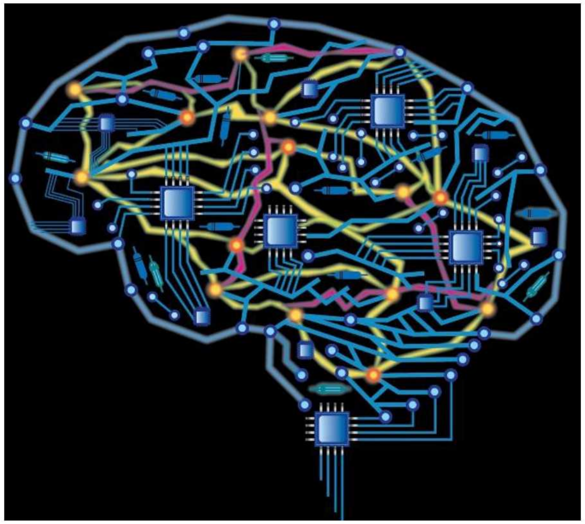
SAND2019-4828C

# ‘Computing with Defects’: Ion Insertion Electrodes for Brain Inspired Computing and Brain Machine Interfaces

**A. Alec Talin**
**Sandia National Laboratories, Livermore, CA**



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# An exponential increase in data is changing demands

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autonomous driving


https://techcrunch.com/2015/10/09/dont-blame-the-robot-drivers/

data classification

Q. Le, *IEEE ICASSP* pp. 8595–8598, (2013)

natural language processing

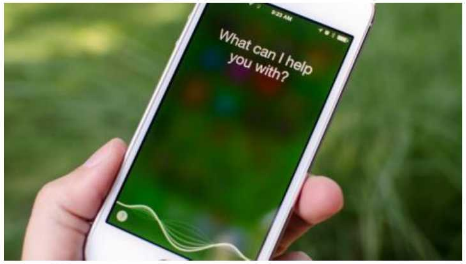
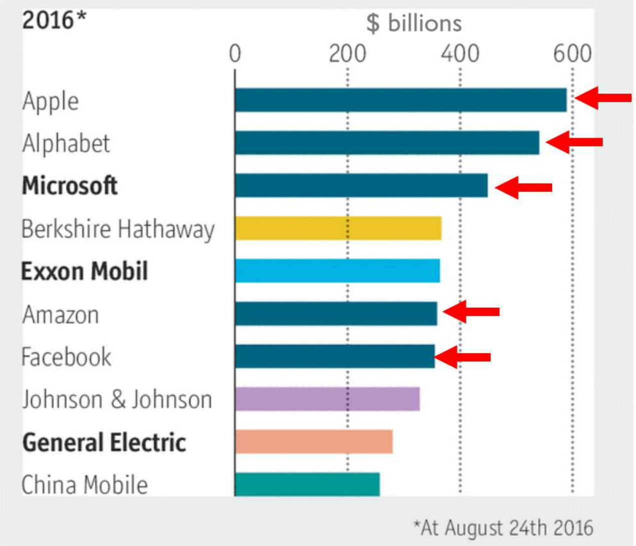



image credit: Apple Computers

brain machine interfaces

image credit: Popular Science

world's largest companies




by market capitalization, source: *The Economist*

new markets utilize **artificial neural networks** that incorporate elements of learning loosely inspired by biology

# Evolution of Computing Machinery

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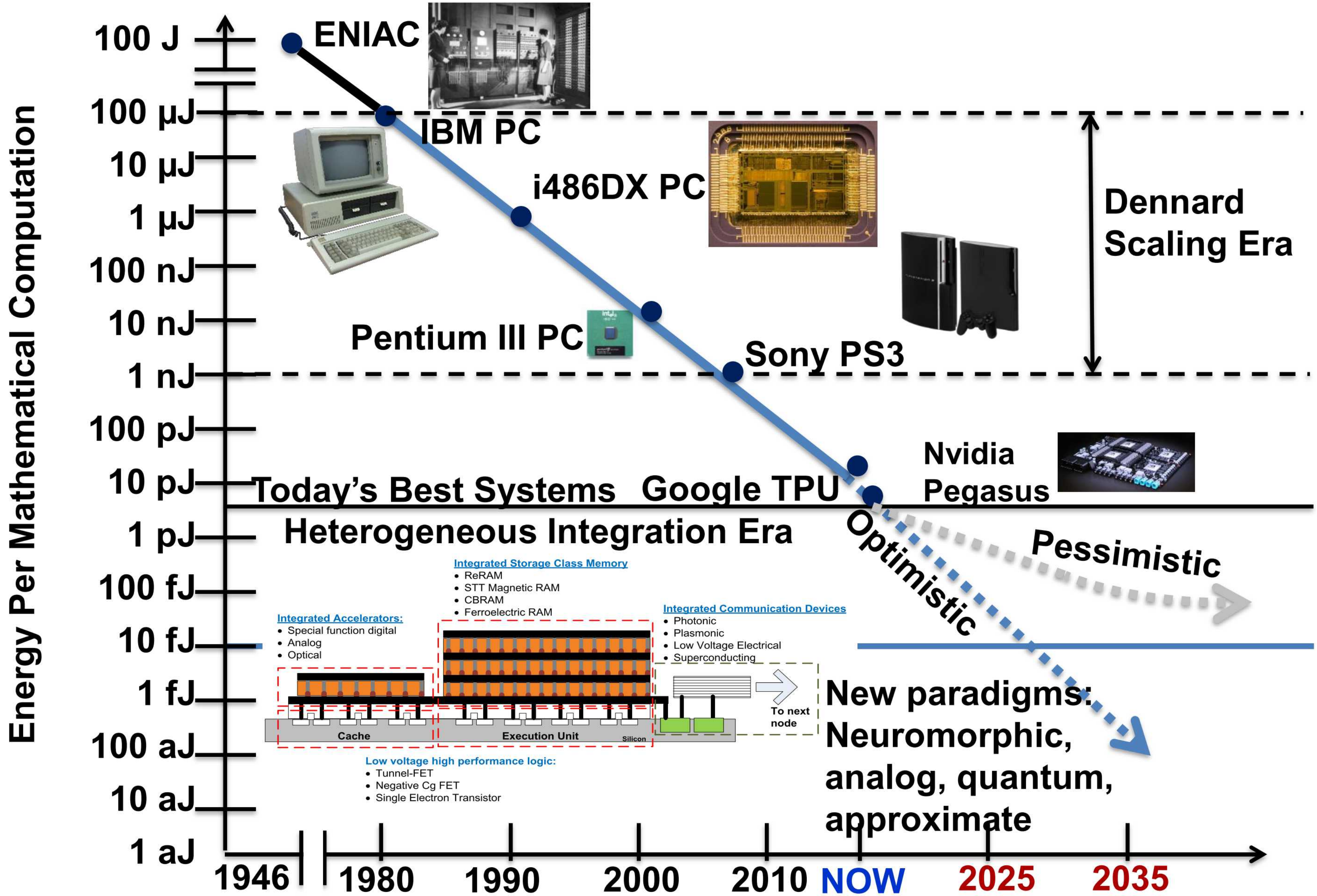
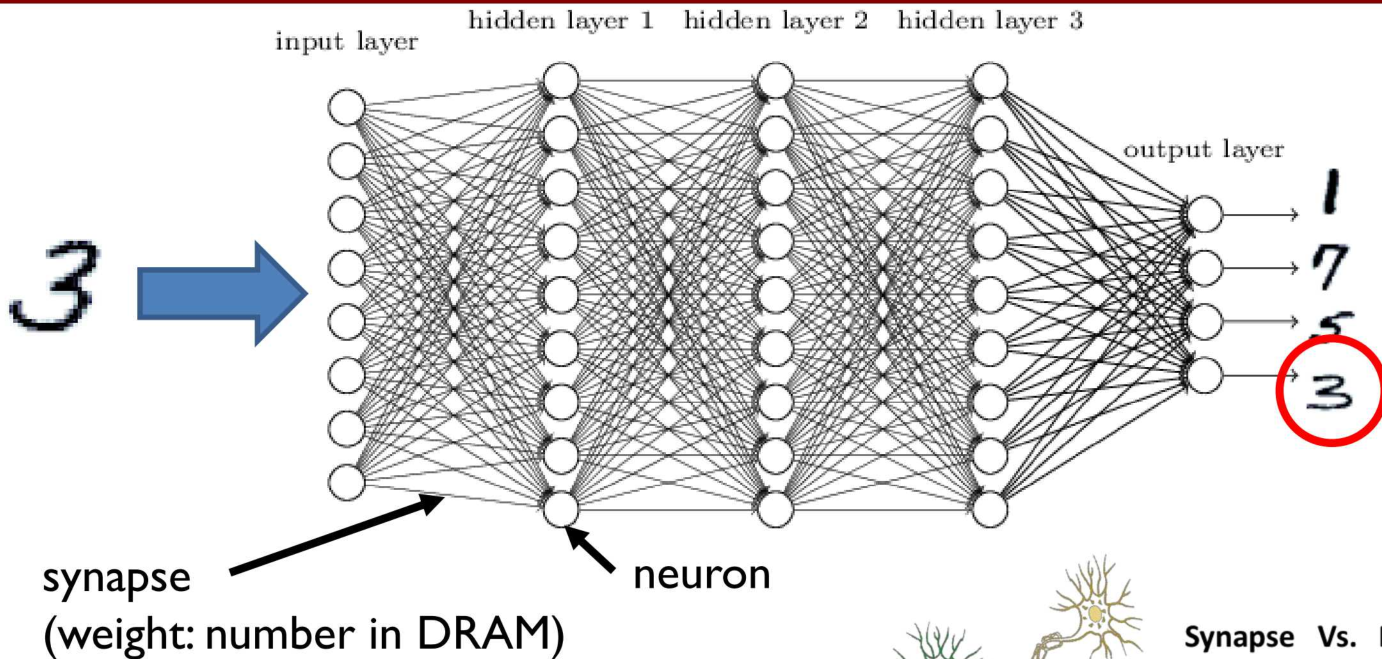
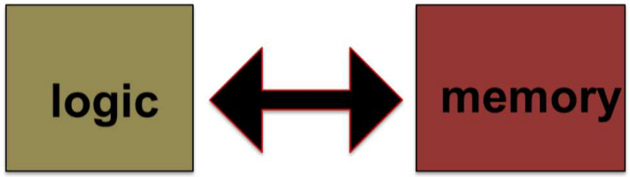
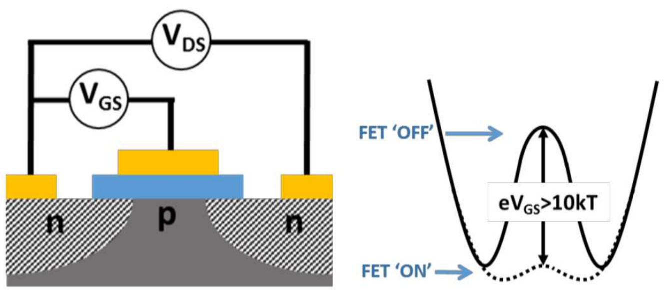
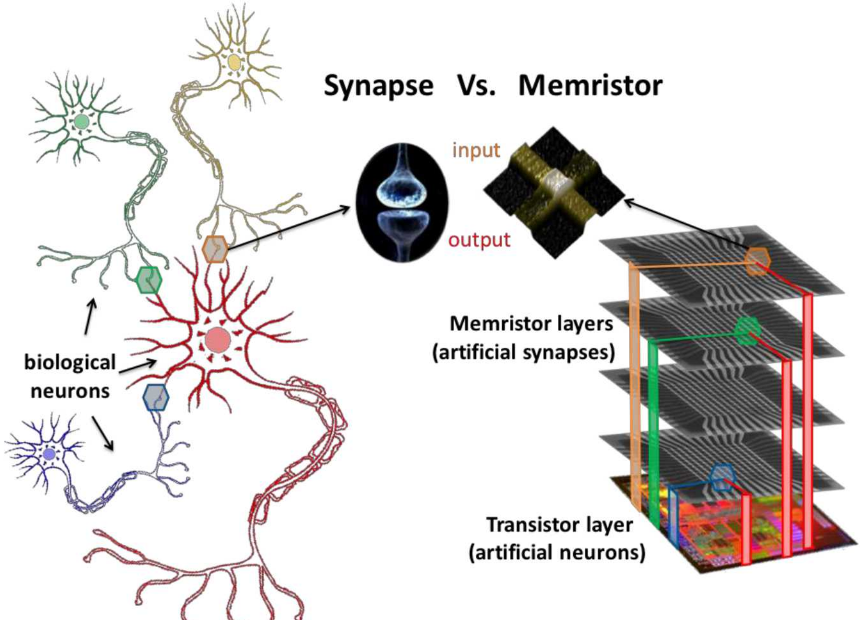


# CMOS architecture not designed for data-driven NNs



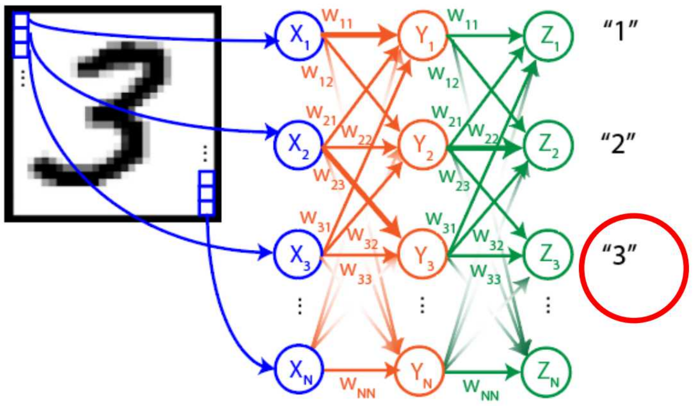



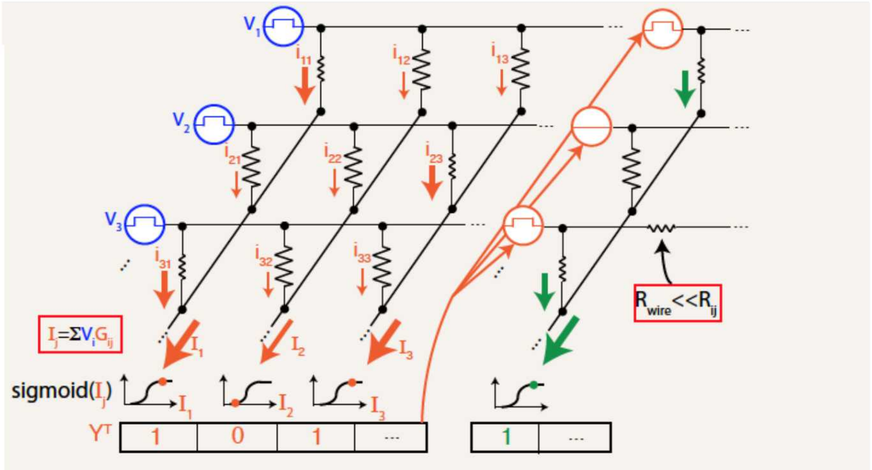




*https://theglobalscientist.com/2015/07/06/computers-inspired-by-the-human-brain/*

# Overcome CMOS bottleneck→in-memory computation



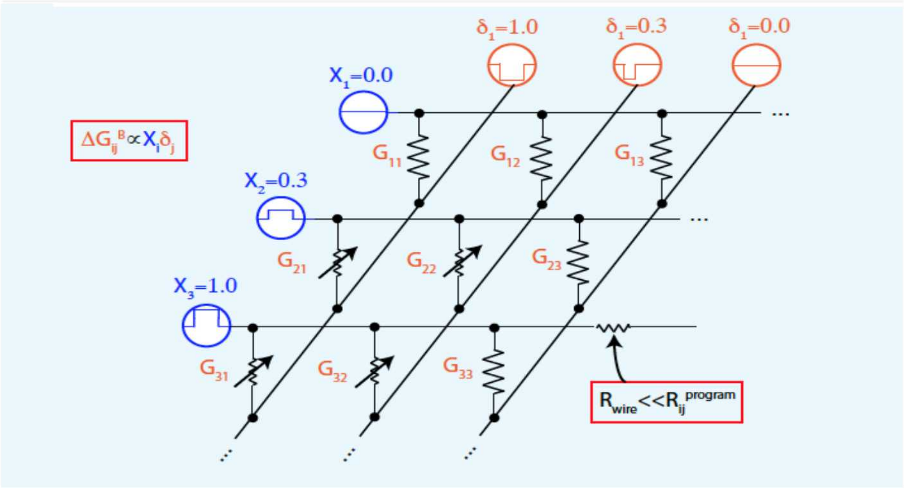



vector-matrix multiply (inference)

**To beat ASICs, GPUs:**

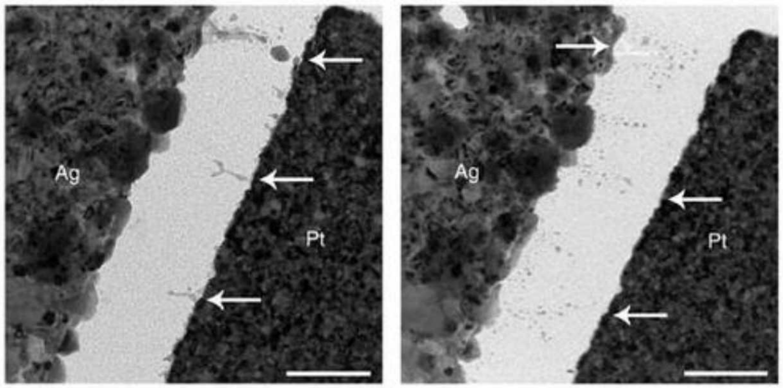
- scalable: analog signals must reach edge of 1,000 x 1,000 matrix (R>100 MΩ)
- "blind writes" with linear and symmetric programmability
- accurate: matrix operations must have CMOS equivalent accuracy
- low variation, degradation: must cycle > billion times without changes




outer product (learning)

