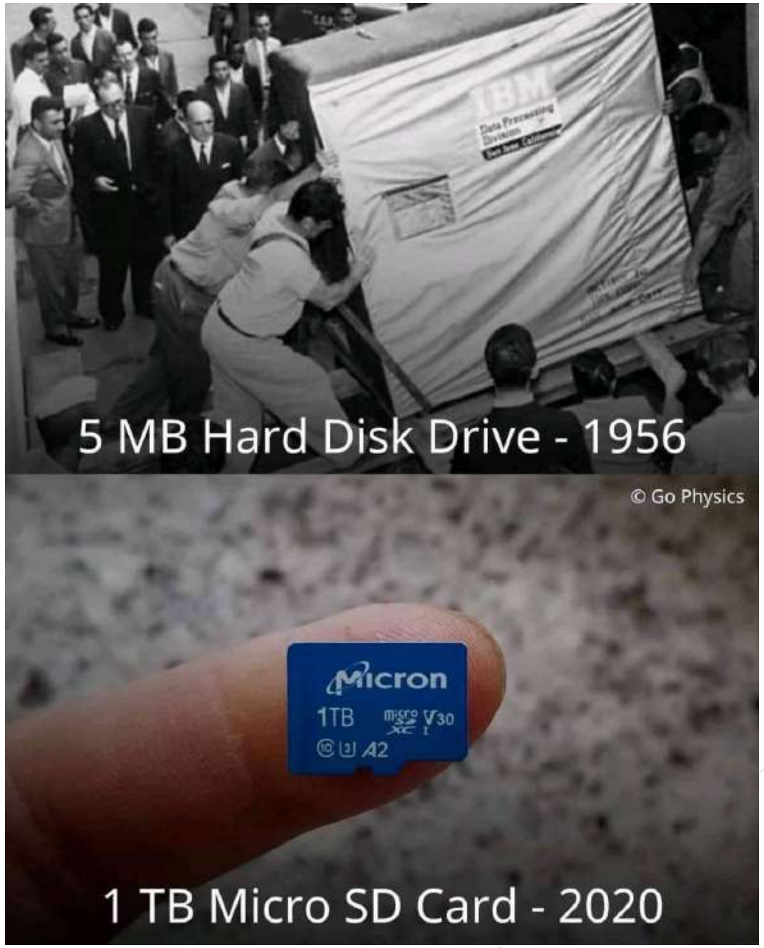
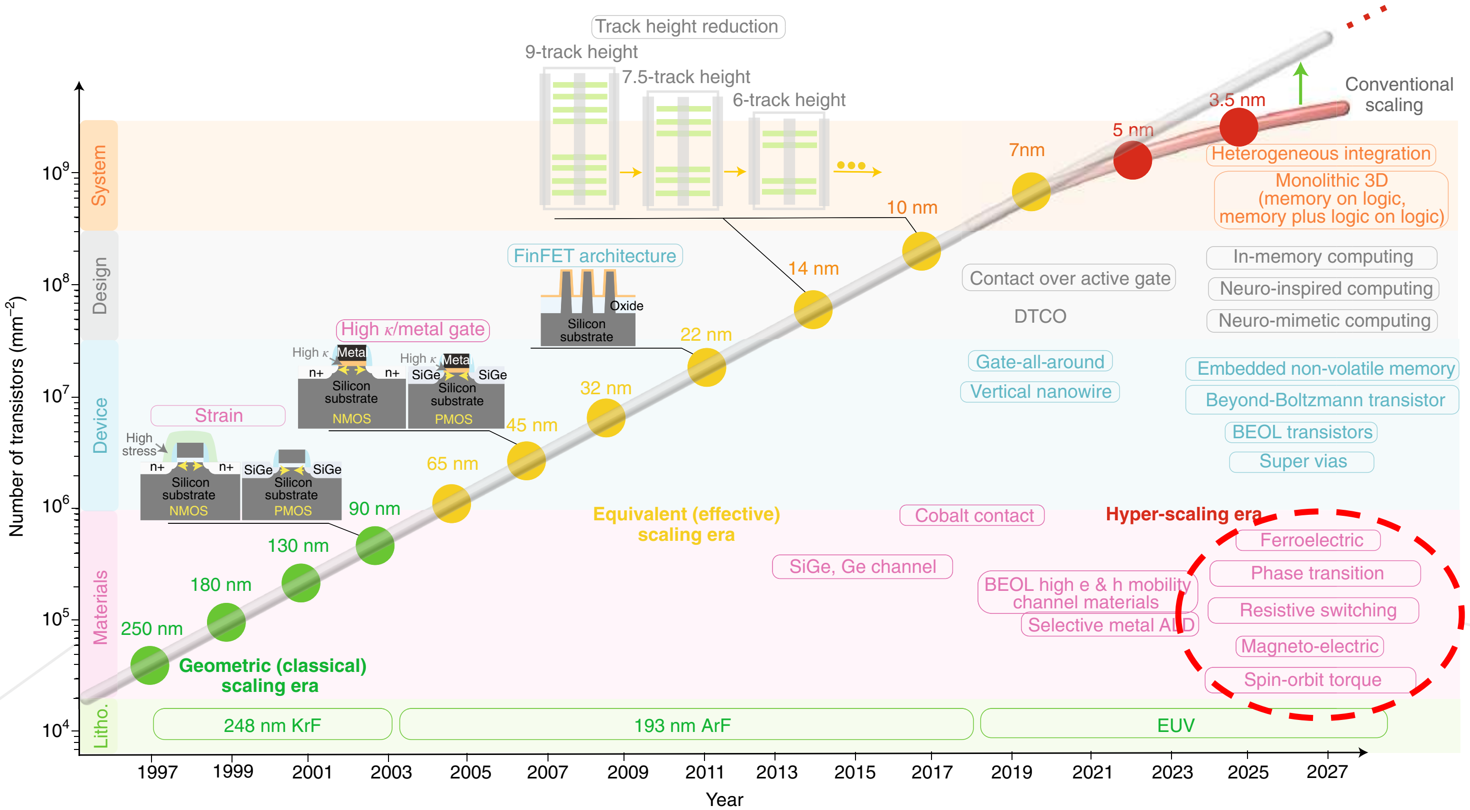


Light: Science & Applications 3:e177 (2014)

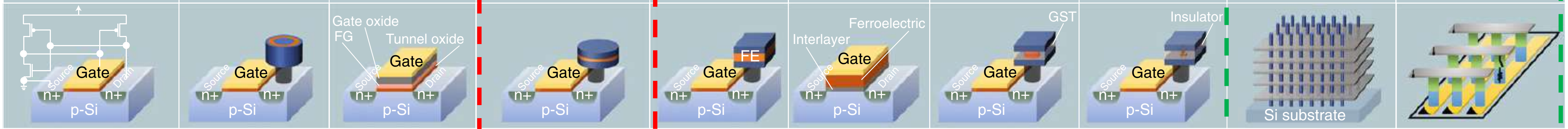




Nature Electronics (2018) 1:442

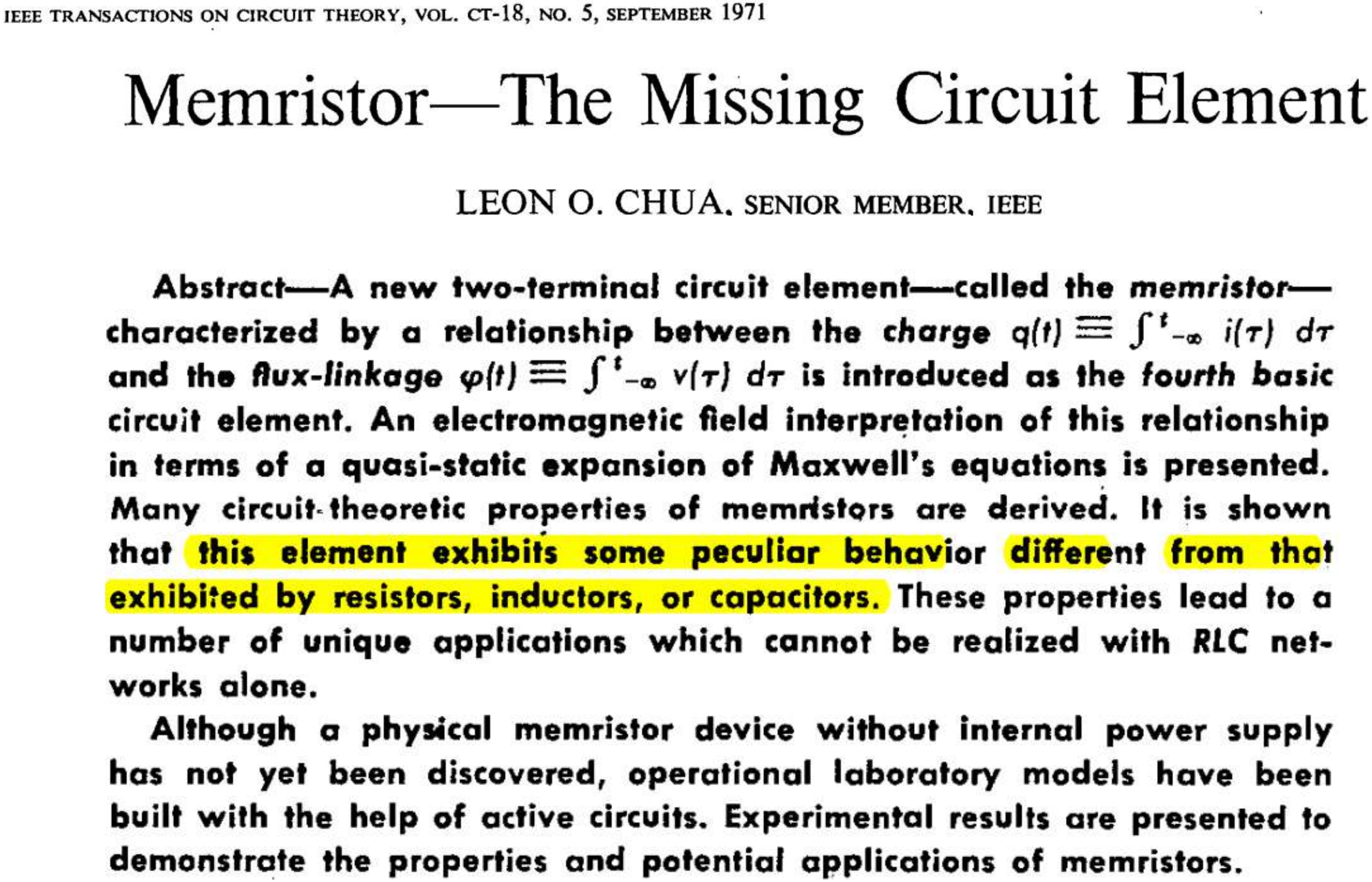
Emerging Technologies

Volatile *Non-Volatile*



	eSRAM	eDRAM	eFLASH	STT-MRAM	FeRAM	FeFET	PCRAM	RRAM	Vertical RRAM	Crossbar RRAM
Cell size	120–150 F^2	10–30 F^2	10–30 F^2	10–30 F^2	10–30 F^2	10–30 F^2	10–30 F^2	10–30 F^2	4 F^2/N	4 F^2/N
Cell structure	6T	1T–1C	1T	1T–1MTJ	1T–1C	1T	1T–1PCM	1T–1R	1S–1R	1S–1R
Non-volatility	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Write voltage	<1 V	<1 V	~10 V	<1.5 V	<3 V	<4 V	<3 V	<3 V	<4 V	<3 V
Write energy	~fJ	~10 fJ	~100 pJ	~1 pJ	~0.1 pJ	~0.1 pJ	~10 pJ	~1 pJ	~10 pJ	~1 pJ
Standby power	High	Medium	Low	Low	Low	Low	Low	Low	Low	Low
Write speed	~1 ns	~10 ns	0.1–1 ms	~5 ns	~10 ns	~10 ns	~10 ns	~10 ns	~100 ns	~50 ns
Read speed	~1 ns	~3 ns	~10 ns	~5 ns	~10 ns	~10 ns	~10 ns	~10 ns	~1 µs	~50 ns
Endurance	10^{16}	10^{16}	10^4–10^6	10^{15}	10^{14}	$>10^5$	$>10^{12}$	$>10^7$	$>10^7$	$>10^8$

Nature Electronics (2018) 1:442



IEEE TRANSACTIONS ON CIRCUIT THEORY, VOL. CT-18, NO. 5, SEPTEMBER 1971

Memristor—The Missing Circuit Element

LEON O. CHUA, SENIOR MEMBER, IEEE

Abstract—A new two-terminal circuit element—called the *memristor*—characterized by a relationship between the *charge* $q(t) \equiv \int_{-\infty}^{t} i(\tau)\, d\tau$ and the *flux-linkage* $\varphi(t) \equiv \int_{-\infty}^{t} v(\tau)\, d\tau$ is introduced as the *fourth basic* circuit element. An electromagnetic field interpretation of this relationship in terms of a quasi-static expansion of Maxwell's equations is presented. Many circuit-theoretic properties of memristors are derived. It is shown that this element exhibits some peculiar behavior different from that exhibited by resistors, inductors, or capacitors. These properties lead to a number of unique applications which cannot be realized with *RLC* networks alone.

Although a physical memristor device without internal power supply has not yet been discovered, operational laboratory models have been built with the help of active circuits. Experimental results are presented to demonstrate the properties and potential applications of memristors.

JOURNAL OF APPLIED PHYSICS VOLUME 33, NUMBER 9 SEPTEMBER 1962

Low-Frequency Negative Resistance in Thin Anodic Oxide Films

T. W. HICKMOTT
General Electric Research Laboratory, Schenectady, New York

(Received February 5, 1962)

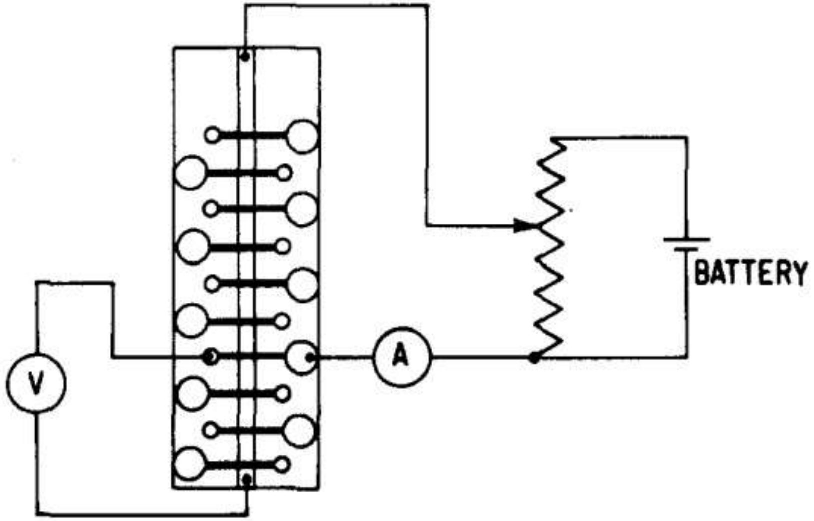


FIG. 1. Preparation of metal-anodic oxide-metal sandwiches. Circuit for measuring electrical characteristics.

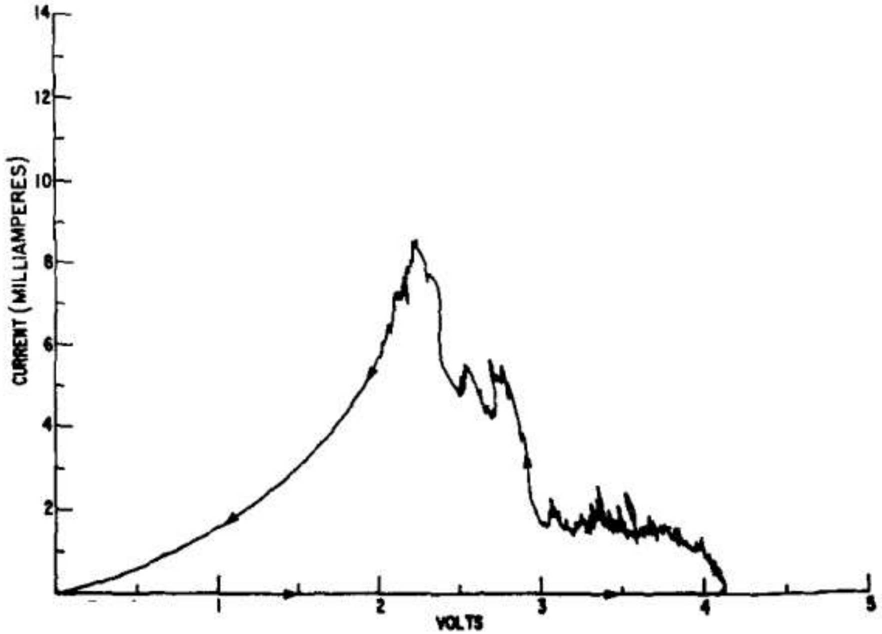


FIG. 2. Tracing of X-Y recorder plot of the establishment of conductivity in a 350-Å aluminum oxide film. Au = +, Al = −.

Solid-State Electronics Pergamon Press 1964. Vol. 7, pp. 785–797. Printed in Great Britain

SWITCHING PROPERTIES OF THIN NiO FILMS*

J. F. GIBBONS and W. E. BEADLE†

Stanford Electronics Laboratories, Stanford, California

(*Received* 30 *March* 1964)

Abstract—This paper describes a two-terminal solid-state switch made from a thin film of nickel oxide. The switch has a typical OFF resistance of 10–20 MΩ and a typical ON resistance of 100–200 Ω. Switching times are in the 0·1–10 μsec range. The switching action is thought to be due to the formation and rupture of a nickel filament in the NiO matrix. The formation process is such that after about 100–1000 switching cycles, the devices to be described fail 'short'; i.e. they cannot be switched out of the ON condition with normal switching signal amplitudes. Several experiments which elucidate the switching mechanism and the terminal properties of the device are described.

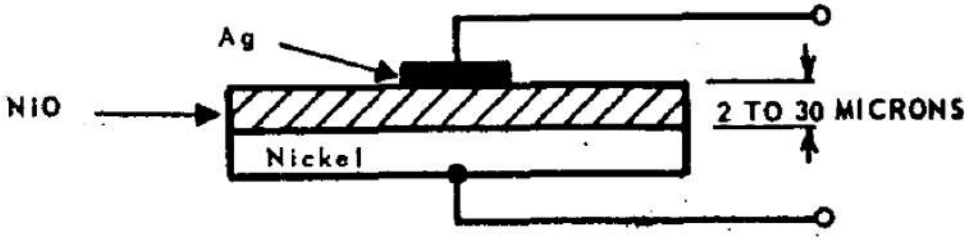


FIG. 1. Schematic representation of basic NiO thin-film device.

nature Vol 453|1 May 2008|

LETTERS

The missing memristor found

Dmitri B. Strukov[1], Gregory S. Snider[1], Duncan R. Stewart[1] & R. Stanley Williams[1]

Anyone who ever took an electronics laboratory class will be familiar with the fundamental passive circuit elements: the resistor, the capacitor and the inductor. However, in 1971 Leon Chua reasoned from symmetry arguments that there should be a fourth fundamental element, which he called a memristor (short for memory resistor)[1]. Although he showed that such an element has many interesting and valuable circuit properties, until now no one has presented either a useful physical model or an example of a memristor. Here we show, using a simple analytical example, that memristance arises naturally in nanoscale systems in which solid-state electronic and ionic transport are coupled under an external bias voltage. These results serve as the foundation for understanding a wide range of hysteretic current–voltage behaviour observed in many nanoscale electronic devices[2–19] that involve the motion of charged atomic or molecular species, in particular certain titanium dioxide cross-point switches[20–22].

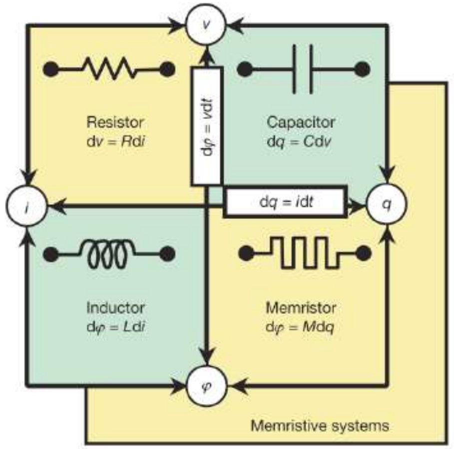
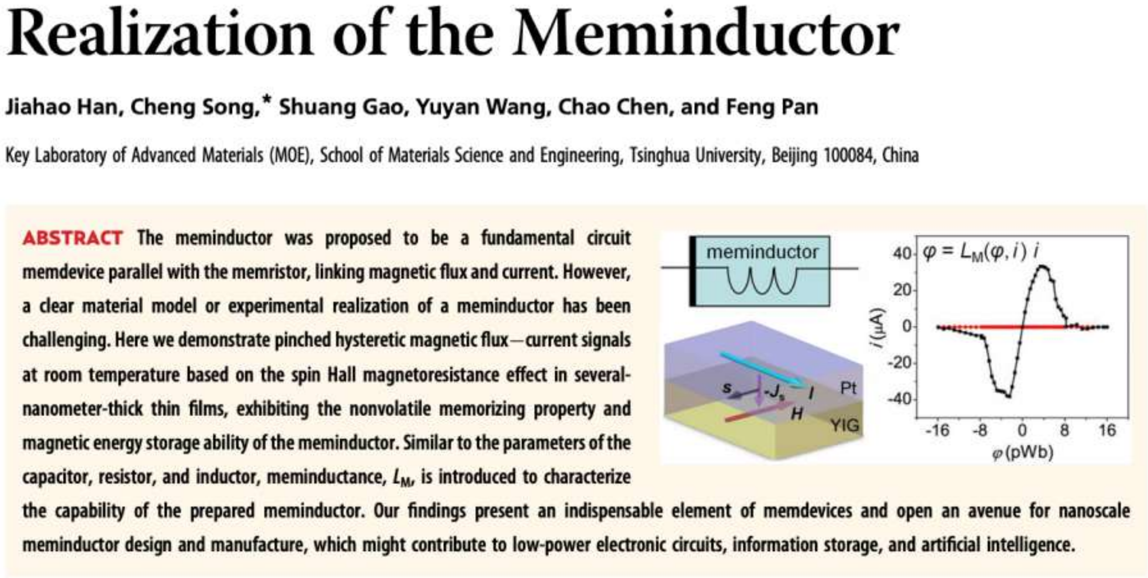


Figure 1 | The four fundamental two-terminal circuit elements: resistor, capacitor, inductor and memristor. Resistors and memristors are subsets of a more general class of dynamical devices, memristive systems. Note that R, C, L and M can be functions of the independent variable in their defining equations, yielding nonlinear elements. For example, a charge-controlled memristor is defined by a single-valued function $M(q)$.



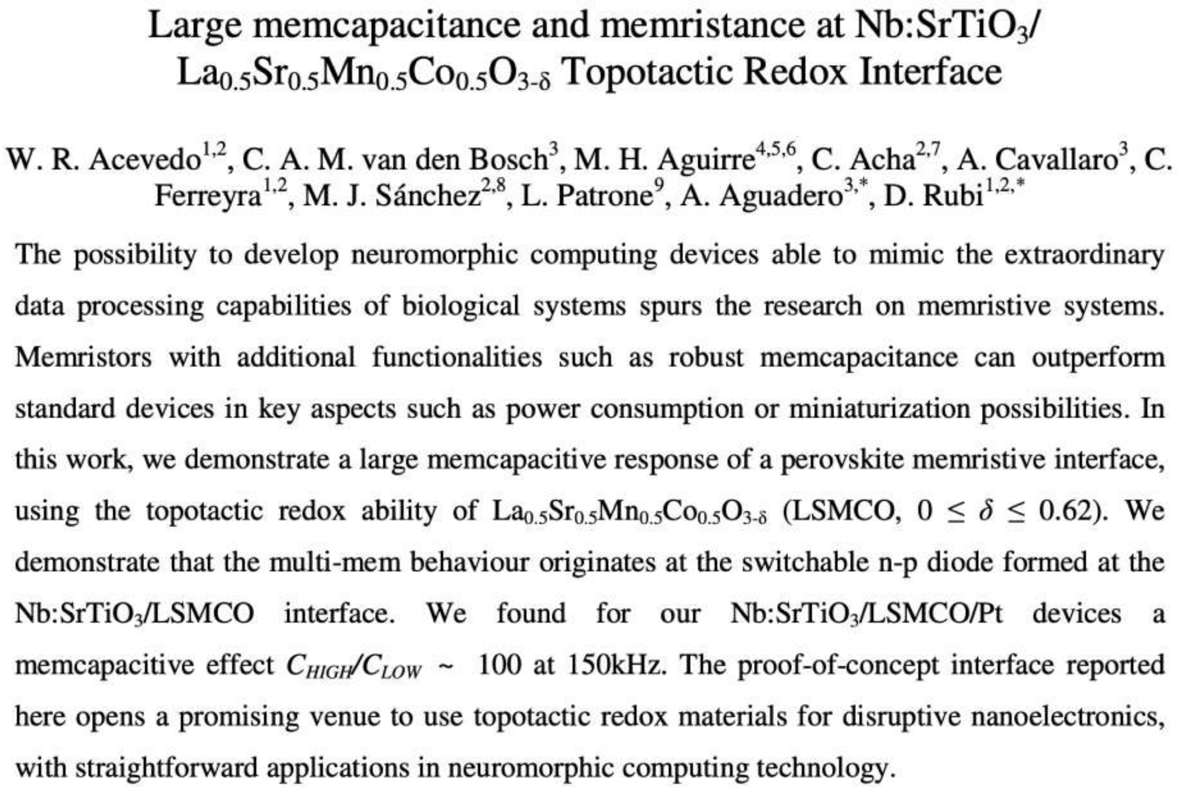
Realization of the Meminductor

Jiahao Han, Cheng Song,* Shuang Gao, Yuyan Wang, Chao Chen, and Feng Pan

Key Laboratory of Advanced Materials (MOE), School of Materials Science and Engineering, Tsinghua University, Beijing 100084, China

ABSTRACT The meminductor was proposed to be a fundamental circuit memdevice parallel with the memristor, linking magnetic flux and current. However, a clear material model or experimental realization of a meminductor has been challenging. Here we demonstrate pinched hysteretic magnetic flux—current signals at room temperature based on the spin Hall magnetoresistance effect in several-nanometer-thick thin films, exhibiting the nonvolatile memorizing property and magnetic energy storage ability of the meminductor. Similar to the parameters of the capacitor, resistor, and inductor, meminductance, L_M, is introduced to characterize the capability of the prepared meminductor. Our findings present an indispensable element of memdevices and open an avenue for nanoscale meminductor design and manufacture, which might contribute to low-power electronic circuits, information storage, and artificial intelligence.

