“Challenges in nanomagnetism and spintronics“

M. Pasquale, INRIM

Outline of the talk

- Background, definitions and motivations ←
- A bit of history:
  - Magnetic storage
  - Signal processing
- Current issues
  - Signal processing
  - Storage
- Open challenges

“Big” Problems in Electromagnetics
CCEM Strategic Planning Document 2011
Technical Challenges

Application Area	Examples	Key Requirements	Competing Technologies
Information Processing	Quantum-dot cellular automata (QCA) cells, **spintronics**, etc. (classical bits)	Surpassing CMOS in terms of speed, usability, reliability, and affordability is difficult. It will probably require mastery of “bottomup” fabrication.	Anything else mentioned in the semiconductor industry (ITRS) roadmap.
	Qubits with charge based readout, quantum limited amplifier for qubit readout	Long coherence time, controlled backaction.	Anything else mentioned in the quantum computing roadmap.

Background: Semiconductor Industry Roadmap More Than Moore/Beyond CMOS

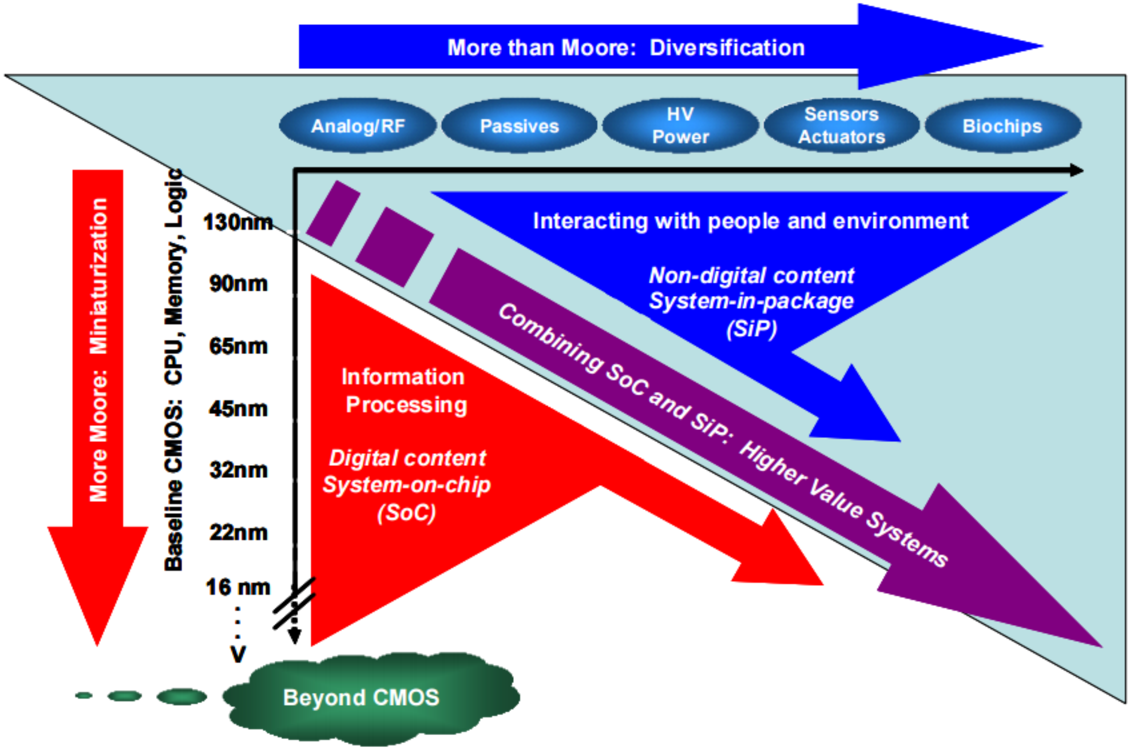


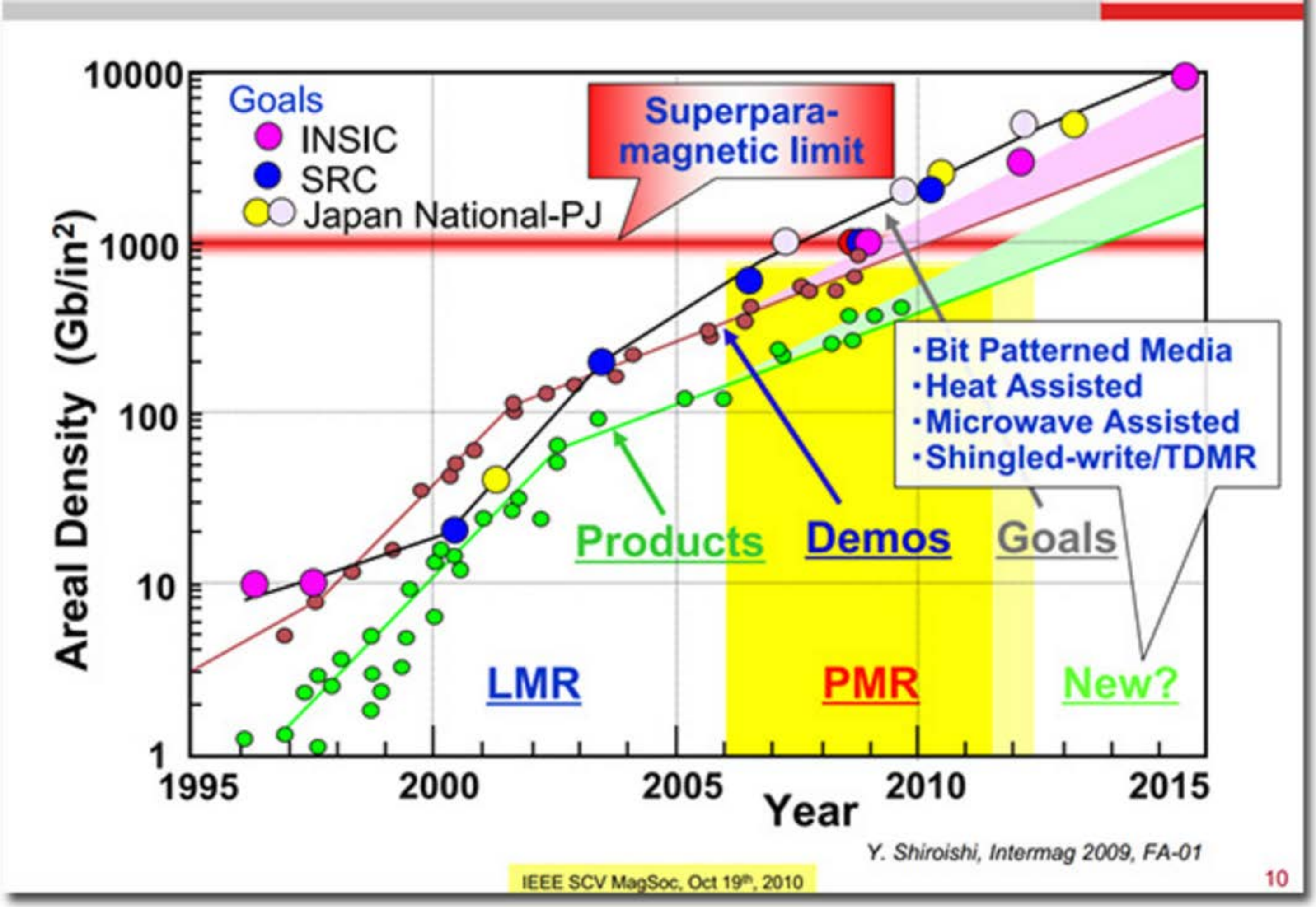
Fig 11. The "hereogeneous integration" domain (light blue triangle).

The primary research vectors defined by NRI (US) for 2020 are:

- **NEW DEVICE** – with alternative state vector (**spin**, phase, magnetic flux quanta, mechanical deformation, dipole orientation, molecular state);
- **NEW WAYS TO CONNECT DEVICES** – including **non-charge data transfer**;
- NEW METHODS FOR COMPUTATION – including non-equilibrium systems;
- NEW METHODS TO MANAGE HEAT – focused on nanoscale phonon engineering;
- NEW METHODS OF FABRICATION –focused on direct self-assembly.

Background: STORAGE

http://www.networkcomputing.com/storage/9-emerging-storage-technologies-watch/475839535



- Bit Patterned Media
- Heat Assisted
- Microwave Assisted
- Shingled-write/TDMR

Y. Shiroishi, Intermag 2009, FA-01

IEEE SCV MagSoc, Oct 19th, 2010

Technologies that will take hard disk areal densities beyond today's approximately 1 terabit per square inch include shingled, two-dimensional and heat-assisted magnetic recording. Image: Hitachi/IEEE

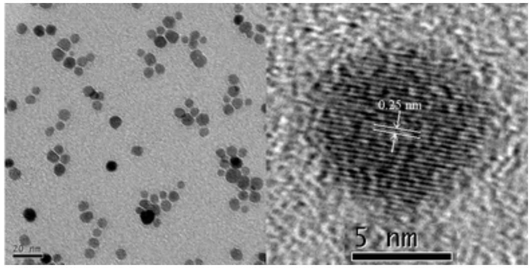
http://www.zdnet.com/article/the-future-of-storage-2015-and-beyond/

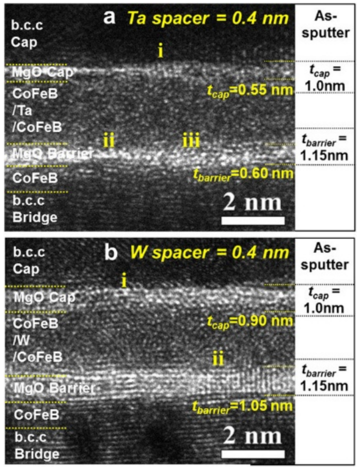
What is Nanomagnetism?

Nanomagnetism encompasses magnetic phenomena in matter where at least one dimension is in the submicron scale:

- **Particles**
- **Dots**
- **Wires**
- **Thin films and multilayers**
- **Nanostructured samples**

Chem. Commun., 2007, 5004-5006 **DOI:** 10.1039/B712795B



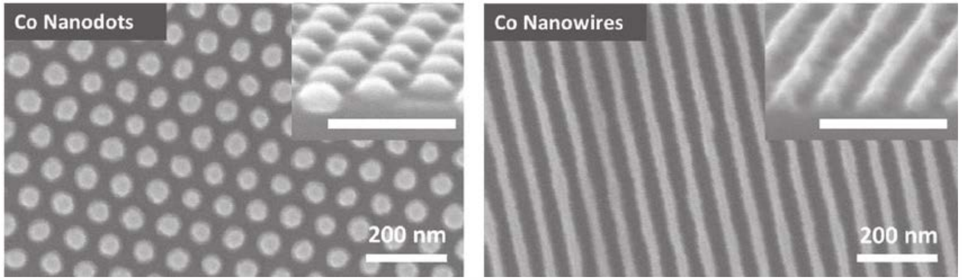


Scientific Reports **6**, Article number: 38125 (2016)
doi:10.1038/srep38125

Applications of nanomagnetism are

- **Spintronics**
- Sensors and biosensors
- Medical applications

Nanotechnology 26(37):375301 · September 2015



Motivation: why Nanomagnets?

- **At the nanoscale** the basic properties of matter start to become size dependent → a novel feature not available in the macroscopic world.
- Quantum phenomena become important
- **Discussion: Impact on Metrology**

What is Spintronics?

- **Spintronics** studies the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge, in solid state devices.
- Spintronic systems can be realized in thin metallic or oxide films or in dilute magnetic semiconductors.

