IEEE Magnetics Society Japan Chapter Tutorial session
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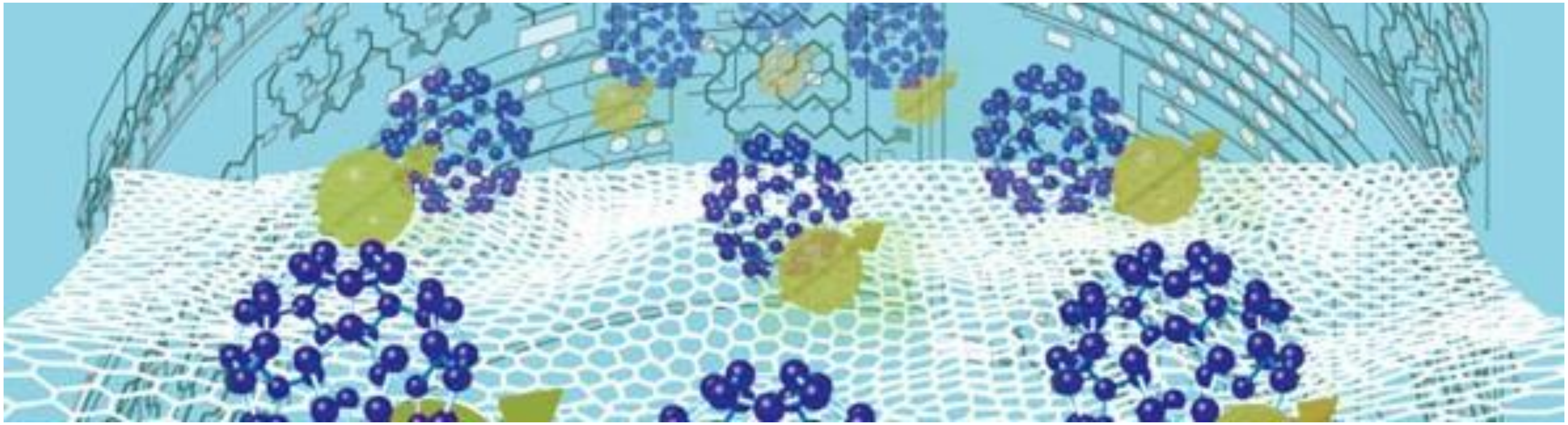

Spin-related Nanosciences for Next Generation Innovative Devices

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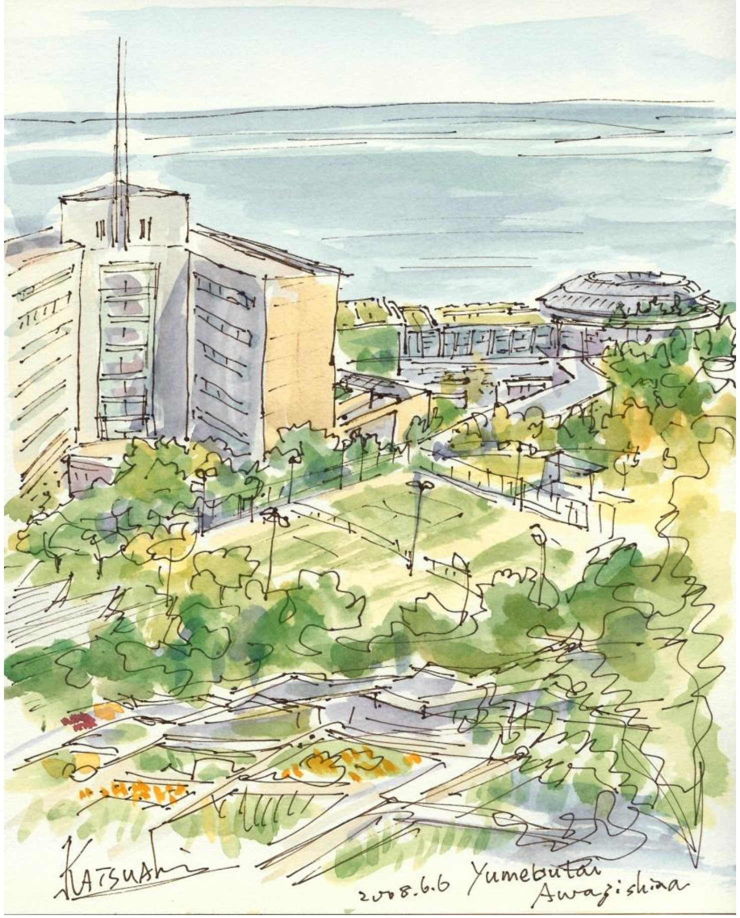
Welcome to Yume-butai



Contents

1. Introduction

- Silicon crystals used for semiconductor integrated circuits represented by CMOS are the materials can be 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 32 nm half pitch is approaching, which in turn requires device development based on new concepts and/or new principles beyond conventional silicon CMOS technologies.

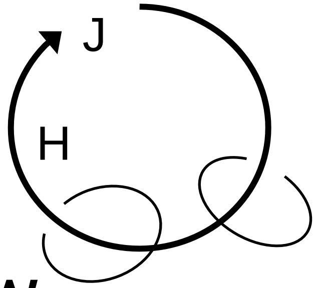
PRESTO Project targeting at Next Generation Devices

- 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.

Mutual Conversion between Electricity and Magnetism

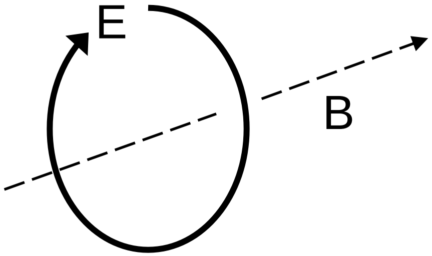
- Electricity→Magnetism. Ampere's Law

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



- 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!*

2. Spin-dependent Electronic Transport and Magneto-resistance

B→E

Long Research History of Spin-Dependent Transport Phenomena

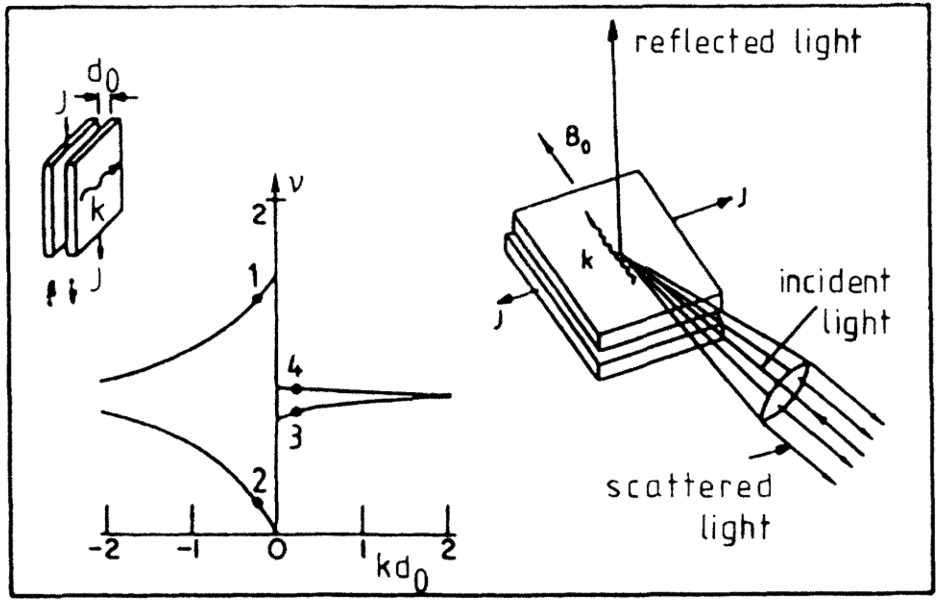
- The phenomena of spin-dependent electrical transport such as spin-disordered scattering just below the Curie temperature and anisotropic magnetoresistance and anomalous Hall effect in ferromagnetic metals have been studied extensively and explained theoretically already in 1960's.
  - For example、G.K. 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*.

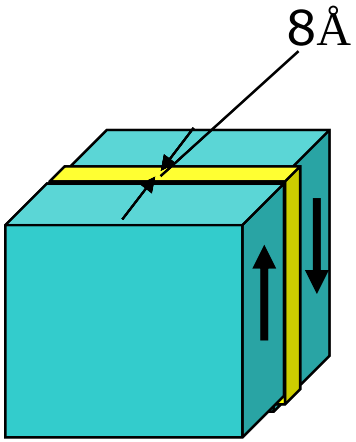
Encounter with nanotechnology (1)

- 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.

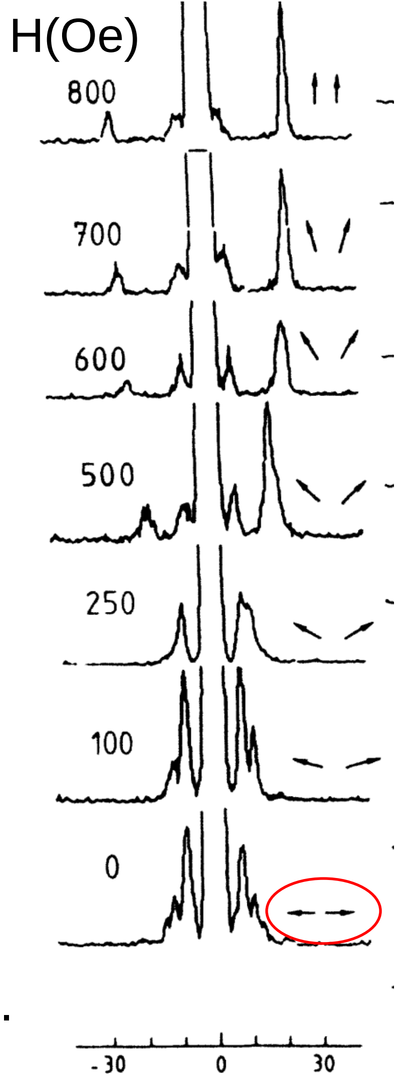
Encounter with nanotechnology (2)

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.

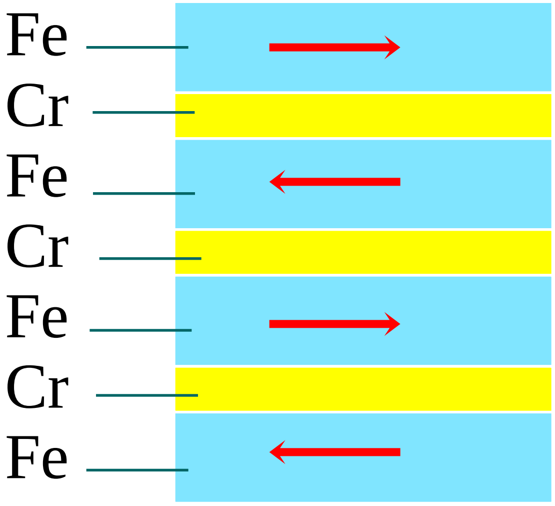


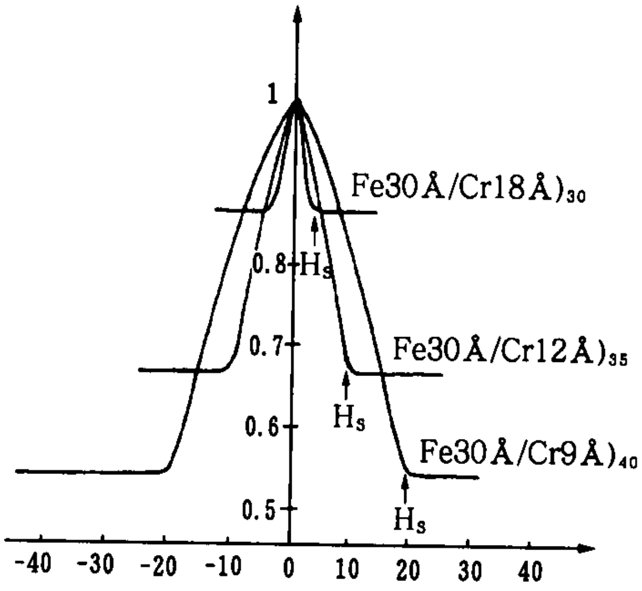
Breakthrough in Spintronics

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



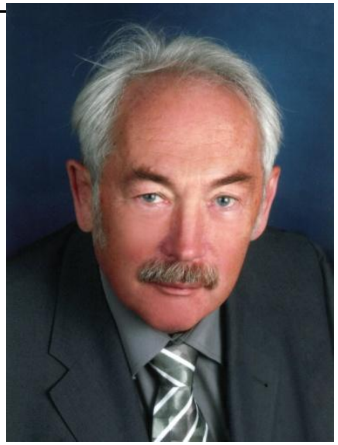


M.N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friedrich, J. Chazelas: Phys. Rev. Lett. 61 (1988) 2472.