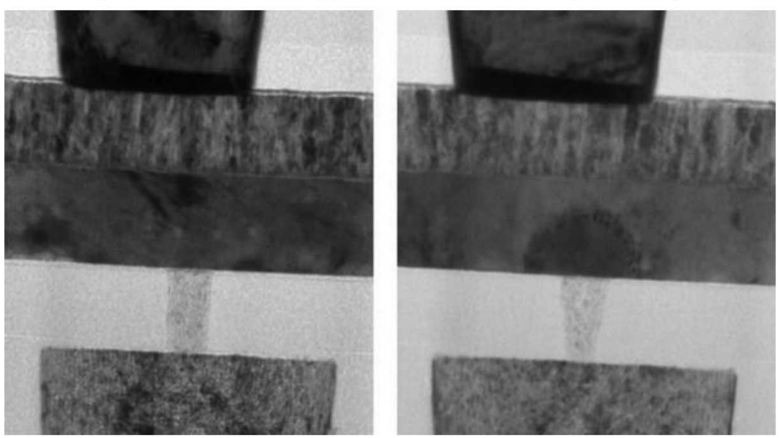
# Fundamental physics dictates memristor I-V

filament forming metal oxides (FFMO)

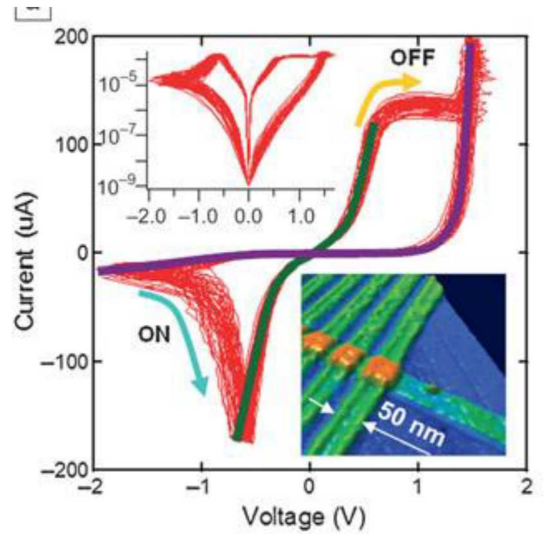



Yang et. al. *Nature Communications* (2012)

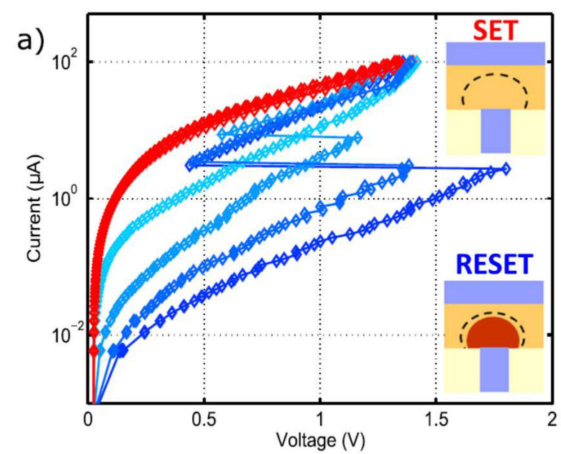
phase change materials (PCM)



Breitwisch, Phase Change Materials: Science and Applications © 2009 by Springer

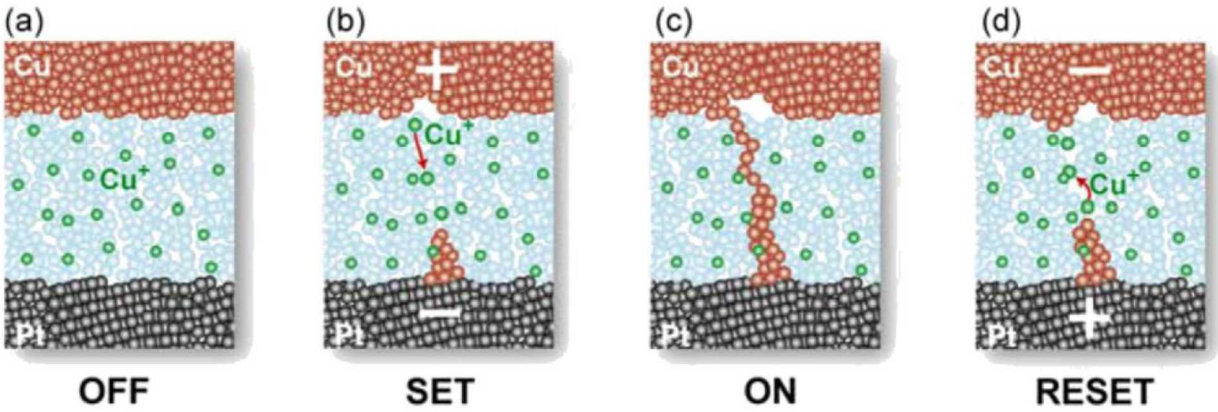



J. J. Yang , I. H. Inoue , T. Mikolajick , C. S. Hwang MRS Bull. 37, 131 2012



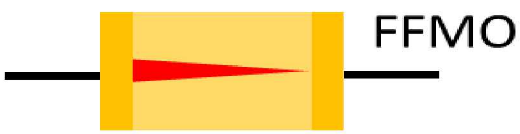

A. Pantazi, S. Woźniak, T. Tuma, E. Eleftheriou, Nanotech. 27 2016

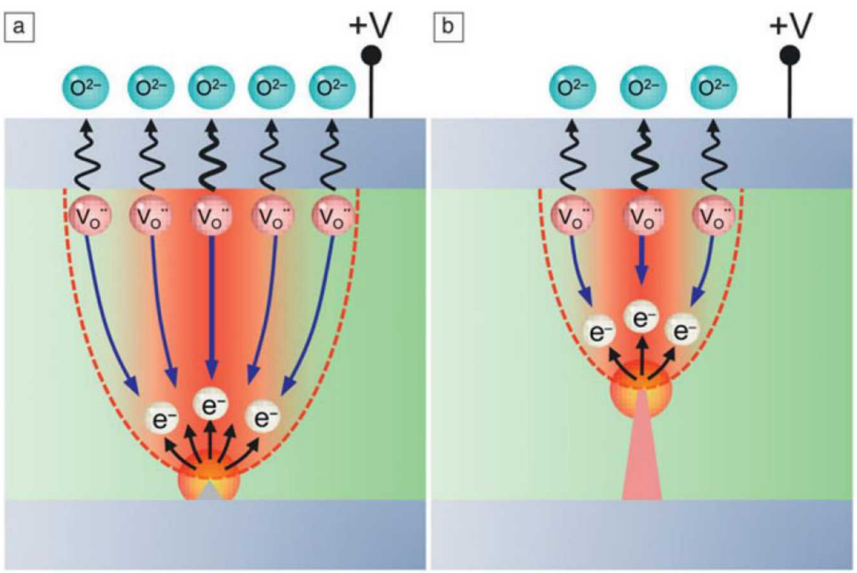
# Fundamental physics dictates memristor I-V



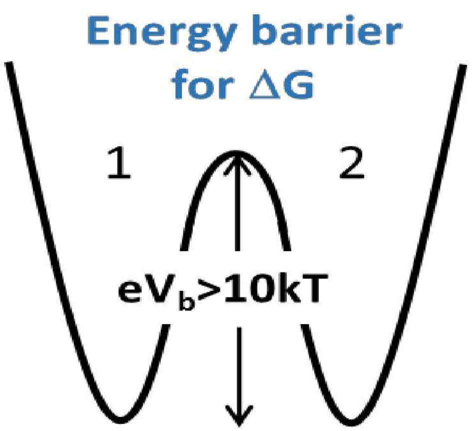

I. Valov J. Phys. D: Appl. Phys. 46 074005 (2013)

**time-voltage dilemma:**
large energy barrier between conductance states needed for retention

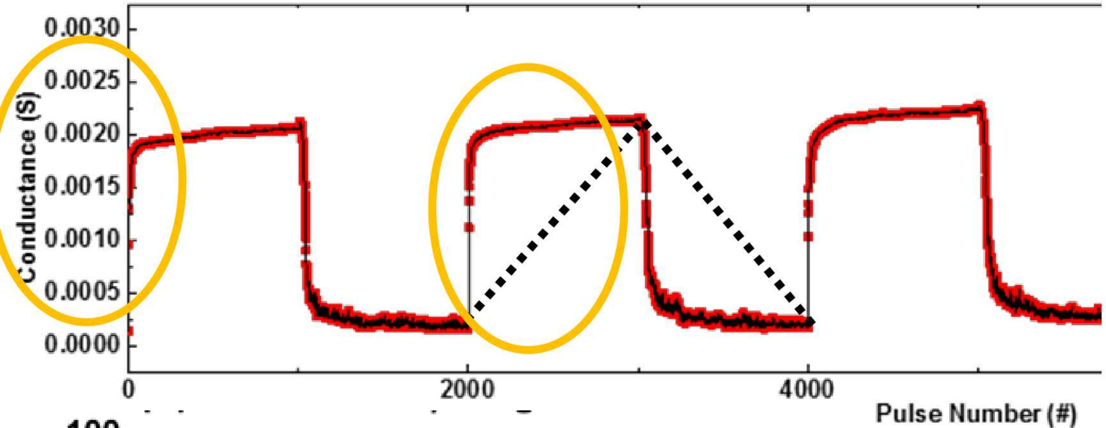



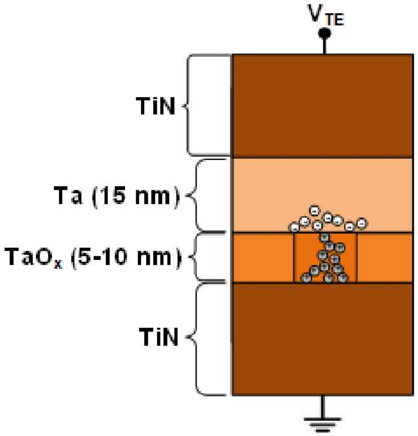



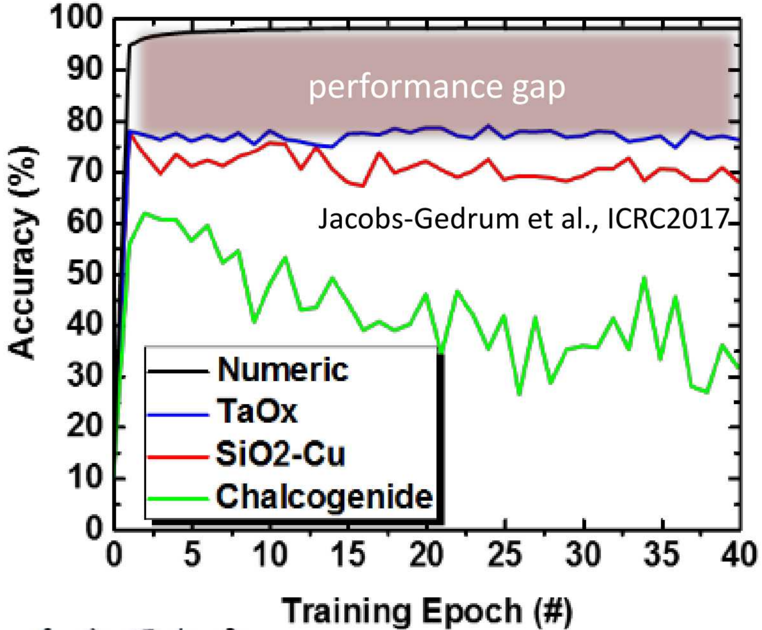

J. J. Yang , I. H. Inoue , T. Mikolajick , C. S. Hwang MRS Bull. 37, 131 2012

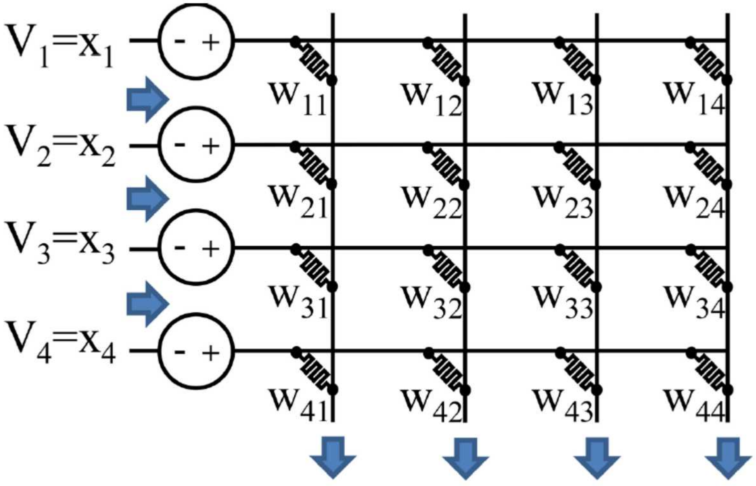


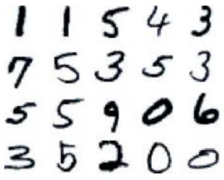
# Non-linearity, high conductance limit accuracy, scaling



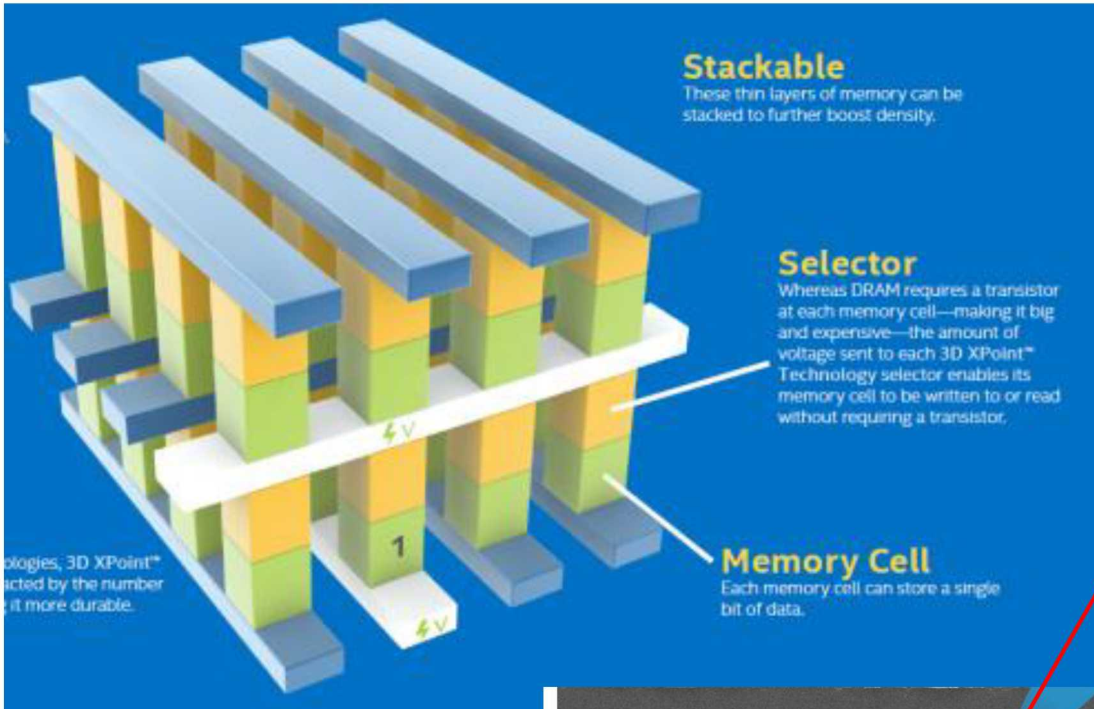



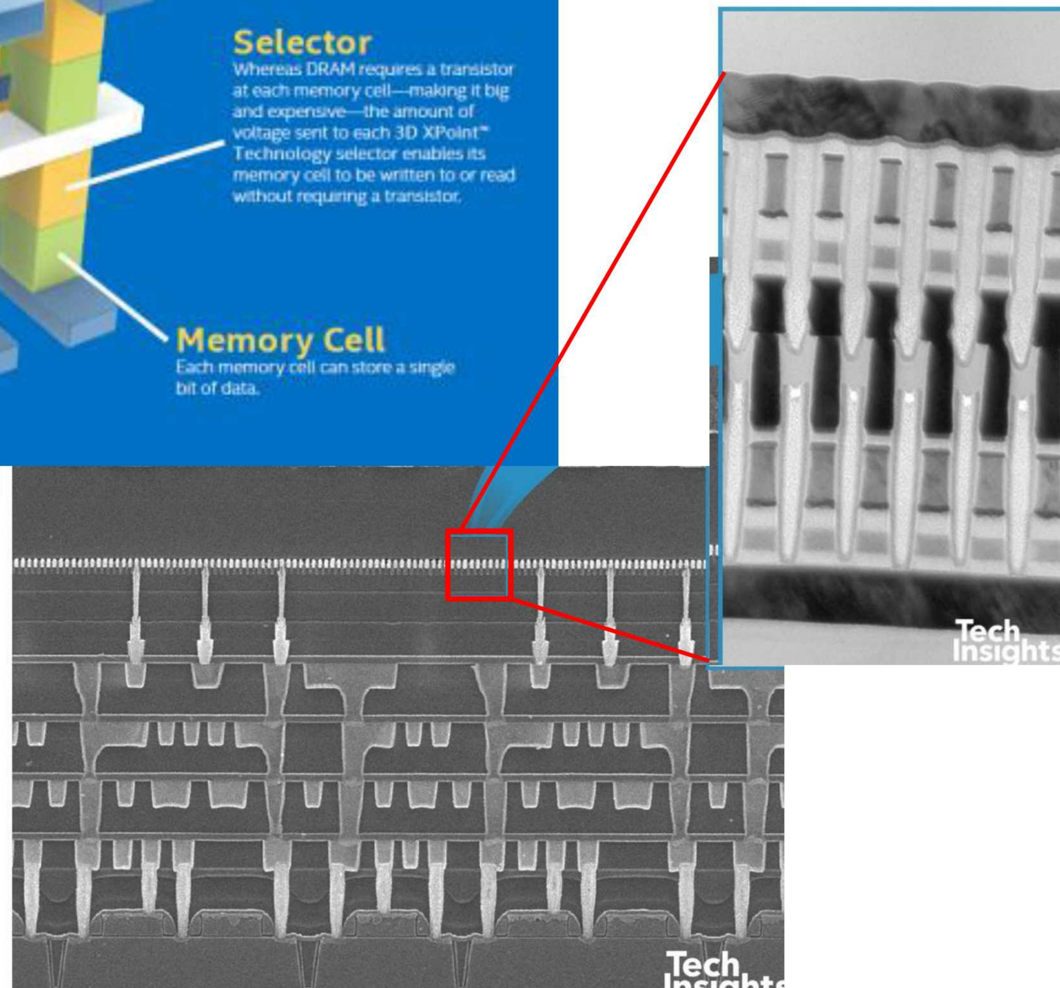



| Data set | # Training Examples | # Test Examples | Network Size |
|---|---|---|---|
| MNIST Large Digits | 60,000 | 10,000 | 784×300×10 |

