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UCLA DRL Device Research Laboratory

Overview of Magnetics and Spintronics

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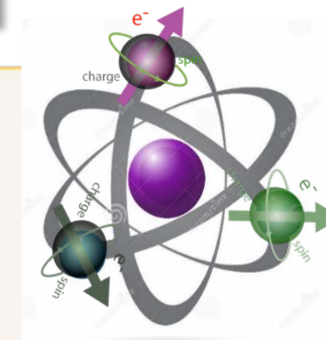
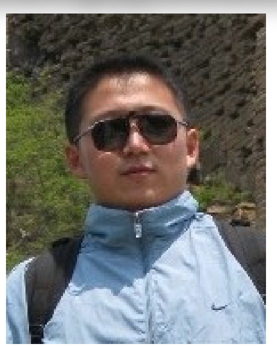
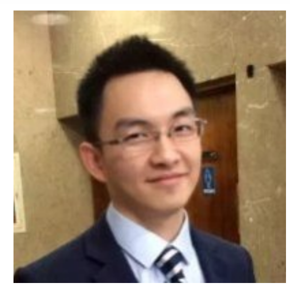



Guoqiang Yu


Cecile Grezes


Pramey Upadhyaya


Qinglin He

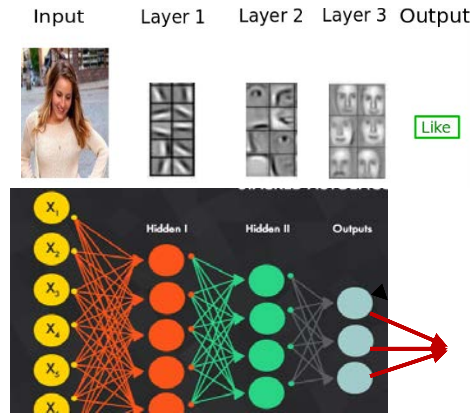

Xiang Li


Alex Grutter

UCLA DARPA FAME TANMS SHINES Spins and Heat In Nanoscale Electronic Systems CEGN

The Need: Energy efficient high performance

- Deep Learning !
- Big data
- Autonomous systems
- Intelligent systems

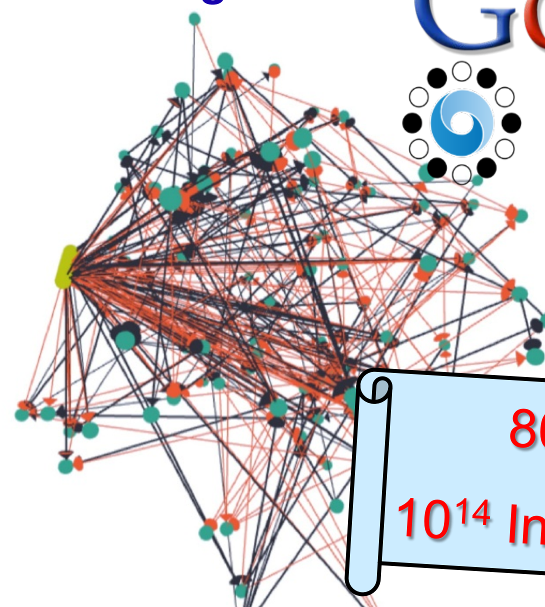


Deep Learning

- Computing in Memory
- Neuromorphics
- Memory intensive systems

Google
AlphaGo

Energy and power dissipation
Memory, Memory… .



80 G neurons
10^{14} Interconnects

The progress in nonvolatile spintronics memory: Low power, High Density and Endurance, ...

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Information/Electronics systems

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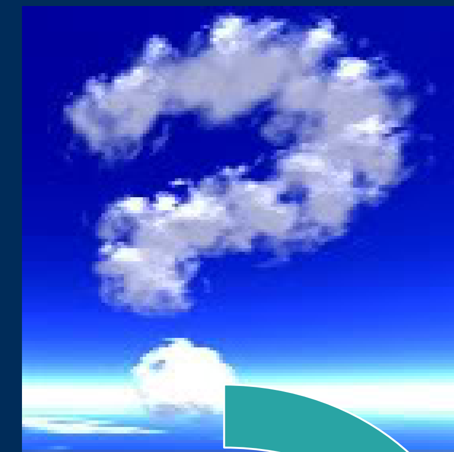
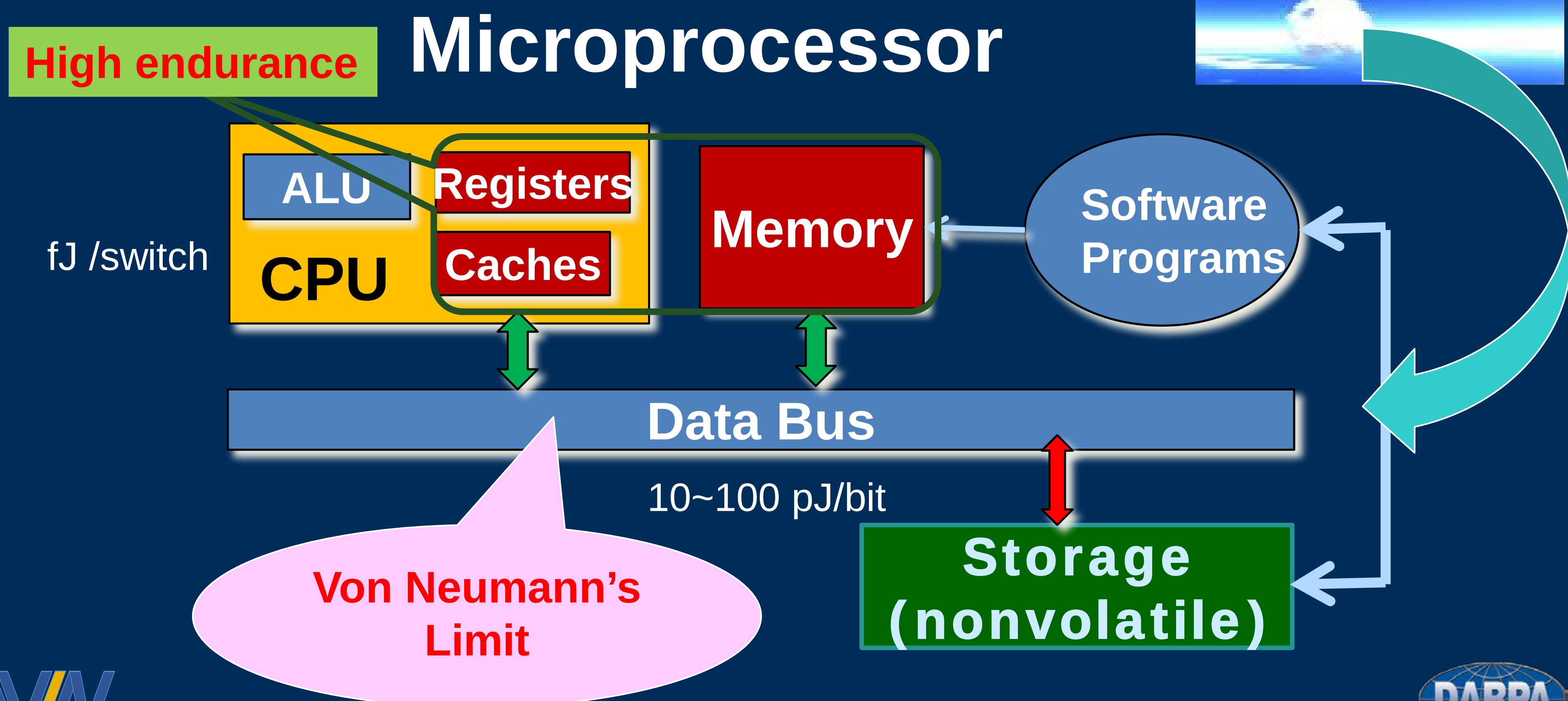
- Device level -Size and V scaling
- System level -Memory (Storage)





Collective Spintronics

Why Spintronics?

Complementary to CMOS

Leakage

nonvolatility

Collective spins

(order parameters)

Heisenberg exchange

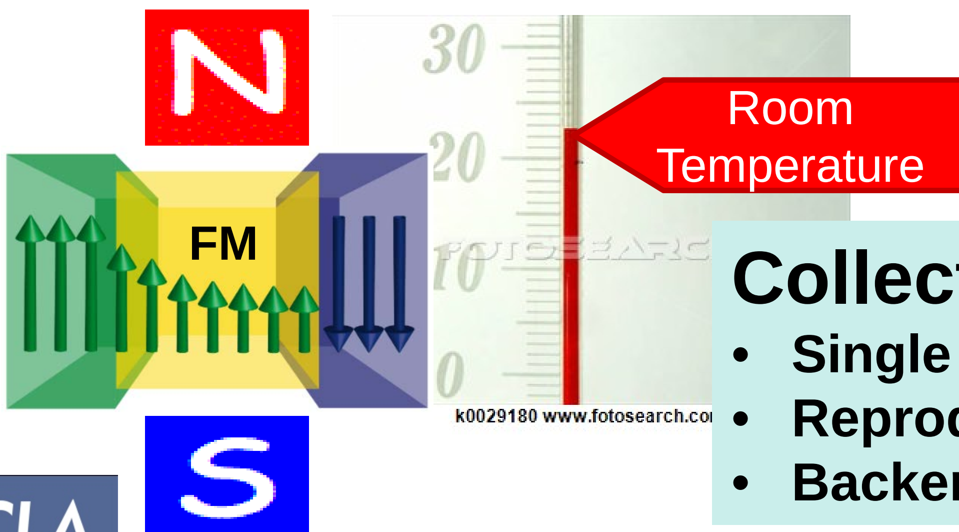
$$H = -1/2 \sum_{i,j} J_{i,j} S_i \cdot S_j$$

