Computing using voltage-controlled dynamics and stochasticity in MRAM

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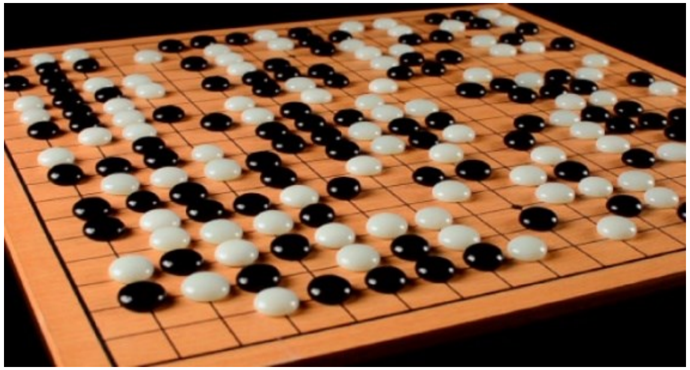
Mondays in Memory (MiM) Webinar Series – July 19, 2021

PERL

Energy Challenges in Electronics

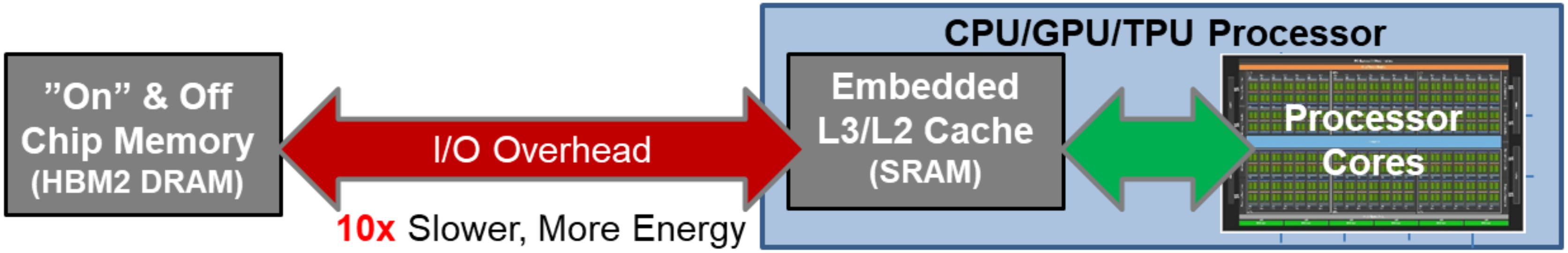

The New York Times
BUSINESS DAY
Google's AlphaGo Defeats Chinese Go Master in Win for A.I.
点击查看本文中文版
By PAUL MOZUR MAY 23, 2017

~20 W

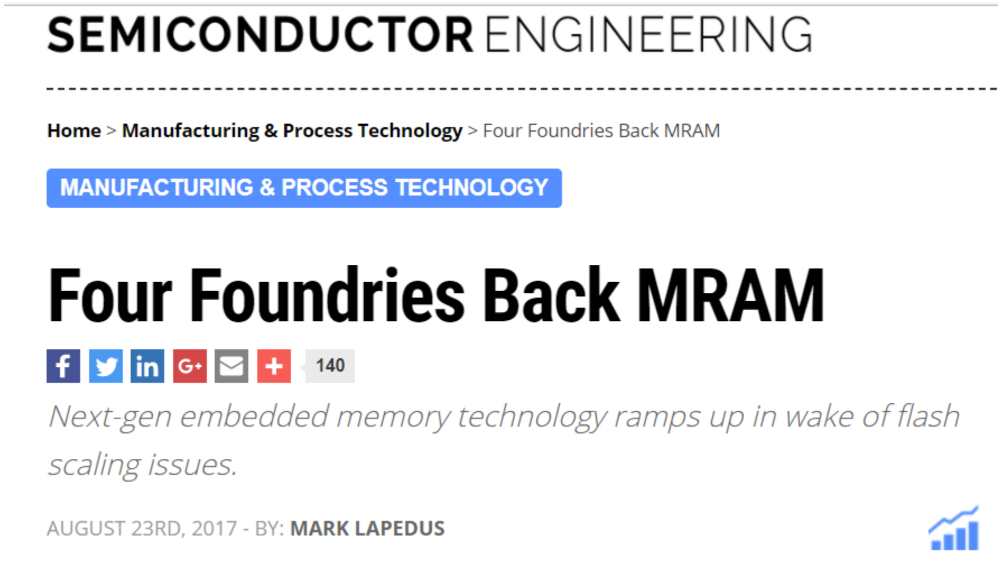


1KW ~ 1MW

= ~200 W x (4…5000 TPUs)



The Future of Computing is Memory-Centric



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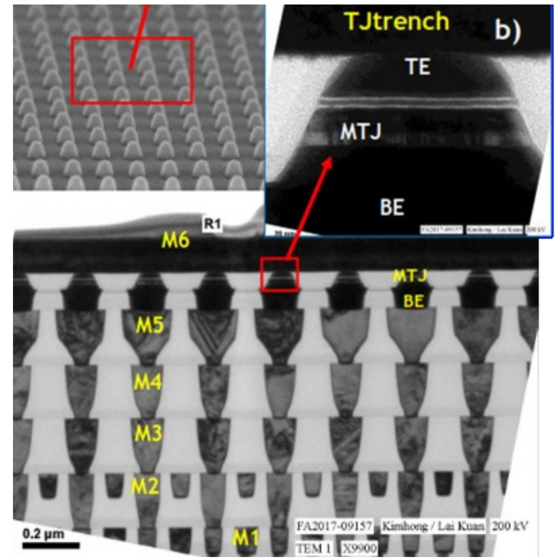
MANUFACTURING & PROCESS TECHNOLOGY

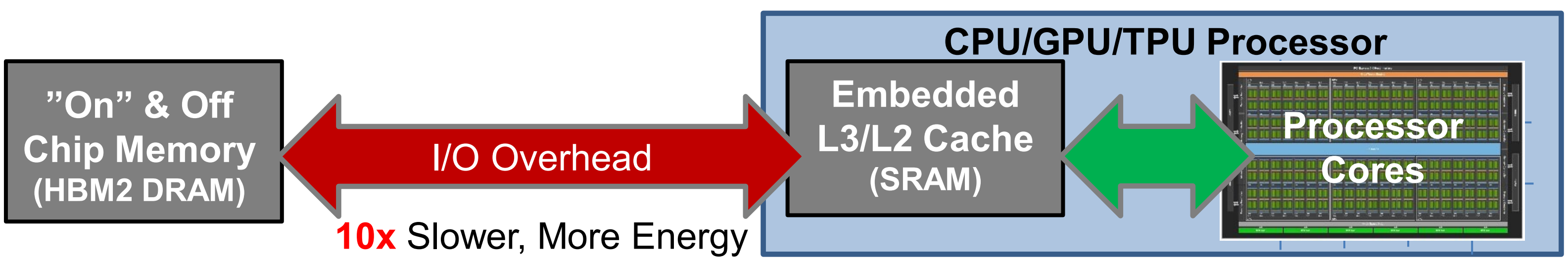
Four Foundries Back MRAM

140

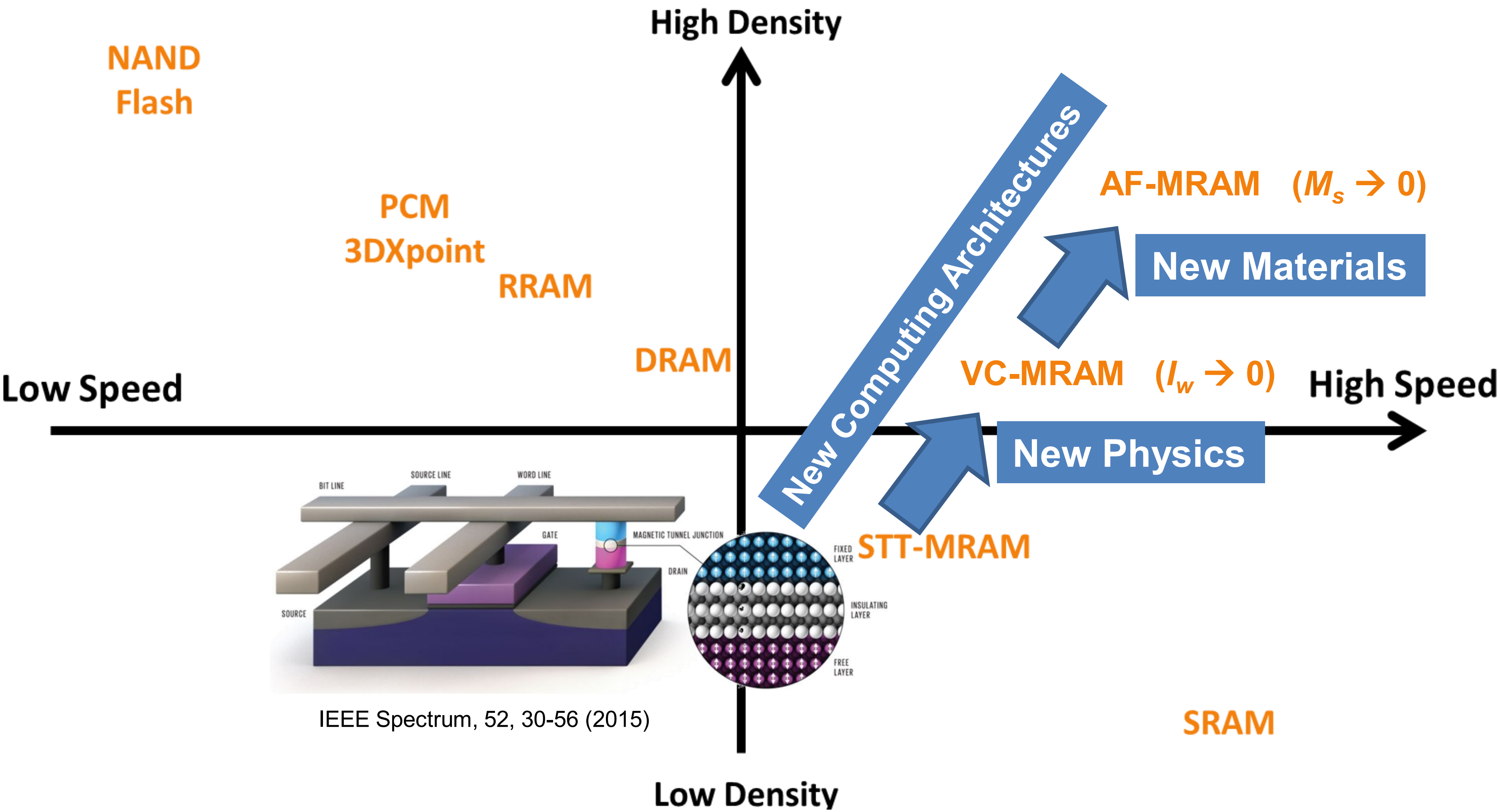
Next-gen embedded memory technology ramps up in wake of flash scaling issues.

