NISE

NANO-SYSTEMS FROM IONS, SPINS AND ELECTRONS

Nanosystems from ions,
spins and electrons

Stuart Parkin

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Spin-Orbitronics for advanced magnetic memories:

chiral domain walls and anti-skyrmions

Max Planck Institute for Microstructure Physics, Halle

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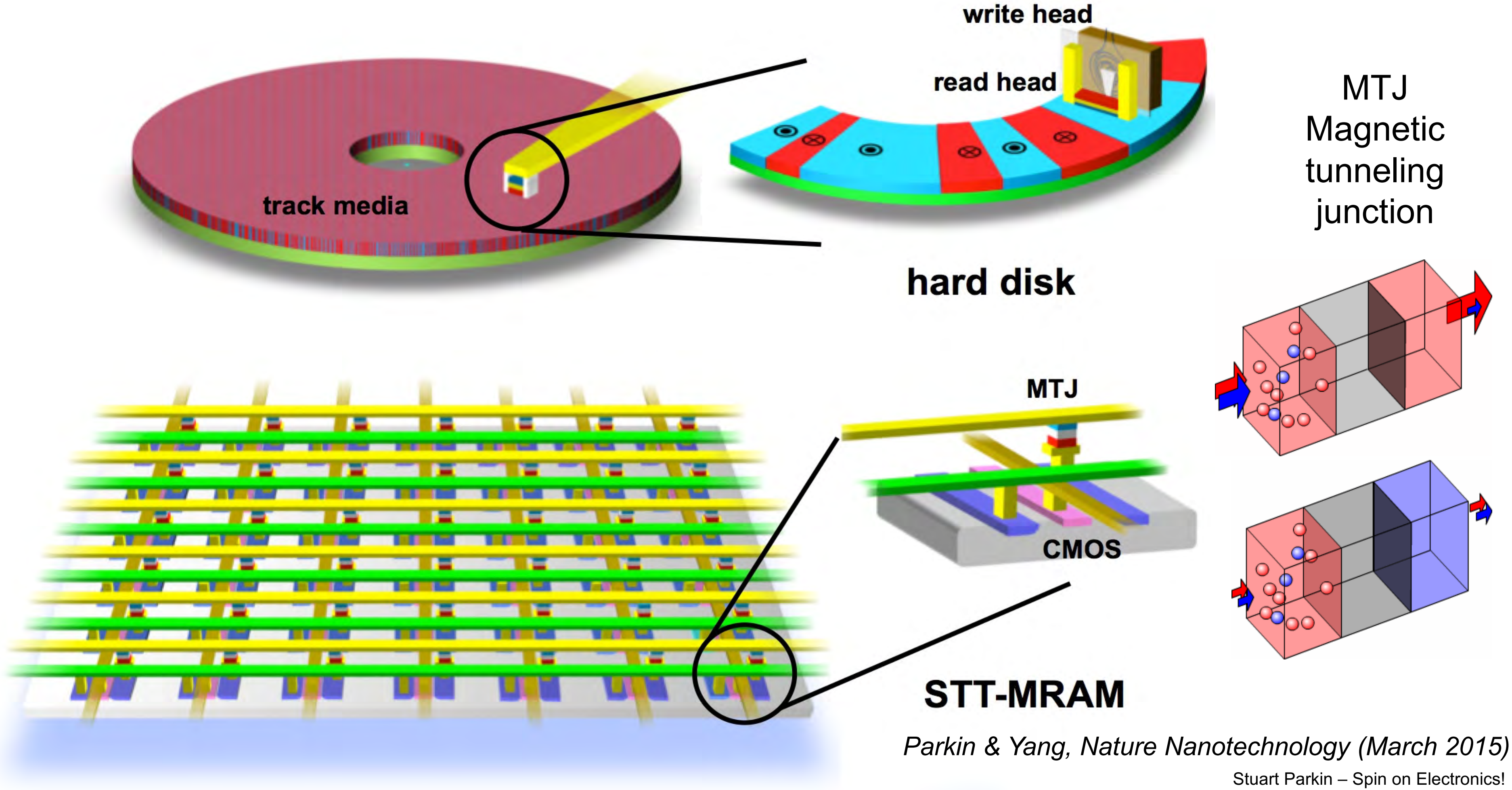
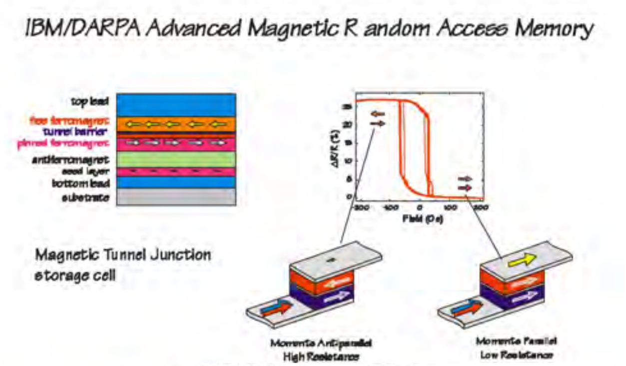
Atomically engineered materials; Spintronics; Cognitive devices; 3D structures; Room temperature superconductivity; Topological matter; Combinatorial materials discovery….

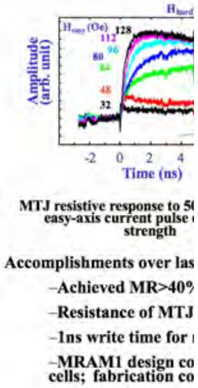
contact: stuart.parkin@mpi-halle.mpg.de

Spintronics – from materials and phenomena to applications



Parkin & Yang, Nature Nanotechnology (March 2015)





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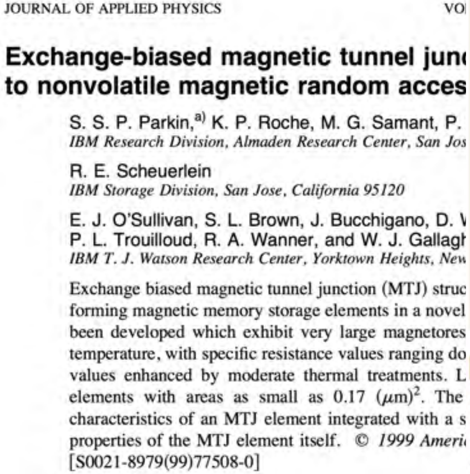

JOURNAL OF APPLIED PHYSICS VO

Exchange-biased magnetic tunnel junc
to nonvolatile magnetic random acces

S. S. P. Parkin,[a] K. P. Roche, M. G. Samant, P.
IBM Research Division, Almaden Research Center, San Jos

R. E. Scheuerlein
IBM Storage Division, San Jose, California 95120

E. J. O'Sullivan, S. L. Brown, J. Bucchigano, D. V
P. L. Trouilloud, R. A. Wanner, and W. J. Gallag
IBM T. J. Watson Research Center, Yorktown Heights, New

Exchange biased magnetic tunnel junction (MTJ) struc
forming magnetic memory storage elements in a novel
been developed which exhibit very large magnetores
temperature, with specific resistance values ranging do
values enhanced by moderate thermal treatments. L
elements with areas as small as 0.17 (μm)^2. The
characteristics of an MTJ element integrated with a s
properties of the MTJ element itself. © *1999 Ameri*
[S0021-8979(99)77508-0]

1999

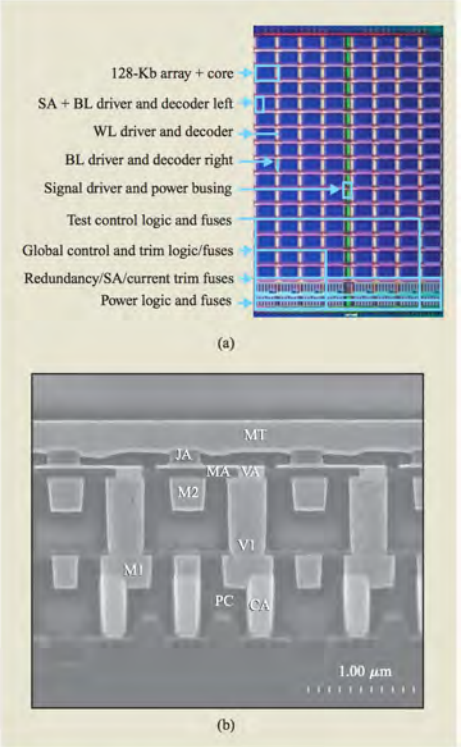


Figure 10

(a) Photograph of 16-Mb product demonstrator chip, with indications of main functional subunits. From [58], with permission; ©2005 IEEE. (b) SEM cross section showing three cells: M1, M2, and M3 are segments of three global wiring layers; VA, V1, and CA are segments of three via layers; PC is a segment of the transistor gate layer; JA is a segment of the tunnel-junction definition layer; and MA is a segment of the local wiring layer.

Innately 2D!

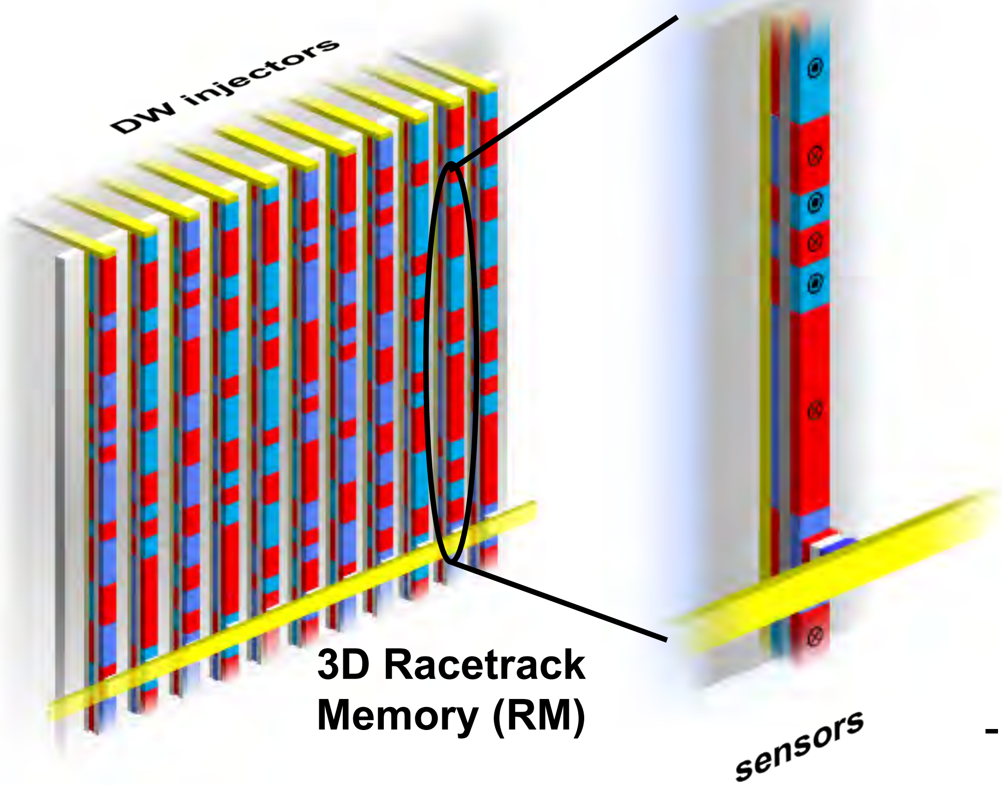
2016

Samsung
MICRON
Global Foundries
Intel
Everspin
Avalanche
Crocus
Spin Transfer Technologies
….

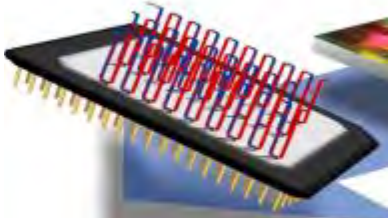
MRAM widely available in 2018!

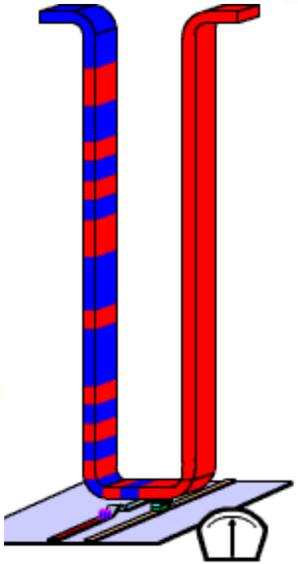
Magnetic Racetrack Memory

- Bits = Domains in the tracks



Parkin, US patents 6834005, 6898132.
*Parkin et al., Science **320**, 190 (2008).*
Parkin, Scientific American (2009).



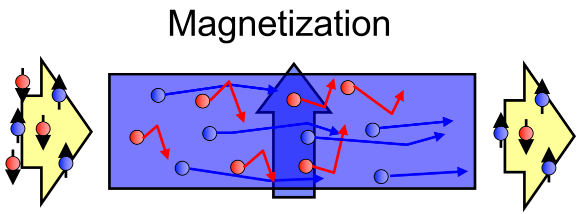


- A novel *three-dimensional* storage-class memory

- The capacity of a hard disk drive

Spin polarized current → manipulate domain walls!

- electrical current in ferromagnetic metals is innately spin-polarized

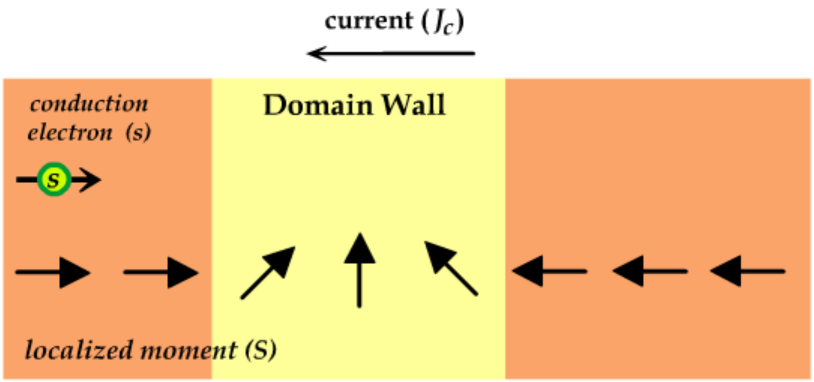


→ Giant magnetoresistance

→ Spin transfer switching

→ Current induced magnetization precession

- Current driven domain wall motion



→ Domain wall moves in direction of flow of spin angular momentum

→ For Ni and Co based soft magnetic alloys domain wall moves in direction of *electron flow*

→ *All domain walls move in same direction!*

First demonstration!

Current-Controlled Magnetic Domain-Wall Nanowire Shift Register

Masamitsu Hayashi, Luc Thomas, Rai Moriya, Charles Rettner, Stuart S. P. Parkin*

The controlled motion of a series of domain walls along magnetic nanowires using spin-polarized current pulses is the essential ingredient of the proposed magnetic racetrack memory, a new class of potential non-volatile storage-class memories. Using permalloy nanowires, we achieved the successive creation, motion, and detection of domain walls by using sequences of properly timed, nanosecond-long, spin-polarized current pulses. The cycle time for the writing and shifting of the domain walls was a few tens of nanoseconds. Our results illustrate the basic concept of a magnetic shift register that relies on the phenomenon of spin-momentum transfer to move series of closely spaced domain walls.

