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Low-voltage synaptic memory based on Li_xTiO_2 redox transistors

PRESENTED BY

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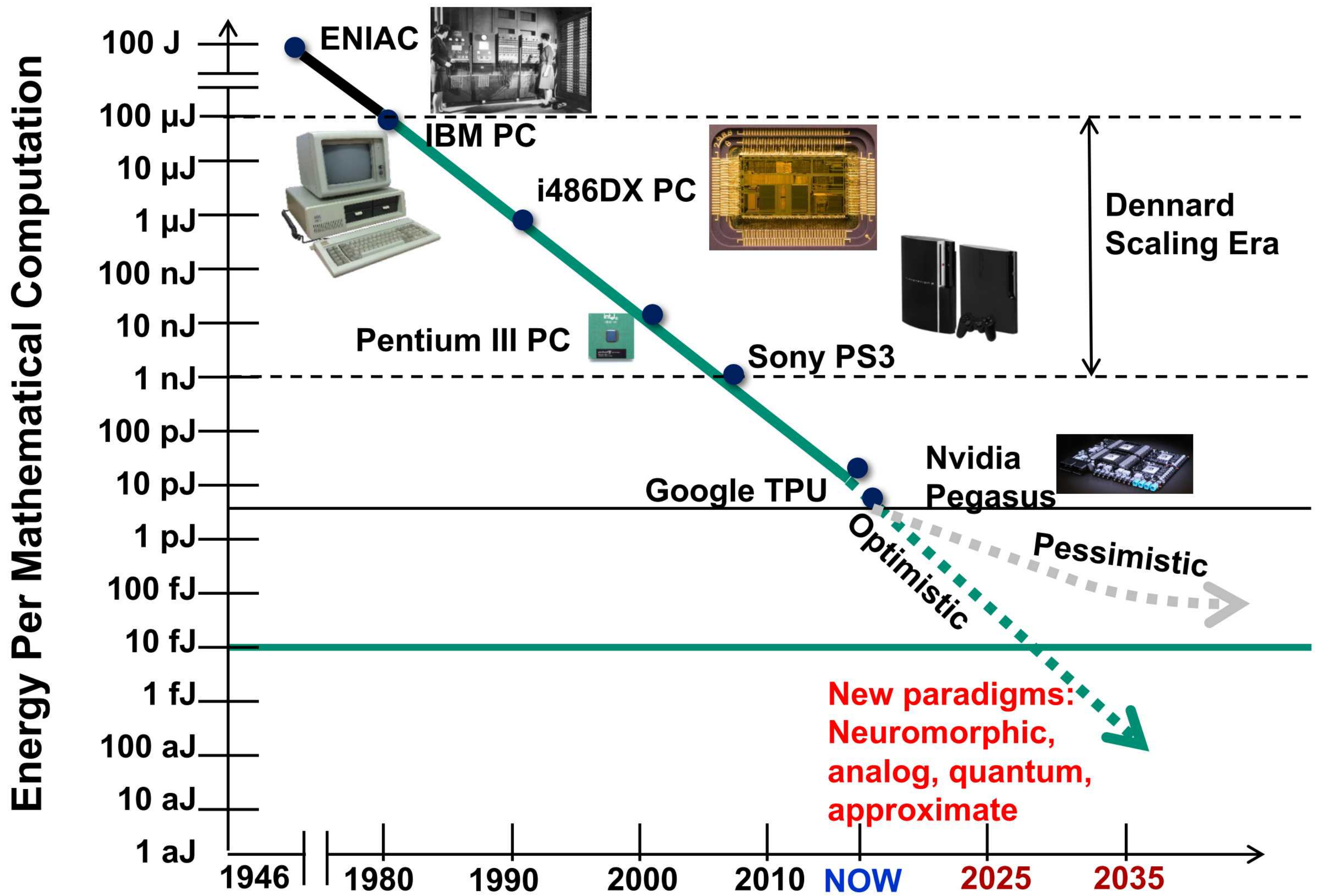
Evolution of Computing Machinery

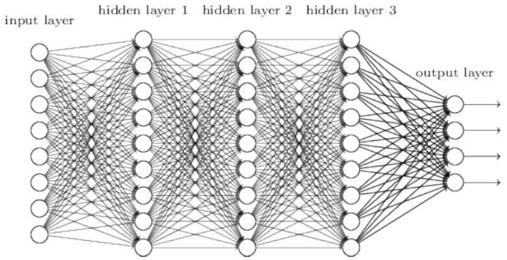


2

Digital and analog implementations of neural networks

$$\begin{bmatrix} y_1 \\ \vdots \\ y_m \end{bmatrix} = \begin{bmatrix} w_{1,1} & \cdots & w_{1,n} \\ \vdots & \ddots & \vdots \\ w_{m,1} & \cdots & w_{m,n} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}$$