AUGUST 23RD, 2017 - BY: **MARK LAPEDUS**



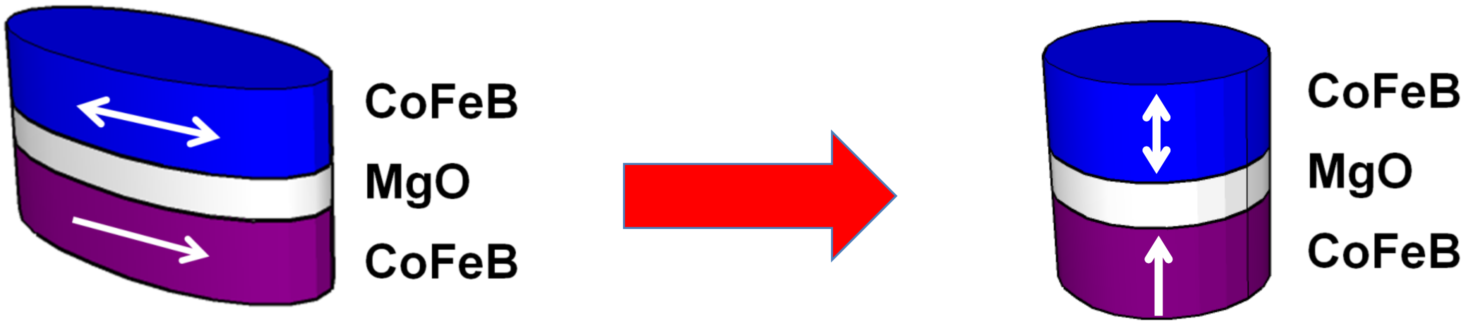


Competitive Memory Landscape



IEEE Spectrum, 52, 30-56 (2015)
Journal of Magnetism and Magnetic Materials, 521, 167506 (2021)

Interfacial Voltage-Controlled Magnetic Anisotropy



In-Plane **Perpendicular**

$$K_{eff}(V) = \frac{M_s H_{k,eff}(V)}{2} = \frac{K_i - \xi \dfrac{V}{d_{MgO}}}{t_{CoFeB}} - 2\pi M_s^2$$

Voltage-Controlled Magnetic Anisotropy (VCMA)

$$\xi\ [\mathrm{fJ/V\text{-}m}] = \frac{\text{Change of Surface Anisotropy } [\mu\mathrm{J/m^2}]}{\text{Electric Field } [\mathrm{V/nm}]}$$

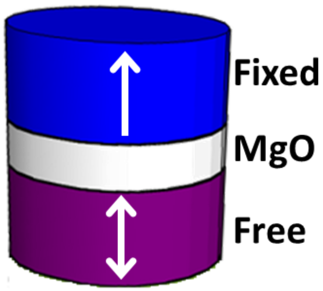
Ikeda et al. Nature Materials, 9, 721 (2010)
Worledge et al. Appl. Phys. Lett., 98, 022501 (2011)
Khalili et al. Appl. Phys. Lett., 98, 112507 (2011)
Maruyama et al. Nature Nano, 4, 158 (2009)

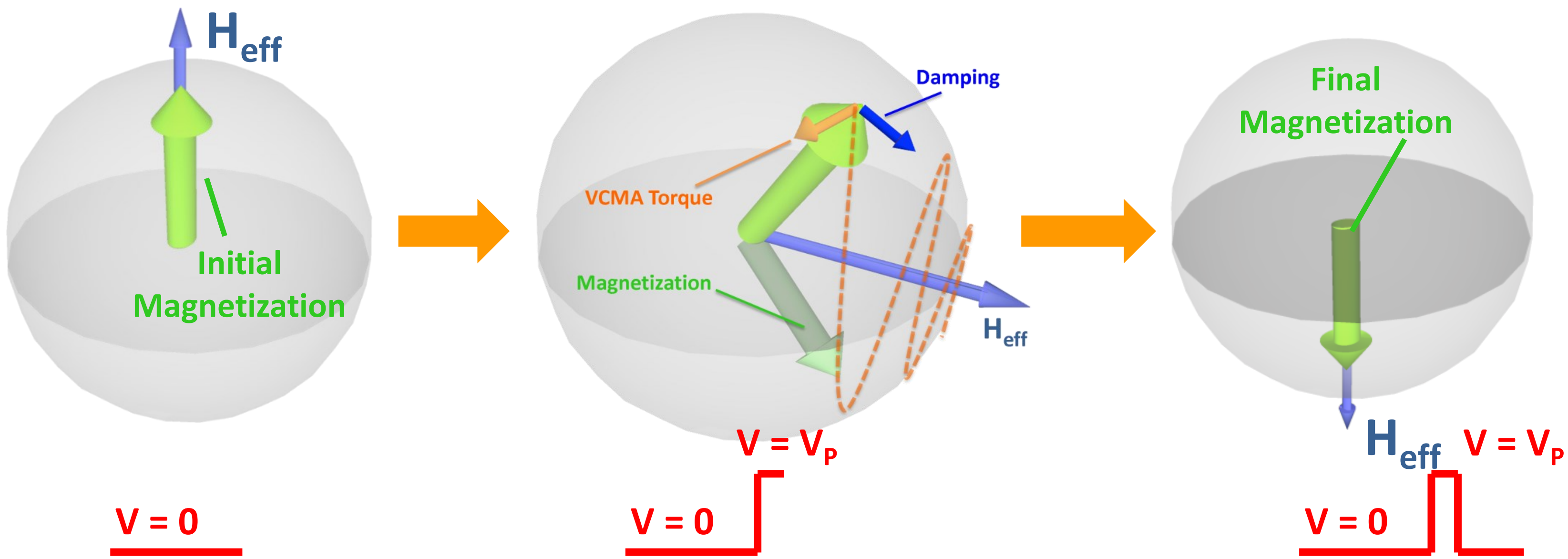
VCMA-Induced Switching

- Electric-field-controlled MTJ
  - Read-out via Tunnel Magnetoresistance (TMR)
  - Non-deterministic (i.e. toggle) writing
    - Requires pre-read step

      Lee et al., IEEE Trans. Magnetics 51, 3400507 (2015)
    - Control of FMR distributions and/or write verification

      Lee et al., IEEE Trans. VLSI Systems 25, 2027 (2017)

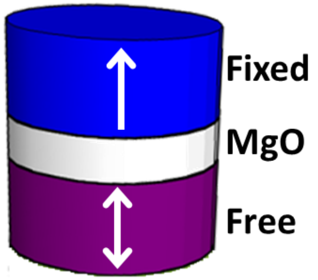


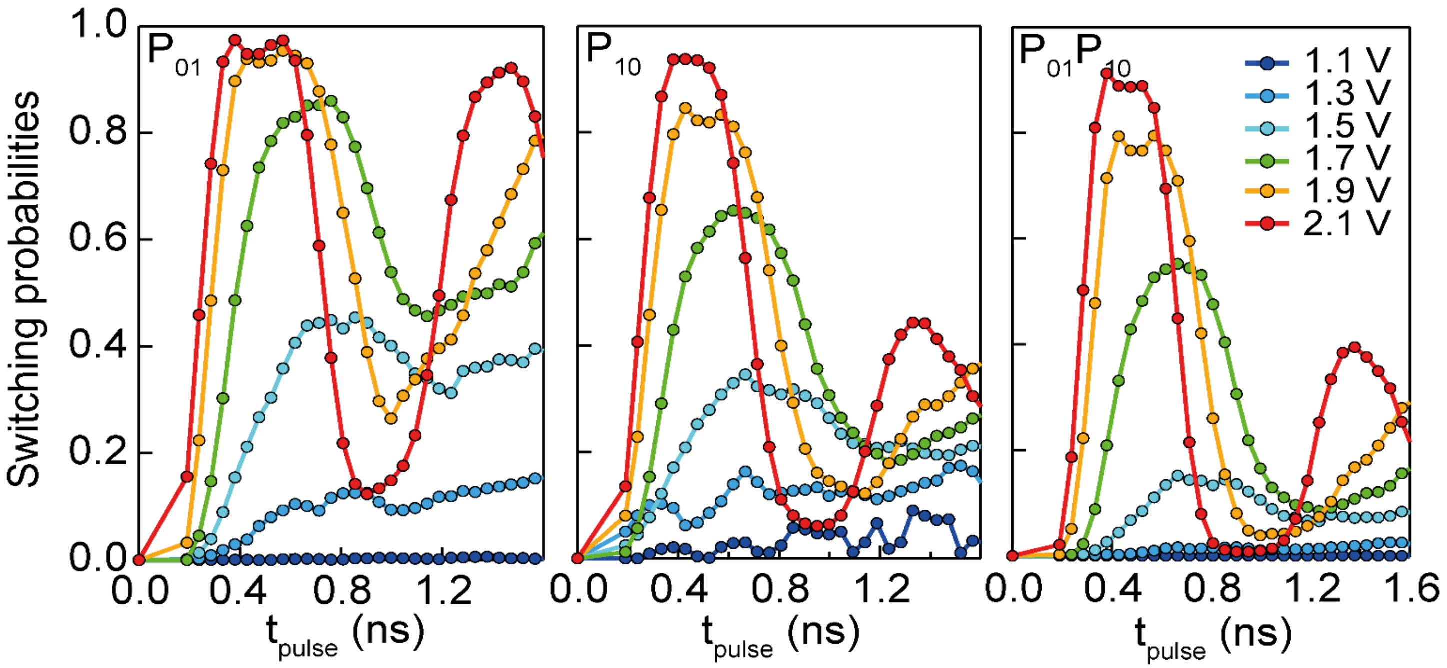


Khalili et al. US Patents 8,841,739; 9,129,691; 9,324,403; 9,355,699
Alzate, Khalili et al. IEDM, 29.5.1 (2012)
Shiota et al. Nature Materials, 11, 39 (2012)
Kanai et al. Applied Physics Letters, 101, 122403 (2012)

VCMA-Induced Switching

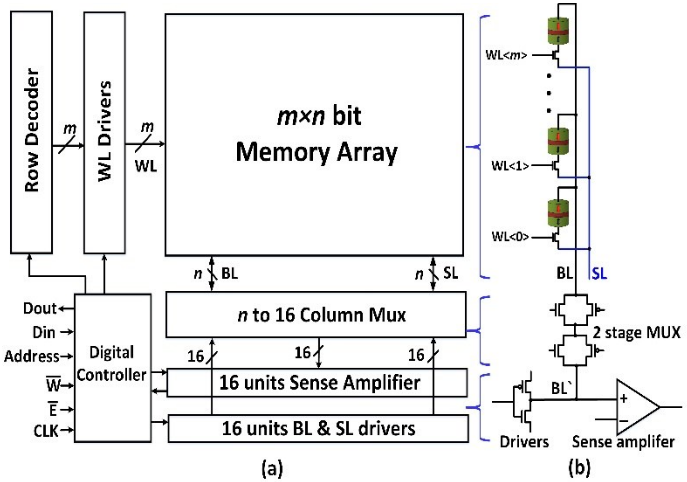
- VCMA-driven writing in perpendicular bits with TMR readout
- Bit diameter: 50 nm
- Write energy < 10 fJ/bit

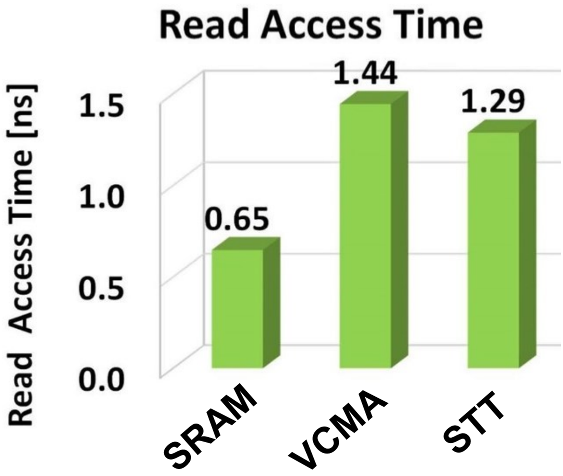


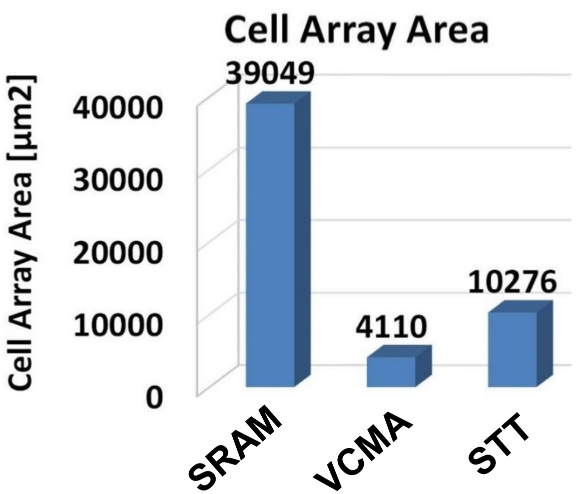


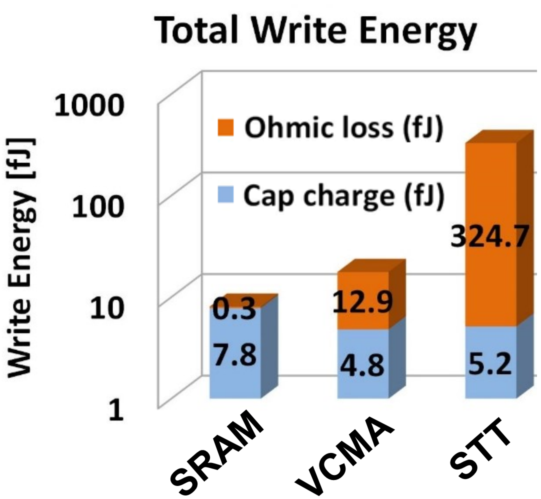
Grezes, Khalili et al. Applied Physics Letters 108, 012403 (2016)
Khalili et al., IEEE Trans. Magnetics 51, 3401507 (2015)