# Intel 3D Xpoint PCM memristor memory

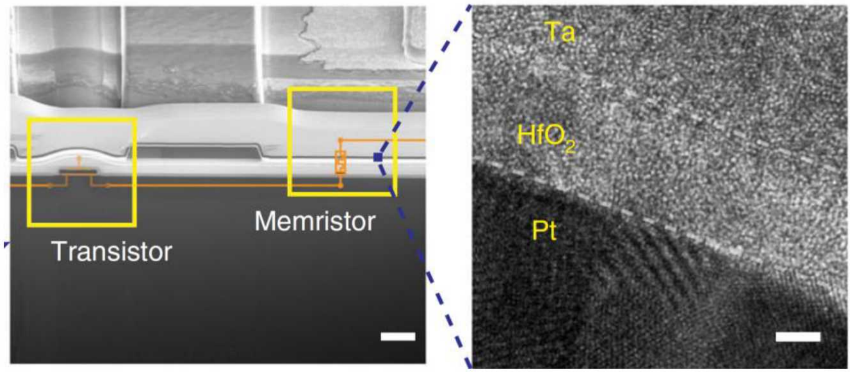


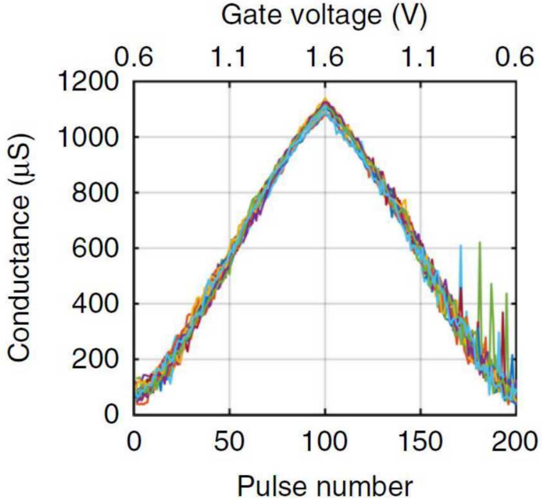
# Linearity demonstrated; conductance remains high



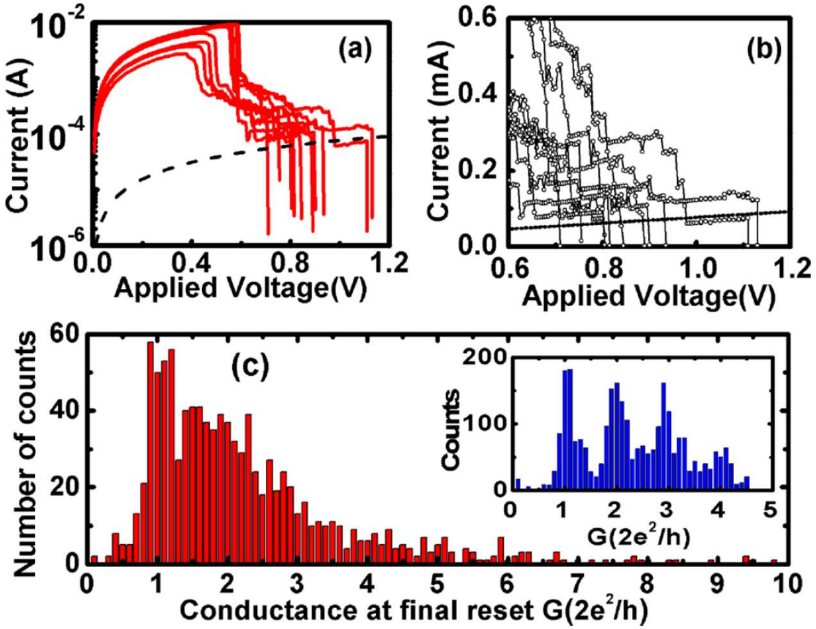
- Increase conductance → synchronized V+ to memristor, FET gate; set I compliance
- Decrease conductance→ reinitialize memristor, then increase conductance as above

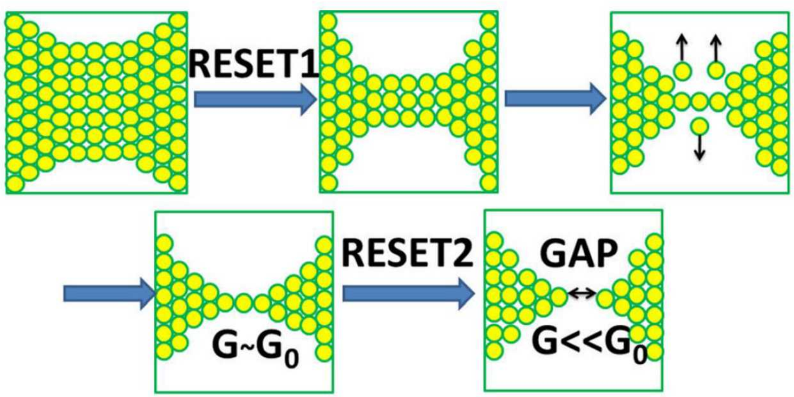



20 cycles for a single device




100 µS→
0.1mA @1V!



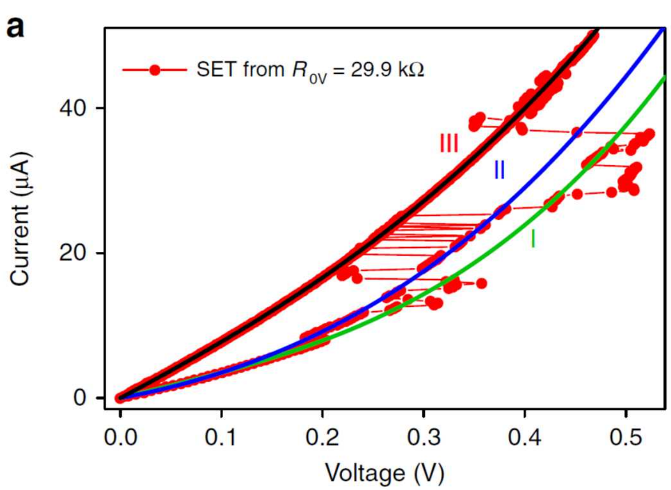

$$G_o = {}^{2e^2}/_{h} = 13k\Omega$$

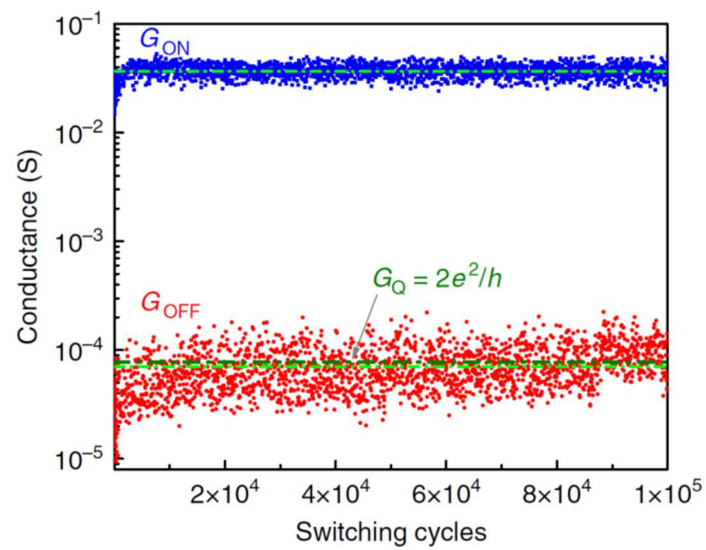
# Operating in conductance limit increases noise

Received 25 Aug 2015 | Accepted 25 Feb 2016 | Published 4 Apr 2016 DOI: 10.1038/ncomms11142 OPEN

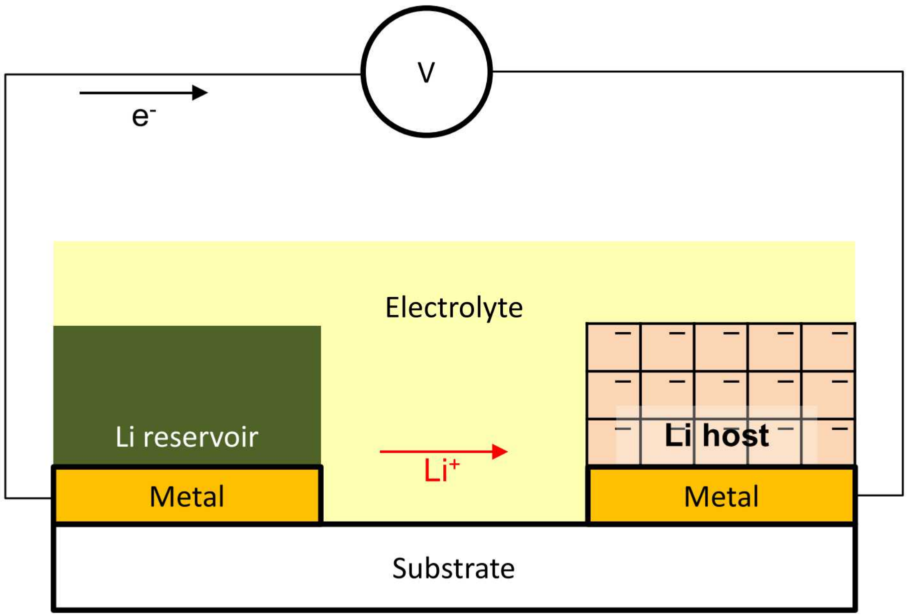
## Quantized conductance coincides with state instability and excess noise in tantalum oxide memristors

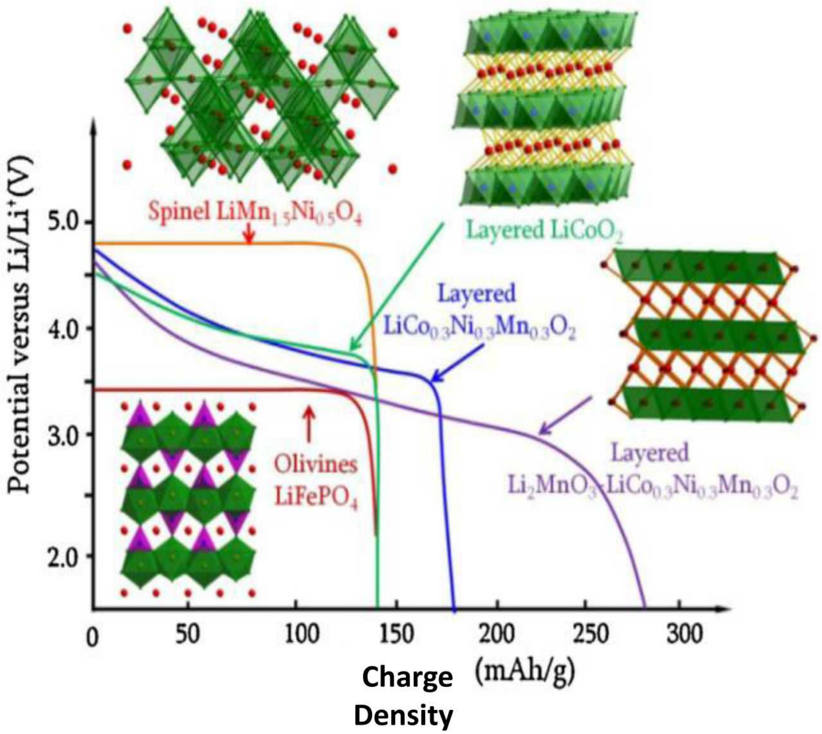
Wei Yi[1,2], Sergey E. Savel'ev[3], Gilberto Medeiros-Ribeiro[1,4], Feng Miao[1,5], M.-X. Zhang[1], J. Joshua Yang[1,6], Alexander M. Bratkovsky[1,7,8] & R. Stanley Williams[1]



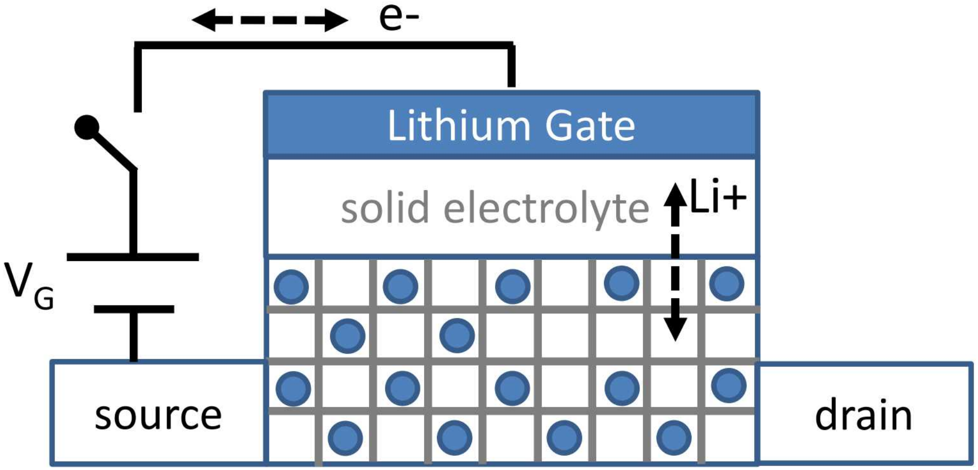



# Ion-insertion electrodes for neuromorphic computing

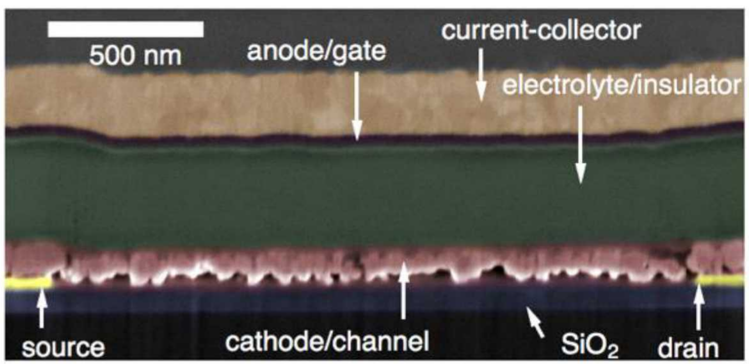


# Lithium-ion synaptic transistor (LISTA) or "NVRT"



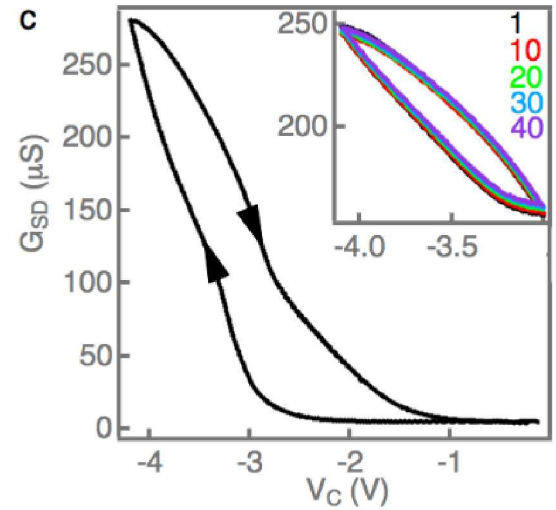

SEM cross section

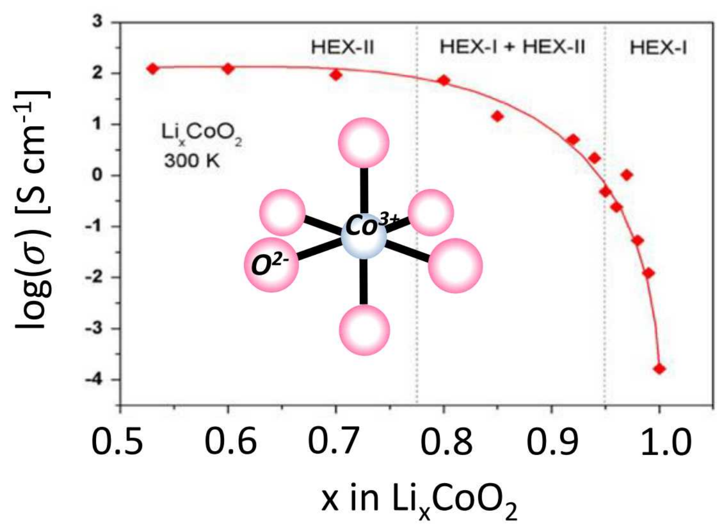



| | |
|---|---|
| channel electrode: | $Li_xCoO_2$ |
| gate electrode: | $Li_xSi$ |
| solid electrolyte: | LiPON |

E. J. Fuller, F. El Gabaly, F. Léonard, S. Agarwal, S. J. Plimpton, R. B. Jacobs-Gedrim, C. D. James, M. J. Marinella, A. A. Talin, Adv. Mat., 29, 1604310, 2017

>$10^4$ ON/OFF




Milewska et al., Solid State Ionics, 263, 110 (2014)

