ICTMC17 Baku, Tutorial session
Date: Sept. 27, 2010 14:00 ~ 15:00

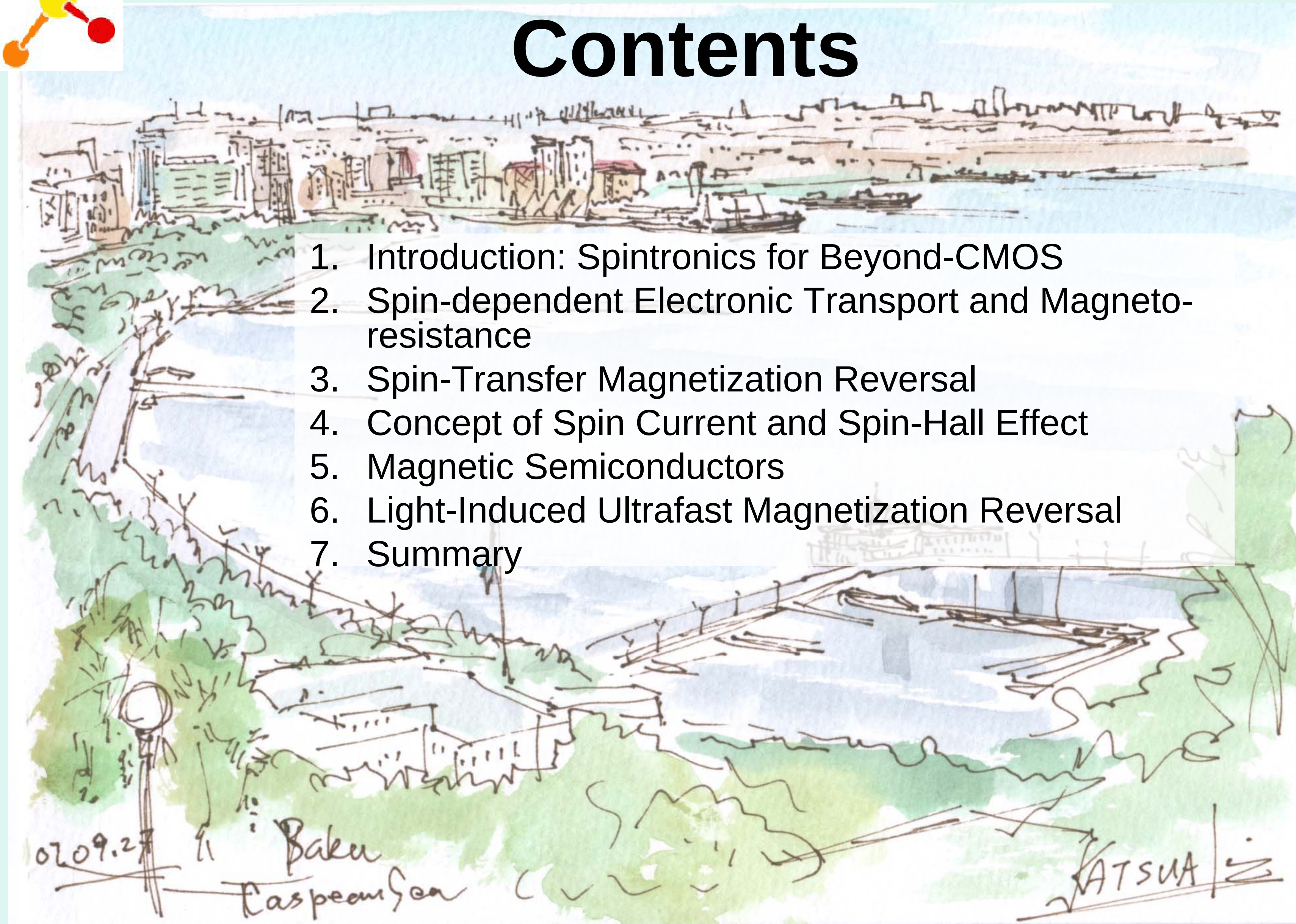
Spintronics for next generation innovative devices

Katsuaki Sato

Research Supervisor, PRESTO Project Japan Science Technology Agency (JST)

Professor Emeritus, Tokyo University of Agriculture and Technology (TUAT)

Contents

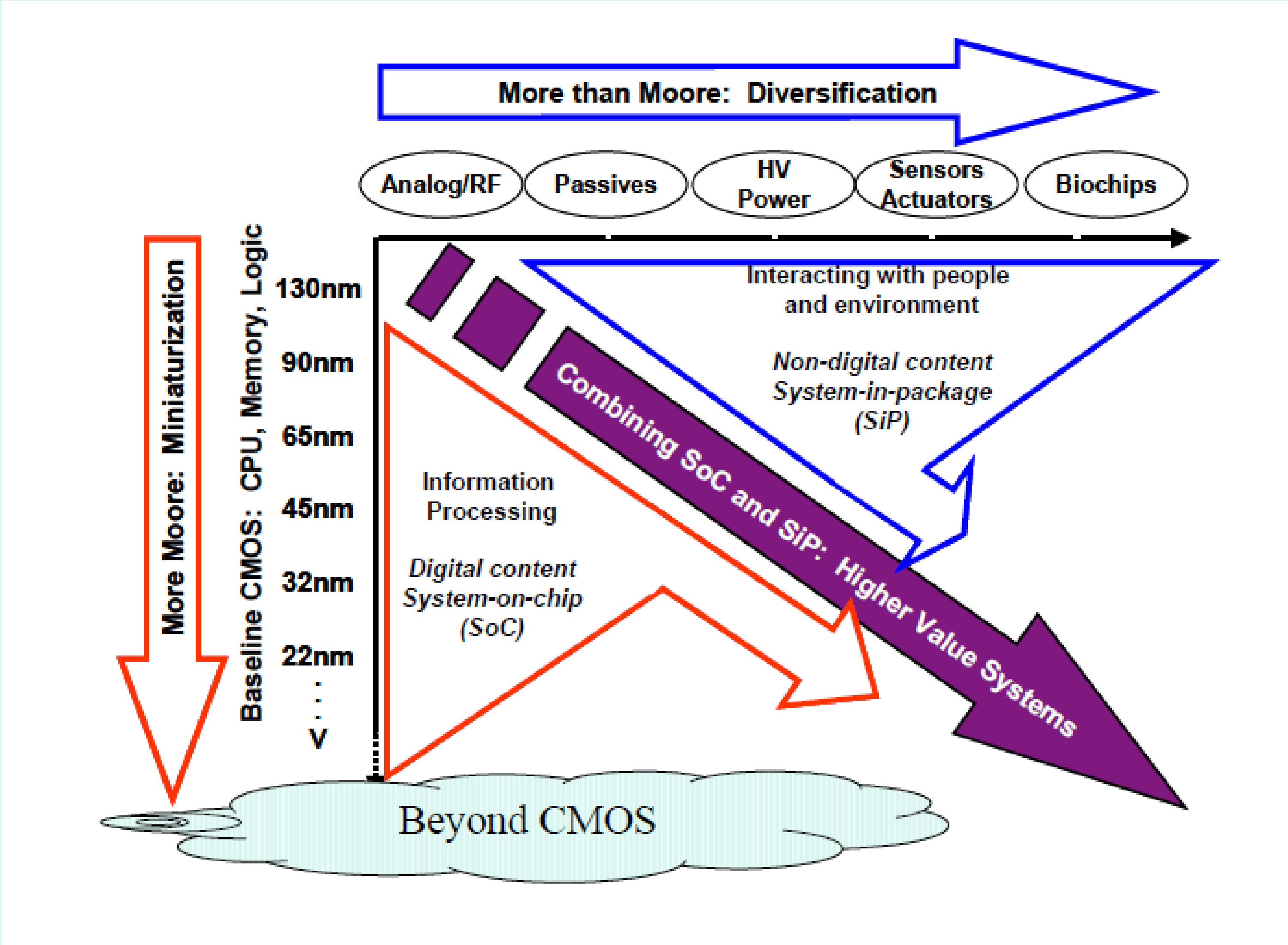


1. Introduction: Spintronics for Beyond-CMOS
2. Spin-dependent Electronic Transport and Magneto-resistance
3. Spin-Transfer Magnetization Reversal
4. Concept of Spin Current and Spin-Hall Effect
5. Magnetic Semiconductors
6. Light-Induced Ultrafast Magnetization Reversal
7. Summary

1. Introduction

- Silicon crystals used for semiconductor integrated circuits represented by CMOS are the materials regarded as the most basic material supporting today's living.
- Semiconductor manufacturing technologies are indivisibly related to nanotechnology, since they become more and more sophisticated as exemplified by the fact that the manufacturing accuracy of the CMOS micro-processing plunges into the nanometer range.
- Consequently the limit of 22 nm half pitch is approaching, which in turn requires device development based on new concepts and/or new principles beyond conventional silicon CMOS technologies.

ITRS Roadmap



Emerging Research Materials

Low Dimensional Materials(Nano-mechanical memory, Nanotube, Nanowire, Graphene・・・)
Macromolecules(Molecular memory, Molecular devices, Resists, Imprint polymers・・・)
Self-Assembled Materials(Sub-lithographic patterns, selective etch・・・)
Spin Materials (MRAM by spin injection, Semiconductor spin transport, FM semiconductors・・)
Complex Metal Oxides (Multiferroics)
Interfaces and Heterointerfaces(Electrical and spin contacts)

Table ERM2 Applications of Emerging Research Materials

MATERIALS	ERD MEMORY	ERD LOGIC	LITHOGRAPHY	FEP	INTERCONNECTS	ASSEMBLY AND PACKAGE
Low Dimensional Materials	Nano-mechanical Memory	Nanotube Nanowire Graphene and graphitic structures	High-index immersion liquids		Nanotubes Metal nanowires	Electrical applications Thermal applications Mechanical applications
Macromolecules	Molecular memory	Molecular devices	Resists Imprint polymers	Novel cleans Selective etches Selective depositions	Low-κ ILD	Polymer electrical and thermal/ mechanical property control
Self Assembled Materials			Sub- lithographic patterns Enhanced dimensional control	Selective etch Selective deposition Deterministic doping	Selective etch Selective deposition	High performance capacitors
Spin Materials	MRAM by spin injection	Semiconductor spin transport Ferromagnetic (FM) semiconductors FM metals Tunnel dielectrics Passivation dielectrics				
Complex Metal Oxides	1T Fe FET Fuse-anti-fuse	Multiferroics (Spin materials) Novel phase change				High performance capacitors
Interfaces and Heterointerfaces	Electrical and spin contacts and interfaces	Electrical and spin contacts and interfaces			Contacts and interfaces	

Spintronics Materials in ITRS Roadmap

Table ERM7 Critical Properties of Spintronics Materials

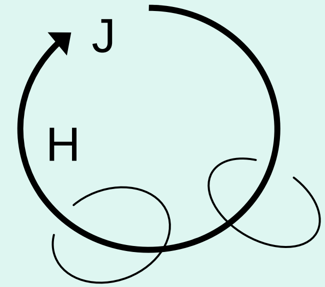
EMERGING SPIN BASED MATERIALS	MATERIAL EXAMPLES	MECHANISM TO READ COMPUTATIONAL STATE	CRITICAL PROPERTIES	CHALLENGES
Ferromagnetic metals	Co, Ni, Fe	Spin injection/extraction	Spin polarization and band symmetry	Interface stability, Schottky barrier control
Half Metals	Fe_3O_4, CrO_2 Heusler–LSMO Mixed mangantites NiMnSb	Spin polarization	Interface properties and spin band symmetry,	Stoichiometry control Method of characterization Reproducible material fabrication
Multiferroic materials	$BiFeO_3$ PZT/$NiFe_2O_4$ $CoFe_2O_4$/$BaTiO_3$ PZT/Terfenol-D	Voltage Magnetic field	Magnetic and electrical coupling coefficients	High electric and magnetic coupling
(Diluted) Magnetic Semiconductors (Collective ferromagnetic spin orientation	Ferromagnetic semiconductors EuO DMS (II,Mn)/VI (III,Mn)/V DMS IV,Mn Silicides	Electrical, control of spin alignment	T_C, Carrier control of ferromagnetism Spin orbit coupling (as manifest in spin lifetimes, and diffusion lengths) g-Factor** Coercivity	Achieving Curie temperature above room temperature Structural homogeneity
Semiconductors	GaAs, etc. Nanotubes Nanowires, etc.	Spin transport	Spin decoherence time	
Dielectric Barrier	MgO	Spin transport or spin selective filter	Spin band symmetry	Control of interfacial properties

*** The g-Factor relates the total magnetic moment to the electron spin angular momentum and the Bohr magneton.*

Mutual Conversion between Electricity and Magnetism

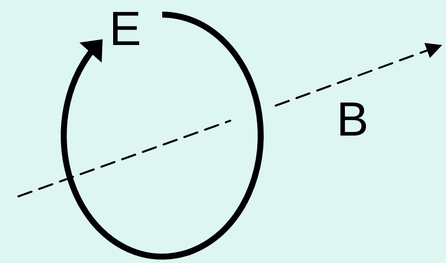
- Electricity→Magnetism. Ampere's Law

  $\nabla\times H=\partial D/\partial t+J$



- Magnetism → Electricity: Faraday's Law

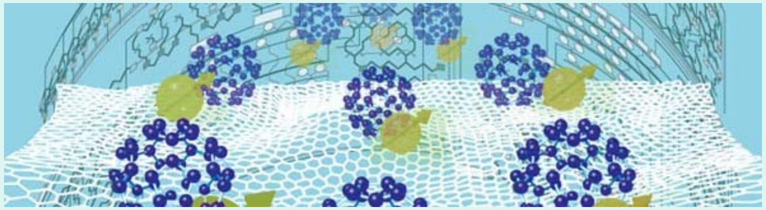
  $\nabla\times E=-\partial B/\partial t$



- Both conversions based on "electromagnetism" require coils.
- *Human beings finally succeeded in mutual conversion without coils by virtue of spintronics!*

PRESTO Project targeting at Next Generation Devices

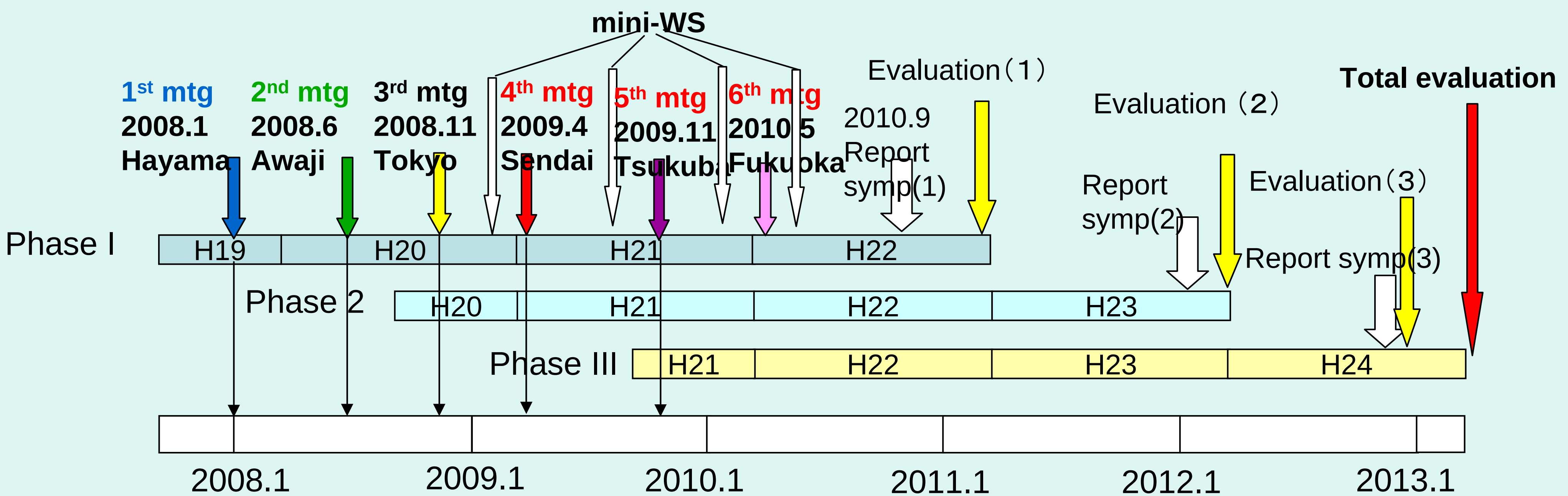
- The PRESTO* project "Materials and Processes for Next Generation Innovative Devices" for which I am dedicating myself as a Research Supervisor started in 2007 to *overcome the limitation and break up a novel paradigm for next-generation device technology.*
- The scope of this project involves spintronics materials, high-mobility wide-gap semiconductors, materials of strongly-correlated system including high temperature superconductors, quantum dots, nano-carbons, and organics.
- Among the topics, the most exciting one may be spintronics. Spintronics is the term to express a field of electronics utilizing both charge and spin degrees of freedom possessed by an electron, which have been treated independently until recently.



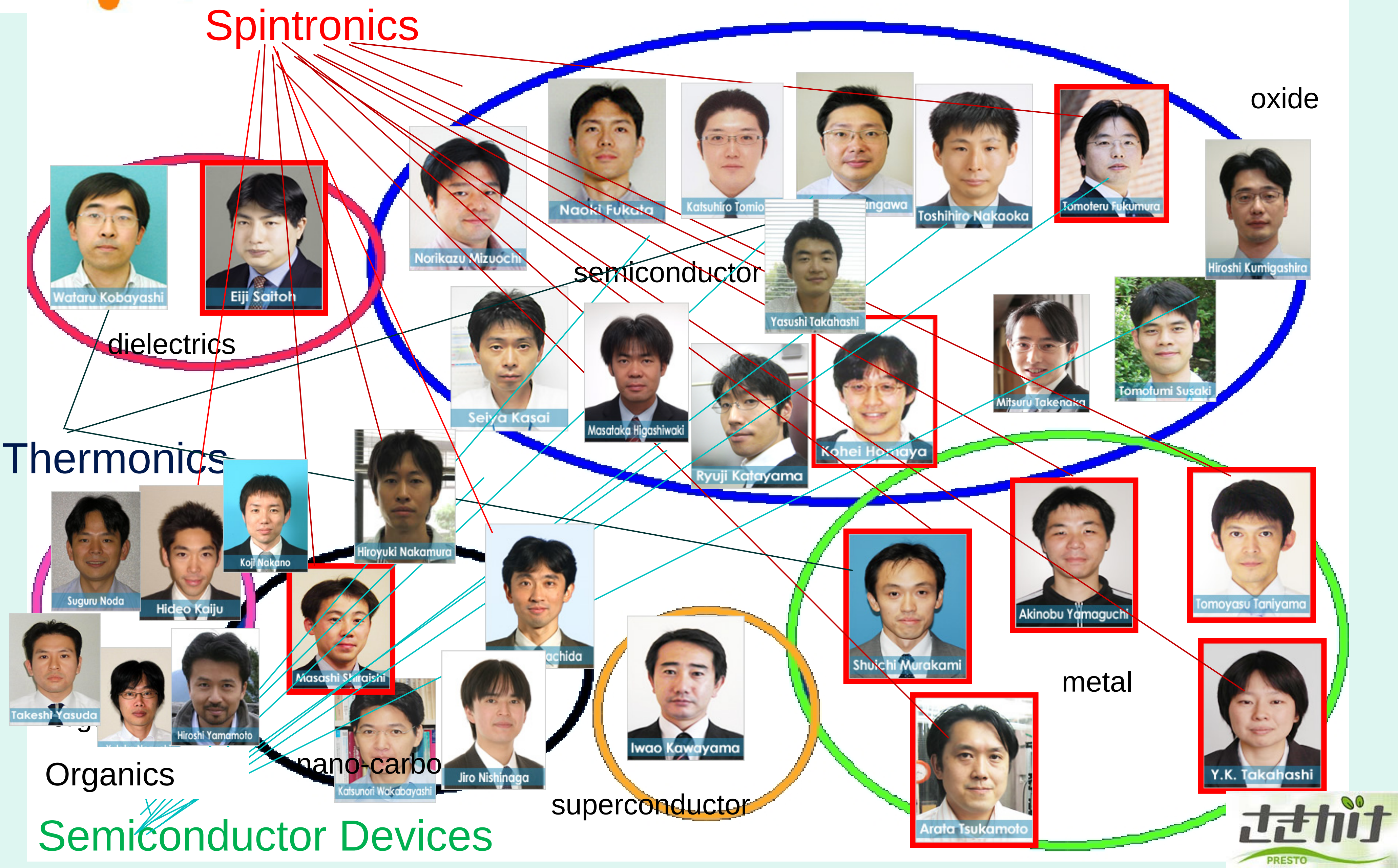
* *Precursory Research for Embryonic Science and Technology* (Sakigake)

PRESTO Projects for “Next Generation Devices”

- The phase I group started on October 2007
- The phase II group joined on October 2008
- The phase III group joined on October 2009



Our Team


ICTMC17
Baku 2010
Spintronics
oxide
semiconductor
dielectrics
Thermonics
Organics
nano-carbo
superconductor
metal
Semiconductor Devices
Naoki Fukata
Katsuhiro Tomio
ngawa
Toshihiro Nakaoka
Tomoteru Fukumura
Hiroshi Kumigashira
Wataru Kobayashi
Eiji Saitoh
Norikazu Mizuochi
Yasushi Takahashi
Seiya Kasai
Masataka Higashiwaki
Ryuji Katayama
Kohei Hamaya
Mitsuru Takenaka
Tomofumi Susaki
Suguru Noda
Hideo Kaiju
Koji Nakano
Hiroyuki Nakamura
Takeshi Yasuda
Hiroshi Yamamoto
Masashi Shiraishi
achida
Katsunori Wakabayashi
Jiro Nishinaga
Iwao Kawayama
Shuichi Murakami
Akinobu Yamaguchi
Tomoyasu Taniyama
Arata Tsukamoto
Y.K. Takahashi
PRESTO

2. Spin-dependent Electronic Transport and Magneto-resistance

2.1 History of Spin-Dependent Transport Phenomena
2.2 Encounter with nanotechnology
2.3 Discovery of giant magnetoresistance (GMR)
2.4 Physical background of GMR
2.5 Spin valve for HDD head
2.6 Artificial control of exchange interaction
2.7 Discovery of room temperature TMR
2.8 History of TMR
2.9 Physical background of TMR
2.10 MRAM (Magnetic random access memory)
2.11 Single crystalline barrier layer of MgO
2.12 Half metal electrodes for MTJ
2.13 Heusler Alloys
2.14 Observation of Dynamic Spin Motion using Rectification Effect

2.1 History of Spin-Dependent Transport Phenomena

- The phenomena of spin-dependent electrical transport such as spin-disordered scattering just below the Curie temperature and anisotropic magnetoresistance and anomalous Hall effect in ferromagnetic metals have been studied extensively and explained theoretically already in 1960's.
  - For example、G.K. White and R.J. Tainsh: Phys. Rev. Lett. **19** (1967) 165.
  - A. Fert and I.A. Campbell: Phys. Rev. Lett. **21** (1968) 1190.
- AMR (Anisotropic Magnetoresistance) and AHE (Anomalous Hall Effect) has been known from 1950's.
  - R.Karplus and J.M. Luttinger: Phys. Rev. 95 (1954) 1154
- The huge negative magnetoresistance in the vicinity of Tc in magnetic semiconductors such as $CdCr_2Se_4$ and EuO has been explained in terms of the spin-disordered scattering.
  - C. Haas: Phys. Rev. 168 (1968) 531
- However, at these times these phenomena are thought to be *built-in* properties and *out of our control*.

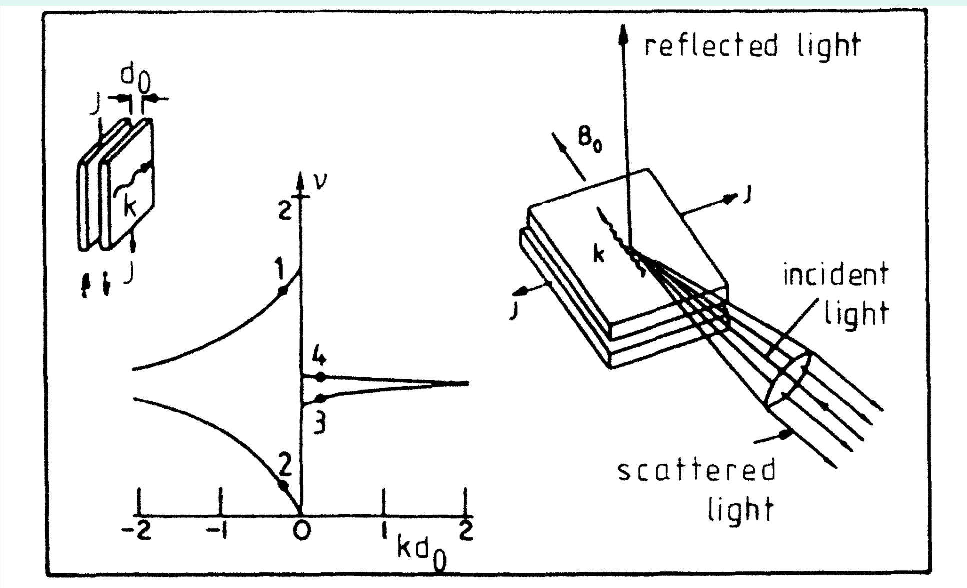
ICTMC17 Baku 2010

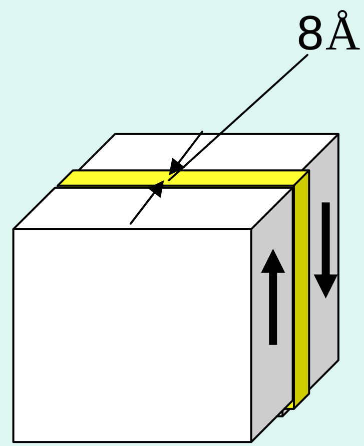
2.2 Encounter with nanotechnology (1)

- Nanotechnology pioneered by Dr. Esaki opened up semiconductor nanoscience such as 2DEG, quantum confinement, energy band modulation by superlattice, leading to novel application field like HEMT, MQW laser.
- Quantum effect showed up at the early stage of nanotechnology where the scale of the structure was relatively large, since the de Broglie wavelength is as large as 10 nm in semiconductor.
- On the other hand in magnetic materials, since extension of 3d electrons is no larger than a few nm, appearance of size effect should wait until nanometer process became possible in the late 80's.

