ICTMC18 Salzburg, Keynote Talk, KN-03
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Comprehensive report on achievements of the JST Project
- Materials and Processes for Next-Generation Innovative Devices-

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Japan Science and Technology Agency

27–31 August 2012
SALZBURG

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Introduction

HOW THE PROJECT WAS DESIGNED AND ORGANIZED?

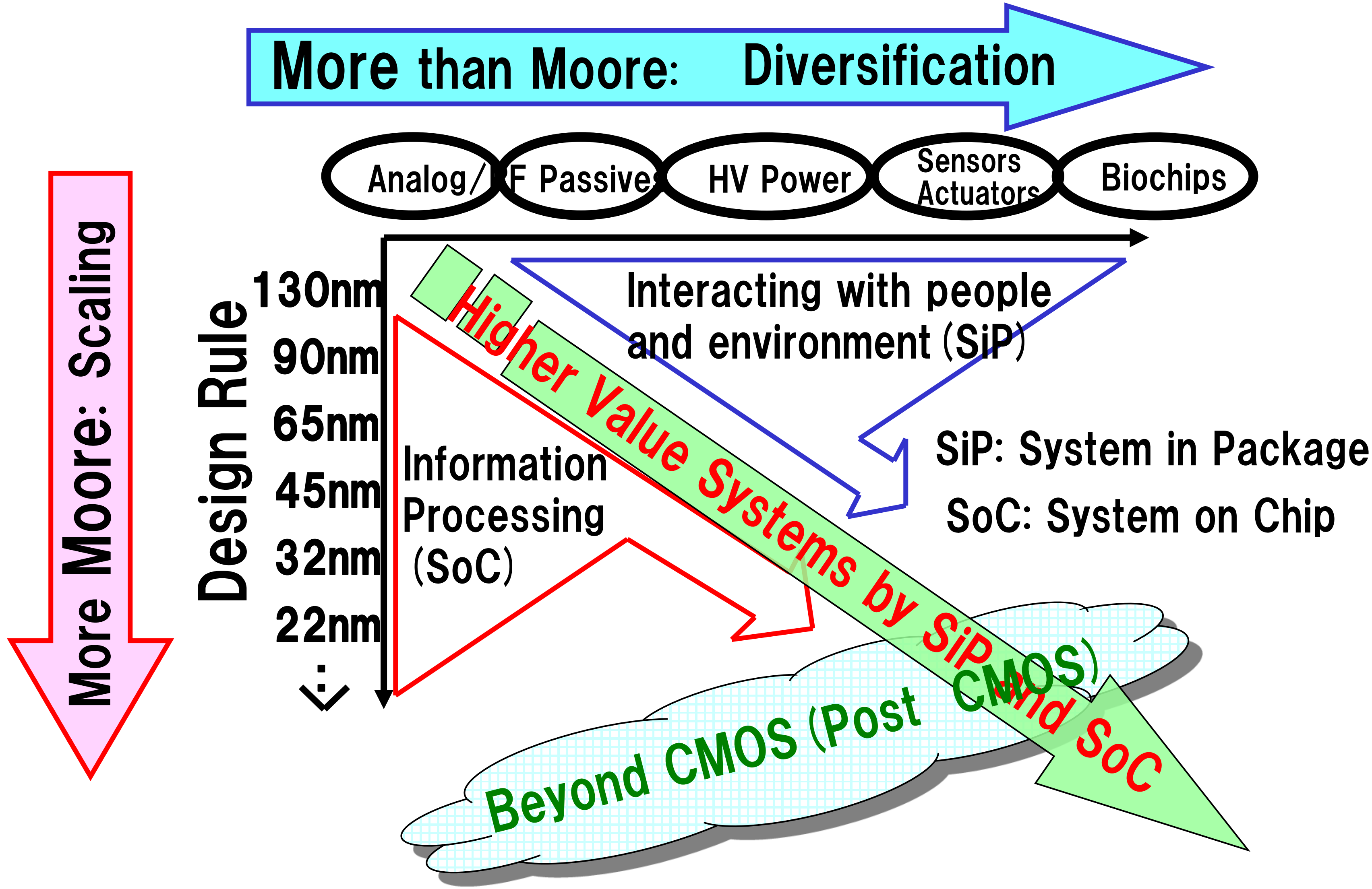
Background of the Project

- Silicon crystals used for semiconductor integrated circuits represented by CMOS are 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.

Three ways to overcome the limit

- ITRS (International Technology Roadmap for Semiconductors) published a roadmap to overcome the limit (2005)
  - More Moore: extension of the limit by invention of novel technologies
  - More than Moore: addition of higher functionalities by integration of different technologies
  - Beyond CMOS: development of devices based on new concept

ITRS roadmap 2005



ITRS International Technology Roadmap for Semiconductors 2005

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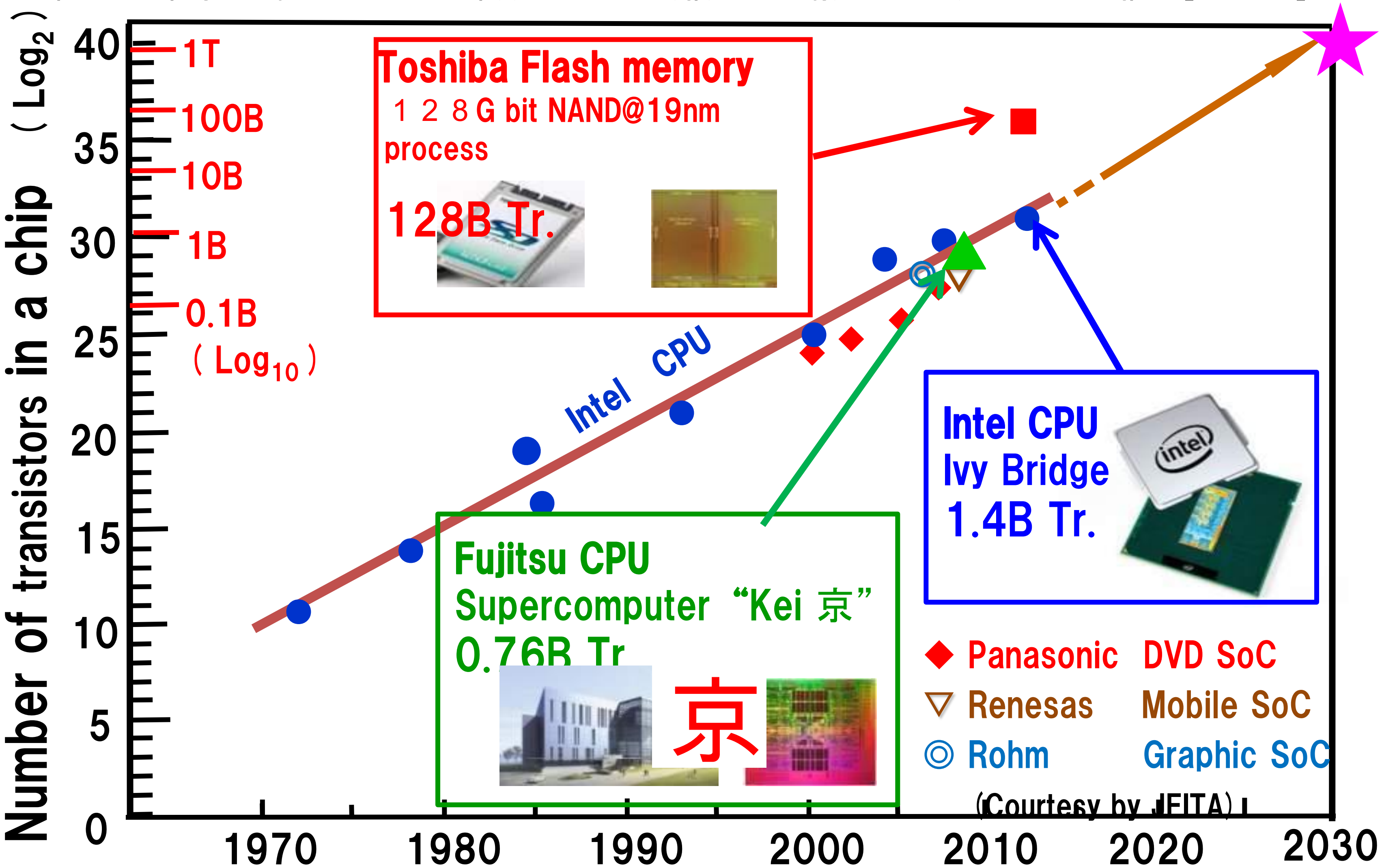
Demand for more integration : Moore's Law

Intel CPU plots, except Ivy Bridge, are shown in http://www.intel.com/jp/technology/mooreslaw/index.htm?iid=jpIntel_tl+moores_law



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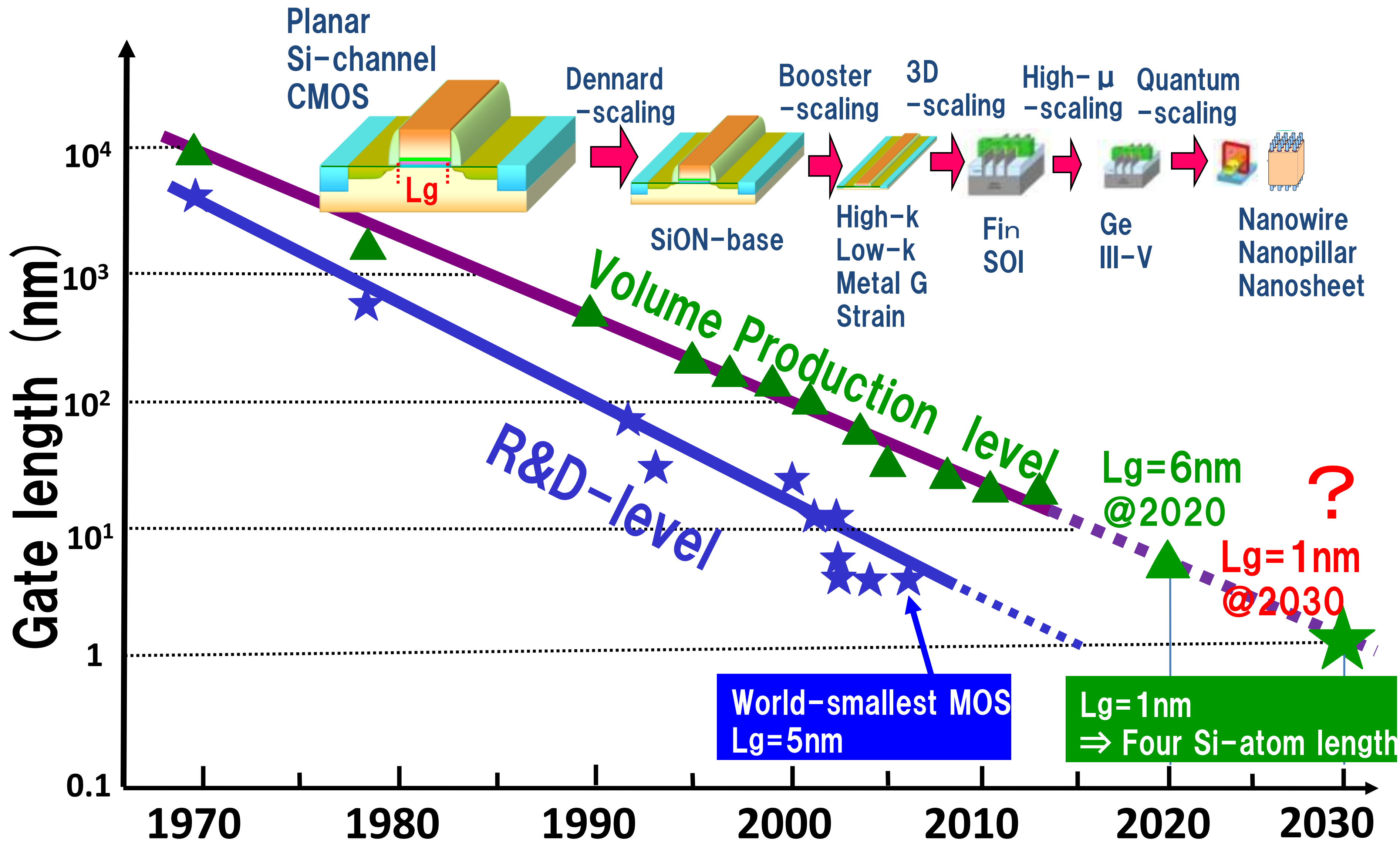
Demand for more miniaturization



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ERM (Emerging research materials)

- ITRS assigned the following materials as ERM.
- 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･･） (Spin-injection MRAM is already out of ERM in 2012)
- Multiferroics (Complex Metal Oxides)
- Interfaces and Heterointerfaces (Electrical and spin contacts)

How the Project was designed

- According to the ITRS roadmap Japanese government determined Nanoelectronics Projects
- **METI / NEDO MIRAI III project (from 2006 FY)**
- **METI Nanoelectronics project**
  Non-Si channel, Nanowire, XMOS (from 2007FY)
- **MEXT→Strategic Sectors for beyond CMOS (2007FY)**
  - **JST Sato-PRESTO project**
  - **JST Watanabe-CREST project**
- **Cabinet selected 30 Researchers for Cutting Edge Research Support Program (FIRST) (Yokoyama, Ohno, Arakawa, Esashi, Kawai, ・・・) (2009FY)**
- **Tsukuba Innovation Arena (TIA) [Japanese version of IMEC] (METI, MEXT, AIST, NIMS, Tsukuba Univ.)**

Strategic Sector (Target of Research)

from MEXT for Next-Generation Devices

- "Research and development of materials and nano-processes to realize devices with novel concept, novel functionality and novel structure"
- It lists following fields as important targets
    1. Development of non silicon materials for beyond-CMOS
    2. Pioneering materials for novel concept-devices by using combined functionalities of photon, electron and spin
    3. Development of novel devices based on nano-scale fabrication
    4. Development of thin flexible resilient materials

Japan's National Projects for Next Generation Nanoelectronics Devices

FY | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015

METI
- METI / NEDO MIRAI III project
- METI Nanoelectronics project (Non-Si channel, Nanowire, XMOS)

MEXT/JST

JST PRESTO (Personal Type)
- JST Sato-PRESTO project
- JST Sato-PRESTO project
- JST Sato-PRESTO project

JST CREST (Team Type)
- JST Watanabe-CREST project (2007start)
- JST Watanabe-CREST project (2008start)
- JST Watanabe-CREST project (2009start)

Cabinet's Cutting Edge Research Support Program (FIRST) 30 Researchers (Yokoyama, Ohno, Arakawa, Esashi, Kawai, ・・・)

METI, MEXT, AIST, NIMS, Tsukuba Univ.
Tsukuba Innovation Arena (TIA)

Sato-PRESTO Project

- The PRESTO* project "**Materials and Processes for Next Generation Innovative Devices**" started in 2007 FY
- The scope of this project involves
- Spintronics devices and materials
- Semiconductor nano-electronics
- Wide-gap semiconductors
- Molecular and organic electronics

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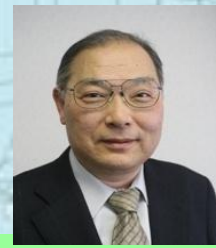
* *Precursory Research for Embryonic Science and Technology* (Sakigake)

Organization



Suprevisor

Advisors

Office

Research Manager
Administrative Manager

JST Staffs

33 Researchers
stage (1): 11, stage (2): 10, stage (3): 12

Duration and Budgets

- Duration: 3.5 years
- Budget: 40MYen (~400KEuros) per person
- Members: 33 (Total 1.4BYen~14MEuro)
- Average age at adoption: 34.5 years old
- Affiliation: Universities: 25, Government Agencies: 8

For Comparison: Case of Watanabe-CREST
Duration Max 5.5 years
Budget 150-500 M Yen (1.5-5 M Euro) per team
Teams: 18

Research Themes

(1st stage) 11 themes

Researchers	Research Themes
S. Kasai	Research on stochastic resonance nanodevices and their integration for novel noise-robust information processing systems
E. Saitoh	Spintronics based on spin currents and spin-photon coupling in dielectrics
S. Shiraishi	Spin current control in molecules
Y. Takahashi	Development of half-metal at RT for spintronics devices
T. Taniyama	Control of spin polarization and its application to tunable spin sources
A. Tsukamoto	Ultrafast manipulation and measurement of spin dynamics by femtosecond laser pulse
N. Fukata	Development of semiconductor nanowires for the realization of vertical three-dimensional semiconductor devices
S. Murakami	Unified theory of spin and heat currents and its applications
T. Yasuda	High-performance organic field-effect transistors using intrachain carrier transport along uniaxially aligned p-conjugated polymers
A. Yamaguchi	Study in novel electromagnetic properties of modulated and/or periodic magnetic strucure composed of nanoscale magnets
K. Wakabayashi	Design and physical properties forecast of nano-carbon electronic devices based on computational methods

spintronics	wide-gap	semiconductor	molecules/organics	others

Research Themes

(2nd stage) 10 themes

Researchers	Research Themes
R. Katayama	Novel optical function using photonic nano-structure of polar wide-gap semiconductors
I. Kawayama	Creation of an optically-generated-flux-quantum nano-device with superconducting nanobridges
Y. Kangawa	Fabrication of III-nitride substrate for optoelectronic integrated circuit and control of its heat transfer
W. Kobayashi	Development of materials for thermoelectronics
T. Susaki	New functionalities at the interfaces of wide-gap oxides
M. Takenaka	Ge Nano Electro-Optic LSI for intrachip optical interconnects
T. Nakaoka	Charge/spin/photon hybrid single-electron device based on quantum dot
K. Hamaya	Development of single-electron spin transistors with silicon-based nanostructures
T. Fukumura	Wide-gap ferromagnetic semiconductor devices
N. Mizuochi	Quantum information devices by single paramagnetic color center in wide-bandgap semiconductor

spintronics	wide-gap	semiconductor	molecules/organics	others

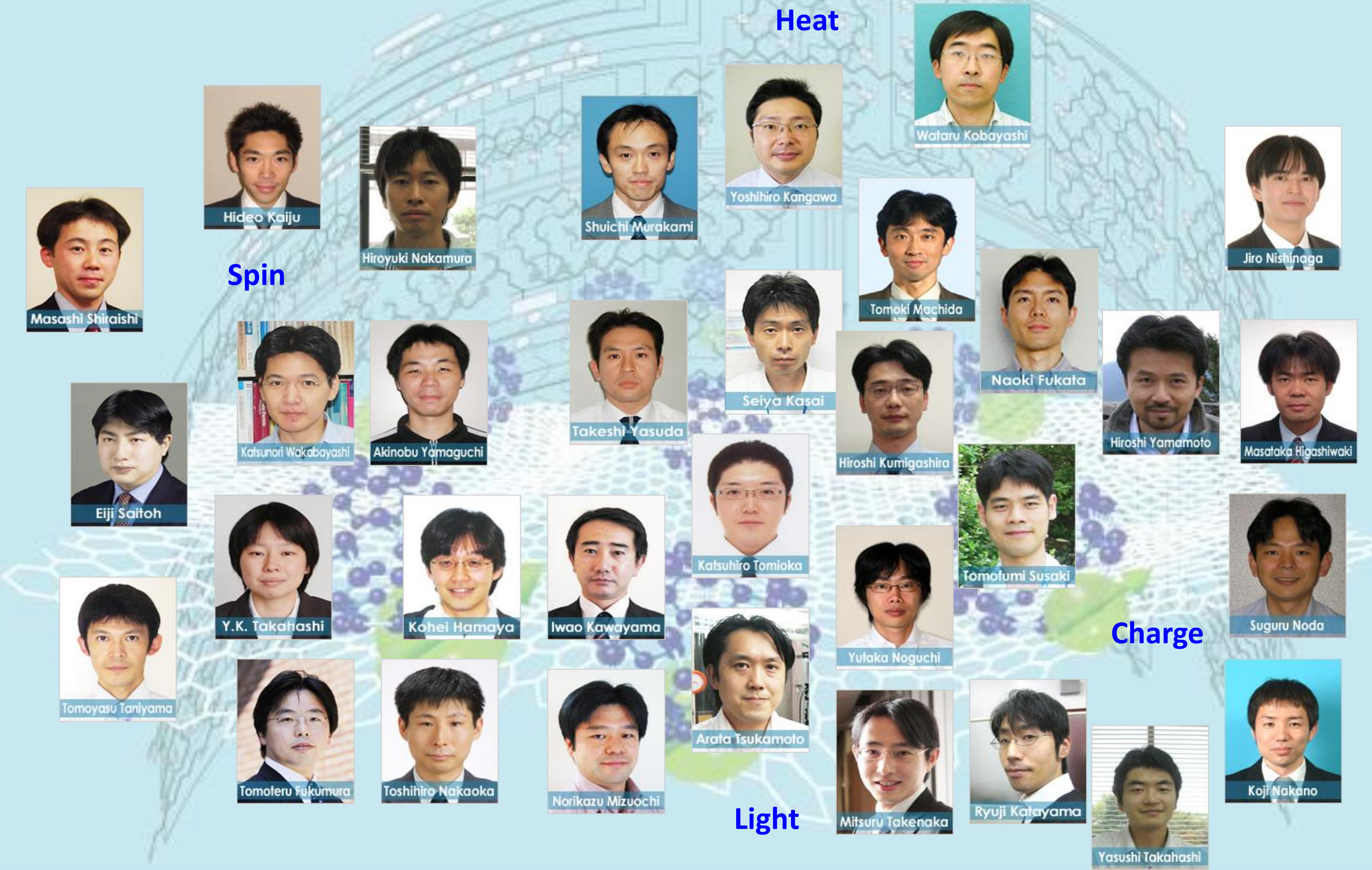
Research Themes

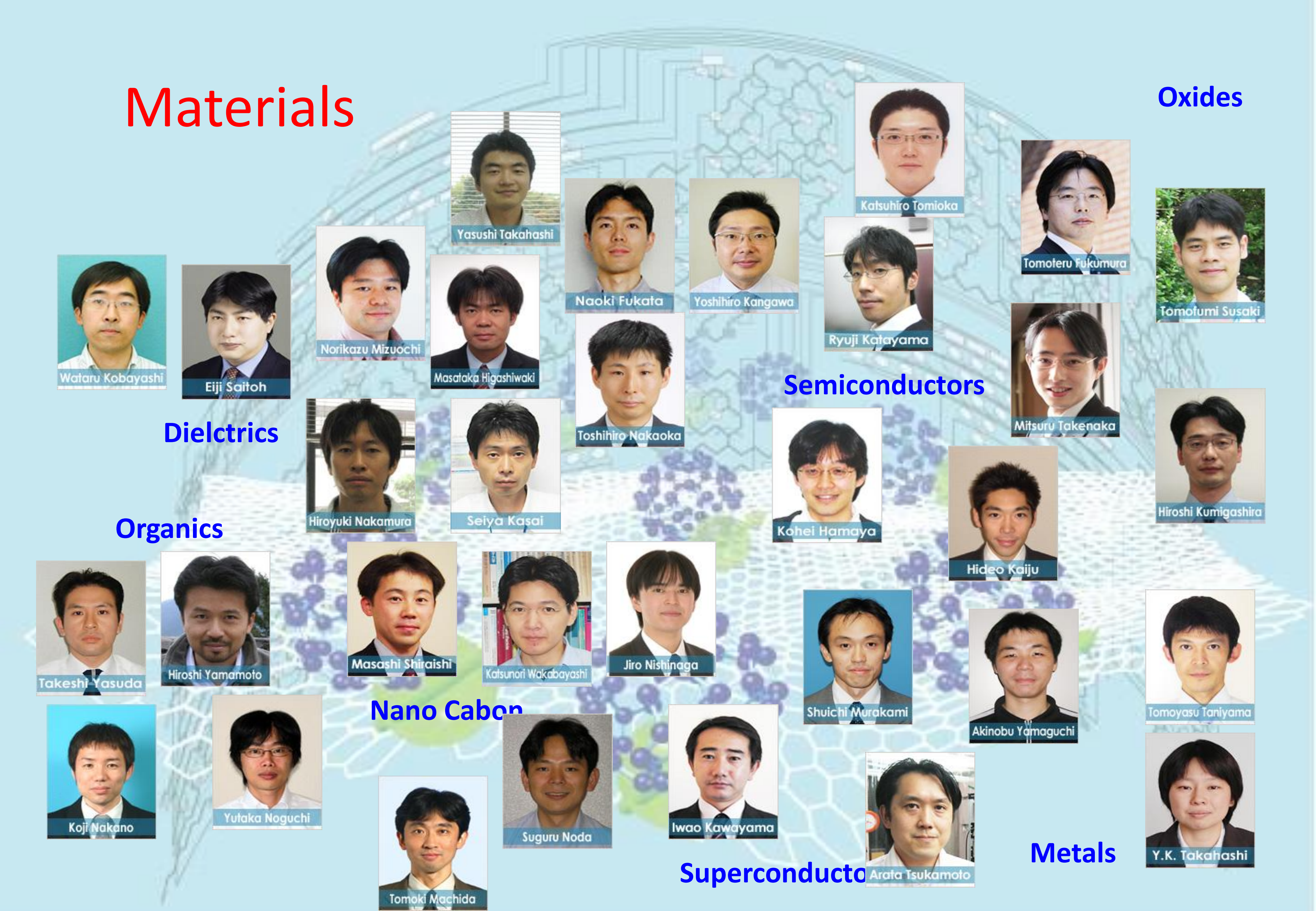
(3rd stage) 12 themes

Researchers	Research Themes
H. Kaiju	Creation of novel high-performance non-volatile memory using spin quantum cross devices
H. Kumigashira	Development of memory with low environmental stress using nano-capasitor structure
Y. Takahashi	Silicon Raman laser using photonic crystal nanocavity
K. Tomioka	Control of Si/III-V super-heterointerface and development of nanowire-based tunneling FETs
K. Nakano	Development of high-performance organic field-effect transistors through the control of molecular arrangement
H. Nakano	Spin manipulation in dielectric-channel transistors
J. Nishinaga	New devices using fullerene / III-V compound semiconductor heterostructures
H. Noguchi	Development of organic single-electron transistors controlled by photo-induced gate signal
S. Noda	Facile implementation of nanocarbons with selectable higher-order structures
M. Higashiwaki	Interface control and device application of III-oxide/nitride semiconductor composite structures
T. Machida	Physics and application of quantum dot devices based on graphene
H. Yamamoto	Development of novel organic devices based on electronic correlation

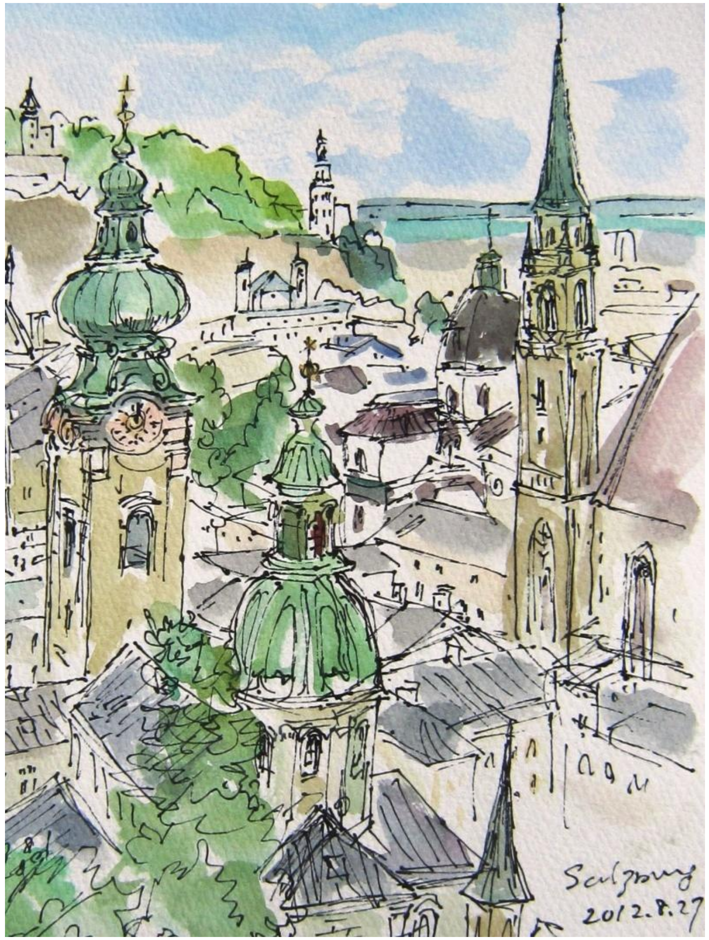
spintronics | **wide-gap** | **semiconductor** | **molecules/organics** | **others**

Fields


Heat
Wataru Kobayashi
Yoshihiro Kangawa
Hideo Kaiju
Hiroyuki Nakamura
Shuichi Murakami
Jiro Nishinaga
Masashi Shiraishi
Spin
Tomoki Machida
Naoki Fukata
Seiya Kasai
Takeshi Yasuda
Katsunori Wakabayashi
Akinobu Yamaguchi
Hiroshi Kumigashira
Hiroshi Yamamoto
Masataka Higashiwaki
Eiji Saitoh
Katsuhiro Tomioka
Tomofumi Susaki
Y.K. Takahashi
Kohei Hamaya
Iwao Kawayama
Suguru Noda
Charge
Yutaka Noguchi
Tomoyasu Taniyama
Arata Tsukamoto
Tomoteru Fukumura
Toshihiro Nakaoka
Norikazu Mizuochi
Koji Nakano
Mitsuru Takenaka
Ryuji Katayama
Light
Yasushi Takahashi


Materials
Oxides
Yasushi Takahashi
Katsuhiro Tomioka
Tomoteru Fukumura
Tomofumi Susaki
Naoki Fukata
Yoshihiro Kangawa
Ryuji Katayama
Wataru Kobayashi
Eiji Saitoh
Norikazu Mizuochi
Masataka Higashiwaki
Toshihiro Nakaoka
Semiconductors
Mitsuru Takenaka
Dielctrics
Hiroyuki Nakamura
Seiya Kasai
Kohei Hamaya
Hiroshi Kumigashira
Organics
Hideo Kaiju
Takeshi Yasuda
Hiroshi Yamamoto
Masashi Shiraishi
Katsunori Wakabayashi
Jiro Nishinaga
Shuichi Murakami
Akinobu Yamaguchi
Tomoyasu Taniyama
Nano Cabon
Koji Nakano
Yutaka Noguchi
Suguru Noda
Iwao Kawayama
Tomoki Machida
Superconducto
Arata Tsukamoto
Metals
Y.K. Takahashi

さきがけ PRESTO



ACHIEVEMENTS

Spintronics devices and materials

Semiconductor nanoelectronics

Wide-gap semiconductors

Molecular and organic electronics

Spintronics devices and materials

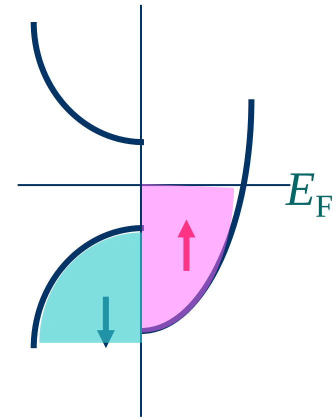
1. **Y. Takahashi developed *Heusler alloy* $Co_2Mn(Ga,Ge)$ with the highest degree of spin polarization**
2. **E. Saitoh succeeded in transfering DC signal through *insulator* by using spin current. He discovered *Spin Seebeck* effect by using thermal spin current**
3. **S. Murakami proposed unified theory of spin and heat and predicted high thermoelectric performance in topological insulators**
4. **S. Shiraishi succeeded in spin injection to single sheet of *graphene***
5. **T. Fukumura succeeded in controlling magnetic properties by gate-voltage in *room temperature ferromagnetic semiconductor* TiO_2:Co**

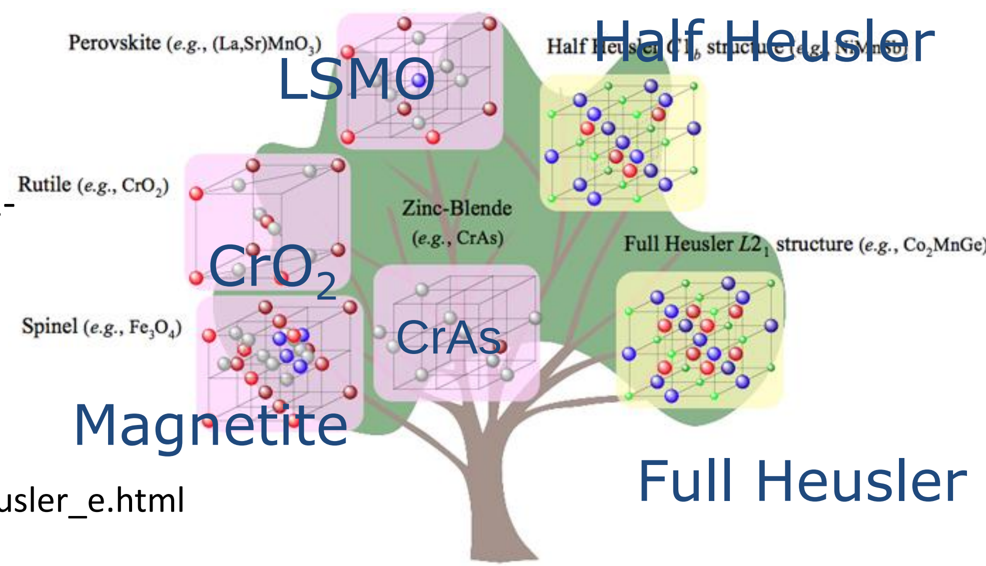
Spintronics devices and materials

HIGH SPIN POLARIZATION
SPIN SOURCE

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.