ACS Nano (2014) 8, 10, 10043



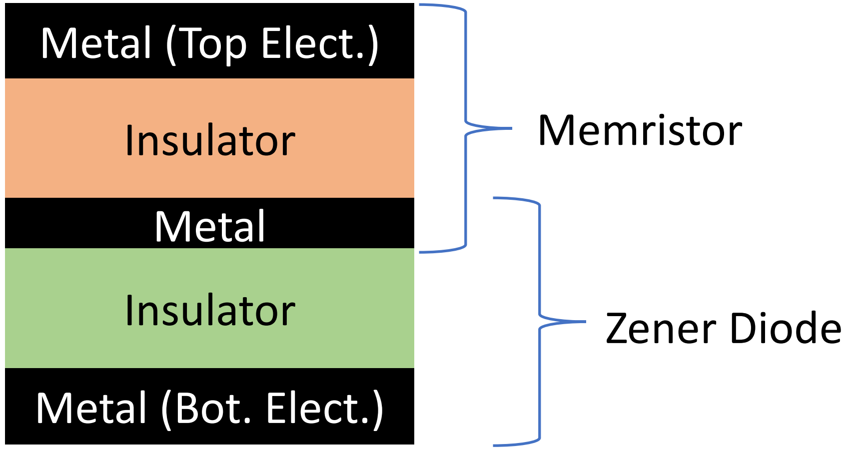
Large memcapacitance and memristance at Nb:SrTiO$_3$/ La$_{0.5}$Sr$_{0.5}$Mn$_{0.5}$Co$_{0.5}$O$_{3-\delta}$ Topotactic Redox Interface

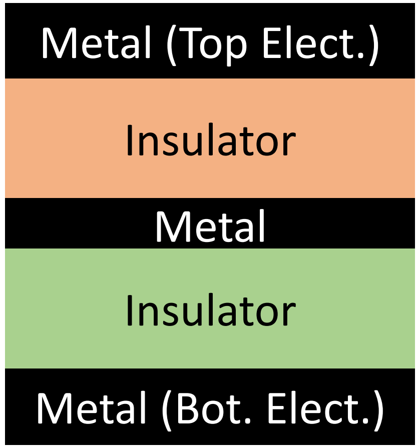
W. R. Acevedo[1,2], C. A. M. van den Bosch[3], M. H. Aguirre[4,5,6], C. Acha[2,7], A. Cavallaro[3], C. Ferreyra[1,2], M. J. Sánchez[2,8], L. Patrone[9], A. Aguadero[3,*], D. Rubi[1,2,*]

The possibility to develop neuromorphic computing devices able to mimic the extraordinary data processing capabilities of biological systems spurs the research on memristive systems. Memristors with additional functionalities such as robust memcapacitance can outperform standard devices in key aspects such as power consumption or miniaturization possibilities. In this work, we demonstrate a large memcapacitive response of a perovskite memristive interface, using the topotactic redox ability of La$_{0.5}$Sr$_{0.5}$Mn$_{0.5}$Co$_{0.5}$O$_{3-\delta}$ (LSMCO, $0 \leq \delta \leq 0.62$). We demonstrate that the multi-mem behaviour originates at the switchable n-p diode formed at the Nb:SrTiO$_3$/LSMCO interface. We found for our Nb:SrTiO$_3$/LSMCO/Pt devices a memcapacitive effect C_{HIGH}/C_{LOW} ~ 100 at 150kHz. The proof-of-concept interface reported here opens a promising venue to use topotactic redox materials for disruptive nanoelectronics, with straightforward applications in neuromorphic computing technology.

arXiv (2020) 1905.05711

Basic Structure of Selector-Memristor Integrated Cell





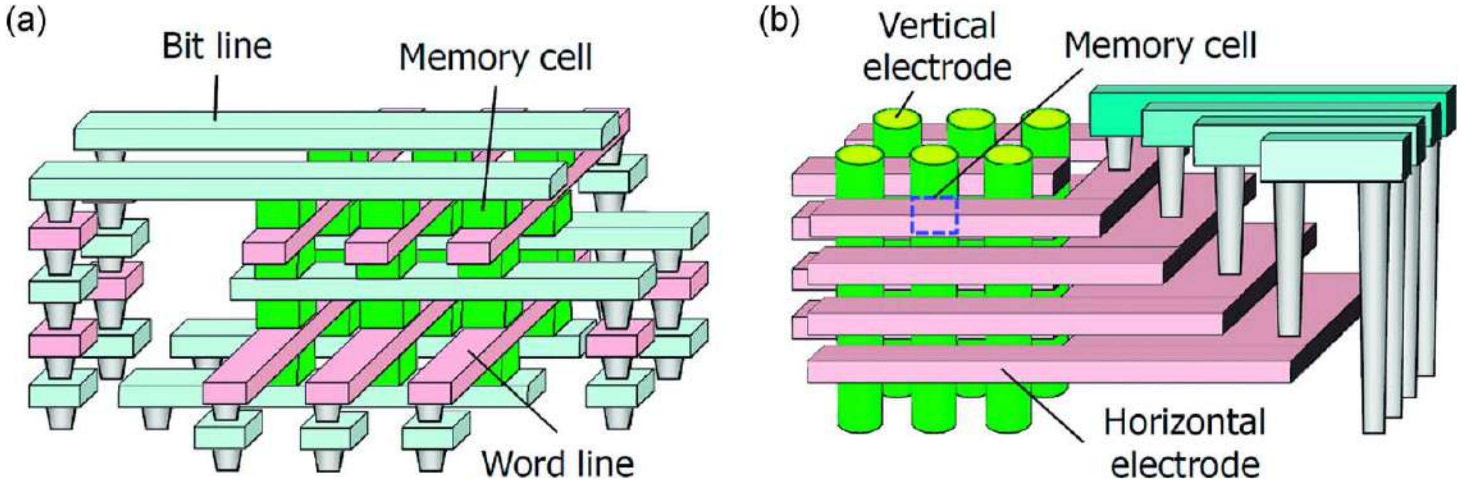
Metal (Top Elect.)

Insulator

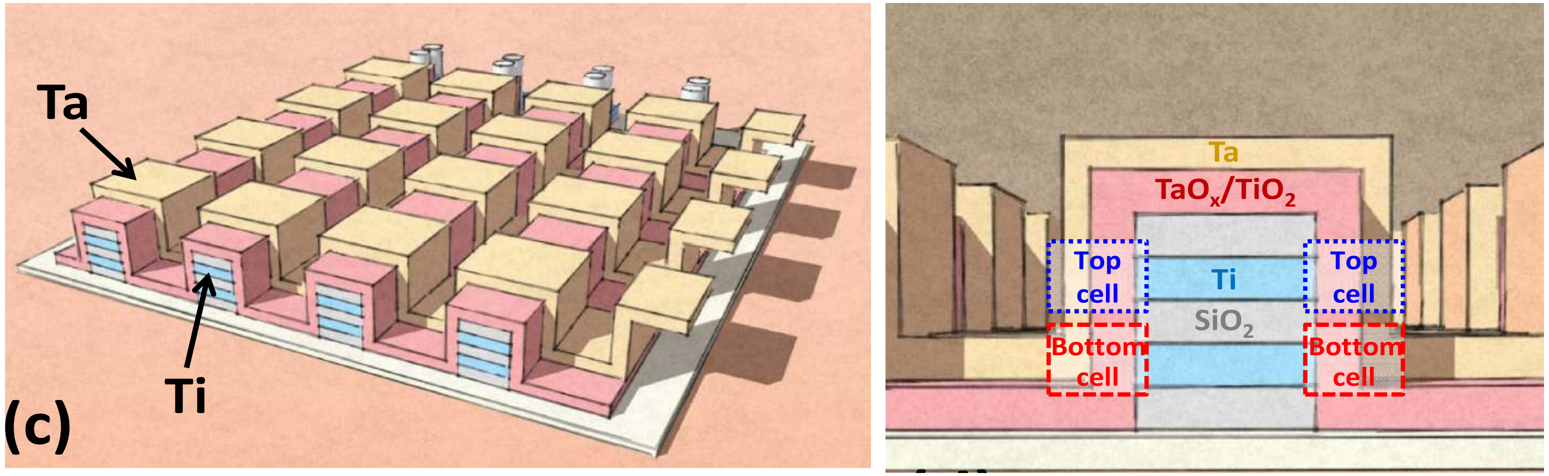
Metal

Insulator

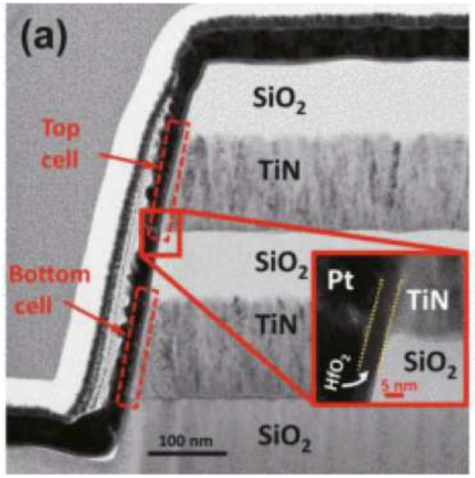
Metal (Bot. Elect.)



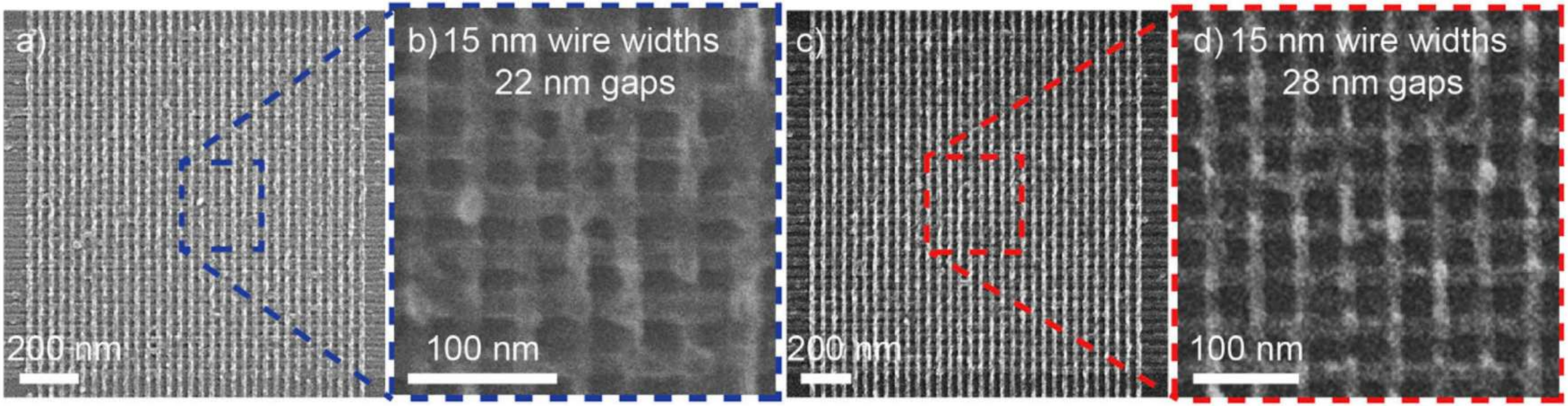
IEEE IEDM (2011) pp. 31.8.1–31.8



Nanotechnology (2016) **27** 365204

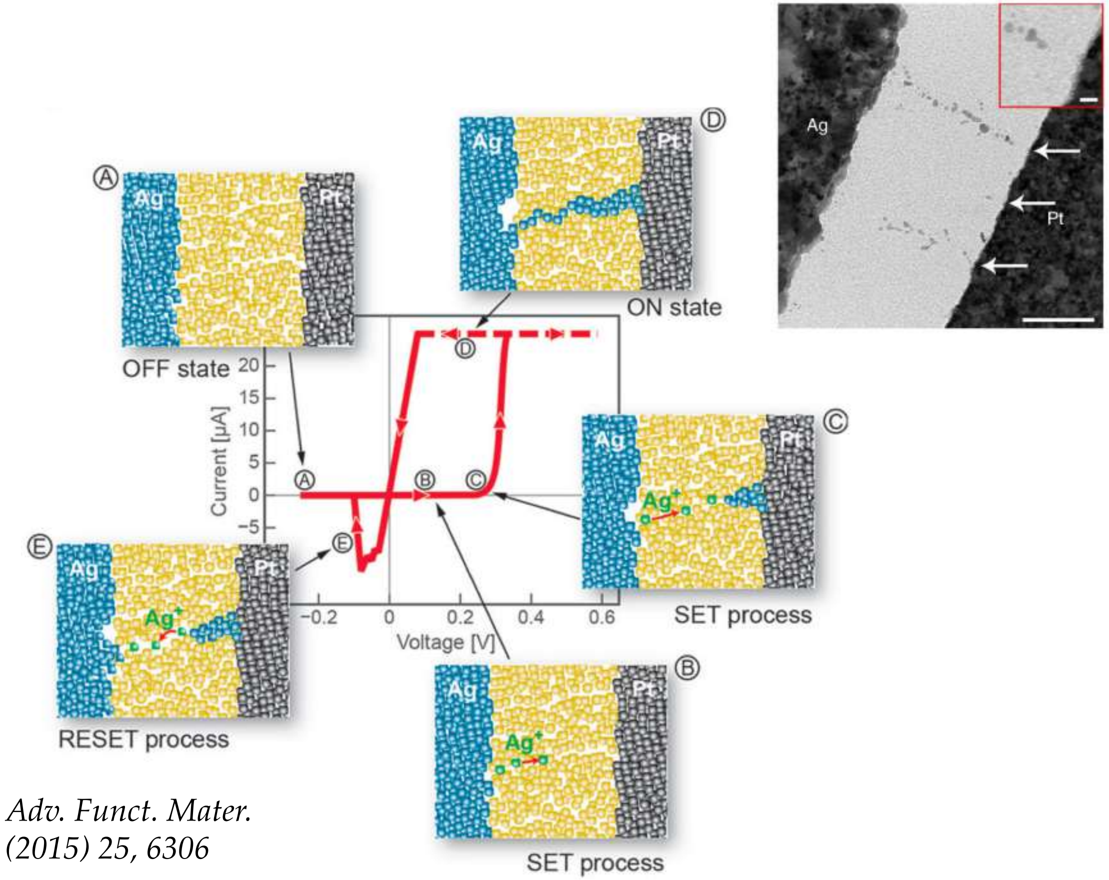


IEEE NANO (2018) 18438073



Sci. Rep. (2016) 6, 32614

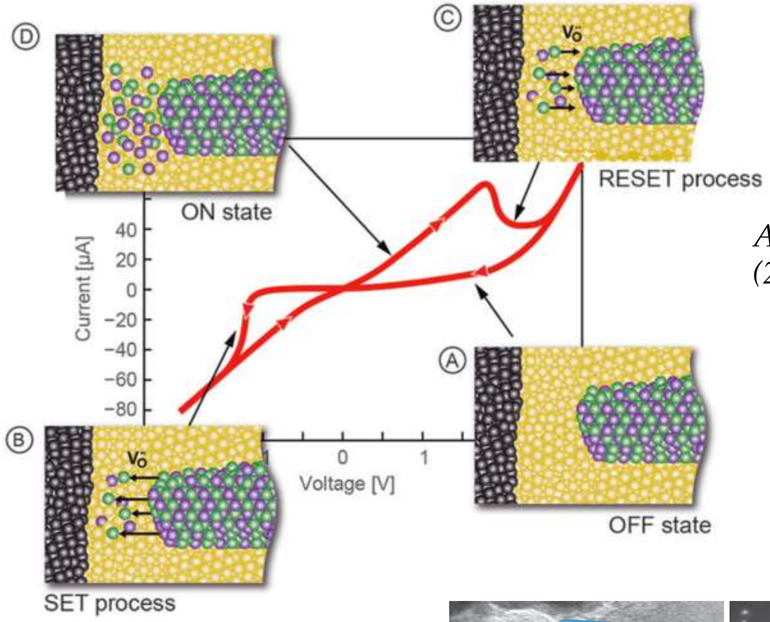
Conductive Bridge-RAM/ Programmable (Electrochemical) Metallization Cell



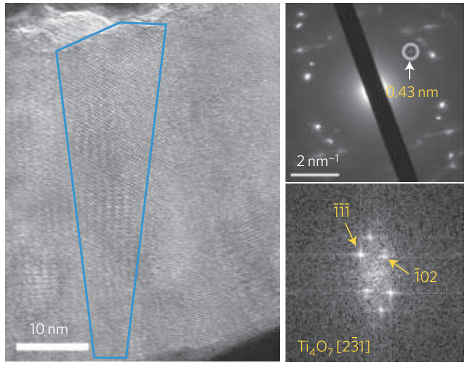
Nat. Commun. (2012) 3, 732

Adv. Funct. Mater. (2015) 25, 6306

Oxygen-based-RAM/ Valence Change Memories



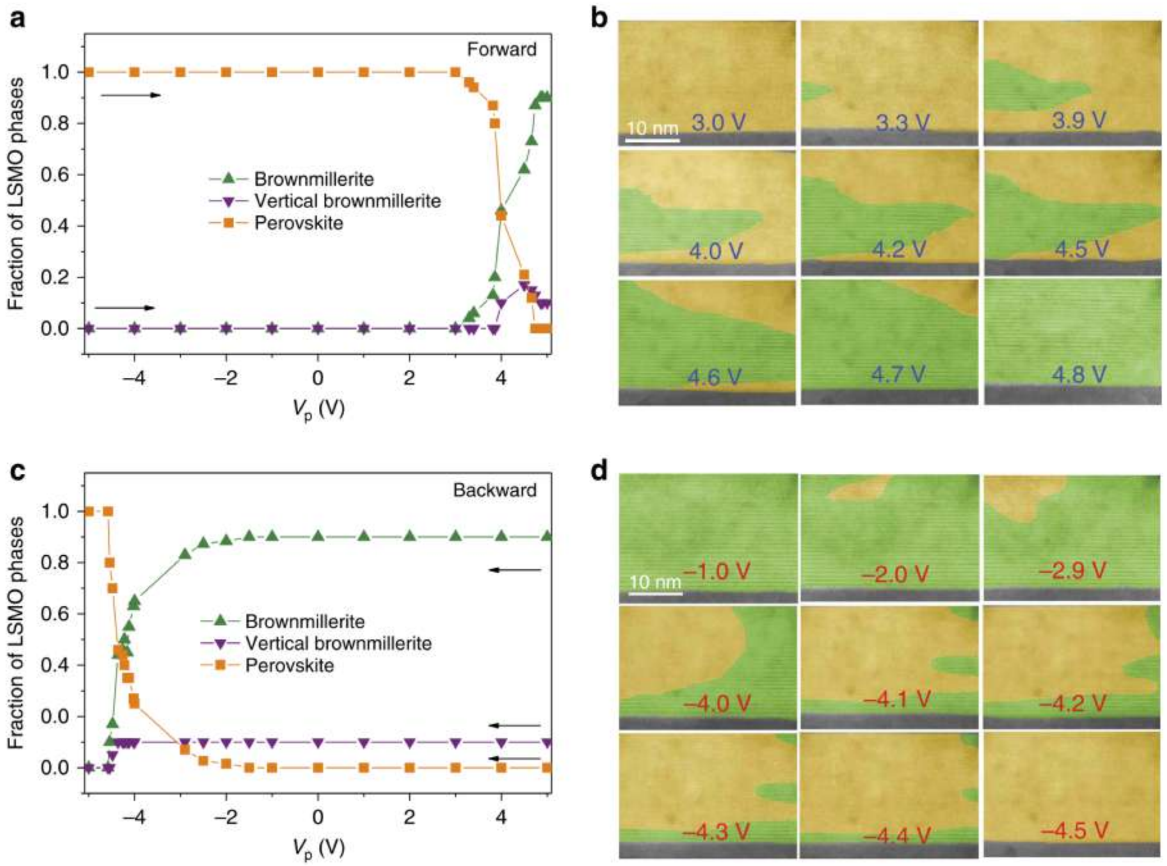
Adv. Funct. Mater. (2015) 25, 6306

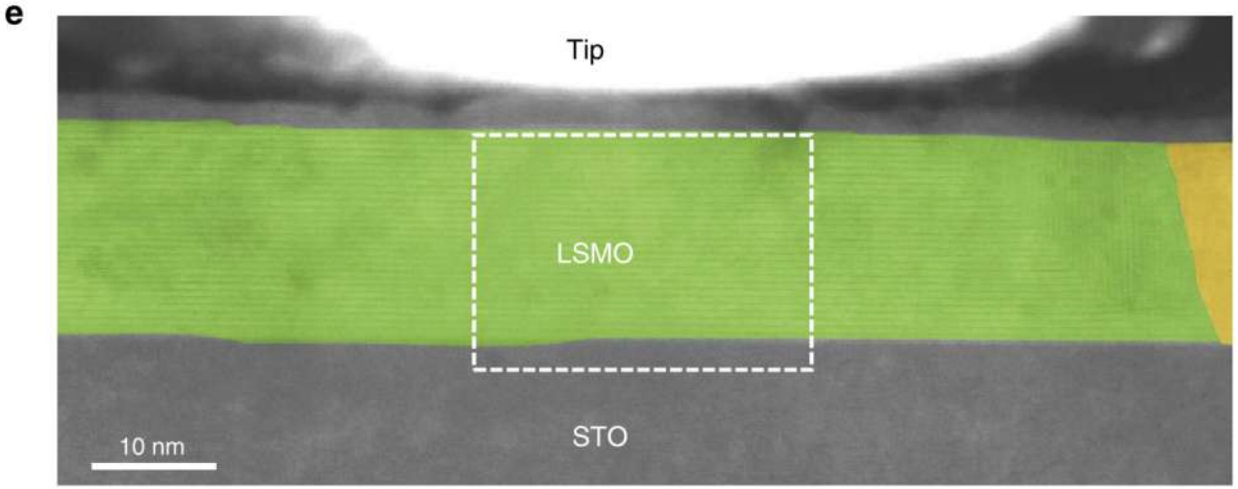


Nat. Nanotech. (2010) 5, 2:148

*Other modes: unipolar, threshold (complementary), rectifying (diode-like), & non-polar.

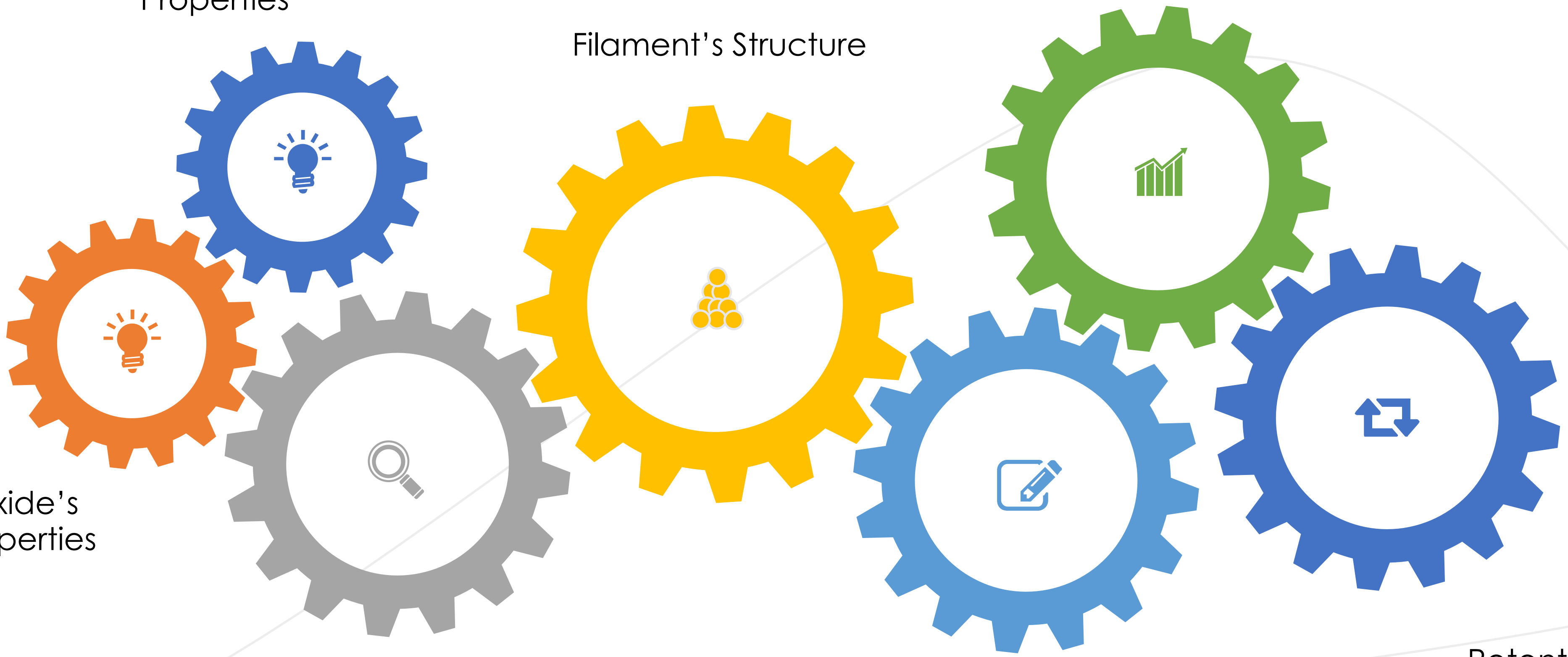
LSMO system (homogeneous)





Nat Comm (2017) 8, 1:14544

Key Parameters



Electrodes' Properties

Filament's Structure

Endurance

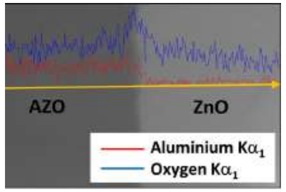
Oxide's Properties

Surfaces & Interfaces

Stress

Retention

Strategies to enhance the performance

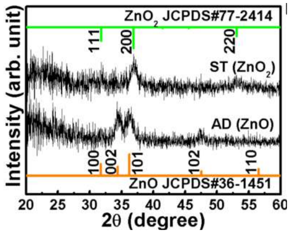


Electrode Engineering

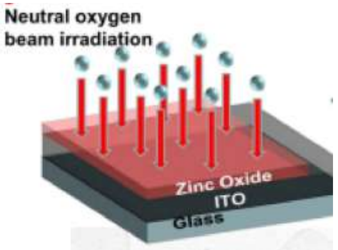
$$Co_{\varkappa}O_{\gamma} \xleftrightarrow{XZnO} \varkappa Co^{x}_{Zn} + \varkappa O^{x}_{o} + (\gamma-\varkappa)\,(O''_{i} + 2h^{o})$$

$$Co_{\varkappa}O_{\gamma} \xleftrightarrow{YZnO} \varkappa Co^{x}_{Zn} + \gamma O^{x}_{o} + (\gamma-\varkappa)\,(V''_{Zn} + 2h^{o})$$