# Highly predictable, stable operation, ~200 states

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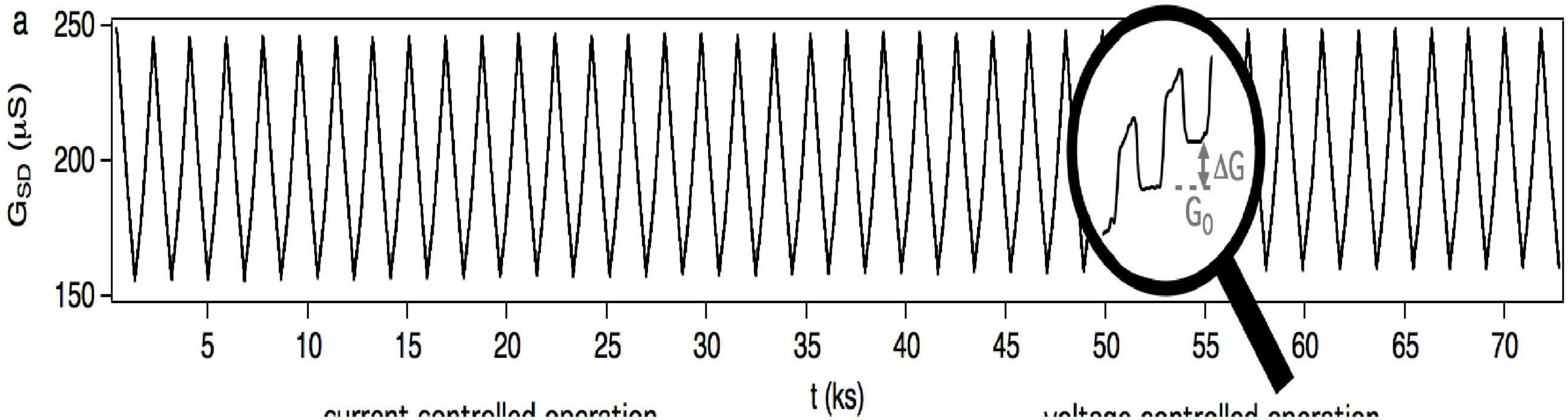
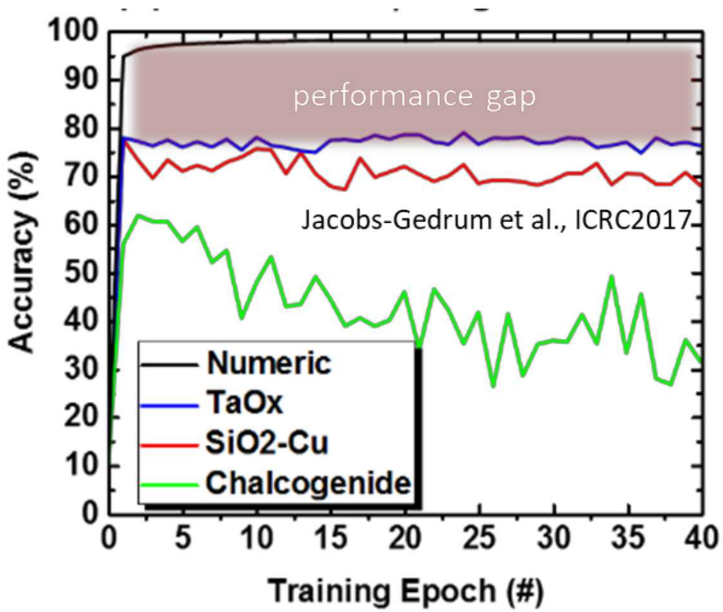
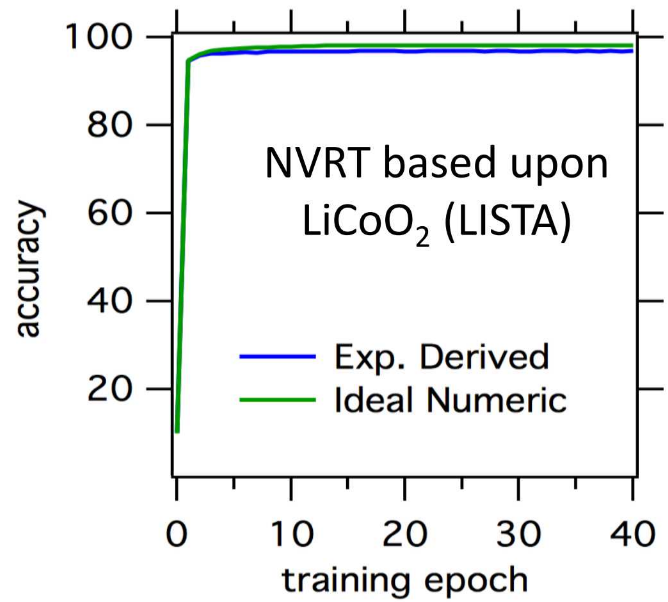


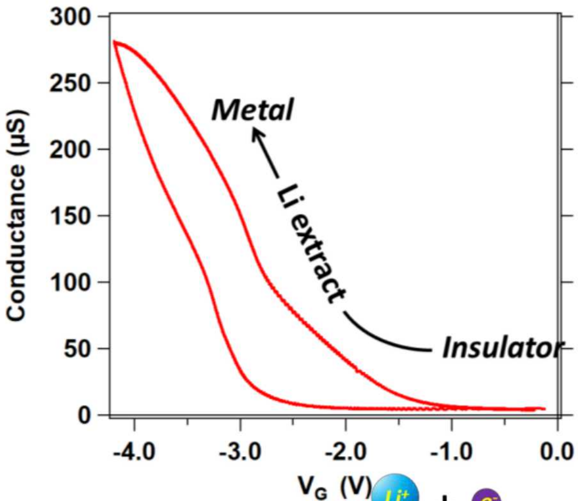



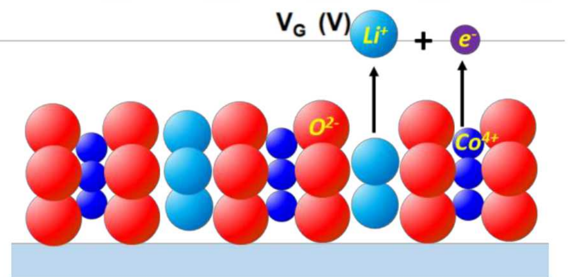



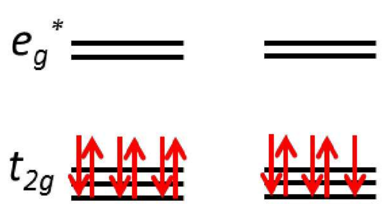

E. J. Fuller, F. El Gabaly, F. Léonard, S. Agarwal, S. J. Plimpton, R. B. Jacobs-Gedrim, C. D. James, M. J. Marinella, A. A. Talin, Adv. Mat., 29, 1604310, 2017

# 2 models for insulator→metal transition in $Li_xCoO_2$

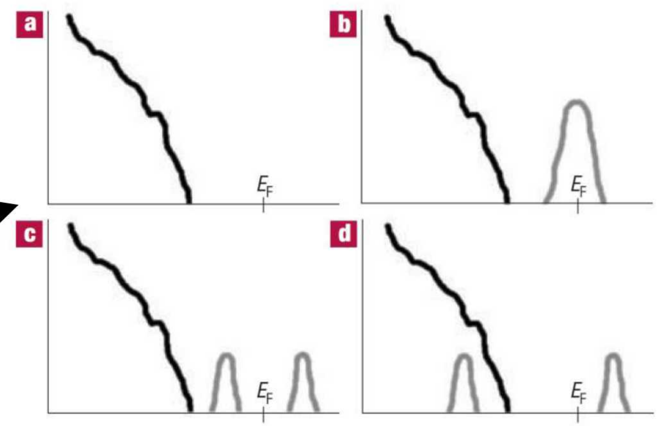




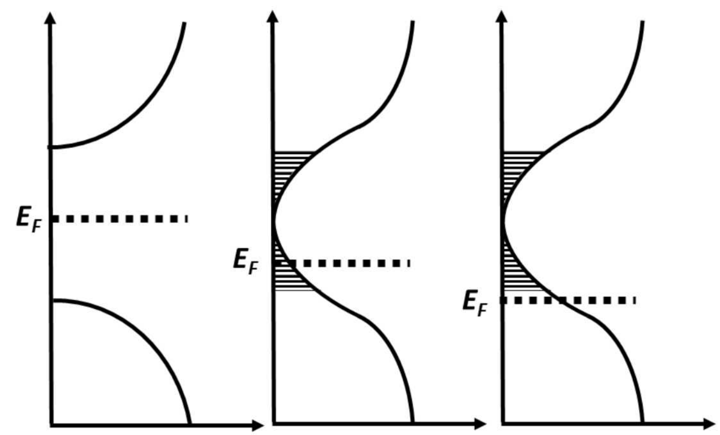




Mott transition



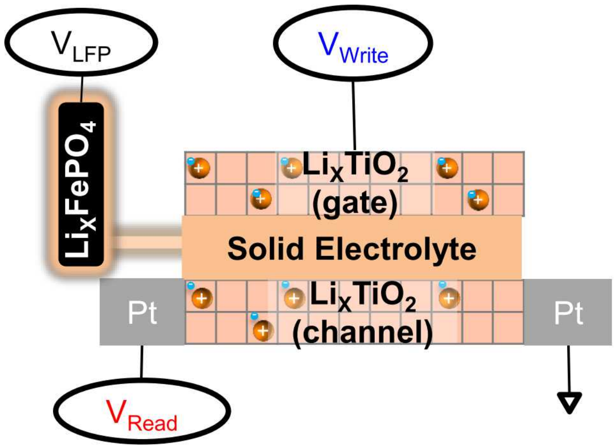

C. A. Marianetti, G. Kotliar, G. Ceder, Nat. Mat. 3, 627, 2004

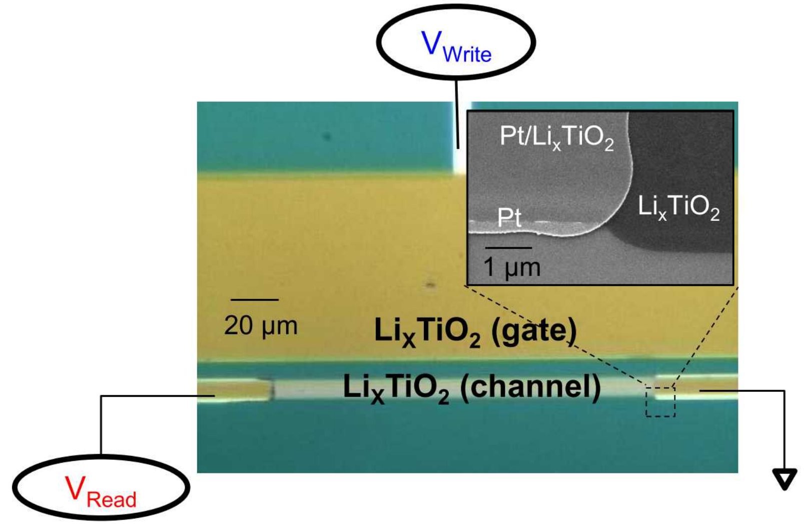
Anderson transition

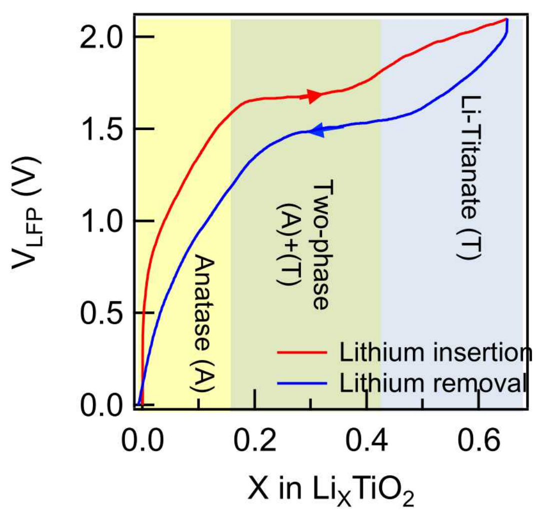


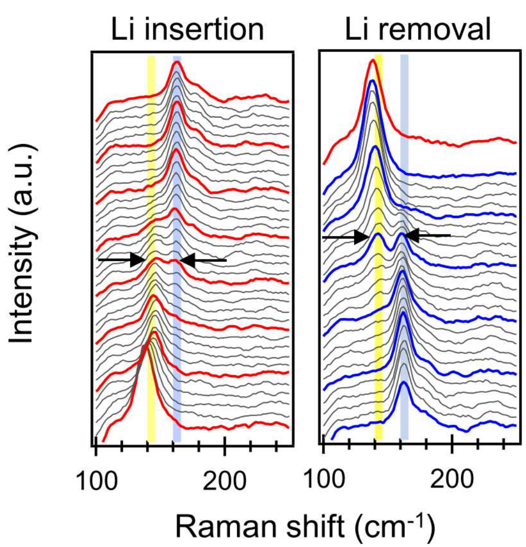

Milewska et al. / Solid State Ionics 263, 110 2014

# Lithium insertion into $Li_xTiO_2$ (anatase)

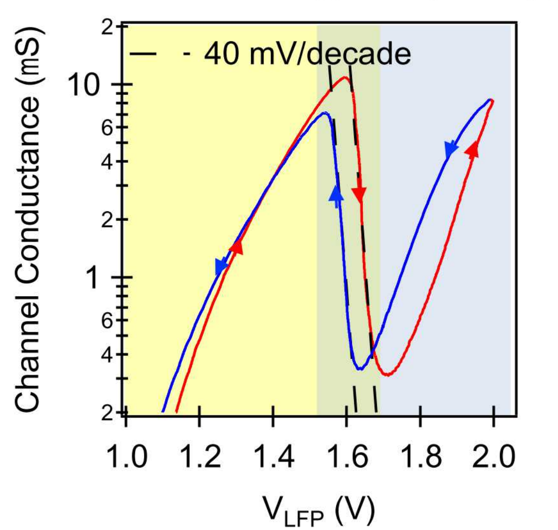


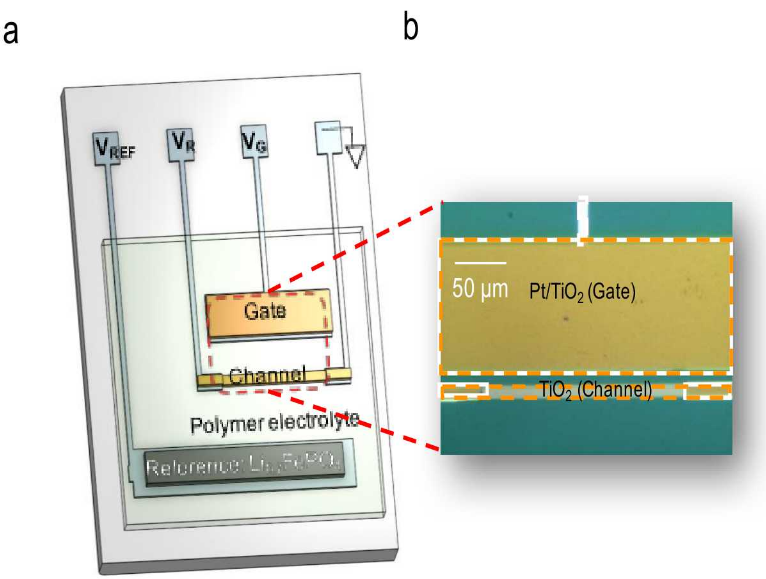



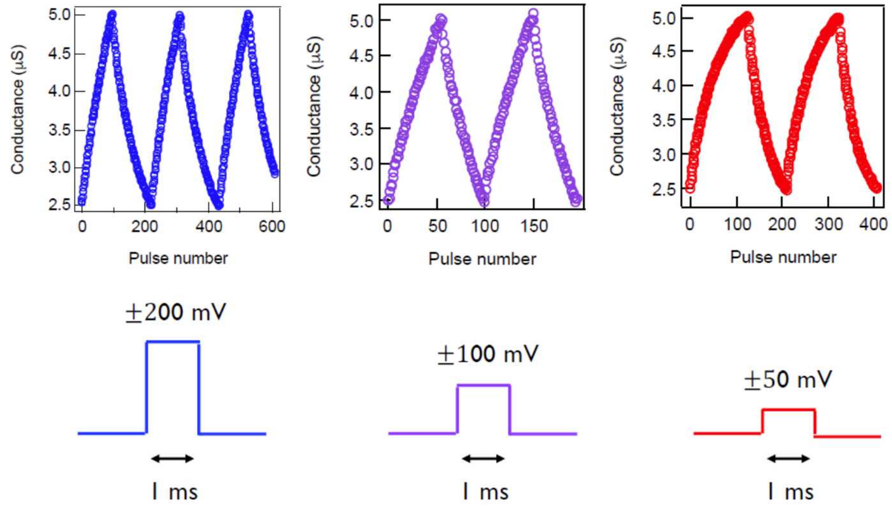




$$Li^{+} + e^{-} + Ti_{Ti}^{X} \rightarrow Li_i^{\circ} + \boldsymbol{Ti'_{Ti}}$$