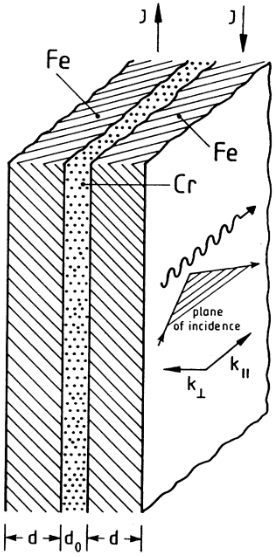
Breakthrough in Spintronics

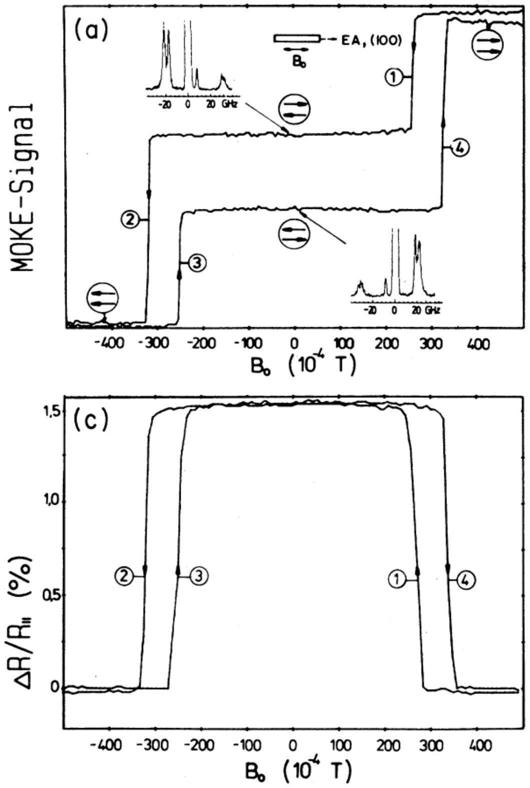
Discovery of giant magnetoresistance(GMR)(2)

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



Dr. Peter Grünberg



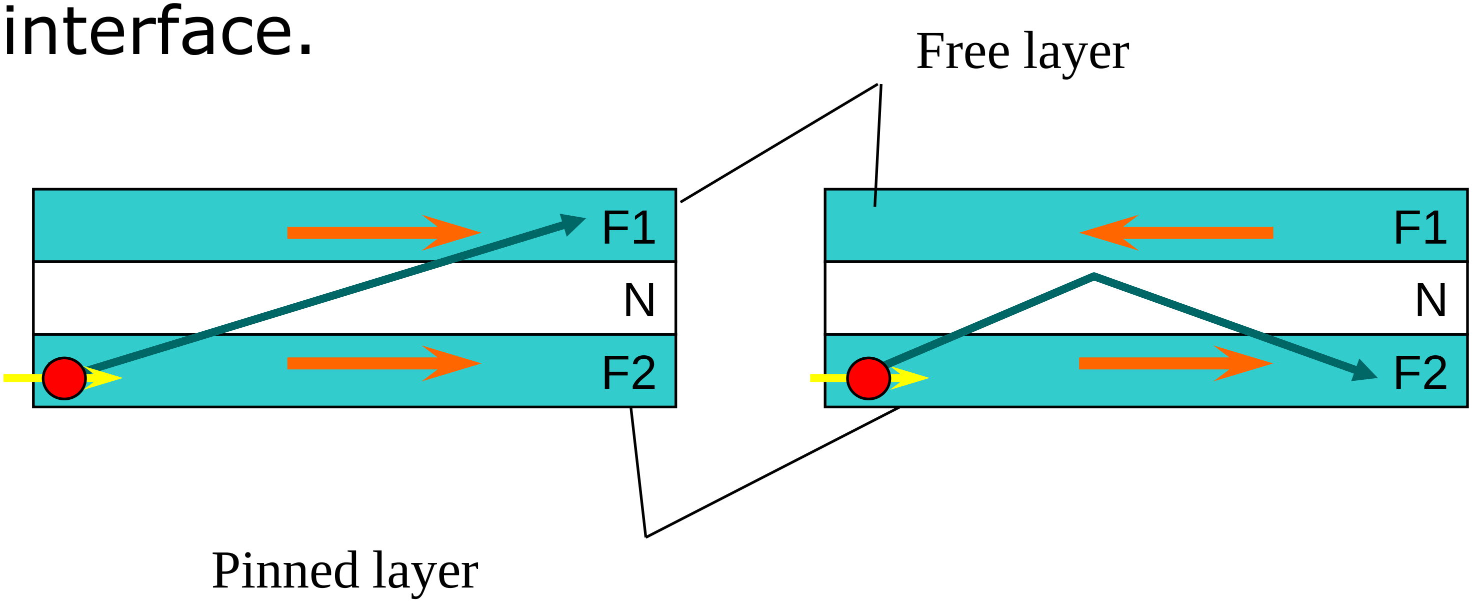


G. Binasch, P. Grünberg, F. Saurenbad, W. Zinn: Phys. Rev. B 39 (1989) 4828.

Physical background of GMR

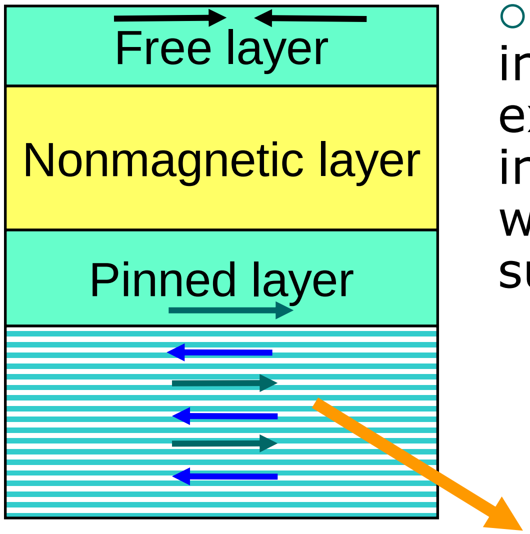
Spin-scattering at layer-interfaces

- 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.



Spin valve for HDD head

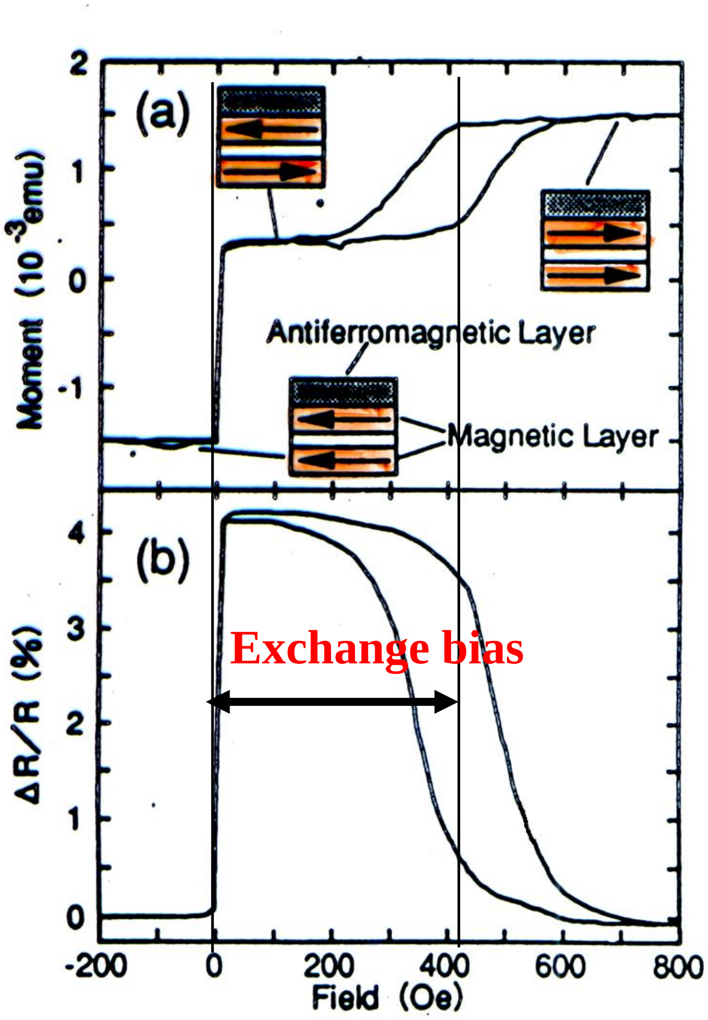
Parkin of IBM elaborated a magnetic field sensor for HDD using uncoupled sandwich structure NiFe/Cu/NiFe/FeMn, and named it as Spin Valve.



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

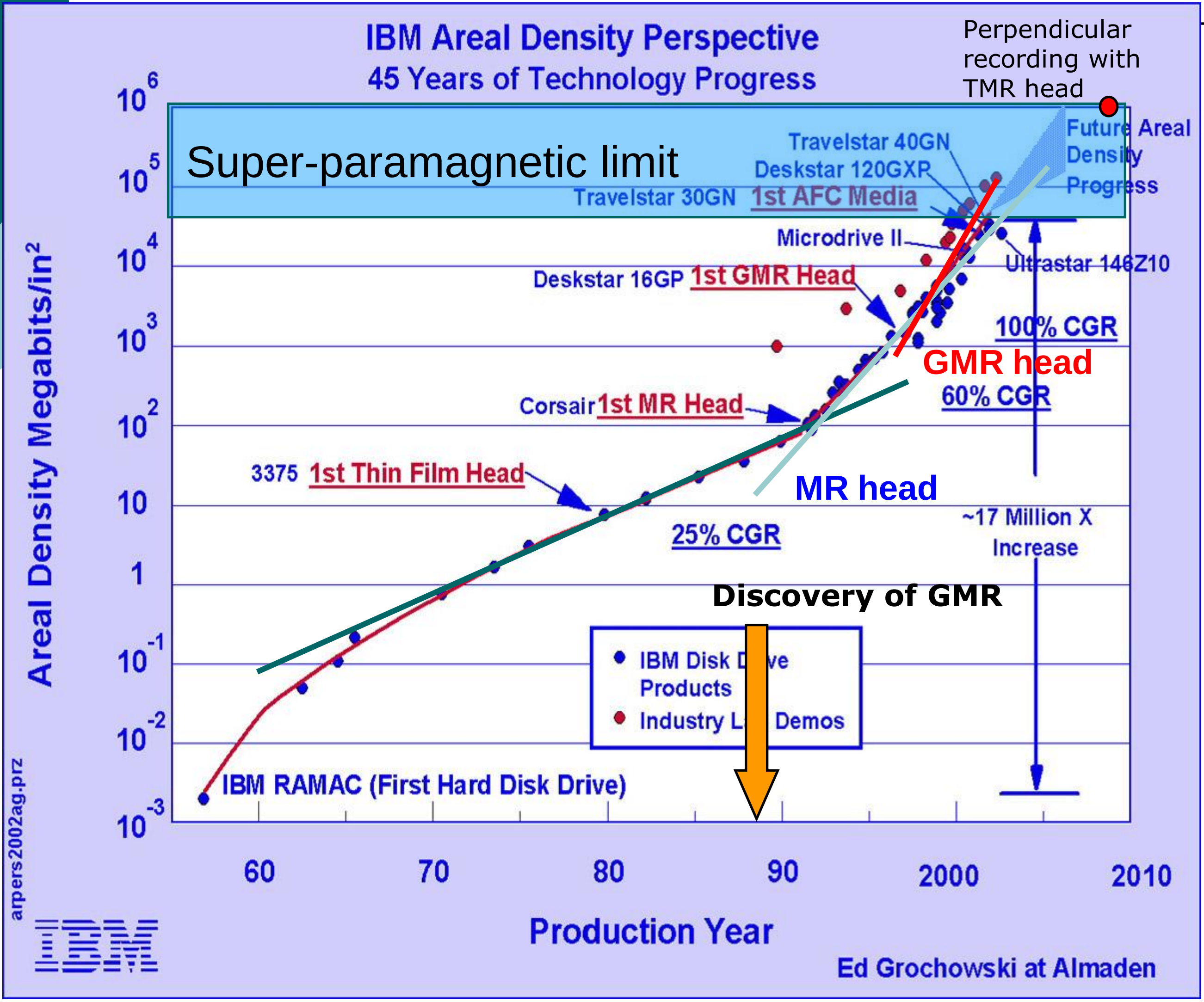
Antiferromagnetic substrate (ex FeMn)

(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

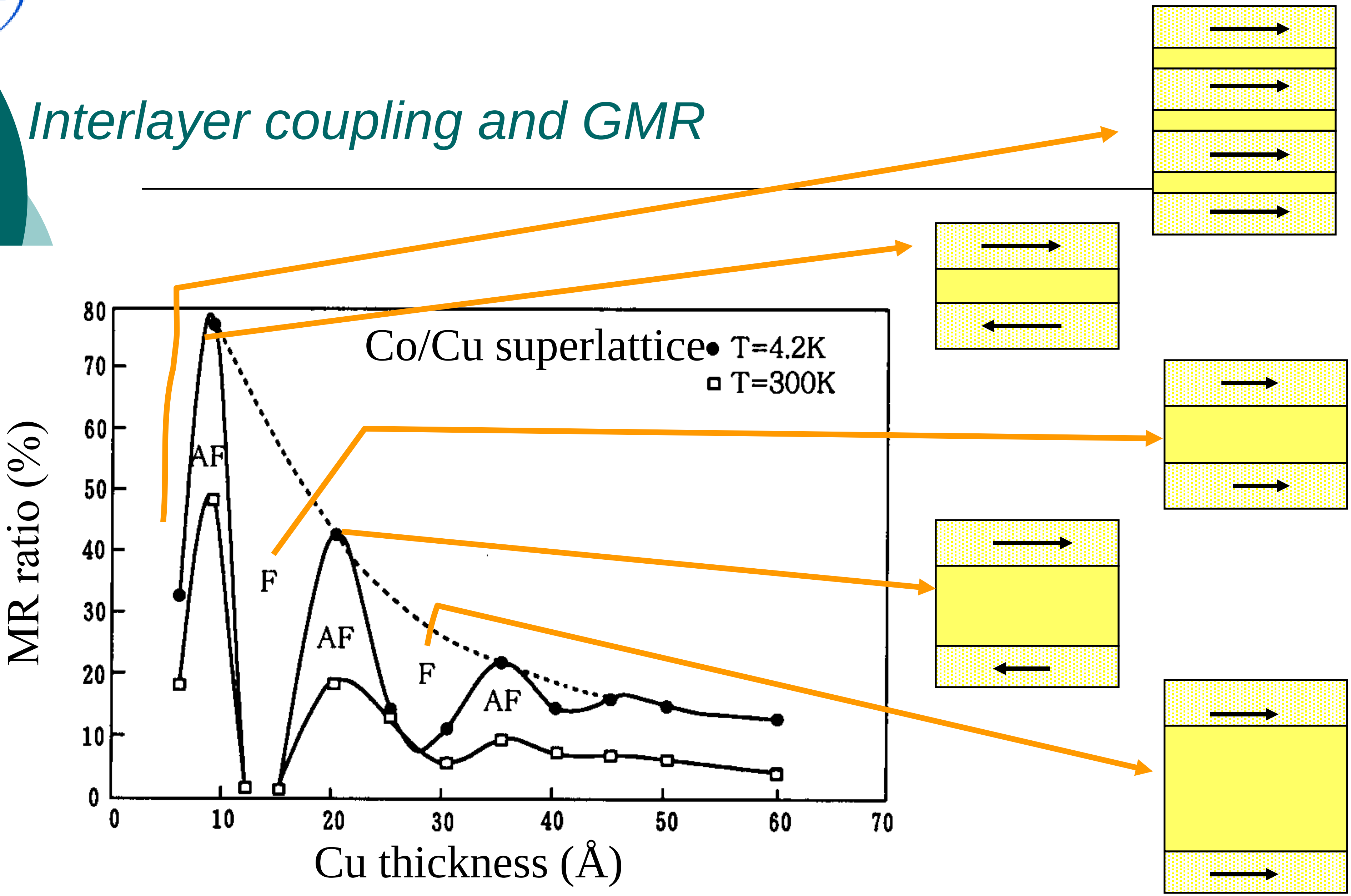


- Introduction of GMR (Spin Valve) head brought a dramatic change in the growth rate of areal recording density of HDD.
- It is quite remarkable that scientific discovery lead to practical applications in such a short period of time.