Doping

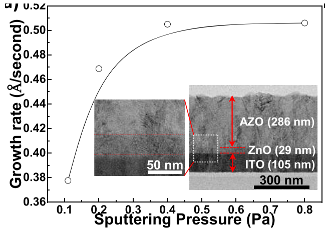


Chemical Oxidation

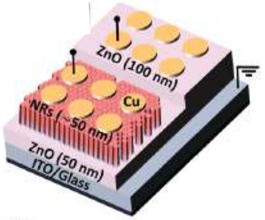


Ion Beam Oxidation

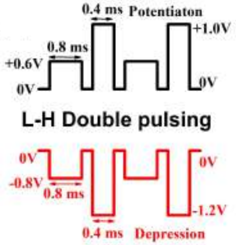
Optimization of Deposition Parameter



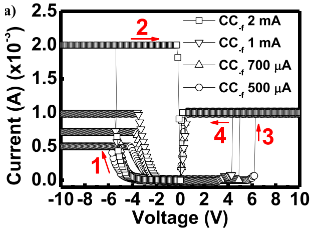
Compact 2D Structures



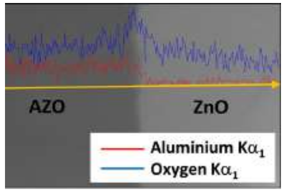
Double Pulsing



Double Forming



Strategies to enhance the performance

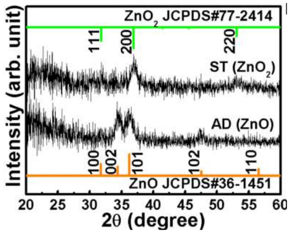


Electrode Engineering

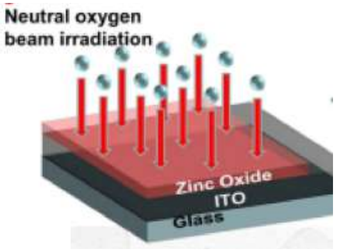
$$Co_{\varkappa}O_{\gamma} \overset{XZnO}{\longleftrightarrow} \varkappa Co_{Zn}^{x} + \varkappa O_{o}^{x} + (\gamma - \varkappa)\left(O_i'' + 2h^{o}\right)$$

$$Co_{\varkappa}O_{\gamma} \overset{YZnO}{\longleftrightarrow} \varkappa Co_{Zn}^{x} + \gamma O_{o}^{x} + (\gamma - \varkappa)\left(V_{Zn}'' + 2h^{o}\right)$$

Doping

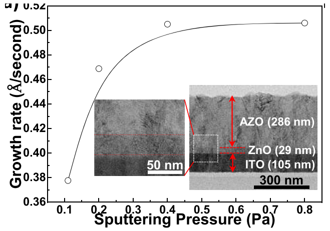


Chemical Oxidation

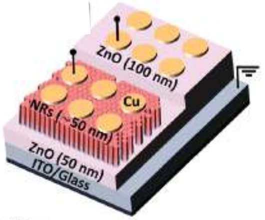


Ion Beam Oxidation

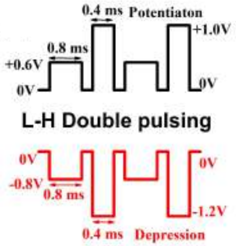
Optimization of Deposition Parameter



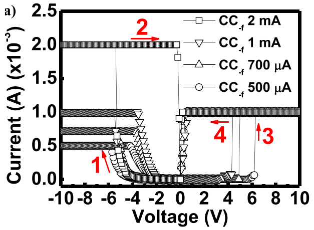
Compact 2D Structures



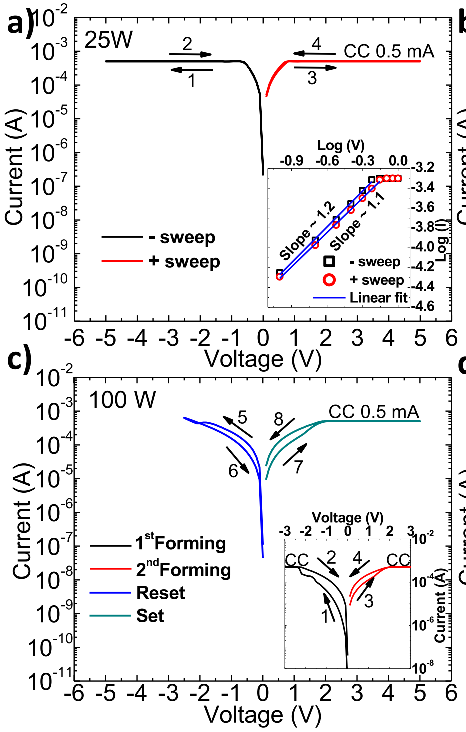
Double Pulsing

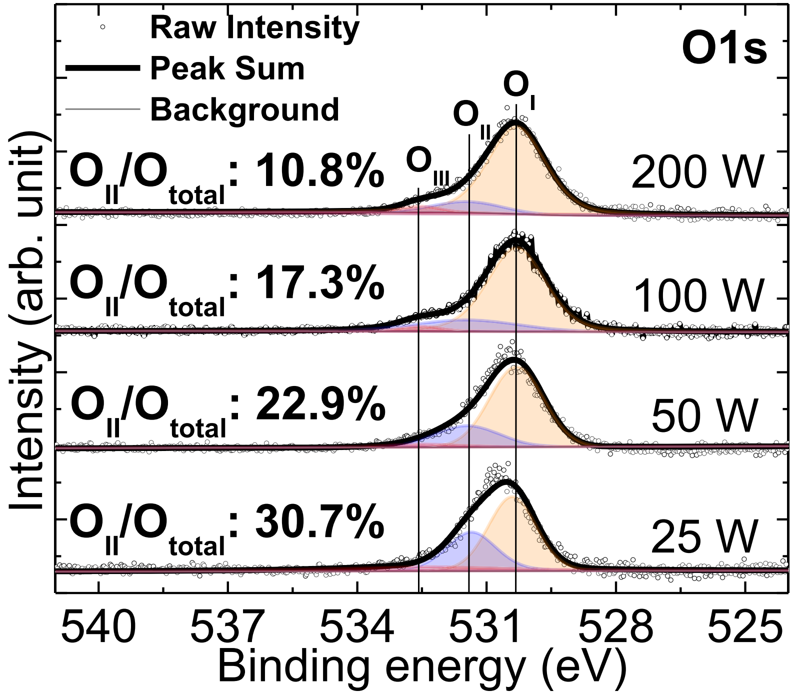


Double Forming



Deposition parameter: Power

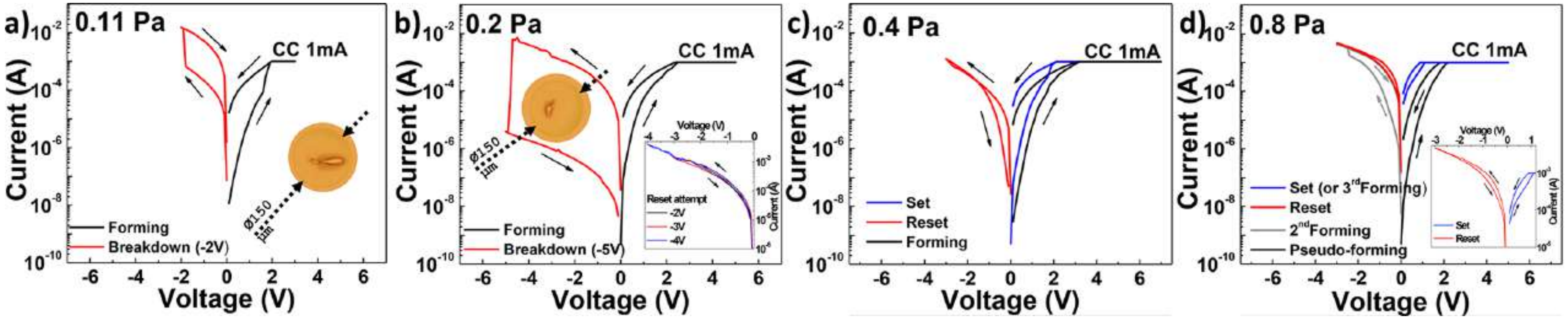


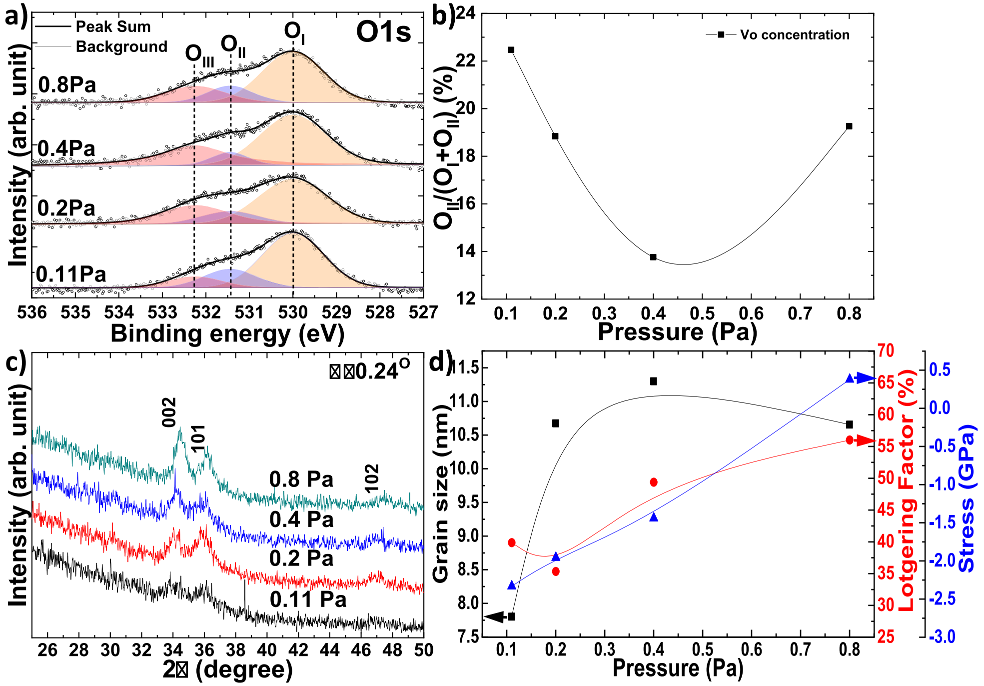


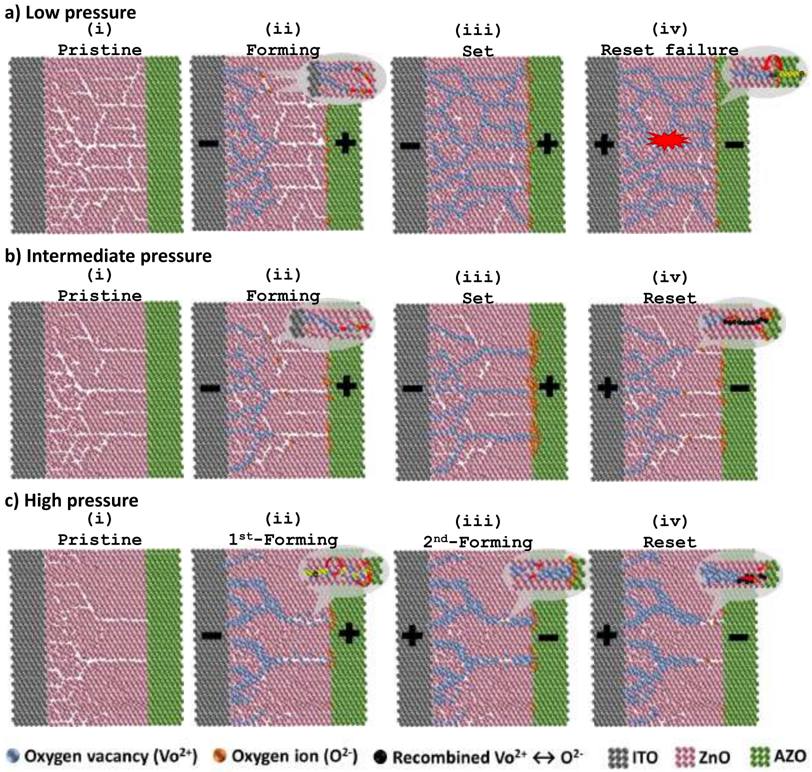
AIP Advances (2019) 9, 105216

Strategies

Deposition parameter: Pressure



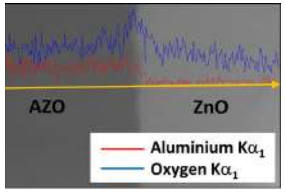




ACS Appl. Electron. Mater. (2019) 1, 11:2184

Strategies

Strategies to enhance the performance



Electrode Engineering

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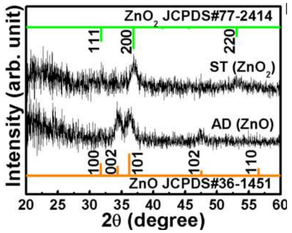
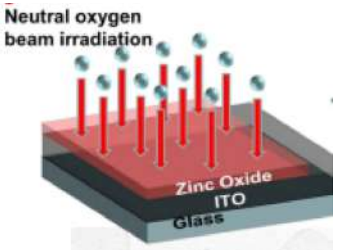
$$Co_\varkappa O_\gamma \overset{YZnO}{\longleftrightarrow} \varkappa Co^x_{Zn} + \gamma O^x_o + (\gamma - \varkappa)\,(V''_{Zn} + 2h^o)$$

Doping

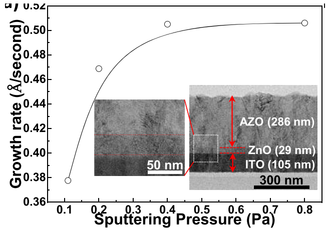


Chemical Oxidation

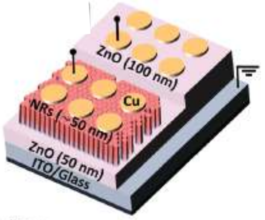


Ion Beam Oxidation

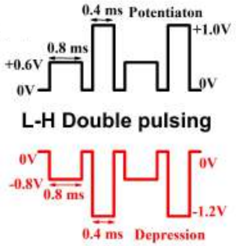
Optimization of Deposition Parameter



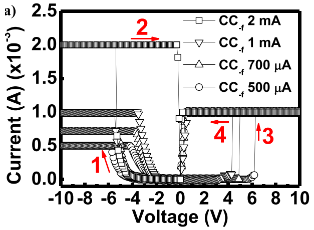
Compact 2D Structures



Double Pulsing

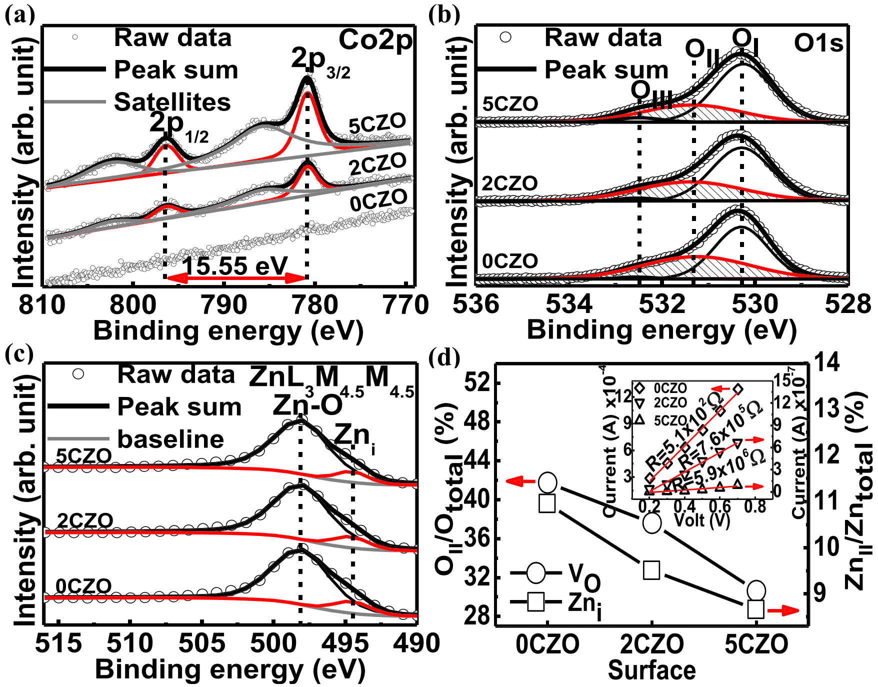


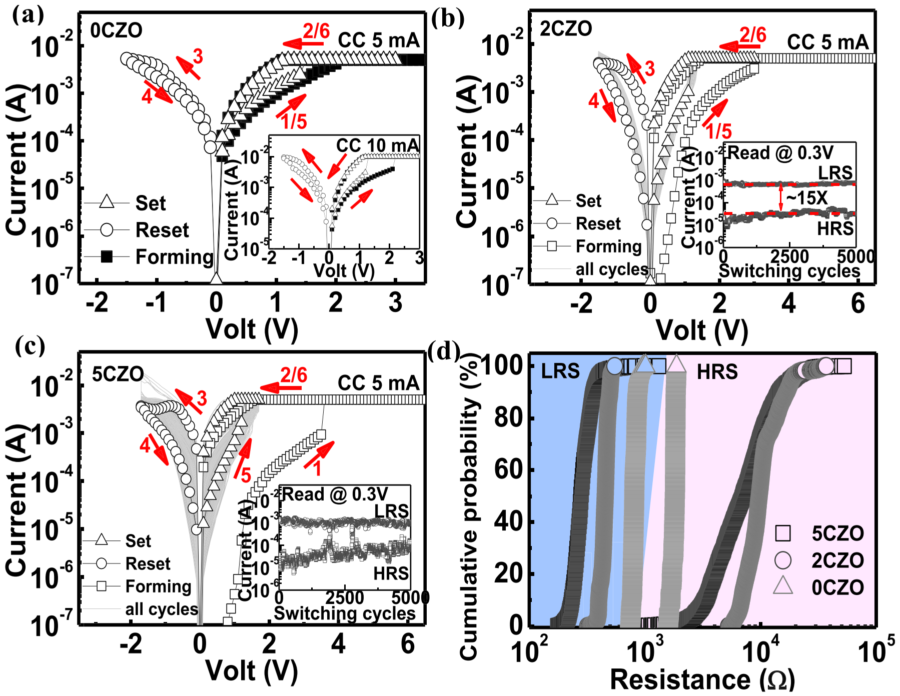
Double Forming



$$Co_{\varkappa}O_{\gamma} \overset{XZnO}{\longleftrightarrow} \varkappa Co_{Zn}^{x} + \varkappa O_{o}^{x} + (\gamma - \varkappa)\left(O_{i}'' + 2h^{o}\right),$$

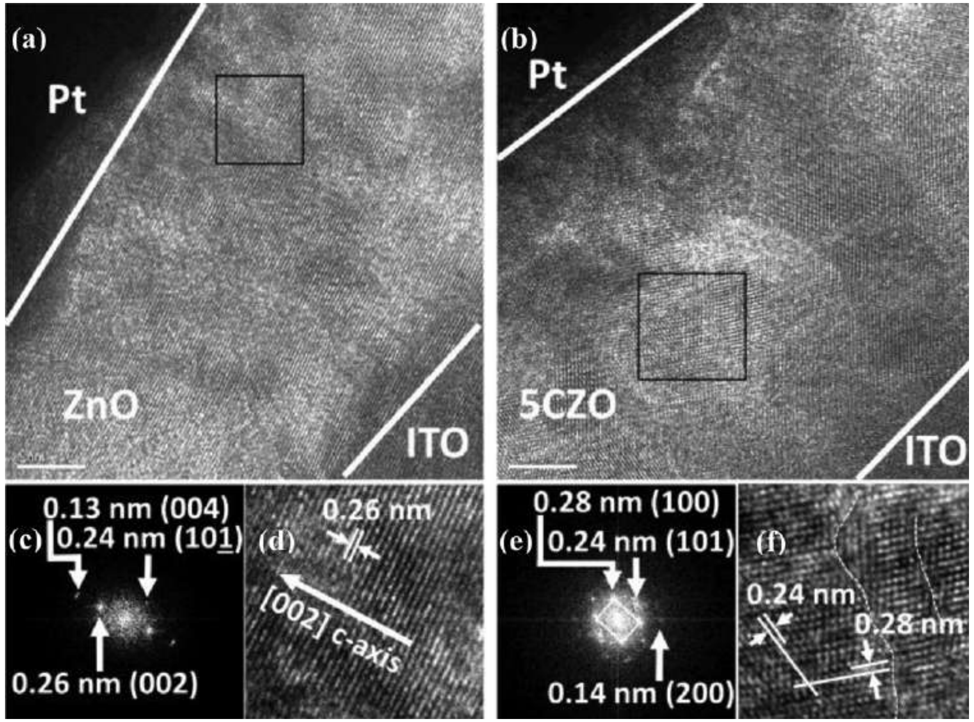
$$Co_{\varkappa}O_{\gamma} \overset{YZnO}{\longleftrightarrow} \varkappa Co_{Zn}^{x} + \gamma O_{o}^{x} + (\gamma - \varkappa)\left(V_{Zn}'' + 2h^{o}\right)$$

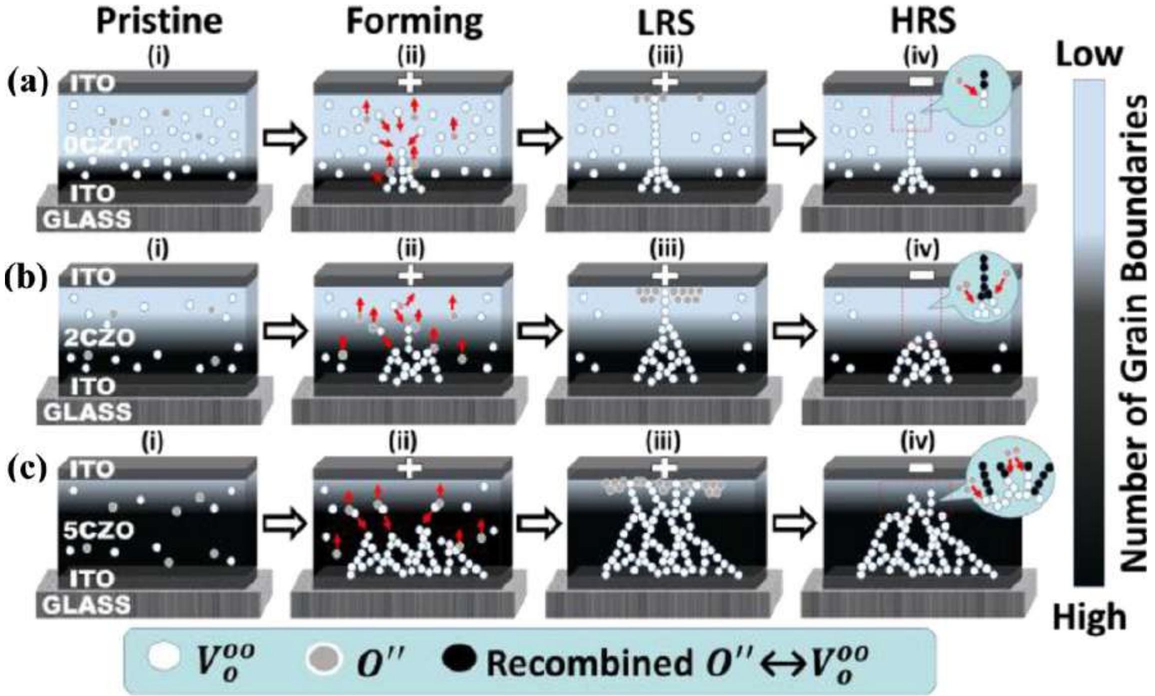




Appl. Phys. Lett.108, 183506 (2016)

Strategies

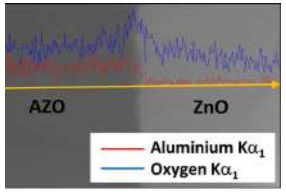




Appl. Phys. Lett.108, 183506 (2016)

Strategies

Strategies to enhance the performance



Electrode Engineering

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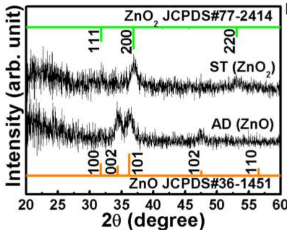
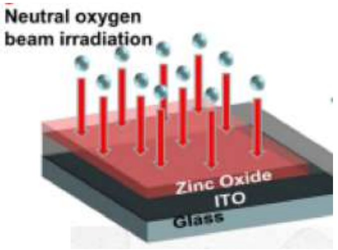
Doping