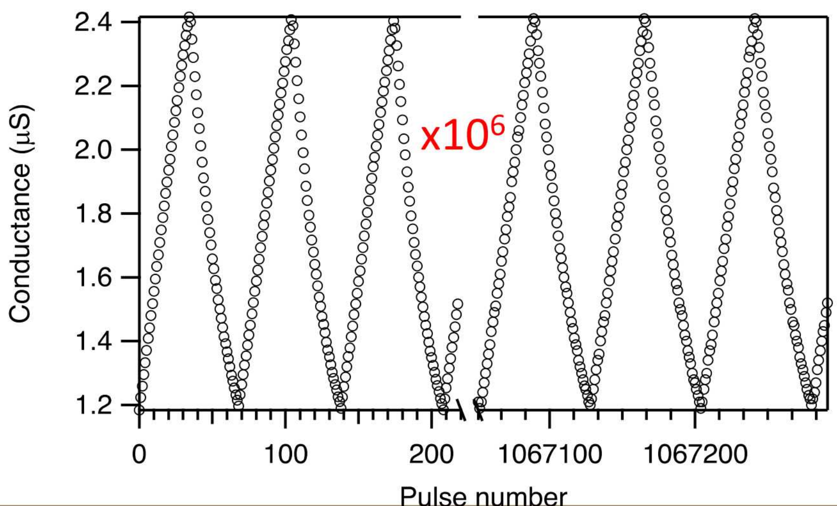


# Low switching V, high endurance with $Li_xTiO_2$ LISTA

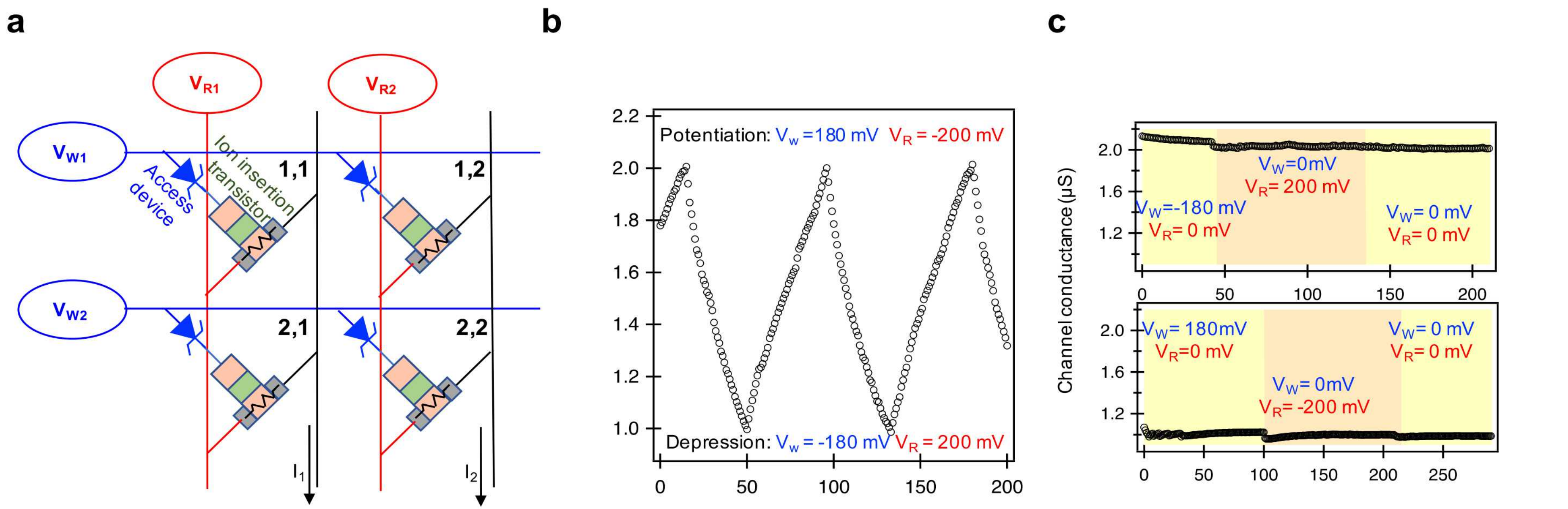


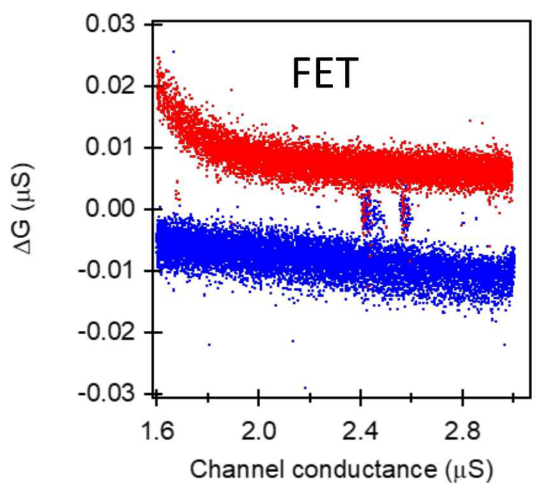



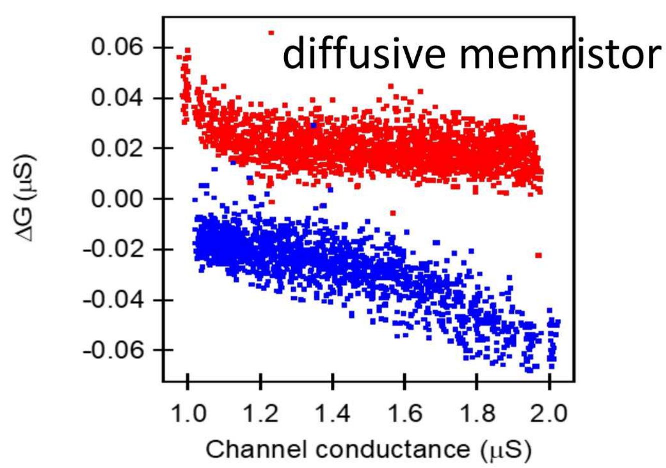

programming currents as low as 10nA,



# $Li_xTiO_2$ LISTA addressability, retention

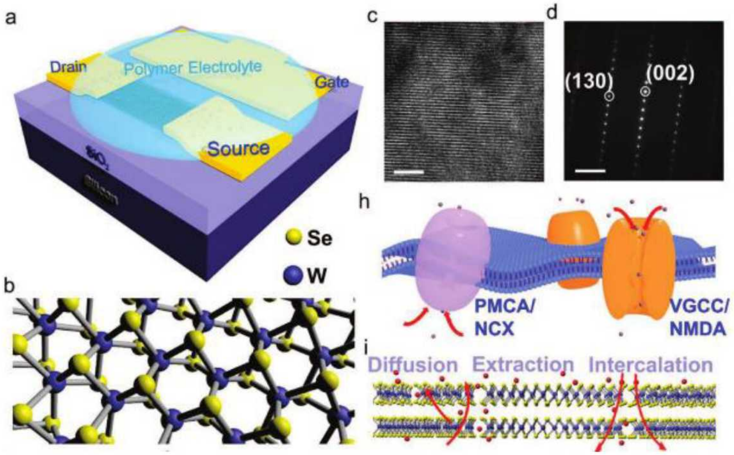


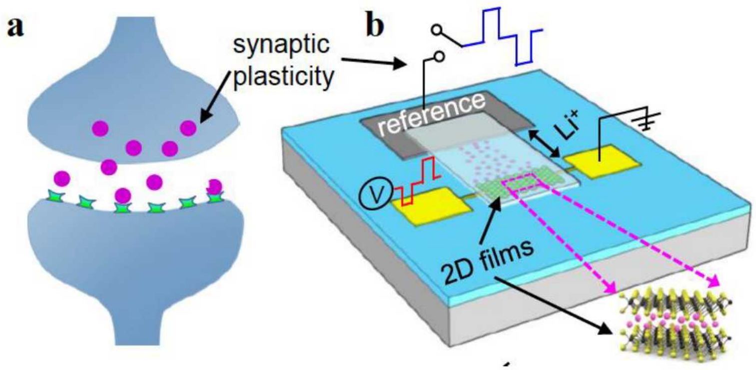
# LISTA work is inspiring new 2D systems

LISTA - $WSe_2$



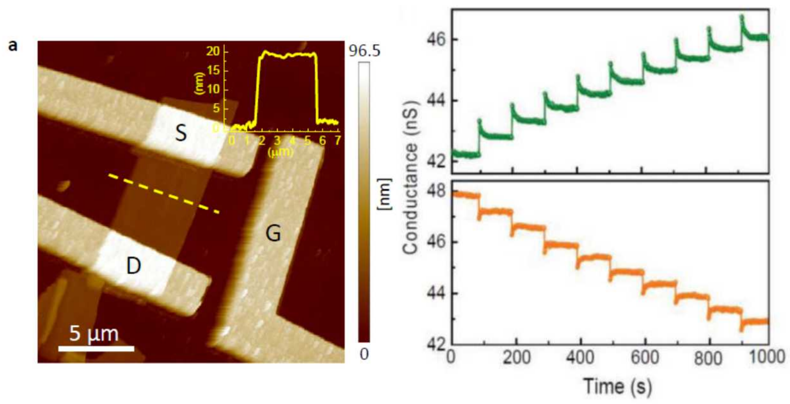

Zhu et al *Advanced Materials* 2018

LISTA - Graphene



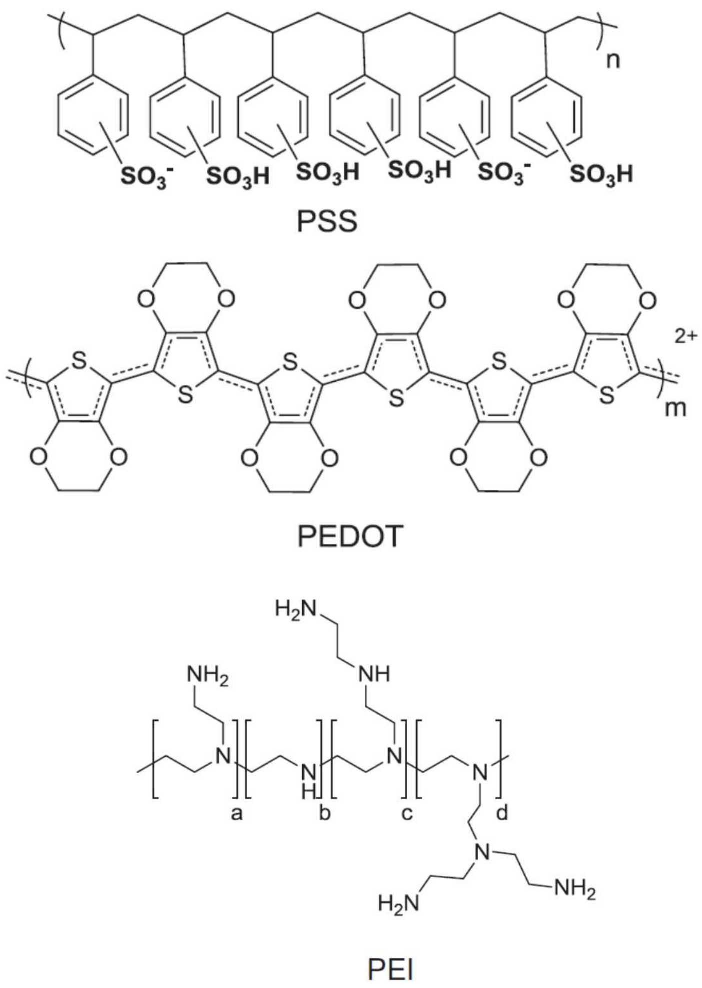

Sharbati et al *in review* 2018

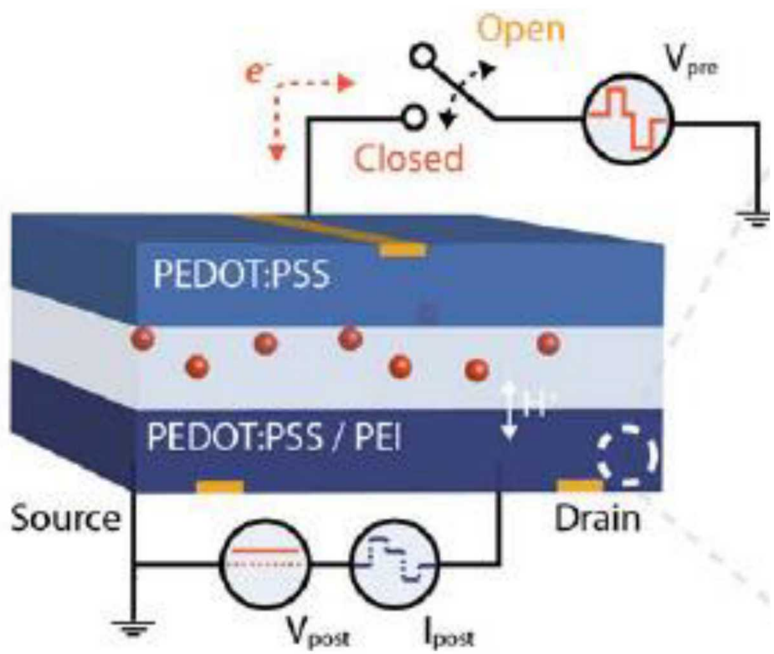
LISTA - $MoO_x$




C-S. Yang, D-S. Shang, N. Liu, E. J. Fuller, S. Agrawal, A. A. Talin,
Y-Q. Li, B-G. Shen, Y. Sun, Adv. Funct. Mat. 1804170 (2018)