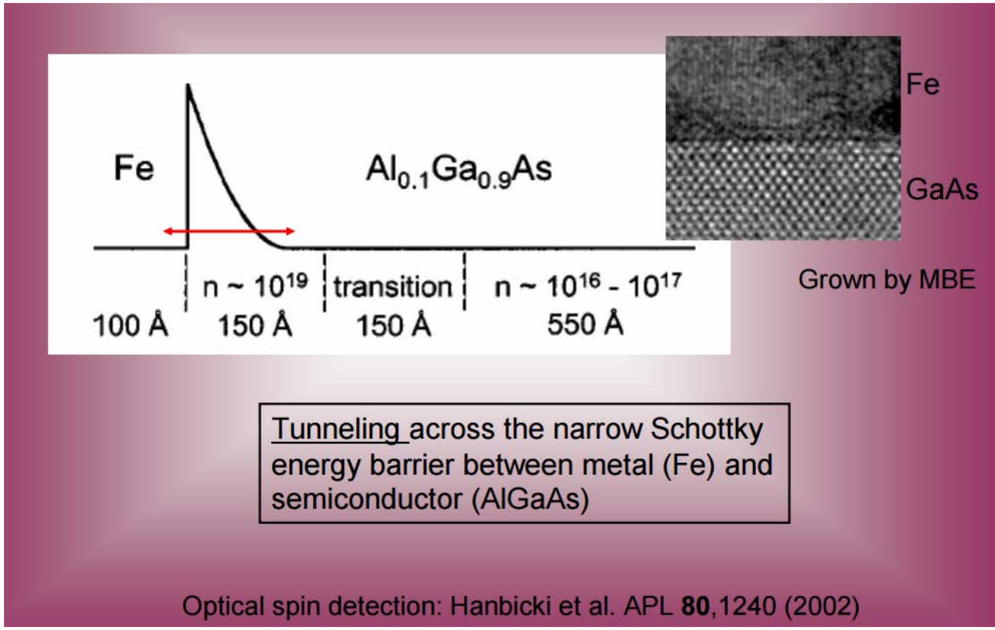
Using spin and not charge

is not trivial

Spin lifetimes of conduction electrons

in metals are < 1 ns and

spin diffusion length ~ nm-um



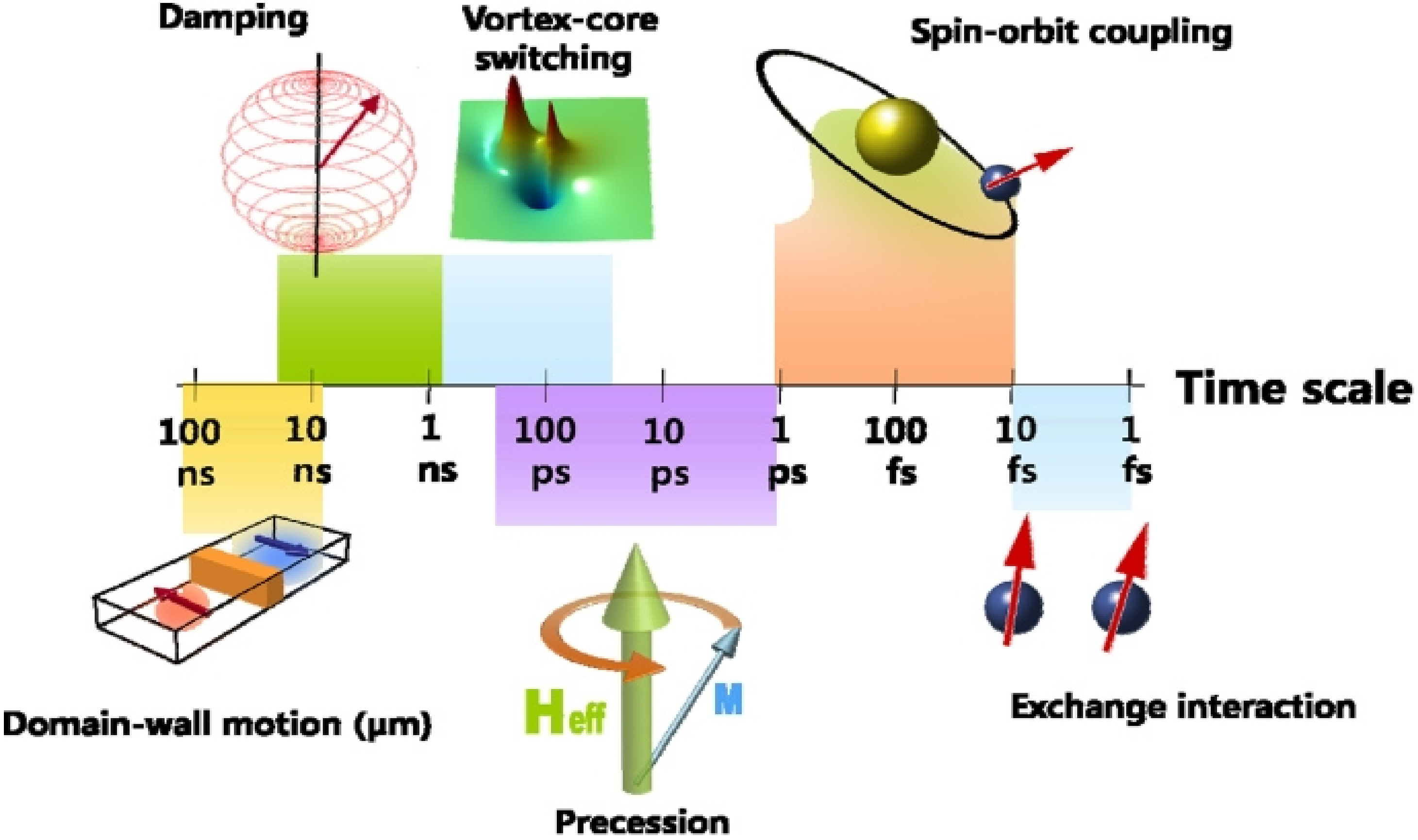
Grown by MBE

Tunneling across the narrow Schottky energy barrier between metal (Fe) and semiconductor (AlGaAs)

Optical spin detection: Hanbicki et al. APL **80**,1240 (2002)

Time and spatial scales

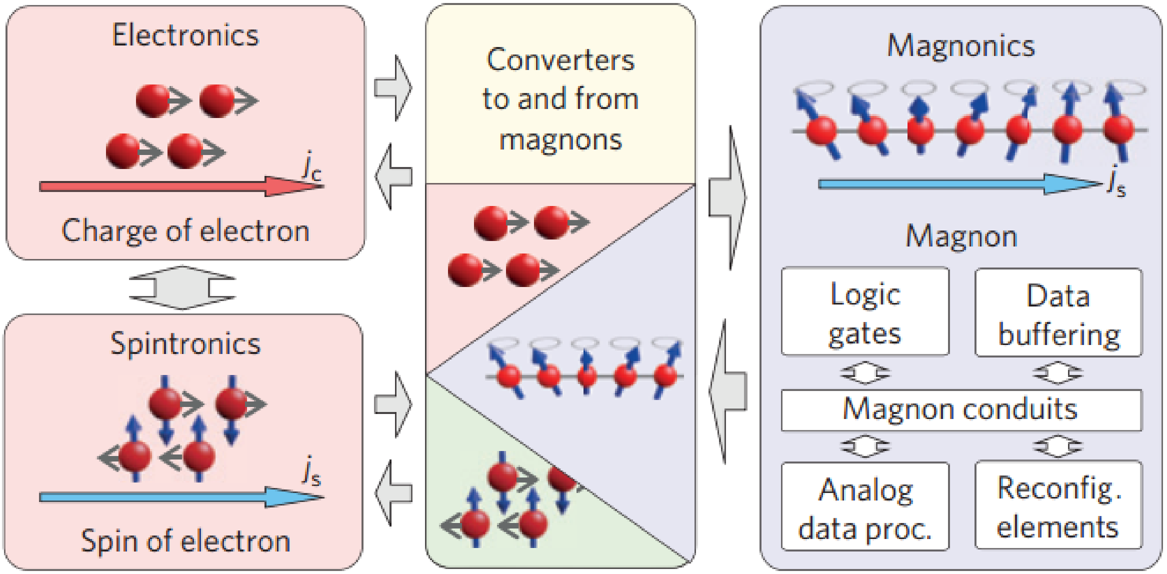
1 µm 100 nm 1 nm



Sang-Koog Kim 2010 J. Phys. D: Appl. Phys. 43 264004 doi:10.1088/0022-3727/43/26/264004

Motivation:Why Spintronics?

- **Electron spins** are exploited in addition to charge state as an additional degree of freedom.
- Perform more functions (MTM).
- High density data storage
- **Data transfer without Joule heating.**



Magnon spintronics A. V. Chumak*, V. I. Vasyuchka, A. A. Serga and B. Hillebrands NATURE PHYSICS | VOL 11 | JUNE 2015

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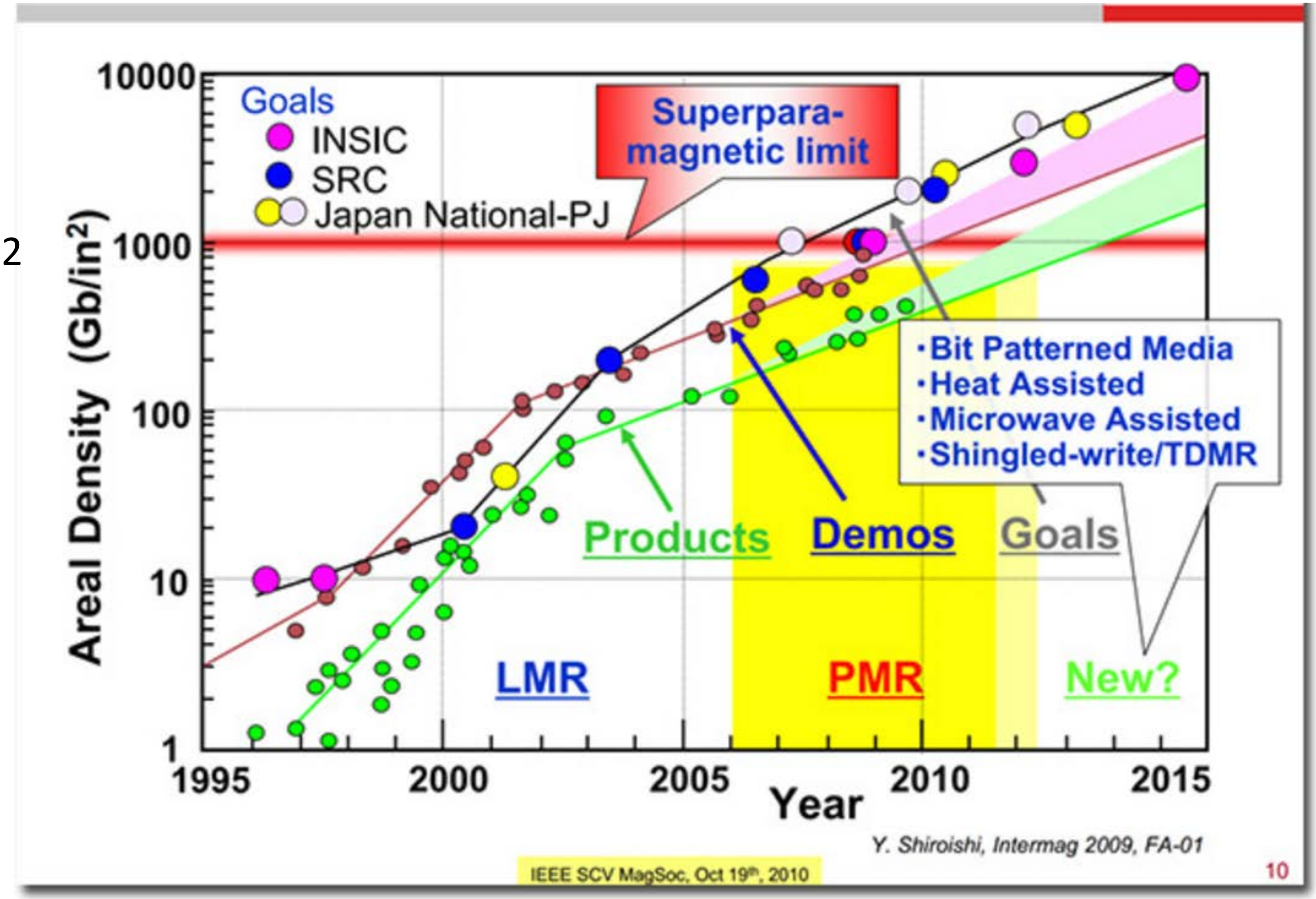
A «bit» of history: STORAGE (MEDIA)

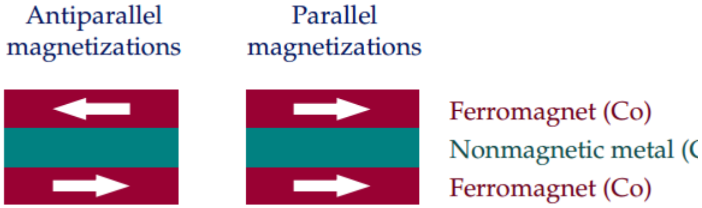
A=6.45 10^-16 m^2
25.4 nm size

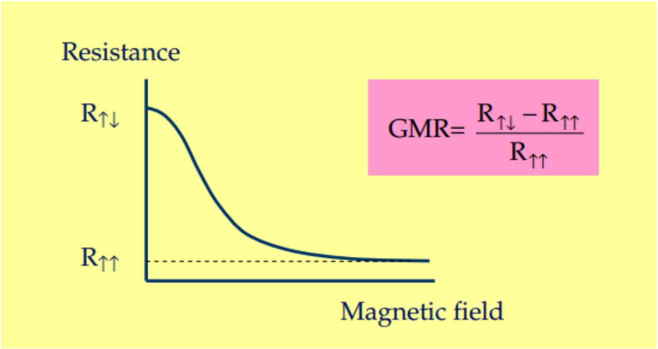


Technologies that will take hard disk areal densities beyond today's approximately 1 terabit per square inch include shingled, two-dimensional and heat-assisted magnetic recording. Image: Hitachi/IEEE

