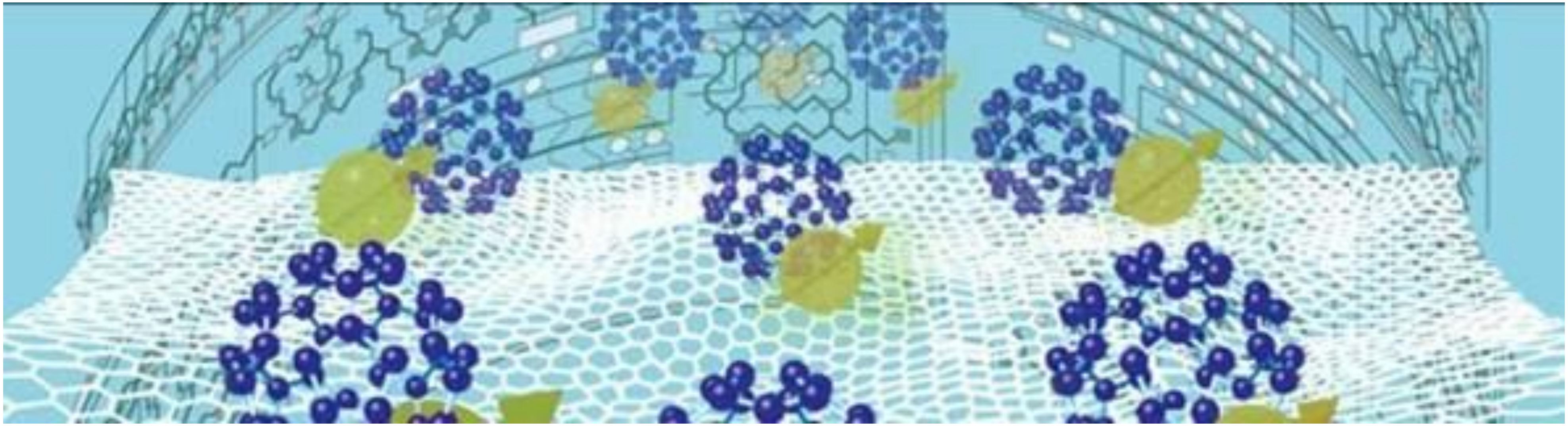
Special Seminar with Moldavian Visitors
Date: Jan 24, 2014



- Materials and Processes for Next-Generation Innovative Devices-

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Professor Emeritus, Tokyo University of Agriculture and Technology

Contents

Introduction

HOW THE PROJECT WAS DESIGNED AND ORGANIZED?

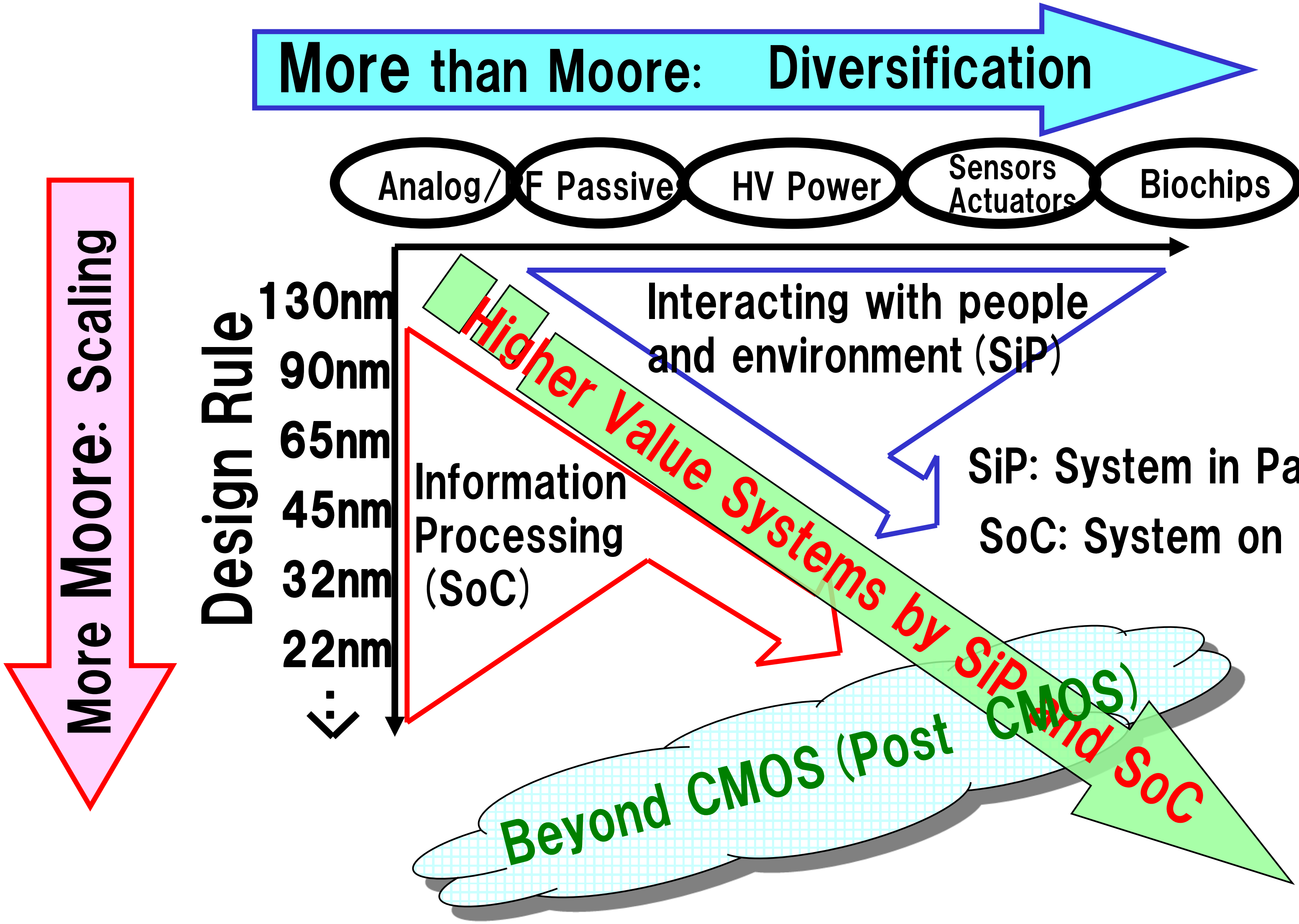
Background of the Project

- 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



More than Moore:　Diversification

Analog/RF

Passives

HV Power

Sensors
Actuators

Biochips

More Moore: Scaling

Design Rule

130nm
90nm
65nm
45nm
32nm
22nm
⋮

Information
Processing
(SoC)

Interacting with people
and environment (SiP)

Higher Value Systems by SiP and SoC

SiP: System in Package

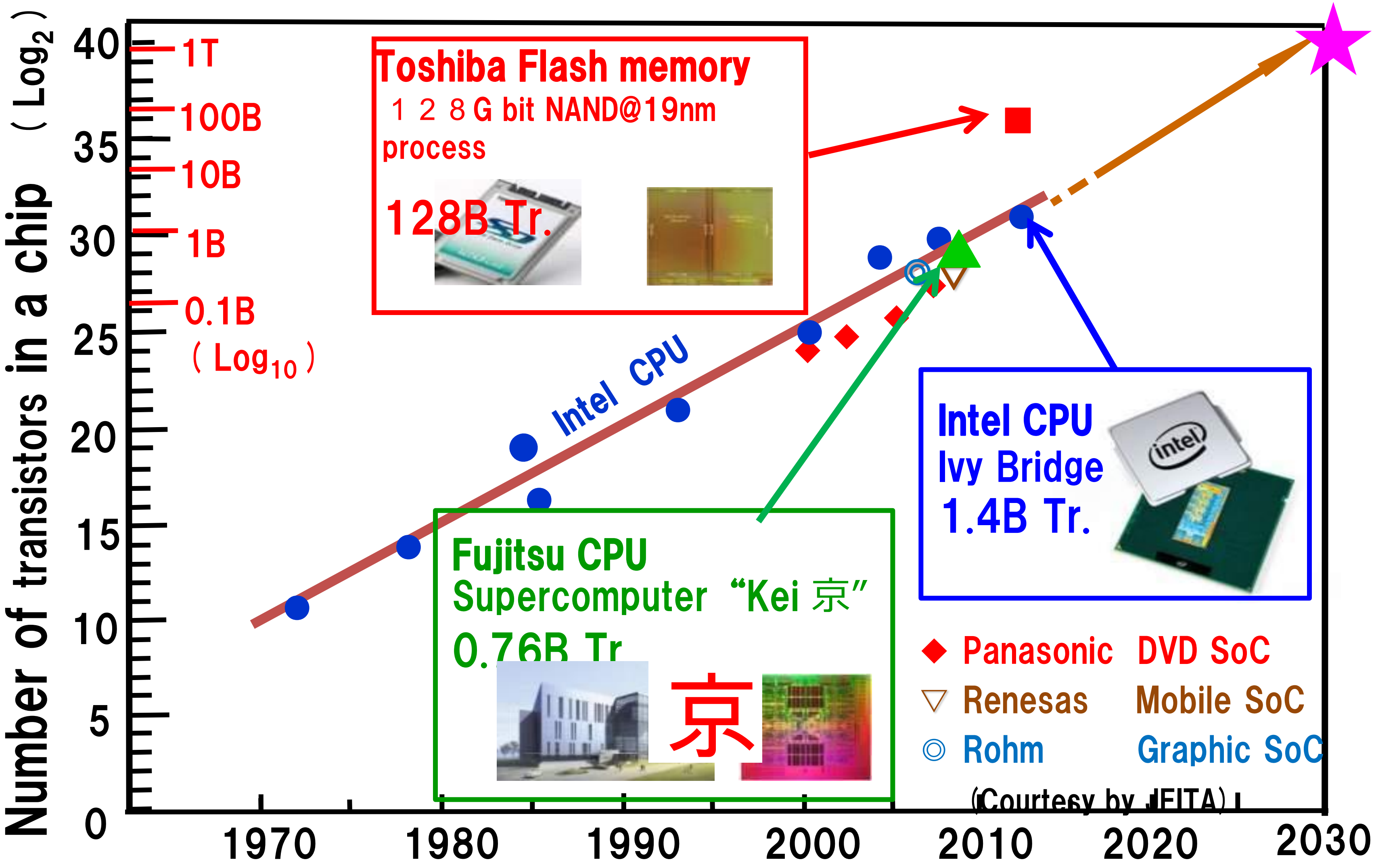
SoC: System on Chip

Beyond CMOS (Post CMOS)

ITRS　International Technology Roadmap for Semiconductors 2005

Demand for more integration : Moore’s Law

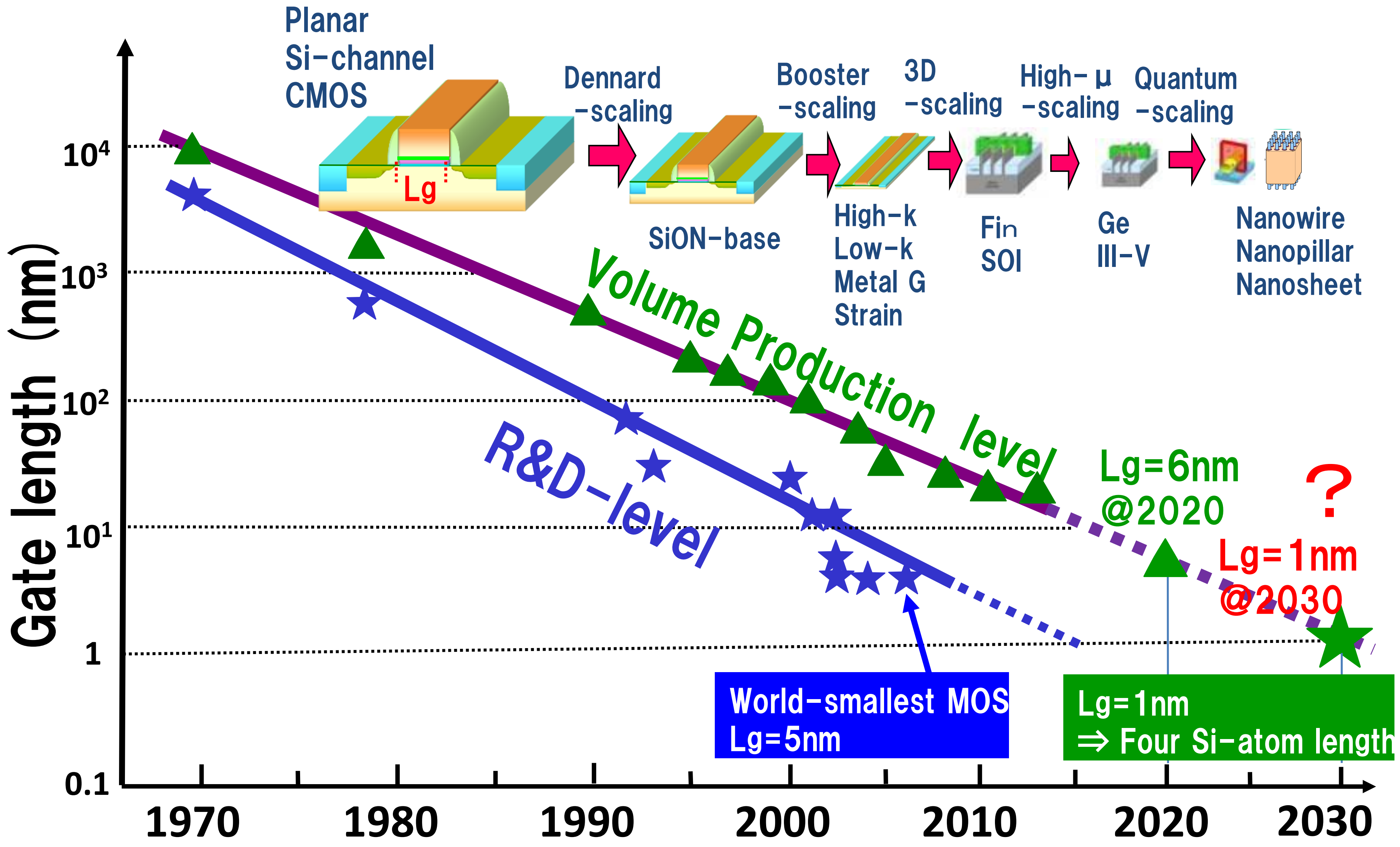
Intel CPU plots, except Ivy Bridge, are shown in http://www.intel.com/jp/technology/mooreslaw/index.htm?iid=jpIntel_tl+moores_law



(Courtesy by JEITA)

Japan Science and Technology Agency

Demand for more miniaturization



Japan Science and Technology Agency

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.）**

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:

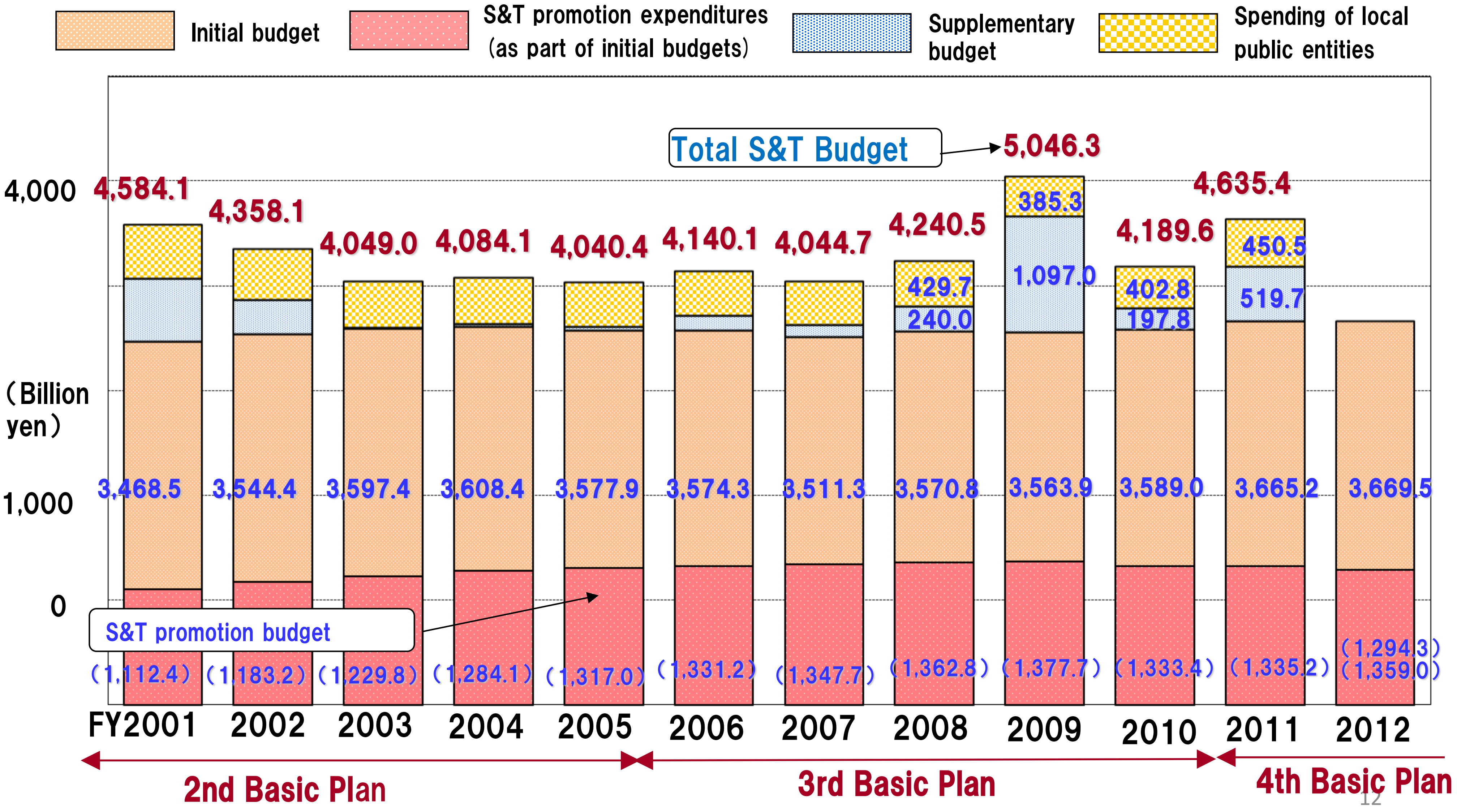
1） Investigations and deliberations on basic policies of S&T
2） Investigations and deliberations on the resource allocation in S&T policy
3） Evaluations of nationally important R&D

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

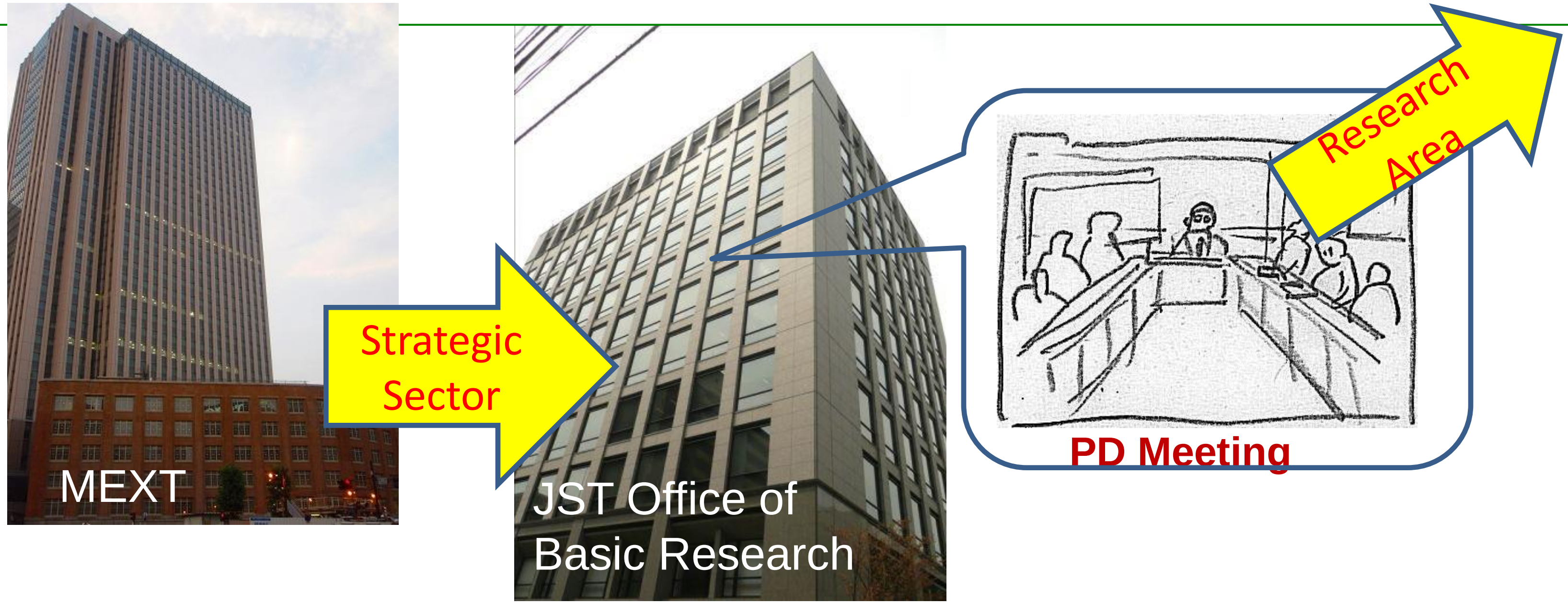


(1)How is the Strategic Sector designated?

- 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

(2)JST establishes Research Areas based on the Strategic Sector

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



Research Office

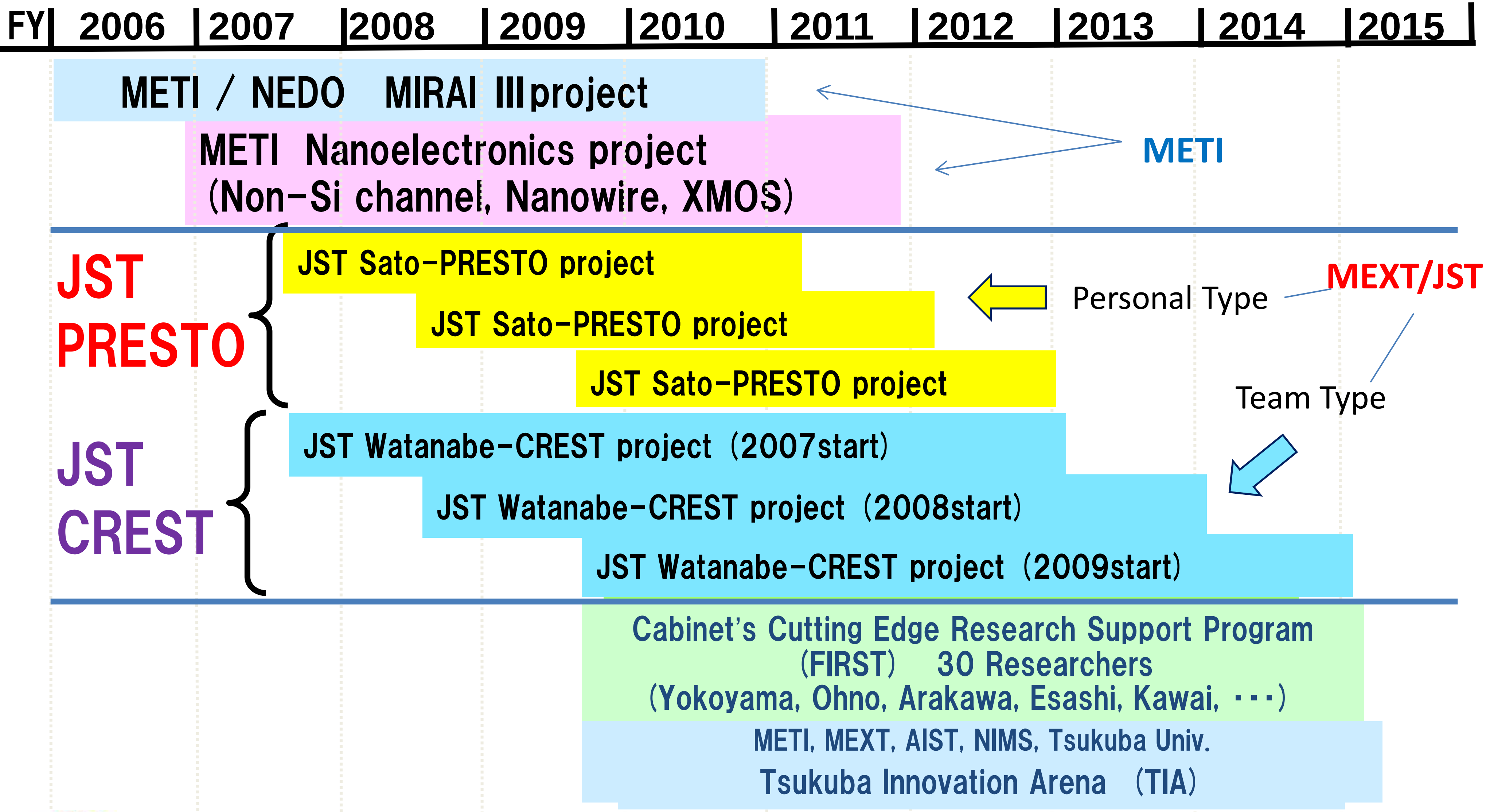
- Research offices are established for each research area and take daily care of researches under the guidance of Supervisors.
- Research managers (who coordinate the research, determine research progress and give support for presentations), administrative managers (who purchase equipment and materials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

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 / NEDO MIRAI Ⅲproject

METI Nanoelectronics project
(Non-Si channel, Nanowire, XMOS)

METI

JST PRESTO

JST Sato-PRESTO project

JST Sato-PRESTO project

JST Sato-PRESTO project

Personal Type

MEXT/JST

Team Type

JST CREST

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)

JST SATO-PRESTO PROJECT

Materials and Processes for
Next-Generation Innovative Devices

HOW THE PROJECT MANAGED?

