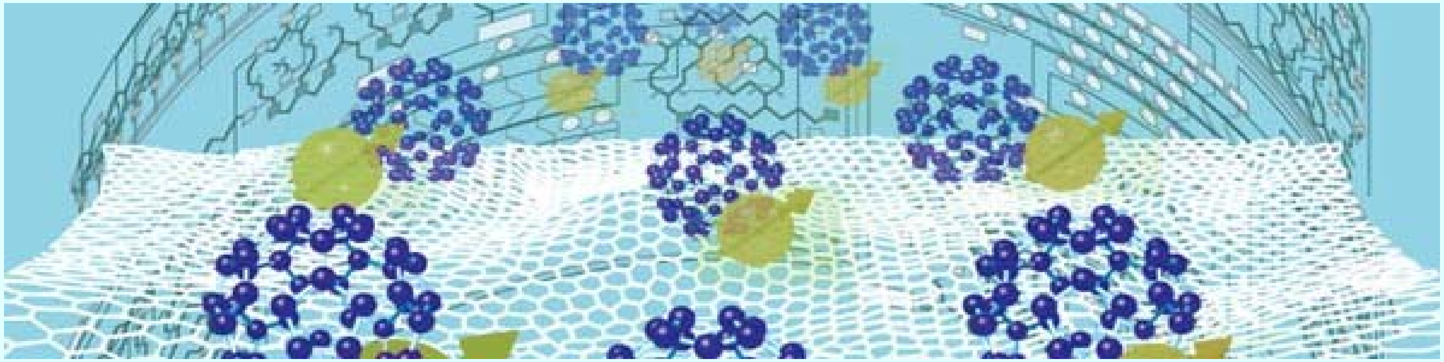
Nanoscience for next generation innovative devices

革新的次世代デバイスをめざすナノサイエンス



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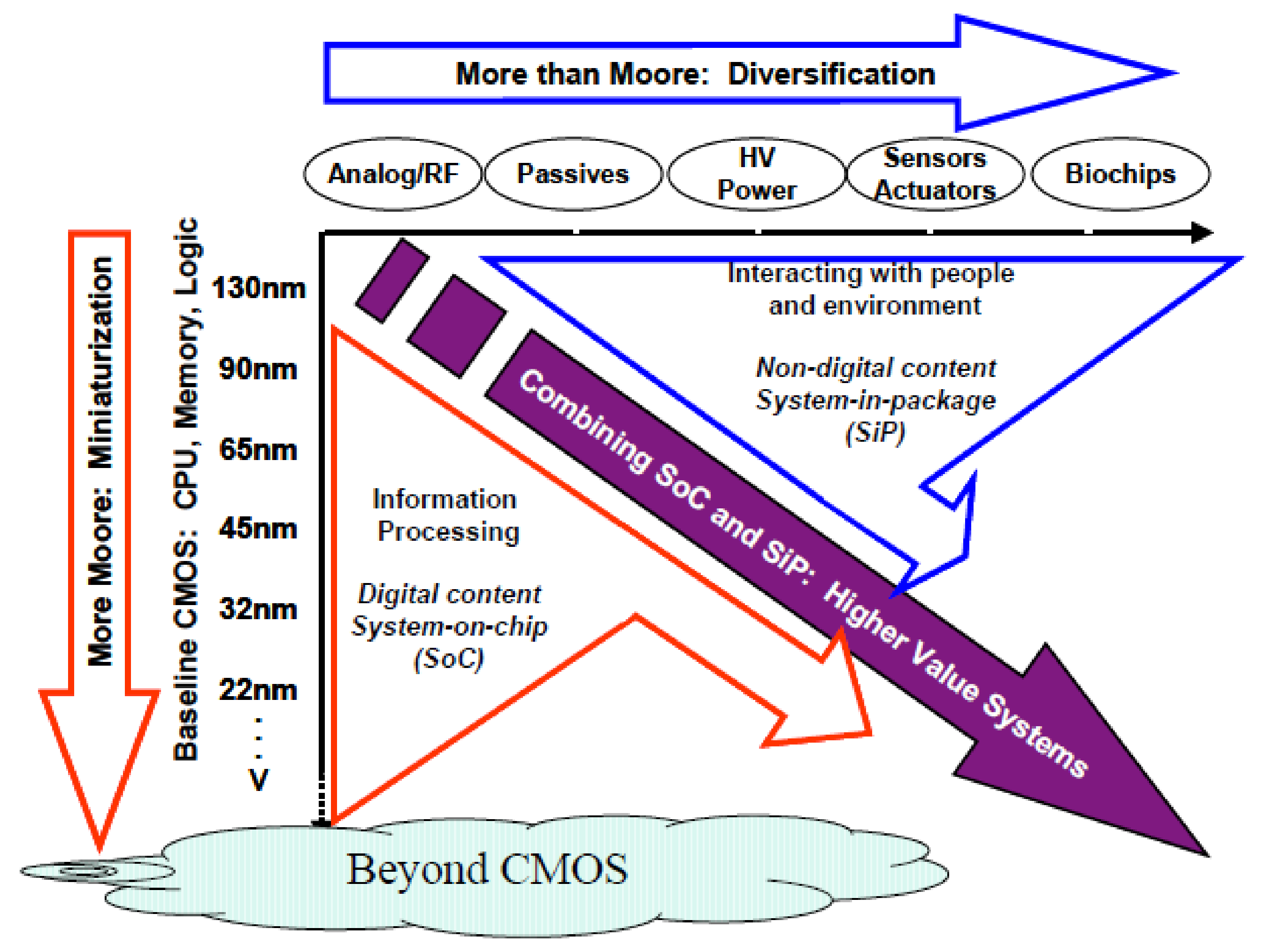
Contents

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 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)

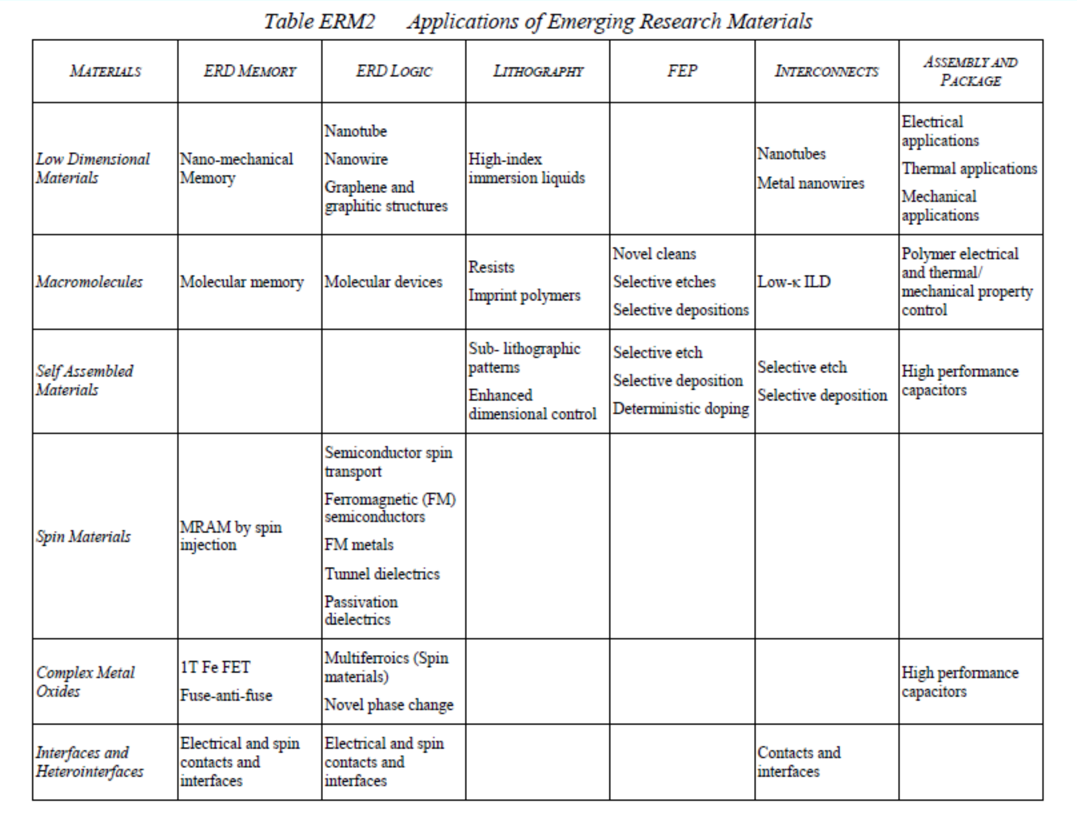


Table ERM2   Applications of Emerging Research Materials

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	

Low Dimensional Materials

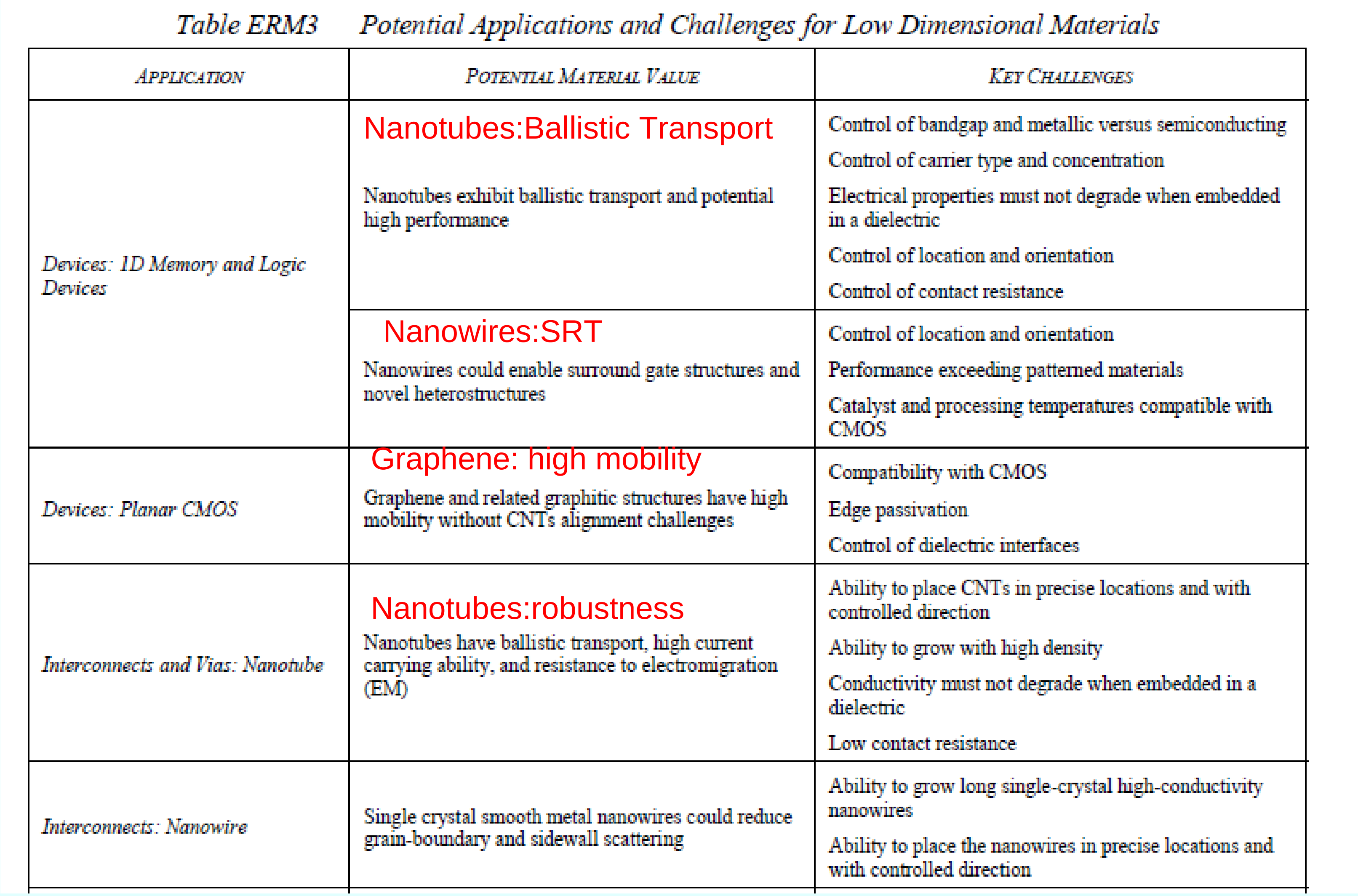


Table ERM3 Potential Applications and Challenges for Low Dimensional Materials

Application	Potential Material Value	Key Challenges
Devices: 1D Memory and Logic Devices	Nanotubes:Ballistic Transport Nanotubes exhibit ballistic transport and potential high performance	Control of bandgap and metallic versus semiconducting Control of carrier type and concentration Electrical properties must not degrade when embedded in a dielectric Control of location and orientation Control of contact resistance
	Nanowires:SRT Nanowires could enable surround gate structures and novel heterostructures	Control of location and orientation Performance exceeding patterned materials Catalyst and processing temperatures compatible with CMOS
Devices: Planar CMOS	Graphene: high mobility Graphene and related graphitic structures have high mobility without CNTs alignment challenges	Compatibility with CMOS Edge passivation Control of dielectric interfaces
Interconnects and Vias: Nanotube	Nanotubes:robustness Nanotubes have ballistic transport, high current carrying ability, and resistance to electromigration (EM)	Ability to place CNTs in precise locations and with controlled direction Ability to grow with high density Conductivity must not degrade when embedded in a dielectric Low contact resistance
Interconnects: Nanowire	Single crystal smooth metal nanowires could reduce grain-boundary and sidewall scattering	Ability to grow long single-crystal high-conductivity nanowires Ability to place the nanowires in precise locations and with controlled direction

Spintronics Materials

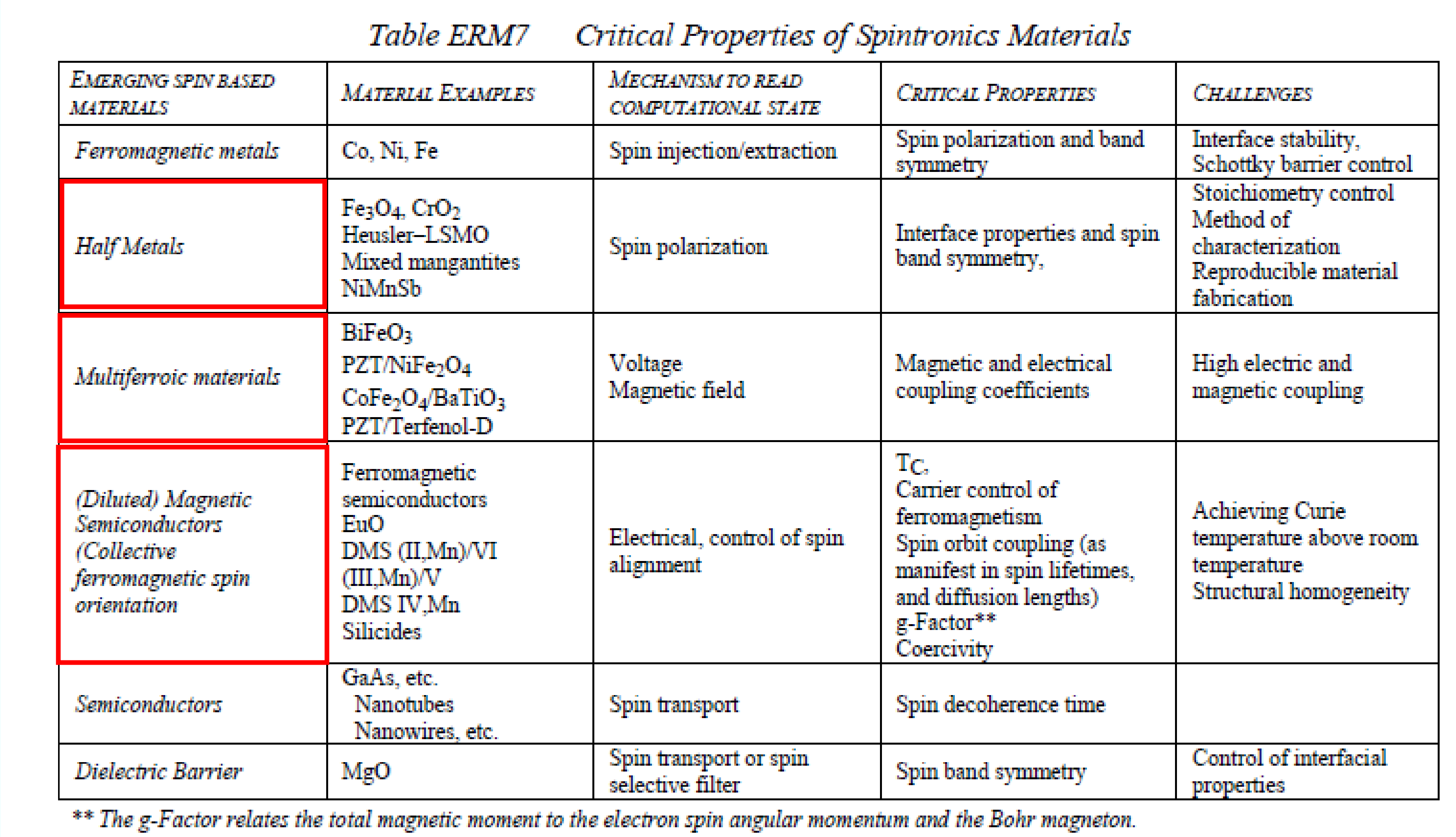


Table ERM7 Critical Properties of Spintronics Materials

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

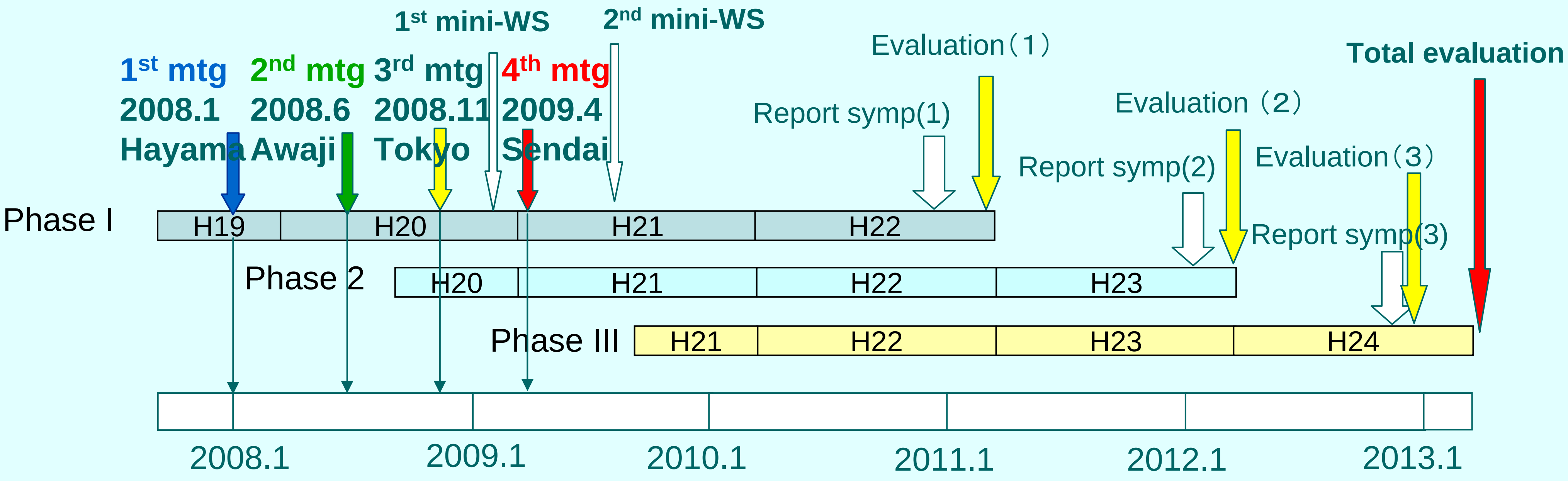
*** The g-Factor relates the total magnetic moment to the electron spin angular momentum and the Bohr magneton.*

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.