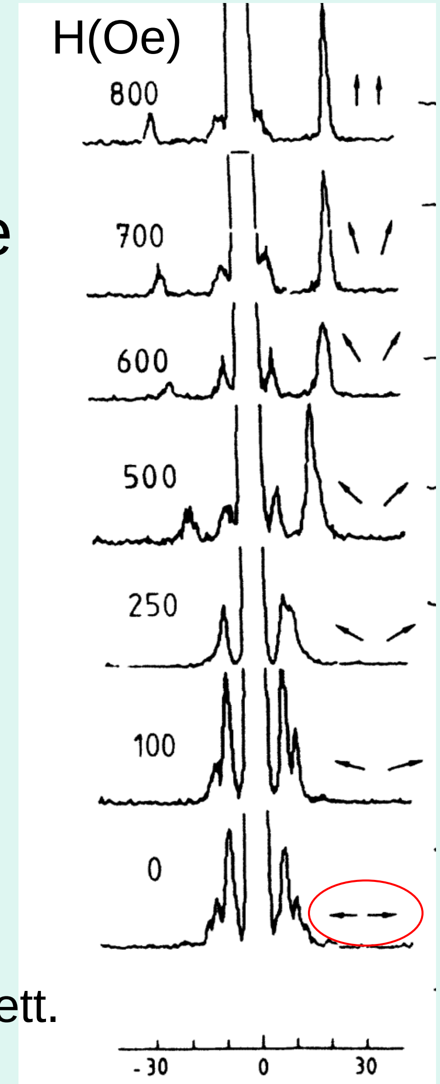
Encounter with nanotechnology (2)

- In 1986 Grünberg's group discovered magnetization of two magnetic layers align antiparallel in the Fe/Cr(8Å)/Fe trilayer structure using the magnon-Brillouin scattering.





P. Grünberg, R. Schreiber and Y. Pang: Phys. Rev. Lett. 57 (1986) 2442.

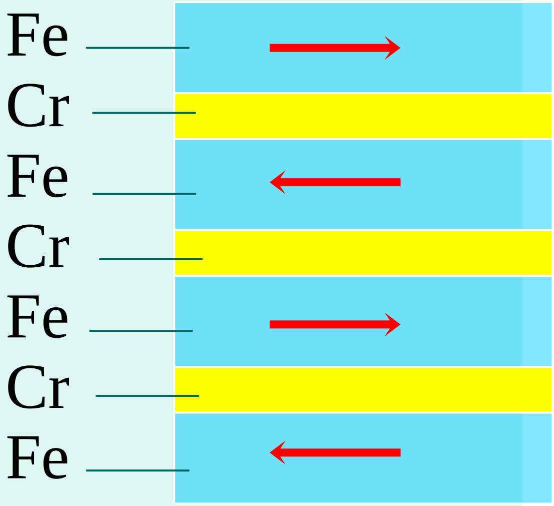


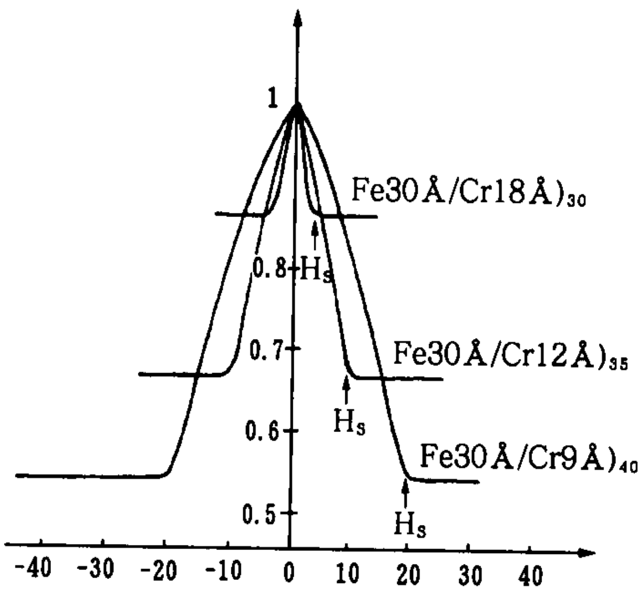
Breakthrough in Spintronics

2.3 Discovery of giant magnetoresistance(*GMR*) (1)

- In 1988 Fert's group discovered magnetoresistance as large as 50 % in Fe/Cr superlattice and named it as GMR.

Dr. Albert Fert



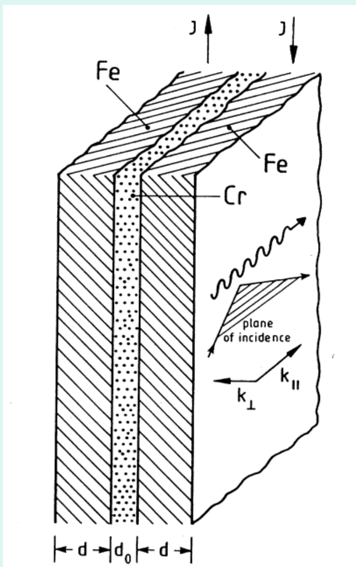


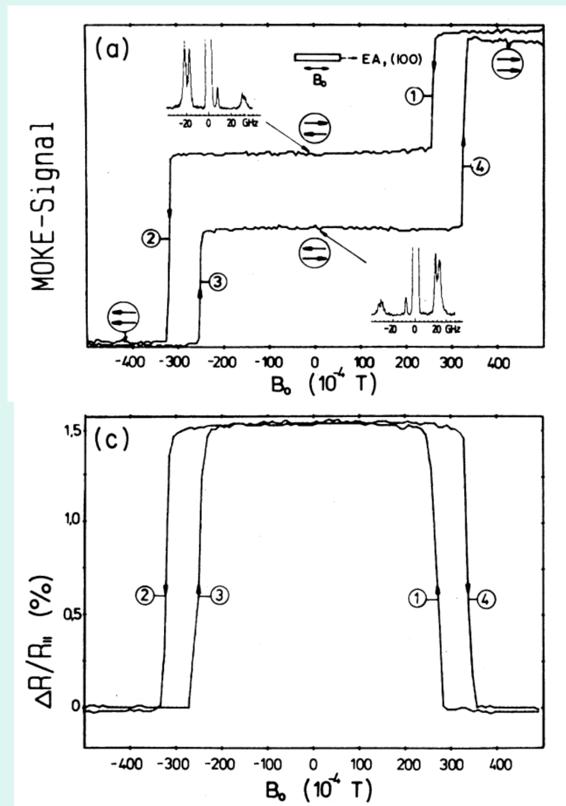
M.N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friedrich, J. Chazelas: Phys. Rev. Lett. 61 (1988) 2472.

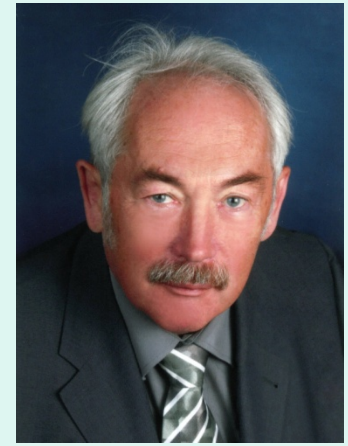
Breakthrough in Spintronics

Discovery of giant magnetoresistance(*GMR*)(2)

- At the same time, Grünberg also discovered GMR (although small) in Fe-Cr-Fe trilayer.







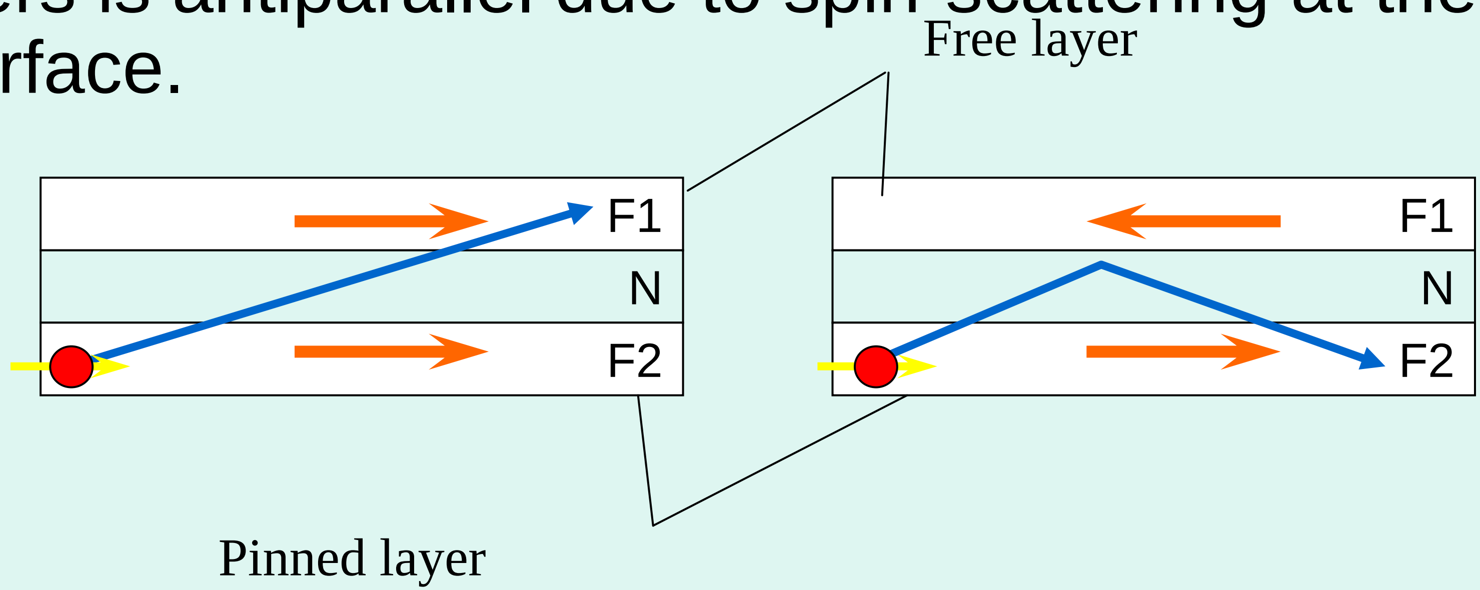
Dr. Peter Grünberg

G. Binasch, P. Grünberg, F. Saurenbad, W. Zinn: Phys. Rev. B 39 (1989) 4828.

ICTMC17 Baku 2010

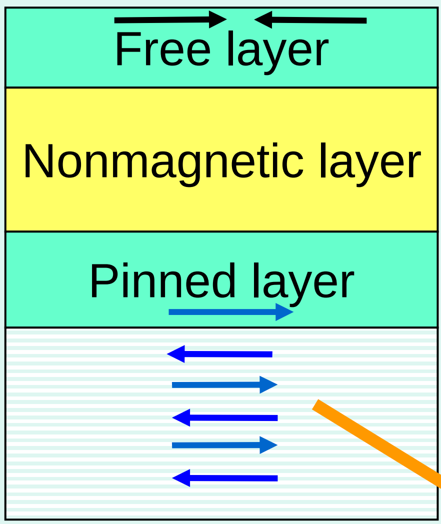
2.4 Physical background of GMR
Spin-scattering at layer-interfaces

- In the ferromagnetic(F1)/nonmagnetic metal(N)/ferromagnetic(F2) structure, electric resistance is low if magnetization of F1 and F2 layer is parallel, while it is high if magnetization of two layers is antiparallel due to spin-scattering at the interface.



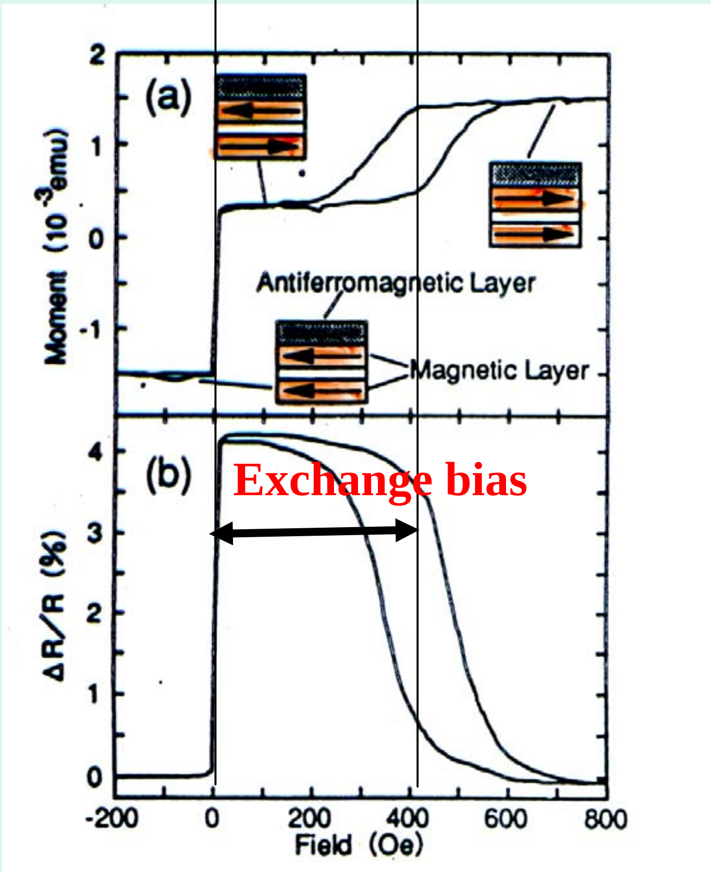
2.5 Spin valve for HDD head

- Parkin of IBM elaborated a magnetic field sensor for HDD using uncoupled sandwich structure NiFe/Cu/NiFe/FeMn, and named it as Spin Valve.



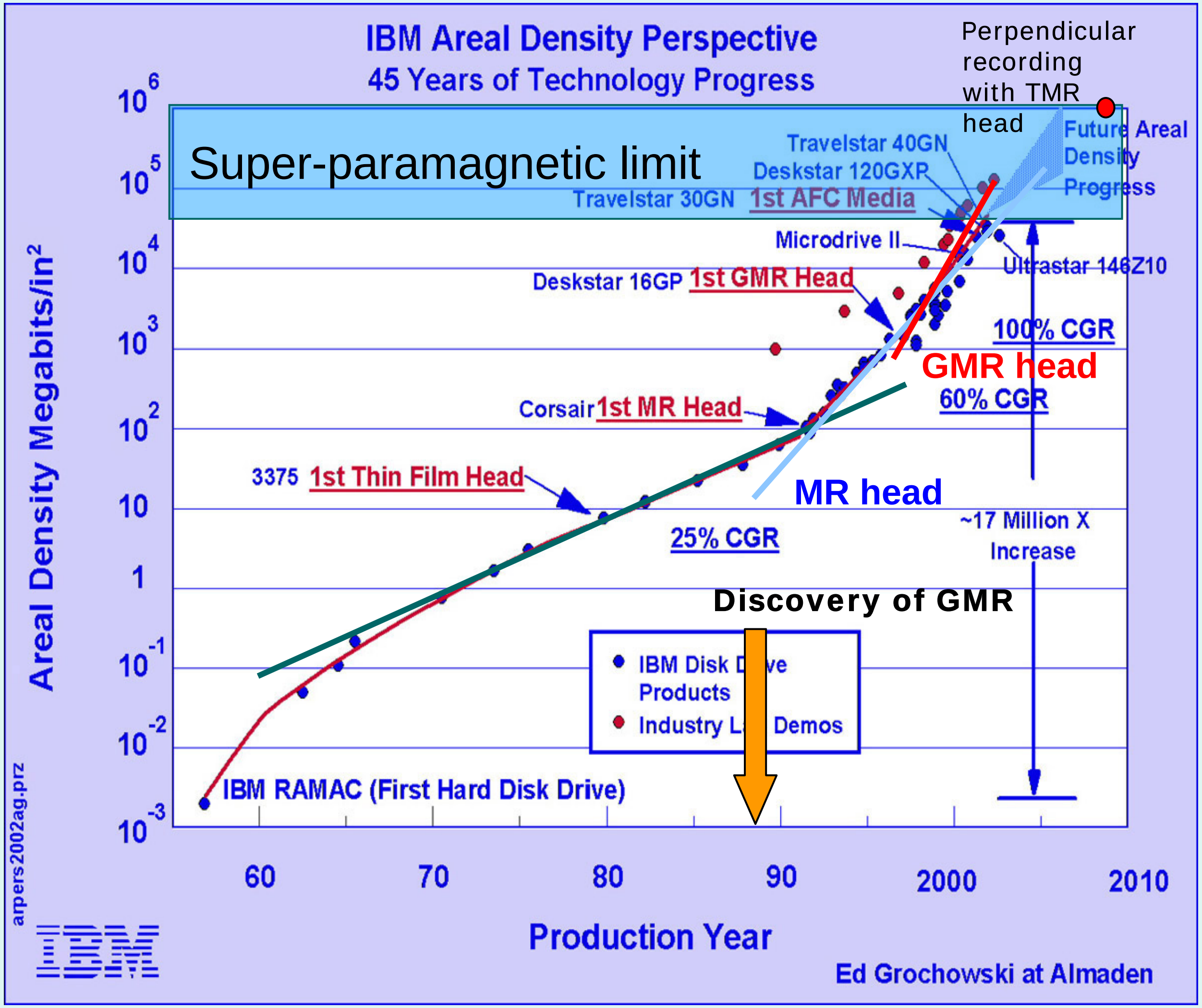
Important point of this invention is a use of the exchange bias effect introduced by coupling with antiferromagnetic substrate.

Antiferromagnetic substrate (ex FeMn)
(Synthetic antiferromagnet)



S. S. P. Parkin, Z. G. Li and David J. Smith: Appl. Phys. Lett. 58 (1991) 2710.

Dramatic increase in the areal density of HDD



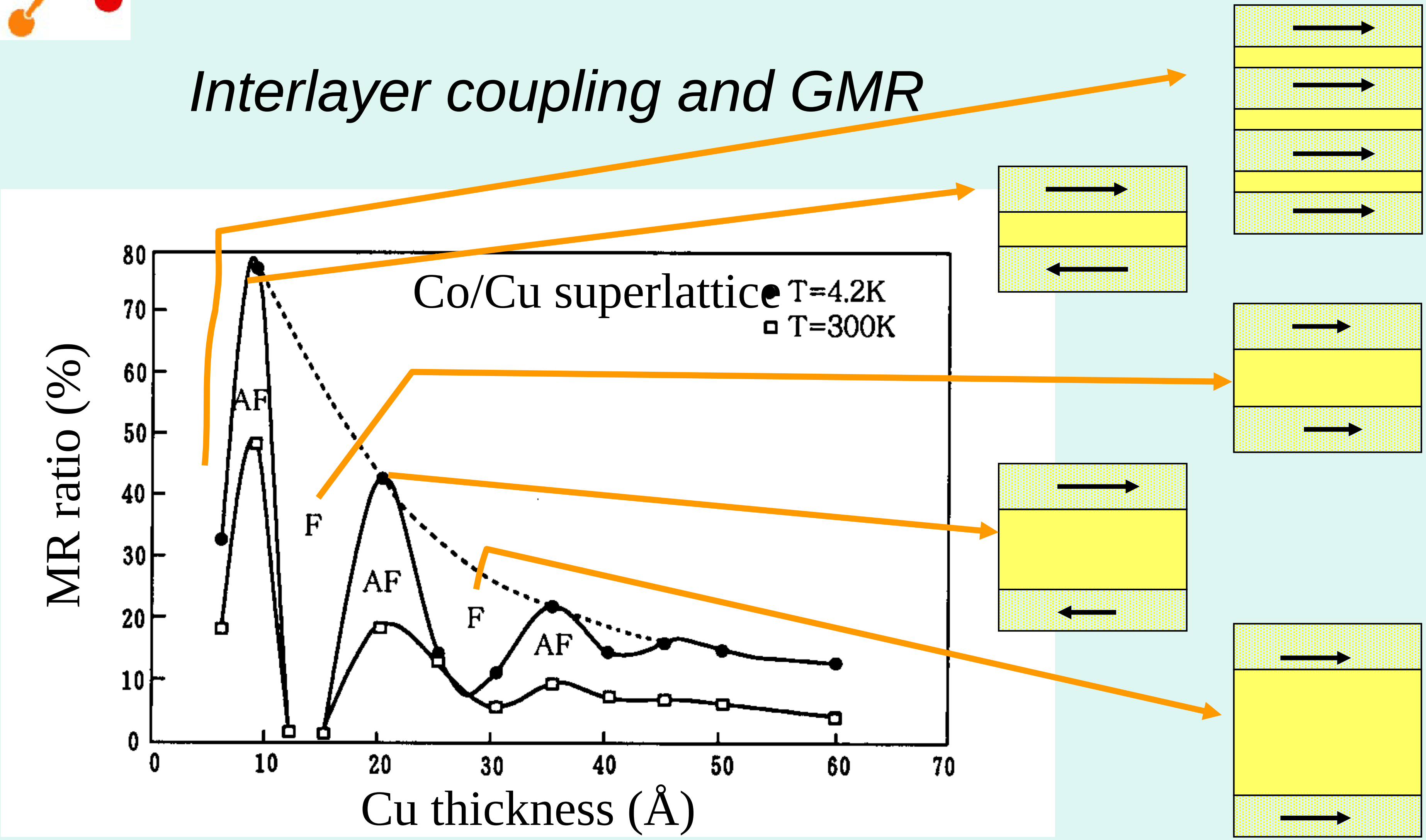
- Introduction of GMR (Spin Valve) head brought a dramatic change in the growth rate of areal recording density of HDD.
- It is quite remarkable that scientific discovery lead to practical applications in such a short period of time.

ICTMC17 Baku 2010

2.6 Artificial control of exchange interaction

- At the same period periodic variation of exchange interaction with the thickness of nonmagnetic layer in magnetic/nonmagnetic superlattice: Magnetic coupling varies ferromagnetic $\rightarrow$antiferromagnetic $\rightarrow$ ferromagnetic with a few nm period.
  - S. S. P. Parkin, N. More, and K. P. Roche:“Oscillations in Exchange Coupling and Magnetoresistance in Metallic Superlattice Structures: Co/Ru, Co/Cr and Fe/Cr”, Phys. Rev. Lett. 64 (1990) 2304.
- *Thus human being obtained a method of artificial control of exchange interaction.*

Interlayer coupling and GMR



D.H. Mosca, F. Petroff, A. Fert, P.A. Schroeder, W.P. Pratt Jr., R. Laloee: JMMM **94** (1991) L1

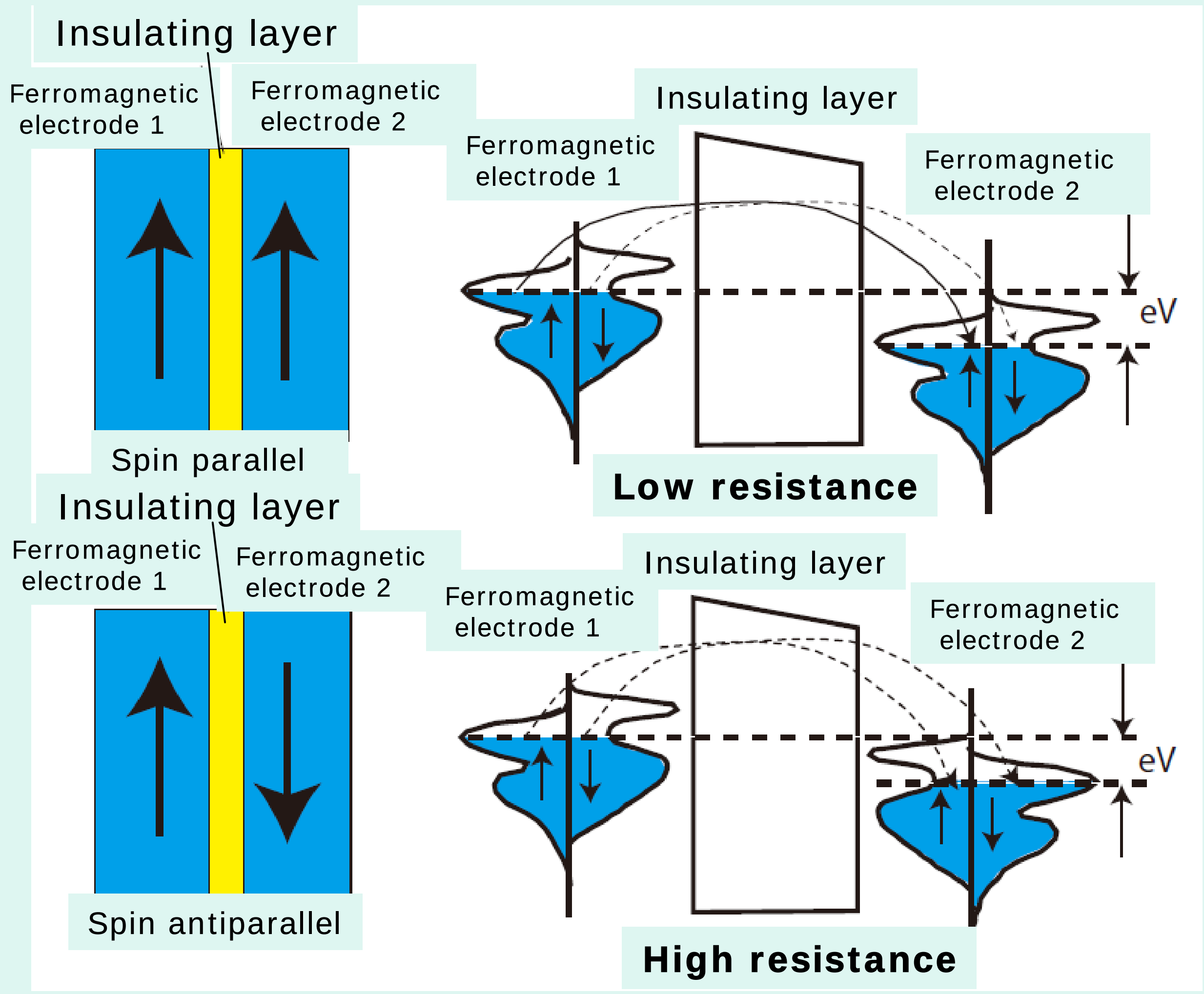
2.7 Discovery of room temperature TMR

- Further breakthrough in spintronics has been brought about by Miyazaki in 1995, who discovered the large tunneling magnetoresistance (TMR) ratio of 18% at room-temperature in the magnetic tunnel junction (MTJ) of ferromagnet/insulator/ferromagnet structure. [1]
  - TMR ratio is defined as TMR(%)=$(R_{\uparrow\uparrow}-R_{\uparrow\downarrow})/R_{\uparrow\uparrow}\times 100$ where $R_{\uparrow\uparrow}$ is resistance for parallel spins and $R_{\uparrow\downarrow}$ is for antiparallel spins.
  - [1] T. Miyazaki, N. Tezuka: J. Magn. Magn. Mater. 139 (1995) L231.

2.8 History of TMR

- Spin-dependent tunneling phenomenon has been investigated from 80's.
  - R. Meservey, P.M. Tedrow, P. Flulde: Magnetic Field Splitting of the Quasiparticle States in Superconducting Aluminum Films; Phys. Rev. Lett. **25** (1970) 1270.
  - S. Maekawa, U. Gäfvert: Electron tunneling between ferromagnetic films; IEEE Trans. Magn. **MAG-18** (1982) 707.
- Practical application of TMR had not been realized due to difficulty in the control of the thin insulating layer until Miyazaki's group succeeded in fabricating very flat insulating layer without pinholes.
  - T. Miyazaki, N. Tezuka:Giant magnetic tunneling effect in Fe/Al2O3/Fe junction; J. Magn. Magn. Mater. 139 (1995) L231.