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

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


Wataru Kobayashi

Heat


Yoshihiro Kangawa


Hideo Kaiju


Shuichi Murakami


Hiroyuki Nakamura


Jiro Nishinaga


Tomoki Machida


Masashi Shiraishi


Naoki Fukata

Spin


Seiya Kasai


Takeshi Yasuda


Hiroshi Yamamoto


Masataka Higashiwaki


Katsunori Wakabayashi


Akinobu Yamaguchi


Hiroshi Kumigashira


Eiji Saitoh


Katsuhiro Tomioka


Tomofumi Susaki


Y.K. Takahashi


Kohei Hamaya


Iwao Kawayama


Suguru Noda


Yutaka Noguchi


Tomoyasu Taniyama


Arata Tsukamoto

Charge


Tomoteru Fukumura


Toshihiro Nakaoka


Koji Nakano


Norikazu Mizuochi


Ryuji Katayama


Mitsuru Takenaka


Yasushi Takahashi

Light

Materials

Oxides


Yasushi Takahashi


Katsuhiro Tomioka


Tomoteru Fukumura


Tomofumi Susaki


Naoki Fukata


Yoshihiro Kangawa


Ryuji Katayama


Norikazu Mizuochi


Wataru Kobayashi


Eiji Saitoh


Masataka Higashiwaki


Toshihiro Nakaoka

Semiconductors


Mitsuru Takenaka

Dielctrics


Hiroshi Kumigashira


Hiroyuki Nakamura


Seiya Kasai


Kohei Hamaya


Hideo Kaiju

Organics


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

Metals

Superconducto


Arata Tsukamoto


Y.K. Takahashi

"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

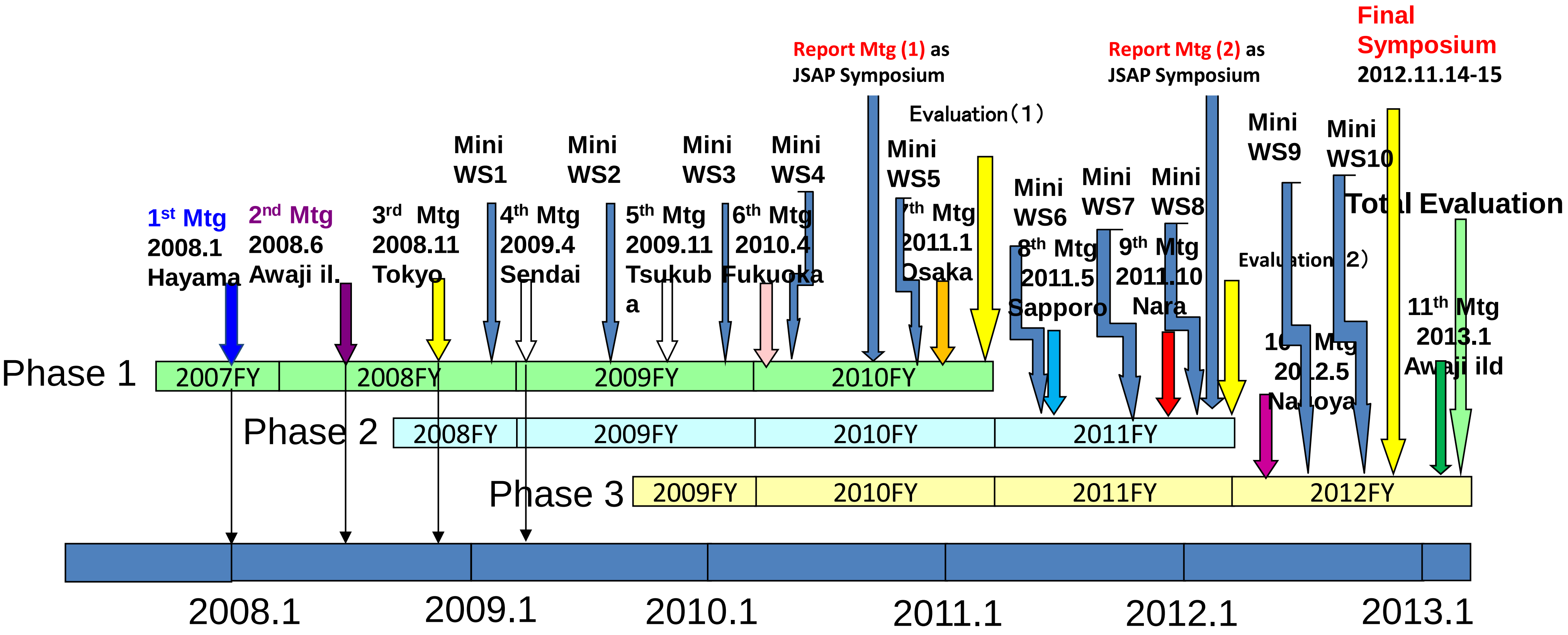

Hot discussion among researchers, advisors and supervisor

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



ACHIEVEMENTS

Spintronics devices and materials

Semiconductor nanoelectronics

Wide-gap semiconductors

Molecular and organic electronics

Spintronics devices and materials

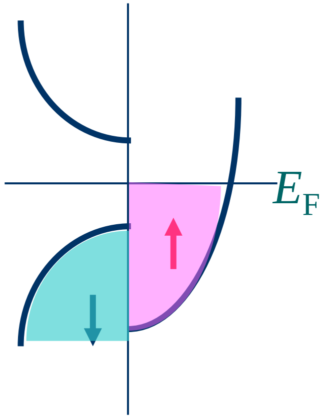
1. Y. Takahashi developed ***Heusler alloy*** **Co$_2$Mn(Ga,Ge) with the highest degree of spin polarization**
2. **E. Saitoh succeeded in transfering DC signal through** ***insulator*** **by using spin current. He discovered** ***Spin Seebeck*** **effect by using thermal spin current**
3. **S. Murakami 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**
6. **A. Tsukamoto succeeded in** ***ultra-high speed magneto-optical recording*** **by using circularly polarized pulse-laser**

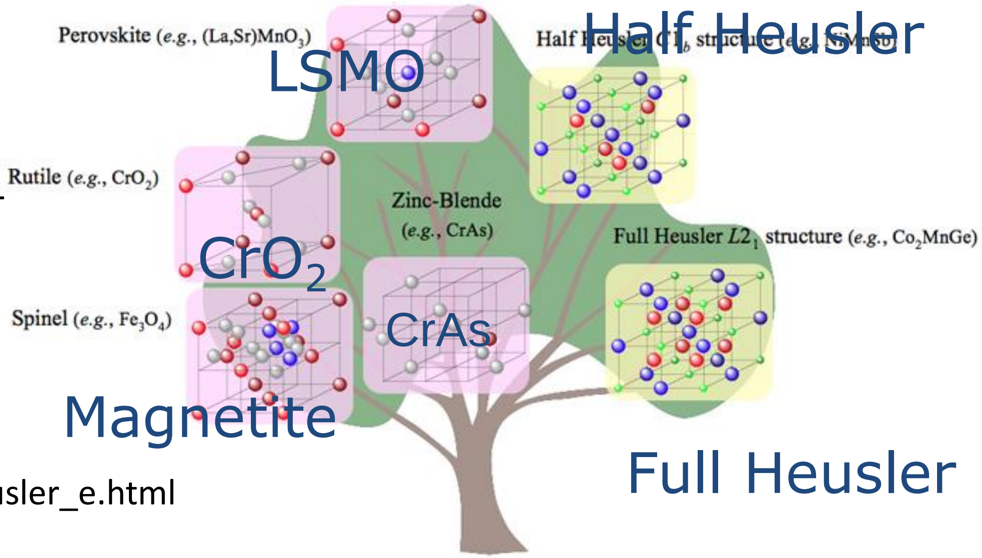
Spintronics devices and materials

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.





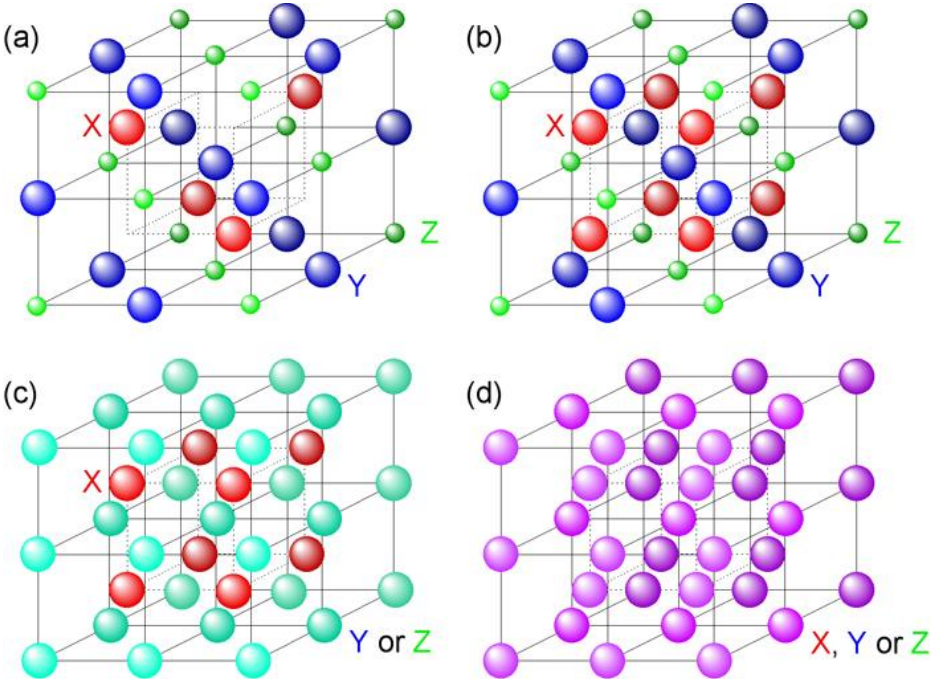
http://www.riken.go.jp/lab-www/nanomag/research/heusler_e.html

Heusler Alloys

- The Heusler alloys are classified into two groups by their crystal structures;
  - Half Heusler alloys with XYZ-type in the *C1b* structure (a)
  - Full Heusler alloys with X_2YZ-type in the $L2_1$ structure (b) *where X and Y atoms are transition metals, while Z is either a semiconductor or a non-magnetic metal*.

Half Heusler alloy
XYZ type $C1_b$ str.

Full Heusler alloy
X_2YZ with $L2_1$ str.



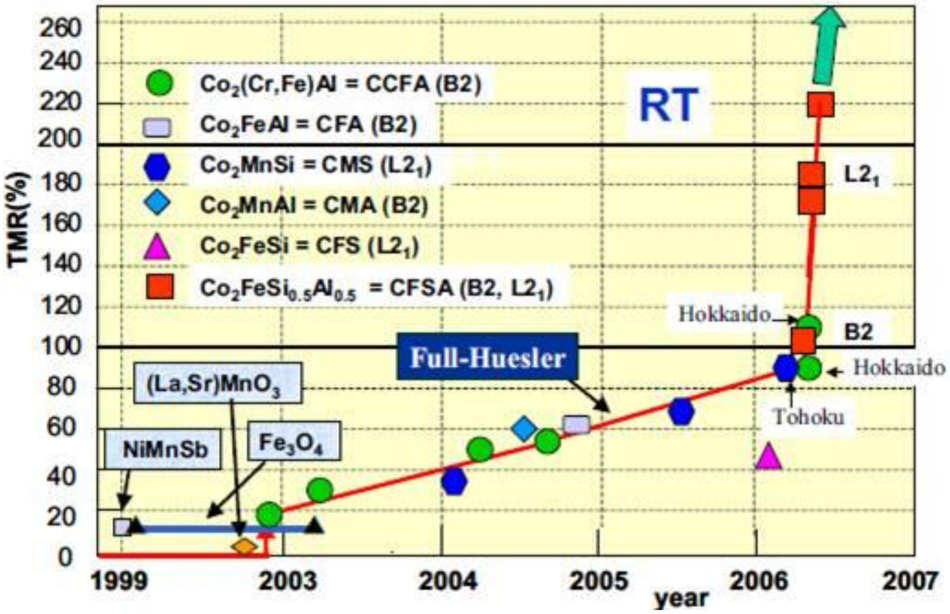
B_2-structure with
Y-Z disorder

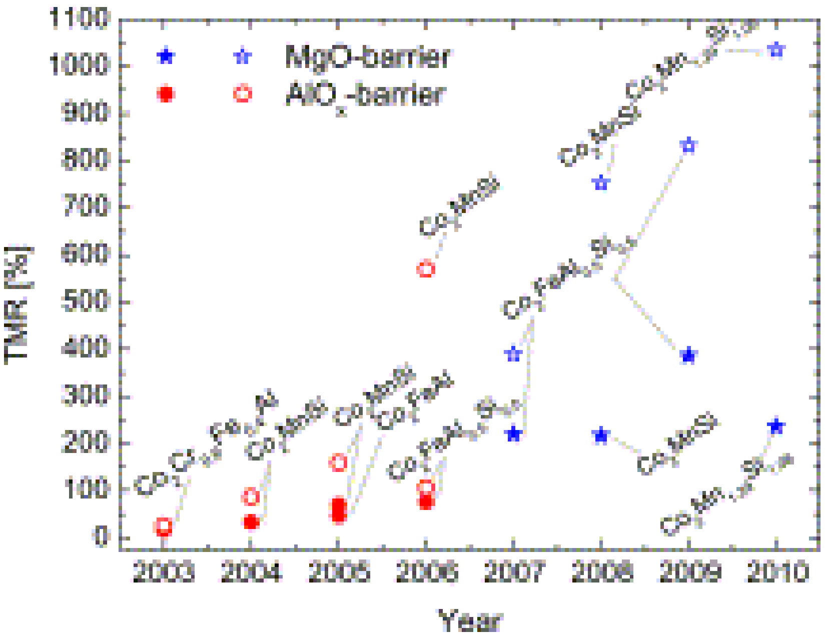
A_2-structure with
X-Y and X-Z disorder

Disordered derivatives

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

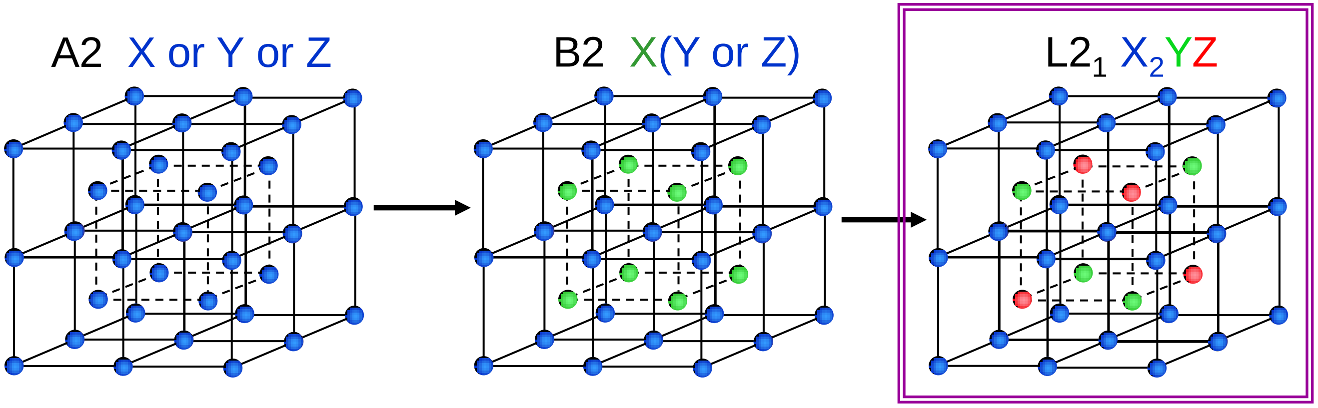
TMR with full Heusler X2YZ alloys





Alloy search for RT half-metal

Co based Heusler alloy、X_2YZ

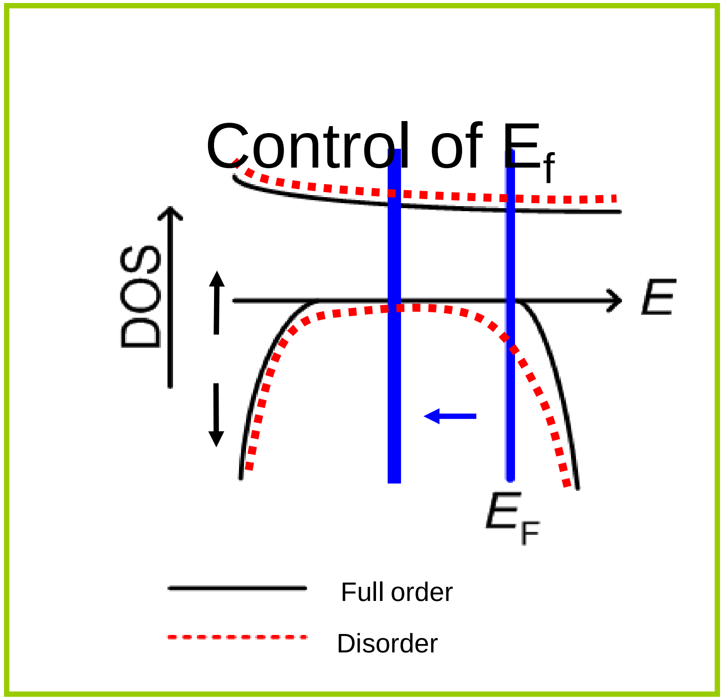


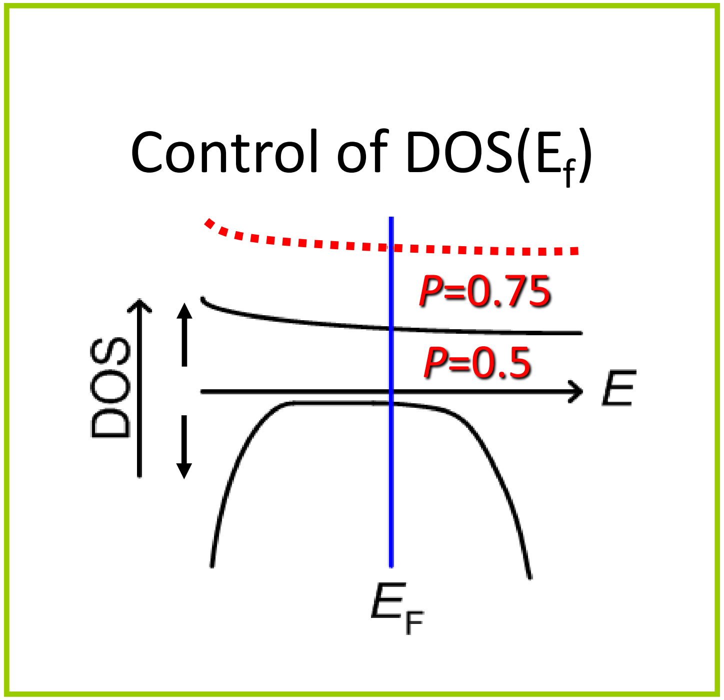
High Tc

Theoretical P=1

However,

Experimental P is low


Control of E_f


Control of DOS(E_f)

Search of high spin-polarization half metals using PCARS

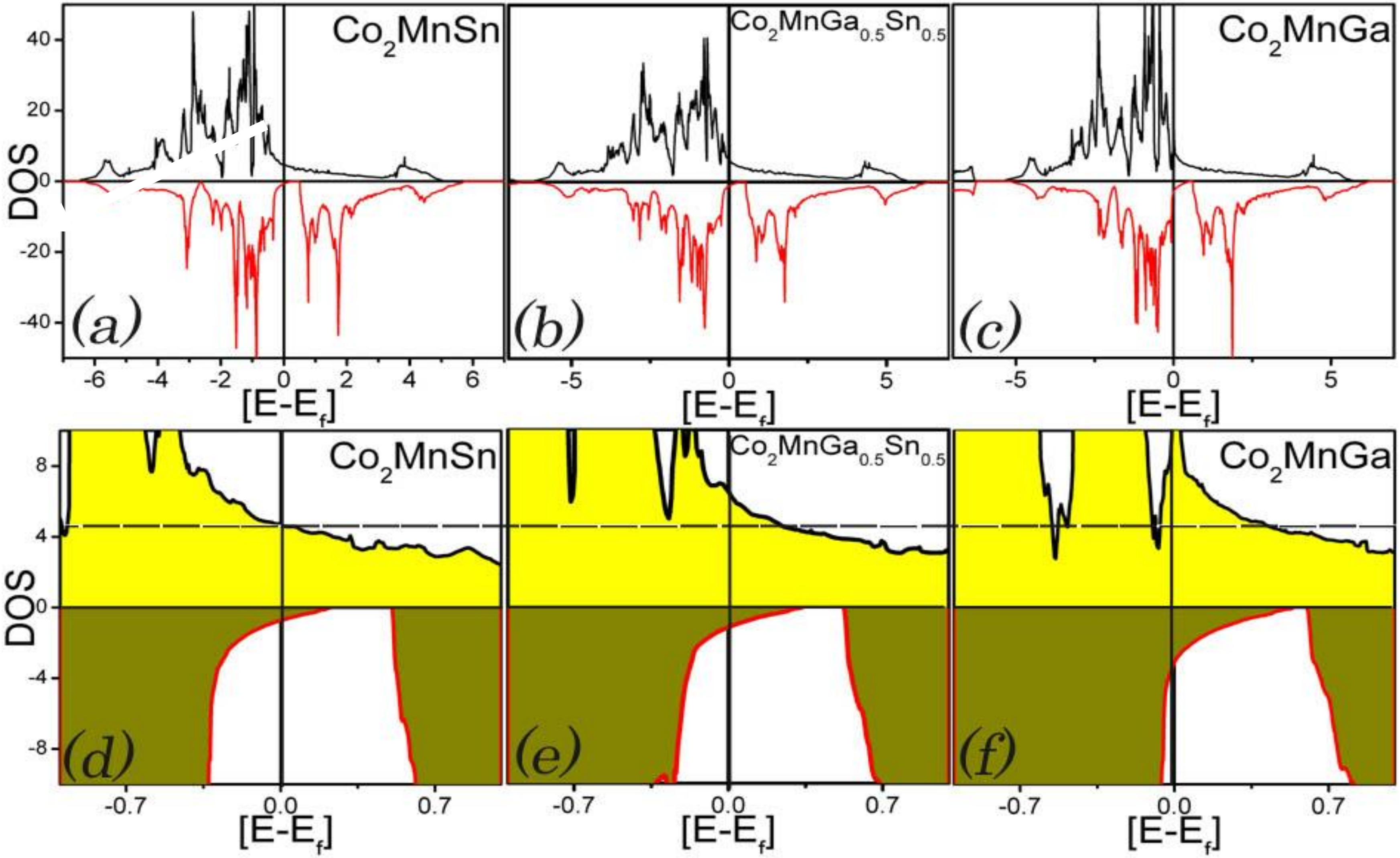
- Aiming at high performance GMR devices Takahashi has investigated as many as 32 full Heusler alloys and found 74% sipn polarization in CoMnGeGa alloy.

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	

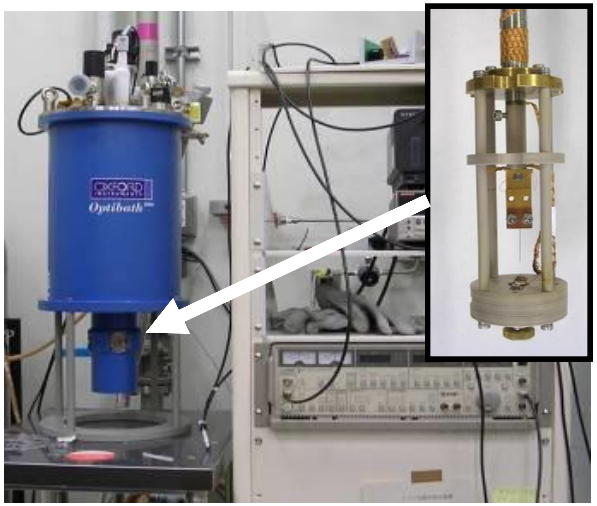
Quaternary alloys	P	Ref.
$Co_2Mn(Ge_{0.75}Ga_{0.25})$	74	
$Co_2Mn(Ga_{0.5}Sn_{0.5})$	72	
$Co_2Fe(Si_{0.75}Ge_{0.25})$	70	
$Co_2FeGa_{0.5}Ge_{0.5}$	68	
$Co_2(Cr_{0.02}Fe_{0.98})Ga$	67	
$Co_2MnGeSn$	67	
$Co_2(Mn_{0.95}Fe_{0.05})Sn$	65	
$(CoFe)_2MnGe$	65	
$Co_2(Mn_{0.5}Fe_{0.5})Ga$	65	
$Co_2(Cr_{0.02}Fe_{0.98})Si$	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	

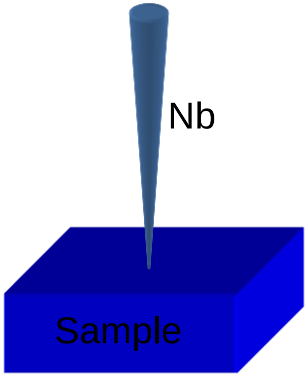
Search of Heusler alloys following band calculation

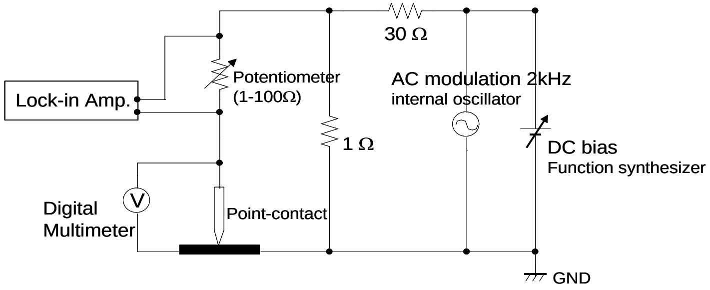


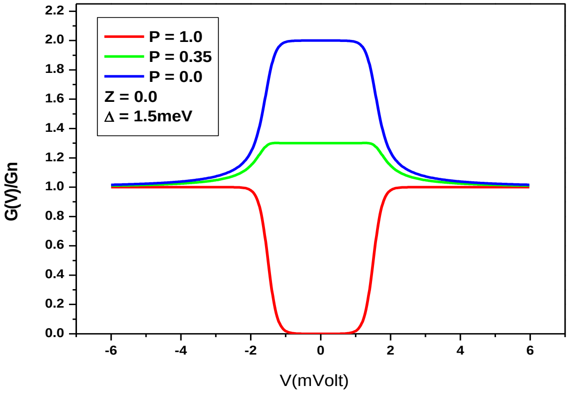
$Co_2MnGa_{1-x}Sn_x$

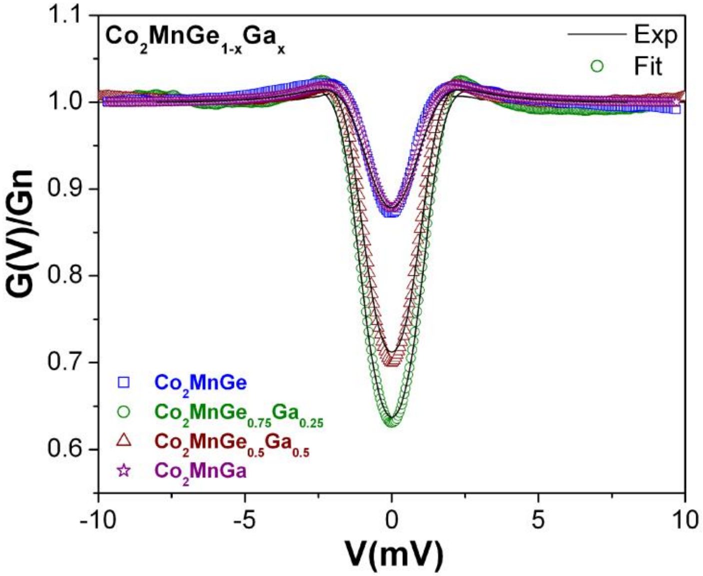
Point contact Andreev reflection (PCAR)

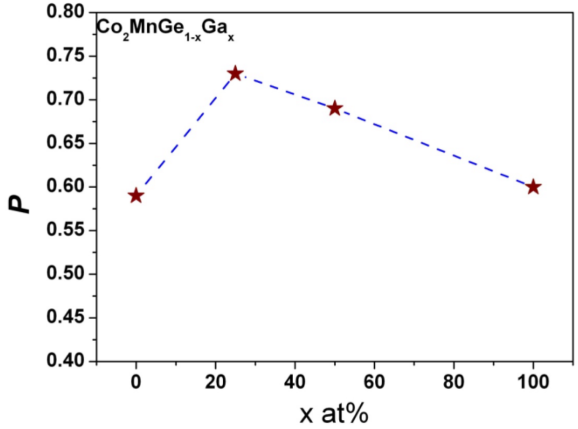












Co$_2$MnGe$_{0.75}$Ga$_{0.25}$ shows highest P

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)**

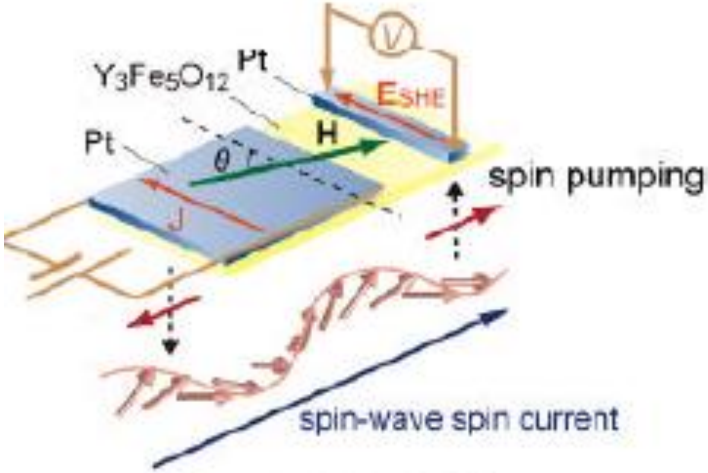
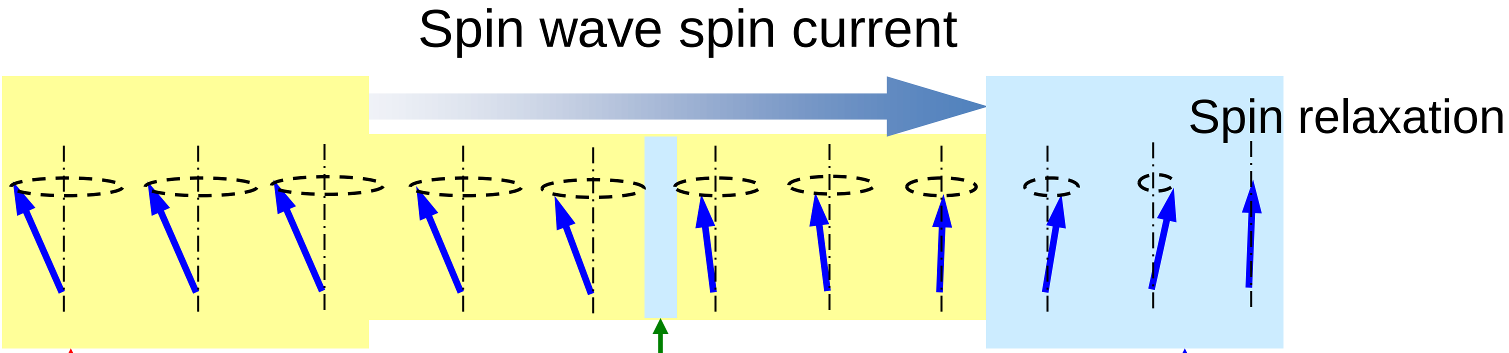


図 1 誘電体スピン流伝送の概念図

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）

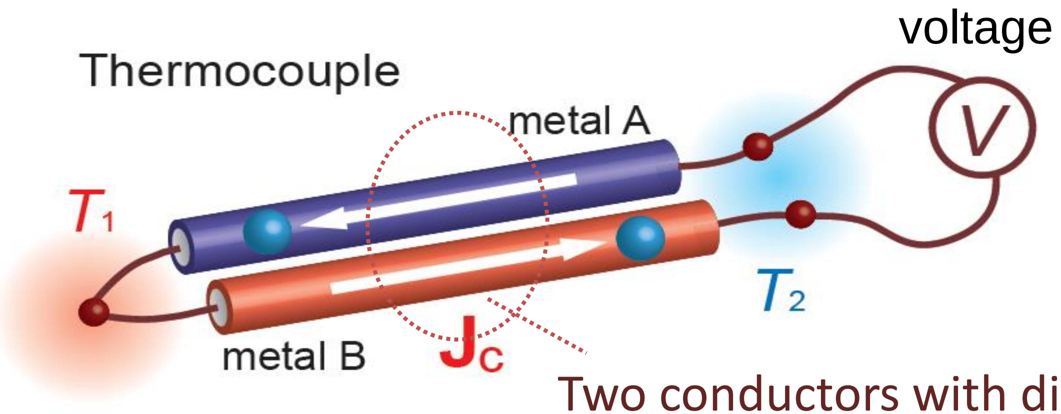
Dielectrics

- 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.