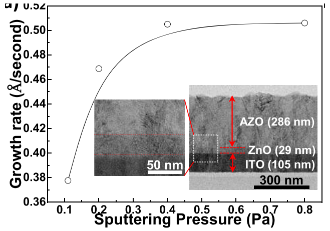


Chemical Oxidation

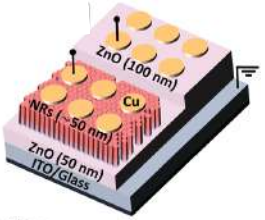


Ion Beam Oxidation

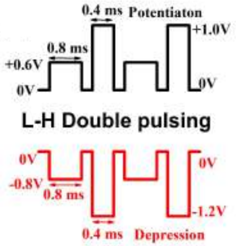
Optimization of Deposition Parameter



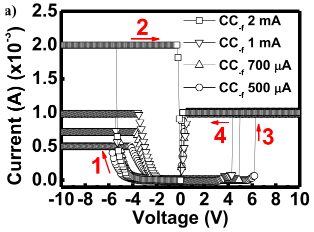
Compact 2D Structures



Double Pulsing



Double Forming

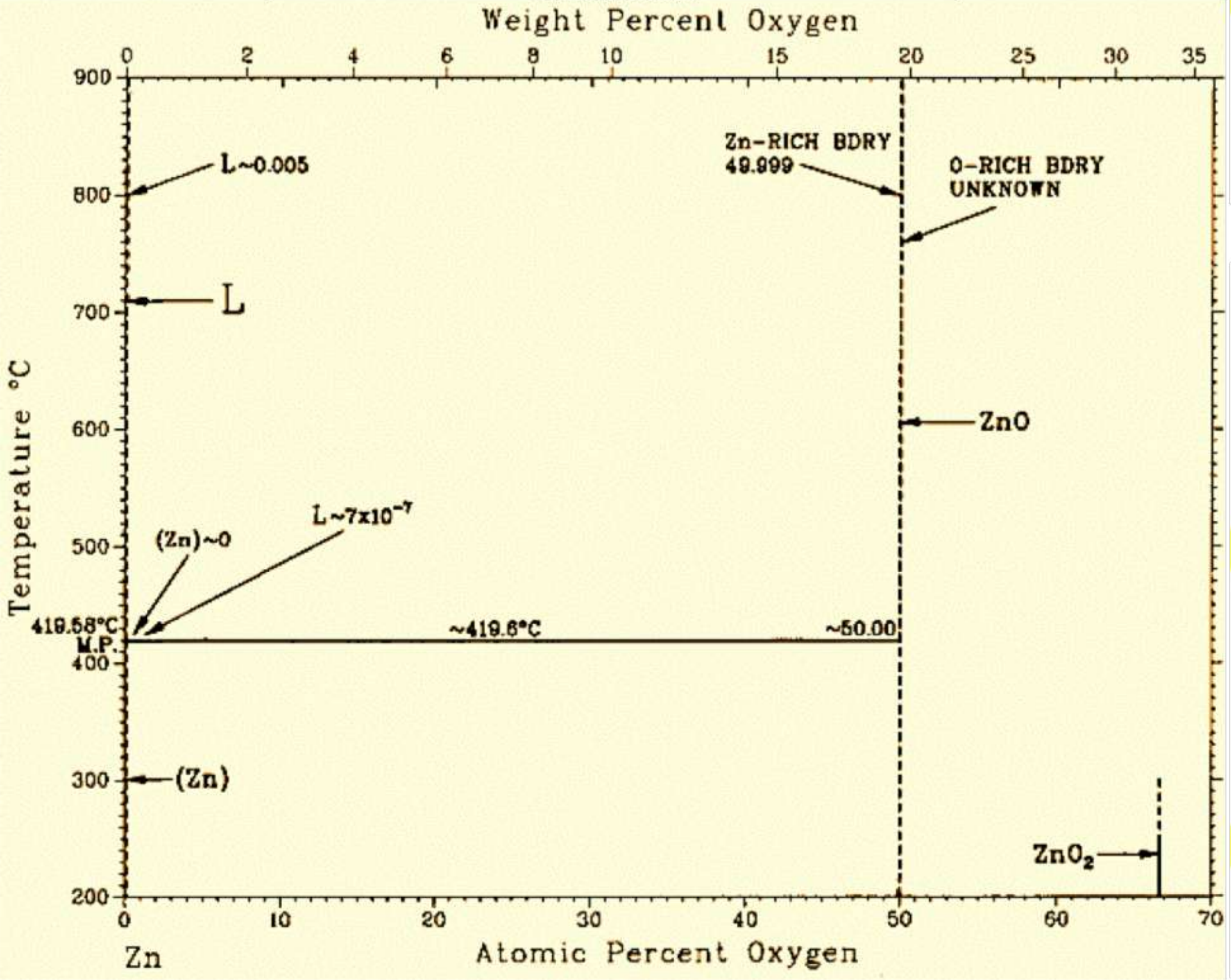


Journal of Phase Equilibria, 8 (2), 166-176, 1987

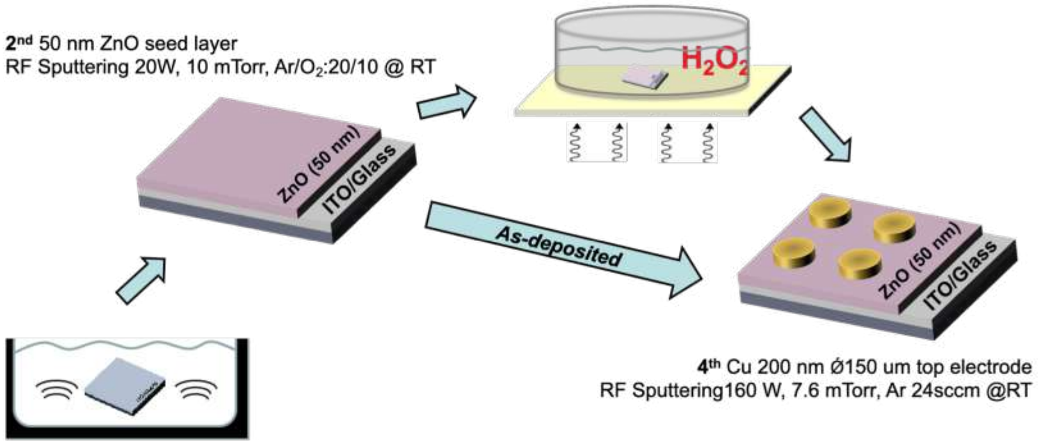
The O-Zn (Oxygen-Zinc) System

15.9994 65.38

By H.A. Wriedt



Fabrication Process



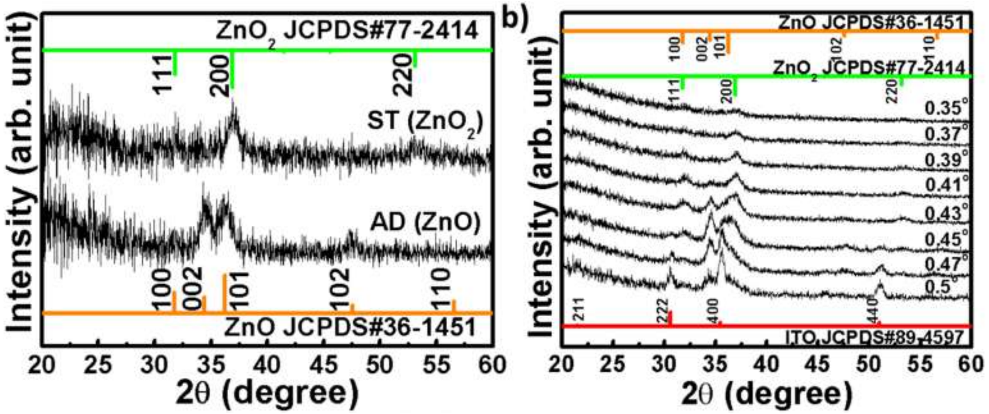
1st 270 nm commercial ITO substrate
Ultrasonicated DI+Ethanol x 10 min.

2nd 50 nm ZnO seed layer
RF Sputtering 20W, 10 mTorr, Ar/O_2:20/10 @ RT

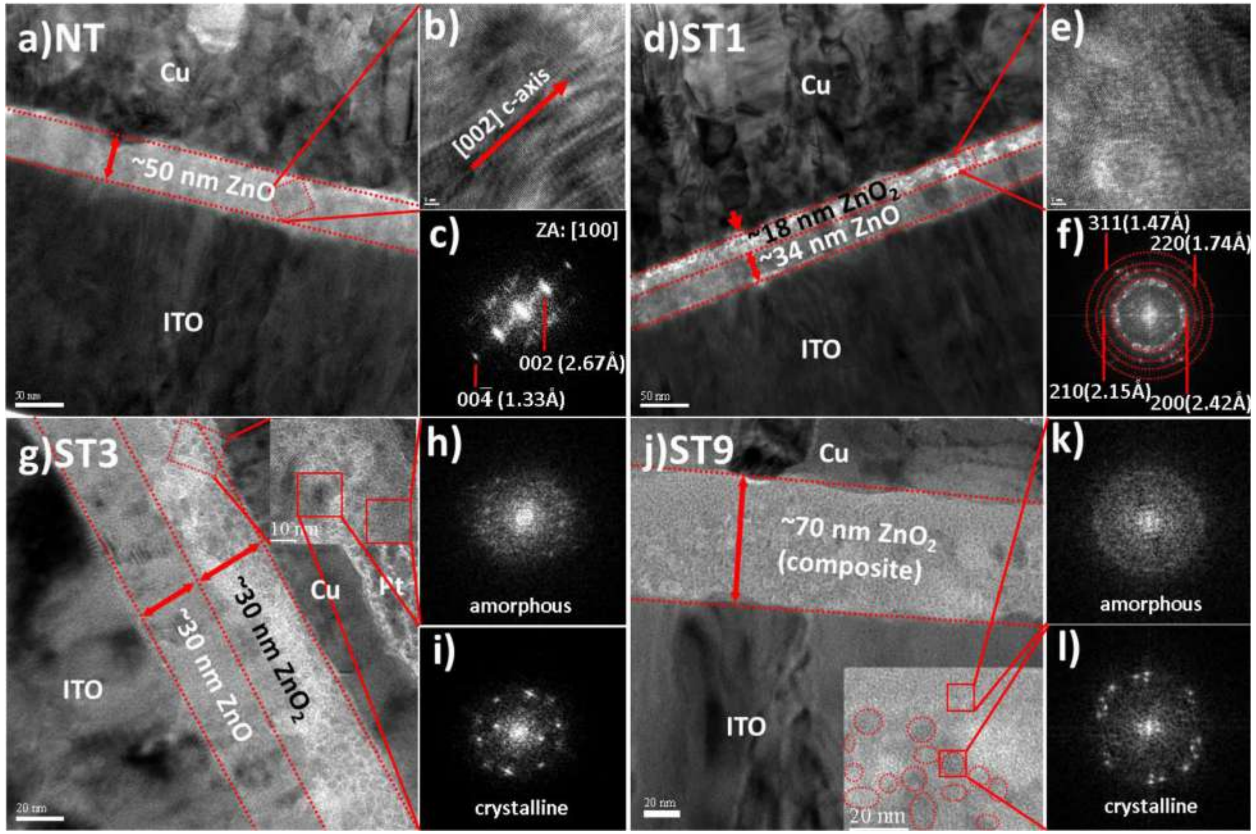
3rd Surface oxidation treatment
100 C x 1 min

4th Cu 200 nm Ø150 um top electrode
RF Sputtering160 W, 7.6 mTorr, Ar 24sccm @RT

Strategies

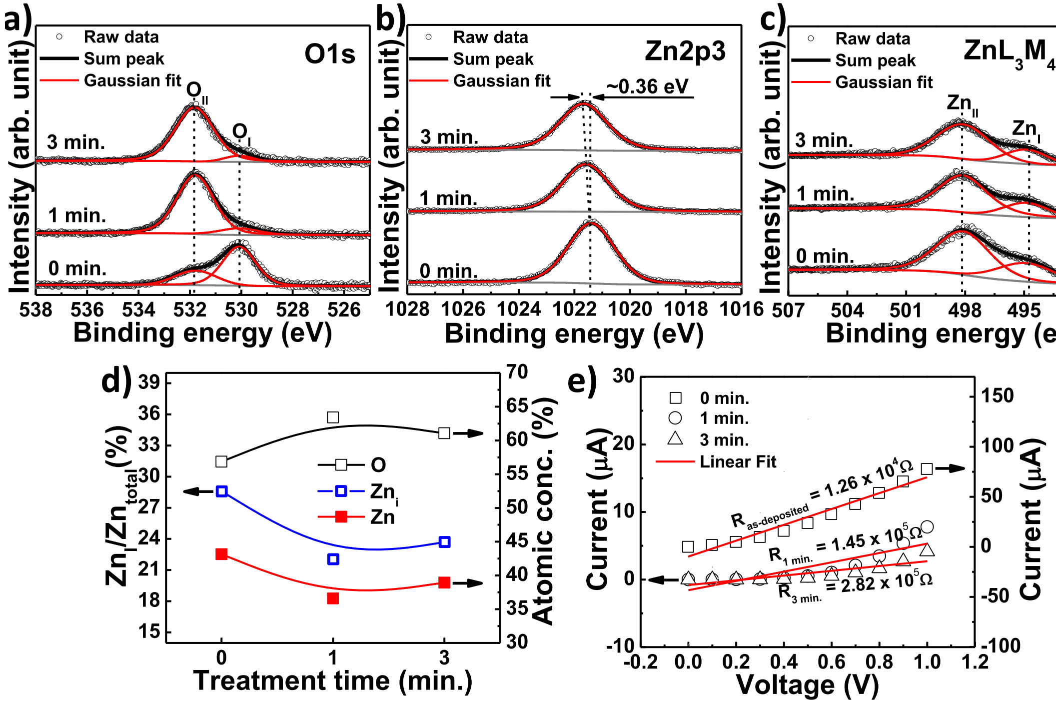


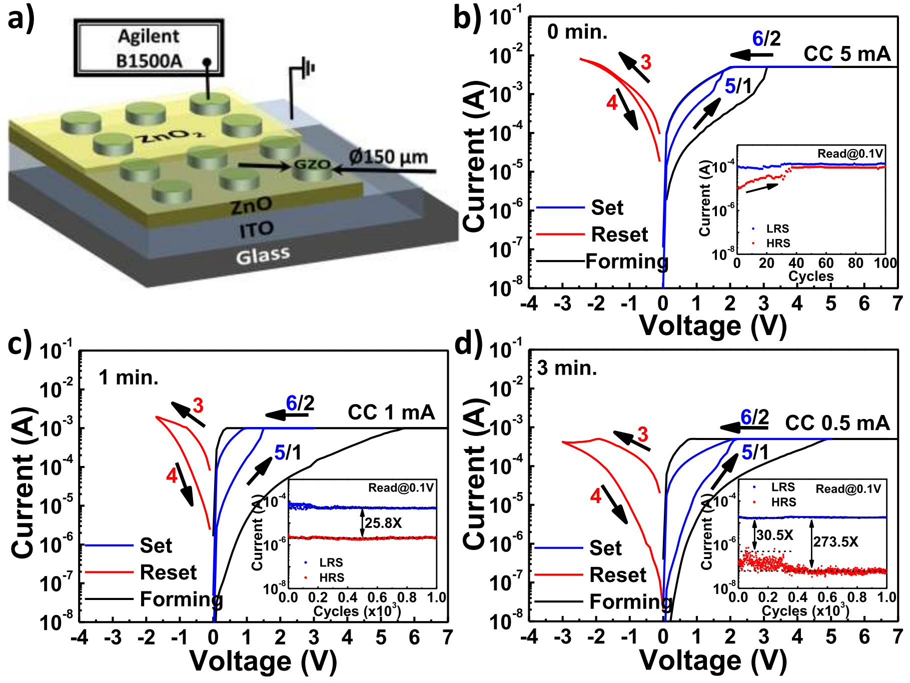
Nanotechnology (2017) 28, 38LT02

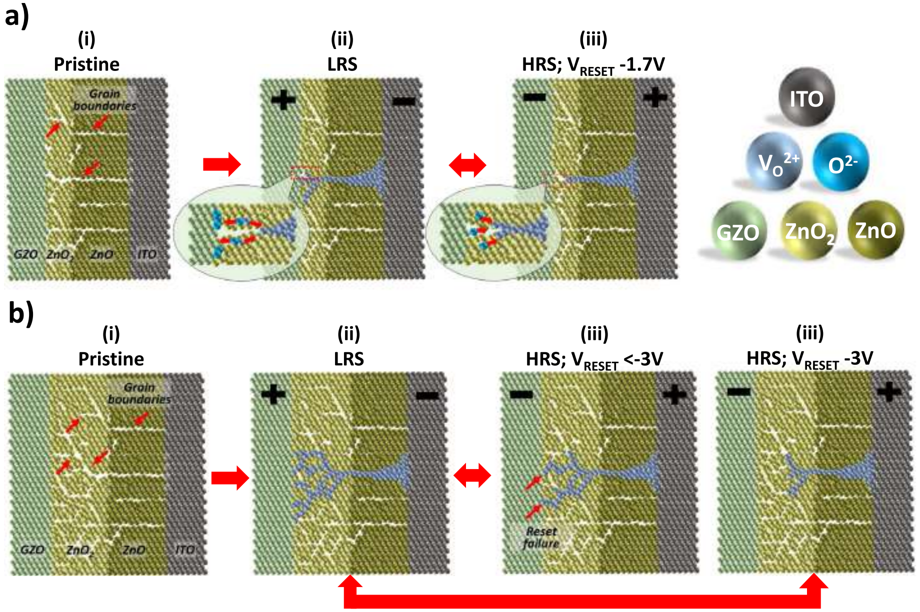


Nanos. Res. Lett. (2018) 13, 327

Strategies



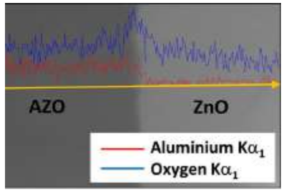




APL Mater. (2019) 7, 051108

Strategies

Strategies to enhance the performance



Electrode Engineering

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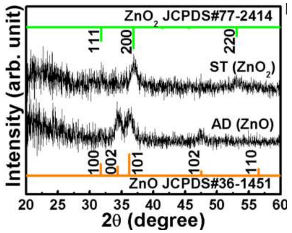
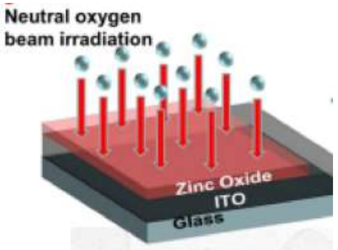
Doping

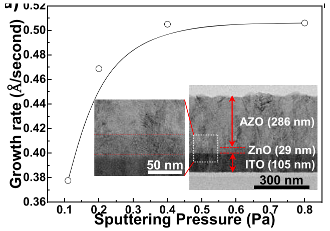


Chemical Oxidation

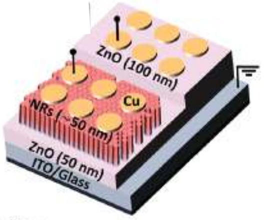


Ion Beam Oxidation

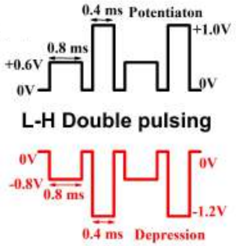
Optimization of Deposition Parameter



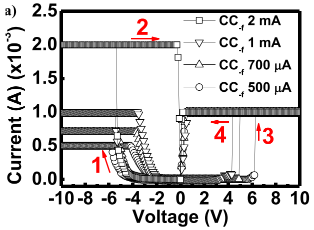
Compact 2D Structures

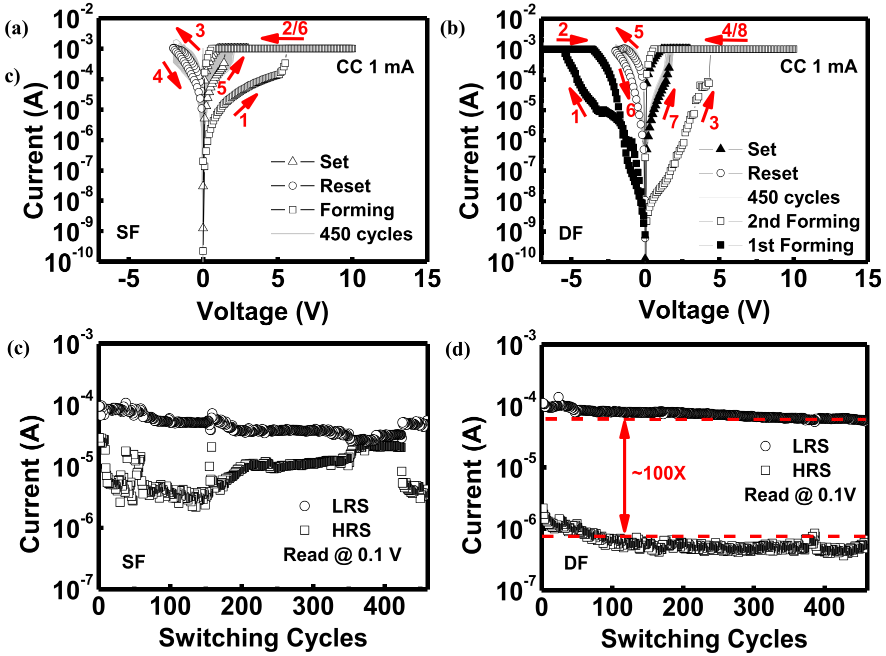


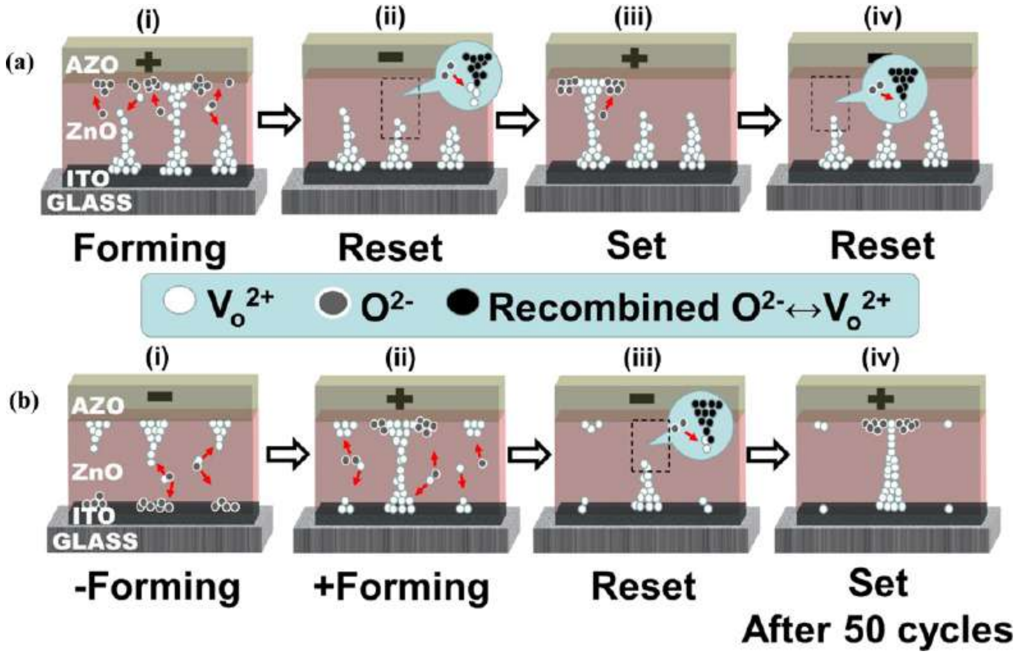
Double Pulsing



Double Forming



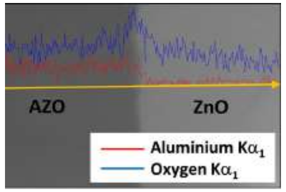




Appl. Phys. Lett. (2015) 107, 033505

Strategies

Strategies to enhance the performance



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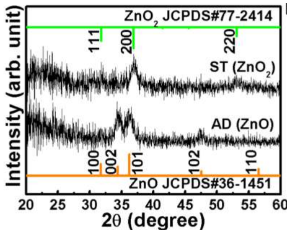
Doping



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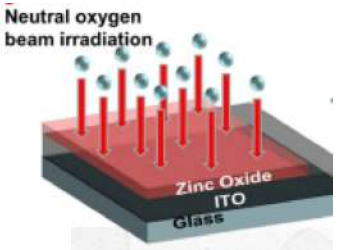
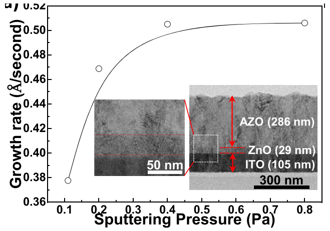
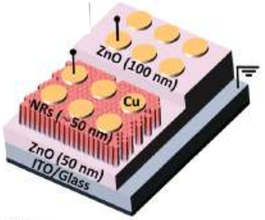