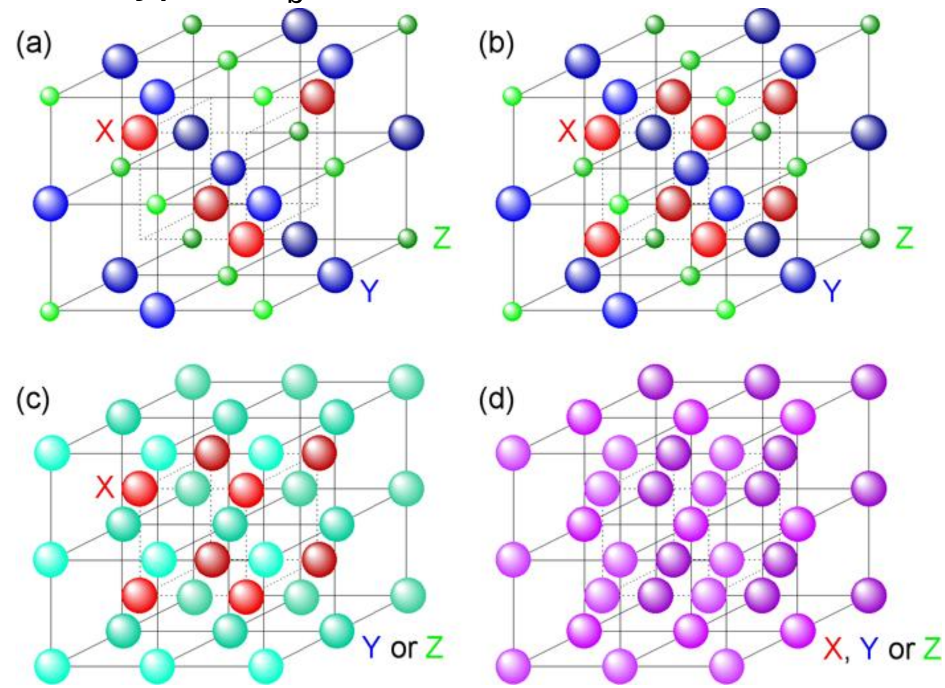
http://www.riken.go.jp/lab-www/nanomag/research/heusler_e.html

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 *L*2_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.



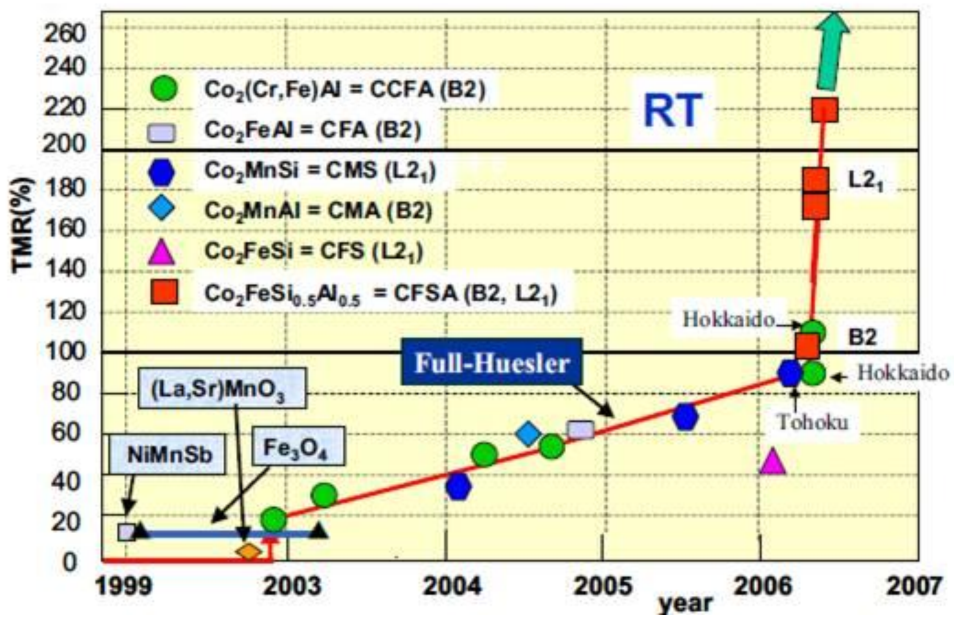
B_2-structure with Y-Z disorder

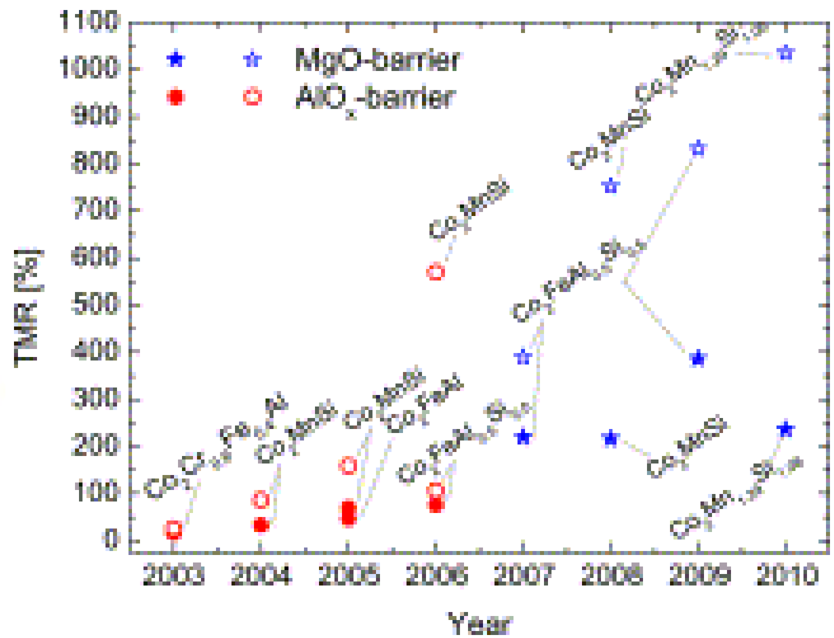
A_2-structure with X-Y and X-Z disorder

Disordered derivatives

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

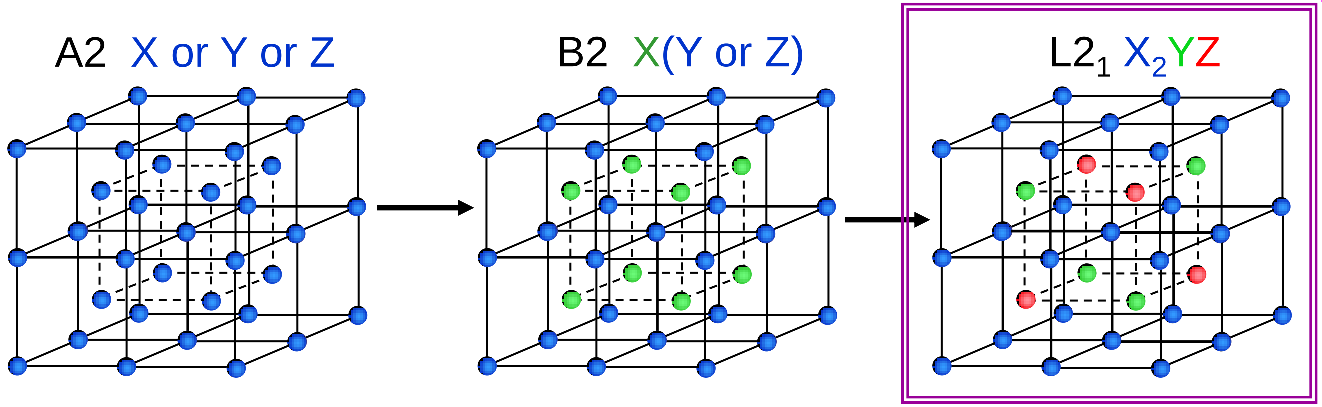
TMR with full Heusler X2YZ alloys





Alloy search for RT half-metal

Co based Heusler alloy、X_2YZ

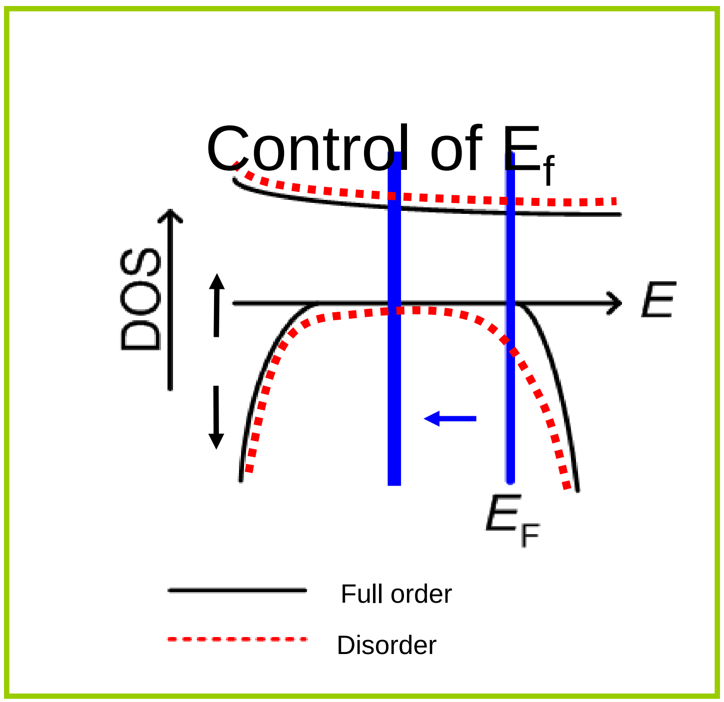


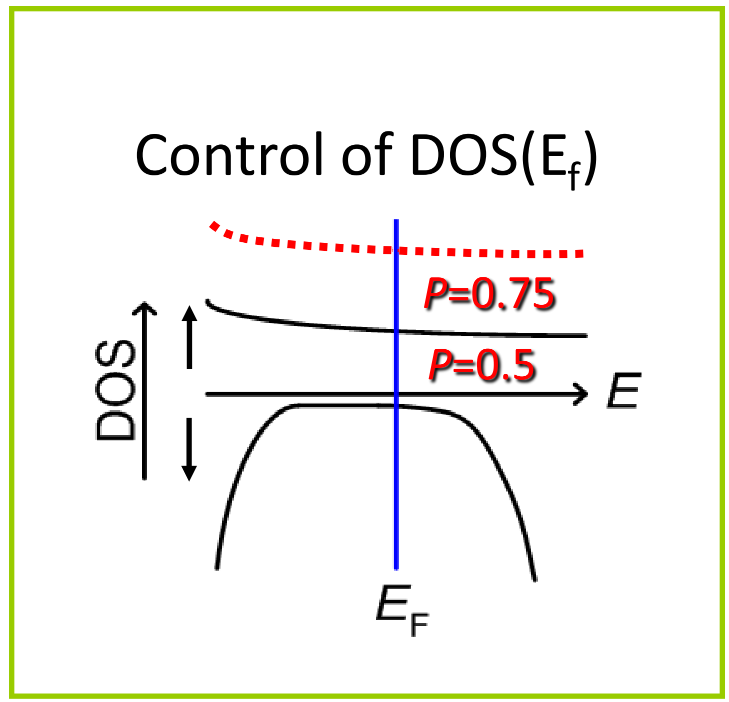
High Tc

Theoretical P=1

However,

Experimental P is low





Search of high spin-polarization half metals using PCARS

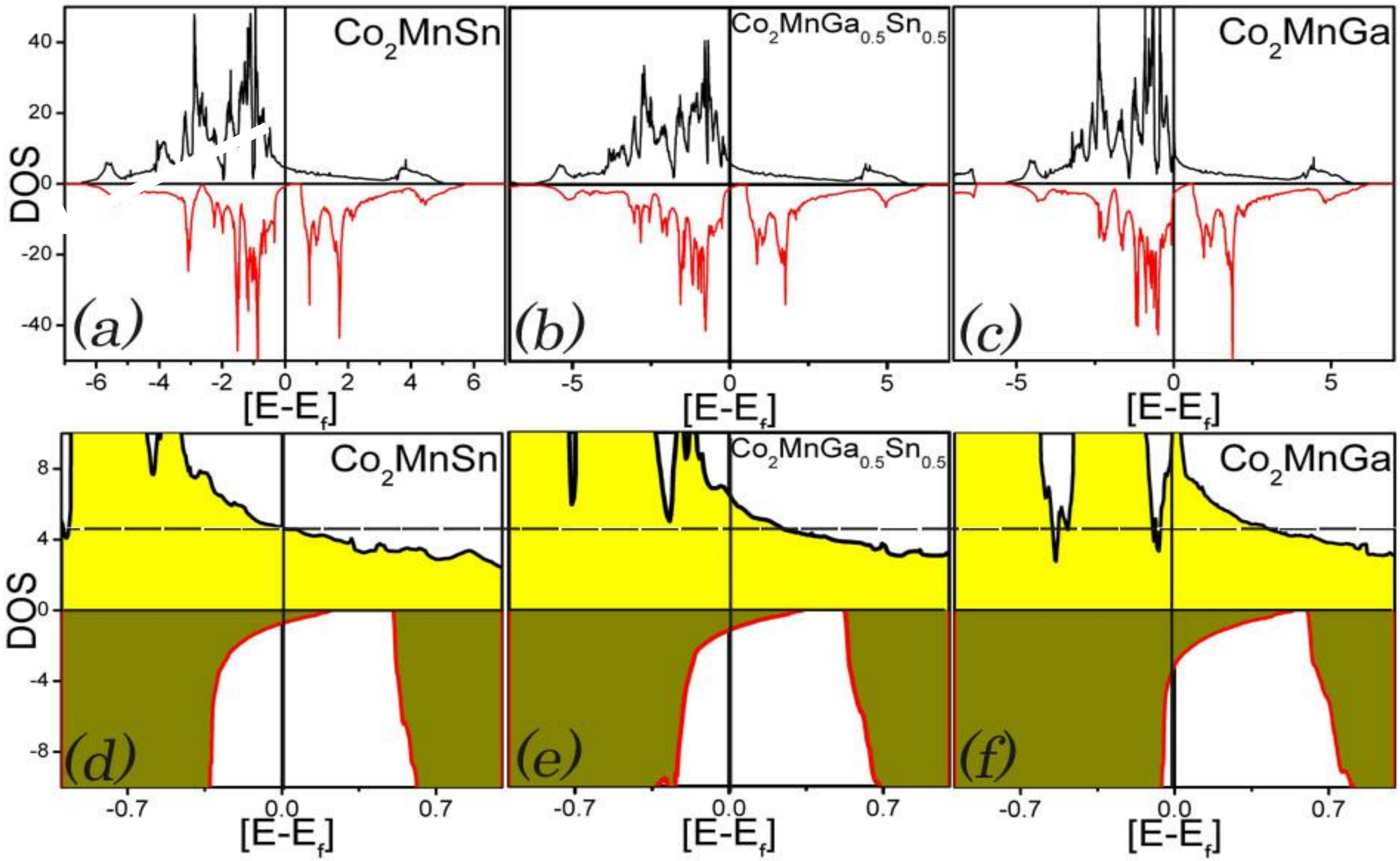
- Aiming at high performance GMR devices Takahashi has investigated as many as 32 full Heusler alloys and found 74% sipn polarization in CoMnGeGa alloy.

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

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

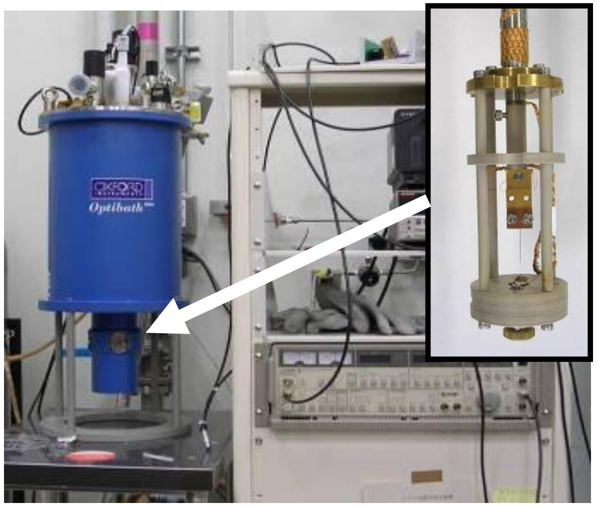
Quaternary alloys	P	Ref.
$Co_2Mn(Ge_{0.75}Ga_{0.25})$	74	
$Co_2Mn(Ga_{0.5}Sn_{0.5})$	72	
$Co_2Fe(Si_{0.75}Ge_{0.25})$	70	
$Co_2FeGa_{0.5}Ge_{0.5}$	68	
$Co_2(Cr_{0.02}Fe_{0.98})Ga$	67	
$Co_2MnGeSn$	67	
$Co_2(Mn_{0.95}Fe_{0.05})Sn$	65	
$(CoFe)_2MnGe$	65	
$Co_2(Mn_{0.5}Fe_{0.5})Ga$	65	
$Co_2(Cr_{0.02}Fe_{0.98})Si$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

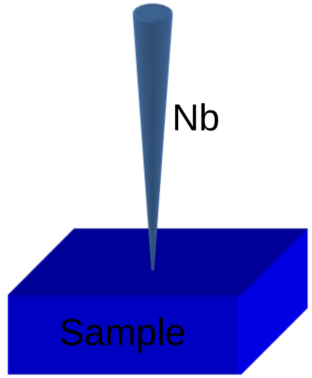
Search of Heusler alloys following band calculation

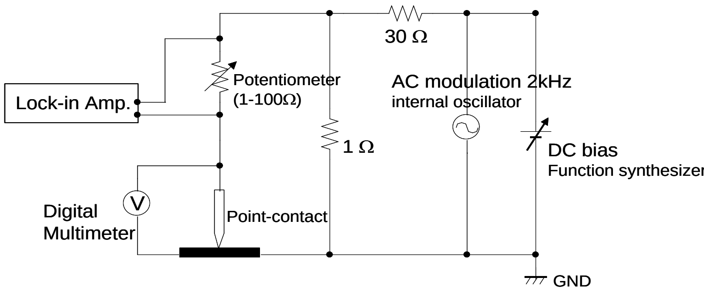


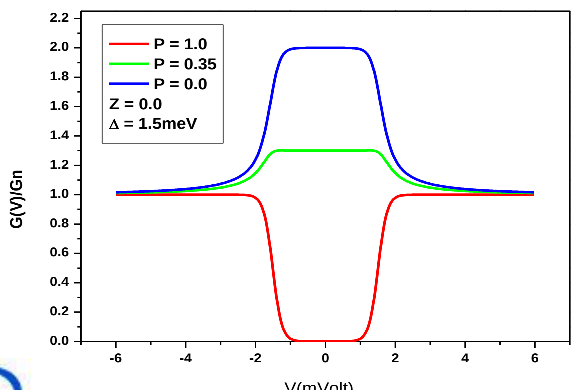
$Co_2MnGa_{1-x}Sn_x$

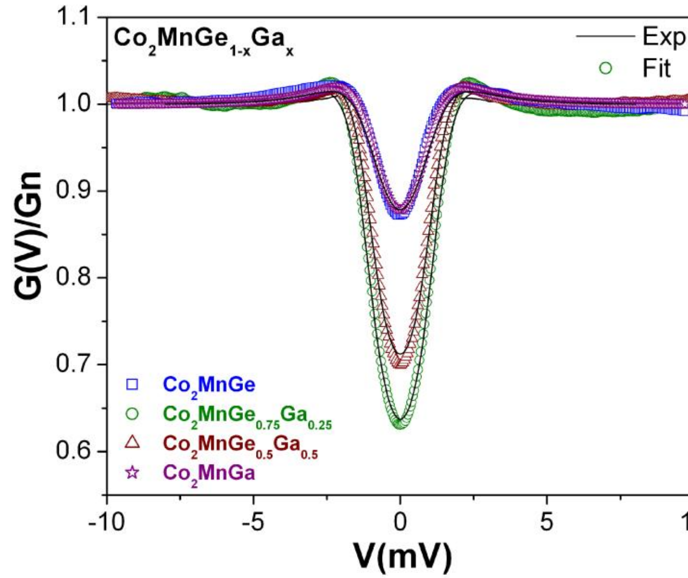
Point contact Andreev reflection (PCAR)

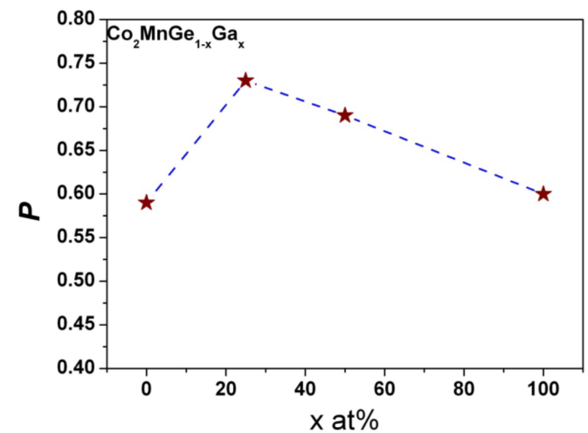












$Co_2MnGe_{0.75}Ga_{0.25}$ shows highest P

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Spintronics devices and materials

SPIN CURRENT

A magnetic insulator transmits electrical signals via spin waves

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

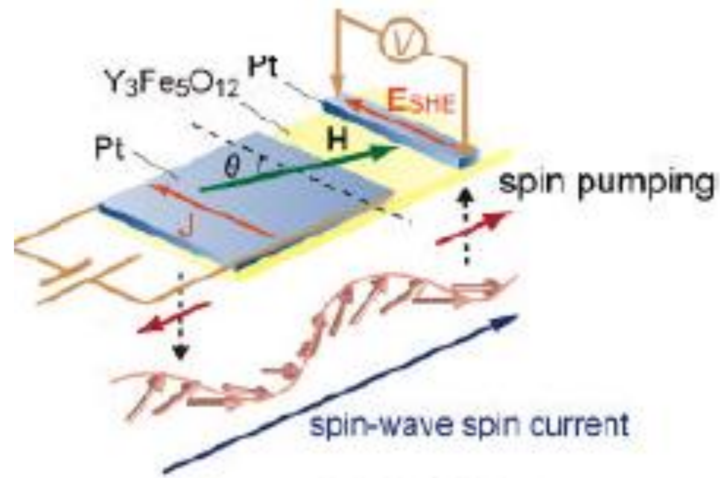
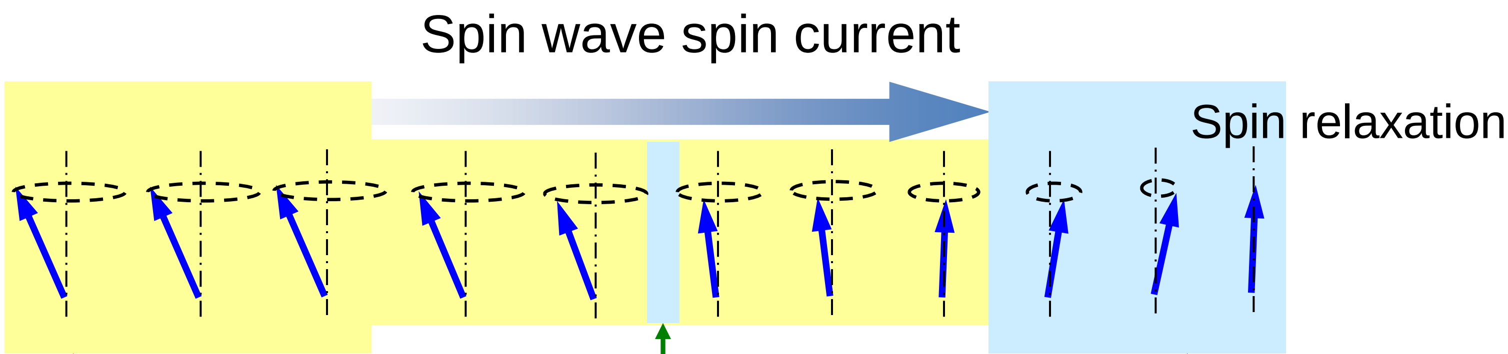


図1 誘電体スピン流伝送の概念図

Y. Kajiwara, K. Harii, S. Takahashi, J. Ohe, K. Uchida, M. Mizuguchi, H. Umezawa, H. Kawai, K. Ando, K. Takanashi, S. Maekawa & E. Saitoh, Nature **464** 262 (2010)

Excitation, modulation and detection of spin wave spin current



Excitation

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

Modulation

- electric field＋SO

Detection

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

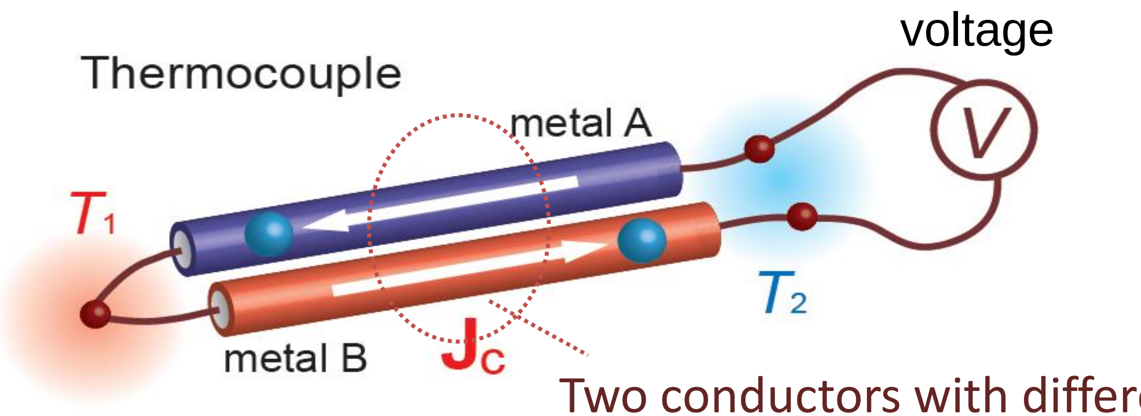
Dielectrics

- application of electric field
- strong interaction with photon

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.