Low dynamic power

Dynamic energy: CV^2f &
The limit: E=NkTln(2)= N3x10^{-21} J

Sub-threshold

Low voltage & subthreshold

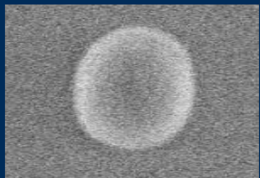


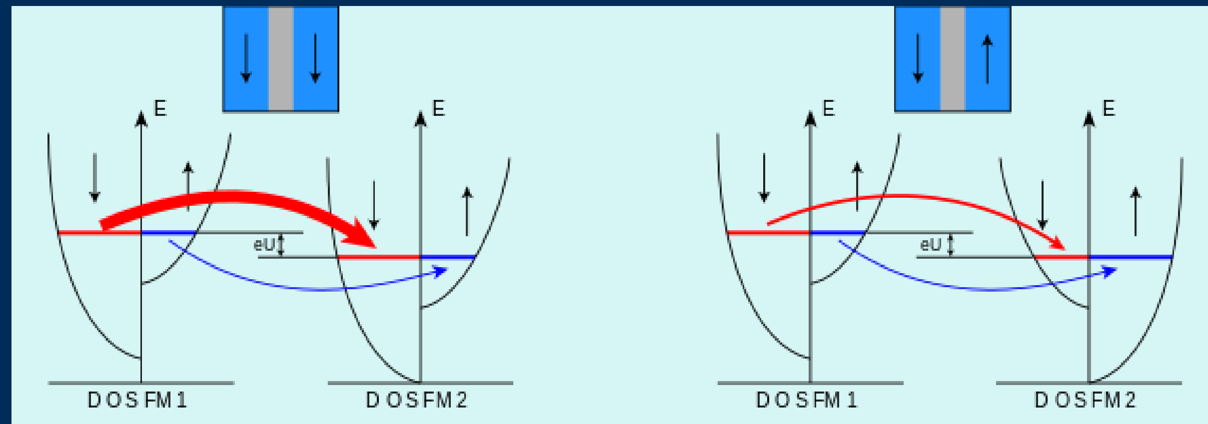
Device & Systems levels

Collective

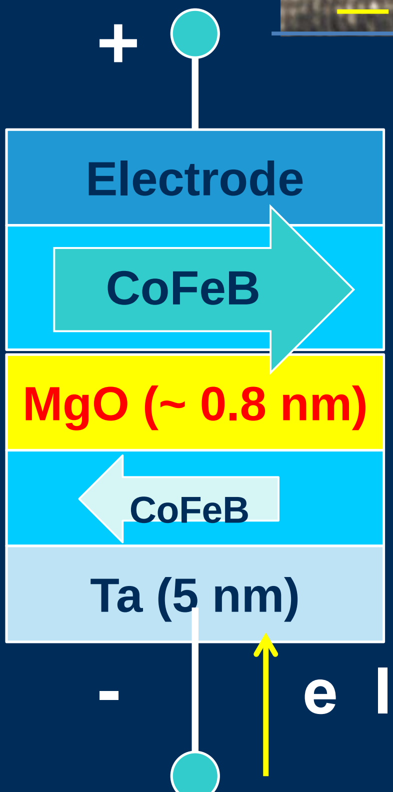
- **Single crystalline not needed – no epi**
- **Reproducible**
- **Backend – $T_{process}$ < 400 C**

Spin Transfer Torque (STT) Memory





MTJ

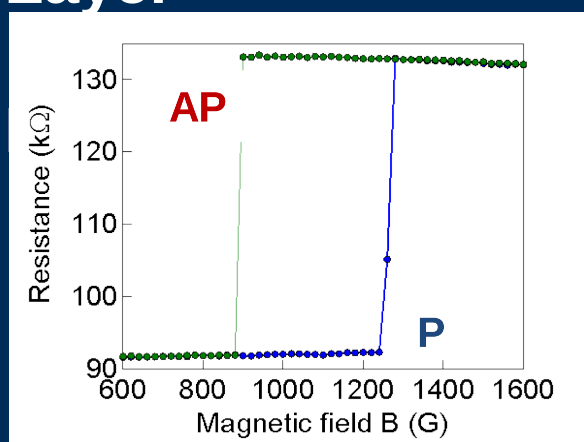


Fixed Layer

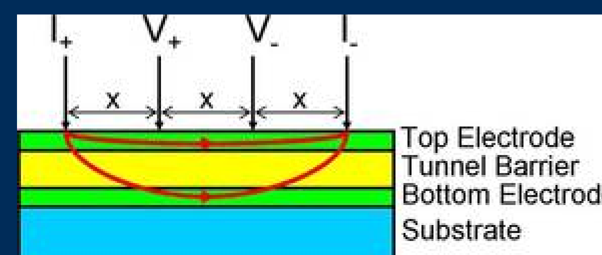
Tunneling resistance:
- AP: Anti-parallel
- P: parallel

Tunneling magneto-resistance ratio

$$TMR = \frac{R_{AP} - R_p}{R_p}$$



CIPT (current-in-plane tunneling)



Slonczewski and Berger in 1996 (J. Magnetism and Magnetic Materials 159 (1996) L 1 -L7

Like MOS technology needing C(V)

Spin Transfer Torque (STT) dynamics

LLG (Landau-Lifshitz-Gilbert Equation:

$$\alpha(\boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{H}))$$

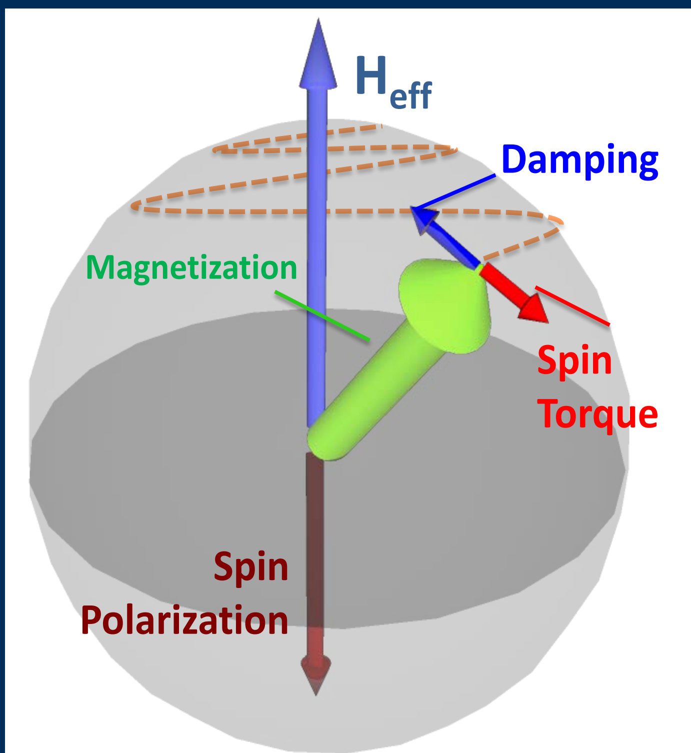
H_{STT}

$$\partial_t \boldsymbol{m} = -\gamma \boldsymbol{m} \times \boldsymbol{H}(\boldsymbol{m}) + \alpha \boldsymbol{m} \times \partial_t \boldsymbol{m} - g J \boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{p})$$

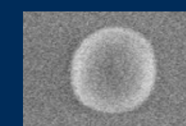
Precessing | damping | STT

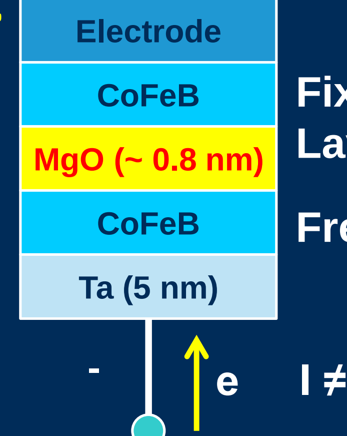
$\neq 0$

If M and p are not colinear



- **During Current Pulse – Spin torque transferred to turn the magnet**
- **Speed: Precessing or FMR (acoustic)**





Predicted by Slonczewski and Berger in 1996 (J. Magnetism and Magnetic Materials 159 (1996) L 1 -L7

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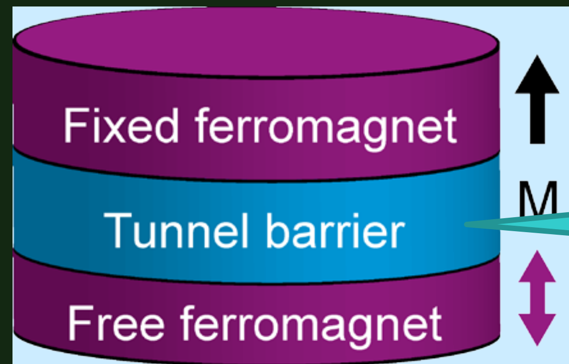
STT Status, Scaling and Voltage-Controlled

Spin Transfer Torque
STT-MRAM (2016) 1 Gb

Everspin,
Avalanches, etc.



< 1 nm

0 Anti-parallel (AP)
1 Parallel (P)

Global, Intel, Samsung, TSMC, SMIC, Toshiba/SK Hynix, … .

Current-driven: Too much power & not scalable!

CMOS at 65 nm: 1 fJ

Type	Flash	PCRAM	FERAM	RRAM	STTRAM
Write Energy/ bit	> 1 nJ	~ 100 pJ	~ 1 pJ	~ 1 pJ	~ 100 fJ
Speed	1 us~1 ms	~ 50 ns	~ 50 ns	~ 10 ns	0.1 – 10 ns
Endurance	Very Low 1000	Low	moderate	Low~ mid	Very High 10^{15}
Density (F^2)	4 – 8	6 – 10	6 – 10	6 – 10	6 – 20
Maturity	Product	Product	Product	R&D	R&D

Slonczewski and Berger in 1996 (J. Magnetism and Magnetic Materials 159 (1996) L 1 -L7

Khalili and Wang, Spin, 2, 1240002 (2012)
Wang, Alzate, and Khalili, J. Phys. D: Appl. Phys., 46, 074003 (2013)

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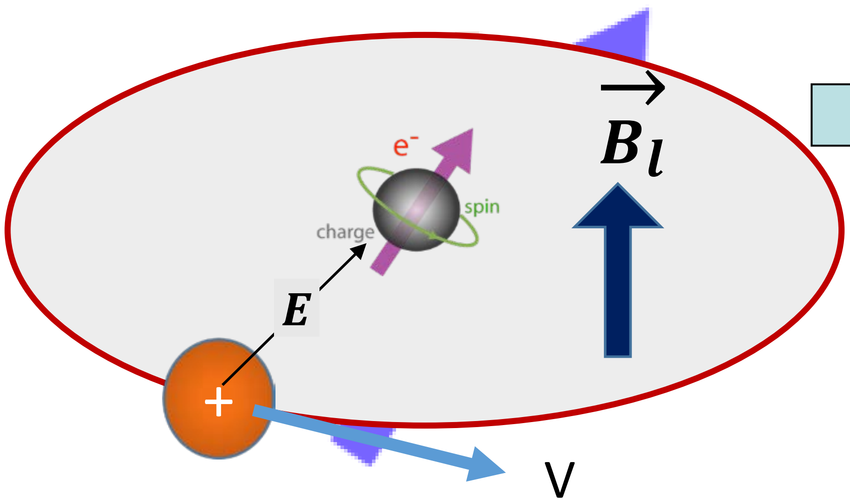
Beyond STT: Riding on the success of it
Spin Orbit Coupling (SOC) Engineering

SOC



Voltage or electric field control of Magnetism!!

$$\mathcal{H}_{SO} = -\frac{\hbar}{4m_0^2c^2}\boldsymbol{\sigma}\cdot\boldsymbol{p}\times\nabla\phi$$

- **Interface of heterostructure:**

$$\mathcal{H}_{\boldsymbol{Rashba}} = \boldsymbol{\alpha}\vec{\boldsymbol{\sigma}}\cdot(\vec{\boldsymbol{p}}\times\vec{\boldsymbol{z}})$$

- **For Bulk: Spin Hall**

Spin Hall, Rashba, Spin Orbit Torque, VCMA, Dzyaloshinskii- Morya Interaction (DMI), Skyrmionics,, Topological matters, etc… .