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 →antiferromagnetic → 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

Further Breakthrough in Spintronics

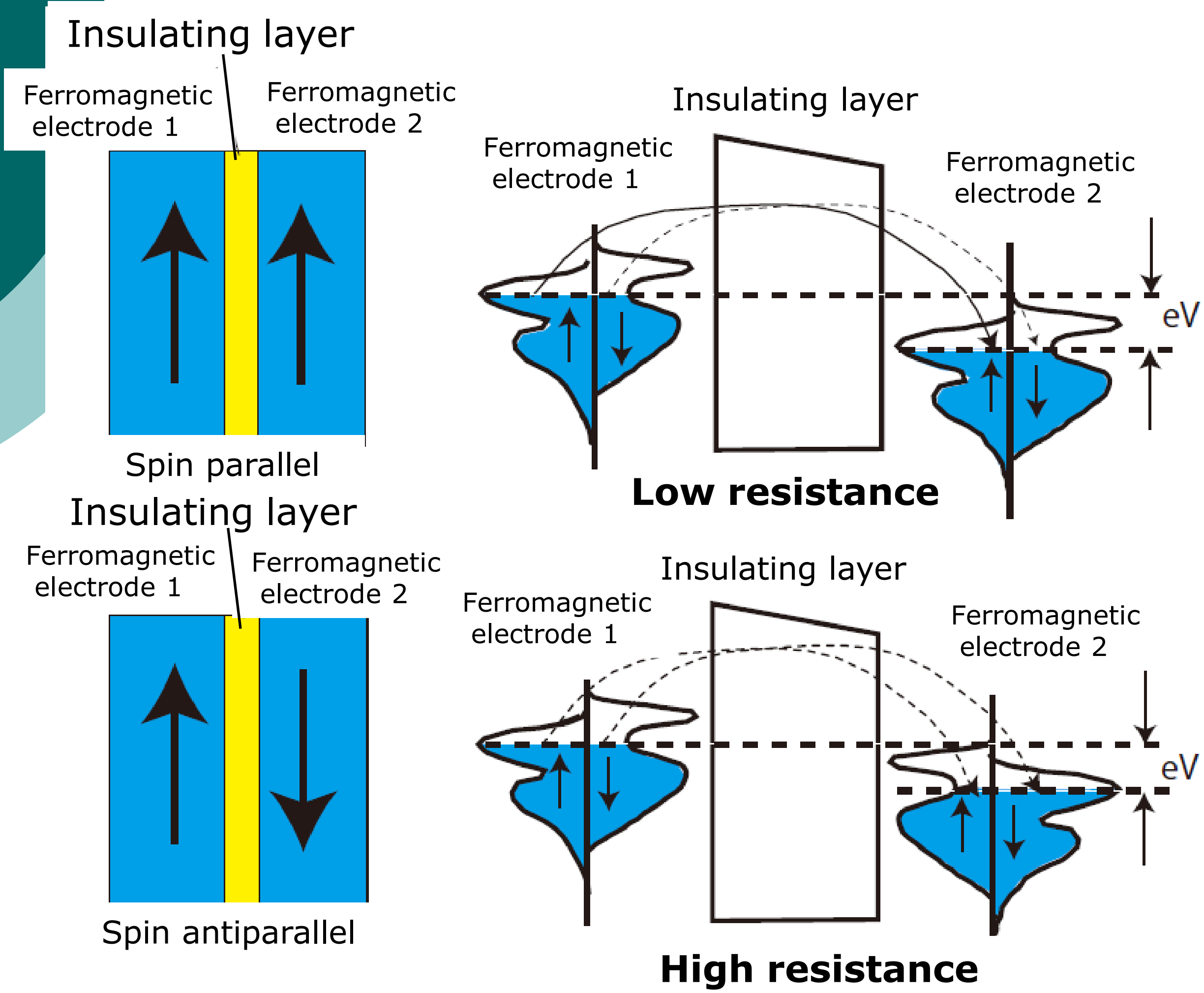
Discovery of room temperature TMR

- 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 $\mathrm{TMR}(\%)=(R_{\uparrow\uparrow}-R_{\uparrow\downarrow})/R_{\uparrow\uparrow}\times 100$ 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.

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.

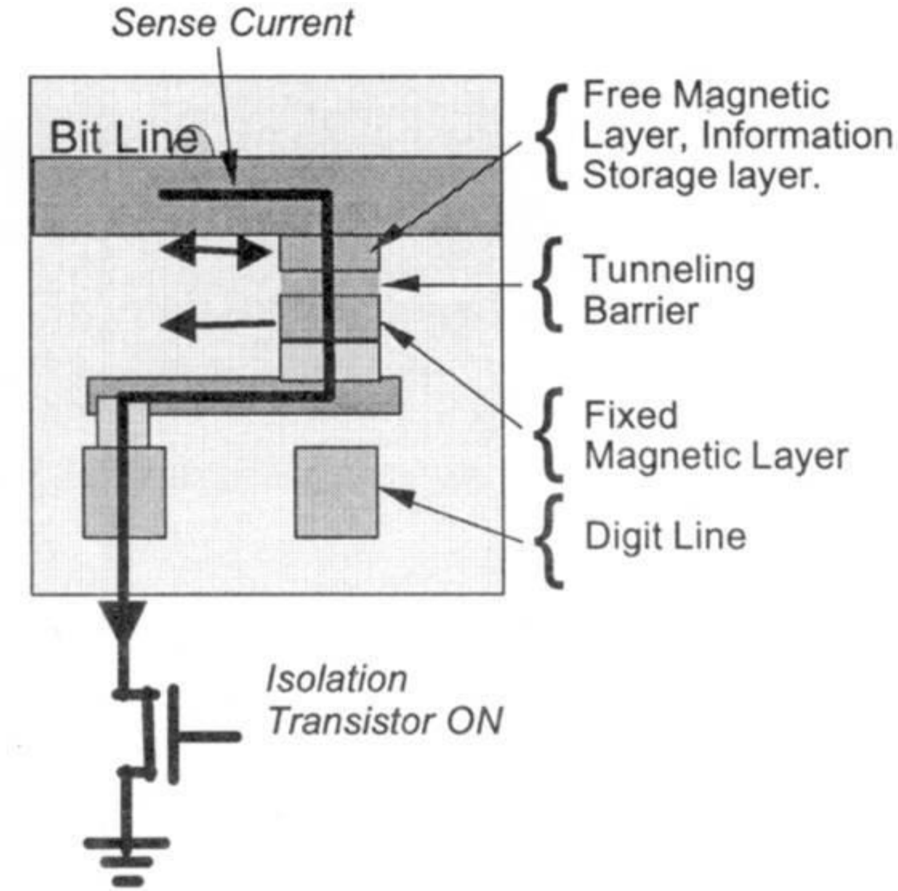
Physical background of TMR



- 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.

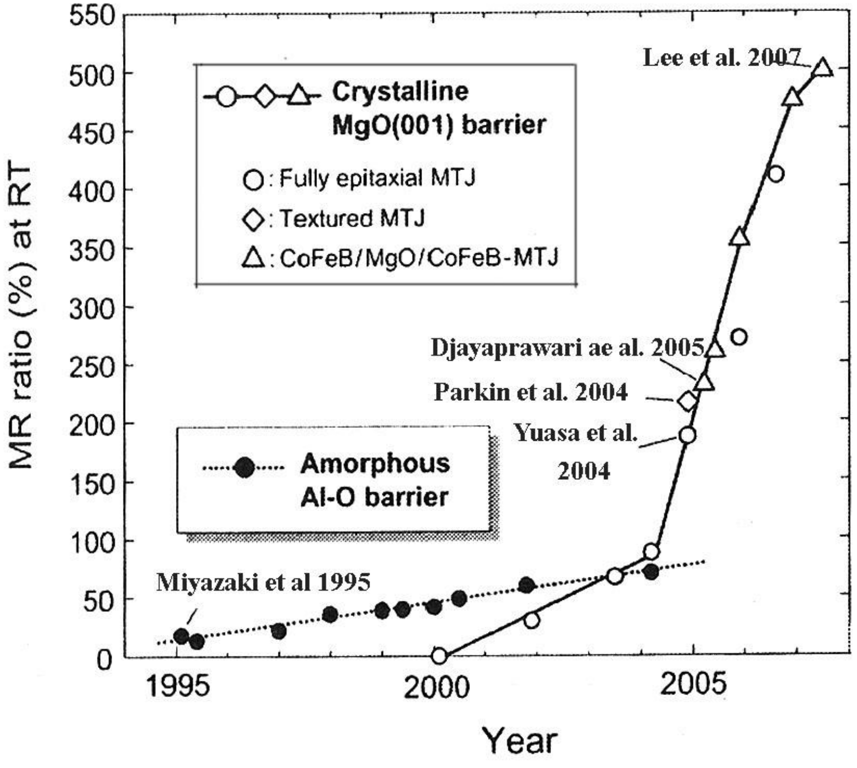
Application of TMR
MRAM (Magnetic random access memory)

- 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.



Breakthrough on MTJ-TMR by adopting 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, i=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

[1] M. Jullier, Phys. Lett. 54A, 225 (1975).
[2] W. H. Butler et al., Phys. Rev. B 63 (2001) 05
J. Mathon and A. Umeski, Phys. Rev. B 63 (20
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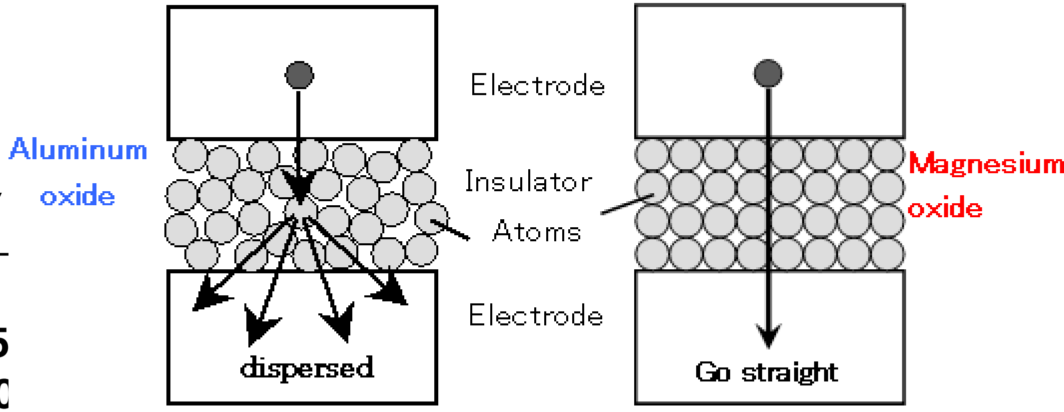
K. Inomata：RIST News No. 42(2006) 35.

○ 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]



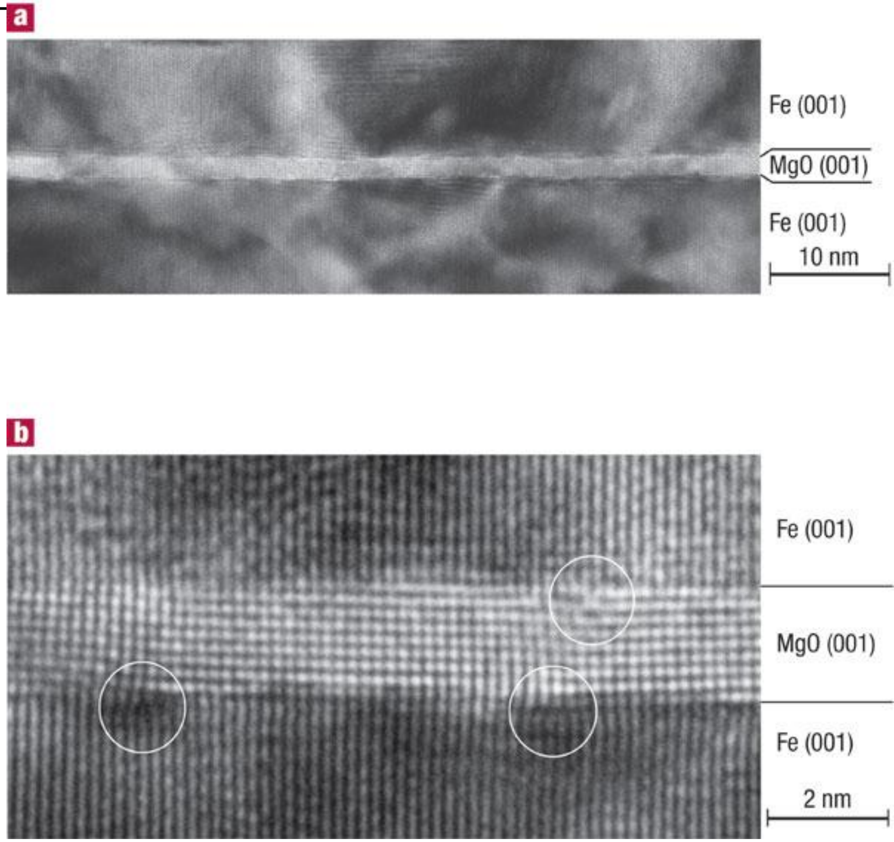
(a) Conventional device
Using aluminum oxide (amorphous). Electrons are scattered due to disorder atom arrangement.