SCIENCE VOL 320 11 APRIL 2008

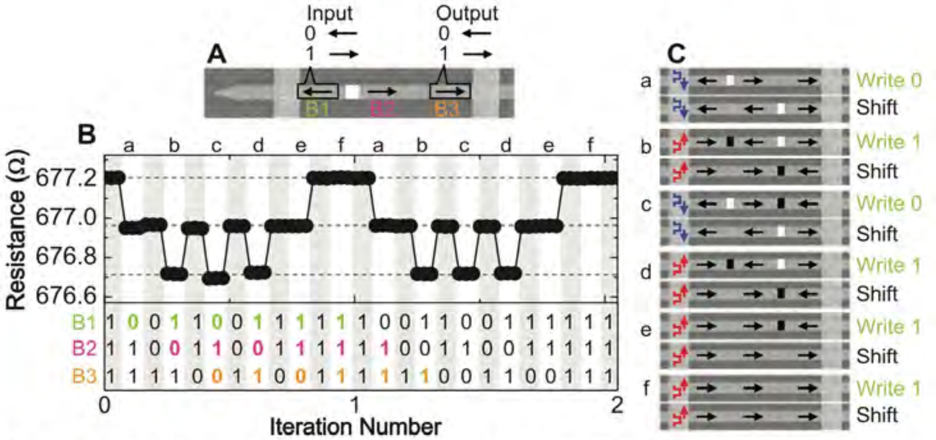
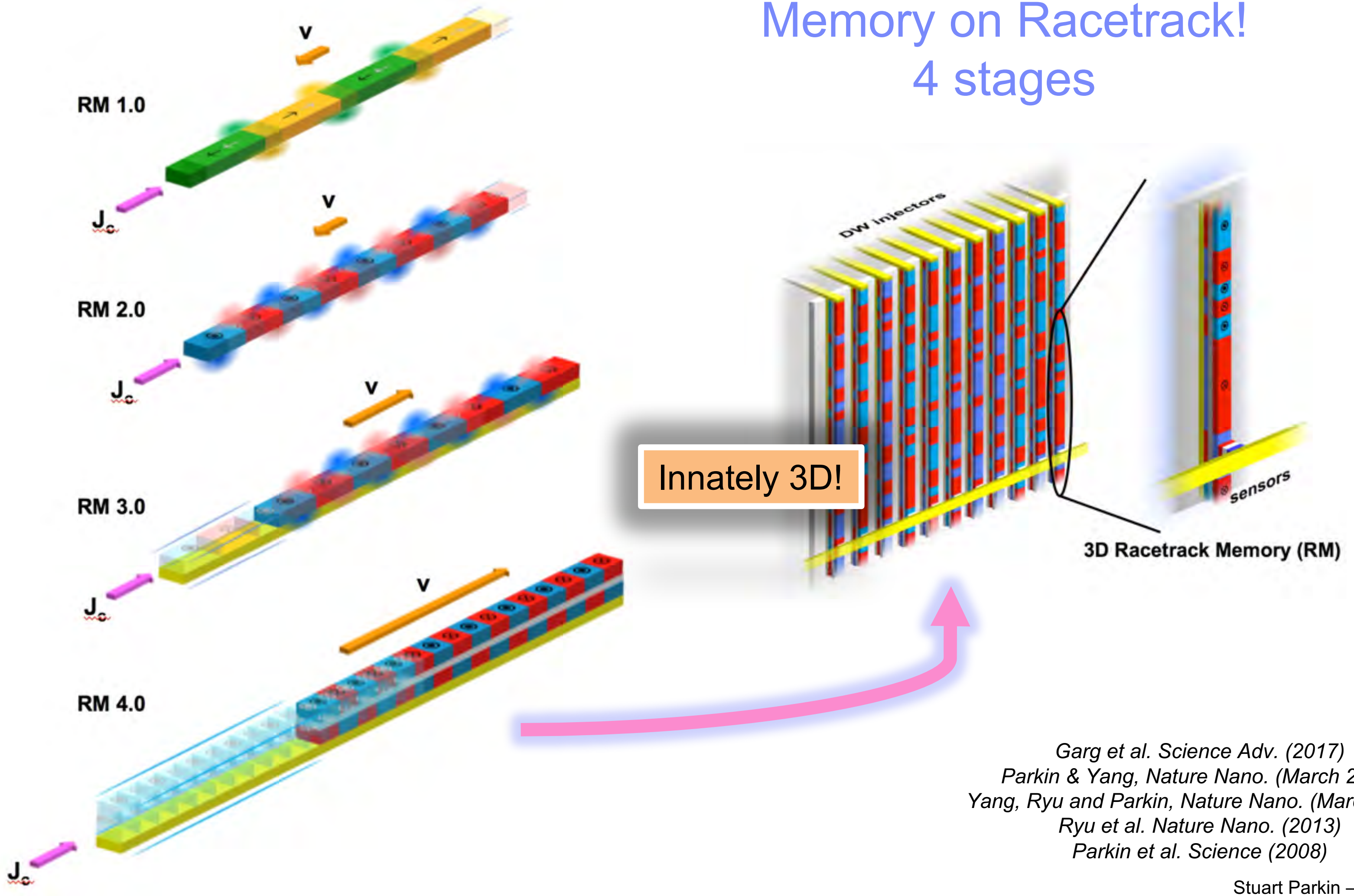


Fig. 4. Demonstration of a three-bit unidirectional magnetic DW shift register. (**A**) Data are encoded by the magnetization direction of three domains in the nanowire. (**B**) Nanowire resistance variation when a pulse sequence is used to write and shift along the register the sequence 010111 two times in succession. The light and dark regions indicate writing and shifting operations, respectively. The table shows the corresponding evolution of the states of the three bits during these operations. The highlighted digits show how the input bit sequence is transferred to the output after two write/shift operations. (**C**) Schematic illustration of the shift-register operation. Black squares and white squares represent HH and TT DWs, respectively. Black arrows represent the magnetization direction within each domain. Blue and red arrows represent the electron flow direction.

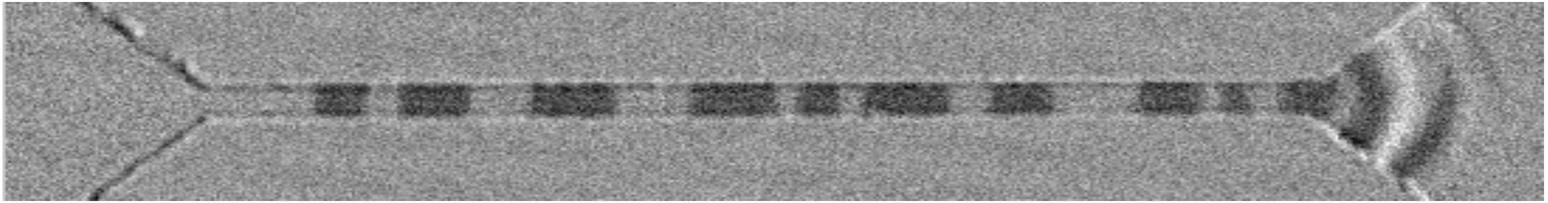
Racetrack Memory 1.0

Memory on Racetrack!
4 stages

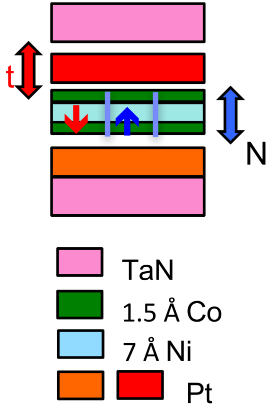


Garg et al. Science Adv. (2017)
Parkin & Yang, Nature Nano. (March 2015)
Yang, Ryu and Parkin, Nature Nano. (March 2015)
Ryu et al. Nature Nano. (2013)
Parkin et al. Science (2008)

Racetrack Memory 3.0



→ 20 domain walls moved in lock step with current pulses
→ High velocity at low current densities
→ Narrow domain walls (~6 nm)
→ Very thin racetracks (~1 nm)



Ryu et al. Nature Nanotechnology (2013)
Yang et al. Nature Nanotechnology (February 2015)
Parkin et al. Nature Nanotechnology (March 2015)

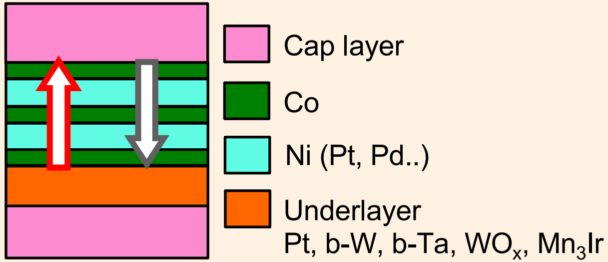
Chiral domain walls from Dzyaloshinskii-Moriya Interaction

(#1) Perpendicular Magnetic anisotropy (PMA)

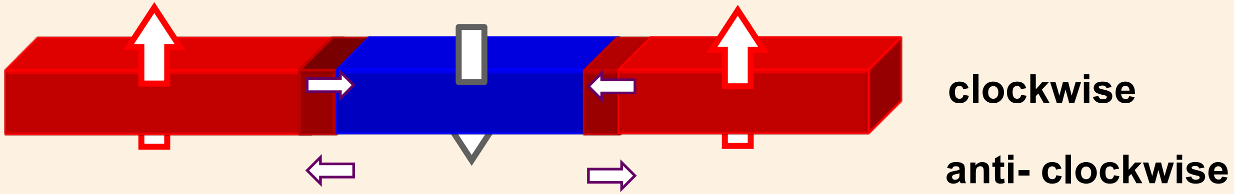
- materials: Co/Ni, Co/Pt, Co/Pd, RE/TM multilayers, low symmetry magnetic materials
- racetracks magnetized perpendicular to the plane of the racetrack

- *Bloch* and *Neel* domain walls
  → *narrow* domain walls

- Dzyaloshinskii-Moriya Interaction
  → *chiral* domain walls



Neel domain walls

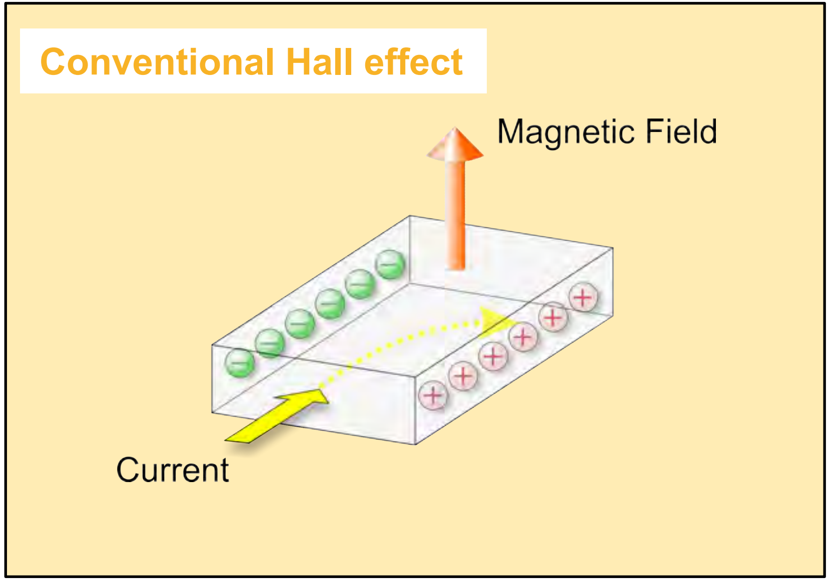


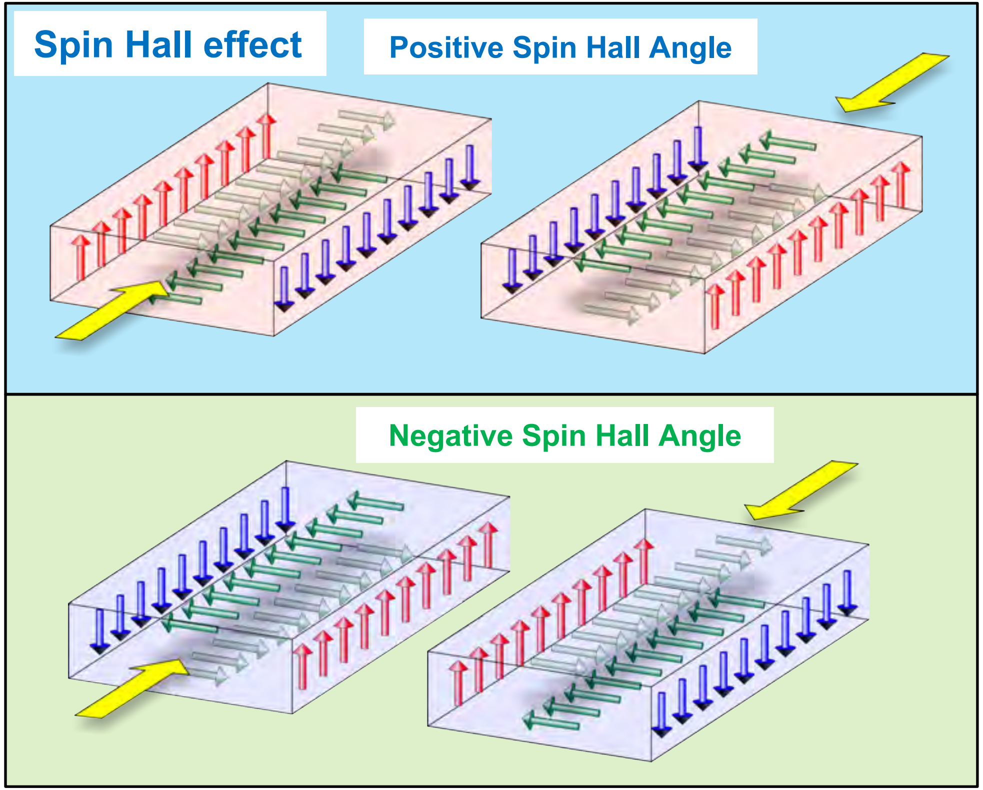
(#2) Dzyaloshinskii–Moriya interaction (DMI)

- *chirality* of domain walls set by interface(s) vector exchange interaction

(#3) Proximity Induced Magnetization (PIM)