n, m > 1000

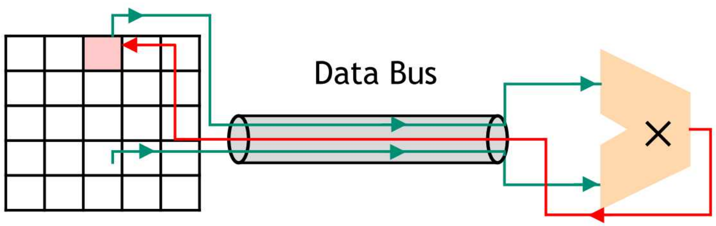


Von Neumann Digital

Separate logic and memory structures

SRAM to store the weights

Arithmetic logic unit for multiplication



Uses established CMOS technology

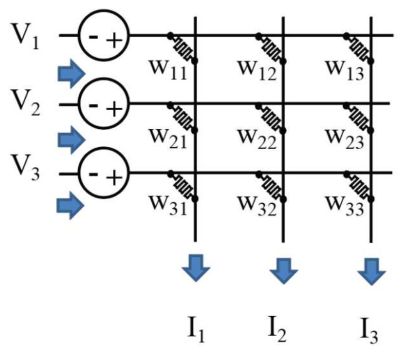
Data bus results in latency and power

In-memory Parallel Analog

Use non-volatile memory

Crossbar for matrix multiplication

Conductance of each element can be changed in a predictable manner



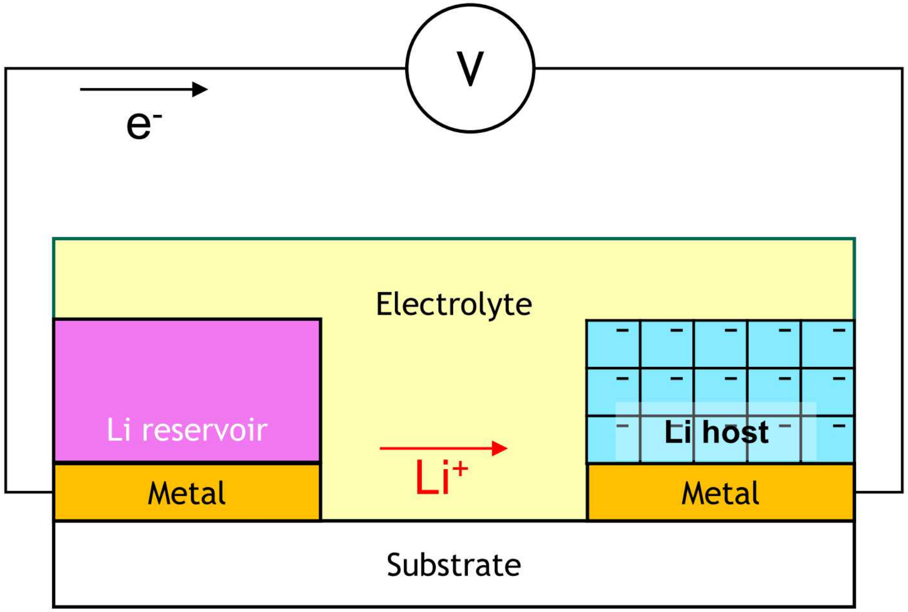
$I_1 = V_1W_{11} + V_2W_{21} + V_3W_{31}$

Simultaneous logic and memory

3 orders of magnitude less power

M. Marinella, *IEEE Circuits and Systems*, 8, 86-101, 2018

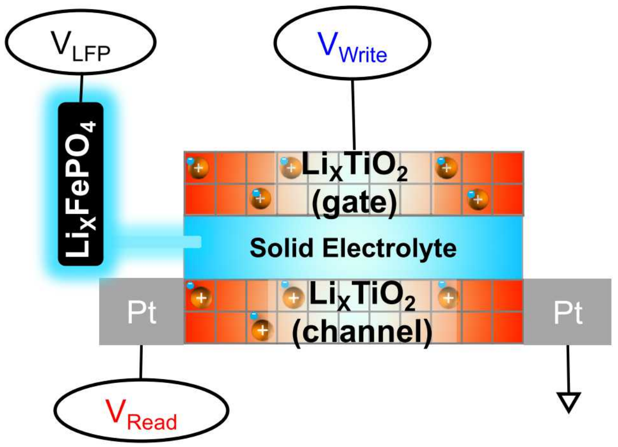
Redox transistors based on electrochemcial ion insertion

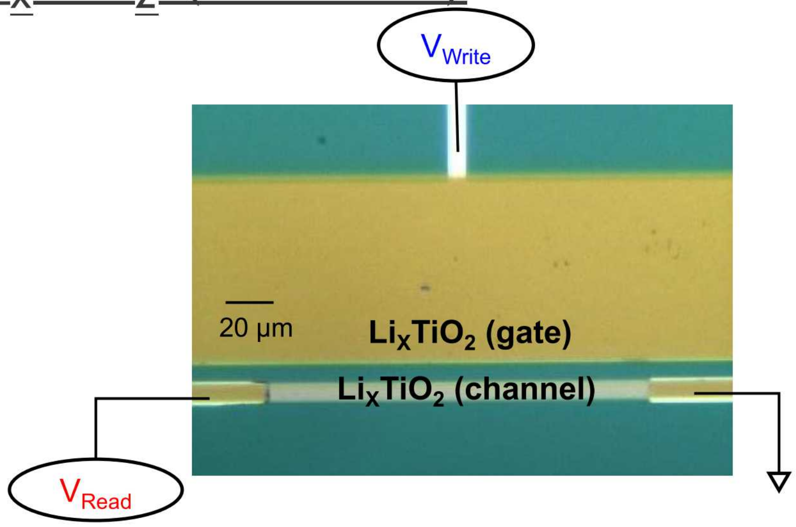


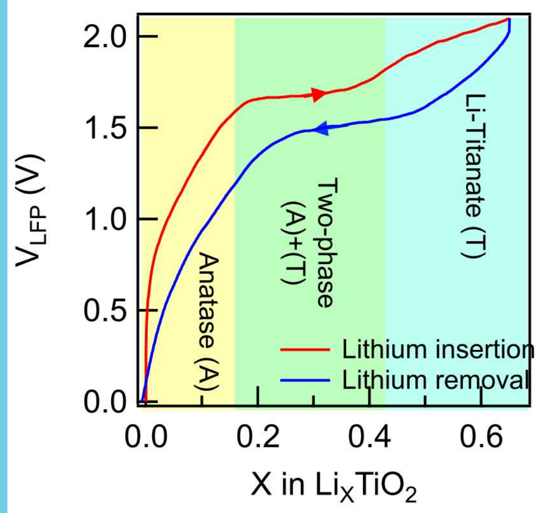
Dynamic control of the lithium doping level
using current and voltage

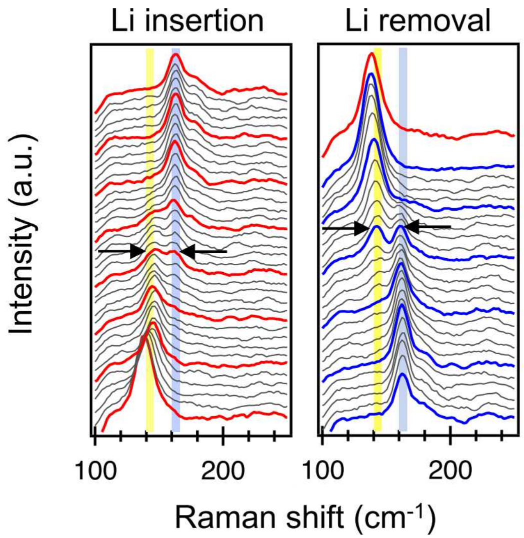
Y. Li, W. Chueh. Ann. Rev. Mater. Res. 48, 137 (2018)