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

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.*



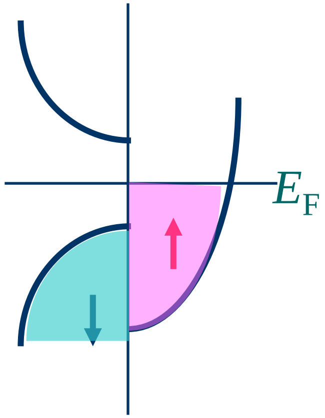
Yuasa et al. Nature Materials **3,** 868–871 (2004)

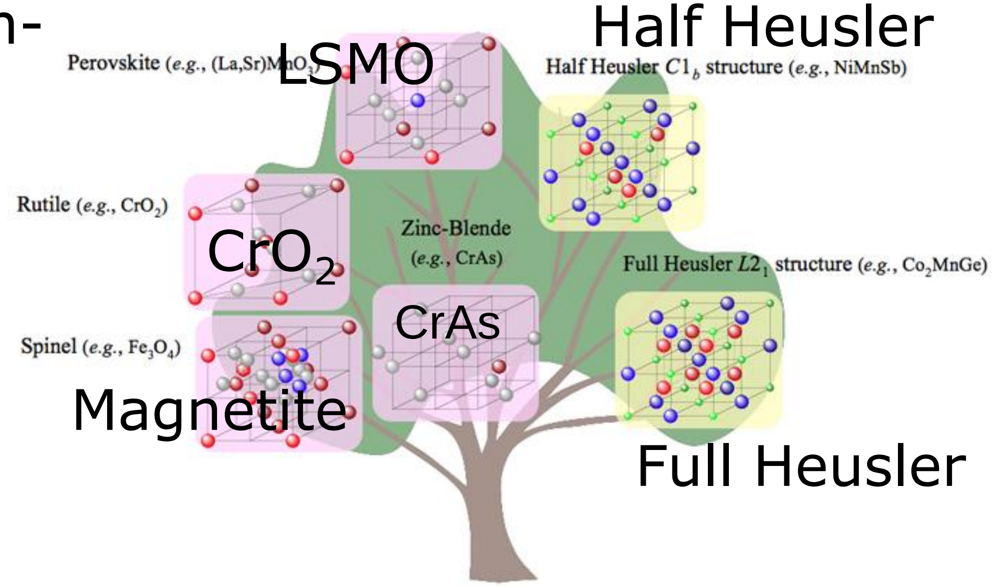
The result of Yuasa is an outcome of the JST-PRESTO Project “Nanotechnology and Material Property”. The Research Theme of Dr. Yuasa was

Development of single-crystal TMR Devices for High-Density Magnetoresistive Random Access Memo**ry**

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.



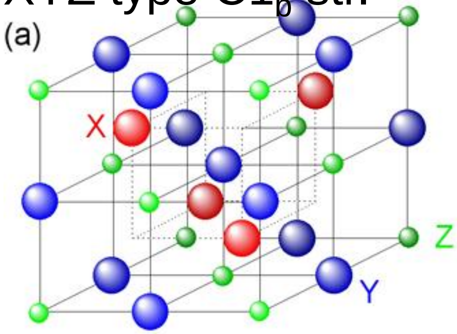


http://www.riken.go.jp/lab-www/nanomag/research/heusler_e.html

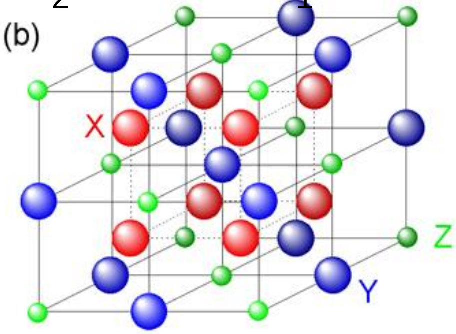
Heusler Alloys

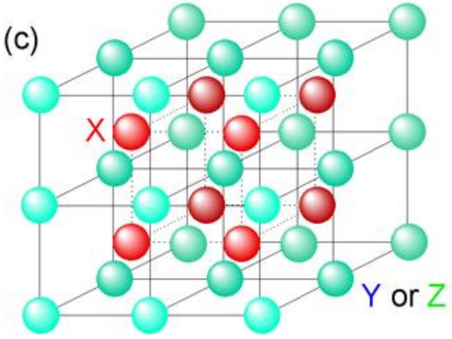
- The Heusler alloys are classified into two groups by their crystal structures;
  - Half Heusler alloys with XYZ-type in the *C*1*b* structure (a)
  - Full Heusler alloys with X_2YZ-type in the $L2_1$ structure (b) *where X and Y atoms are transition metals, while Z is either a semiconductor or a non-magnetic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

Half Heusler alloy
XYZ type $C1_b$ str.

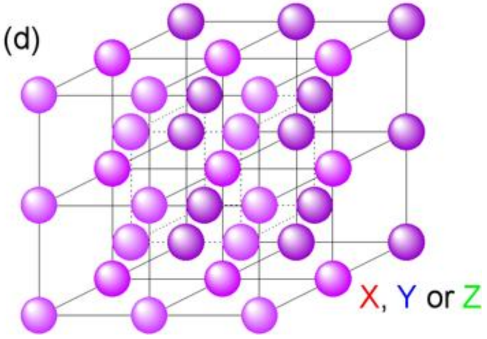


Full Heusler alloy
X_2YZ with $L2_1$ str.





B_2-structure with
Y-Z disorder

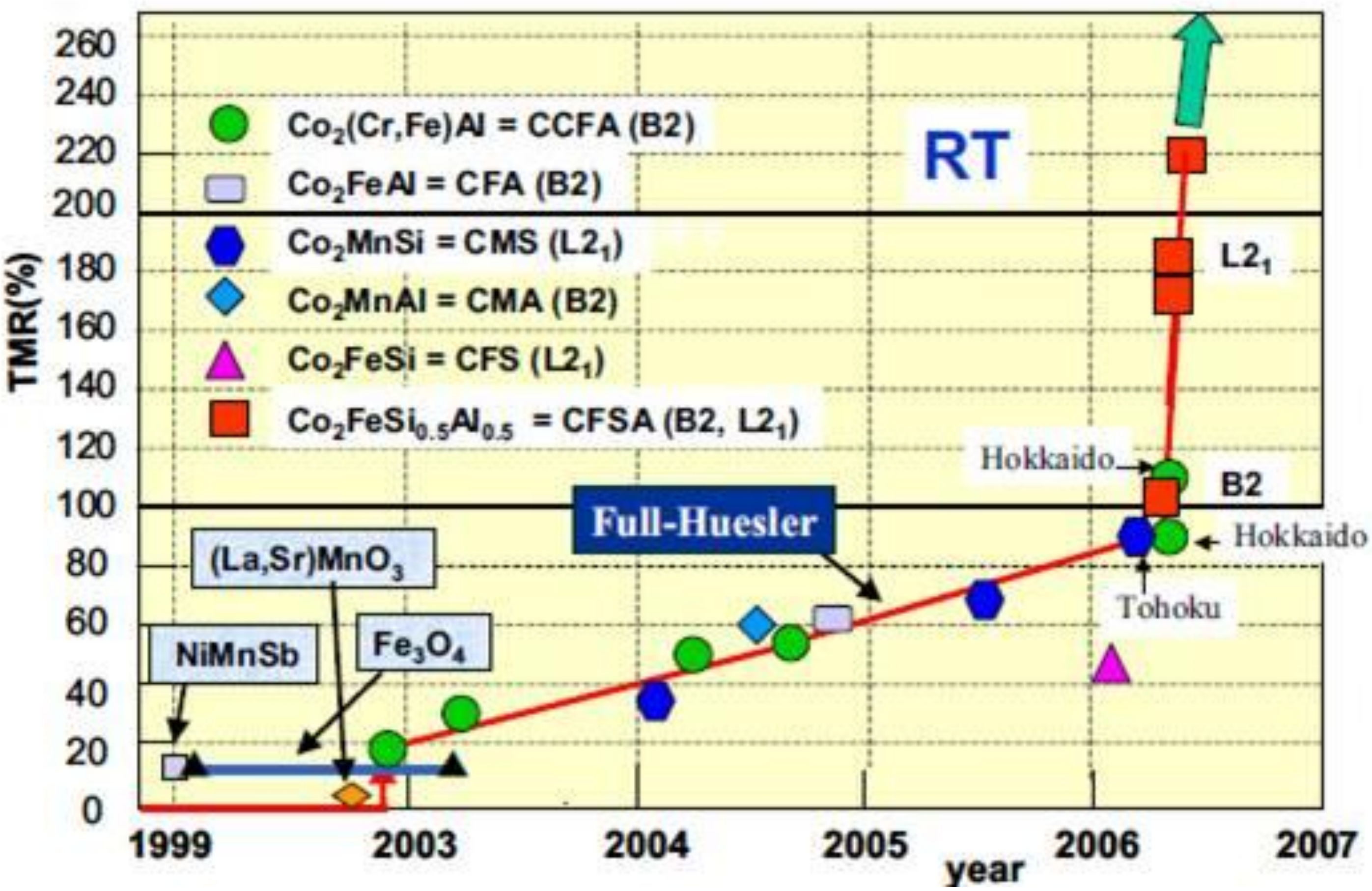


A_2-structure with
X-Y and X-Z disorder

Disordered derivatives

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

TMR with full Heusler alloys



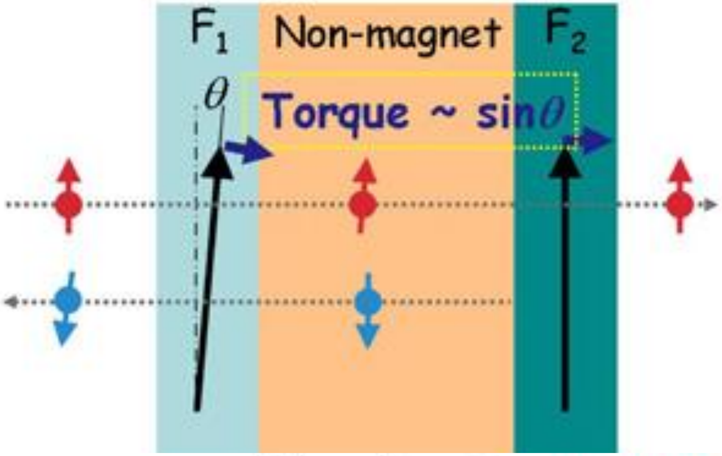
3. Spin-Transfer Magnetization Reversal

$$E \rightarrow B$$

Proposals and Experimental Verification of Spin-Transfer Magntization Reversal

- ○ 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.

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

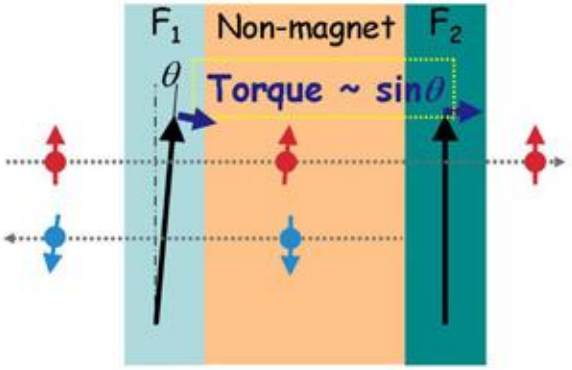
↓

Torque is exerted on either F_1 or F_2

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

Two perspectives of current-induced magnetization switching

- One is based on spin transfer, suggesting that the spin current *transfers* the transverse componer 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.



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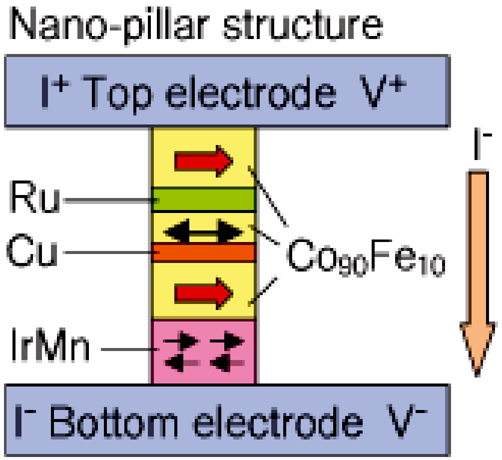
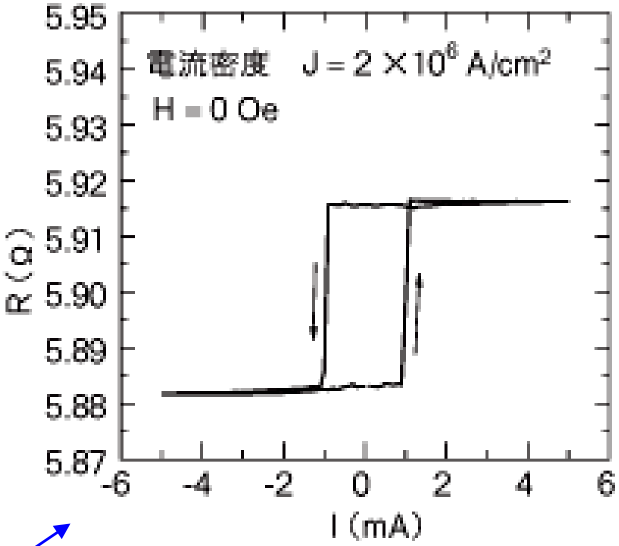
Spin-Transfer Magnetization Reversal: Experiment

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).

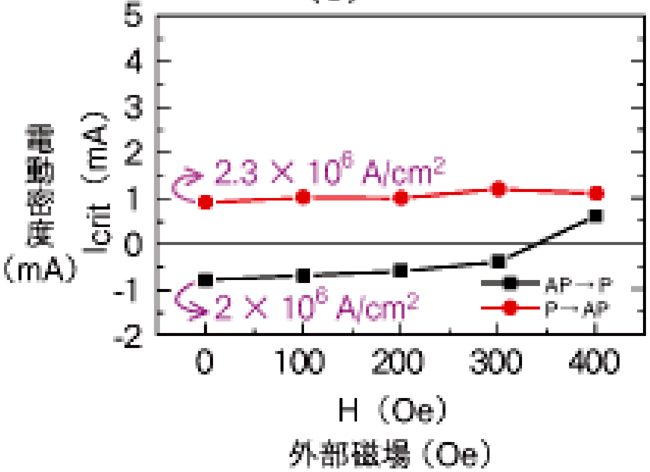
(a)



(b)



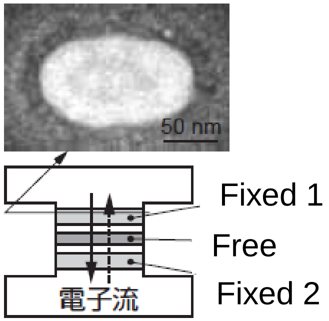
(c)



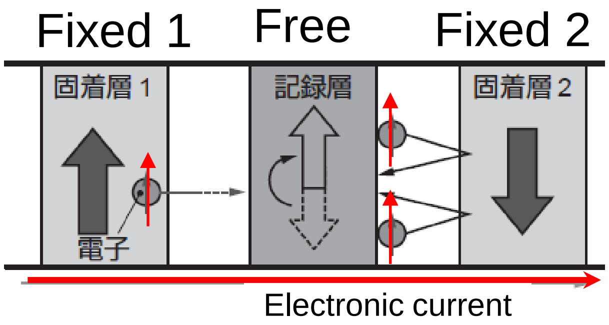
- ○ Magnetization direction of free $Co_{90}Fe_{10}$ layer is changed depending on the current direction.