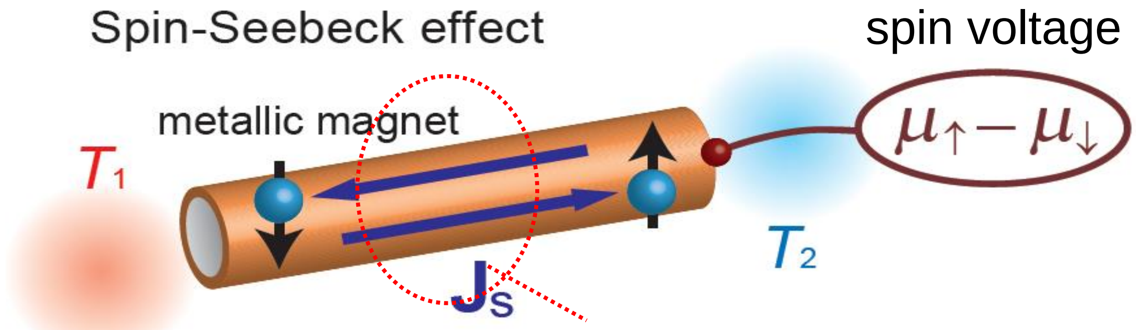
Seebeck and “spin-Seebeck” effects



Electric voltage

Two conductors with different Seebeck coefficients

depending on the density of electrons

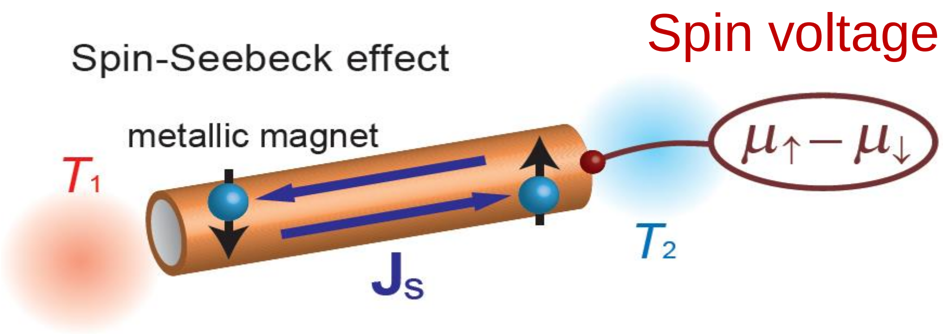


Spin voltage

+ spin currents

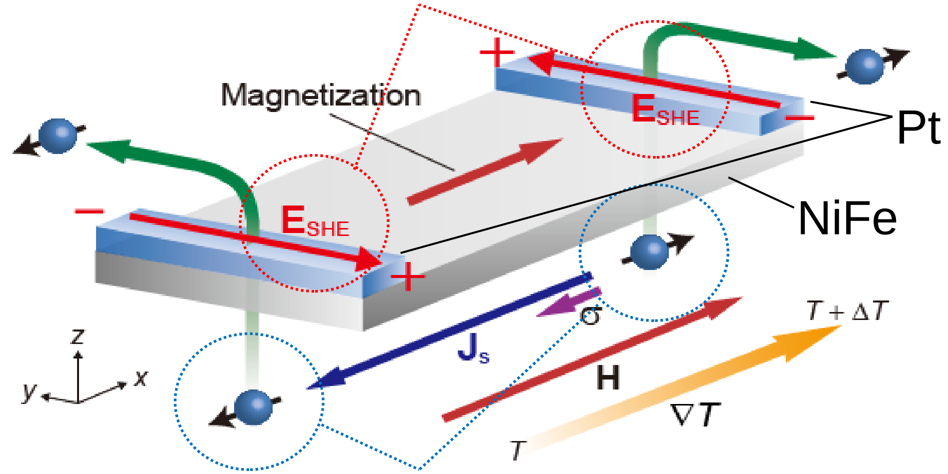
Two spin channels **(up / down)**
with different Seebeck coefficients

Observation of spin-Seebeck effect



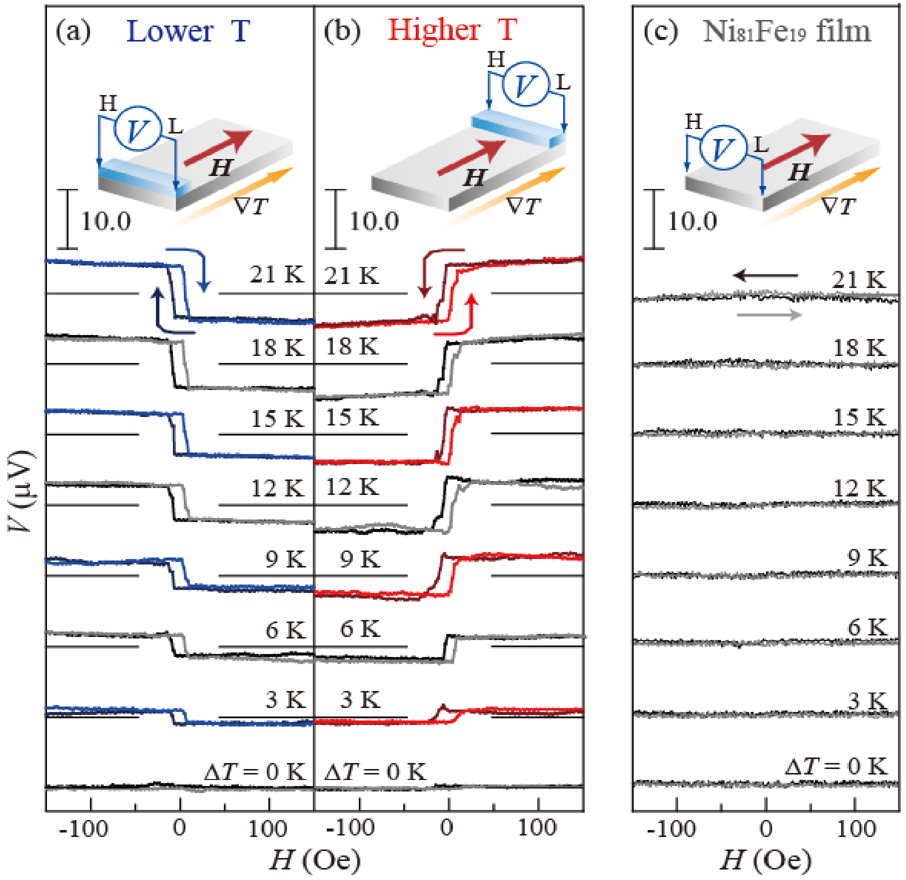
using the inverse spin-Hall effect (ISHE)

electromotive force of opposite signs



Spin voltage of opposite sign

Magnetic field dependence of V



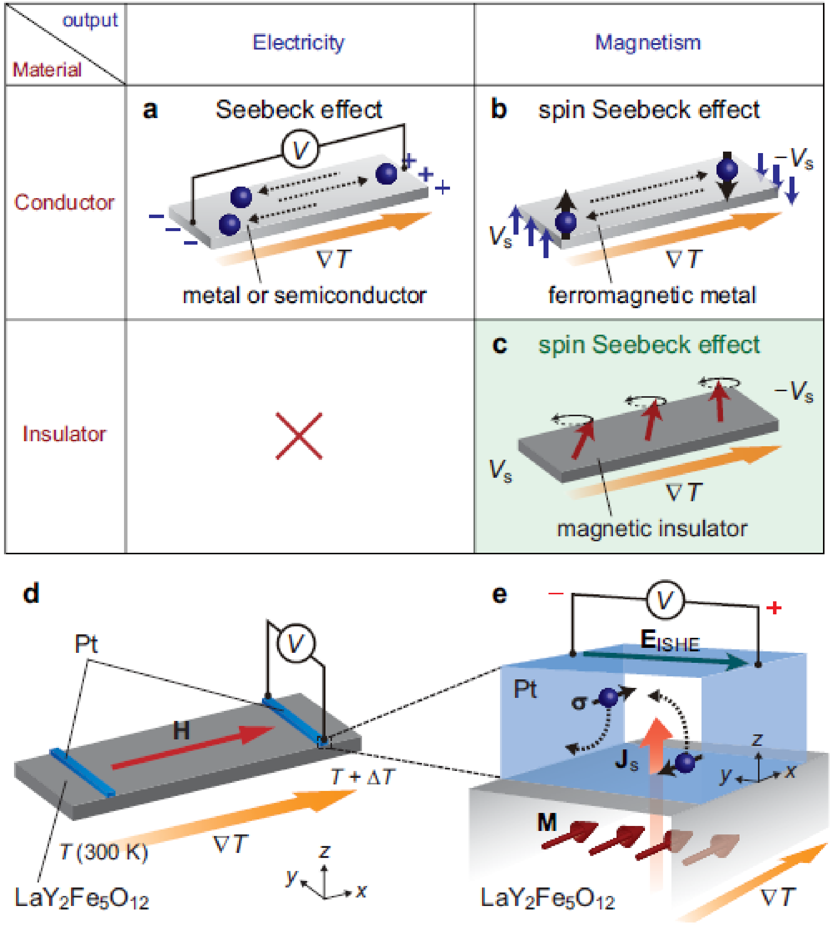
ISHE voltage induced by the spin-Seebeck effect

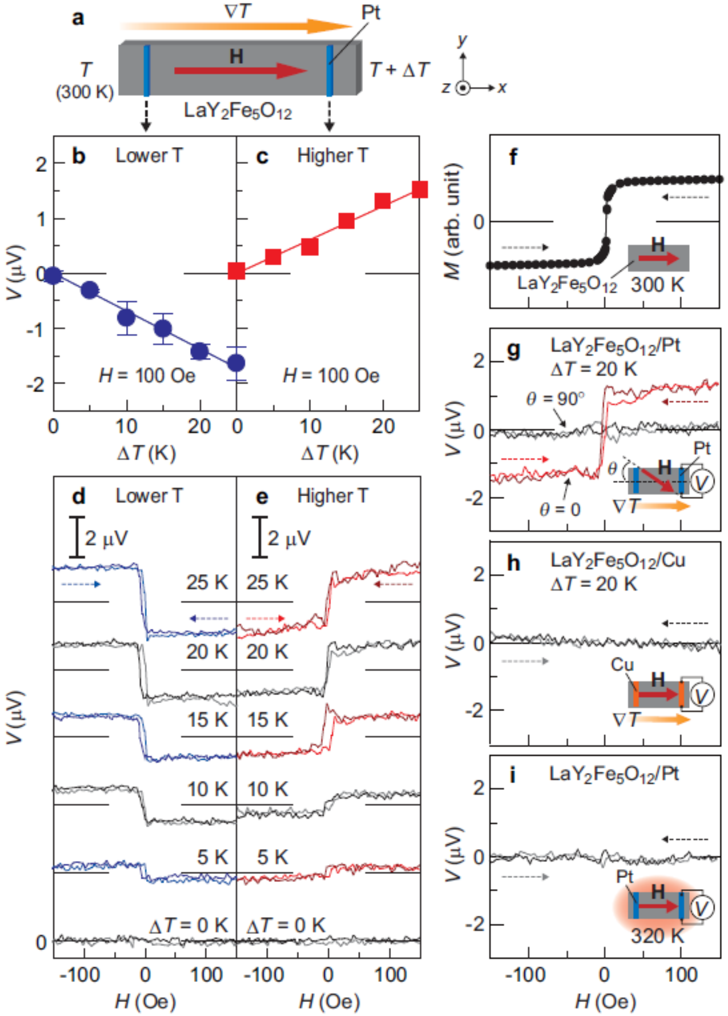
K. Uchida, E. Saitoh *et al.* Nature (2008).

Spin Seebeck insulator

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

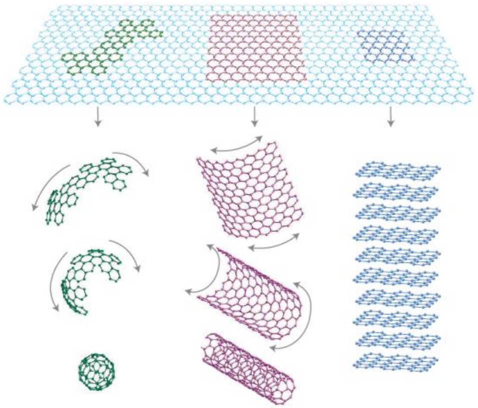
K. Uchida, E. Saitoh et al.:
Nature Mat. (online Sept 27, 2010)



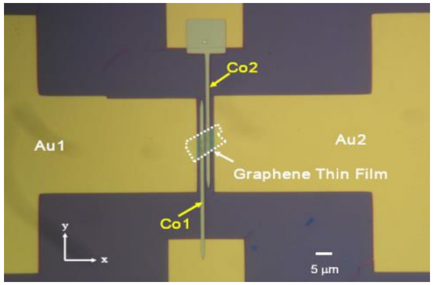


Graphene Spintronics

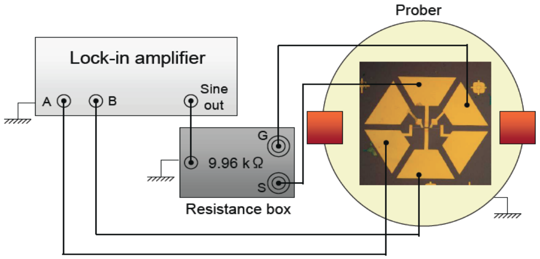
Graphene

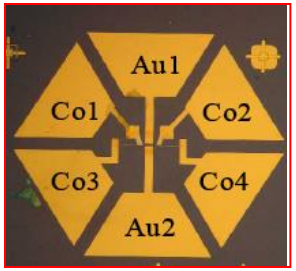


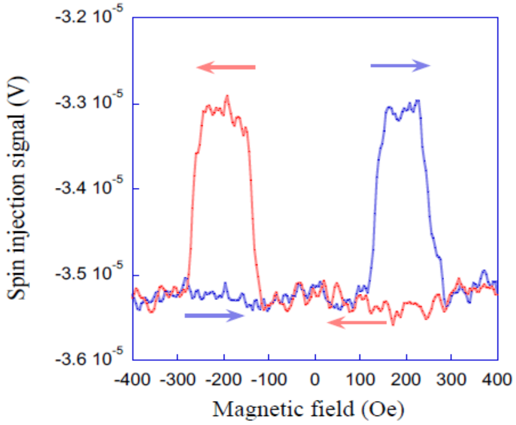
1. Generation of a pure spin current
2. Injection of spins in graphene at ROOM TEMPERATURE

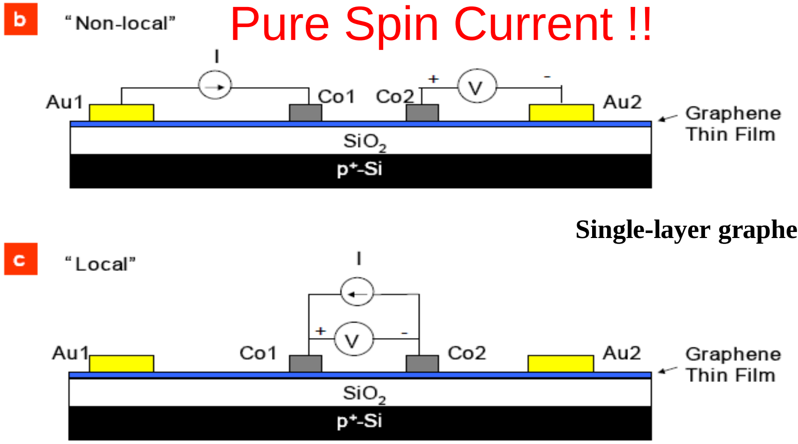


Non-local measurement
(Experimental setup)





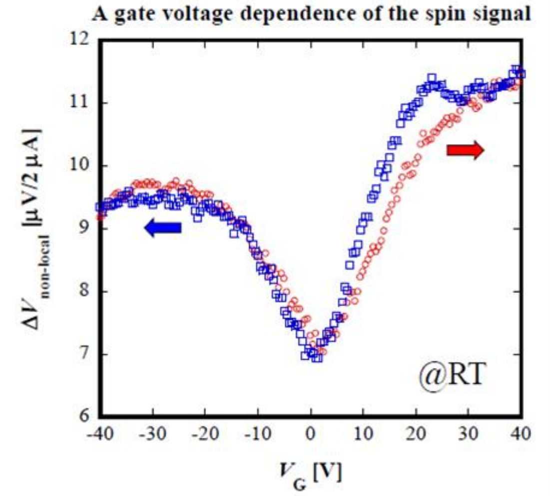




Pure Spin Current !!

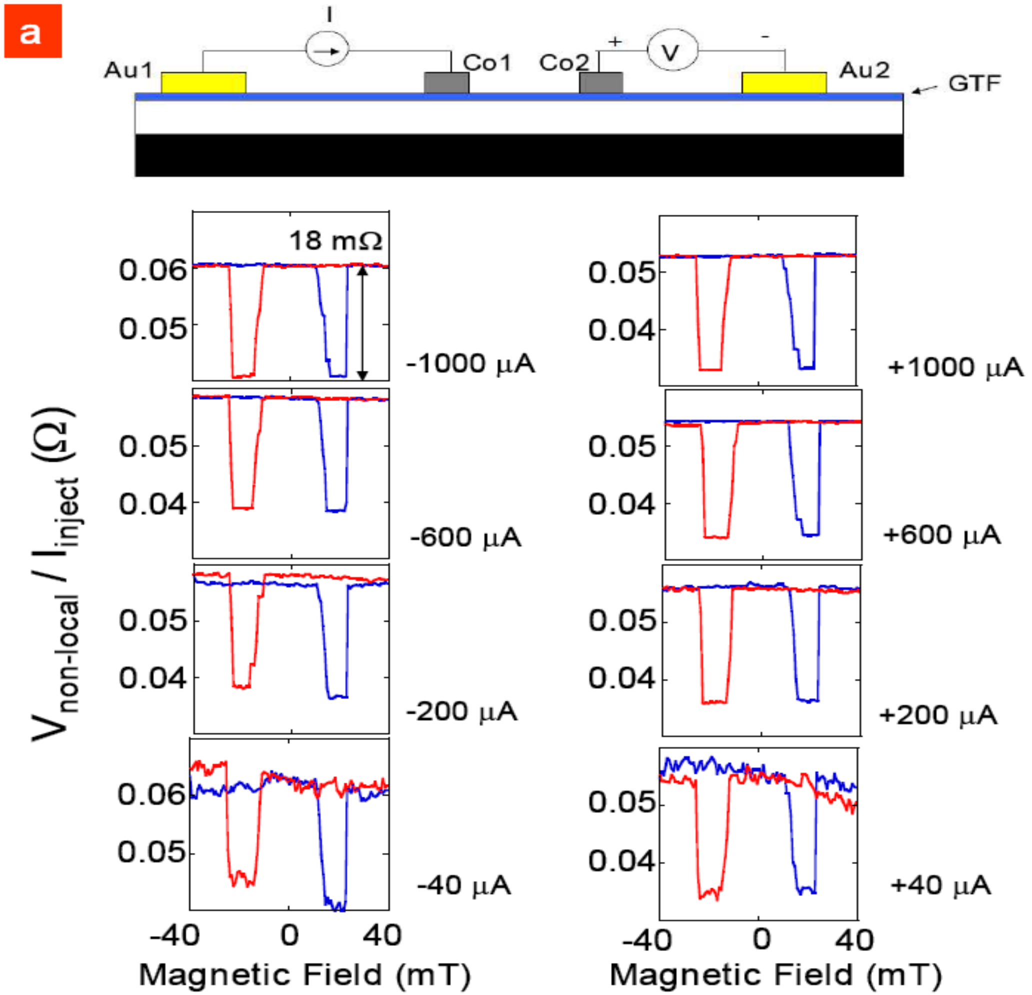
Single-layer graphene

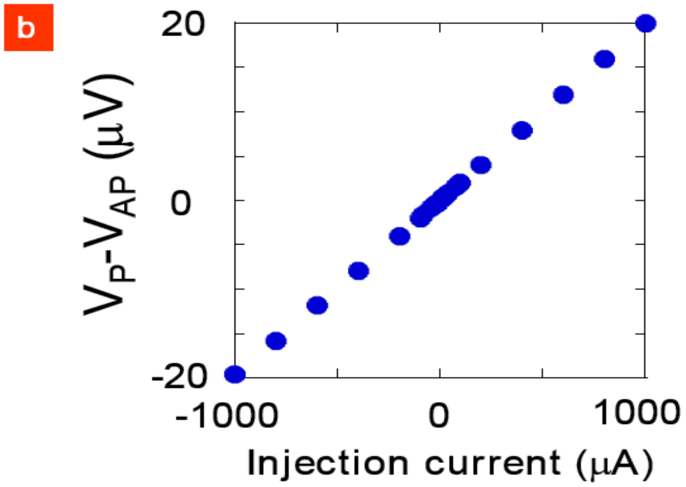
Gate-induced Modulation of Spin Signals in single-layer graphene



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

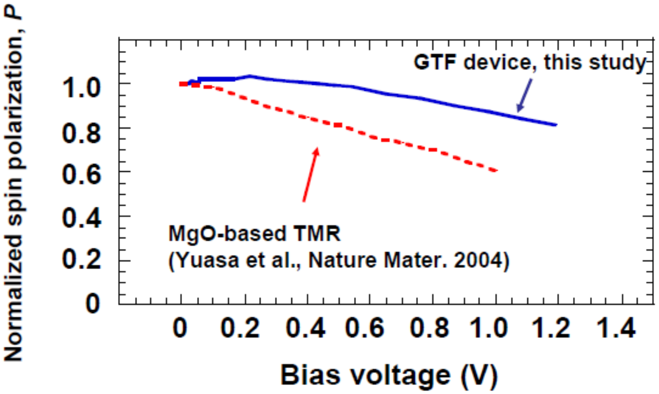
Graphene Spintronics





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

Spin polarization is CONSTANT.

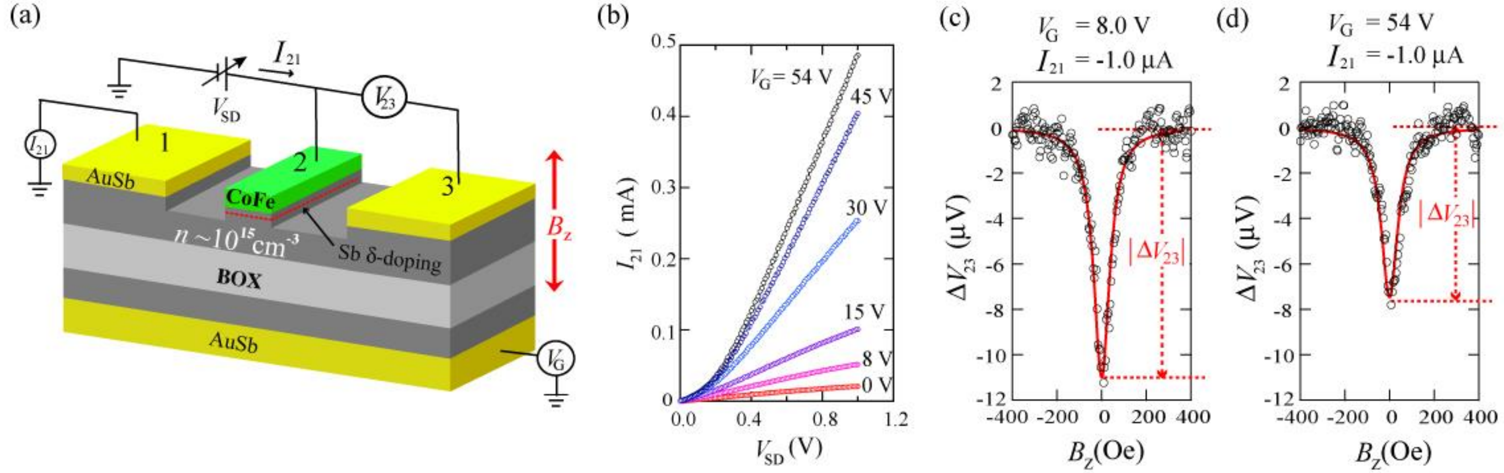


Better robustness than that in MgO-TMR

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

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.



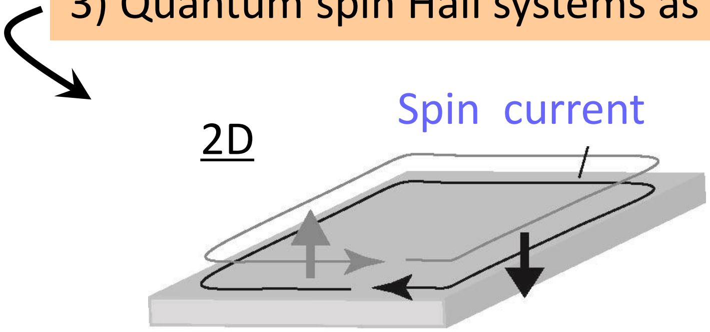
M. Ishikawa, H. Sugiyama, T. Inokuchi, K. Hamaya, Y. Saito, "Effect of the interface resistance of CoFe/MgO contacts on spin accumulation in silicon", Appl. Phys. Lett. 100, 252404 (2012).

Spintronics devices and materials

TOPOLOGICAL INSULATOR

Theory of spin current and heat current

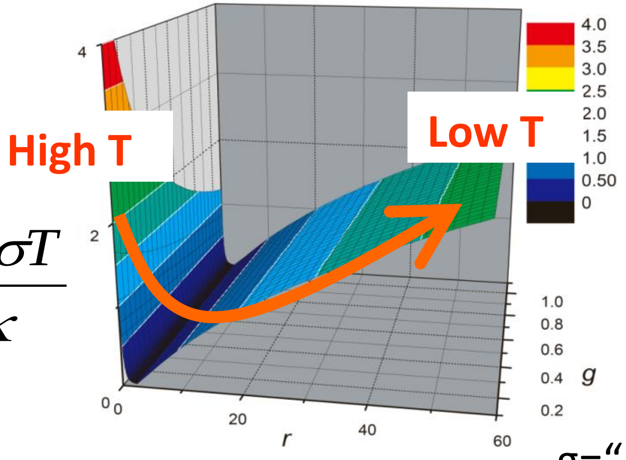
1) Bismuth ultrathin films as quantum spin Hall phases
2) Universal Phase Diagrams for 2D and 3D quantum spin Hall phases
3) Quantum spin Hall systems as candidates for efficient thermoelectrics



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.)

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



r=" bulk/edge "

g=" phonon/bulk "

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

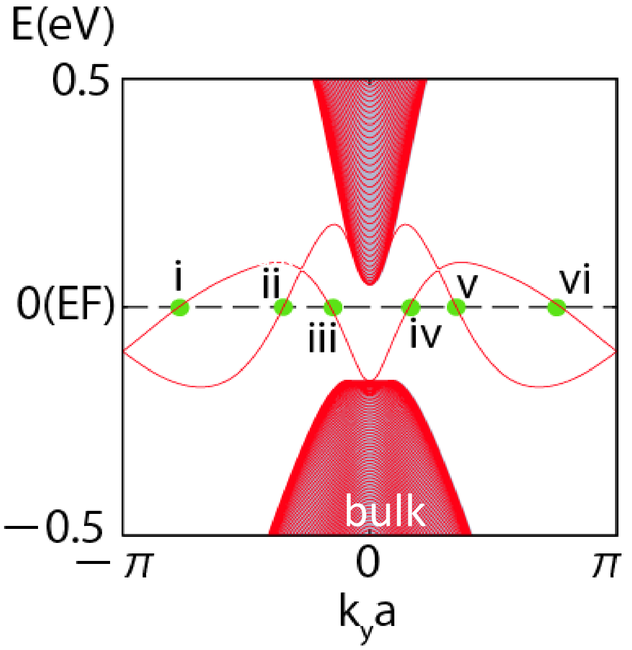
Quantum spin Hall systems can be good thermoelectrics at low temp.