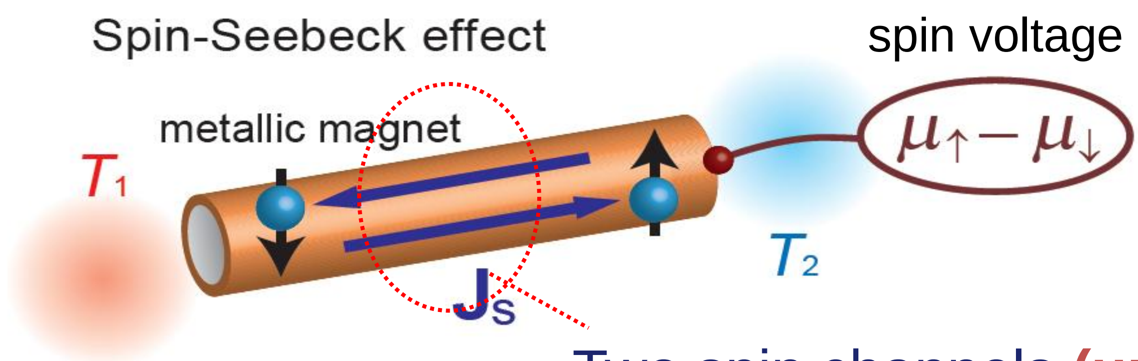
Seebeck and "spin-Seebeck" effects



Electric voltage

Two conductors with different Seebeck coefficients

depending on the density of electrons

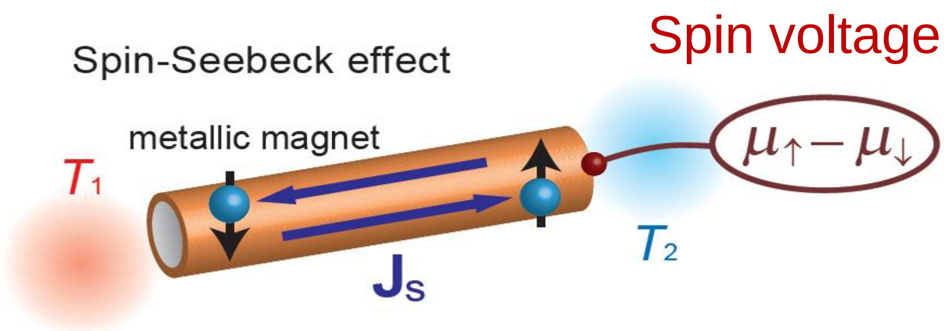


Spin voltage

+ spin currents

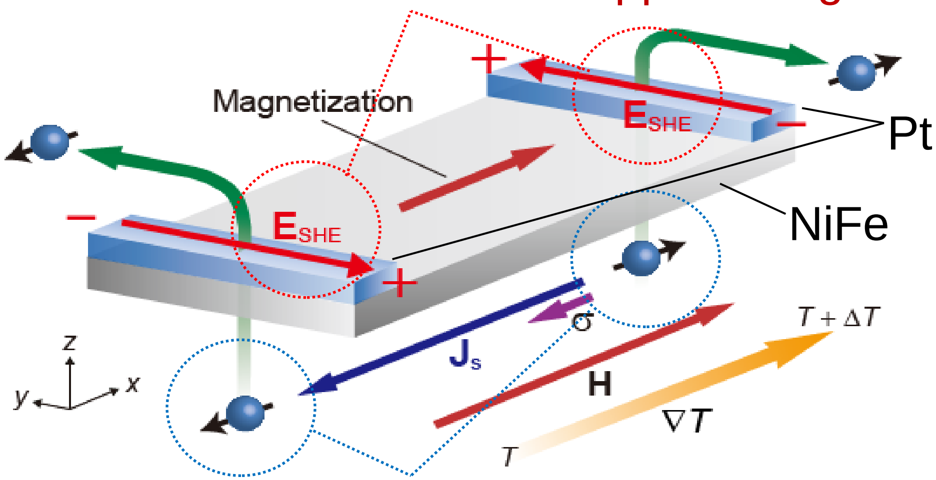
Two spin channels **(up / down)**
with different Seebeck coefficients

Observation of spin-Seebeck effect



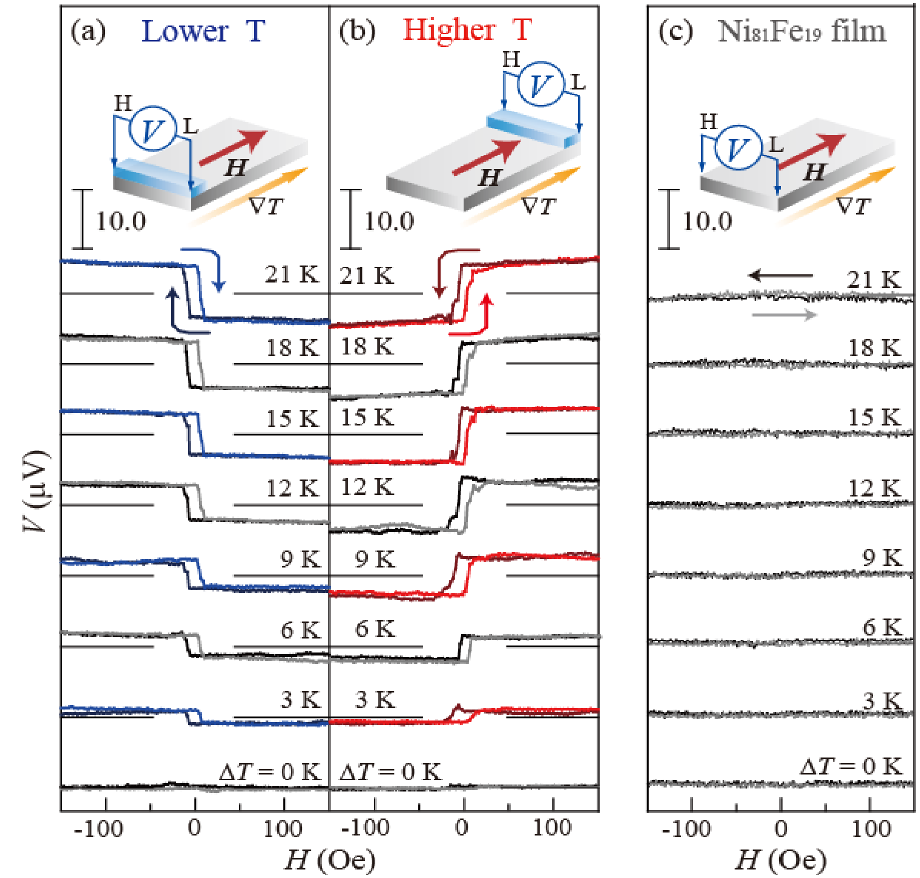
using the inverse spin-Hall effect (ISHE)

electromotive force of opposite signs



Spin voltage of opposite sign

Magnetic field dependence of V



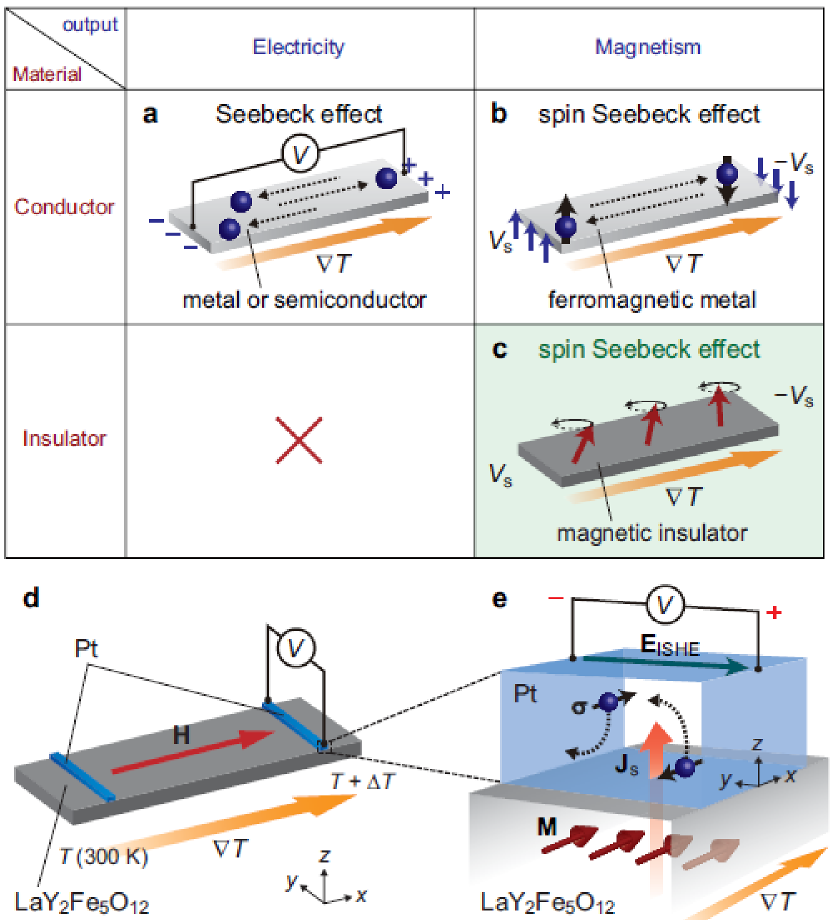
ISHE voltage induced by the spin-Seebeck effect

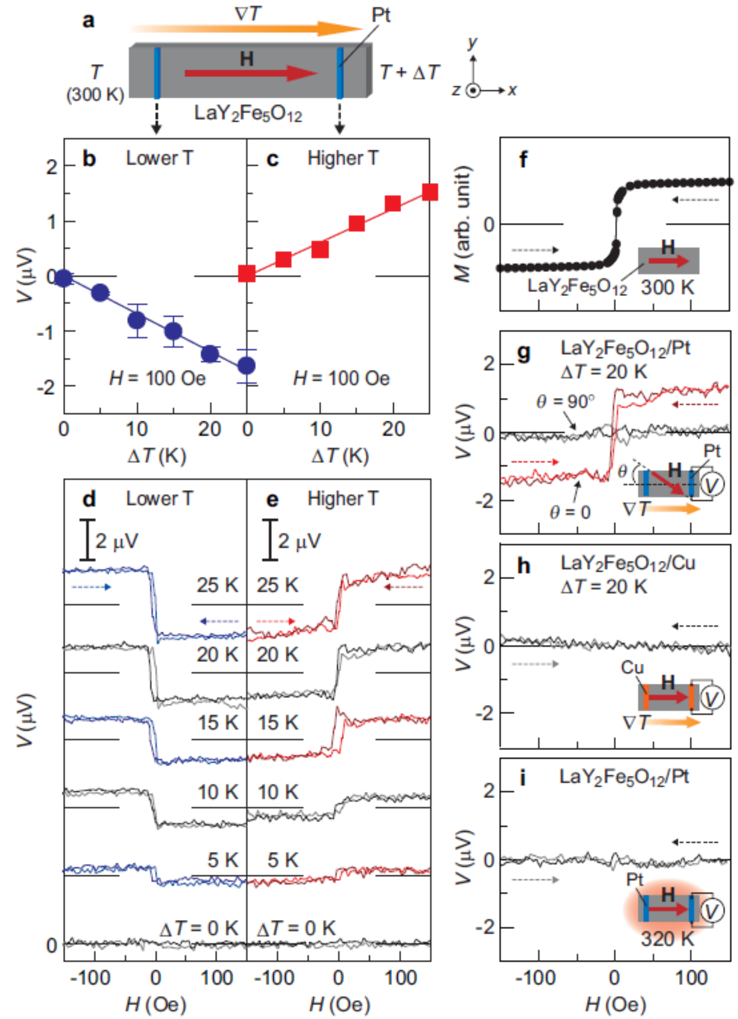
K. Uchida, E. Saitoh *et al.* Nature (2008).

Spin Seebeck insulator

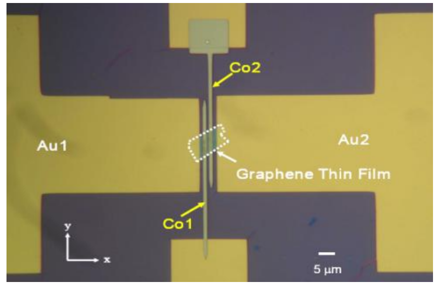
- Saito succeeded in observing spin Seebeck effect in insulating $LaY_2Fe_5O_{12}$

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



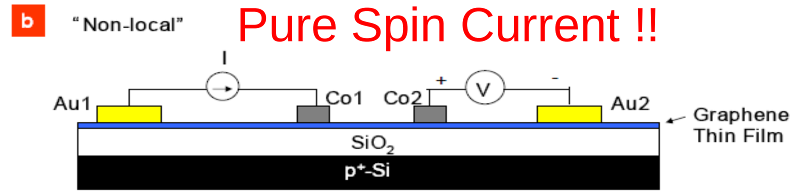


Graphene Spintronics

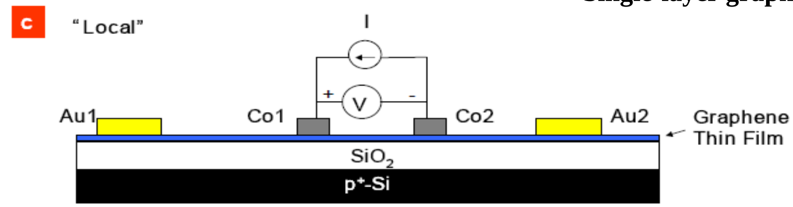


Non-local measurement
(Experimental setup)

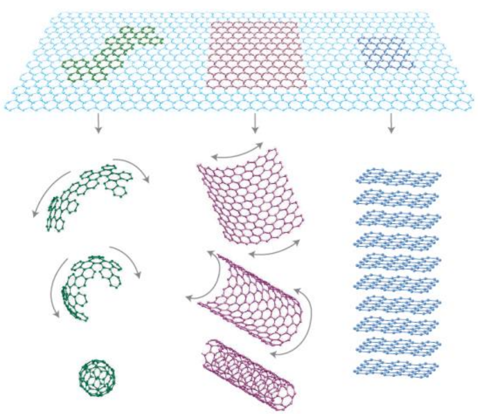
Pure Spin Current !!

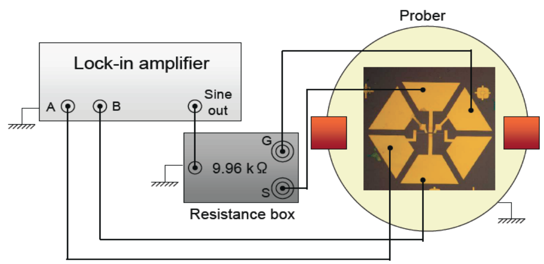


Single-layer graphene

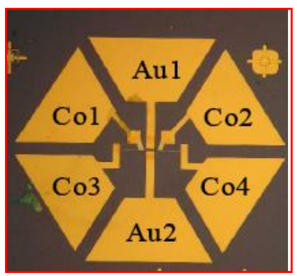


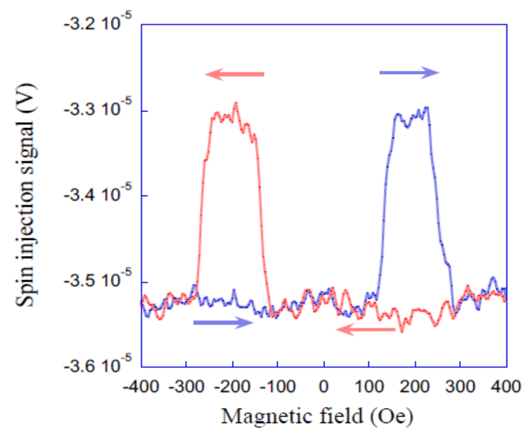
Graphene

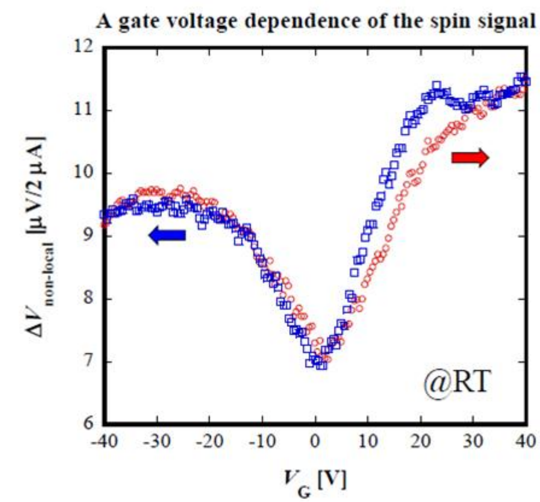




Gate-induced Modulation of Spin Signals in single-layer graphene



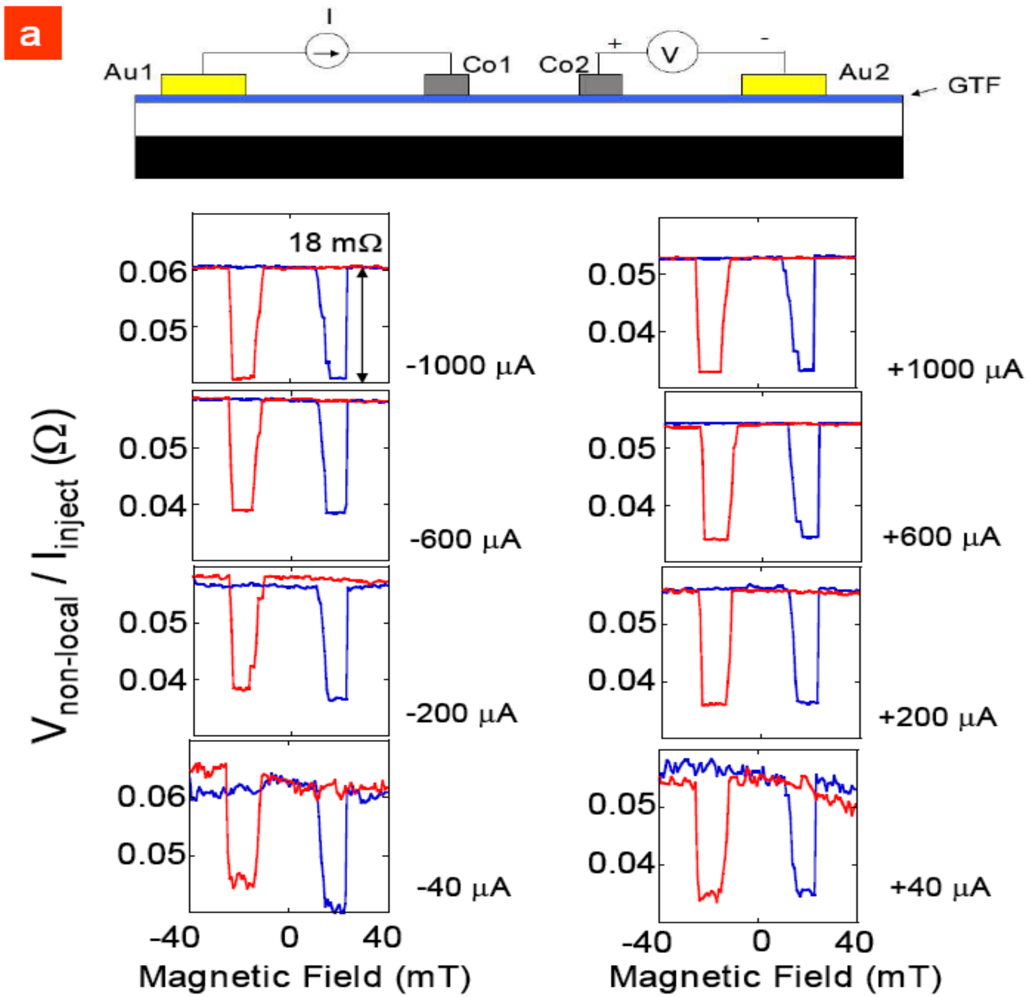




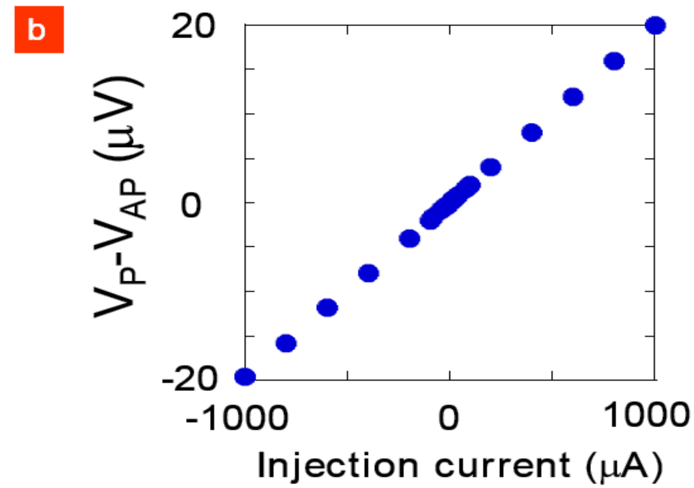
1. Generation of a pure spin current
2. Injection of spins in graphene at ROOM TEMPERATURE

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

Graphene Spintronics

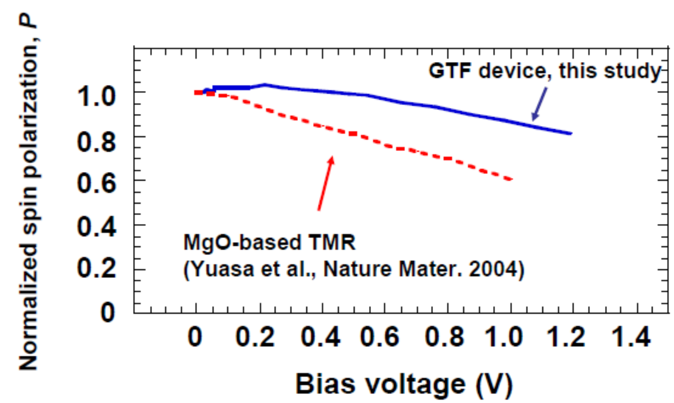


M. Ohishi, M.Shiraishi et al., JJAP 46, L605 (2007).
M. Shiraishi et al., Adv. Func. Mat.,19, 3711 (2009) .
M. Shiraishi et al., Appl. Phys. Express 2, 123004 (2009).



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

Spin polarization is CONSTANT.

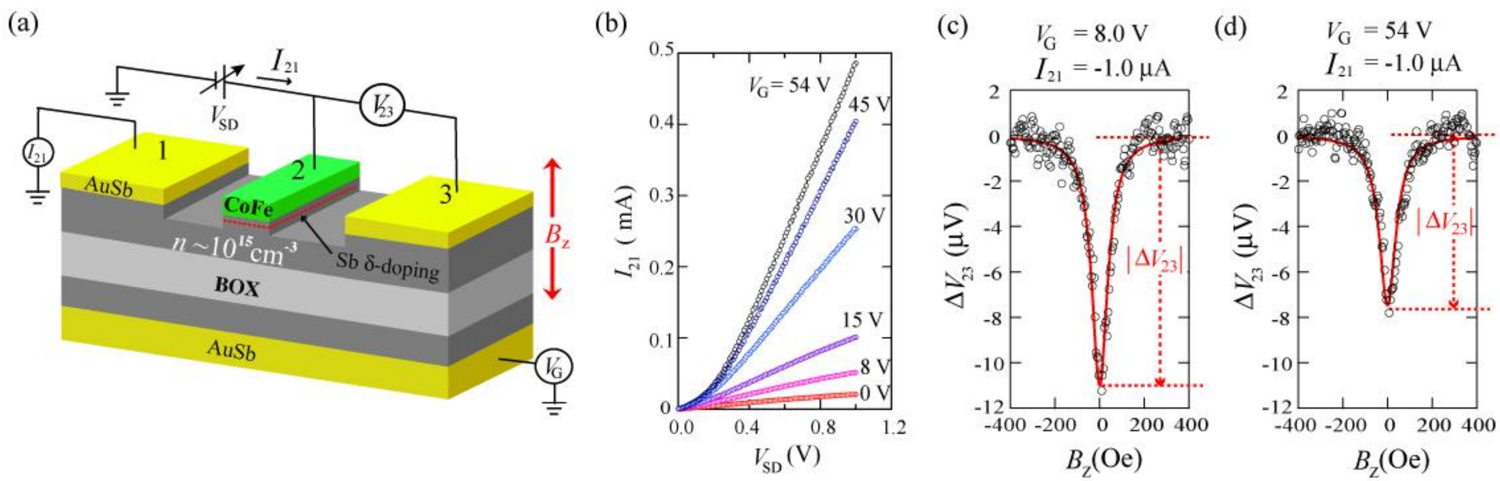


Better robustness than that in MgO-TMR

Japan Science and Technology Agency

Silicon Spintronics

- For application of spintronics, combination with Si technology is very important.
- Previous studies of Si spintronics used only highly doped metallic Si, which is not suited for gate-control devices.
- Hamaya successfuly utilized low-doped Si for spintronics application.



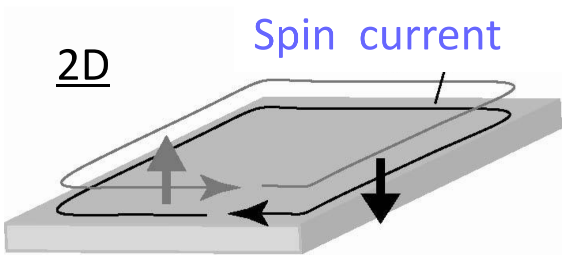
M. Ishikawa, H. Sugiyama, T. Inokuchi, K. Hamaya, Y. Saito, "Effect of the interface resistance of CoFe/MgO contacts on spin accumulation in silicon", Appl. Phys. Lett. 100, 252404 (2012).

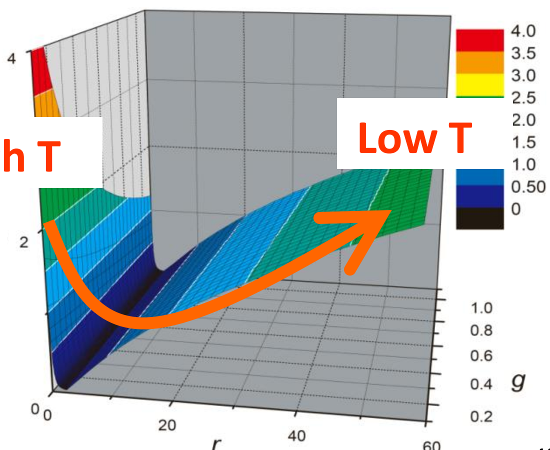
Spintronics devices and materials

TOPOLOGICAL INSULATOR

Theory of spin current and heat current

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





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

r=“ bulk/edge ”

g=“ phonon/bulk ”

Expectation : QSH systems can be good thermoelectric.