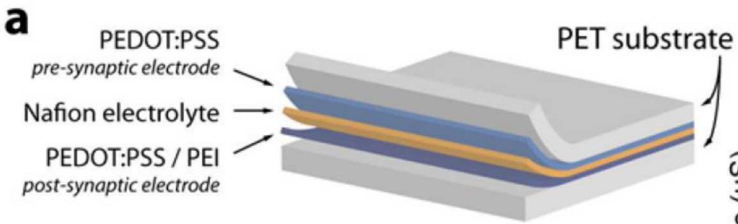
# Polymer non-volatile redox cell

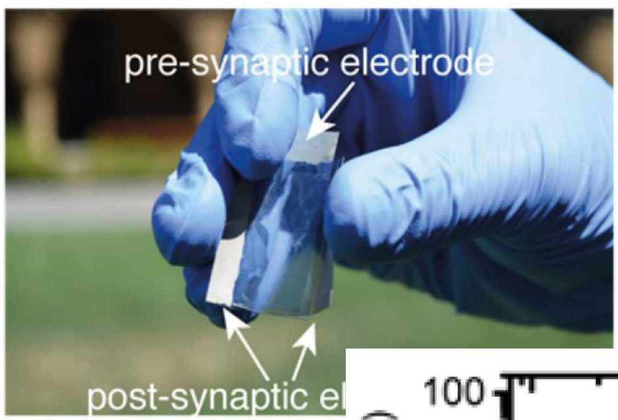


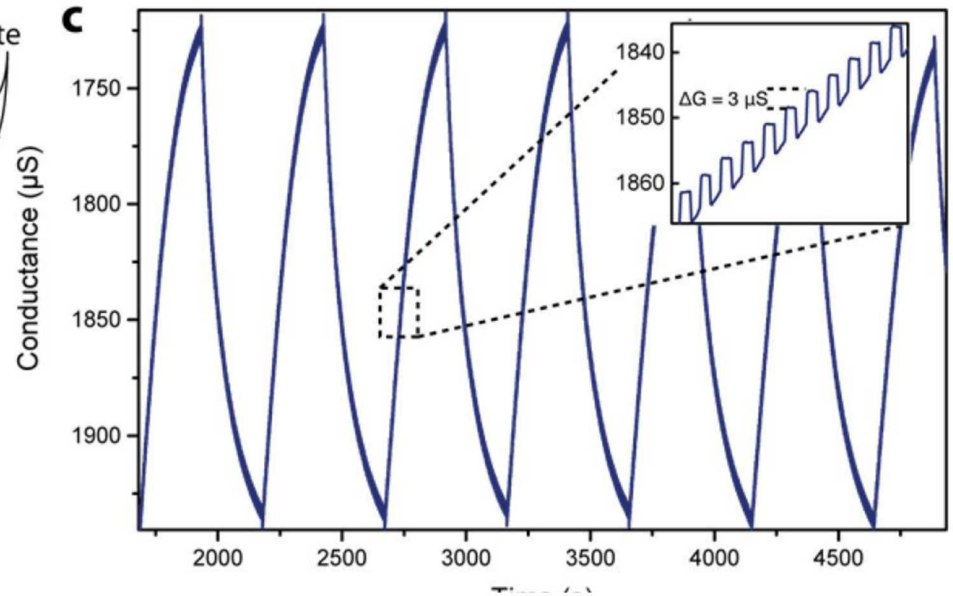



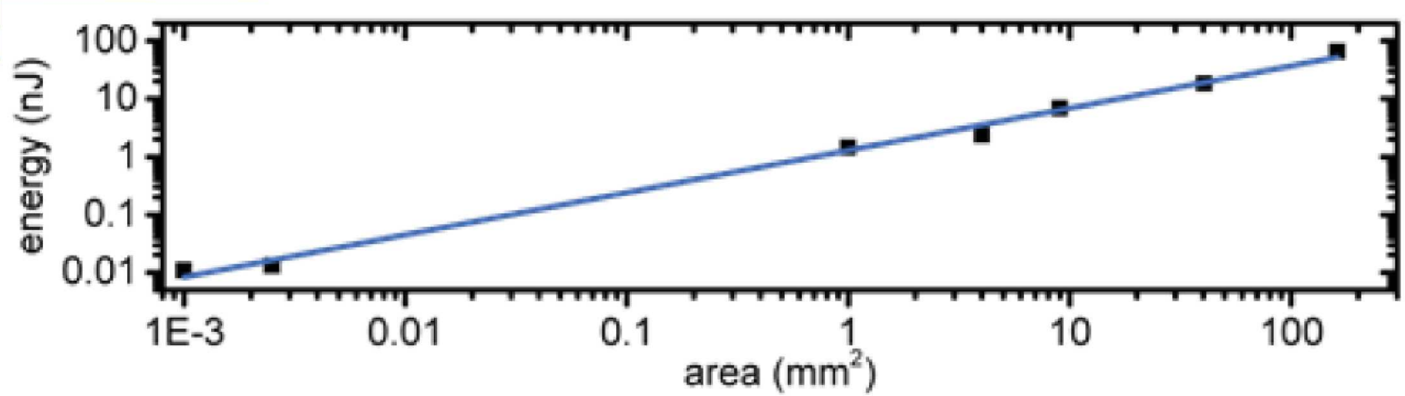
# Organic non-volatile redox transistor





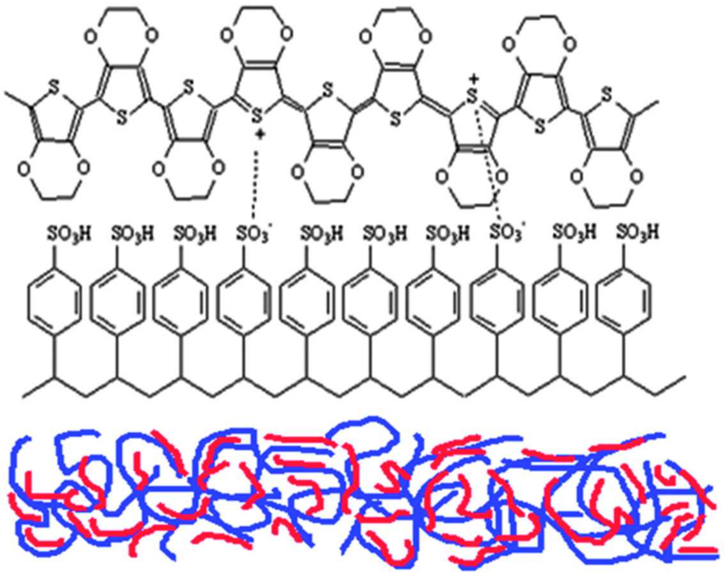



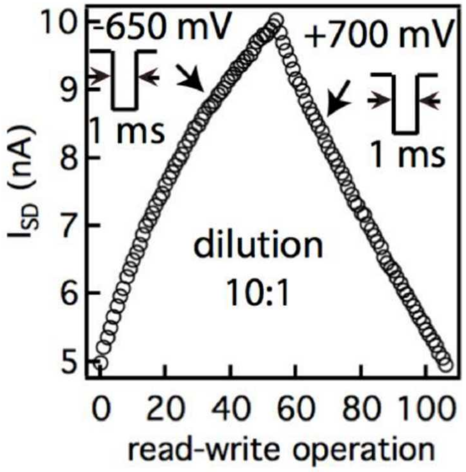

**35 aJ switching for $0.3 \times 0.3$ μm device**

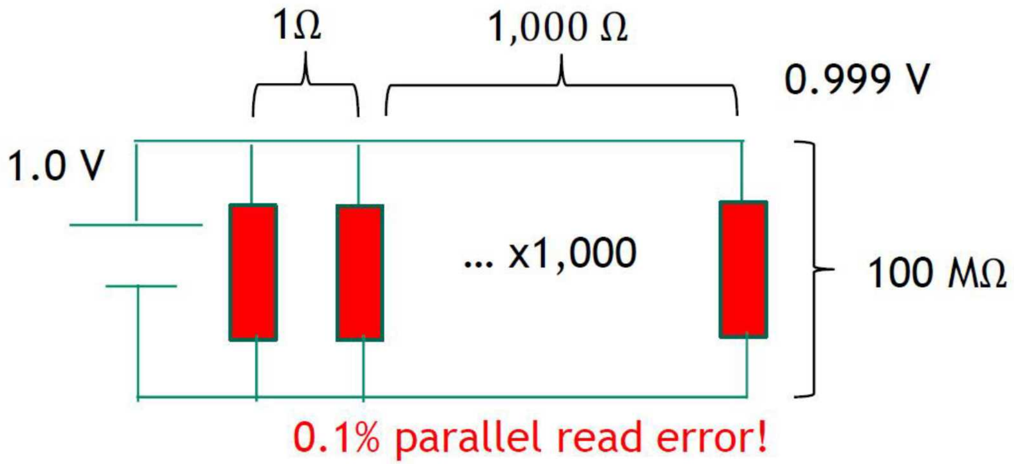
Y.B. van de Burgt, E. Lubberman, E.J. Fuller, S.T. Keene, G.C. Faria, S. Agarwal, M.J. Marinella, A.A. Talin*, A. Salleo*, Nature Materials 16, 414, 2017

# PSS increase decreases conductance, maintains linearity

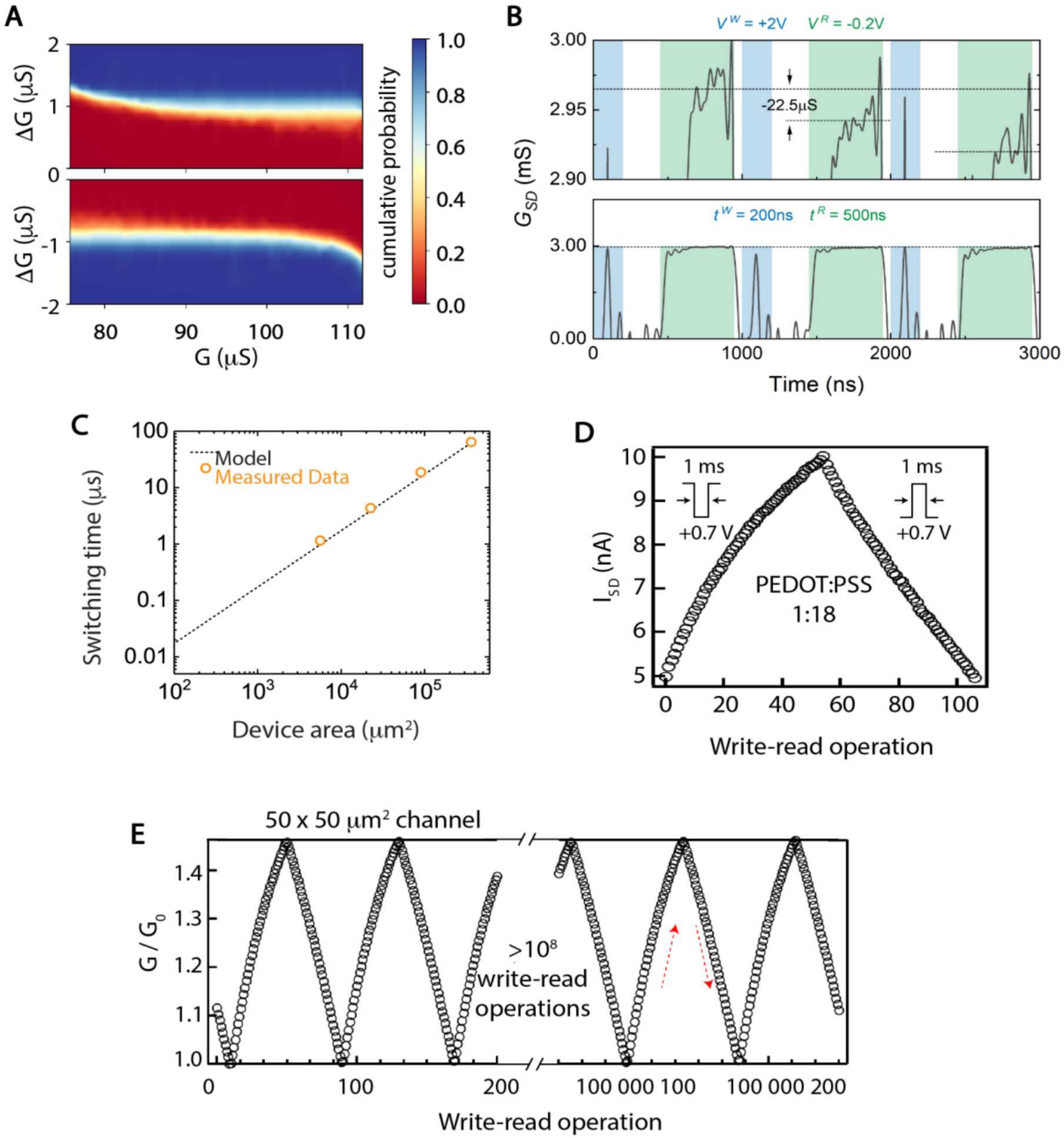


PSS is electrically insulating



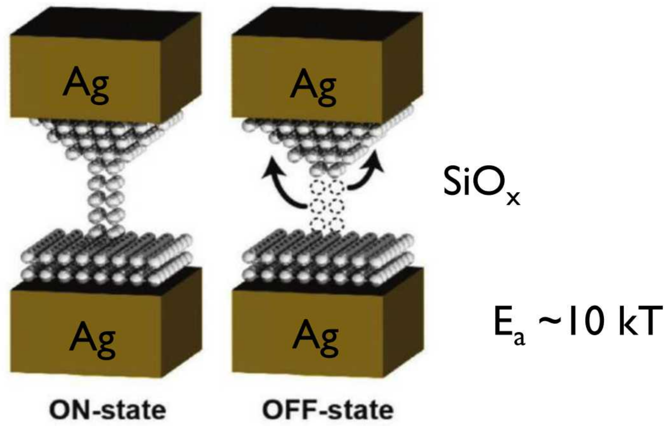



# Low read/write current, MHz speed, high endurance



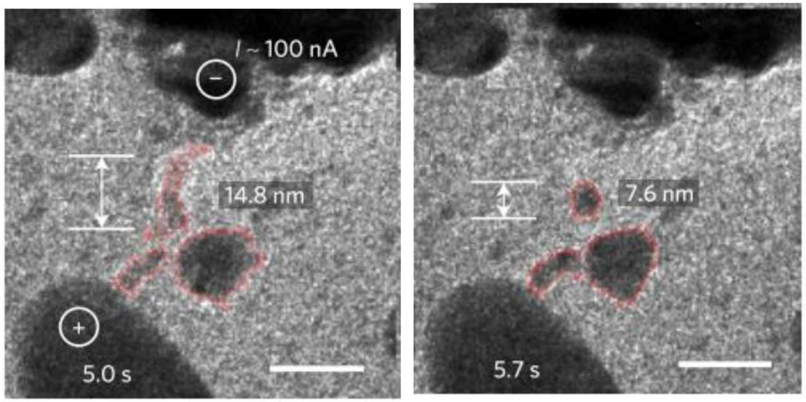
# Use binary, volatile selector for outer-product update

selector: diffusive memristor
normally OFF, $V_T = 150 - 400\ \mathrm{mV}$

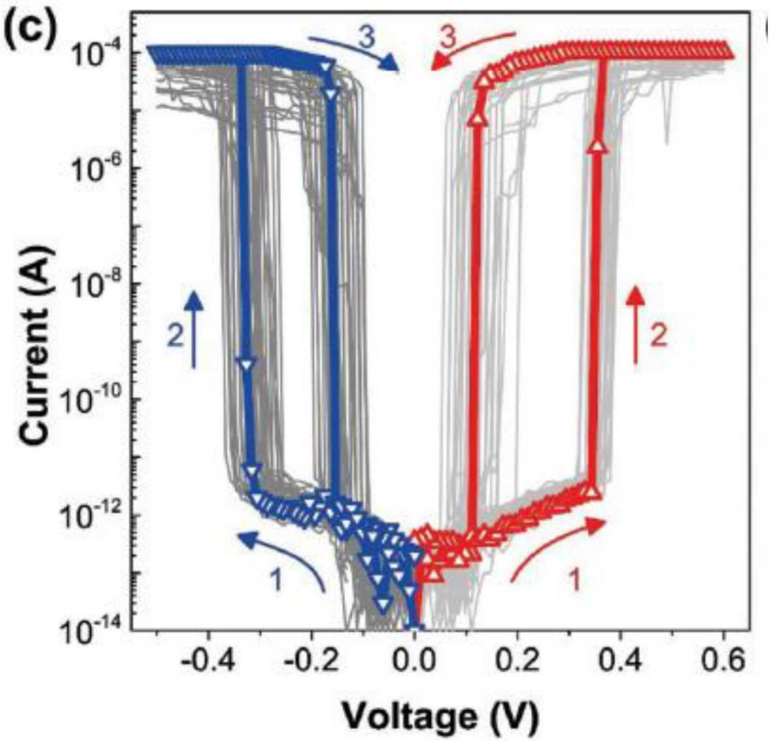



Pt/Ag/SiO$_x$:Ag/Ag/Pt

Midya et. al., *Advanced Materials*, 29(12), 2017



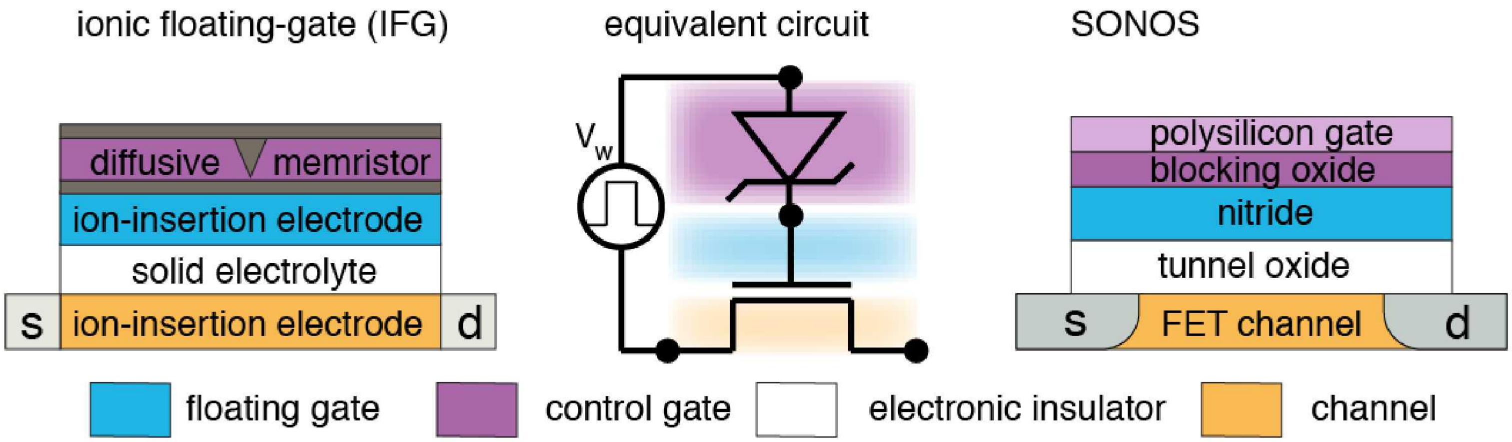

Wang et. al. *Nature Materials* 16, 101-108 (2016)



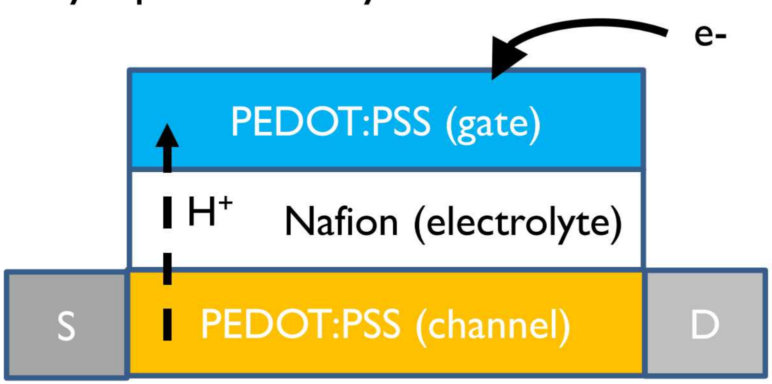

symmetric thresholding mechanism for program selectivity within array

1 mV/decade slope

# Ionic floating-gate memory



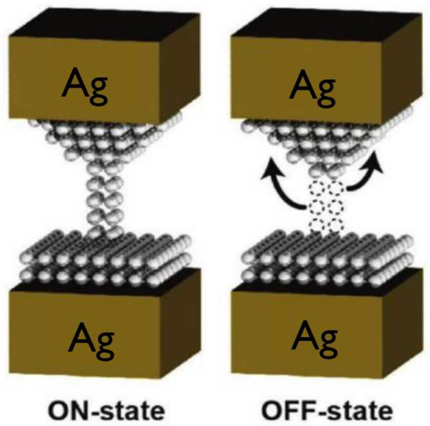

synaptic memory: redox transistor




*van de Burgt, Nature Materials* 16, 414, (2017)