(#4) Spin Hall effect: conversion of charge to spin current

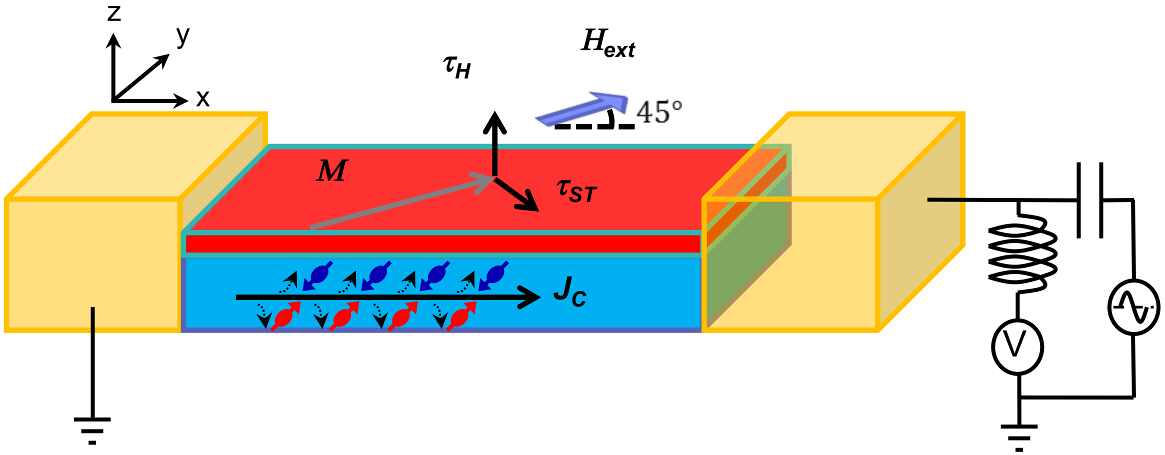




SHA: Spin Hall Angle
charge to spin conversion efficiency: ~10-30 %

Measurement of Spin orbit torque → Spin Hall angle

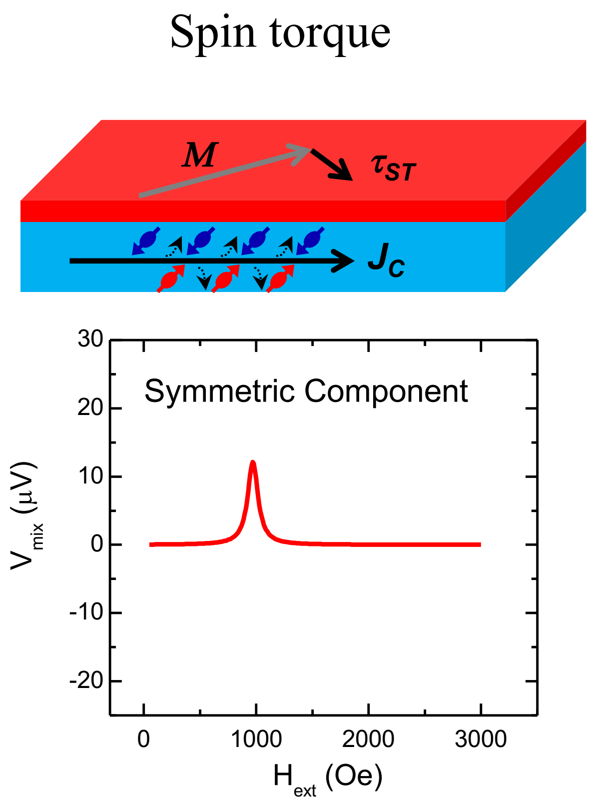
ST-FMR: Spin Torque Ferromagnetic Resonance

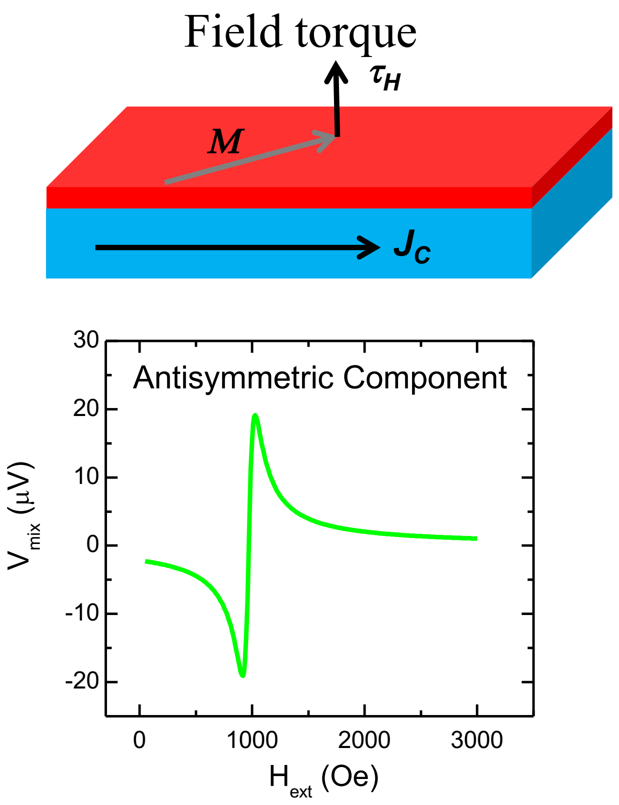


- Spin Hall torque and Oersted Field torque
- Ratio → charge to spin conversion efficiency

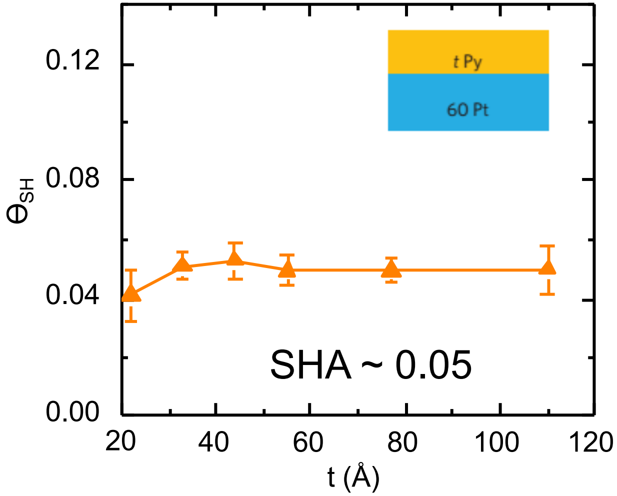
Liu *et al.*, Phys. Rev. Lett. (2011)

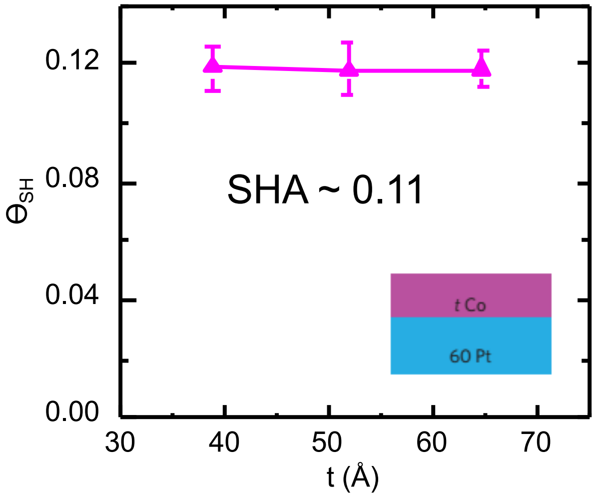
ST-FMR: Spin Torque Ferromagnetic Resonance

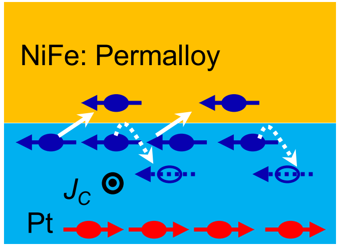


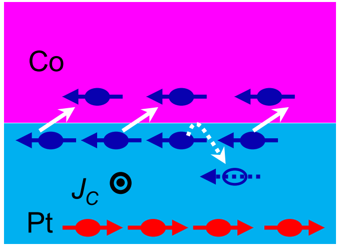


Interface is important!







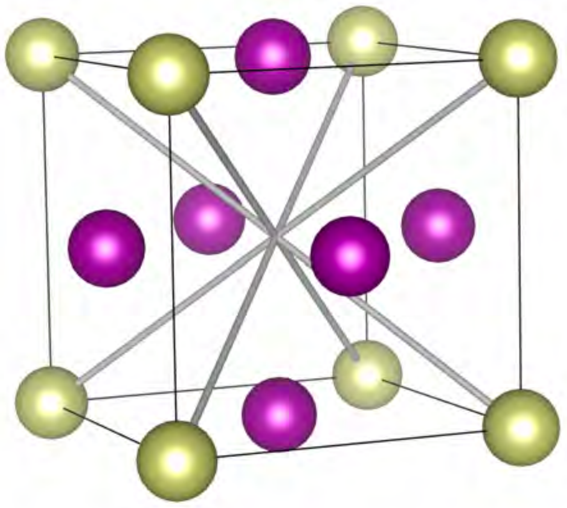


→ Transparency of NiFe/Pt and Co/Pt interfaces not 100 % → NiFe/Pt: 25%; Co/Pt: 50%

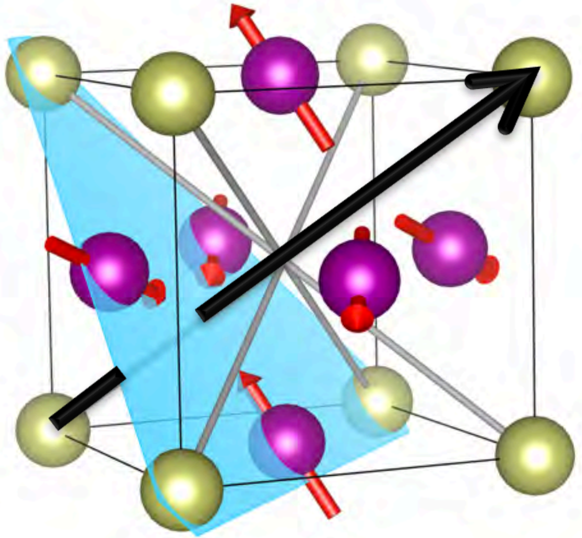
→ Correct for transparency then Spin Hall Angle: SHA of Pt = 0.20

Zhang *et al.*, Nature Phys. (2015)

IrMn$_3$ – fcc structure - a triangular antiferromagnet

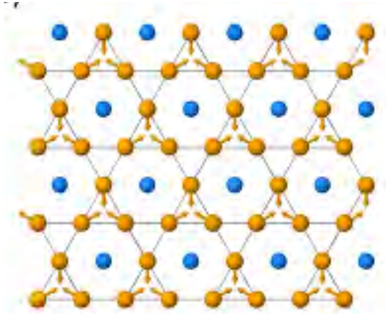


Lattice without magnetism
Four equivalent axes
[1 1 1]
[1-1 1]
[1 1-1]
[1-1-1]



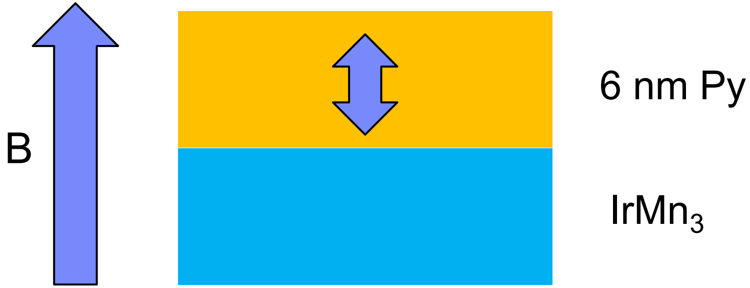
Lattice with noncollinear AF
[1 1 1] → one special plane

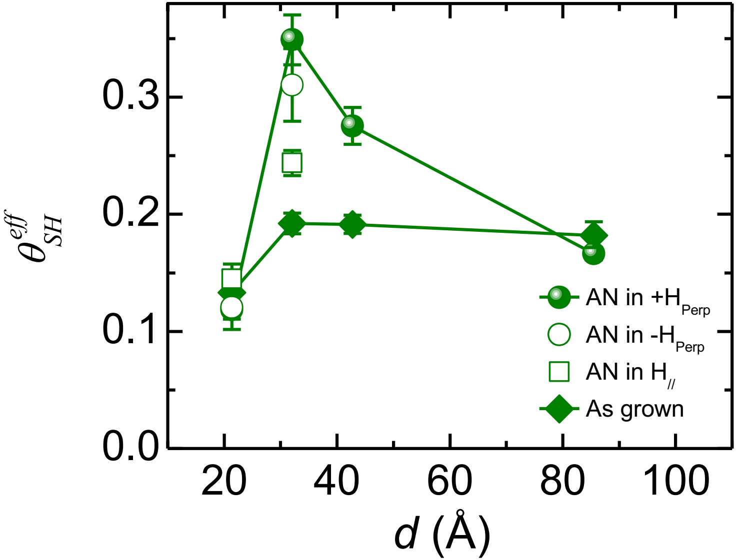
[1-1 1]
[1 1-1]
[1-1-1]



Zhang *et al.* Sci. Adv. (2016)

Strong effect on SHA of field annealing in *perpendicular* field → change in AF domain structure in $IrMn_3$



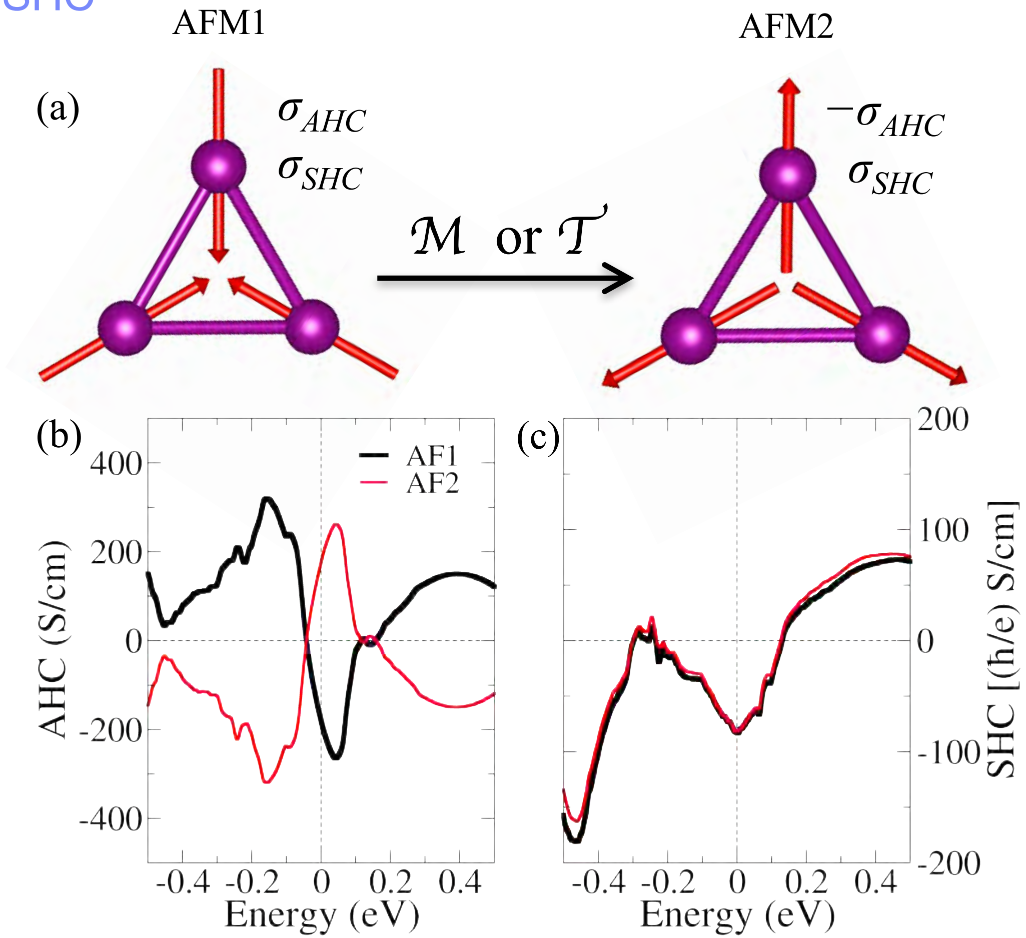


→ Tunes the AFM domain configuration at the $IrMn_3$ interface

→ Only effective for thicknesses of IrMn3 for which the AF domains can be reset i.e. the blocking temperature $T_B < T_{AN}$

N.B. in-plane annealing → changes in-plane exchange bias field → no effect on SHA