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

Result

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

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

Japan Science and Technology Agency

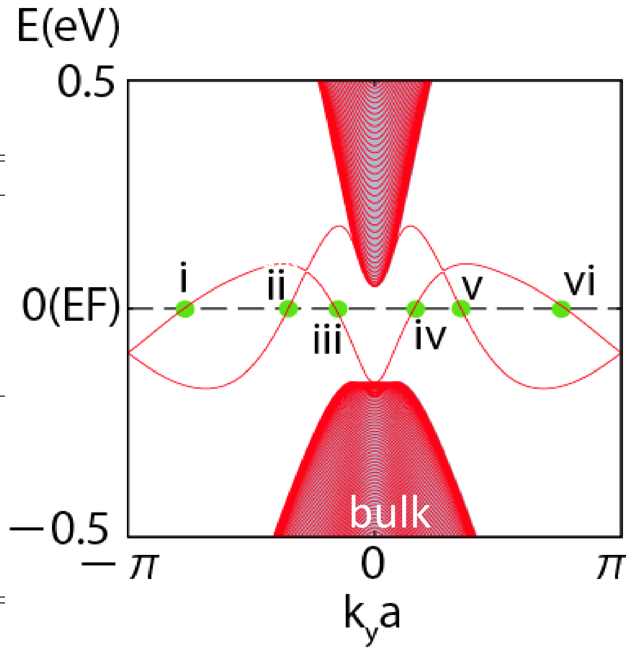
R. Takahashi, S. Murakami: Phys. Rev. B, 81, 161302 (2010)

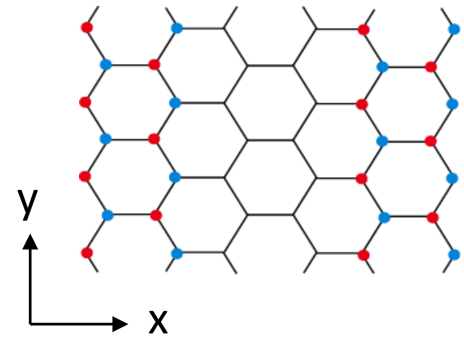
PRESTO

(a) (111) 1-bilayer: spin polarization on edges

Zigzag edge

	S_x	S_y	S_z
i-U	0.822	-0.000	-0.229
i-L	-0.822	0.000	0.229
ii-U	-0.680	0.000	-0.217
ii-L	0.680	-0.000	0.217
iii-U	0.141	0.000	-0.095
iii-L	-0.141	-0.000	0.095
iv-U	-0.141	-0.000	0.095
iv-L	0.141	0.000	-0.095
v-U	0.680	-0.000	0.217
v-L	-0.680	0.000	-0.217
vi-U	-0.822	0.000	0.229
vi-L	0.822	-0.000	-0.229



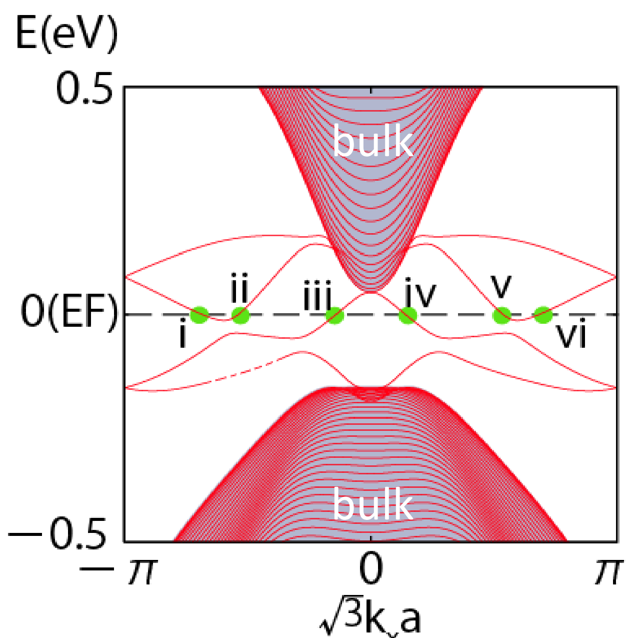


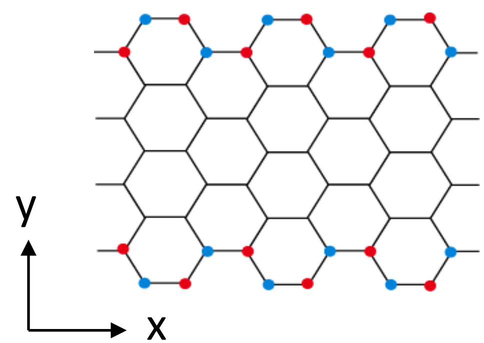
スピン: xz 面内

スピンはほぼ薄膜面に垂直
(// z)
10%-20% 程度傾いている

Armchair edge

	S_x	S_y	S_z
i-U	0.763	0.000	-0.010
i-L	-0.763	-0.000	0.010
ii-U	0.395	0.000	-0.237
ii-L	-0.395	-0.000	0.237
iii-U	0.250	-0.000	-0.395
iii-L	-0.250	0.000	0.395
iv-U	-0.250	0.000	0.395
iv-L	0.250	-0.000	-0.395
v-U	-0.395	-0.000	0.237
v-L	0.395	0.000	-0.237
vi-U	-0.763	-0.000	0.010
vi-L	0.763	0.000	-0.010

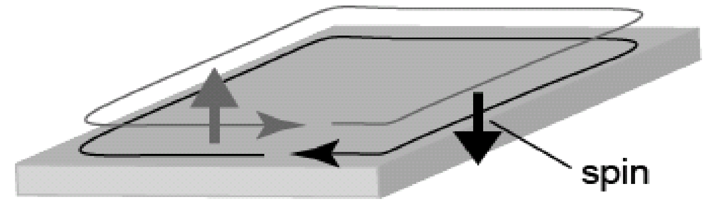




スピン: xz 面内

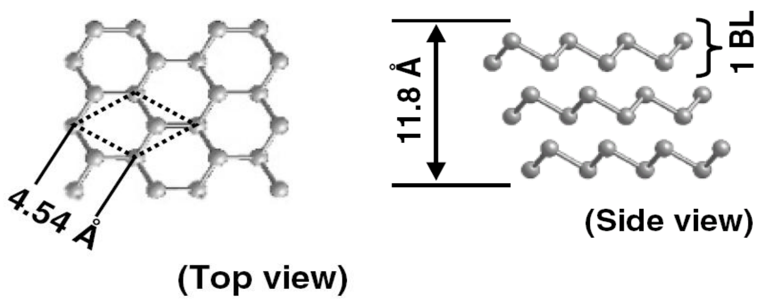
Theoretical Approach

Quantum Spin Hall Effect in Bismuth

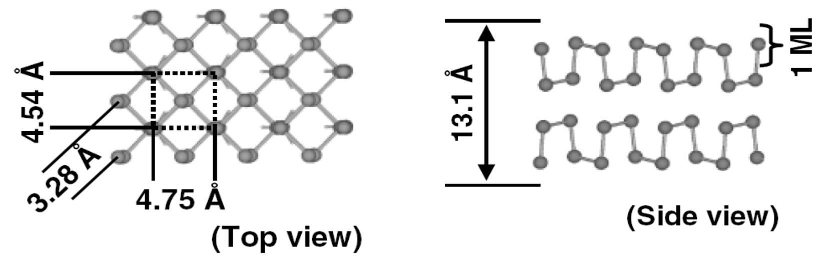


– Bulk Bi show no gap, while edge is gapless.
– Bi ultra thin film (*topological insulator*)

(111) 1-bilayer = quantum spin Hall phase



{012} 2-monolayer= insulating phase



- Thermoelectric figure of merit

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

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

Idealized model (perfect conductor on the edge)

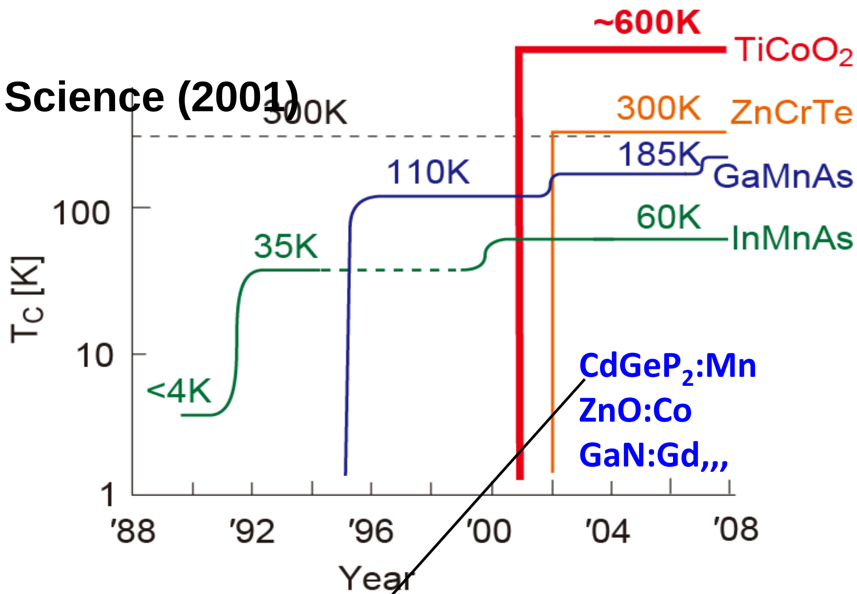
- In the quantum spin Hall phase, figure of merit ZT of thermoelectric conversion is determined by the balance between the edge and the bulk.
- ZT is large if the chemical potential is close to the band edge.
- ZT is large if the length of system is long. ← edge states dominantly determine ZT.
- ZT increases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

Spintronics devices and materials

MAGNETIC SEMICONDUCTOR

High T_C FM semiconductor: cobalt-doped TiO_2

Extraordinary high T_C



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

TiO2:Co Room temperature FM semiconder

Giant MO effect at RT

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

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

Anomalous Hall effect at RT

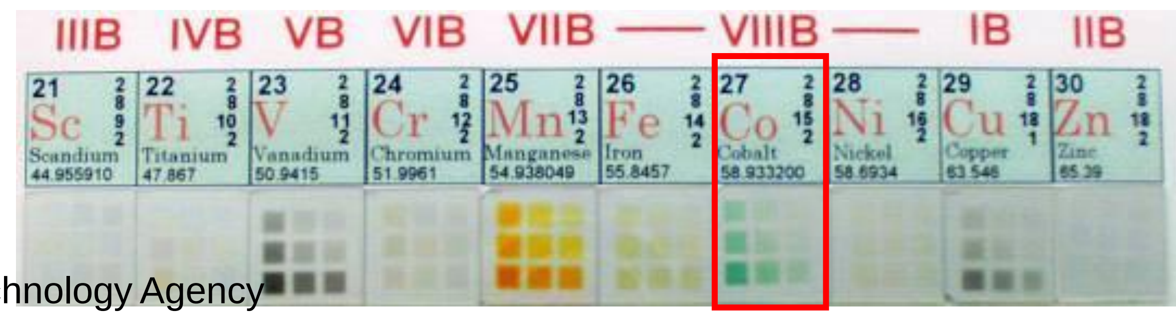
H. Toyosaki, Nature Mater. (2004)

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

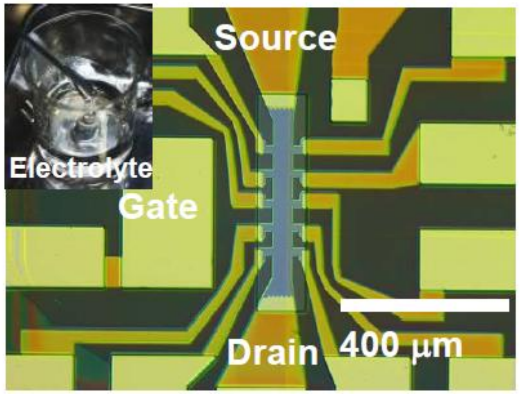
Tunneling Magnetoresistance

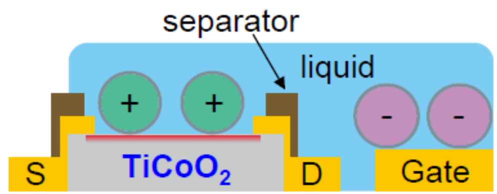
H. Toyosaki, Jpn. J. Appl. Phys. (2005)

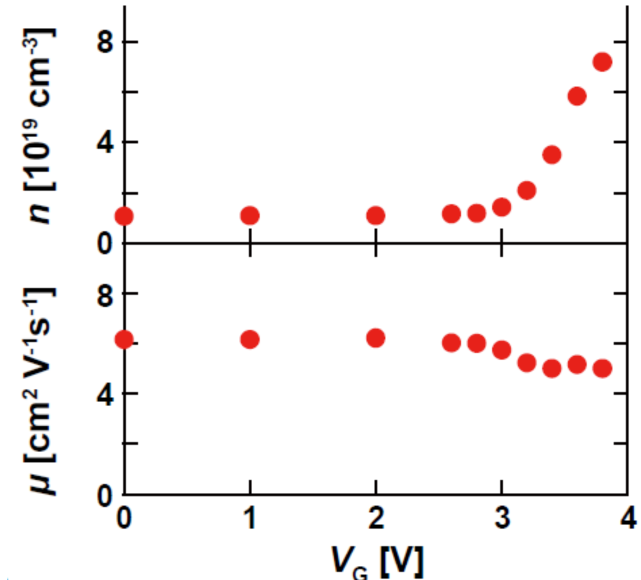
$Zn_{1-x}TM_xO$ combinatorial library



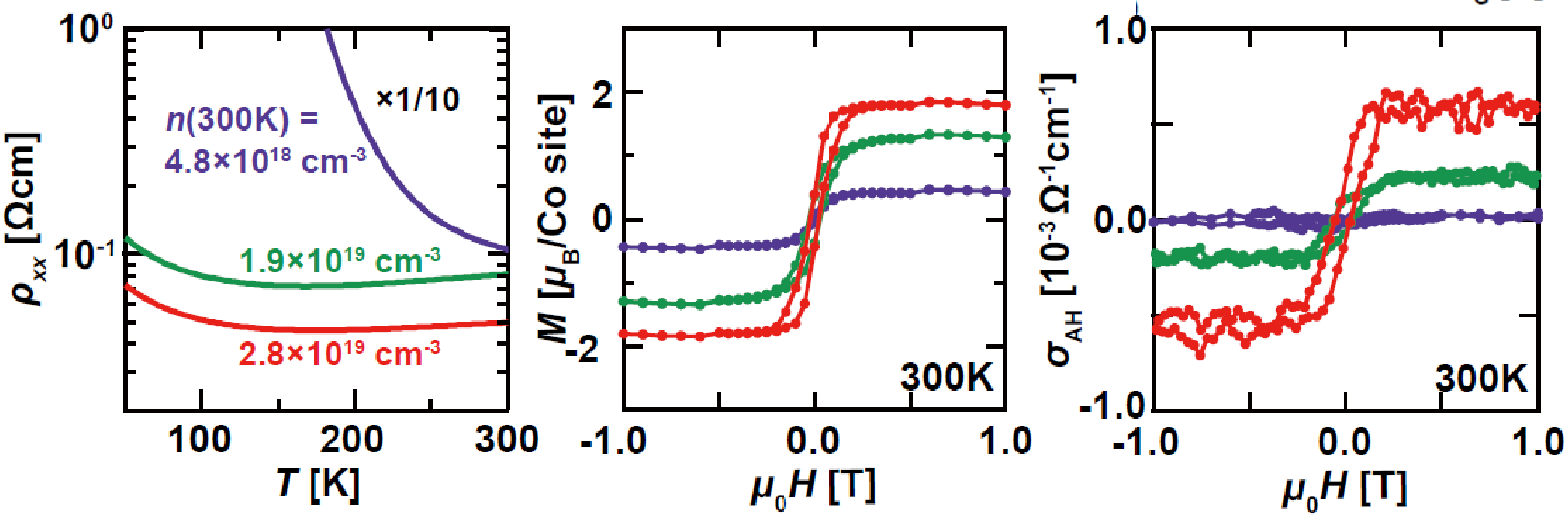
Carrier control of magnetism in TiO_2:Co by gate voltage





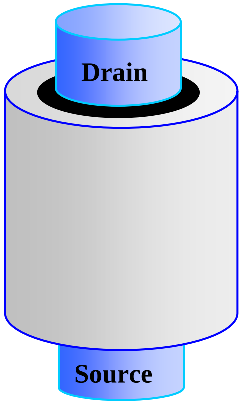


$Ti_{0.90}Co_{0.10}O_{2-\delta}$ **PM insulator → FM metal**



Semiconductor nanoelectronics

1. N.Fukata succeded in characterization of ***small amount of dopant in nanowire*** **Si using EPR and Raman spectroscopy**
2. **K.Tomioka successfully fabricated** ***InAs nanowire/Si tunnel-FET*** **with record SS (subthreshold slope) of 21mV/dec much smaller than theoretical limit of 60**
3. **M.Takenaka developed high performance** ***Ge n-MOS FET*** **and low noise Ge PD for optical interconnection**
4. **S.Kasai realized a novel signal processing technology under the concept of** ***Stochastic Resonance***



Semiconductor Nanoelectronics

NANO-WIRE TRANSISTORS

Surrounding Gate Transistors

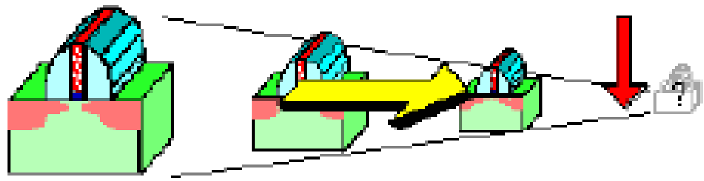
- Advances in performance and integration through conventional scaling of device geometries are now reaching their practical limits in planar MOSFETs. To overcome the limiting factors in planar MOSFETs, vertical structural arrangements called surrounding gate transistors (SGT) have been suggested as 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.

Vertical type MOSFET using semiconductor nanowires

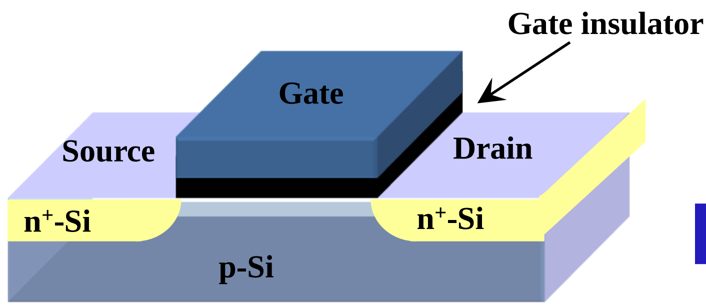
Transistor size scaling

Limit of scaling ?



2-orders of magnitude reduction in transistor size in 30 years.

Present: Planar type



Miniaturization of FET

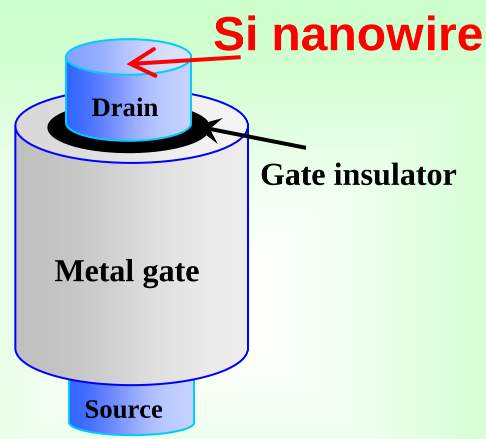
⇩

Increase in power consumption & leak current

⇩

Enhancement of the heating

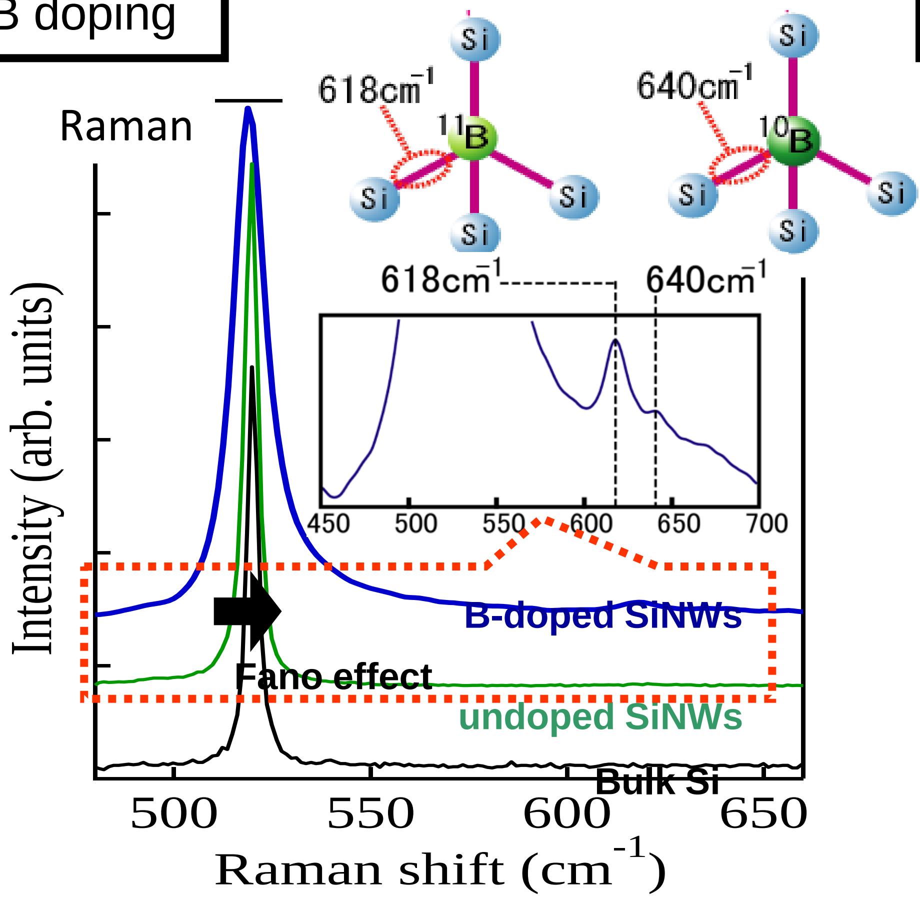
Next generation : Vertical type



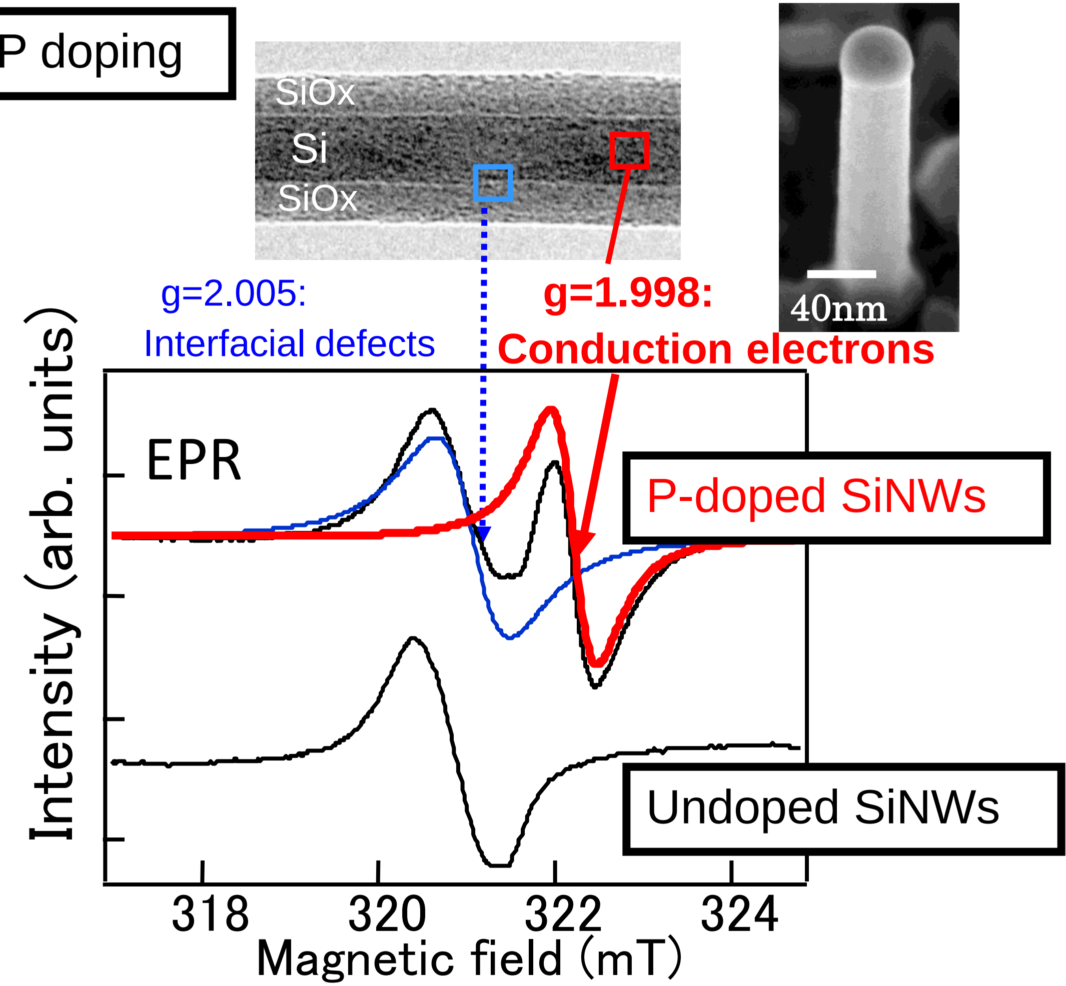
Vertical-type MOSFET using Si nanowires !

Synthesis & Impurity doping in Si nanowires

B doping



P doping



First observation of B local vibrational peak and Fano effect in B-doped SiNWs

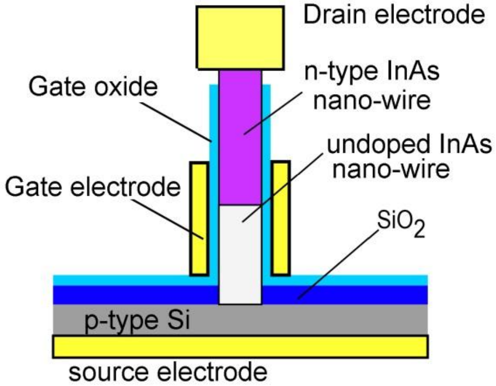
Formation of p-type SiNWs

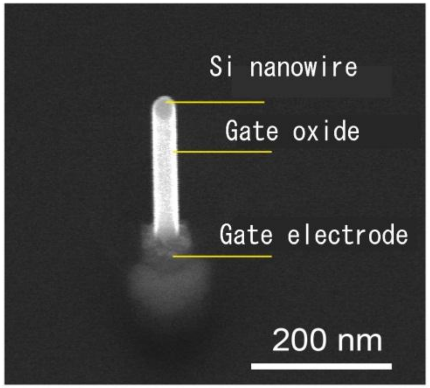
First observation of conduction electron signals in P-doped SiNWs

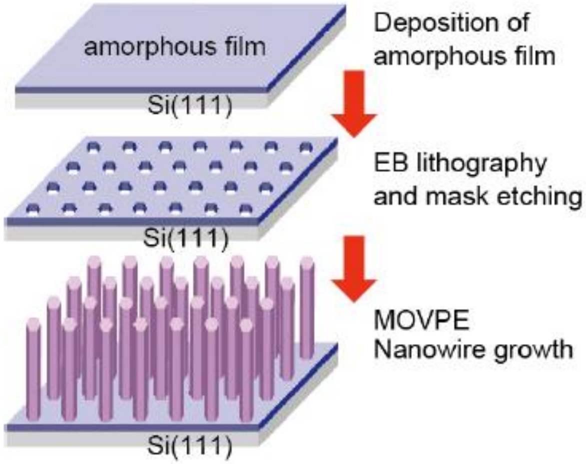
Formation of n-type SiNWs

InAs nanowire Tunnel FET

- Tomioka succeeded in fabricating a Tunnel MET using InAs nanowire on Si substrate by MOVPE through holes fabricated on SiO_2 insulator by electron beam lithography.

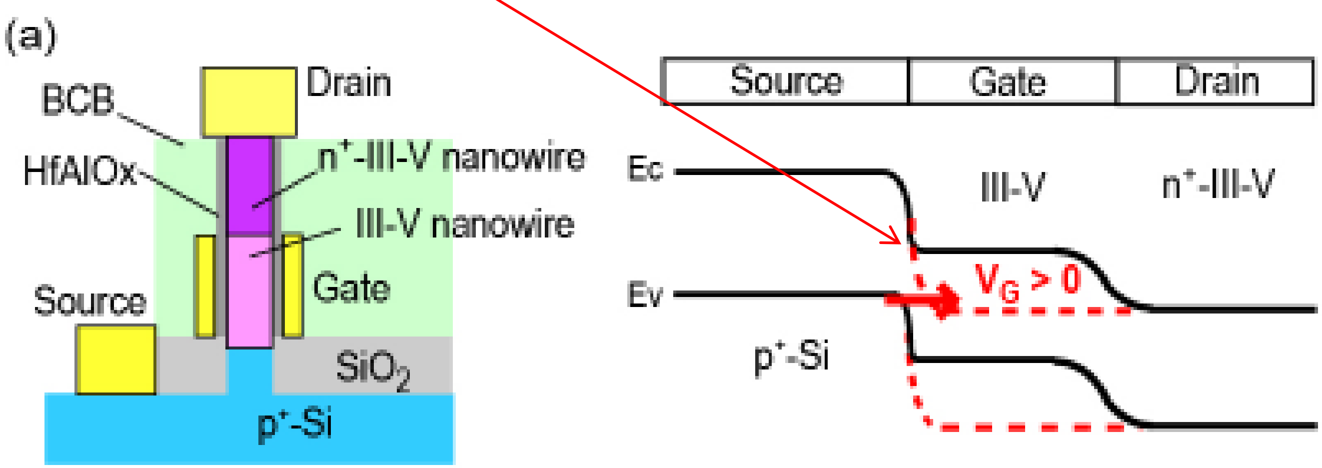






How the InAs nanowire TFET works

- Figure illustrates TFET using III-V NWs/Si heterojunctions. Each TFETs are composed of a combination of III-Vs and Si in order to utilize Zener tunnel mechanism working at a band discontinuities across the III-V and Si junctions.



InAs nanowire Tunnel FET

- He attained subthreshold slope of SS=21meV/dec far below the theoretical limit of 60meV/dec of ordinary FET

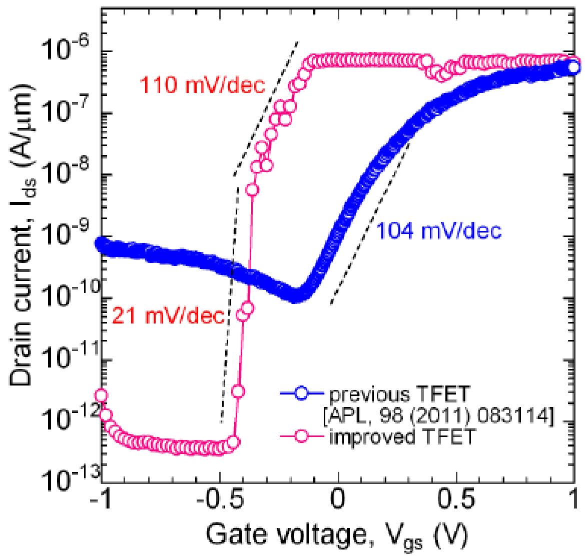


Fig. 9 Experimental transfer characteristics of optimized TFET with a NW-diameter of 30 nm (red cureve) $V_{DS} = 1.00$ V.

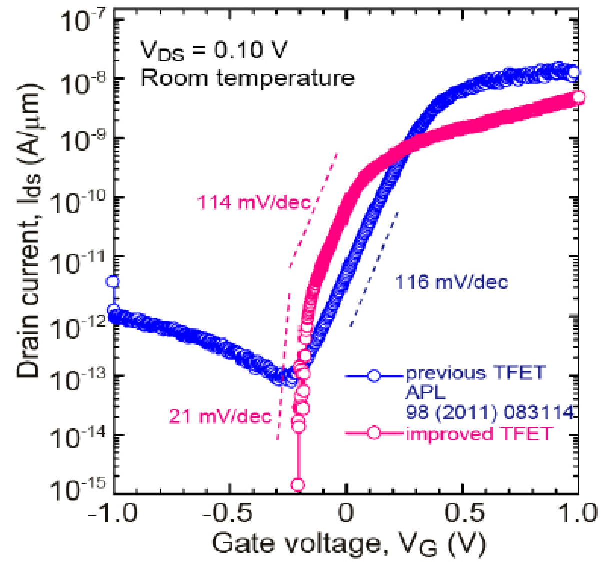
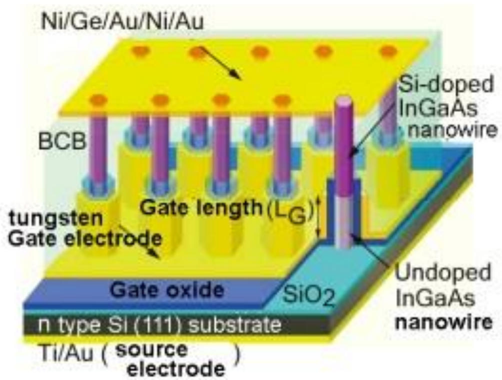
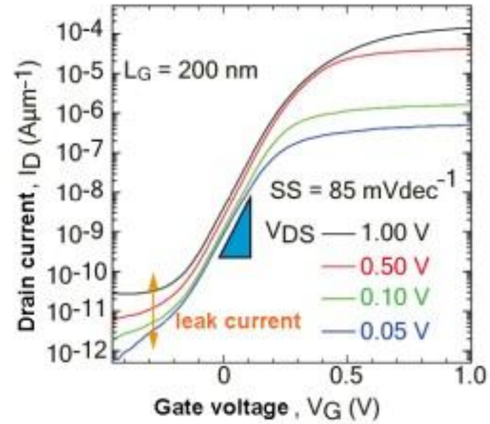


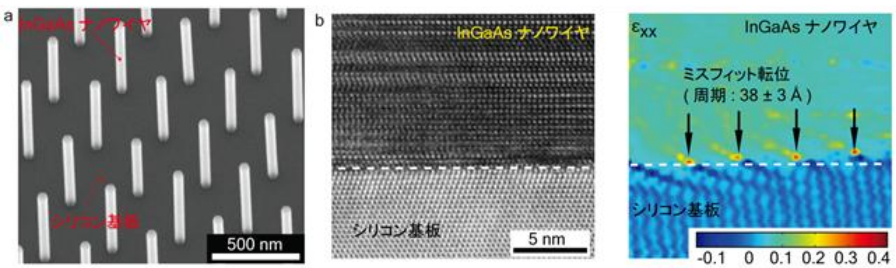
Fig. 10 Experimental transfer characteristics of optimized TFET with a NW-diameter of 30 nm (red cureve) $V_{DS} = 0.10$ V.