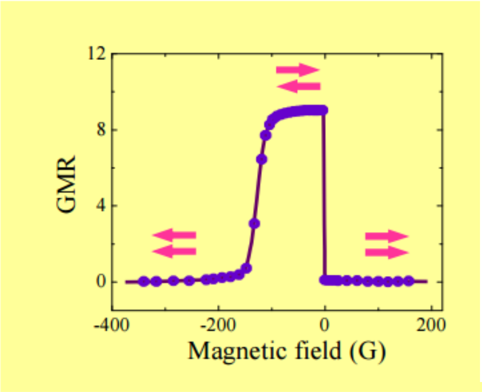
A «bit» of history: STORAGE (HEADS)

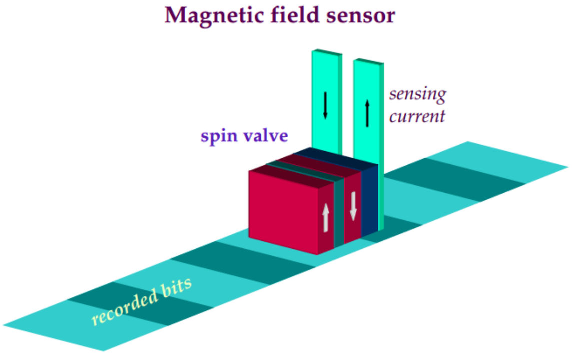
- Physics: spin-polarized electron injection from a FM metal to a normal metal by Johnson and Silsbee (1985); Giant Magnetoresistance in FM Metal/nonmagnetic Metal thin film structures. Fert and Grünberg (1988)
- **Technology: Conversion of magnetic information into electric signals without coils Hard Disks Read Heads/Magnetic sensors**





$$GMR=\frac{R_{\uparrow\downarrow}-R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}}$$





http://unlcms.unl.edu/cas/physics/tsymbal/tsymbal_files/Presentations/JMW-1999.pdf

A «bit» of history: PROCESSING

- **Physics: Tunnel Magnetoresistance Effect at RT (1991-1994-2004 MgO)**
- Technology: Magnetoresistive Random Access Memory (MRAM)/Sensors

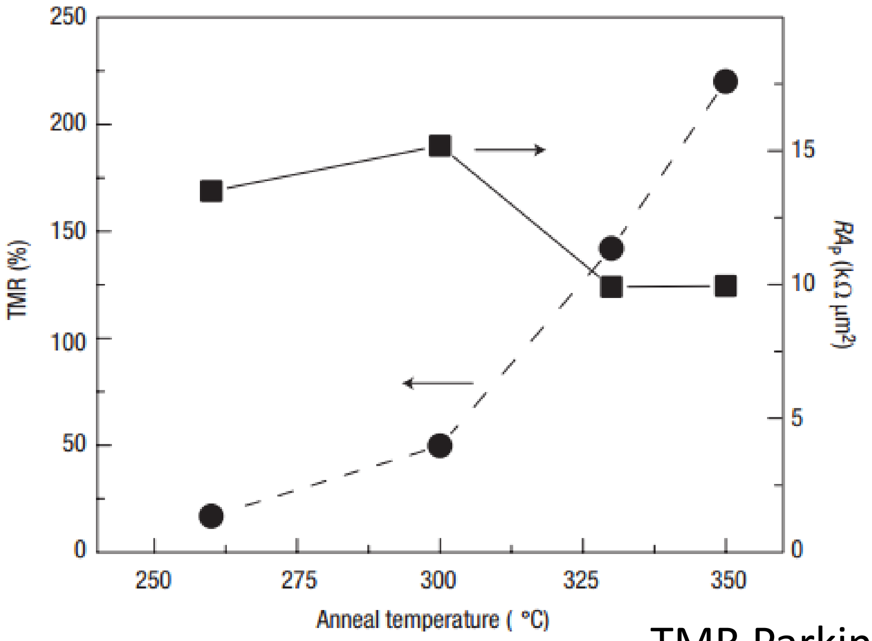


Figure 3 Anneal dependence of TMR and *RA* measured using the current-in-plane tunnelling measurement technique on an unpatterned MTJ film. TMR and *RA* in the parallel state, RA_P, measured at room temperature versus anneal temperature. The MgO tunnel barrier is ~20 Å thick. The structure is similar to that of Fig. 1e except that the IrMn layer is ~150 Å thick, the lower electrode comprises 35 Å $Co_{70}Fe_{30}$, and the upper electrode comprises 75 Å of $(Co_{70}Fe_{30})_{80}B_{20}$. In addition a 75 Å Ru cap layer is used for improved electrical contacts. The parallel state *RA* product is ~10^4 Ω μm², which is about 20 times smaller than the sample of Fig. 1c and d due to the smaller MgO thickness. After annealing at 350 °C the TMR attains a value of 220 ± 10%.

TMR Parkin

July 2006- Freescale. In 2008 >1 M chips

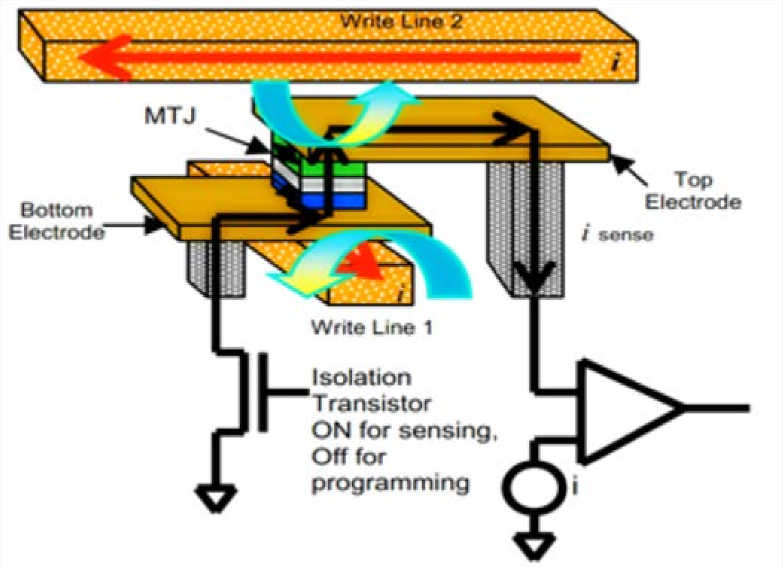
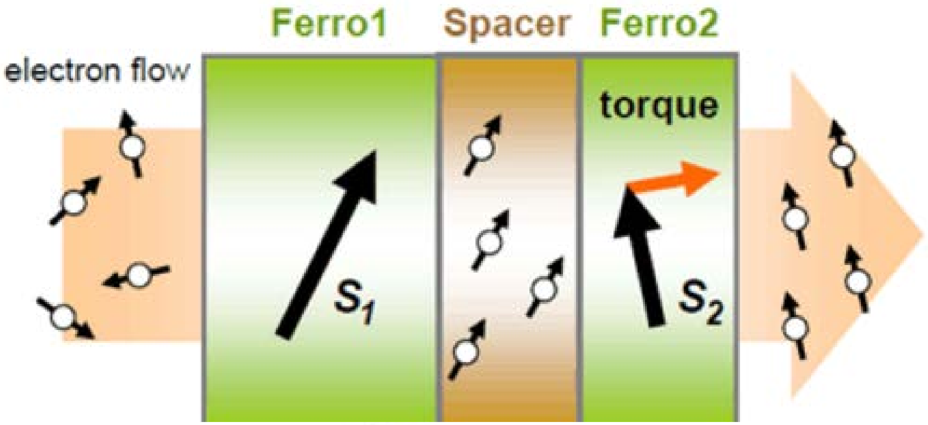


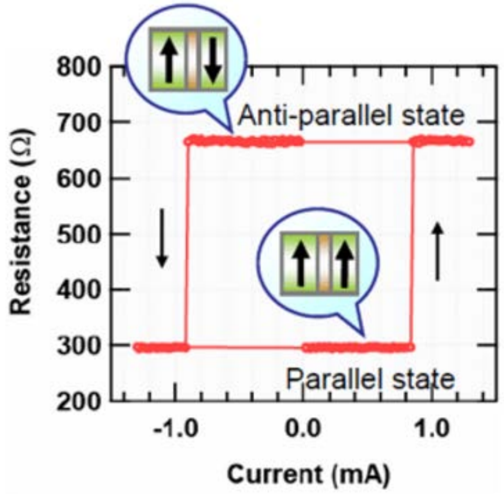
Figure 3. MRAM bit cell structure

http://www.iwavesystems.com/blog/spintronics-a-spin-to-remember/

A «bit» of history: PROCESSING

- Physics: Magnetization reversal by Spin Transfer Torque (STT) - Conversion of electric current into magnetic information without coils

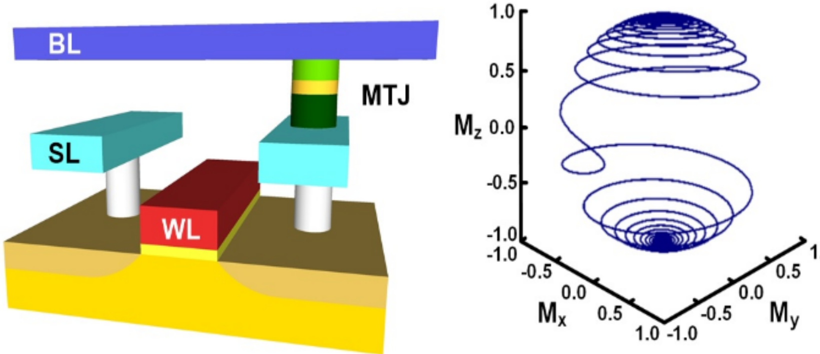




Everspin (Freescale) announces new MRAM customers and products Mar 10, 2017

STT-MRAM

http://www.mram-info.com/everspin-announces-new-mram-customers-and-products



This figure shows a birds-eye view of a STT-MRAM memory cell along with the dynamic spin motion

http://www.wpi-aimr.tohoku.ac.jp/mizukami_lab/spintorque.htm

Metrology challenges

- **Metrology challenges (still actual): traceability of measurements on nanostructures (size, field)**
- **EMPIR SIB NanoMag**
- **Traceability of micro-scale magnetic field measurements:** Today 50 µm can be realized by scanning Hall microscopy and magneto optical indicator film (MOIF) microscopy→ 250 nm and field resolution down to 10 µT
- **Traceability of magnetic force microscopy (MFM):** nano-scale stray field materials, planar field coils, and measurements of the tip stray field by nano Hall sensors, and will be supported by modelling. Quantitative analysis of MFM measurements taken with different tips with spatial resolution down to 10 nm and below.
- **Dimensional traceability of MFM**: traceability of dimensional information of nano-magnetic structures to the SI meter standard is established.
- **Magnetic stray field reference materials:** MFM calibration materials with variable magnetic pattern size from several µm down to below 10 nm.

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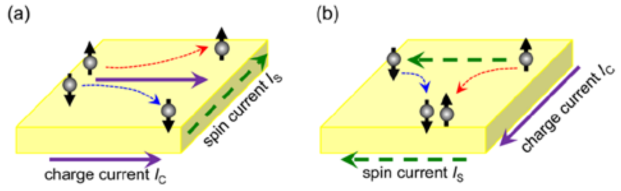
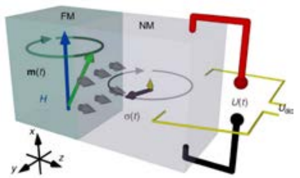
- A bit of history: Magnetic storage
  - Storage
  - Signal processing
- Current issues
  - Signal processing: Spin Currents ←
  - Storage: Topological spin structures/AF
- Open challenges