Lithium insertion into Li_xTiO_2 (anatase)

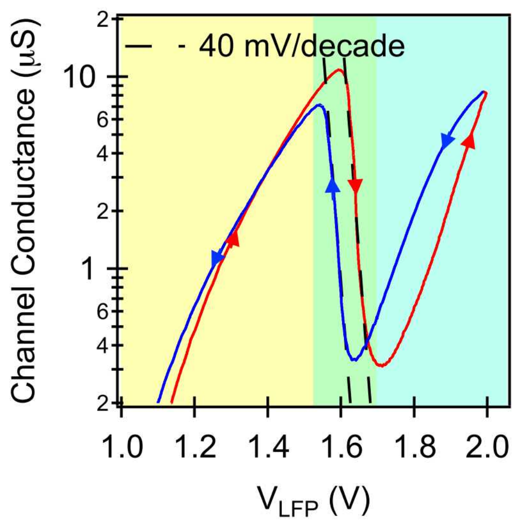




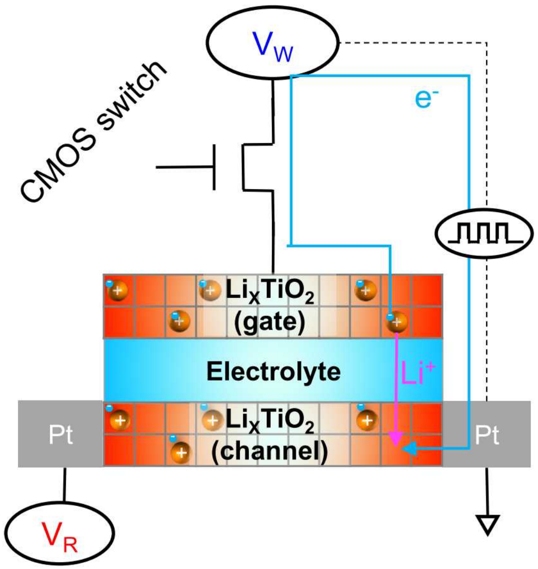


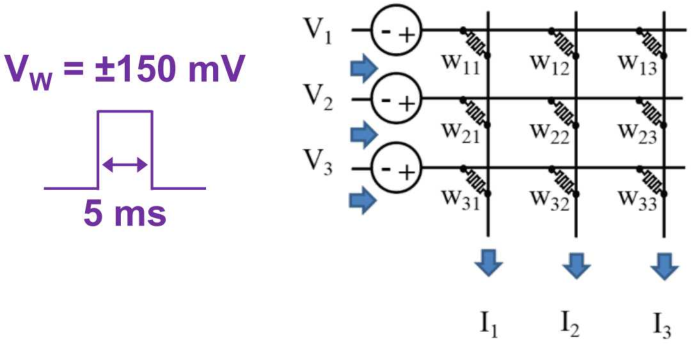


$$Li^{+} + e^{-} + Ti_{Ti}^{X} \rightarrow Li_{i}^{\circ} + \boldsymbol{Ti'_{Ti}}$$

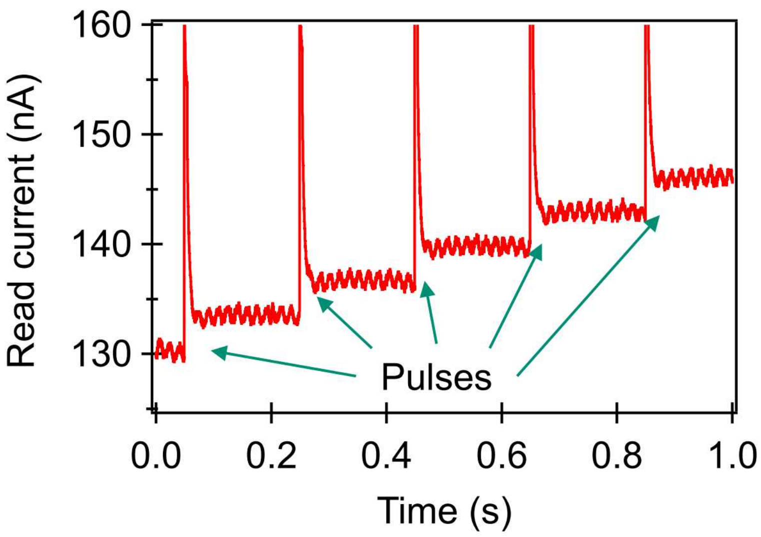


Redox transistor using Li_XTiO_2 (anatase)