Low voltage & Low power

SOC ~ $Z^{3\sim4}$

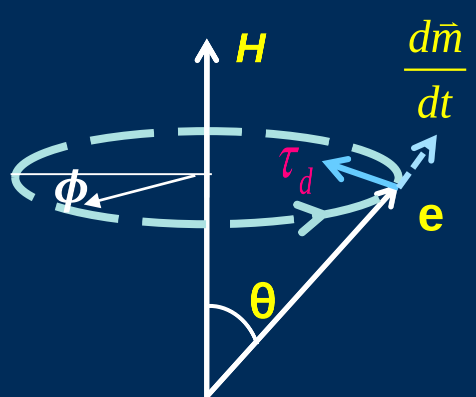
SOC Engineering: (VCMA)

1. Magnetoelectric Effect (Interface SOC)

Better Approach: Use Voltage-Controlled Magnetic Anisotropy (VCMA)

LLG: $\partial_t \vec{m} = -|\gamma|(\vec{m} \times \vec{H}_{eff}) + \alpha(\boldsymbol{m} \times (\boldsymbol{m} \times \boldsymbol{H_{eff}}))$

$$\boldsymbol{H_{eff}} = \boldsymbol{H_{app}} + \boldsymbol{H}(\boldsymbol{STT}) + \boldsymbol{H}_{SOC}\,(I, V, m, \partial_r m)$$

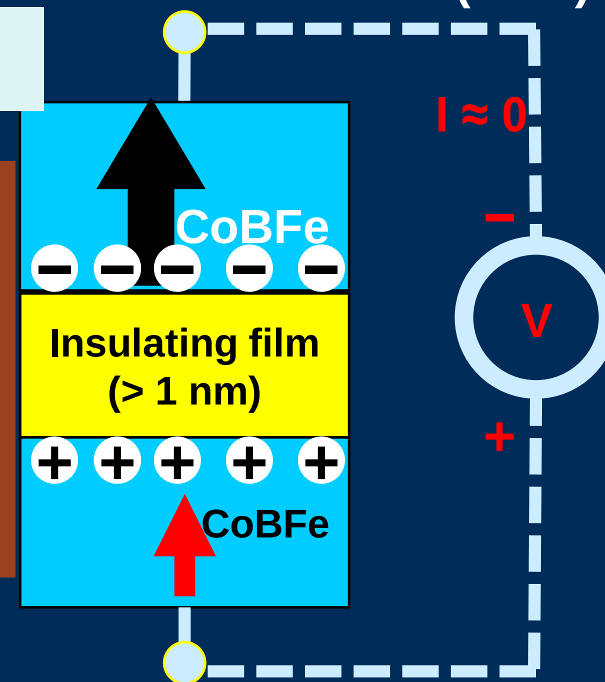


- Voltage-Controlled interfacial Magnetic Anisotropy (VCMA)

$$\mathrm{K_i(V) = K_i(V = 0) - \xi \frac{V}{t_d}}$$

Determination of ξ ?

ME Stack (MES)



$$\boldsymbol{H}(\boldsymbol{V}) = H_{VC} m_z \boldsymbol{z}$$

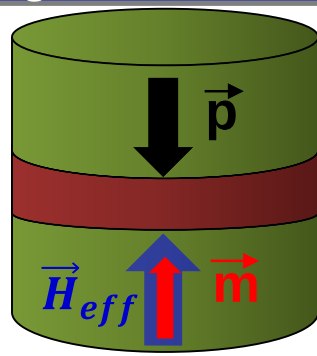
MeRAM (MagnetoElectric RAM)

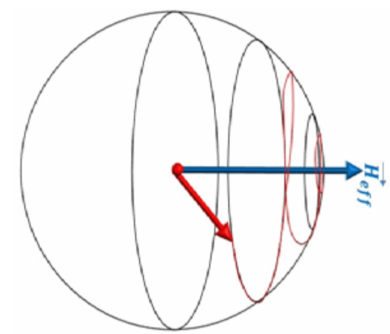
- **Very Energy-Efficient: < 1 fJ**
- **Very High-Density: ~ NAND Flash**
- **Scalable**

Maruyama et al., Nat Nano 4, 158 (2009);
Zhu, KW , IK, et al., Phy Rev Lett, 108, 977203 (2012)
Stewart, et al., Scientific Reports, 4, 4105 (2014)
Alzate, KL Wang, et al., IEDM, 681-684 (2012)
Khalili, KL Wang et al., J. Appl. Phys. 113, 013912 (2013)
Dorrance, KLWang et al., IEEE Elec. Dev. Lett., (20134

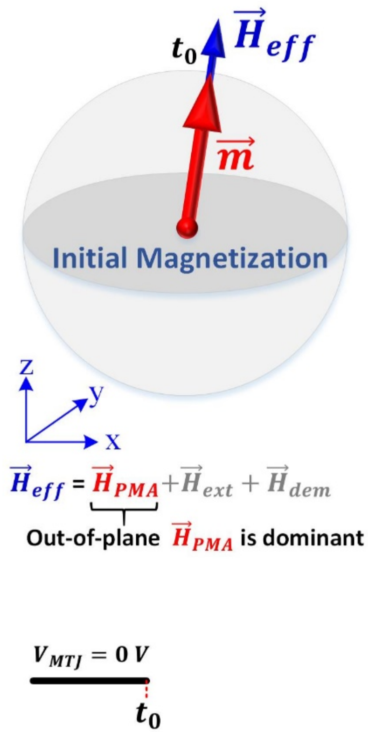
Switching Mechanism: VCMA driven precession

Voltage controlled magnetic anisotropy (VCMA) driven precessional switching



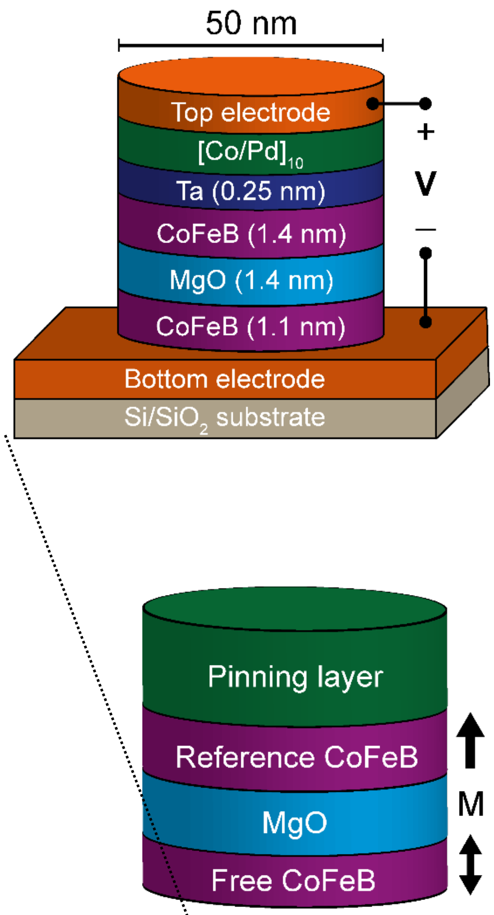


- **With every properly timed pulse, the magnetization rotates 180 degrees**



(a)

Magnetic tunnel junction device



Perpendicular anisotropy, 50 nm junction diameter

- **Resistance-area product = 650 $\Omega\mu m^2$**

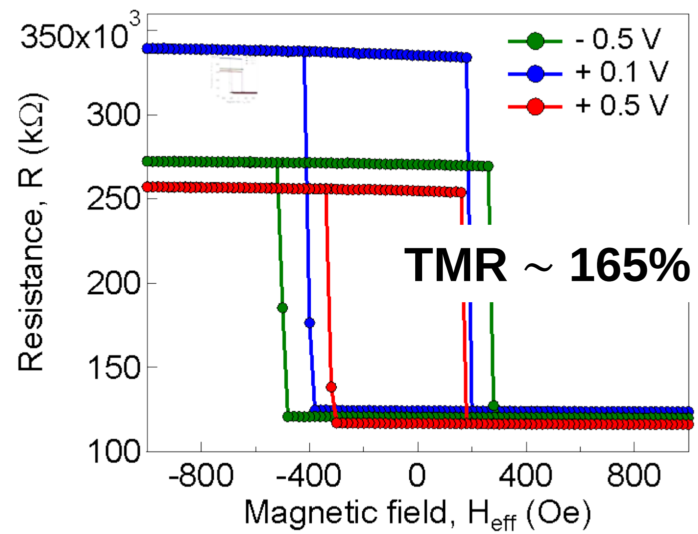
  10^2 x larger than STT-MTJs

  ➢ **Reduce the Ohmic dissipation**

- **TMR up to 250 %**

- **Modulation of interfacial anisotropy by applied voltage Negative (positive) voltages increase (decrease) the perpendicular coercivity**

Electric-field modulation of perpendicular coercivity:
ξ =140 Oe/V (~ 30 fJ/Vm)