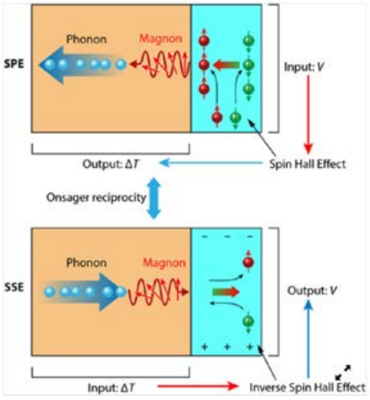
Howto: Spin Currents + waves



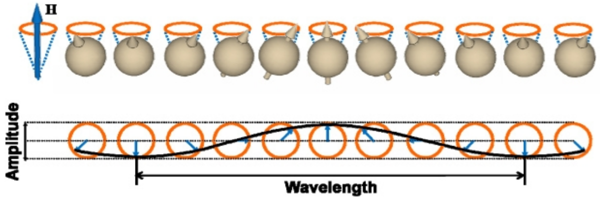
- Spin Hall
- Spin Pumping



- Spin Seebeck
- Spin Peltier

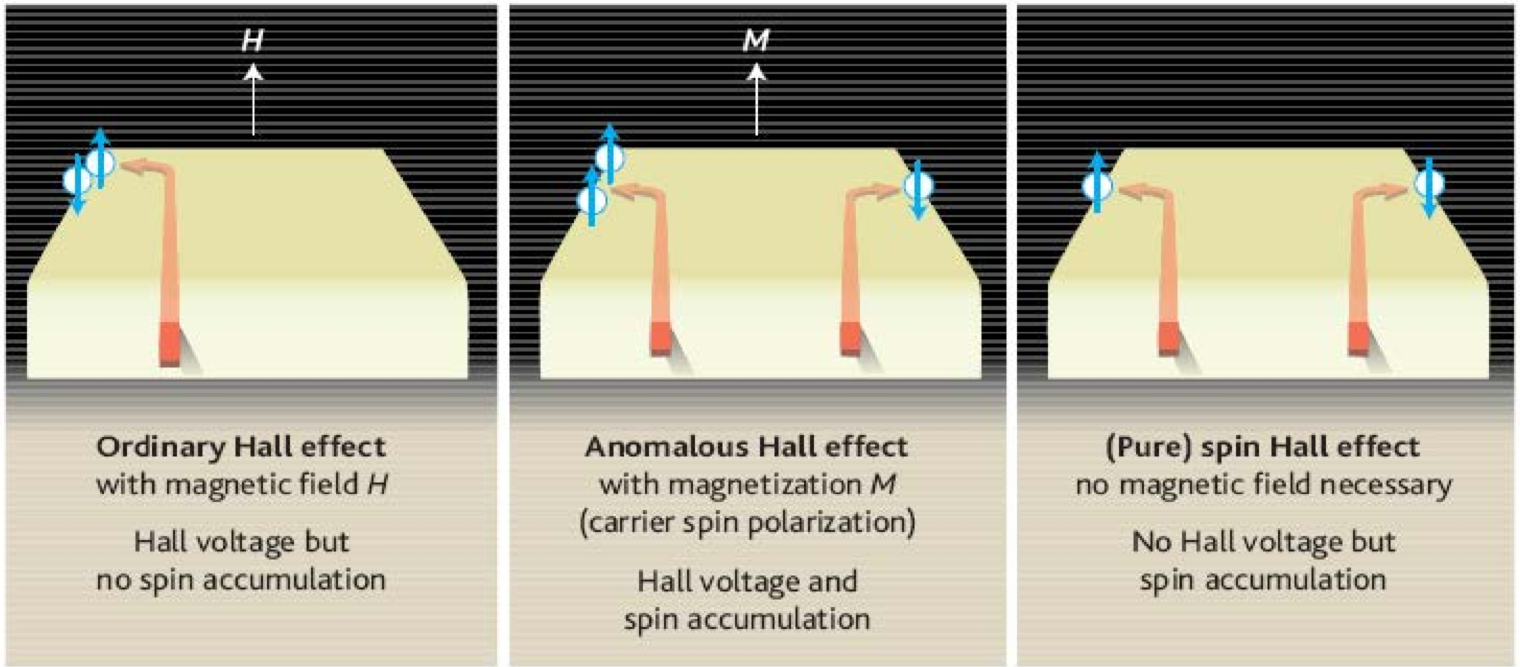


- Spin Wave Antennas



Signal processing: Spin currents

- **Physics: Pure Spin Currents – Possibility of transmission of information without Joule heating/energy dissipation in nanostructures**
- Tecnology: Spin Hall Effect, Spin Pumping, Spin Caloritronics, Spin Waves
- **Metrology: Measurement challenges**



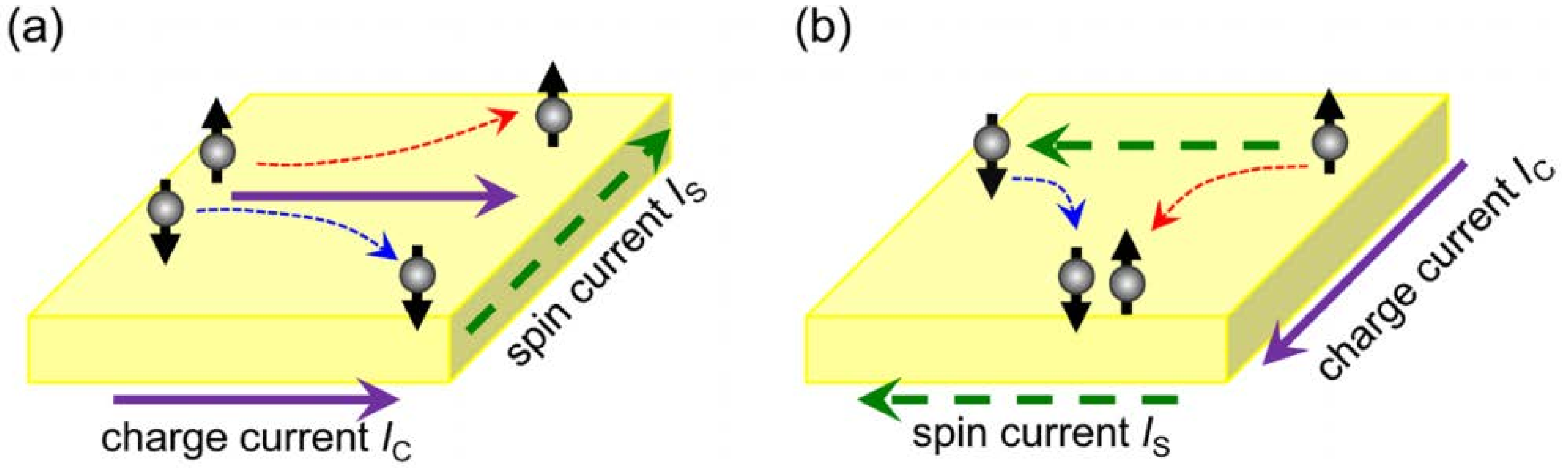
Inuoe, Ohno *Science* 23 Sep 2005: Vol. 309, Issue 5743, pp. 2004-2005

Signal processing:Spin Currents

Spin Hall Effect (direct and inverse)

- The efficiency of the spin-charge conversion can be quantified by a single material-specific parameter, i.e., the spin Hall angle (SHA), SH θ defined as the ratio of the spin Hall and charge conductivities. **Spin-Orbit coupling**

Z. Feng Spin Hall angle quantification... 10.1103/PhysRevB.85.214423

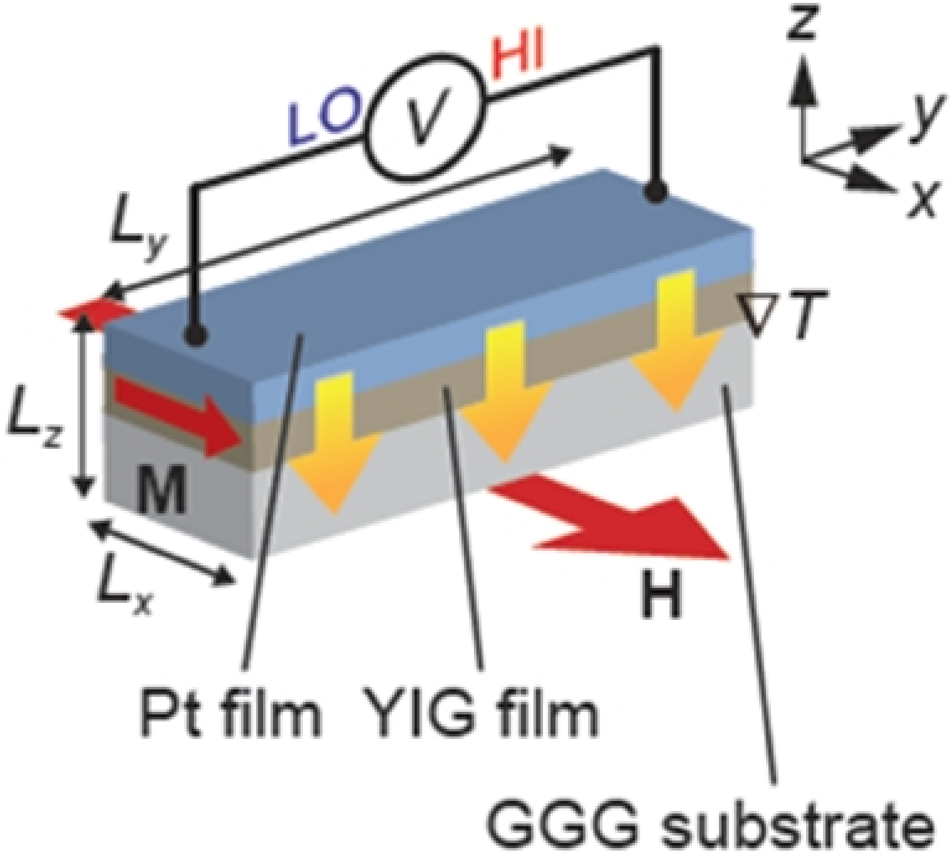


(a) Direct SHE (DSHE) and (b) inverse SHE (ISHE). The solid, broken, and dotted arrows indicate the directions of electric charge current, spin current, and the motions of spin-up and spin down electrons. Niimi, Otani Rep. Prog. Phys. 78 (2015) 124501

Signal processing:Spin Currents

Longitudinal Spin Seebeck

Voltage is generated in Pt by the Inverse spin Hall effect when a spin current is injected from a nearby YIG sample through thermal gradient.

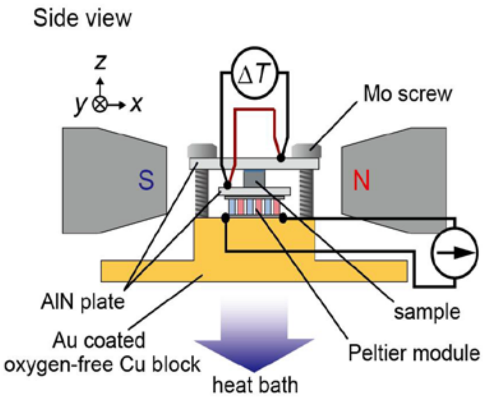


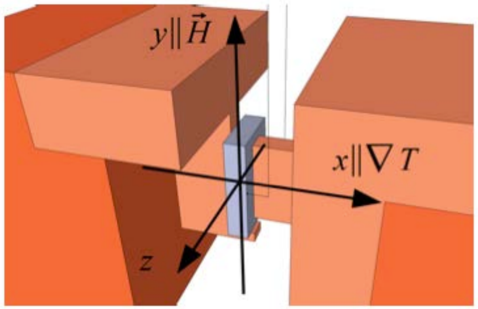
EMRP JRP EXL04 “SpinCal” 2013-2016

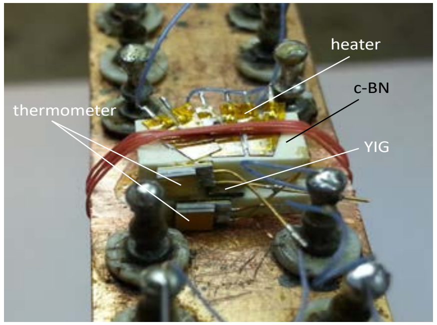
(transversal SSE Nernst)