2.9 Physical background of TMR

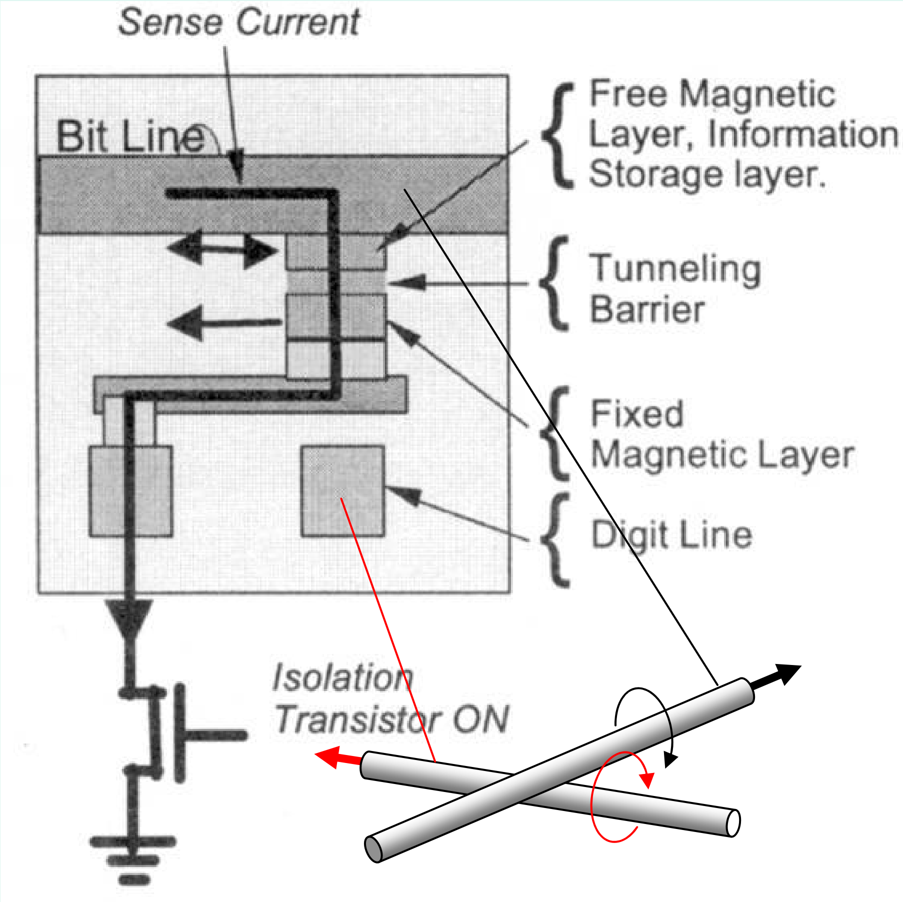


- TMR can be explained by spin-polarized energy band structure.
- Density of states at the Fermi level is different between up-spin and down-spin band.
- In the parallel case, electron transfer channel between up-spin states is wide leading to low resistivity.
- In the antiparallel case, both channels are wide leading to high resistivity.

Application of TMR

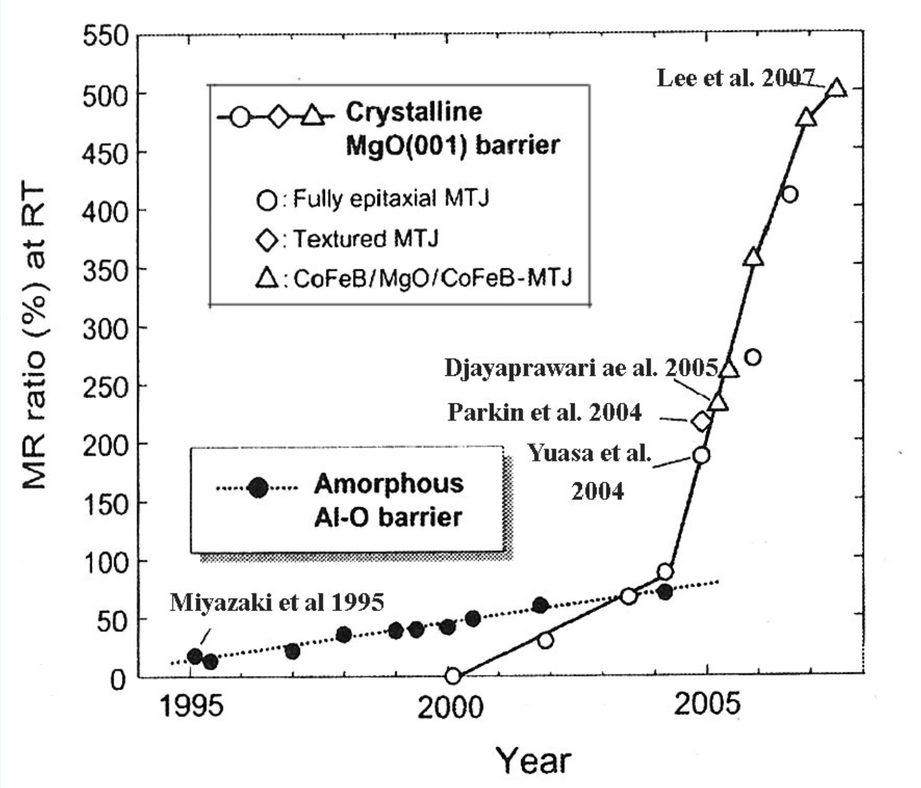
2.10 MRAM (Magnetic random access memory)

- MRAM is a nonvolatile memory device combining MTJ and CMOS logic.
- Writing is acomplished by changing magnetization of MTJ free layer by application of electric current to two crossing wires generating magnetic field above Hk of the free layer.
- MRAM is expected to be a next-generation universal memory with an addressing access time of 10ns and cycle time of 20ns.



2.11 Single crystalline barrier layer of MgO

- Extremely high TMR was theoretically predicted for a use of MgO single-crystalline insulating layer instead of the amorphous Al-O layer, which initiated experimental challenges.
- In 2004, Yuasa and Parkin independently succeeded in realizing a TMR ratio as large as 200% at room temperature by the introduction of a high quality MgO insulating layer.
  - S. Yuasa, A. Fukushima, T. Nagahama, K. Ando, Y. Suzuki: Jpn. J. Appl. Phys. 43 (2004) L588.
  - S. S. P. Parkin et al., Nature Mater. 3 (2004) 862–867.
- The ratio has still been improved to as high as 500% at room temperature.
  - Y. M. Lee, J. Hayakawa, S. Ikeda, F. Matsukura, H. Ohno : Appl. Phys. Lett. 90 (2007) 212507.



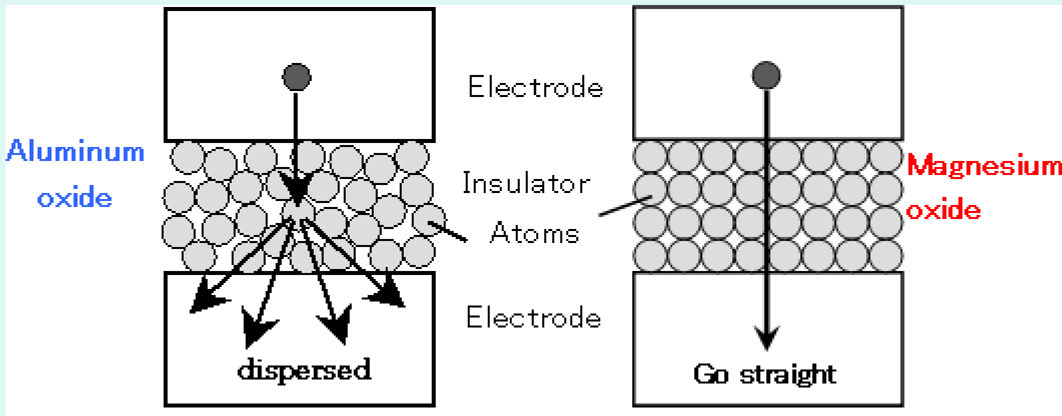
[S. Yuasa: Digest of Kaya Conference (2007.8.19) p.19]

Physical Background of High TMR by MgO Insulator

Diffuse Tunneling and Coherent Tunneling

- Usually spin is conserved during tunneling and TMR ratio of diffuse tunneling is expressed by Jullier's formula
  - $TMR=2P_1P_2/(1-P_1P_2)$
    where $P_{i,j}$ $(i, j=1,2)$ stand for spn polarization of i-th layer[1]
- Degree of spin polarization in MTJ is not an intrinsic property to each magnetic material but is related to interfacial electronic states depending on barrier material and interface morphology.

- On the contrary, since magnesium oxide is in a single-crystal state, the electrons can move straight without suffering dispersion. In this case, theoretical study predicts huge tunnel magnetoresistive effect as large as 1000 %. [2]



(a) Conventional device
Using aluminum oxide (amorphous). Electrons are scattered due to disorder atom arrangement.

(b) Novel single-crystal device
Using magnesium oxide (single-crystal). Electrons can move straight without suffering dispersion.

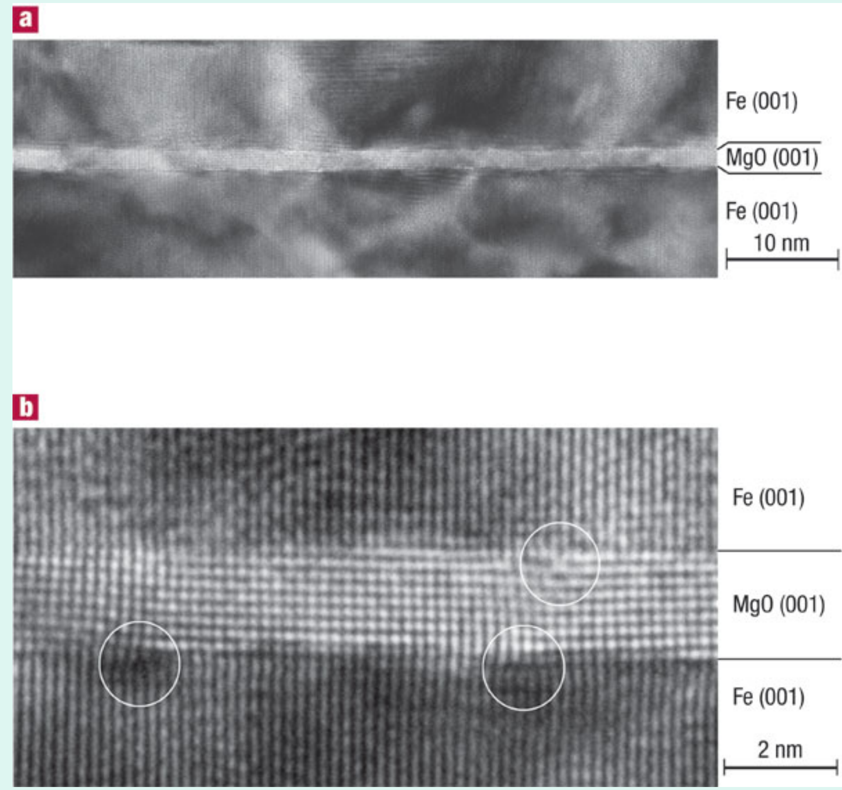
[1] M. Jullier, Phys. Lett. 54A, 225 (1975).
[2] W. H. Butler et al., Phys. Rev. B 63 (2001) 054416, J. Mathon and A. Umeski, Phys. Rev. B 63 (2001) 220403R

K. Inomata：RIST News No. 42(2006) 35.

TEM image of Fe/MgO/Fe structure

Cross sectional TEM image of epitaxially grown Fe(001)/MgO(001)/Fe(001)shows a well ordered MgO layer without Fe-oxide layer.

•*Establishment of preparation technique of high quality MgO epi-layer is the key point of the success.*

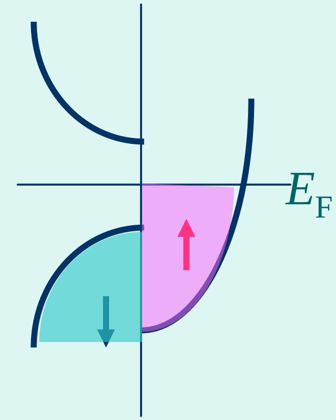


Yuasa et al. Nature Materials **3,** 868–871 (2004)

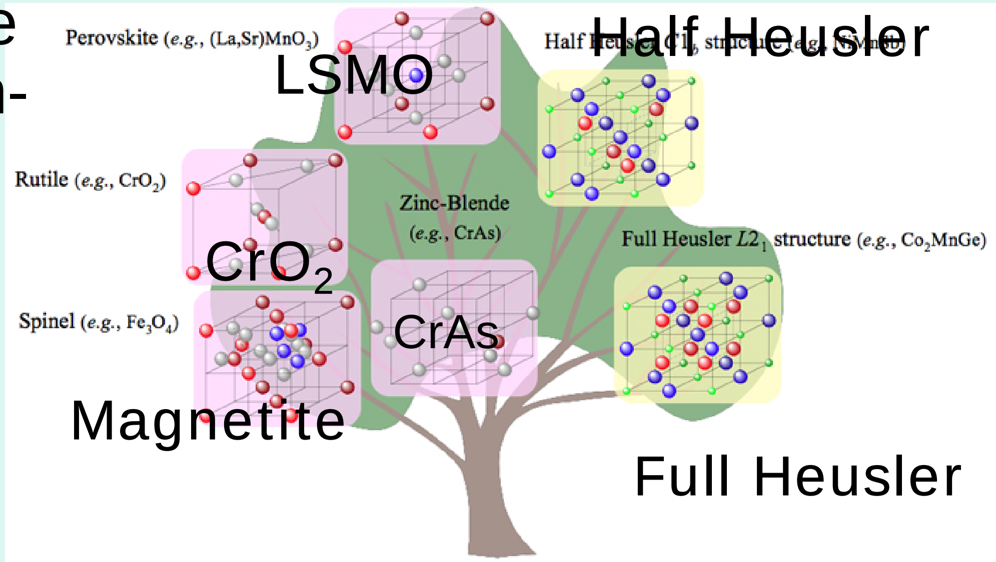
The result of Yuasa is an outcome of the JST-PRESTO Project “Nanotechnology and Material Property”.

The Research Theme of Dr. Yuasa was Development of single-crystal TMR Devices for High-Density Magnetoresistive Random Access Memory

2.12 Half metal electrodes for MTJ



- Half metal is a magnetic material in which electronic state for ↑ spin is metallic while that for ↓ spin is semiconducting.
- Therefore the electronic state at the Fermi level is fully spin-polarized in half metals.
- Heusler compounds, LSMO ($La_{1-x}Sr_xMnO_3$), magnetite (Fe_3O_4), chromium oxide (CrO_2) are candidates of half metals.



http://www.riken.go.jp/lab-www/nanomag/research/heusler_e.html

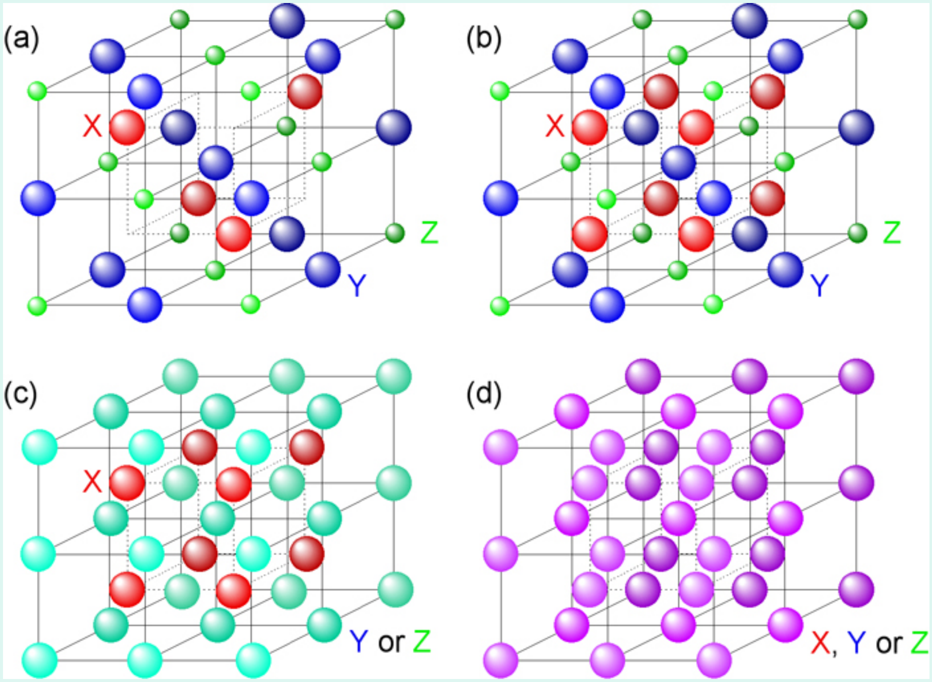
2.13 Heusler Alloys

- The Heusler alloys are classified into two groups by their crystal structures;
  - Half Heusler alloys with XYZ-type in the *C*1*b* structure (a)
  - Full Heusler alloys with X_2YZ-type in the $L2_1$ structure (b)
    where X and Y atoms are transition metals, while Z is either a semiconductor or a non-magnetic metal.

http://www.riken.go.jp/lab-www/nanomag/research/heusler_e.html

Half Heusler alloy XYZ type $C1_b$ str.

Full Heusler alloy X_2YZ with $L2_1$ str.



B_2-structure with Y-Z disorder

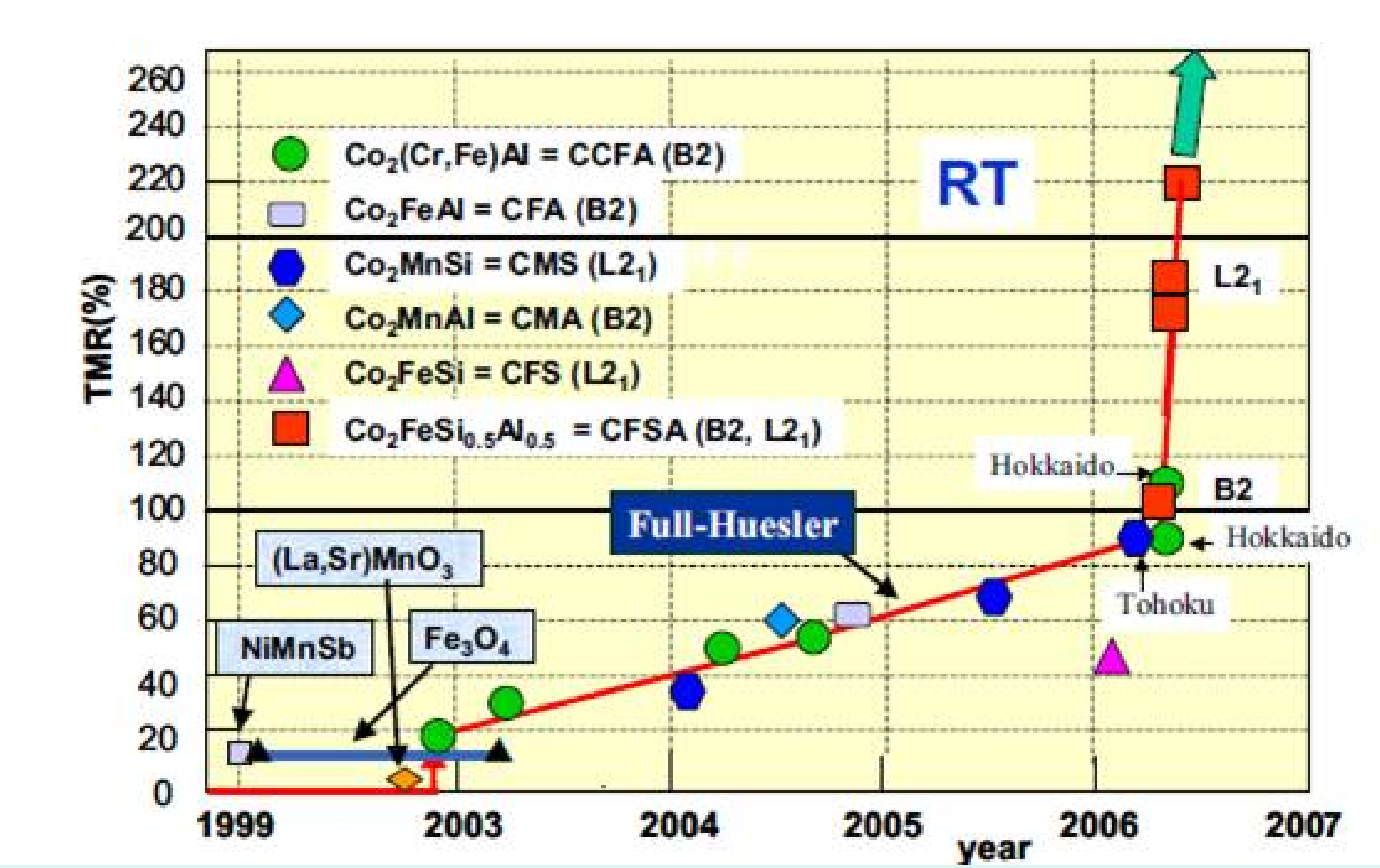
A_2-structure with X-Y and X-Z disorder

Disordered derivatives

Japan Science and Technology Agency

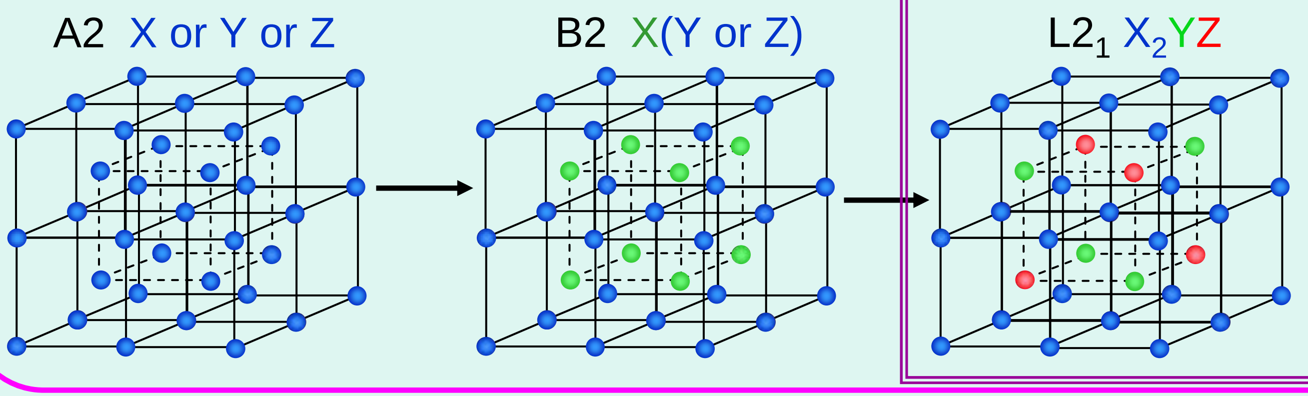
ICTMC17 Baku 2010

TMR with full Heusler X_2YZ alloys



Alloy search for RT half-metal

Co based Heusler alloy、X_2YZ

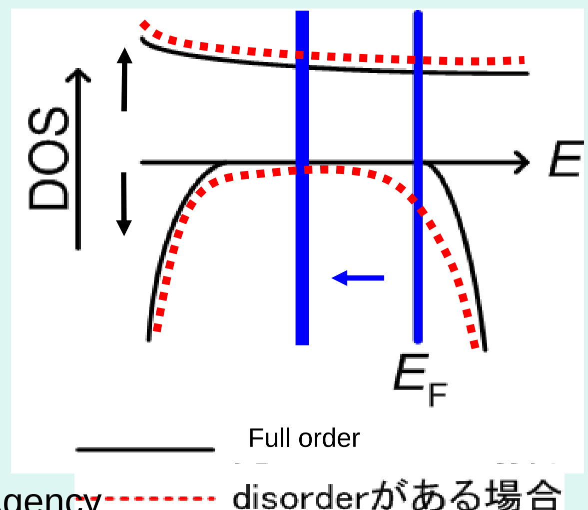


High Tc
Theoretical P=1

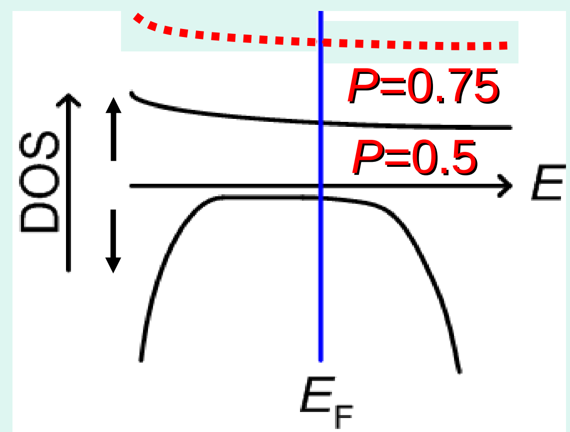
However,
Experimental P is low

How to search?

Control of E_f



Control of DOS(E_f)



ICTMC17 Baku 2010

Search of high spin-polarization half metals using PCARS

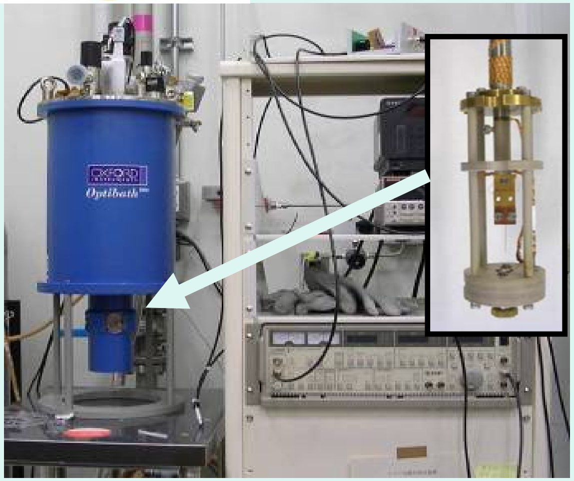
- Aiming at high performance GMR devices Takahashi has investigated as many as 32 full Heusler alloys and found 74% sipn polarization in CoMnGeGa alloy.