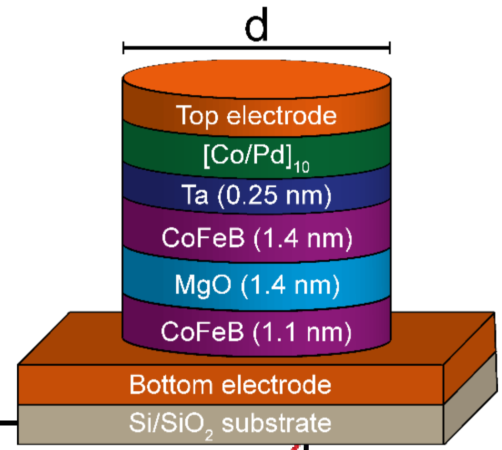


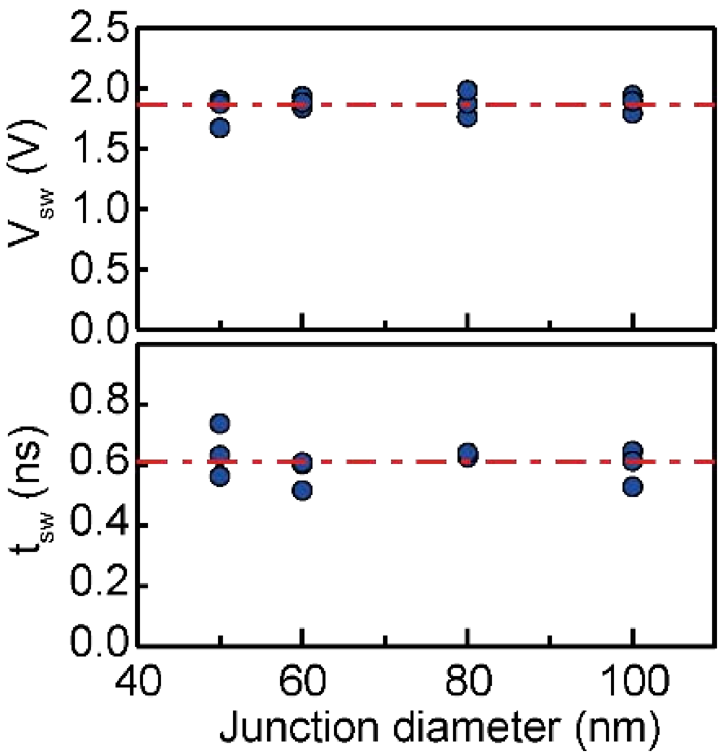
Perpendicular anisotropy

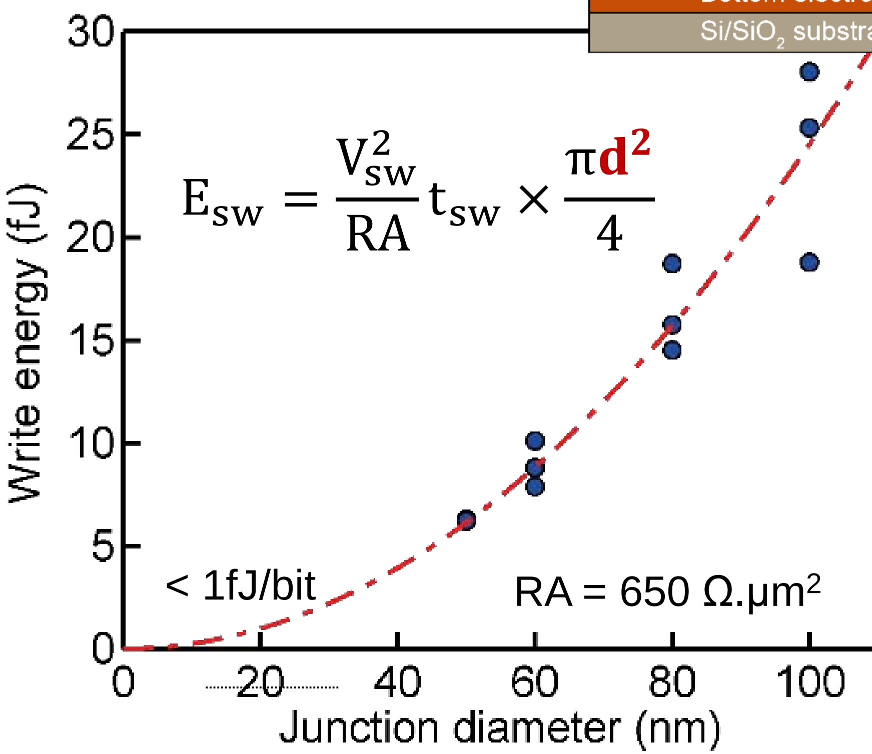
Scaling of the write performance

- **Size independent write voltage and speed**
- **Write energy scales as ~ d^2**

➢ **Write energy** <1fJ/bit for bit size < 20 nm







This is based on earlier work of ξ= 30fJ/Vm; Now we have **130 fJ/Vm.**
Our target is > 200 fJ/Vm