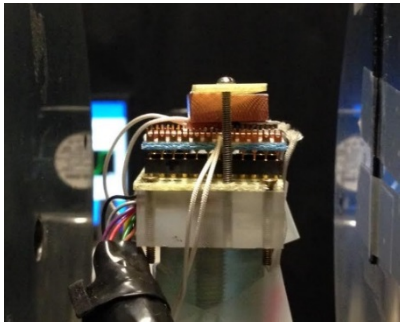
Signal processing:Spin Currents

Longitudinal Spin Seebeck: ΔT exp









T. Kikkawa,
K. Uchida,
E. Saitoh

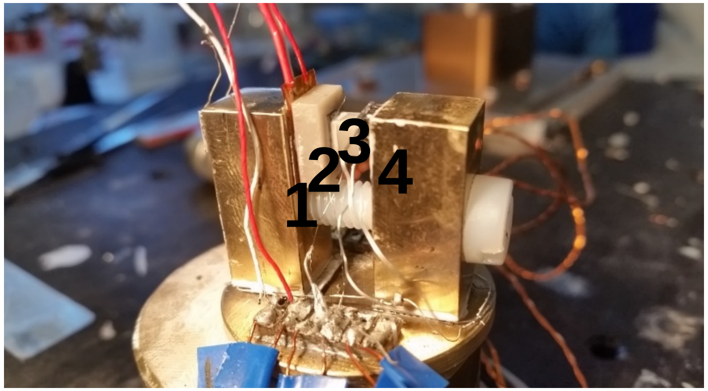
T. Kuschel
D. Meier

H. Jin,
S. Boona,
S. Watzman,
J. Heremans

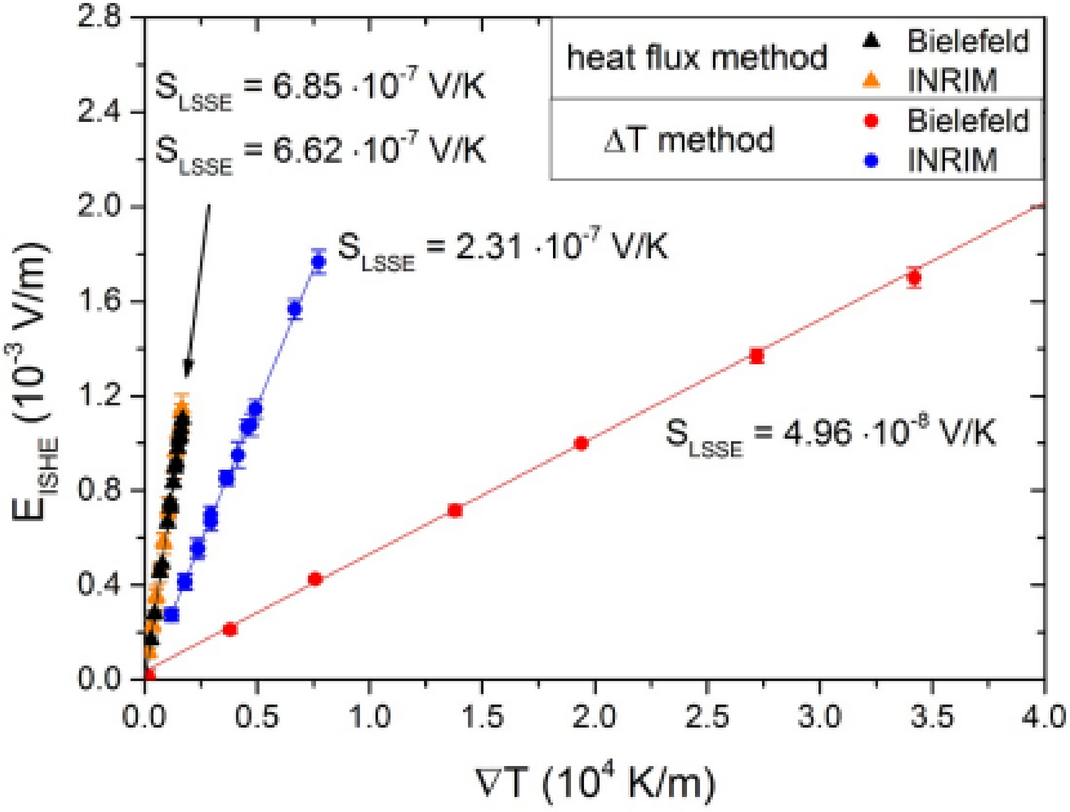
W. Zhang
A. Hoffmann

EMRP JRP EXL04 “SpinCal” 2013-2016

Longitudinal Spin Seebeck: Heat Flux vs. ΔT



1. Heat flux sensor
2. Aluminum nitride elements (180 W/mK)
3. Sample
4. Peltier sensor

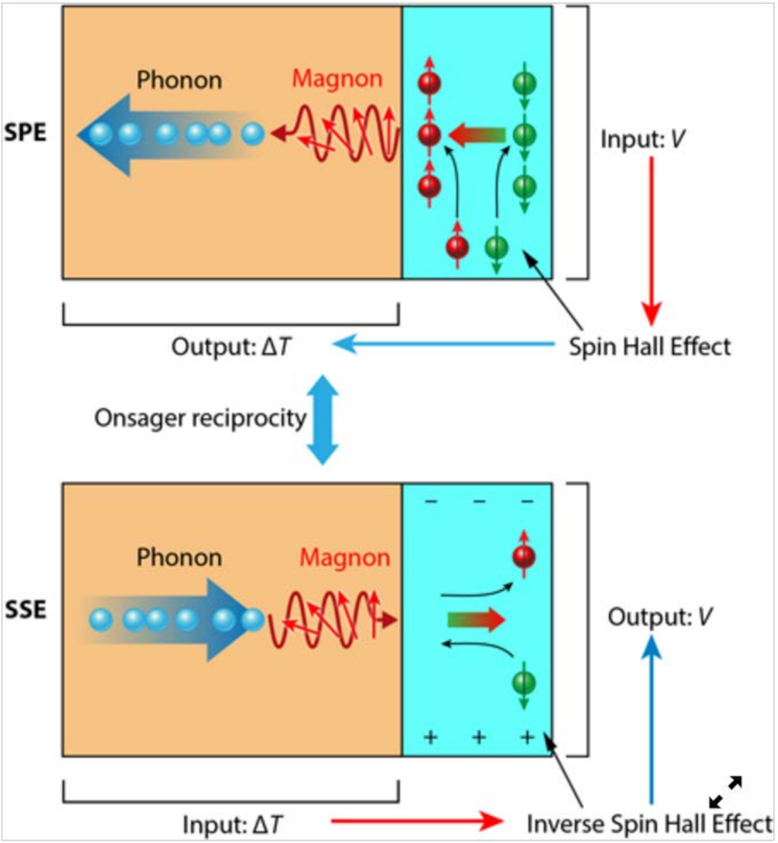


https://arxiv.org/abs/1701.03285 to appear on Scientific Reports

Signal processing:Spin Currents

Spin Peltier - Spin Seebeck- close the loop

- Physics: Spin Seebeck Effect - thermal spin current, spin current in a spin valve, interaction between the spin current and phonons
- Tecnology: Spin Hall Effect, Spin Pumping, Spin Caloritronics, Spin Waves



In the Spin Peltier Effect (top), a voltage VV drives a current in the Pt, where the spin Hall effect (SHE) spin polarizes conduction electrons near the interface with YIG. This spin accumulation launches a spin flux in the magnons in the YIG. The magnons in turn couple to the phonons and thus give rise to a measurable heat flux and temperature difference ΔT in YIG

In Spin Seebeck Effect (bottom), a temperature difference applied to the YIG results in a phonon flow. The phonons couple to the magnons in YIG and result in a spin flux, which polarizes some conduction electrons in the Pt. Spin-polarized electrons in Pt give rise to an electric field in the Pt by the inverse spin Hall effect (ISHE), itself the Onsager reciprocal of the SHE

J. P. Heremans, Ohio State University, July 7, 2014• *Physics* 7, 71

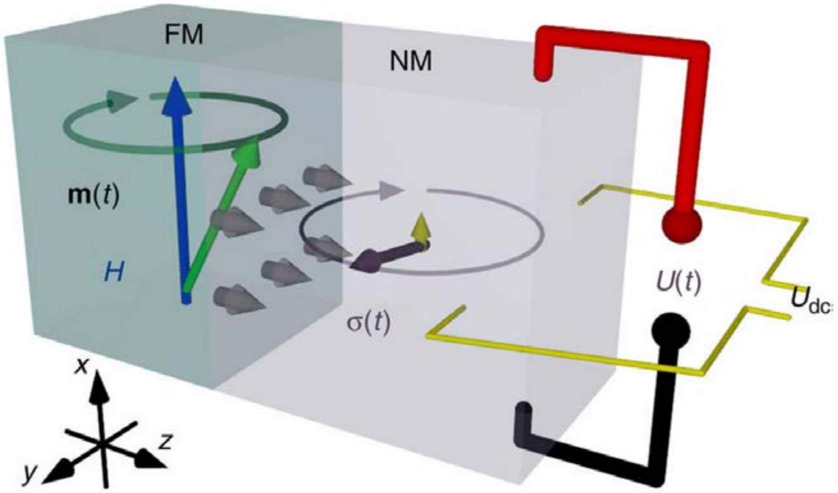
Signal processing:Spin Currents

Spin Pumping

- **Spin pumping** is a method for generating a spin current, the spintronic analog of a battery.
- In order to make a spintronic device, one needs a system that can generate a current of spin-polarized electrons, as well as a system that is sensitive to the spin polarization.
- Candidates for such devices include injection schemes based on magnetic semiconductors and FM.
- FMR devices, and a variety of spin-dependent pumps. Optical, thermal, microwave and electrical methods are being explored.
- These devices could be used for low-power data transmission and processing in spintronic devices or to transmit signals through insulators.

Signal processing:Spin Currents

FMR-Spin Pumping



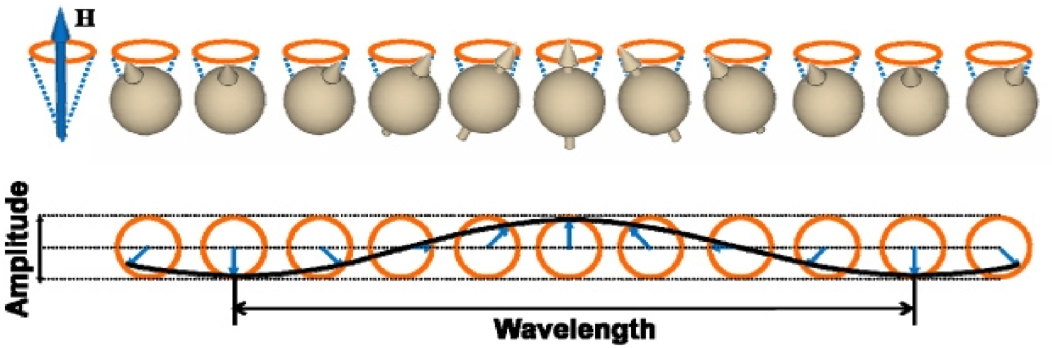
Ferromagnet–Normal metal junctions are efficient sources of pure spin currents

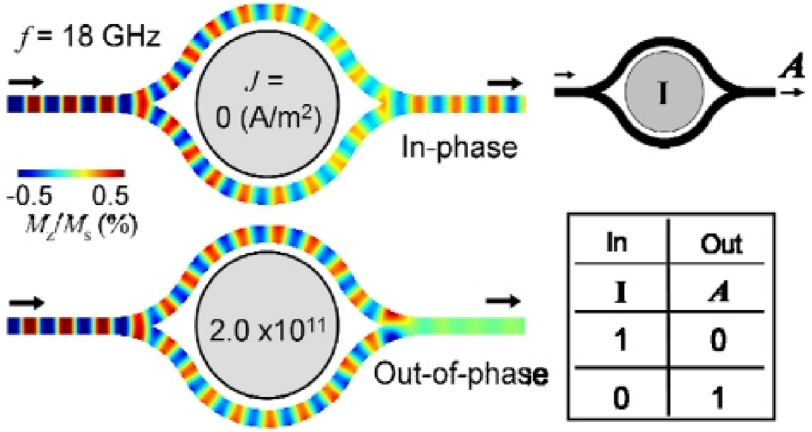
A spin current is generated by spin pumping at the FM–NM interface (grey arrows). The time-dependent spin polarization of this current (indicated as purple arrow) rotates almost entirely in the y–z plane. The small time-averaged d.c. component (yellow arrow) appears along the x axis. Due to the inverse spin Hall effect both components lead to charge currents in NM and can be converted into a.c. and d.c. voltages by placing probes along the x and y directions, respectively.

Dahai Wei *Nature Communications* **5** 3768 (2014) doi:10.1038/ncomms4768

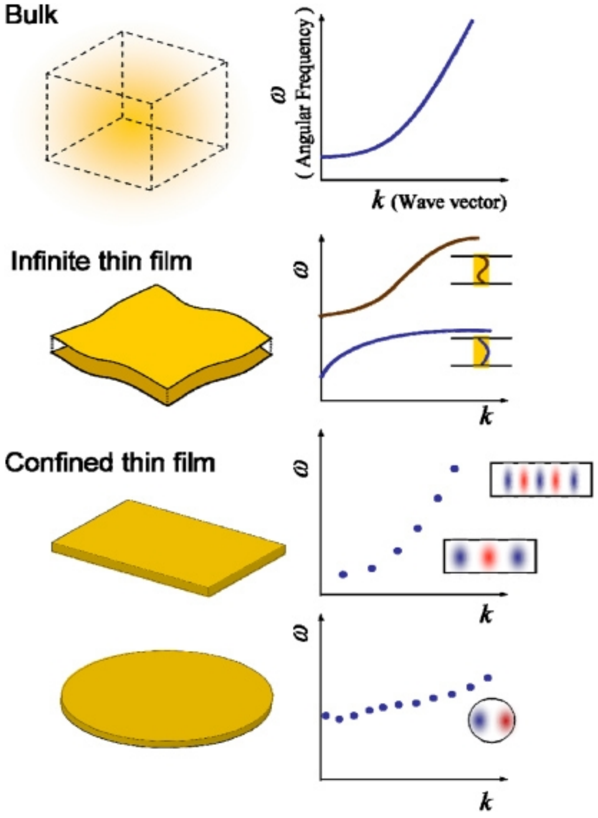
Signal processing:Spin Waves

Generation, transmission, processing and detection





In	Out
I	A
1	0
0	1



Sang-Koog Kim 2010 J. Phys. D: Appl. Phys. 43 264004 doi:10.1088/0022-3727/43/26/264004