Array-Level Comparison (256 Kb, 28 nm)



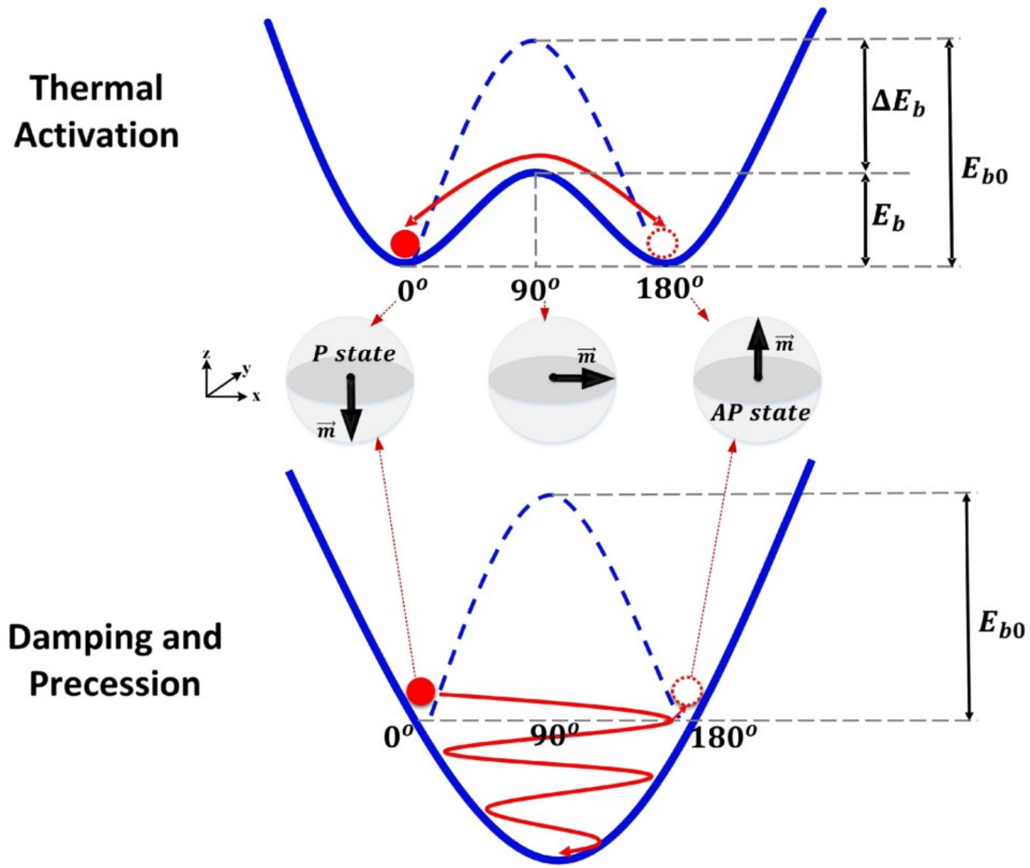






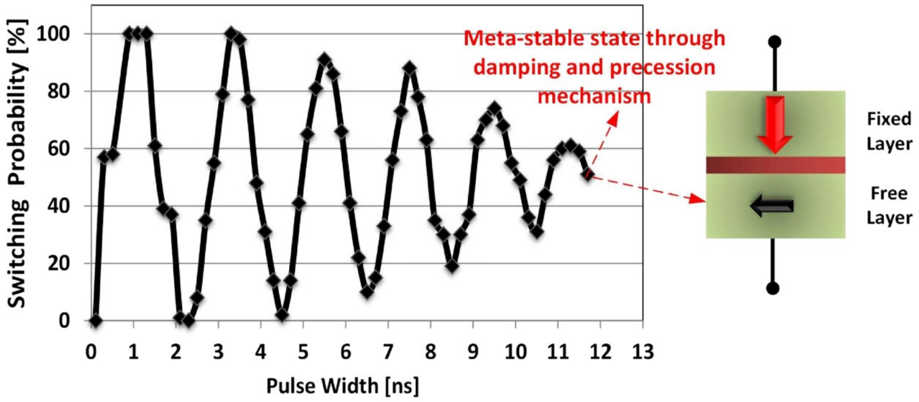
Lee, Khalili et al. IEEE Magnetics Letters 8, 4305905 (2017)

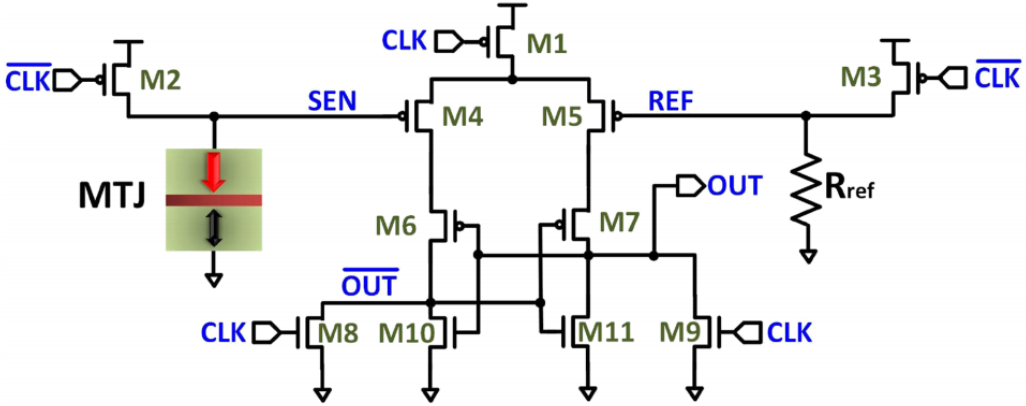
VCMA-based Random Number Generation



Lee, Khalili et al., AIP Advances 7, 055934 (2017)

VCMA-based Random Number Generation





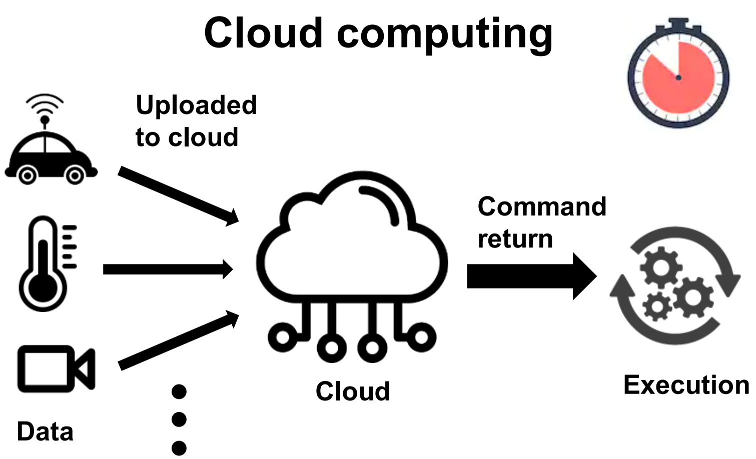
Area and performance of 64×64 MTJs Array based multi-bits-MRNG (45 nm technology node).

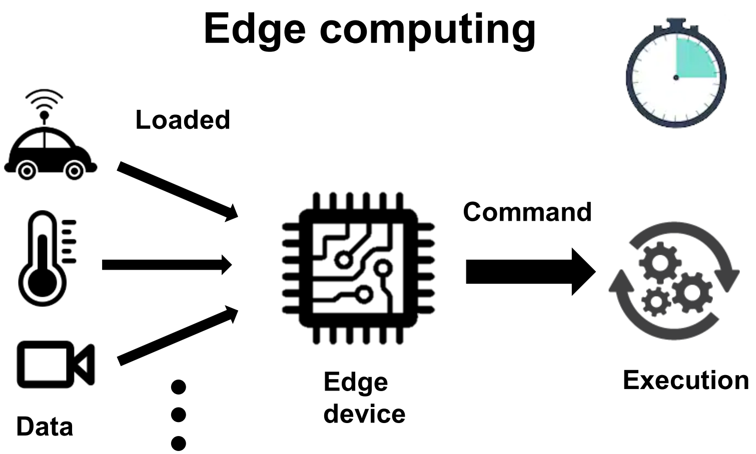
Performance	Value
Area	139.96 μm^2
Throughput	29.6 Gbps
Energy	311 fJ/bit

Lee, Khalili et al., AIP Advances 7, 055934 (2017)

Machine Learning (ML) at the Edge

- Edge ML advantages:
  - Low latency (no need for Cloud connection)
  - Better security
- Edge ML neural network requirements:
  - Low power dissipation
  - Small area





Conventional Binary Arithmetic Computing → Stochastic Computing

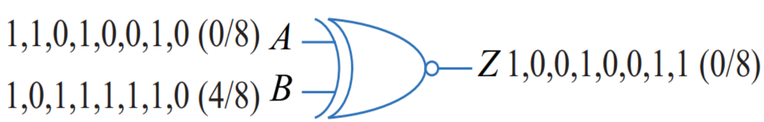
Stochastic Computing (SC)

- Stochastic bit-streams → decimal number
  - Fewer logic gates for basic arithmetic operations
    → Low energy dissipation, compact circuits
  - Tunability of accuracy by length of bit-streams
    → Accuracy can be traded off for energy savings

Mapping:

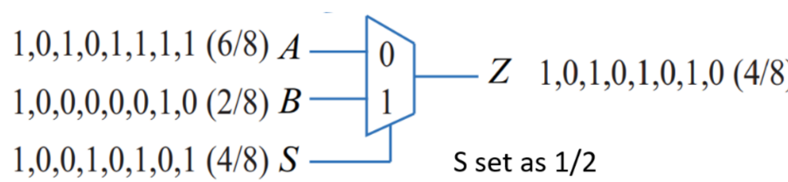
$$X = 2p_X - 1, or\ p_X = \frac{1}{2}(X+1), -1 < X < 1$$

Multiplication (XNOR):



$$\begin{gathered} z = 2P_Z - 1 \\ = (2P_A - 1)(2P_B - 1) \\ = ab \end{gathered}$$

Addition (MUX):