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 members are under selection



1st mini-WS

2nd mini-WS

Evaluation（1）

Total evaluation

1st mtg 2008.1 Hayama

2nd mtg 2008.6 Awaji

3rd mtg 2008.11 Tokyo

4th mtg 2009.4 Sendai

Report symp(1)

Evaluation（2）

Report symp(2)

Evaluation（3）

Report symp(3)

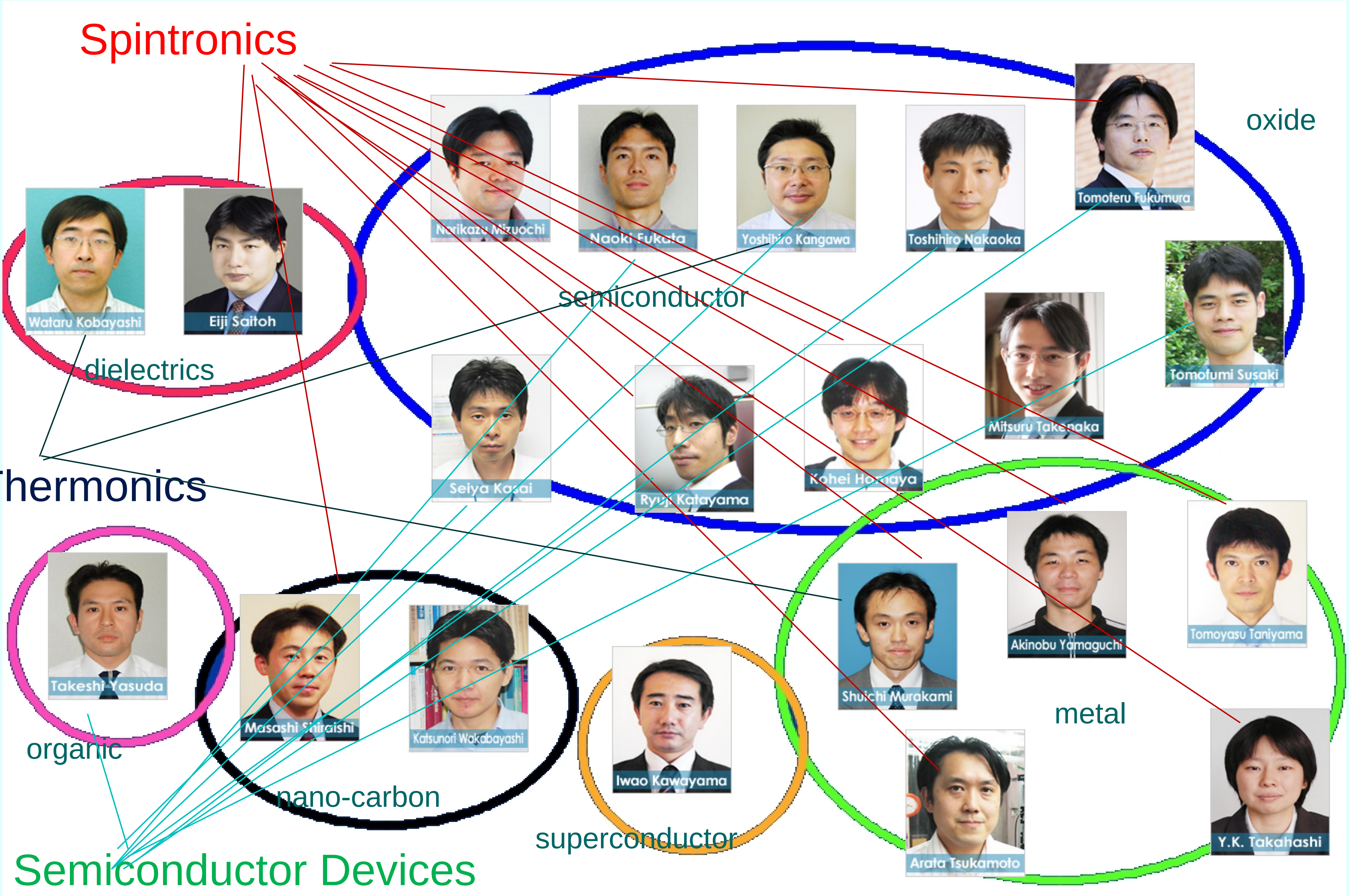
Phase I: H19, H20, H21, H22

Phase 2: H20, H21, H22, H23

Phase III: H21, H22, H23, H24

2008.1, 2009.1, 2010.1, 2011.1, 2012.1, 2013.1

Our Team



Spintronics

Thermonics

Semiconductor Devices

oxide

semiconductor

dielectrics

organic

nano-carbon

superconductor

metal

Norikazu Mizuochi

Naoki Fukata

Yoshihiro Kangawa

Toshihiro Nakaoka

Tomoteru Fukumura

Wataru Kobayashi

Eiji Saitoh

Tomofumi Susaki

Mitsuru Takenaka

Seiya Kasai

Ryuji Katayama

Kohei Hamaya

Takeshi Yasuda

Masashi Shiraishi

Katsunori Wakabayashi

Iwao Kawayama

Shuichi Murakami

Akinobu Yamaguchi

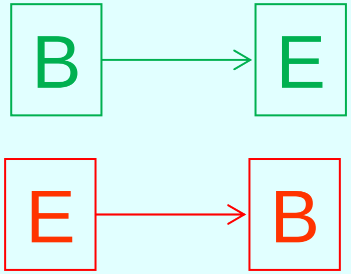
Tomoyasu Taniyama

Arata Tsukamoto

Y.K. Takahashi

2. Spintronics

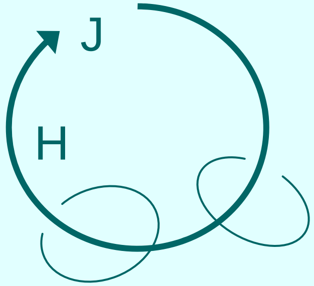
2.1.Spin-dependent Electronic Transport and Magneto-resistance
2.2.Spin-Transfer Magnetization Reversal
2.3.Concept of Spin Current and Spin-Hall Effect
2.4.Magnetic Semiconductors
2.5.Light-Induced Ultrafast Magnetization Reversal
2.6.Brief Summary



B → E

E → B

Mutual Conversion between Electricity and Magnetism

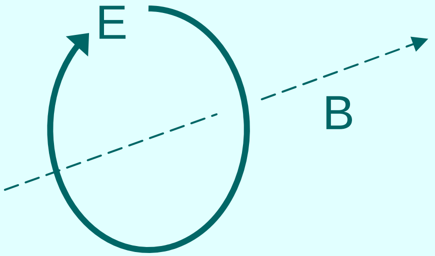


- Electricity→Magnetism. Ampere’s Law

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

- 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!*

2.1 Spin-dependent Electronic Transport and Magneto-resistance

B→E

Long Research History of Spin-Dependent Transport Phenomena

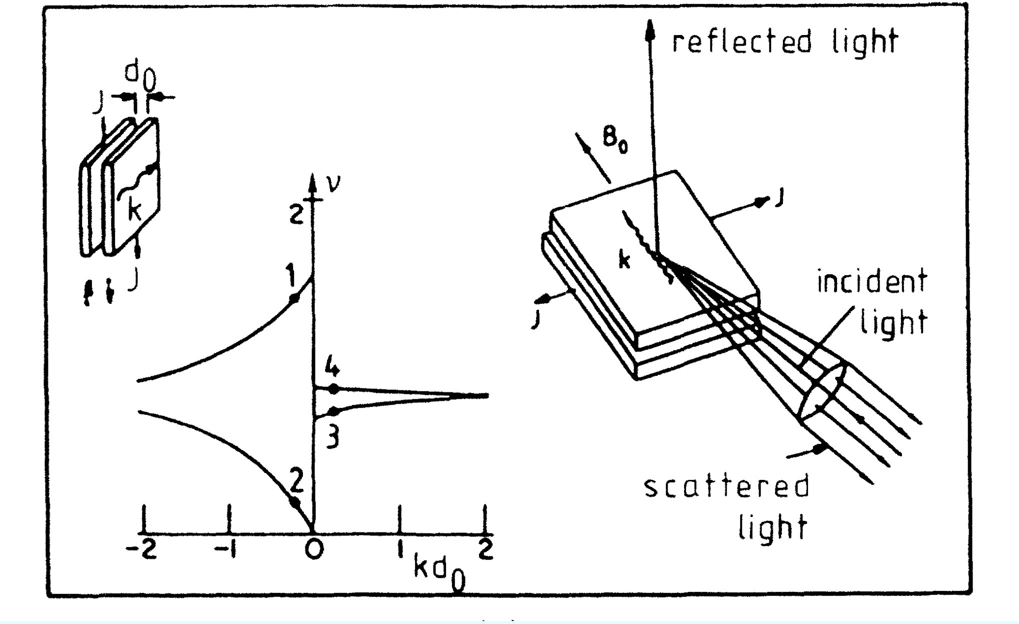
- The phenomena of spin-dependent electrical transport such as spin-disordered scattering just below the Curie temperature and anisotropic magnetoresistance and anomalous Hall effect in ferromagnetic metals have been studied extensively and explained theoretically already in 1960’s.
  - For example、G.K.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

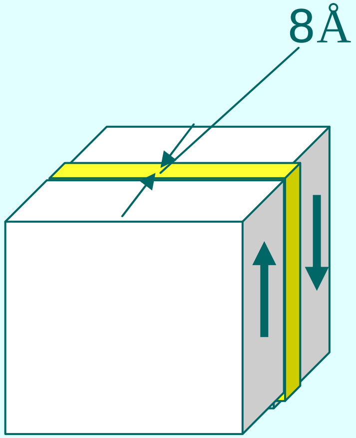
Encounter with nanotechnology (1)

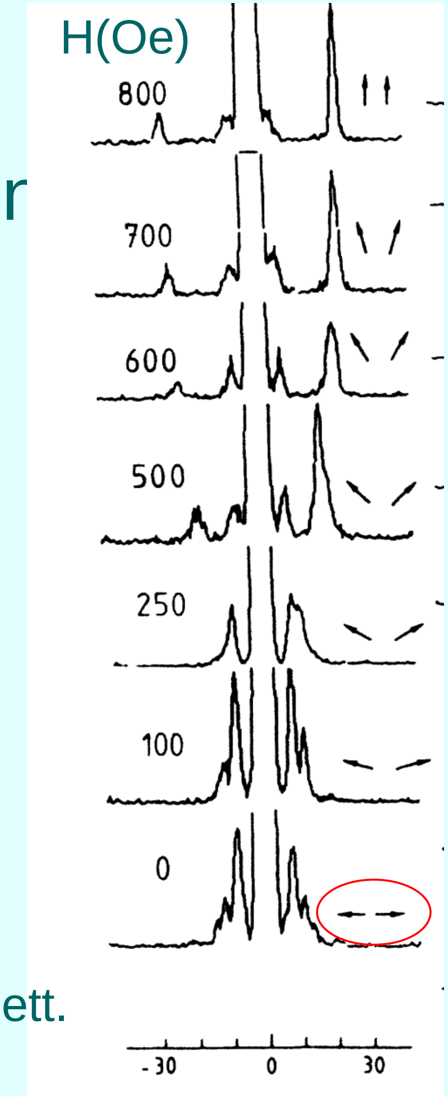
- Nanotechnology pioneered by Dr. Esaki opened up semiconductor nanoscience such as 2DEG, quantum confinement, energy band modulation by superlattice, leading to novel application field like HEMT, MQW laser.
- Quantum effect showed up at the early stage of nanotechnology where the scale of the structure 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 aligr antiparallel in the Fe/Cr(8Å)/Fe trilayer structure using the magnon-Brillouin







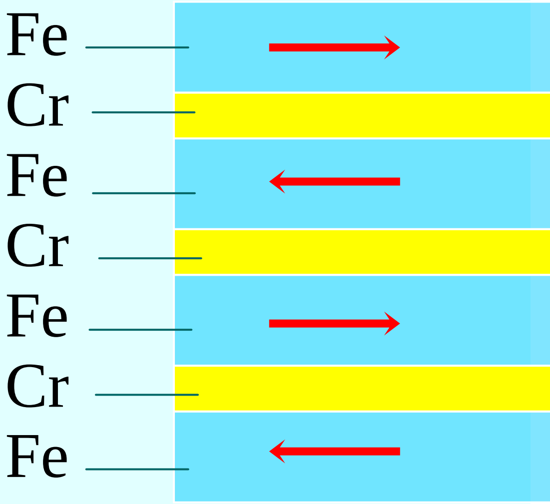
P. Grünberg, R. Schreiber and Y. Pang: Phys. Rev. Lett. 57 (1986) 2442.

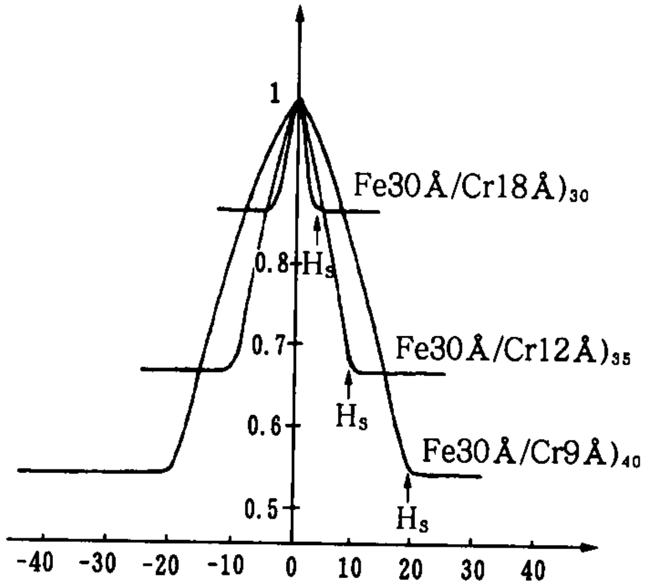
Breakthrough in Spintronics

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





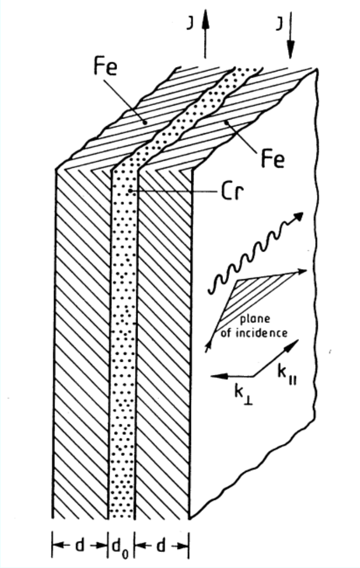
M.N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friedrich, J. Chazelas: Phys. Rev. Lett. 61 (1988) 2472.

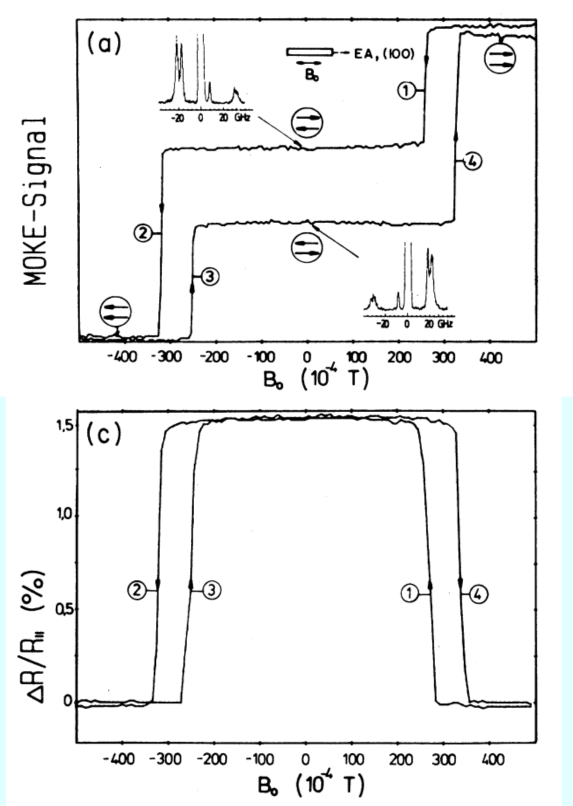
Breakthrough in Spintronics

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

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

Dr. Peter Grünberg



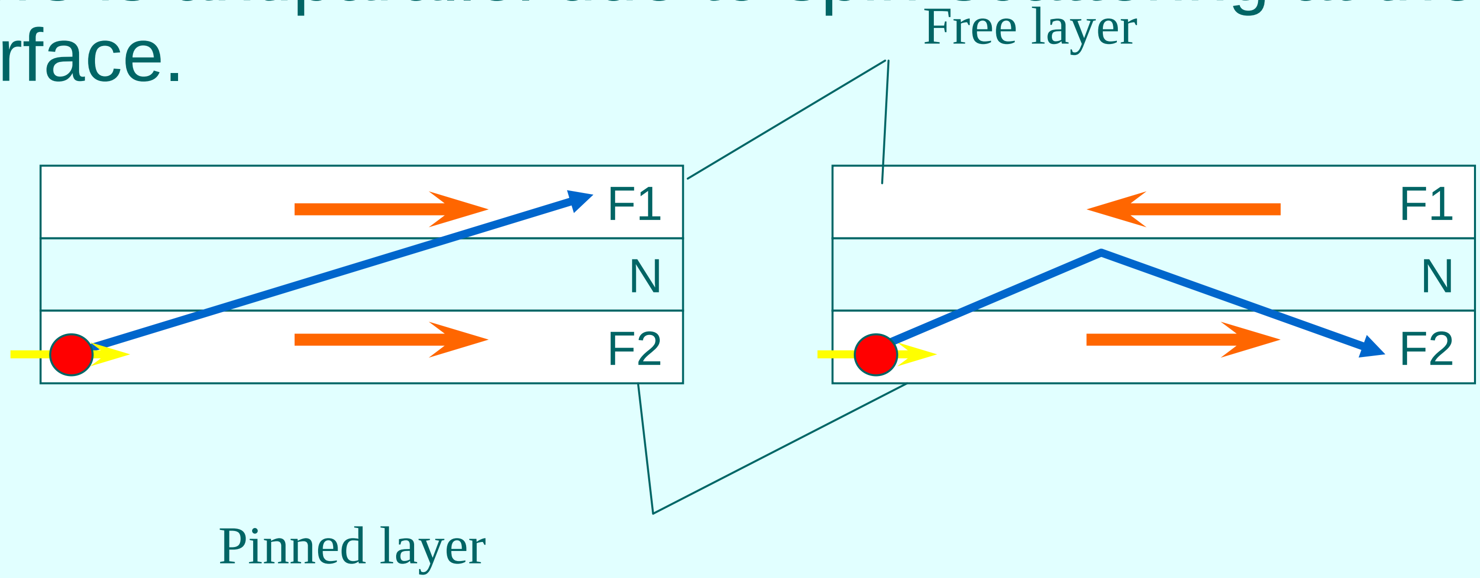


G. Binasch, P. Grünberg, F. Saurenbad, W. Zinn: Phys. Rev. B 39 (1989) 4828.

Physical background of GMR

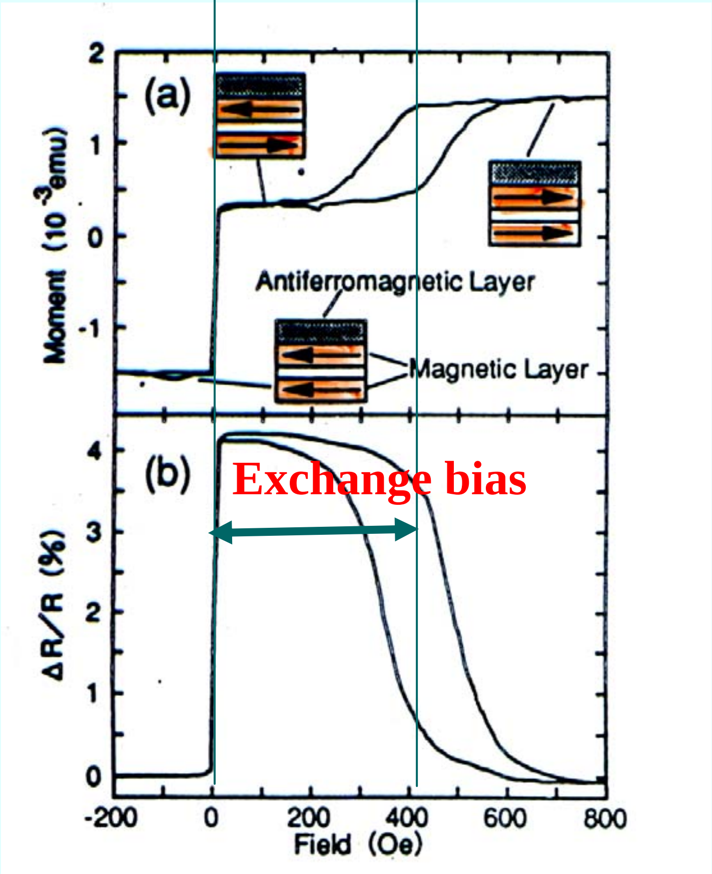
Spin-scattering at layer-interfaces

- 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.