Ion Beam Oxidation

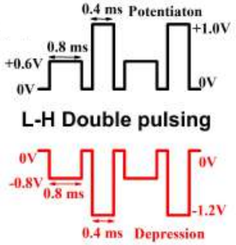
Optimization of Deposition Parameter



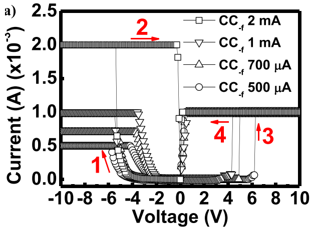
Compact 2D Structures

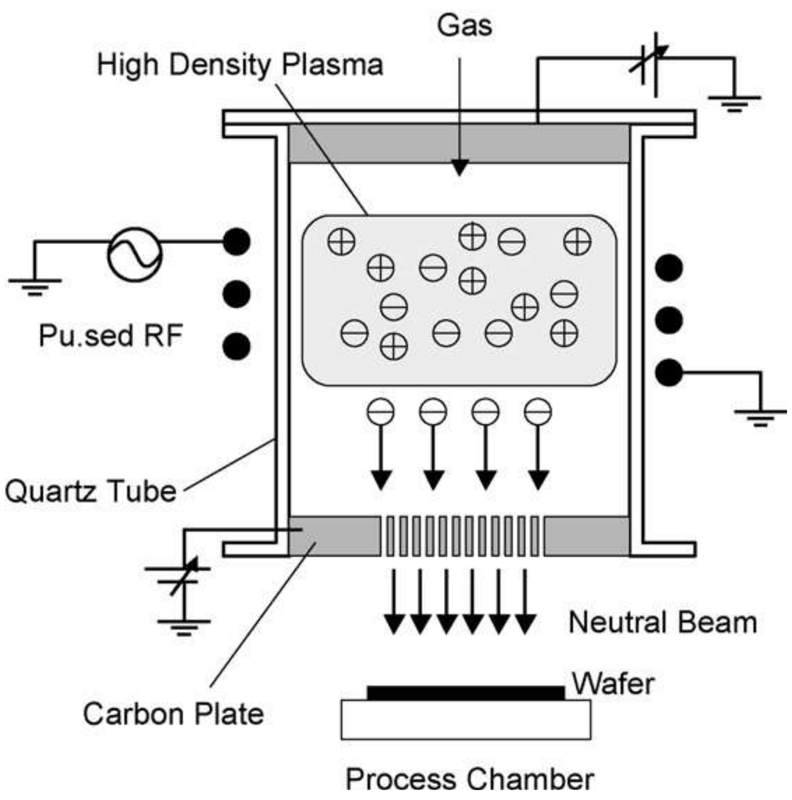


Double Pulsing

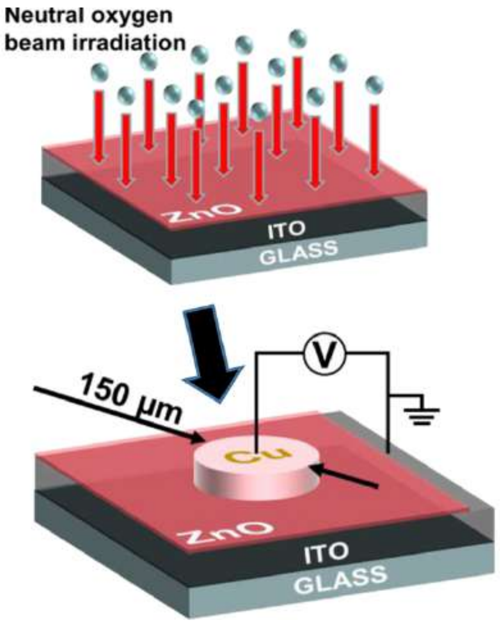


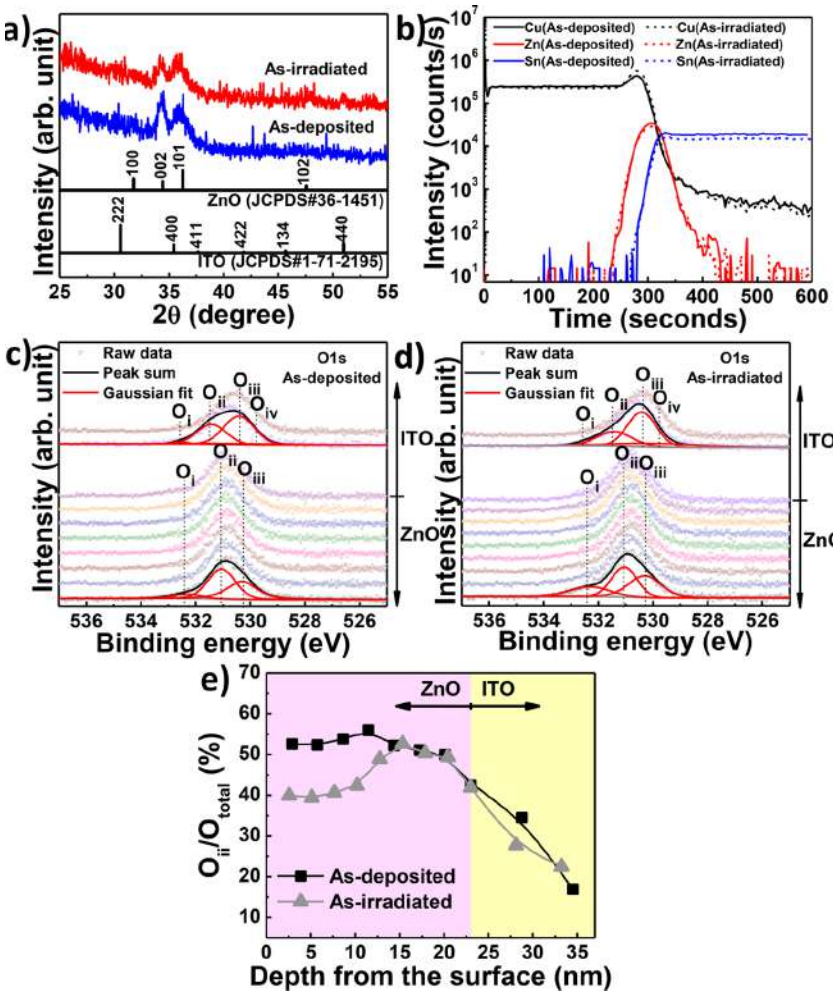
Double Forming





Samukawa S. Appl. Surf, Sci. (2007) 253, 6681

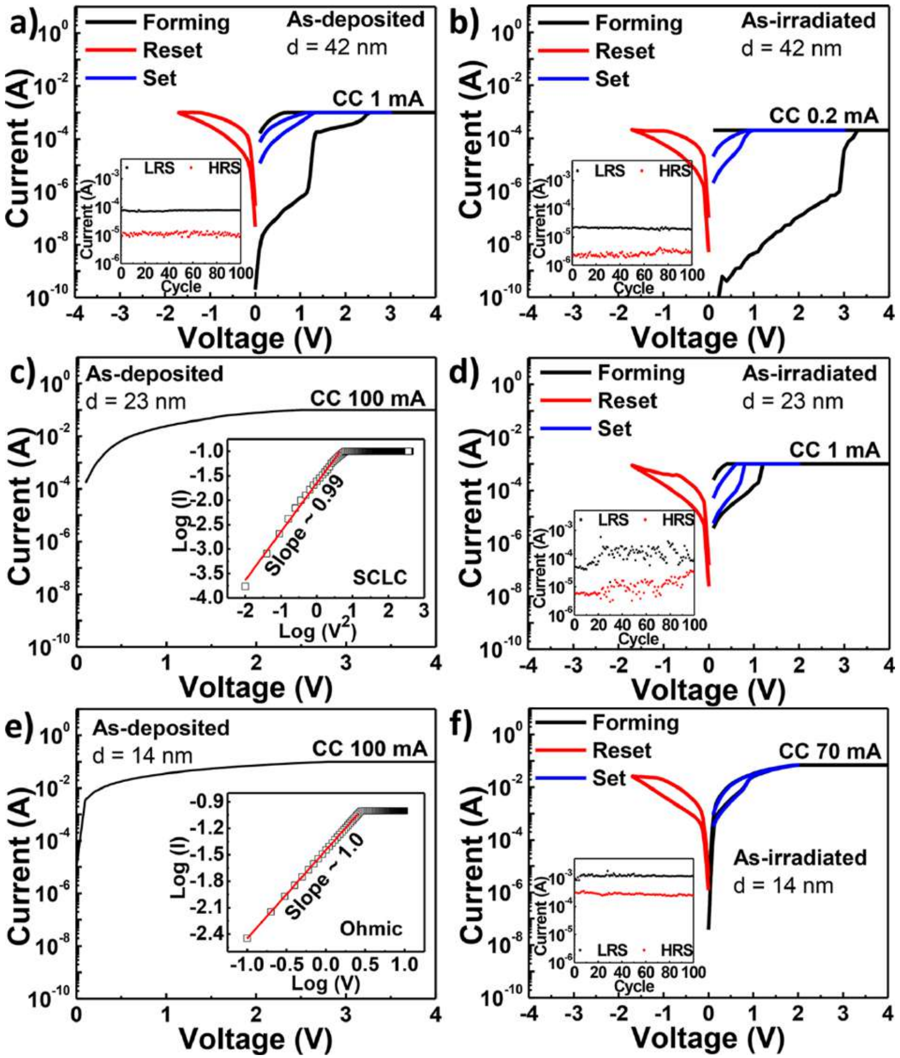




ACS Appl. Electron. Mater. (2019) 1, 1:18

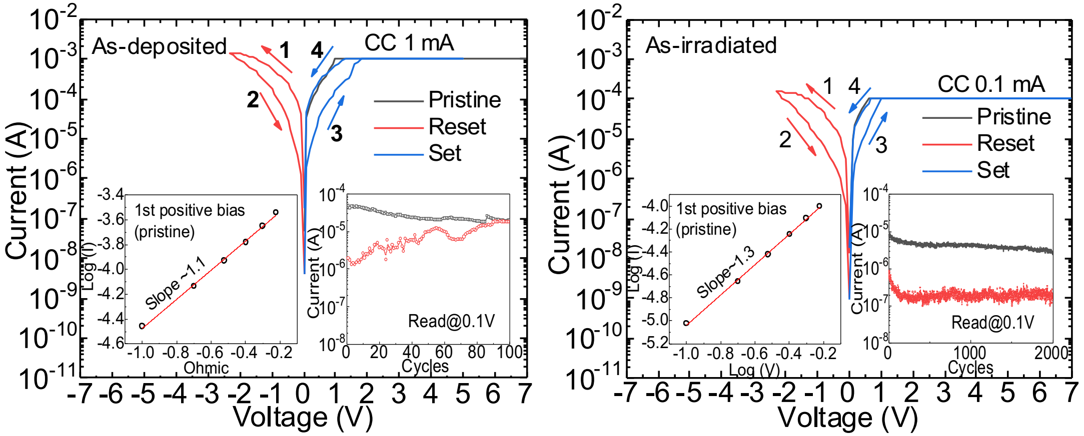
Strategies

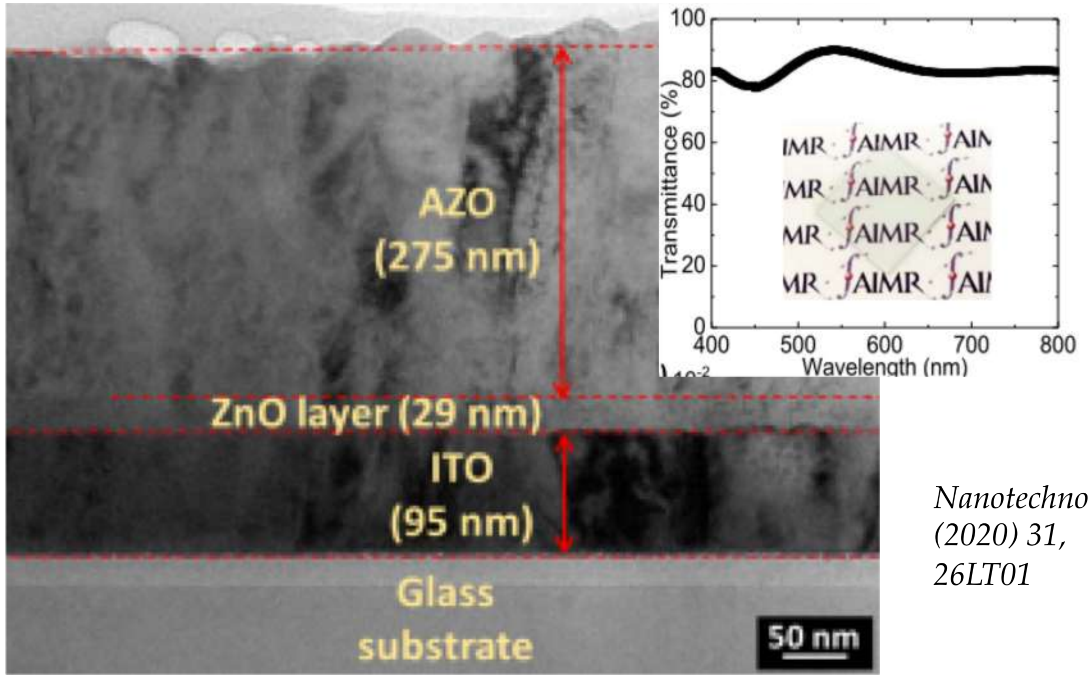
Cu/ZnO/ITO CBRAM



ACS Appl. Electron. Mater. (2019) 1, 1:18

ITO/ZnO(29nm)/ITO FTRRAM





Nanotechnology (2020) 31, 26LT01

Strategies

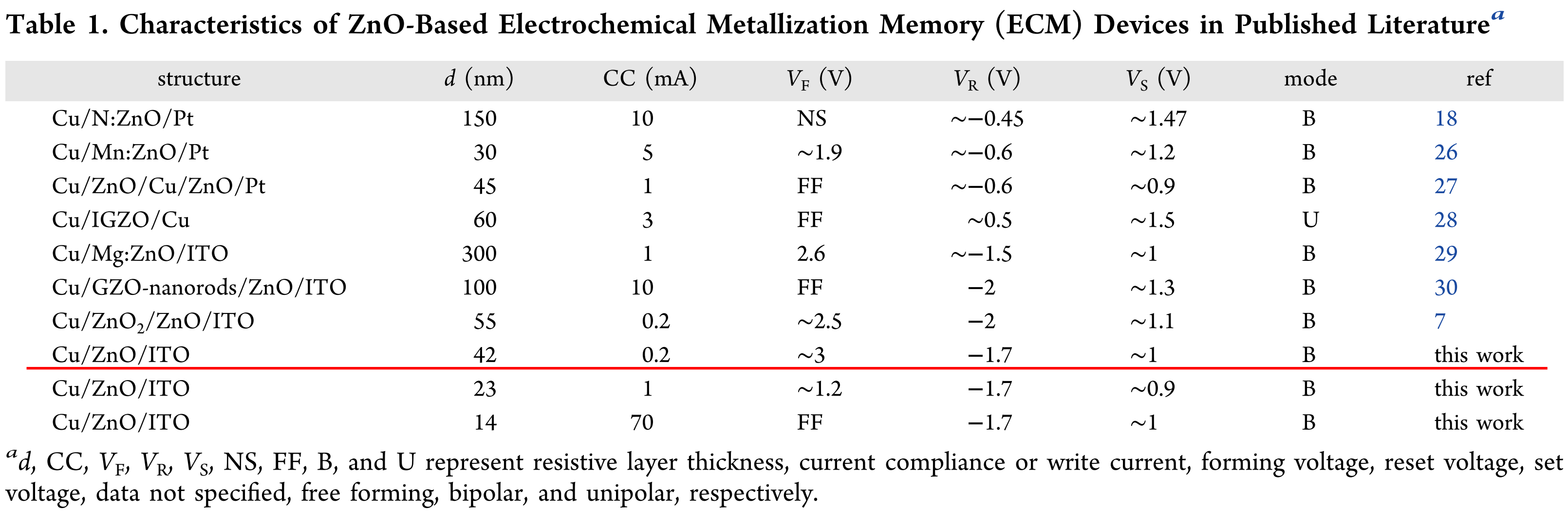


Table 1. Characteristics of ZnO-Based Electrochemical Metallization Memory (ECM) Devices in Published Literature[a]

structure	d (nm)	CC (mA)	V_F (V)	V_R (V)	V_S (V)	mode	ref
Cu/N:ZnO/Pt	150	10	NS	∼−0.45	∼1.47	B	18
Cu/Mn:ZnO/Pt	30	5	∼1.9	∼−0.6	∼1.2	B	26
Cu/ZnO/Cu/ZnO/Pt	45	1	FF	∼−0.6	∼0.9	B	27
Cu/IGZO/Cu	60	3	FF	∼0.5	∼1.5	U	28
Cu/Mg:ZnO/ITO	300	1	2.6	∼−1.5	∼1	B	29
Cu/GZO-nanorods/ZnO/ITO	100	10	FF	−2	∼1.3	B	30
Cu/ZnO_2/ZnO/ITO	55	0.2	∼2.5	−2	∼1.1	B	7
Cu/ZnO/ITO	42	0.2	∼3	−1.7	∼1	B	this work
Cu/ZnO/ITO	23	1	∼1.2	−1.7	∼0.9	B	this work
Cu/ZnO/ITO	14	70	FF	−1.7	∼1	B	this work

[a] d, CC, V_F, V_R, V_S, NS, FF, B, and U represent resistive layer thickness, current compliance or write current, forming voltage, reset voltage, set voltage, data not specified, free forming, bipolar, and unipolar, respectively.

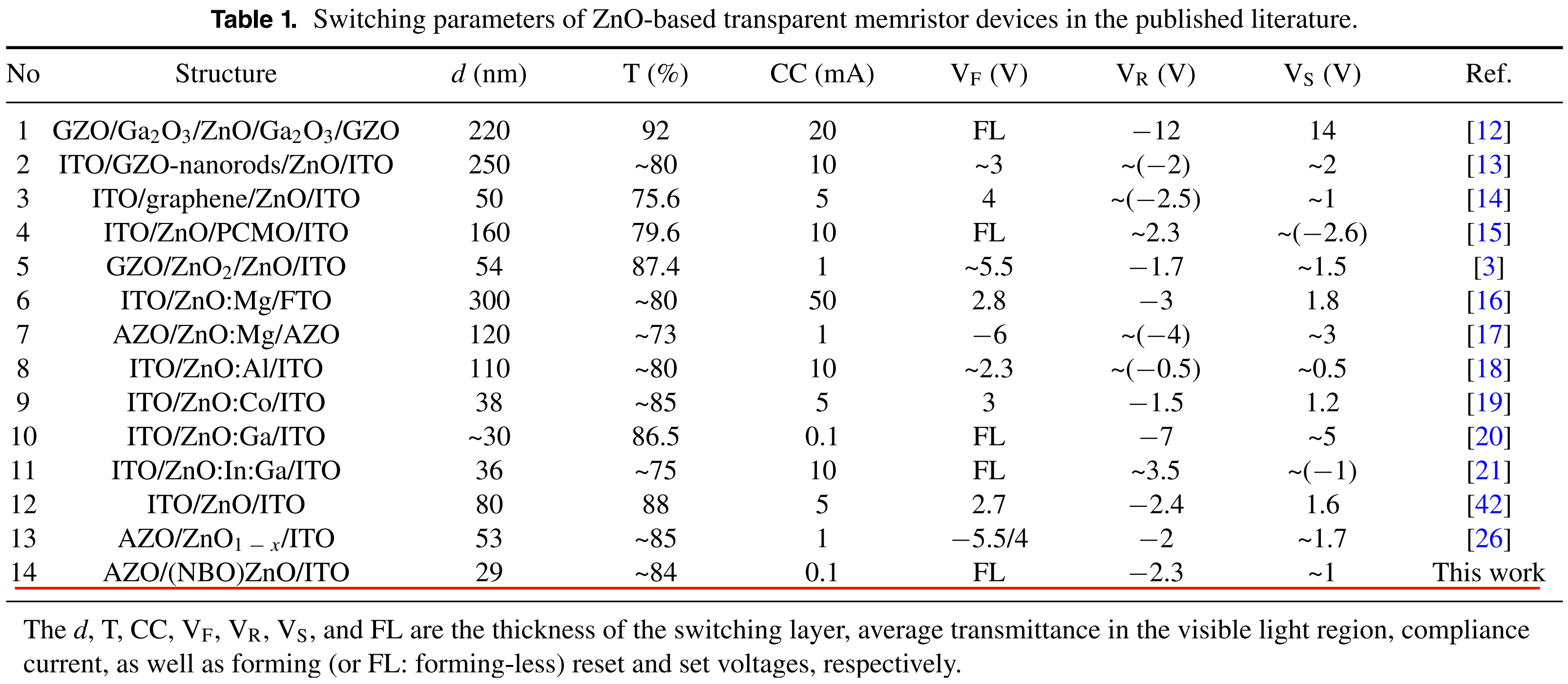


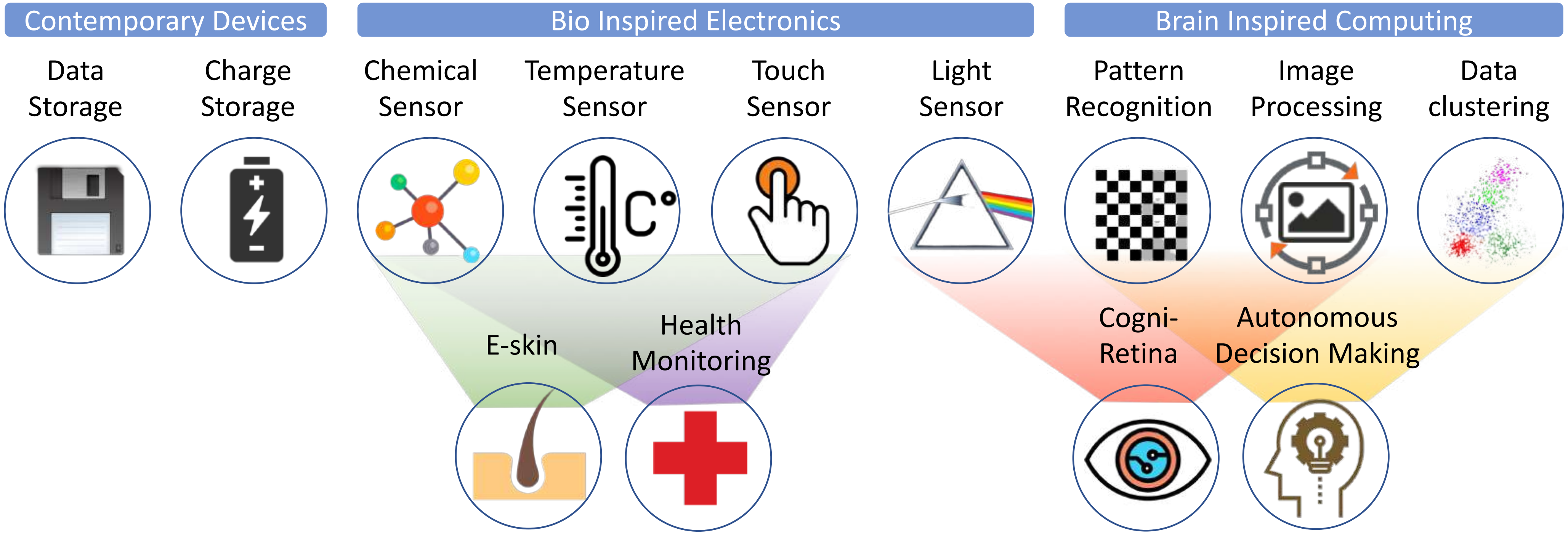
Table 1. Switching parameters of ZnO-based transparent memristor devices in the published literature.

No	Structure	d (nm)	T (%)	CC (mA)	V_F (V)	V_R (V)	V_S (V)	Ref.
1	GZO/Ga_2O_3/ZnO/Ga_2O_3/GZO	220	92	20	FL	−12	14	[12]
2	ITO/GZO-nanorods/ZnO/ITO	250	~80	10	~3	~(−2)	~2	[13]
3	ITO/graphene/ZnO/ITO	50	75.6	5	4	~(−2.5)	~1	[14]
4	ITO/ZnO/PCMO/ITO	160	79.6	10	FL	~2.3	~(−2.6)	[15]
5	GZO/ZnO_2/ZnO/ITO	54	87.4	1	~5.5	−1.7	~1.5	[3]
6	ITO/ZnO:Mg/FTO	300	~80	50	2.8	−3	1.8	[16]
7	AZO/ZnO:Mg/AZO	120	~73	1	−6	~(−4)	~3	[17]
8	ITO/ZnO:Al/ITO	110	~80	10	~2.3	~(−0.5)	~0.5	[18]
9	ITO/ZnO:Co/ITO	38	~85	5	3	−1.5	1.2	[19]
10	ITO/ZnO:Ga/ITO	~30	86.5	0.1	FL	−7	~5	[20]
11	ITO/ZnO:In:Ga/ITO	36	~75	10	FL	~3.5	~(−1)	[21]
12	ITO/ZnO/ITO	80	88	5	2.7	−2.4	1.6	[42]
13	AZO/ZnO_{1-x}/ITO	53	~85	1	−5.5/4	−2	~1.7	[26]
14	AZO/(NBO)ZnO/ITO	29	~84	0.1	FL	−2.3	~1	This work

The d, T, CC, V_F, V_R, V_S, and FL are the thickness of the switching layer, average transmittance in the visible light region, compliance current, as well as forming (or FL: forming-less) reset and set voltages, respectively.

Strategies

Beyond storage..



Contemporary Devices

Data Storage

Charge Storage

Bio Inspired Electronics

Chemical Sensor

Temperature Sensor

Touch Sensor

Light Sensor

E-skin

Health Monitoring

Brain Inspired Computing

Pattern Recognition

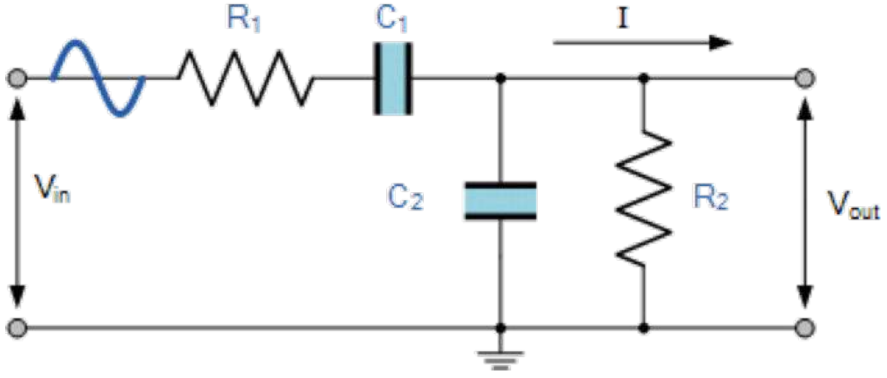
Image Processing

Data clustering

Cogni-Retina

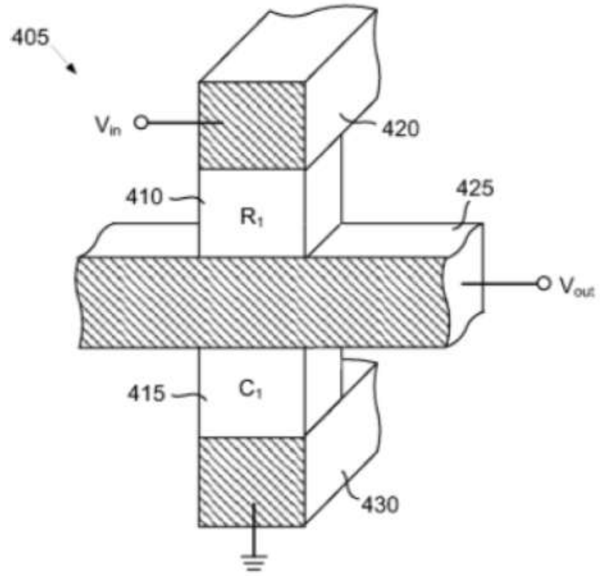
Autonomous Decision Making

Beyond storage : Memristor could replace tuning transistor



Electronics-tutorial.ws

Memristor can substitute conventional resistor making passive circuit tunable.