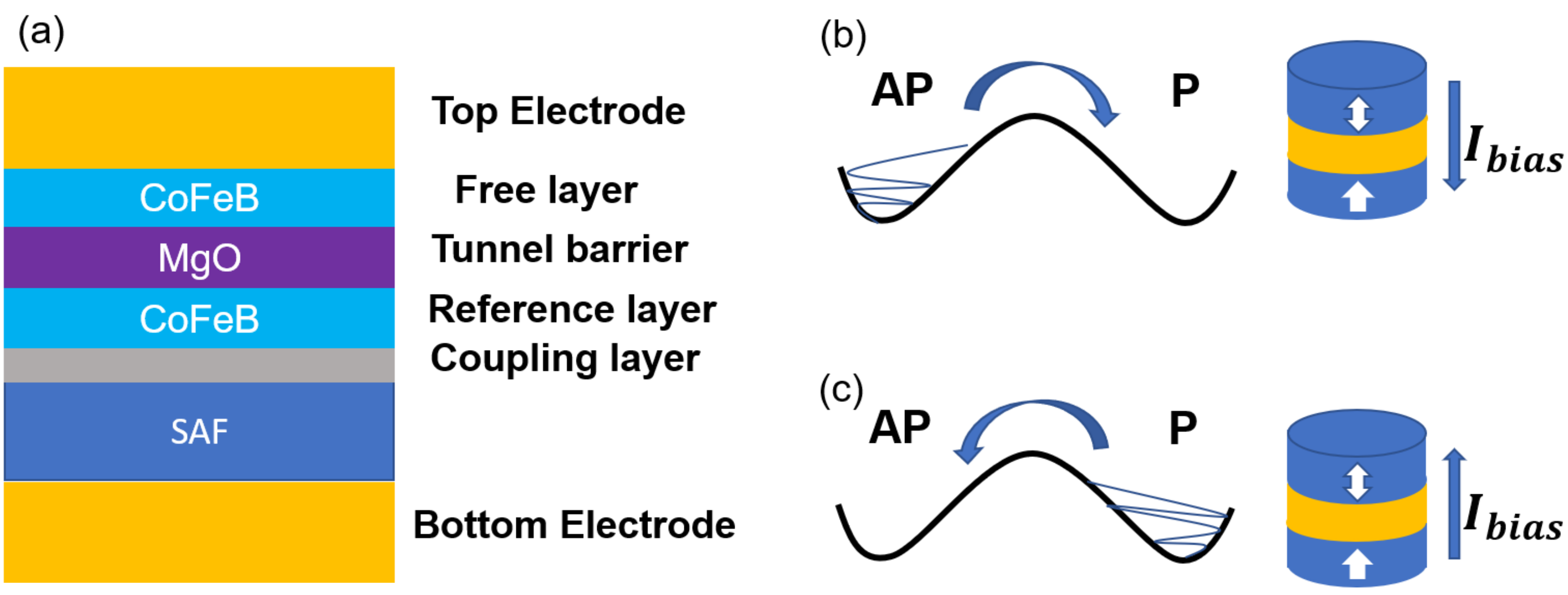


$$\begin{gathered} z = 2P_Z - 1 \\ = \frac{1}{2}[(2P_A - 1) + (2P_B - 1)] = \frac{a+b}{2} \end{gathered}$$

Y. Shao, P. Khalili Amiri et al., IEEE Magnetics Letters 12, 4501005 (2021)

Tunable true random number generators (TRNGs)

- Magnetic tunnel junctions (MTJs) with 50 nm diameter designed for TRNGs
  - Stochastically switching under room temperature
  - Tuned by spin transfer torque (STT) with ultralow current of < 5 μA (= 0.25 MA cm^{-2})



Y. Shao, P. Khalili Amiri et al., IEEE Magnetics Letters 12, 4501005 (2021)

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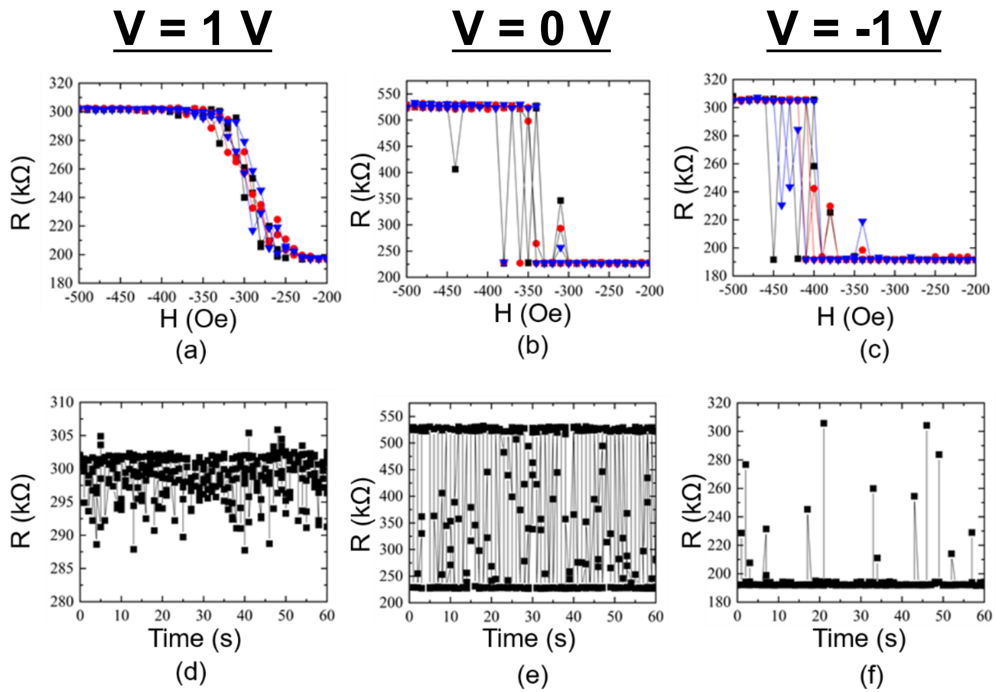
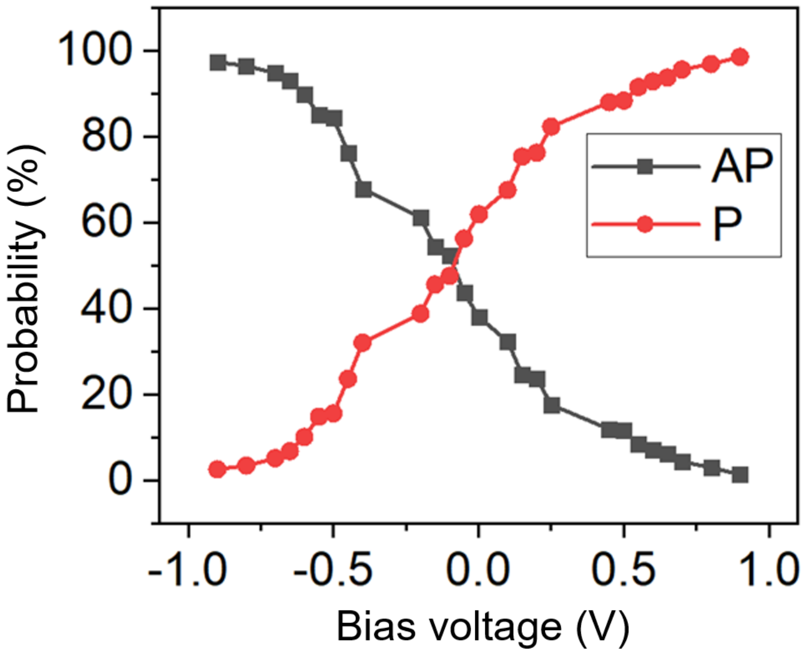
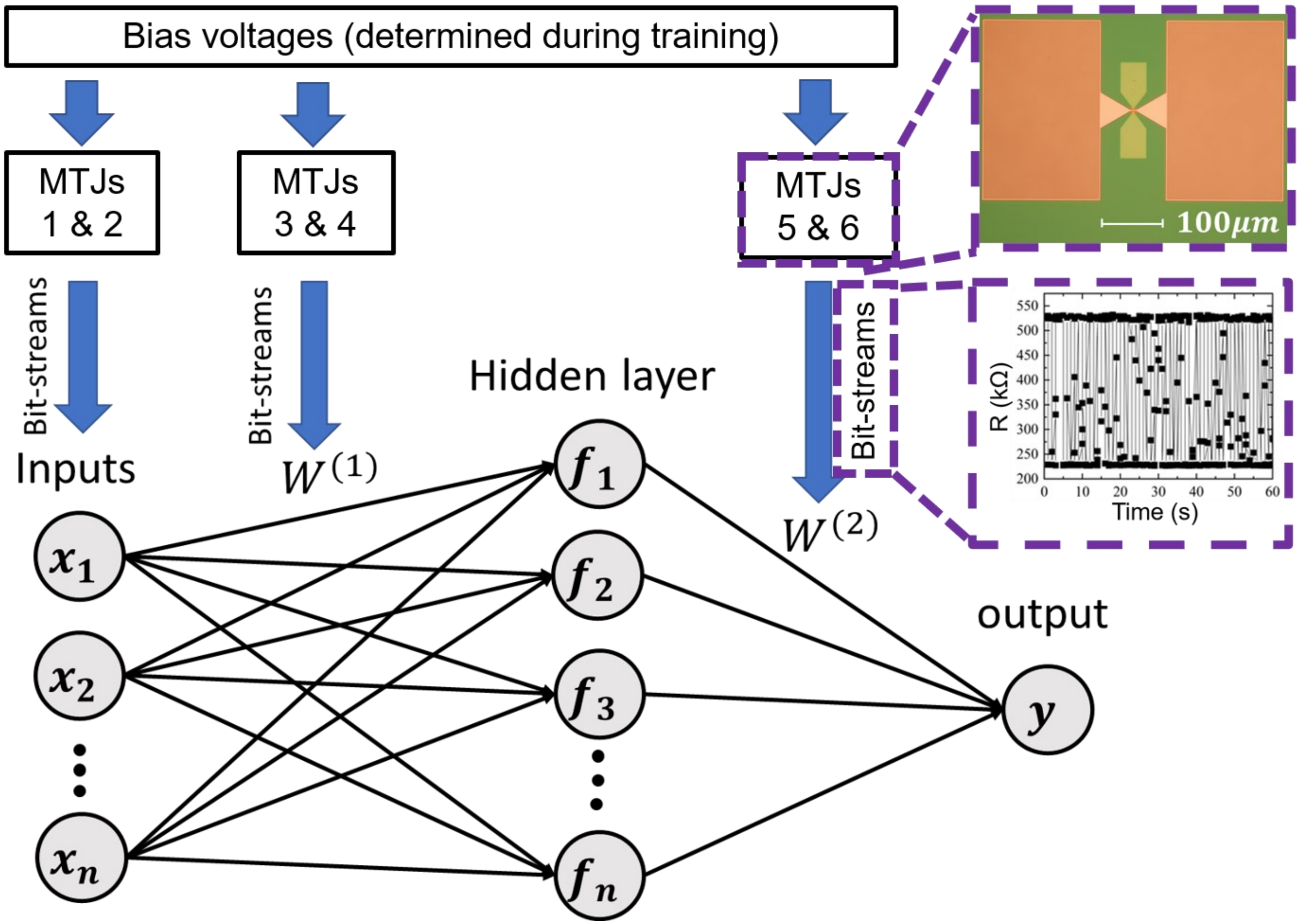




Y. Shao, P. Khalili Amiri et al., IEEE Magnetics Letters 12, 4501005 (2021)

Implementation of Artificial Neural Networks (ANNs)

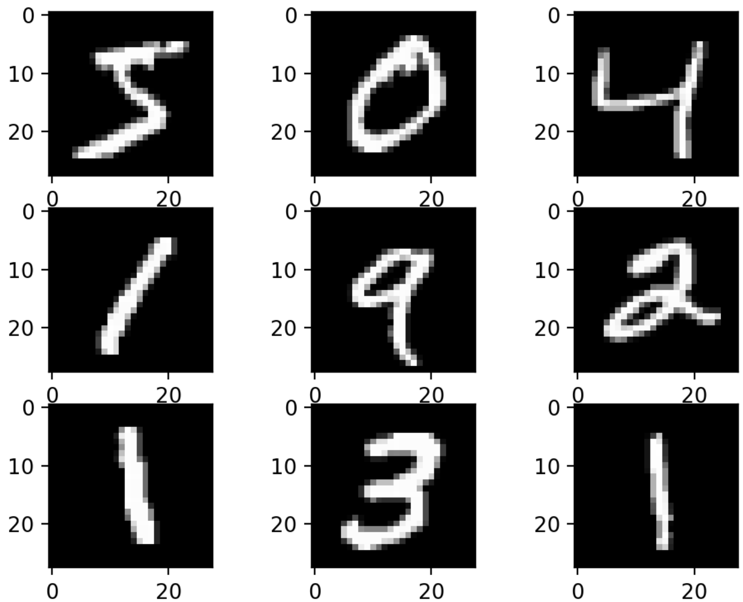
- Data from 6 MTJs were used to generate stochastic bit-streams for inference
  - 3 bit-stream sets were constructed by XNOR of each two MTJ outputs