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

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

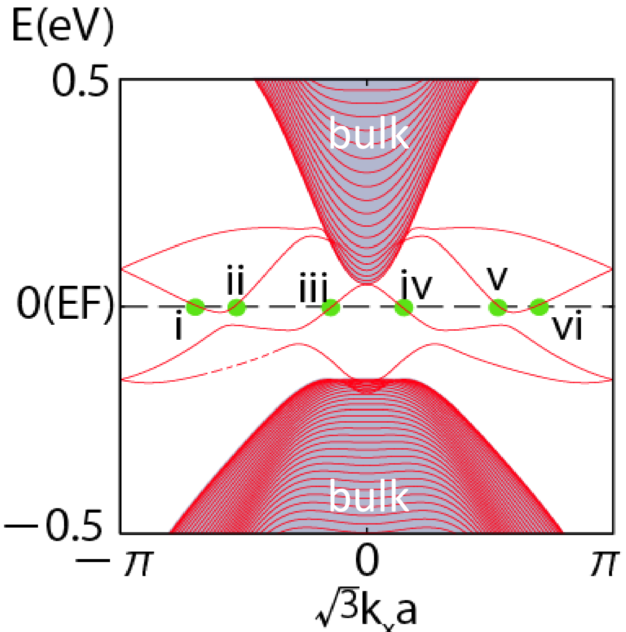
Zigzag edge

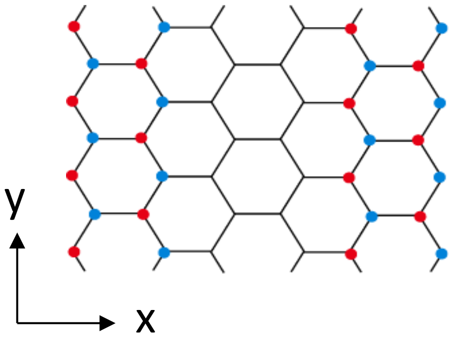
	S_x	S_y	S_z
i-U	0.822	-0.000	-0.229
i-L	-0.822	0.000	0.229
ii-U	-0.680	0.000	-0.217
ii-L	0.680	-0.000	0.217
iii-U	0.141	0.000	-0.095
iii-L	-0.141	-0.000	0.095
iv-U	-0.141	-0.000	0.095
iv-L	0.141	0.000	-0.095
v-U	0.680	-0.000	0.217
v-L	-0.680	0.000	-0.217
vi-U	-0.822	0.000	0.229
vi-L	0.822	-0.000	-0.229



Armchair edge

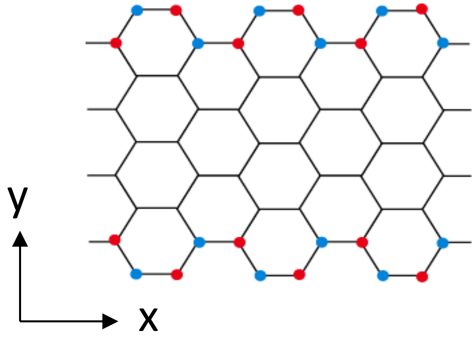
	S_x	S_y	S_z
i-U	0.763	0.000	-0.010
i-L	-0.763	-0.000	0.010
ii-U	0.395	0.000	-0.237
ii-L	-0.395	-0.000	0.237
iii-U	0.250	-0.000	-0.395
iii-L	-0.250	0.000	0.395
iv-U	-0.250	0.000	0.395
iv-L	0.250	-0.000	-0.395
v-U	-0.395	-0.000	0.237
v-L	0.395	0.000	-0.237
vi-U	-0.763	-0.000	0.010
vi-L	0.763	0.000	-0.010



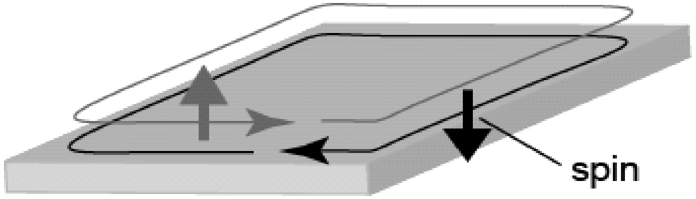


スピン: xz 面内

スピンはほぼ薄膜面に垂直
(// z)
10%-20% 程度傾いている



スピン: xz 面内

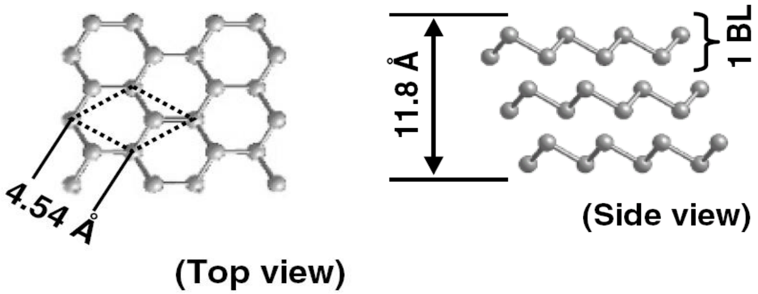


Theoretical Approach

Quantum Spin Hall Effect in Bismuth

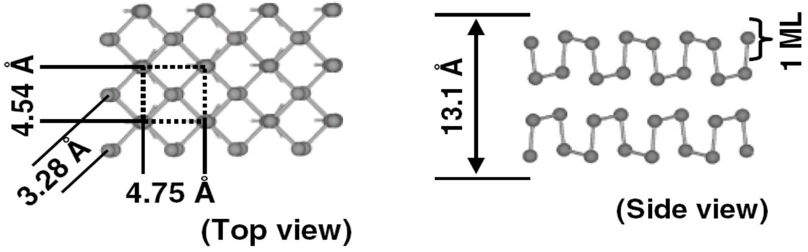
- Bulk Bi show no gap, while edge is gapless.
- Bi ultra thin film (*topological insulator*)

(111) 1-bilayer = quantum spin Hall phase



(Top view) (Side view)

{012} 2-monolayer= insulating phase



(Top view) (Side view)

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

- Thermoelectric figure of merit

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

Idealized model (perfect conductor on the edge)

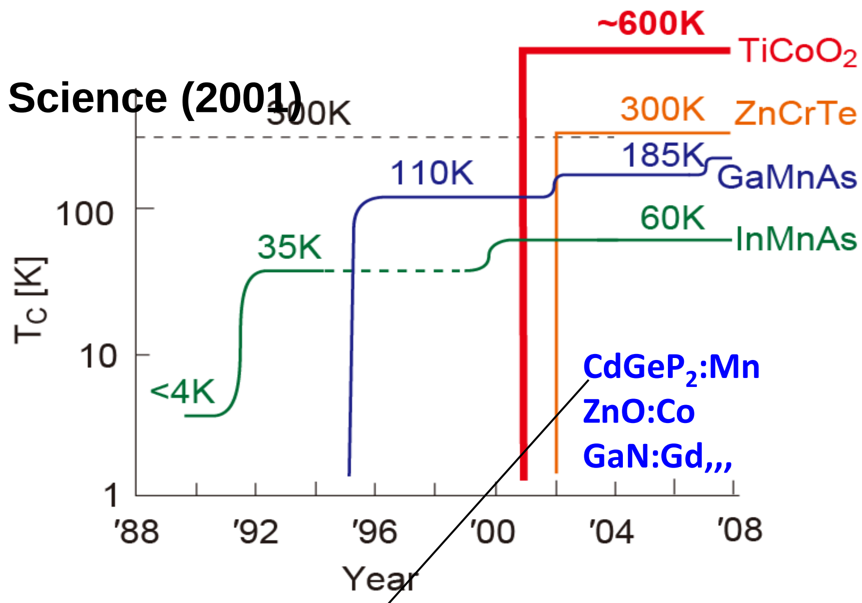
- In the quantum spin Hall phase, figure of merit ZT of thermoelectric conversion is determined by the balance between the edge and the bulk.
- ZT is large if the chemical potential is close to the band edge.
- ZT is large if the length of system is long. ← edge states dominantly determine ZT.
- ZT increases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

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)

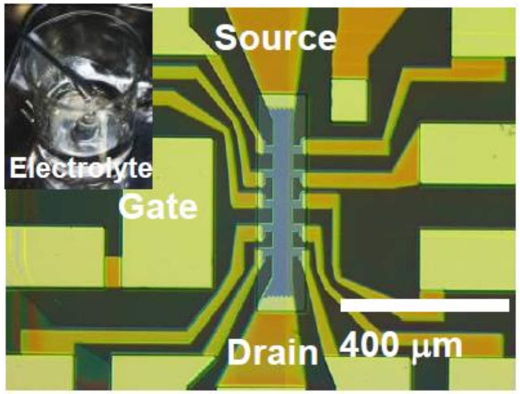
T. Fukumura, Jpn. J. Appl. Phys. (2007)

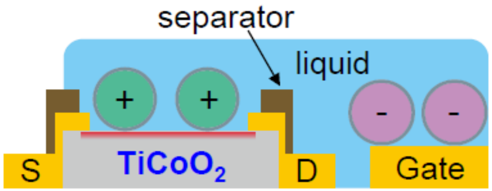
Tunneling Magnetoresistance

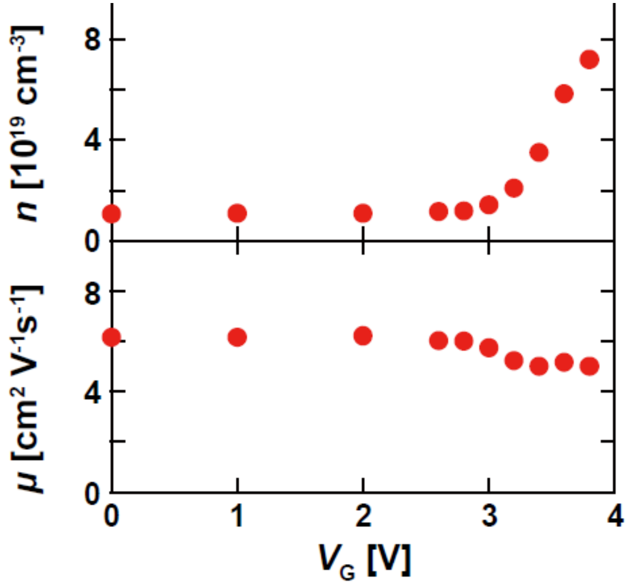
H. Toyosaki, Jpn. J. Appl. Phys. (2005)

$Zn_{1-x}TM_xO$ combinatorial library

Carrier control of magnetism in TiO_2:Co by gate voltage

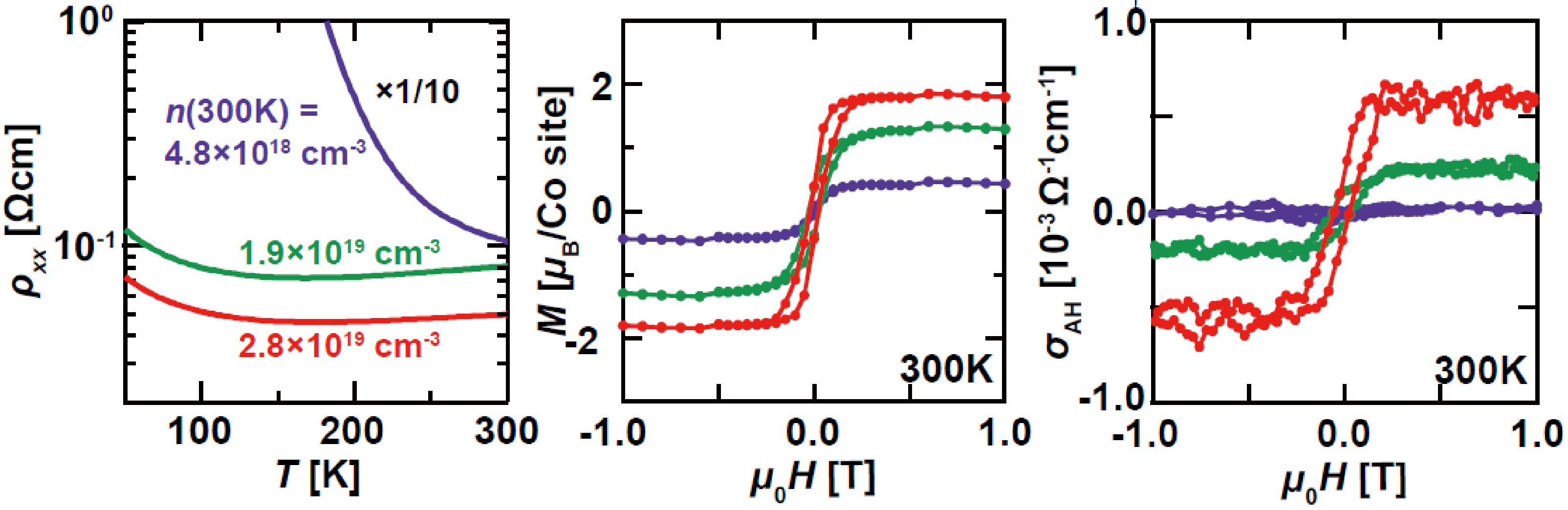






$Ti_{0.90}Co_{0.10}O_{2-\delta}$

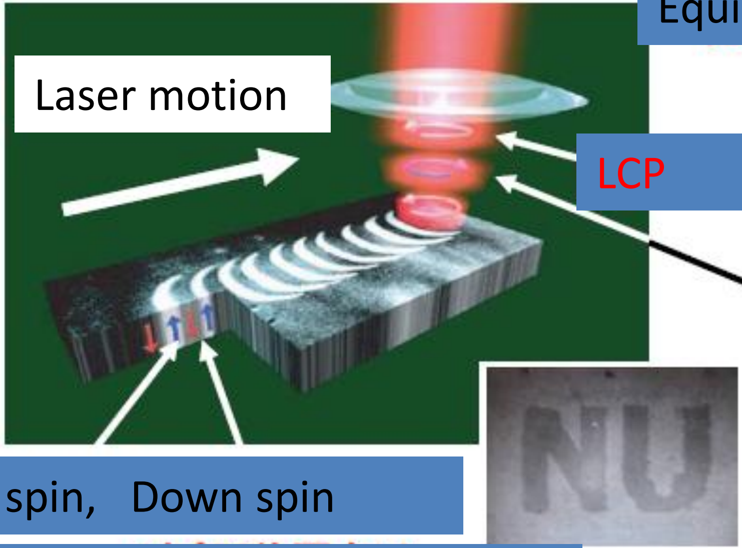
PM insulator → FM metal



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

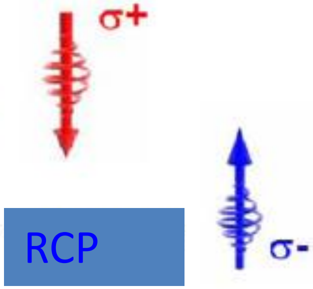
RCP

Up spin,　Down spin

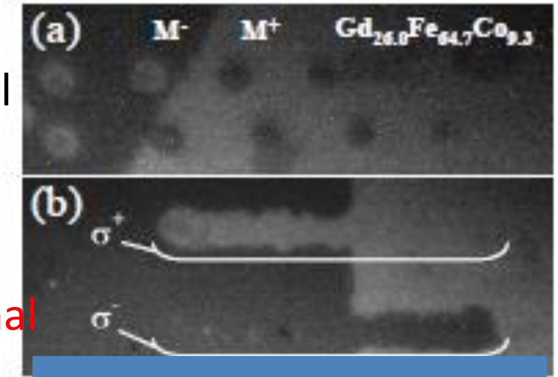
Complete magnetization by 40 fs irradiation of CP.
Reversal without ext. field

PRL 99, 047601 (2007)

Equivalent magnetic field produced by photon



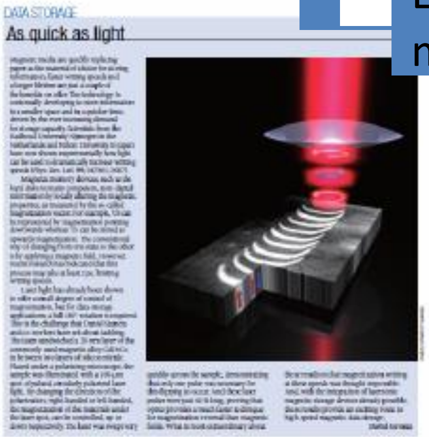
thermal



nonthermal

Nature Photonics

Light-induced ultrafast magnetic recording

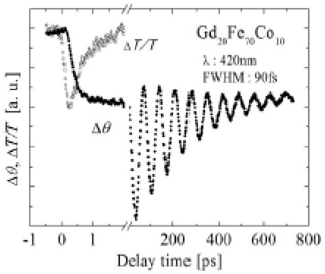


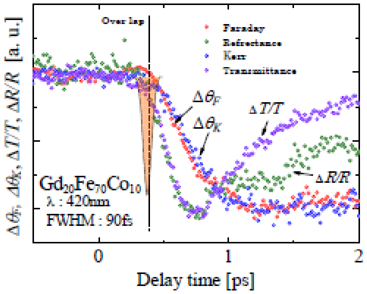
DATA STORAGE

As quick as light

Science、Physics today他

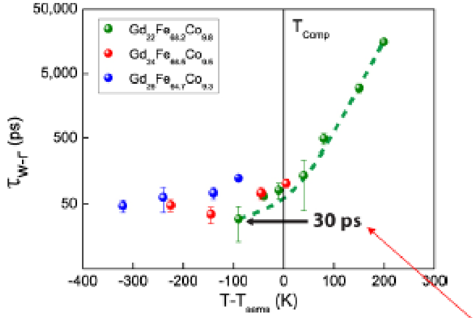
Analysis of light-induced ultrafast magnetization reversal





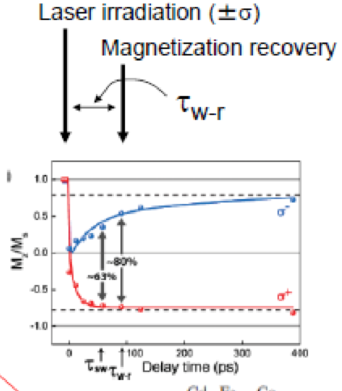
The magnetization
modified monotonically
reaches to a temporal state within 1ps

Composition and temperature dependence of
Photo-magnetic switching time



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

Cooperated work with Radboud Univ. et. al.



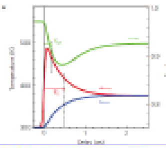
Gd$_{24}$Fe$_{66.5}$Co$_{9.5}$
@room temp.

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

Classification of ultrafast dynamics

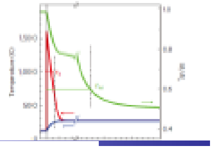
Type I material

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

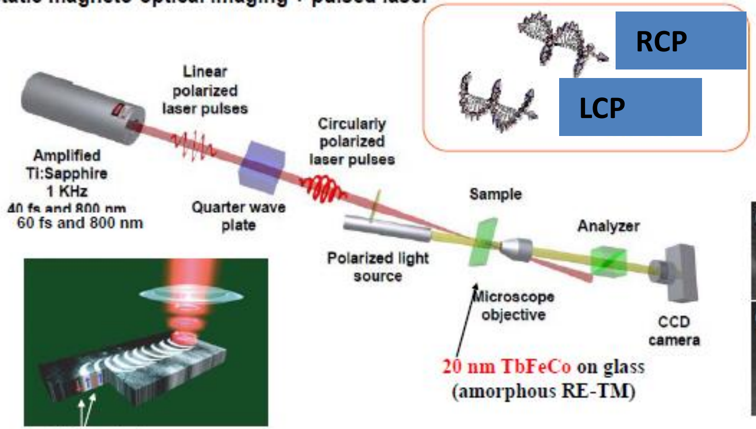


Type II material

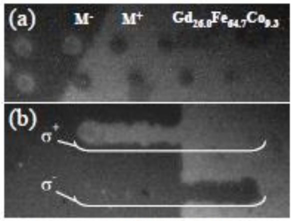
- Weaker magnetic coupling
- 2step demagnetizations very fast (first picosecond) slower demagnetization
- Ga, TbFe



Static magneto-optical imaging + pulsed laser

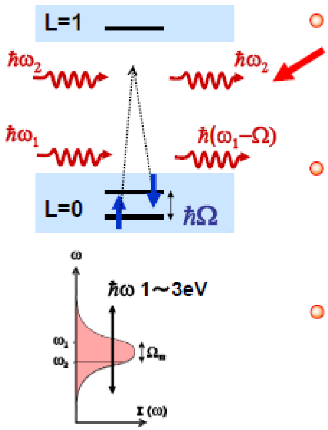


Magnetization direction



Light-induced ultrafast magnetic recording

Origin of photo induced magnetization phenomena



- **Spectroscopic measurements**
  Wave length > photon energy

  Pulse width
  Intensity
- **Distinguish thermal, non-thermal contribution**

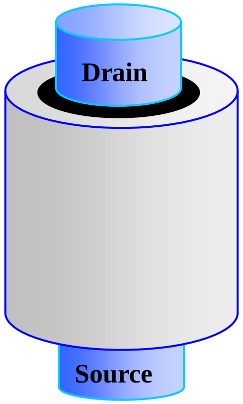
\+

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

  > Suppress Precessional motion

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*
5. Ya.Takahashi succeeded in realization of silicon Raman laser using photonic crystal technology



Semiconductor Nanoelectronics

NANO-WIRE TRANSISTORS

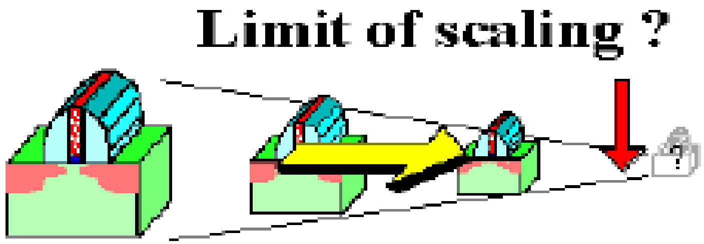
Surrounding Gate Transistors

- 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.

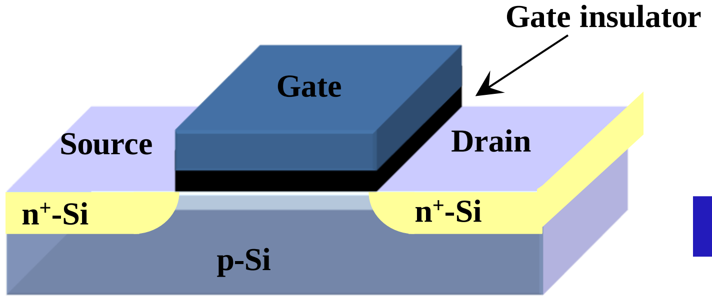
Vertical type MOSFET using semiconductor nanowires

Transistor size scaling



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

Present: Planar type

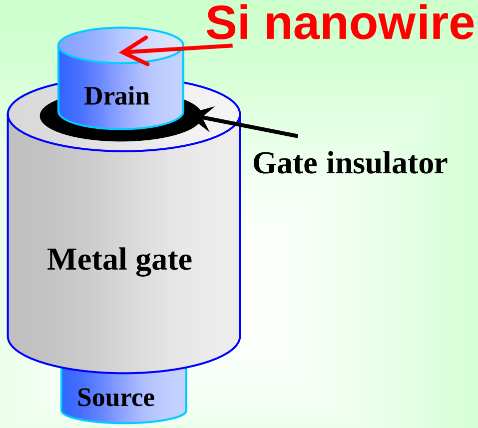


Miniaturization of FET

Increase in power consumption & leak current

Enhancement of the heating

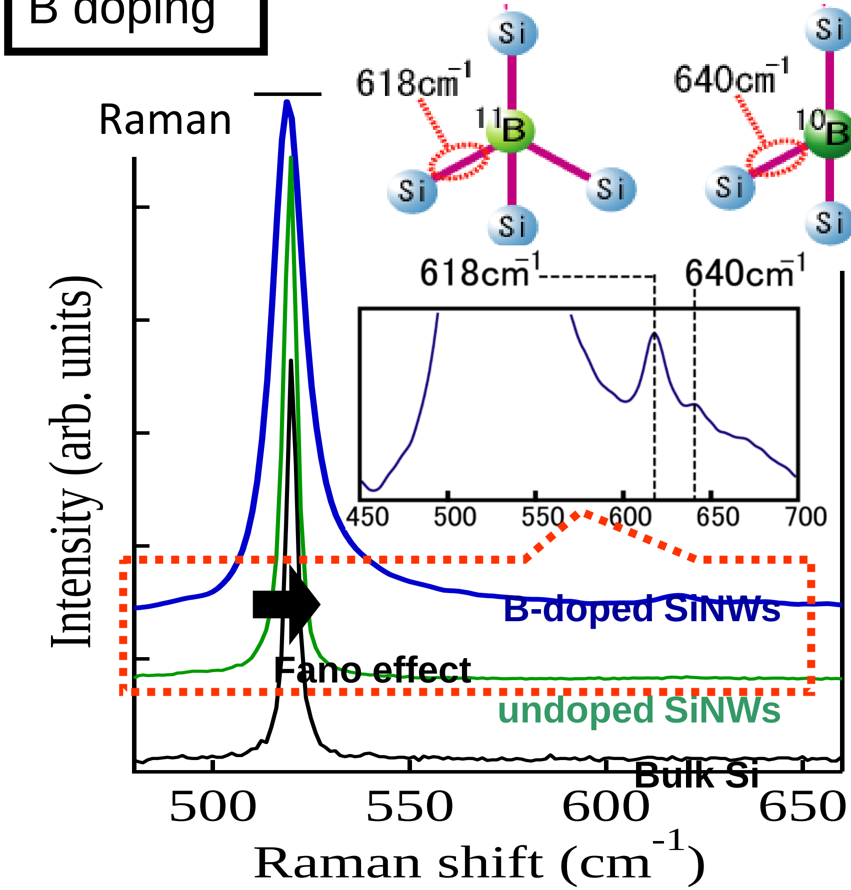
Next generation：Vertical type



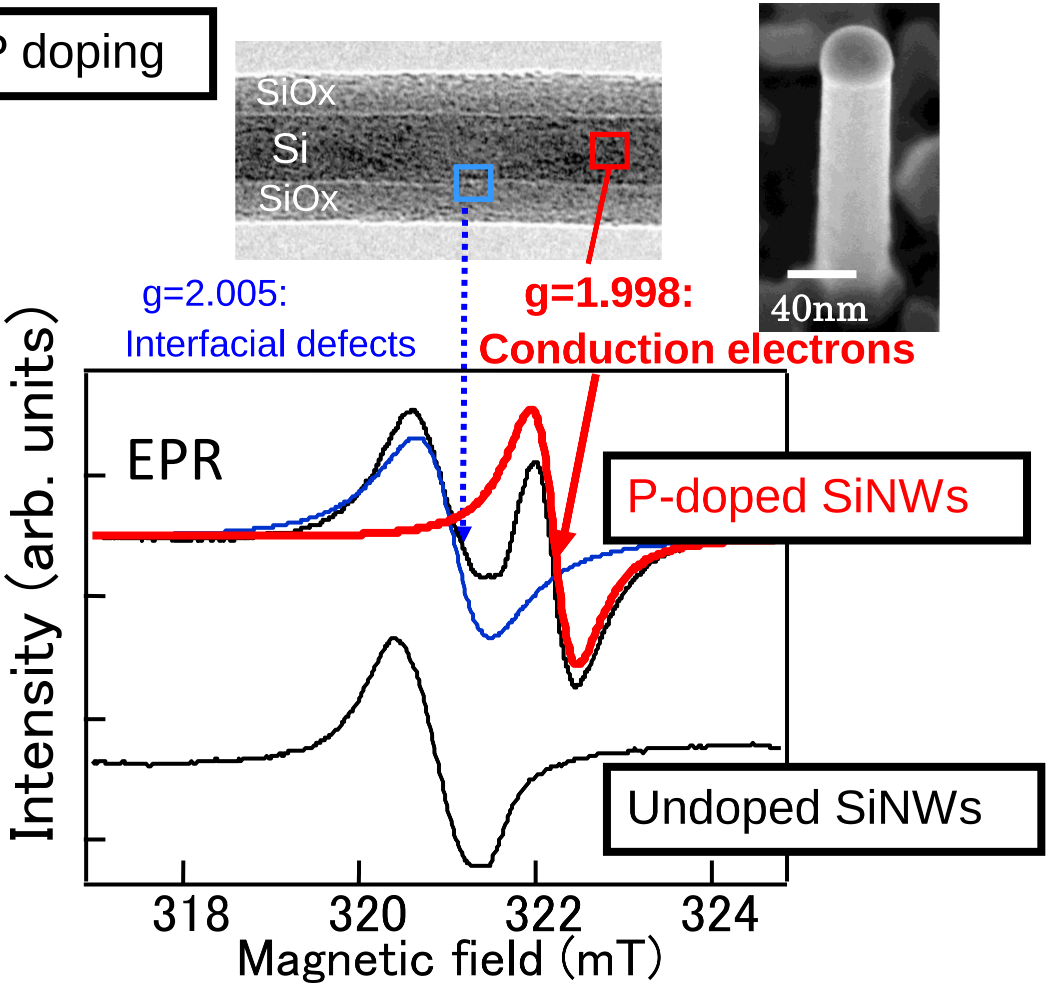
Vertical-type MOSFET using Si nanowires !

Synthesis & Impurity doping in Si nanowires

B doping



P doping



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

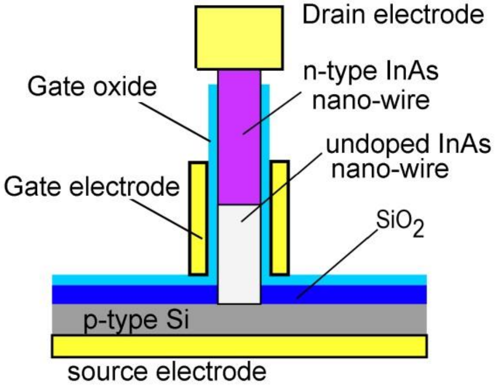
Formation of p-type SiNWs

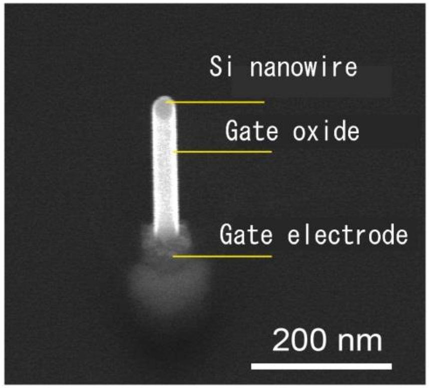
First observation of conduction electron signals in P-doped SiNWs

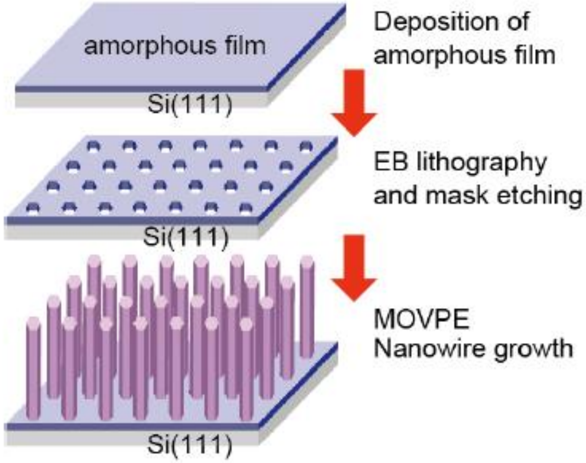
Formation of n-type SiNWs

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.