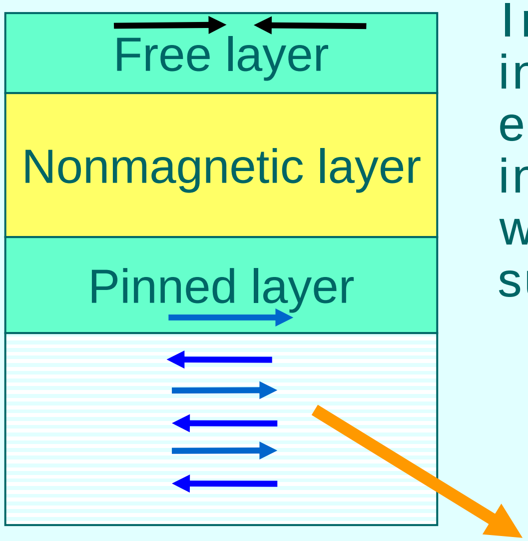


Spin valve for HDD head

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



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

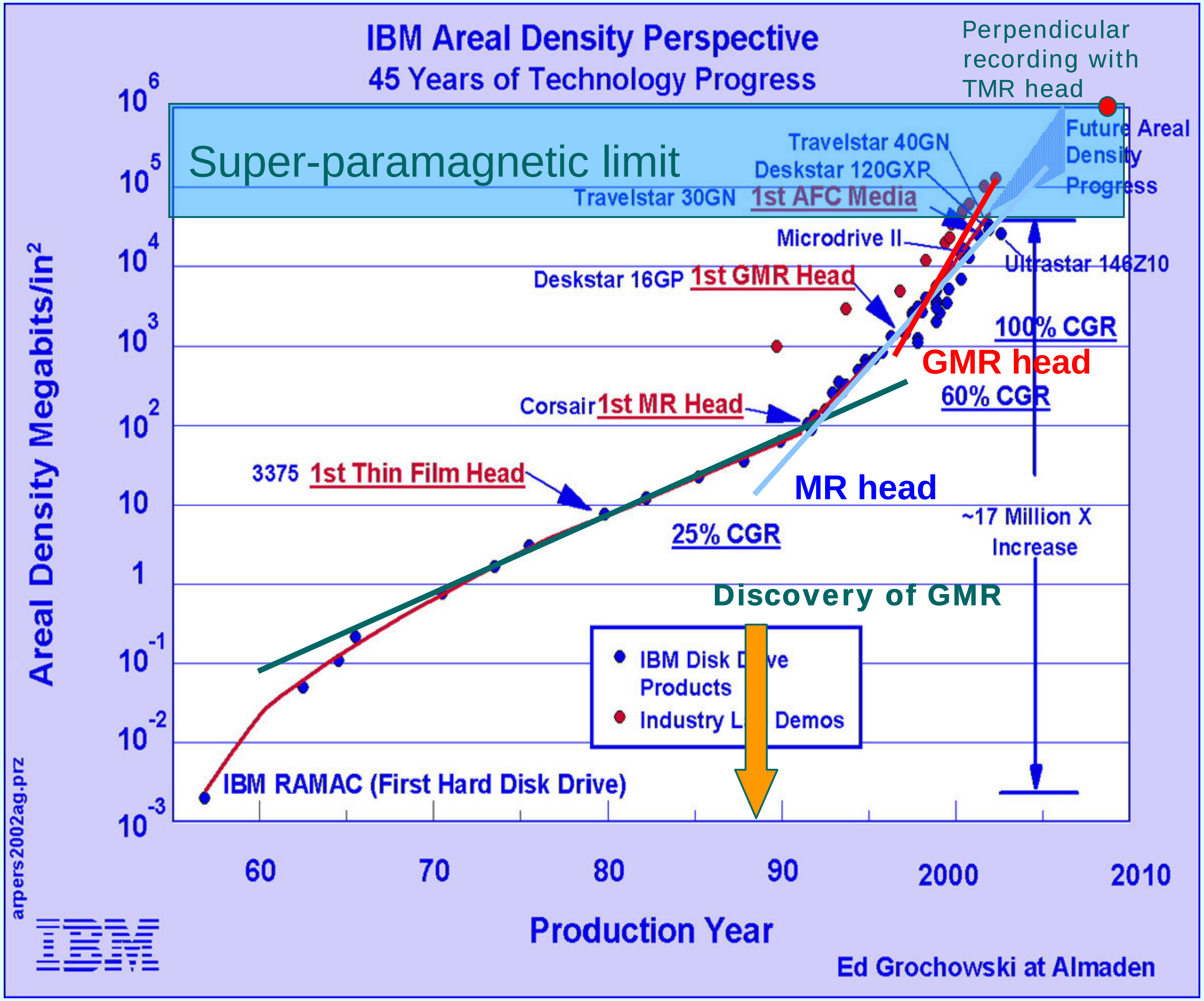


Important point of this invention is a use of the exchange bias effect introduced by coupling with antiferromagnetic substrate.

Antiferromagnetic substrate (ex FeMn)

(Synthetic antiferromagnet)

Dramatic increase in the areal density of HDD

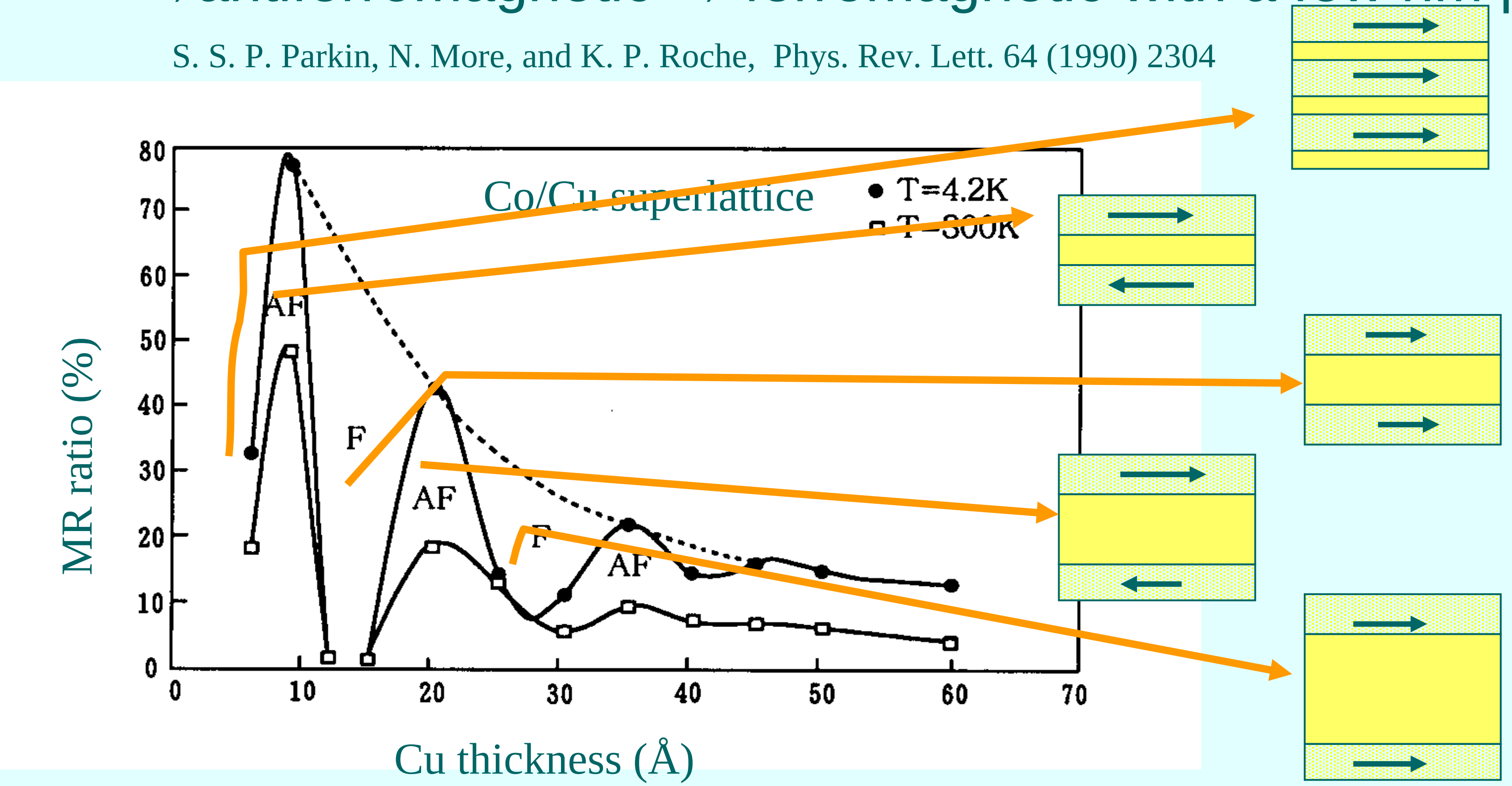


- Introduction of GMR (Spin Valve) head brought a dramatic change in the growth rate of areal recording density of HDD.
- It is quite remarkable that scientific discovery lead to practical applications in such a short period of time.

Interlayer coupling and GMR

- At the same period periodic variation of exchange interaction with the thickness of nonmagnetic layer in magnetic/ non-magnetic superlattice: Magnetic coupling varies ferromagnetic →antiferromagnetic → ferromagnetic with a few nm period.

S. S. P. Parkin, N. More, and K. P. Roche, Phys. Rev. Lett. 64 (1990) 2304



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

Further Breakthrough in Spintronics

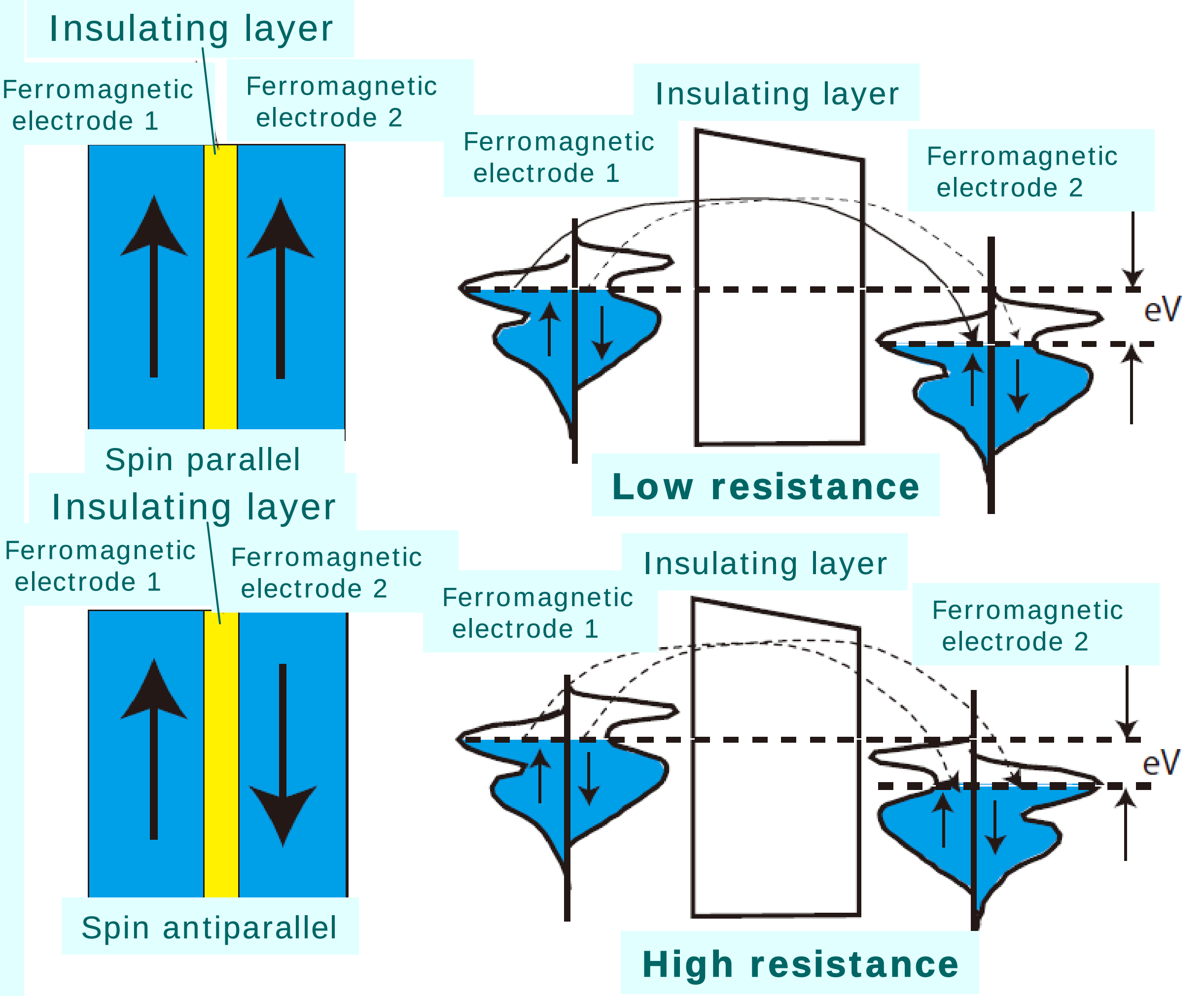
Discovery of room temperature TMR

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

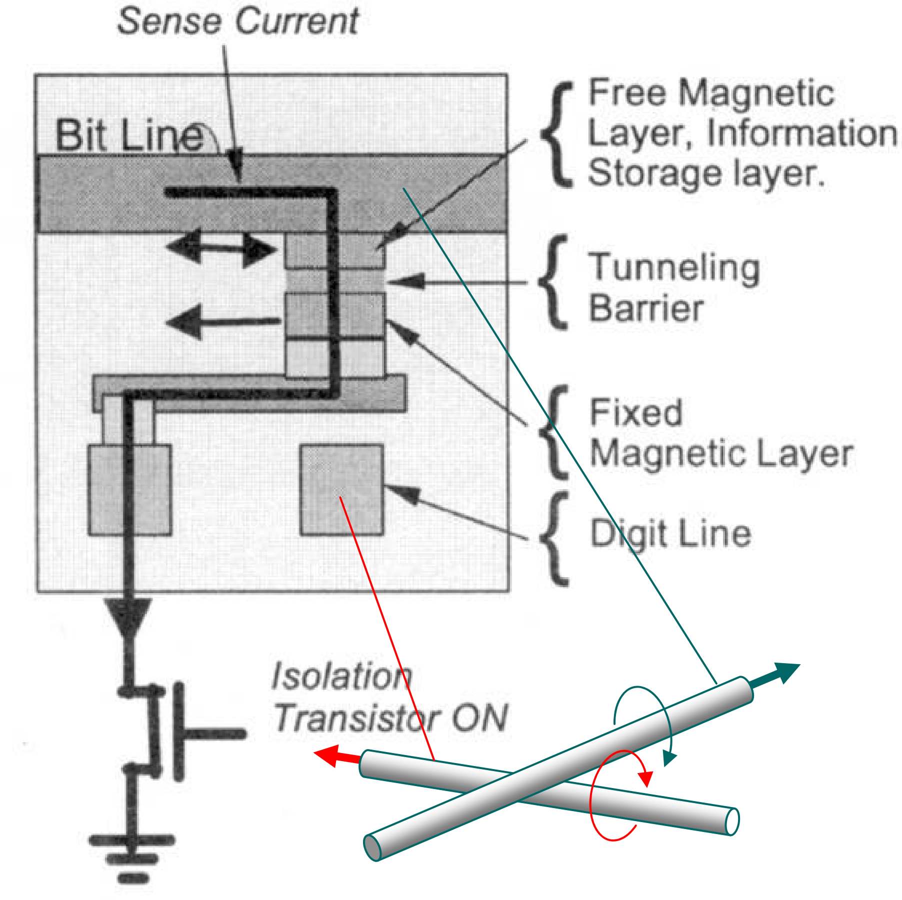
Physical background of TMR



- 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.

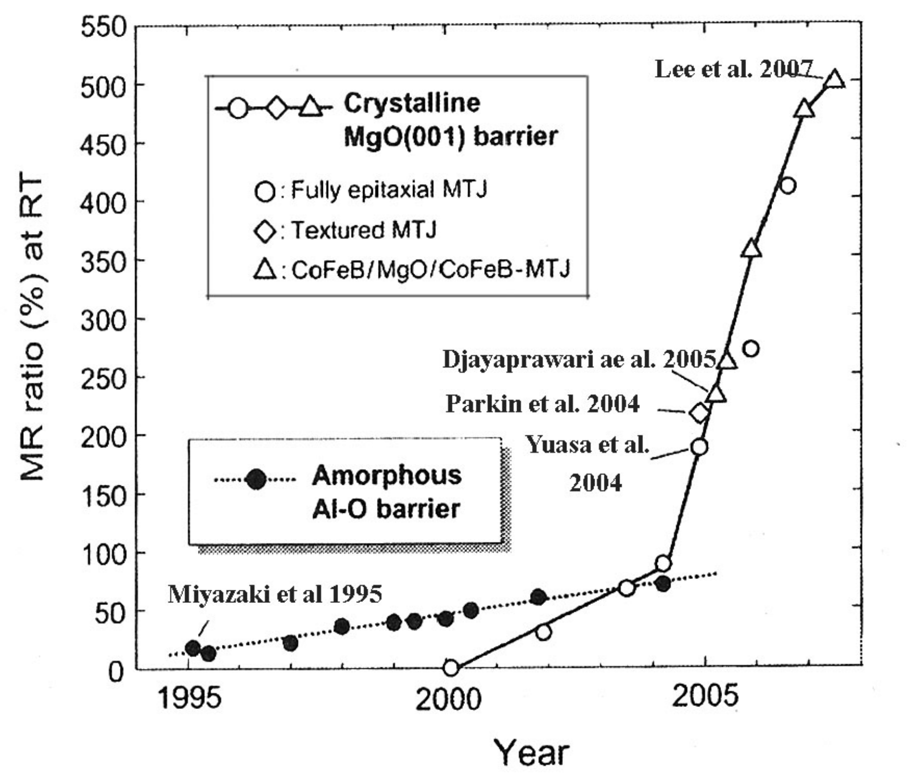
Application of TMR
MRAM (Magnetic random access memory)

- 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

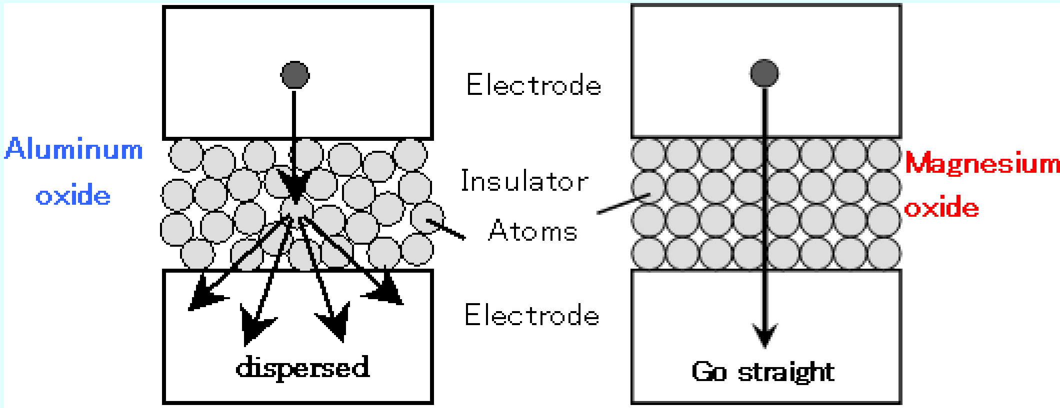
Diffuse Tunneling and Coherent Tunneling

- Usually spin is conserved during tunneling and TMR ratio of diffuse tunneling is expressed by Jullier's formula
  - $\mathrm{TMR}=2P_1P_2/(1-P_1P_2)$
    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.

[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

- 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.