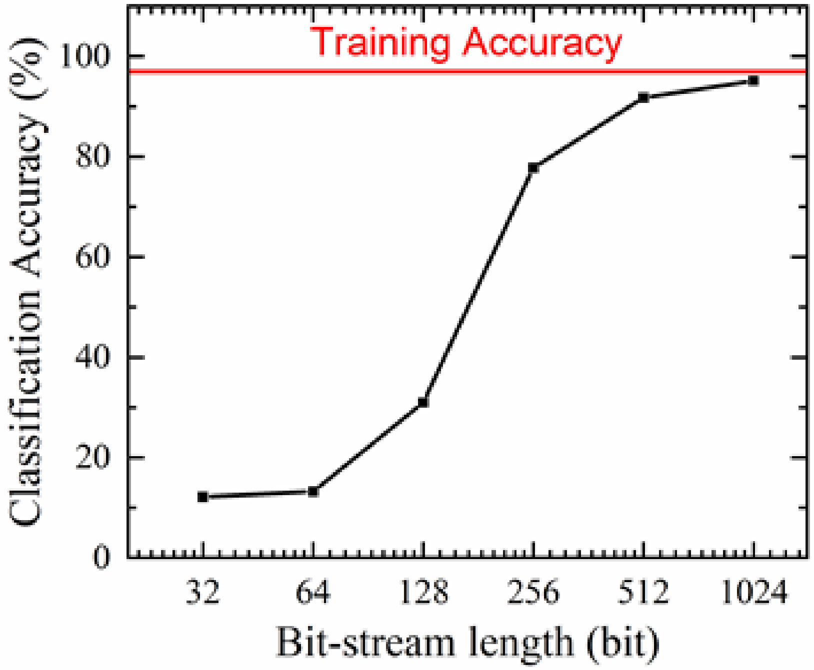


Y. Shao, P. Khalili Amiri et al., IEEE Magnetics Letters 12, 4501005 (2021)

Inference on MNIST dataset and results

- SC-ANNs were trained and evaluated on handwritten digits from MNIST dataset
  - > 90% accuracy with bit-stream length > 512 bits
  - Longer bit-streams provide better accuracy

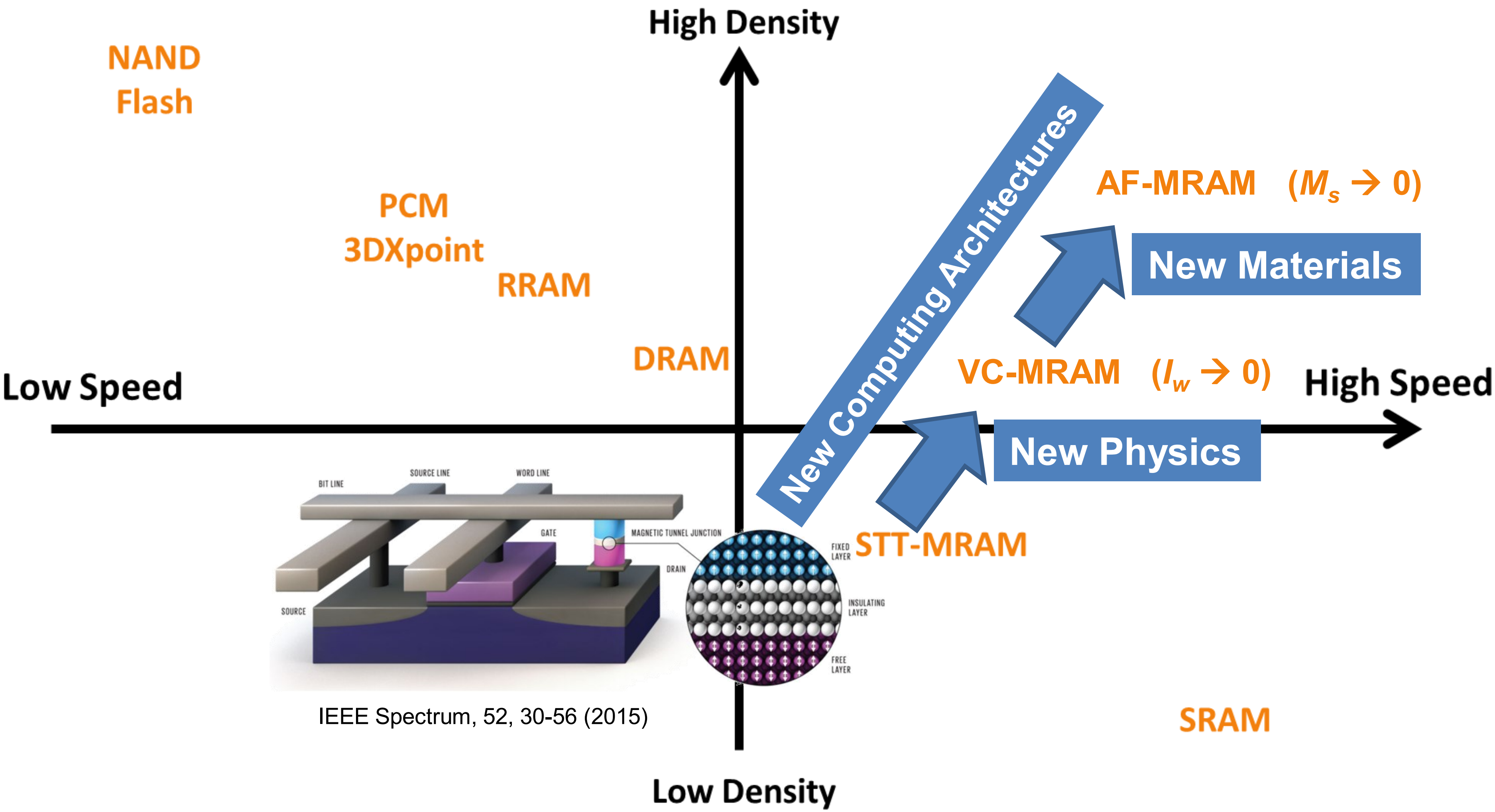




- Accuracy can be adjusted in real time (traded off against energy), by changing the length of the bit-streams.

Y. Shao, P. Khalili Amiri et al., IEEE Magnetics Letters 12, 4501005 (2021)

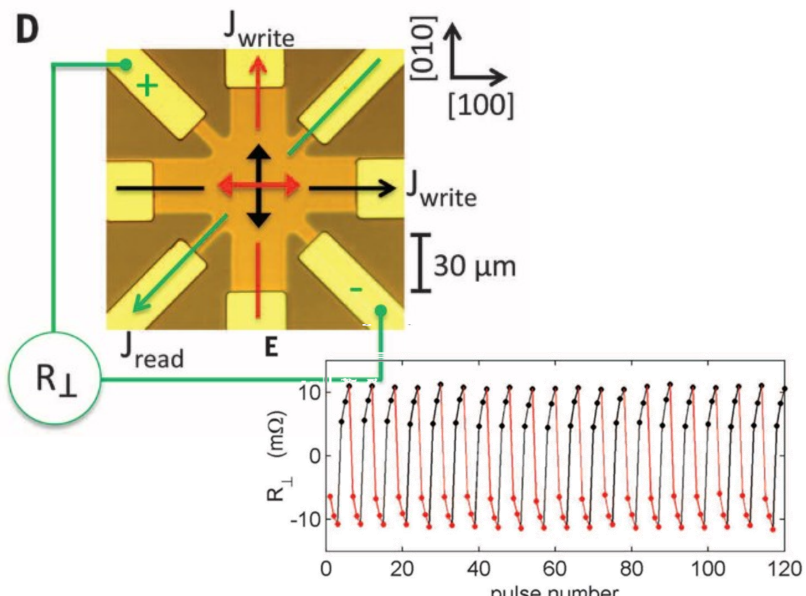
Competitive Memory Landscape



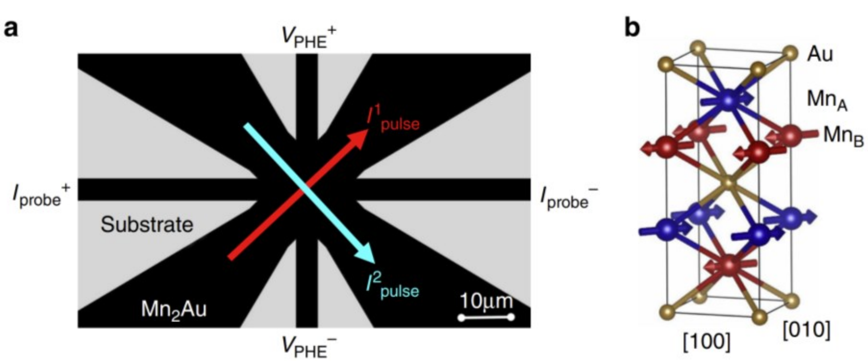
IEEE Spectrum, 52, 30-56 (2015)

Background: SOT Switching Experiments in AFMs

Bulk SOT (CuMnAs, Mn_2Au)

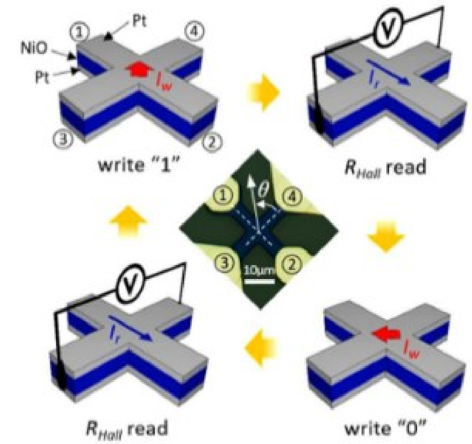


Wadley et al. Science 351, 587 (2016)
Grzybowski et al. Physical Review Letters 118, 057701 (2017)
Godinho et al. Nature Communications 9, 4686 (2018)

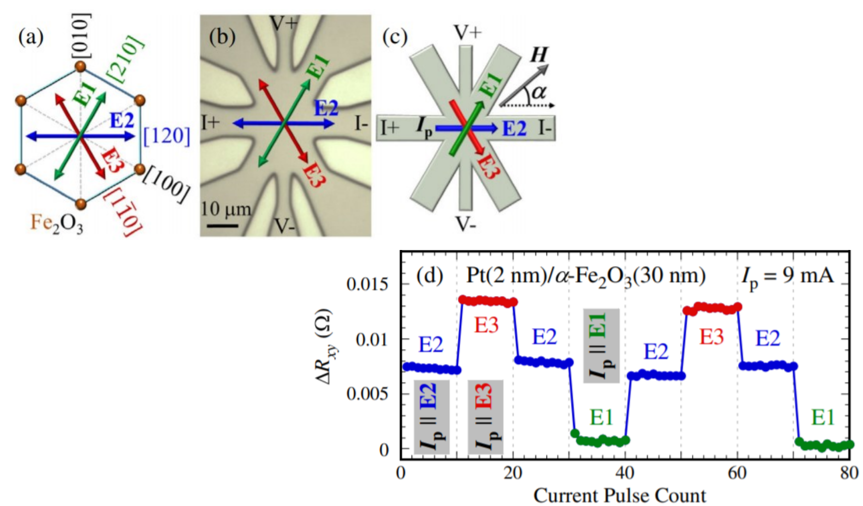


Bodnar et al. Nature Communications 9, 348 (2018)

Interfacial SOT (Pt/NiO, Pt/α-Fe_2O_3)