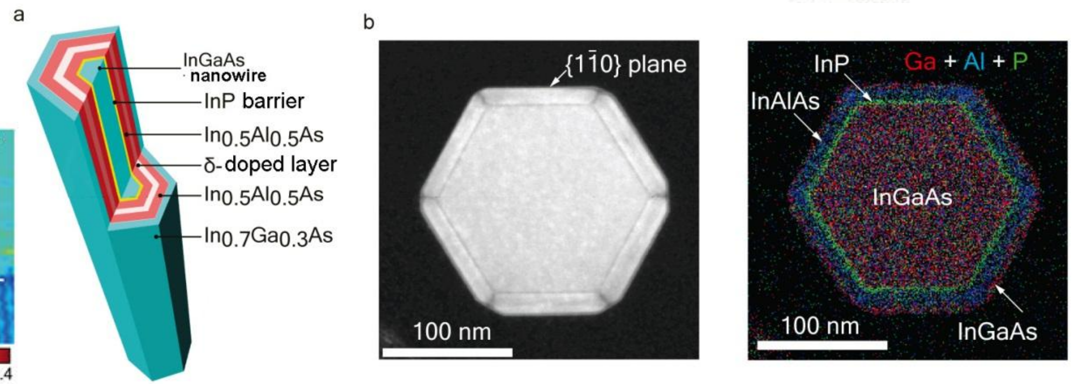
Nanowire FET with core-shell HEMT structure

- Tomioka fabricated high performance FET using InAs nanowire with core-shell HEMT structure.









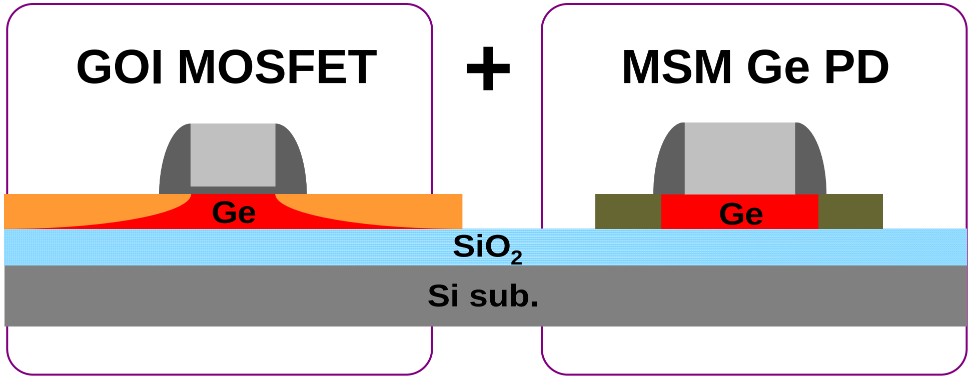
For optical interconnects

- 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]
-

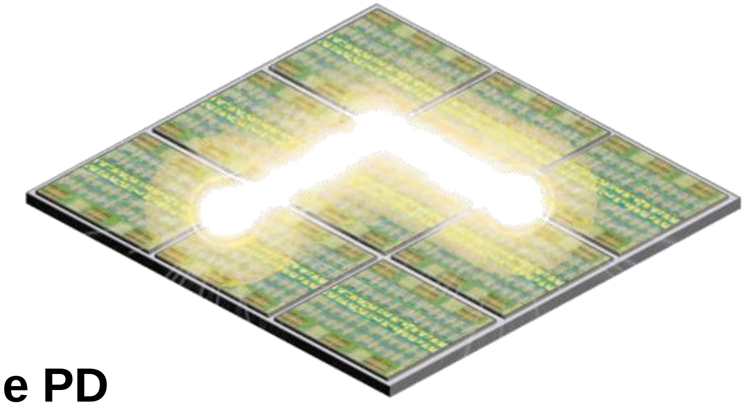
[i] M. Takenaka, S. Tanabe, S. Dissanayake, S. Sugahara, S. Takagi: 21st Annual Meeting of the IEEE Laser & Electro-Optics Society, Newport Beach, US (2008) Paper MN2.

Ge-based LSI with on-chip optical interconnects

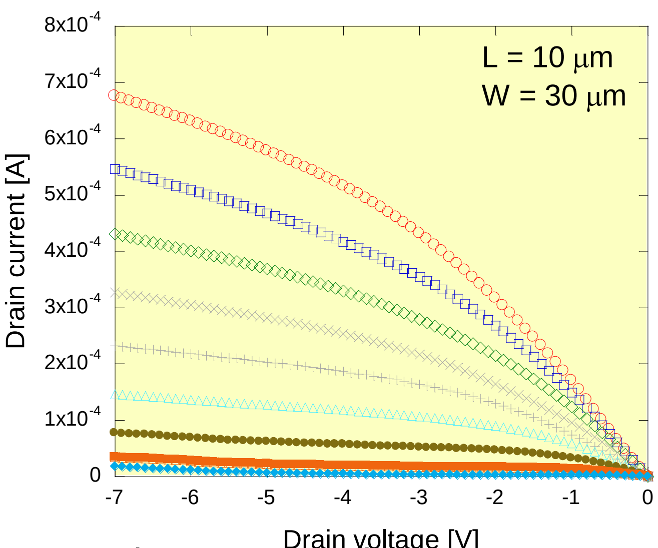
Monolithic integration:



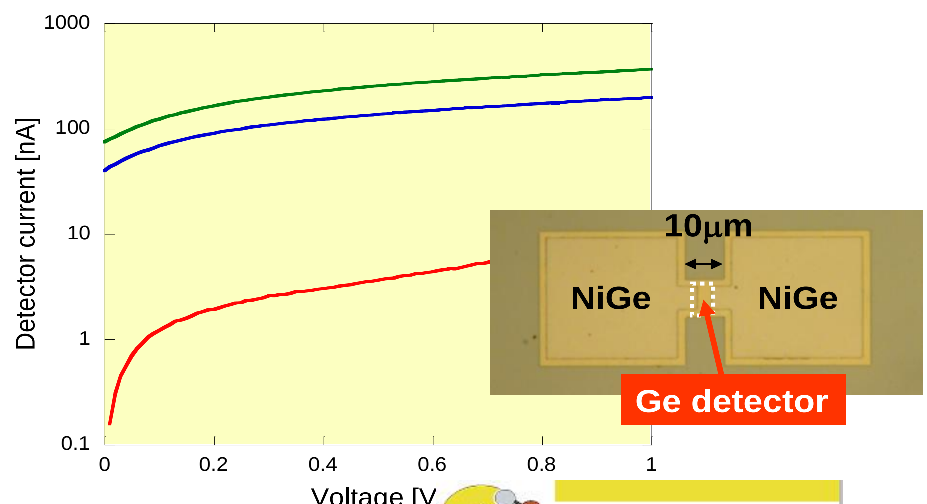
Ge based LSI with on-chip optical interconnects

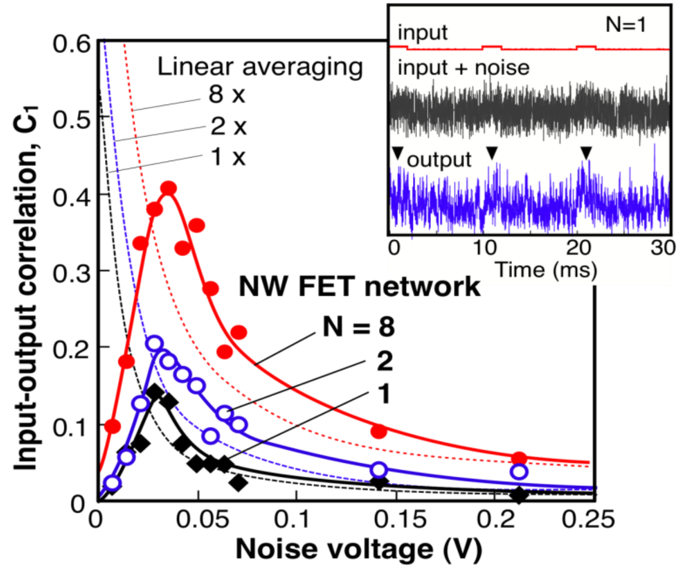


GOI MOSFET



Ge PD





Semiconductor Nanoelectronics

STOCHASTIC RESONANCE

Japan Science and Technology Agency

27–31 August 2012 SALZBURG

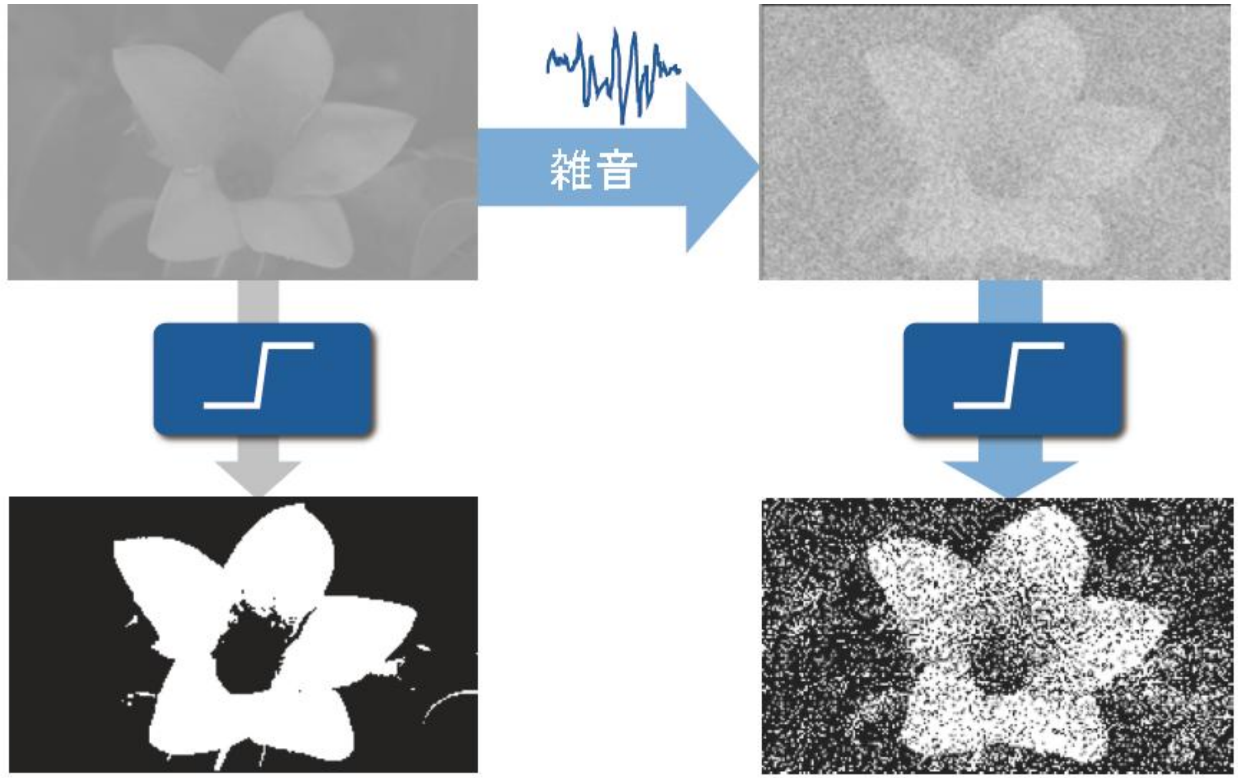
Stochastic Resonance

- 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.

Improvement of SNR by using noise

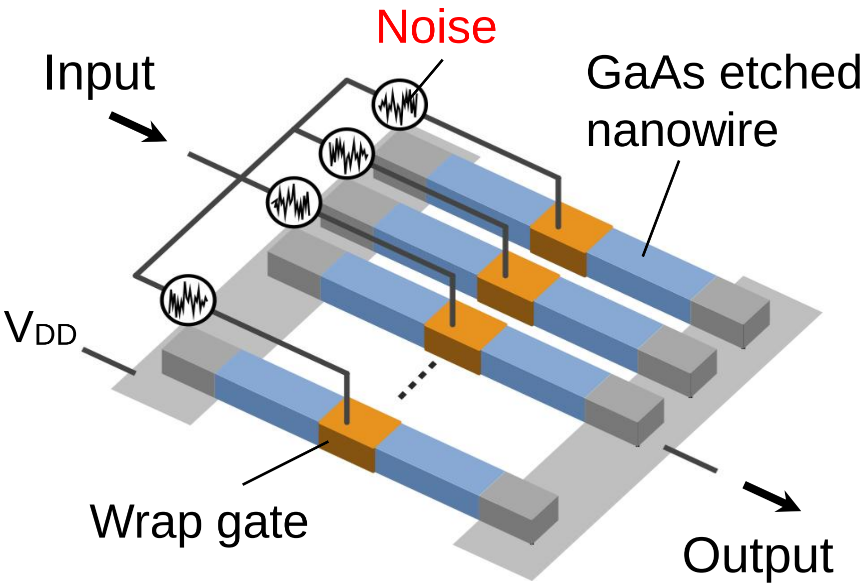
- Stochastic resonance improve grey scale reproduction



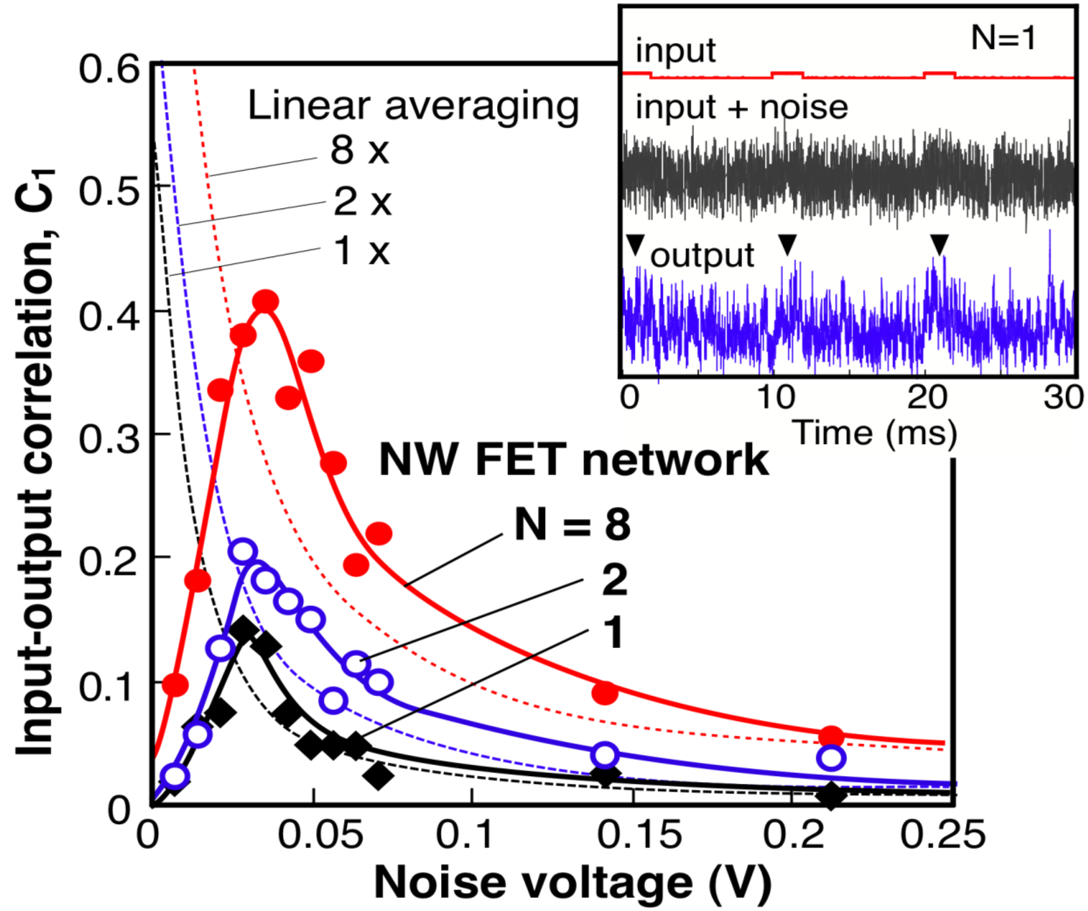
High contrast but lose grey scale

recover grey scale by addition of noise

Stochastic Resonance in Nanowire FET Network



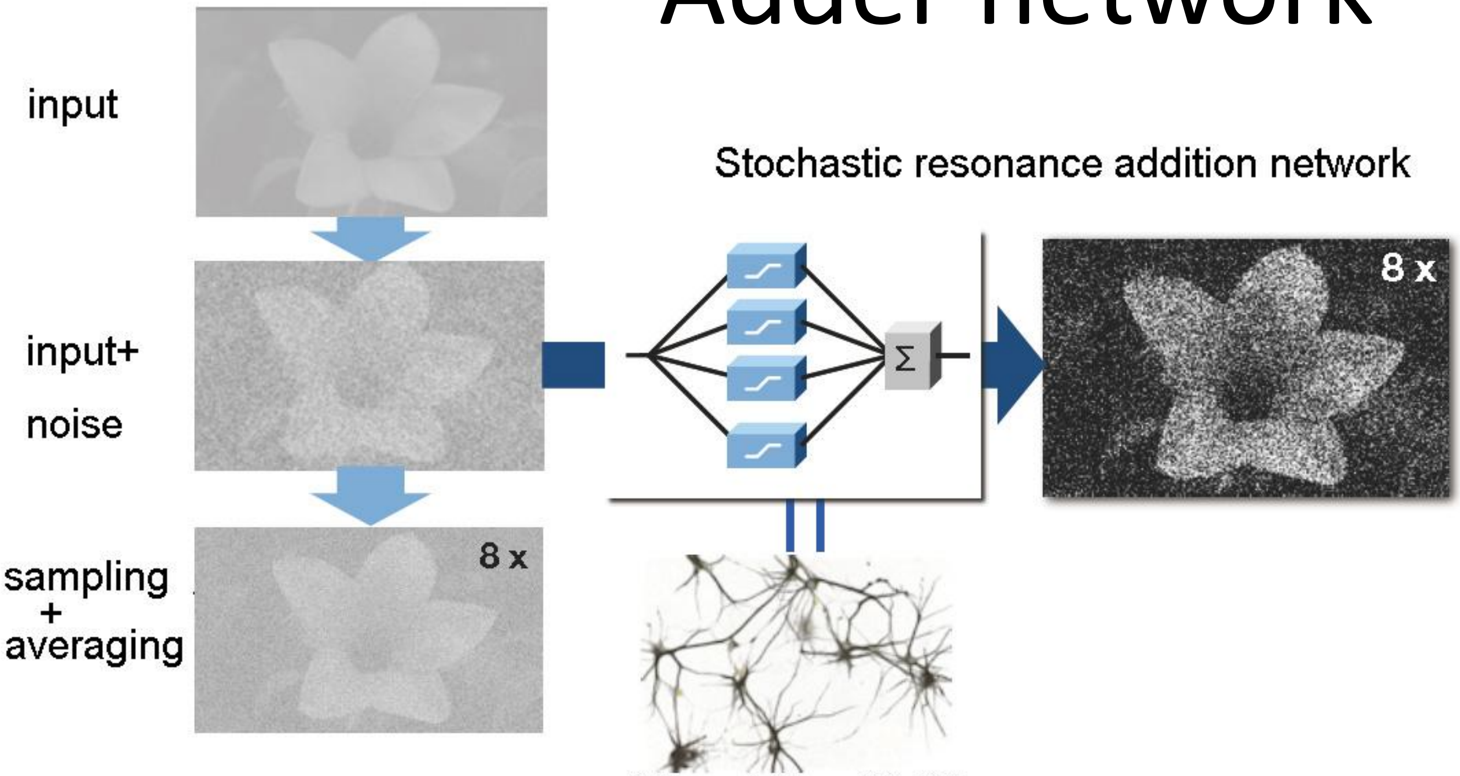
S.Kasai et al., Appl. Phys. Express 1, 083001 (2008)



Stochastic resonance (SR) is a phenomenon that many bio-systems use to enhance their response in noisy environment.

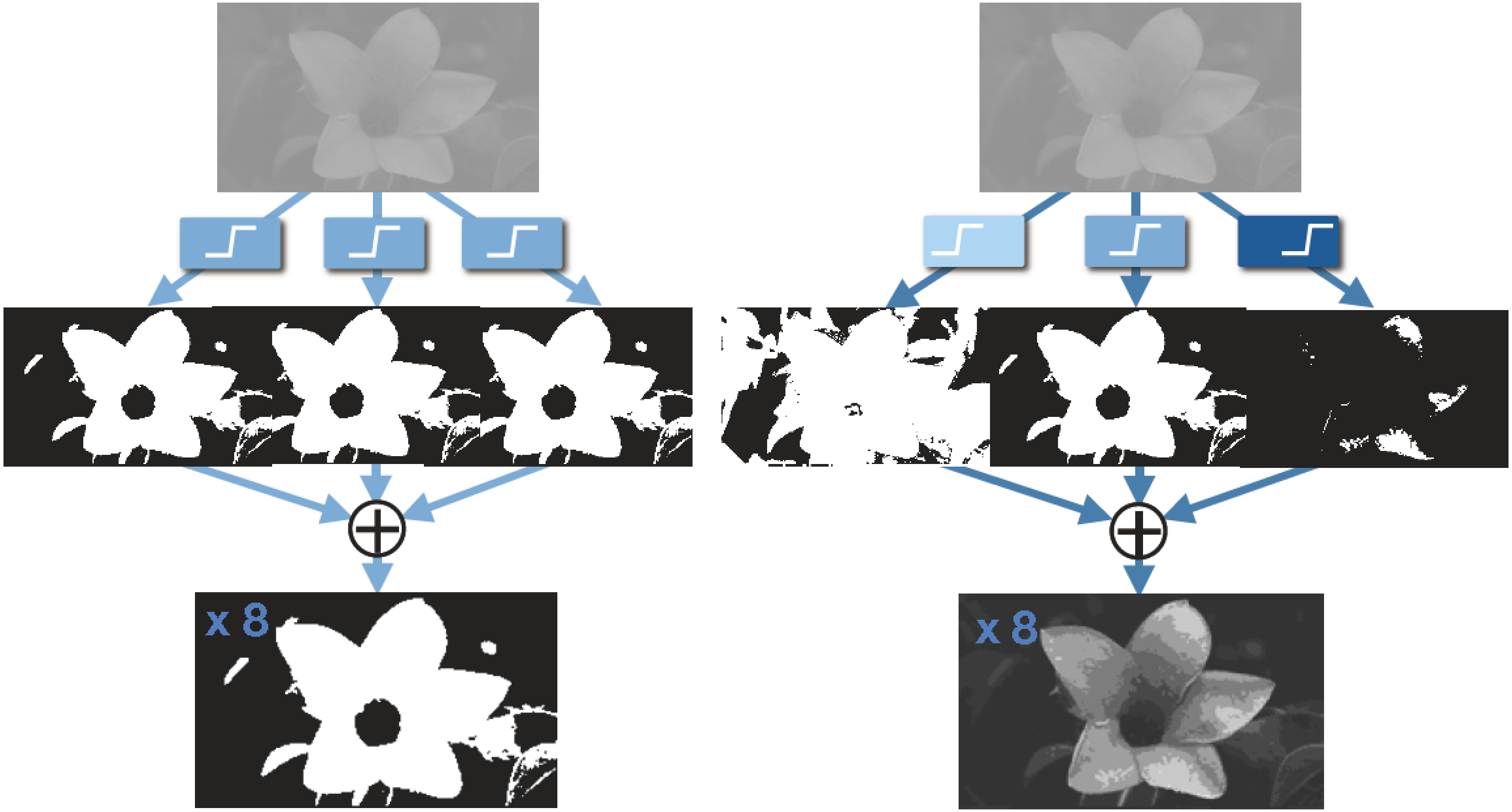
The SR was realized in GaAs nanowire FET networks and enhanced weak-signal detection was successfully demonstrated.

Adder network



Collins et al., Nature 376, 1995

Scatter of threshold

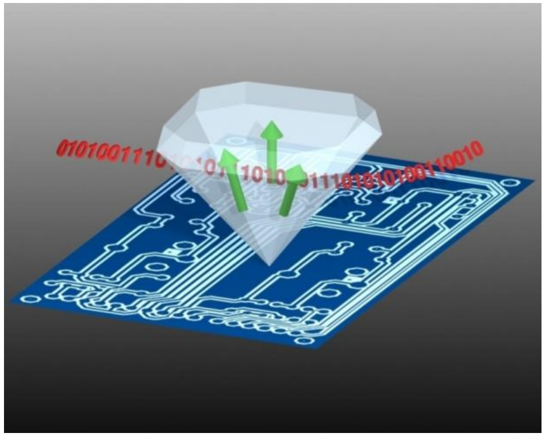


Uniform Threshold

With scatte

Wide-gap semiconductors

1. N.Mizuochi succeeded in room temperature operation of quantum information processing solid state device and current-induced single photon source by using *NV center in diamond p-i-n junction*
2. Y.Kangawa succeeded in *LPE growth of AlN single crystal* for III-N substrate using solid state nitrogen source (LiN)
3. R. Katayama fabricated GaN thin film *with periodic modulation of polarity* for nonlinear optics
4. M.Higashiwaki succeeded in fabricating *Ga_2O_3 –based device* for power electronics



Wide Gap Semiconductors

QUNTUM INFORMATION PROCESSING USING DIAMOND NV CENTER

Japan Science and Technology Agency

27–31 August 2012
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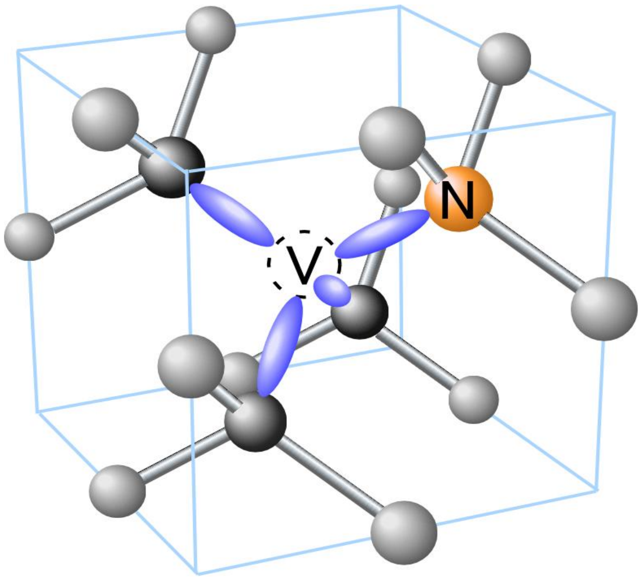
Single NV center in diamond

NV center: (NV^-, 6 electrons, C_{3v})

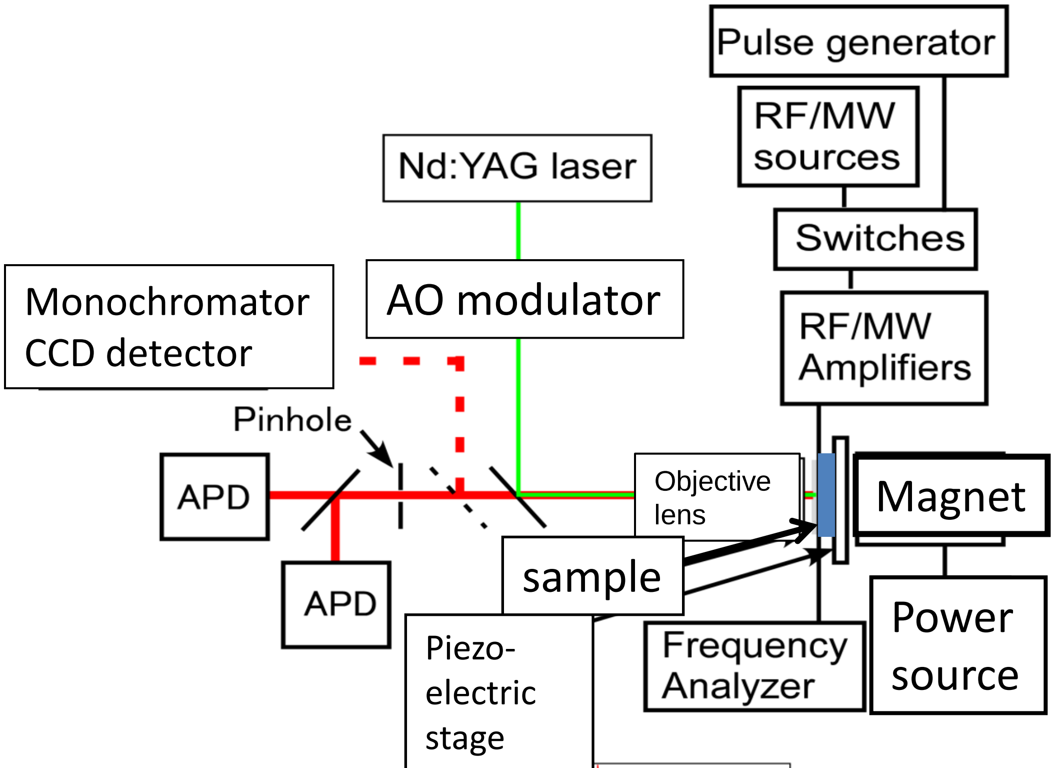


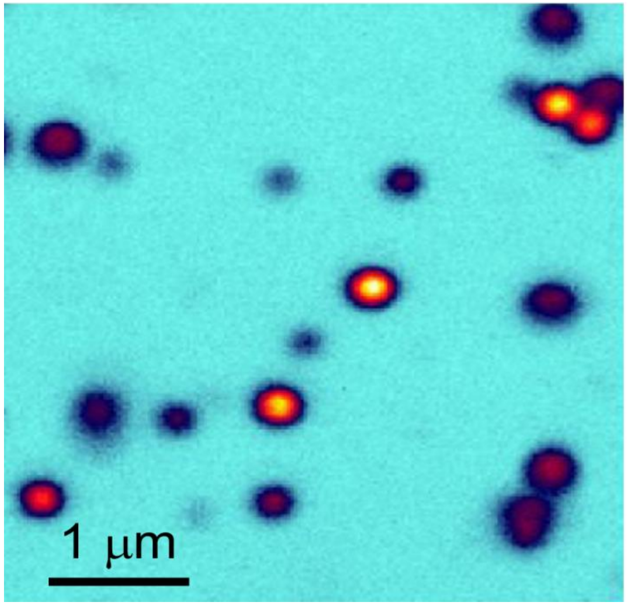
- Ground state: spin triplet(electron spin S=1)
- Long coherence length.
- Observation of single NV center and single spin manipulation is possible
- Initialization of electron spin states by light irradiation is possible