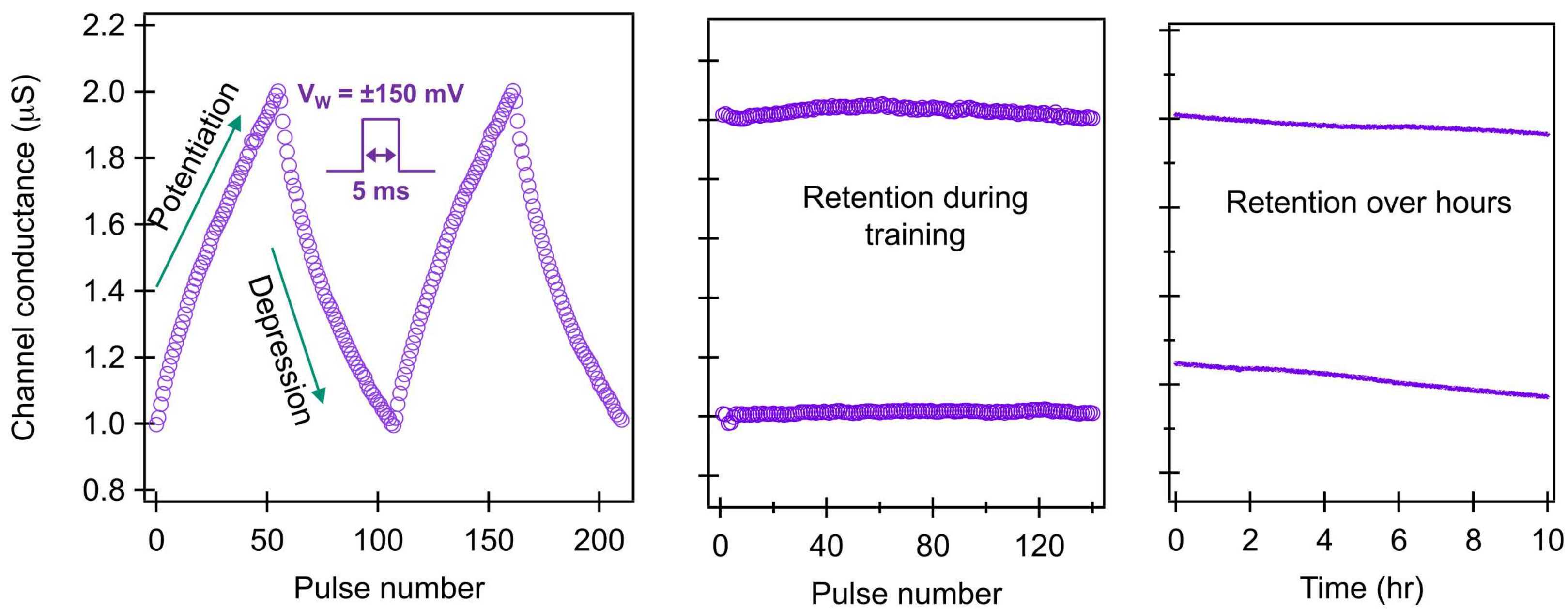




- Linear and symmetric programming
  - 150-mV write pulses
- Analog, non-volatile states

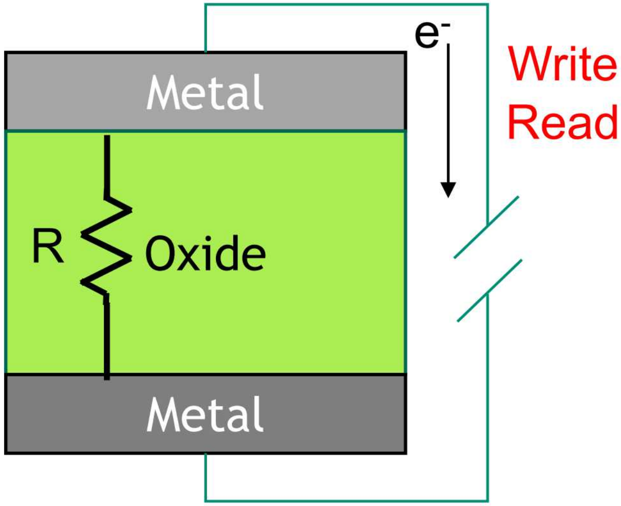


Redox transistor using Li_XTiO_2 (anatase)



Two-terminal vs three-terminal synaptic memory

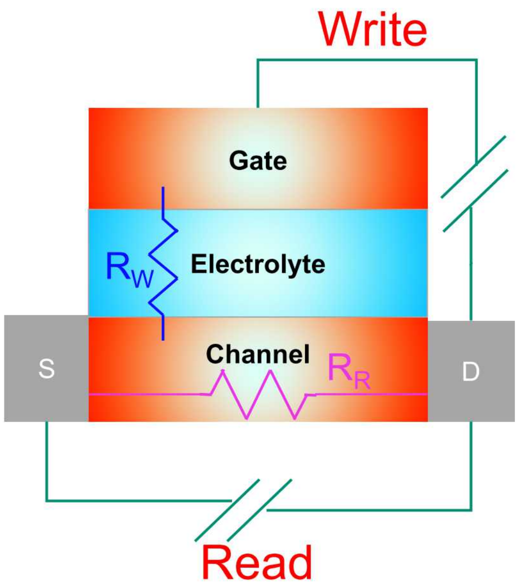
Memristor



Read and write signals through the same channel

During write, most electrons used for joule heating rather than weight updates

Redox transistor

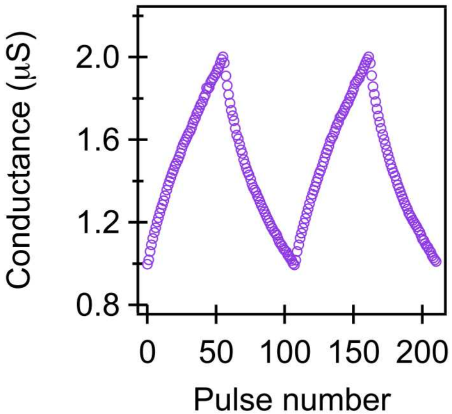


Separate read and write channels; All "write electron" used for weight updates (R_R)

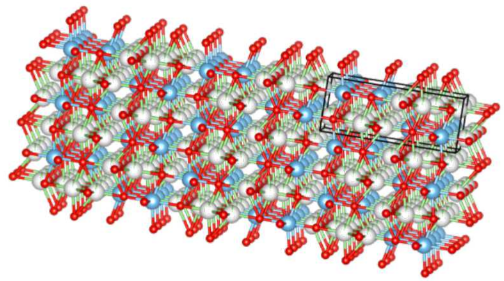
Predictable and linear weight updates
Low write energy