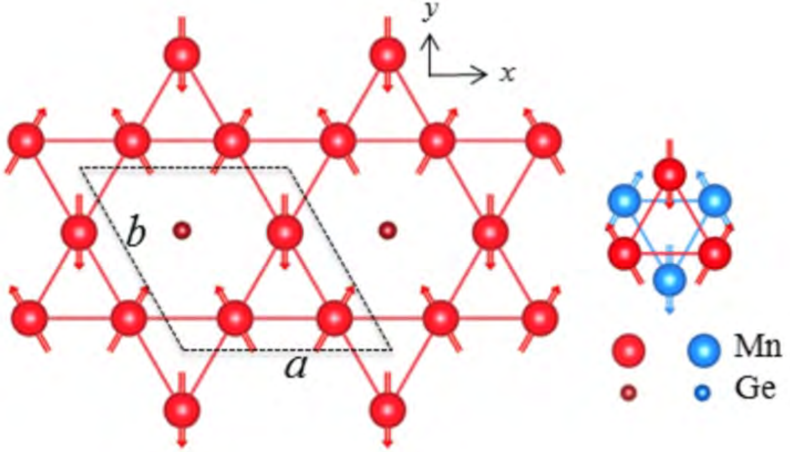
IrMn$_3$: Calculation of AHC and SHC

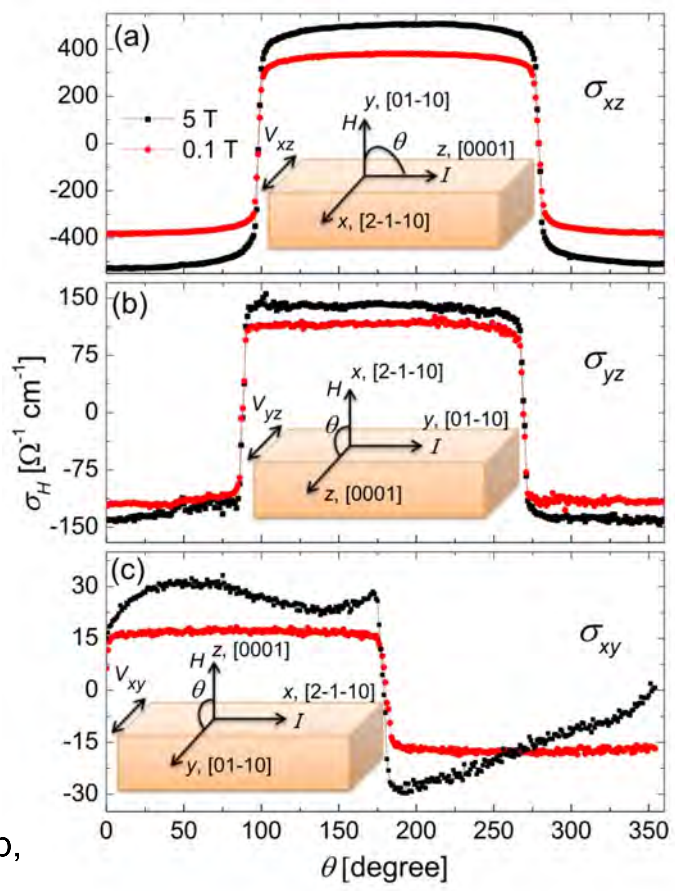


Calculations by Binghai Yan et al.

Zhang *et al.* Sci. Adv. (2016)

AHE in *hexagonal* Mn_3Ge: a triangular AF





→ Results on single crystals

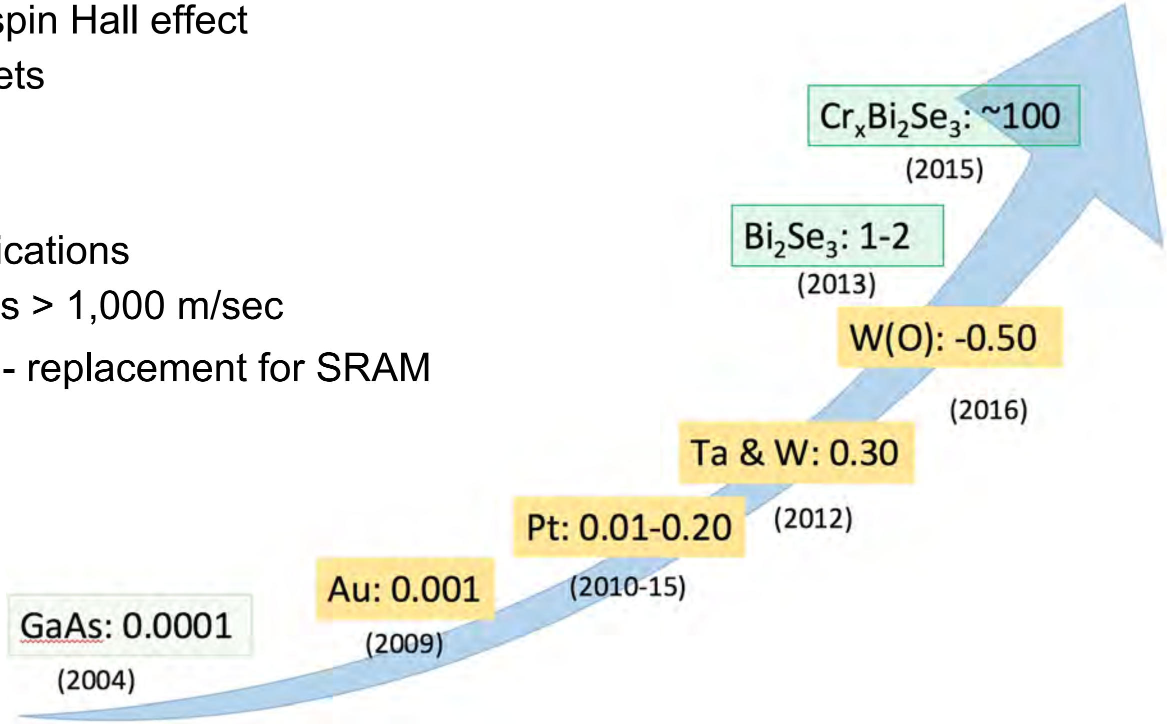
→ Facet dependent AHE conductivity in Mn_3Ge: a non-collinear AFM

→ Anticipate strong SHE/ SHC in this and related materials (*h*-Mn_3Sb, *h*-Mn_3Sn)

Nayak *et al.* Sci. Adv. (2016)

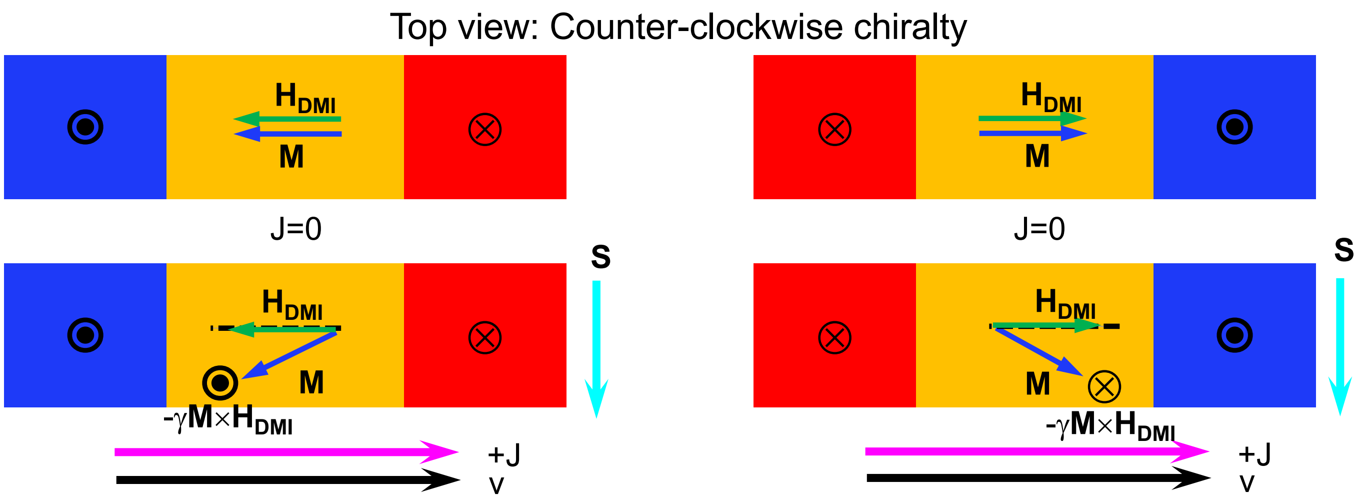
Charge to spin conversion vias the Spin Hall Effect

- Spin Hall effect: dramatic evolution
- Novel materials show large spin Hall effect
  - Triangular antiferromagnets
  - Novel crystalline phases
- Important technological applications
  - Racetrack – DW velocities > 1,000 m/sec
  - 3T Single DW Racetrack - replacement for SRAM



Zhang *et al.* Nat. Phys. (2015)
Demasius *et al.*, Nat. Comm. (2016)
Nayak *et al.* Sci. Adv. (2016)
Zhang *et a.* Sci. Adv. (2016)

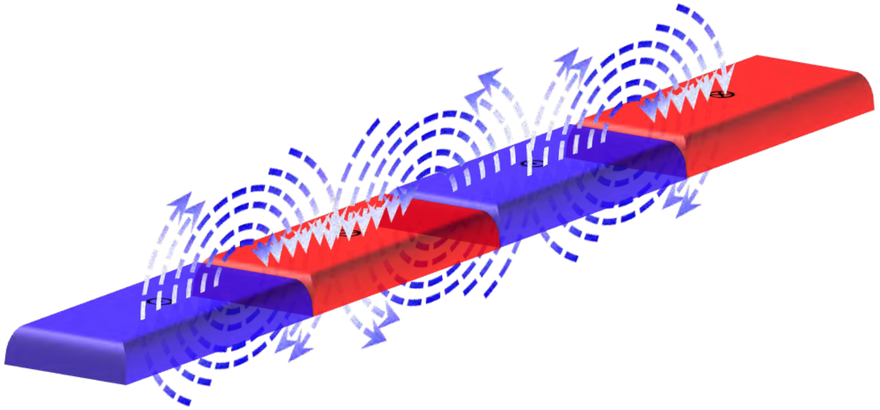
Chiral Spin Torque → drives domain walls very fast!



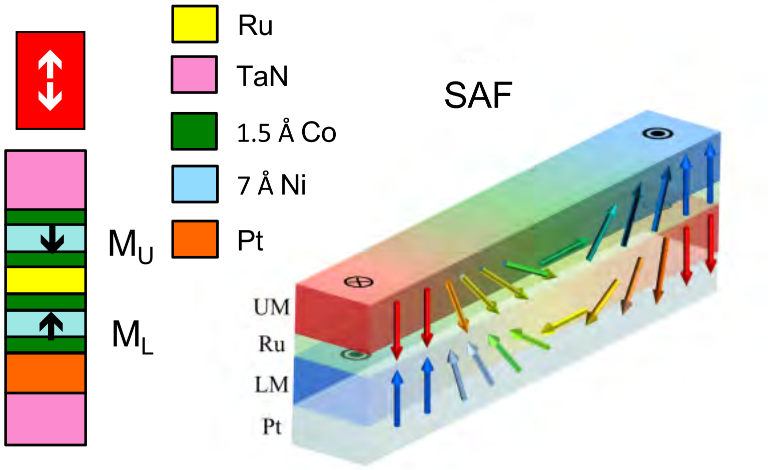
- DMI local field → Neel domain walls
- DMI field $\mathbf{H}_{DMI}$ sets a specific chirality the Neel domain Walls
- spin Hall torque causes **M** to rotate towards spin accumulation **S**
- DMI field torque moves all the DWs along the current flow direction.

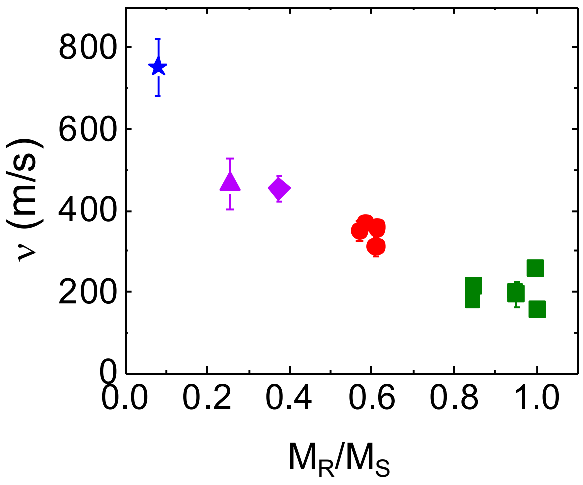
Ryu et al., Nat. Nanotech. (2013); Yang et al., Nat. Nanotech. (2015)

Dipolar fringing fields emitted from Domains



RM 4.0: Very High DW Speeds in SAF PMA racetracks

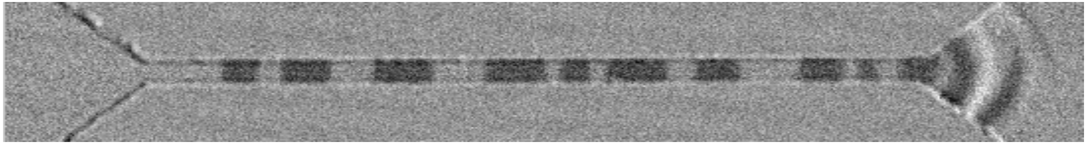




- → SAF: Synthetic antiferromagnet: upper racetrack = exact mirror image of lower
- → DW velocity increases as degree of compensation of moments in upper and lower racetracks increased
- → 4x highest DW velocity yet reported → Speeds exceed 1.5- 5 km/sec
- → AF exchange field > DMI field

Yang et al. Nature Nanotechnology (2015)

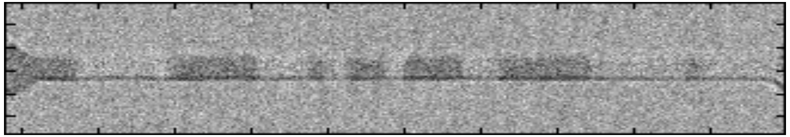
Racetrack Memory 4.0



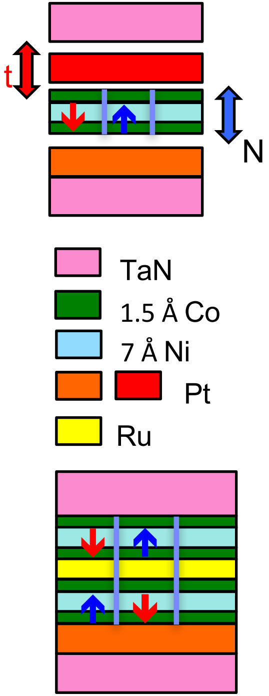
→ 20 domain walls moved in lock step with current pulses
→ High velocity at low current densities
→ Narrow domain walls (~6 nm)

→ Very thin racetracks (~1 nm)

→ Giant domain wall velocities in Synthetic Antiferromagnet racetracks



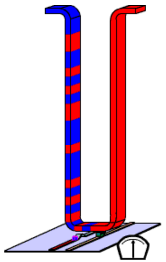
Ryu et al. Nature Nanotechnology (2013)
Yang et al. Nature Nanotechnology (February 2015)
Parkin et al. Nature Nanotechnology (March 2015)