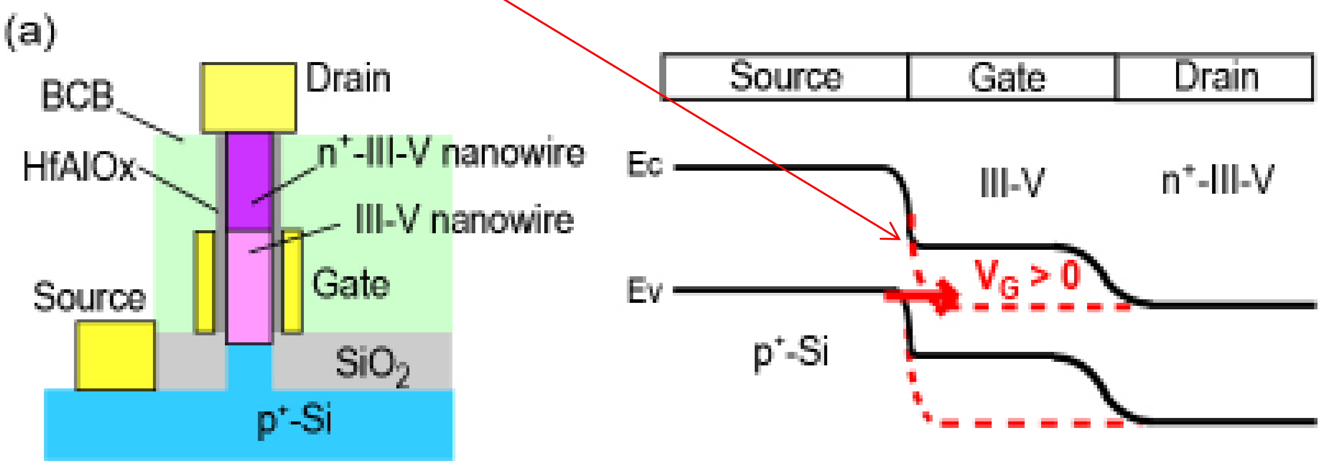






How the InAs nanowire TFET works

- 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

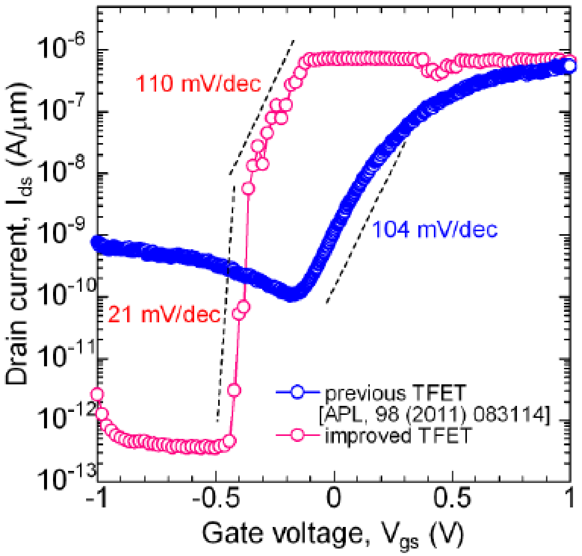


Fig. 9 Experimental transfer characteristics of optimized TFET with a NW-diameter of 30 nm (red cureve) $V_{DS} = 1.00$ V.

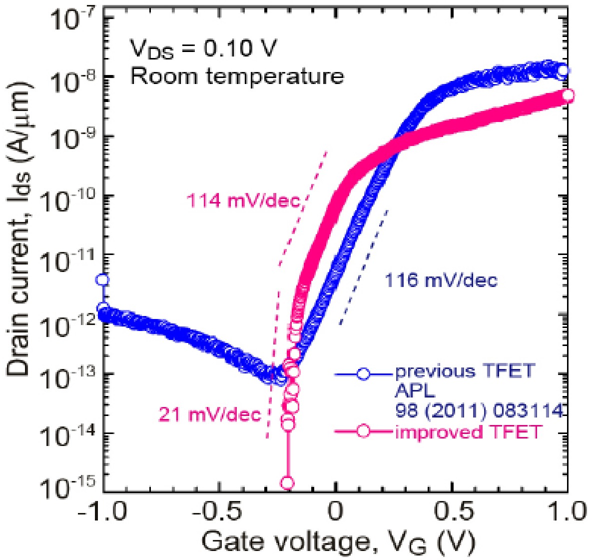
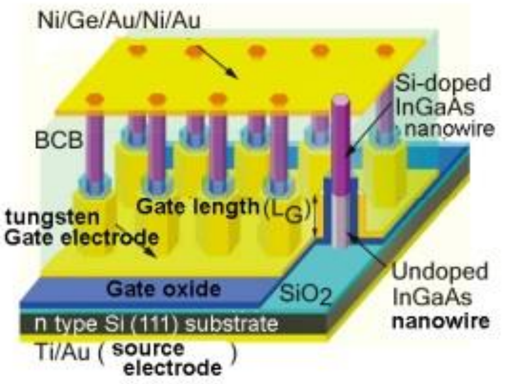
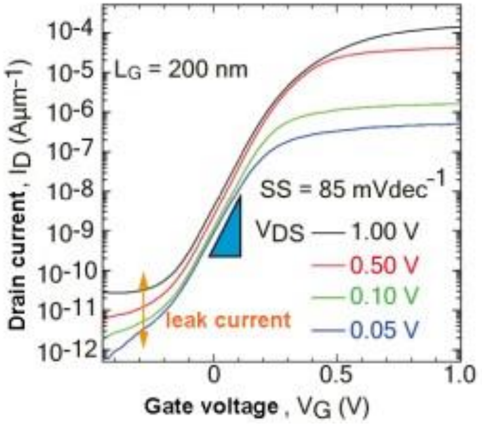


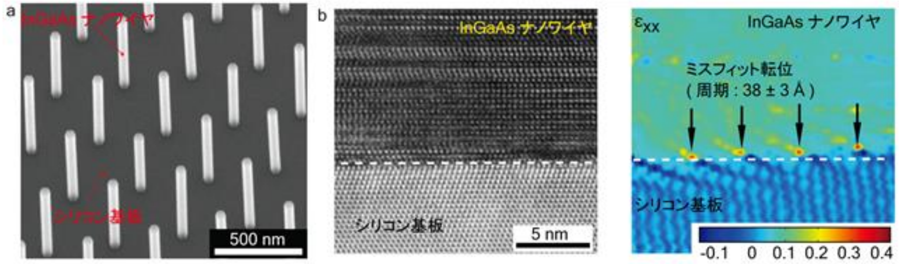
Fig. 10 Experimental transfer characteristics of optimized TFET with a NW-diameter of 30 nm (red cureve) $V_{DS} = 0.10$ V.

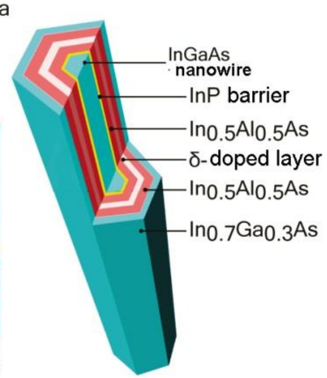
Nanowire FET with core-shell HEMT structure

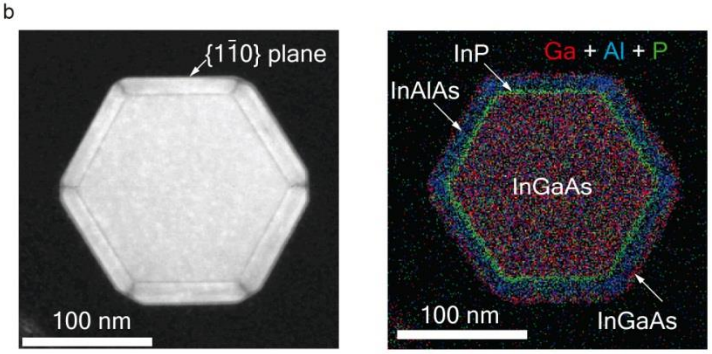
- Tomioka fabricated high performance FET using InAs nanowire with core-shell HEMT structure.











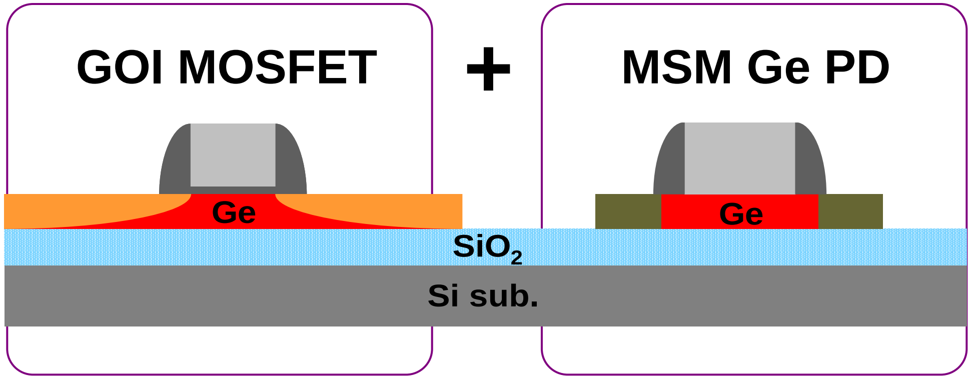
For optical interconnects

- 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]
-

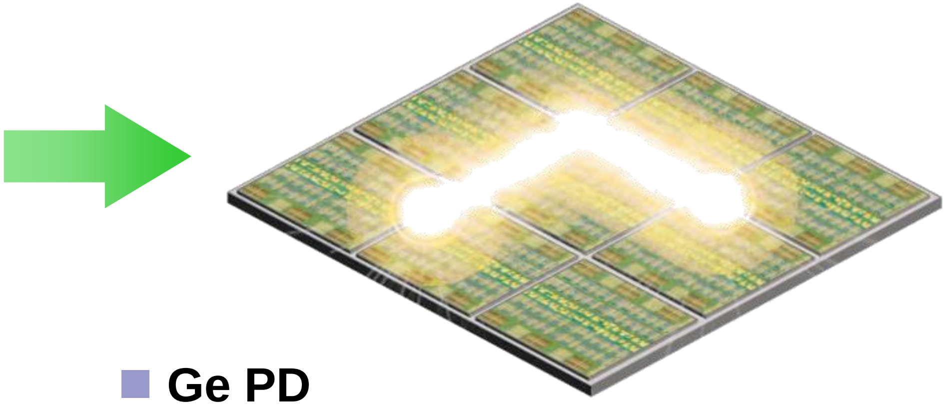
[i] M. Takenaka, S. Tanabe, S. Dissanayake, S. Sugahara, S. Takagi: 21st Annual Meeting of the IEEE Laser & Electro-Optics Society, Newport Beach, US (2008) Paper MN2.

Ge-based LSI with on-chip optical interconnects

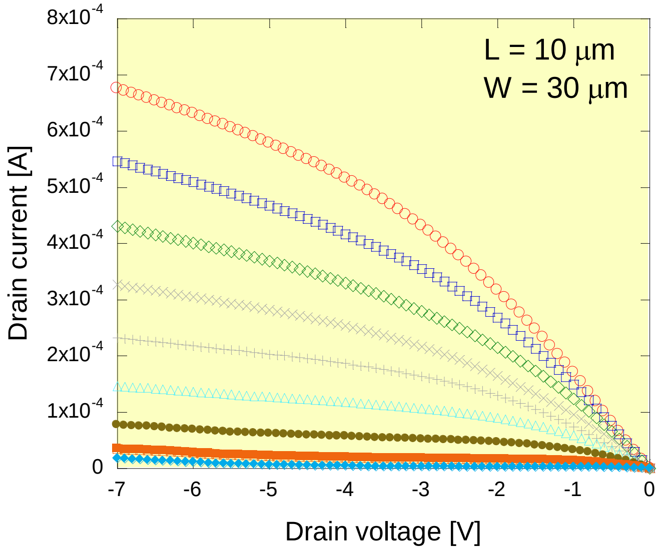
Monolithic integration:



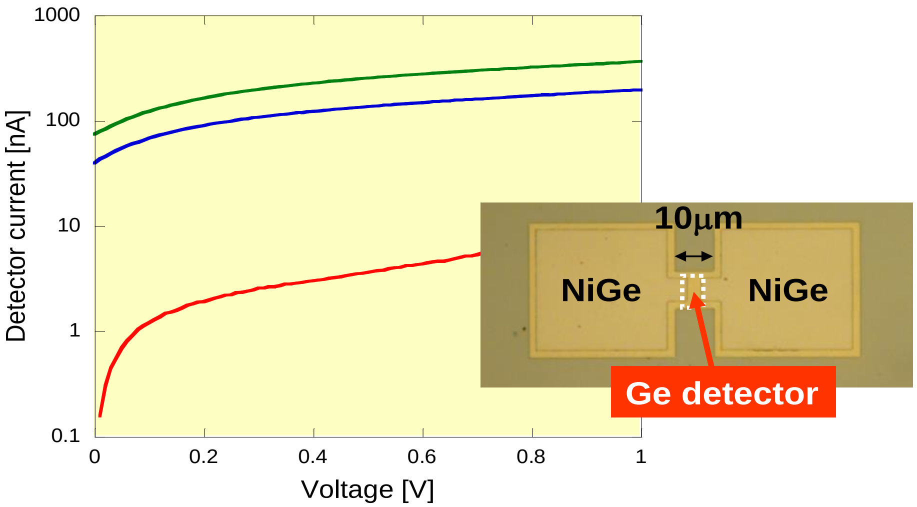
Ge based LSI with on-chip optical interconnects

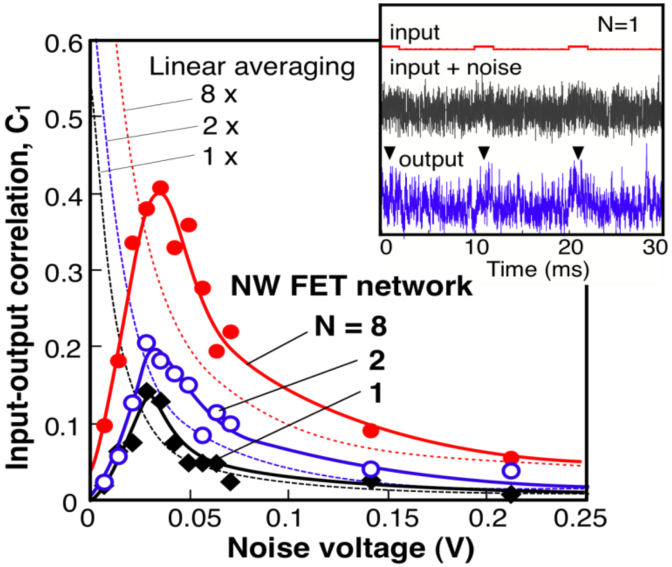


- GOI MOSFET



- Ge PD





Semiconductor Nanoelectronics

STOCHASTIC RESONANCE

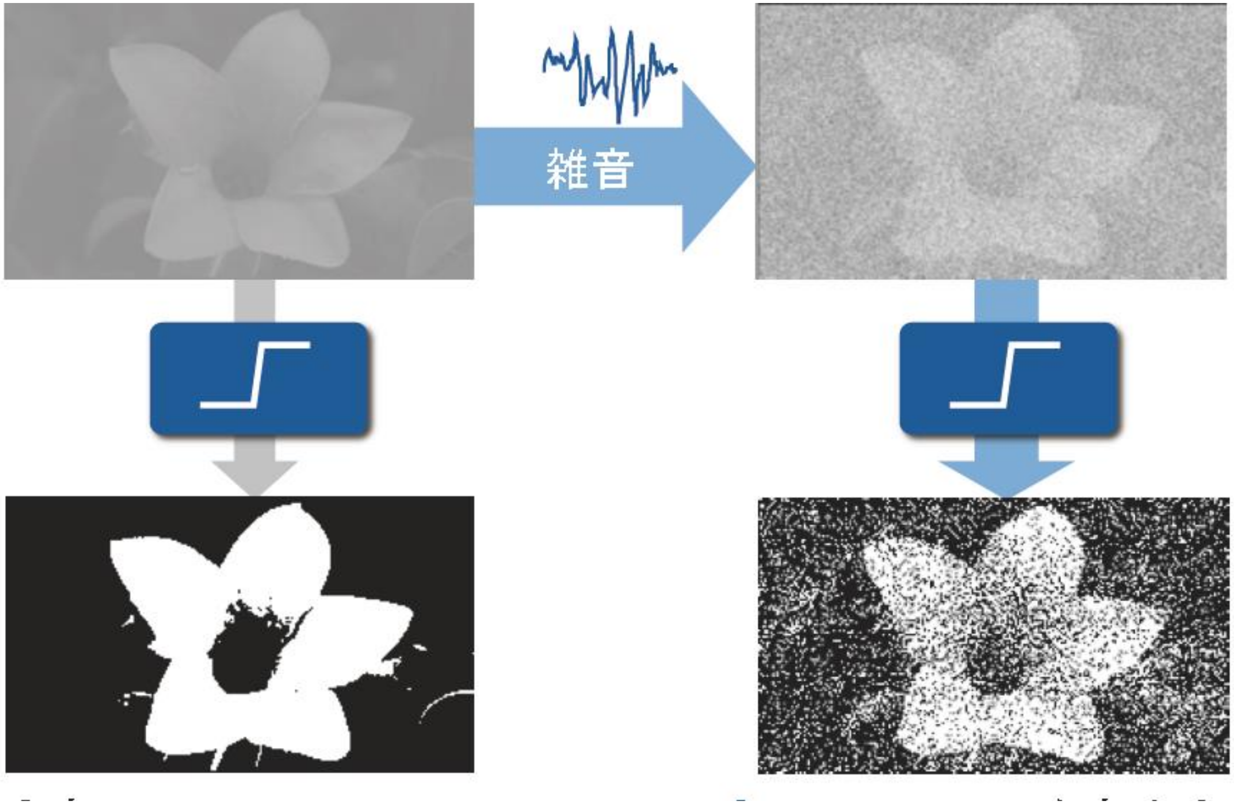
Stochastic Resonance

- 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

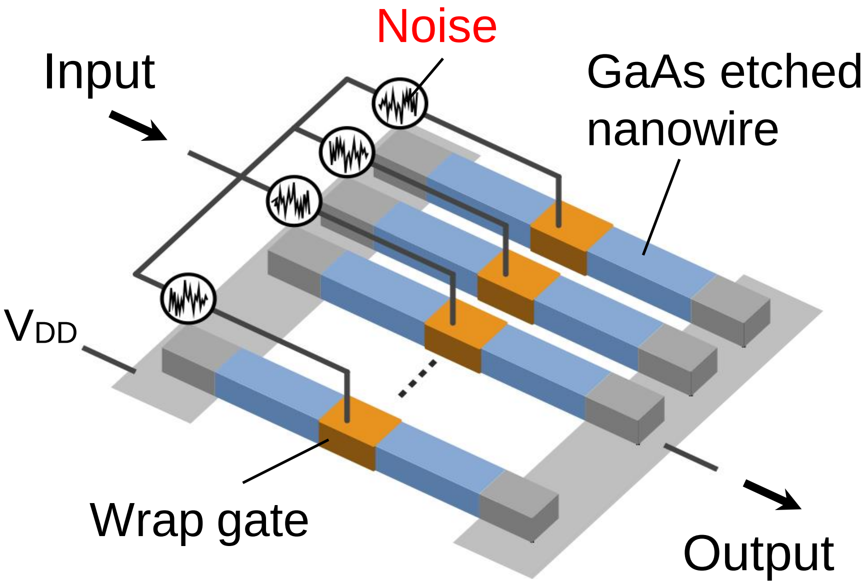
- Stochastic resonance improve grey scale reproduction



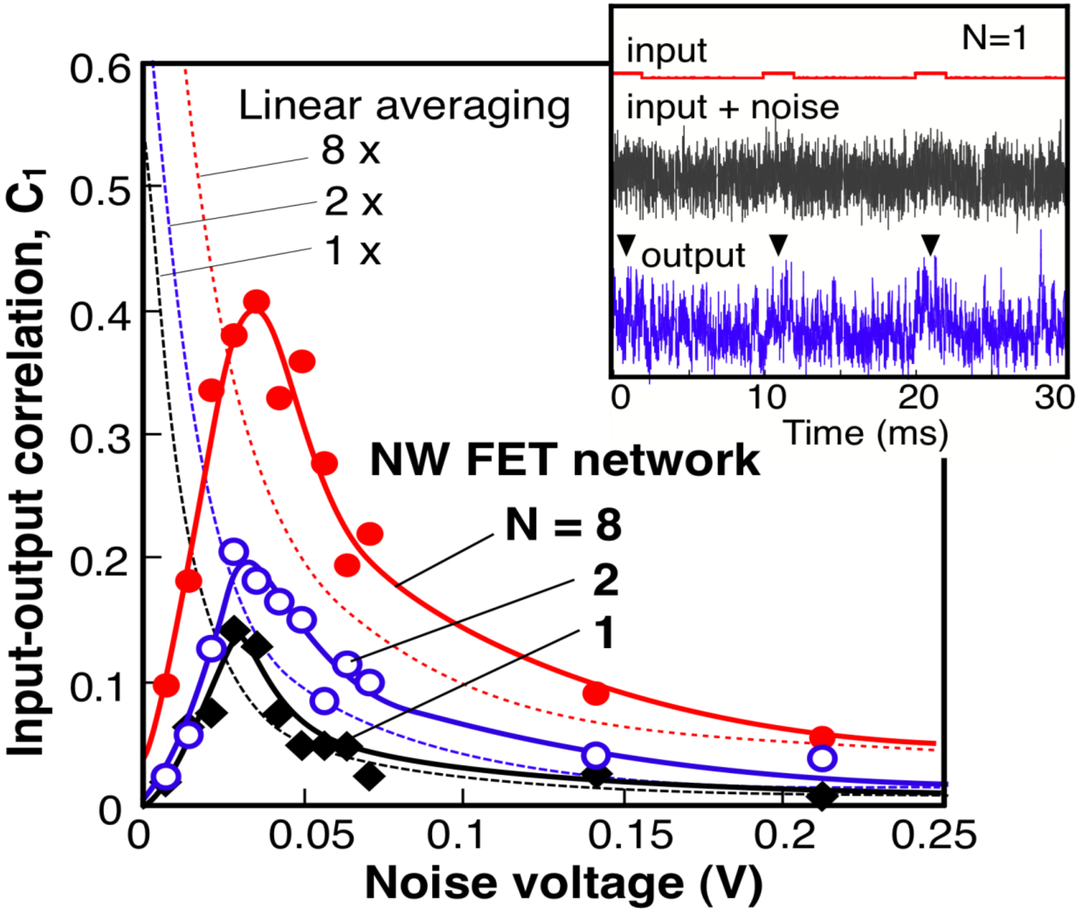
High contrast but lose grey scale

recover grey scale by addition of noise

Stochastic Resonance in Nanowire FET Network



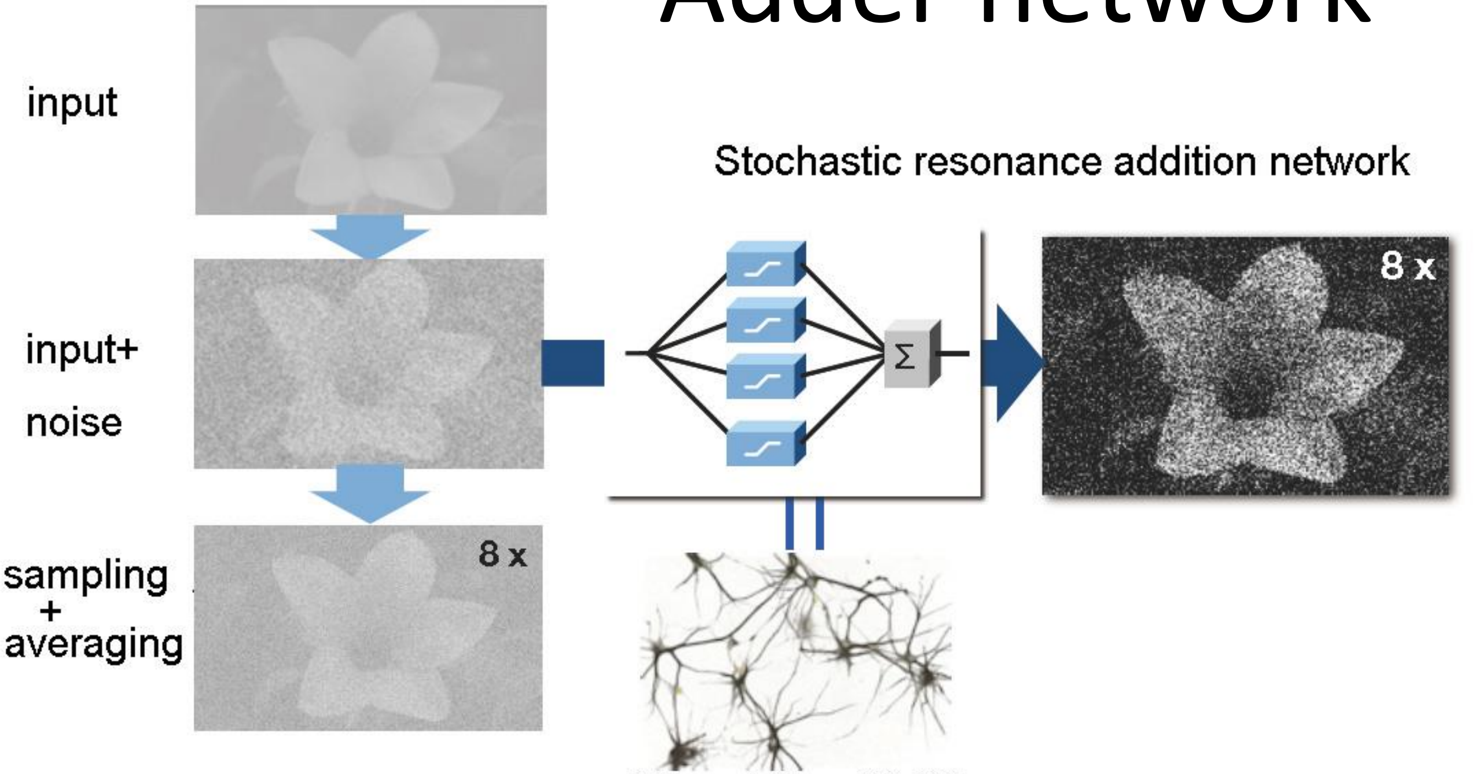
S.Kasai et al., Appl. Phys. Express 1, 083001 (2008)



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

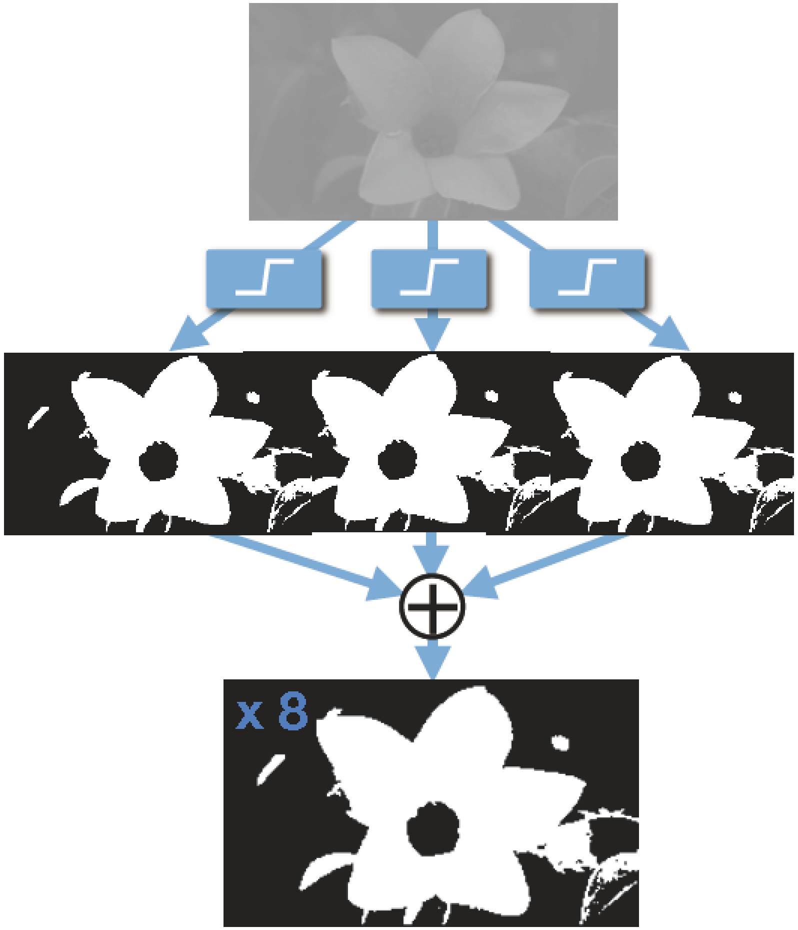
The SR was realized in GaAs nanowire FET networks and enhanced weak-signal detection was successfully demonstrated.