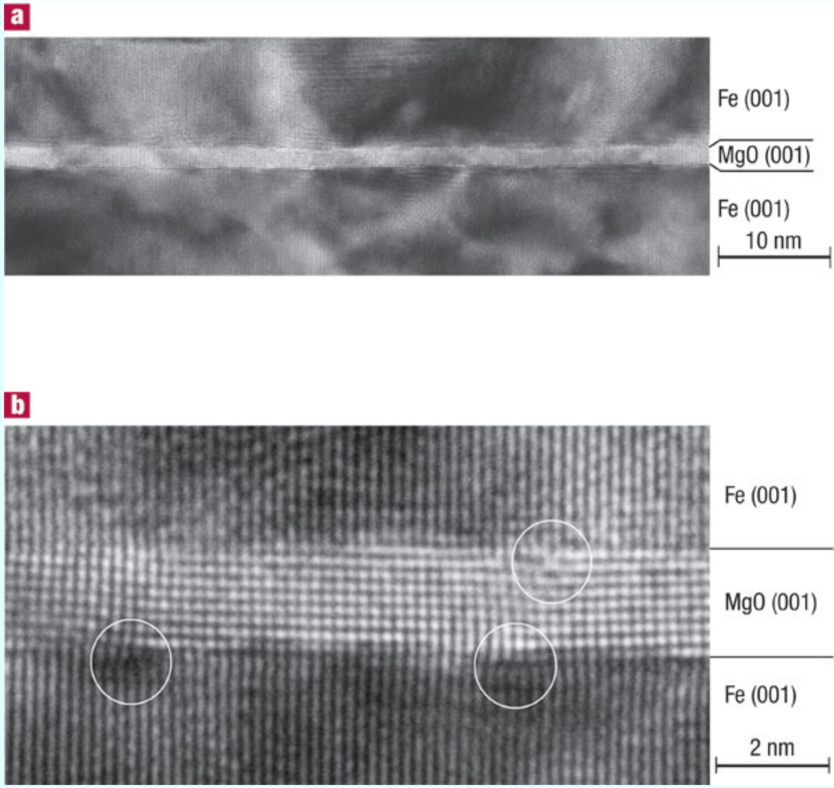
(b) Novel single-crystal device
Using magnesium oxide (single-crystal). Electrons can move straight without suffering dispersion.

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.*

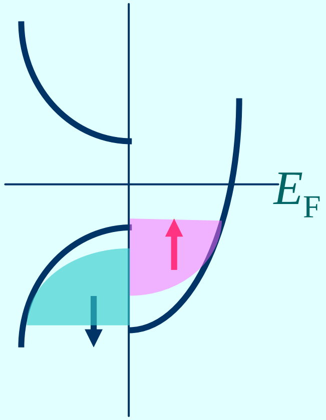


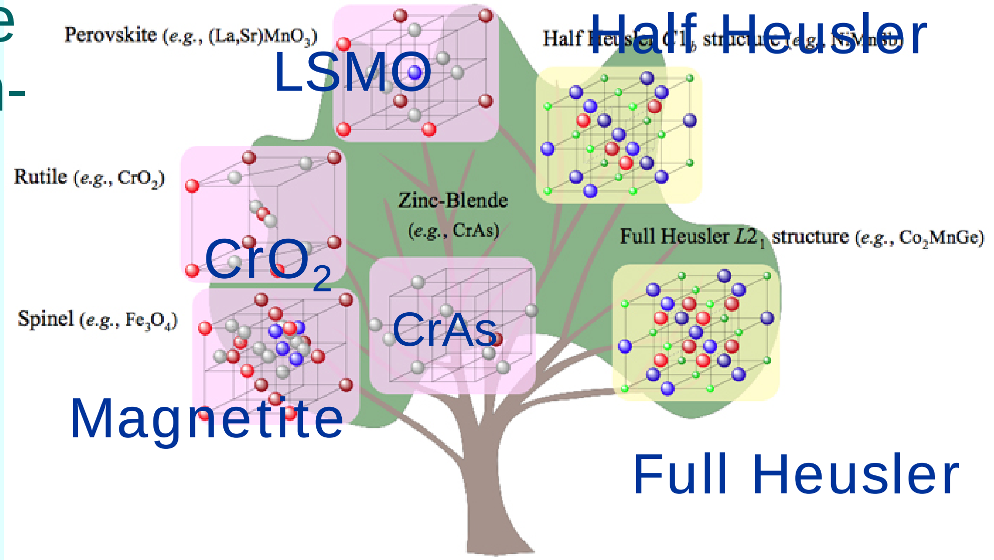
Yuasa et al. Nature Materials **3,** 868–871 (2004)

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

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.





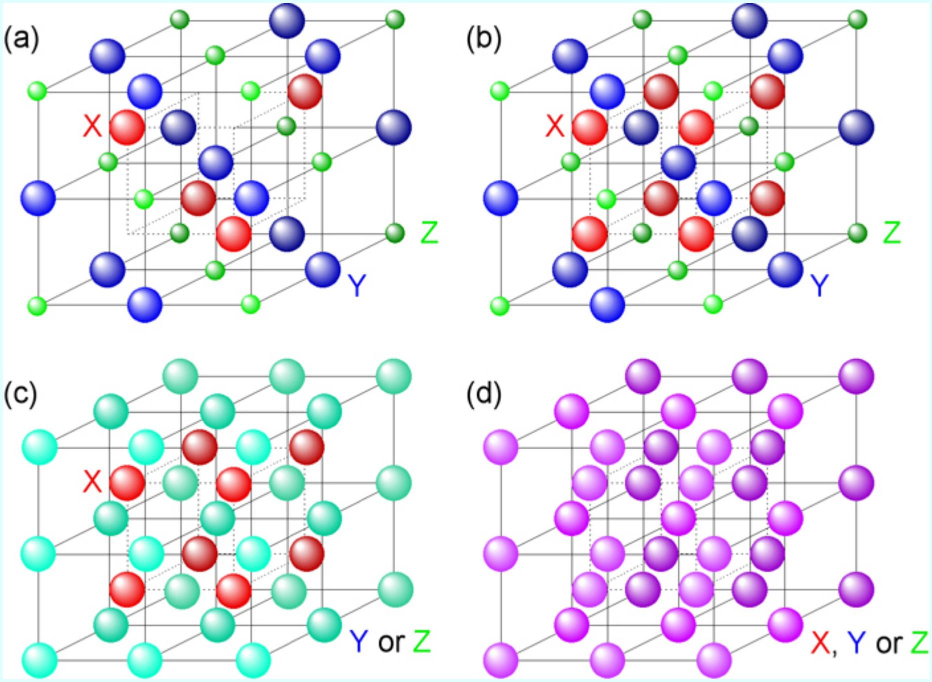
http://www.riken.go.jp/lab-www/nanomag/research/heusler_e.html

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

Atomic Disorder in X2YZ Heusler Alloy

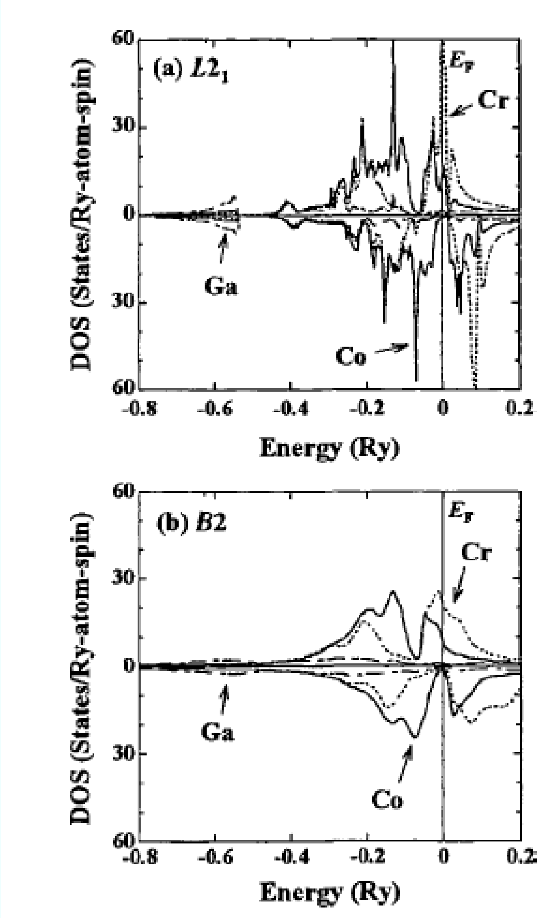


FIG. 2. Density of states of the Co2CrGa alloy with (a) the *L*21-type structure and (b) the *B*2-type structure. The upper and lower curves in each panel correspond to the majority and the minority spin states, respectively.

- A2-structure with X-Y and X-Z disorder is not half-metallic,
- While B2-structure with Y-Z disorder is half-metallic.

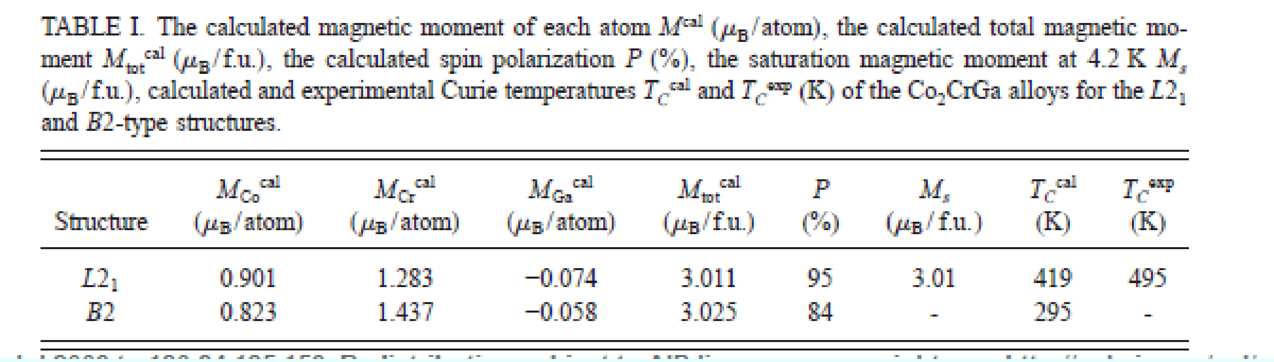
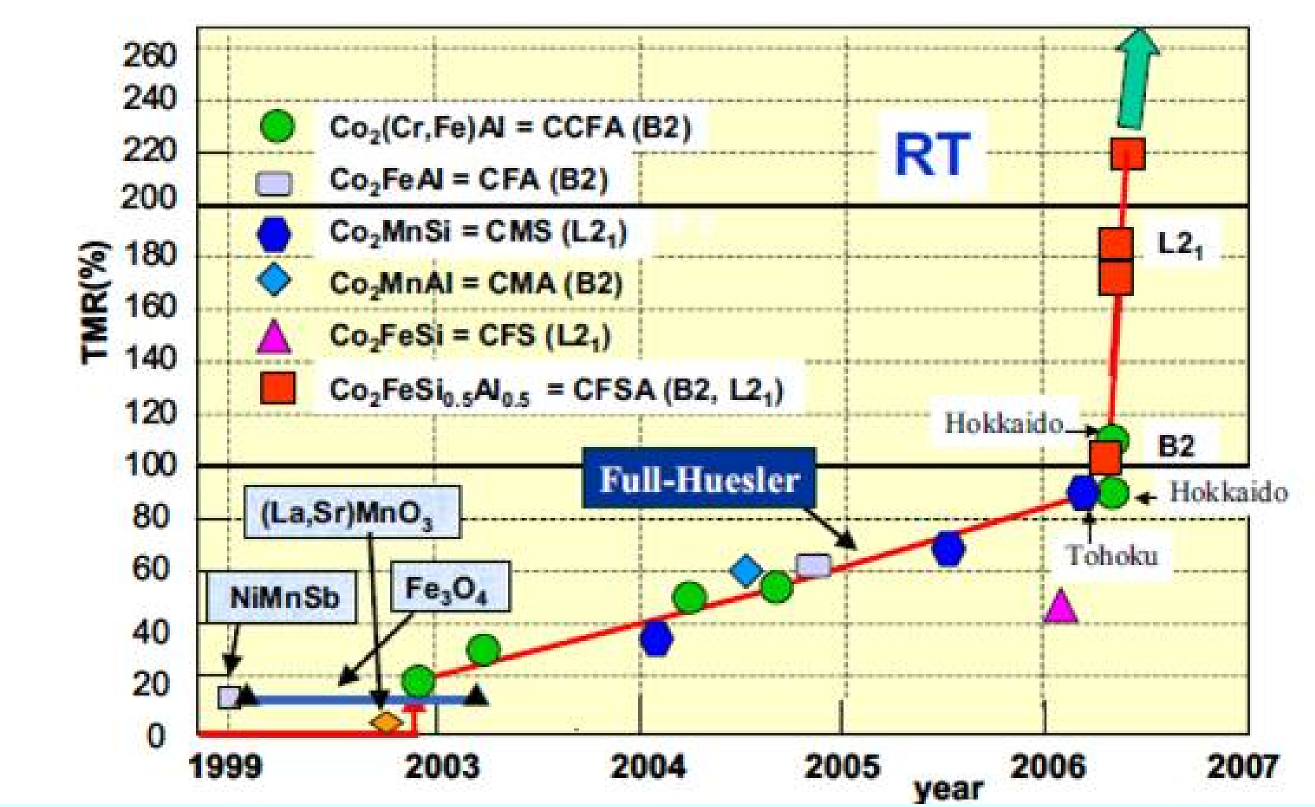


TABLE I. The calculated magnetic moment of each atom M^{cal} (μ_B/atom), the calculated total magnetic moment M_{tot}^{cal} (μ_B/f.u.), the calculated spin polarization P (%), the saturation magnetic moment at 4.2 K M_s (μ_B/f.u.), calculated and experimental Curie temperatures T_C^{cal} and T_C^{exp} (K) of the Co_2CrGa alloys for the $L2_1$ and $B2$-type structures.

Structure	M_{Co}^{cal} (μ_B/atom)	M_{Cr}^{cal} (μ_B/atom)	M_{Ga}^{cal} (μ_B/atom)	M_{tot}^{cal} (μ_B/f.u.)	P (%)	M_s (μ_B/f.u.)	T_C^{cal} (K)	T_C^{exp} (K)
$L2_1$	0.901	1.283	−0.074	3.011	95	3.01	419	495
$B2$	0.823	1.437	−0.058	3.025	84	-	295	-

TMR with full Heusler X2YZ alloys



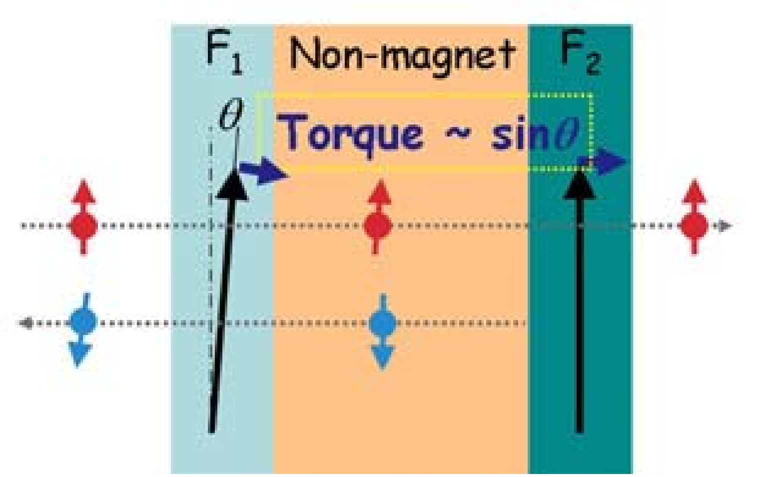
2.2 Spin-Transfer Magnetization Reversal

E → 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

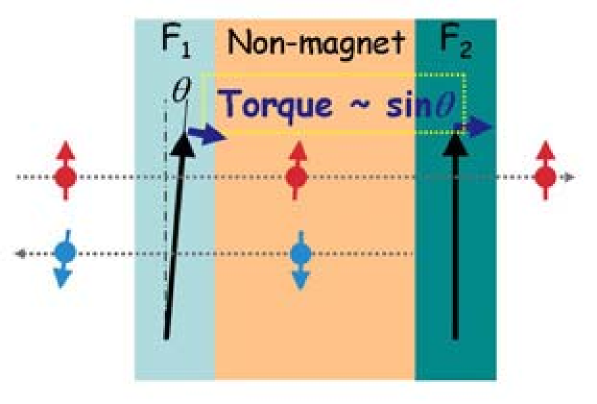
↓

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

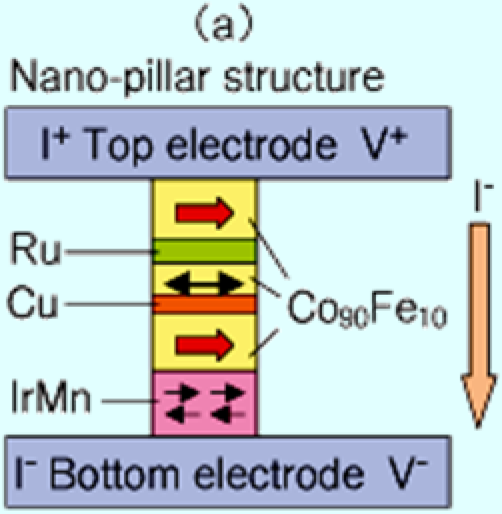
- One is based on spin transfer, suggesting that the spin current *transfers* the transverse component of the spin angular momentum to the local magnetic moment at the interface whereby a torque is exerted on the local magnetic moment (*spin-torque*).
- Another is based on *spin accumulation*, by which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

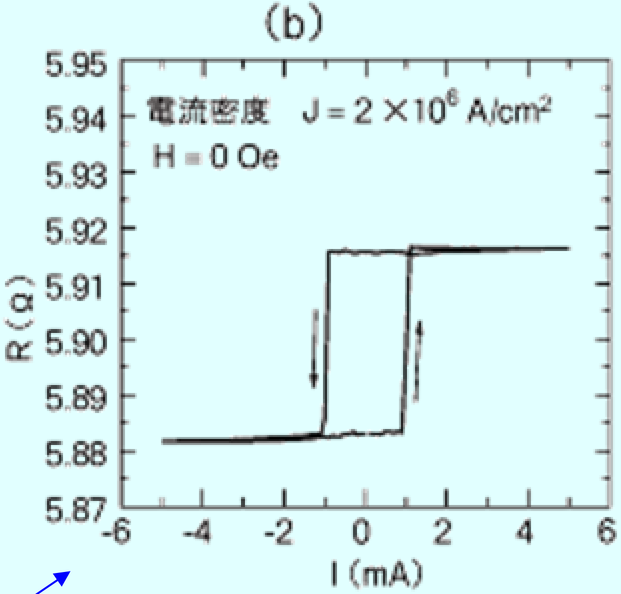


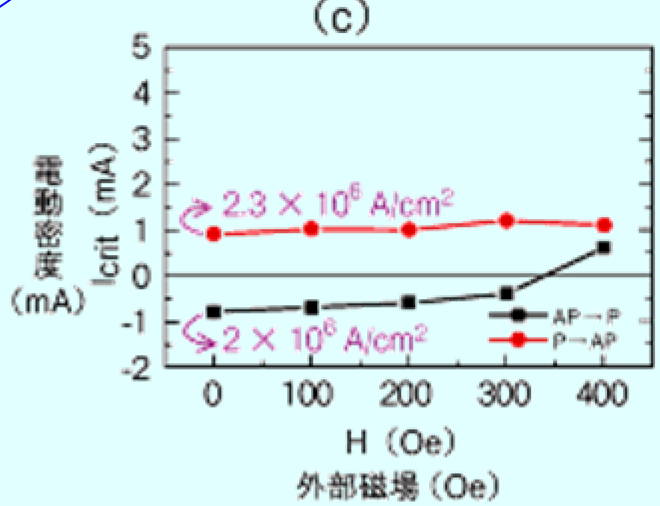
http://www.riken.go.jp/lab-www/nanomag/research/cims_e.html

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).