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

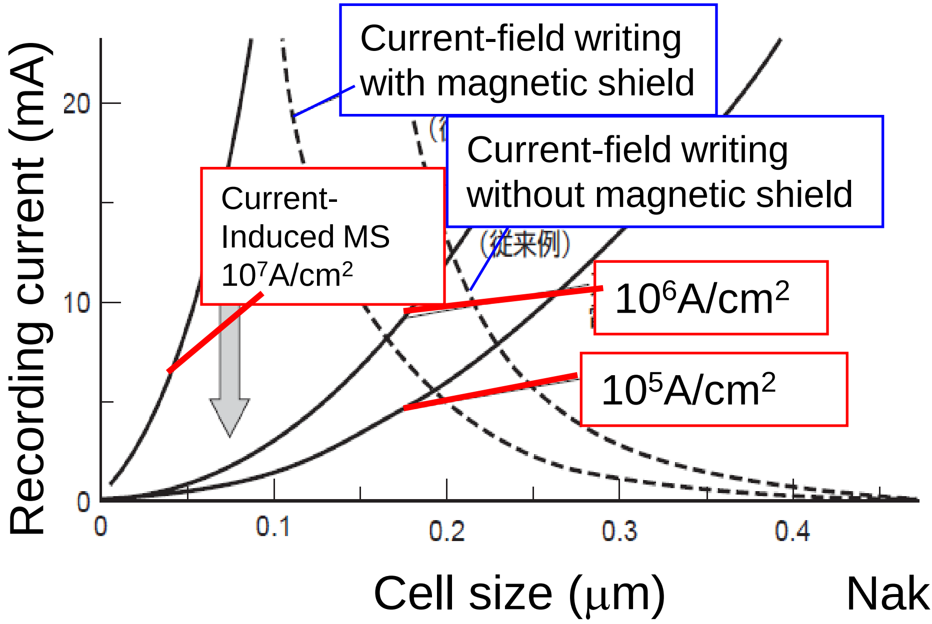
- Switching current for spin-transfer magnetization reversal is proportional to the area of devices.
- This technique is superior to the previous method if the scale becomes less than 0.2μm.

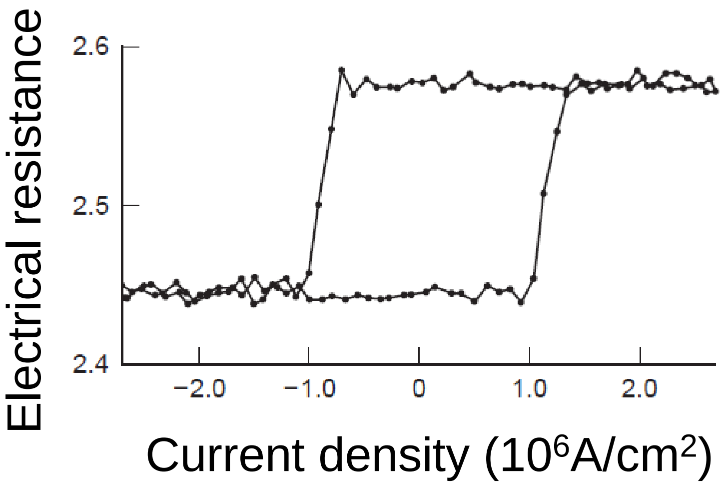


Device structure



Switching mechanism





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

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.

Current-to-Magnetization Conversion

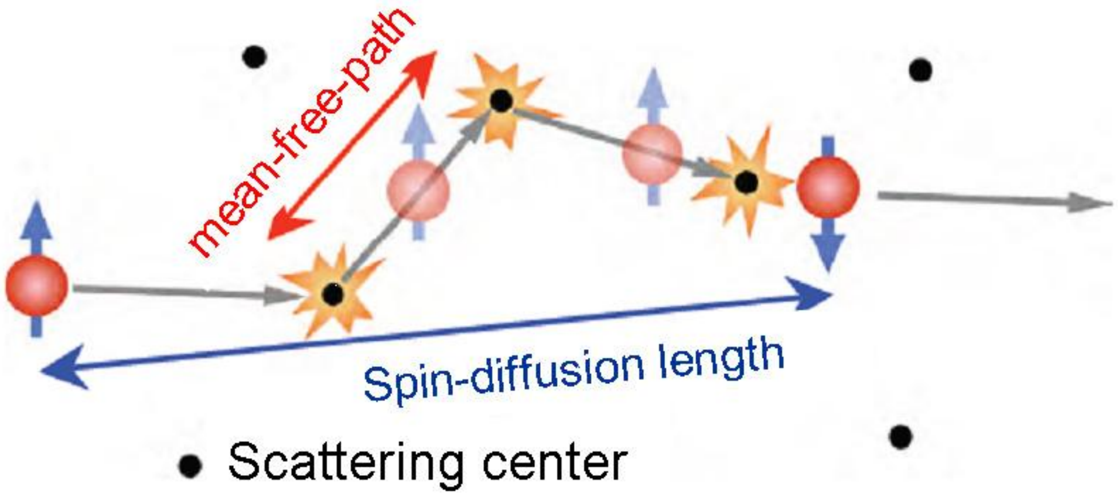
- ○Recently NEDO succeeded in reducing the current density to the level as small as 3 x $10^5 A/cm^2$, which is practical level, http://www.nedo.go.jp/iinkai/kenkyuu/bunkakai/20h/chuukan/2/1/5-1.pdf
- ○*Thus human being succeeded in converting electricity to magnetic field without using coils*.

4. Concept of Spin Current and Spin-Hall Effect

Opening New Paradigm!

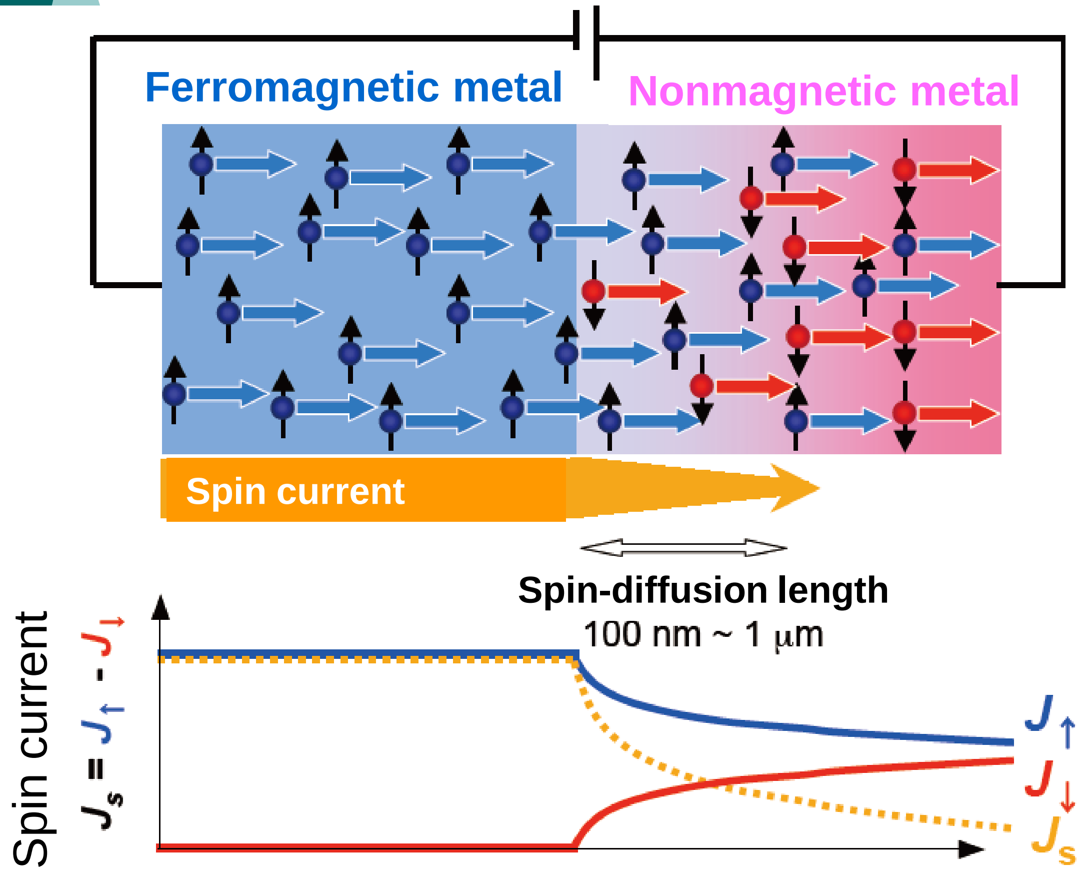
New Concept of "Spin Current"

- 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

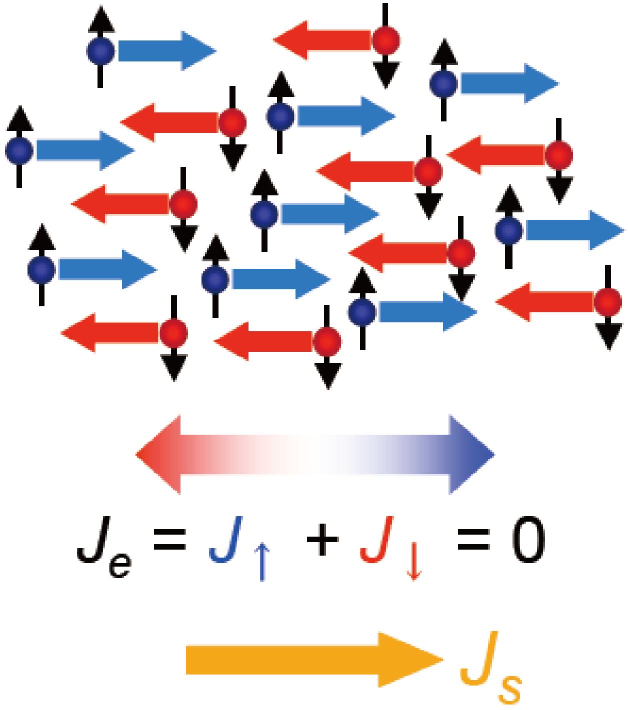
（1）*Spin current with charge current*



- 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 λs from the surface.

Courtesy of Prof. Takanashi

(2) *Spin current without charge current*

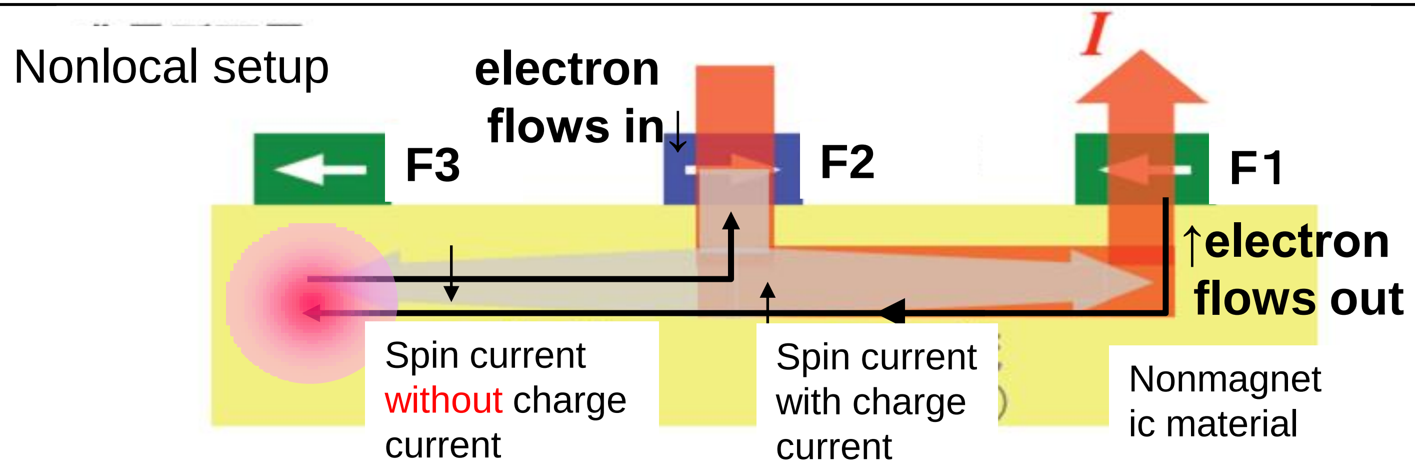


Nonlocal Spin Injection
and Spin-Hall effect.

- 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

Creating spin current



Nonlocal setup

electron flows in↓

F3

F2

F1

I

↑electron flows out

Spin current without charge current

Spin current with charge current

Nonmagnetic material

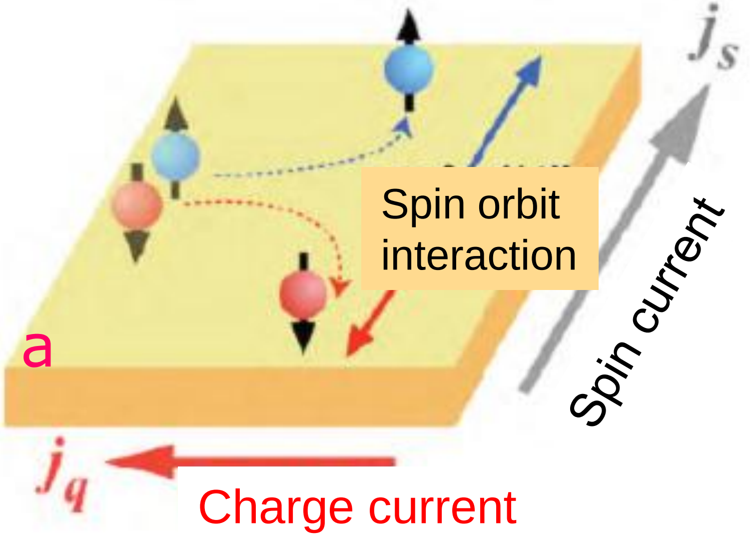
- Suppose magnetization of F_2 is antiparallel to F_1 and parallel to F_3.
- If electrons flow from F_2 to F_1, down spin from F_2 cannot enter F_1 and flow to F_3 direction.
- Since current should flow form F_1 to F_2 up spin electrons are supplied from F_3 electrode, resulting in no net charge flow 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

（1）*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.