Recent results from Suzuki's group: 290 fJ/Vm

Energy Scaling of STT and Voltage- controlled MeRAM

STT-MRAM

$$E_C = \frac{I_{op}^2 RA}{A} t_w$$

1. $I_{op} \propto \frac{\alpha}{\eta} \Delta$ 2. $RA \propto d_{MgO}$

- Reduced α/η and d_{MgO}

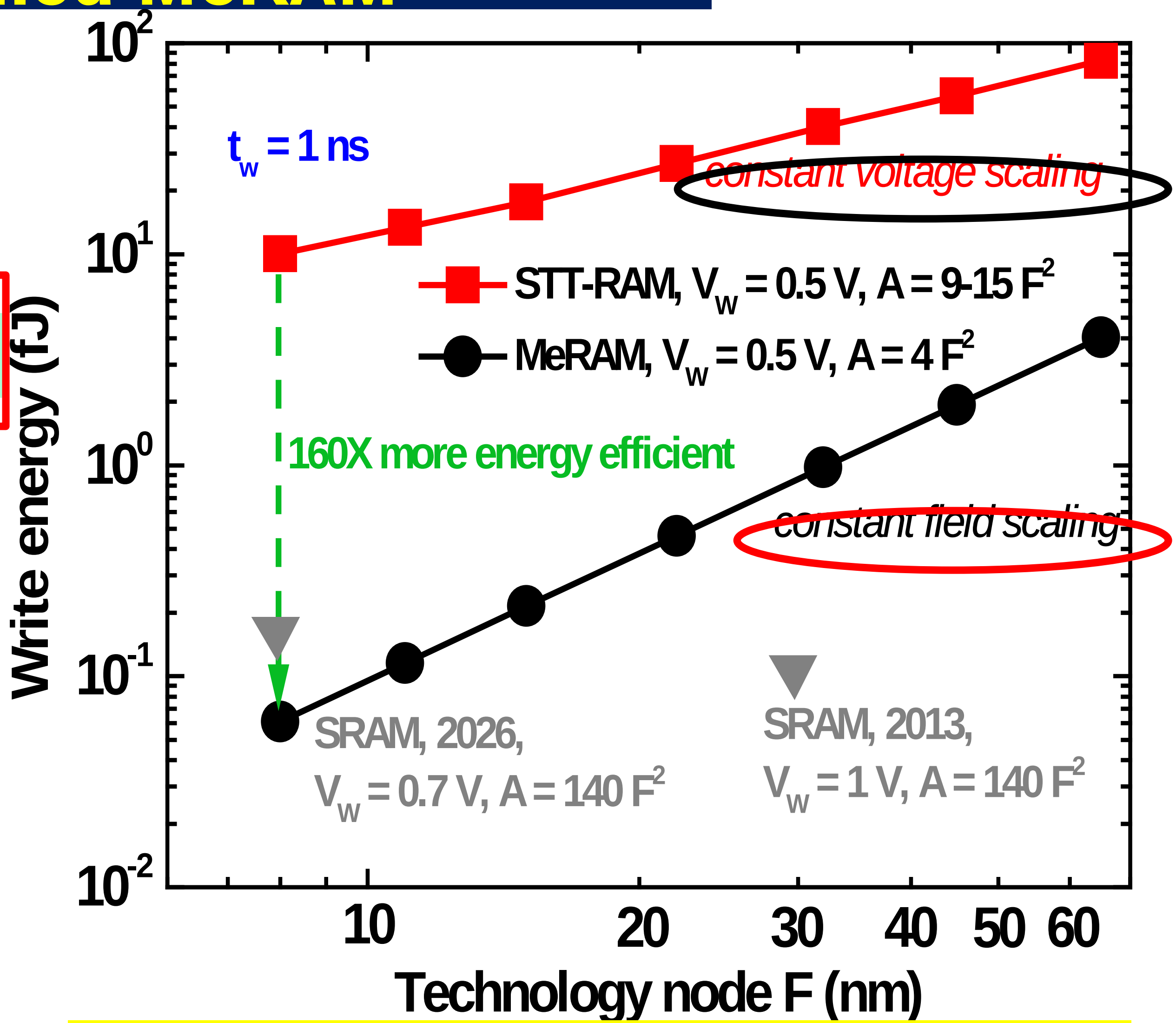
MeRAM

$$E_V = \frac{V_{op}^2}{R} t_w + C_{MEJ} V_{op}^2$$

$$\propto A \propto \frac{1}{D^2}$$

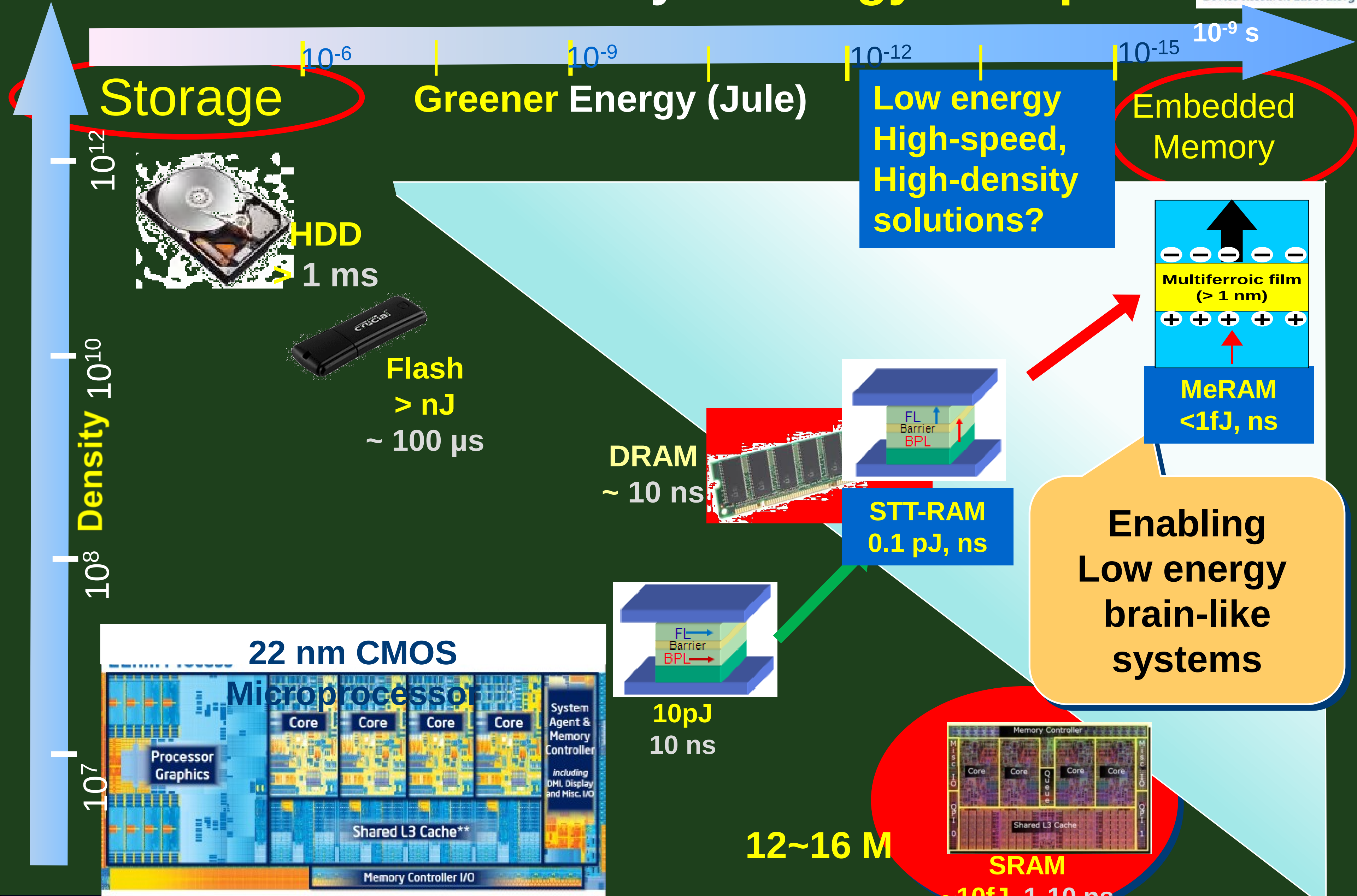
Fixed V_{op} and d_{MgO}

$$\frac{V_{op}}{\Delta} = \frac{kTd_{MgO}}{\zeta A}$$



MeRAM Cost??
Smaller areas, higher density (cross bar)

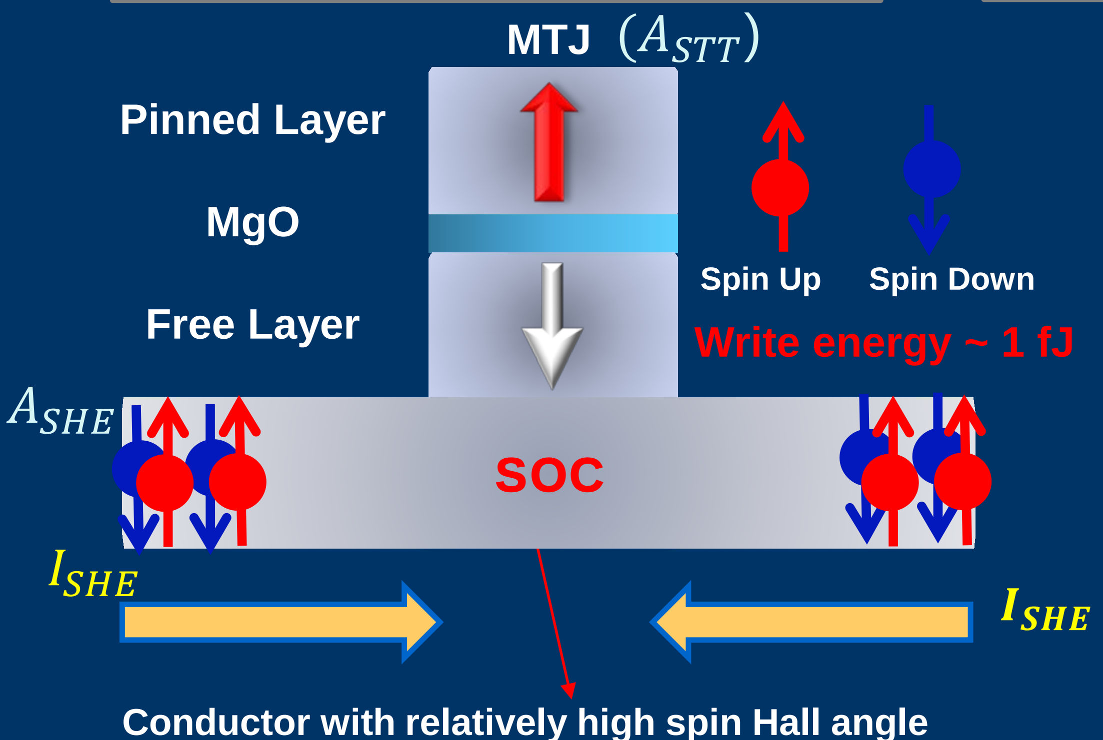
Electronic Memory – Energy Dissipation



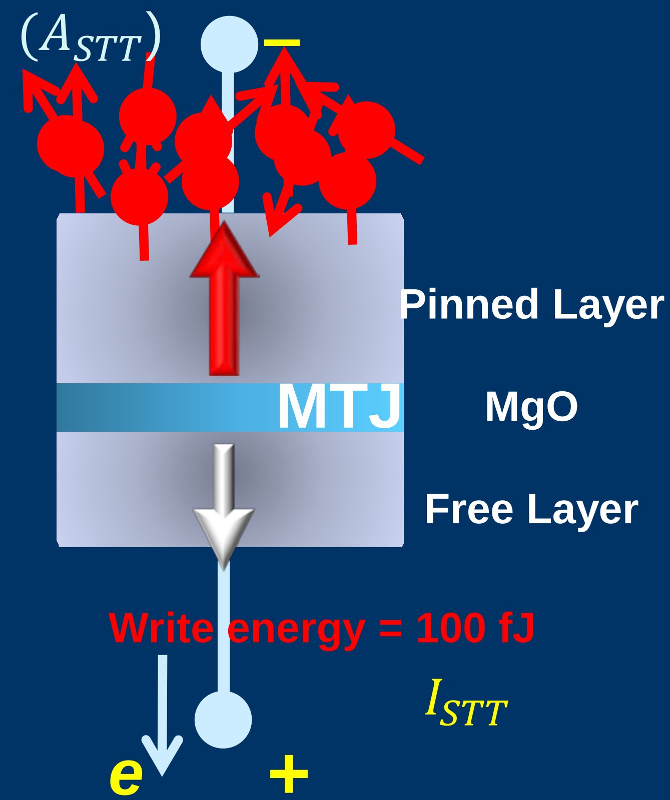
Memory: over 70% of power consumption of smart phones;
50% for data centers.(J Howard, ISSCC 2010) KL Wang, Lee and Khalali, TNANO 2105

Spin Orbit Torque (SOT)

Spin Hall Effect



Spin Transfer Torque



$$\frac{I_{SHE}}{I_{STT}} \propto \frac{\eta}{\theta_{SH}} \frac{A_{SH}}{A_{MTJ}}$$

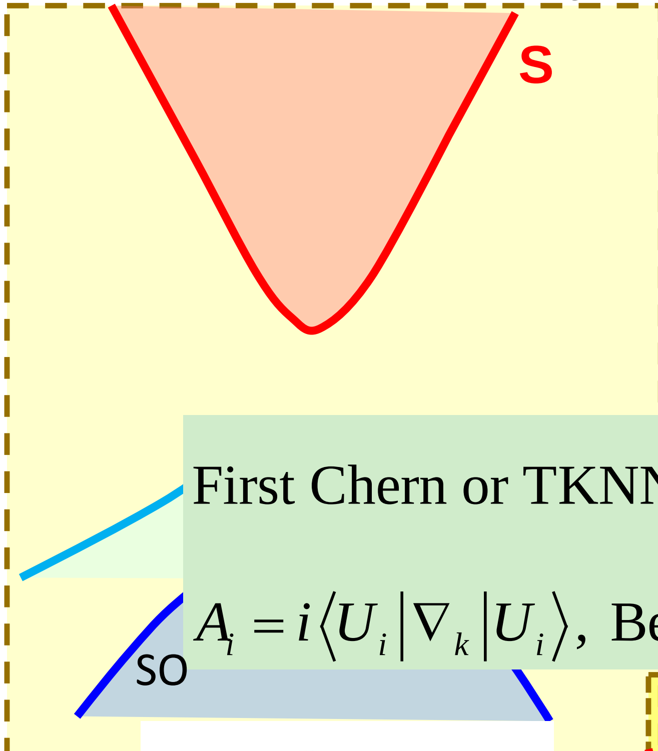
Advantage of SHE:

- Small operation voltage due to lower resistance
- More energy efficient because of high spin current injection efficiency
- Fast switching without reliability concerns (No tunneling in writing)

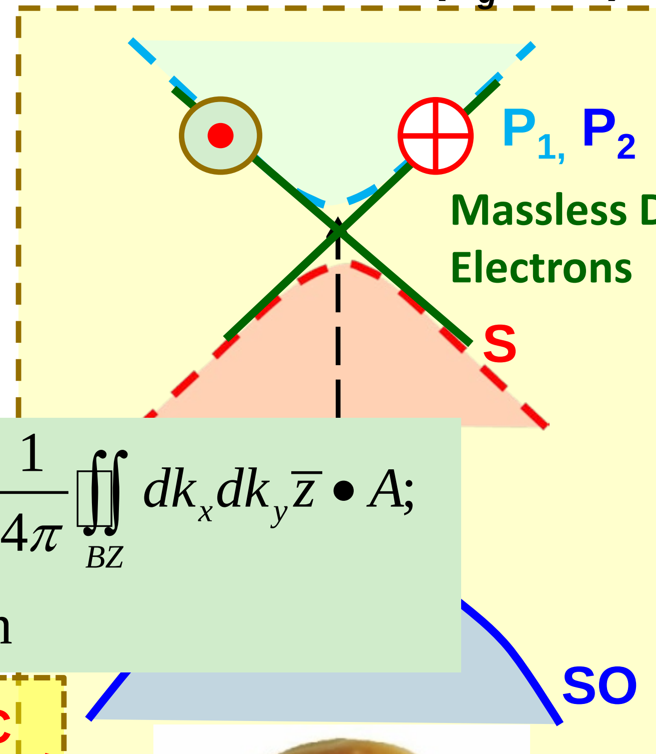
[1] Liu L *et al, Science* **336** 555–8 (2012)
[2] Y, Fan, KL Wang, *et al. Nature Materials* 2014