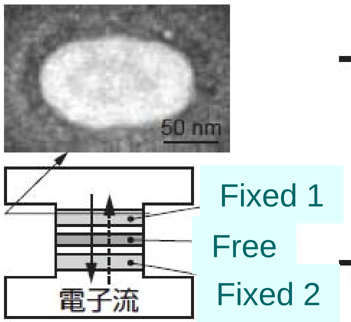




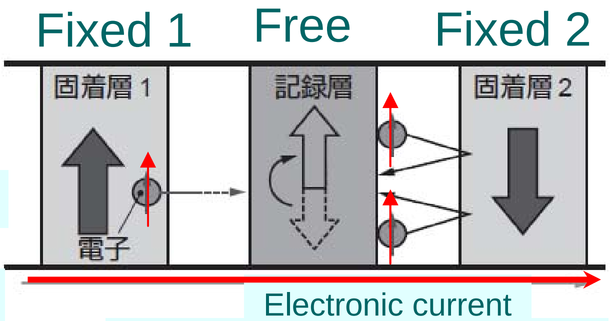
- Magnetization direction of free $Co_{90}Fe_{10}$ layer is changed depending on the current direction.

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

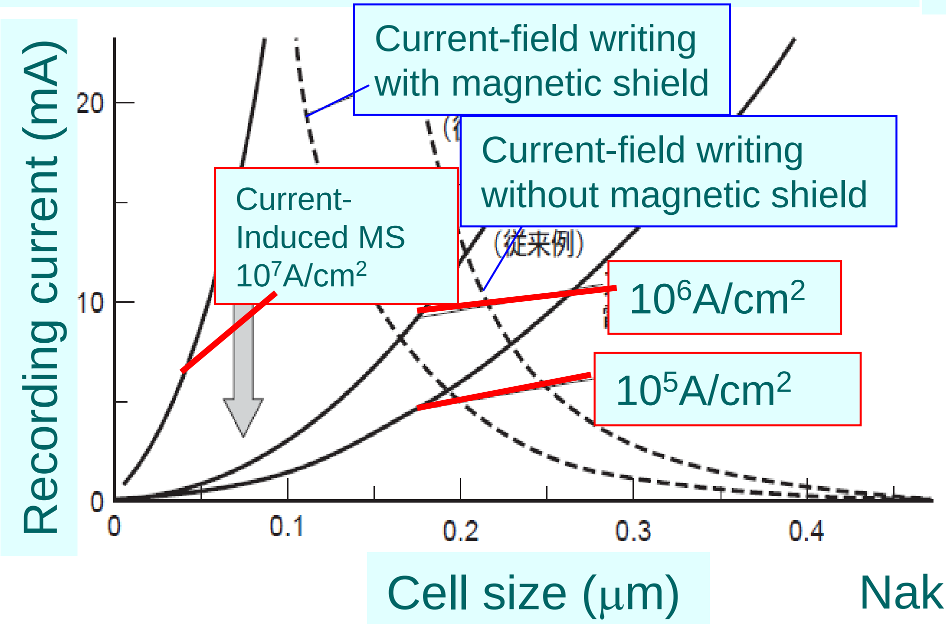
- Switching current for spin-transfer magnetization reversal is proportional to the area of devices.
- This technique is superior to the previous method if the scale becomes less than 0.2μm.

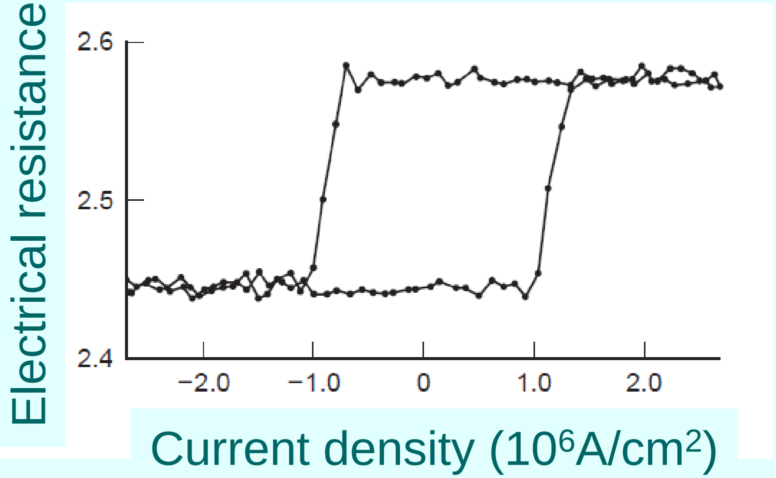


Device structure



Switching mechanism





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

Current Density necessary for Spin-Transfer Magnetization Switching to occur

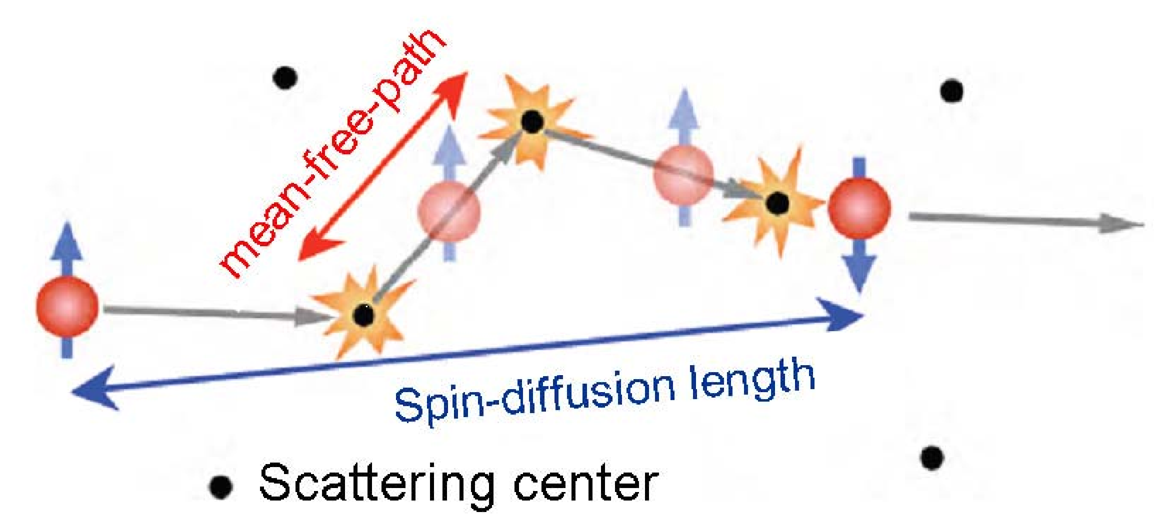
- Spin-polarized current injected from a ferromagnetic electrode transfers the spin-angular momentum to the counter ferromagnetic electrode to give rise to a magnetization reversal. Although a huge current density as large as 10^7-10^8A/cm^2 was necessary in the early stage of experiment using a GMR device, the recent technical development enabled to reduce it to a practical level of 10^6A/cm^2 by using a MgO-TMR device.
- 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*.

2.3 Concept of Spin Current and Spin-Hall Effect

Opening a New Paradigm!

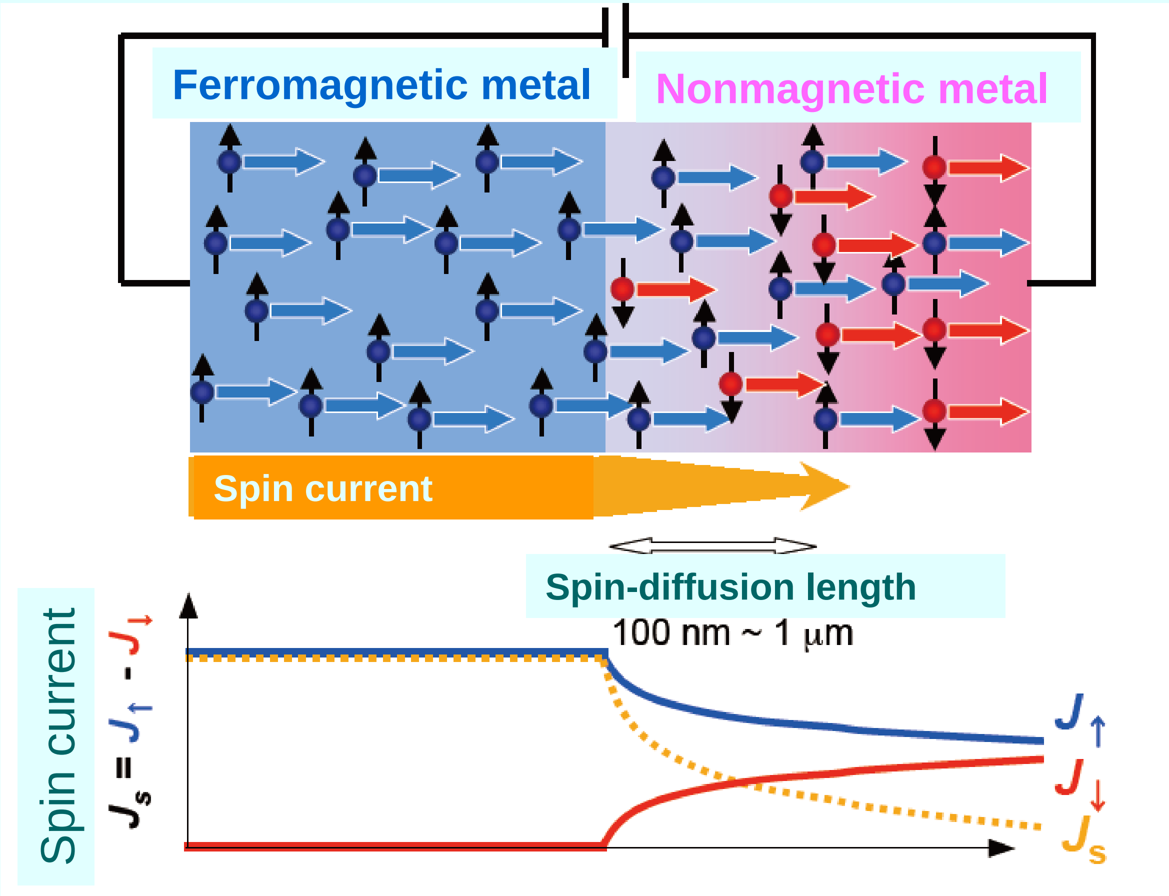
New Concept of “Spin Current”

- 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



Courtesy of Prof. Takanashi

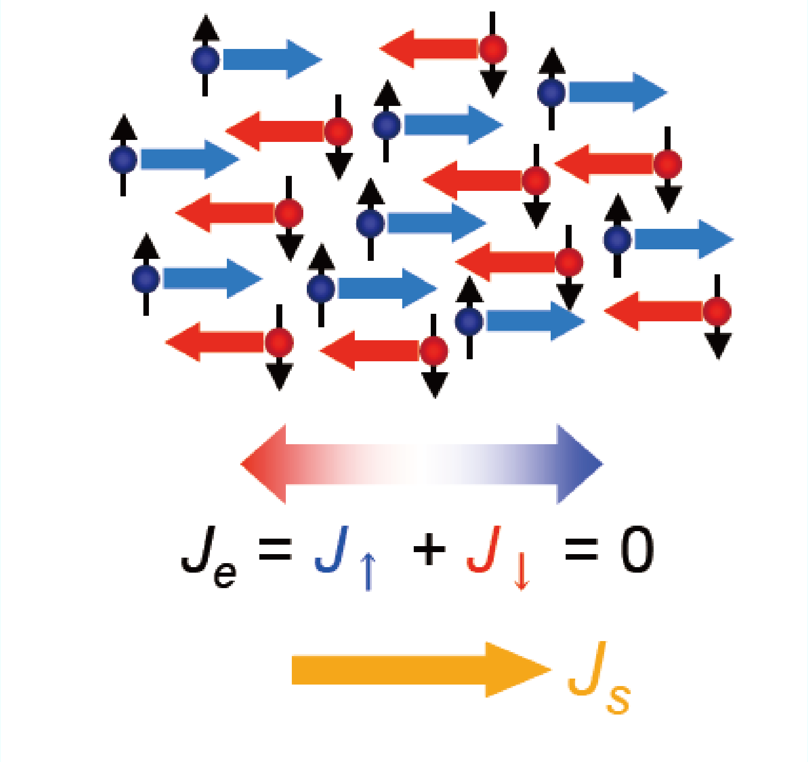
（1）*Spin current with charge current*



- 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*

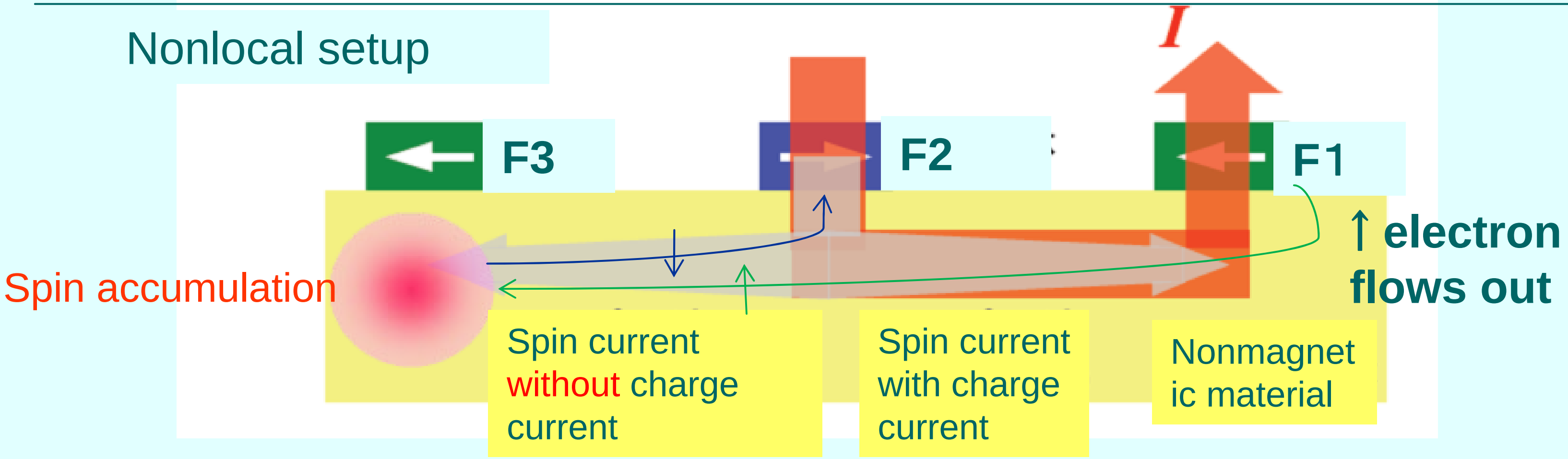


Nonlocal Spin Injection
and Spin-Hall effect.

- 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

I

F3

F2

F1

↑ electron flows out

Spin accumulation

Spin current without charge current

Spin current with charge current

Nonmagnetic material

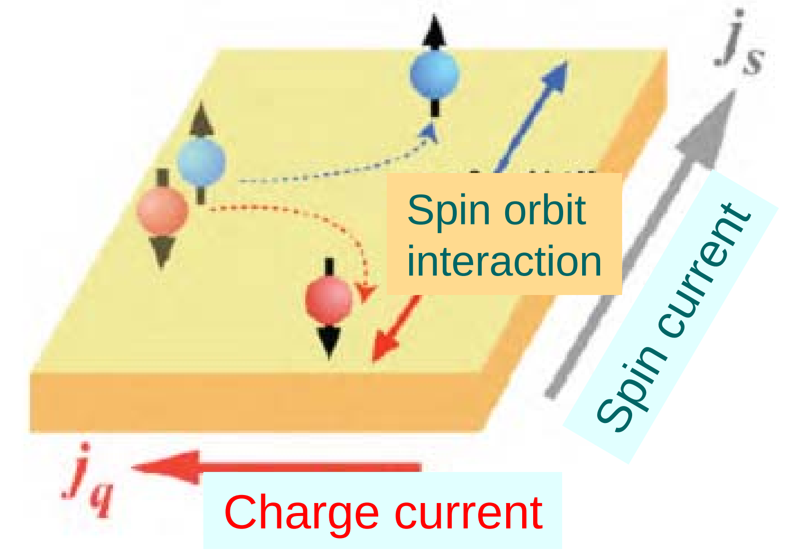
- Suppose magnetization of F_2 is antiparallel to F_1 and parallel to F_3.
- If electrons flow from F_1 to F_2, up spin from F_1 cannot enter F_2 and flow to F_3 direction.
- Since current should flow form F_2 to F_1 down spin electrons are supplied from F_3 electrode, resulting in no net charge flow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

（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

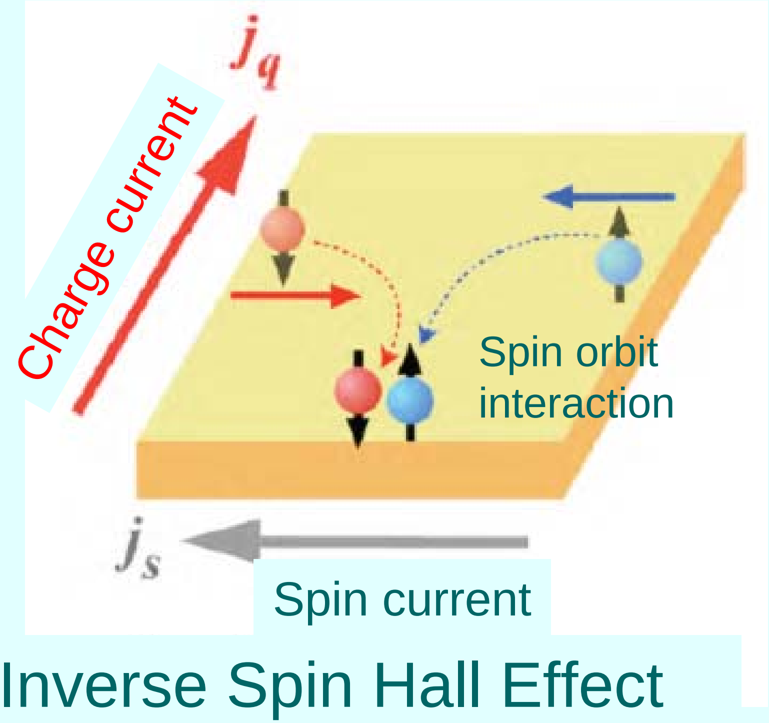
History of SHE Research

- 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.

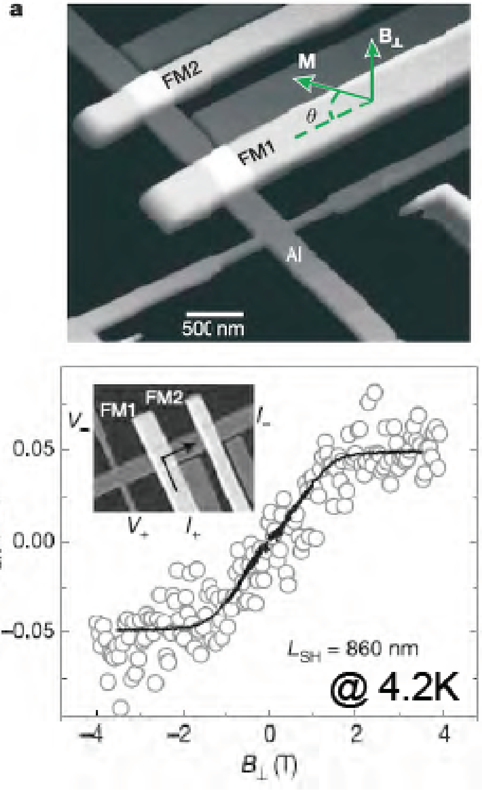


Inverse Spin Hall Effect

Courtesy of Prof. Takanashi

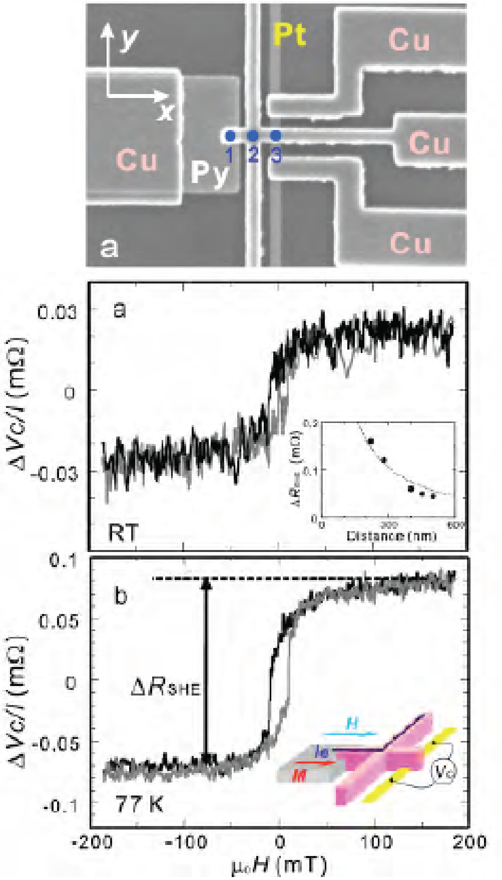
SHE and ISHE

CoFe / Al



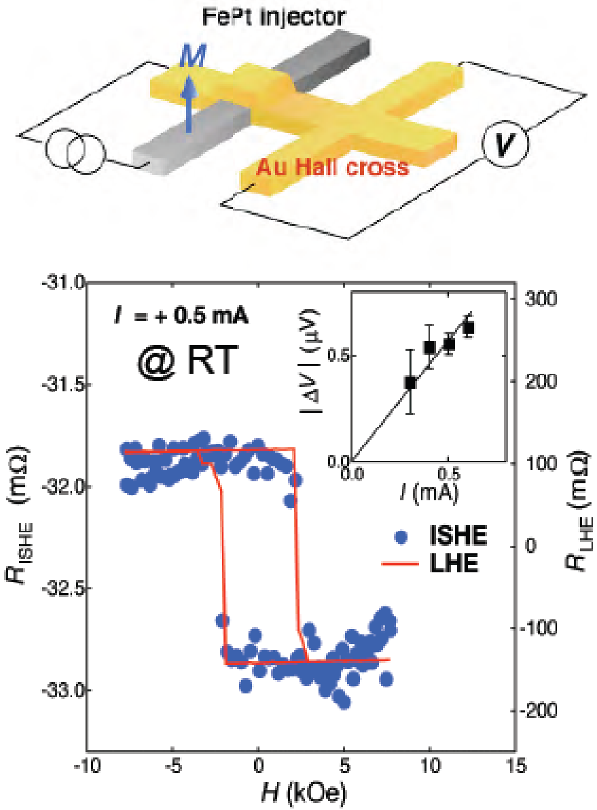
S. O. Valenzuela, M. Tinkham,
Nature **442**, 176 (2006).