Spin Hall Effect

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

Courtesy of Prof. Takanashi

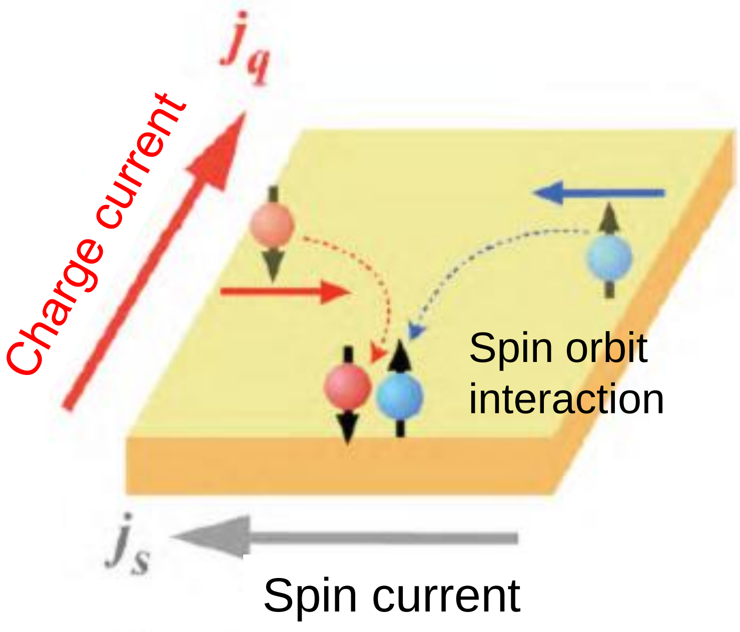
History of SHE Research

- 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.

Observation of spin current

(2) Inverse Spin Hall Effect

- *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.

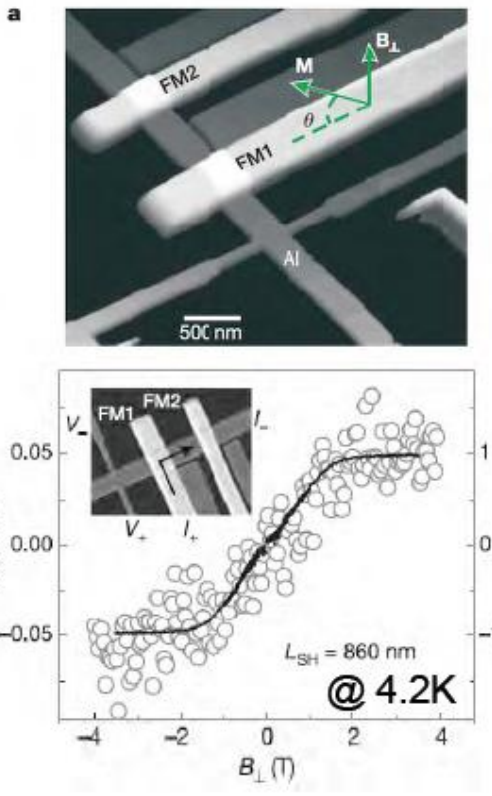


Inverse Spin Hall Effect

Courtesy of Prof. Takanashi

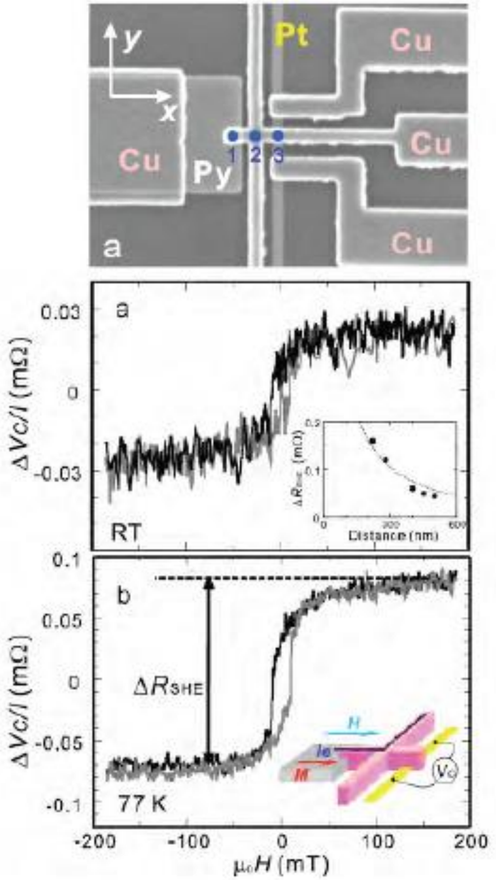
SHE and ISHE

CoFe / Al



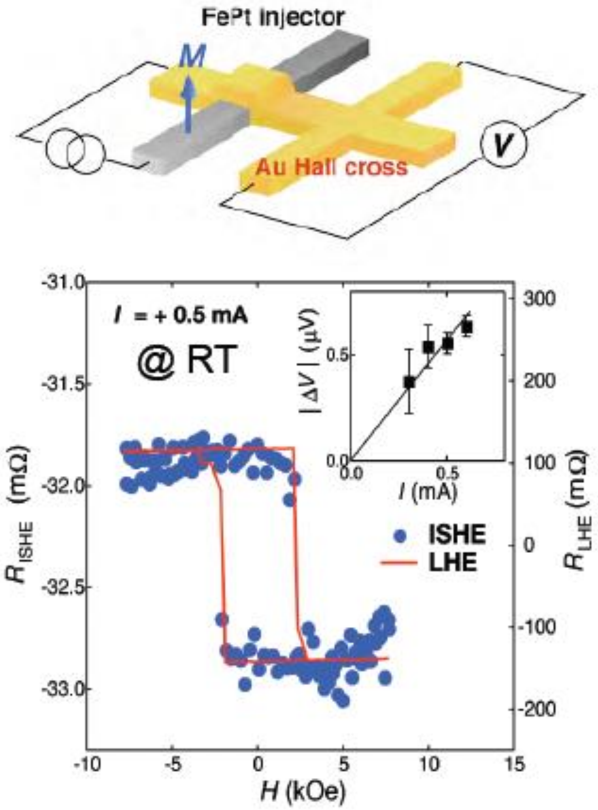
S. O. Valenzuela, M. Tinkham,
Nature **442**, 176 (2006).

Py / Cu / Pt



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

FePt / Au



α_H ~ 0.1

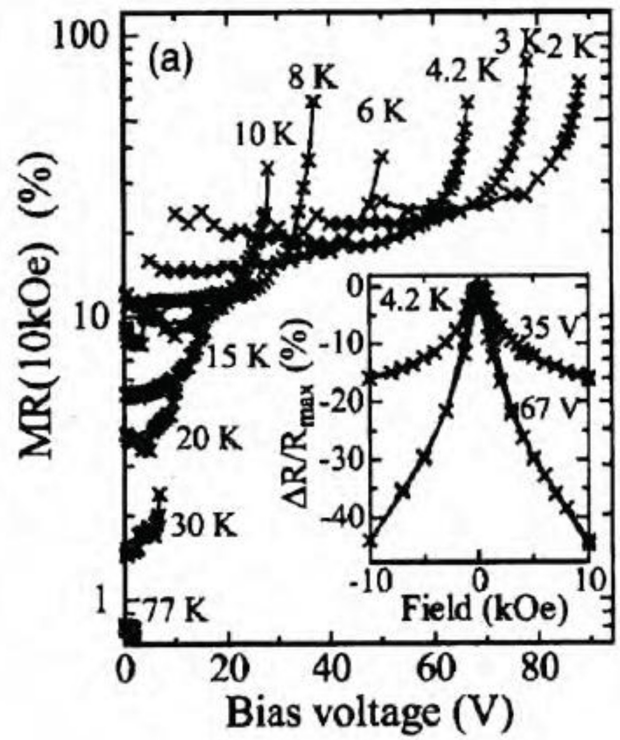
T. Seki *et al.*, **14pC-11**

Courtesy of Prof. Takanashi

Molecular Spintronics

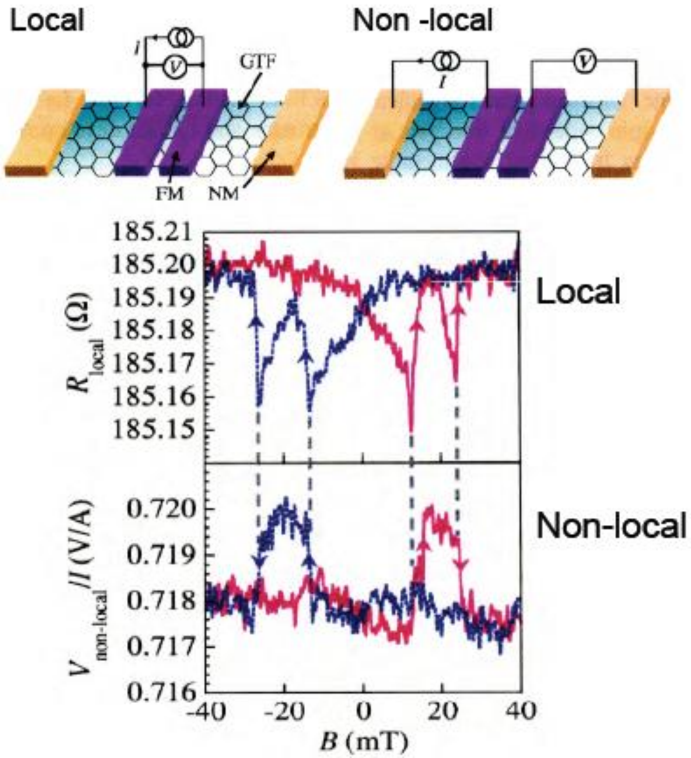
- The spin-current can be observed not only in magnetic materials but in non-magnetic metals or even in nano-carbons: It was demonstrated by Shiraishi et al. that the spin current can be injected to a sheet of graphene by a careful experiment using a non-local magnetoresistance measurement.[i]
  [i] M. Ohishi, M. Shiraishi, R. Nouchi, T. Nozaki, T. Shinjo, and Y. Suzuki: Jpn. J. Appl. Phys. **46** (2006) L605.

MR for a Co-C_{60} granular film



S. Sakai *et al.*, Appl. Phys. Lett., 89 (2006) 113118.
境誠司ら, 13aC-12.

Spin injection into graphene at RT

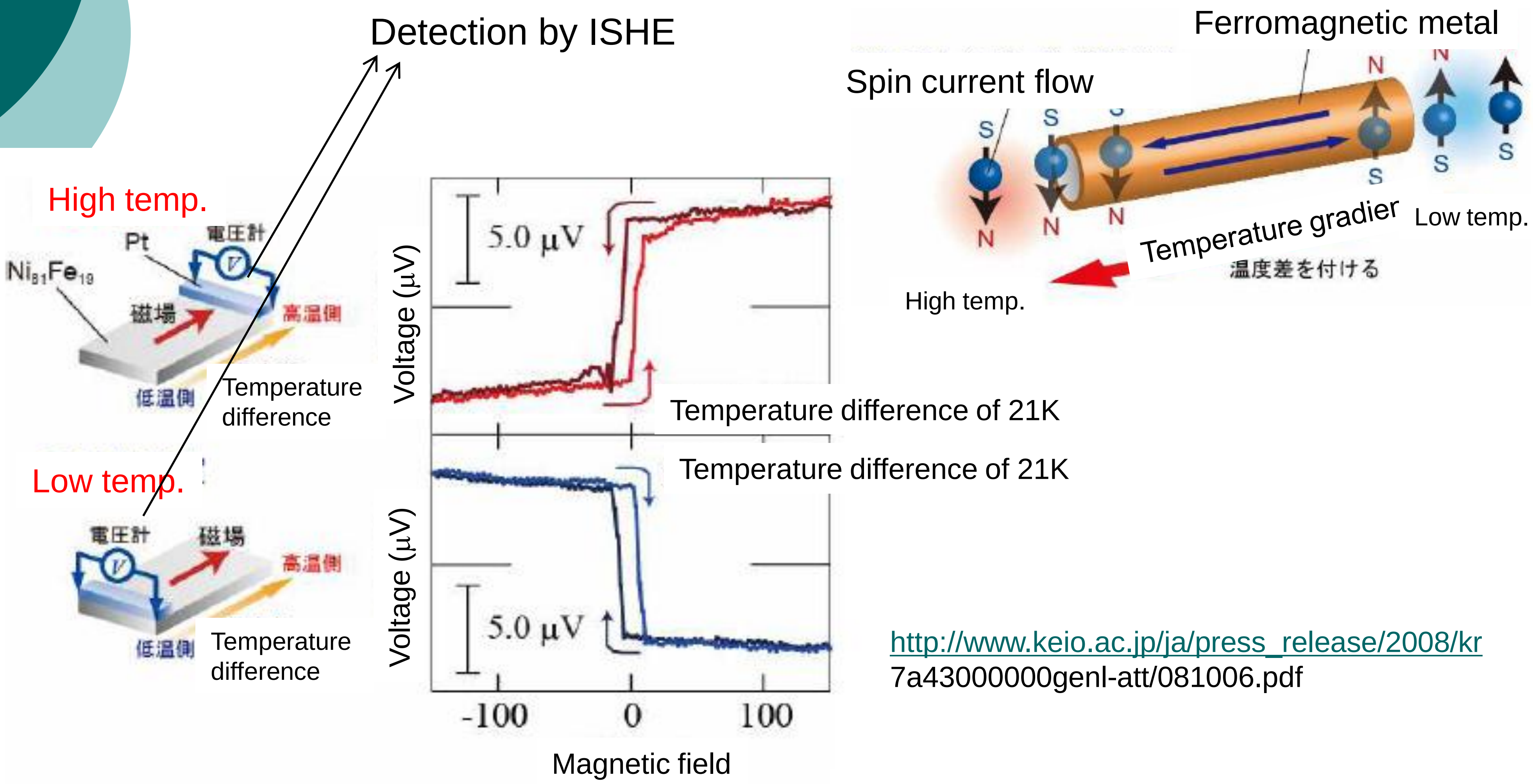


M. Ohishi *et al.*, Jpn. J. Appl. Phys, 46 (2007) L605.
白石誠司ら, 14pC-10.

Spin current and heat flow

- 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.
  - K. Uchida, S. Takahashi, K. Harii, J. Ieda, W. Koshibae, K. Ando, S. Maekawa and E. Saitoh: Nature **455** (2008) 778.