Topological Spintronics (due to SOC)
Combining with Topological Insulator

Normal Semiconductor (E_g > kT)



Band Inversion (E_g < kT)

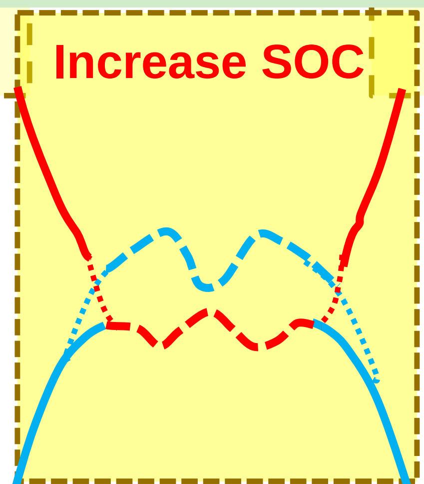


First Chern or TKNN number: $n = \frac{1}{4\pi} \iint_{BZ} dk_x dk_y \bar{z} \bullet A;$

$A_i = i \langle U_i | \nabla_k | U_i \rangle$, Berry connection

Chern Number C1=0

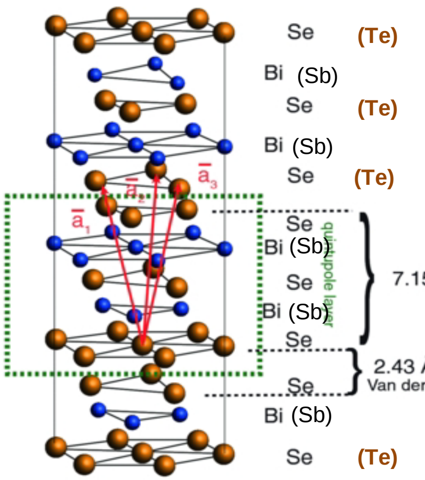
Sphere (C1=0)

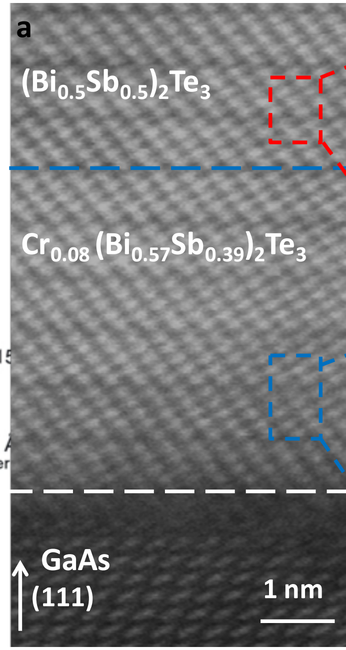


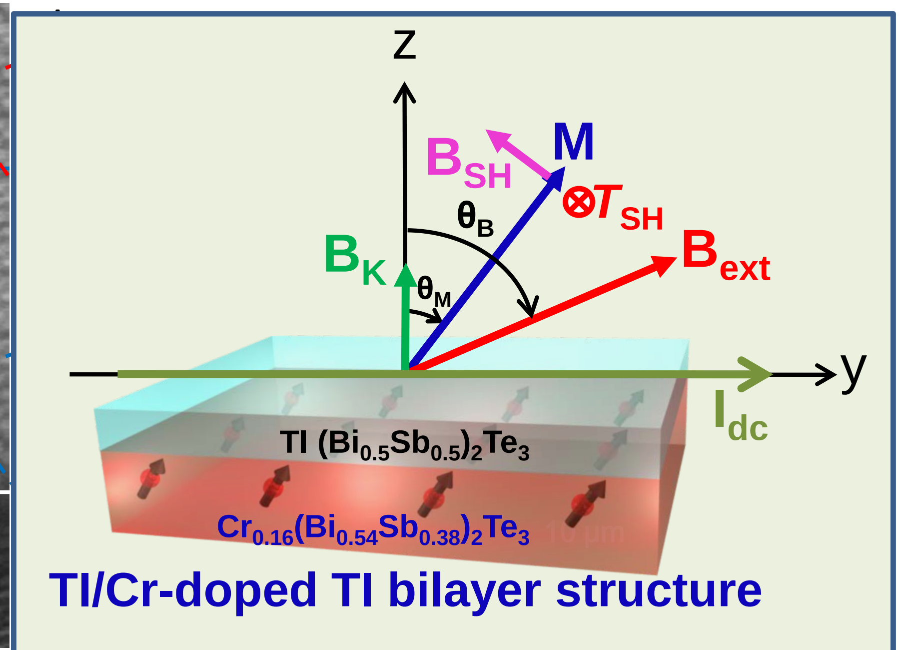
Torus (C1=1)

Chern Number C1=1

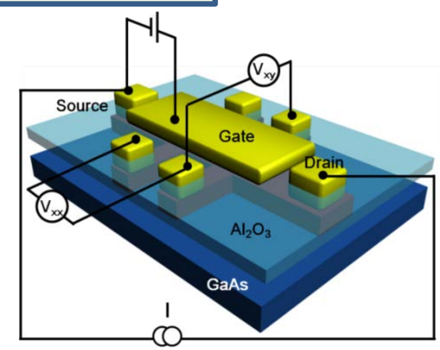
SOT in TI / Cr-doped Ferromagnetic TI bilayer heterostructure







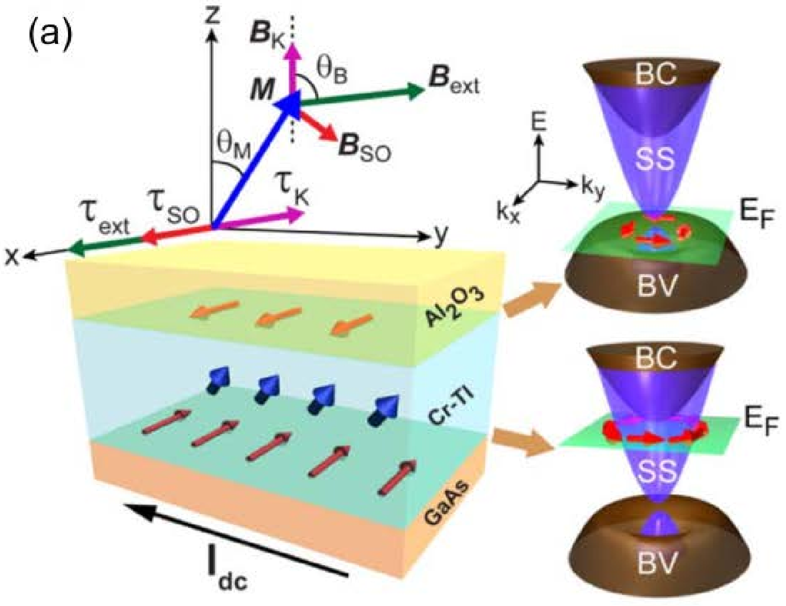
- ~5000X giant spin-orbit field
- Magnetic switching a magnetic topological insulator hetero-structure

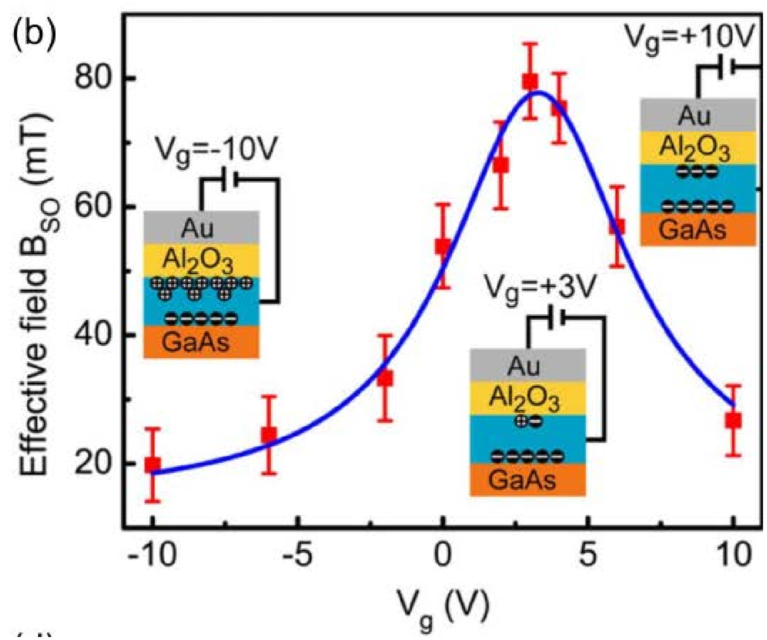


[1]:Junyeon Kim et al., Nature Materials, 12, 240 (2013).
[2]:Yabin Fan,, .., Y Tserkovnyiak, K. Wang, Nature materials, April 28 (2014)

Topological Spintronics

- Topological surface states
- Strong spin-orbit coupling (SOC)





	TI/Cr-doped TI	Ta/CoFeB/MgO
Switching current density	~ 10^4 (Acm^{-2})	~ 10^7 (Acm^{-2})
Spin-torque ratio	140~425 (1.9K) 1-3 (300k)	~0.1- 0.2 (300K)

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K L Wang, et al., Proceedings of the IEEE **104** (10), 1974 (2016).