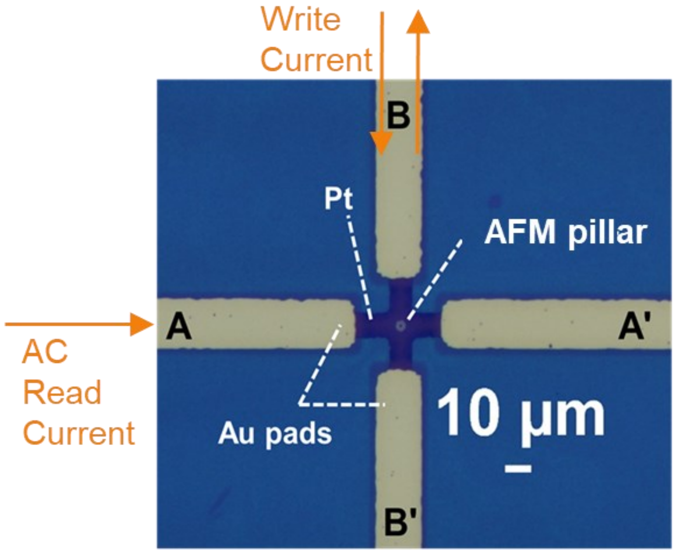


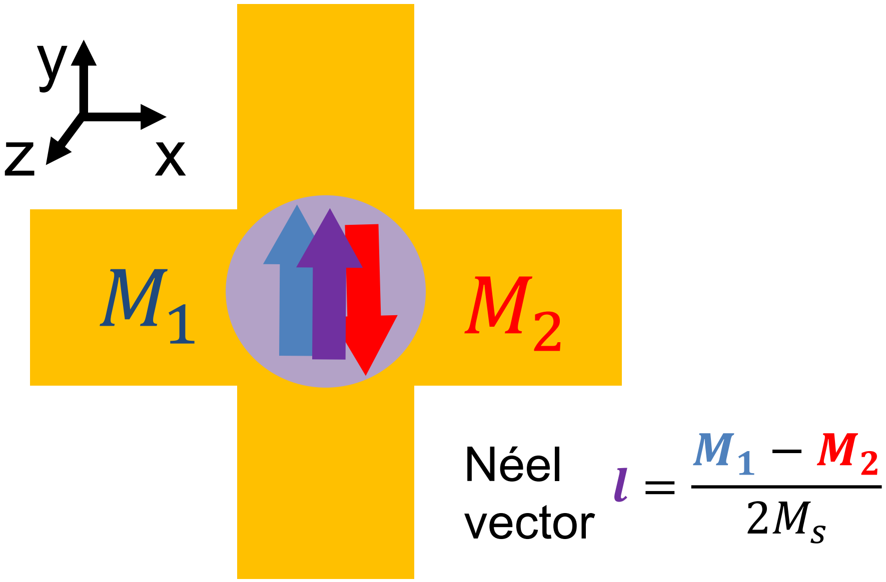
Moriyama et al. Scientific Reports 8,14167 (2018)

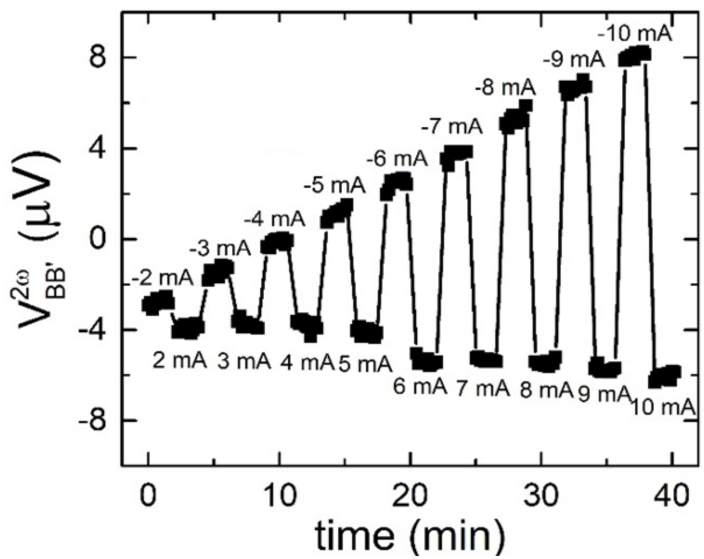


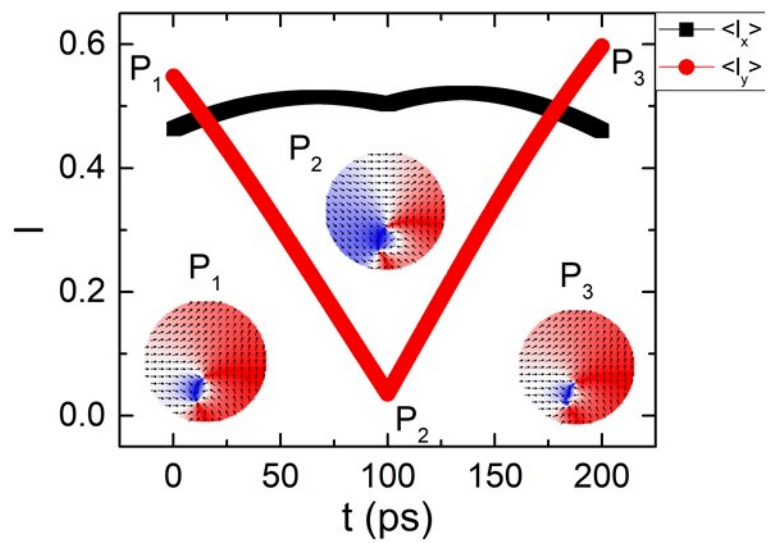
Cheng et al. Physical Review Letters 124, 027202 (2020)

Current-Induced Switching in Pt/PtMn Devices



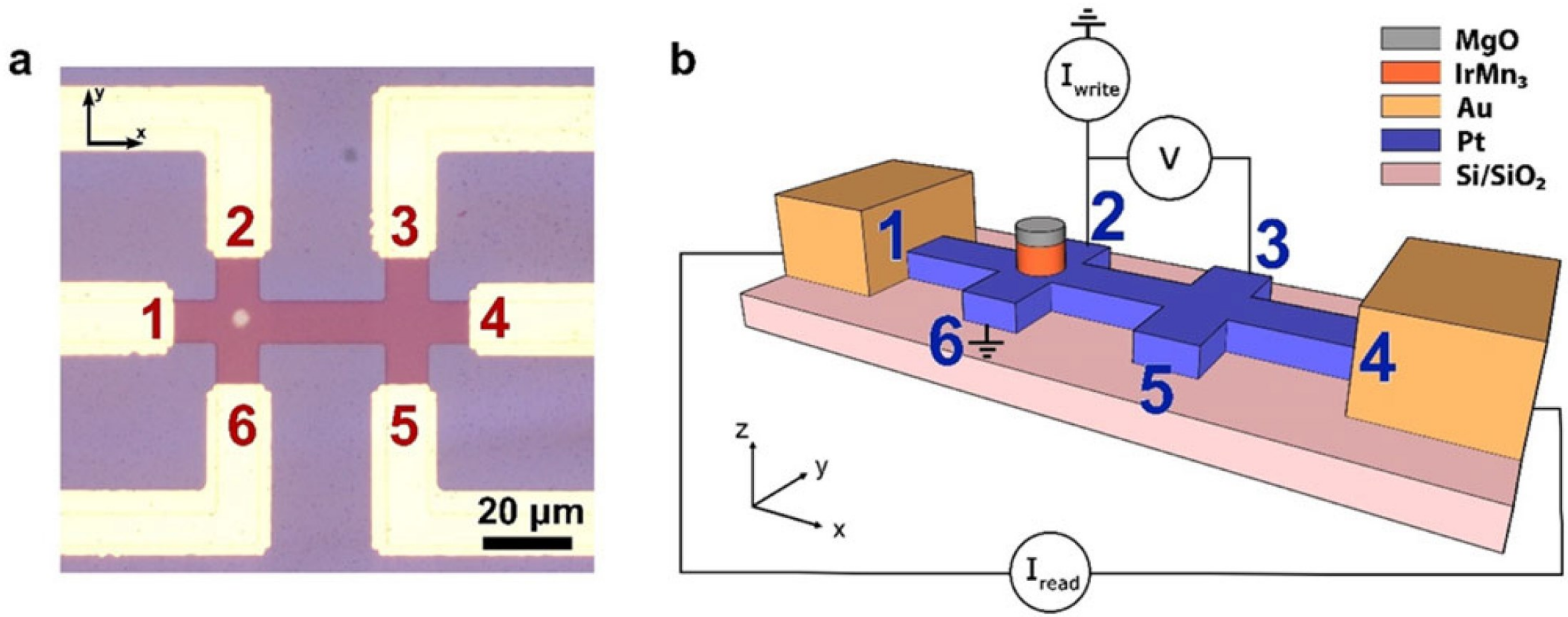






J. Shi, V. Lopez-Dominguez, P. Khalili Amiri et al., Nature Electronics, 3, 92 (2020)

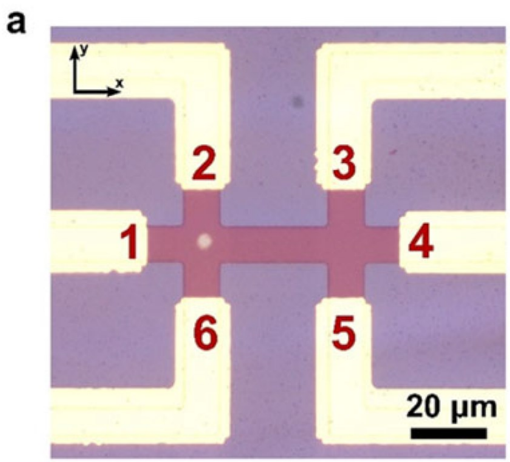
Differential Measurements of Switching in Pt/$IrMn_3$

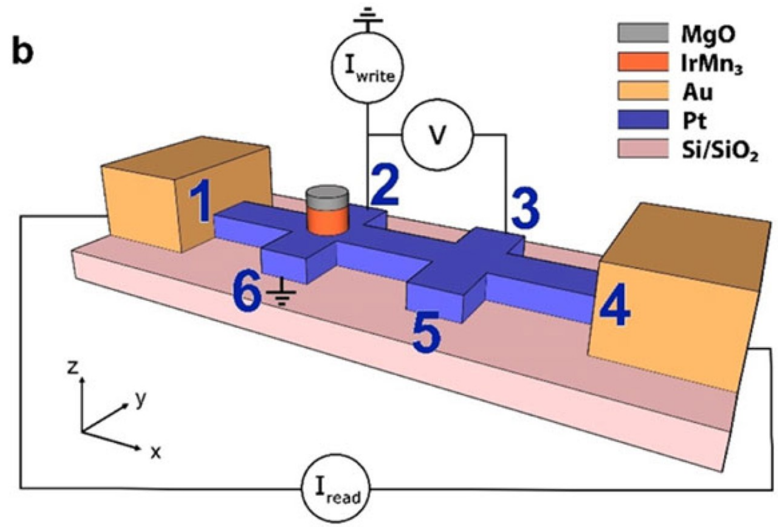


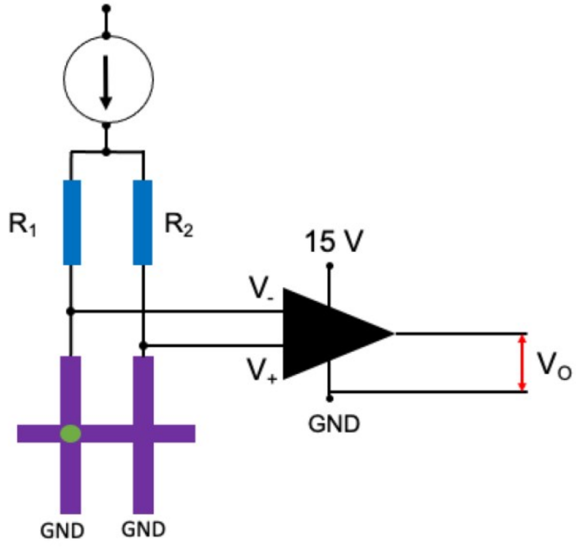
- 6 - terminal measurement geometry:
  - Allows for both 180˚ and 90˚ degree switching configurations
  - In-situ reference measurements on cross without $IrMn_3$
  - Differential measurements (subtraction of $IrMn_3$ and Pt signals)