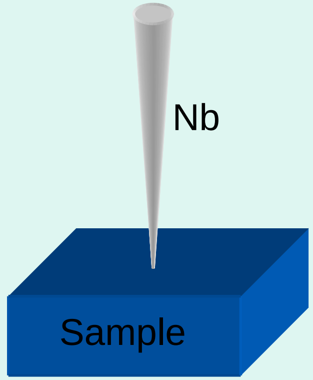
Metals and binary	P	Ref.
Fe	46	
Co	45	
FeCo	50	
Co75Fe25	58	
B2-FeCo	60	
$[Co/Pd]_n$	60	

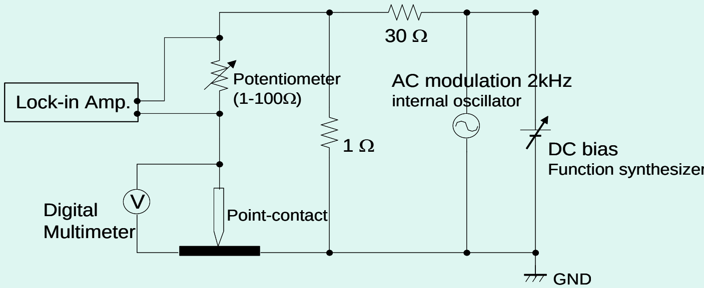
Ternary alloys	P	Ref.
Co_2MnSi	56	
Co_2MnGe	58	
Co_2MnSn	60	
Co_2MnAl	60	
Co_2MnGa	60	
Co_2CrAl	62	
Co_2FeAl	59	
Co_2FeSi	60	
Co_2FeGa	58	
Co_2CrGa	61	
Co_2TiSn	57	
Co_2VAl	48	
Fe_2VAl	56	

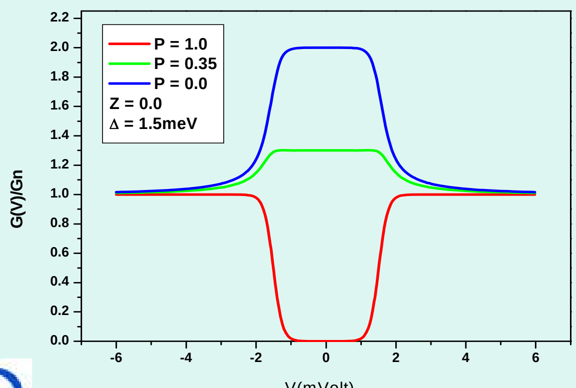
Quaternary alloys	P	Ref.
$Co_2Mn(Ge_{0.75}Ga_{0.25})$	74	
$Co_2Mn(Ga_{0.5}Sn_{0.5})$	72	
$Co_2Fe(Si_{0.75}Ge_{0.25})$	70	
$Co_2FeGa_{0.5}Ge_{0.5}$	68	
$Co_2(Cr_{0.02}Fe_{0.98})Ga$	67	
$Co_2MnGeSn$	67	
$Co_2(Mn_{0.95}Fe_{0.05})Sn$	65	
$(CoFe)_2MnGe$	65	
$Co_2(Mn_{0.5}Fe_{0.5})Ga$	65	
$Co_2(Cr_{0.02}Fe_{0.98})Si$	65	
$Co_2MnTiSn$	64	
$Co_2MnAl_{0.5}Sn_{0.5}$	63	
$Co_2MnGa_xSi_{1-x}$	63	
$Co_2FeAlGa$	63	
$Co_2MnSiGe$	63	
$Co_2(Mn_{0.5}Fe_{0.5})Si$	61	
$Co_2Mn(Al_{0.5}Si_{0.5})$	60	
$Co_2FeGa_{0.5}Si_{0.5}$	60	
$Co_2Fe(Al_{0.5}Si_{0.5})$	60	

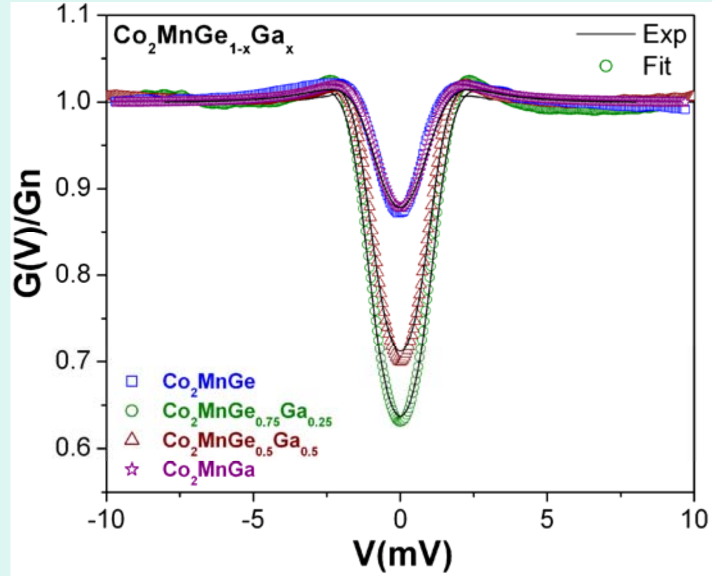
Point contact Andreev reflection (PCAR)

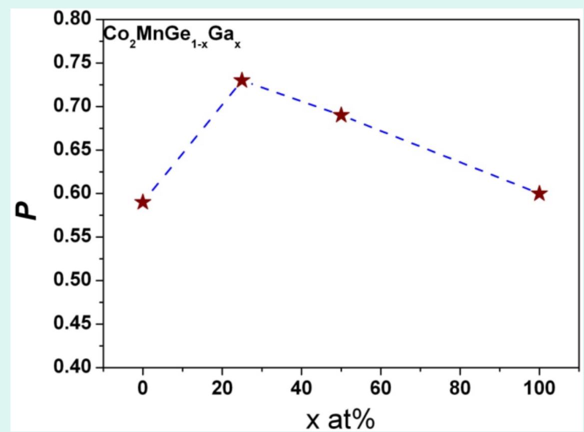








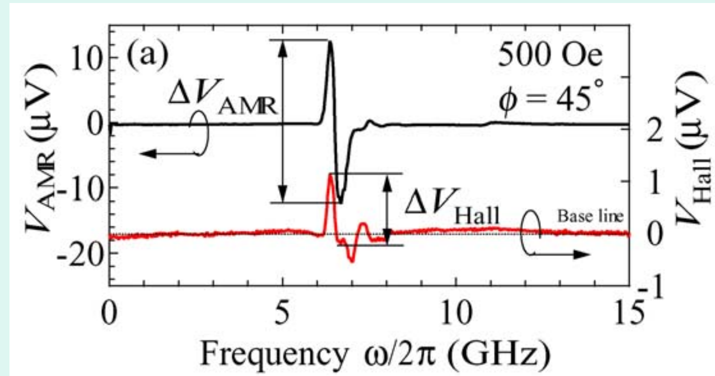


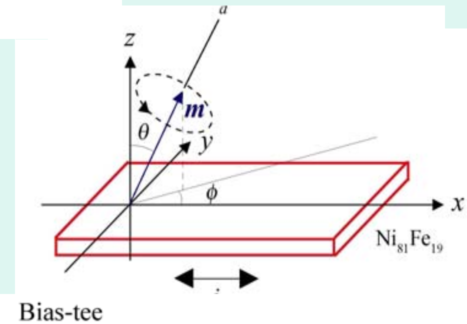


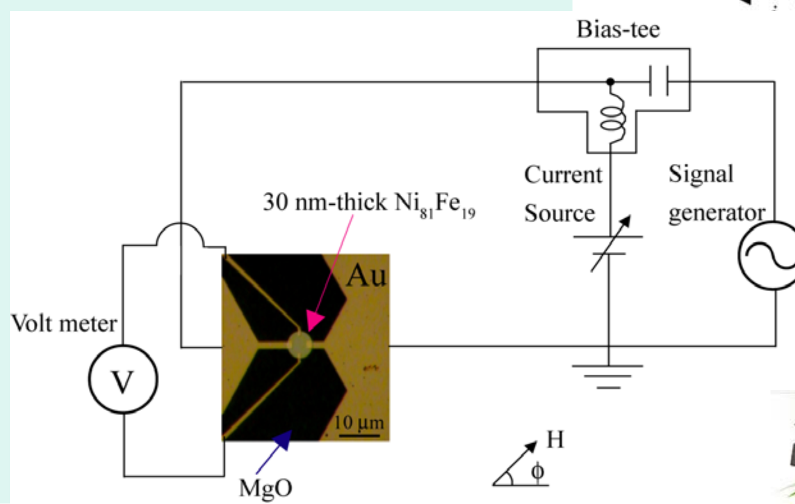
$Co_2MnGe_{0.75}Ga_{0.25}$ shows highest P

2.14 *Observation of Dynamic Spin Motion using Rectification Effect*

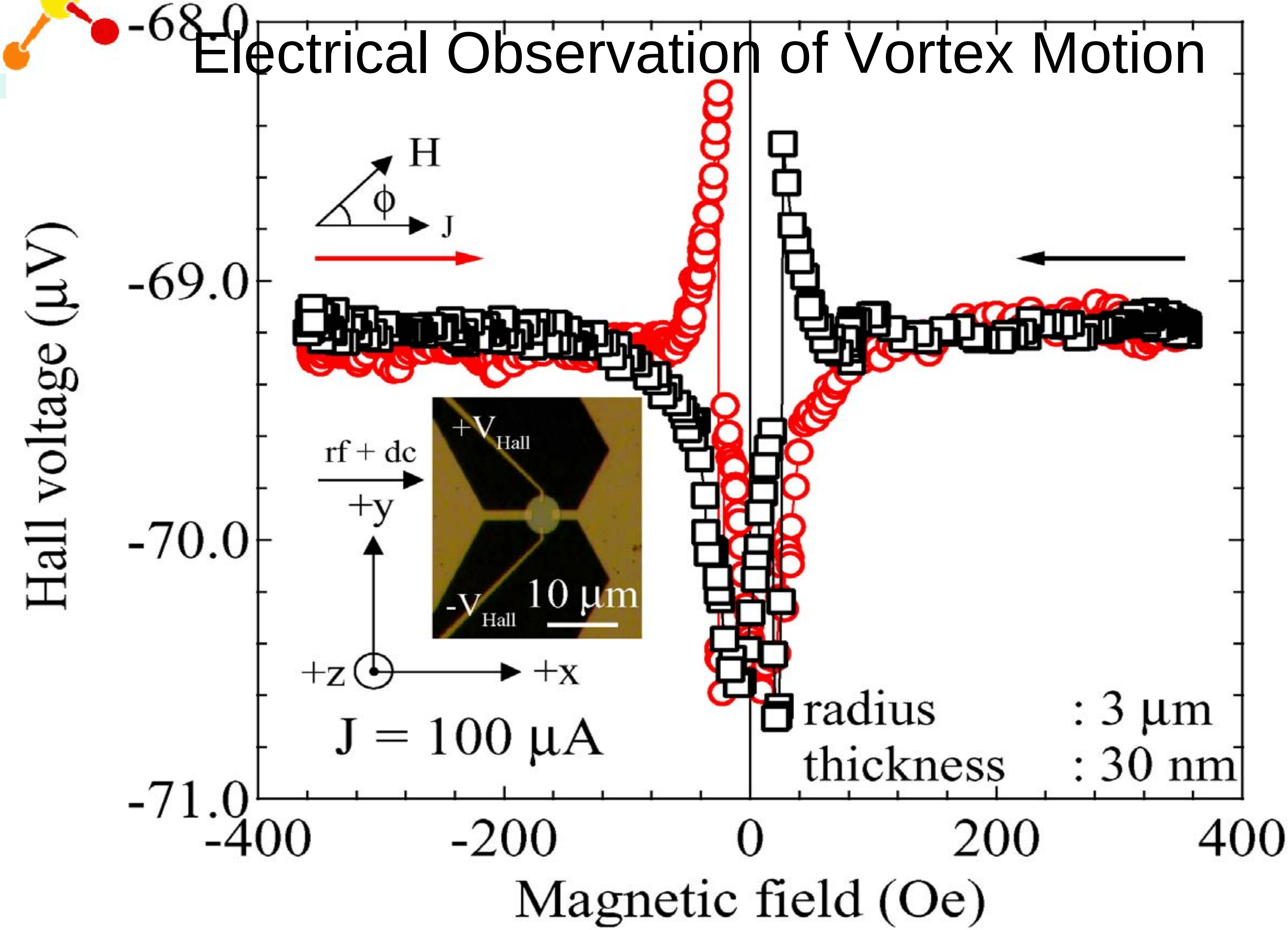
- Yamaguchi discovered *microwave-induced DC voltage generation in ferromagnetic nanowire* and explained the phenomenon in terms of coupling between spin-precession and electric transport.
- Dynamic motion of magnetic vortices in feromagnetic $Fe_{19}Ni_{81}$ disk via was discovered the *rectification effect*. The self-bistability state was detected experimentally, which is consistent with the physical model.







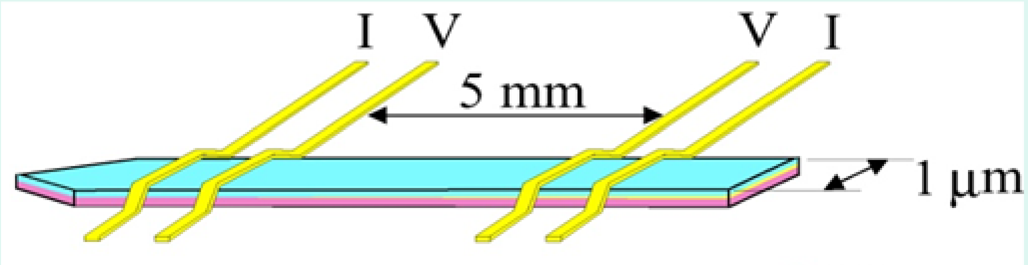
Electrical Observation of Vortex Motion

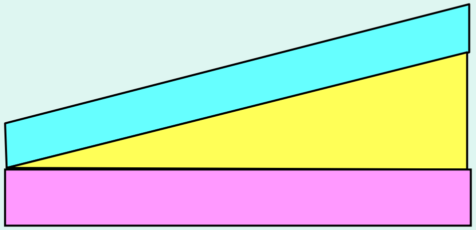


APL **95**, (2009) 122506.

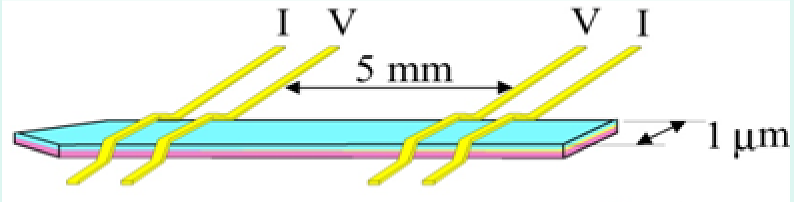
Domain wall motion in spatially modulated GMR nanowire: new spin-latchet effect

- The quantum interference effect in th FM/NM/FM structure was successfully modulated through modulation of boundary conditions. The periodic potential can be measured as a force by detecting the wall motion. The wall motion was found one-way!

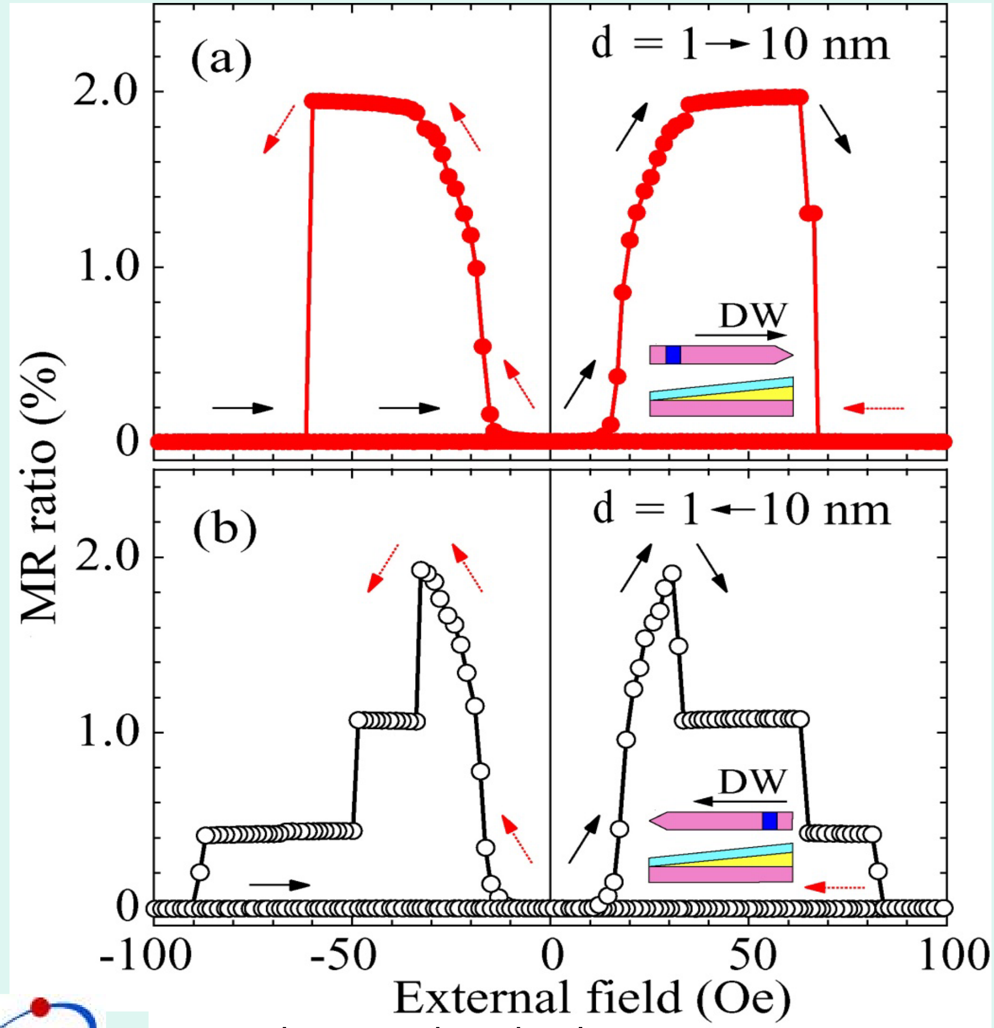




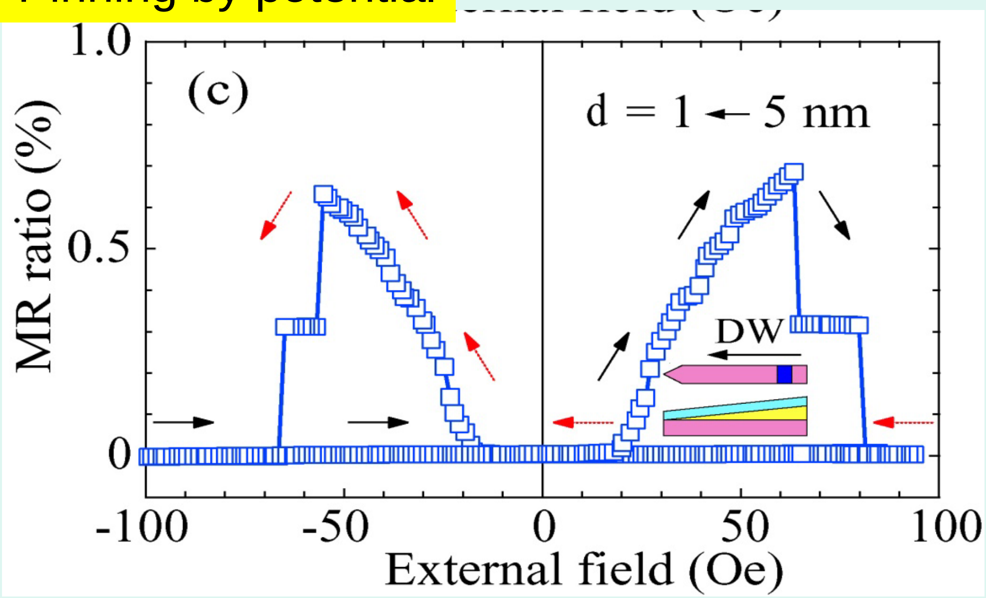
Domain wall motion in spatially modulated GMR nanowire



Wall motion in pinned layer
(a)Left to right ⇨ abrupt inversion
(b)Right to left ⇨ step-like



Pinning by potential



Variation of potential dips due to change in inclination

Yamaguchi et al.: APEX 3, 093004 (2010).

3. Spin-Transfer Magnetization Reversal

3.1 Spin-Transfer Magntization Reversal: Proposals and Experimental Verification

3.2 Two perspectives of current-induced magnetization switching

3.3 Spin-Transfer Magnetization Reversal: Experiment

3.4 Merit of Current-Induced Magnetization Switching by Spin-Transfer Torque for Spin-RAM

3.5 Current Density necessary for Spin-Transfer Magnetization Switching to occur

3.6 Current-induced antiferromagnet-ferromagnet transition in FeRh

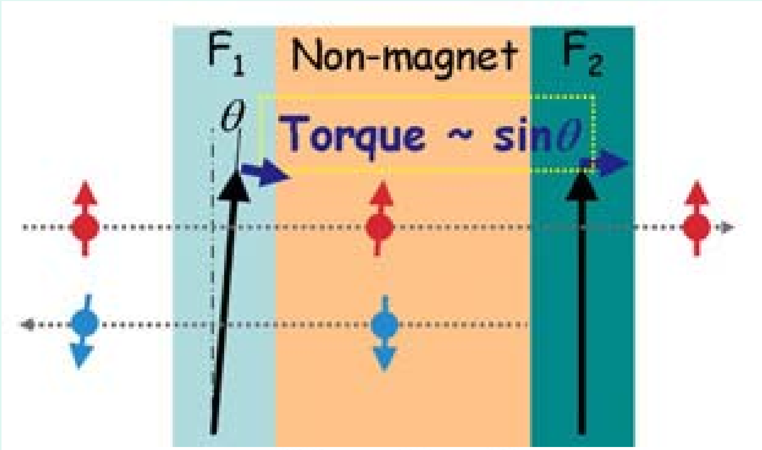
ICTMC17 Baku 2010

3.1 Spin-Transfer Magntization Reversal: Proposals and Experimental Verification

- In 1996, a new theoretical concept of the current-driven spin-transfer magnetization reversal was proposed by Slonczewski[1] and Berger [2] and was experimentally supported by Myers et al. in 2000 [3].
  - [1] J. Slonczewski: J. Magn. Magn. Mater. 159 (1996) L1.
  - [2] L. Berger: Phys. Rev. B 54 (1996) 9353.
  - [3] E. B. Myers, D. C. Ralph, J. A. Katine, R. N. Louie, R. A. Buhrman: Science 285 (2000) 865.

http://www.riken.go.jp/lab-www/nanomag/research/cims_e.html

Mechanism of spin angular momentum transfer.



Spins parallel to F_1 or F_2 : transmit
Spins anti-parallel to F_1 or F_2 : reflected

↓

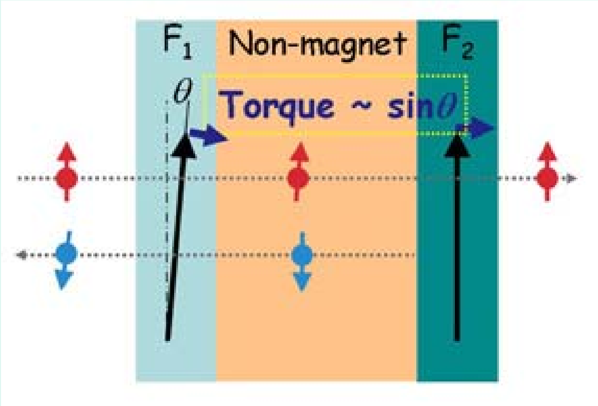
Transverse spin angular momentum is transferred to the local magnetic moment

↓

Torque is exerted on either F_1 or F_2

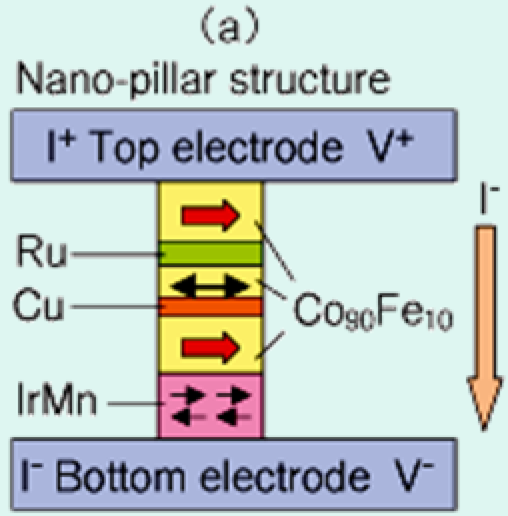
3.2 Two perspectives of current-induced magnetization switching

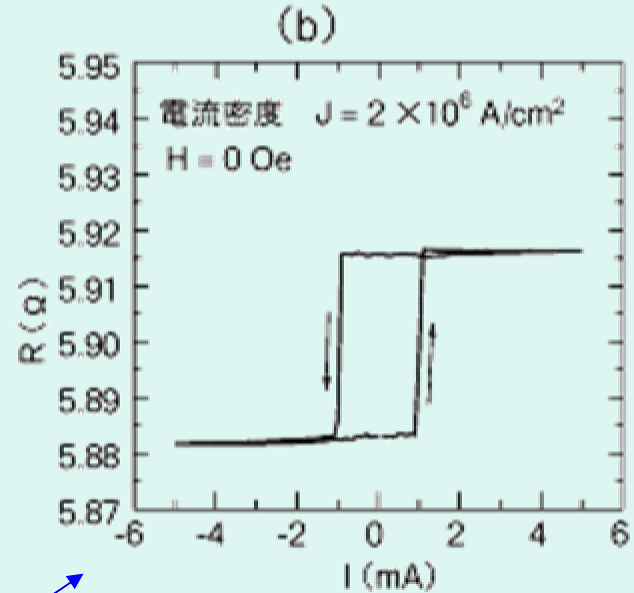
- One is based on spin transfer, suggesting that the spin current *transfers* the transverse component of the spin angular momentum to the local magnetic moment at the interface whereby a torque is exerted on the local magnetic moment (*spin-torque*).
- Another is based on *spin accumulation*, by which the generated non-equilibrium magnetization exerts an exchange field on the local moment.



http://www.riken.go.jp/lab-www/nanomag/research/cims_e.html

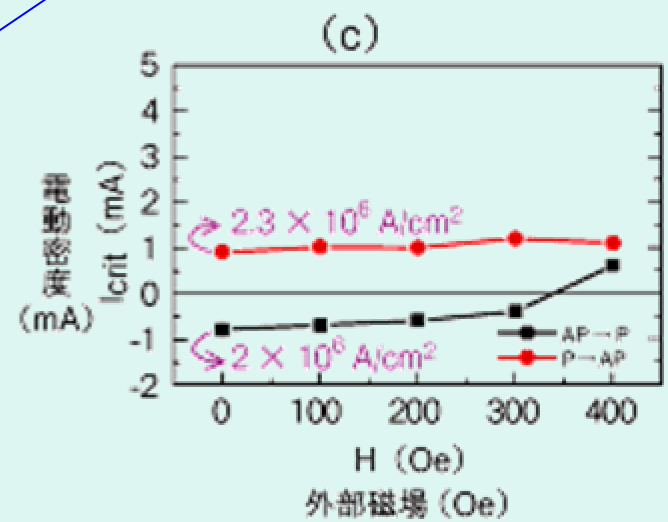
3.3 Spin-Transfer Magnetization Reversal: Experiment





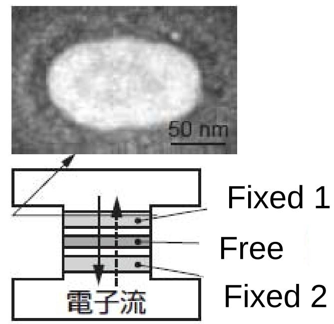
Inomata's group fabricated $IrMn/Co_{90}Fe_{10}/Cu/Co_{90}Fe_{10}/Ru/Co_{90}Fe_{10}$ CPP GMR device (a) and confirmed the current-induced magnetization reversal (b).

- Magnetization direction of free $Co_{90}Fe_{10}$ layer is changed depending on the current direction.