Linear programming and high accuracy

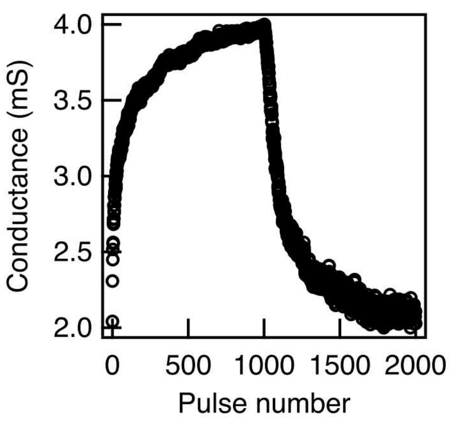
Li_XTiO_2 transistor
Voltage: ± 0.15 V



Redox transistors store information continuously as dopants in a crystal

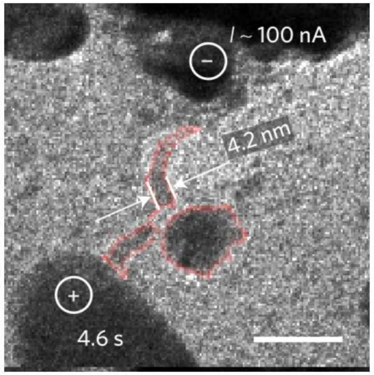


TaO_x Memristor
Voltage: ±1 V



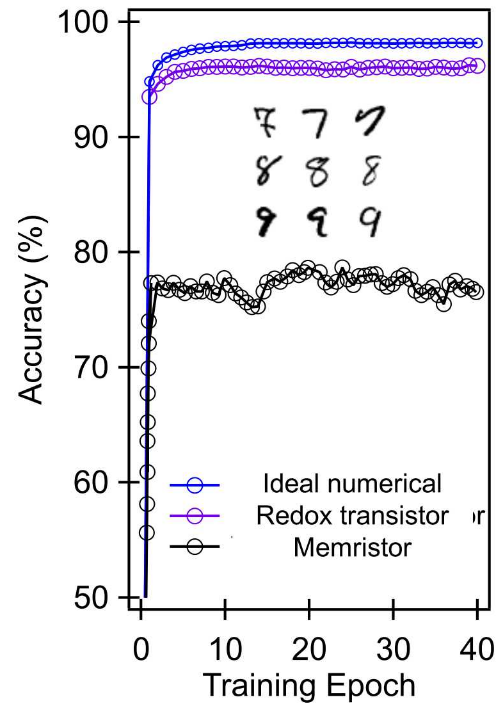
R. Jacobs-Gedrim et al. *ICRC*, 2017

Memristors store information at filaments



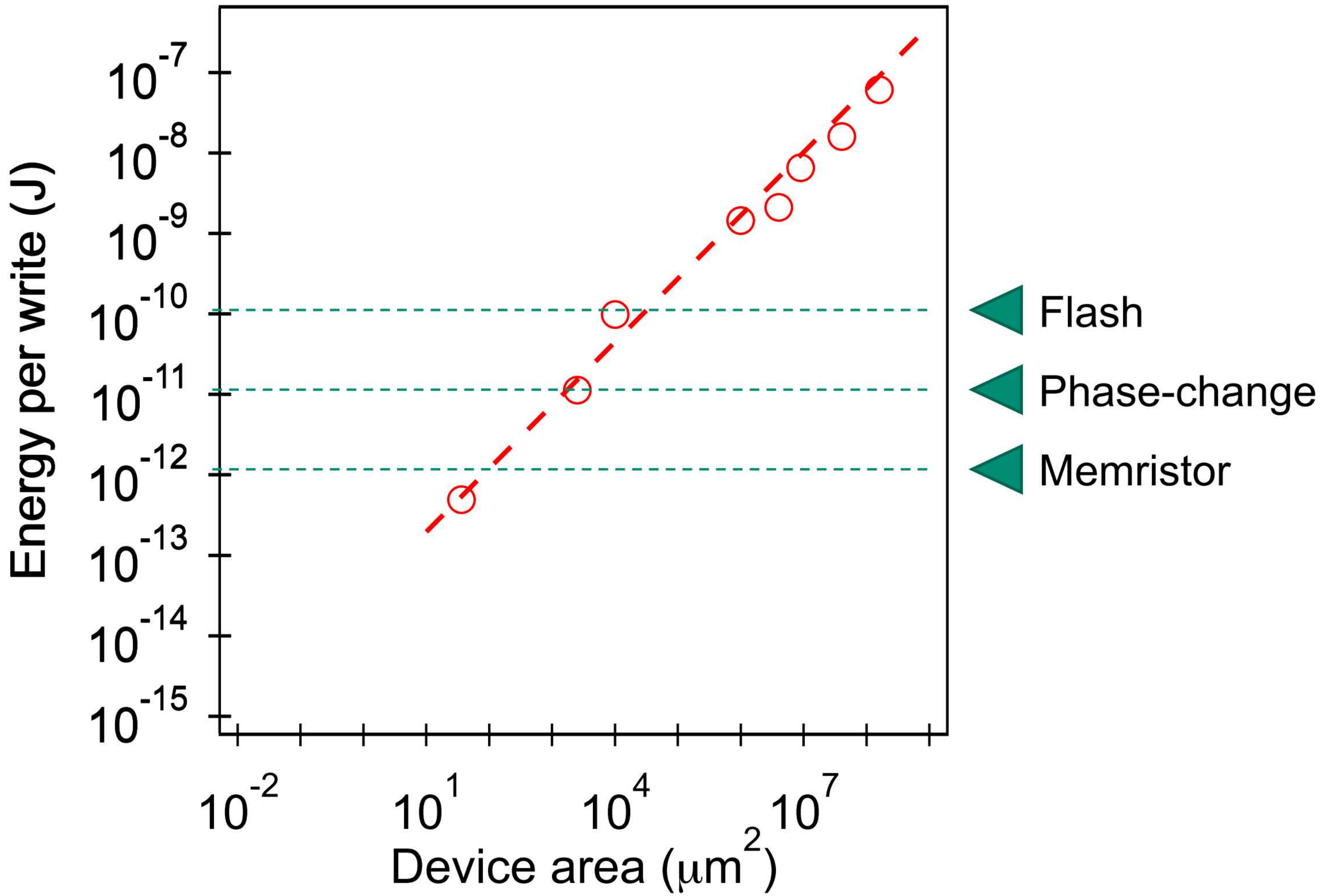
Wang et al. *Nat Mater.* 2017

Linearity is essential to train an accurate neural network