Quantum information processing solid state device for room temperature operation

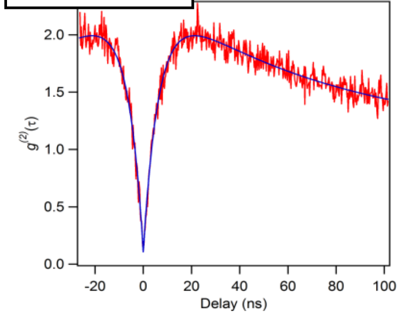
(Quantum register, Quantum repeater, single photon emitter …)

Measurement Instruments for single NV center





Fluorescent image of single NV center by confocal laser microscope



Anti-bunching measurement using Hanbury-Brown Twiss interferometer

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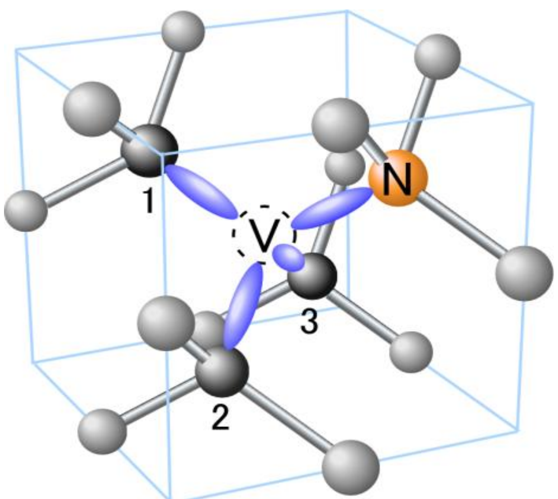
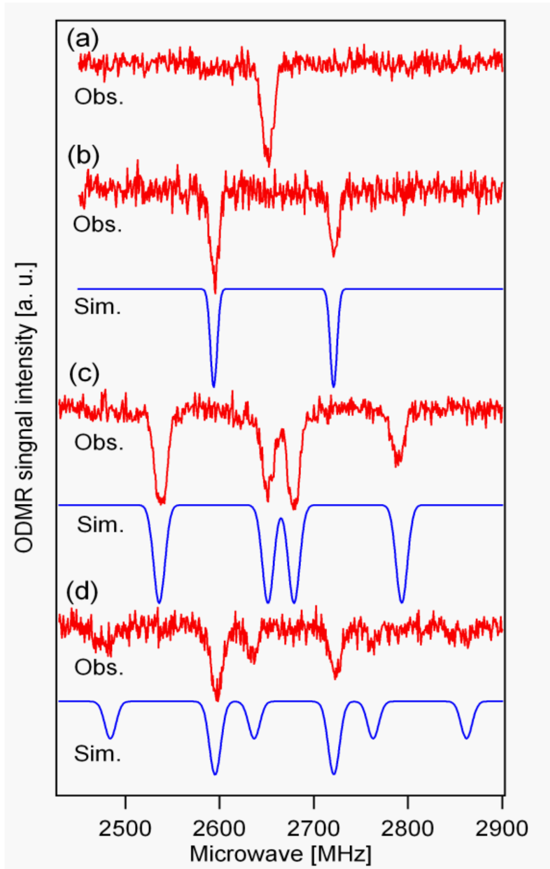
Multiple quantum bit

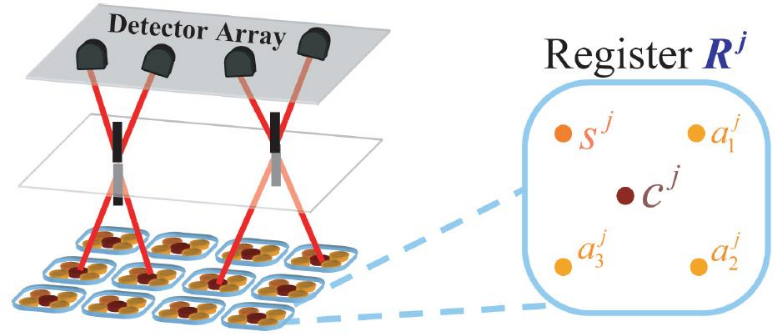
Quantum resister: multiple q-bits of single NV-center

^{13}C-doped system



N:nitrogen. V: Vacancy (V).
Carbon atoms labeled at 1-3 are called as nearest-neighbor carbon atom from vacancy.





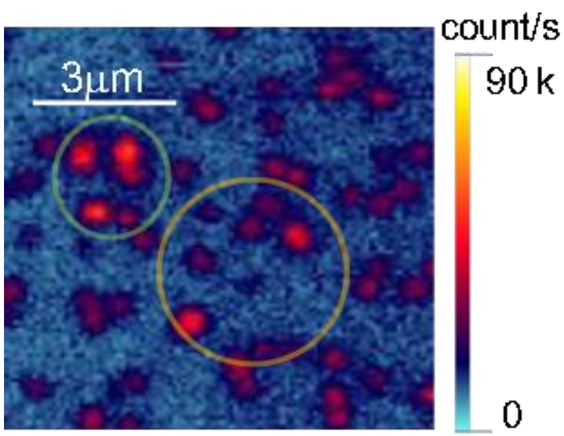
Jiang et al., PRA 76, 062323 (2007)

Experimental and simulated ODMR spectra of nearest neighbor carbon atoms assigned as consisting of (a)0, (b)1, (c)2, (d)3 ^{13}C-center(s)

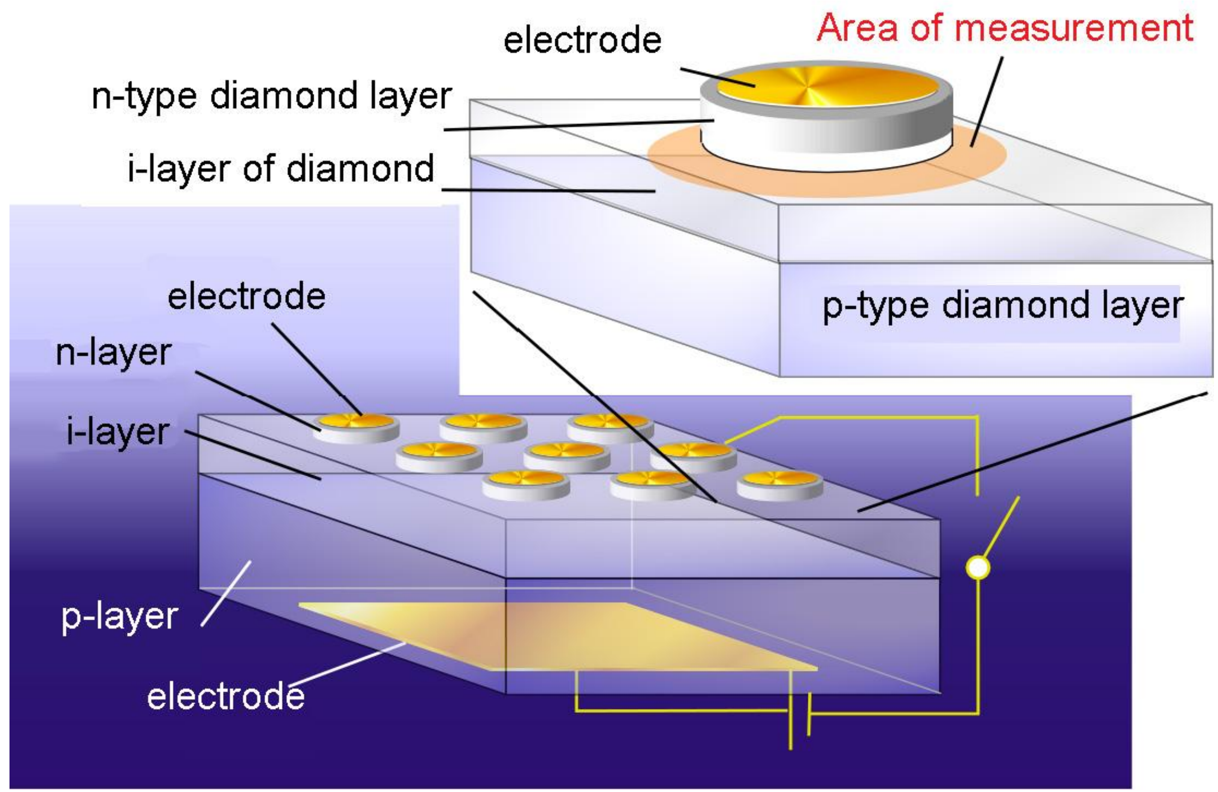
G. Balasubramanian, P. Neumann, D. Twitchen, M. Markham, R. Kolesov, N. Mizuochi, J. Isoya, J. Achard, J. Beck, J. Tissler, V. Jacques, F. Jelezko, J. Wrachtrup, "Ultralong spin coherence time in isotopically engineered diamond", **Nature materials**, v. 8, p. 383-387 (2009)

Room temperature single photon emission from NV^0 center in diamond LED

- Mizuochi succeeded in observing single photon emission from p-i-n light emitting diode of diamond.



EL image of single NV center



N. Mizuochi, T. Makino, H. Kato, D. Takeuchi, M. Ogura, H. Okushi, M. Nothaft, P. Neumann, A. Gali, F. Jelezko, J. Wrachtrup, S. Yamasaki, "Electrically driven single photon source at room temperature in diamond", **Nature Photonics**, 6, 299-303 (2012).

Molecules and Organics

1. **K. Wakabayashi theoretically predicted edge state spins in nano structured graphene**
2. **H. Yamamoto fabricated organic FET with high field effect mobility using *voltage controlled Mott-transition*. He also succeeded in *electrical control of superconductivity* in organic material**
3. **S. Noda succeeded in growing single *graphene sheet on insulating substrate* by metal-free process**
4. **J. Nishinaga succeeded in *delta-doping of C_{60} in GaAs* thin film during MBE growth**

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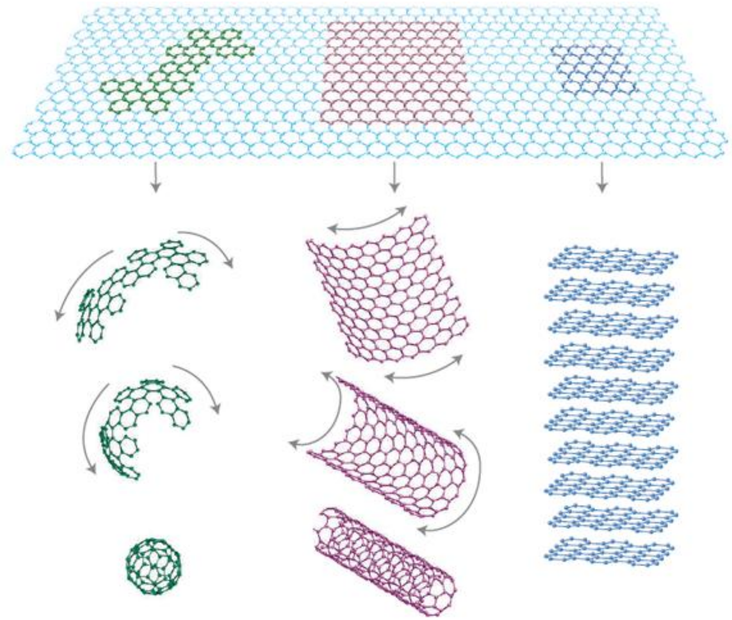
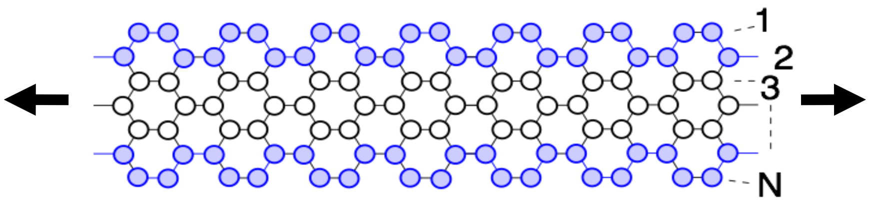


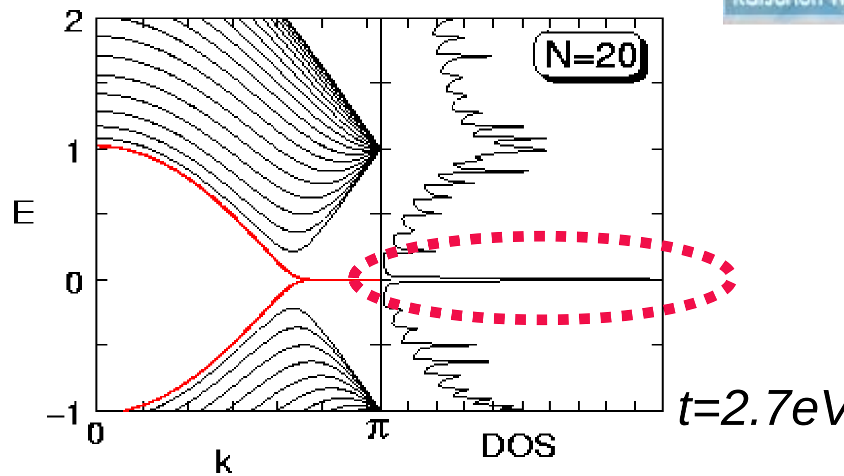
Molecules and Organics

GRAPHENE ELECTRONICS

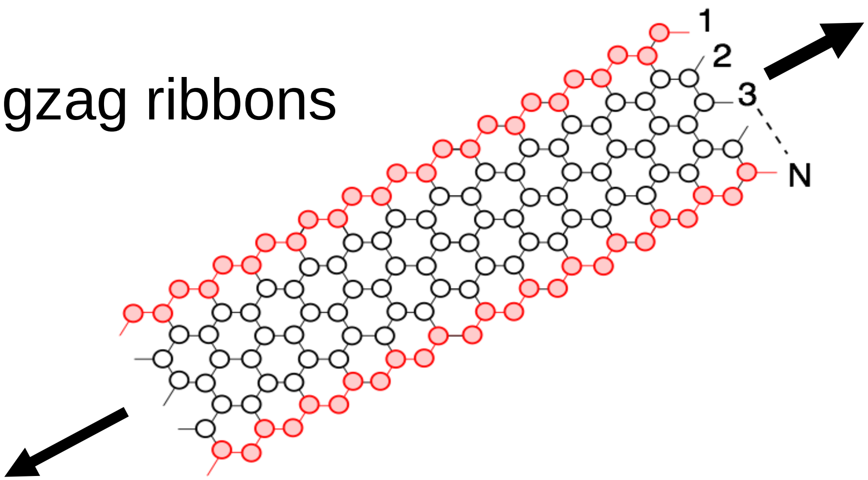
Graphene nanoribbons and strong nanoscale effect

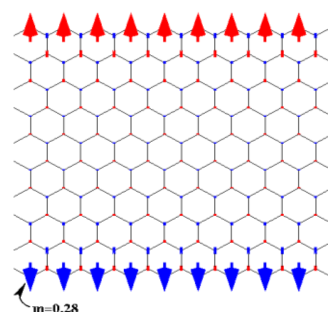
Armchair ribbons



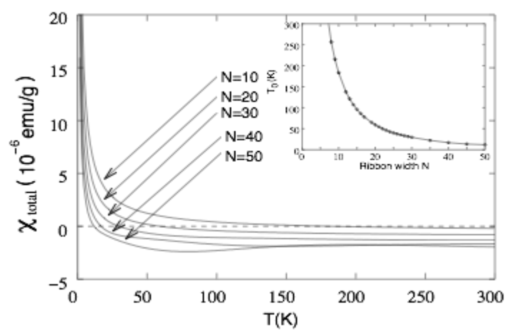


Zigzag ribbons





ferrimagnetic spin correlation

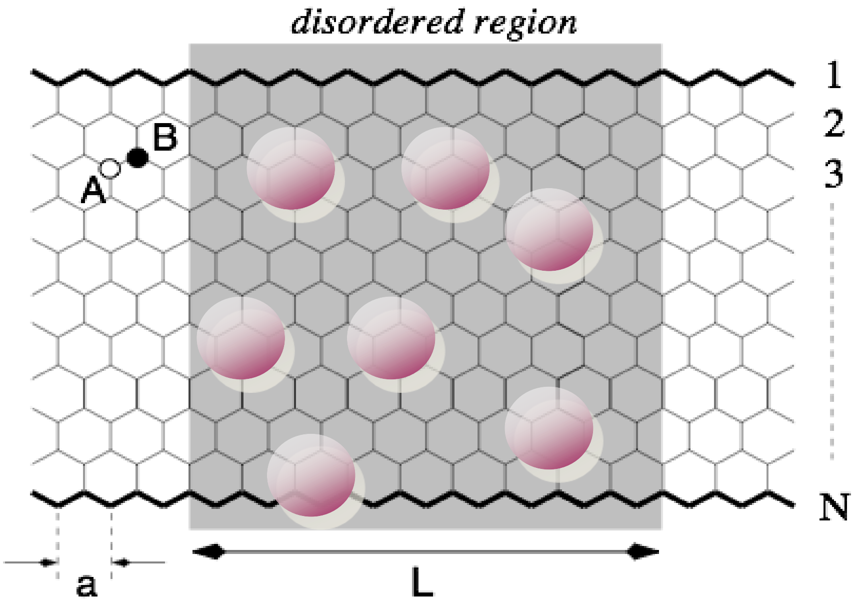


Crossover from dia- to para magnetism

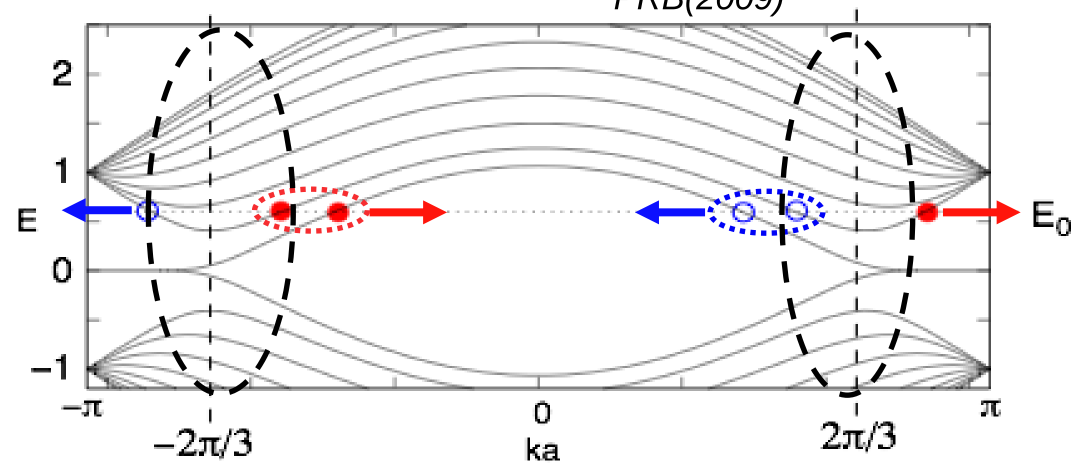
New class of quantum wires

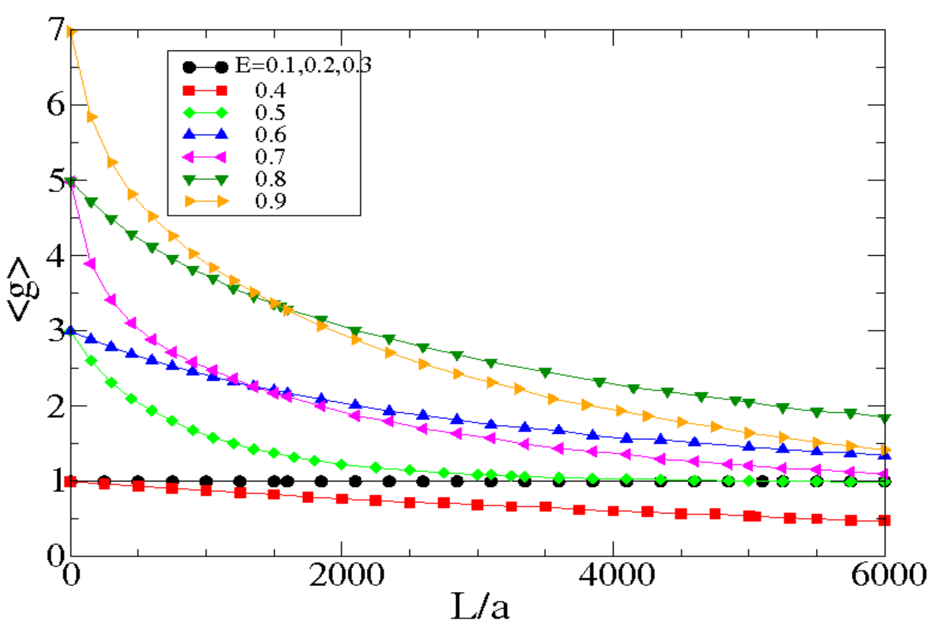
M. Fujita, K. Wakabayashi, K. Nakada, K. Kusakabe, *J. Phys. Soc. Jpn.* (1996).
K. Nakada, M. Fujita, et. al. *Phys. Rev.* B (1996).
K. Wakabayashi, M. Fujita, et. al., *Phys. Rev.* B (1999).

Perfectly Conducting Channel



K. Wakabayashi et. al., PRL(2007), Carbon(2009), PRB(2009)





dimensionless conductance:

$$g = \mathrm{Tr}\left(t^\dagger t\right)$$

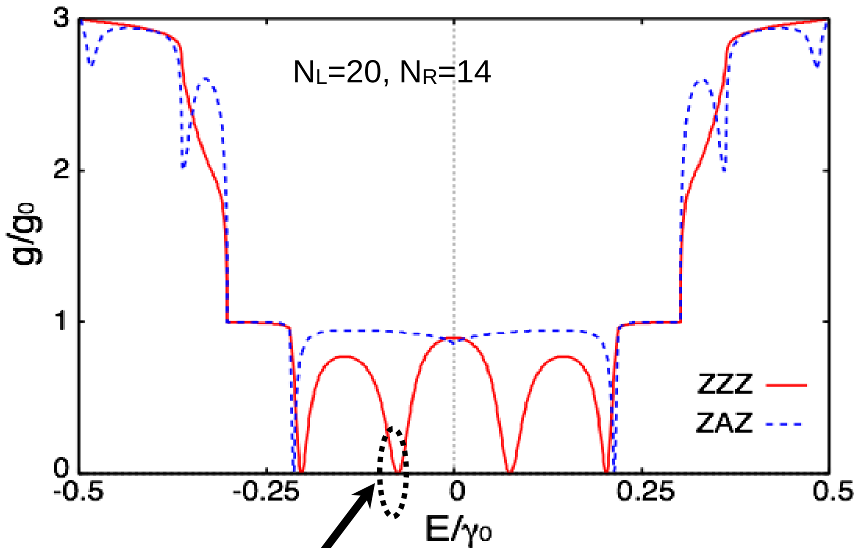
ensemble average for various impurity configuration

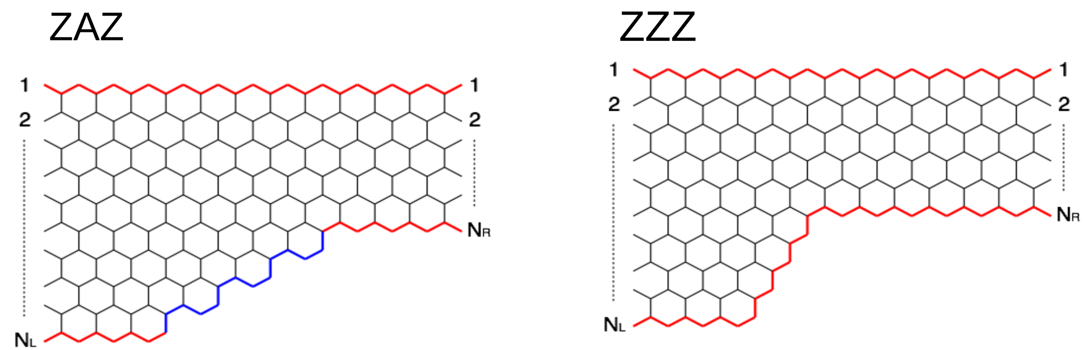
#of samples > 10000

Averaged conductance <g> converges to 1.
Perfectly Conducting Channel

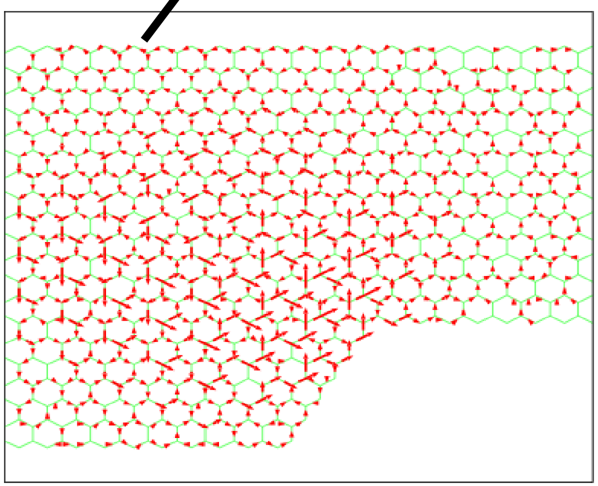
Absence of Anderson localization

Electronic transport through graphene junction





(1) Multiple zero conductance dips appear in ZZZ junction, which serve as the charge current switching.
(2) Visible condition at T=300K : W< 12.5nm



Internal circular current is induced at the energy in the vicinity of zero conductance dips.