Py / Cu / Pt



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

FePt / Au



$\alpha_H \sim 0.1$

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

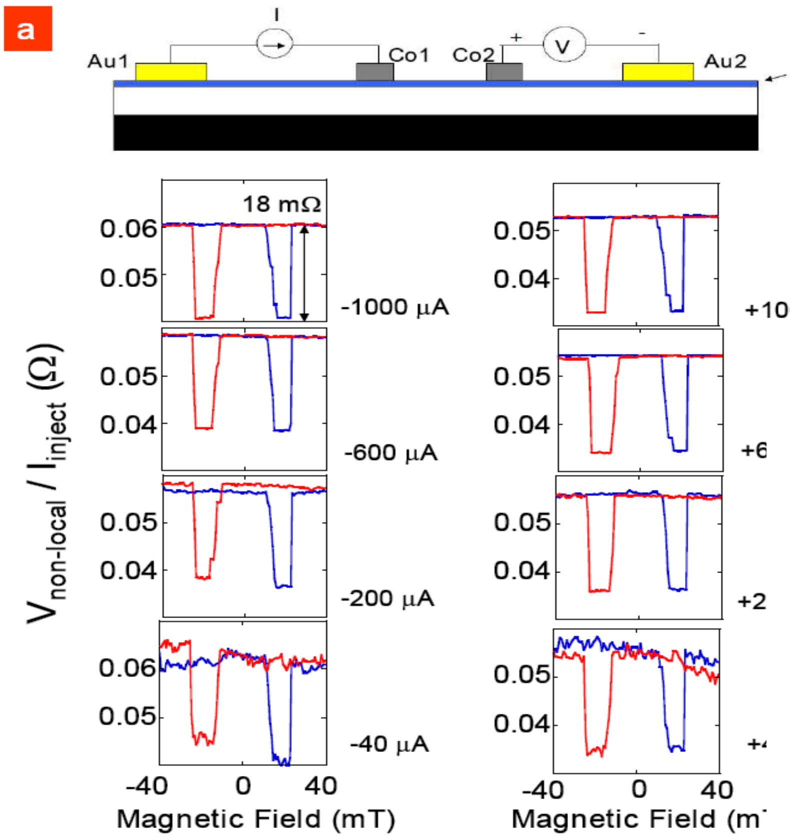
Courtesy of Prof. Takanashi

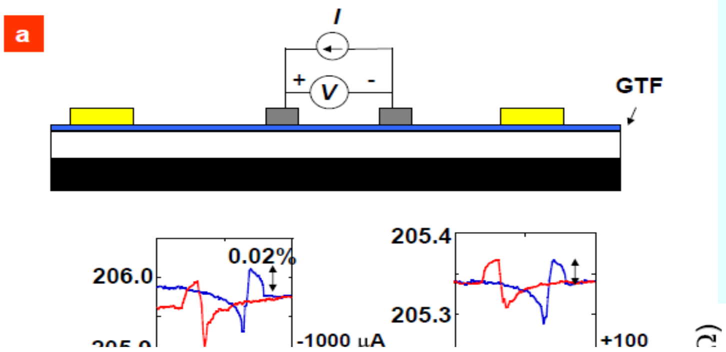
Molecular Spintronics

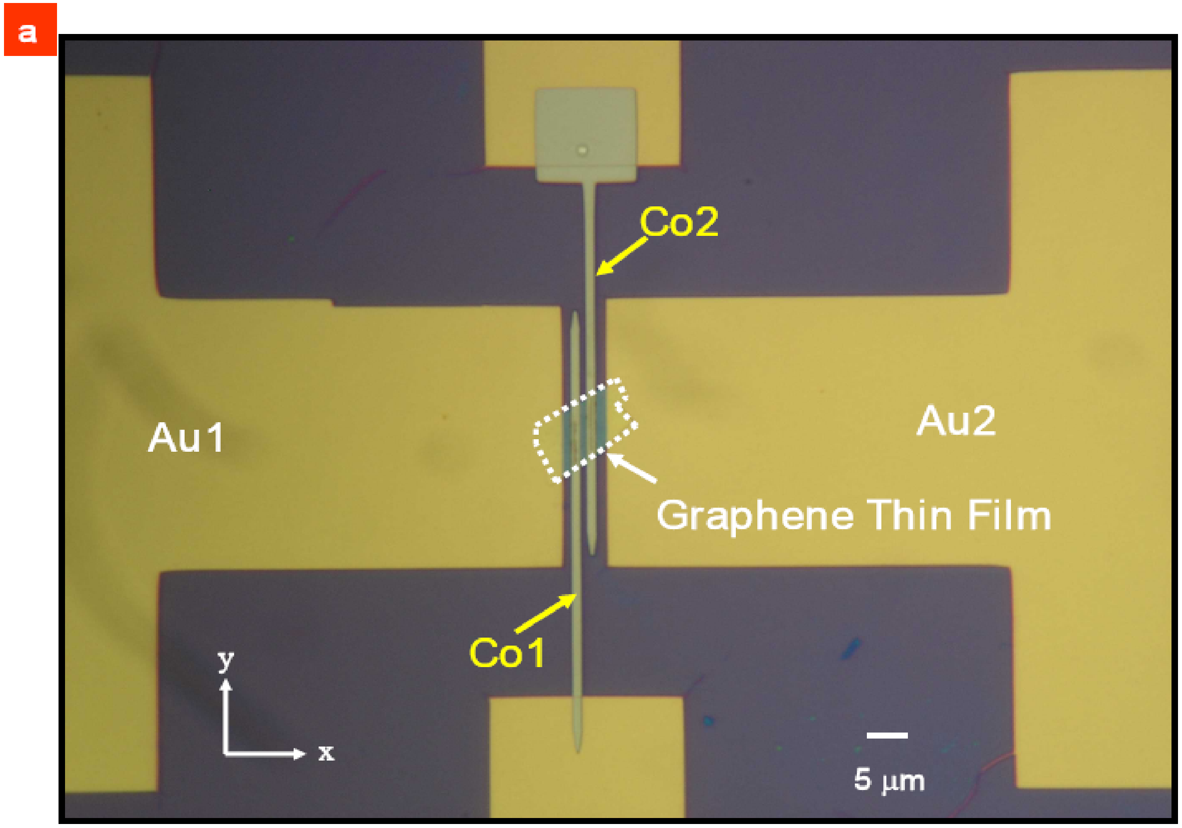
- The spin-current can be observed not only in magnetic materials but in non-magnetic metals or even in nano-carbons: It was demonstrated by Shiraishi et al. that the spin current can be injected to a sheet of graphene by a careful experiment using a non-local magnetoresistance measurement.[i]

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

Local and nonlocal setups





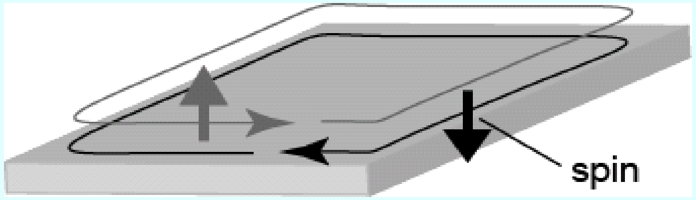


- Clear spin injection was con
  local arrangements.

M. Shiraishi, "Spin Transport in
Workshop on Physics and C
(2009/11/17-19)

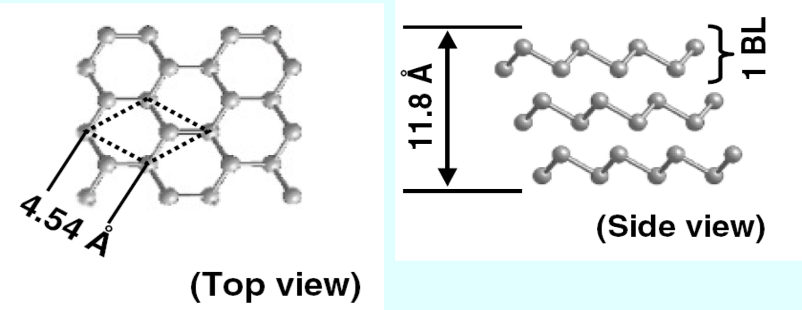
Theoretical Approach

Quantum Spin Hall Effect in Bismuth

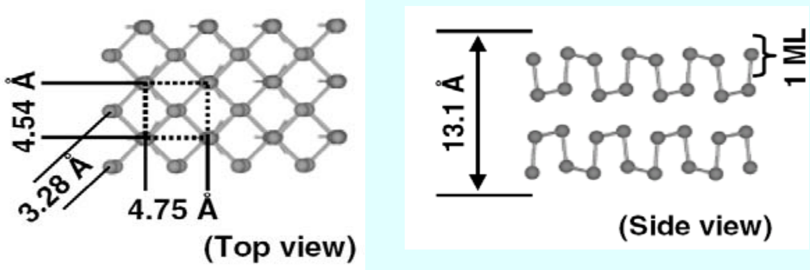


- Bulk Bi show no gap, while edge is gapless.
- Bi ultra thin film

(111) 1-bilayer = quantum spin Hall phase



{012} 2-monolayer= insulating phase



- Thermoelectric figure of merit $ZT = \dfrac{S^2 \sigma T}{\kappa}$

Idealized model (perfect conductor on the edge)

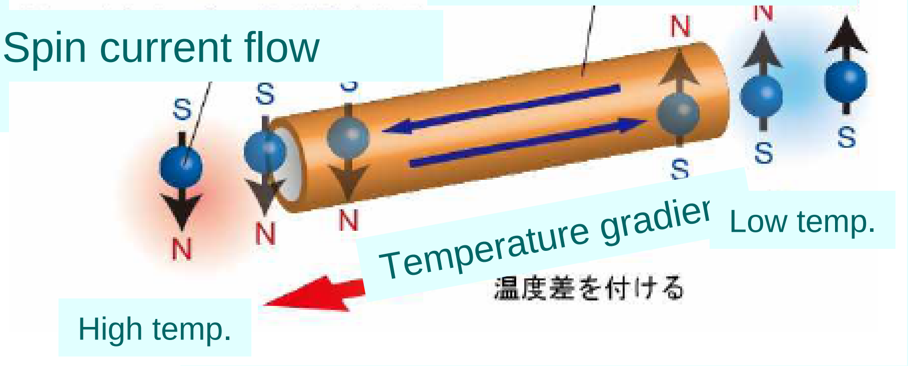
- In the quantum spin Hall phase, figure of merit ZT of thermoelectric conversion is determined by the balance between the edge and the bulk.
- ZT is large if the chemical potential is close to the band edge.
- ZT is large if the length of system is long. ← edge states dominantly determine ZT.
- ZT increases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

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

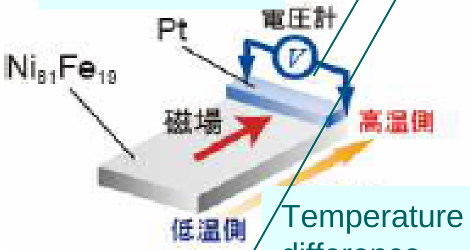
Spin current flow

Temperature gradier

Low temp.

High temp.

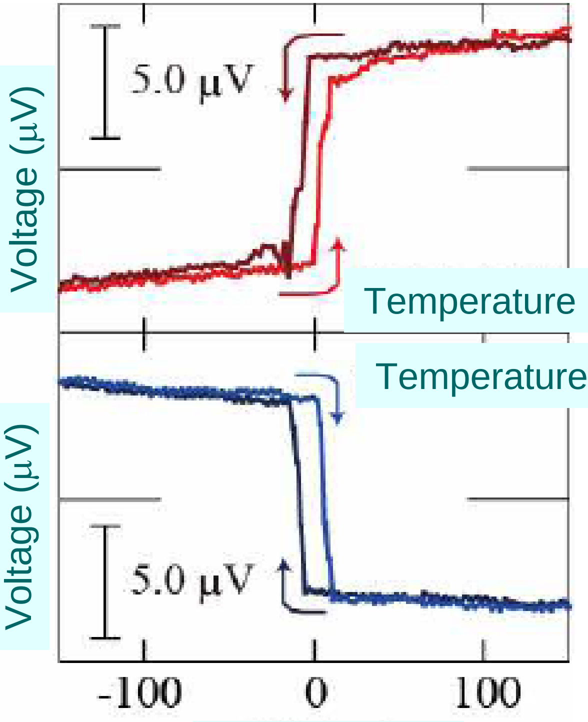
High temp.



Temperature difference

Low temp.

Temperature difference



Voltage (μV)

Temperature difference of 21K

Temperature difference of 21K

Voltage (μV)

Magnetic field

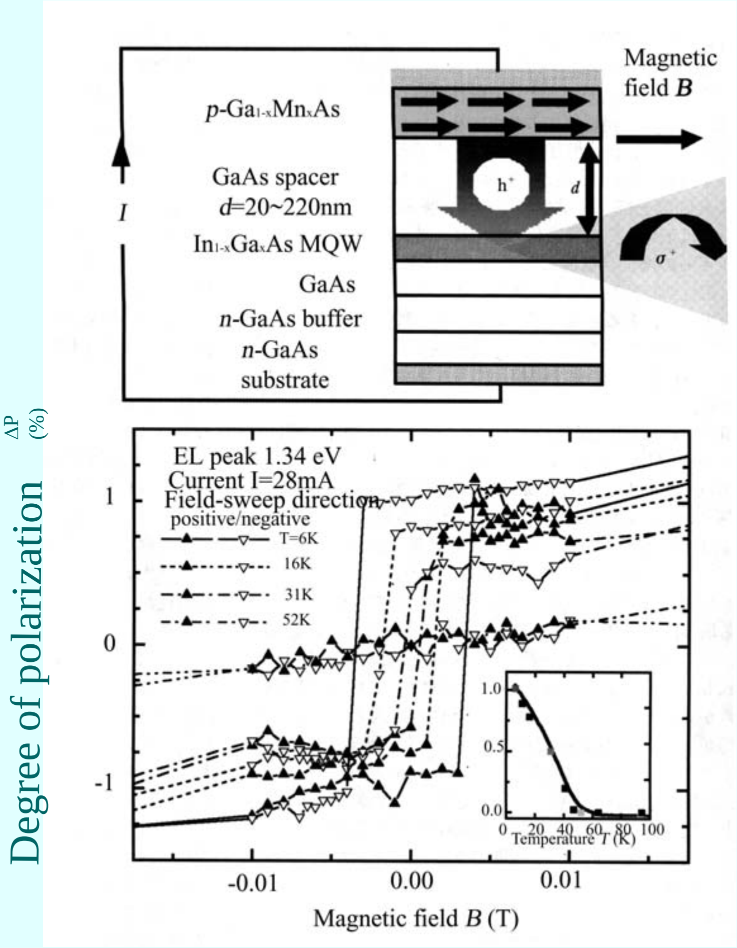
http://www.keio.ac.jp/ja/press_release/2008/kr7a43000000genl-att/081006.pdf

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

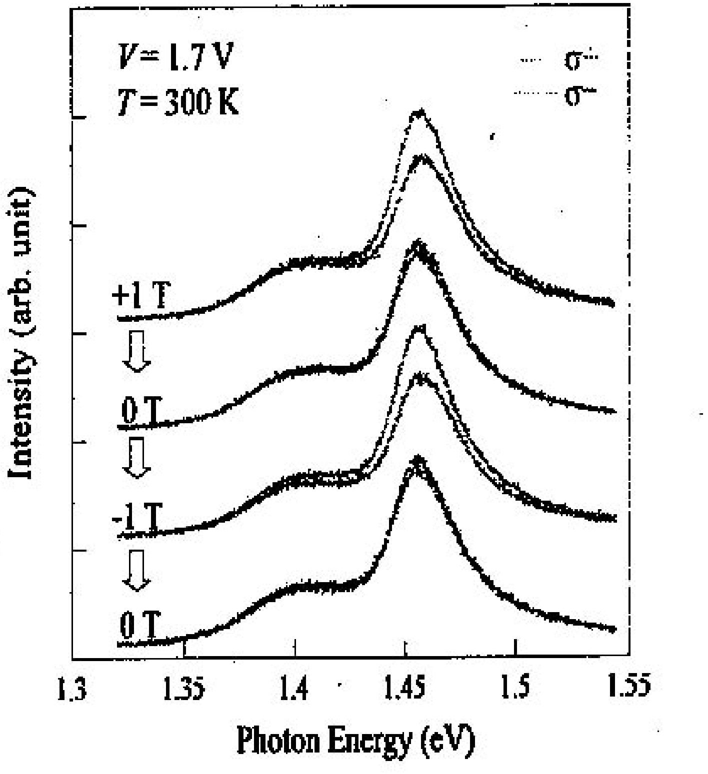
Spin-injection through junction



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.