Crossbar Simulator

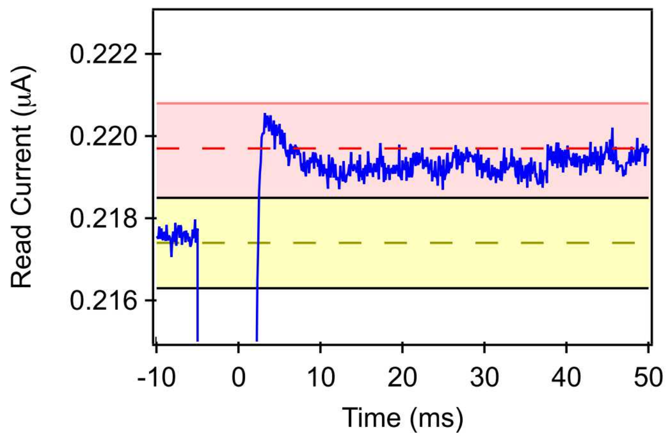
Exceptional low-power consumption

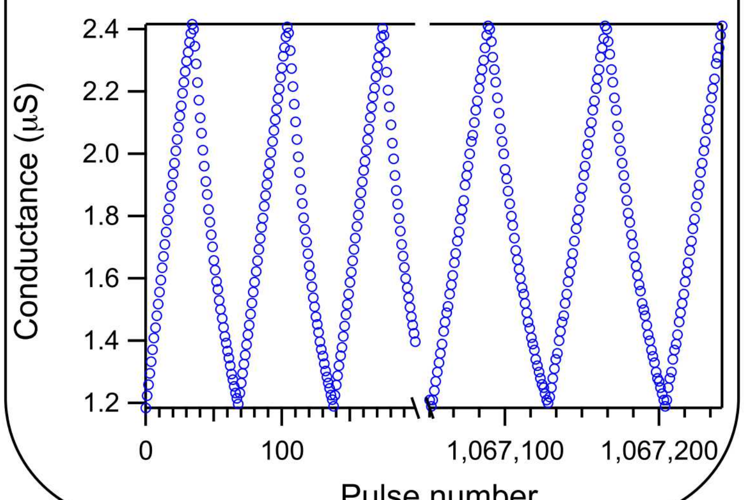


Y. Van de Burgt, *Nat Mater*, 16, 414(2017)
M. Sharbati *Adv. Mater.* 30, 1802353 (2018)
J. Yang et al. *Nat. Nano.* 8, 13(2012)

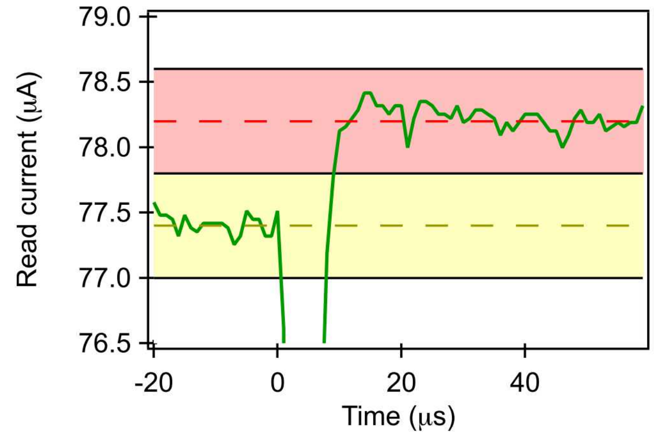
Switching speed and endurance

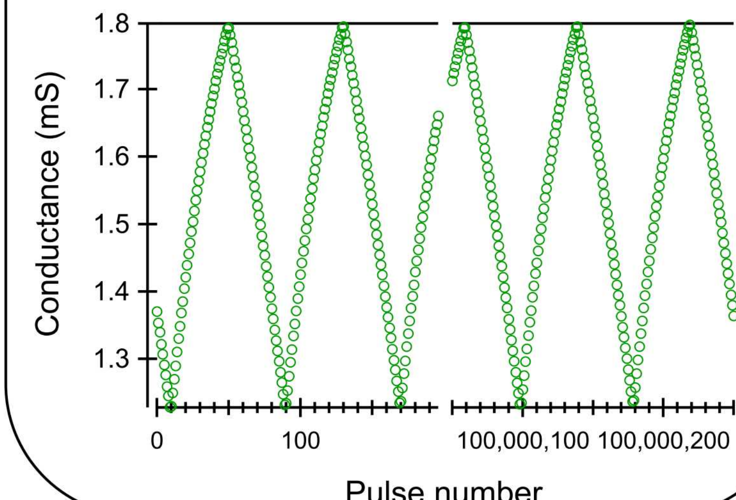
Inorganic (Li_xTiO_2) ~5 ms, 10^6 read/write cycles





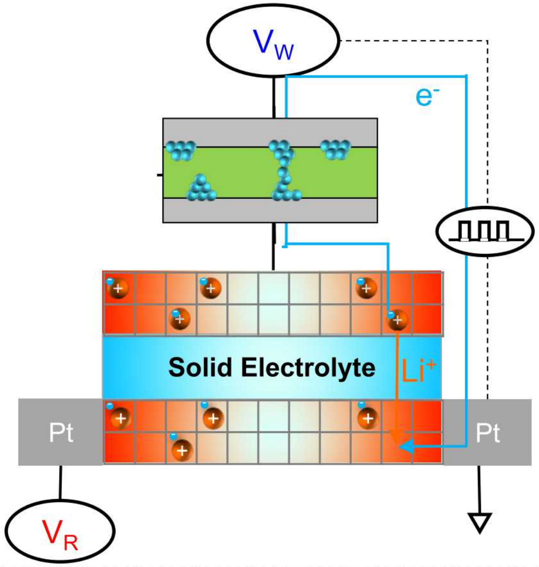
Organic (PEDOT/PSS) ~10 μs 10^8 read/write cycles