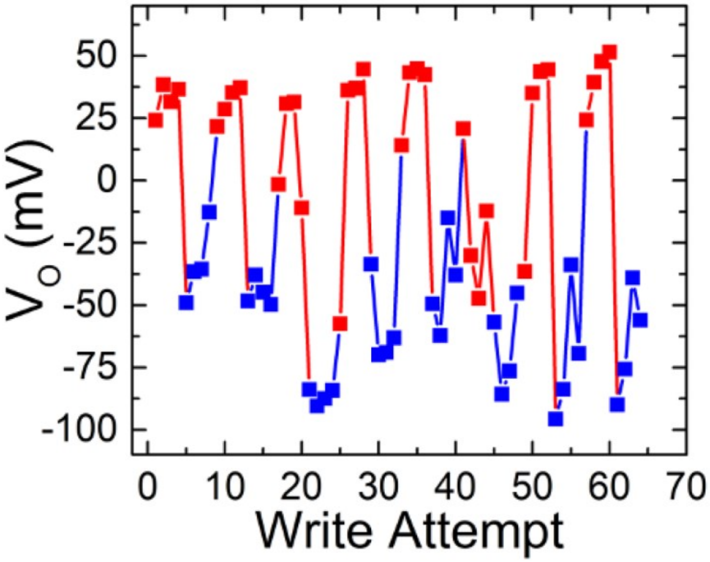
S. Arpaci, V. Lopez-Dominguez, G. Finocchio, P. Khalili Amiri et al., Nature Communications, 12, 3828 (2021)

Switching in Pt/IrMn$_3$ Pillars: Active Readout



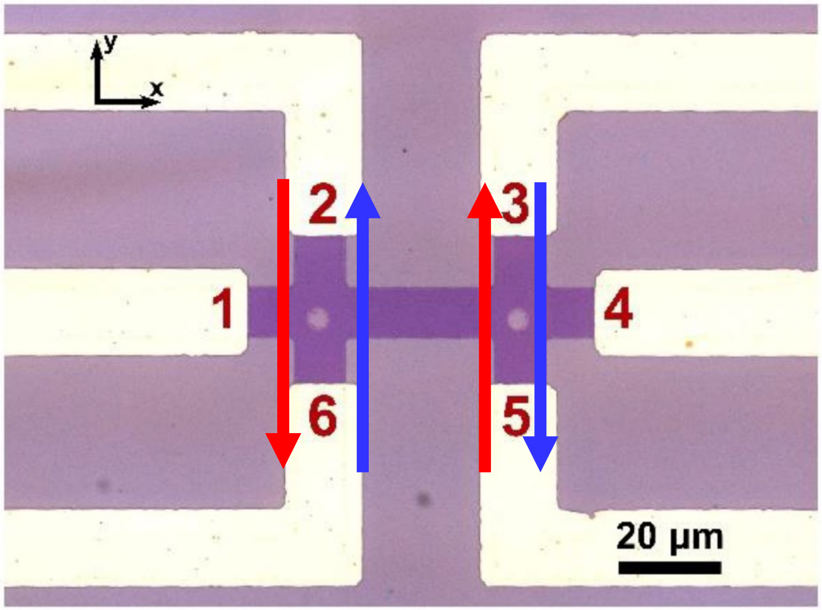


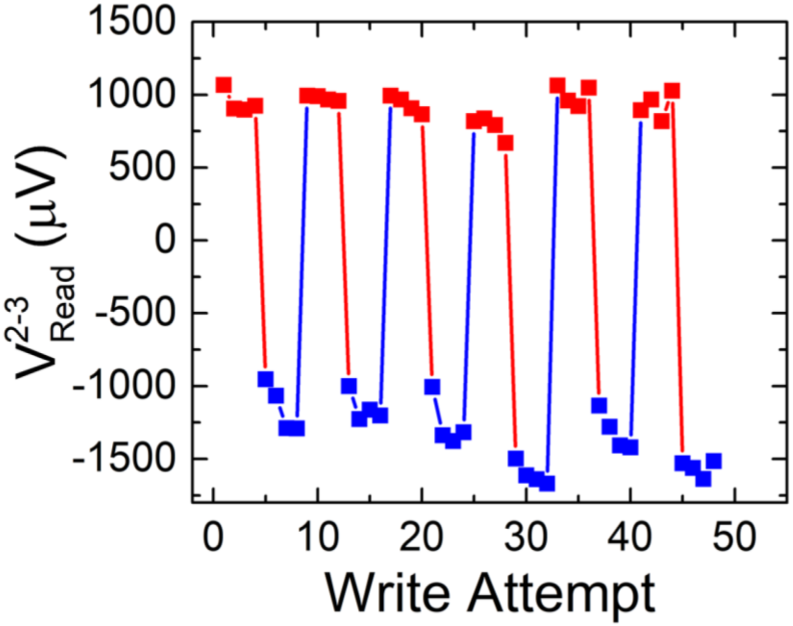




S. Arpaci, V. Lopez-Dominguez, G. Finocchio, P. Khalili Amiri et al., Nature Communications, 12, 3828 (2021)

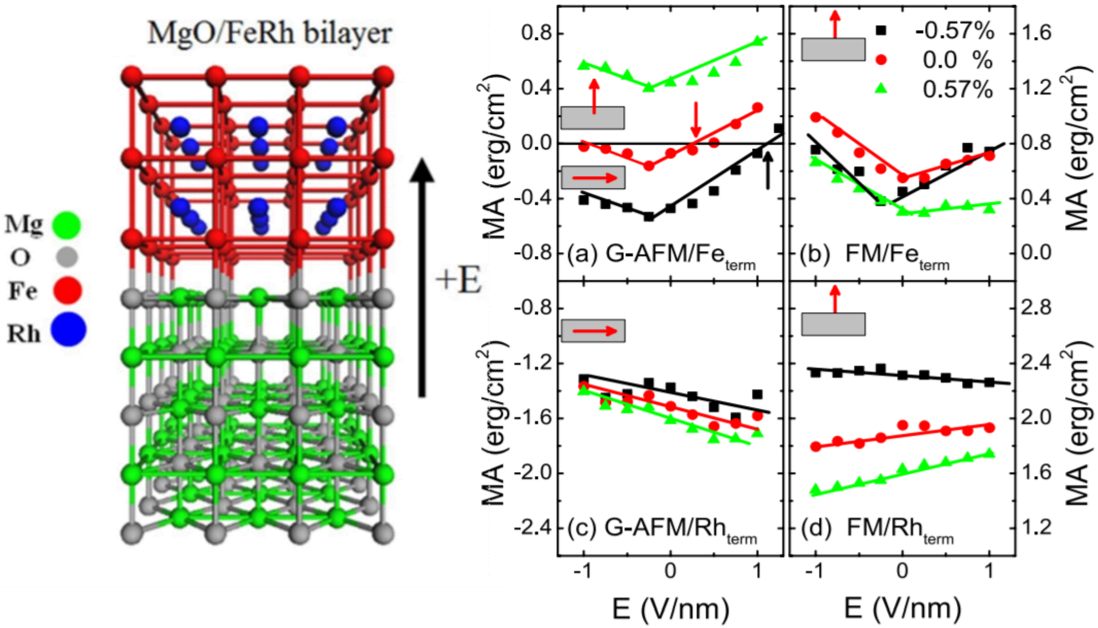
Differential Switching in Pt/$IrMn_3$ Double-Pillars



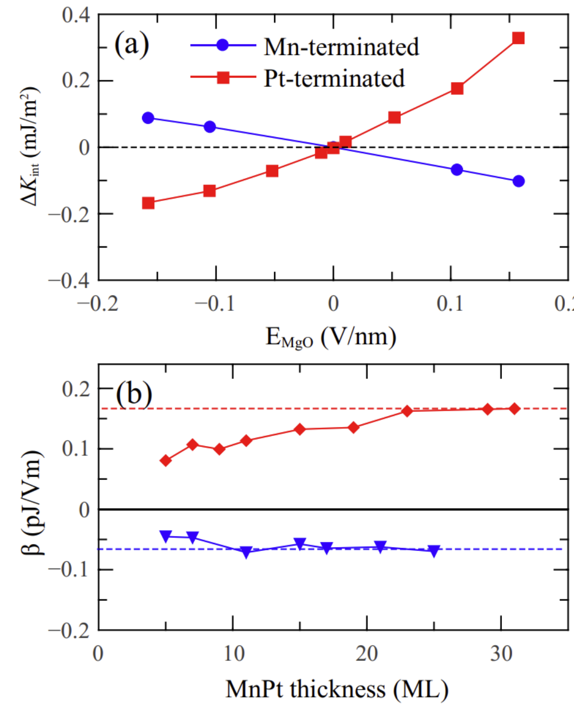


S. Arpaci, V. Lopez-Dominguez, G. Finocchio, P. Khalili Amiri et al., Nature Communications, 12, 3828 (2021)

Voltage Control of Anti-ferromagnets



Zheng et al., Scientific Reports 7, 5366 (2017)

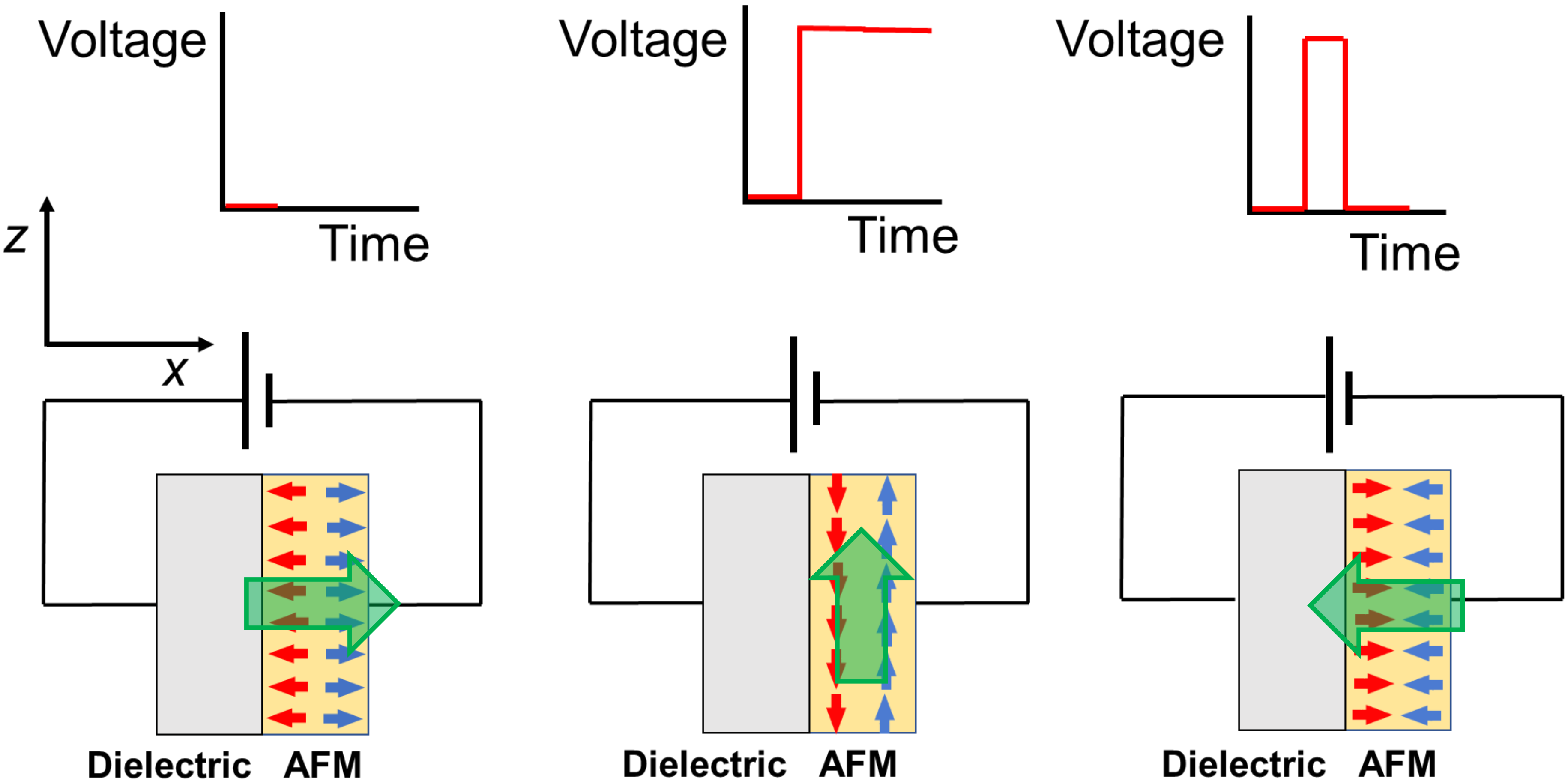


Chang et al., Phys. Rev. Materials 5, 054406 (2021)