Adder network

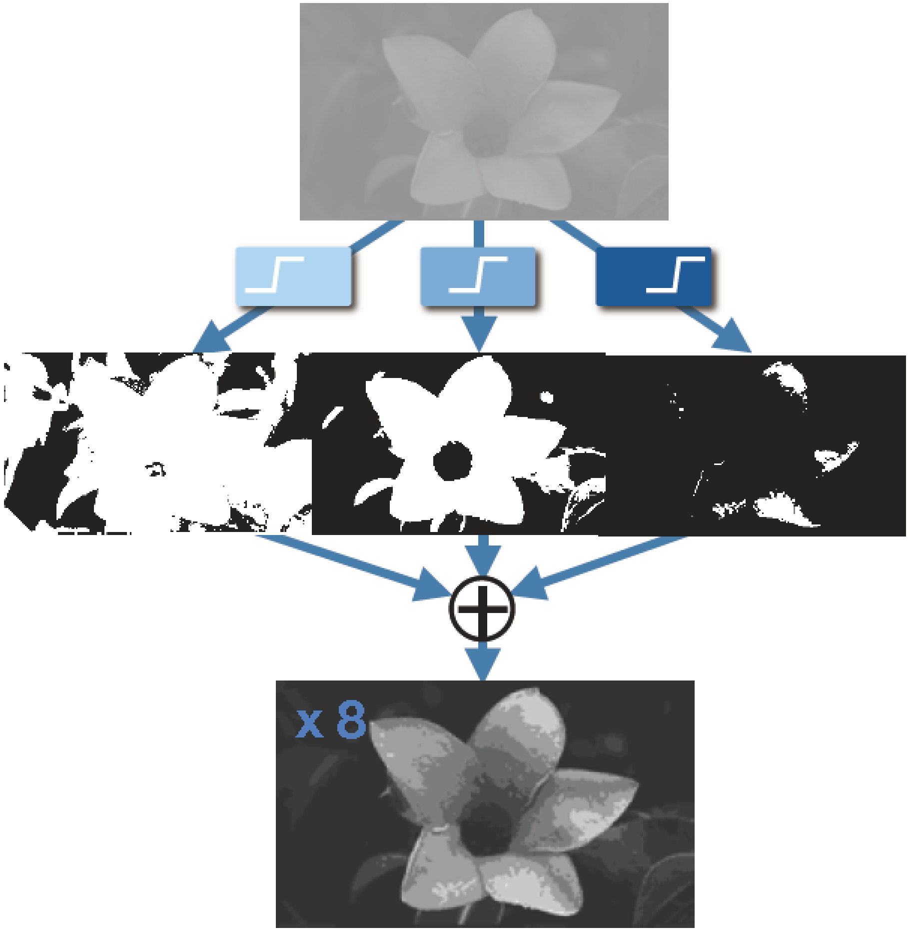


Collins et al., Nature 376, 1995

Scatter of threshold



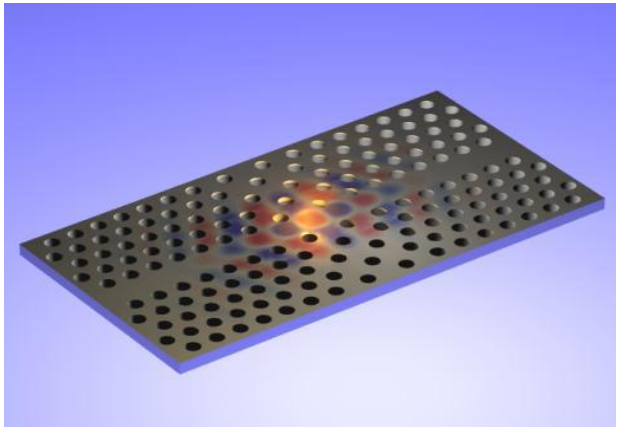
Uniform Threshold



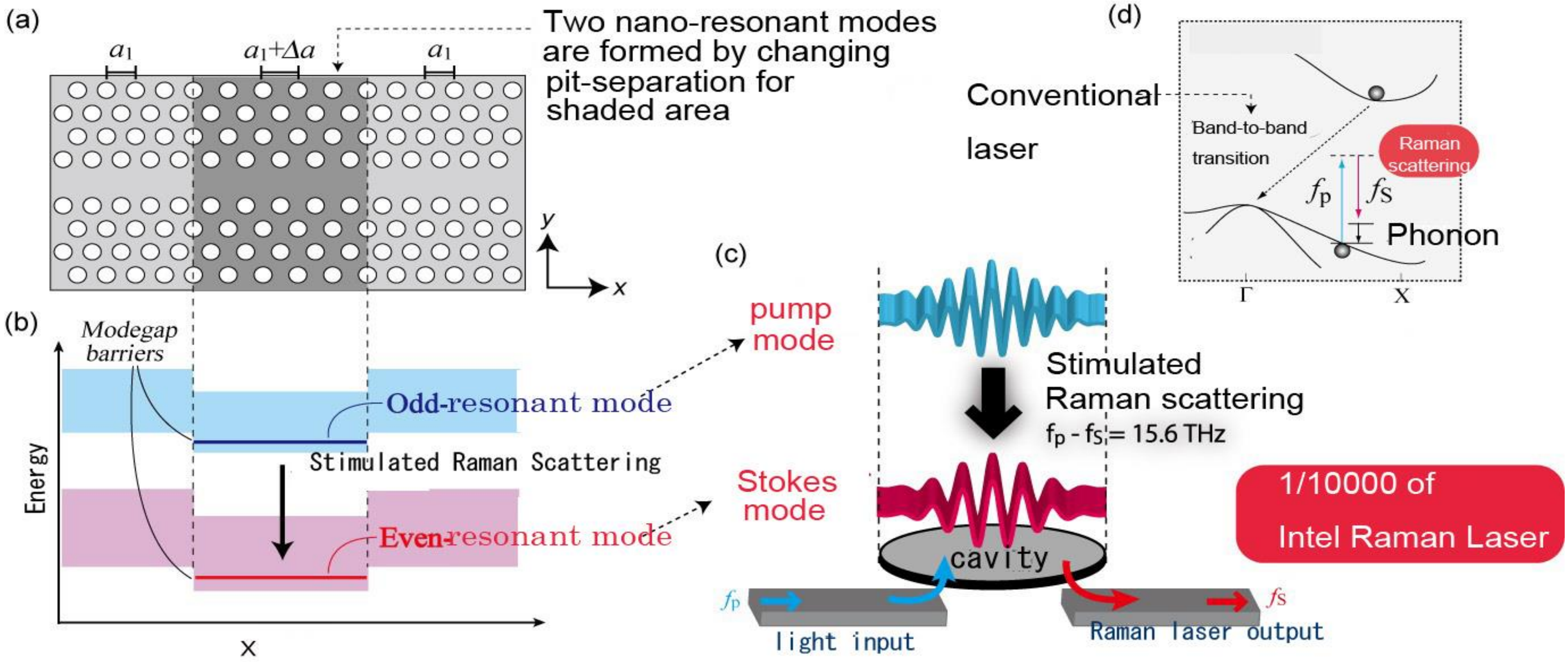
With scatter of threshold

Silicon Raman Laser using Photonic Crystal Nanocavity

Nanocavities in two-dimensional photonic crystal slabs have high quality factors and small modal volumes approaching one cubic wavelength.
They can enhance the light-matter interactions including nonlinear optical effects. Using the nanocavities, silicon Raman lasers with small sizes and low thresholds may be realized, which have many advantages such as the low energy consumption, dense integration, CMOS compatibility, and operation at telecom wavelengths.



Explanation of Silicon Raman Laser



Two nano-resonant modes are formed by changing pit-separation for shaded area

Conventional laser

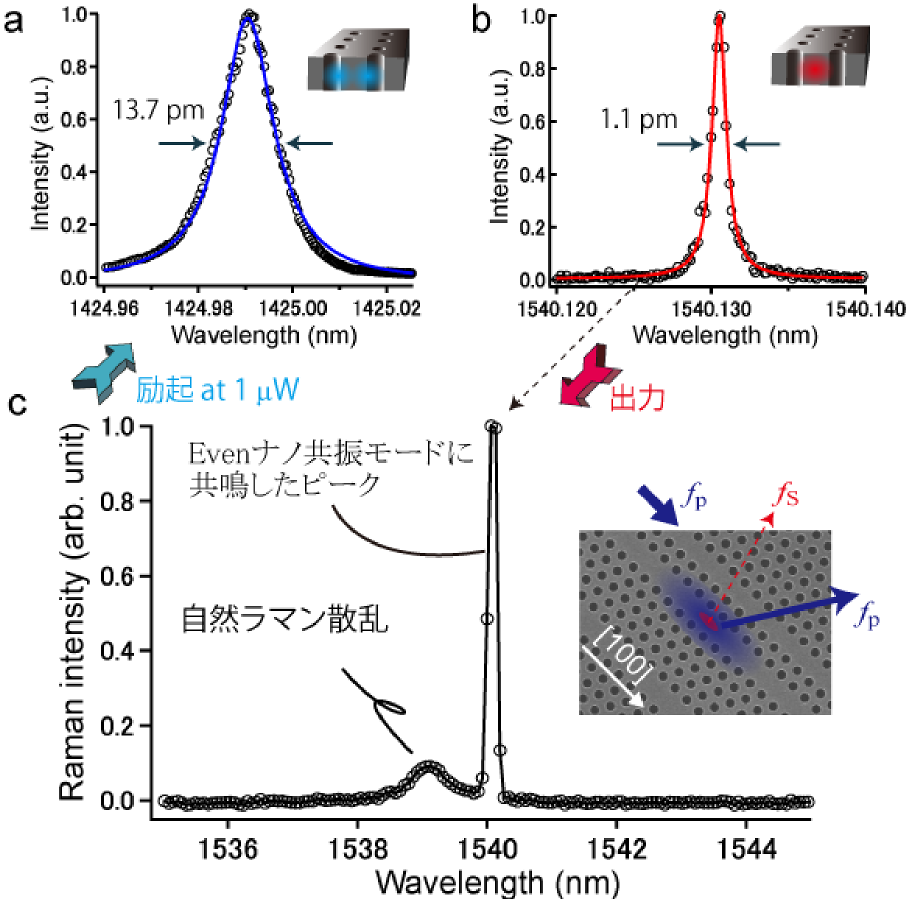
Stimulated Raman scattering
$f_P - f_S = 15.6$ THz

1/10000 of Intel Raman Laser

Measurement

Fig(c) shows a Raman scattering spectrum observed when odd-resonant mode is excited by 1mW input power,

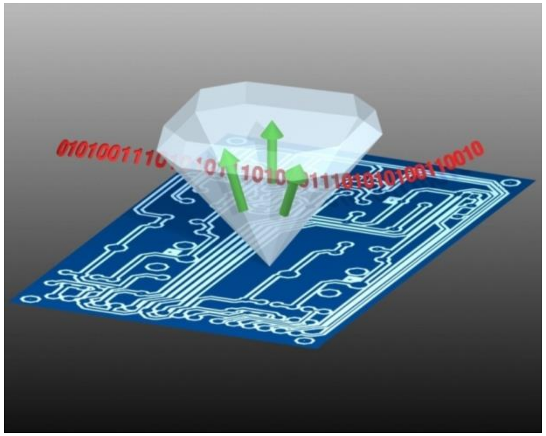
Excitation-power dependence clearly shows nonlinear enhancement of the resonant Raman peak, indicating symptom of stimulated Raman emission,



(a),(b) are spectra of odd and even resonant modes, (c) Raman spectrum by exciting odd nano resonant mode

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**

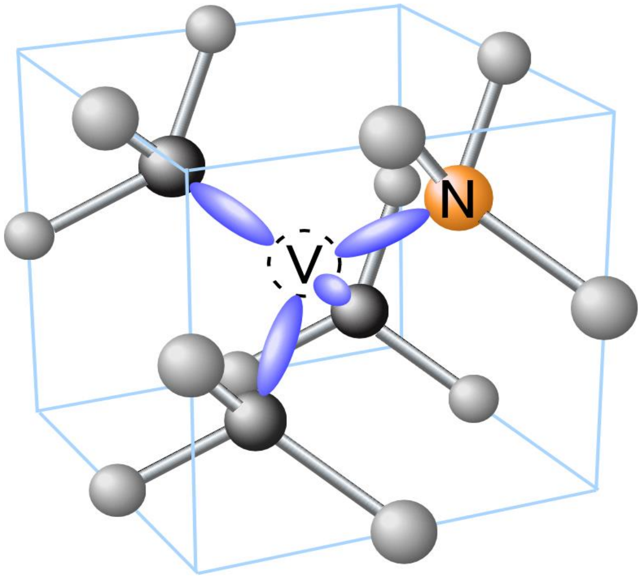


Wide Gap Semiconductors

QUNTUM INFORMATION PROCESSING USING DIAMOND NV CENTER

Single NV center in diamond

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

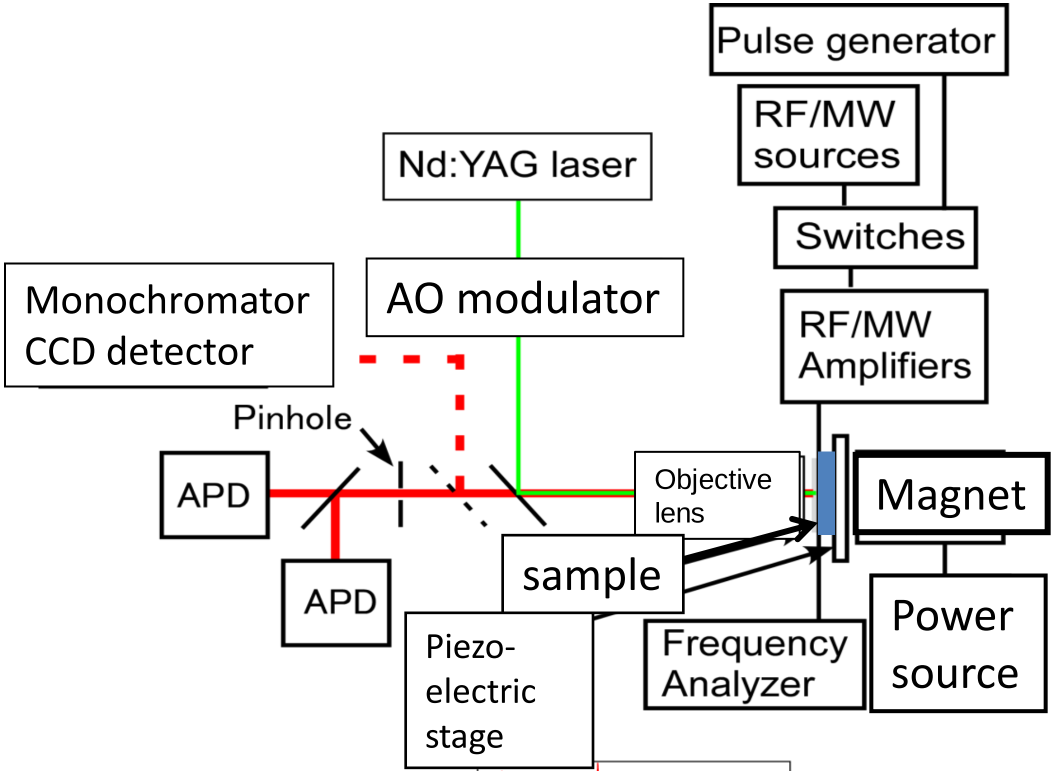


- Ground state: spin triplet(electron spin S=1)
- Long coherence length.
- Observation of single NV center and single spin manipulation is possible
- Initialization of electron spin states by light irradiation is possible

Quantum information processing solid state device for room temperature operation

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

Measurement Instruments for single NV center



Pulse generator

RF/MW sources

Switches

RF/MW Amplifiers

Nd:YAG laser

AO modulator

Monochromator CCD detector

Pinhole

APD

APD

Objective lens

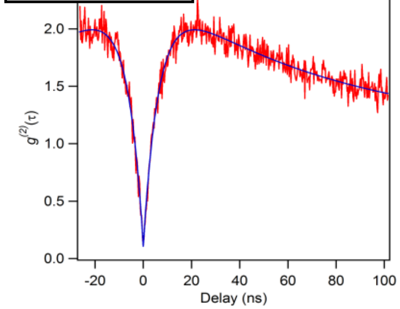
Magnet

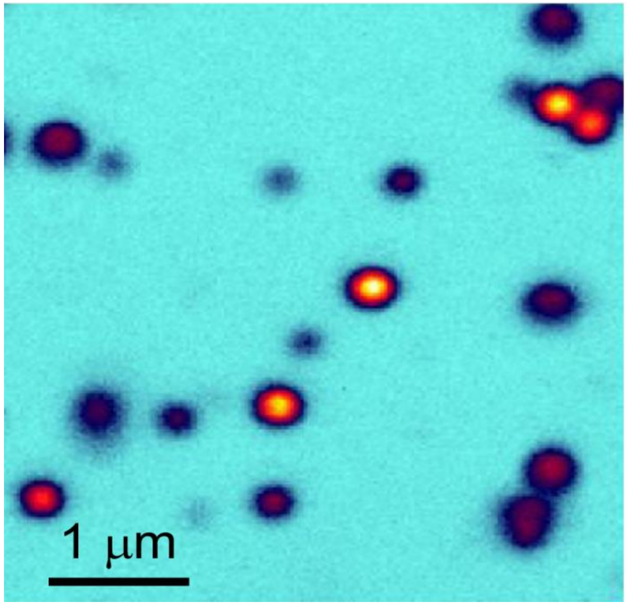
sample

Piezo-electric stage

Frequency Analyzer

Power source





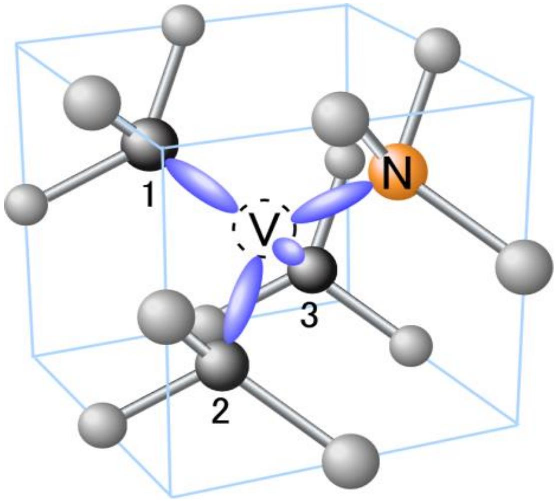
Fluorescent image of single NV center by confocal laser microscope

Anti-bunching measurement using Hanbury-Brown Twiss interferometer

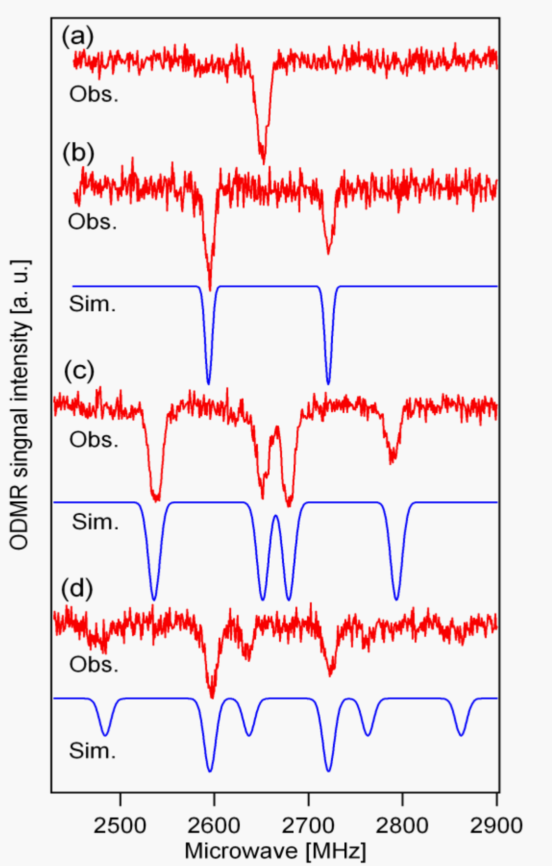
Multiple quantum bit

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

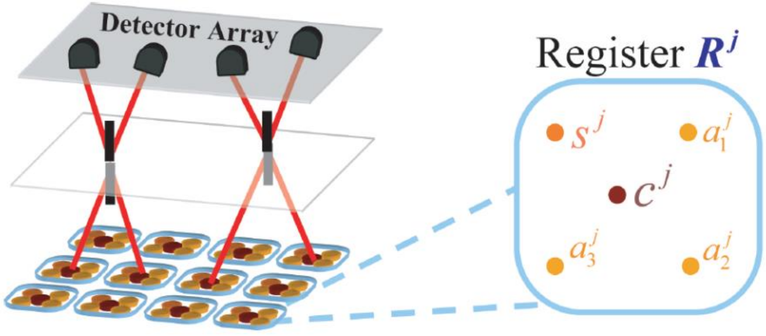
^{13}C-doped system



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



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)

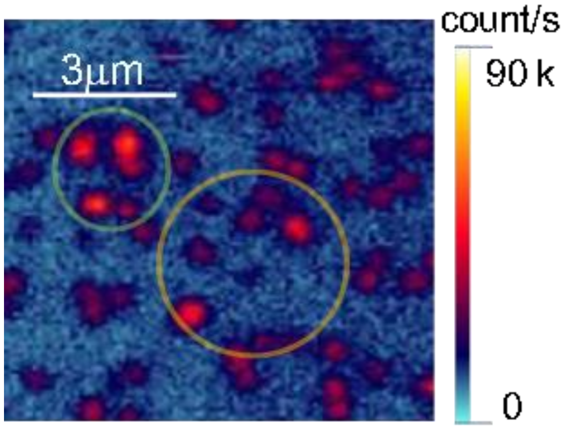


Jiang et al., PRA 76, 062323 (2007)

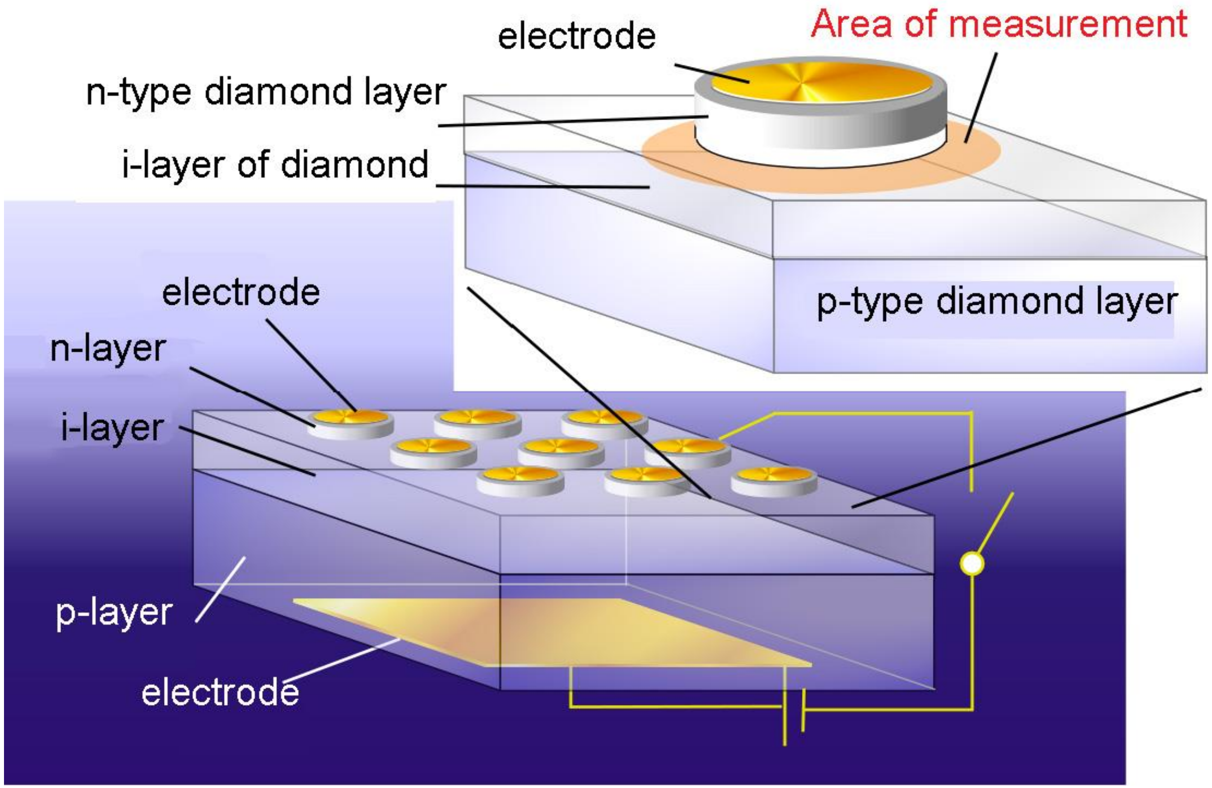
Experimental and simulated ODMR spectra of nearest neighbor carbon atoms assigned as consisting of (a)0, (b)1, (c)2, (d)3 ^{13}C-center(s)

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.



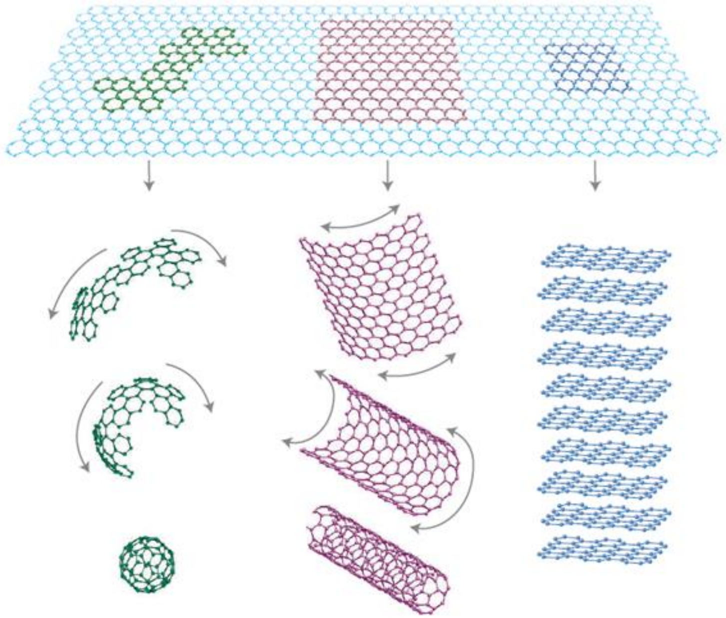
EL image of single NV center



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**

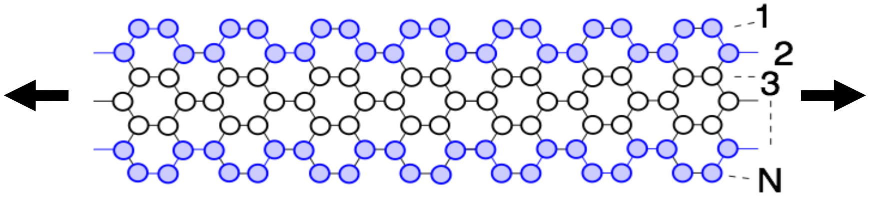


Molecules and Organics

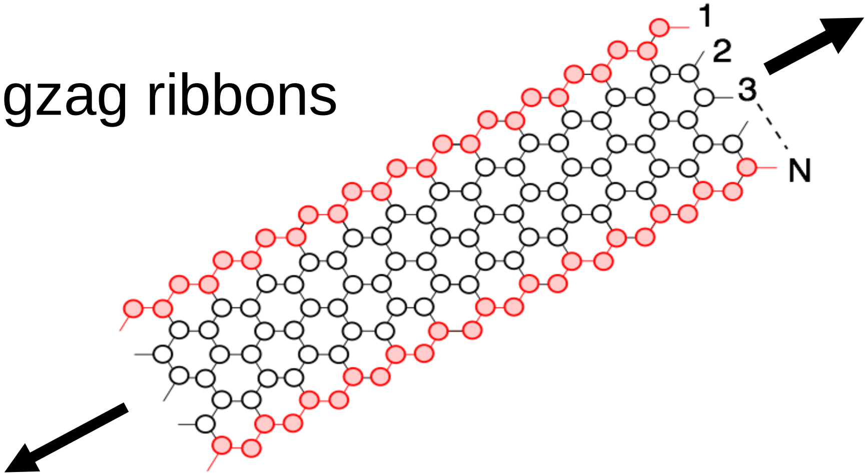
GRAPHENE ELECTRONICS

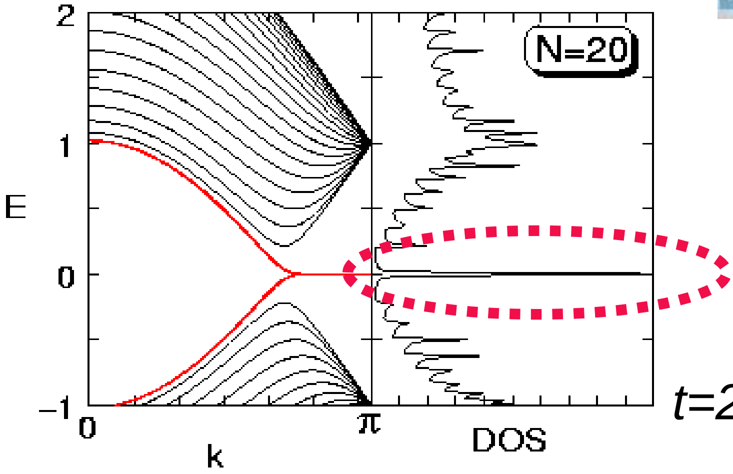
Graphene nanoribbons and strong nanoscale effect