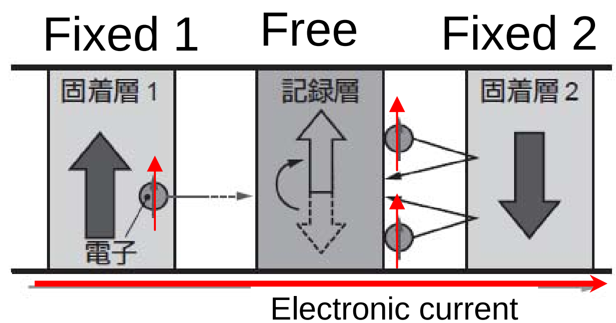


3.4 Merit of Current-Induced Magnetization Switching by Spin-Transfer Torque for Spin-RAM

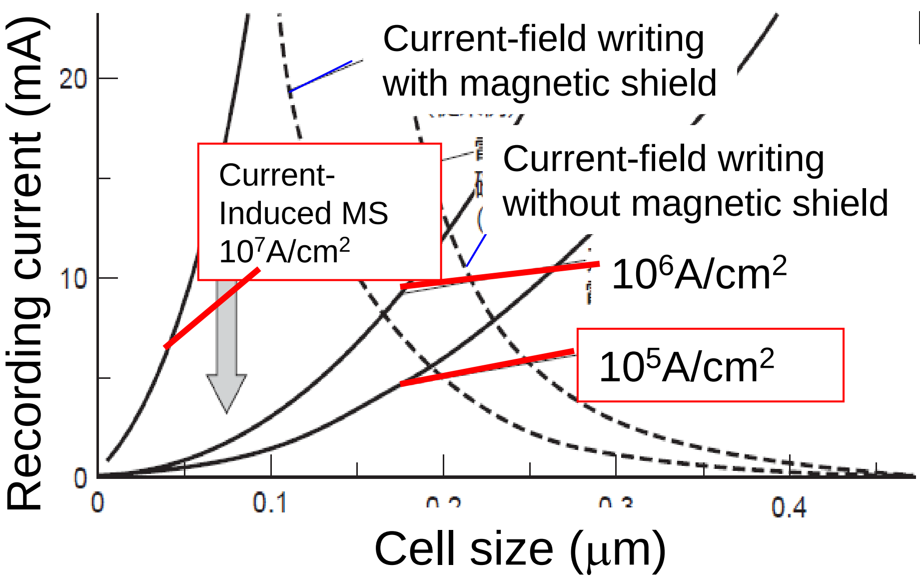
- Switching current for spin-transfer magnetization reversal is proportional to the area of devices.
- This technique is superior to the previous method if the scale becomes less than 0.2μm.

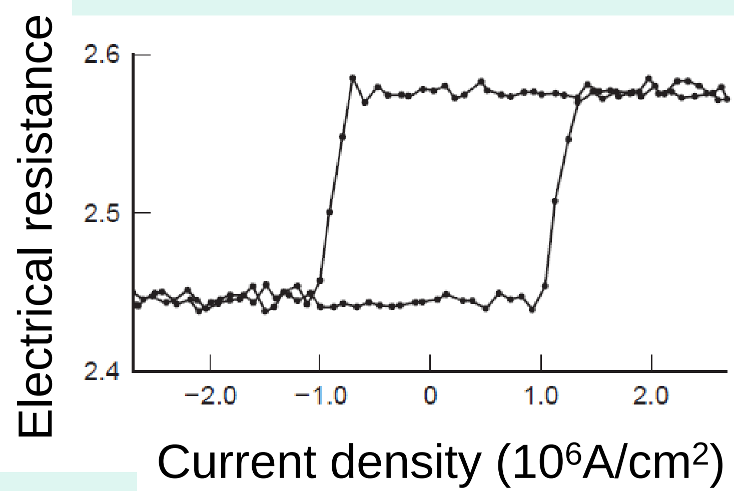


Device structure



Switching mechanism





Nakamura et al. Toshiba Review Vol.61 No.2（2006）

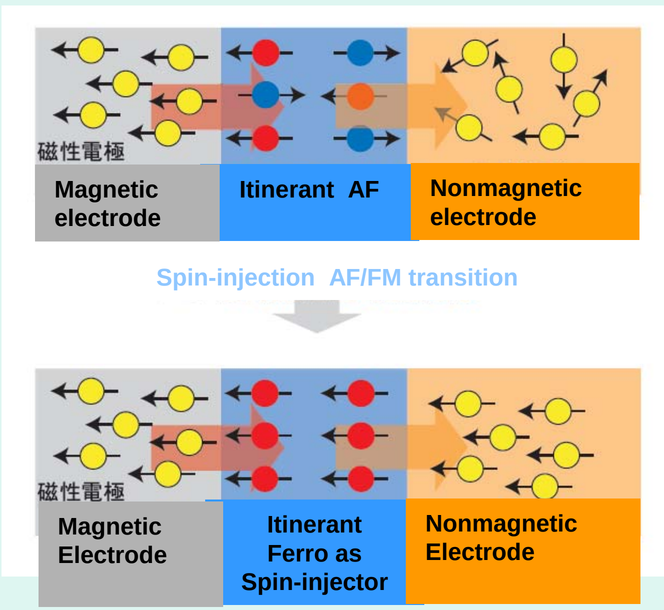
ICTMC17 Baku 2010

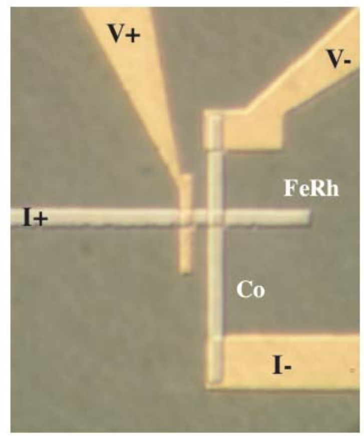
3.5 Current Density necessary for Spin-Transfer Magnetization Switching to occur

- Spin-polarized current injected from a ferromagnetic electrode transfers the spin-angular momentum to the counter ferromagnetic electrode to give rise to a magnetization reversal. Although a huge current density as large as 10^7-10^8A/cm^2 was necessary in the early stage of experiment using a GMR device, the recent technical development enabled to reduce it to a practical level of 10^6A/cm^2 by using a MgO-TMR device.
- Recently NEDO succeeded in reducing the current density to the level as small as 3 x 10^5A/cm^2, which is practical level, http://www.nedo.go.jp/iinkai/kenkyuu/bunkakai/20h/chuukan/2/1/5-1.pdf
- *Thus human being succeeded in converting electricity to magnetic field without using coils*.

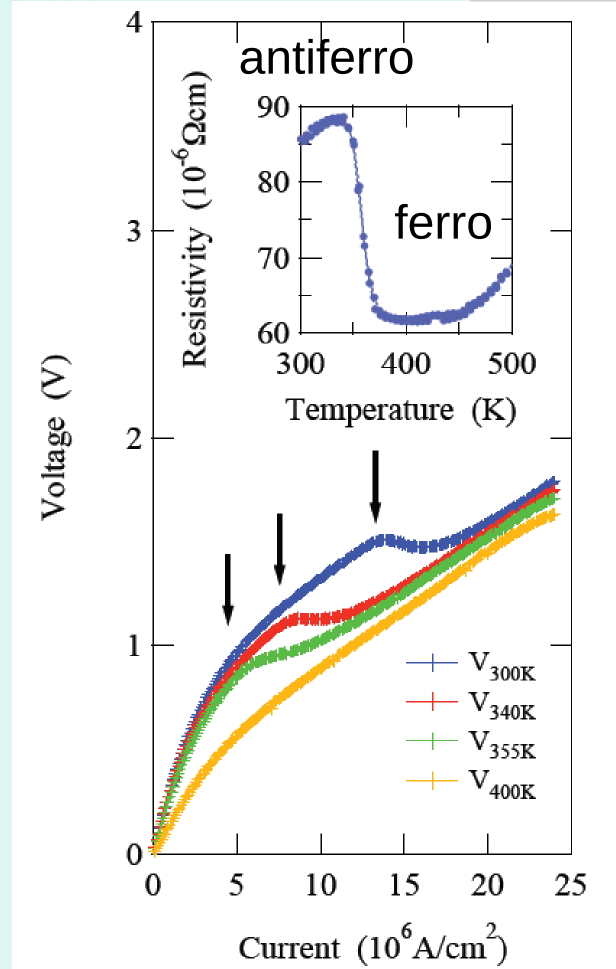
3.6 Current-induced antiferromagnet-ferromagnet transition in FeRh

- Taniyama succeeded in observation of current induced phase change due to spin-transfer torque phenomenon.





Co／FeRhスピン注入構造



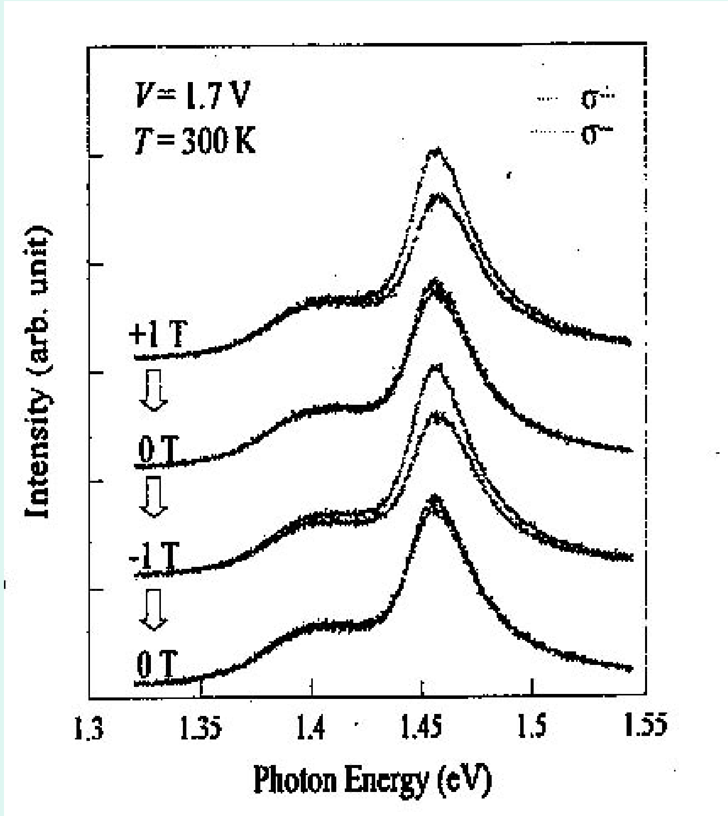
4.15 Optical Observation of Spin Injection and Spin Accumulation

- Optical observation of spin injection to nonmagnetic metals were first carried out in the III-V based magnetic semiconductor, in which circular dichroism of luminescence was observed by injection of spin-polarized current. [i]
- Spatial imaging of the spin Hall effect and current-induced polarization in two-dimensional electron gases was demonstrated by the same group. [ii]。
- Recently, spin-injection was confirmed by measuring degree of spin-polarization in FePt/MgO/GaAs through circular polarization of photoluminescence emission. [iii]。
  - [i] Y. Ohno, D. K. Young, B. Beschoten, F. Matsukura, H. Ohno, D. D. Awschalom: Nature 402, 790 (1999).
    [ii] Y. K. Kato, R. C. Myers, A. C. Gossard, and D. D. Awschalom: Phys. Rev. Lett. 93, 176601 (2004)
    [iii] A. Sinsarp, T. Manago, F. Takano, H Akinaga: J. Nonlinear Opt. Phys. Mater., 17, 105 (2008).

Spin Injection to LED

- Manago's group fabricated FePt/MgO/LED structure and measured field-dependence of degree of circular polarization.
- Degree of circular polarization was 1.5% at zero field.

A. Sinsarp, T. Manago, F. Takano, H Akinaga: J. Nonlinear Opt. Phys. Mater., 17, 105 (2008).



Magnetic field dependence of EL spectra for different chirality of circularly polaized light

ICTMC17 Baku 2010

Magneto-optical observation of spin transfer switching

- Aoshima (NHK Lab) succeeded in magneto-optical observation of spin-transfer magnetization reversal in CPP-GMR device using Co_2FeSi. (1)
- Enhancement of magneto-optical effect by using GdFeCo CPP device is under study.

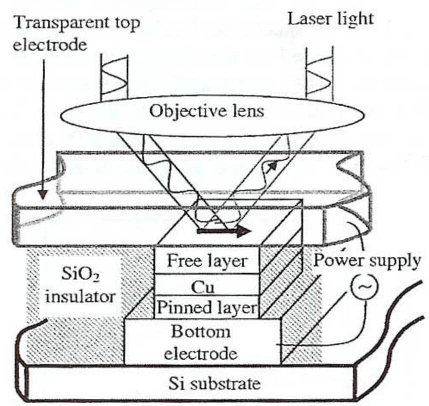


FIG. 1. Schematic illustration of spin-valve device with transparen electrode, and experimental setup. The plain arrow in the free layer indi the direction of the magnetization. The device includes the bc electrode of [Ta(3)/Cu(50)/Ta(3)/Cu(50)/Ru(5)], the pinned of [Ru(5)/Cu(20)/$Ir_{22}Mn_{78}$(10)/$Co_{66}Fe_{34}$(5)/Ru(0.9)/$Co_{66}Fe$; Co_2FeSi(10)], an intermediate layer of Cu(6), and the free layer with ping of [Co_2FeSi(6)/Cu(3)/Ru(3)], all in nanometers.

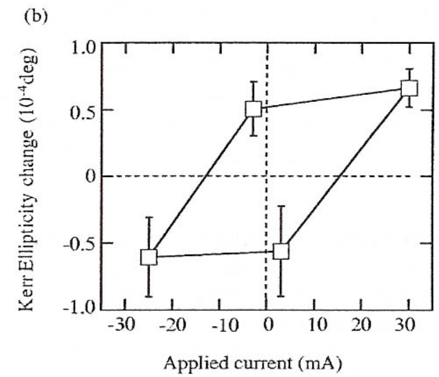


FIG. 4. (a) STS ´and the (b) Kerr ellipticity characteristics for three spin-valve elements. Open circles in (a) indicate resistance as a function of the applied current of ±30 mA with an increment of 2 mA. (b) The changes are defined as $[\eta_K - \langle \eta_K \rangle]$ in Kerr ellipticity for various applied currents of −3, −25, +3, and +30 mA. Kerr measurements are synchronized with resistance measurements [solid squares in (a)]. Averaged values over 60 points at each four different currents are plotted with error bars of standard deviation.

(1)K. Aoshima et al.: Spin transfer switching in current-perpendicular-to-plane spin valve observed by magneto-optical Kerr effect using visible light
Appl. Phys. Lett. 91, 052507 (2007);

ICTMC17
Baku 2010

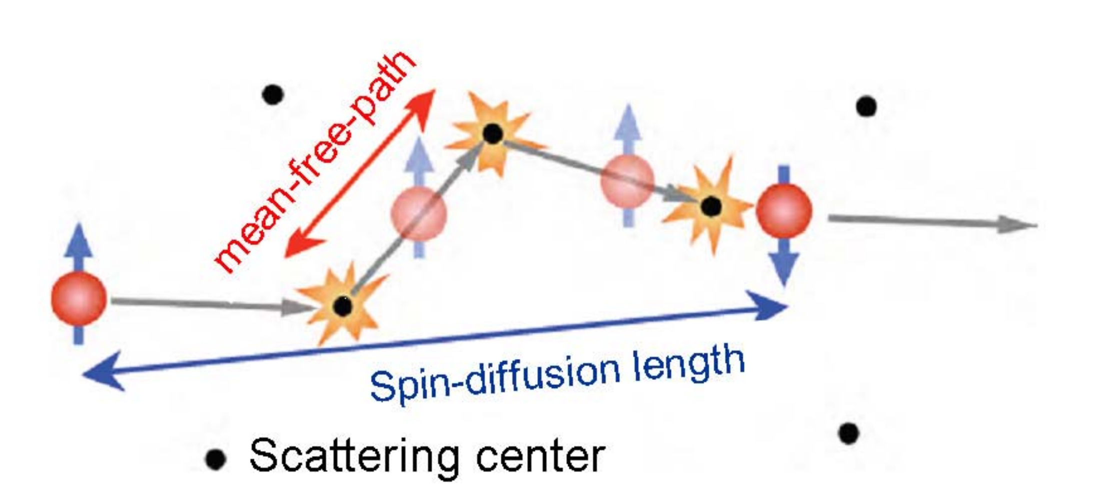
Opening a New Paradigm!

4. Concept of Spin Current and Spin-Hall Effect

4.1 New Concept of "Spin Current"
4.2 Spin current with charge current
4.3 Spin current without charge current
4.4 Creating a spin current
4.5 Spin Hall Effect (SHE)
4.6 History of SHE Research
4.7 Inverse Spin Hall Effect (ISHE)
4.8 Molecular Spintronics
4.9 Graphene Spintronics
4.10 Silicon Spintronics
4.11 Theory of spin current and heat current
4.12 A magnetic insulator transmits electrical signals via spin waves
4.13 Spin current and heat flow: spin Seebeck effect
4.14 Spin Seebeck insulator

4.1 New Concept of “Spin Current”

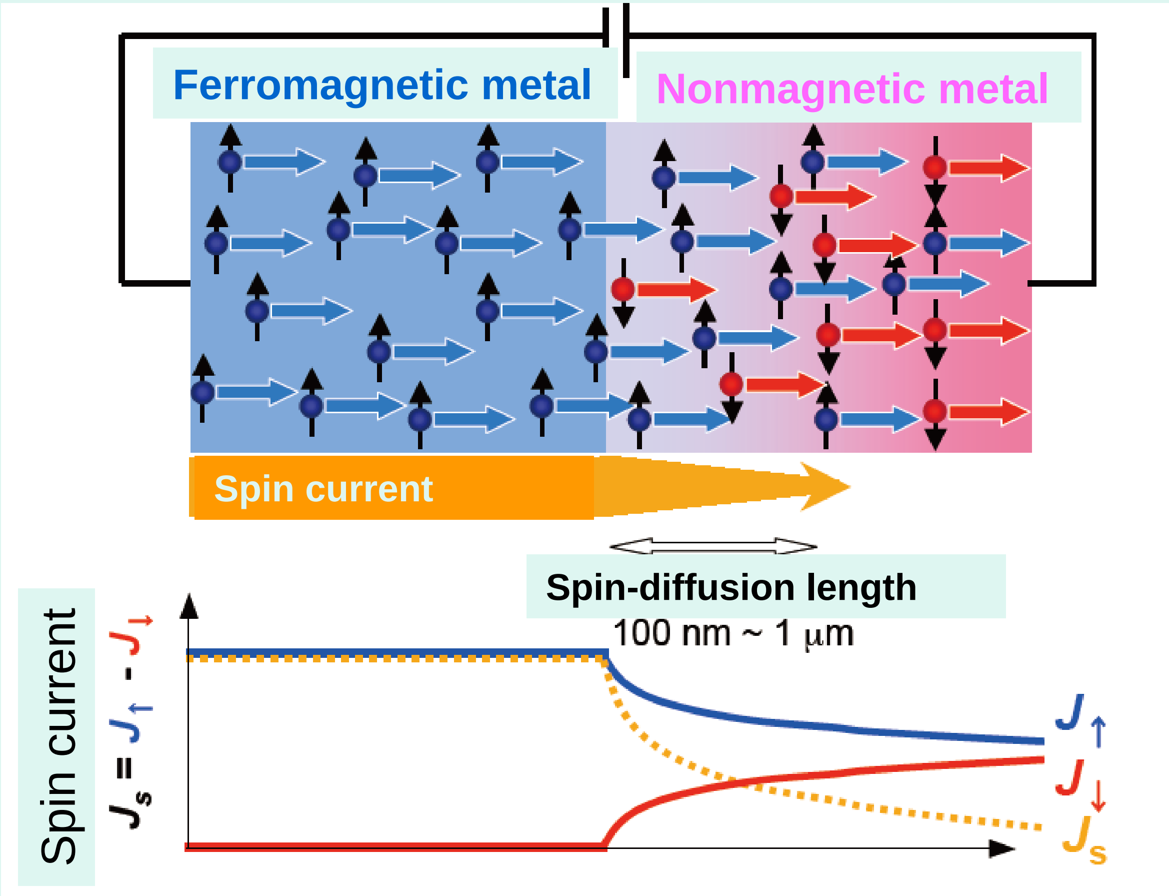
- Charge current, a flow of electronic charge, is subjected to a scattering represented by the mean-free-path（1-10nm）.
- On the other hand, spin current, a flow of electronic spin, is not much subjected to scattering at a moment of collision with an impurity or the phonon, spin diffusion length is considered to be much longer than the mean-free-path; 5-10nm in magnetic metals and as long as 100nm-1μm in non-magnetic metals.
- Some nonmagnetic dielectric show a spin diffusion length of the order of mm.



Courtesy of Prof. Takanashi

ICTMC17 Baku 2010

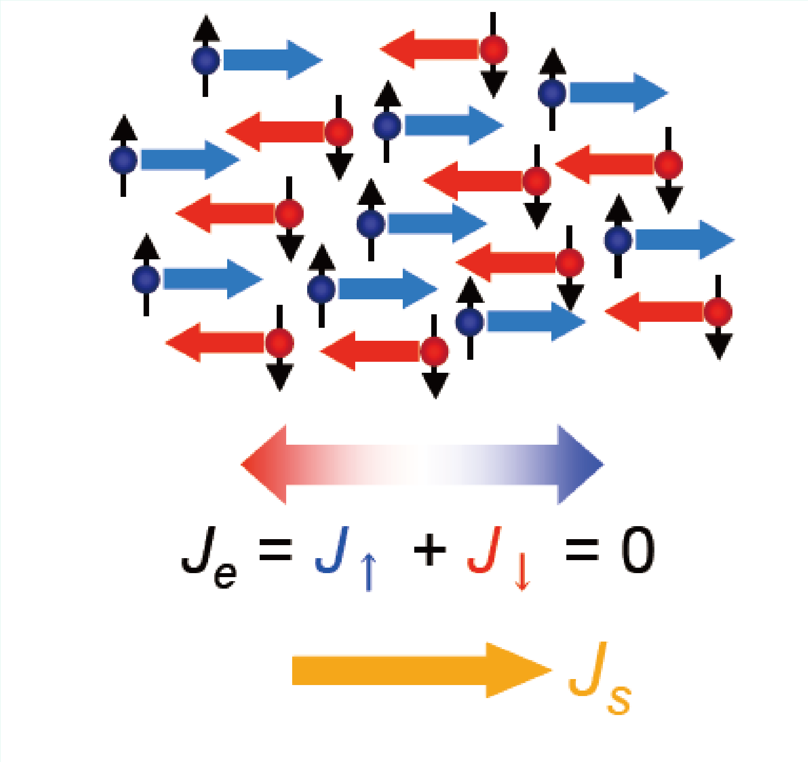
4.2 Spin current with charge current



- In nonmagnetic metals number of ↑spin electrons and ↓spin electrons is equal.
- When ↑spin electron is transferred from ferromagnetic to nonmagentic metals, number of electrons are unbalanced λ s from the surface.

Courtesy of Prof. Takanashi

4.3 Spin current without charge current “Pure spin current”

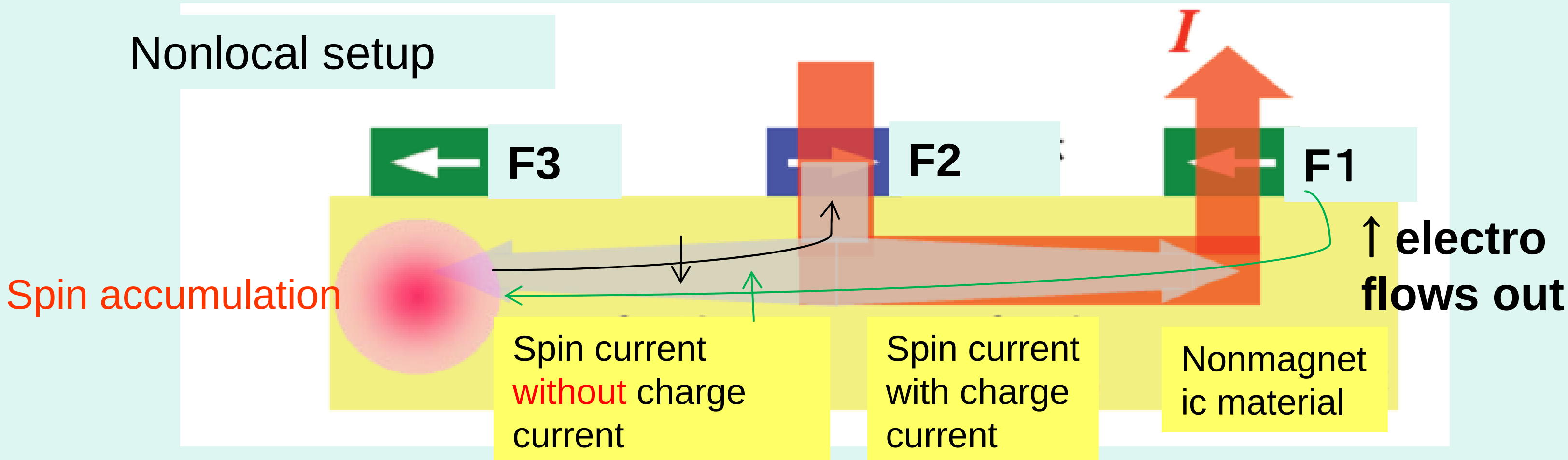


Nonlocal Spin Injection and Spin-Hall effect.

- If ↑spin current moves toward right, and if ↓spin current moves toward left, no net charge current flows, while a net spin current $J_\uparrow - J_\downarrow$ flows from the left to right.

Courtesy of Prof. Takanashi

4.4 Creating a spin current



- Suppose magnetization of F_2 is antiparallel to F_1 and parallel to F_3.
- If electrons flow from F_1 to F_2, up spin from F_1 cannot enter F_2 and flow to F_3 direction.
- Since current should flow form F_2 to F_1 down spin electrons are supplied from F_3 electrode, resulting in no net charge flow between F_2 and F_3.
- Consequently, spin current $Js=(J_{\uparrow}-J_{\downarrow})$ flows to the left.
- As a result spin accumulation occurs in the vicinity of F_3 electrode.

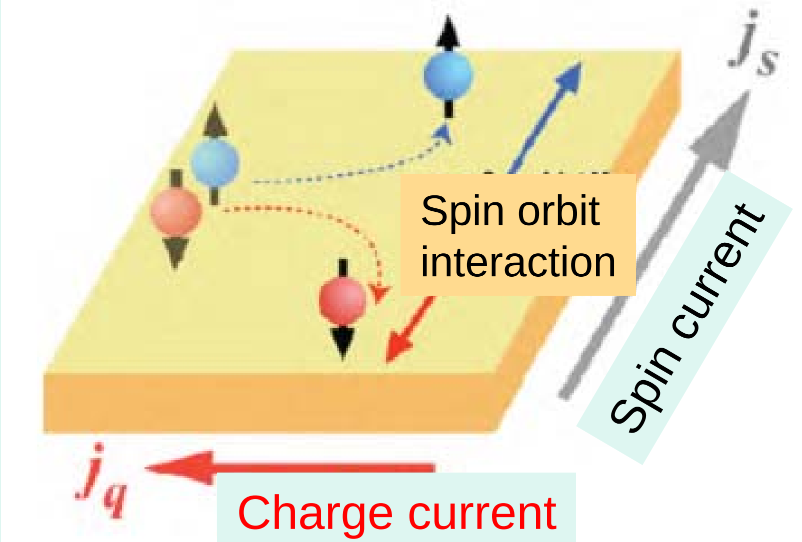
Courtesy of Prof. Takanashi

Observation of spin current

4.5 Spin Hall Effect (SHE)

- Spin Hall Effect is a characteristic of spin current.
- Contrary to the ordinary Hall effect, Spin-Hall effect occurs *without external magnetic field*, only when charge current flows.
- Spin current due to SHE occur perpendicular to the current. Due to spin-orbit interaction, ↑spin and ↓spin are separated, bringing about a spin current js perpendicular to the charge current jq.