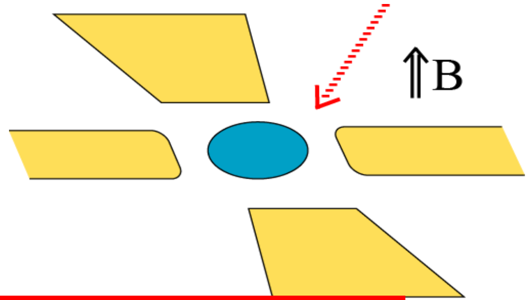
Lead	Junction	Position of anti-resonance
A	A	
	Z	$E = 0$
Z	A	$E = \pm\delta$; just before 2ch. is opened in wider ribbon.
	Z	$E = \pm\Delta_1, \Delta_2, \ldots$

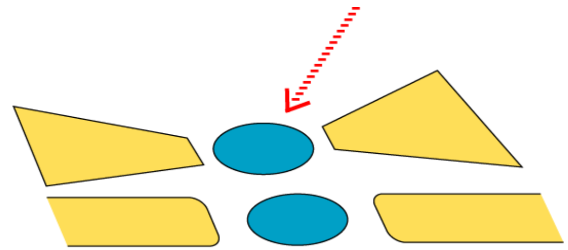
A: armchair
Z: zigzag

App. Phys. Lett. (2009)

Graphene Quantum Dot

Ultra high sensitivity THz detector

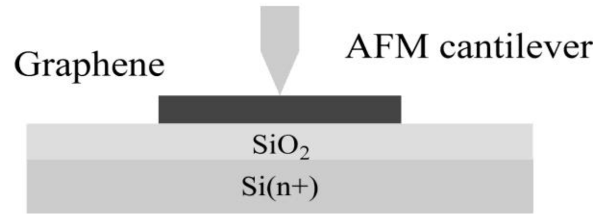




- Single electron transistor + quantum Hall effect
- Parallel double q-dot

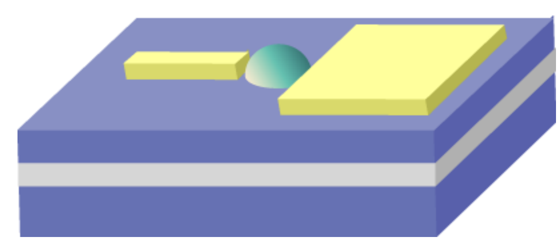
Room temperature SET

- Local anode oxidation using AFM

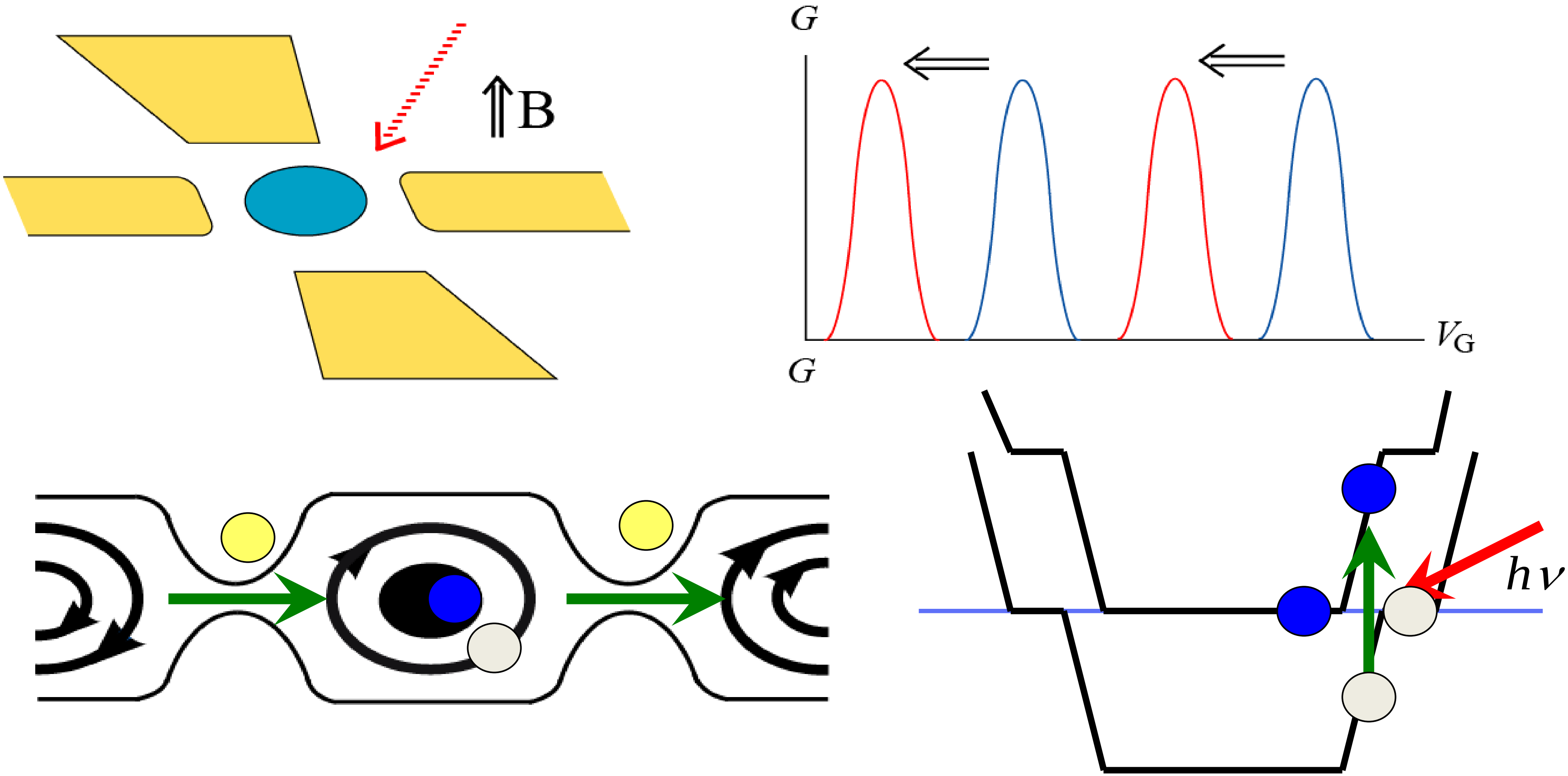


Q-dot spin valve

- FM electrode + Graphene Q-dot

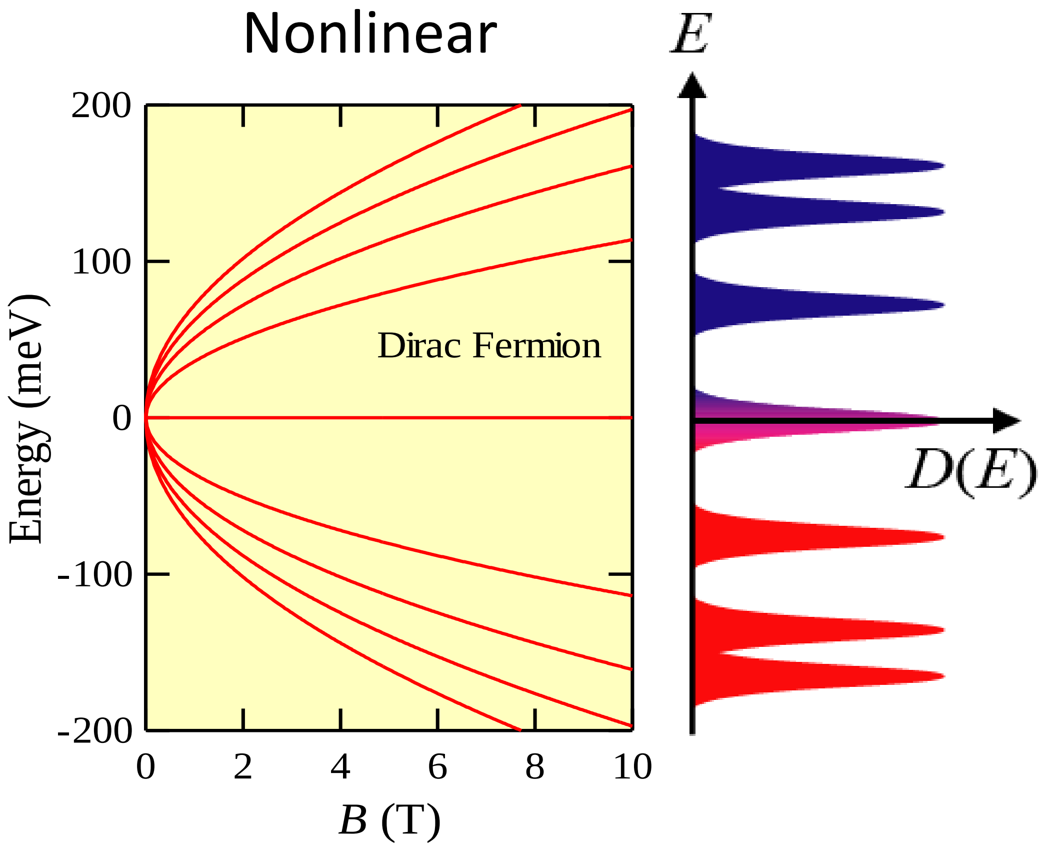


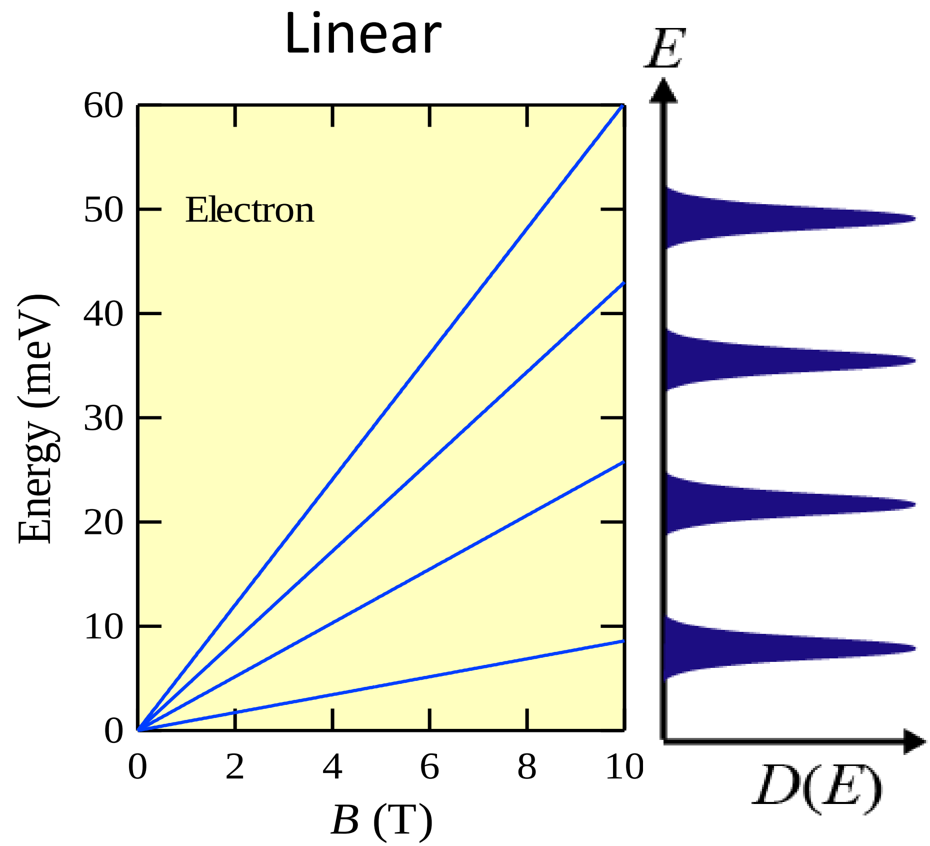
Ultra high sensitivity THz detector



Q-Hall effect＋Single electron tunneling +Cyclotron resonance

Landau quantization : Dirac Fermion v.s. electron





$$E_n = \tilde{c}\sqrt{2|n|\hbar eB}$$

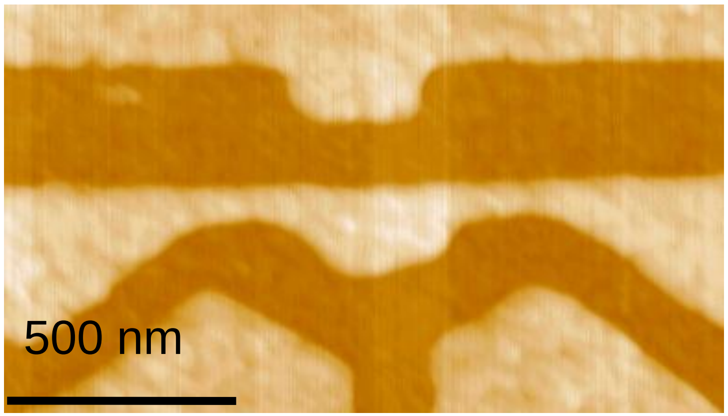
$$\sigma_{xy} = \frac{2e^2}{h} n$$

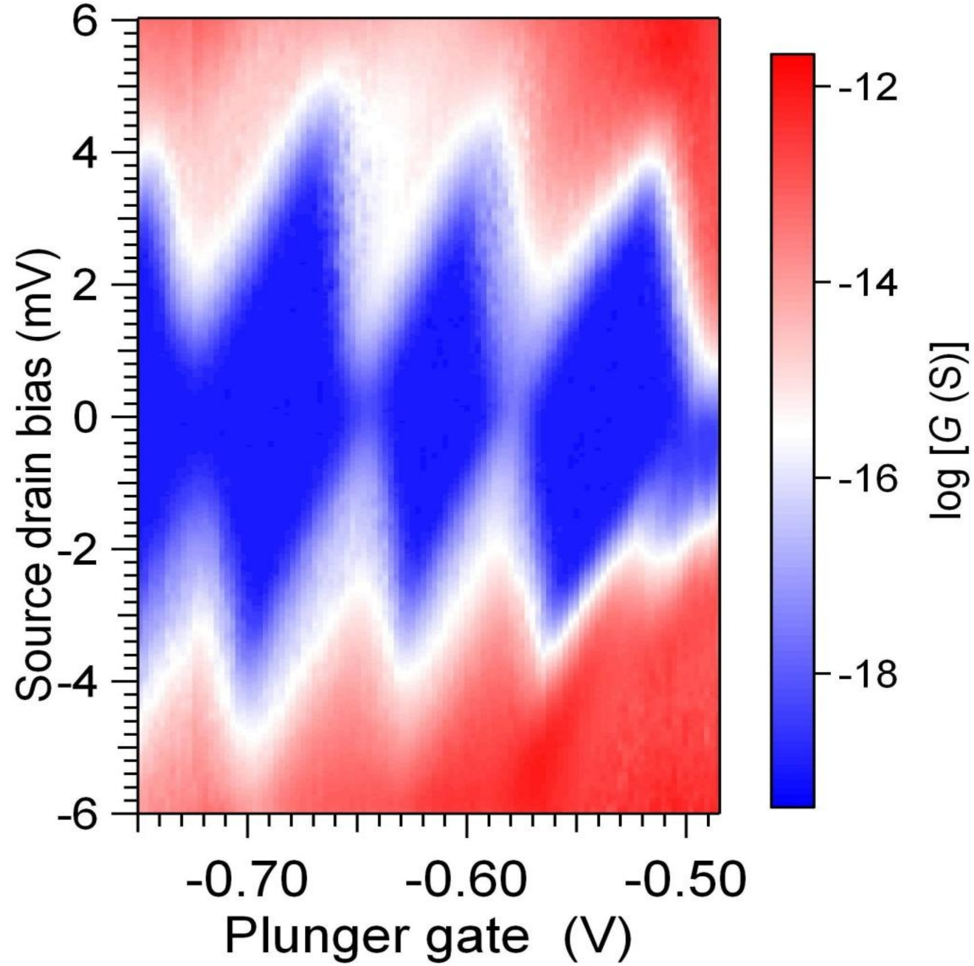
>>

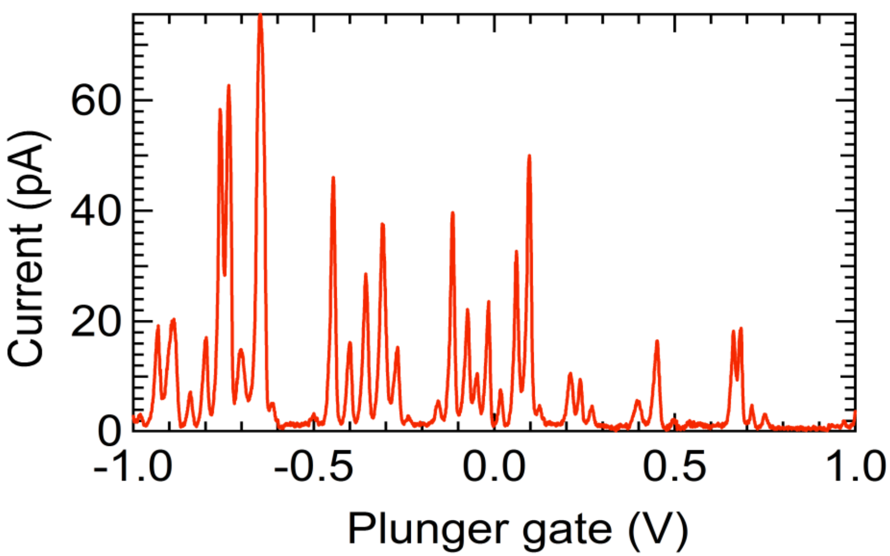
$$E_n = \left(n + \frac{1}{2}\right)\frac{\hbar e}{m^*} B$$

$$\sigma_{xy} = \frac{4e^2}{h}\left(n + \frac{1}{2}\right)$$

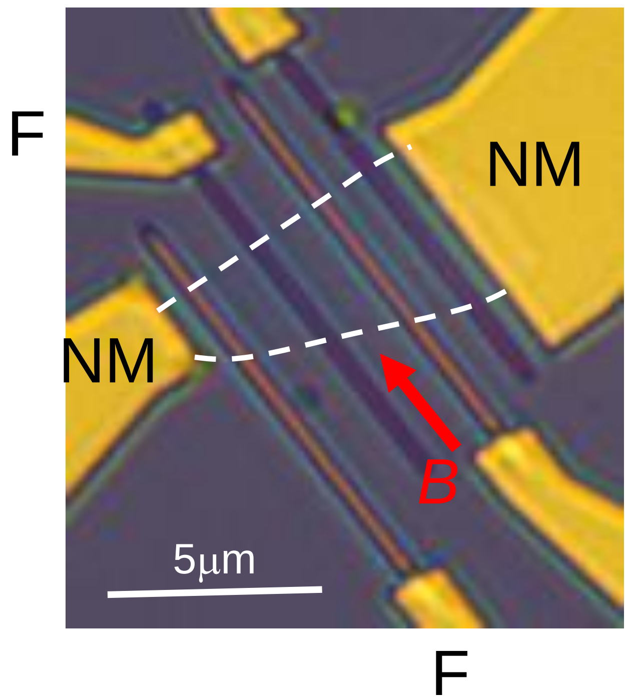
Graphene single QD

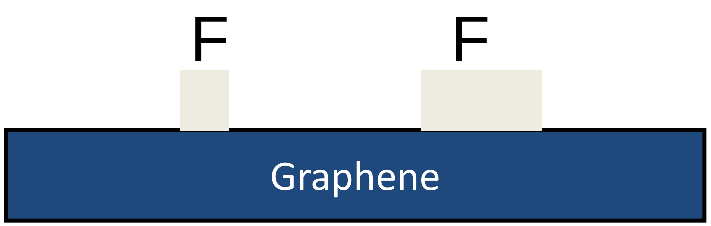


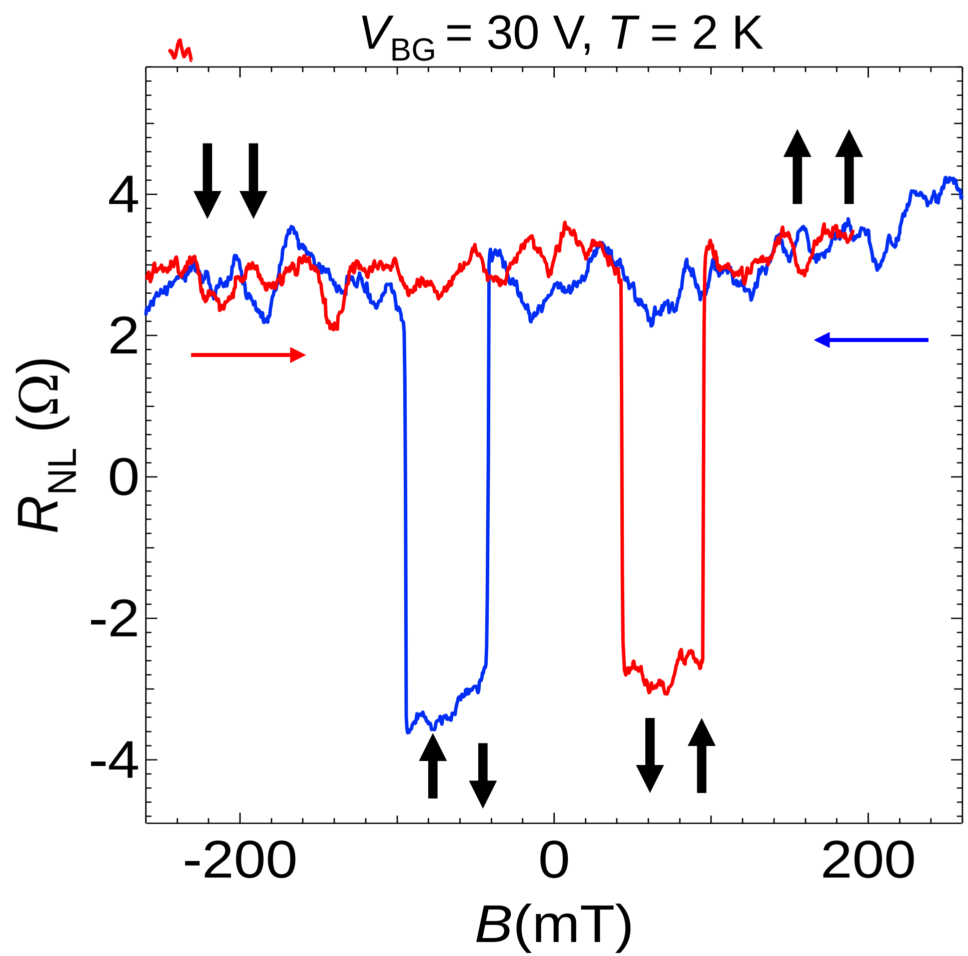




Nonlocal Magnetoresistance



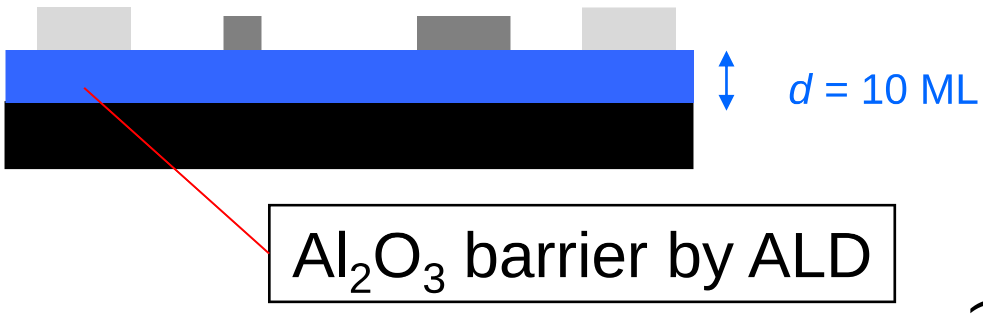


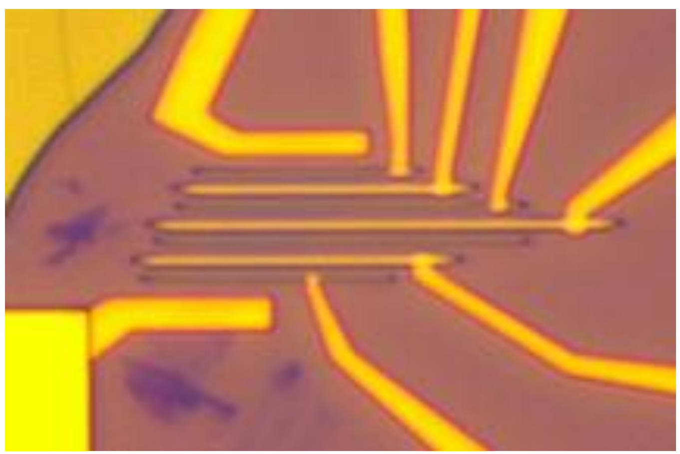


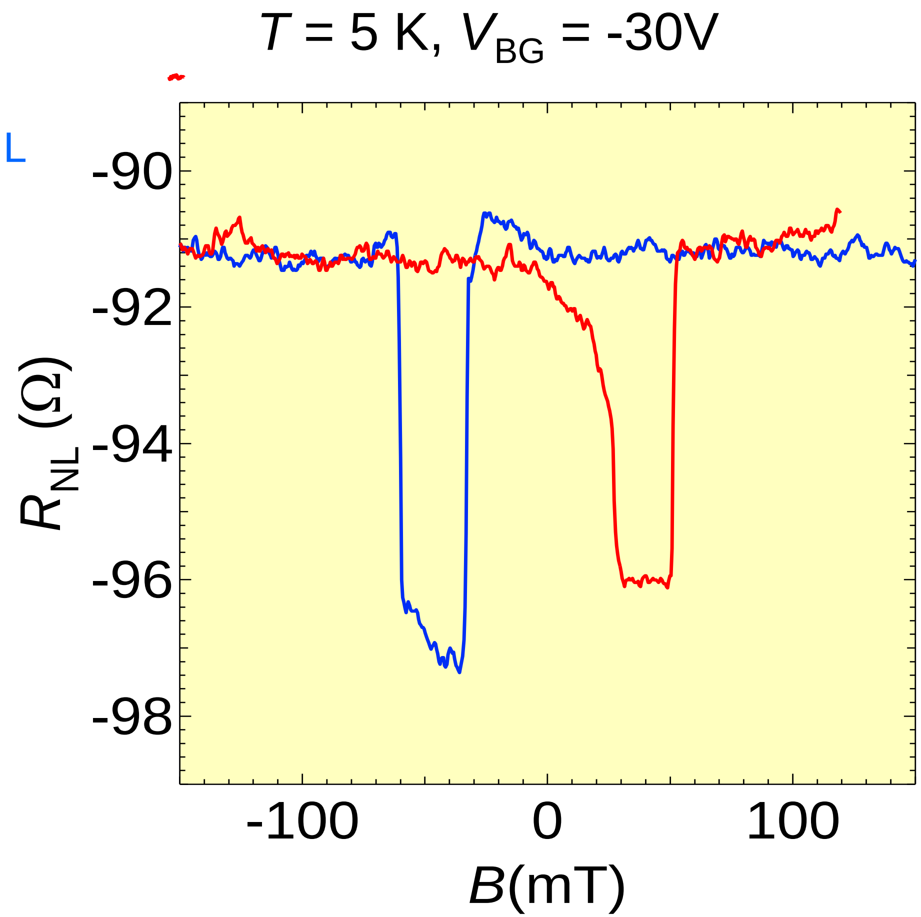
FM/Graphene/FM
Spin valve

Without barrier

Graphene spin valve with tunnel barrier





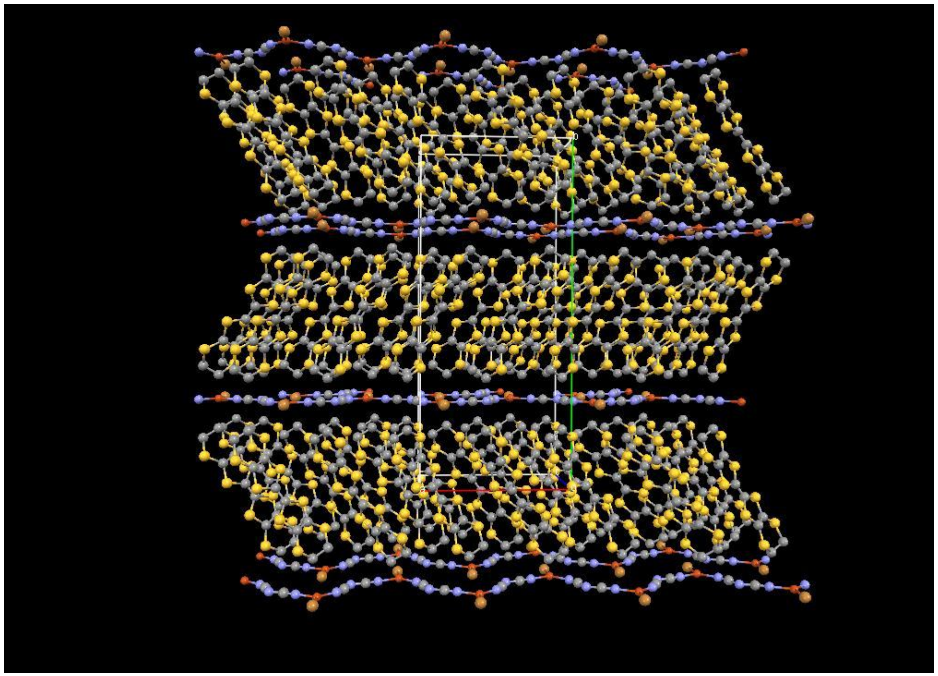


FM/Al_2O_3/graphene/ Al_2O_3/FM
Spin valve

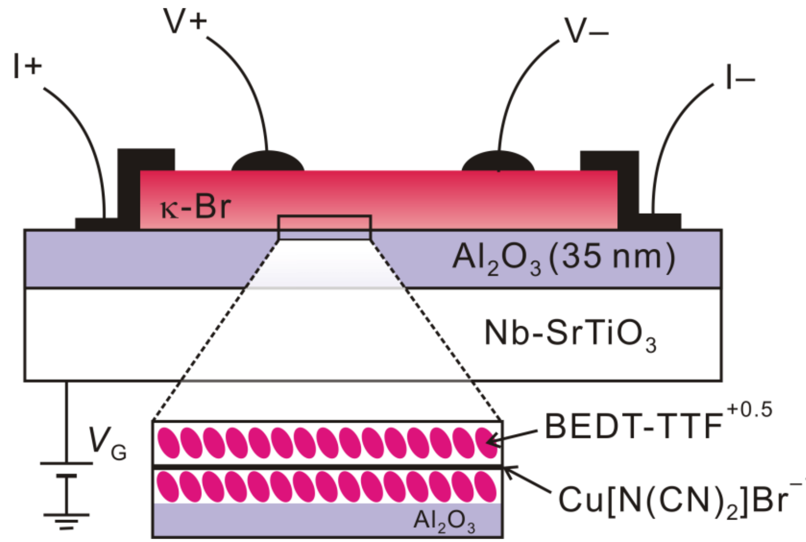
Molecules and Organics

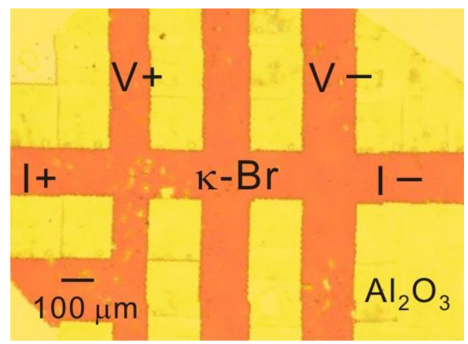
ORGANIC FET USING ELECTRONIC CORRELATION