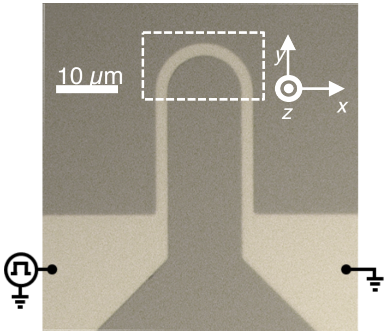


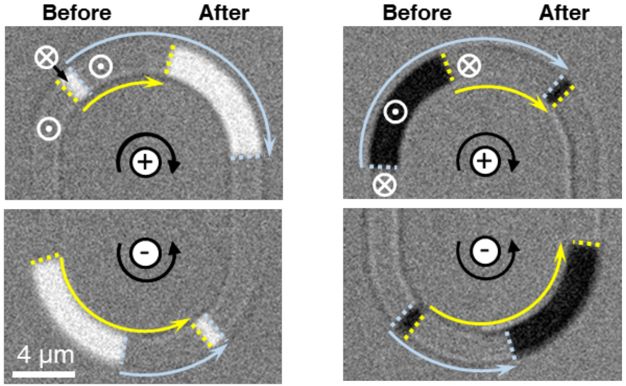
SORBET - complex interplay of 4 spin-orbit derived phenomena

1. Perpendicular magnetic anisotropy – from broken symmetry from interfaces
2. Proximity induced magnetization
3. Chiral domain walls – DMI
4. Spin currents – from spin Hall effect (SHE)

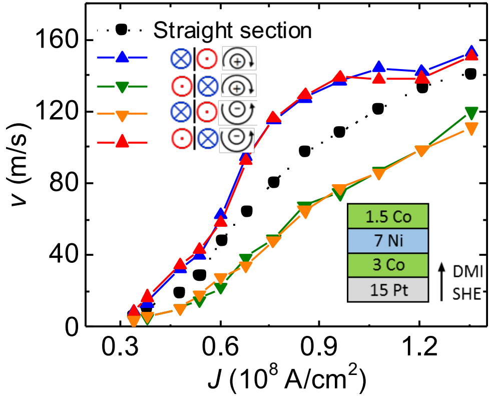
Dramatic dependence of DW velocity on Curvature







DW motion after 2 pulses (0.6 x 10^8 A/cm² for 100ns)



R = 7 *μm* and w = 2 *μm*

→ Domain size decreases or increase by 10 times depending on curvature

- DW velocities are different for all J.
- CW (CCW) DW motion : $\kappa > 0$ ($\kappa < 0$)
- $\odot \mid \otimes$ $\kappa > 0$ = $\otimes \mid \odot$ $\kappa < 0$ → slower
- $\odot \mid \otimes$ $\kappa < 0$ = $\otimes \mid \odot$ $\kappa > 0$ → faster
- DW velocity in straight wire ($\kappa = 0$) is in-between $\kappa > 0$ and $\kappa < 0$.

Garg *et al.* Science Advances (May 5, 2017)

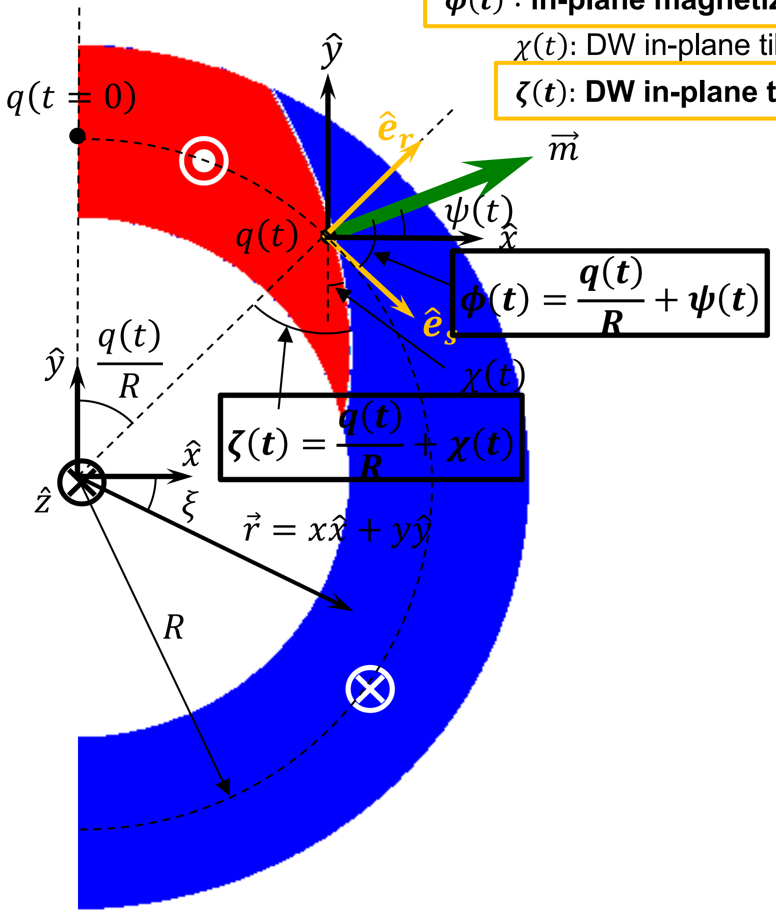
Quasi 2D Model for curved wires with radius dependent current

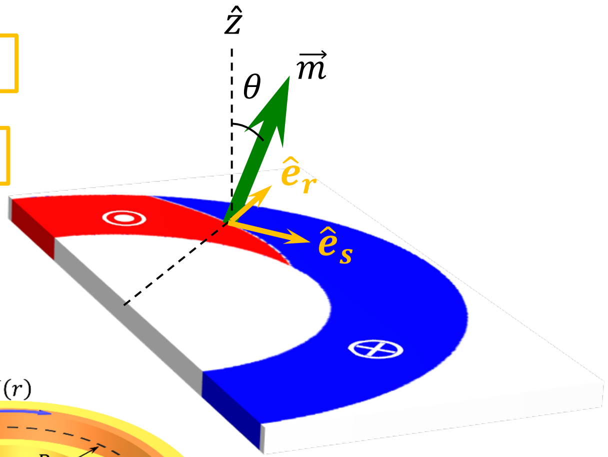
$\psi(t)$: in-plane magnetization angle in static frame

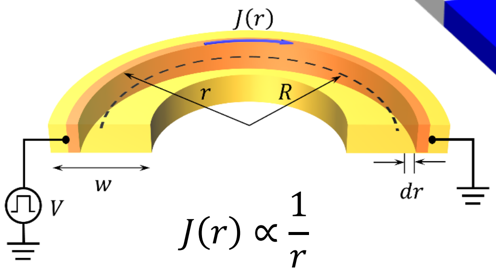
$\phi(t)$: in-plane magnetization angle in moving frame

$\chi(t)$: DW in-plane tilting angle in static frame

$\zeta(t)$: DW in-plane tilting angle in moving frame

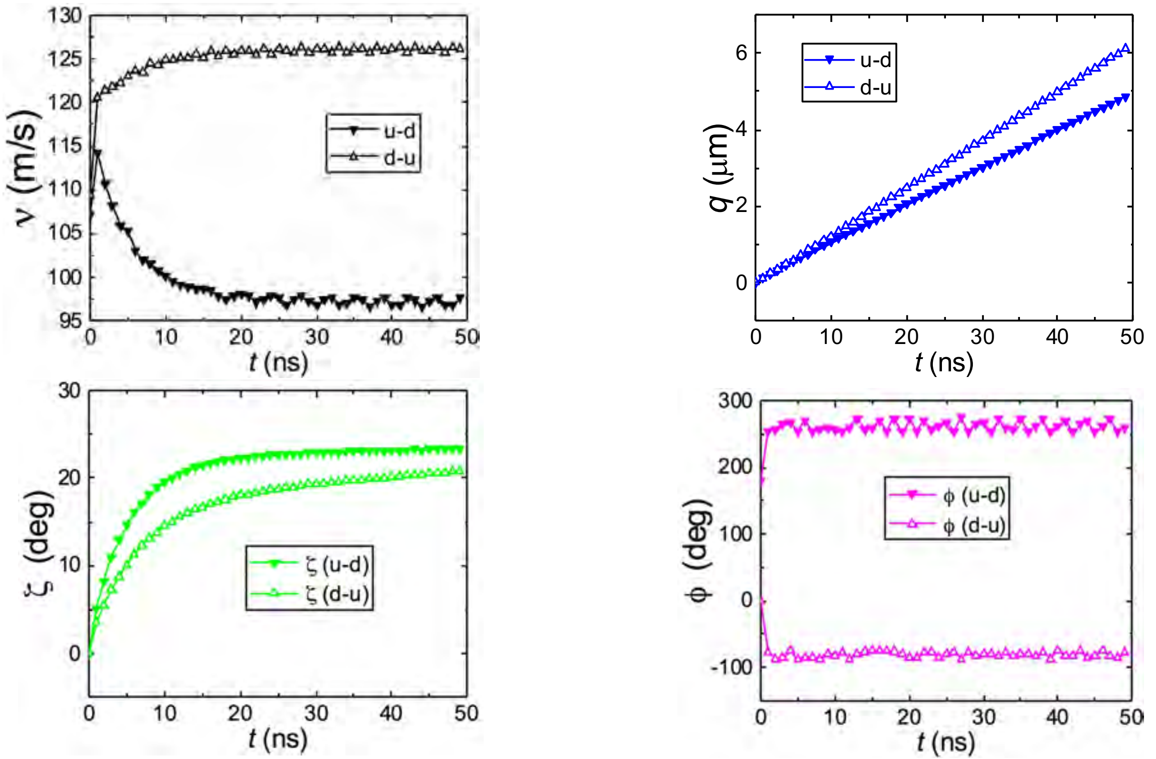






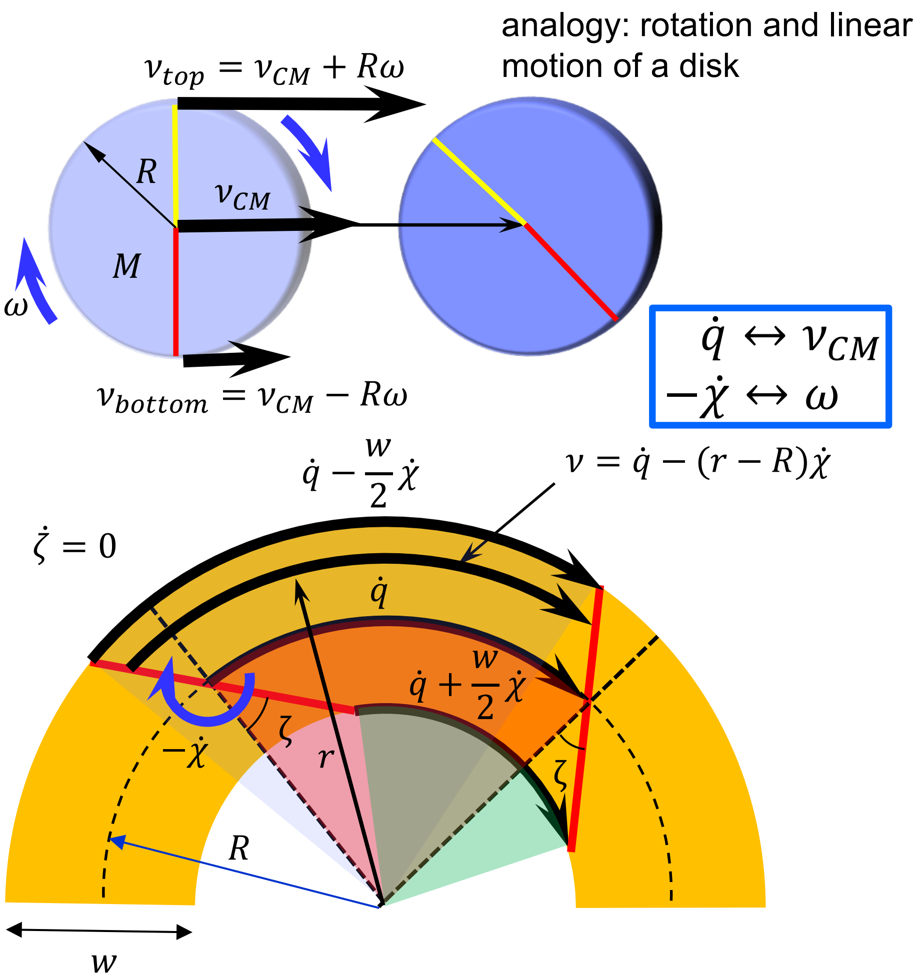
- DW is not straight but **curved** due to the cylindrical symmetry of experimental parameters such as electrical current, SHE and DMI.
- Key point → transformation between cylindrical moving frame and cartesian static coordinates → DW magnetization and DW tilting angle in static coordinates are a function of DW position.

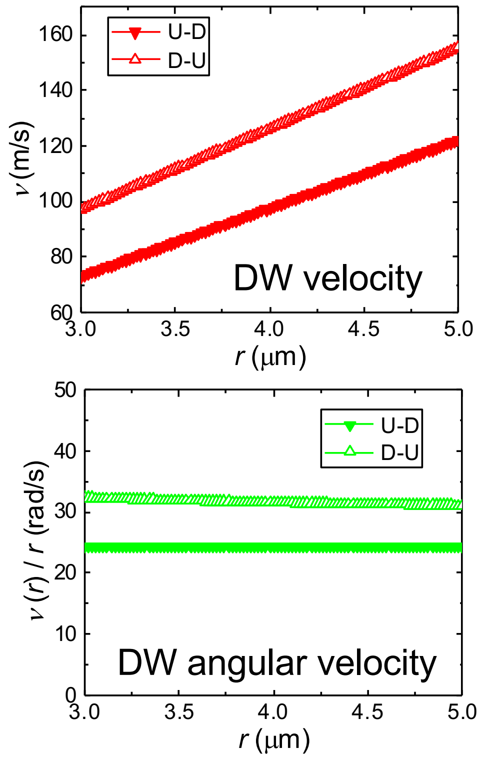
Quasi Two Dimensional Model Results for curved wires: time-resolved



- Terminal velocity for ⊙ | ⊗ with κ > 0 is larger than that for ⊗ | ⊙ with κ > 0.
- It takes shorter for ⊙ | ⊗ with κ > 0 (~ 10 ns) to reach the terminal velocity than for ⊗ | ⊙ with κ > 0 (~20 ns).
- DW magnetization reaches steady state much faster (< 1ns) than DW tilting angle (> 20 ns).