Topological Spin Texture in Real Space (Skyrmion)

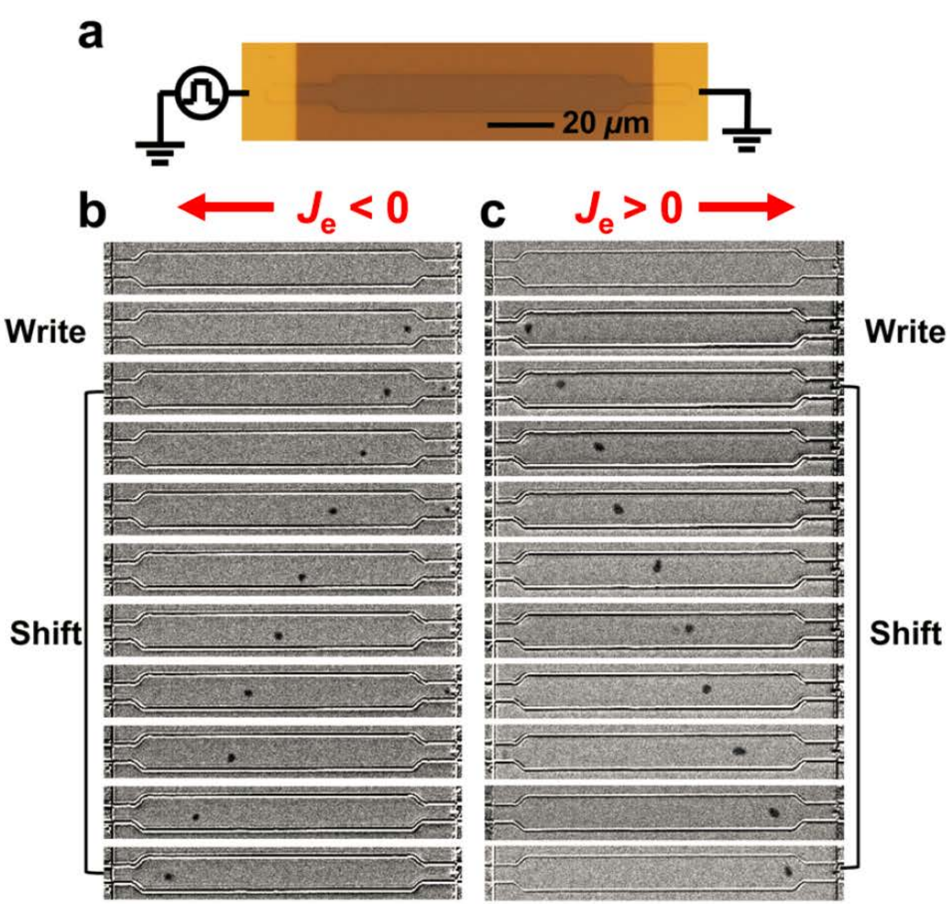
- **Dzyaloshinskii-Moriya interaction (DMI):** $\mathcal{H} = E = \boldsymbol{D}_{ij} \cdot \boldsymbol{S}_{\mathrm{i}} \times \boldsymbol{S}_j$

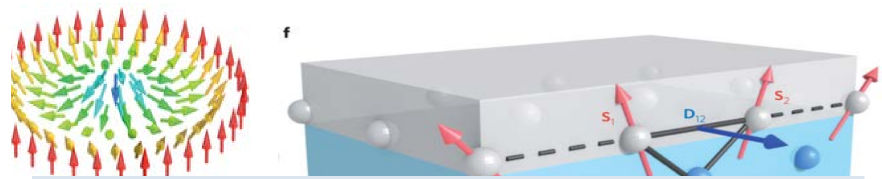
Bulk DMI:

$$\mathcal{H} = E^{B}_{DMI} = D_B \mathbf{m} \cdot \nabla \times \boldsymbol{m}$$

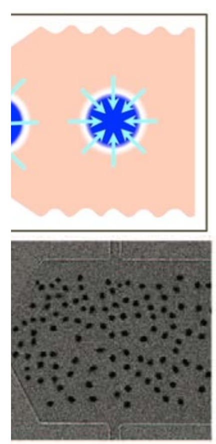
Interfacial DMI:

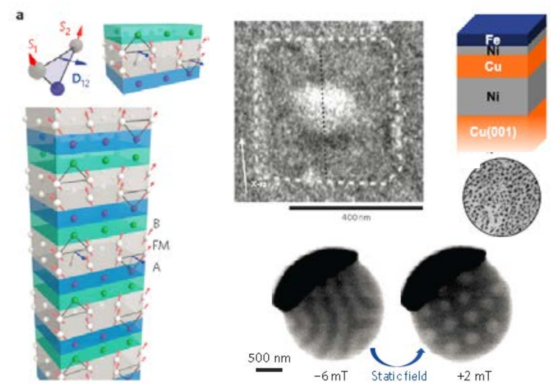
$$\mathcal{H}^{I}_{DMI} = E^{I}_{DMI} = D_I m_z \nabla \cdot \boldsymbol{m}$$





$$N_{sk} = \frac{1}{4\pi} \iint d^2 r \mathbf{n} \cdot \left(\frac{\partial \mathbf{n}}{\partial x} \times \frac{\partial \mathbf{n}}{\partial y} \right)$$

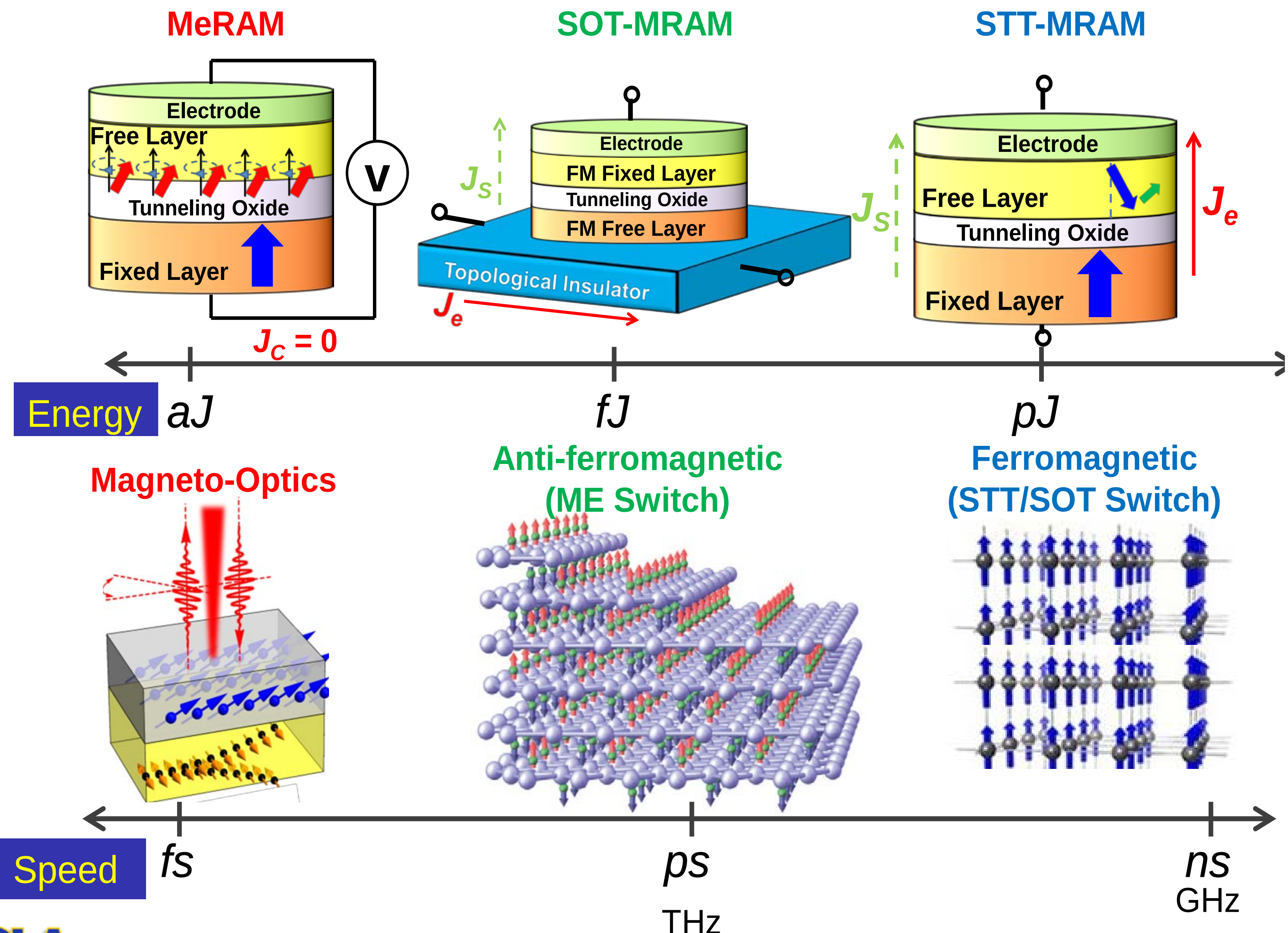




ya, W. Zhang, G. Q. Yu,
ın, *et al*. Science (2015)

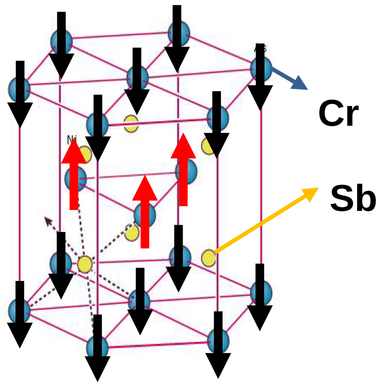
C. Luchaire, *et al.*, Nat. Nano (2016)
O. Boulle, *et al.*, Nat. Nano (2016)
S. Woo, *et al.*, Nat. Mat. (2016)
G. Chen, *et al.*, APL (2015)
G. Q. Yu,, K L. Wang, *et al.*,, Nano Letters, (2016)

Scaling of Magnetic Interactions



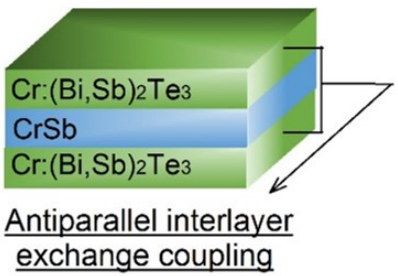
K L Wang, et al., Proceedings of the IEEE **104** (10), 1974 (2016).