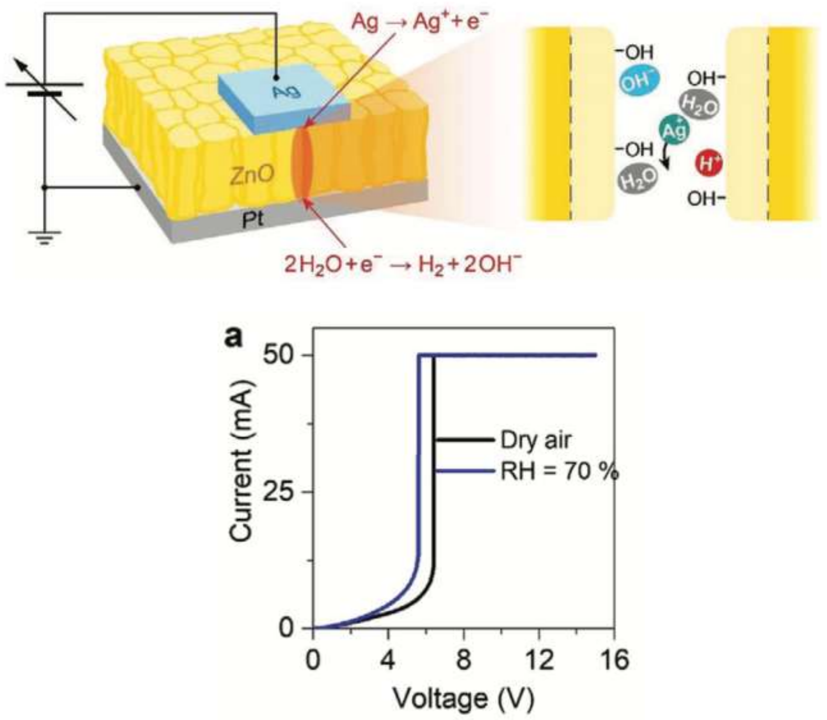


Programmable analog filter

(Patent No. US9013177B2) / HP

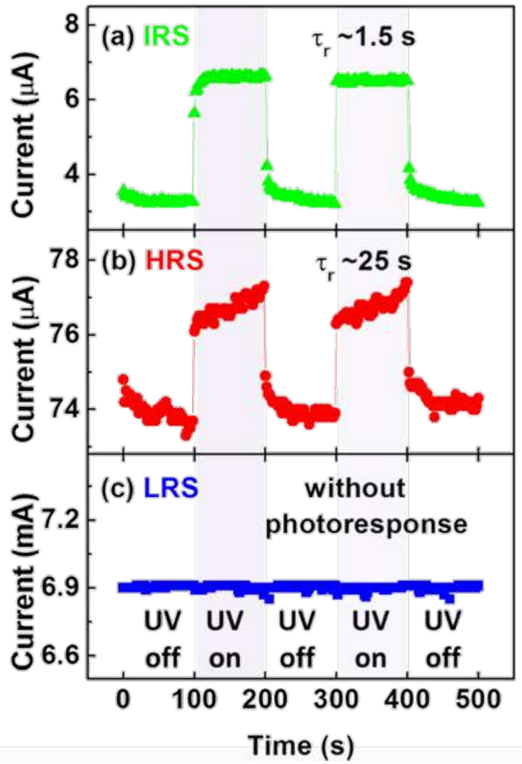
Beyond storage : Memristor as sensor

Humidity



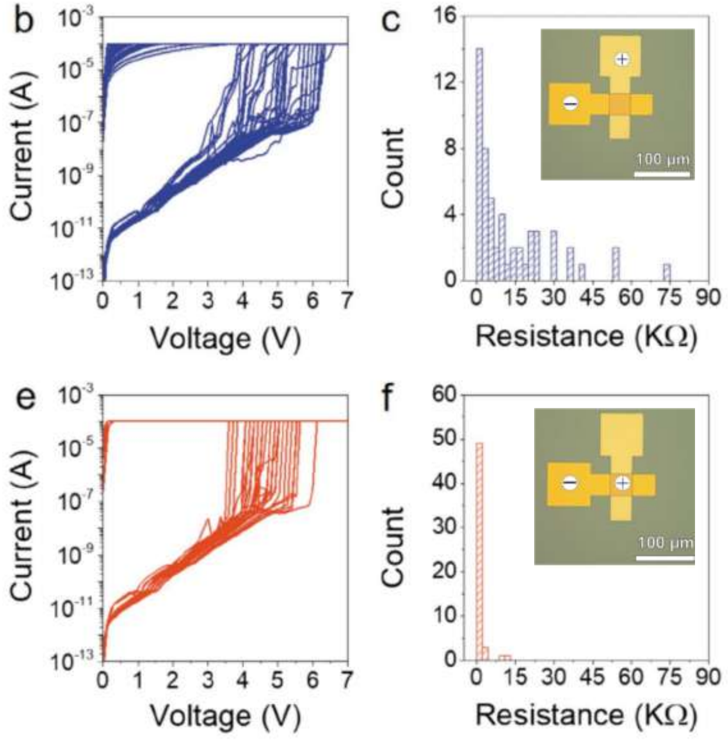
Ag/ZnO/Pt device in dry air and 70% N_2 ambient. *Adv. Mater. Interfaces (2021) 2100915*

Light



Pt/ZnO/Pt shows photoconductivity under UV radiation. *Appl. Phys. Lett. (2014) 105, 253111*

Pressure

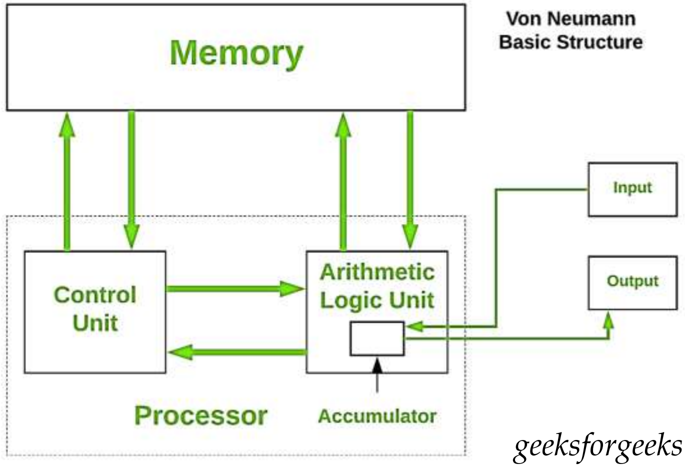


Ni/HfO2/Ni exhibits sensitivity toward mechanical pressure. *Adv. Electron. Mater. 2020, 6, 1901226*

Beyond storage : Memristor as an AI element

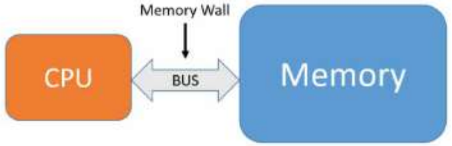
J. von Neumann

proposed a modern computer
architecture in 1945



geeksforgeeks.org

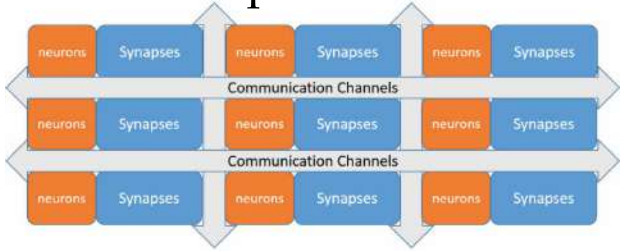
von Neumann's architecture



- Memory wall
- Power-hungry
- Huge unwanted heat

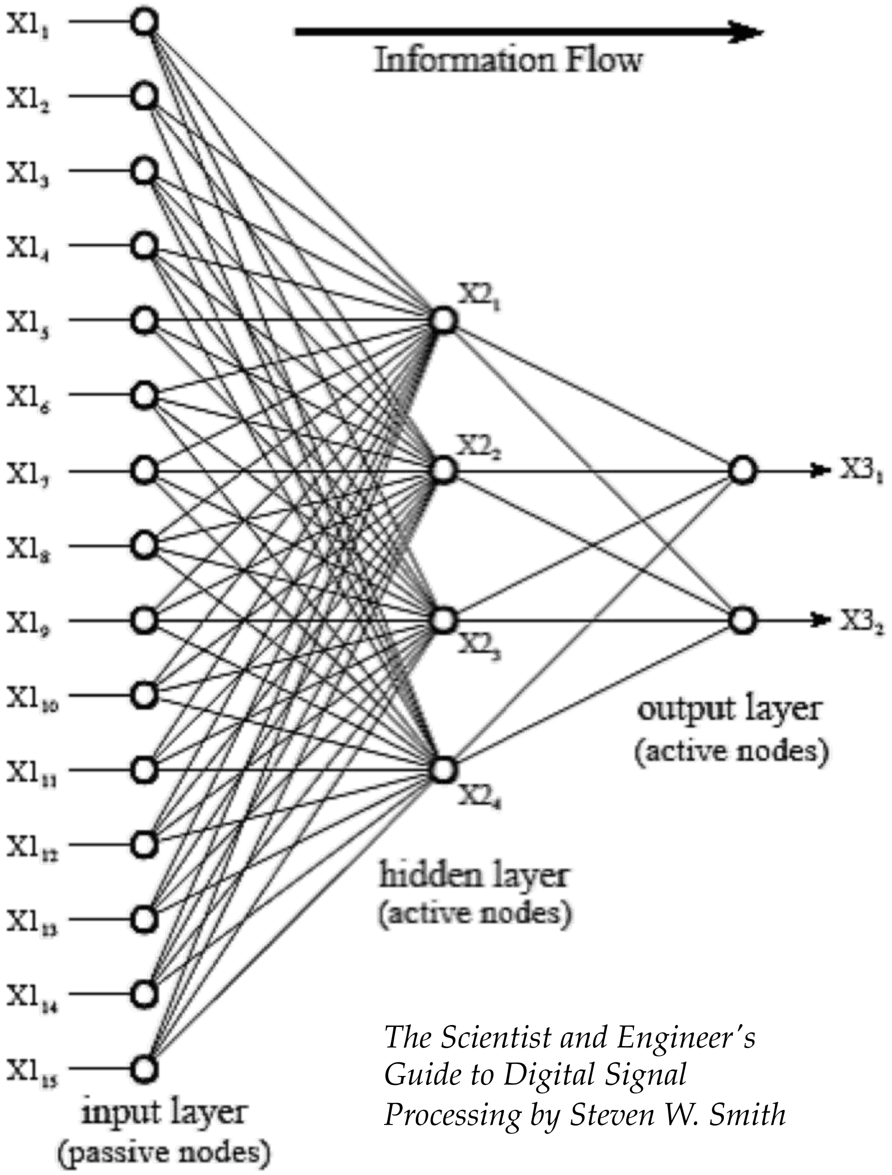
VS

Neuromorphic architecture

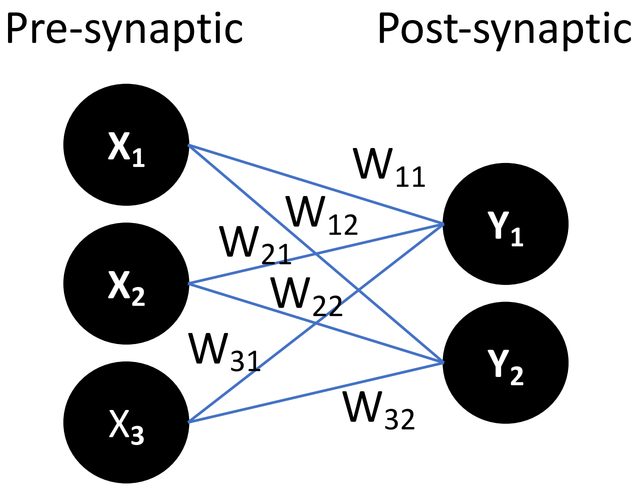


- + Save power
- + More reliable
- + Quicker response
- + Save network bandwidth

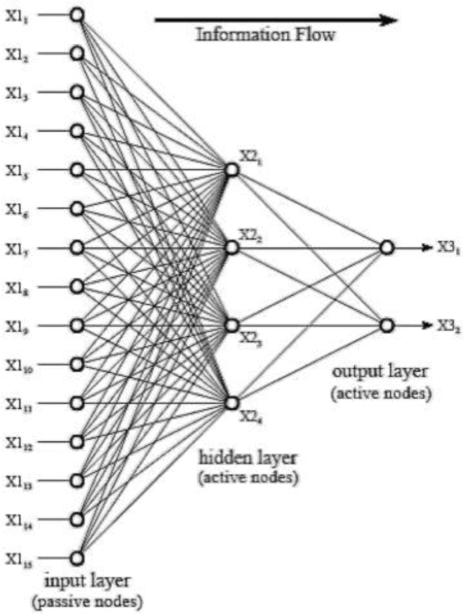
Proceedings of the IEEE (2018) 106, 2



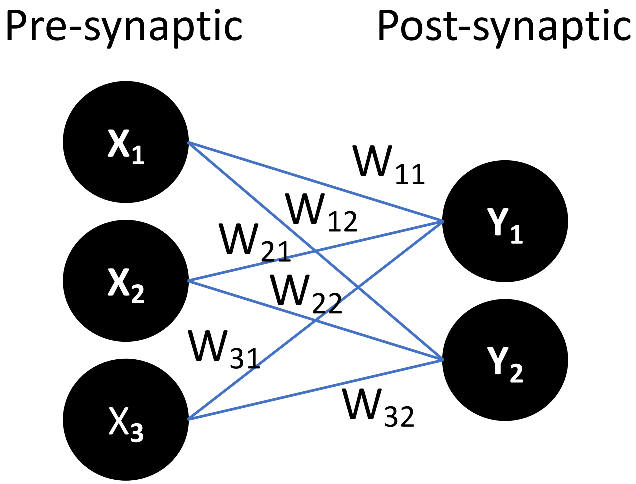
The Scientist and Engineer's Guide to Digital Signal Processing by Steven W. Smith

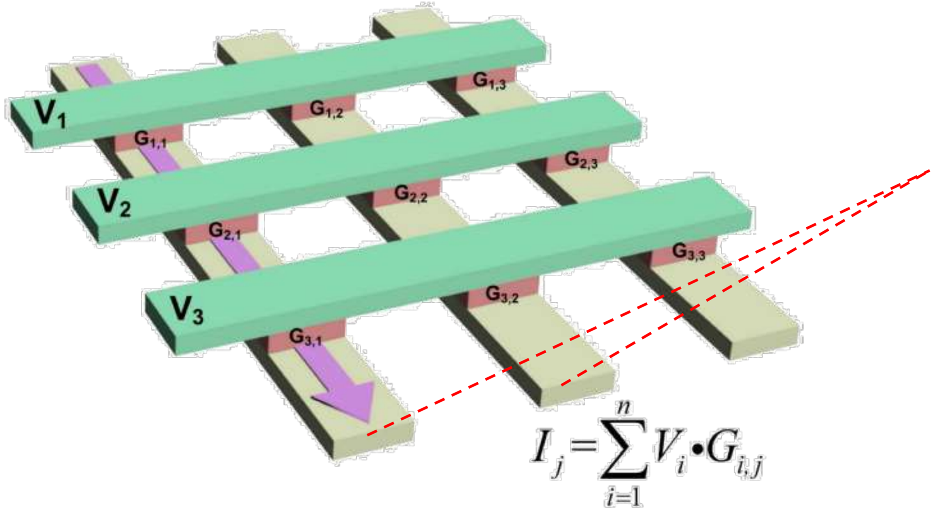


Vector-matrix multiplication is the fundamental computation in neural network model.



The Scientist and Engineer's Guide to Digital Signal Processing by Steven W. Smith

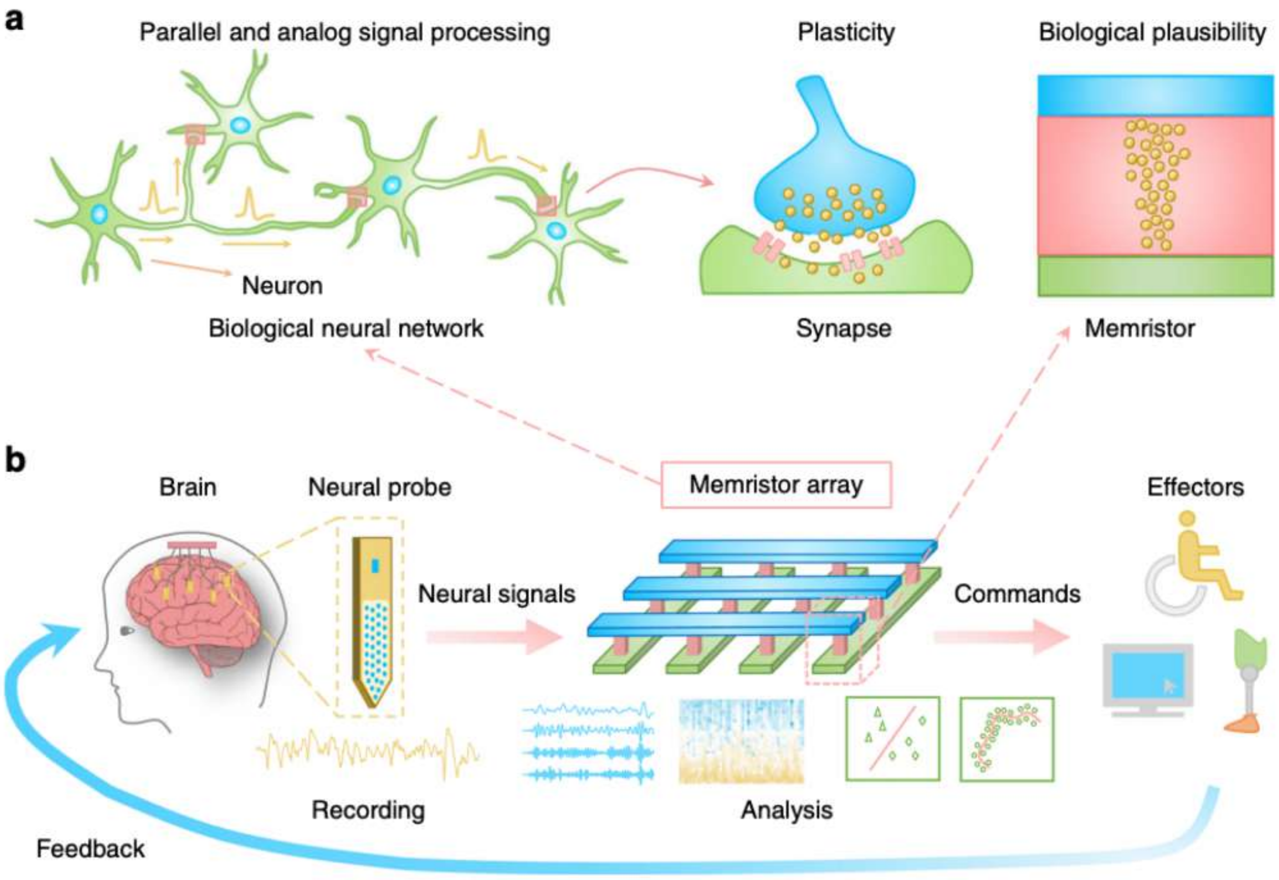


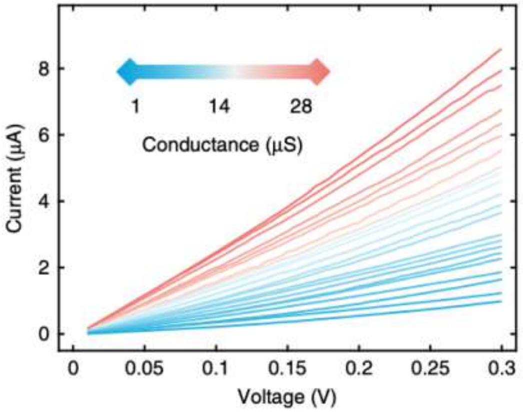


$$I_j = \sum_{i=1}^{n} V_i \bullet G_{i,j}$$

Proceedings of the IEEE (2021) 109, 14

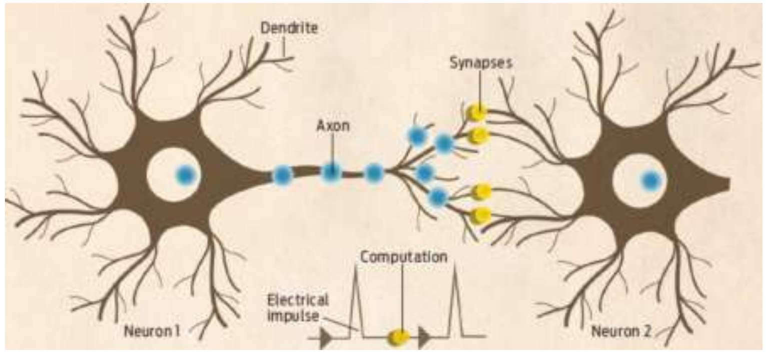
$$[I_1\ I_2] = [V_1\ V_2\ V_3]\begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \\ G_{31} & G_{33} \end{bmatrix}$$



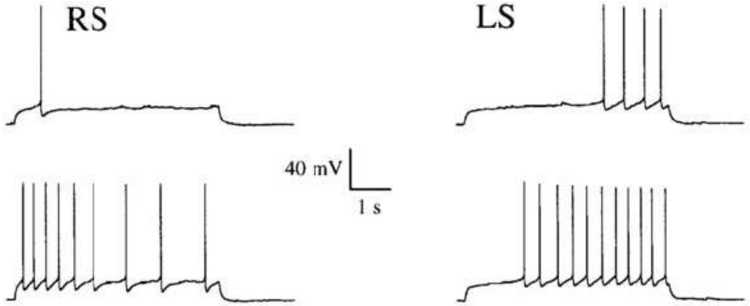


Nat. Commun. (2020) 11, 4234

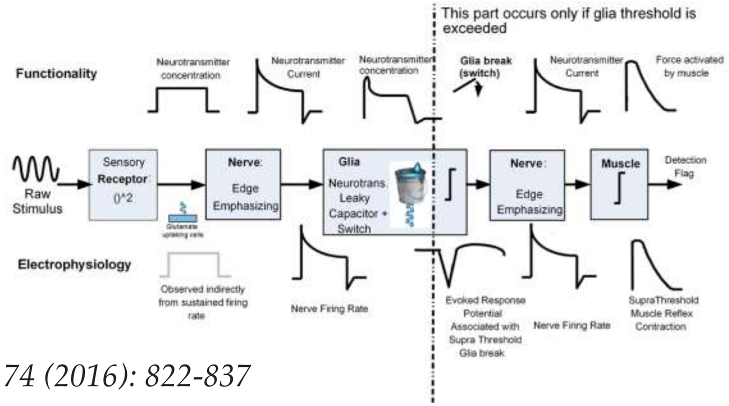
Biological synapse



Nanoscale Res. Lett., 2017, 12:347

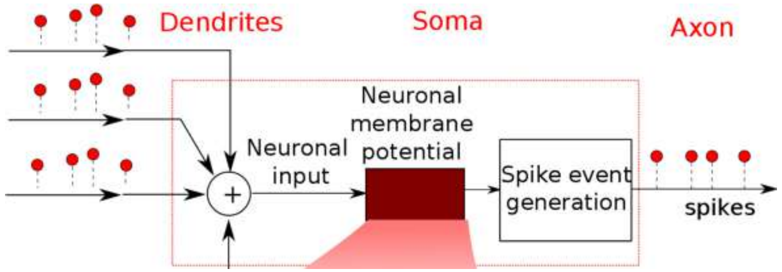


Characteristics of regular spiking (RS) and late spiking (LS) neurons in layer II/III of rat perirhinal cortex. *J. Neurophysiol. 83(6):3294-8*