Armchair ribbons

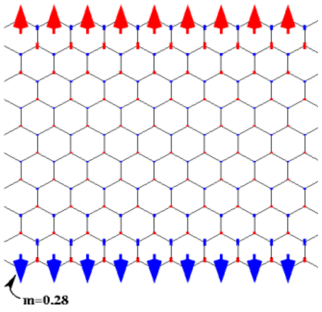


Zigzag ribbons

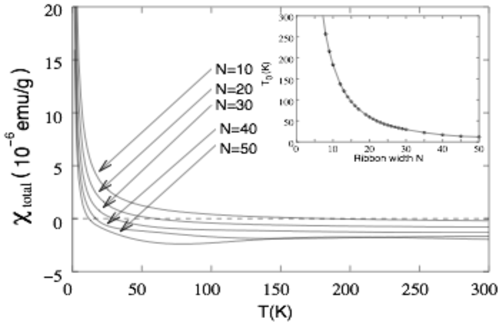




t=2.7eV



ferrimagnetic spin correlation

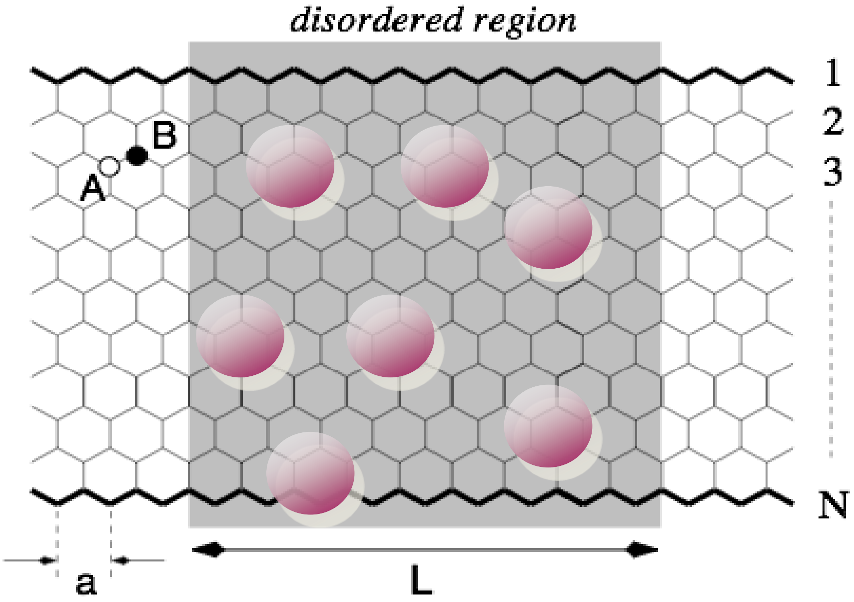


Crossover from dia- to para magnetism

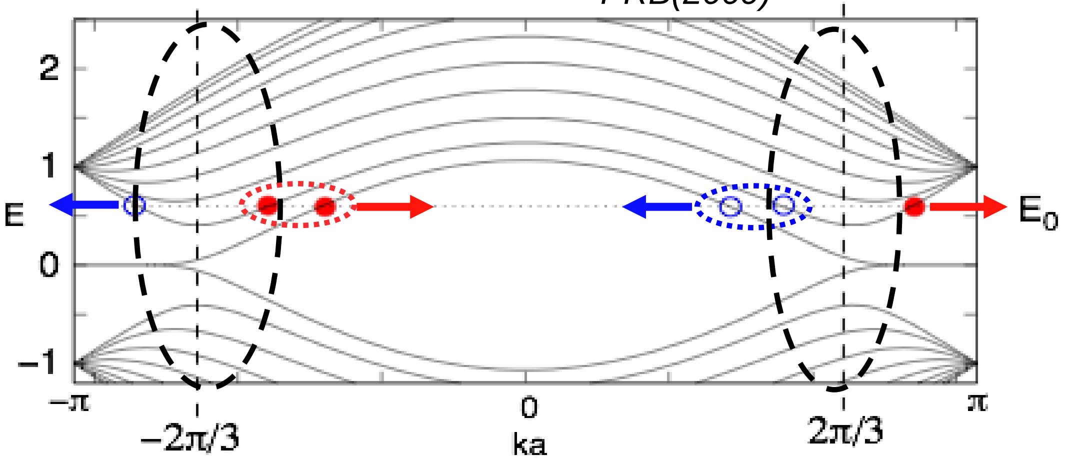
New class of quantum wires

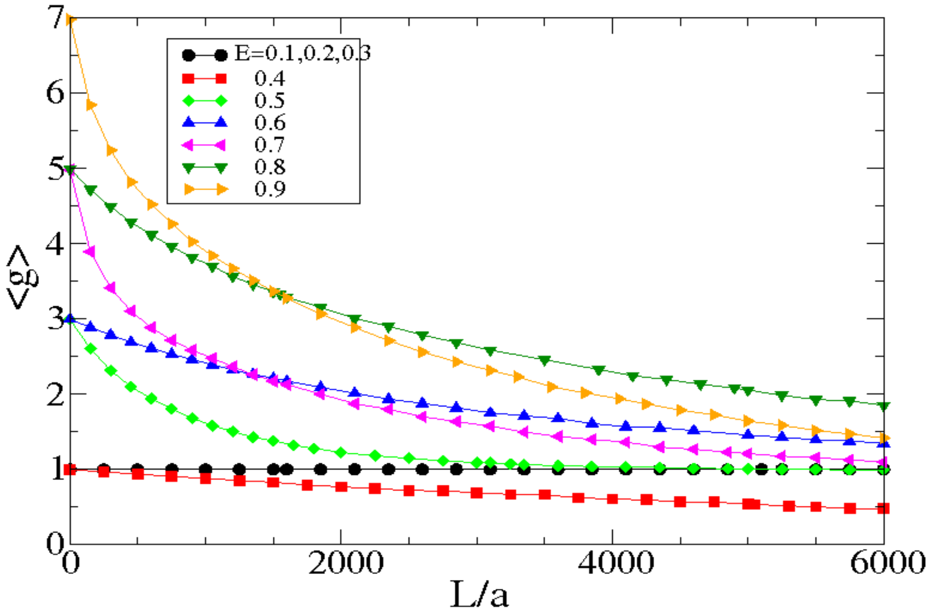
M. Fujita, K. Wakabayashi, K. Nakada, K. Kusakabe, *J. Phys. Soc. Jpn.* (1996).
K. Nakada, M. Fujita, et. al. *Phys. Rev.* B (1996).
K. Wakabayashi, M. Fujita, et. al., *Phys. Rev.* B (1999).

Perfectly Conducting Channel



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





dimensionless conductance:

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

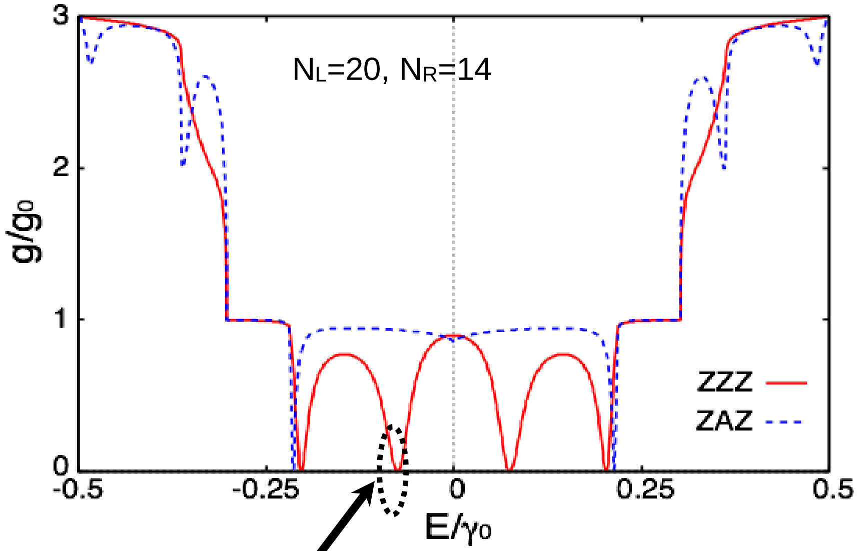
ensemble average for various impurity configuration

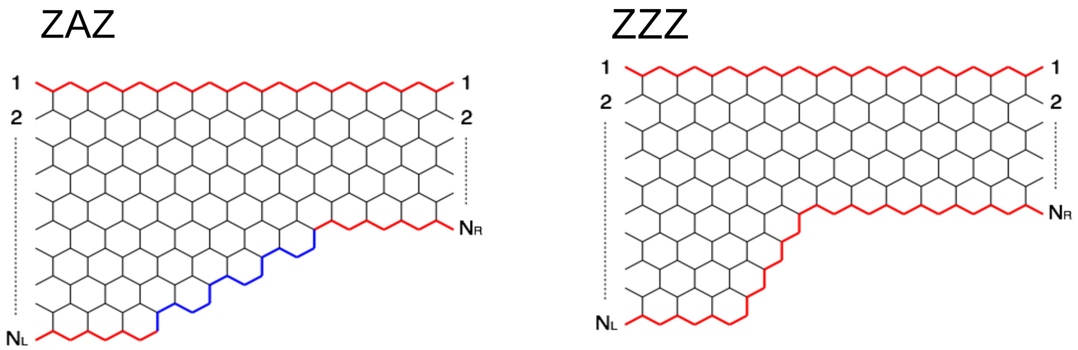
#of samples > 10000

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

Absence of Anderson localization

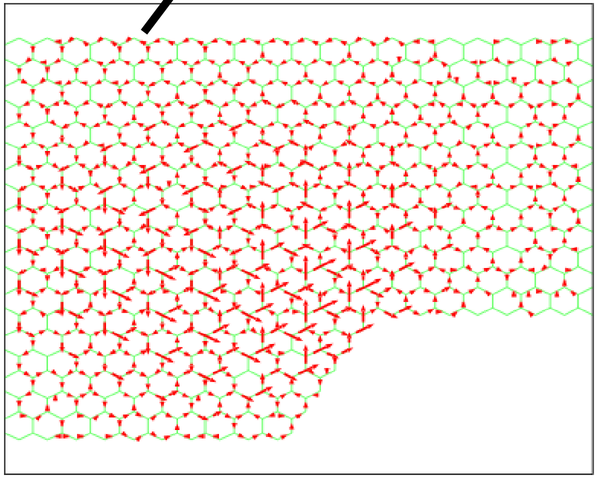
Electronic transport through graphene junction





(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.

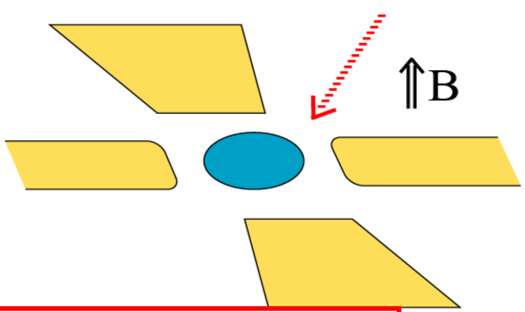
Lead	Junction	Position of anti-resonance
A	A	
	Z	$E = 0$
Z	A	$E = \pm\delta$; just before 2ch. is opened in wider ribbon.
	Z	$E = \pm\Delta_1, \Delta_2, \dots$

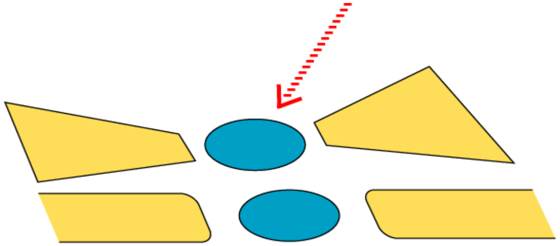
A: armchair
Z: zigzag

App. Phys. Lett. (2009)

Graphene Quantum Dot

Ultra high sensitivity THz detector



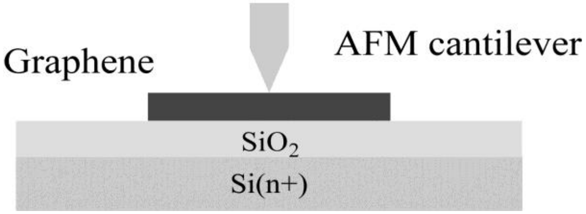


- Single electron transistor＋quantum Hall effect

- Parallel double q-dot

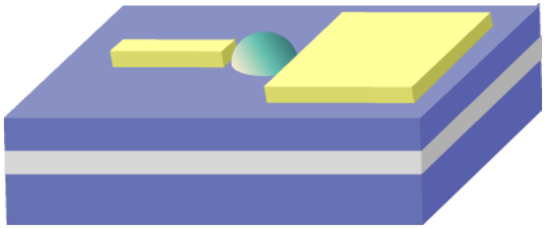
Room temperature SET

- Local anode oxidation using AFM

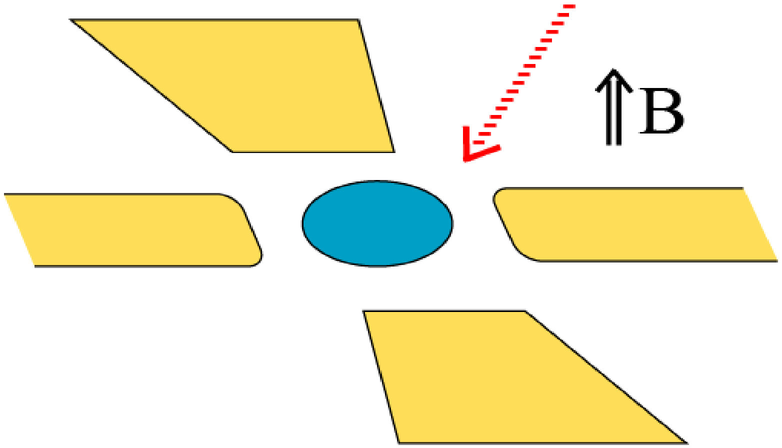


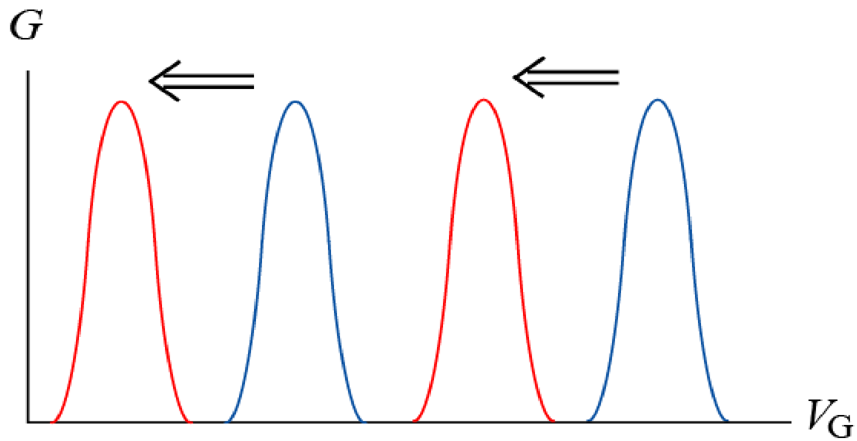
Q-dot spin valve

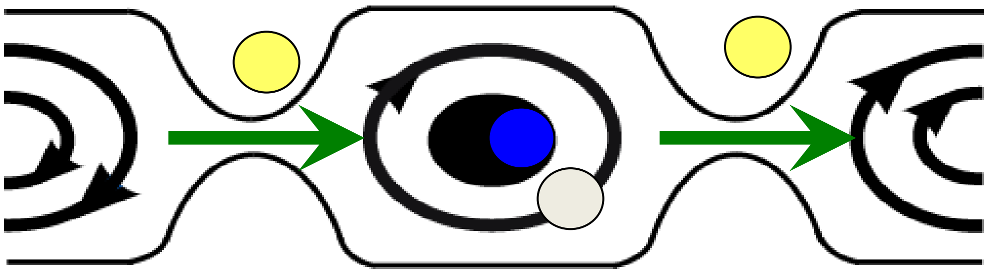
- FM electrode＋Graphene Q-dot

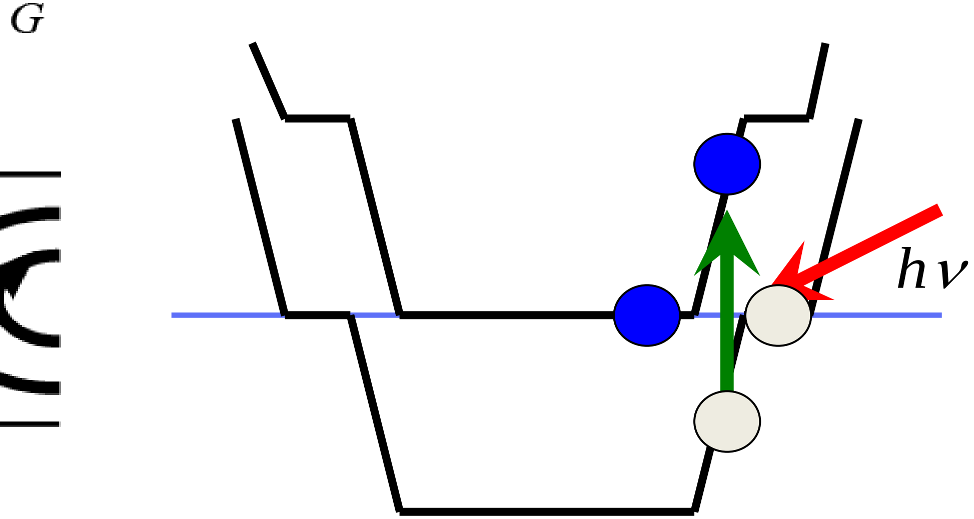


Ultra high sensitivity THz detector



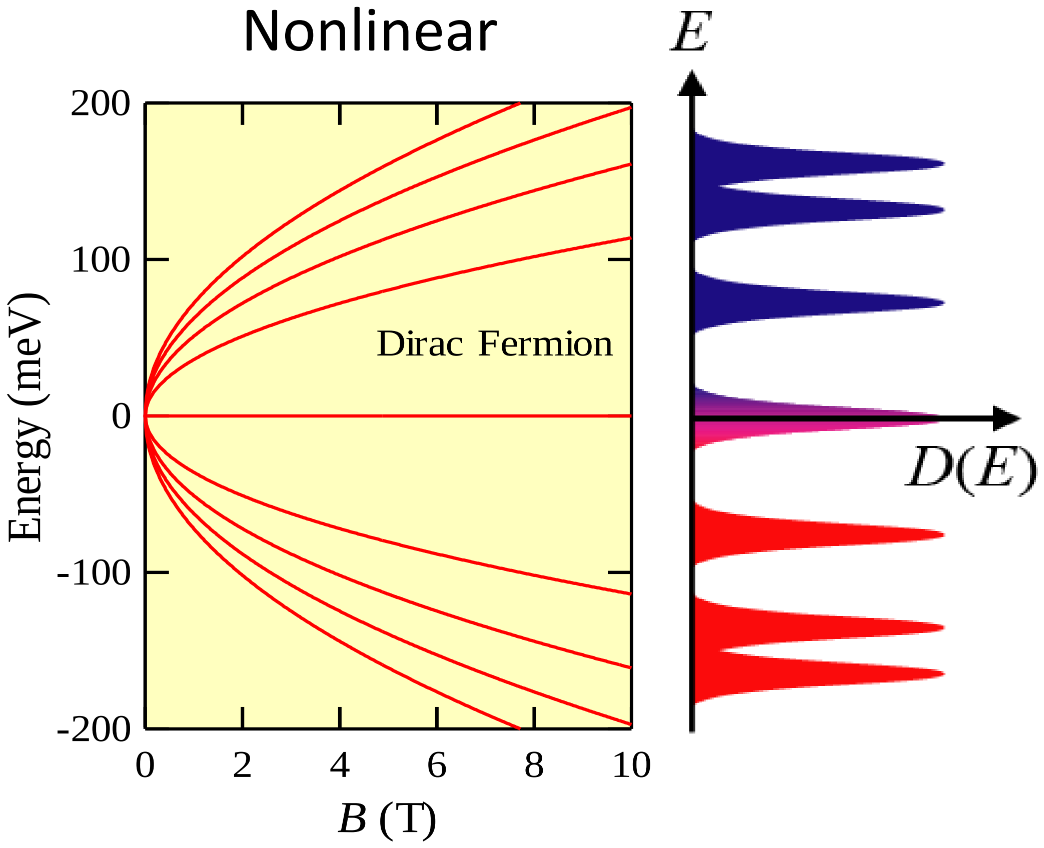


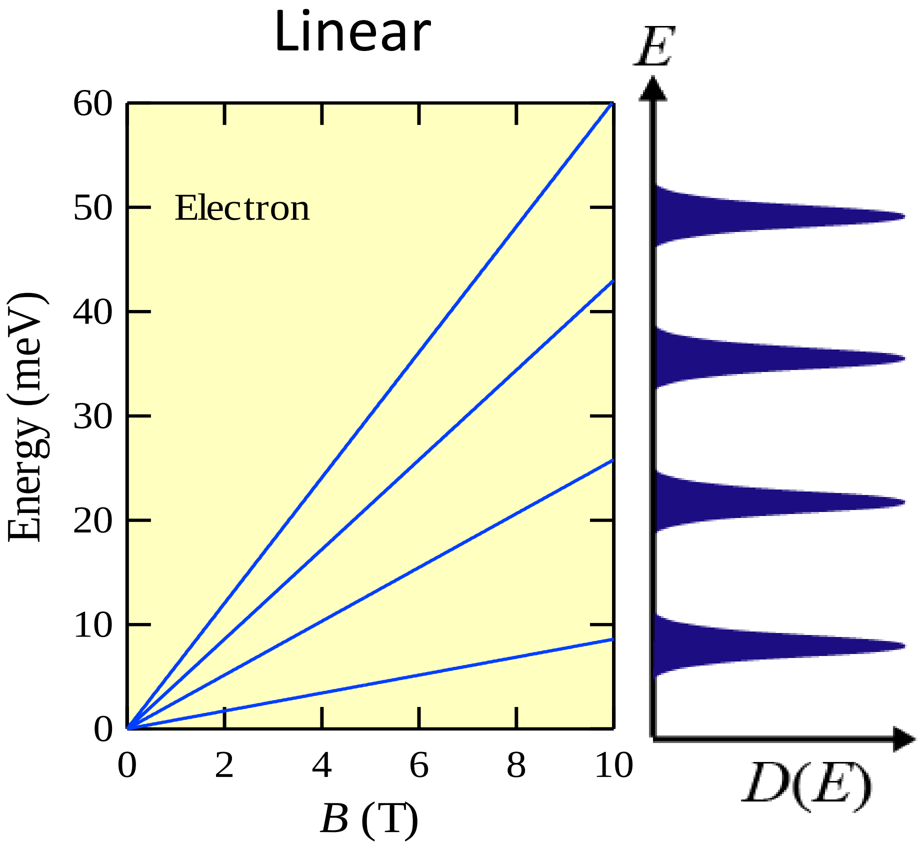




Q-Hall effect＋Single electron tunneling +Cyclotron resonance

Landau quantization : Dirac Fermion v.s. electron





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

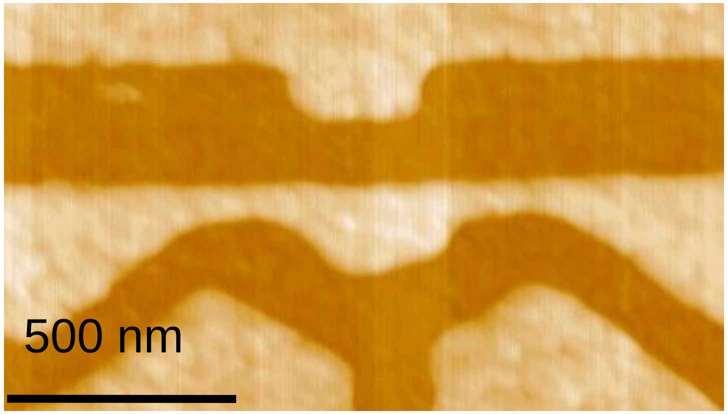
>>

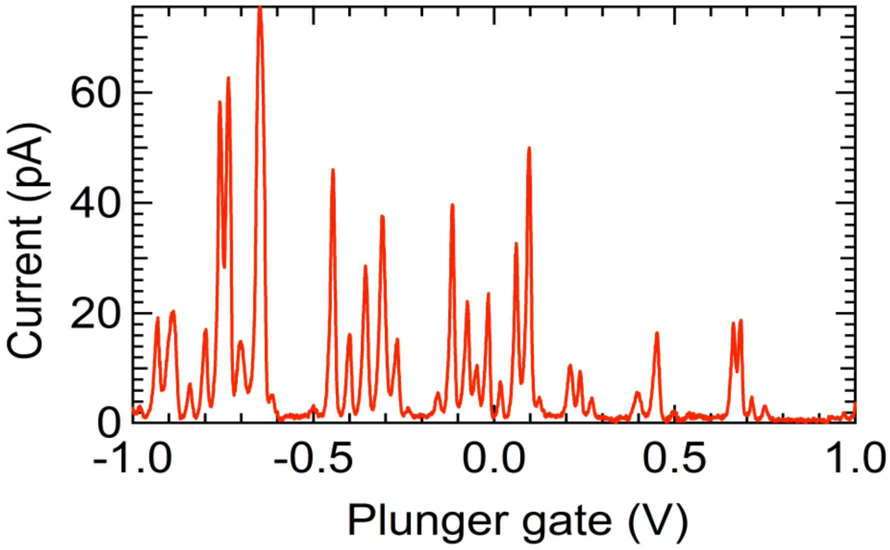
$$E_n = \left(n+\frac{1}{2}\right)\frac{\hbar e}{m^*}B$$