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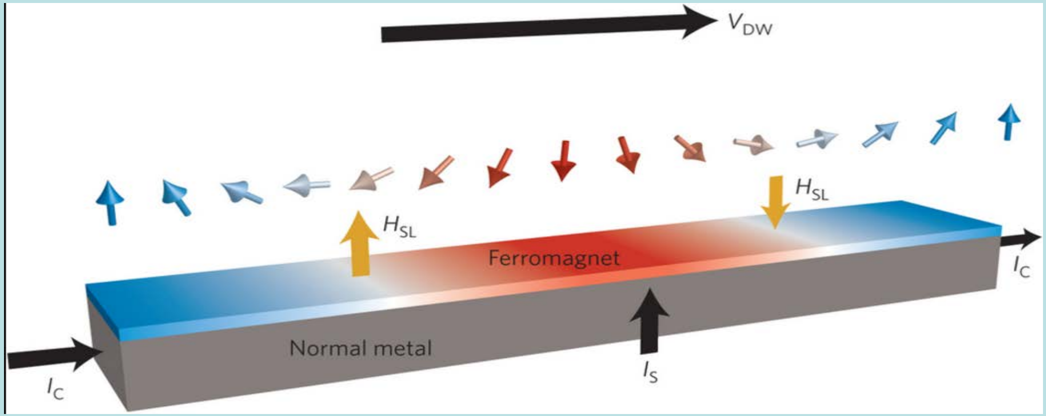
Topological spin structures 1/2

Spins in solids might be arranged in specific topological geometries

- Chiral domain walls in PMA (LH)

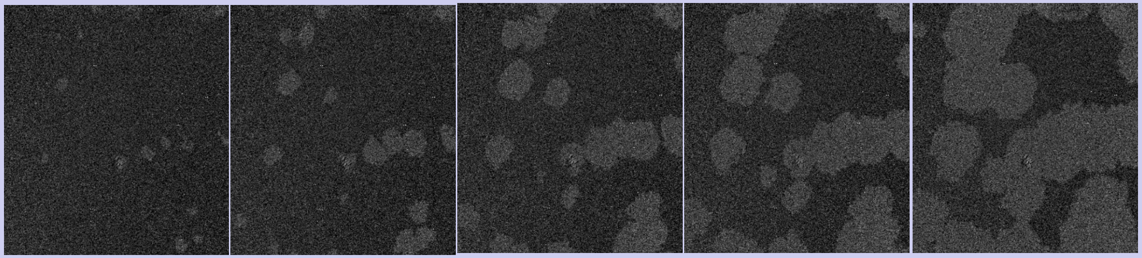
Arne Brataas
Nature Nanotechnology 8, 485–486 (2013)

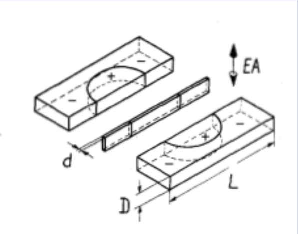


- PMA Bubbles

INRIM Korea U

Pt(3 nm)Co(0,5 nm)Pt(3 nm)



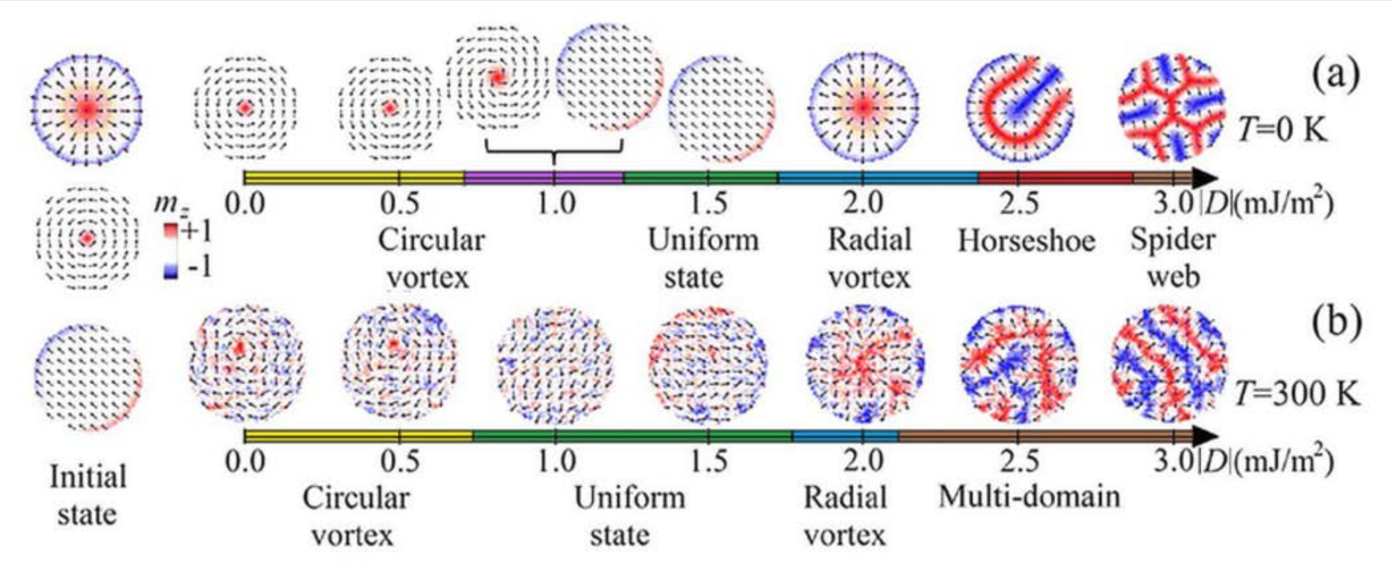


Topological spin structures 2/2

Spins in solids might be arranged in specific topological geometries

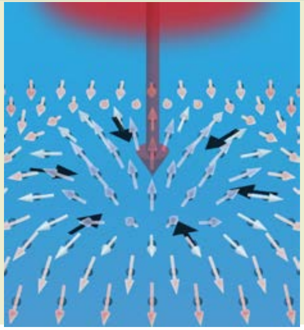
- Vortices

G. Siracusano PRL 117, 087204 (2016)



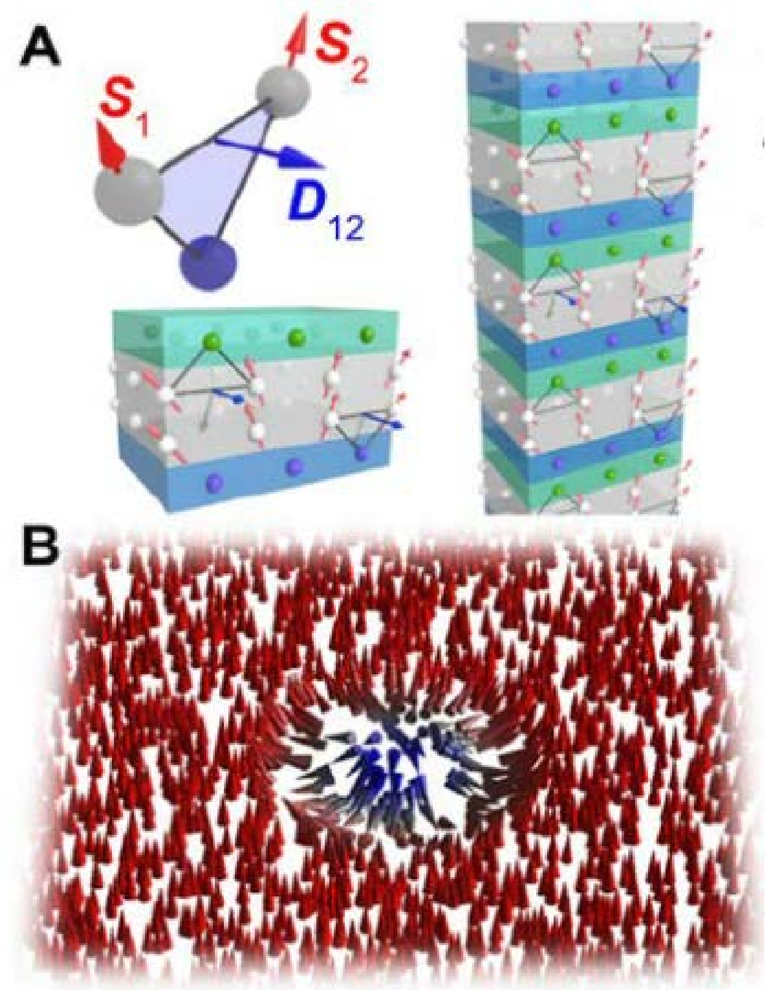
- Skyrmions

C. Marrows 2015• Physics 8, 40



Dzyaloshinskii Moriya

- The anisotropic (antisymmetric) exchange is a contribution to the total magnetic exchange interaction between two neighboring magnetic spins, Si and Sj due to the spin-orbit coupling $H_{DM} = D_{ij}{}^{\cdot}\left(S_i x S_j\right)$.
- In magnetically ordered systems, it favors a spin canting of otherwise (anti)parallel aligned magnetic moments and thus, e.g., is a source of weak ferromagnetic behavior in an antiferromagnet.



  - Interfacial Dzyaloshinskii-Moriya interaction (DMI) in asymmetric magnetic multilayers. (A) The DMI for two magnetic atoms close to an atom with large spin-orbit coupling in the Fert-Levy picture.
  - Zoom on a single trilayer composed of a magnetic layer (gray) sandwiched between two different heavy metals A (blue) and B (green) that induce the same chirality (same orientation of D) when A is below and B above the magnetic layer, and finally on an asymmetric multilayer made of several repetition of the trilayer. (B) Sketch of an isolated hedgehog skyrmion stabilized by interfacial chiral interaction in a magnetic thin film.

Magnetic skyrmions

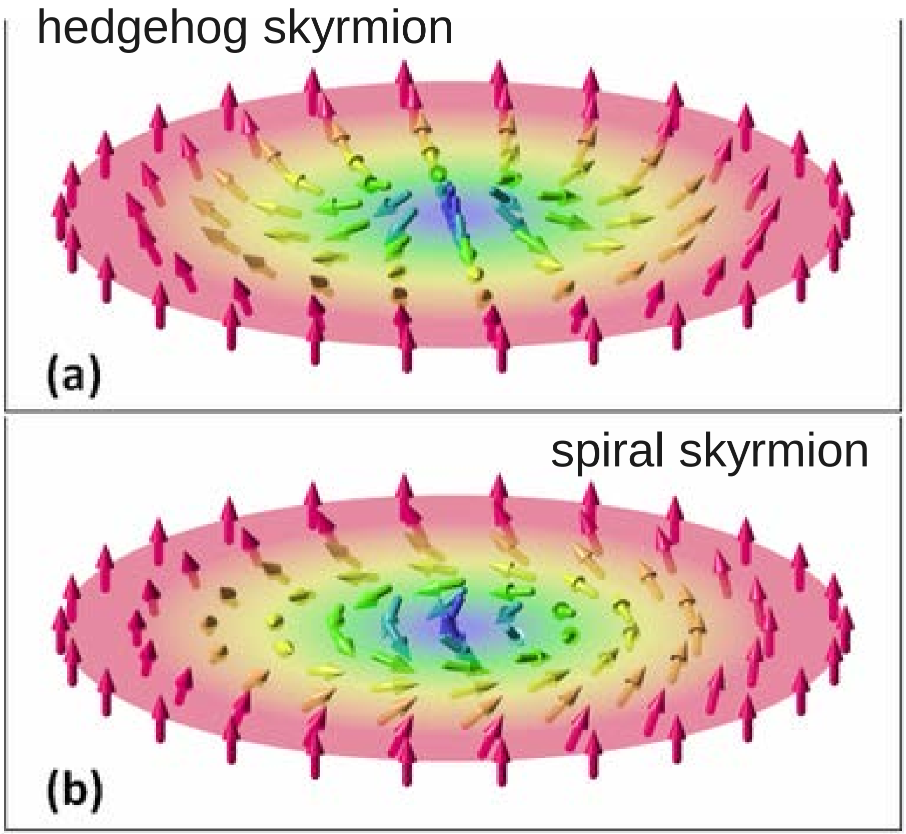
Magnetic skyrmions are localized spin textures.

They are multidimensional, static, topological solitons.

The twisting skyrmions' magnetization profile leads to a lower energy state with respect to a homogeneously magnetized ferromagnetic state.