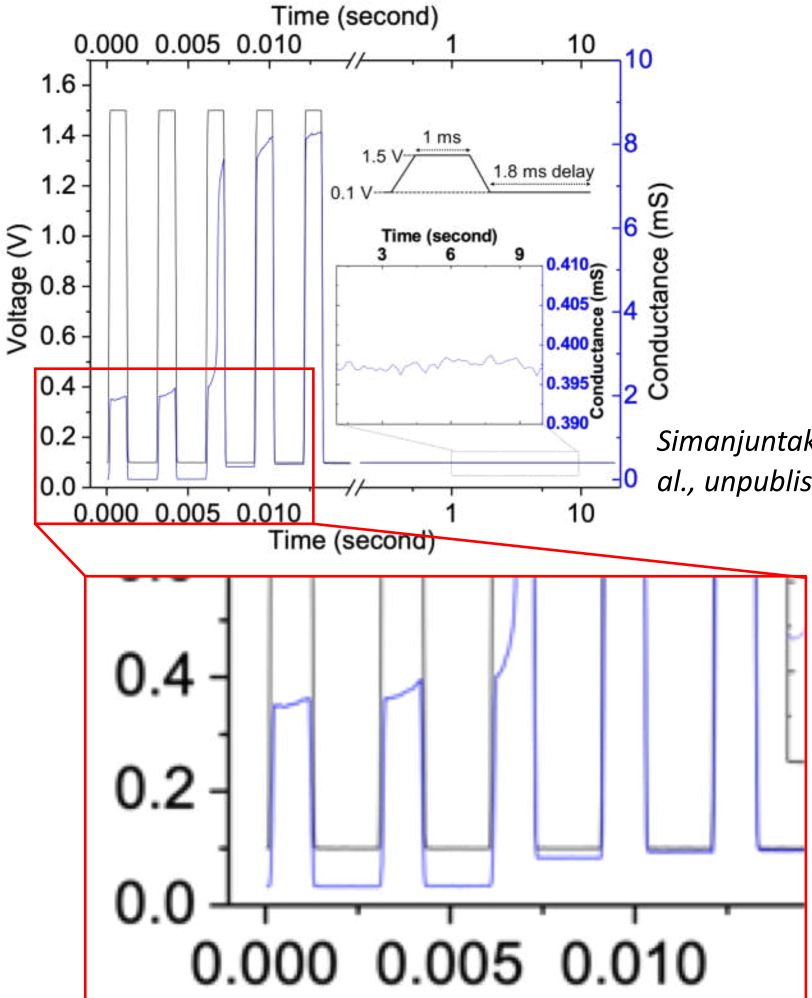


Neurocomputing 174 (2016): 822-837

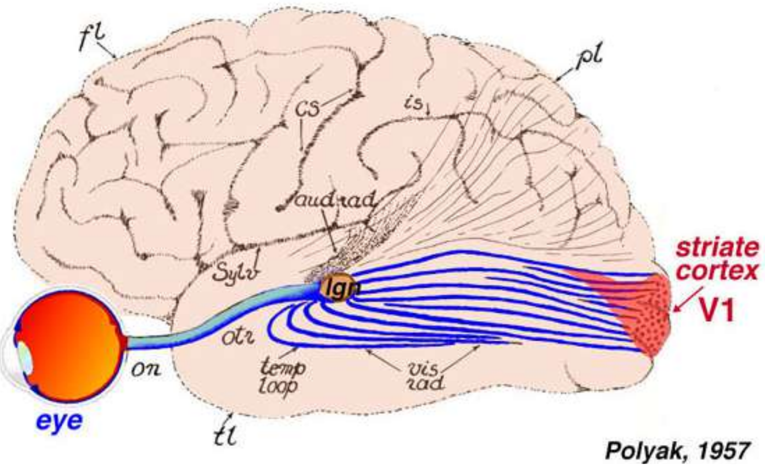
Artificial synapse



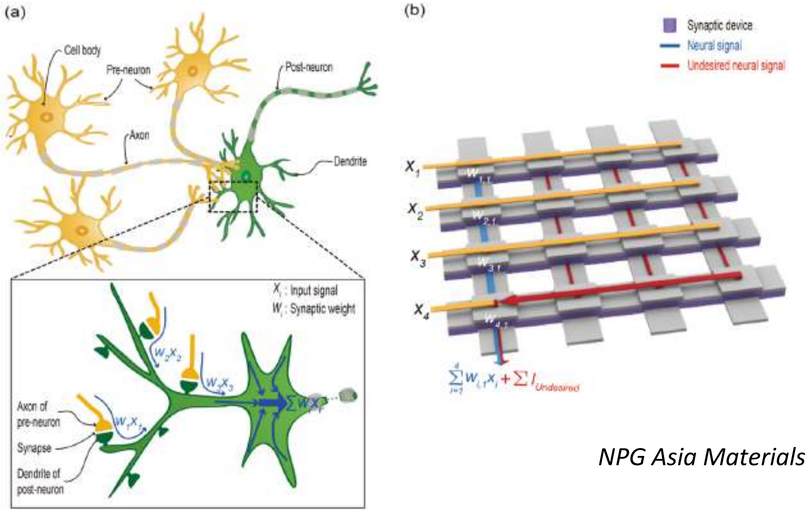
J. Appl. Phys., 2018, 124, 111101



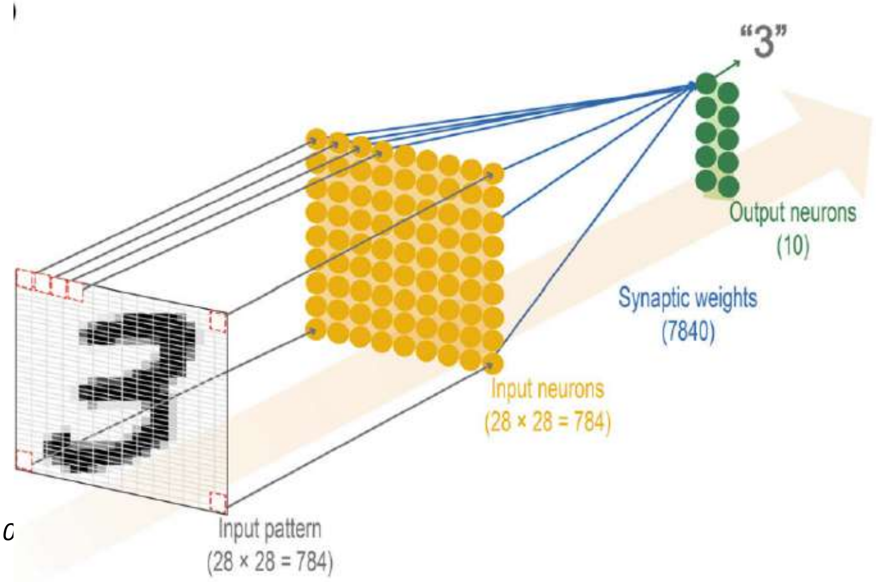
Simanjuntak et al., unpublished

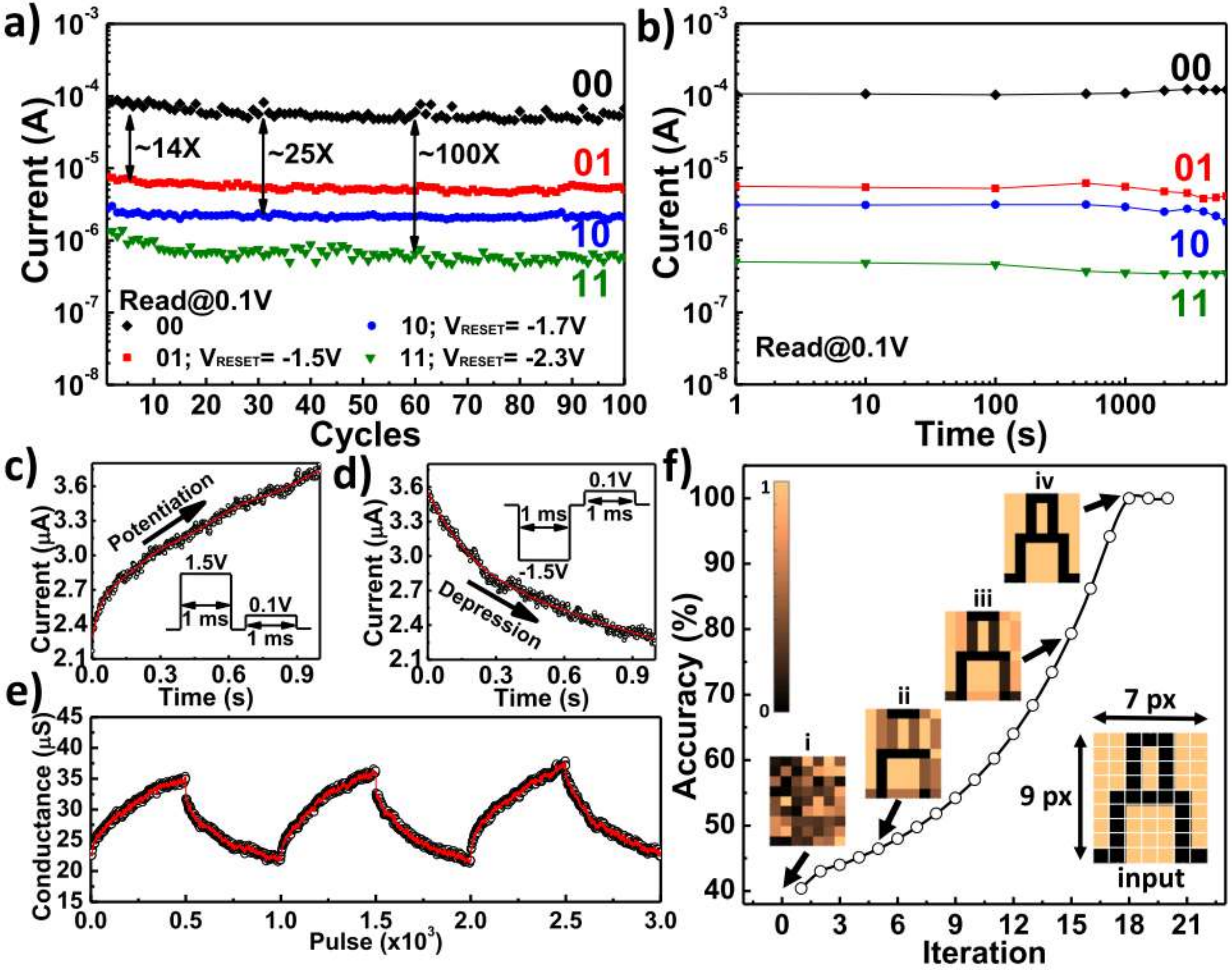


Polyak, 1957

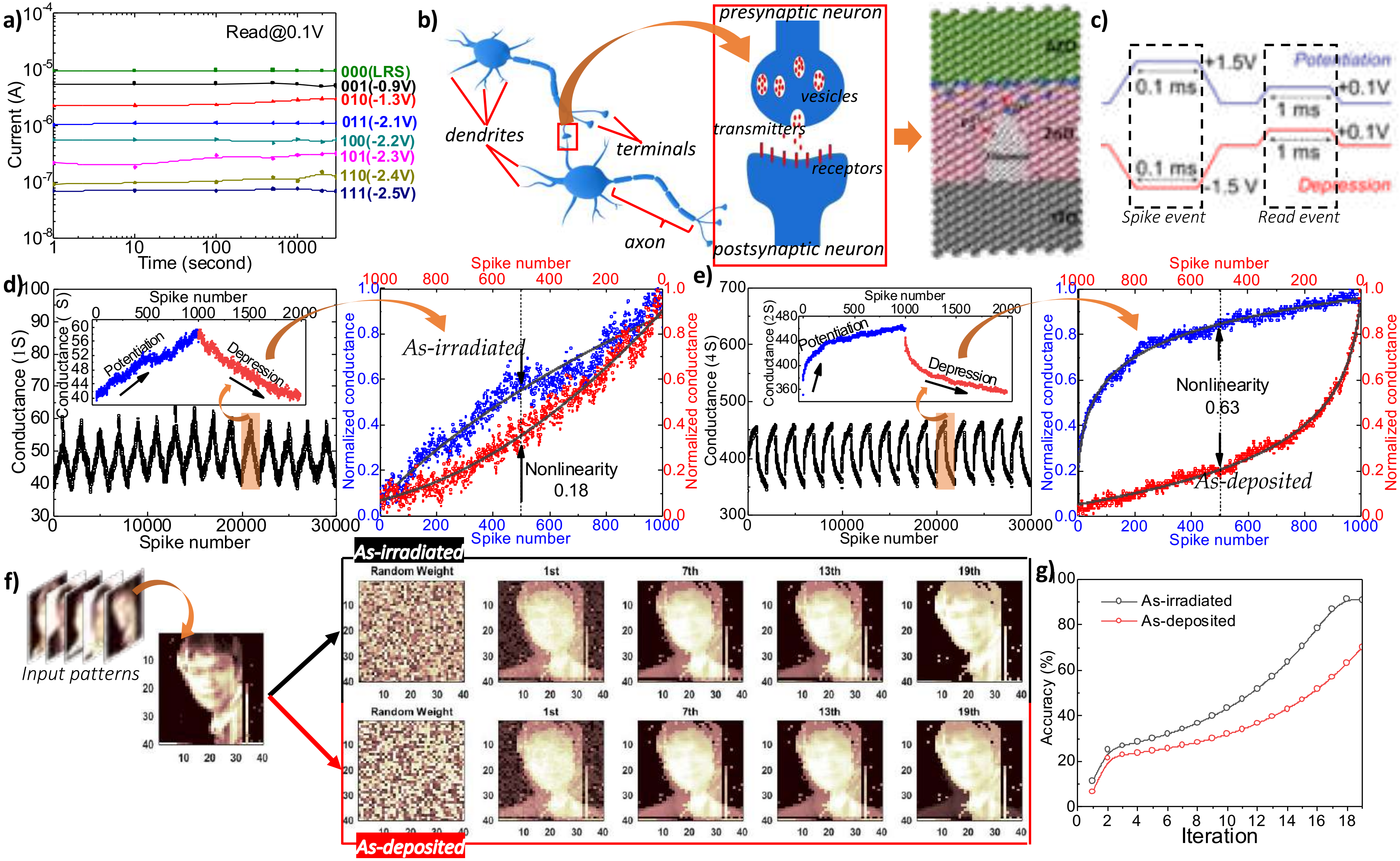


NPG Asia Materials (2018) 10: 10

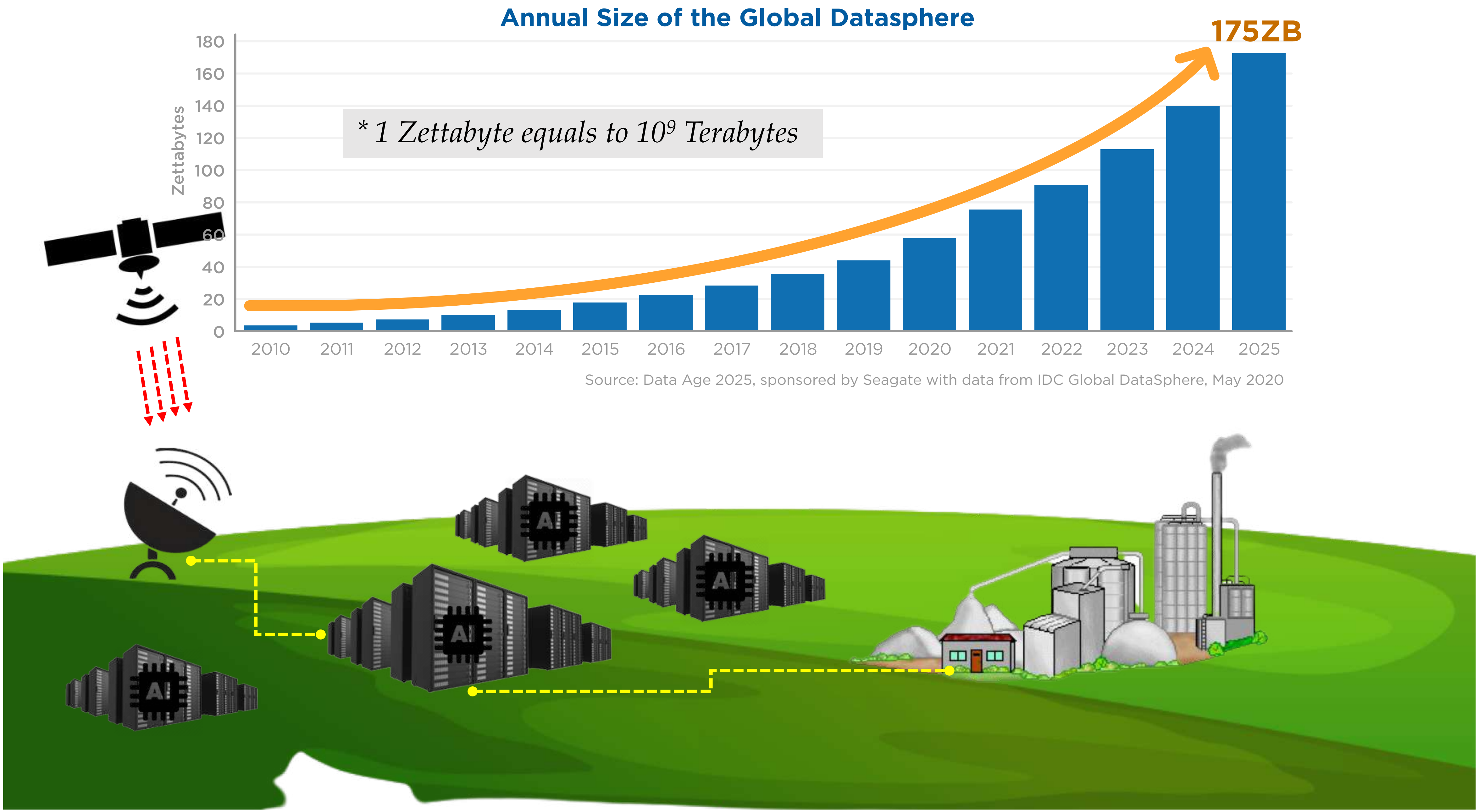




APL Mater. (2019) 7, 051108

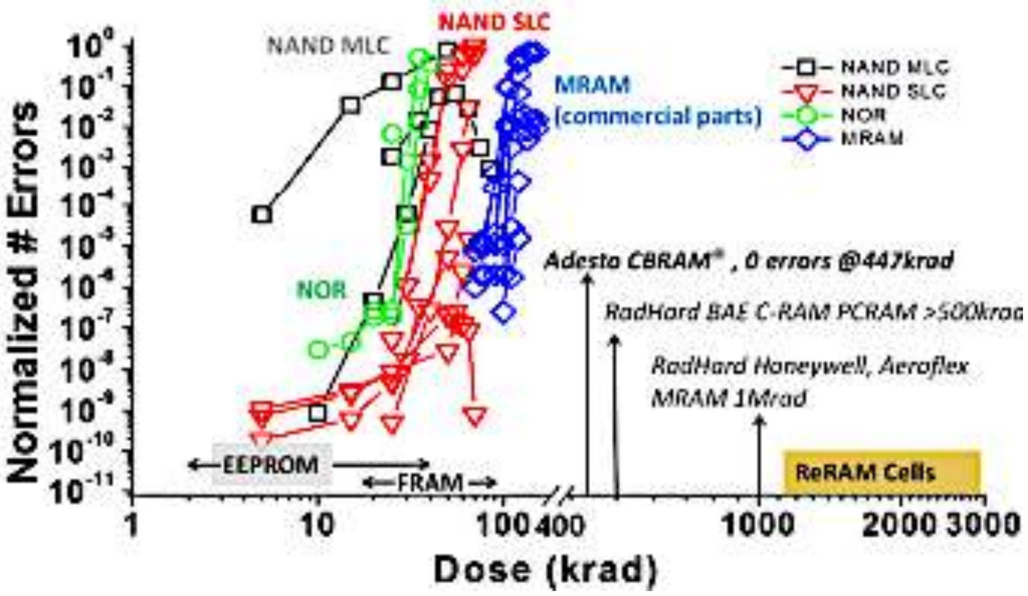


Nanotechnology (2020) 31, 26LT01

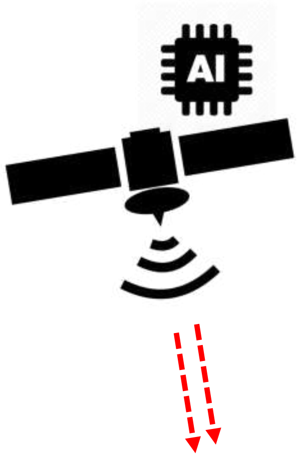


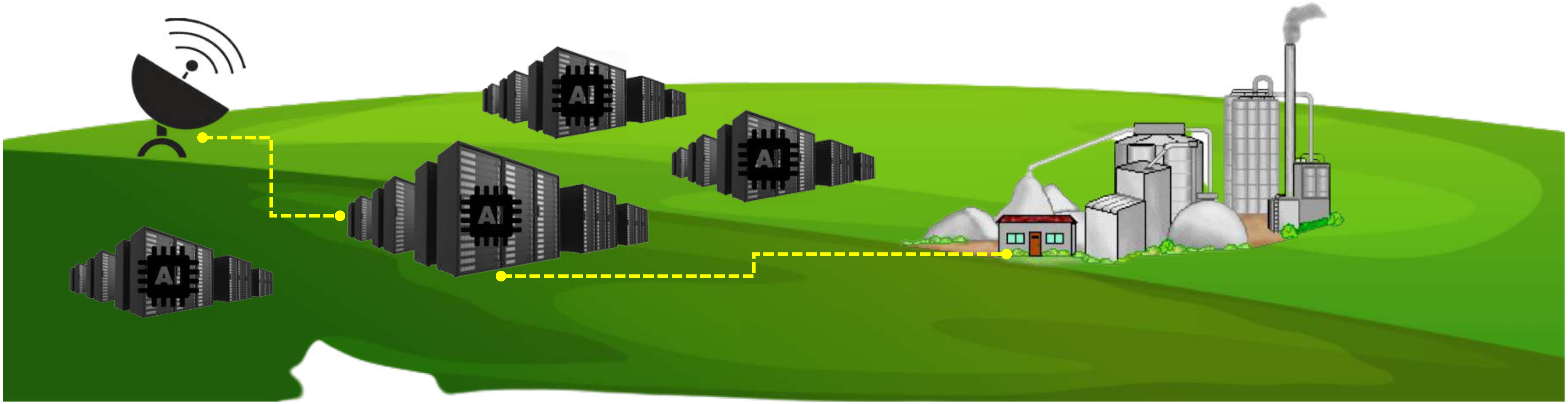
** 1 Zettabyte equals to 10^9 Terabytes*

Source: Data Age 2025, sponsored by Seagate with data from IDC Global DataSphere, May 2020



IEEE Trans. Nucl. Sci. (2016) 63, 4:2145

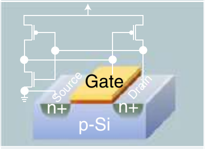
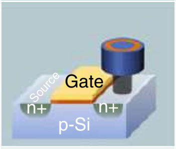
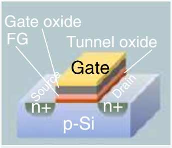
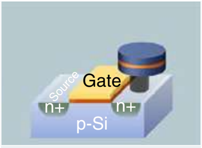
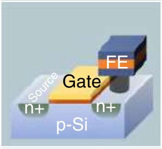
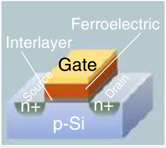
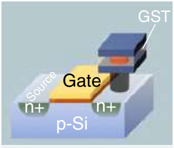
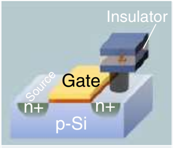
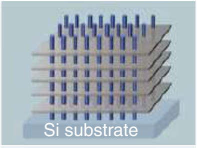
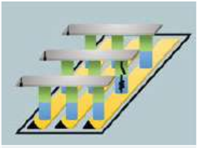




Emerging Technologies

Volatile

Non-Volatile

	eSRAM	eDRAM	eFLASH	STT-MRAM	FeRAM	FeFET	PCRAM	RRAM	Vertical RRAM	Crossbar RRAM
										
Cell size	120–150 F^2	10–30 F^2	10–30 F^2	10–30 F^2	10–30 F^2	10–30 F^2	10–30 F^2	10–30 F^2	4 F^2/N	4 F^2/N
Cell structure	6T	1T–1C	1T	1T–1MTJ	1T–1C	1T	1T–1PCM	1T–1R	1S–1R	1S–1R
Non-volatility	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Write voltage	<1 V	<1 V	~10 V	<1.5 V	<3 V	<4 V	<3 V	<3 V	<4 V	<3 V
Write energy	~fJ	~10 fJ	~100 pJ	~1 pJ	~0.1 pJ	~0.1 pJ	~10 pJ	~1 pJ	~10 pJ	~1 pJ
Standby power	High	Medium	Low	Low	Low	Low	Low	Low	Low	Low
Write speed	~1 ns	~10 ns	0.1–1 ms	~5 ns	~10 ns	~10 ns	~10 ns	~10 ns	~100 ns	~50 ns
Read speed	~1 ns	~3 ns	~10 ns	~5 ns	~10 ns	~10 ns	~10 ns	~10 ns	~1 µs	~50 ns
Endurance	10^{16}	10^{16}	10^4–10^6	10^{15}	10^{14}	$>10^5$	$>10^{12}$	$>10^7$	$>10^7$	$>10^8$

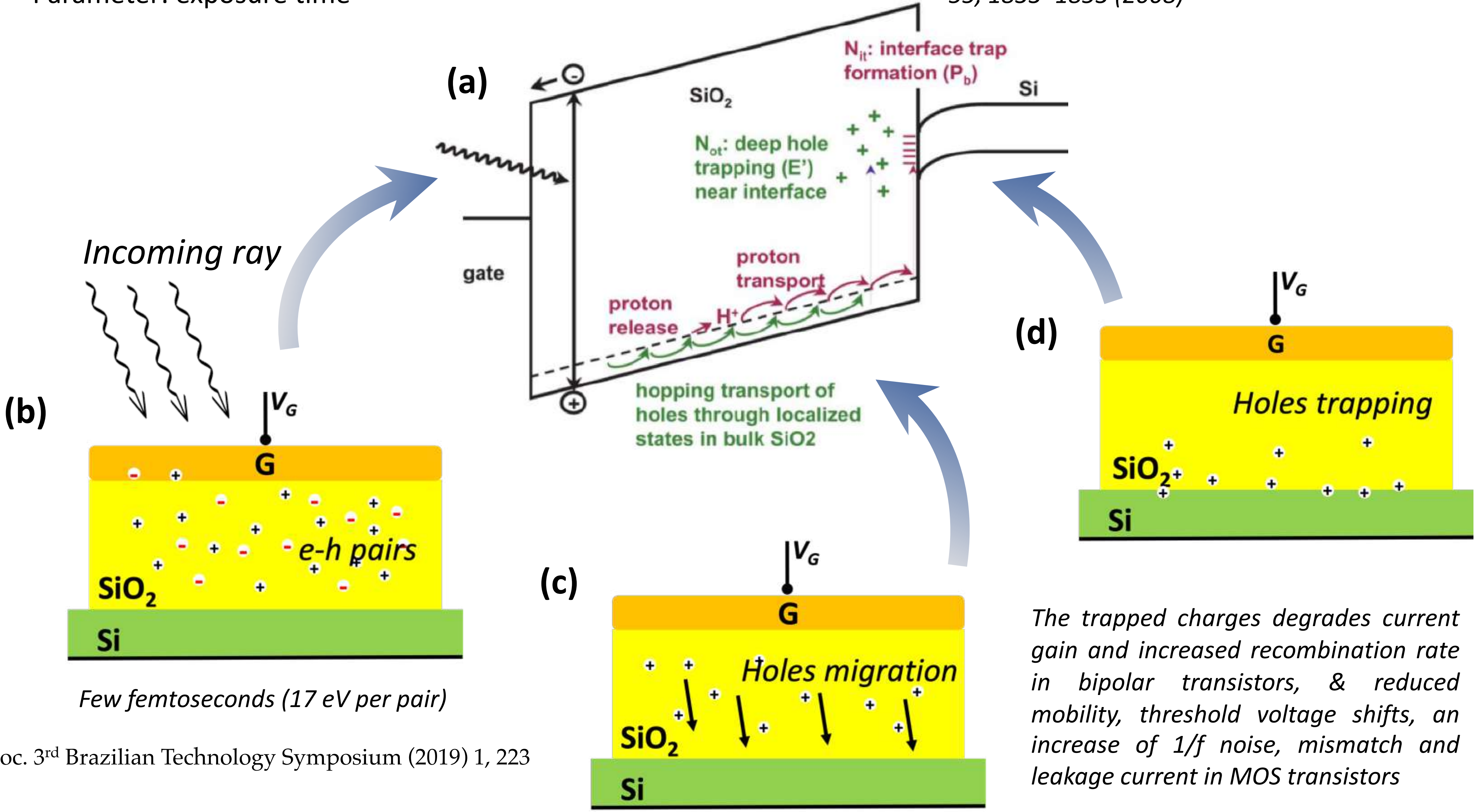
Nature Electronics (2018) 1:442

Radiation-induced Electronic Failures

1. **TID** (mainly photons)

Parameter: exposure time

IEEE Trans. Nucl. Sci.
55, 1833–1853 (2008)



Few femtoseconds (17 eV per pair)

Proc. 3rd Brazilian Technology Symposium (2019) 1, 223

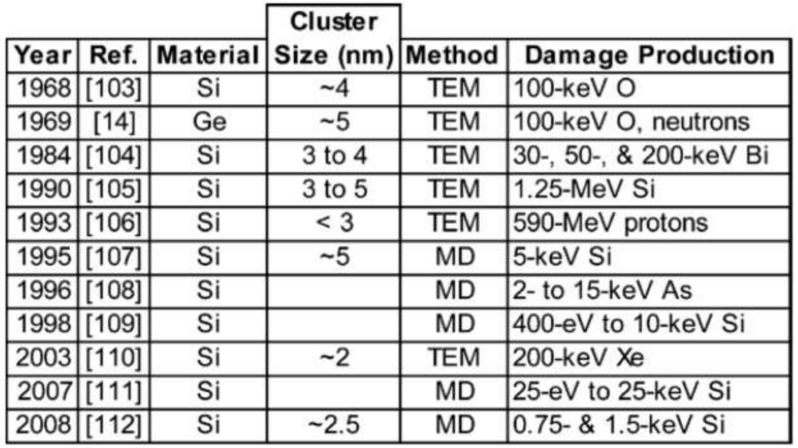
The trapped charges degrades current gain and increased recombination rate in bipolar transistors, & reduced mobility, threshold voltage shifts, an increase of 1/f noise, mismatch and leakage current in MOS transistors

Radiation-induced Electronic Failures

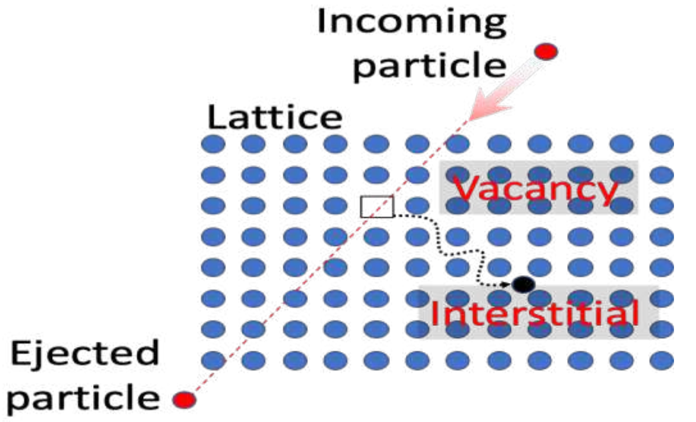
2. **DD** (mainly particles)

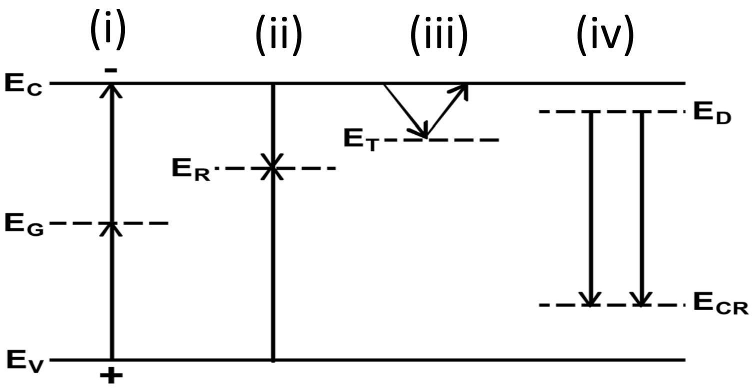
Photons-induced DD, indirectly, by producing secondary electrons.