Organic FET structure

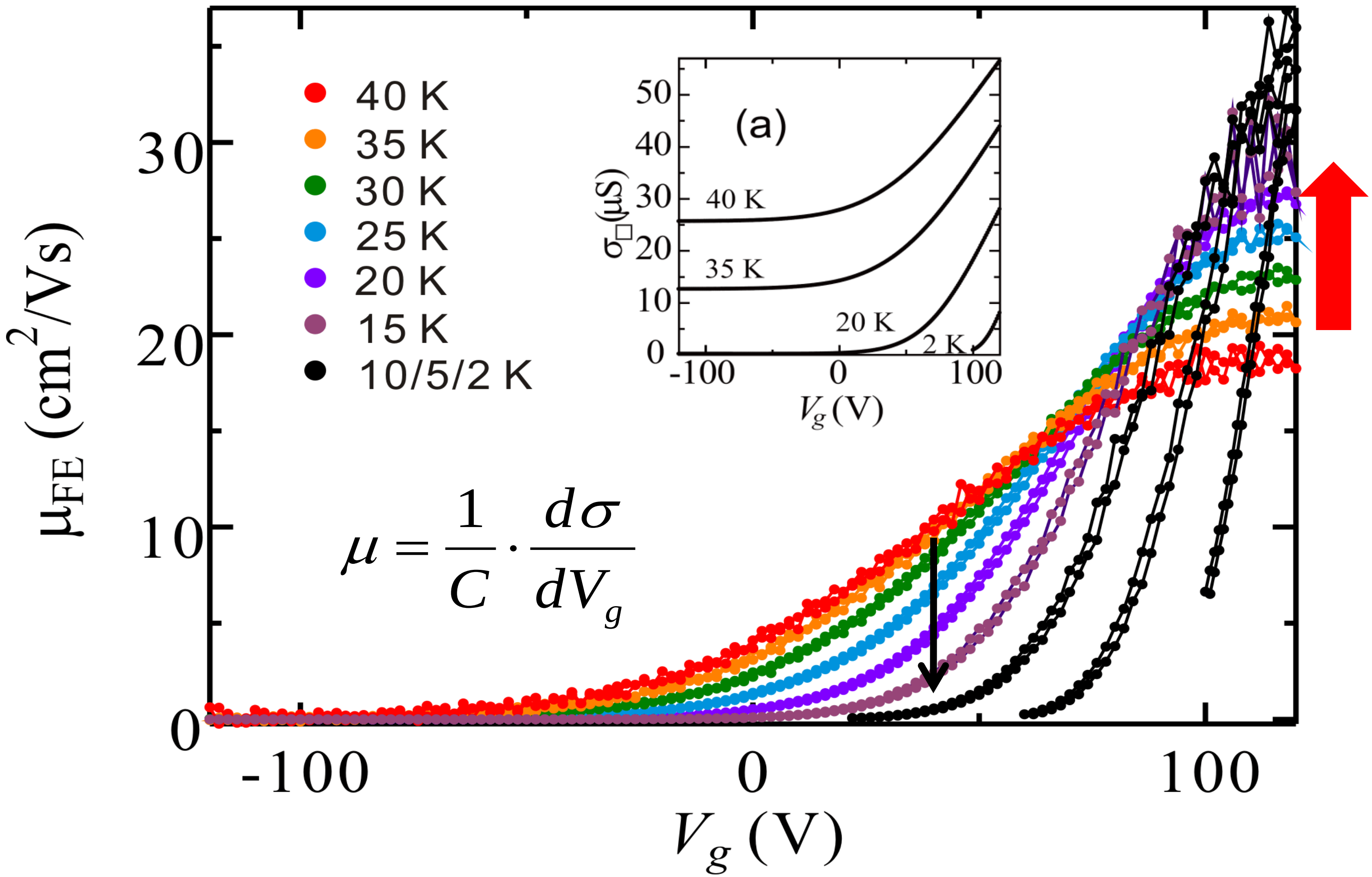


κ-Br (Cu[N(CN)2]Br^{-1}) crystal structure

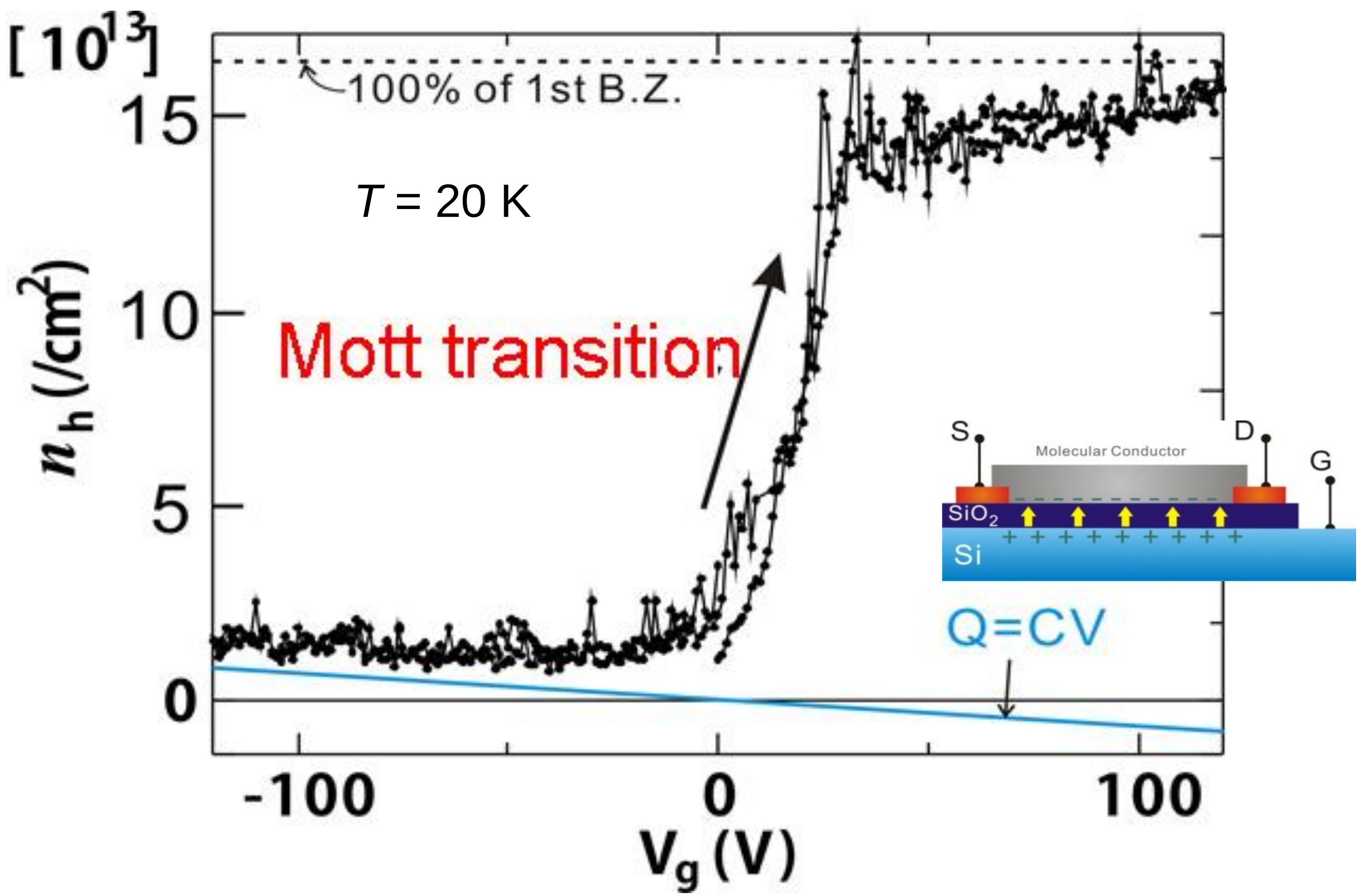


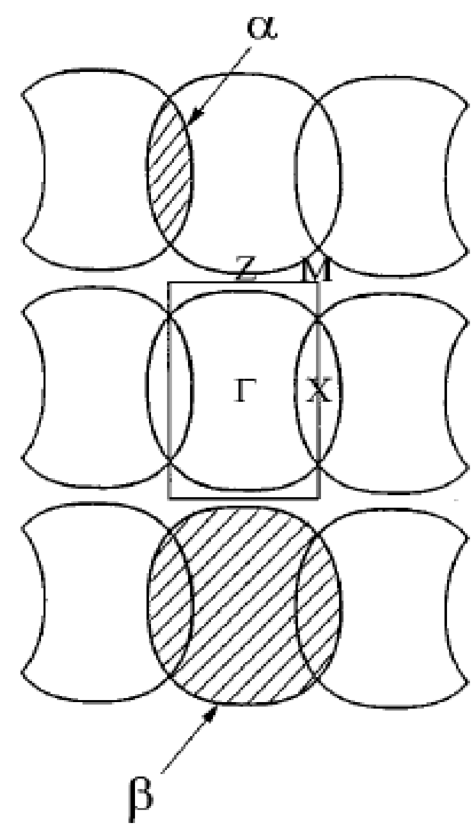


Temperature dependence of carrier mobility



Gate-voltage dependence of carrier concentration





90% of 1st BZ carriers appear by application of gate voltage of 40V assuming 1monolayer active layer

計算より求めた
κ-Br のフェルミ面

Other achievements

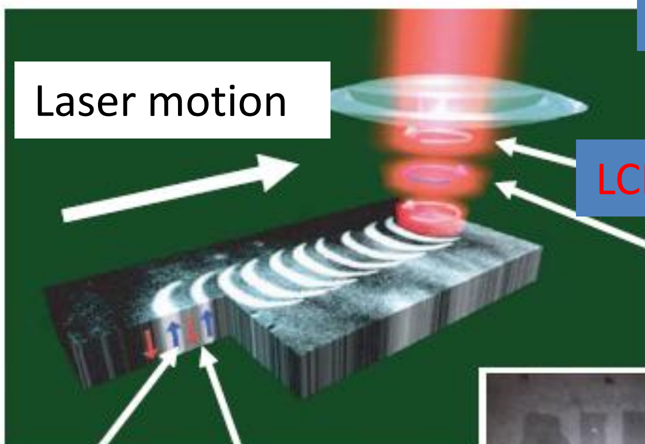
1. H. Kumigashira succeeded in 2D-confineiment of strongly-correlated electrons
2. W. Kobayashi developed thermal diode with the record rectification ratio
3. A. Tsukamoto succeeded in ultra-high speed magneto-optical recording by using circularly polarized pulse-laser of sub-pico second width

Light-Induced ultrafast magnetization reversal

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

Demonstration of direct magneto-optcal recording by circular polarization modulation

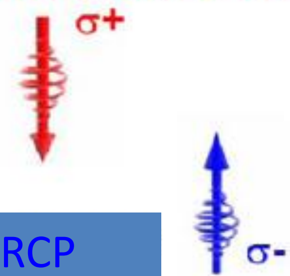
Equivalent magnetic field produced by photon



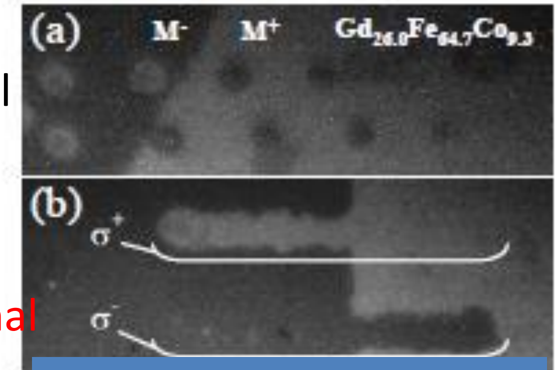
Laser motion

LCP

RCP



thermal



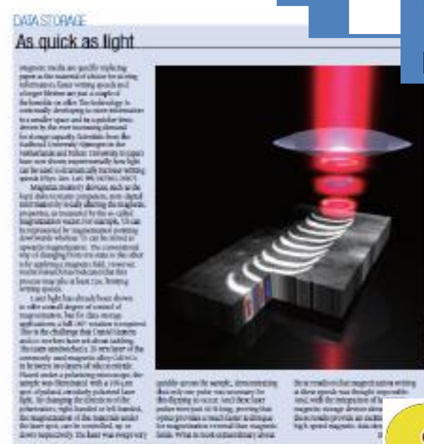
nonthermal

Up spin,　Down spin

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

PRL 99, 047601 (2007)

Nature Photonics



Light-induced ultrafast magnetic recording

Science、Physics toda

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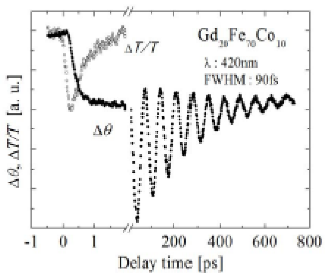
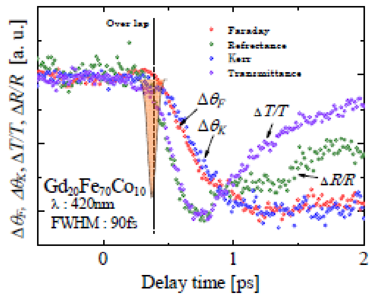
Analysis of light-induced ultrafast magnetization reversal

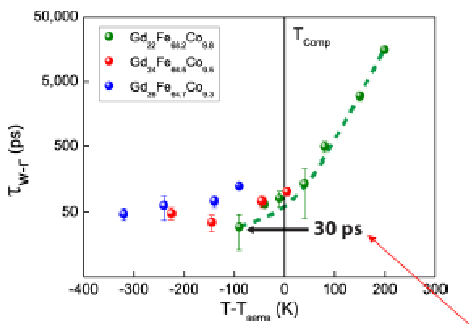
PRESTO





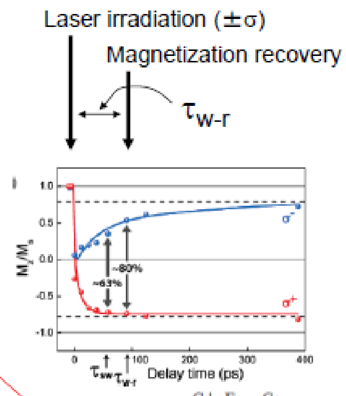
The magnetization
modified monotonically
reaches to a temporal state within 1ps

Composition and temperature dependence of
Photo-magnetic switching time



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

Cooperated work with Radboud Univ. et. al.

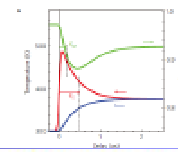


$Gd_{24}Fe_{66.5}Co_{9.5}$
@room temp.

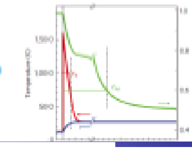
Fastest write-read event
demonstrated for magnetic recording so far.

Classification of ultrafast dynamics

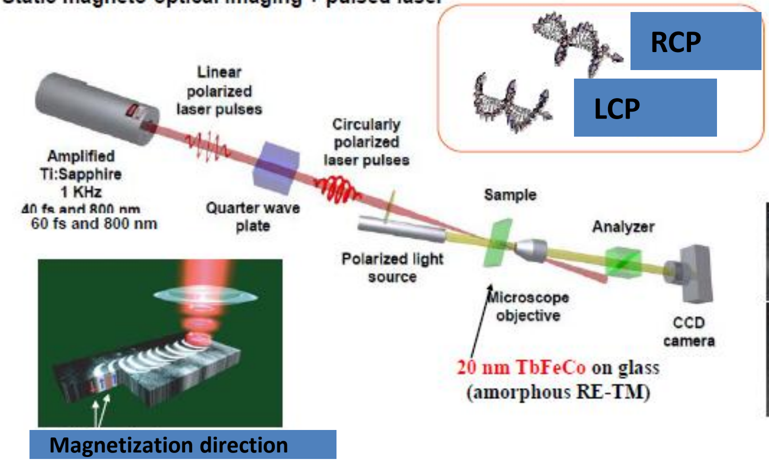
Type I material
- Strong spin scattering
- Fast demagnetization follows the electron temperature
- Ni, Fe and Co

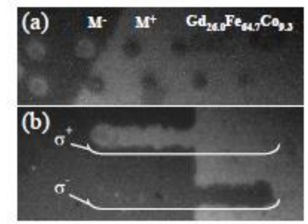


Type II material
- Weaker magnetic coupling
- 2step demagnetizations very fast (first picosecond) slower demagnetization
- Ga, TbFe



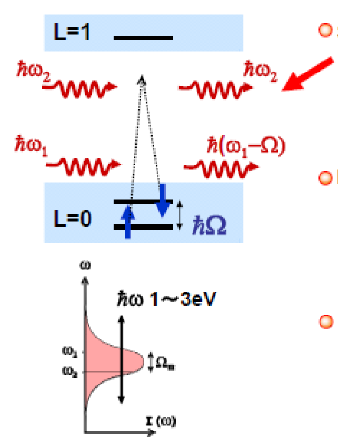
Static magneto-optical imaging + pulsed laser





Light-induced ultrafast magnetic recording

Origin of photo induced magnetization phenomena



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

+

- **Control of dynamic motion of spins**
  - **･Angular momentum compensa**
  - **･Linear reversal**
  - **> Suppress Precessional motion**

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SUMMARY

Outputs

- Presentations: about 1400
 (289 international journals, 279 international conference of which 144 invited)
- Patent applications: 40
- Awards: 45
- Press release: 10
- Promotion:
professor , associate, assistant: 0,11,22 → 11,14,8

Outcomes

- Scientific
  - New Paradigm of spintronics opened up
    Spin wave spin current in insulator→ Low power circuit
    Spin Seebeck effect→ Energy Harvesting
- Technical
  - Diamond NV center → Safety information processing and communication
  - Nanowire transistors → Higher integration and low power

Are our achievements in accordance with the *Strategic Sector* (initial target) provided by MEXT?

(1) Development of non silicon materials for beyond-CMOS→

Yes : Vertical T-FET using InAs nanowire (Tomioka), Ge-n MOSFET and PD(Takenaka), C60 doped GaAs thin film(Nishinaga), polarity-control of GaN (Katayama)…

(2) Pioneering materials for novel concept-devices by using combined functionalities of photon, electron and spin→

Yes : Spin current devices (Saitoh), Quantum information devices using diamond NV-center (Mizuochi), TiO2-based room temperature ferromagnetic semiconductors (Fukumura), Heusler alloys with highest spin polarization (Y.Takahashi), Femtsecond magneto-optical recording (Tsukamoto)

(3) Development of novel devices based on nano-scale fabrication→

Yes : Graphene Q-dot (Machida), Nanogap single electron device (Noguchi)…

(4) Development of thin flexible resilient materials→

Yes : Graphene growth on sapphire (Noda), Graphene spintronics (Shiraishi) , Heteroacene-based organic semiconductor (Nakano) , Electron correlation driven organic FET (Yamamoto)

JST SATO-PRESTO PROJECT

Materials and Processes for
Next-Generation Innovative Devices

HOW THE PROJECT MANAGED?

Japan Science and Technology Agency

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PRESTO Project targeting at Next Generation Devices

- The PRESTO* project "**Materials and Processes for Next Generation Innovative Devices**" started in 2007 FY
- The scope of this project involves
  - spintronics materials
  - wide-gap materials
  - Semiconductor nanoelectronics
  - molecules and organics.

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

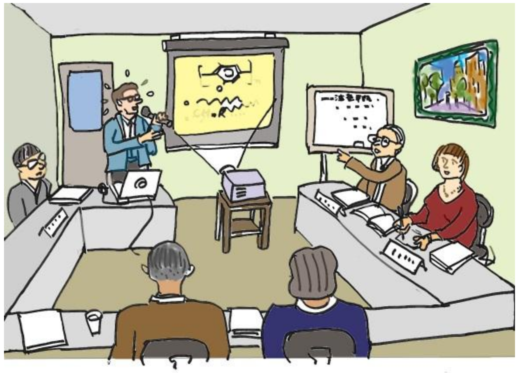
Duration and Budgets

- Duration: 3.5 years
- Budget: 40MYen (~400KEuros) per person
- Members: 33 (Total 1.4BYen~14MEuro)
- Average age at adoption: 34.5 years old
- Affiliation: Universities: 25, Government Agencies: 8

For Comparison: Case of Watanabe-CREST
Duration Max 5.5 years
Budget 150-500 M Yen (1.5-5 M Euro) per team
Teams: 18

Two stage screening; (1) papers (2) interview

- The Research Supervisor conducts two-stage screening of the application together with advisors from the research area.
- **Screening by Papers**: Research Supervisor select candidates for interview by examining submitted application papers with a help of area advisors
  EX: *25 interviewees from nearly 100 applicants*
- **Screening by Interview**: Research Supervisor select candidates by interview consulting with advisors
  EX: *10 from 25 interviewees*
- *Based on the selection, JST determines individual researchers and research themes*



Organization

Suprevisor

Advisors

Office

Research Manager
Administrative Manager

JST Staffs

33 Researchers
stage (1): 11, stage (2): 10, stage (3): 12

Japan Science and Technology Agency

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"Site-Visit" to individual researcher's labs

- The Research Supervisor visits the laboratories of individual researcher's affiliation and *grasp research environment* and *explain to his or her boss about the mission of the Program* and *ask to allow to conduct an independent research*.
  - This process has an indispensable importance for researcher to conduct researches on a theme independent from the affiliation.
  - Supervisor can conduct careful management in accordance with the situation of the researcher.




Research Area Meetings

- JST holds *Research Meetings* sponsored by the Supervisor twice a year to discuss the research plan, to report the progress or to promote communication among researches in the research area.
- Researchers are very much activated by joining the Meeting through severe discussion with Supervisor, Advisors and other researchers.
- These research meetings help researchers to build wide personal networks across the organization and position.

Active discussion among researchers

Discussion continues to late at night

Hot discussion among researchers, advisors and supervisor

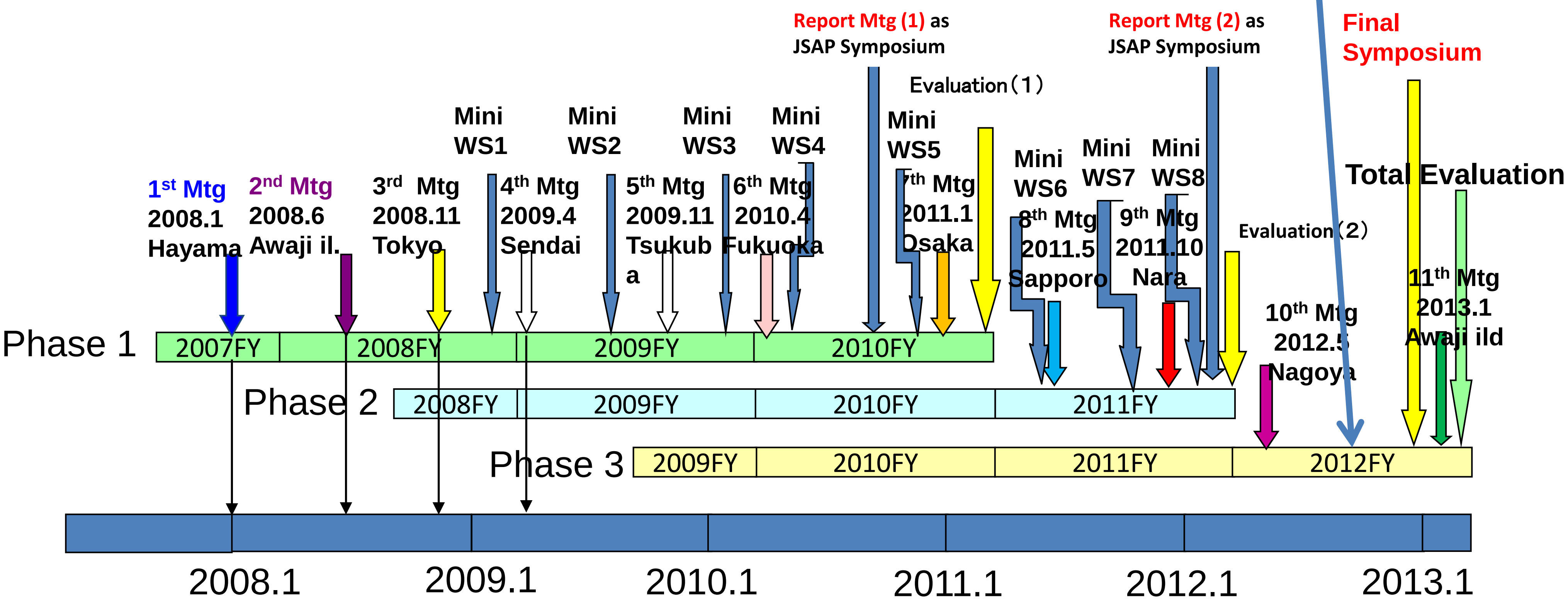
Publicity of Achievements by JST staffs

- Dept. of Public Relations & Science Portal help Press Release
  - Press releases and press lecture of research achievements are conducted by JST specialist of publicity.
  - JST News, a monthly magazine, introduce the research outcomes
- Science Communication Center send introduction video to Web
  - Science News, a JST Web Animation Site dispatches the contents of researches

Project Flow

- The phase I group: October 2007→March 2011
- The phase II group: October 2008→March 2012
- The phase III group: October 2009→March 2013

Now we are
in the final stage!



PRESTO is a unique virtual laboratory to promote young researchers

- Individual Research Themes independent from affiliation
- Reasonable amount of budget
- Flexible managements of research fund
- Acceleration of research by leadership of Supervisor
- Management such as Research Meetings, Site-Visits as Virtual Institute
- Support by Research Office：Research Administrators
- Recommendation to Awards
- Confidence and Aggressive Minds by stimulation by Colleagues
- Interdisciplinary relationship to build wide personal networks across the organization and position.

THANK YOU FOR YOUR ATTENTION

APPENDIX

Promotion System of S &T Policy in Japan

Cabinet Office

Prime Minister

Consultation ⇩ ⇧ Response ⇧ ⇧ Opinion

Council for Science & Technology Policy (CSTP)

Member:
- Prime Minister (Chair)
- 6 Ministers
- 8 Executive members
  - Academia: 6
  - Industry: 2

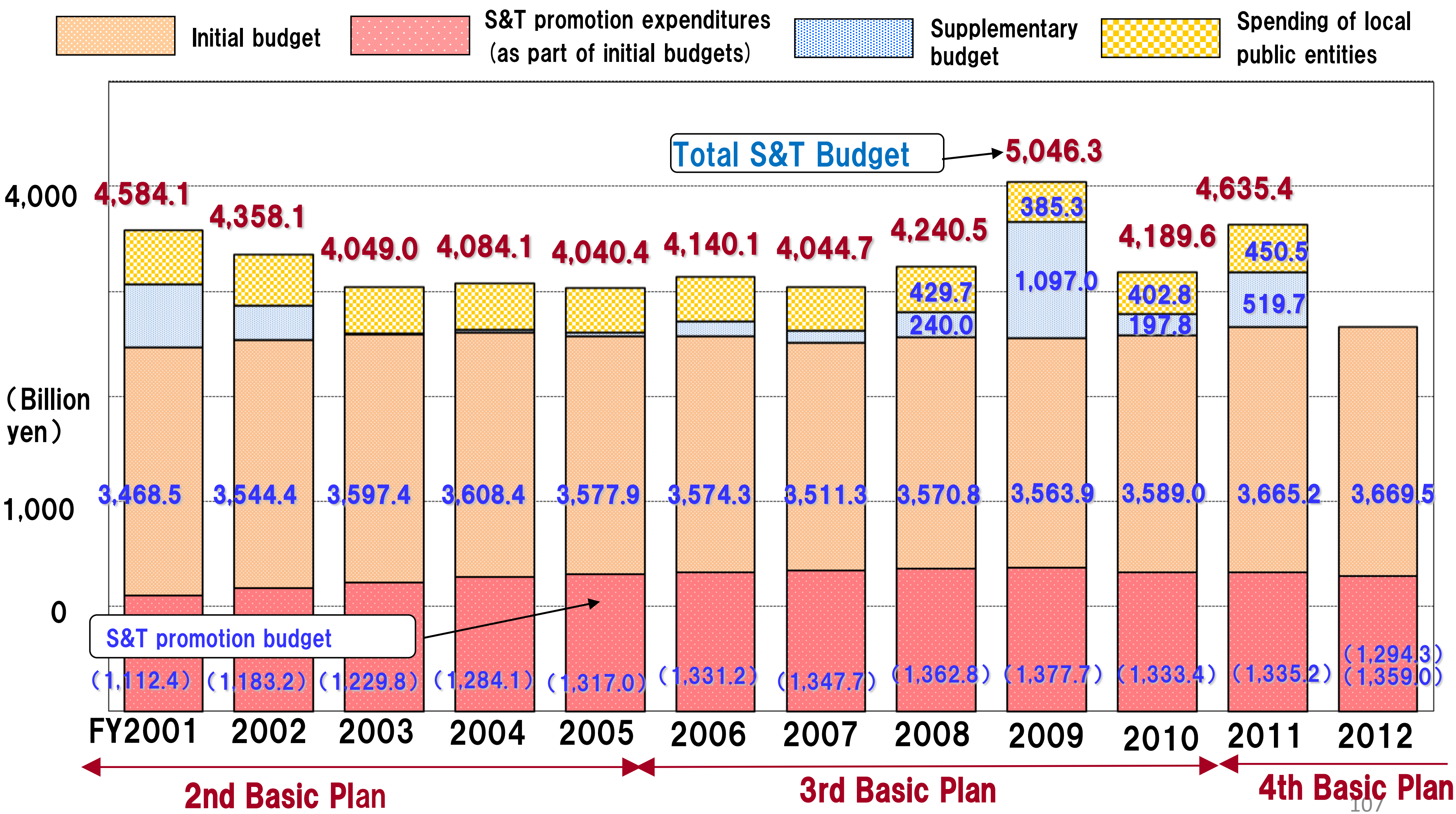
Mission:
1) Investigations and deliberations on basic policies of S&T
2) Investigations and deliberations on the resource allocation in S&T policy
3) Evaluations of nationally important R&D

Consultation ⇧ ⇩ Response ⇩ ⇩ Opinion

Relevant Ministries and Agencies

- Internal Affairs and Communications (IAC)
- Education, Culture, Sports, S&T (MEXT)
- Health, Labor and Welfare (MOH)
- Agriculture, Forestry and Fisheries (MAFF)
- Economy, Trade and Industry (METI)
- Land, Infrastructure and Transport (MLIT)
- Environment (MOE)

Japanese Government S&T Budget



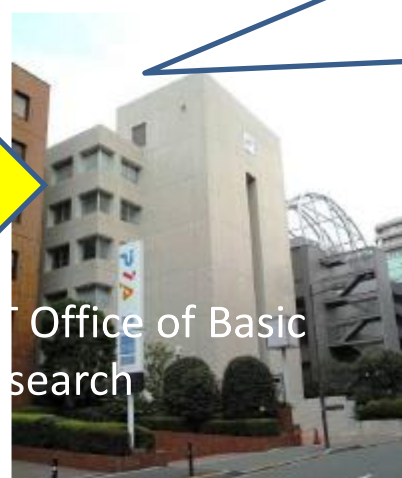
Strategic Sector (Target of Research)

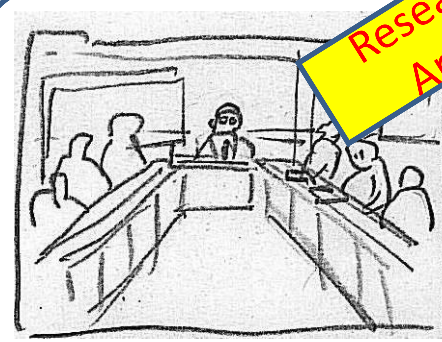
- Center of R&D Strategy (CRDS), a *think-tank of JST*, works out proposals through survey S&T fields, by drawing "bird's-eye view maps", and by listing up important R&D subjects
  →MEXT designates Strategic Sectors using the proposals as well as those from other government sections including those of CSTP

Research Areas
based on the Strategic Sector

- Based on strategic sectors, JST establishes research areas.
  - My case：
    Strategic Sector is “R & D for beyond-CMOS Devices”
    Designated Project Name is
    “Materials and Processes for Next-Generation Innovative Devices”

Strategic Sectors





PD Meeting

Research Areas

Research Office

- Research offices are established for each research area and take daily care of researches under the guidance of Supervisors.
- Research managers (who coordinate the research, determine research progress and give support for presentations), administrative managers (who purchase equipment and materials and deal with procedures for business trips) and office staffs are stationed in all research offices.