E. J. Fuller, et al. *Science.* Accepted

Low-voltage, Si-free electrochemical memory



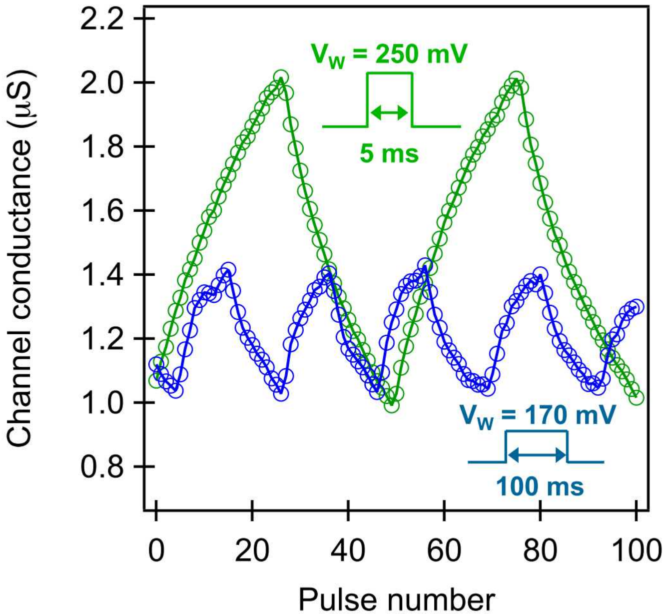
Diffusive memristor (Ag in SiO_X): high ON/OFF ratio

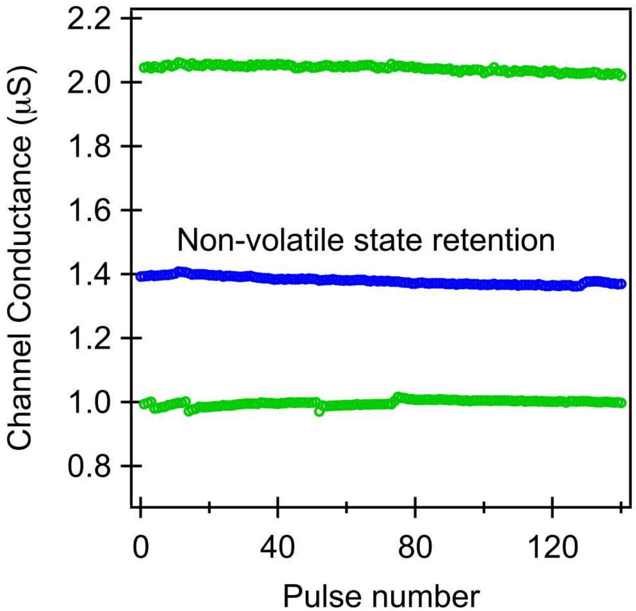
Redox transistor: high charge density via bulk storage

Both: Low switching voltages

Wang et al. Nat. Mater. 2017

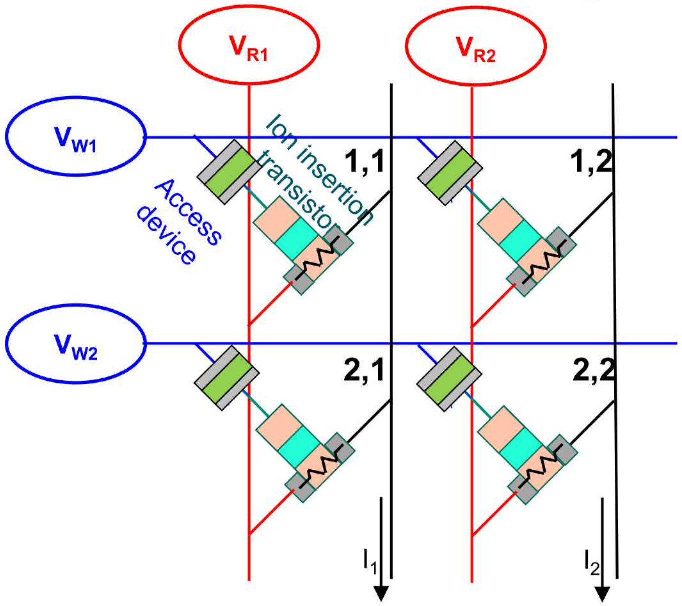
Non-volatile memory that switches at just 6 times the thermal voltage



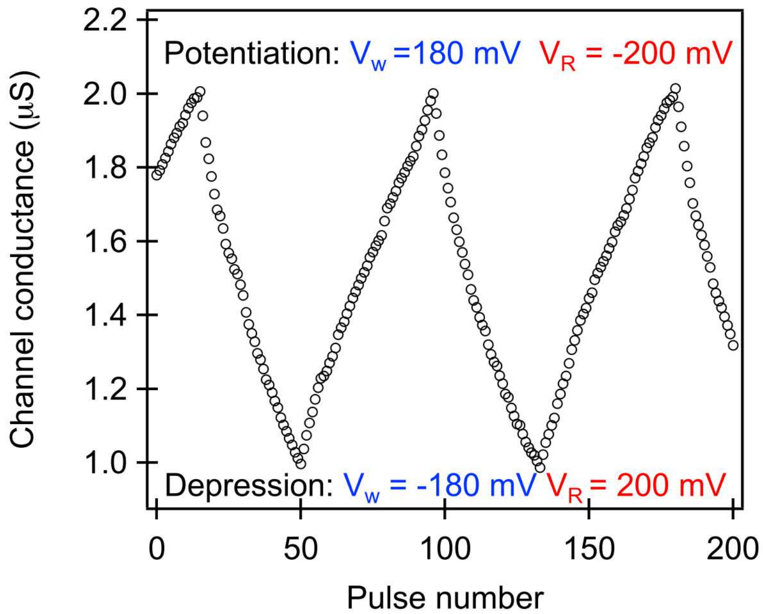


V/2 crossbar programming scheme

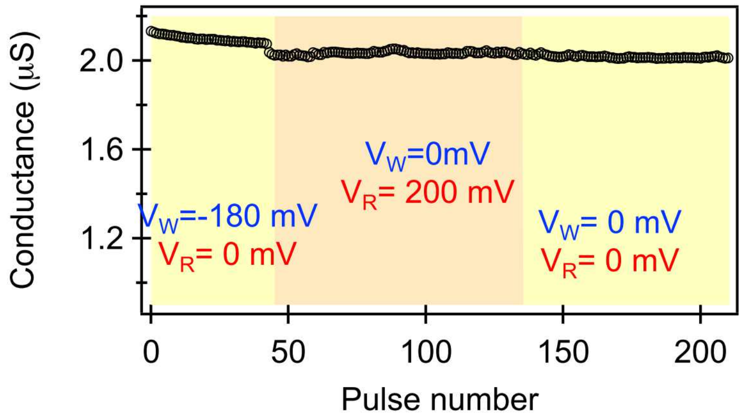
Devices are selected through applying the row and column voltages