Parameter: exposure time, type of particle (mass & energy)

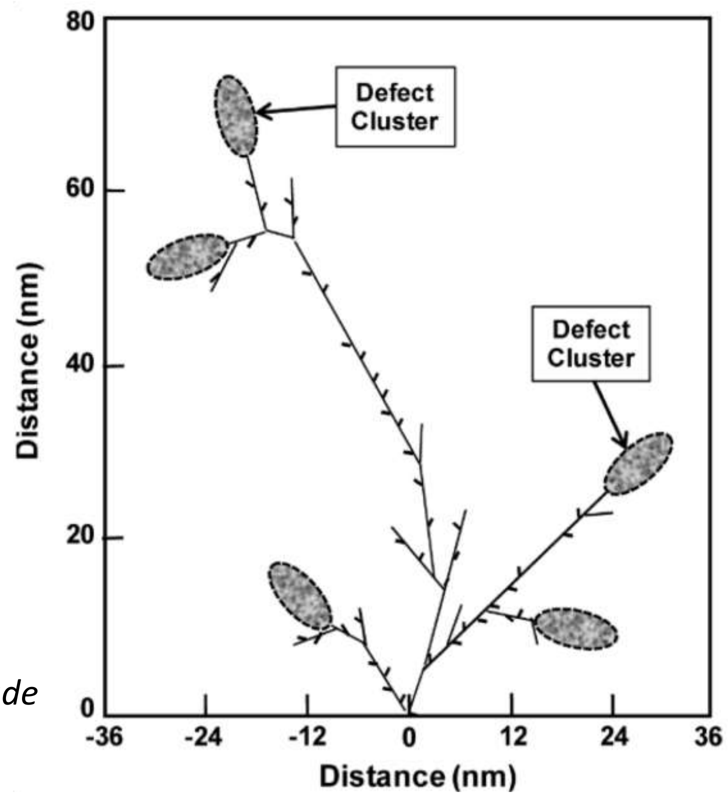


Year	Ref.	Material	Cluster Size (nm)	Method	Damage Production
1968	[103]	Si	~4	TEM	100-keV O
1969	[14]	Ge	~5	TEM	100-keV O, neutrons
1984	[104]	Si	3 to 4	TEM	30-, 50-, & 200-keV Bi
1990	[105]	Si	3 to 5	TEM	1.25-MeV Si
1993	[106]	Si	< 3	TEM	590-MeV protons
1995	[107]	Si	~5	MD	5-keV Si
1996	[108]	Si		MD	2- to 15-keV As
1998	[109]	Si		MD	400-eV to 10-keV Si
2003	[110]	Si	~2	TEM	200-keV Xe
2007	[111]	Si		MD	25-eV to 25-keV Si
2008	[112]	Si	~2.5	MD	0.75- & 1.5-keV Si





(i) Thermal generation of carriers
(ii) Carrier recombination
(iii) Temporary trapping
(iv) Reduction in carrier concentration



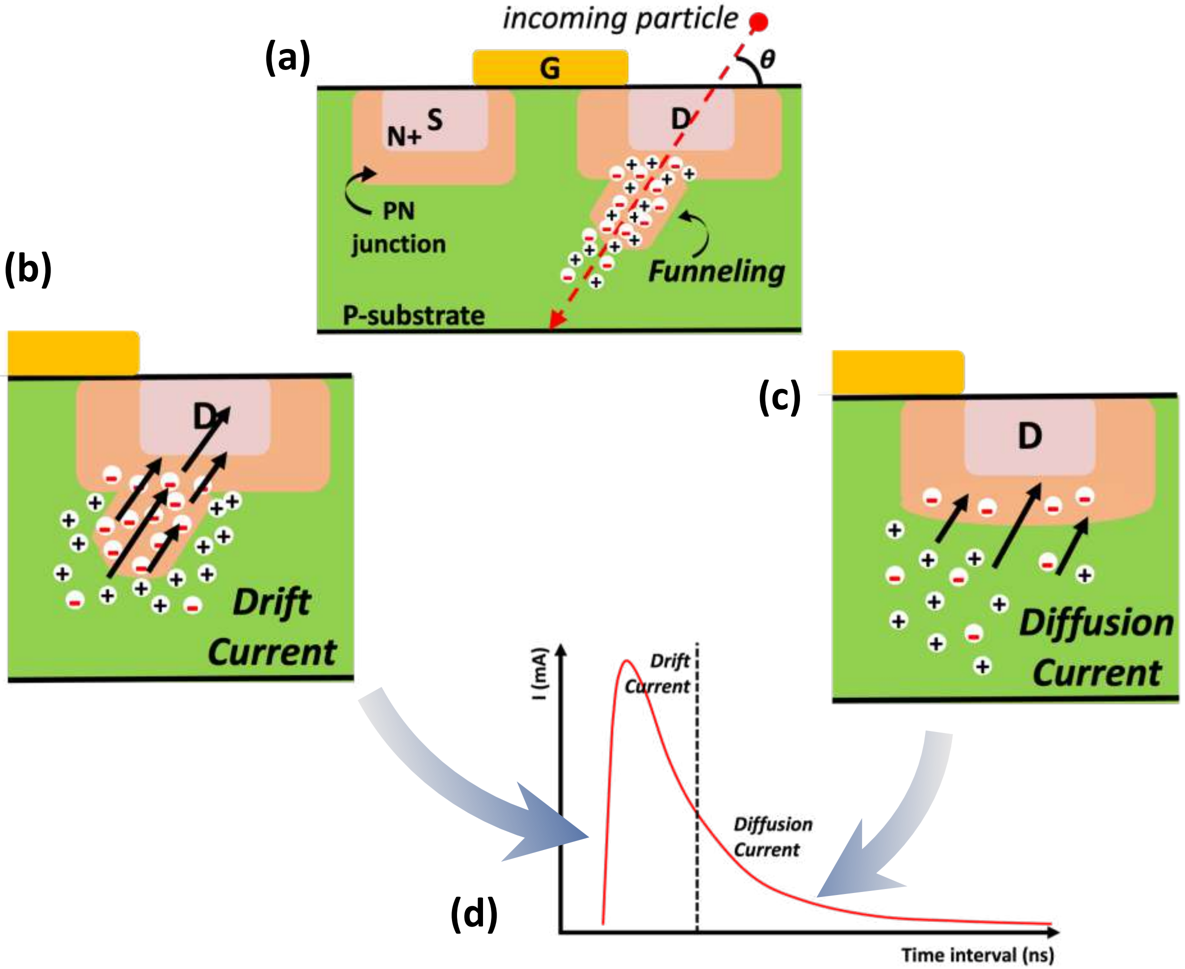
IEEE Trans. Nucl. Sci. 60, 1740–1766 (2013).

Bipolar transistors start to degrade at neutron fluxes of 10^{10} while MOSFETs is above 10^{15} n^0 cm^{-2}

Radiation-induced Electronic Failures

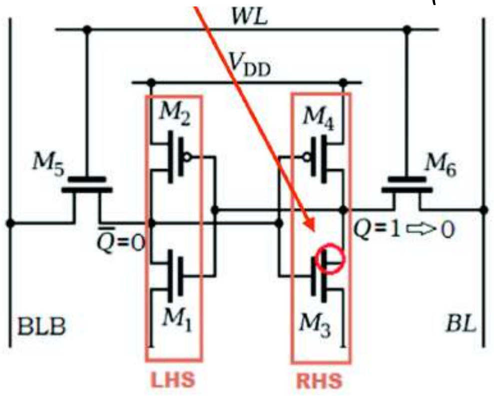
3. SEE

Parameter: type of particle (mass & energy), trajectory

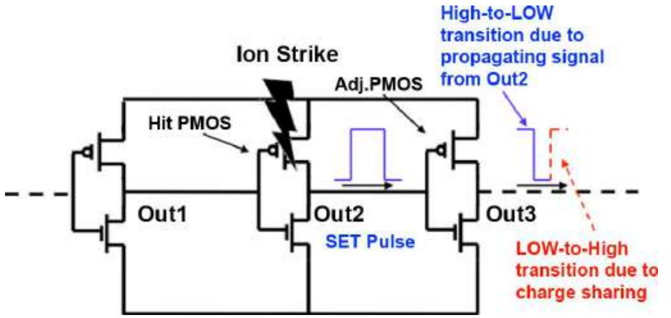


Proc. 3rd Brazilian Technology Symposium (2019) 1, 223

Microelectronics Reliability
78 (2017) 11–16

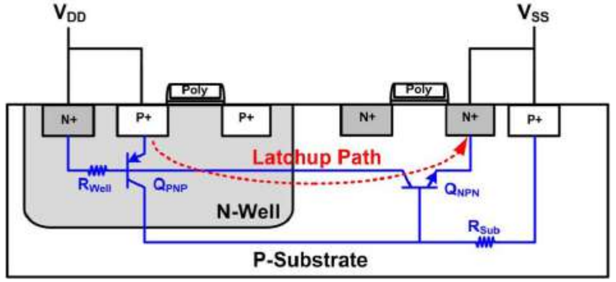


SEU



SET

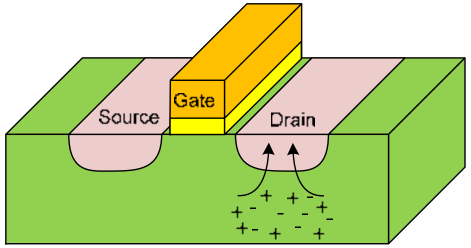
IEEE Trans. Nucl. Sci. 56, 3050-3056 (2009).



SEL

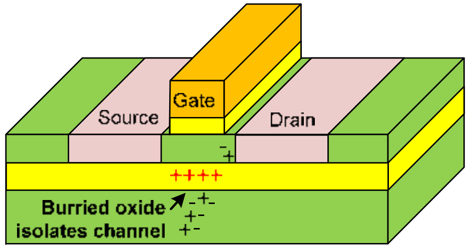
IEEE Trans. Elect. Dev. 63, 2449-2454, 2016

Impact of Device Architecture
(Keep in mind that SRAM, DRAM & Flash are based on transistor-based architecture)



Traditional planar bulk CMOS

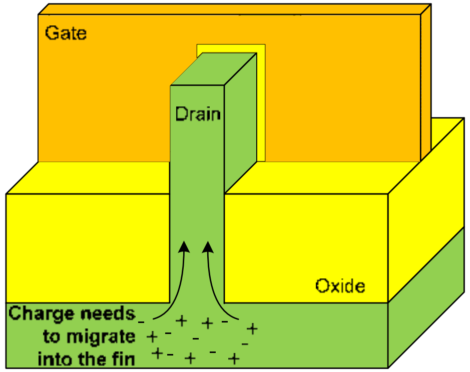
- SEE tolerance ☹
- TID tolerance ☹
- Scale ☹



SOI design

- SEE tolerance 😐
- TID tolerance 😐
- Scale ☹

- SEE tolerance 🙂
- TID tolerance 🙂
- Scale 😐

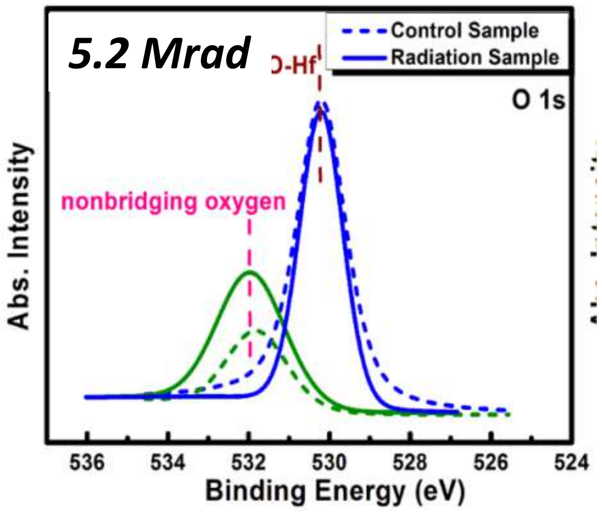


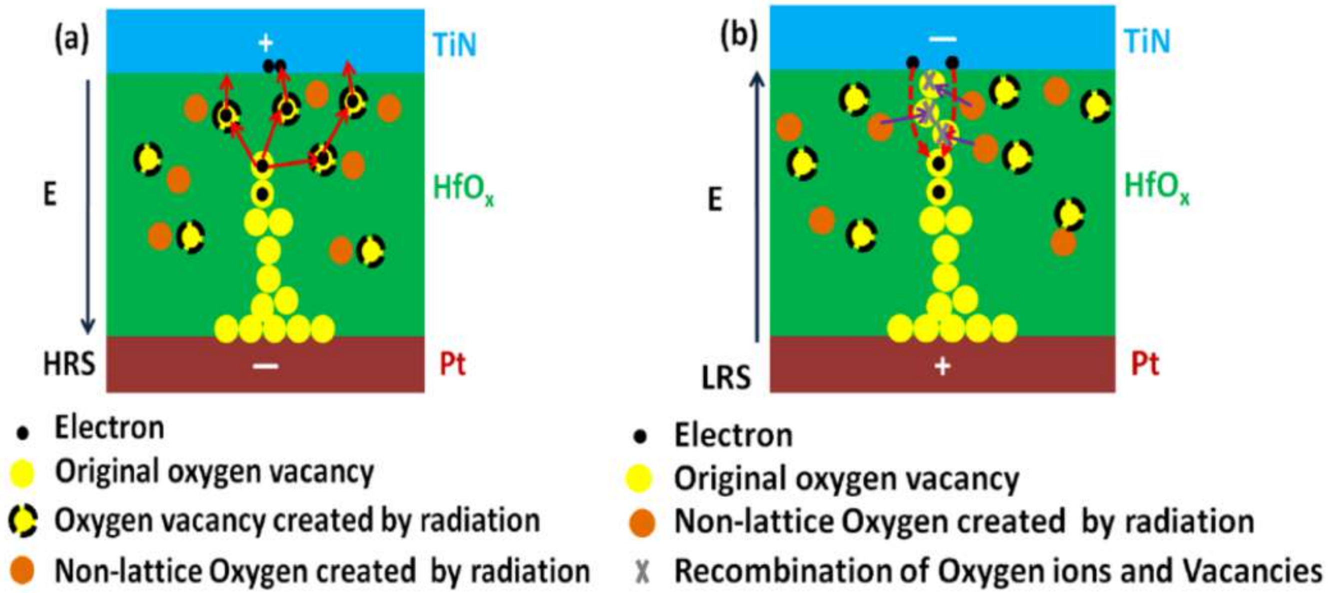
FinFET

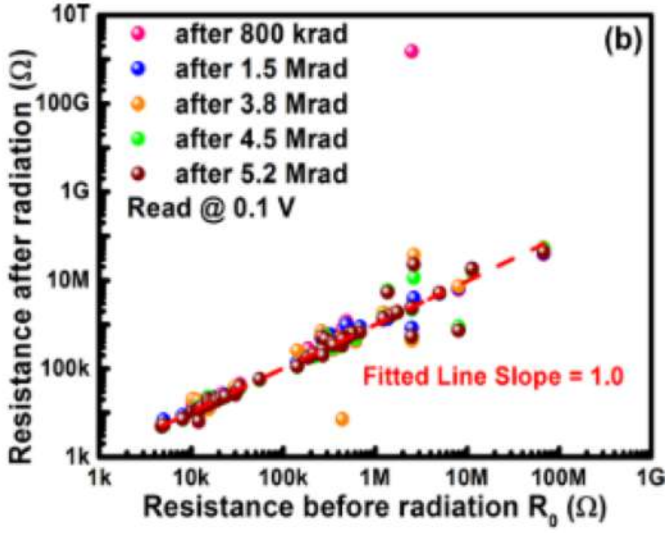
GAA ??

Adopted from Nature Electronics (2021) 4, 243

TID effect on memristor



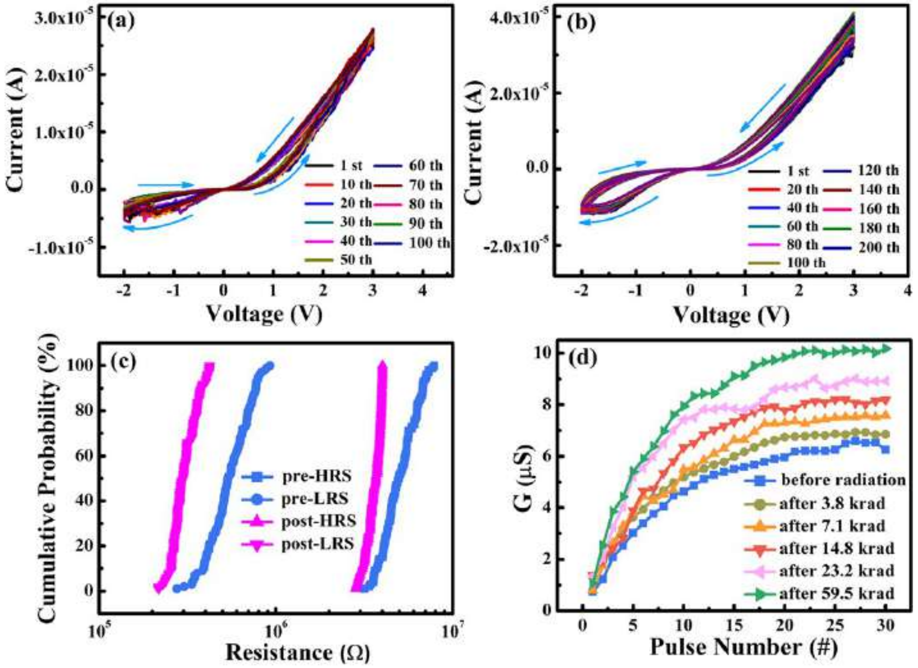




Appl. Phys. Lett. (2014) 104, 183507

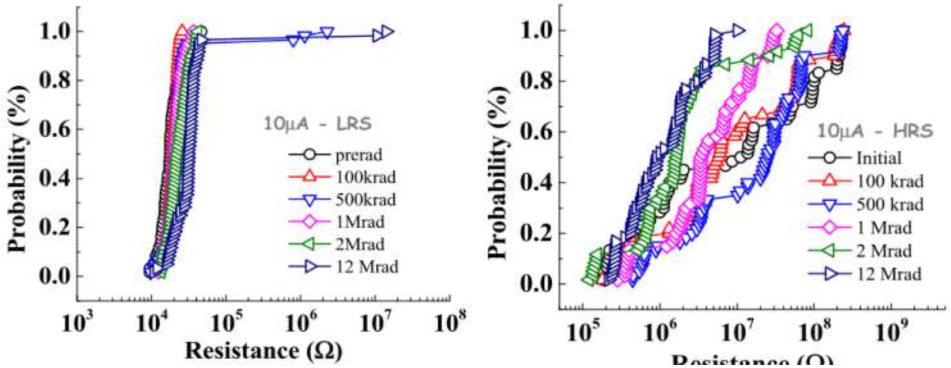
More on TID/DD

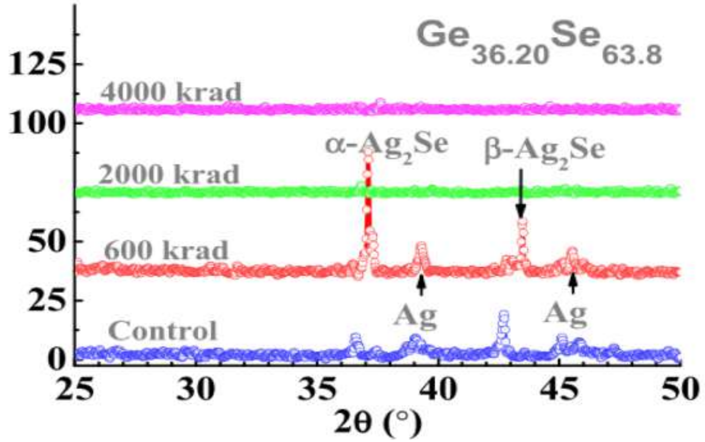
Gamma-ray-irradiated
Ta/TaOx/AlOx/IGZO memristor



Appl. Phys. Lett. (2018) 113, 122907

100keV e⁻irradiated
Ag/Ag-doped GeSe/Ni memristor

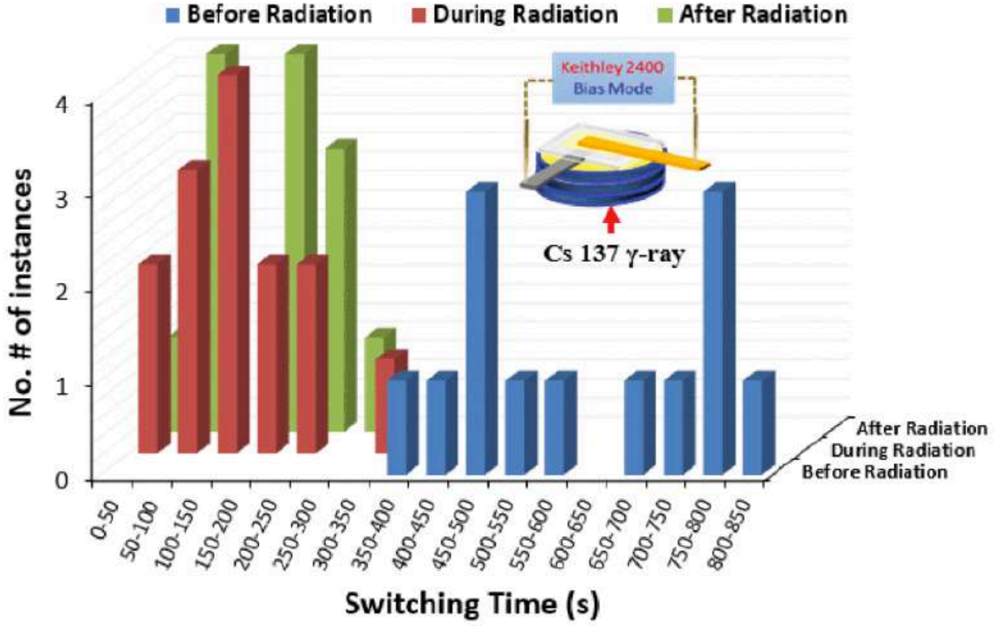




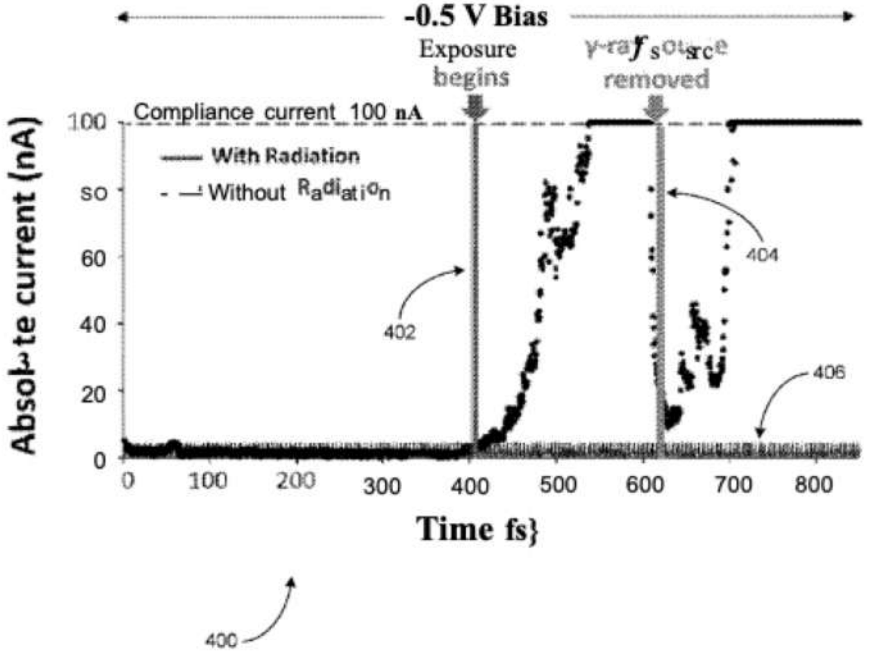
Semicond. Sci. Technol. 32 (2017) 083002

Beyond storage : Rad-sensors

Ag/TiO_2/Cu Memristors under 0.15V stress

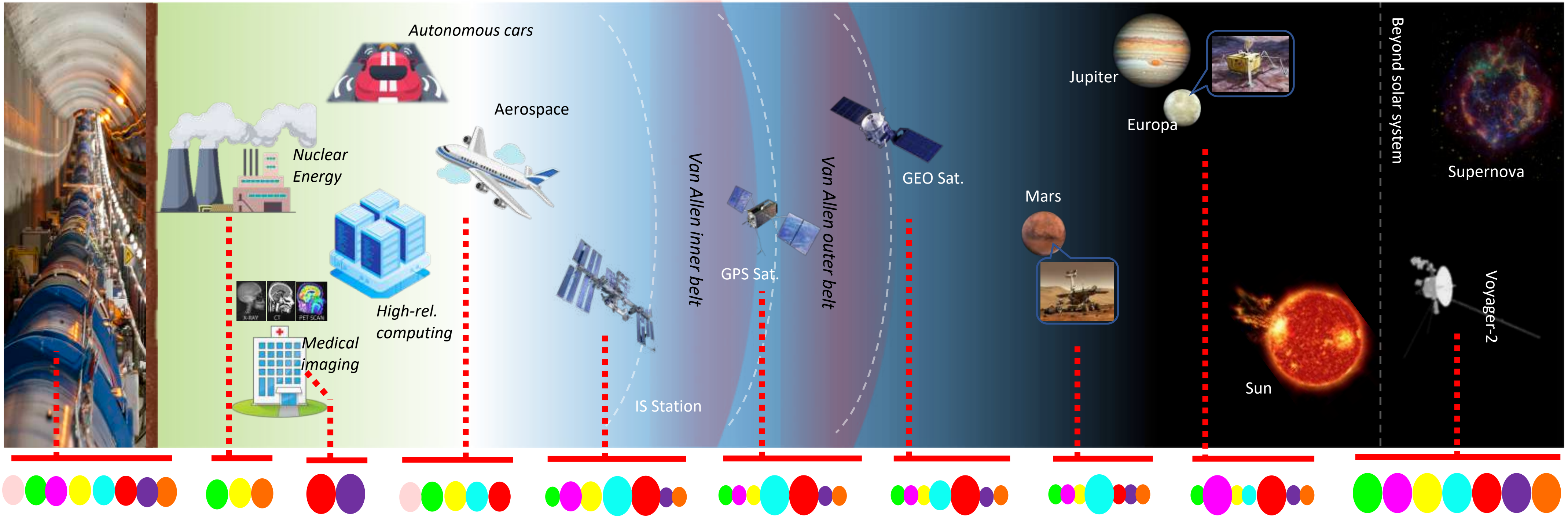


IEEE Sensors, 18, 8 (2018)



Patent No. PCT/IB2016/058126

Rad-hard Electronics Applications



●	α	●	e^- or e^+
●	n^o	●	X-ray
●	p^+	●	γ-ray
●	Ions	●	others

Source of radiation (particles and photons):

- Natural: extraterrestrial (supernova, pulsar, star) & terrestrial (atmospheric reaction, radioactive materials)
- Artificial: intentionally (medical & high-energy physics experiments) & waste product (nuclear power plant)

Open positions
PhD in Radiation-Hard Electronics

A. Nanodevice engineering

Focuses on the device fabrication of rad-hard artificial synapse memristor (1R) and selector (1S) stacks, their integration (1S1R) in cross-bar array configurations, and exploits their radiation tolerance and sensitivity.

B. Materials and/or electrical (device) modelling

Focuses on numerical analysis or simulation of the physical, chemical, and/or electrical behavior of the fabricated nanodevices to elucidate the observed phenomenon or anomaly due to radiation.

C. Neural network modelling

Focuses on the simulation and implementation of the fabricated devices for neuromorphic computing applications (such as image processing, pattern recognition, data clustering, etc.) and investigate the training accuracy irregularity due to the radiation damage and explore the mitigation algorithm and/or exploit such irregularity for making adaptive electronics.

https://jobs.soton.ac.uk/Vacancy.aspx?ref=1374221PN

Collaborators for this project

UK

- **Rutherford Appleton Laboratory**
  (ISIS neutron and muon source)
- **Surrey Sattelites Ltd.**
- **ArcOne Instruments Ltd.**
- **Defence Science & Technology Laboratory**

Italy

- **RedCat Devices**

Belgium

- **KU Leuven**

UEA

- **Khalifa University**

Useful links:

https://cef.soton.ac.uk/
https://www.southampton-nanofab.com/