S. Murakami, N. Nagaosa, S.C. Zhang:
Science 301 (2003) 1348.



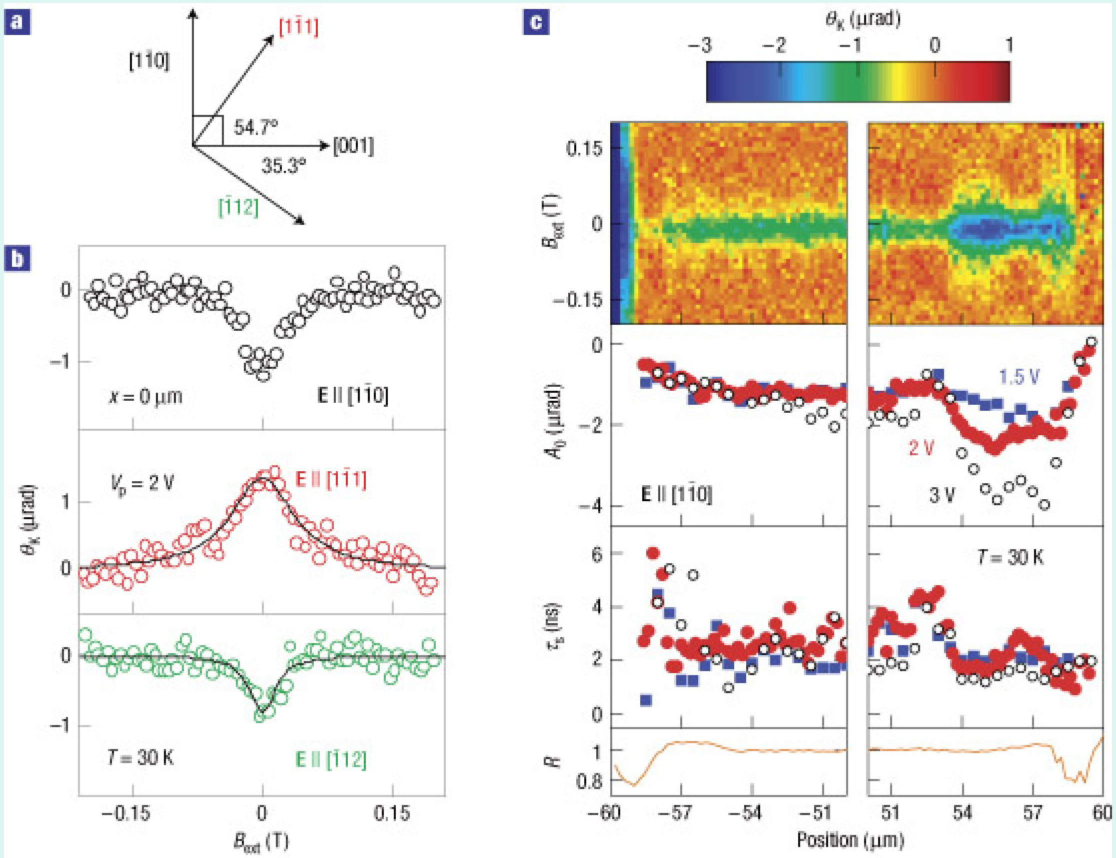
Spin Hall Effect

Courtesy of Prof. Takanashi

4.6 History of SHE Research

- The idea of SHE have been proposed by Russian in early 70's [1],
- theoretically explained by Murakami et al. quite recently [2] and
- experimentally observed in n-type semiconductor by Kato et al.[3]
  - [1] M. I. Dyakonov and V. I. Perel: Sov. Phys. JETP Lett. 13 (1971) 467; M.I. Dyakonov and V.I. Perel: Phys. Lett. A **35** (1971) 459.
  - [2] S. Murakami, N. Nagaosa, S.C. Zhang: Science **301** (2003) 1348.
  - [3] Y.K. Kato, R.C. Myers, A.C.Gossard, D.D. Awschalom: Science **306** (2004) 1910.

Imaging of SHE by magneto-optical Kerr effect



a, Relative orientations of crystal directions in the (110) plane. **b**, Kerr rotation (open circles) and fits (lines) as a function of *B*ext for **E** (black), **E** (red) and **E** (green) at the centre of the channel. **c**, *B*ext scans as a function of position near the edges of the channel of a device fabricated along with *w*=118 m and *l*=310 m for *V*p=2 V. Amplitude *A*0, spin-coherence time s and reflectivity *R* are plotted for *V*p=1.5 V (blue filled squares), 2 V (red filled circles) and 3 V (black open circles).

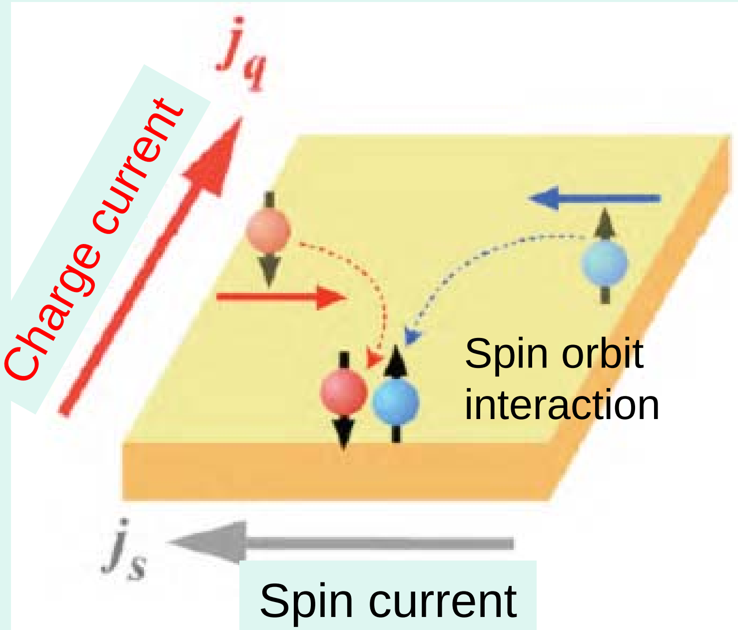
Spatial imaging of the spin Hall effect and current-induced polarization in two-dimensional electron gases

V. Sih, R. C. Myers, Y. K. Kato, W. H. Lau, A. C. Gossard and D. D. Awschalom, ***Nature Physics*** **1**, 31 - 35 (2005)

Observation of spin current

4.7 Inverse Spin Hall Effect (ISHE)

- *Inverse Spin Hall Effect is an inverse effect of the SHE: If one flow the spin current js, jq flows perpendicular to charge current.*
- ↑spin is deflected to the left and ↓spin to the right, leading to a charge current perpendicular to the charge current.

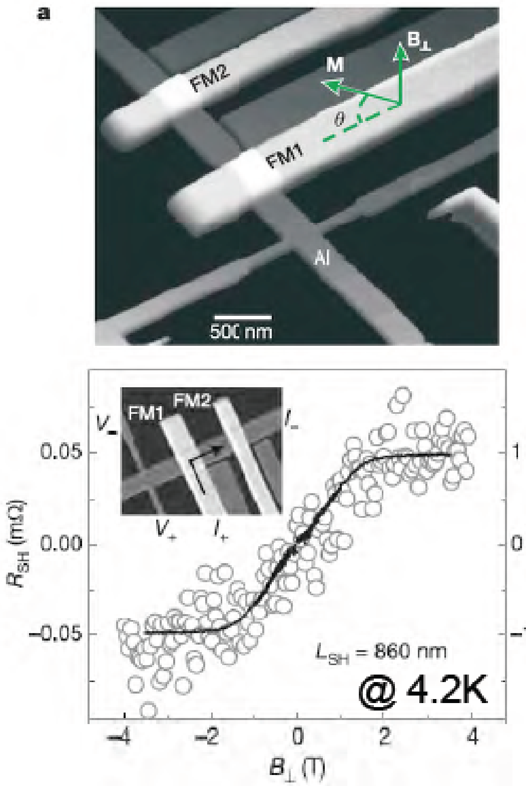


Inverse Spin Hall Effect

Courtesy of Prof. Takanashi

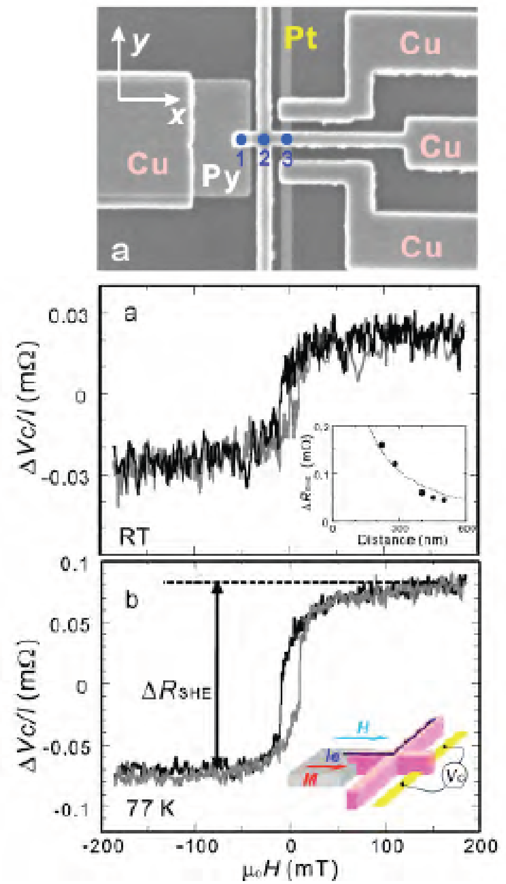
SHE and ISHE

CoFe / Al



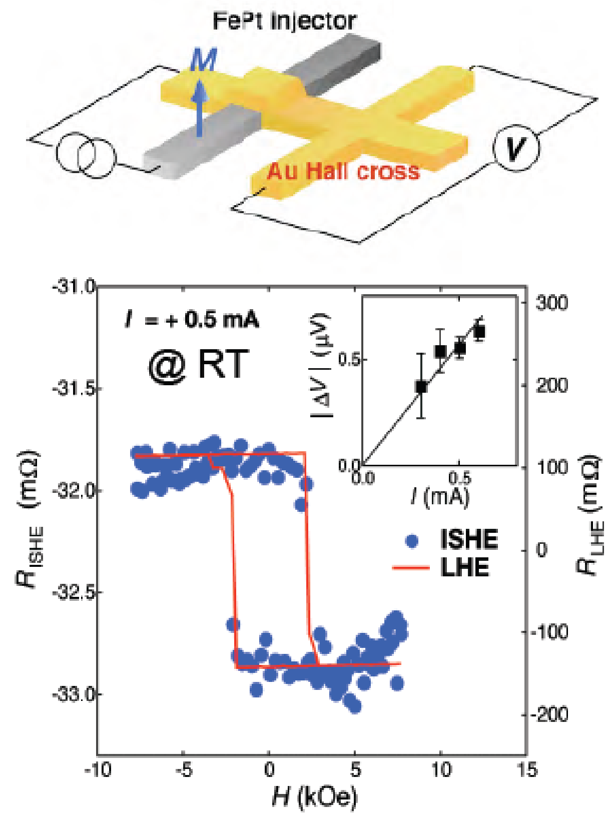
S. O. Valenzuela, M. Tinkham, *Nature* **442**, 176 (2006).

Py / Cu / Pt



T. Kimura *et al.*, *Phys. Rev. Lett.*, **98**, 156601 (2007).

FePt / Au



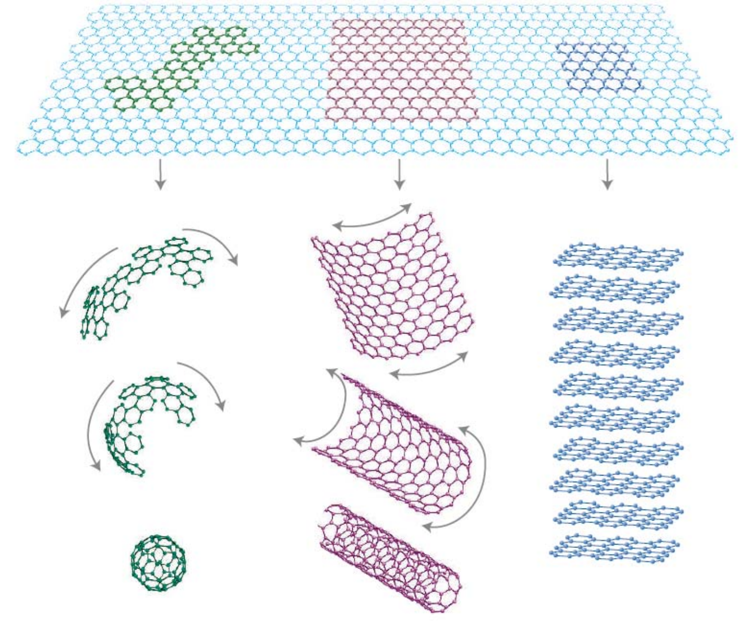
$\alpha_H \sim 0.1$

T. Seki *et al.*, **14pC-11**

Courtesy of Prof. Takanashi

4.8 Molecular Spintronics

- The spin-current can be observed not only in magnetic materials but in non-magnetic metals and semiconductors or even in nano-carbons: It was demonstrated by Shiraishi et al. that the spin current can be injected to a sheet of graphene by a careful experiment using a non-local magnetoresistance measurement.[i]



C_{60} SWNT Graphite

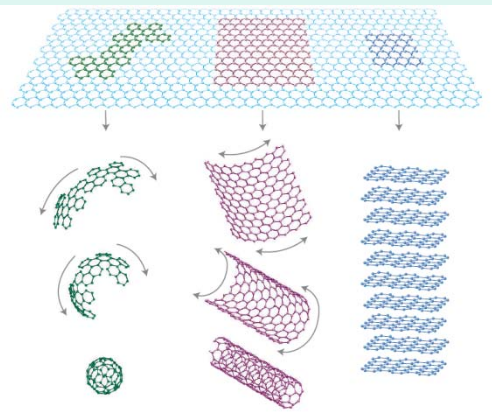
- [i] M. Ohishi, M. Shiraishi, R. Nouchi, T. Nozaki, T. Shinjo, and Y. Suzuki: Jpn. J. Appl. Phys. **46** (2006) L605.

4.9 Graphene Spintronics (1)

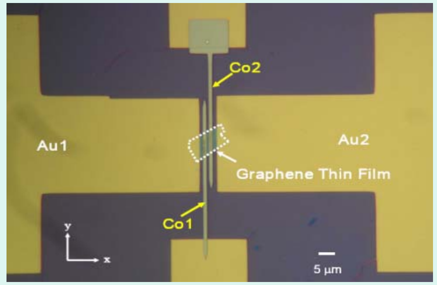
M. Shiraishi, "Graphene Spintronics", "Graphene : The New Frontier" (World Scientific Press, 2010/6/22).

ICTMC17 Baku 2010

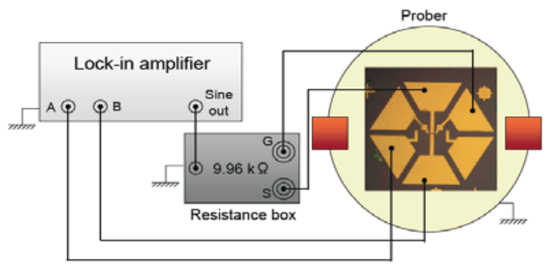
Graphene

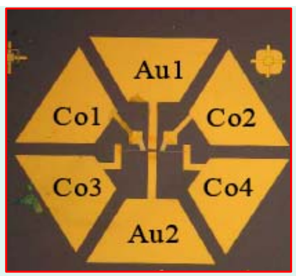


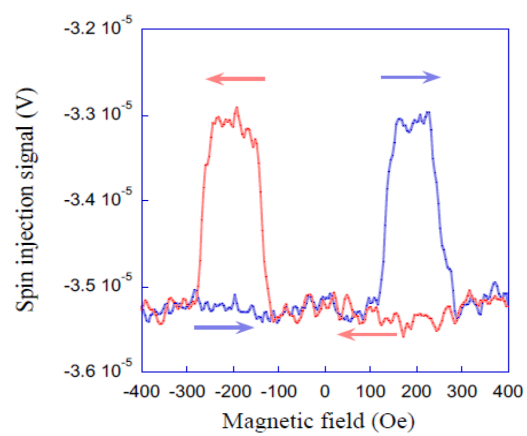
1. Generation of a pure spin current
2. Injection of spins in graphene
   at ROOM TEMPERATURE

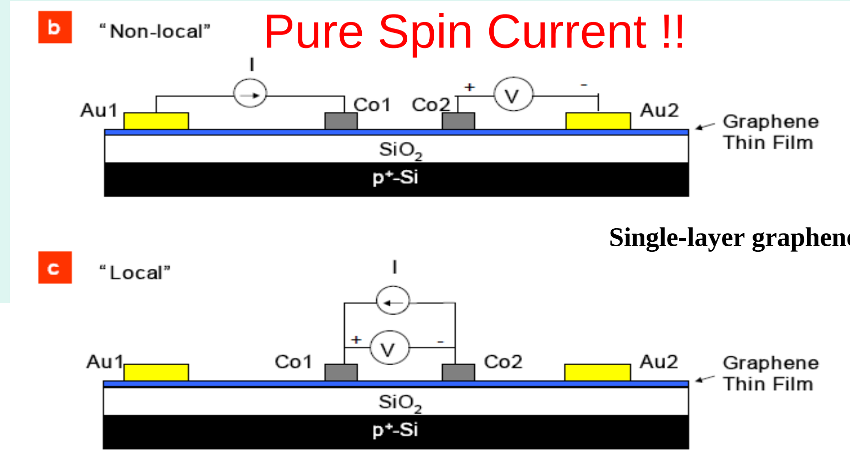


Non-local measurement
(Experimental setup)

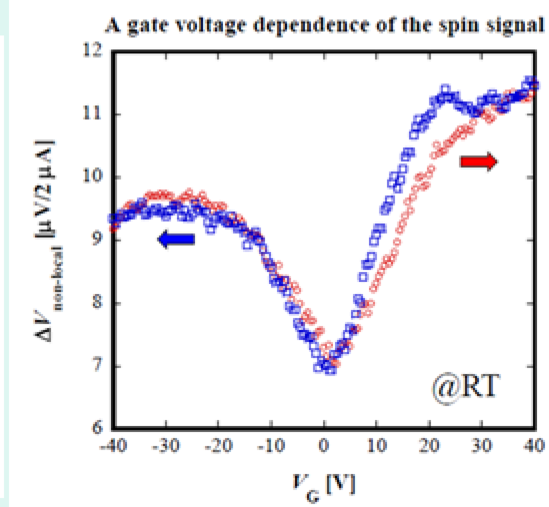








Gate-induced Modulation of Spin Signals in single-layer graphene

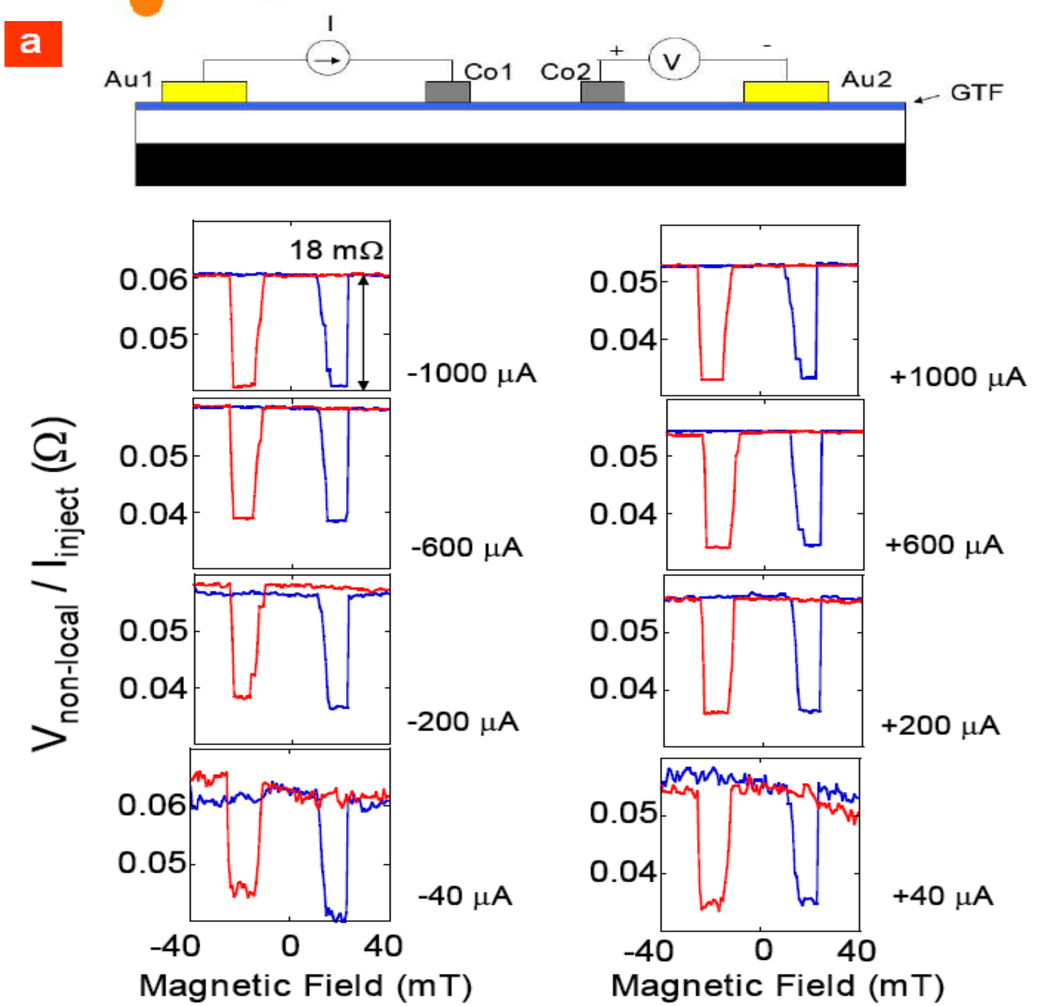


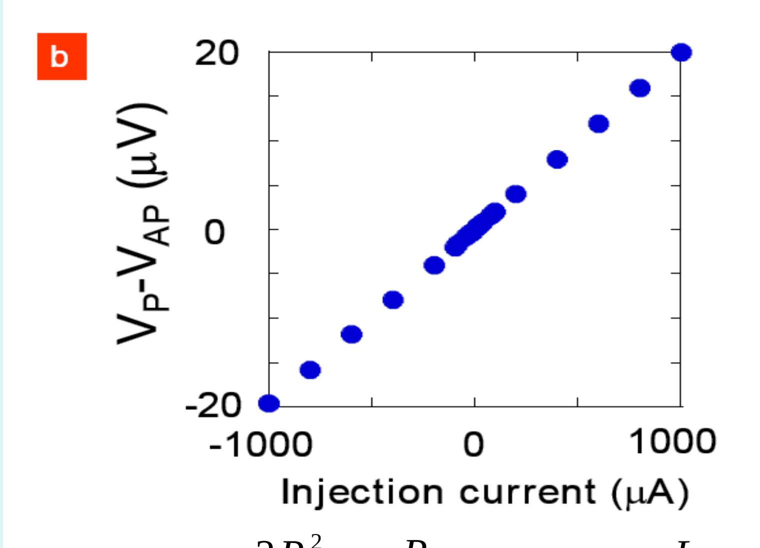
Japan Science and Technology Agency

JST

PRESTO

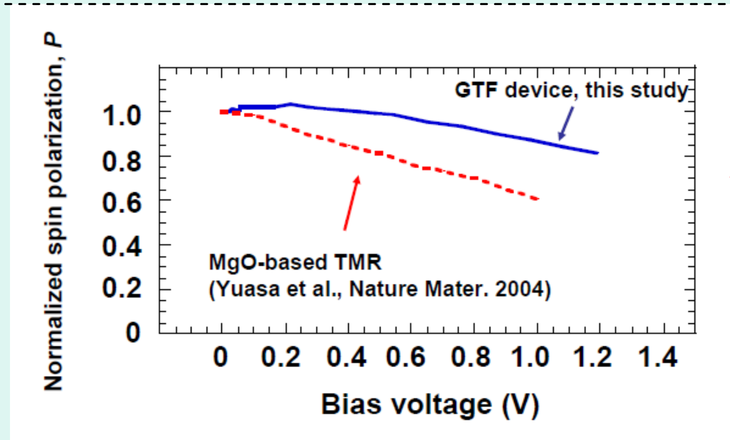
Graphene Spintronics (2)





$$\Delta V_{non-local} = \frac{2P^2}{(1-P^2)^2}\left(\frac{R_F}{R_N}\right)R_F \cdot [\sinh(\frac{L}{\lambda_{sf}})]^{-1} \cdot I_{inject} ,$$

Spin polarization is CONSTANT.



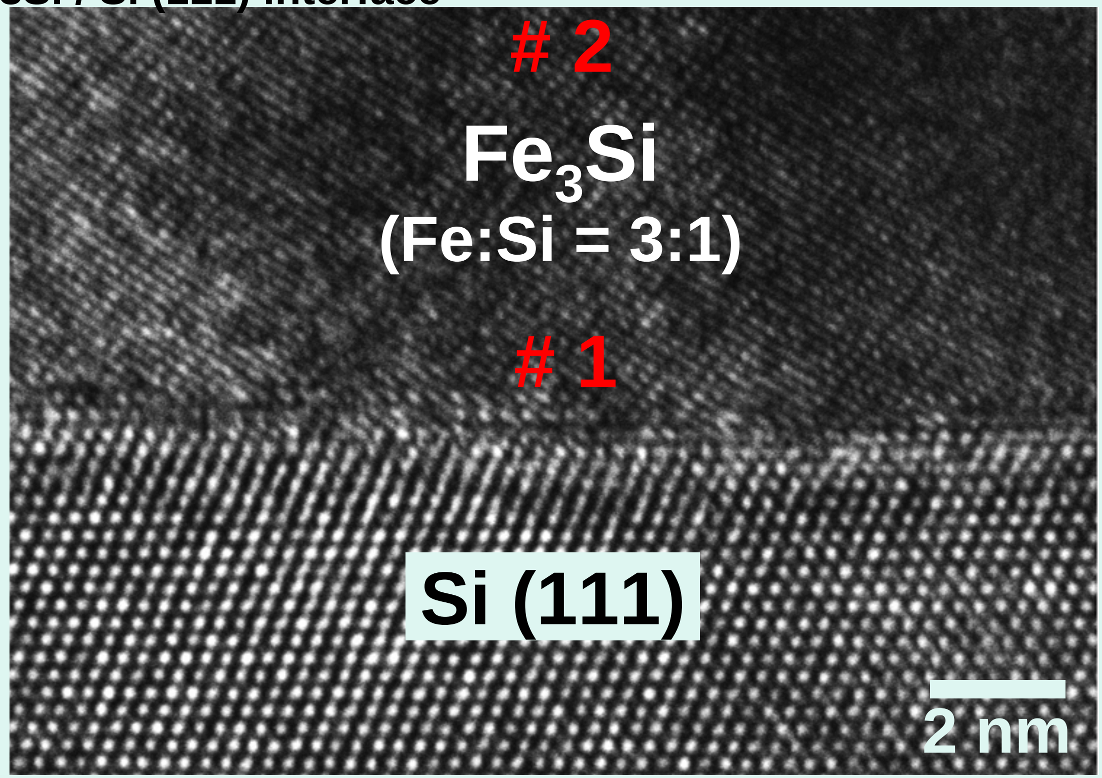
Better robustness than that in MgO-TMR

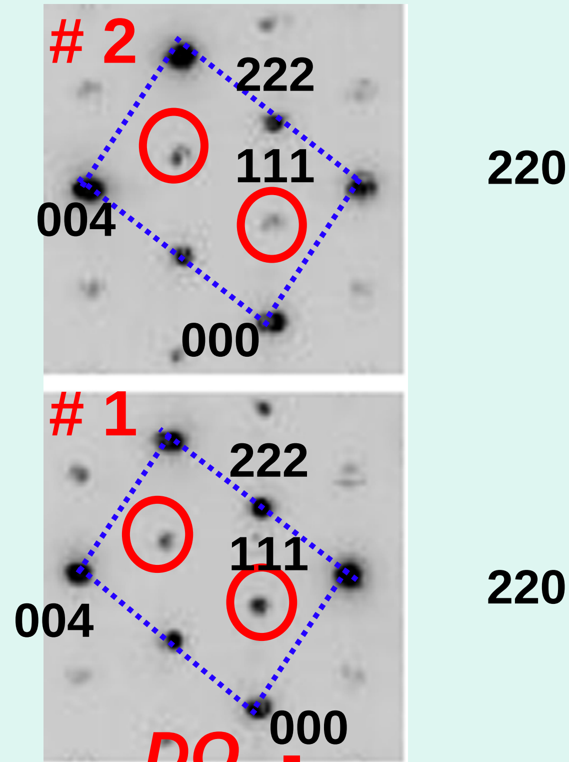
M. Ohishi, M.Shiraishi et al., JJAP 46, L605 (2007).
M. Shiraishi et al., Adv. Func. Mat.,19, 3711 (2009) .
M. Shiraishi et al., Appl. Phys. Express 2, 123004 (2009).