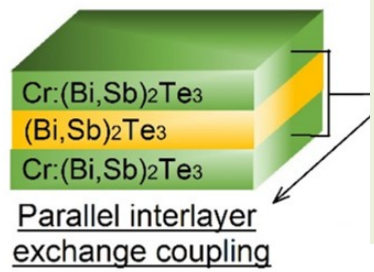
Exchange Coupling in Magnetic TI / Antiferromagnet heterostructure

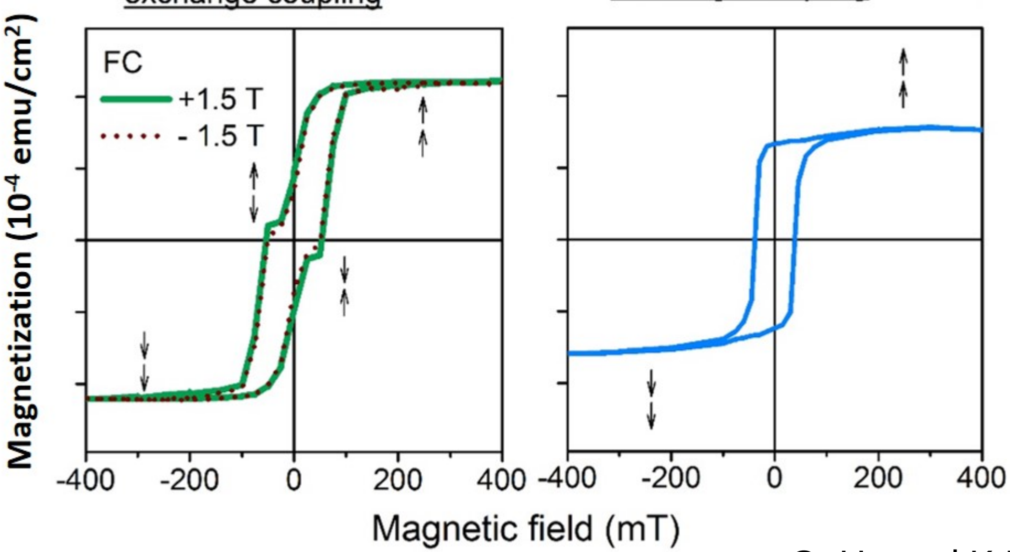


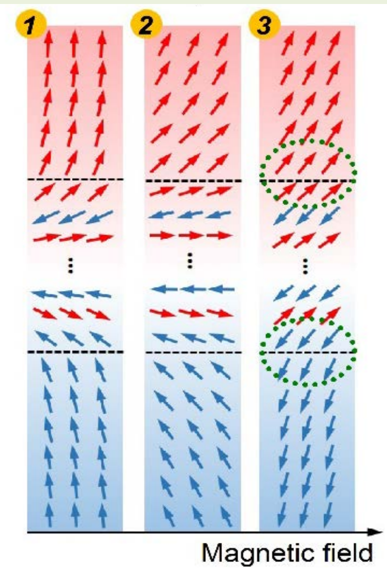
Materials	Lattice constant *a* (Å)	Magnetic ordering temperature (K)
Cr-doped $(Bi_{1-x}Sb_x)_2Te_3$	4.26~4.38	T_c ~ 30 K
CrSb	4.12	T_N ~ 700 K

- **Neutron Scattering at NIST (Alex Grutter)**
  - Magnetization mostly confined in the MTI
  - Significant magnetizations are detected in the AFM layers



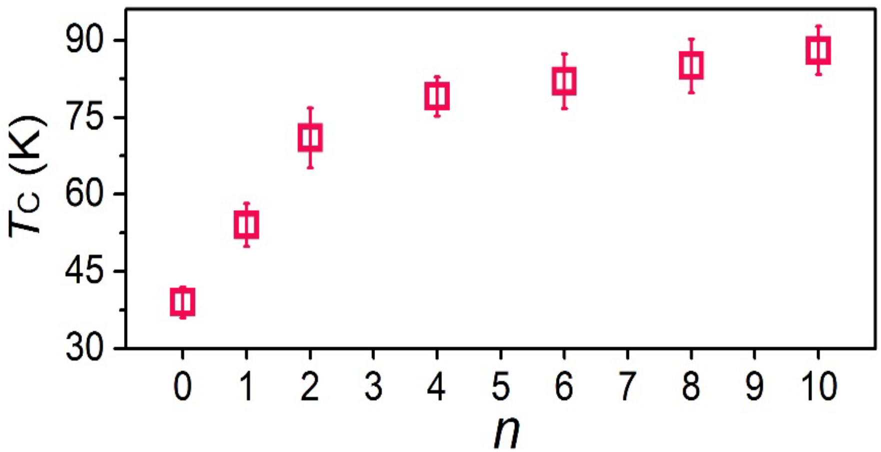






Q. He and K L. Wang, et al., Nature Materials 16, 94 (2017)

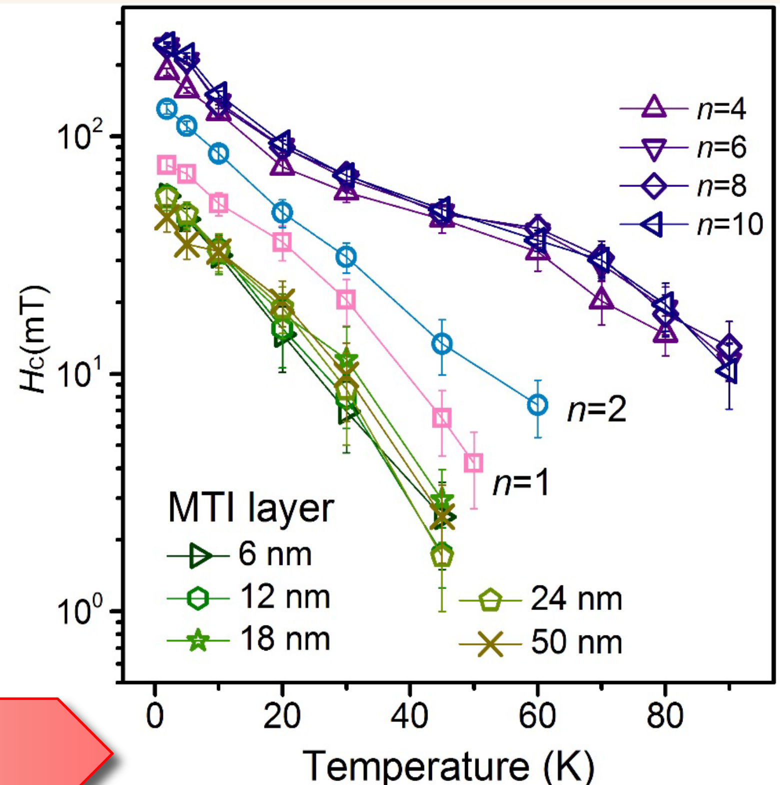
Magnetic ordering enhancement due to coupling to antiferromagnets



- T_C values extracted from the transport measurements (the Arrott's plots)
- An increase up from < 30 K to ~ 90 K, a factor of three enhancement

- Increase in coercive field H_C -- Comparison between (AFM/MTI) superlattices and isolated MTI thin films
- In superlattices, the maximum H_C is close to 100x comparing to those of single layers of magnetic TIs.

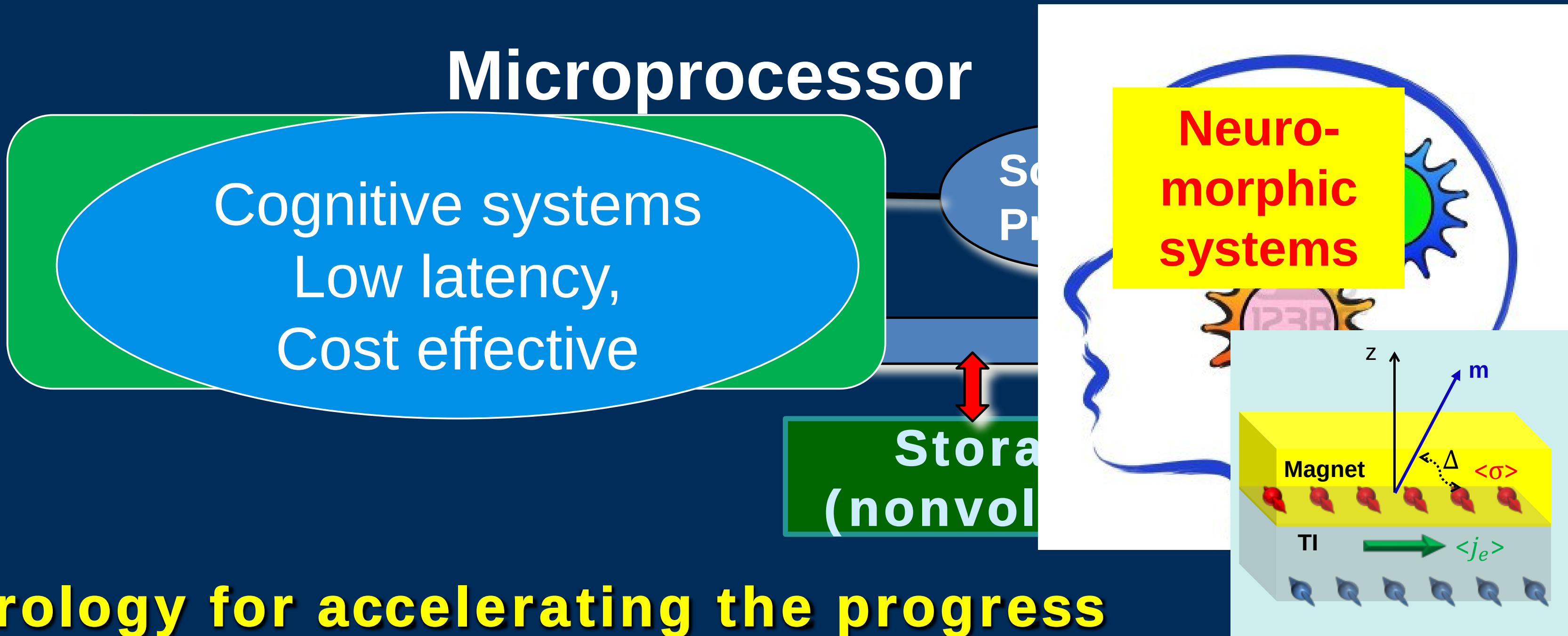
Q. He and K L. Wang, et al., Nature Materials 16, 94 (2017)



- AFM, High temperature Doped TI and undoped Ferro TI

Summary and Outlook

- **Spintronics: Energy scaling Low dissipation, fast, high endurance, cost effective nonvolatile memory (& logic)**
- **SOC engineering - Voltage write MeRAM low dissipation**
- **Topological Spintronics**



- **Metrology for accelerating the progress**
  - **VCMA, SOT, Skyrmions, etc..**
- **Atomic scaling imaging, dynamics and understanding**
  - **XMCA, neutron, Magnetic probe, NV cell probe, Lorentz TEM, ..**

KL Wang, et al., IEEE Proc. 104, 1976-2008, Oct 2016; J of Spin, 2, 1250009, 2012

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  Allan MacDonald (UT Austin), Yaroslav Tserkovnyak (UCLA, So Takei (UCLA), Pramey Upadhyaya (UCLA), S. K. Kim (UCLA), Shoucheng Zhang (Stanford), Jing Wang (Stanford)

Thank you very much!

ARO

25 minutes and 5 minutes questions