Voltage-Controlled Magnetic Anisotropy (VCMA) = 100 ~ 300 fJ/Vm

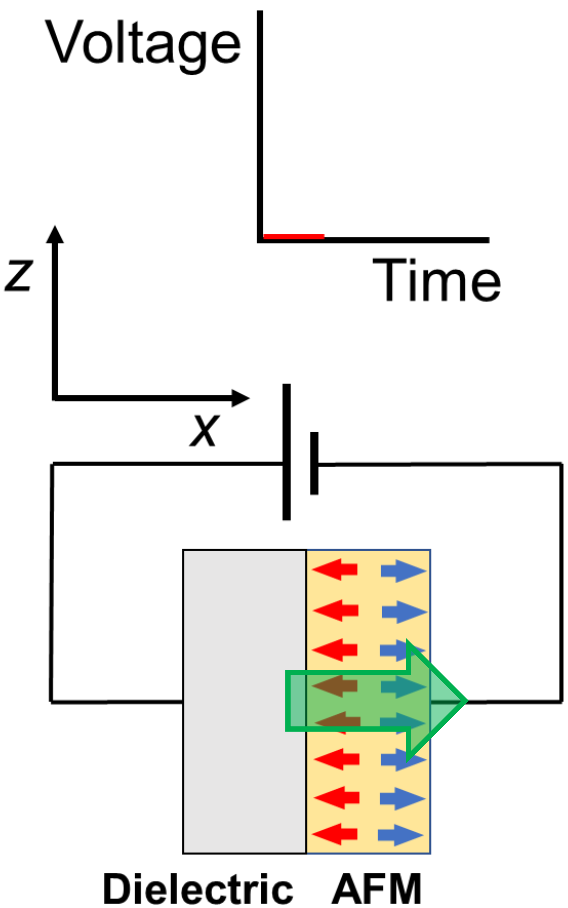
$$\xi\ [\mathrm{fJ/V\text{-}m}] = \frac{\text{Change of Surface Anisotropy } [\mu\mathrm{J/m^2}]}{\text{Electric Field } [\mathrm{V/nm}]}$$

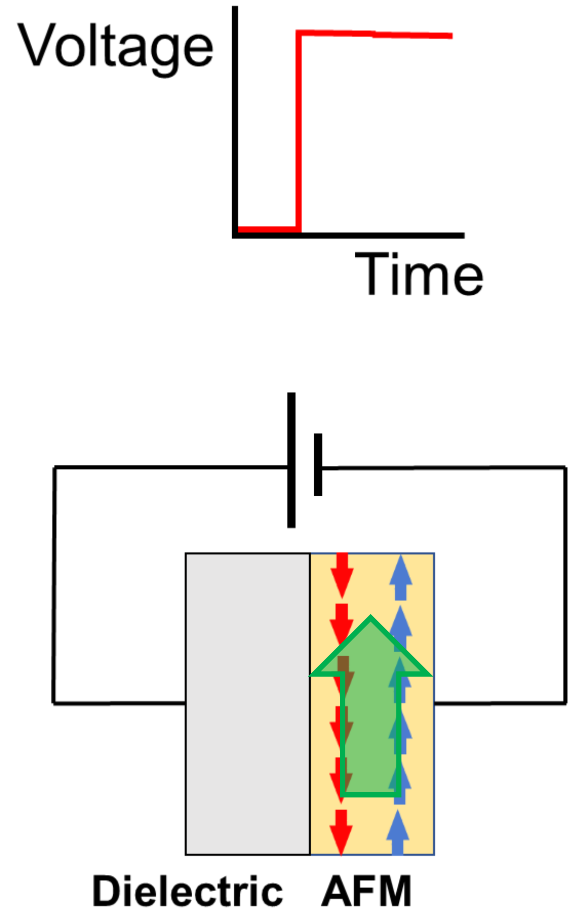
Voltage-Induced Switching of Anti-ferromagnets

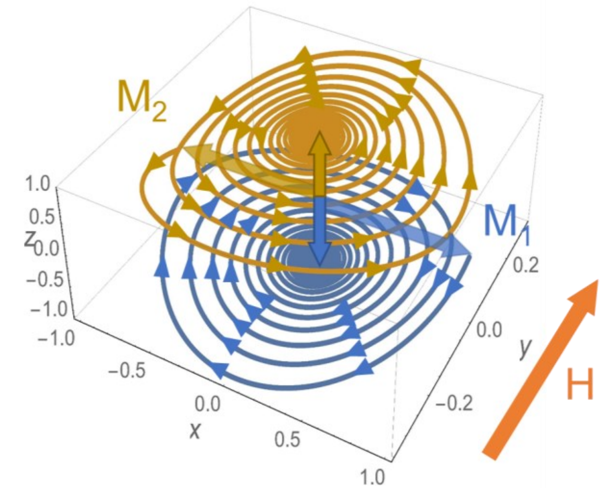


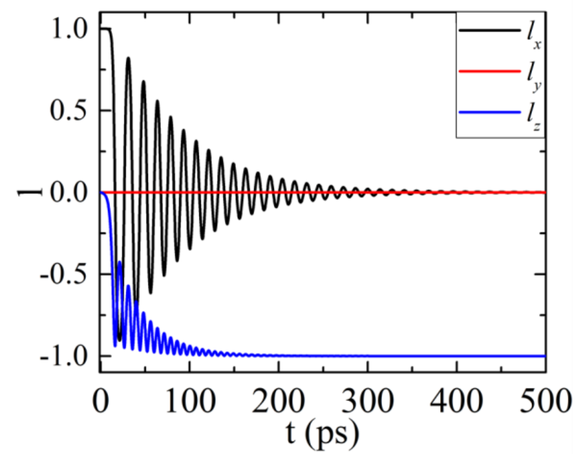
V. Lopez-Dominguez, H. Almasi, P. Khalili Amiri, Physical Review Applied, 11, 024019 (2019)

Voltage-Induced Switching of Anti-ferromagnets









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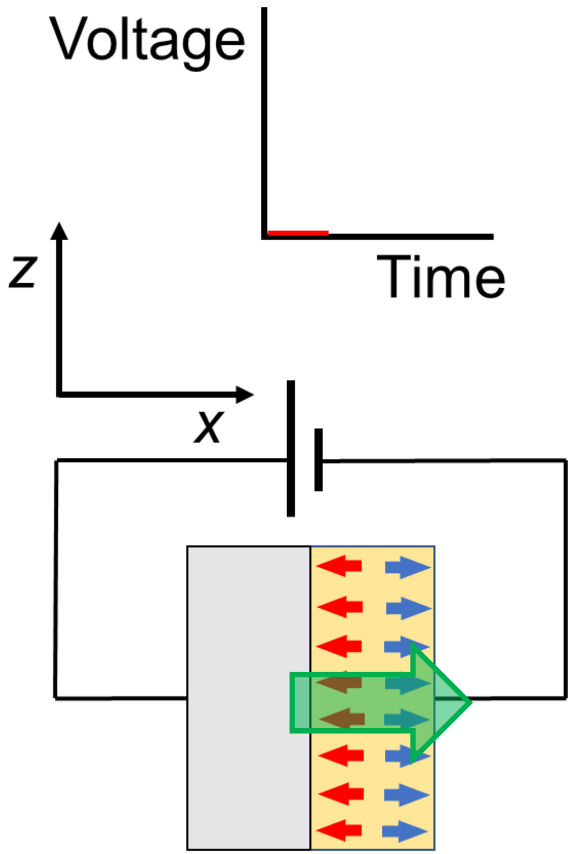
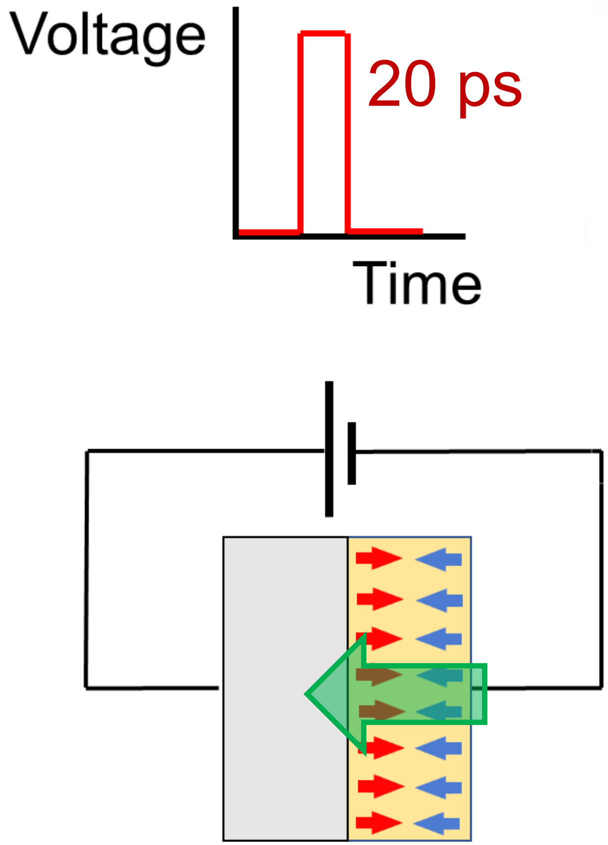
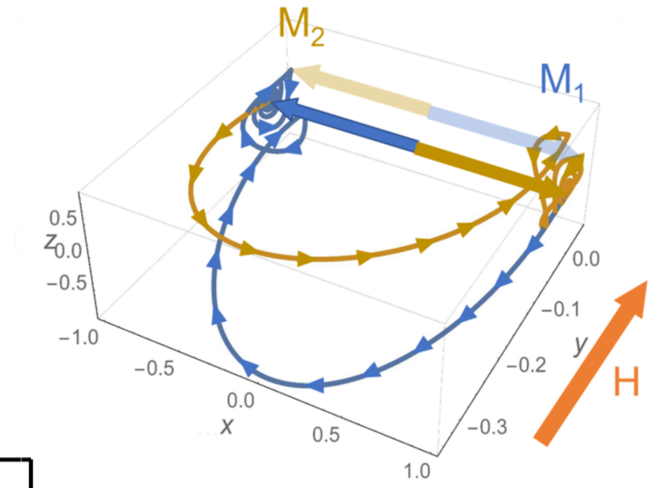
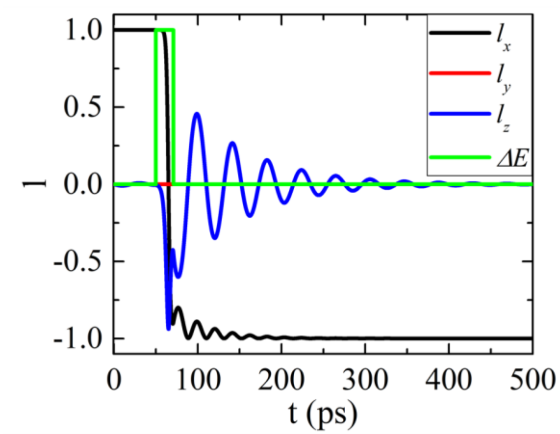
Voltage-Induced Switching of Anti-ferromagnets









- Reversal of Néel vector in response to voltage pulse
- Switching electric field is set by anisotropy (small) ~ 0.1 V/nm
- Switching time is set by exchange (large) ~ THz

V. Lopez-Dominguez, H. Almasi, P. Khalili Amiri, Physical Review Applied, 11, 024019 (2019)

Summary

- Stochastic MRAM bits for SC-ANN implementation

  Y. Shao, P. Khalili Amiri et al., IEEE Magnetics Letters 12, 4501005 (2021)

- Increase of throughput via high-speed ferro/anti-ferromagnetic dynamics

  V. Lopez-Dominguez, H. Almasi, P. Khalili Amiri, Physical Review Applied, 11, 024019 (2019)

- Electrical switching of CMOS-compatible antiferromagnets

  S. Arpaci, V. Lopez-Dominguez, P. Khalili Amiri et al., Nature Communications, 12, 3828 (2021)

  J. Shi, V. Lopez-Dominguez, P. Khalili Amiri et al., Nature Electronics, 3, 92 (2020)

- Demonstration of voltage-controlled MRAM bits with write voltage < 1 V