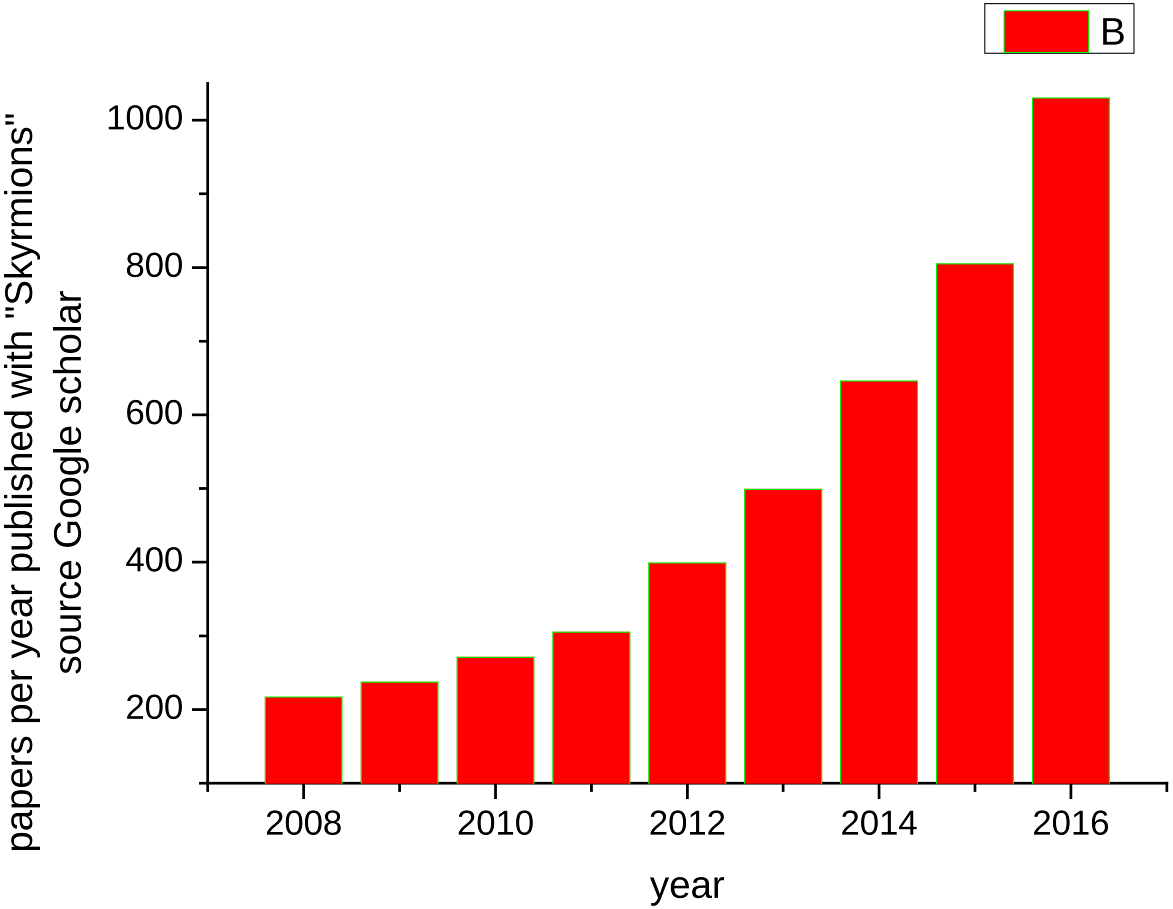
Due to the M twisting, skyrmions have non-trivial topological properties, described by a topological charge, and are topologically protected against a transition into topologically trivial states.

Skyrmionic states are stable due to the Dzyaloshinskii-Moriya interaction found in materials exhibiting large spin-orbit coupling and a lack of inversion symmetry, in contrast magnetic bubbles are stabilized by dipolar magnetic interactions.



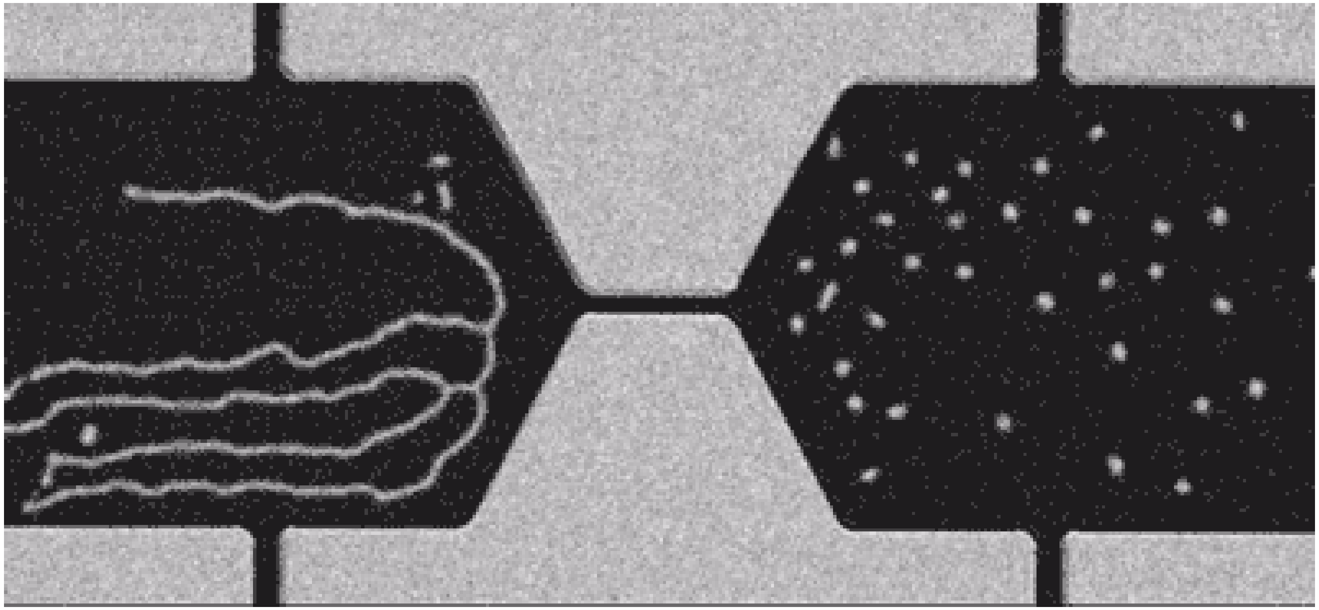
The vector field of two, two-dimensional magnetic skyrmions: a) a hedgehog skyrmion and b) a spiral skyrmion. https://en.wikipedia.org/wiki/Magnetic_skyrmion

Magnetic skyrmions (publications)



Magnetic skyrmions

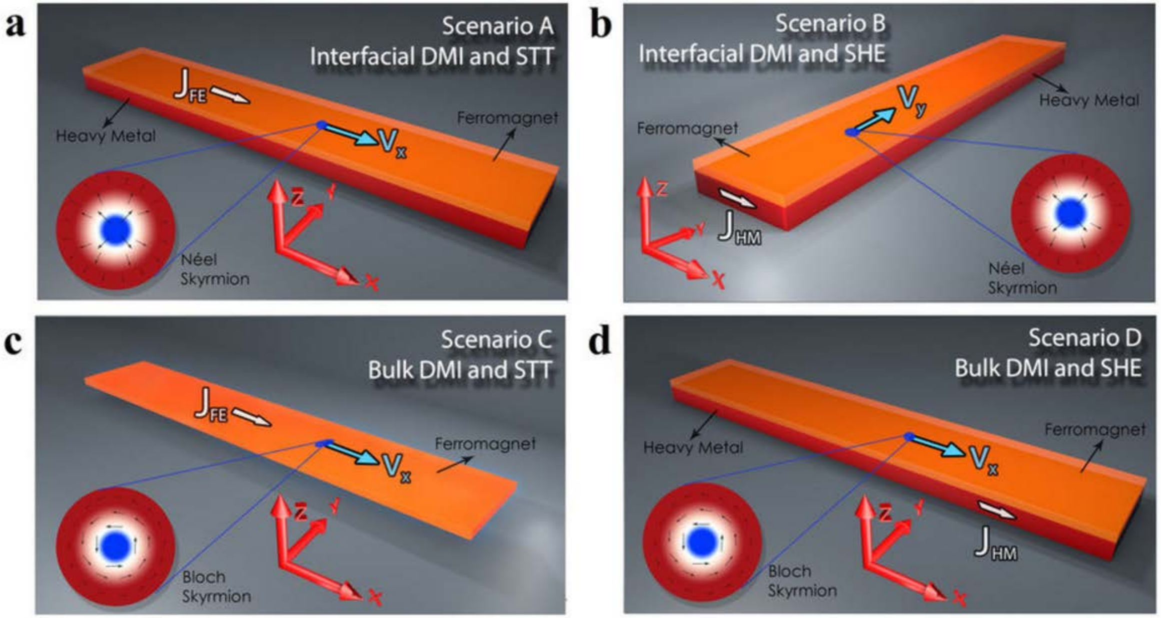
- Skyrmions can interact very efficiently with electrons and magnons, and exhibit a high mobility which can be driven by current densities several orders of magnitude smaller than magnetic domain walls.
- It has been shown both experimentally and theoretically that magnetic skyrmions in ultrathin film systems can be as small as one nanometer in diameter and that their properties can largely be tuned by the choice of the substrate and overlayer materials.

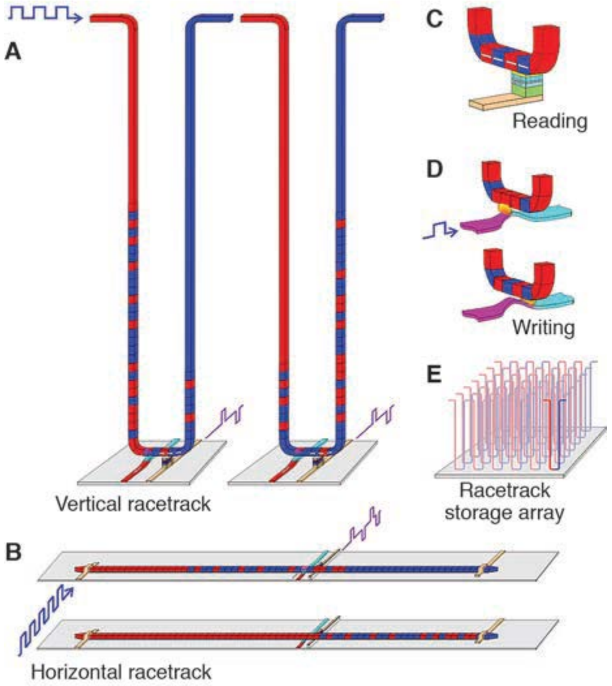


Constriction of 3 um

Blowing magnetic skyrmion bubbles
W.Jiang *Science* 11 Jun 2015:
aaa1442 DOI: 10.1126/science.aaa1442

Magnetic skyrmions and racetrack memories

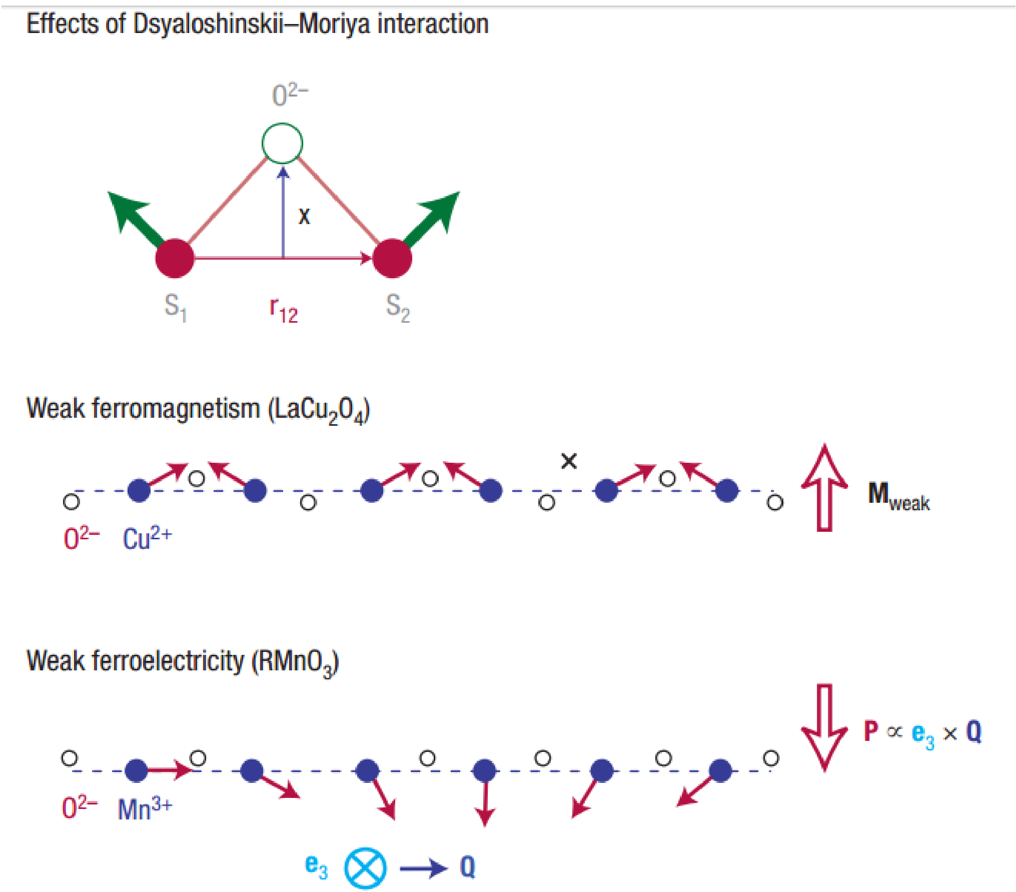




- (a), Néel skyrmion motion driven by the STT. (b), Néel skyrmion motion driven by the SHE. (c), Bloch skyrmion motion driven by the STT. (d), Bloch skyrmion motion driven by the SHE. The four insets show the spatial distribution of the Néel and Bloch skyrmion, where the background colors refer to the z-component of the magnetization (blue negative, red positive), while the arrows are related to the in-plane components of the magnetization. The current flows along the x-direction. The skyrmion moves along the x-direction in the scenarios A, C, and D and along the y-direction in the scenario
- A strategy for the design of skyrmion racetrack memories R. Tomasello Scientific Reports 4, Article number: 6784 (2014) doi:10.1038/srep06784

Multiferroics and DMI

- The anisotropic exchange is of importance for the understanding of **magnetism induced electric polarization** in a recently discovered class of multiferroics.
- Small shifts of the ligand ions can be induced by magnetic ordering, because the systems tends to enhance the magnetic interaction energy on the cost of lattice energy.
- This mechanism is called “inverse Dzyaloshinskii-Moriya effect”. In certain magnetic structures, all ligand ions are shifted into the same direction, leading to a net electric polarization.