Concept of Spin Seebek Effect



Detection by ISHE

Ferromagnetic metal

Spin current flow

Temperature gradier

Low temp.

High temp.

High temp.

Temperature difference

Low temp.

Temperature difference

Voltage (μV)

Voltage (μV)

Temperature difference of 21K

Temperature difference of 21K

Magnetic field

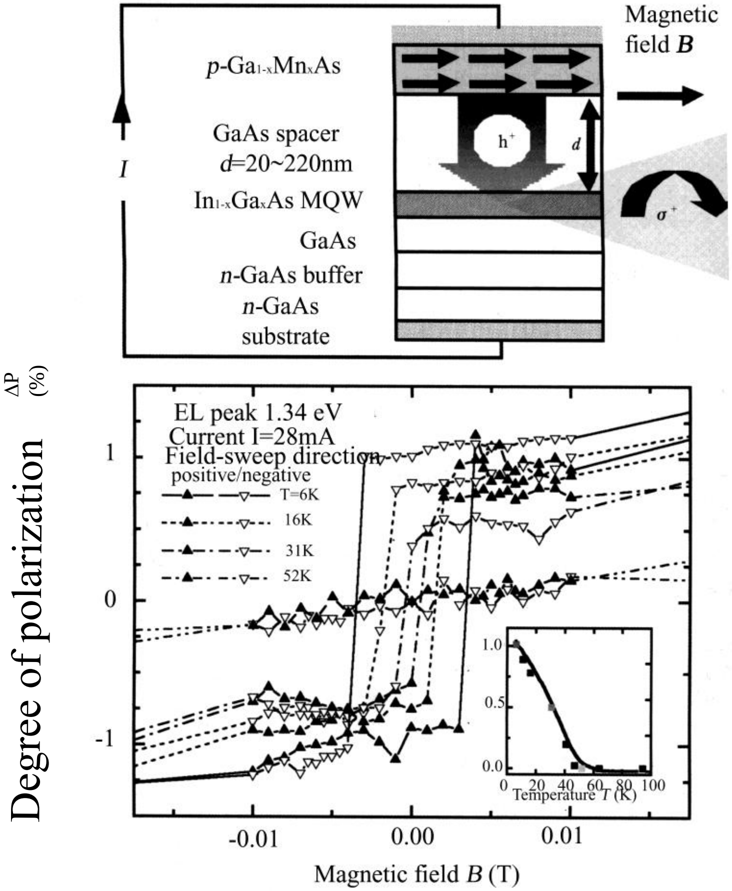
http://www.keio.ac.jp/ja/press_release/2008/kr7a43000000genl-att/081006.pdf

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).

Heterostructure devices of III-V DMS

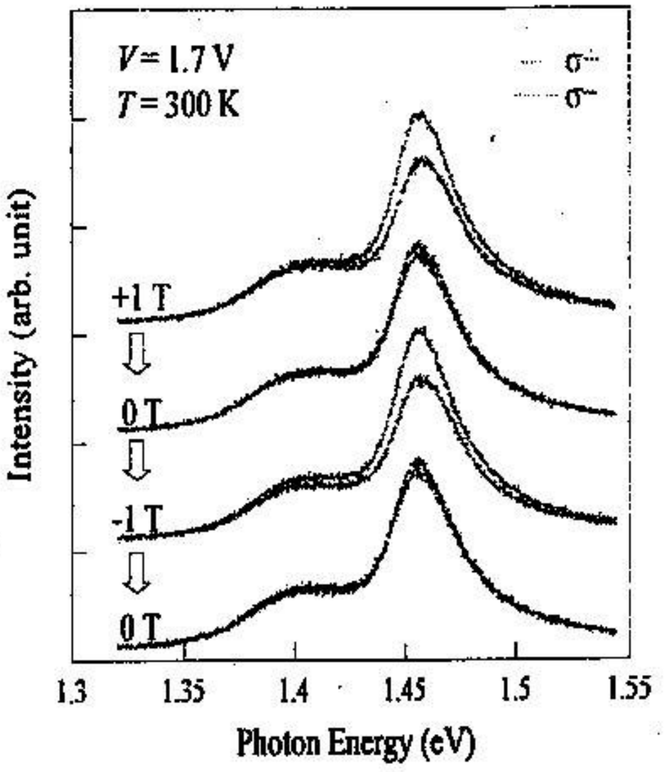
Spin-injection through junction



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

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.



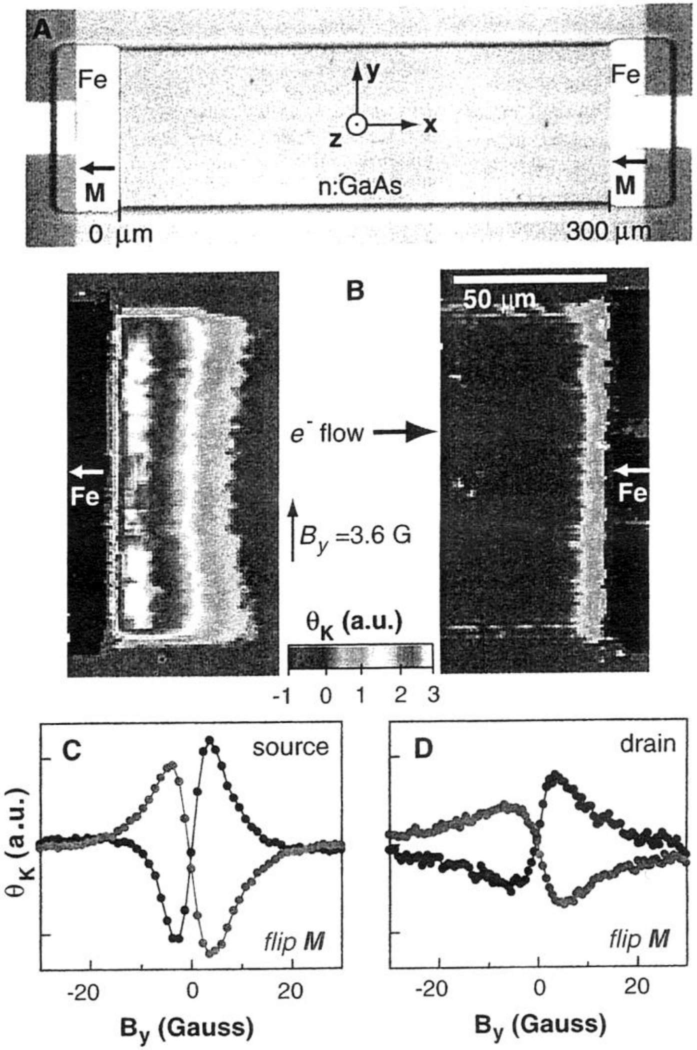
ＥＬスペクトルの磁場依存

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

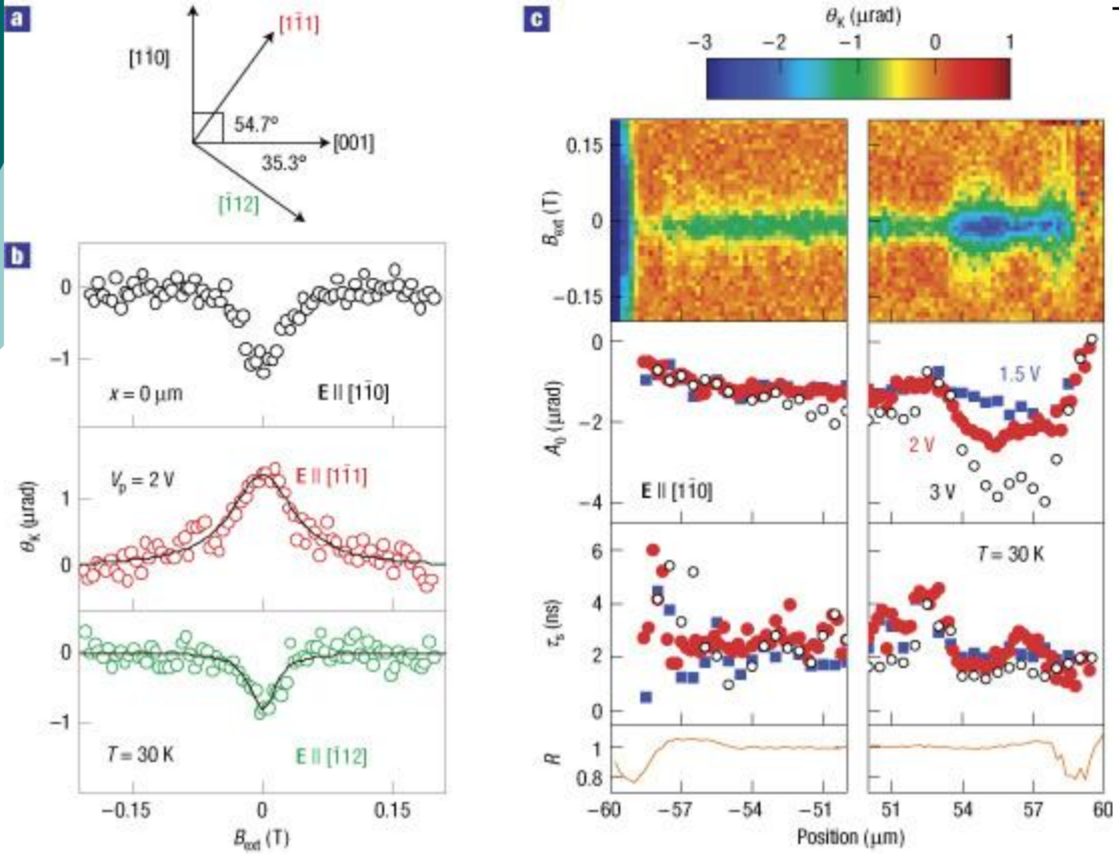
Magneto-optical evaluation of Spin Injection

- Crooker et al. observed spin-injection from Fe to GaAs in the Fe/GaAs/Fe lateral structure by means of magneto-optical effect

S. A. Crooker et al.: Imaging Spin Transport in Lateral Ferromagnet/Semiconductor Structures; *Science* Vol. 309. no. 5744, pp. 2191 - 2195 (2005)



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)

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.

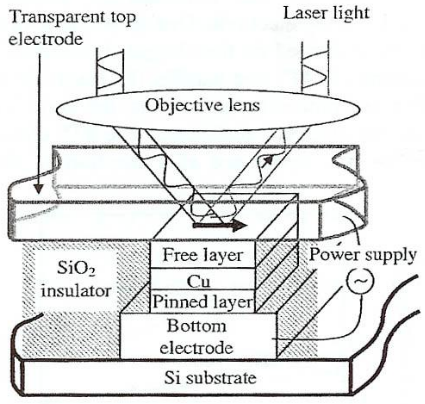


FIG. 1. Schematic illustration of spin-valve device with transparen electrode, and experimental setup. The plain arrow in the free layer indi the direction of the magnetization. The device includes the bo electrode of [Ta(3)/Cu(50)/Ta(3)/Cu(50)/Ru(5)], the pinned of [Ru(5)/Cu(20)/$Ir_{22}Mn_{78}$(10)/$Co_{66}Fe_{34}$(5)/Ru(0.9)/$Co_{66}Fe$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

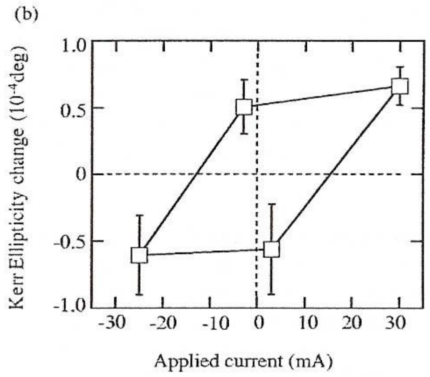
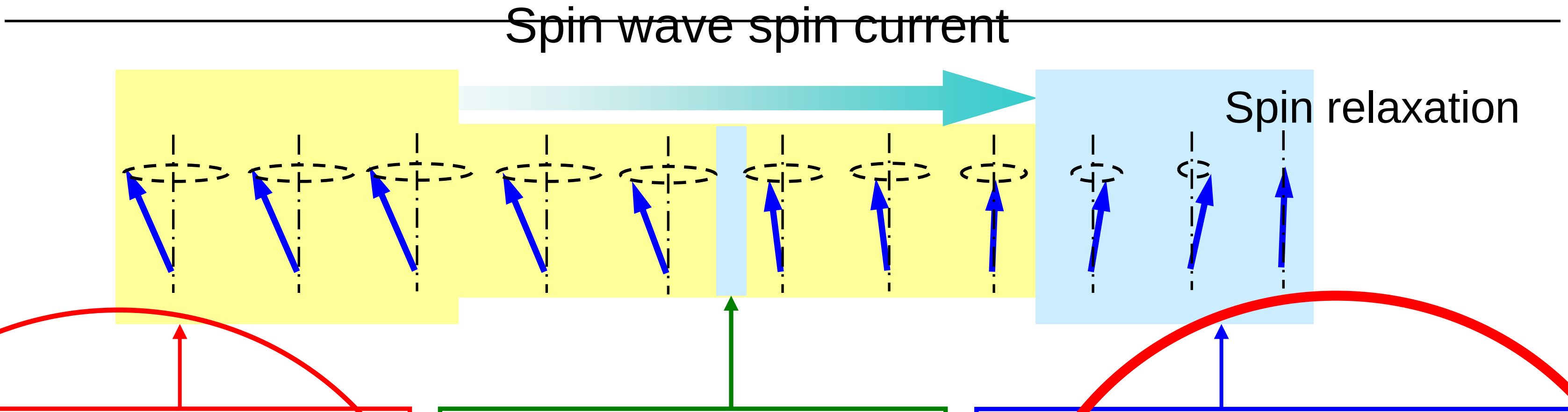


FIG. 4. (a) STS and the (b) Kerr ellipticity characteristics for three spin-valve elements. Open circles in (a) indicate resistance as a function of the applied current of ±30 mA with an increment of 2 mA. (b) The changes are defined as $[\eta_K - \langle\eta_K\rangle]$ in Kerr ellipticity for various 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);

Excitation, modulation and detection of spin wave spin current

（3 year tasrget）



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

5. Magnetic Semiconductors

- Another important trend in spintronics is the magnetic semiconductor (MS). Mn-doped III-V semiconductors such as In1-xMnxAs 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 Ga1-xMnxAs. [iv] Carrier-driven domain-wall motion with very low carrier density (~105A/cm2) 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. Among them Co-doped TiO2 is considered as the most reliable MS material exhibiting carrier induced ferromagnetism at room temperature. [vi]

- [i] H. Munekata, H. Ohno, S. von Molnar, A. Segmüller, L.L. Chang, L. Esaki: Phys. Rev. Lett. **63** (1989) 1849.
- [ii] H. Ohno, A. Shen, F. Matsukura, A. Oiwa, A. Endo, S. Katsumoto, Y. Iye: Appl. Phys. Lett. **69** (1969) 363.
- [iii] H. Ohno, D. Chiba, F. Matsukura, T. Omiya, E. Abe, T. Dietl, Y. Ohno, K. Ohtani: Nature **408** (2000) 944.
- [iv] M. Tanaka and Y. Higo: Phys. Rev. Lett. **87** (2001) 026602.
- [v] M. Yamanouchi, D. Chiba, F. Matsukura, T. Dietl, and H. Ohno. Phys. Rev. Lett. **96** (2006) 96601.
- [vi] T. Yamasaki, T. Fukumura, M. Nakano, K. Ueno, M. Kawasaki: Appl. Phys. Express **1** (2008) 111302.