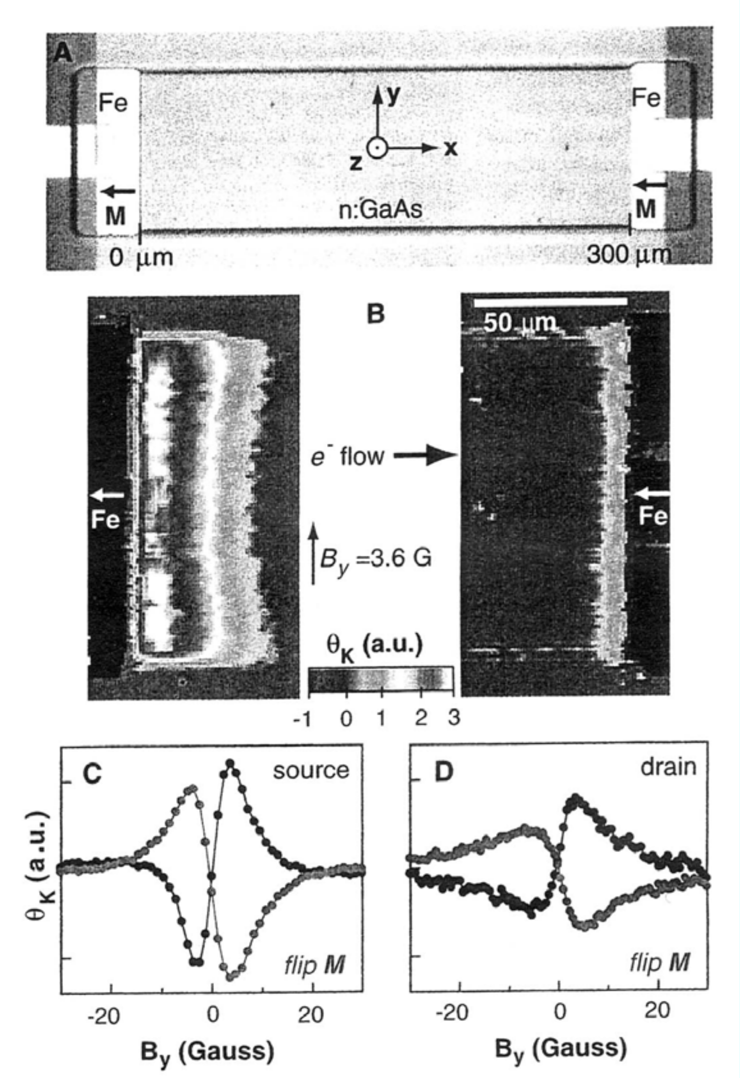
ＥＬスペクトルの磁場依存

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

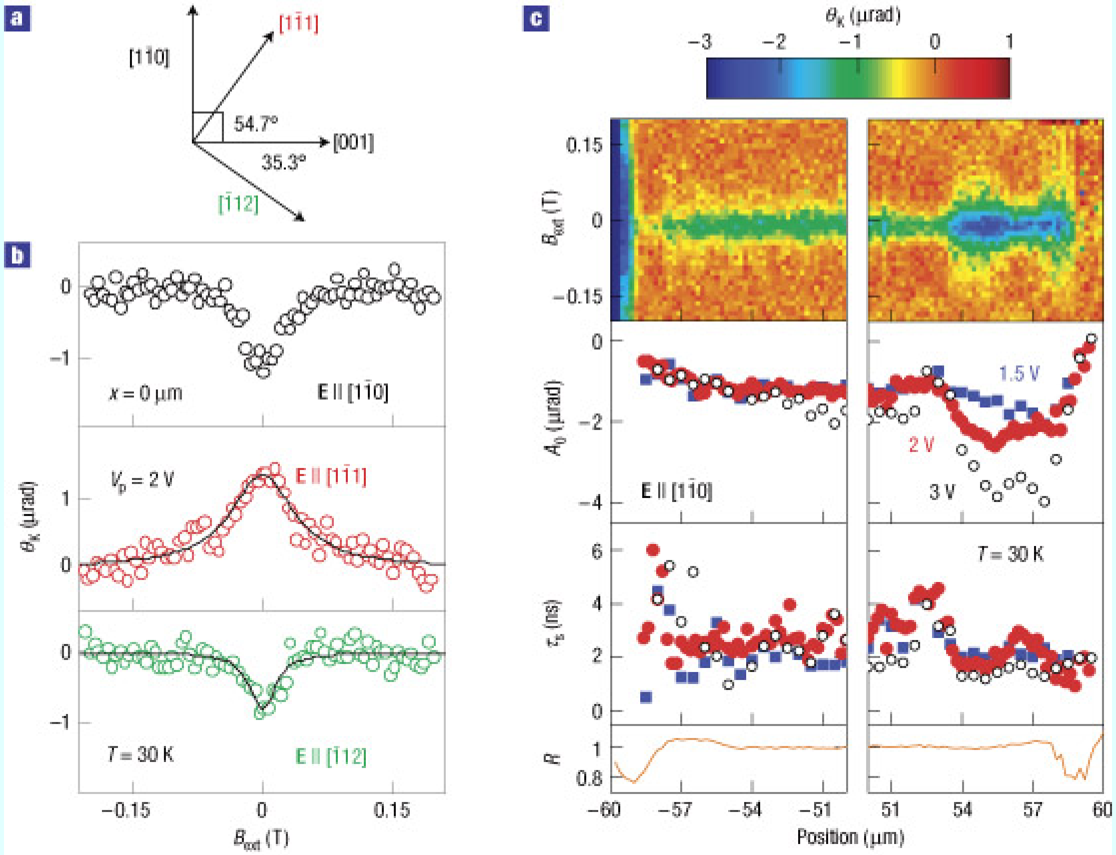
Magneto-optical observation of Spin Injection

- 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.

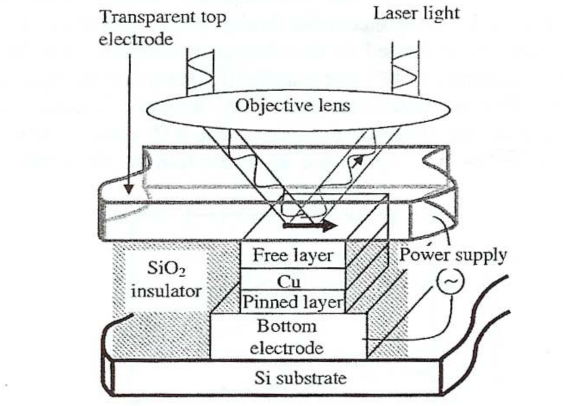


FIG. 1. Schematic illustration of spin-valve device with transparen electrode, and experimental setup. The plain arrow in the free layer indi the direction of the magnetization. The device includes the bc electrode of [Ta(3)/Cu(50)/Ta(3)/Cu(50)/Ru(5)], the pinned of [Ru(5)/Cu(20)/$Ir_{22}Mn_{78}$(10)/$Co_{66}Fe_{34}$(5)/Ru(0.9)/$Co_{66}Fe$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

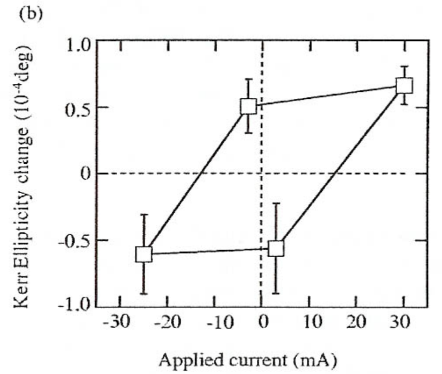
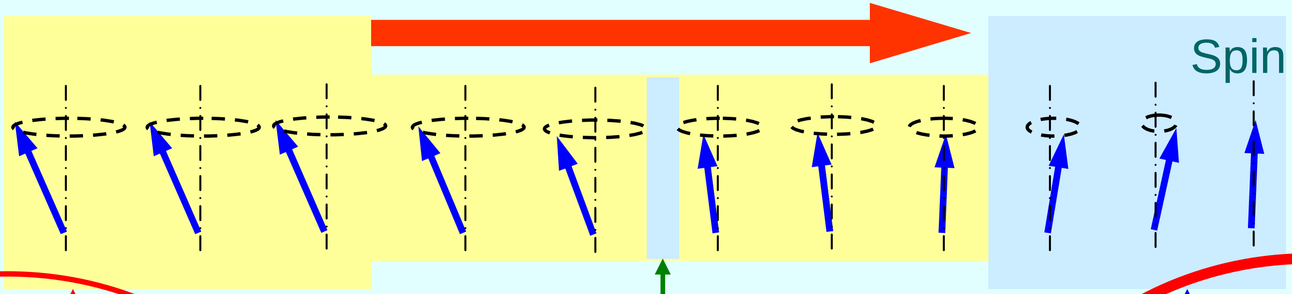


FIG. 4. (a) STS ´and the (b) Kerr ellipticity characteristics for three spin-valve elements. Open circles in (a) indicate resistance as a function of the applied current of ±30 mA with an increment of 2 mA. (b) The changes are defined as $[\eta_K - \langle \eta_K \rangle]$ in Kerr ellipticity for various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

Excitation, modulation and detection of spin wave spin current

（3 year target）



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

2.4. 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

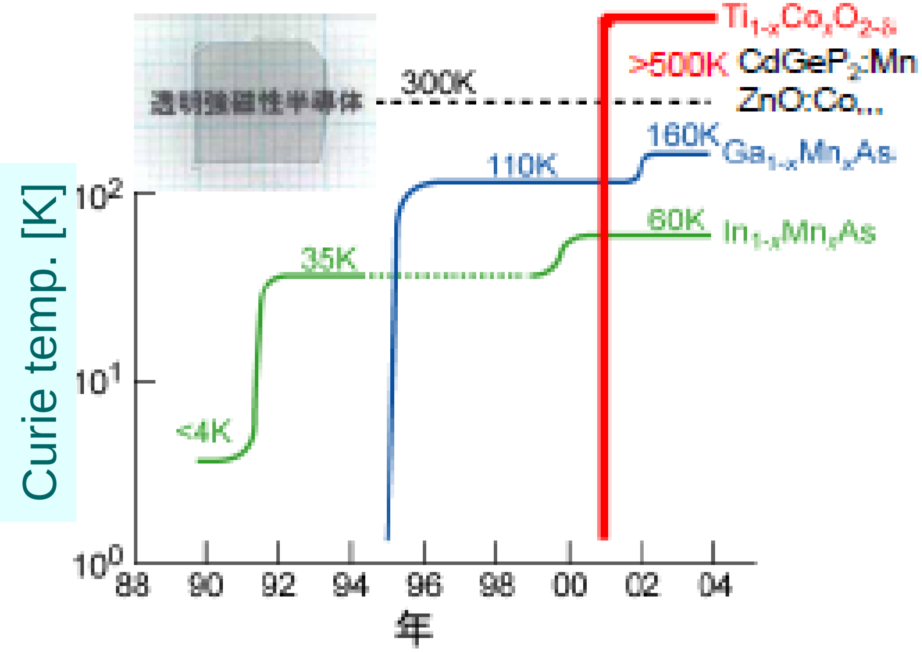
JJAP(2000) APL(2005)

Anomalous Hall Effect

Nature Mat. (2004), APL (2007)

Tunnel Magnto-resistance

JJAP (2005), JAP (2006)

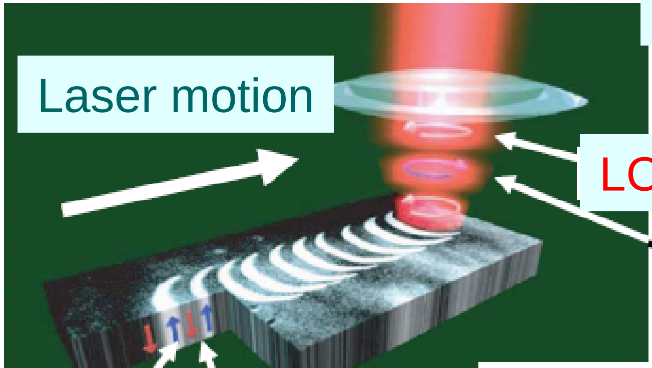


Transparent conductive+ environmental + room temp.

2.5. 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

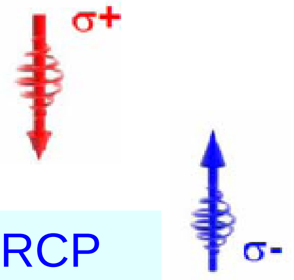


Laser motion

LCP

RCP

Equivalent magnetic field produced by photon

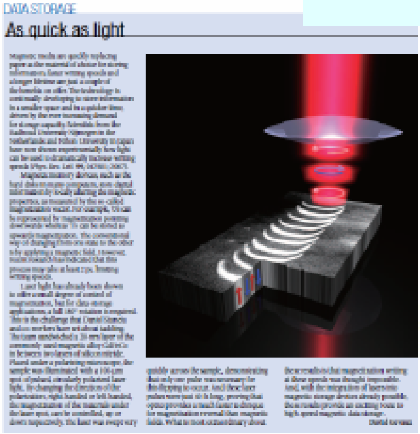


Up spin, Down spin

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

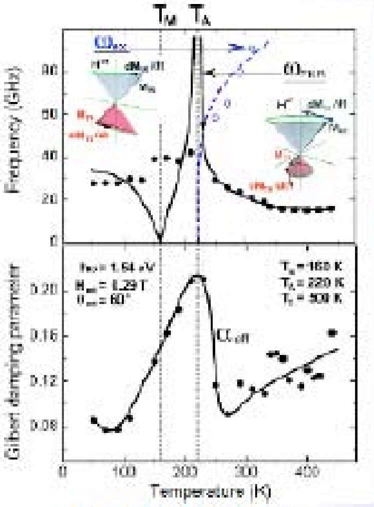
Previous technology

Direct optical control
Irradiation 40-100 fs

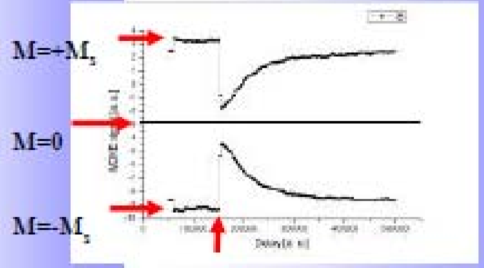
Angular momentum
Compensation heat-assist
Dynamic behavior f α

連携

Short time thermal
Demagnetization
~ps order

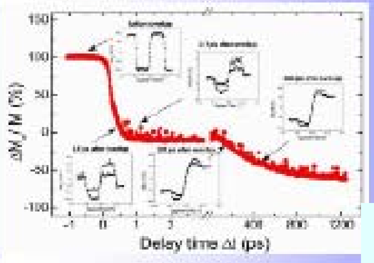


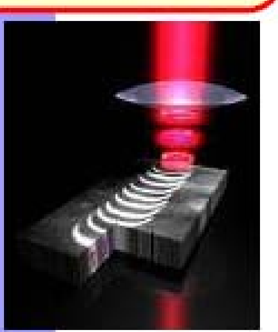
PRB(R)2006



Pomp

サブピコ秒磁化反転デモ

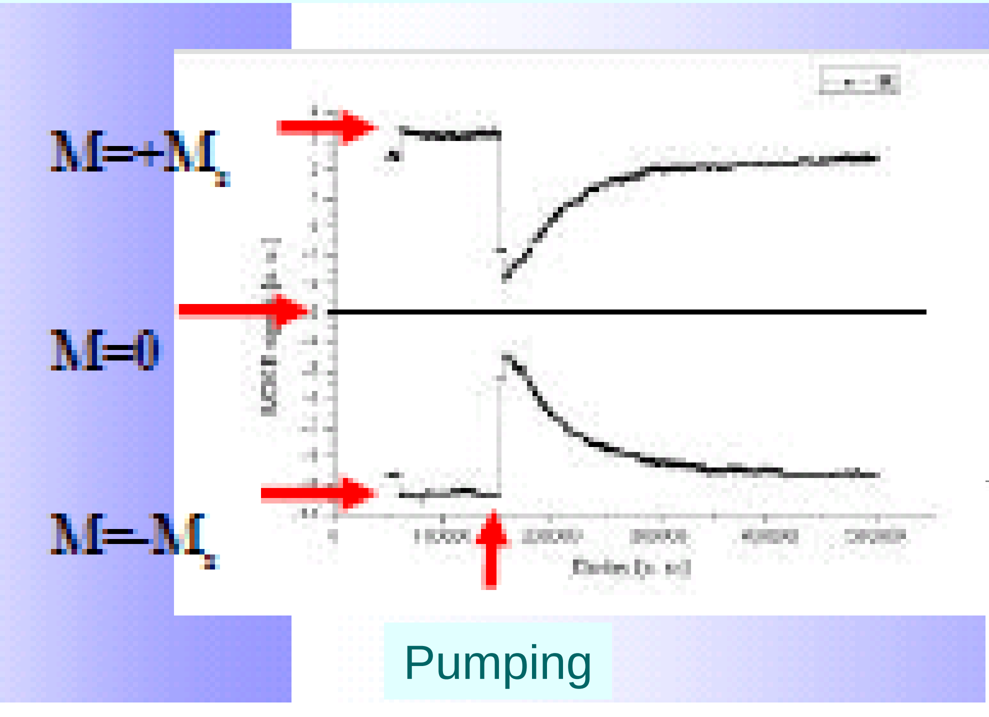


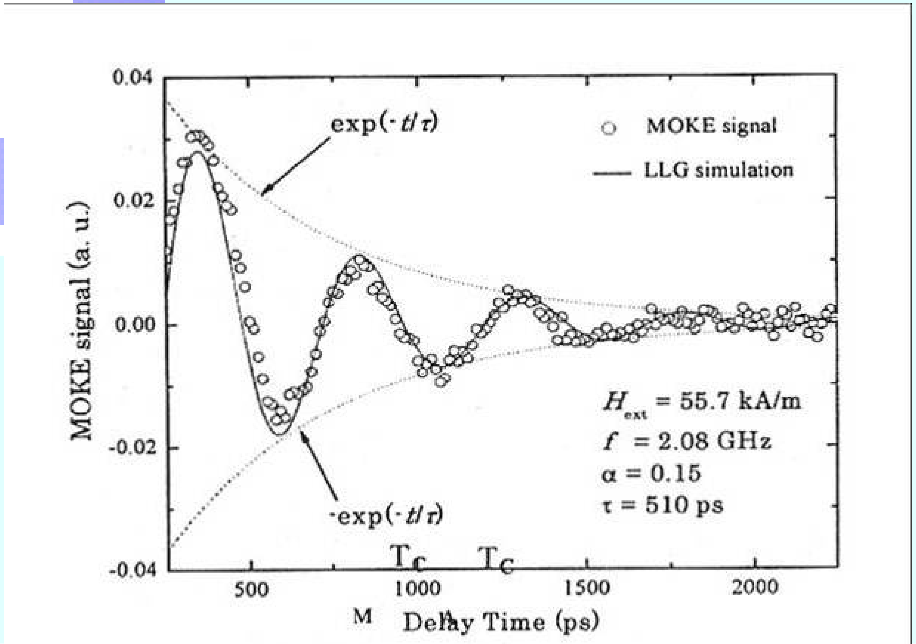


PRL2007

Tsukamoto (Nihon U.)

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



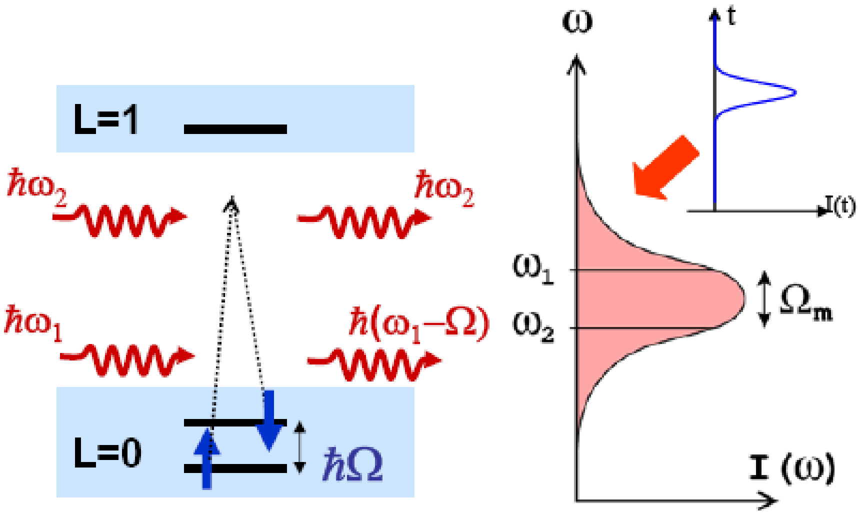


Microscopic mechanism of the inverse Faraday effect

- ***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

2.6.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).

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.