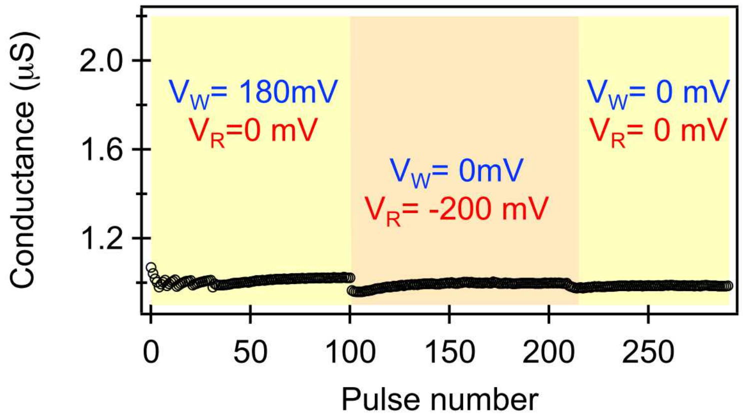


A device is programs when both the row and column is selected



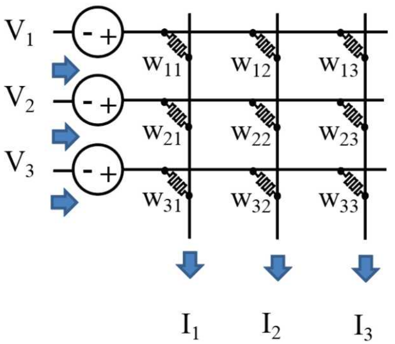
Selecting a row or column will not disturb the device



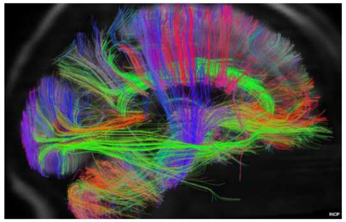


Redox transistors for neuromorphic computing

Analog neuromorphic computing provides lower energy and more parallelism compared to digital computing.

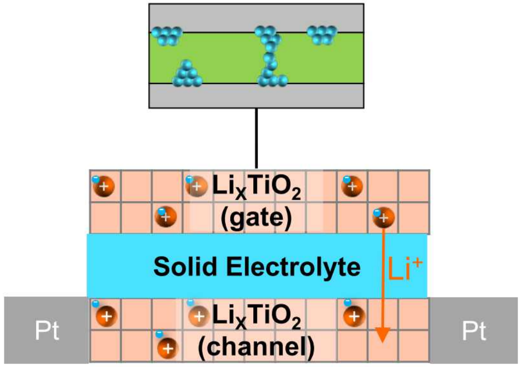


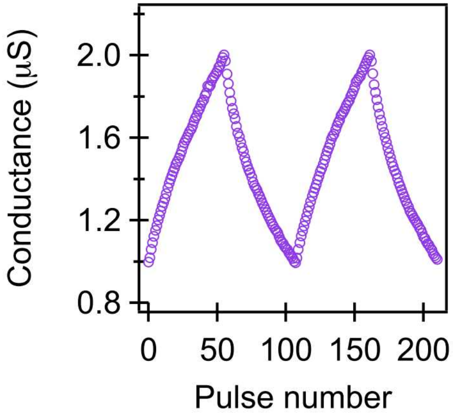
the brain ~10 Hz



100 billion neurons
100 trillion synapses

Electrochemical ion insertion can be used to create highly linear, low voltage non-volatile analog transistors





Acknowledgements

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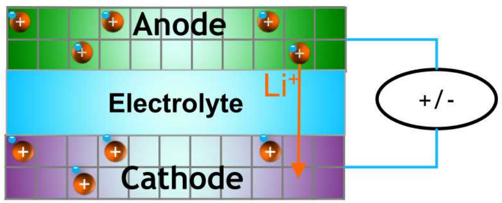
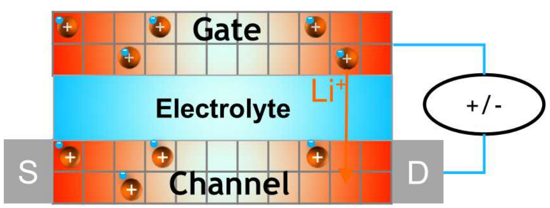
From batteries to redox transistors

Batteries: Maximize open-circuit voltage to store energy

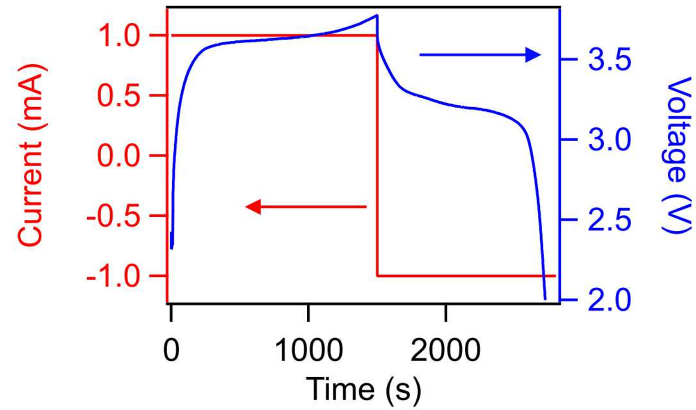


Redox transistors: Minimize open-circuit voltage for array integration



Materials should have a significant change in conductance with a minimal change in write voltage

Batteries: Current control



Redox transistors: Voltage control