Room temperature ferromagnetism in MS

FM in Co-doped TiO2

Science (2001) JJAP (2000)

Giant Magneto-optical Effect

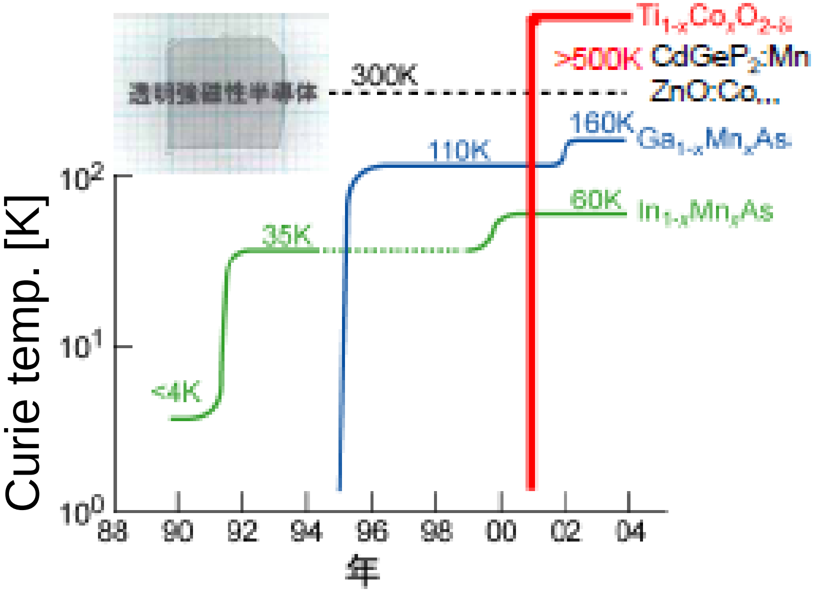
JJAP(2000) APL(2005)

Anomalous Hall Effect

Nature Mat. (2004), APL (2007)

Tunnel Magnto-resistance

JJAP (2005), JAP (2006)

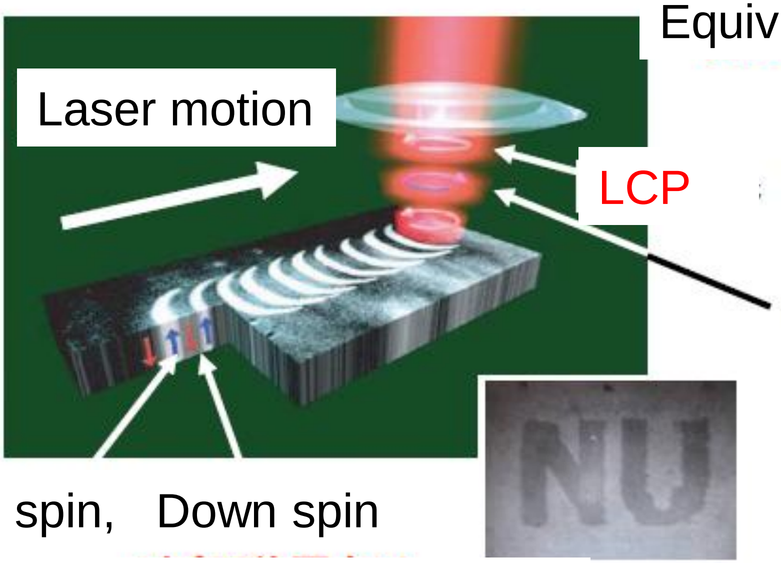


Transparent conductive+ environmental + room temp.

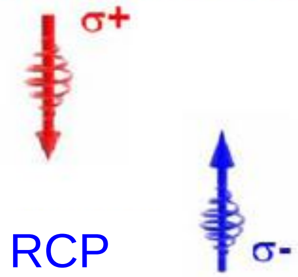
6. Light-Induced ultrafast magnetization reversal at angular momentum compensation point

- 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 -



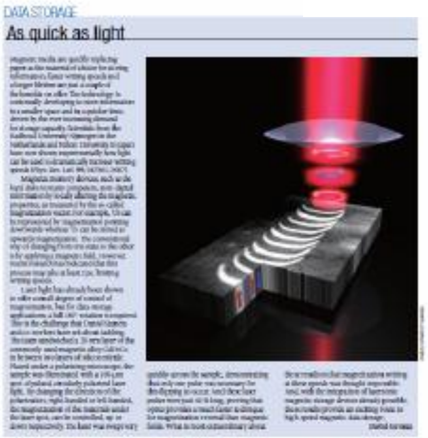
Equivalent magnetic field produced by photon



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

PRL 99, 047601 (2007)

Nature Photonics


DATA STORAGE

As quick as light

Science、Physics today他

Direct optical spin control

ns
GHz

ps
THz

fs
PHz

FMR limit

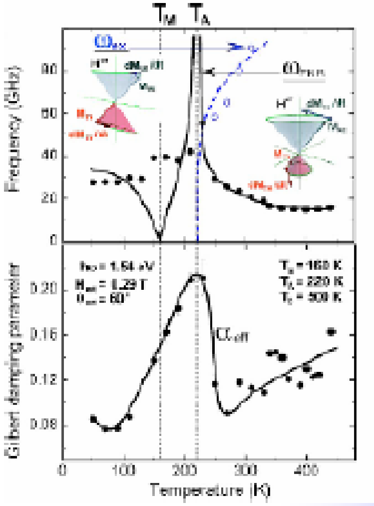
Previous technology

Angular momentum
Compensation heat-assist
Dynamic behavior f α

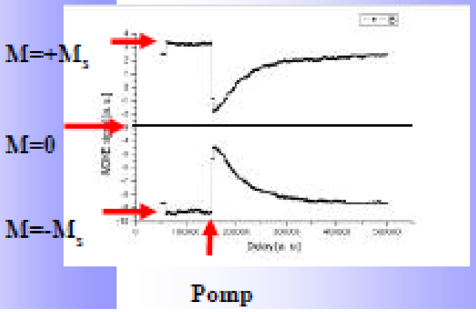
Direct optical control
Irradiation 40-100 fs

連携

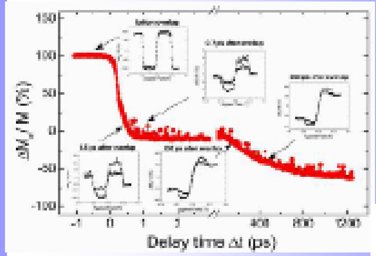
Short time thermal
Demagnetization
~ps order

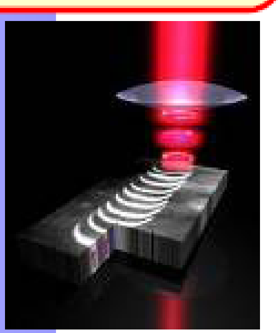


PRB(R)2006



サブピコ秒磁化反転デモ

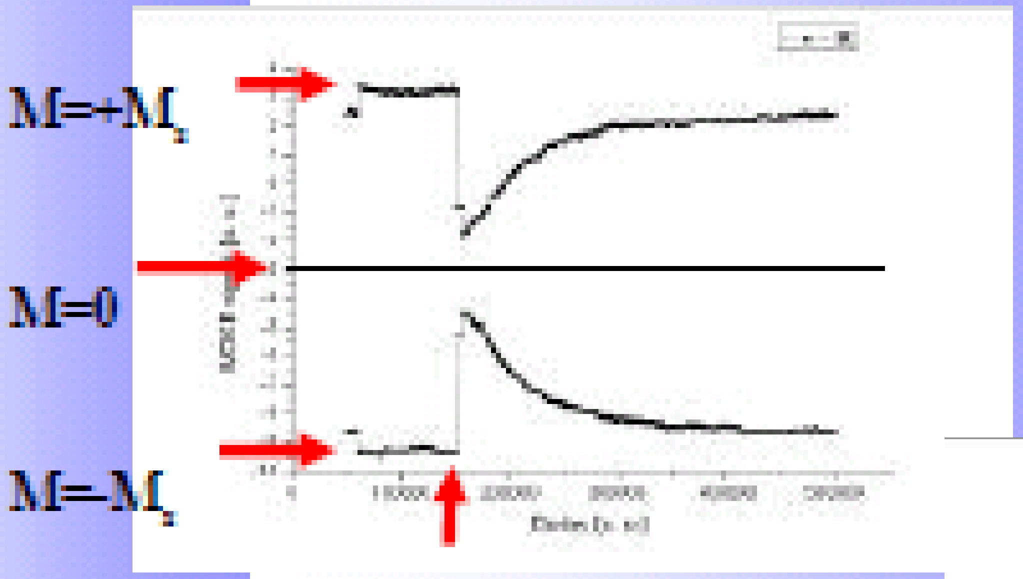




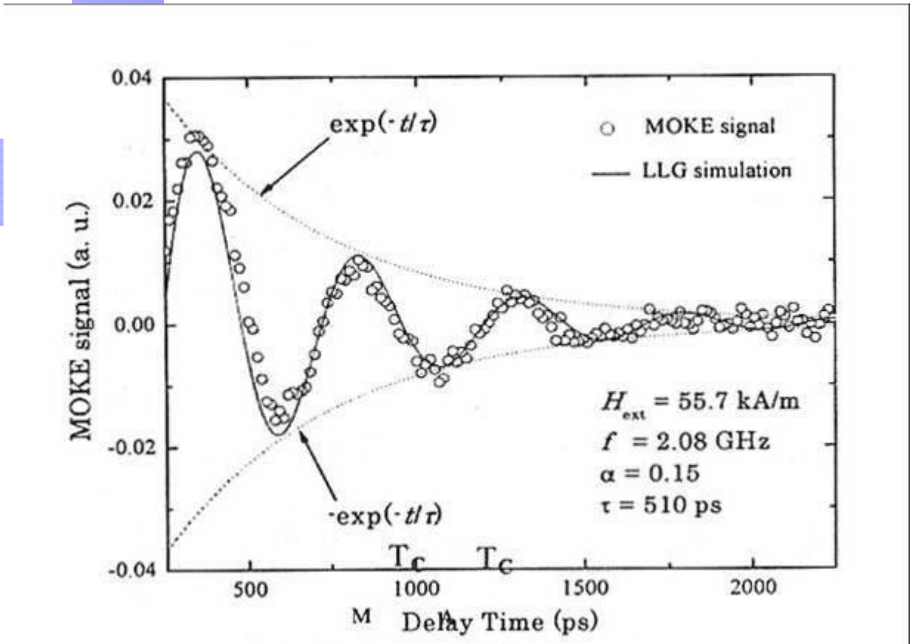
PRL2007

Tsukamoto (Nihon U.)

Fast response sub picosecond
Slow response 2ns (obeys LLG eq.)



Pumping

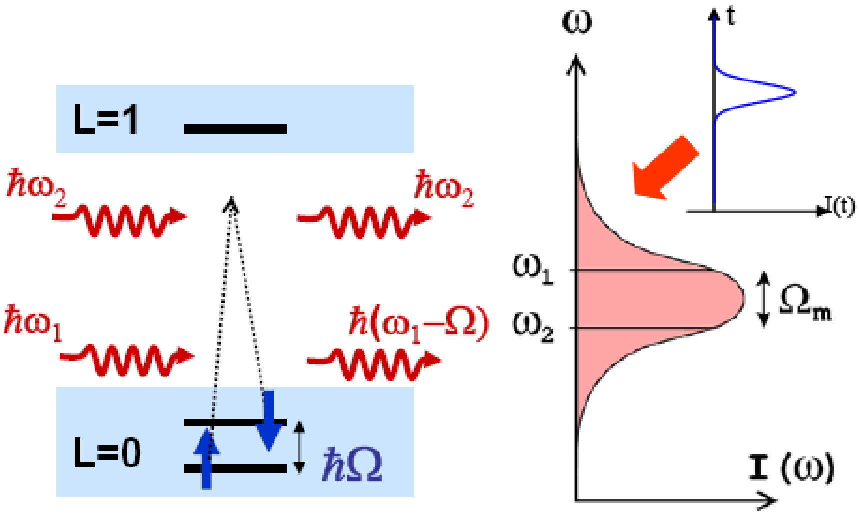


Microscopic mechanism of the inverse Faraday effect

- ***Multiphoton-induced spin-flip:***

  Stimulated Raman scattering on magnons (2-photon process)

[Shen et al, Phys. Rev. (1966)]



➡ **Number of photons is conserved**

➡ **Process can be fast**
$\tau \sim 1/\omega \sim 1$ fs

light helicity must also be conserved

Needs further investigation

- Despite the fact Tsukamoto et al. have shown that light can directly interact with spin and demonstrated optical/thermal assisted control of spin dynamics in ferrimagnetic medium in less than picosecond timescale. Mechanism of the fast magnetization reversal has not still been understood and under investigation.
- A. Tsukamoto, K. Nakagawa, A. Itoh, A. Kimel, A. Tsvetkov, H. Awano, N. Ohta, A. Kirilyuk, and Th. Rasing: IEEE Trans. Magn. **40** (2004) 135.
- C. D. Stanciu, A. V. Kimel, F. Hansteen, A. Tsukamoto, A. Itoh, A. Kirilyuk, and Th. Rasing：Phys. Rev. **B 73** (2006) 220402(R).

Emerging Filed 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 .
- 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)