control gate: volatile, filamentary switch

normally OFF, $V_T = 150 - 400$ mV



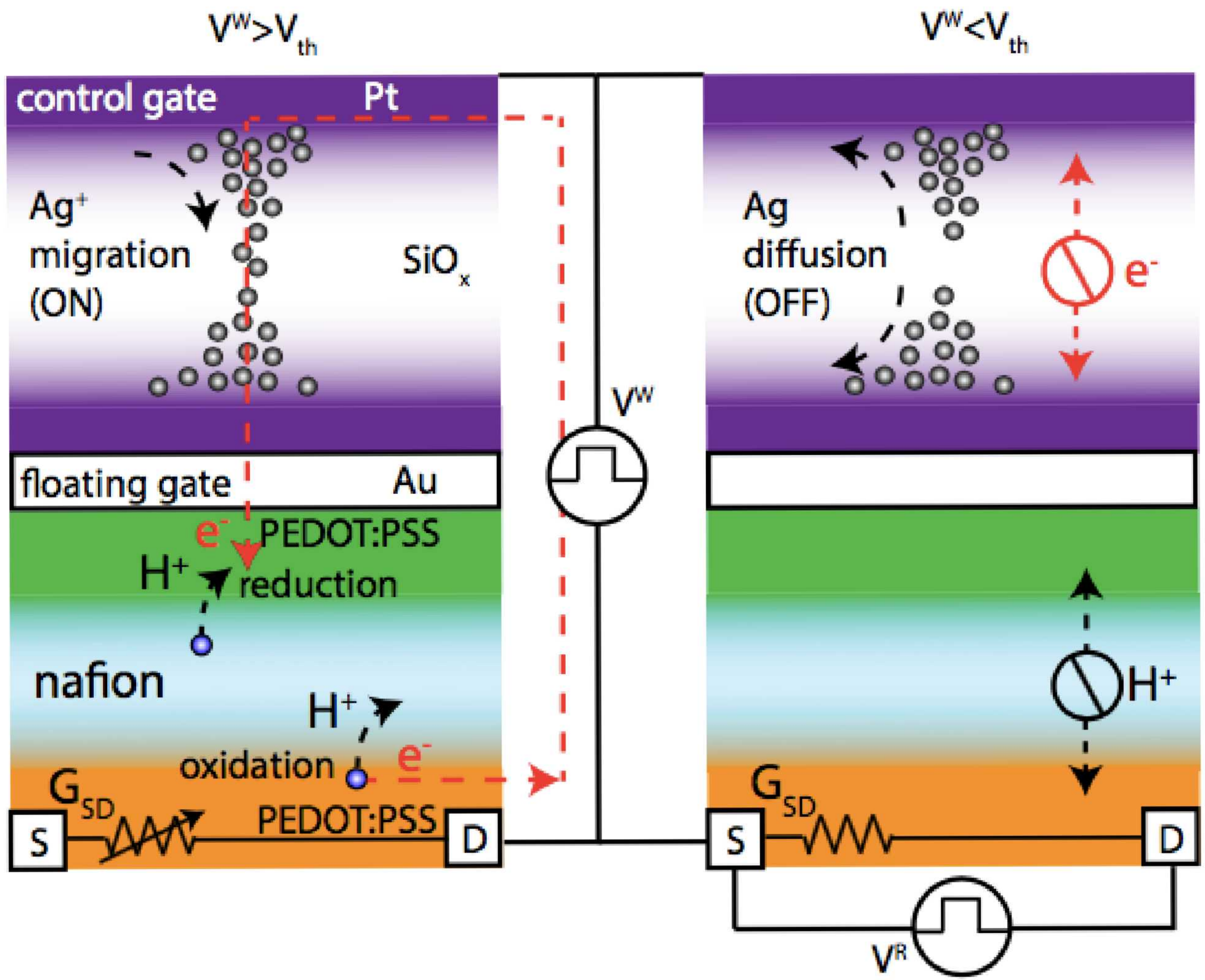

$E_A \approx 10\mathrm{kT}$

$SiO_x$

Pt/Ag/$SiO_x$:Ag/Ag/Pt

Midya et. al., *Advanced Materials*, 29(12), 2017

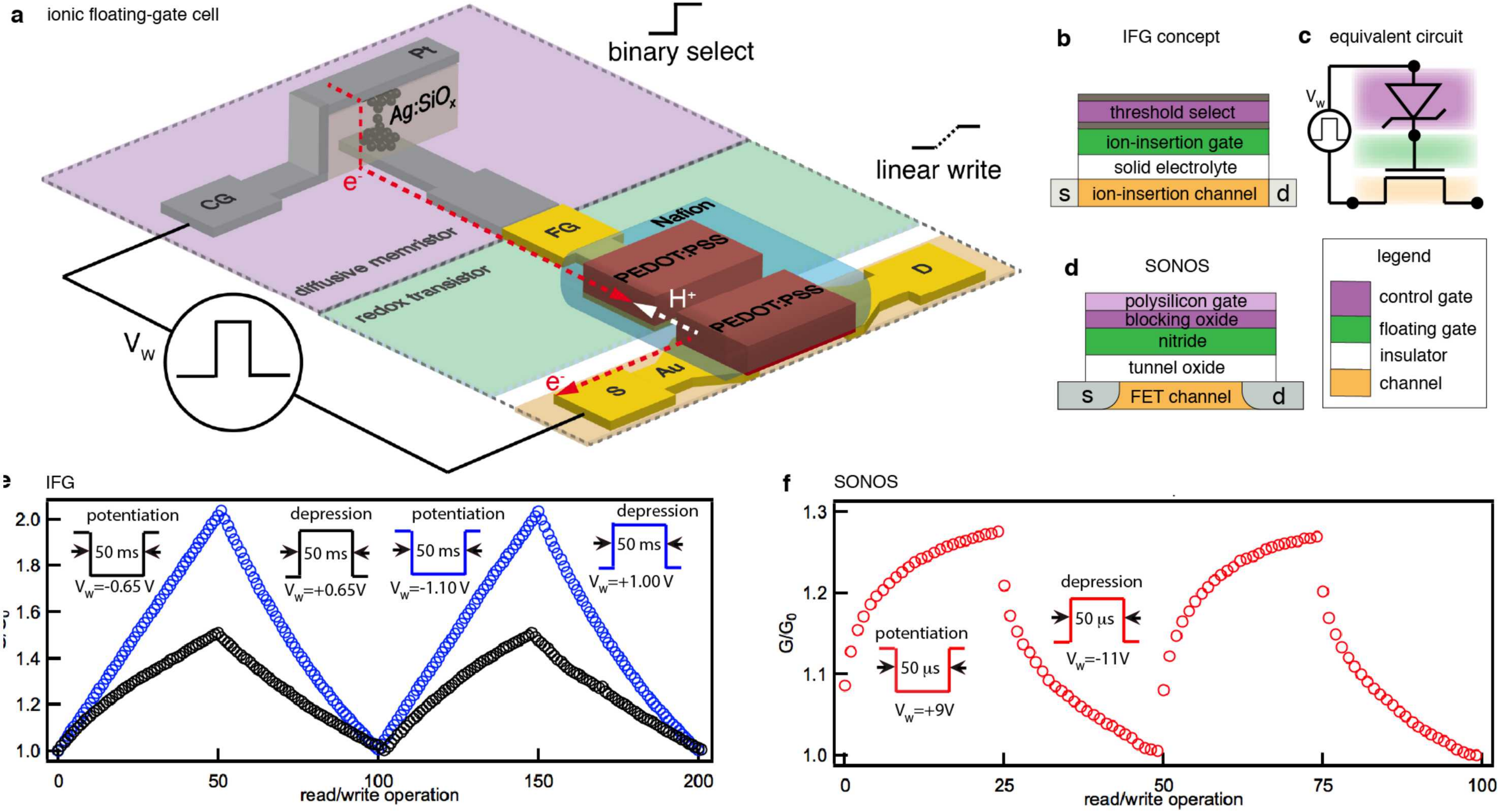
# Non-volatile redox memory – a floating gate memory



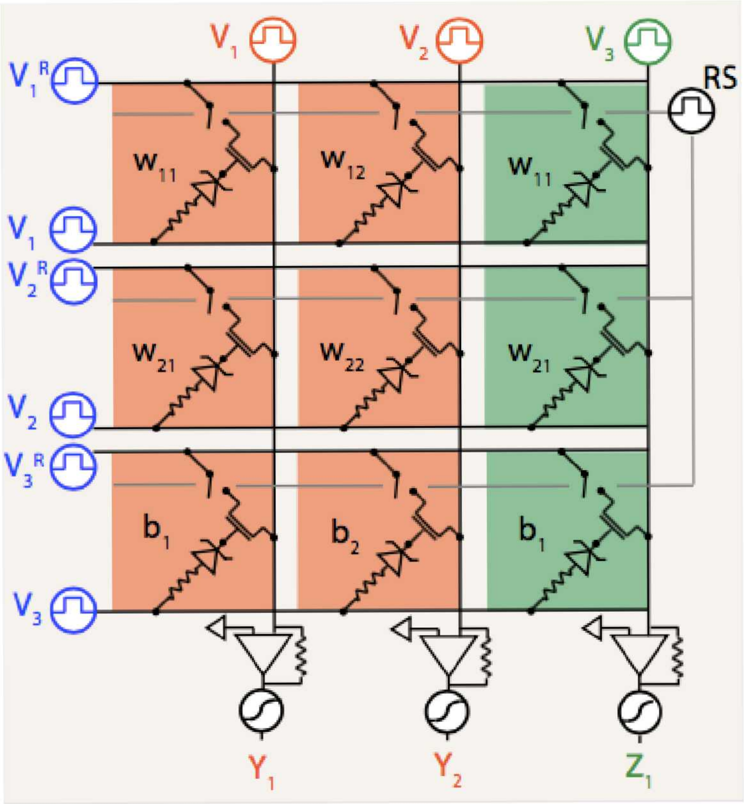

(aside: Li device programs at 170 mV, retains state)

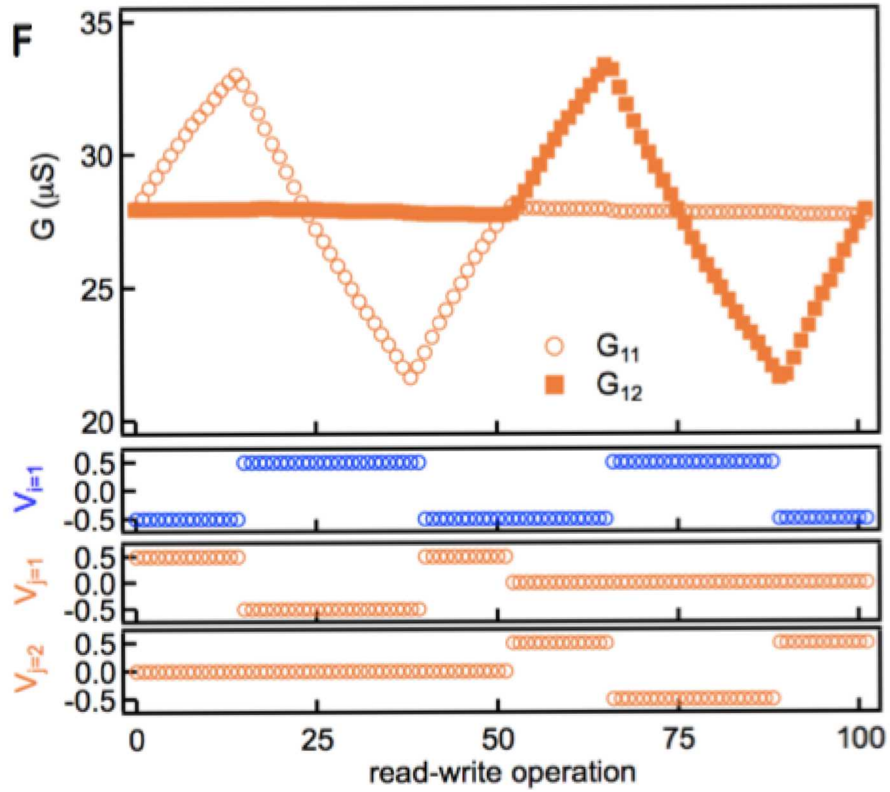
# Diff. memristor + NVRT → Ionic Floating Gate Memory





# First test of addressability

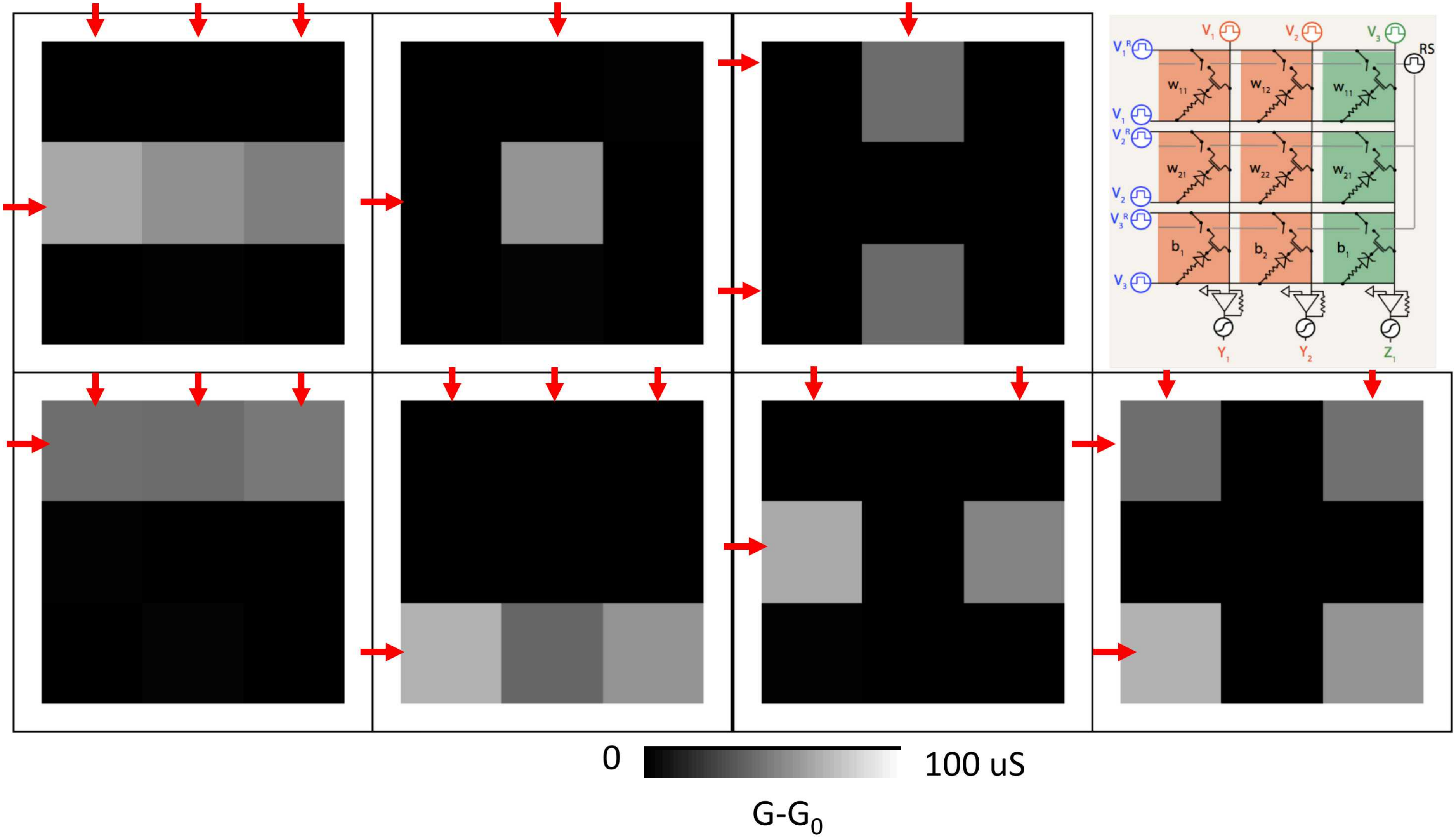


# Parallel updates in a 3x3 array



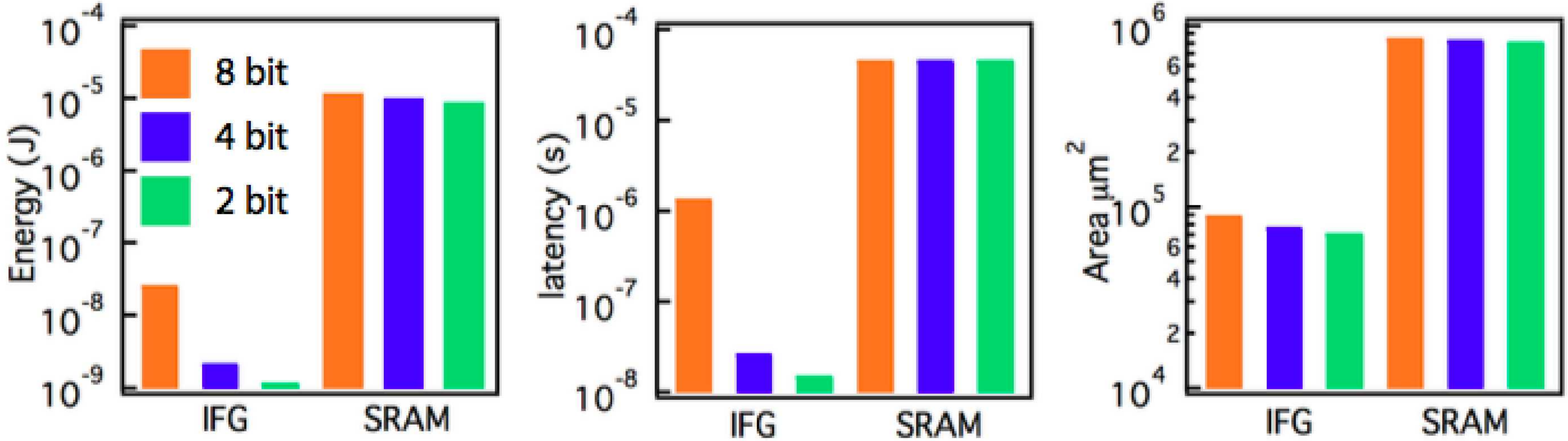





**Scalable → program an entire 1,000 x 1,000 matrix in a single operation**

# Simulations

Combined costs for three full matrix operations: VMM, MVM, OPU
(one training epoch, one layer 1,024 x 1,024 weights)