Japan Science and Technology Agency

4.10 *Silicon Spintronics*-Fe_3Si/Si

Fe3Si / Si (111) interface

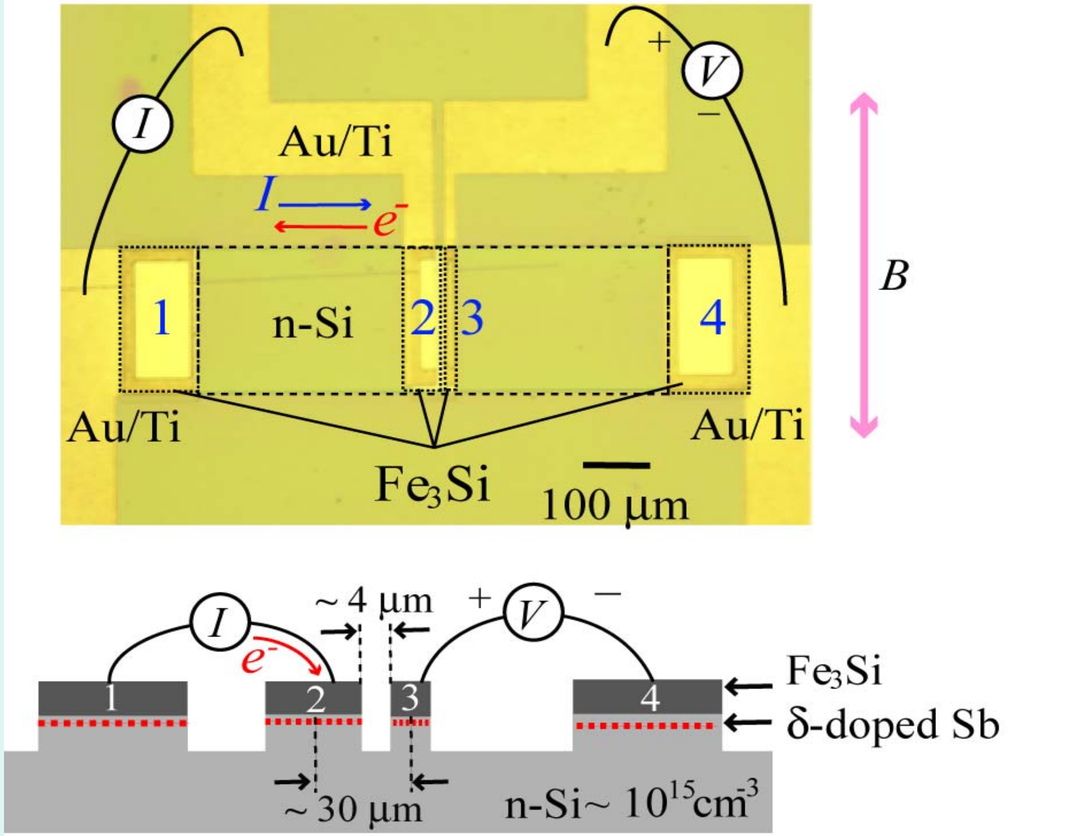




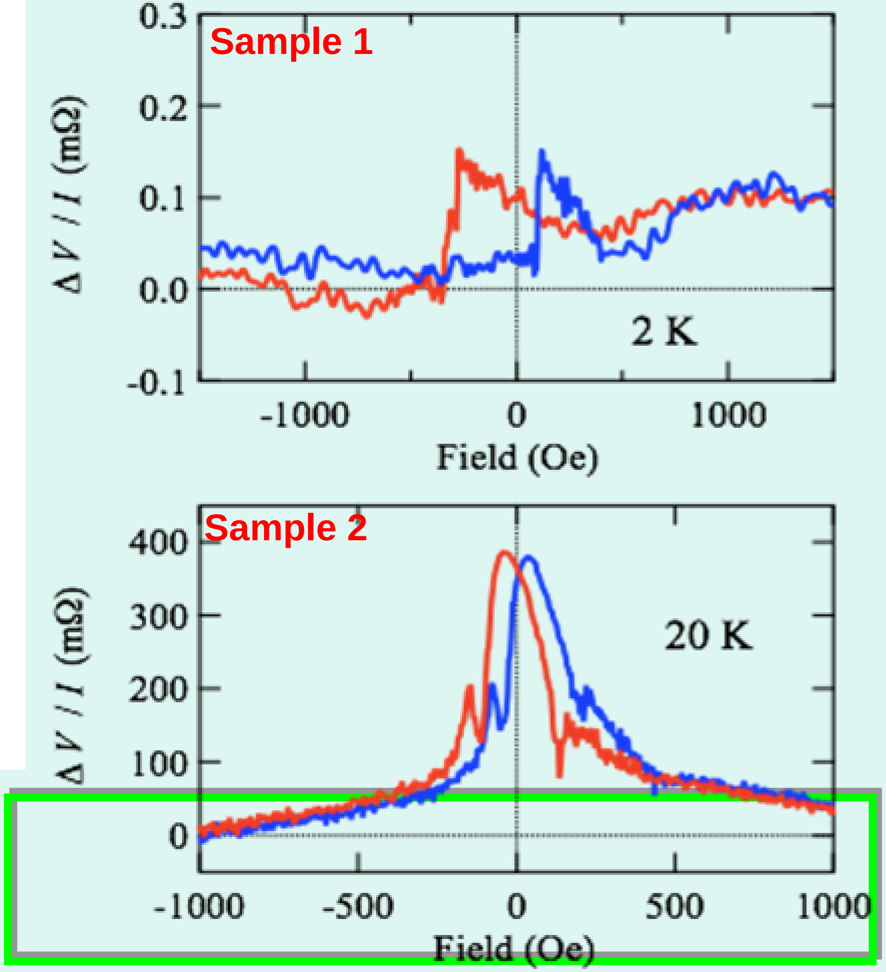
K. Hamaya *et al*., APL 93, 132117 (2008).

High quality epitaxial growth of the ferromagnetic half-metal on silicon !

Nonlocal voltage detection for Fe_3Si / Si lateral devices



NL resistance



Electrical detection of spin transport in silicon using Schottky tunnel contacts

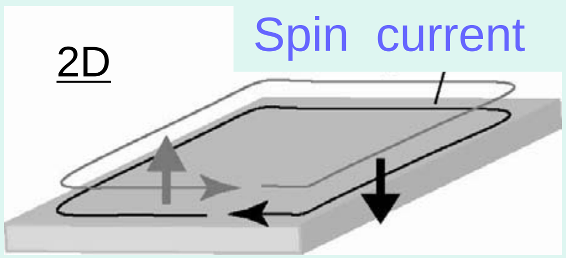
Japan Science and Technology Agency

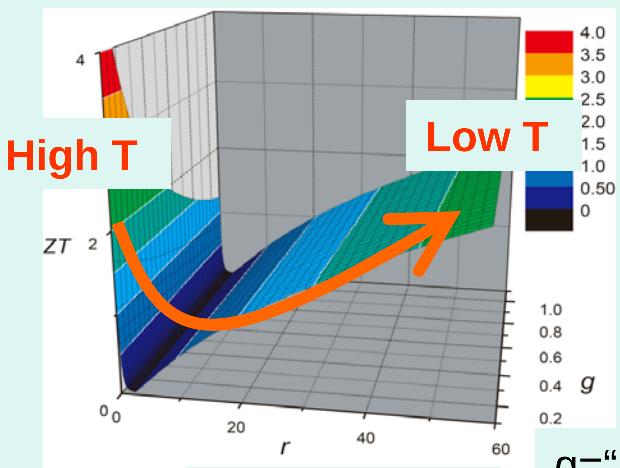
K. Hamaya *et al*., APL 94, 182105 (2009).

ICTMC17 Baku 2010

4.11 Theory of spin current and heat current

1) Bismuth ultrathin films as quantum spin Hall phases
2) Universal Phase Diagrams for 2D and 3D quantum spin Hall phases
3) Quantum spin Hall systems as candidates for efficient thermoelectrics





$$ZT = \frac{S^2 \sigma T}{\kappa}$$

r=“ bulk/edge ”

g=“ phonon/bulk ”

Expectation : QSH systems can be good thermoelectric.

- * suppress phonon conduction, keeping electron conduction
- * Low-dimensional states (edge states, surface states)
- * Similar materials involved ($Bi_{1-x}Sb_x$, Bi_2Se_3 etc.)

Result

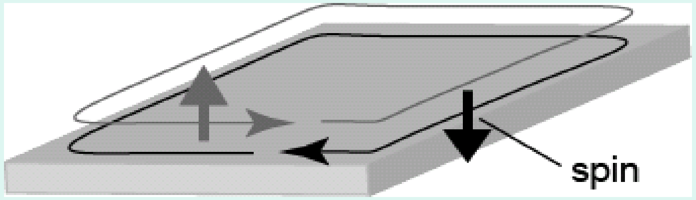
- Lower temp.
  → longer inelastic scattering length for edge states
  → edge states become dominant
  bulk-to-edge crossover of thermoelectric transport
- Ultrathin & narrow ribbon (of QSH system)
  → crossover occurs at around 10K

Quantum spin Hall systems can be good thermoelectrics at low temp.

Japan Science and Technology Agency

R. Takahashi, S. Murakami: Phys. Rev. B, 81, 161302 (2010)

PRESTO

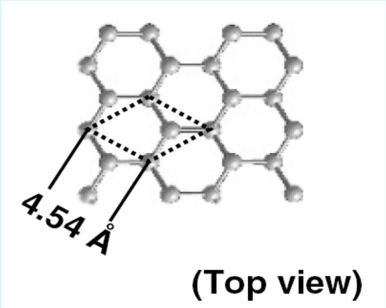


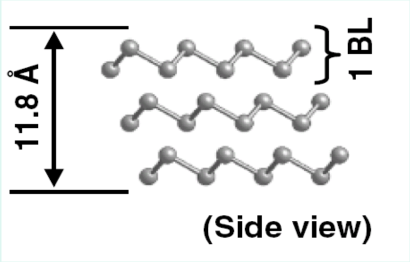
Theoretical Approach

Quantum Spin Hall Effect in Bismuth

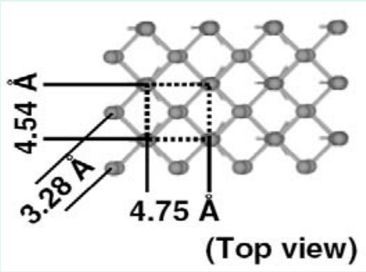
- Bulk Bi show no gap, while edge is gapless.
- Bi ultra thin film (*topological insulator*)

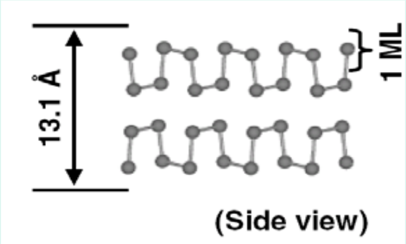
(111) 1-bilayer = quantum spin Hall phase





{012} 2-monolayer= insulating phase





Wada, Murakami: "Well-localized edge states in two-dimensional topological insulator: bismuth film", APS March Meeting 2010(2010), Oregon, USA (2010/3/15).

- Thermoelectric figure of merit

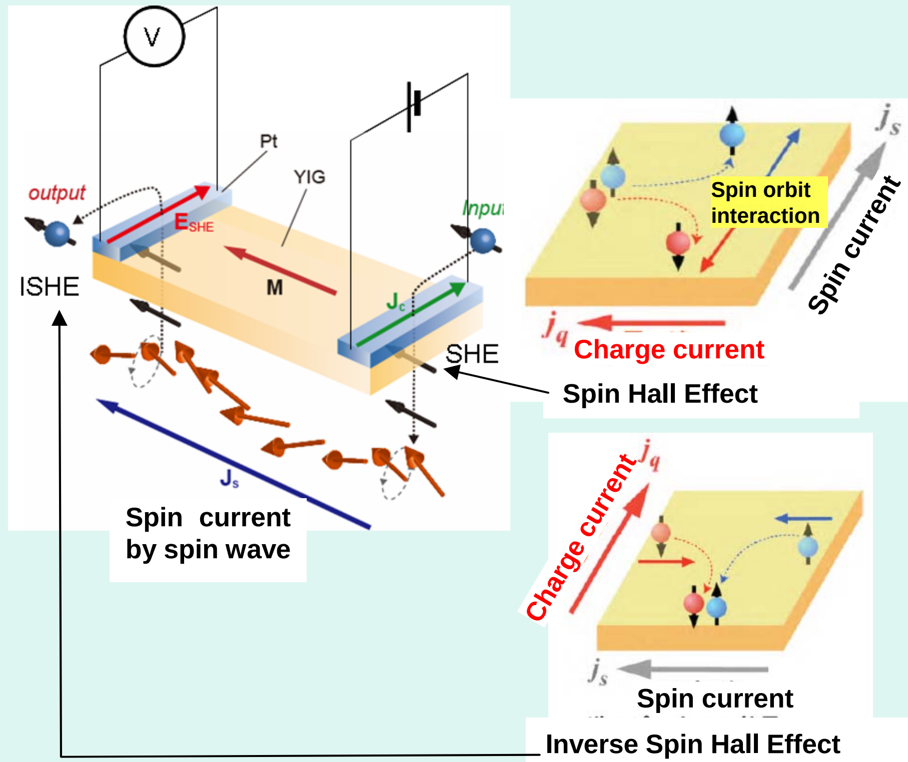
$$ZT = \frac{S^2 \sigma T}{\kappa}$$

Idealized model (perfect conductor on the edge)

- In the quantum spin Hall phase, figure of merit ZT of thermoelectric conversion is determined by the balance between the edge and the bulk.
- ZT is large if the chemical potential is close to the band edge.
- ZT is large if the length of system is long. ← edge states dominantly determine ZT.
- ZT increases with temperature. ← Higher energy carriers contribute to ZT.

4.12 A magnetic insulator transmits electrical signals via spin waves

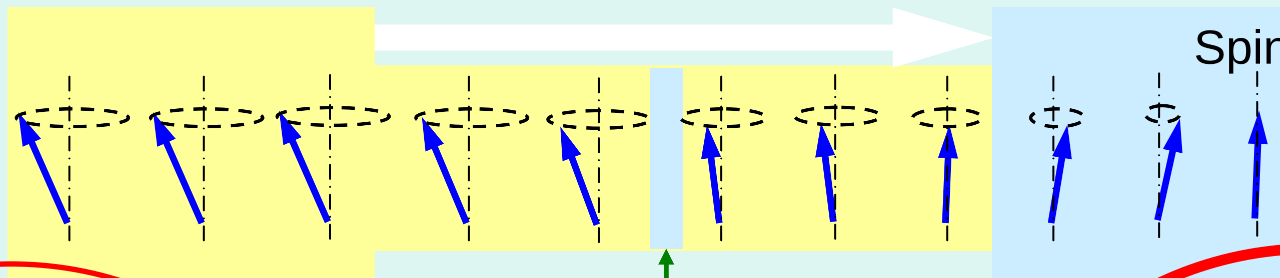
- Saito succeeded in transmitting electric signals through YIG using spin waves (pure spin current) in the insulator.
- *The spin Hall effect, which converts the charge current to a spin current, and its inverse forms the basis for a proof of principle.* **(Physic Today)**



Y. Kajiwara, E. Saitoh et al.,
Nature **464** 262 (2010)

Excitation, modulation and detection of spin wave spin current

Spin wave spin current



Excitation

- local FMR
- electrical excitation (oscillating current + ME)

Modulation

- electric field + SO

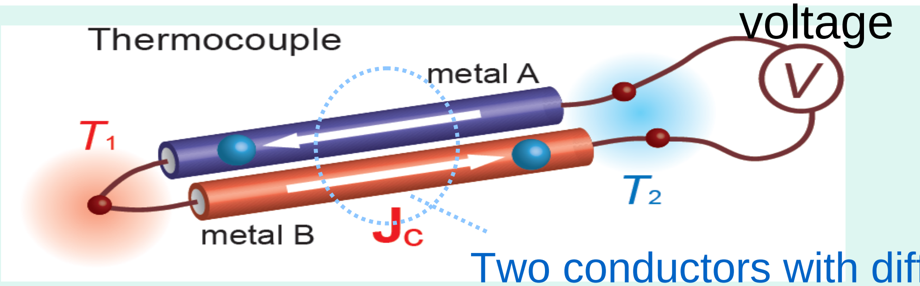
Detection

- spin torque meter
- Faraday effect
- electrical detection (ISHE)

Dielectrics
- application of electric field
- strong interaction with photon

4.13 Spin current and heat flow: spin Seebeck effect

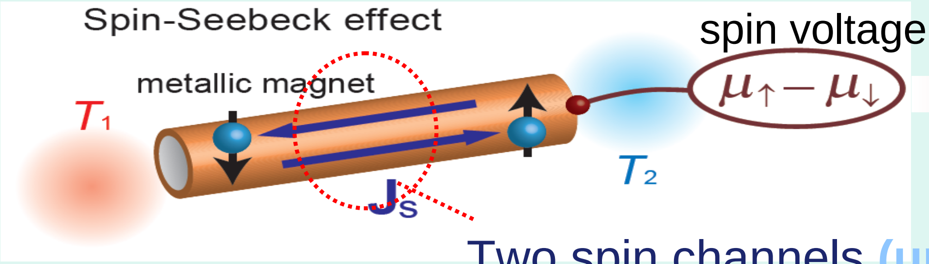
- Saito et al. observed the spin voltage generated from a temperature gradient in a metallic magnet and name the phenomenon as *spin-Seebek effect* using a recently developed spin-detection technique that involves the SHE.



Electric voltage — Seebeck effect

Two conductors with different Seebeck coefficients

depending on the density of electrons



Spin voltage — spin-Seebeck" effect

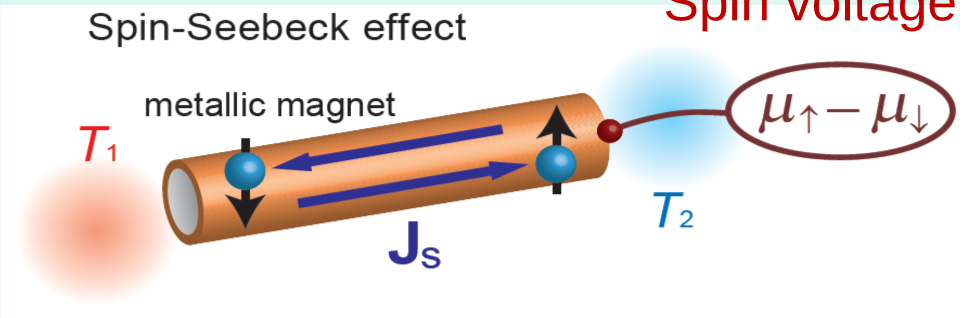
+ spin currents

Two spin channels (up / down) with different Seebeck coefficients

K. Uchida, E. Saitoh, et al.: Nature 455 (2008) 778.

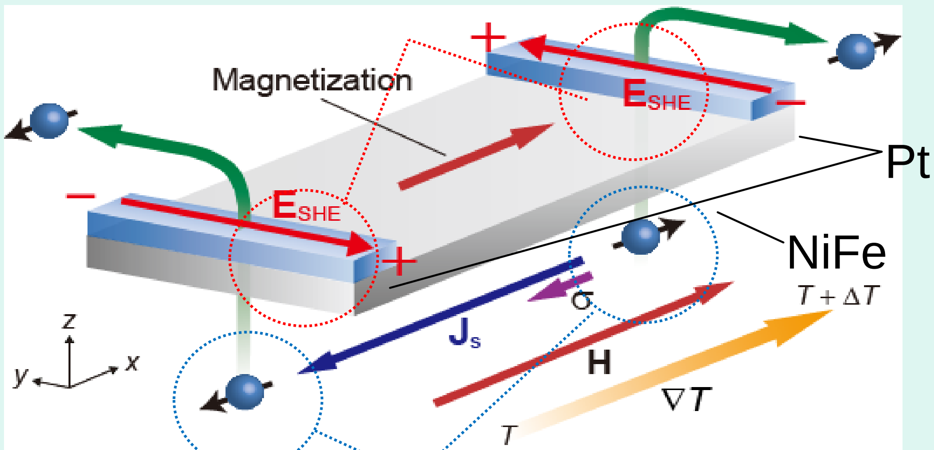
Observation of spin-Seebeck effect in NiFe

Spin voltage



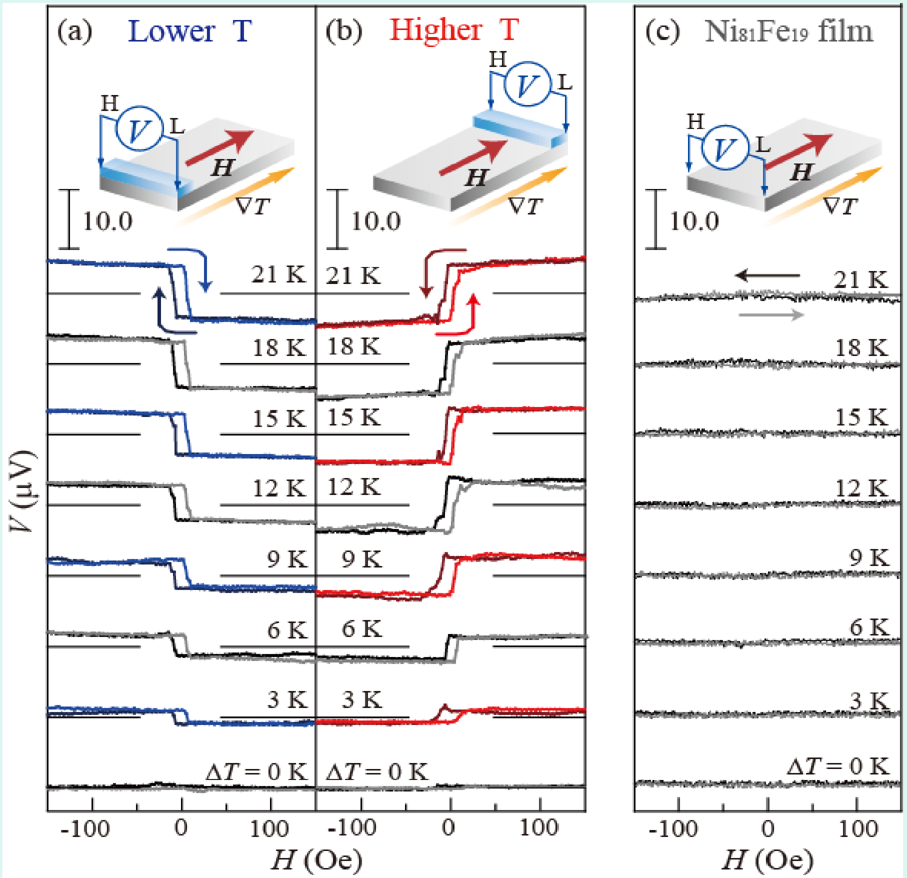
using the inverse spin-Hall effect (ISHE)

electromotive force of opposite signs



Spin voltage of opposite sign

Magnetic field dependence of *V*



ISHE voltage induced by the spin-Seebeck effect

K. Uchida, E. Saitoh, et al.: Nature 455 (2008) 778.

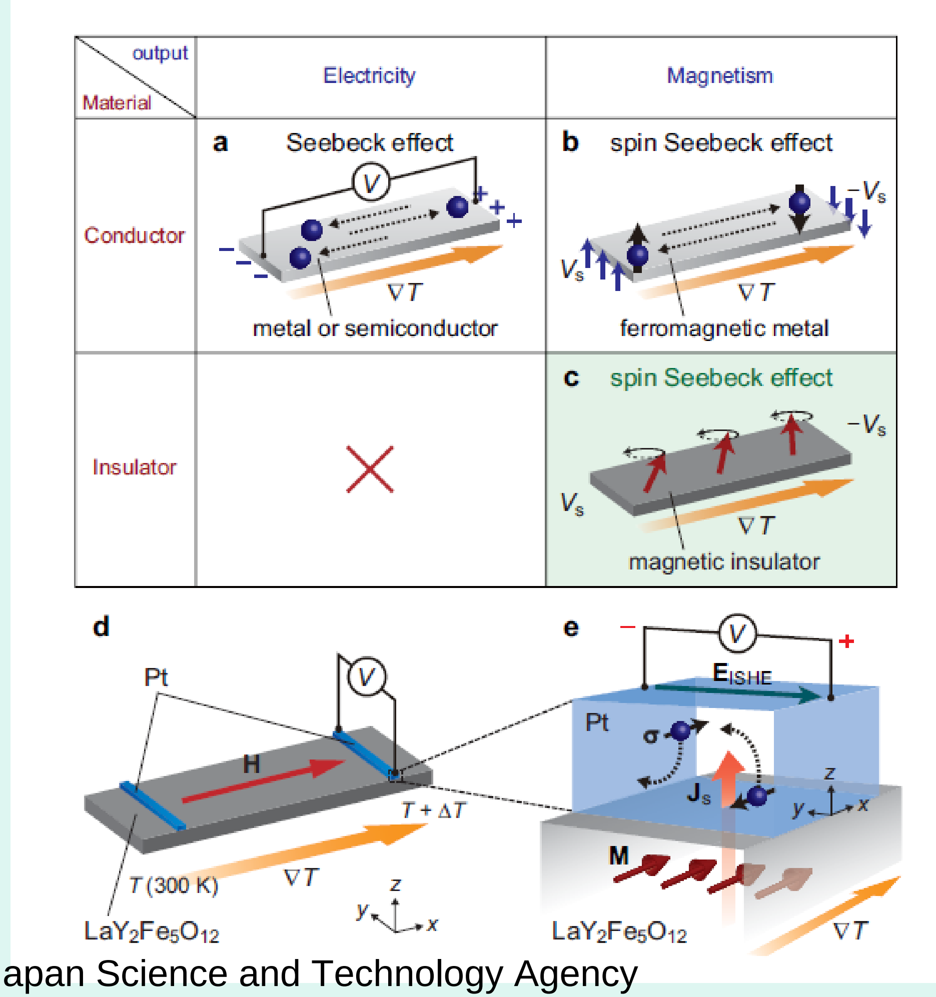
ICTMC17 Baku 2010

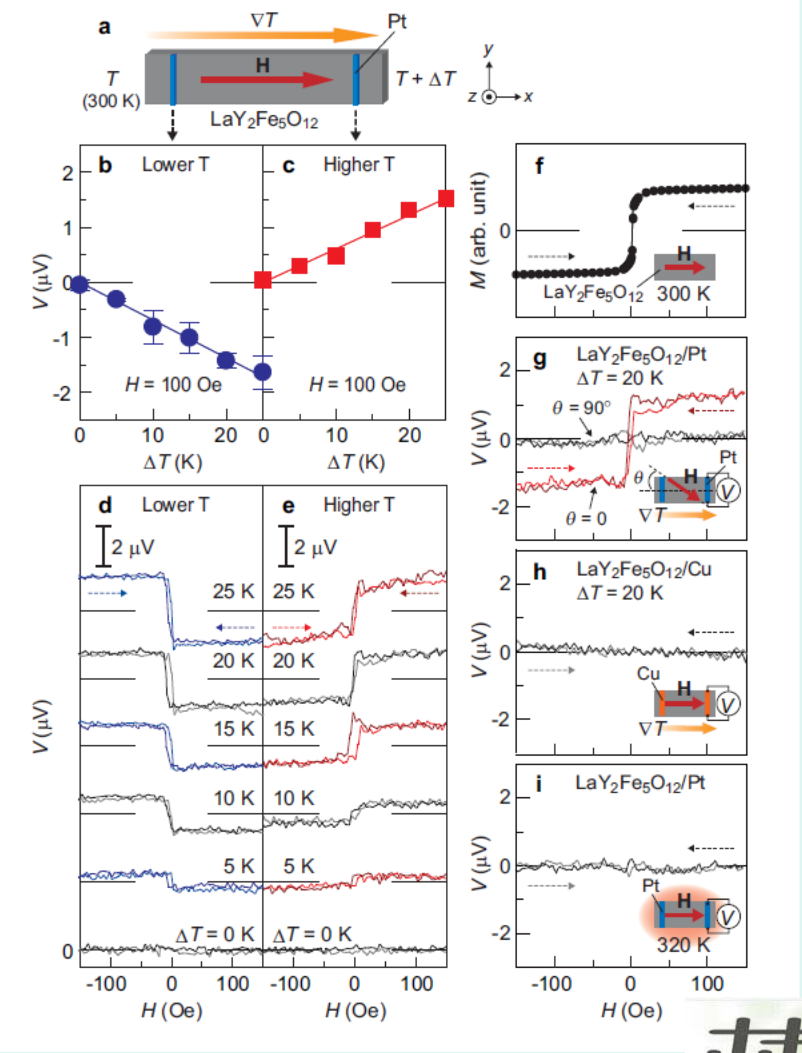
4.14 Spin Seebeck insulator

Today!