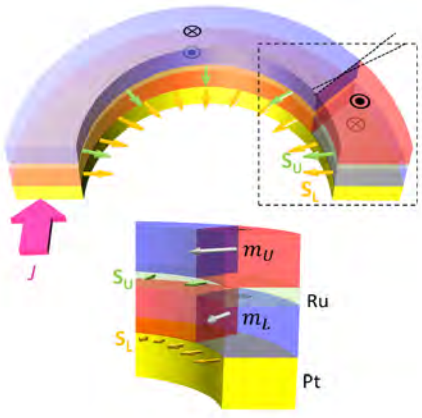
Torque along the radial direction in curved wires

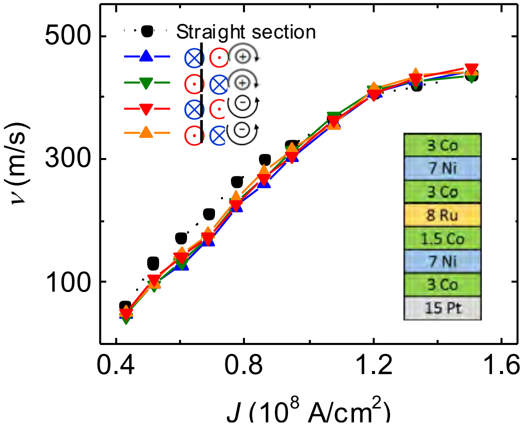


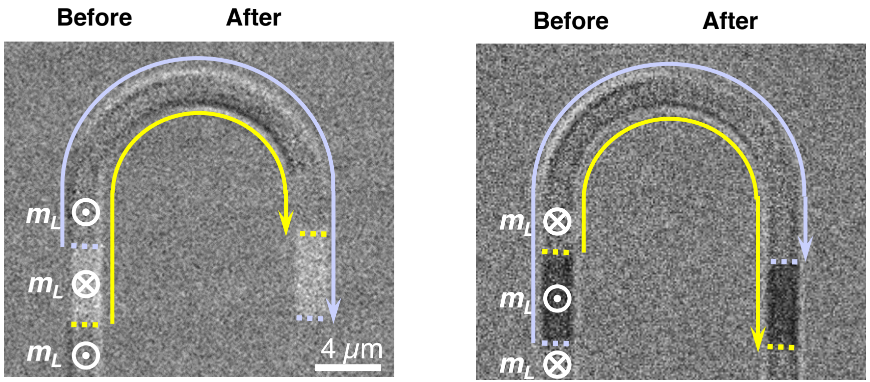


- DW velocity (torque) at outer rim is faster than at inner rim.
- Angular velocity is the same along the DW in steady state.

DW motion in synthetic antiferromagnetic curved wires → no change !



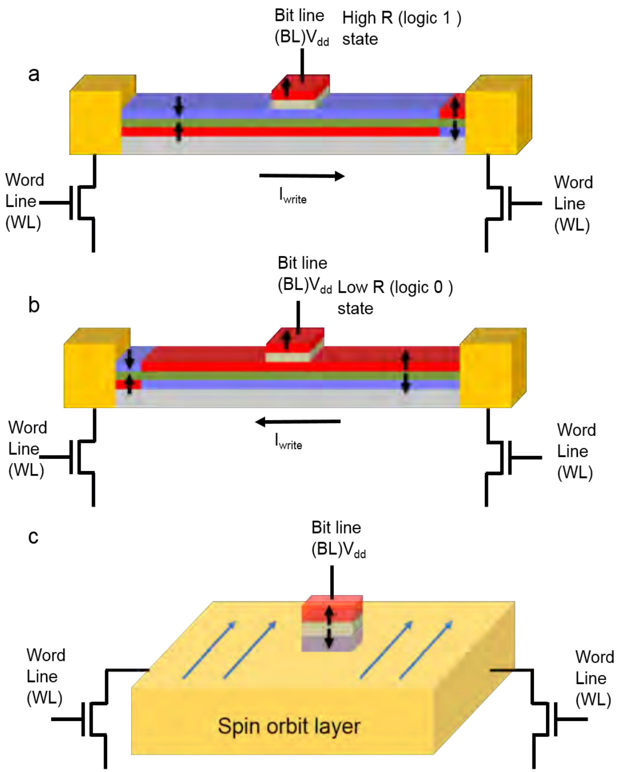




- Curvature does not affect DW motion in SAF nanowires.
- Exchange coupling torque dominant → insensitive to DW tilting
- Curvature induced lock-step motion breakdown problem resolved !!

Garg *et al.* Science Advances (May 5, 2017)

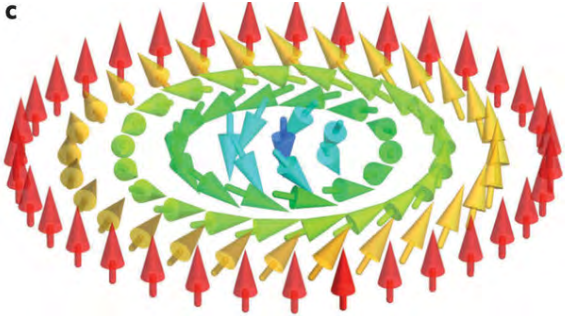
3T single domain wall Racetrack → SRAM replacement

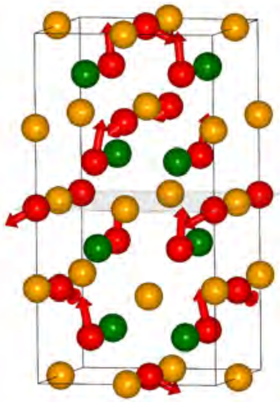


	ultra dense SRAM	1DWRM 6 Q layout	3T-SOT-MRAM 6 Q layout	1DWRM 8 Q layout	3T-SOT-MRAM 8 Q layout
Fins/FET	1	1	1	2	2
Feature size (F) (nm)	14	14	14	14	14
Fin pitch (FP) (nm)	42.67	42.67	42.67	42.67	42.67
contact poly pitch (CPP) (nm)	80	80	80	80	80
Bit line pitch (BLP) (FP)	8	4	4	4	4
Bit line pitch (BLP) (nm)	341.3	170.7	170.7	170.7	170.7
Word line pitch (WLP) (CPP)	2	1.5	1.5	2	2
Word line pitch (WLP) (nm)	160	120	120	160	160
Cell (Q)	16	6	6	8	8
Cell (nm^2)	54613	20480	20480	27307	27307
Cell (F^2)	278.6	104.5	104.5	139.3	139.3
Cell/SRAM	1	0.375	0.375	0.5	0.5
Energy (fJ)	96	9.6	9.6	19.2	19.2
Switching speed (ps)	667	< 200	< 200	< 200	< 200
Max transistor current (μA)	30	30	30	60	60

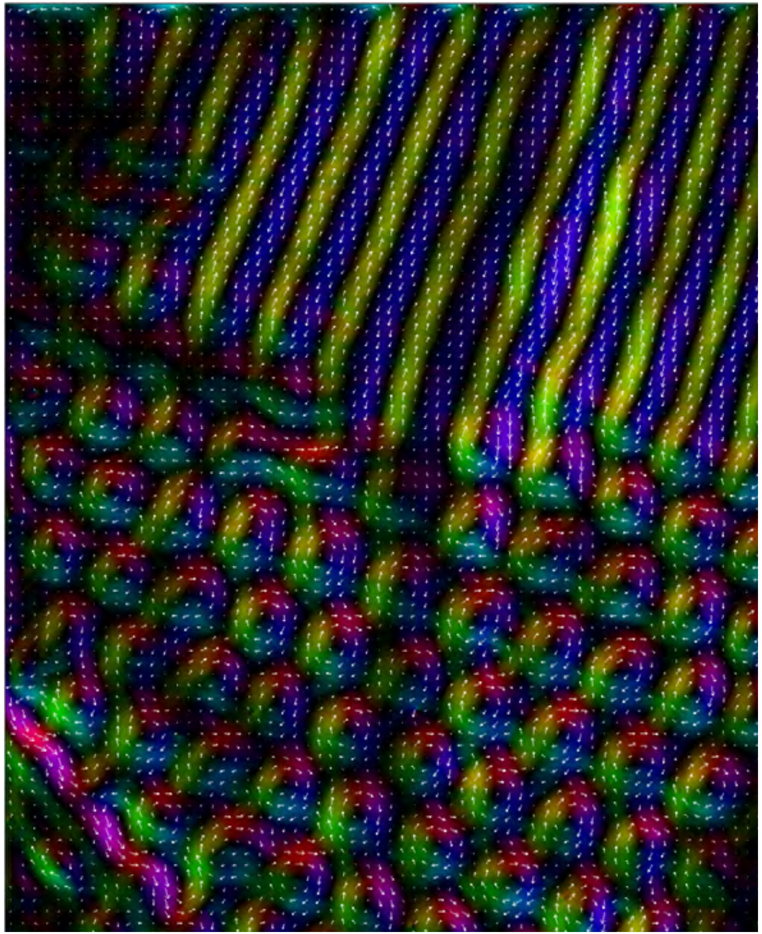
- 100 picosecond writing speed
- Non-volatile & very low energy
- 40% size of SRAM

Skyrmions at room temperature in $Mn_2(Pd_{40}Pt_{60})_1Sn$

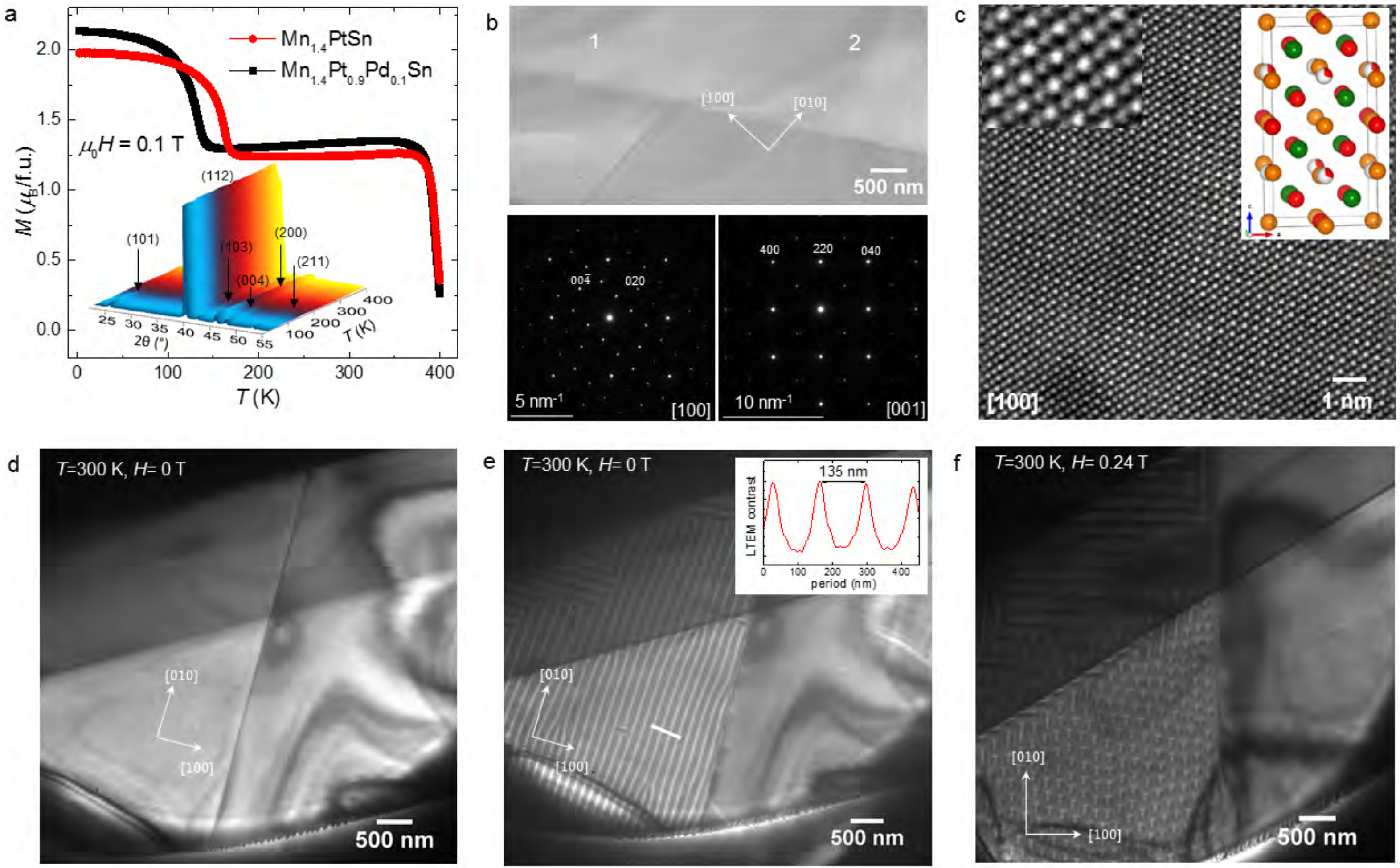




Nayak *et al.* (unpublished)