500x 16x 2x

# Contributors:

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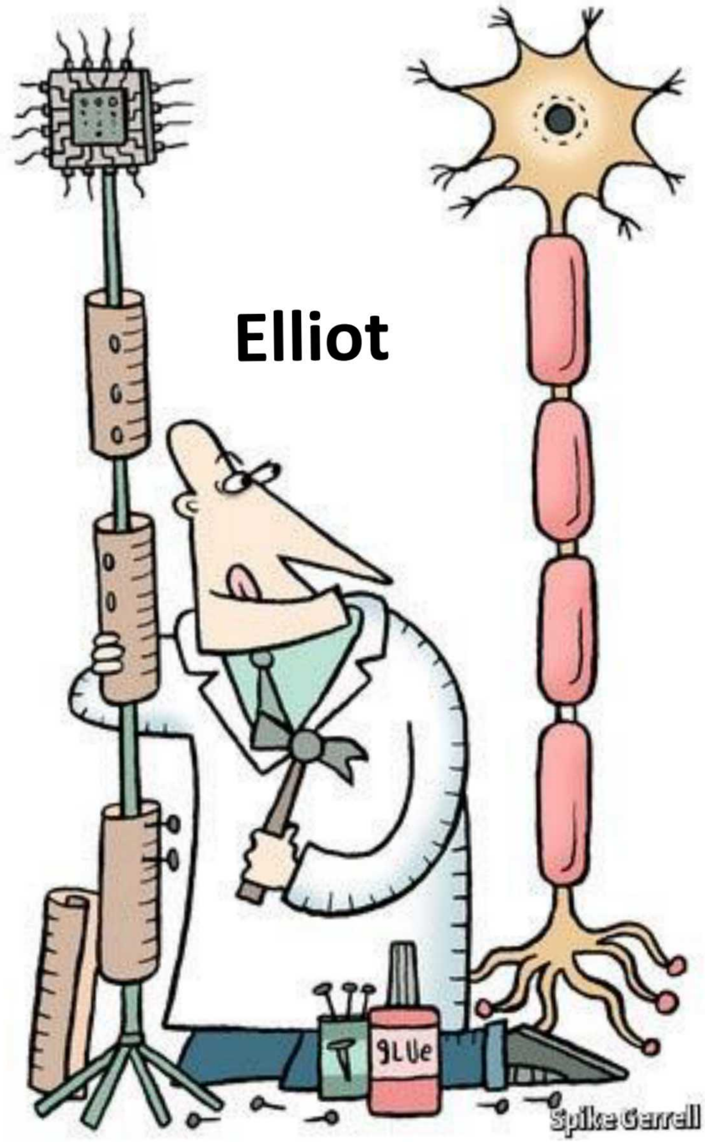
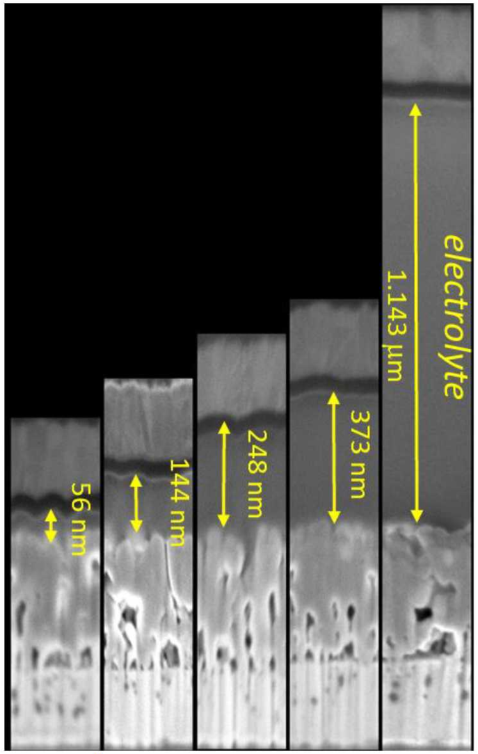
Support: LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT; U.S. DEPARTMENT OF ENERGY | Office of Science; NEES II NANOSTRUCTURES for ELECTRICAL ENERGY STORAGE

Elliot



# Speed for Li devices requires scaling below 100 nm

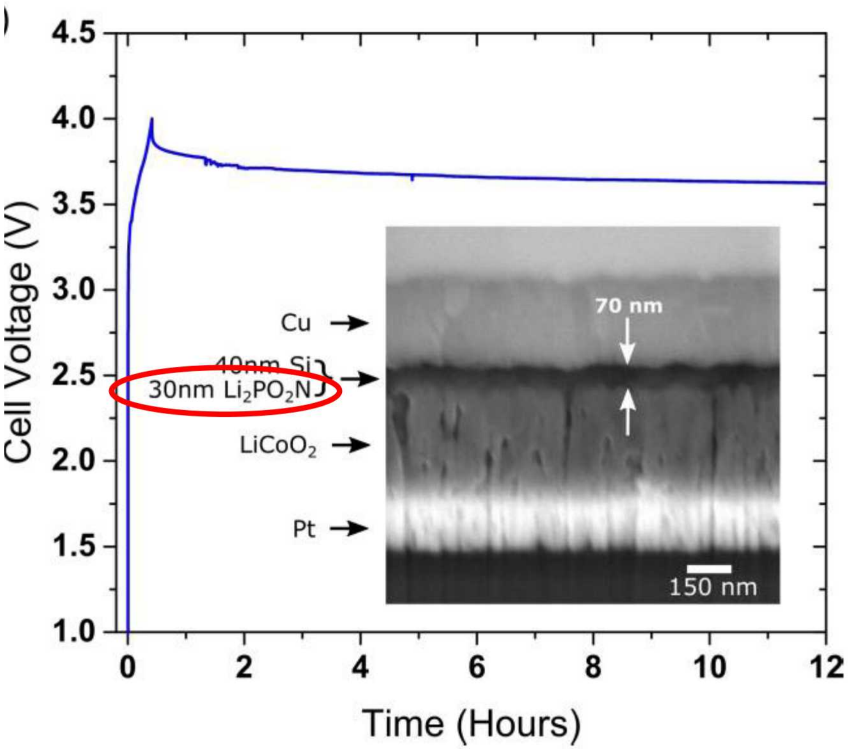
**Sputtered LiPON**




breakdown

stable

**ALD LiPON 30 nm**

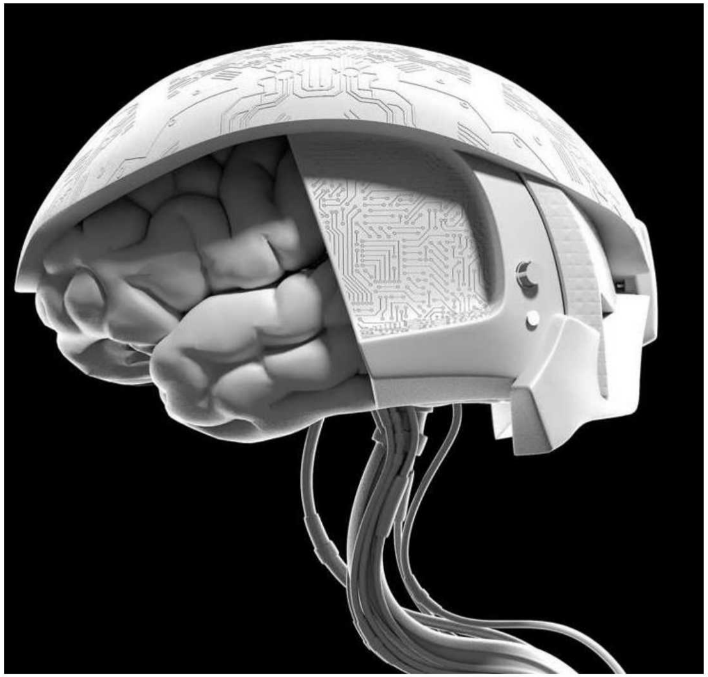


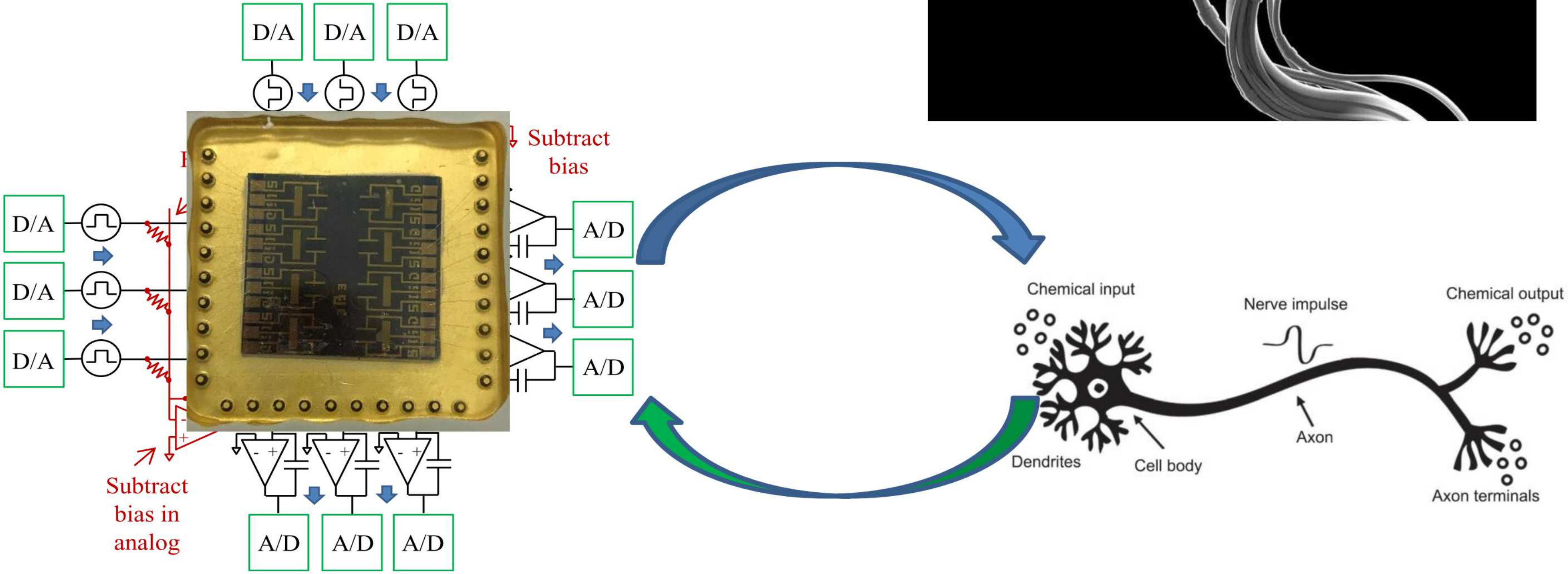

A. J. Pearse, T. E. Schmitt, E. J. Fuller, F. El-Gabaly, C-Fu Lin, K. Gerasopoulos, A. C. Kozen, A. A. Talin, G. Rubloff, K. E. Gregorczyck, Mat. Chem. 29, 3740, 2017

# The Pentagon’s Push to Program Soldiers’ Brains

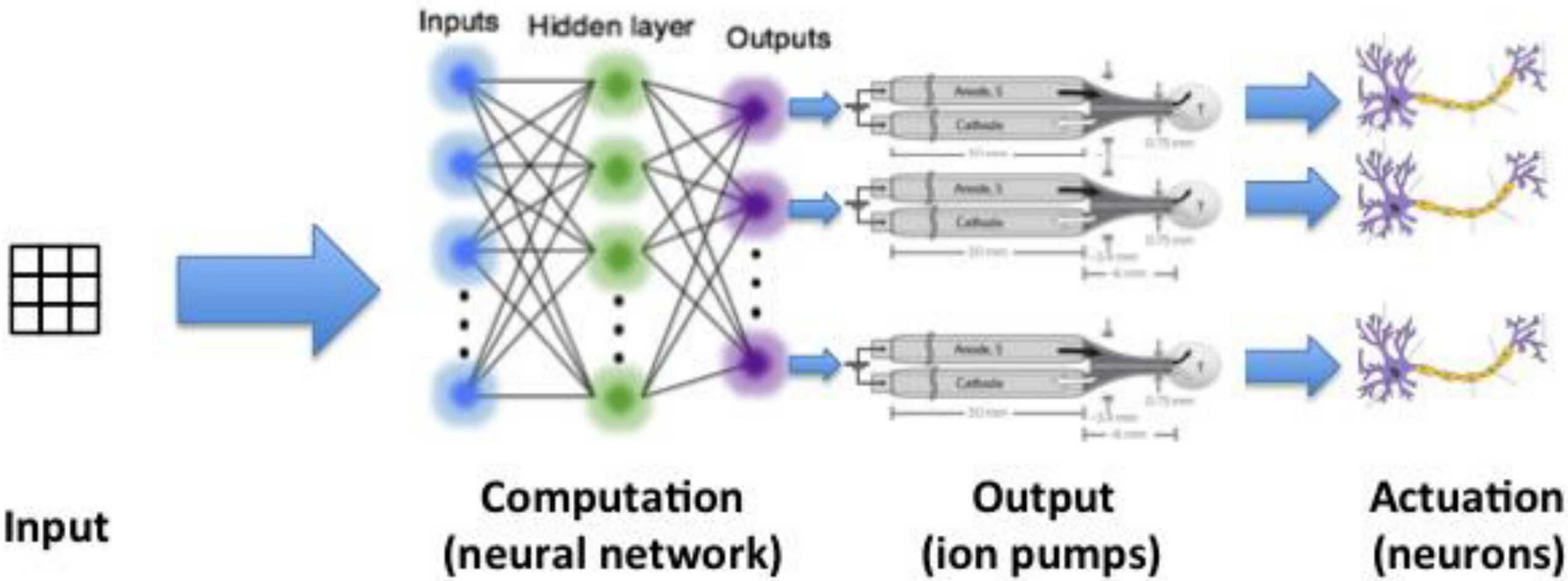
**The mission is to make human beings something other than what we are, with powers beyond the ones we’re born with.**

https://www.theatlantic.com/magazine/archive/2018/11/the-pentagon-wants-to-weaponize-the-brain-what-could-go-wrong/570841/

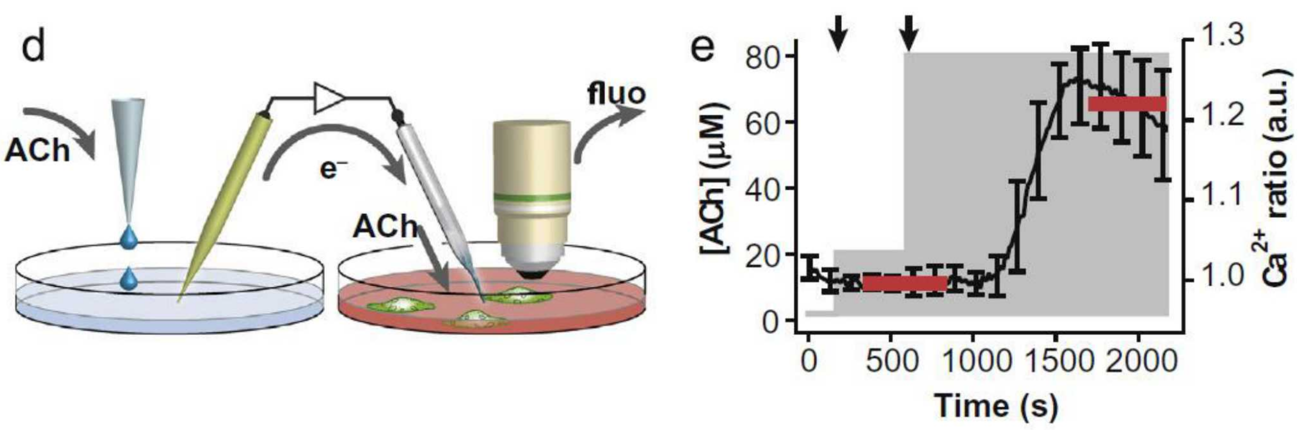




# Polymer NVRM for brain-machine interface

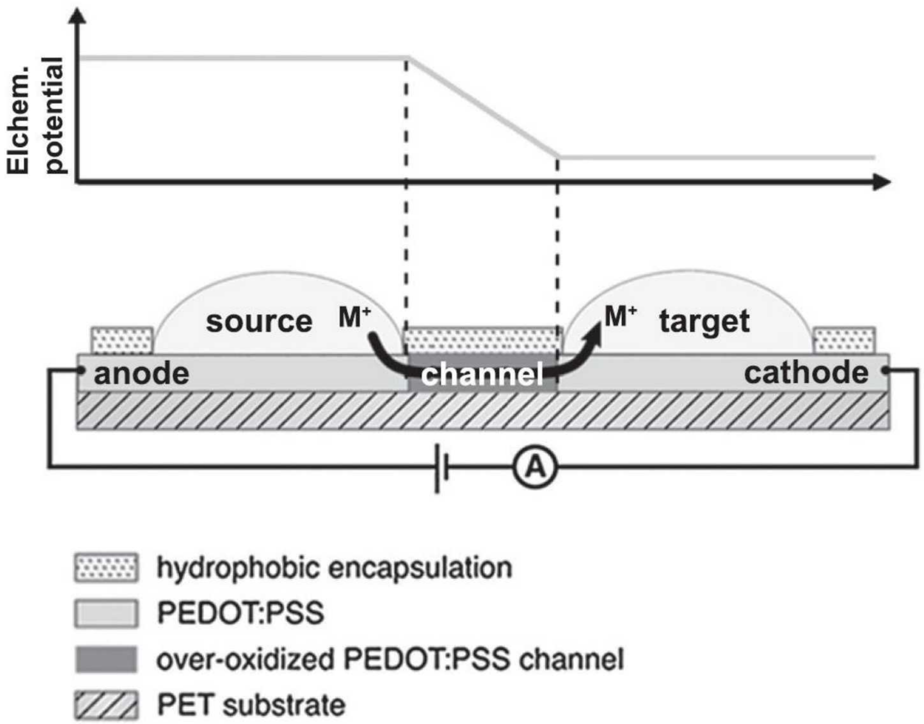


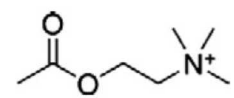
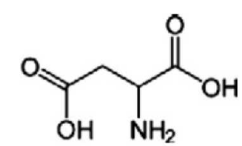
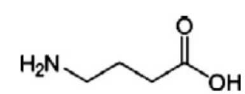
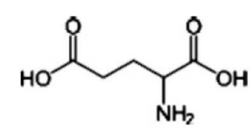

*Simon et al., Biosensors andBioelectronics 71 359 (2015)*



# PEDOT:PSS ionic-electronic neurotransmitter pumps

Sandia National Laboratories




| | | | |
|---|---|---|---|
| *Ions* | | | |
| $Na^+$ | Involved in the initiation of action potentials. | | 80% |
| $K^+$ | Maintain the resting potential in excitable cells. | | 100% |
| $Ca^{2+}$ | Important second messenger in cell signaling, dictates release of neurotransmitters. | | 100% |
| *Neurotransmitters* | | | |
| Acetylcholine | Neurotransmitter in the CNS and PNS. |  | 100% |
| Aspartate | Excitatory neurotransmitter in the CNS. |  | 16% |
| GABA | Major inhibitory neurotransmitter in CNS. |  | 77% |
| Glutamate | Major excitatory neurotransmitter in the CNS. |  | 37% |

*K. C. Larsson, P. Kjäll, A. Richter-Dahlfors, Biochimica et Biophysica Acta 1830 (2013) 4334*

# Polymer FET bio-sensors coupled with plastic NNs


In the case of the PlasticARMPit project, Unilever was the one who came with the business case. The idea is to couple a flexible and multi-analyte e-Nose sensor with a plastic NN onto a wearable patch to detect armpit malodour composition and determine how effective the company's antiperspirants and deodorants are. In this particular research project running until March 2020, PragmatIC will integrate organic TFT bio-sensors developed at the University of Manchester, but outside of this