- Saito succeeded in observing spin Seebeck effect in insulating $LaY_2Fe_5O_{12}$

K. Uchida, E. Saitoh et al.: Nature Mat. (online Sept 27, 2010)





5. Magnetic Semiconductors

- Another important trend in spintronics is the *magnetic semiconductor* (MS).
- Mn-doped III-V semiconductors such as $In_{1-x}Mn_xAs$ and discovered by Munekata and Ohno are the first MS in which carrier-induced ferromagnetic coupling is confirmed. [i],[ii] The most remarkable point is the voltage-controlled ferromagnetic coupling observed in the FET structure. [iii] Tanaka succeeded in fabricating MTJ with high TMR ratio in $Ga_{1-x}Mn_xAs$. [iv] Carrier-driven domain-wall motion with very low carrier density (~10^5 A/cm^2) has also been observed in MS.[v]
- However, in spite of a number of intensive studies, the Curie temperature Tc stays no higher than 250 K in Mn-doped III-V.
- Although a number of reports have been published on room temperature MS, origin of the magnetism is still under controversy. [vi] Among them Co-doped TiO_2 is considered as the most reliable MS material exhibiting carrier induced ferromagnetism at room temperature. [vii]

[i] H. Munekata, H. Ohno et al.: Phys. Rev. Lett. **63** (1989) 1849.

[ii] H. Ohno, et al.: Appl. Phys. Lett. **69** (1969) 363.

[iii] H. Ohno, et al.: Nature **408** (2000) 944.

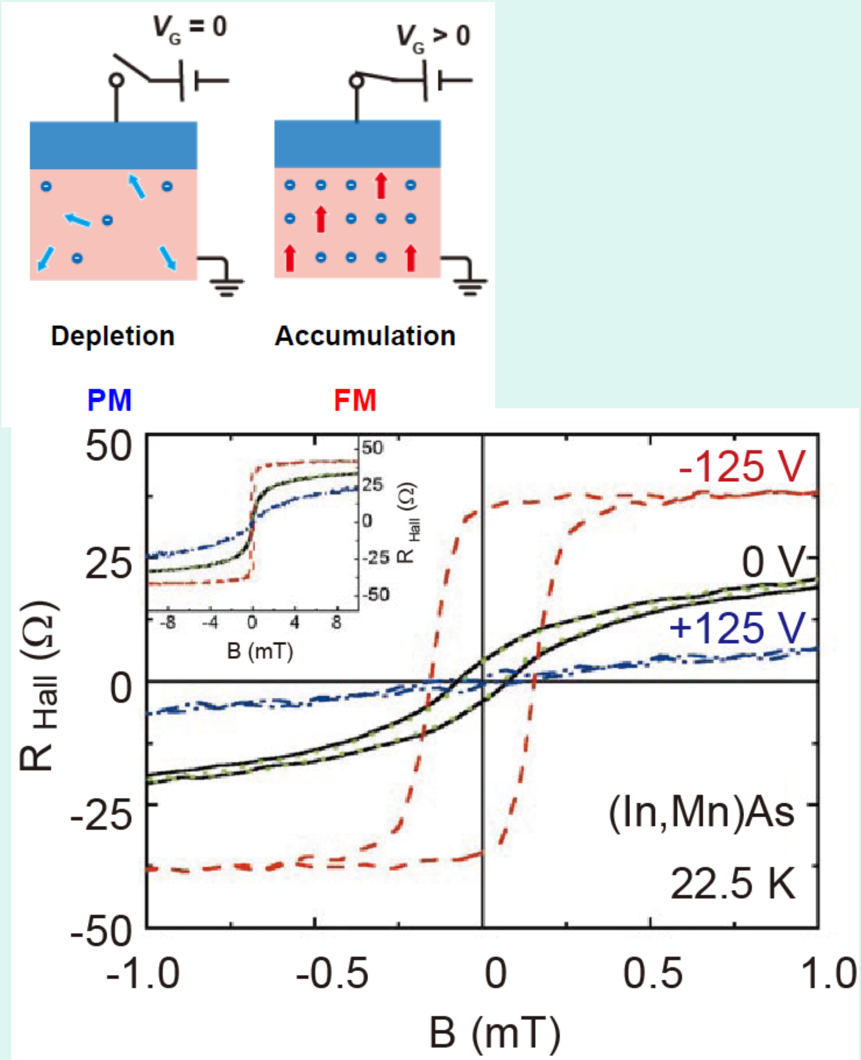
[iv] M. Tanaka and Y. Higo: Phys. Rev. Lett. **87** (2001) 026602.

[v] M. Yamanouchi, et al.: Phys. Rev. Lett. **96** (2006) 96601.

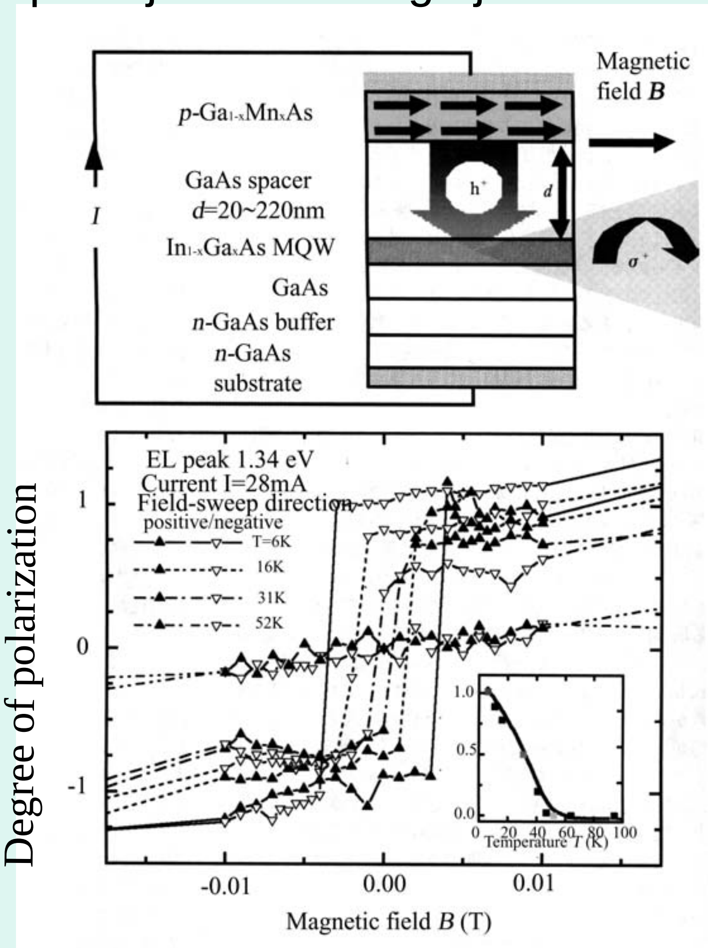
[Vi] G.A. Medvedkin, K. Sato, et al.: Jpn. J. Appl. Phys. 39 Part 2 [10A] (2000) L949-L951

[vii] T. Yamasaki, T. Fukumura, et al.: Appl. Phys. Express **1** (2008) 111302.

Heterostructure devices of III-V DMS



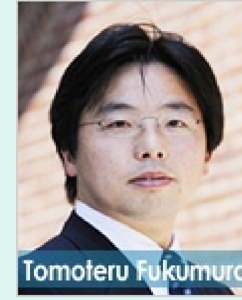
Spin-injection through junction



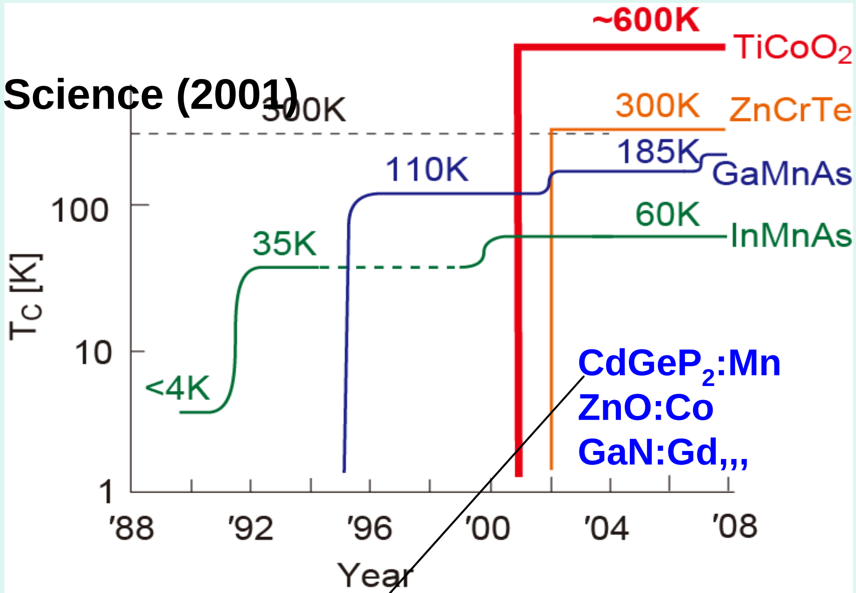
Y. Ohno et al., Nature **402** (1999) 790

ICTMC17 Baku 2010

High T_C FM semiconductor: cobalt-doped TiO_2



Extraordinary high T_C



G.A. Medvedkin, T. Ishibashi, T. Nishi, K. Hayata, Y. Hasegawa and K. Sato: Jpn. J. Appl. Phys. 39 Part 2 [10A] (2000) L949-L951

TiO2:Co Room temperature FM semiconder

Giant MO effect at RT

T. Fukumura, Jpn. J. Appl. Phys. (2003)

H. Toyosaki, Appl. Phys. Lett. (2005)

Anomalous Hall effect at RT

H. Toyosaki, Nature Mater. (2004)

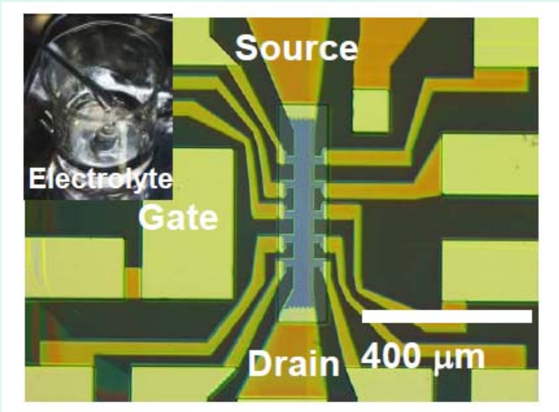
T. Fukumura, Jpn. J. Appl. Phys. (2007)

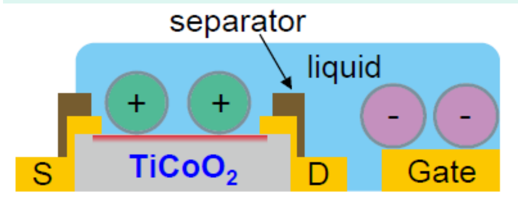
Tunneling Magnetoresistance

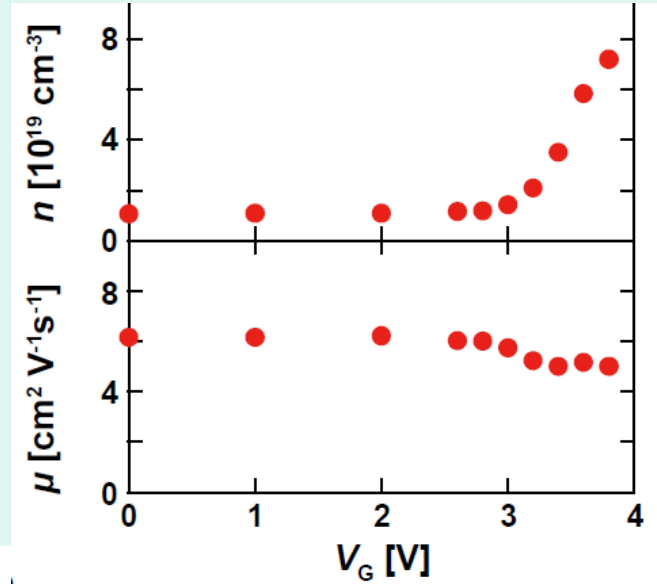
H. Toyosaki, Jpn. J. Appl. Phys. (2005)

$Zn_{1-x}TM_xO$ combinatorial library

Carrier control of magnetism in TiO_2:Co by gate voltage

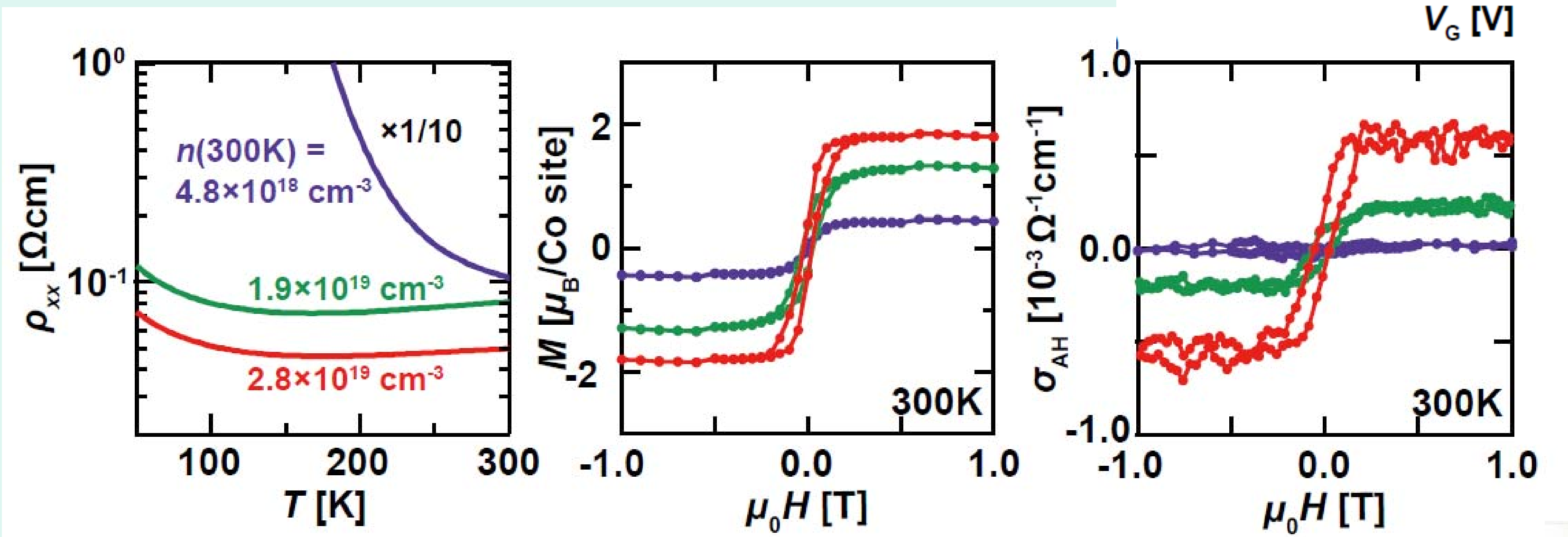






$Ti_{0.90}Co_{0.10}O_{2-\delta}$

PM insulator → FM metal

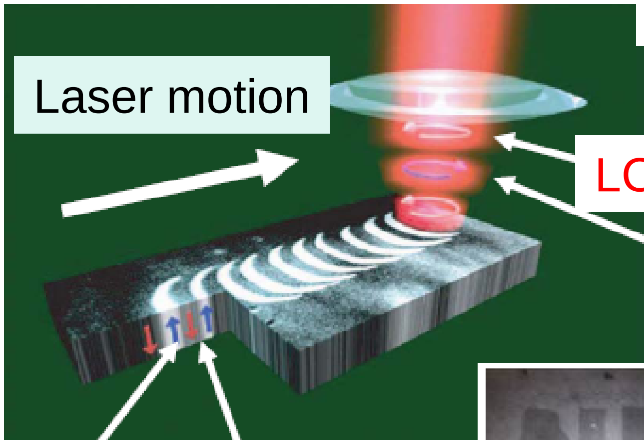


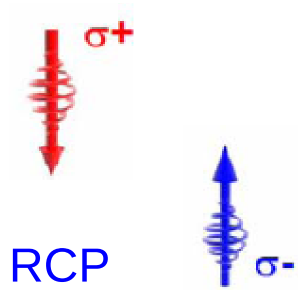
6. Light-Induced ultrafast magnetization reversal

- The response time of magnetization reversal is usually limited by the spin dynamics which follow Landau-Lifshitz-Gilbert equation.
- By a collaboration of Nihon Univ. group and Radbout Univ. group, ultrafast magnetization switching (less than ps) was accomplished in the vicinity of the compensation point of MO-recording media.

Demonstration of direct magneto-optcal recording by circular polarization modulation

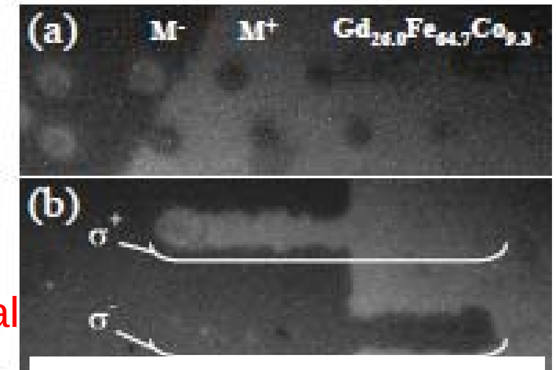
Equivalent magnetic field produced by photon





thermal

nonthermal



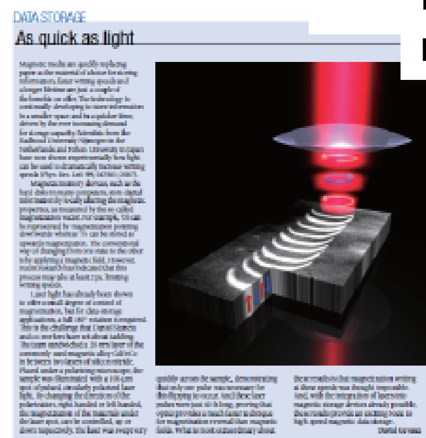
Light-induced ultrafast magnetic recording

Nature Photonics

Up spin, Down spin

Complete magnetization by
40 fs irradiation of CP.
Reversal without ext. field

PRL 99, 047601 (2007)

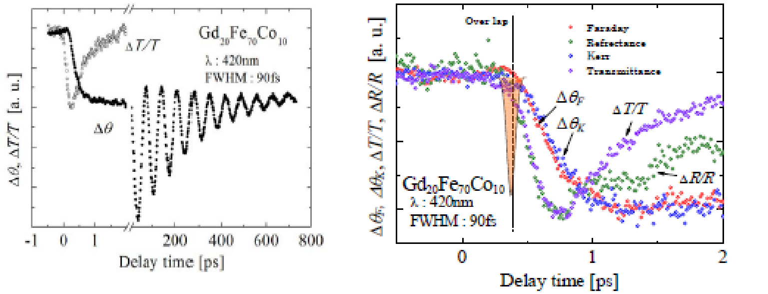


DATA STORAGE

As quick as light

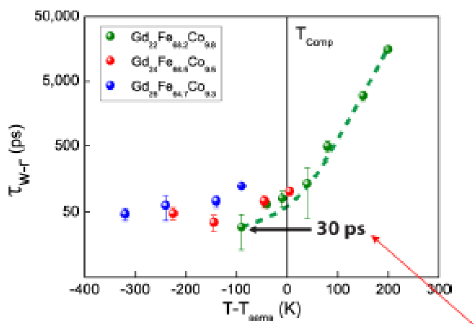
Science、Physics today他

Analysis of light-induced ultrafast magnetization reversal



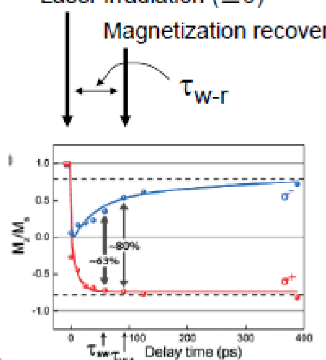
The magnetization
modified monotonically
reaches to a temporal state within 1ps

Composition and temperature dependence of Photo-magnetic switching time



Laser irradiation (±σ)

Magnetization recovery



$Gd_{24}Fe_{66.5}Co_{9.5}$
@room temp.

K. Vahaplar et al., Phys. Rev. Lett. 103, 117201 (2009)

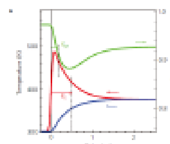
Cooperated work with Radboud Univ. et. al.

Fastest write-read event
demonstrated for magnetic recording so far.

Classification of ultrafast dynamics

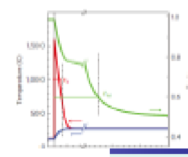
Type I material

- Strong spin scattering
- Fast demagnetization follows the electron temperature
- Ni, Fe and Co

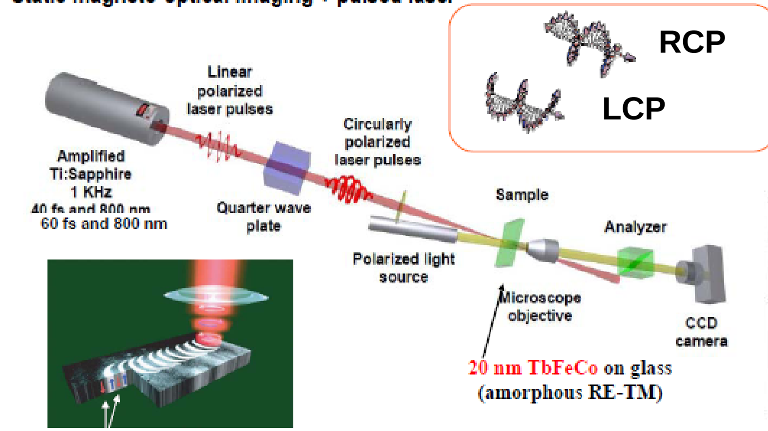


Type II material

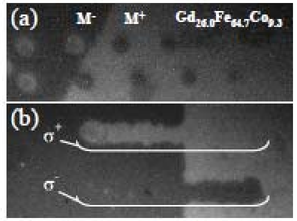
- Weaker magnetic coupling
- 2step demagnetizations very fast (first picosecond) slower demagnetization
- Ga, TbFe



Static magneto-optical imaging + pulsed laser

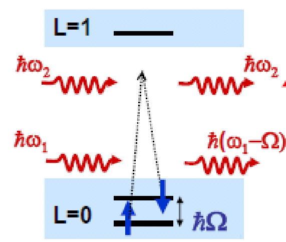


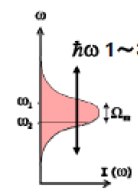
Magnetization direction



Light-induced ultrafast magnetic recording

Origin of photo induced magnetization phenomena





- Spectroscopic measurements
  Wave length > photon energy
  Pulse width
  Intensity
- Distinguish thermal, non-thermal contribution

\+

- Control of dynamic motion of spins
  - Angular momentum compensation
  - Linear reversal

  > Suppress Precessional motion

Japan Science and Technology Agency

7. Summary

Spintronics: Emerging field attracting Hot Attention

- As mentioned above, control and manipulation of spin current (injection, accumulation, relaxation) is expected as a bud for next-generation innovative devices beyond CMOS.
- Spin science is growing rapidly bigger and bigger on the playground of nano science.
- Nagaosa, theoretician describes that spin Hall effect and anomalous Hall effect in terms of Berry phase and insists that he find the universe in solids. [i]
- I feel hot enthusiasm in this emerging field and expect a big change in the near field.

[i] N. Nagasa：Kotaibutsuri 41 (2006) 877, ibid 42 (2007) 1, ibid 42 (2007) 487. (In Japanese)

Thank you for kind attention!