SW Cheong nature materials | VOL 6 | JANUARY 2007

Outline of the talk

- Definitions and motivations
- A bit of history: Magnetic storage
  - Storage
  - Signal processing
- Current issues
  - Signal processing: Spin Currents
  - Storage: Topological spin structures/AF
- Open challenges ←

Materials for Spintronics

- **FM materials**

  NiFe CoFeB YIG

- **Materials with High Polarization for Spin Injection**

  Heusler compounds have been intensively studied. The compounds are predicted by electronic structure calculations as half-metals: at the Fermi level, half of the spin-polarized band has a finite value of density of state while the other half has zero density of state, leading to a 100% degree of spin polarization in ideal cases

- **Carbon as a waveguide for spin currents**

  In Cu and Al the spin diffusion lengths are small while longer spin diffusion length is expected in lighter atoms with a reduced spin–orbit coupling due to smaller relativistic effect. Carbon nanotubes(CNT), graphene sheets, organic compounds

- **Silicon Spintronics**

Antiferromagnetic materials

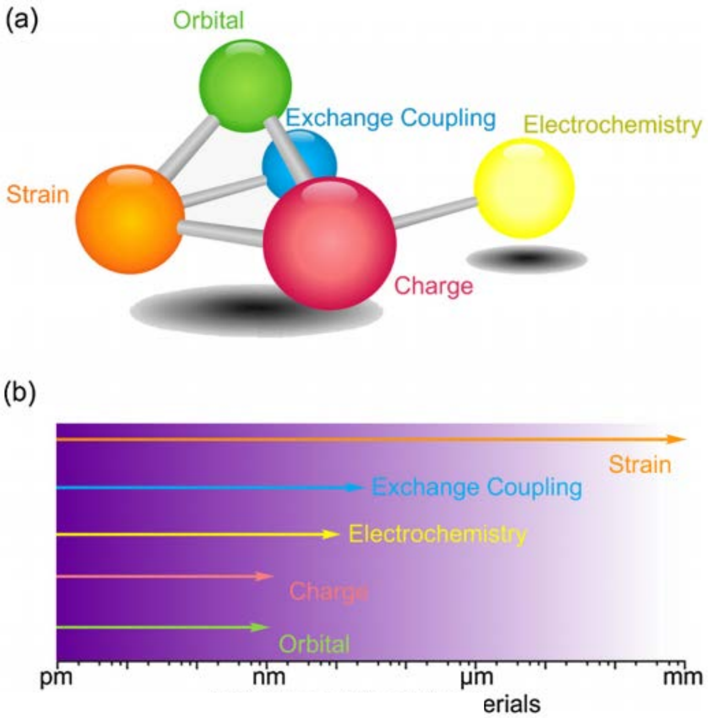
- Antiferromagnetic storage media have been studied as an alternative to ferromagnetism, especially since with antiferromagnetic material the bits can be stored as well as with ferromagnetic material. Instead of the usual definition
- 0 -> 'magnetisation upwards', 1 -> 'magnetisation downwards', the states can be, e.g.,
- 0 -> 'vertically-alternating spin configuration' and 1 -> 'horizontally-alternating spin configuration'..

The main advantages of antiferromagnetic material are:

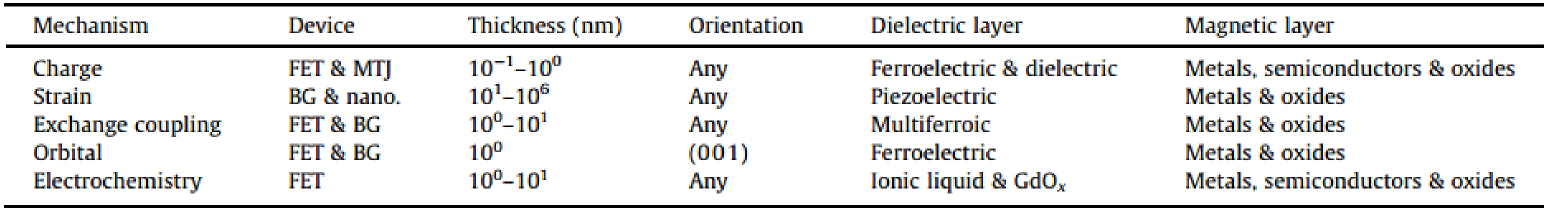
- non-sensitivity against perturbations by stray fields;
- far shorter switching times;
- no effect on near particles.

Electric voltage control of magnetic properties

- Control the magnetic properties by using an electric voltage instead of an electric current
- Open issues:
- (i) enhancement of operating temperature upon room temperature for practical systems; (ii) decreasing the switching voltage to a level far below the breakdown threshold of magnetic tunnel junction; (iii) switching the magnet (U = 10–30 nm) with enough thermal stability (D = KuV/kBT > 60, where Ku and V are anisotropy constant and volume, respectively, kB and T parameter Boltzmann’s constant and temperature, respectively); (iv) device preparation and integration for VCM; (v) reducing the error rate down to 10^-15.



Comparison of five different mechanisms. The conclusions are appropriate to most cases.



Mechanism	Device	Thickness (nm)	Orientation	Dielectric layer	Magnetic layer
Charge	FET & MTJ	10^{-1}–10^{0}	Any	Ferroelectric & dielectric	Metals, semiconductors & oxides
Strain	BG & nano.	10^{1}–10^{6}	Any	Piezoelectric	Metals & oxides
Exchange coupling	FET & BG	10^{0}–10^{1}	Any	Multiferroic	Metals & oxides
Orbital	FET & BG	10^{0}	(001)	Ferroelectric	Metals & oxides
Electrochemistry	FET	10^{0}–10^{1}	Any	Ionic liquid & GdO_x	Metals, semiconductors & oxides

Hu JM Adv Mater 2016;28:15–39
C. Song et al. / Progress in Materials Science 87 (2017) 33–82

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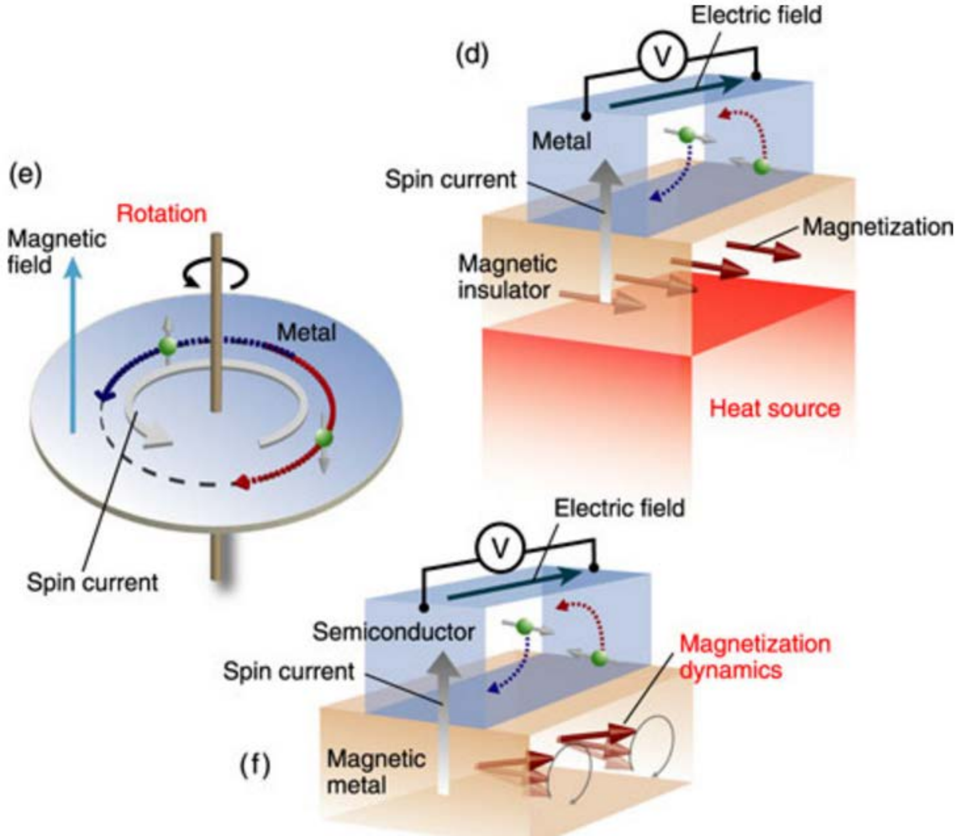
  - Signal processing: Spin Currents
  - Storage: Topological spin structures/AF
- Open challenges METROLOGY ←

Metrology challenges 2020 and beyond

- reliably measure
  - spin currents
  - spin polarization (of currents)
  - spin hall angles



(d) Heating a magnetic insulator produces a spin current along with heat flow. The spin current is converted to electric power in an attached metal. (e) In a rotating metallic disk in a magnetic field, a spin current is generated around the axis of rotation. (f) Ferromagnetic resonance of a magnet injects a spin current into the adjacent semiconductor with high efficiency.

Metrology challenges 2020 and beyond

Open issues

- scaling macro to nano
- quantum based magnetic field measurements down to the nano scale

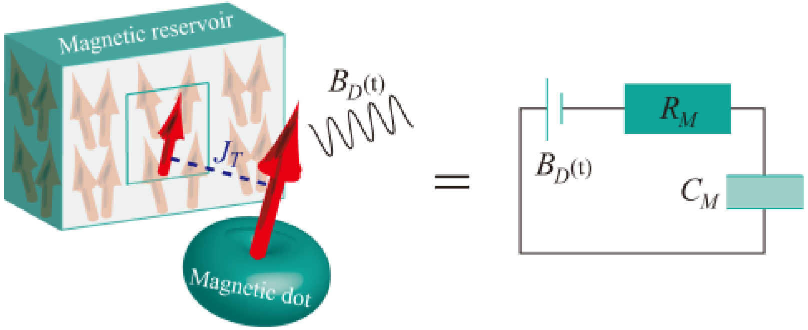


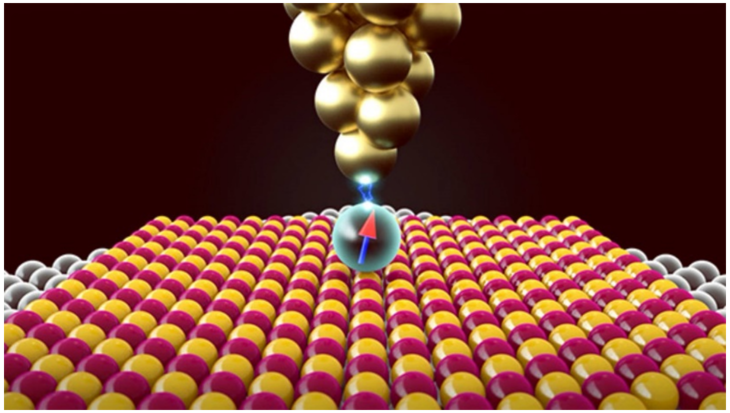
FIG. 3: (Color online) Schematic representation of a quantum magnetic RC circuit proposed in Ref. [23], which consists of the magnetic resistance R_M, the capacitance C_M, and the applied magnetic field B_D. The magnetic dot and the reservoir are weakly coupled by the exchange interaction J_T and both of them are modeled as one-dimensional chains.

Proposal for a quantum magnetic RC circuit
K.A. van Hoogdalem Phys. Rev. Lett. **113**, 037201 – Published 14 July 2014

Metrology challenges 2020 and beyond

Longer term

measuring and detecting single spin states in electronic devices and circuits



The magnetism of the holmium atom can be changed or read by flowing current through the STM tip. Image credit: Fabian D. Natterer *et al*.

END