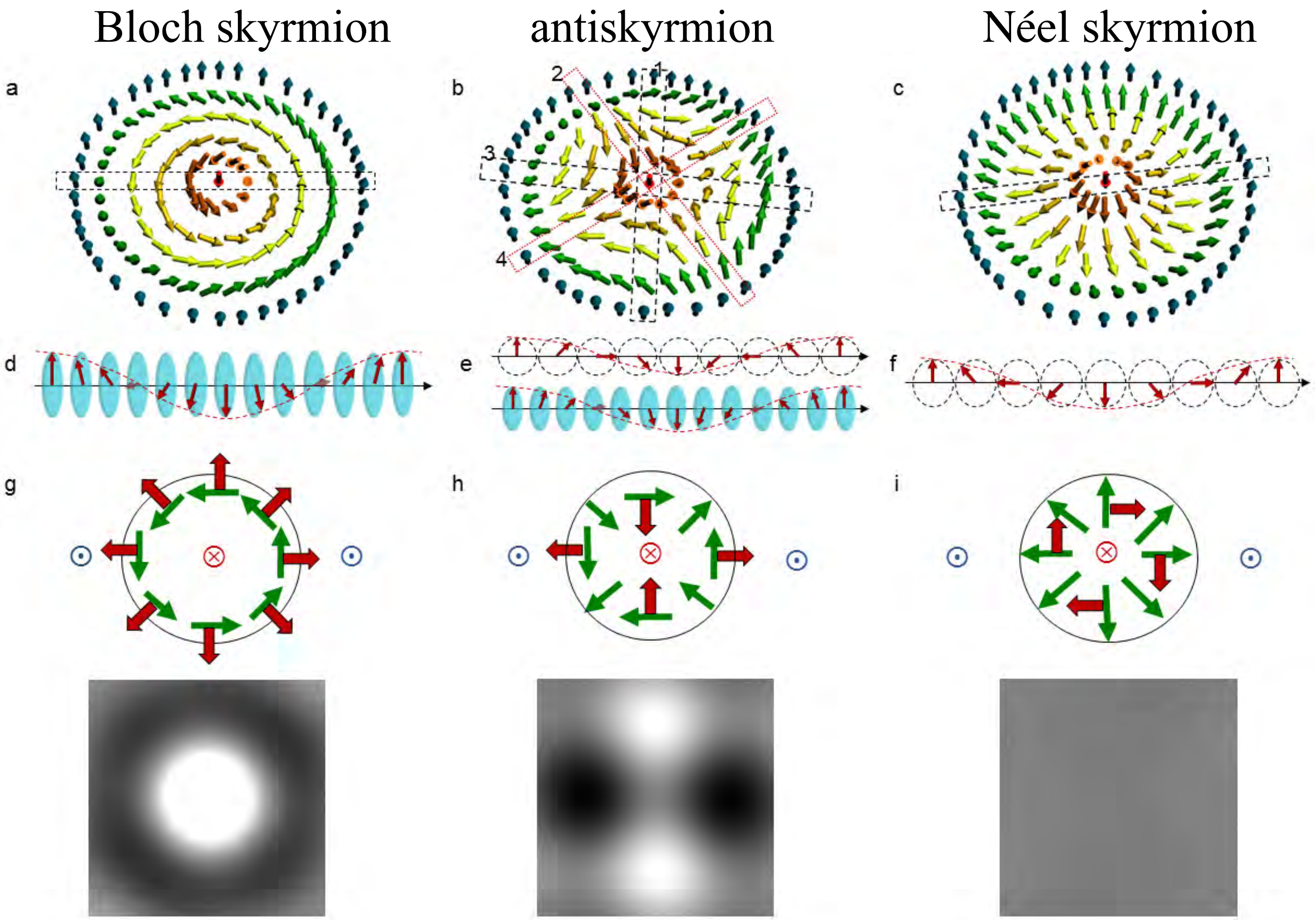


Non collinear spin structures in $Mn_{1.4}(Pt_{0.9}Pd_{0.1})Sn$



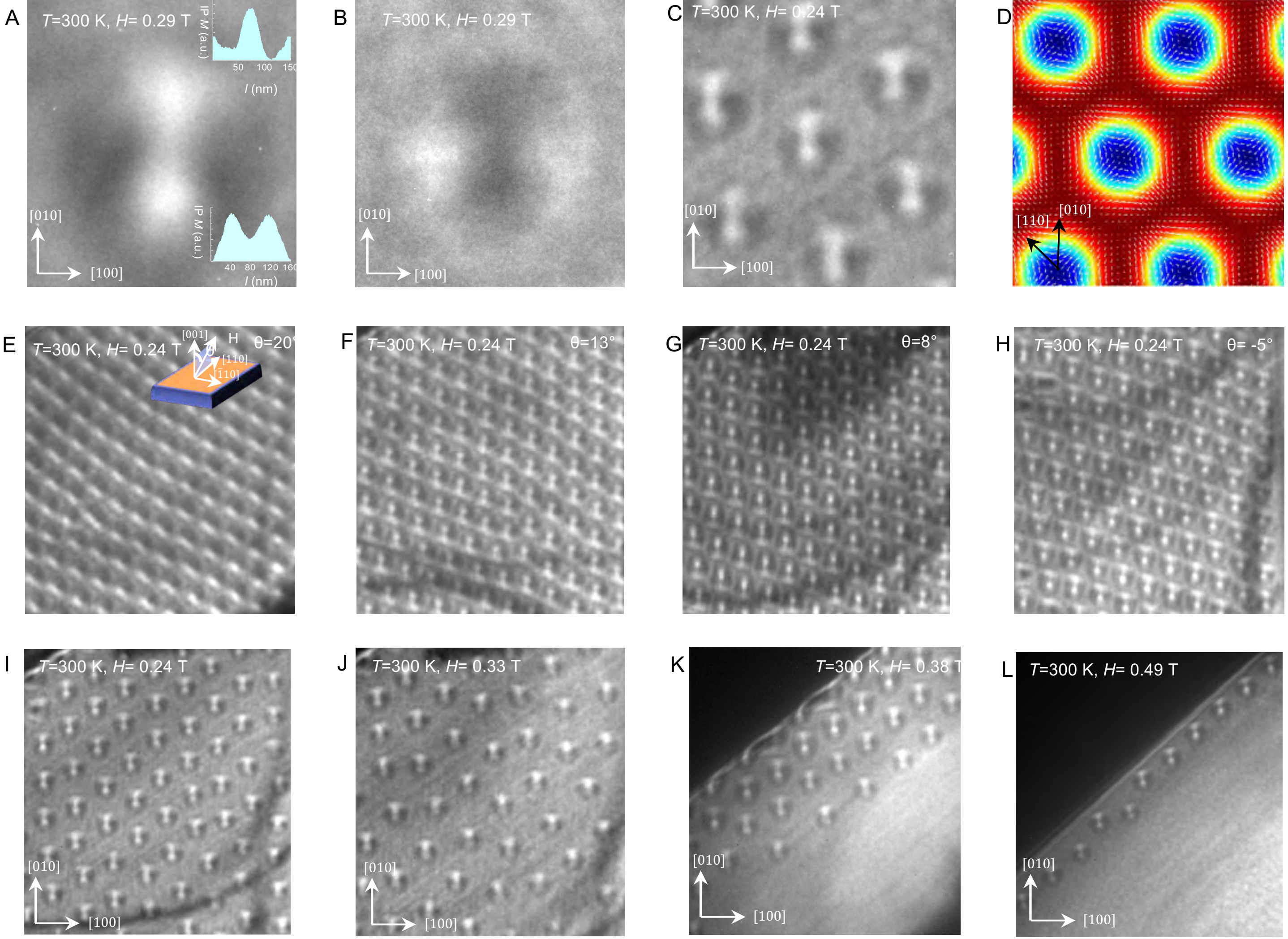
lectronics!

Skyrmions and anti-skyrmions



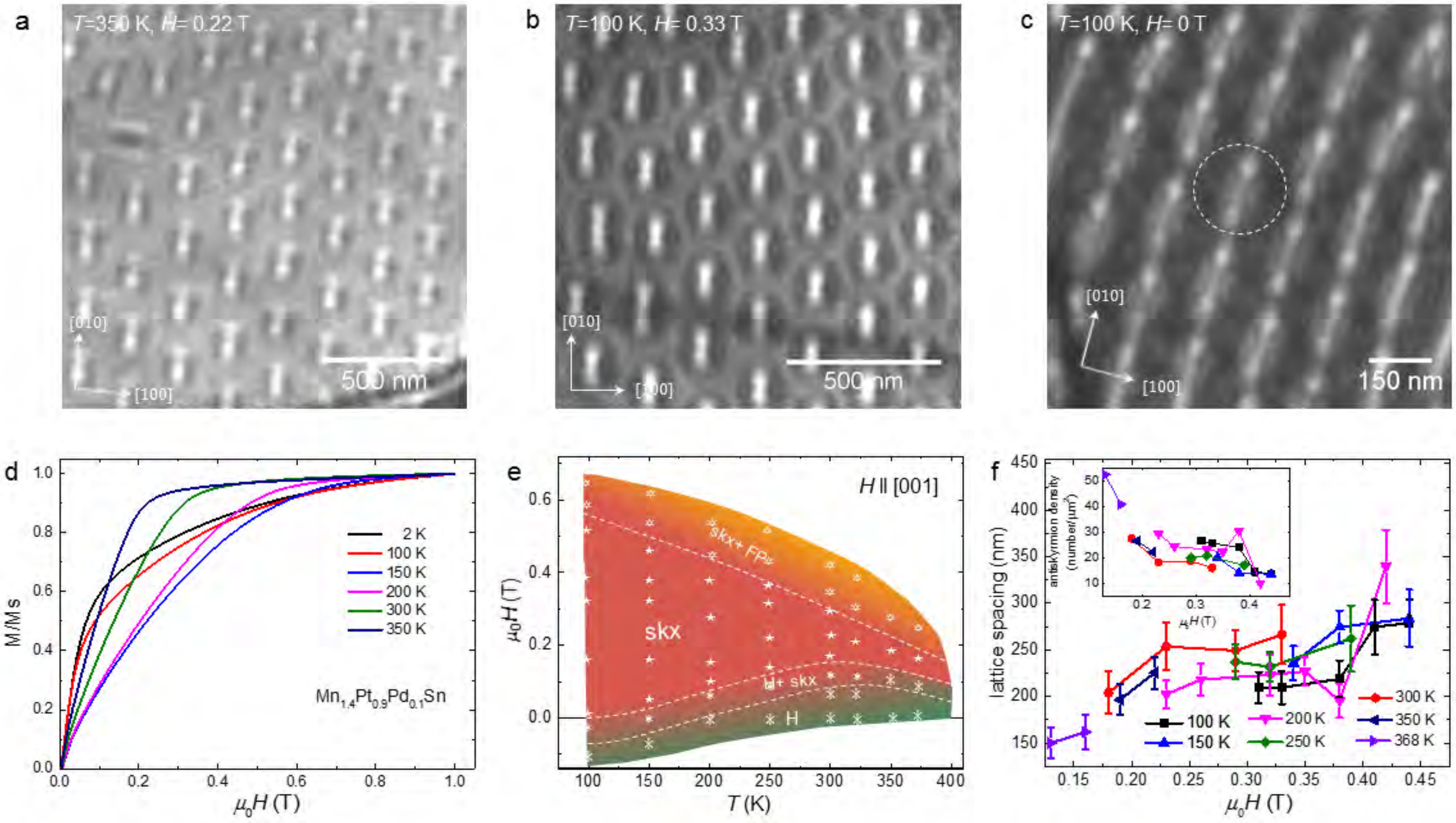
Anti-Skyrmions!

1st observation
- Stable above 300 K



Nayak *et al.* (2017)

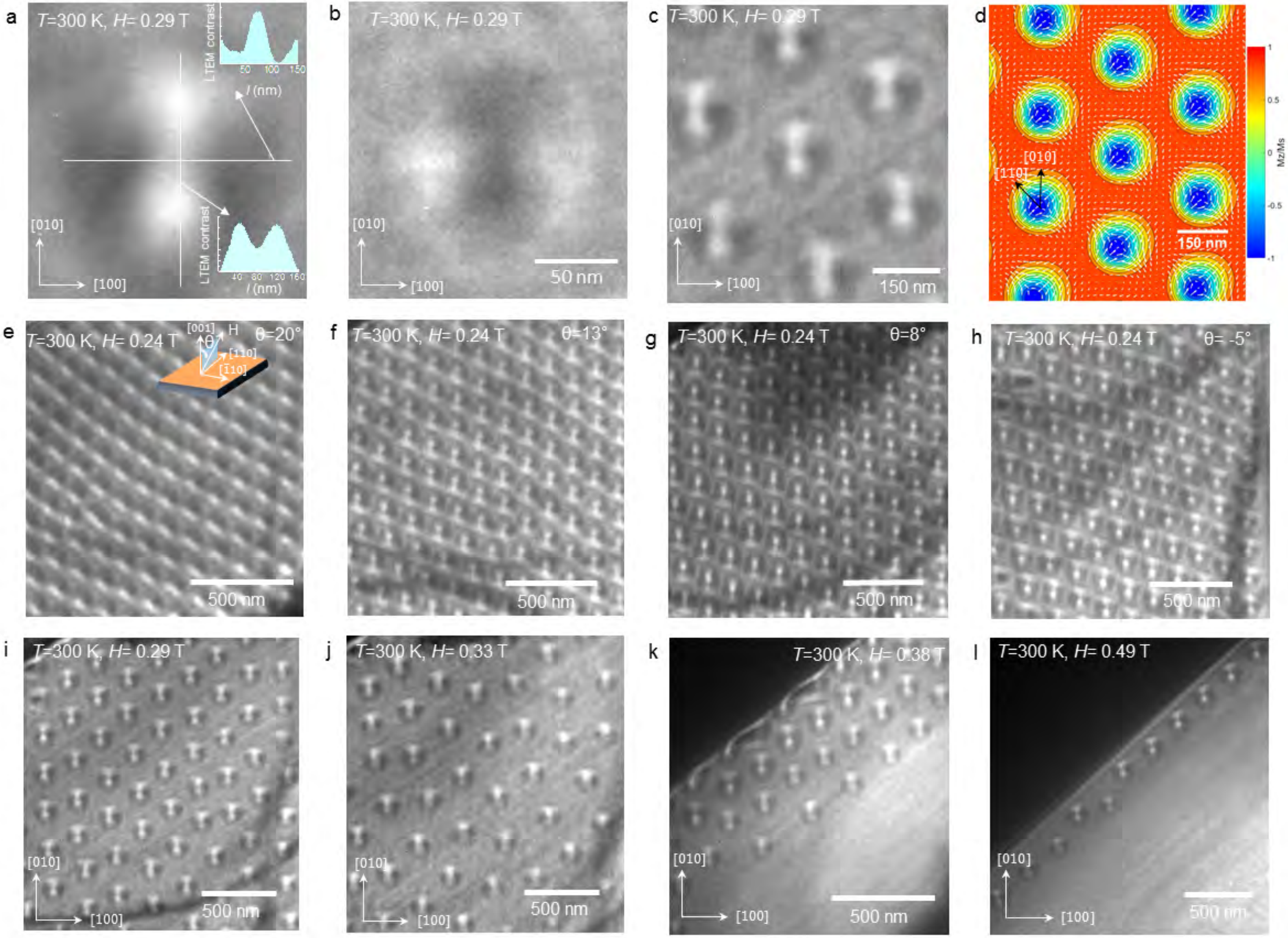
Phase diagram: $Mn_{1.4}(Pt_{0.9}Pd_{0.1})Sn$



Nayak *et al.* (submitted)

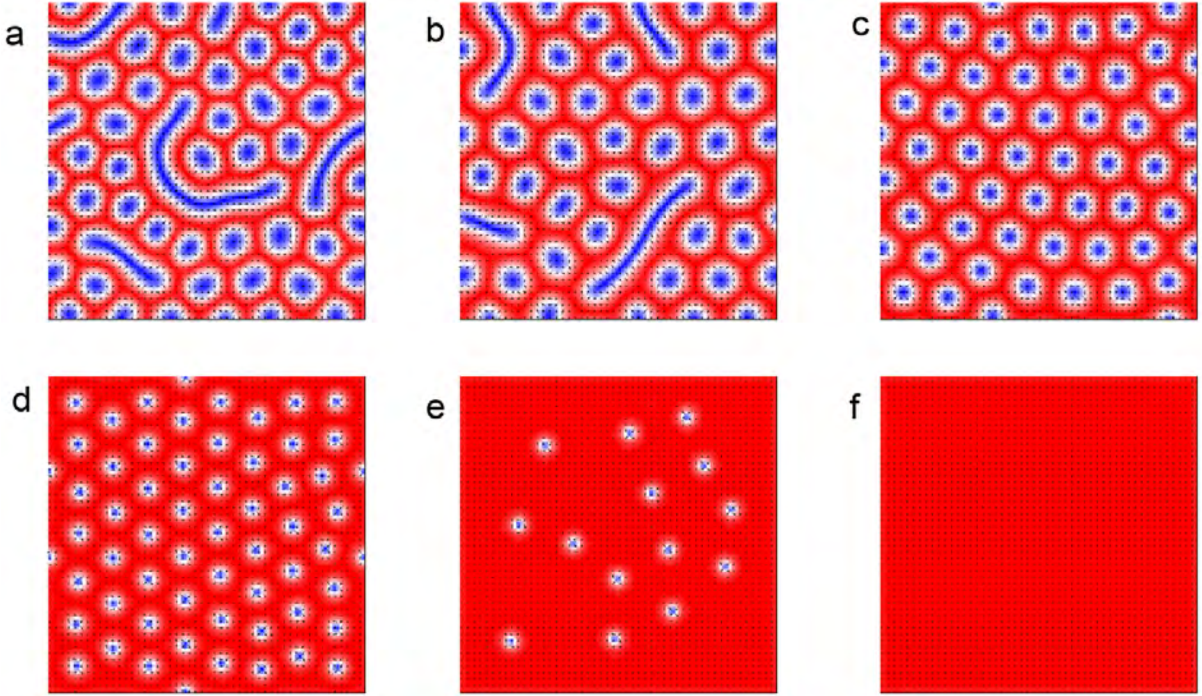
Anti-Skyrmions!