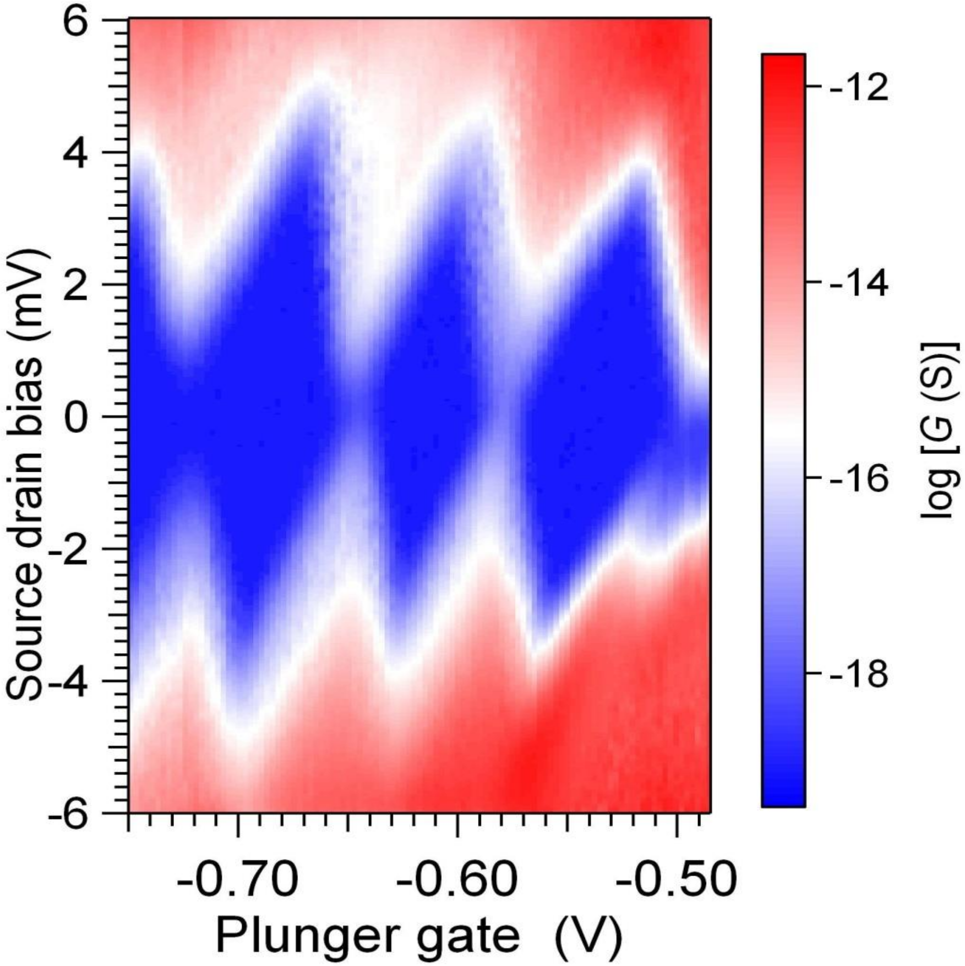
$$\sigma_{xy} = \frac{2e^2}{h}n$$

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

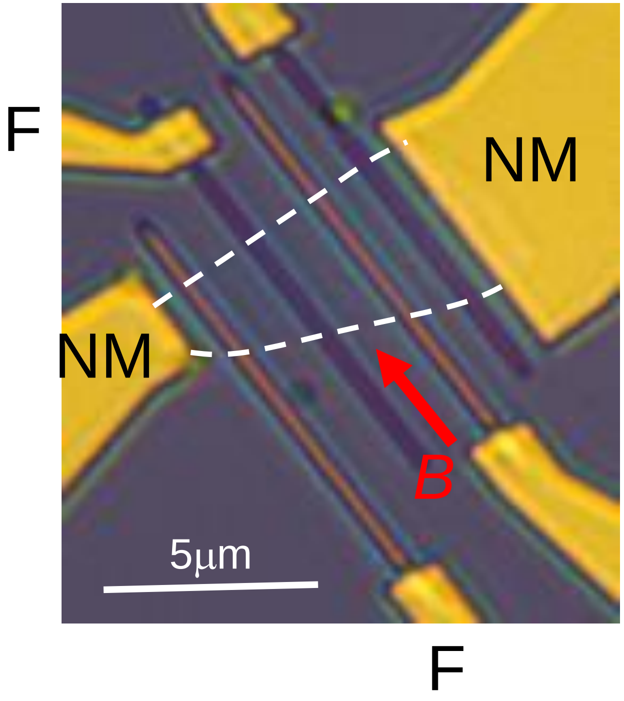
Graphene single QD

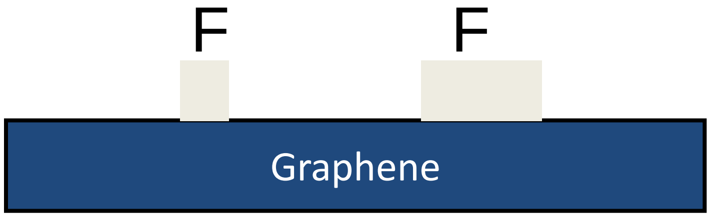




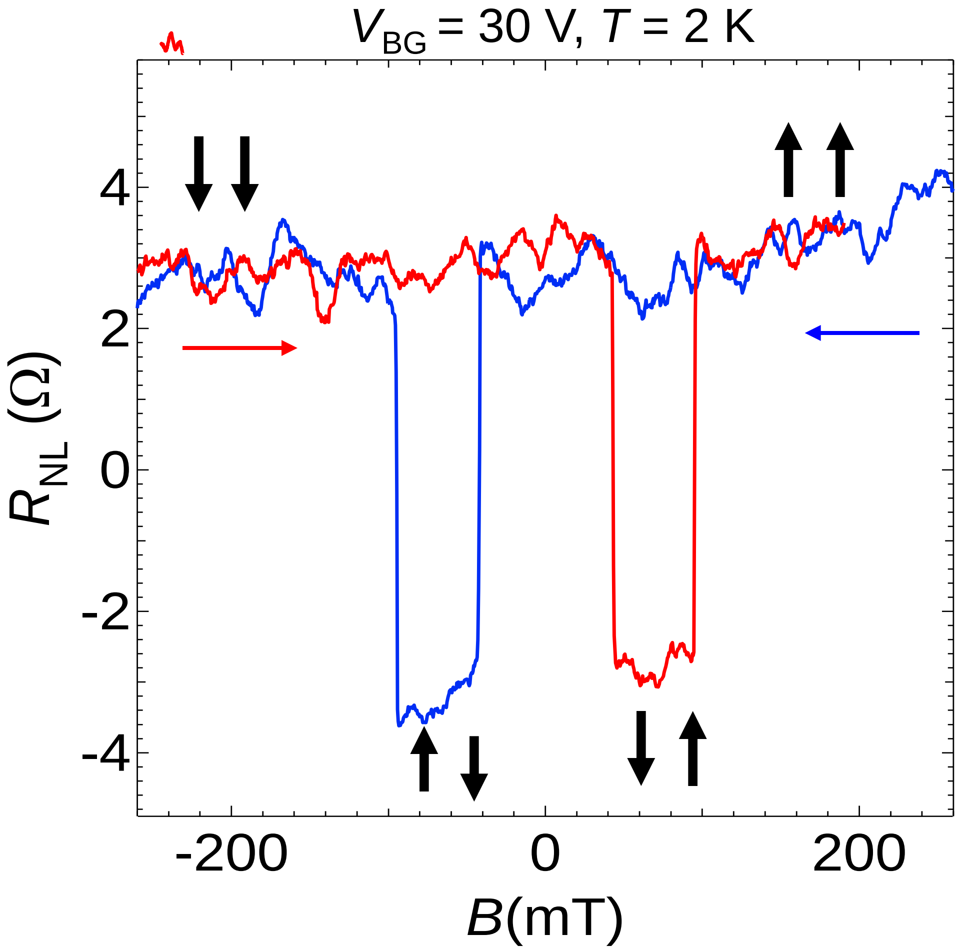


Nonlocal Magnetoresistance



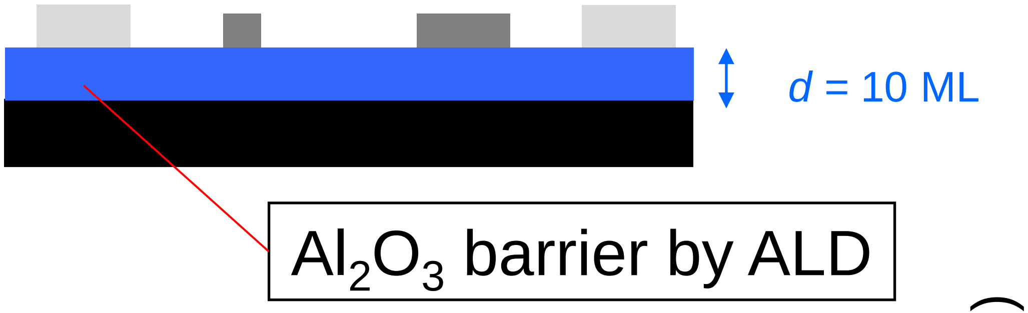


FM/Graphene/FM
Spin valve



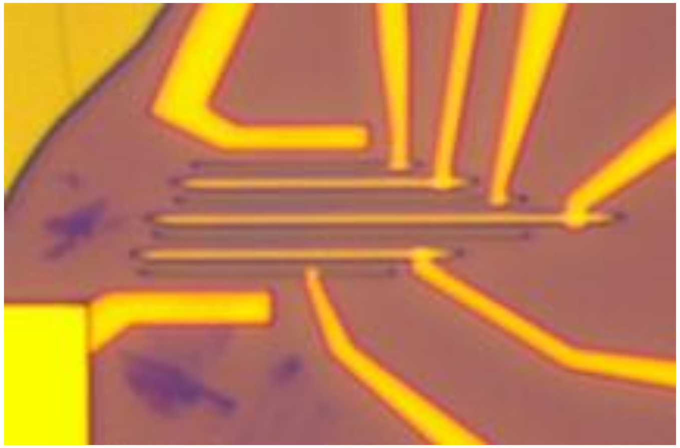
Without barrier

Graphene spin valve with tunnel barrier

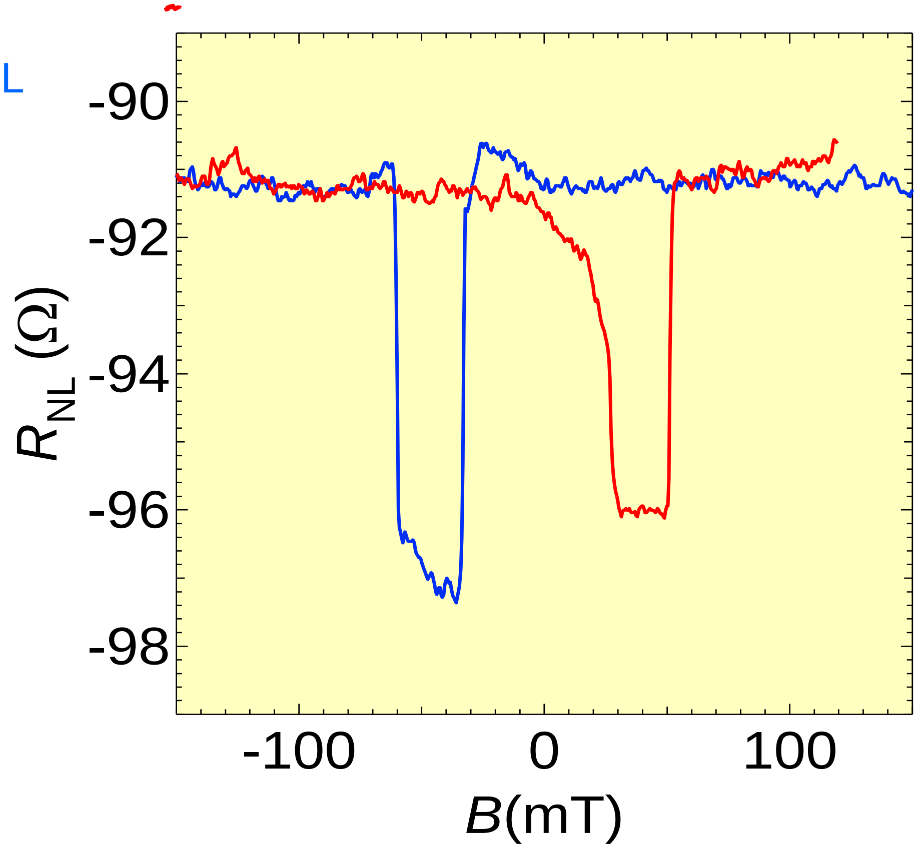


d = 10 ML

Al_2O_3 barrier by ALD



T = 5 K, V_{BG} = -30V

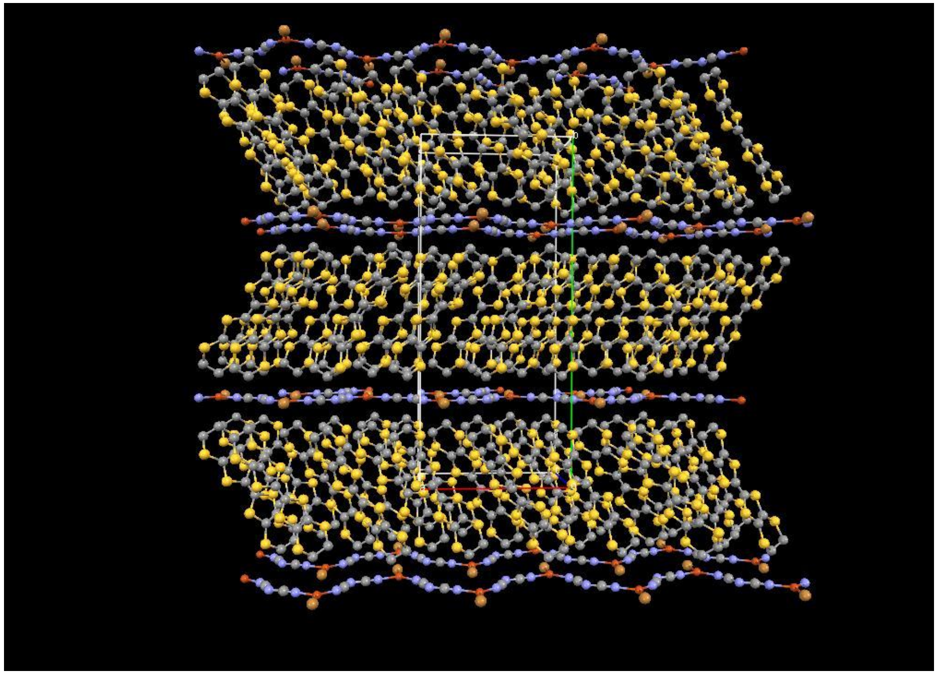


FM/Al_2O_3/graphene/ Al_2O_3/FM
Spin valve

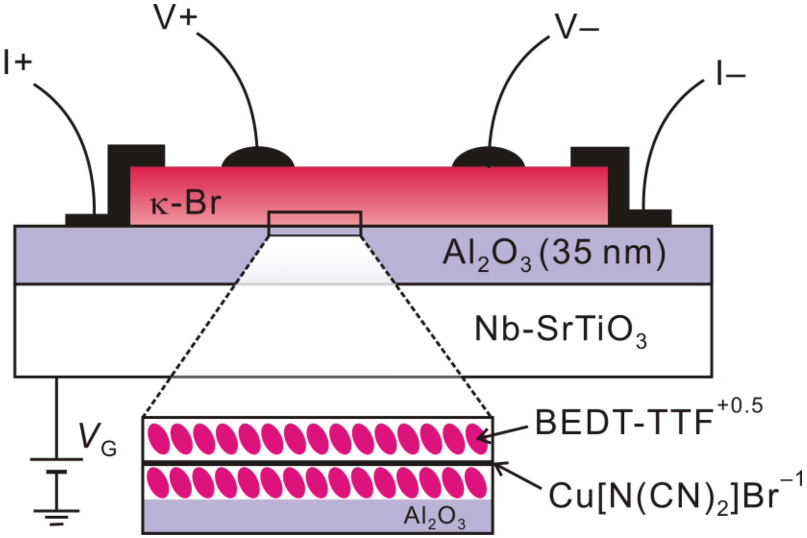
Molecules and Organics

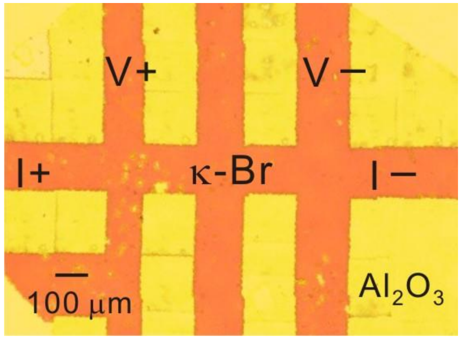
ORGANIC FET USING ELECTRONIC CORRELATION

Organic FET structure

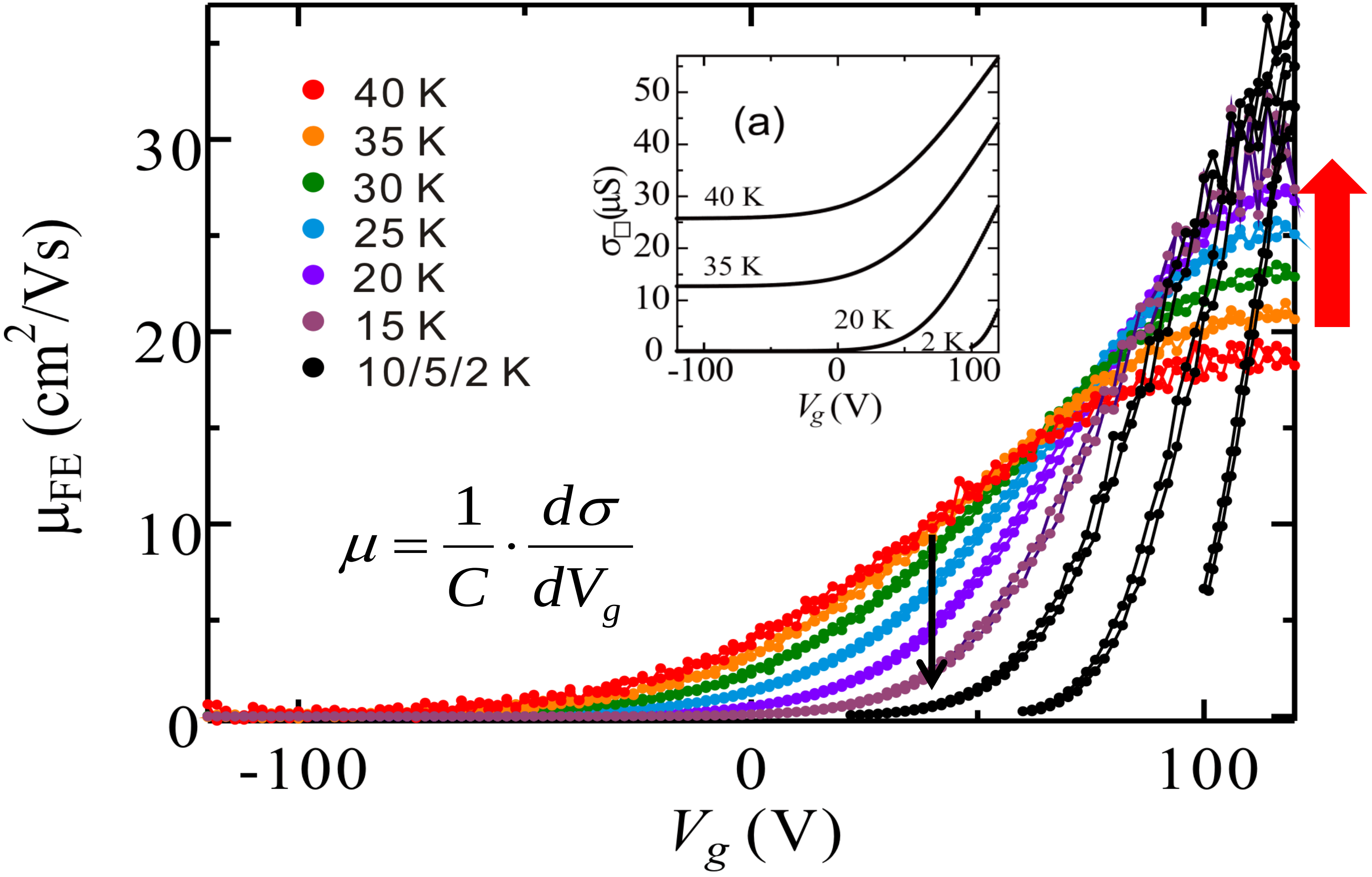


κ-Br (Cu[N(CN)2]Br^{-1}) crystal structure



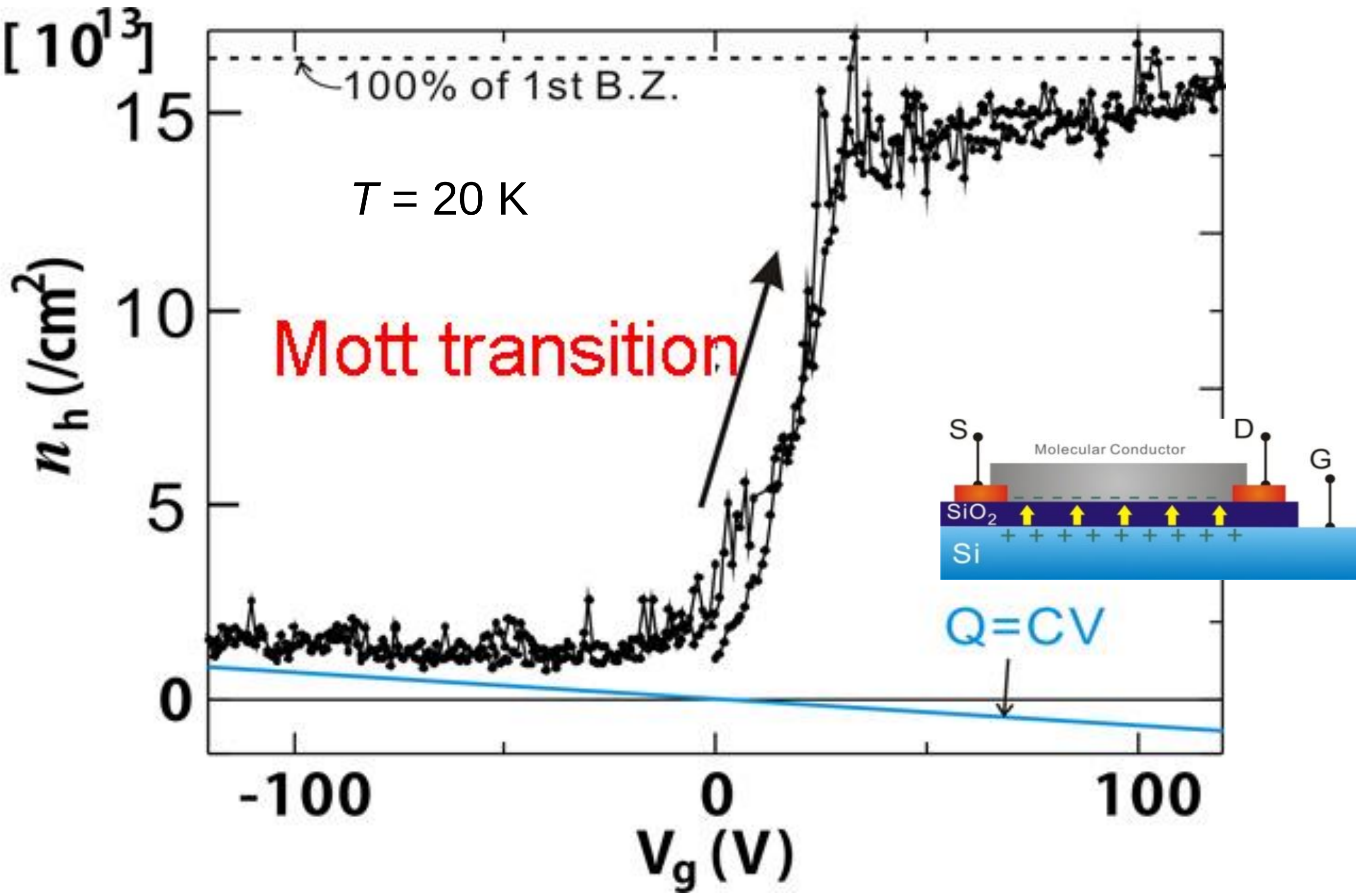


Temperature dependence of carrier mobility

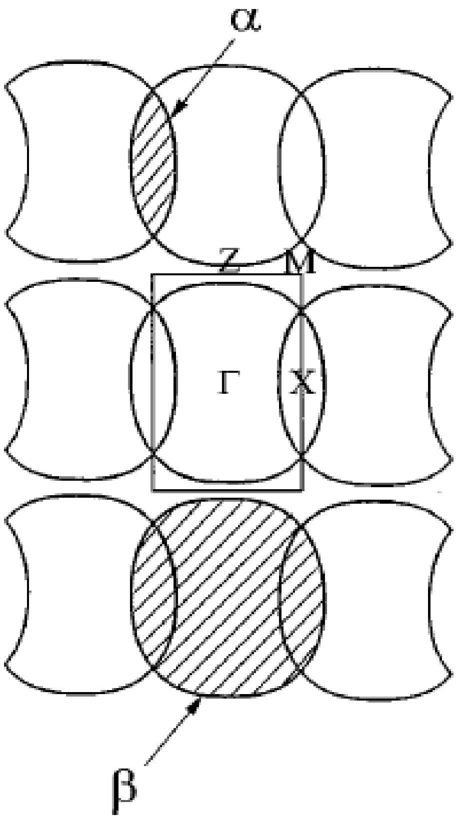


$$\mu = \frac{1}{C} \cdot \frac{d\sigma}{dV_g}$$

Gate-voltage dependence of carrier concentration



90% of 1^{st} 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

SUMMARY

Total Number of Publications and Patents

	Papers		Conferences		Books		Invited Talks		Total (w/o Patents)	Patents	
	Int’l	Domestic	Int’l	Domestic	Int’l	Domestic	Int’l	Domestic		Domestic	International
1st Phase 2007–2011	194	8	159	234	1	37	107	75	815	26	5
2st Phase 2008–2012	77	5	97	159	0	6	42	23	409	10	2
3rd Phase 2009–2013	68	10	95	176	6	7	46	24	432	16	9
Total	**339**	**23**	**351**	**569**	**7**	**50**	**195**	**122**	**1656**	**52**	**16**

Publications and Patents

	Papers		Conference		Books		Invited		Total（w/o Patents）	Patents	
	Int'l	Domestic	Int'l	Domestic	Int'l	Domestic	Int'l	Domestic		Dom	Intn'l
07FY 2nd half	28	1	9	26	0	5	11	5	85	4	1
08FY 1st half	18	3	14	29	0	4	7	10	85	6	1
08 2nd half	26	0	27	36	1	5	16	11	122	5	0
09FY 1st half	30	1	51	66	0	2	16	14	180	4	2
09 2nd half	45	1	52	100	1	10	19	22	250	5	1
10FY 1st half	47	3	49	92	0	7	34	22	254	5	2
10 2nd half	51	6	39	68	0	10	20	16	210	3	0
11FY 1st half	41	1	51	35	1	2	16	1	148	13	1
11 2nd half	32	4	24	66	1	5	20	4	156	5	1
12FY 1st half	19	2	24	38	2	0	18	13	116	2	7
12 2nd half	2	1	9	13	1	0	14	4	44	0	0
13FY 1st half	0	0	2	0	0	0	4	0	6		
Total	**339**	**23**	**351**	**569**	**7**	**50**	**195**	**122**	**1656**	**52**	**16**

Patents

International

Researcher	Application Number	Date of Application	Title of Invention	Inventors
S. Kasai	PCT/JP2008/065758	2008/09/02	Signal reproducing device	S. Kasai
E. Saitoh	PCT/JP2009/060225	2009/06/04	Spintronic device and information transmitting method	S.Saitoh、K.Naito、Y. Kajiwara、K. Ando
E. Saitoh	PCT/JP2009/060317	2009/06/05	Thermoelectric conversion device	K.Uchida, Y.Kajiwara; Yosuke, H.Nakayama, E.Saitoh
S. Noda	PCT/JP2012/054810	2012/2/27	Method for producing graphene, graphene produced on substrate, and graphene on substrate	S.Noda, S.Takano
K. Tomioka	PCT/JP2010/005862	2011/04/25	Tunnel field effect transistor and method for manufacturing same	K.Tomioka.T.Fukui, T.Tanaka
K. Tomioka	PCT/JP2010/003762	2010/6/4	Light emitting element and method for manufacturing same	K.Tomioka.T.Fukui

AWARDS

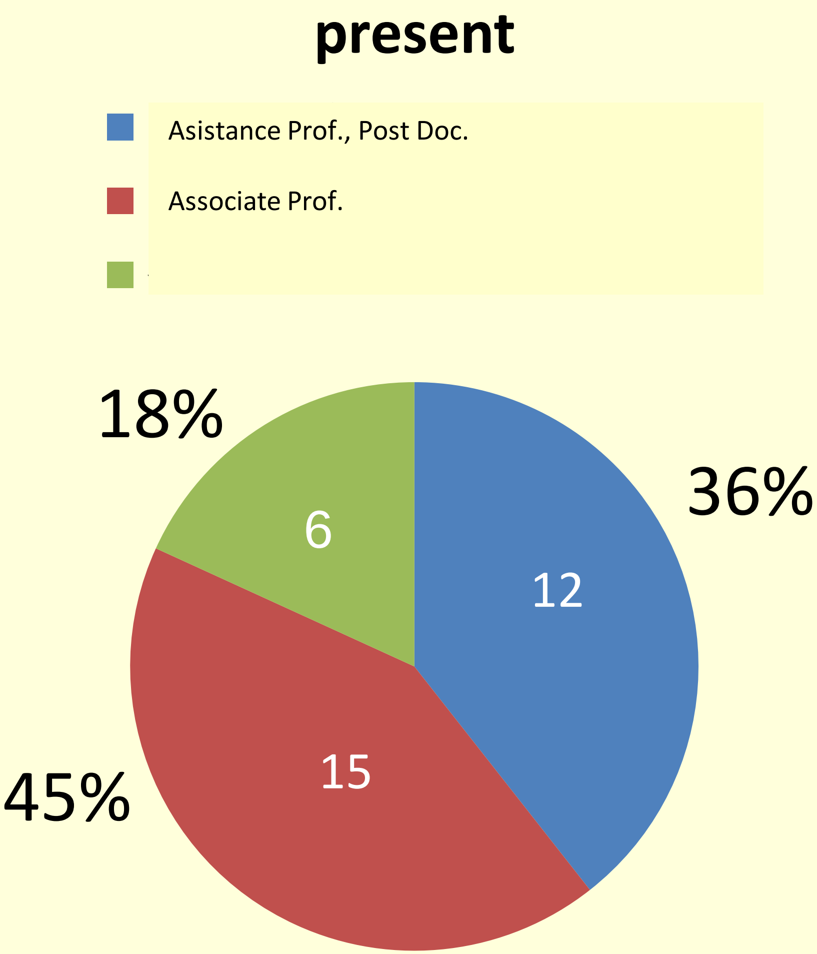
Evaluation to this project members is quite high: such as two Sir Martin Wood Awards, three JSPS Awards, one Japan Academic Council Award, two IBM Science Awards, total of 55awardees.

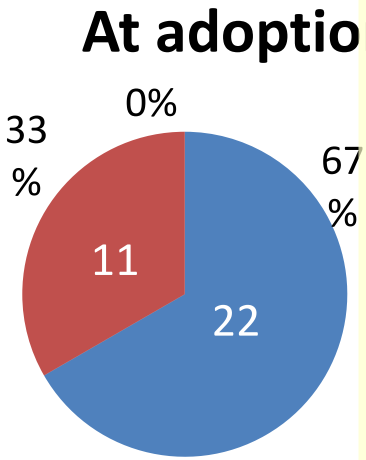
Major Award

氏名	年月日	名称
E.Saitoh	2008.11.12	Sir Martin Wood Award
	2011.2.3	JSPS Award
	2011.2.14	Japan Academic Council Award
	2011.12.2	IBM Science Award
	2011.4.12	MEXT Minister Award
	2011.4	Funai Award
S.Murakami	2010.2.19	Honda Memorial Award
	2010.10.6	Sir Martin Wood Award
	2011.12.2	IBM Science Award
	2012.12.18	JSPS Award
	2010.4.6	MEXT Minister Award
Y.K.Takahashi	2011.5.13	Honda Memorial Award
	2012.4.17	MEXT Minister Award
N.Mizuochi	2012.9.28	Nagase Award
K.Wakabayashi	2010.4.6	MEXT Minister Award
K.Hamaya	2011.4.12	MEXT Minister Award
T.Nakaoka	2012.4.17	MEXT Minister Award
T.Fukumura	2011.2.3	JSPS Award

output

Promotion





output

Publication of a Book

- A book titled “Spintronics for Next-Generation Innovative Devices” will be published from John Wiley & Sons in the Book series “Materials for Electronic and Optoelectronic Applications” based on the achievements of this project, with editors being K.Sato and E.Saitoh.

Outputs

- Presentations: 1656
 (339 international journals, 351 international conference of which 195 invited)
- Patent applications: 52(domestic) +16(international)
- 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)

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