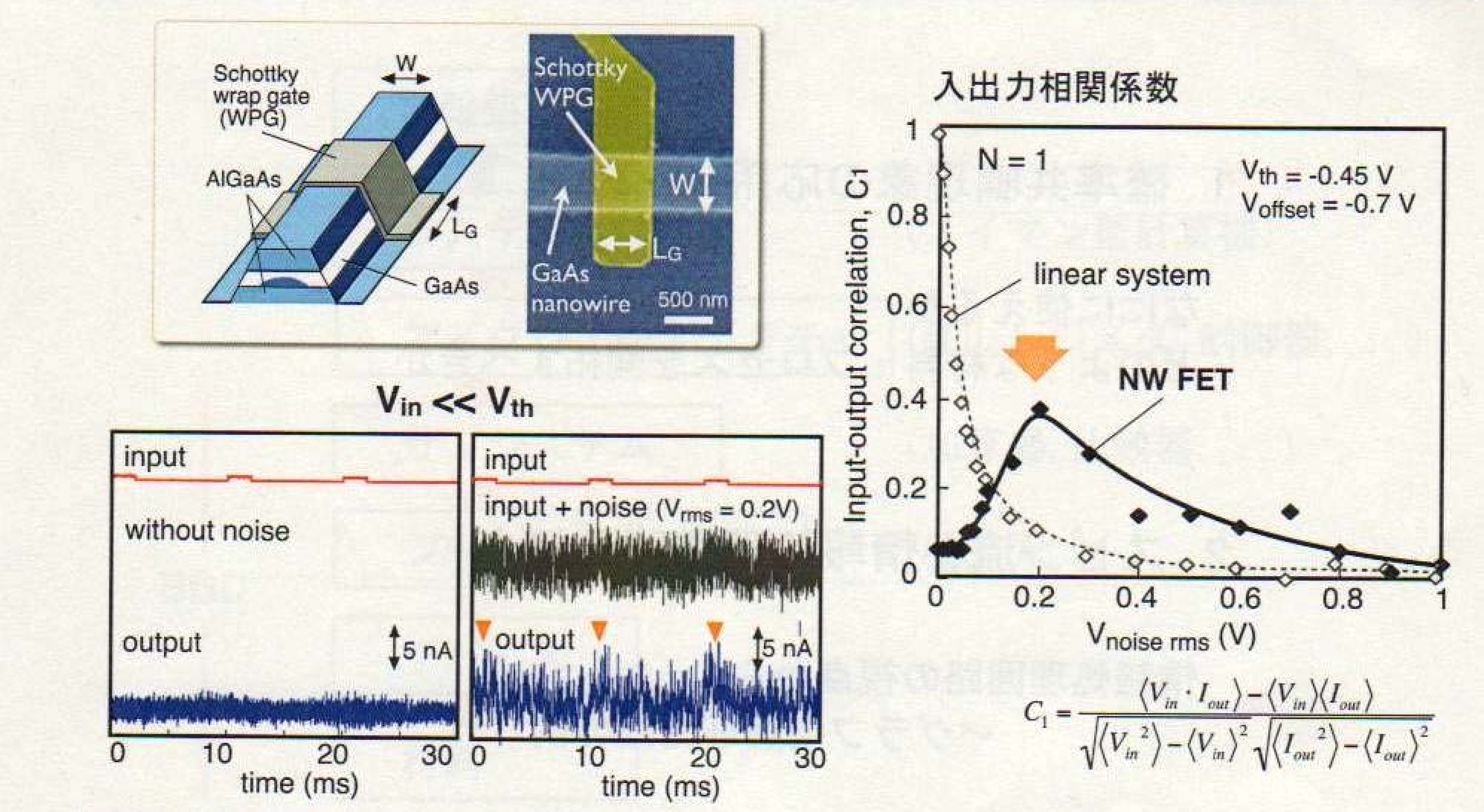
[i] N. Nagasa：Kotaibutsuri 41 (2006) 877, ibid 42 (2007) 1, ibid 42 (2007) 487. (In Japanese)

3. Semiconductor technologies beyond Si-CMOS

Stochastic Resonance

- Novel semiconductor nanodevices utilizing "stochastic resonance"[i] and their integration are now under investigation to realize state-of-the-art electronics hardware for noise-robust information processing. The stochastic resonance is a phenomenon that noise enhances response of a system, which plays an important role in nature and living things. Kasai designed, fabricated and characterized artificially controllable nanodevices in which the stochastic resonance takes place electrically. He integrated on semiconductor nanowire network structure to realize functionality for noise-robust information processing.[ii]
- [i] A. Bulsara and L. Gammaitoni: Physics Today 49 (1996) 39.
- [ii] S. Kasai and T. Asai: Appl. Phys. Express 1 (2008) 083001.

Realization of SR using Nanowire FET



$$C_1 = \frac{\langle V_{in} \cdot I_{out} \rangle - \langle V_{in} \rangle \langle I_{out} \rangle}{\sqrt{\langle V_{in}^2 \rangle - \langle V_{in} \rangle^2} \sqrt{\langle I_{out}^2 \rangle - \langle I_{out} \rangle^2}}$$

S. Kasai and T. Asai: Appl. Phys. Express 1 (2008) 083001

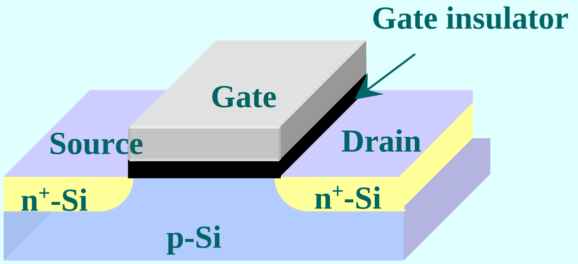
Surrounding Gate Transistors

- Advances in performance and integration through conventional scaling of device geometries are now reaching their practical limits in planar MOSFETs. To overcome the limiting factors in planar MOSFETs, vertical structural arrangements called surrounding gate transistors (SGT) have been suggested as the basis for next-generation semiconductor devices. Fukada studies one dimensional Si and Ge semiconductor nanowires which are expected for the components in SGT.[i]
-

[i] N. Fukata, M. Mitome, Y. Bando, M. Seoka, S. Matsushita, K. Murakami, J. Chen, and T. Sekiguchi: Appl. Phys. Lett. 93 (2008) 203106.

Planar to Vertical Geometry

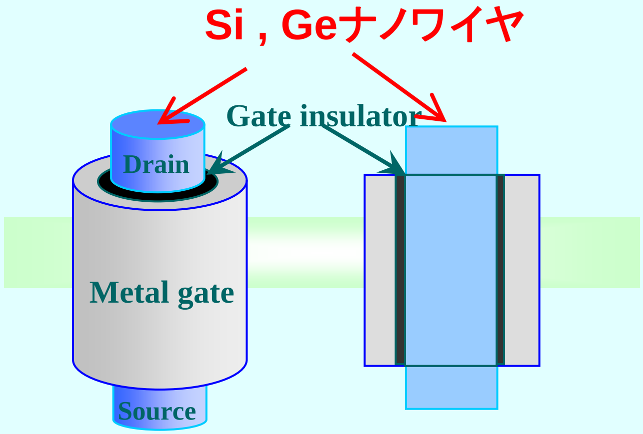
従来型:平面構造



・リーク電流の増大　　・発熱の増大

※従来の平面型構造では集積化と性能向上の両立に限界

次世代型:縦型立体構造

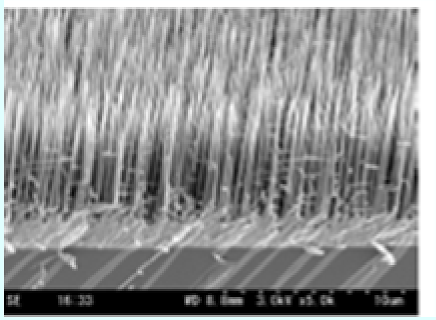


Surrounding Gate Transistor

・高集積　　・高制御性

SGTを実現する上での課題

1)ナノレベルでの位置・構造制御
2)不純物ドーピングの確立と制御
3)ナノレベルでの特性評価
4)ナノレベルでの不純物、欠陥、界面、構造ゆらぎ等の制御



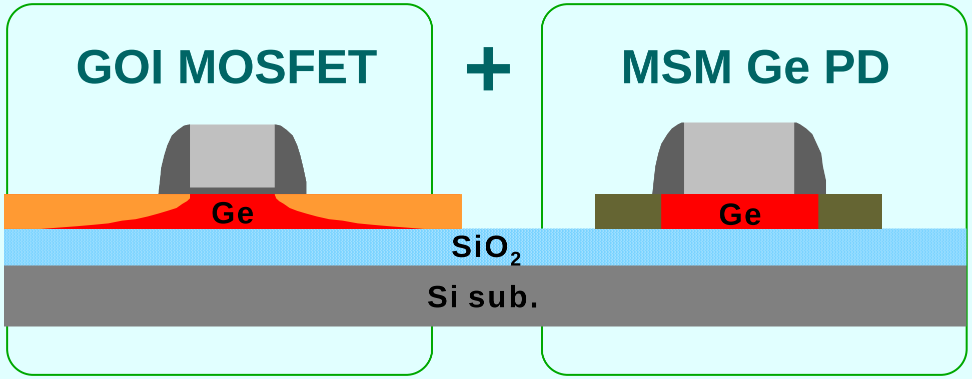
For optical interconnects

- Transmission delay of wiring in a chip is a serious problem limiting the performance of the LSI. Intrachip optical interconnects will make it possible to enhance the performance of LSIs even in the post-scaling era. Takenaka is aiming at establishing fundamental technologies for one-chip super computers and photonic router chips using monolithic integration of Ge MOSFETs and Ge photodetectors on a Si substrate.[i]
-

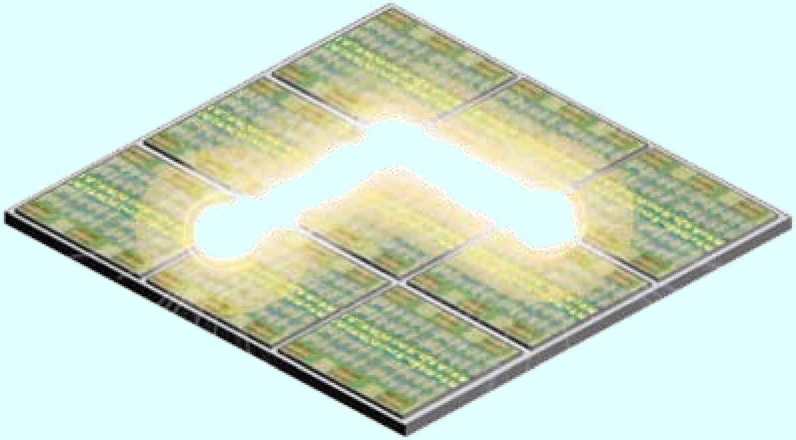
[i] M. Takenaka, S. Tanabe, S. Dissanayake, S. Sugahara, S. Takagi: 21st Annual Meeting of the IEEE Laser & Electro-Optics Society, Newport Beach, US (2008) Paper MN2.

For optical interconnect Ge LSI

GOI MOSFETとGe PDの集積化が必須



超高性能光配線Ge LSIを実現



光配線Ge LSIの技術課題

- ■ 集積化技術

選択酸化濃縮技術

Ge MOSFET, Ge PD, 光導波路を一括集積可能。

低コスト化が可能。

- ■ 接合形成技術

気相ドーピング技術

低リーク電流PN接合が実現。

雪掻き効果を組み合わせて、高感度、高速MSM Ge PDが実現可能。

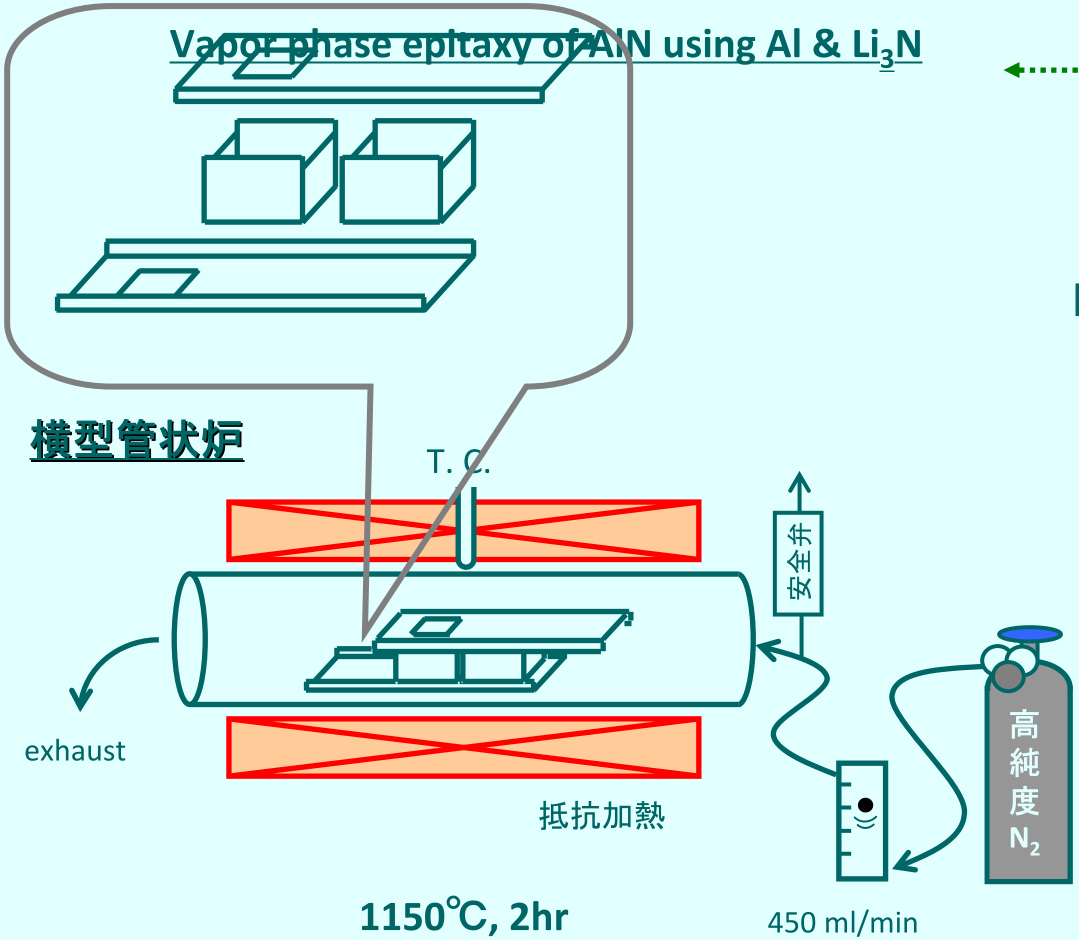
M. Takenaka

Wide gap semiconductors for power switching applications for high frequency devices

- Wide gap semiconductors can replace silicon in high-temperature and power switching applications for high frequency devices, since they show higher saturation velocity and higher break-down voltage than conventional semiconductors.
- Among many wide gap materials III-V nitrides are the most intensively investigated materials for application to light emitting devices. It should also be noted that wide gap nitrides show quite large *thermal conductivity*, and is suited for solving the heat dissipation problem. Wide gap nitrides are therefore expected to have high potential in *optical, electrical and thermal properties suited for optical interconnects* and *OEIC applications*.
- However, the crystalline quality of the nitrides is far below that of silicon, because most of them suffer *high density of misfit dislocations* due to the lattice mismatch caused by heteroepitaxy on sapphire substrates. Use of nitride substrates for homoepitaxy has crucial importance to improve crystallinity of nitride materials. In our project Kangawa proposes a novel crystal growth process for AlN based on the first principle thermodynamic analysis. [i]
-

  [i] T. Nagano, Y. Kangawa, and K. Kakimoto, "Influence of compositional changes of source materials on AlN synthesis using Li-Al-N solvent", *Phys. Stat. Solidi*, C6, No.52, (2009) S336-S339.

For high quality AlN substrate

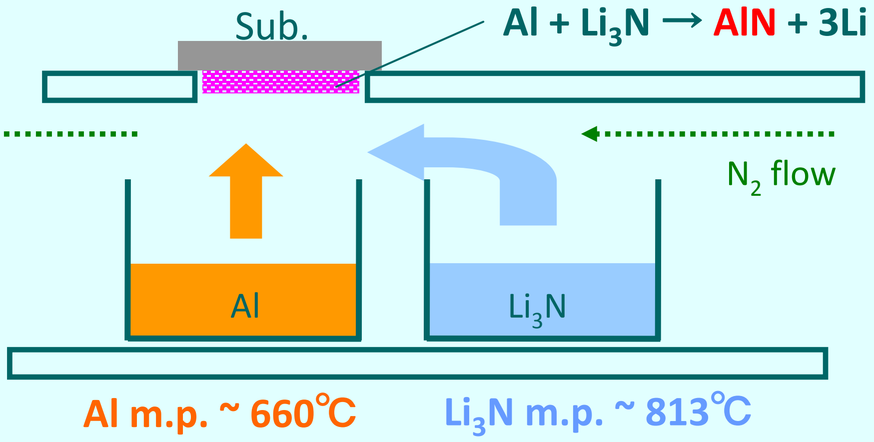


Vapor phase epitaxy of AlN using Al & Li_3N

横型管状炉

1150℃, 2hr

450 ml/min



$Al + Li_3N \rightarrow AlN + 3Li$

Al m.p. ~ 660℃

Li_3N m.p. ~ 813℃

AlN / AlON / Sapphire
RIAM, Kyushu Univ.

7mm角

4. Nanocarbons and molecular electronics

Carbon Nanotubes

- Carbon nanotube (CNT) was discovered by Iijima when he was observing carbon fibers using a high-resolution transmission electron microscope. [i] CNT is a seamless cylinder of carbon network by rolling a sheet of graphene, in which carbon atoms align to make a honeycomb-type hexagonal arrangement. Carbon nanotubes are classified into single wall nanotubes (SWNT) and multi wall nanotubes (MWNT). The radius of the cylinder ranges between 1 to 10 nm, and the length may be as long as 10 μm. On rolling up to form a cylinder the carbon network can be connected obliquely with a chiral vector ***Ch*** defined by a linear combination of two unit vectors $\boldsymbol{a}1$ and $\boldsymbol{a}2$ of hexagonal lattice as $\boldsymbol{Ch}=n\boldsymbol{a}1+m\boldsymbol{a}2$, where n and m are integers. Carbon atoms align in zigzags when n and m are zero. If n and m take equal nonzero values, i.e., $n=m\neq0$, and if the difference between n and m takes a value of multiple of three, carbon atoms make pairs to form an uneven armchair-like structure. CNTs with an armchair-like structure become metallic. On the other hand, for other combinations of (n, m), CNTs take the zigzag structure and become semiconducting.
-

  [i] S. Iijima: Nature 354 (1991) 56.

CNT can be an ideal conductor

- Metallic CNT possesses a ballistic electronic transport property originated from the linear relationship between wavenumber *k* and energy *E* in the energy band dispersion curve.
- From the I-V characteristics it has been elucidated that the electron mean free path is as long as a few micrometers. Contrary to the copper wiring which suffers breaking down due to an *electromigration* for the current density exceeding 10^7A/cm^2, CNT is robust to a current density as large as 10^{10}A/cm^2.
- So the CNT can be an *ideal conductor for wiring via in the next-generation devices*.[i]
- The thermal conductivity of SWNT-CNT has been theoretically estimated by Berber et al. to be 6600 W/m·K, [ii] which is far above that of diamond, 2000 W/m·K and is proved to be a promising material to overcome the *heat dissipation problem* in ULSI.

[i] Y. Awano: IEICE Trans. Electron. E89-C(11) (2006) 1499.

- [ii] S. Berber, Y.-K. Kwon and D. Tomanek: Phys. Rev. Lett., 84 (2000) 4613.

Semiconducting Nanocarbons for FET

- Field effect transistor (FET) employing the semiconducting CNT shows *superior properties exceeding the Si MOSFET*.[i] However, there are so many problems to be solved. The technology for discrimination and *control of the chirality* of CNT is still under development. It is also difficult to fabricate CNTs by *self-organization* at arbitrary point at which we design.
- Recent research has revealed the peculiar nanoscale effects and *edge effects* in physical properties of *graphene*. In addition, the fine processing technology enables us to fabricate the electronic devices based on the nanographenes, and nano-carbon materials.
- Thus nano-carbons are attracting much attention all over the world as a promising key material for the innovative next-generation electronic devices. In our research project, Wakabayashi studies the electronic physical properties in the nano-carbon materials, and attempts to design the new electronic/spintronic devices based on nano-carbon with the support of the computational method.[ii]
-

  [i] "IBM Creates World's Highest Performing Nanotube Transistors", http://domino.research.ibm.com/comm/pr.nsf/pages/news.20020520_nanotubes.html
- [ii] K. Wakabayashi, Y. Takane, M. Yamamoto, and M. Sigrist: CARBON (Elsvier) (2008) in press,

5. Organic Materials for flexible electronics

Organic transistors

- Flexible electronics made with organic transistors may enable technologies such as low-cost sensors on product packaging and electronic paper displays. Thanks to recent development in organic LED, organic electronics has become the matter of interest for practical use.
- However, organic materials show electrical performances far below inorganic semiconductors. Therefore it is necessary to improve electronic transport properties represented by the low carrier mobility. Yasuda of our team aims to fabricate high-performance organic field-effect transistors using enhanced intrachain carrier transport along uniaxially aligned π-conjugated polymers.[i]

- [i] T. Yasuda, M. Saito, H. Nakamura, and T. Tsutsui: Chem. Phys. Lett. 452 (2008) 110.

6. Summary

- I have introduced recent development in materials researches targeting next-generation innovative devices based on nanoscience, with a particular emphasis to spintronics.
- Some of recent achievements of the JST-PRESTO project “Materials and Processes for Next Generation Innovative Devices” are also briefly reviewed.