1^{st} observation
- Stable above 300 K



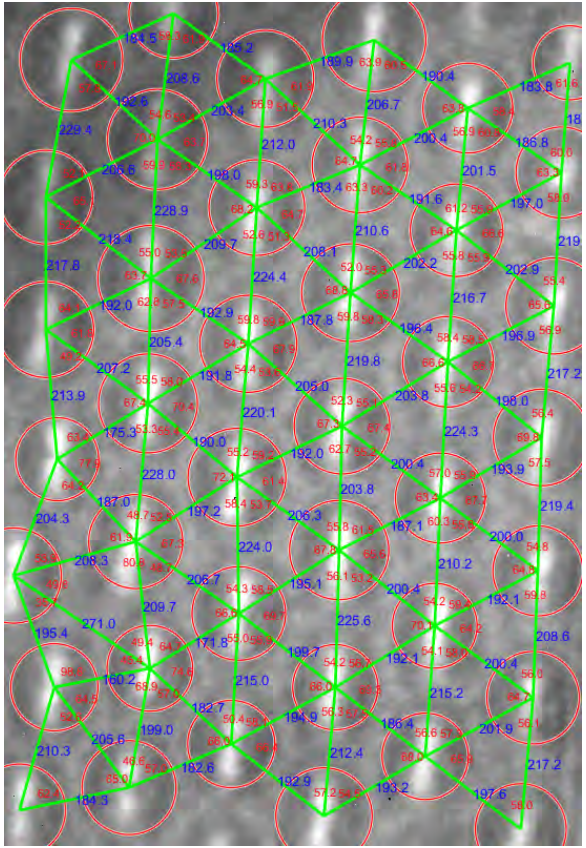
Nayak *et al.* (submitted)

Micromagnetic simulations - phase diagram

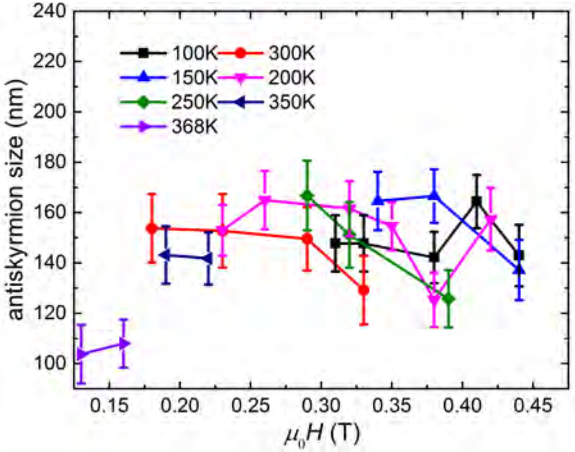


OOMMF simulation of phase change as a function of perpendicular field strength, with: (a) H_z=0.09T, helix+antiskyrmion phase, (b) H_z=0.15T, helix+antiskyrmion phase, (c) H_z=0.21T, antskyrmion phase, (d) H_z=0.39T, antikyrmion phase, (e) H_z=0.47T, antiskyrmion + spin polarized phase and (f) H_z=0.50T, spin polarized phase.

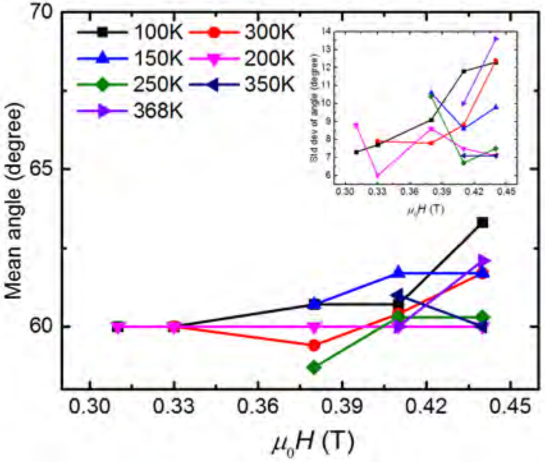
LTEM – anti-skyrmion lattice evolution



Analysis of a LTEM image of the antiskyrmion lattice at 200K under a perpendicular field of H=0.23T.



Field dependence of the antiskyrmion size at various temperatures. The error bar is the standard deviation of the size distribution.

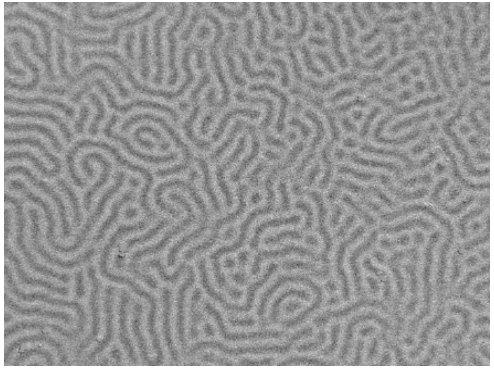


Field dependence of the antiskyrmion lattice mean angle at several different temperatures. The inset show the corresponding standard deviation of the lattice angles.

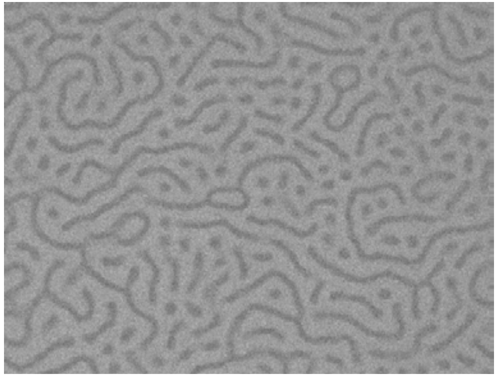
Magnetic bubbles / skyrmions in W | CoFeB films

Hz

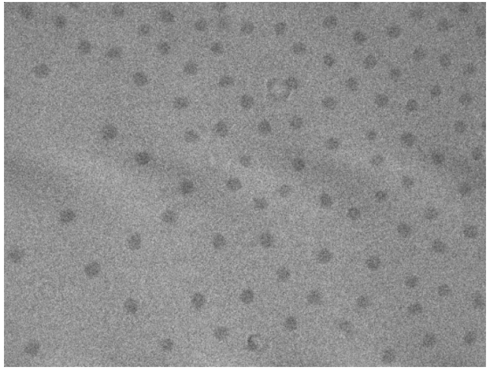
⊗



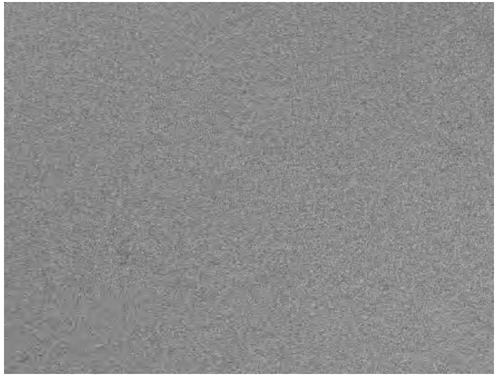
0 Oe : Stripe + Bubble



1.2 Oe : Stripe + Bubble



2 Oe : Bubble

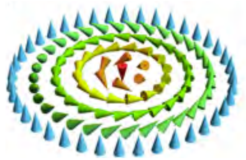


4 Oe : Single domain

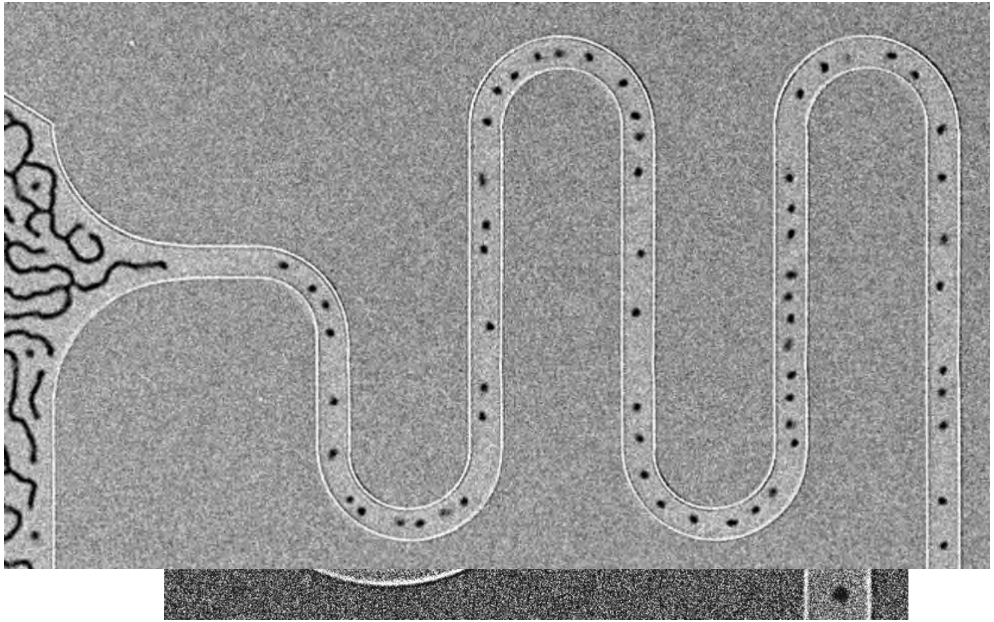
Skyrmions on the "Racetrack"

Skyrmions in CoFeB → speed 0.000001 m/sec at j= 10^5 A/cm^2

"hedgehog" (Néel) type
Examples: thin Fe/Ir
→ SOC + interface sets chirality



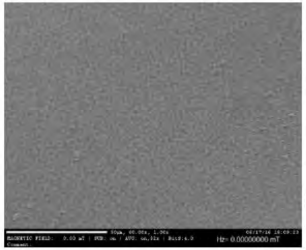
"vortex type" (Bloch) chiral phase examples: MnSi; films with perpendicular anisotropy plus magnetic dipolar coupling (achiral)



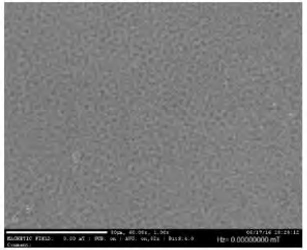
Jiang et al. Science (2015)

Skyrmions in CoFeB thin films

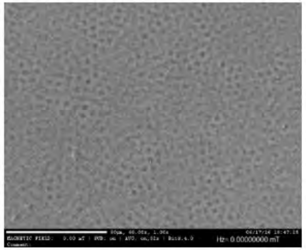
Hz=0 @ different temperature



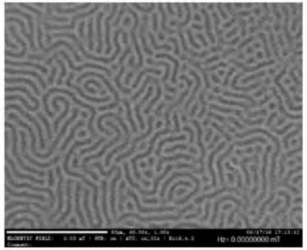
300.2K
bubble



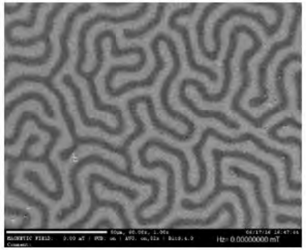
299.2K
bubble



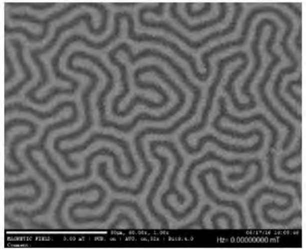
298.2K
bubble



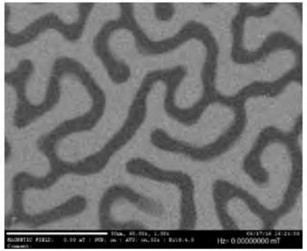
297.2K
bubble+stripe



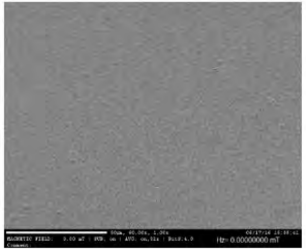
292.4K
stripe



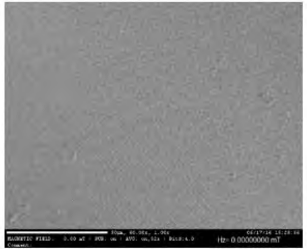
293.9K
stripe



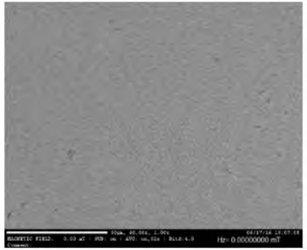
287.5K
stripe



282.6K
uniform



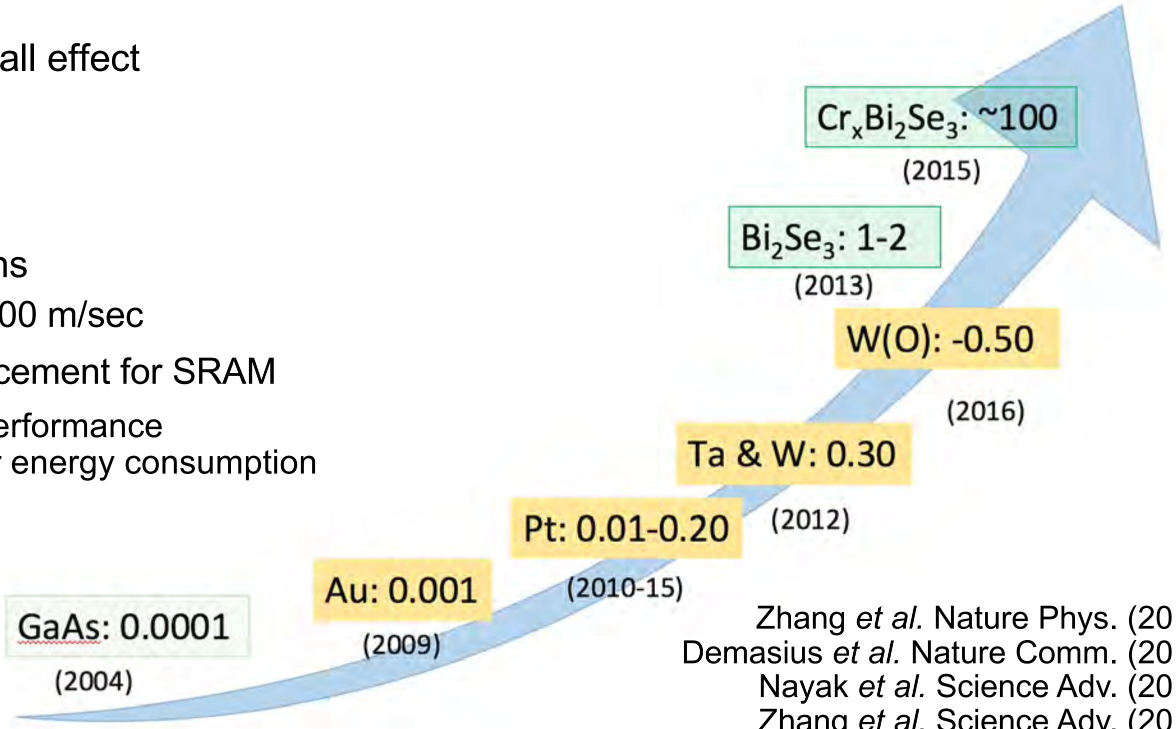
277.7K
uniform



272.9K
uniform

Spin Orbitronics

- Chiral spin torque and giant exchange torque
  - Ultrafast current induced DW velocities in racetracks with no magnetization!
  - Curvature strongly affects DW velocity but eliminated in SAF racetrack
- Novel materials show large spin Hall effect
  - Triangular antiferromagnets+
  - Novel crystalline phases ++
- Important technological applications
  - Racetrack – DW velocities > 1,000 m/sec
  - 3T Single DW Racetrack - replacement for SRAM
  - Promises 3T device with SRAM performance
    but increased density, much lower energy consumption
    & non-volatility (fast start-up)
- Non collinear spin textures!
  - Anti-skyrmions…



Zhang *et al.* Nature Phys. (2015)
Demasius *et al.* Nature Comm. (2016)
Nayak *et al.* Science Adv. (2016)
Zhang *et al.* Science Adv. (2016)
Nayak *et al.* (2017)

Max Planck Institute for Microstructure Physics, Halle

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contact: stuart.parkin@mpi-halle.mpg.de