

# Materials and Processes for Next-Generation Innovative Devices

Katsuaki Sato

Prof. Emeritus, Tokyo University of Agriculture and  
Technology

Fellow, Center of Research and Development Strategy,  
Japan Science and Technology Agency (JST)



**BIT's 3<sup>rd</sup> Annual**

**World Congress of Advanced Materials-2014**

Theme: Dream of Ubiquitous Smartness

Time: June 6-9, 2014 Venue: Chongqing Yuelai International Conference & EXPO Center, Chongqing, China

# Objectives

This presentation is a report on the achievements of the JST-PRESTO project “Materials and Processes for Next Generation Innovative Devices”, which started on October 2007 and ended on March 2013.

*I dedicated myself as a Research Supervisor of this Project.*

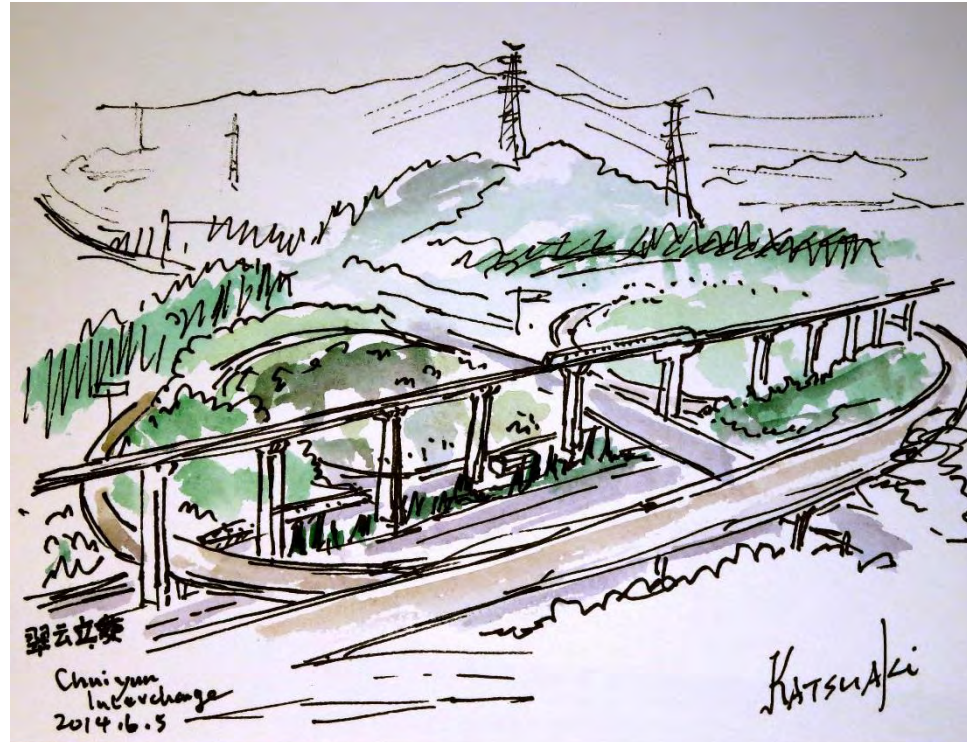
# Contents

1. Target of the Project
2. Achievements of the Project
  1. Spintronics devices and materials
  2. Molecular and organic electronics
  3. Semiconductor nanoelectronics
  4. Wide-gap semiconductors
3. Outcomes
4. Summary



Yuelai  
2014.6.6

KATSUAKI



Chuiyuan Interchange from 14F of  
Grand Metropark Hotel

## Introduction

# Target of the Project

# 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.

*These messages are those at the age of 2005,  
when the Project was proposed*

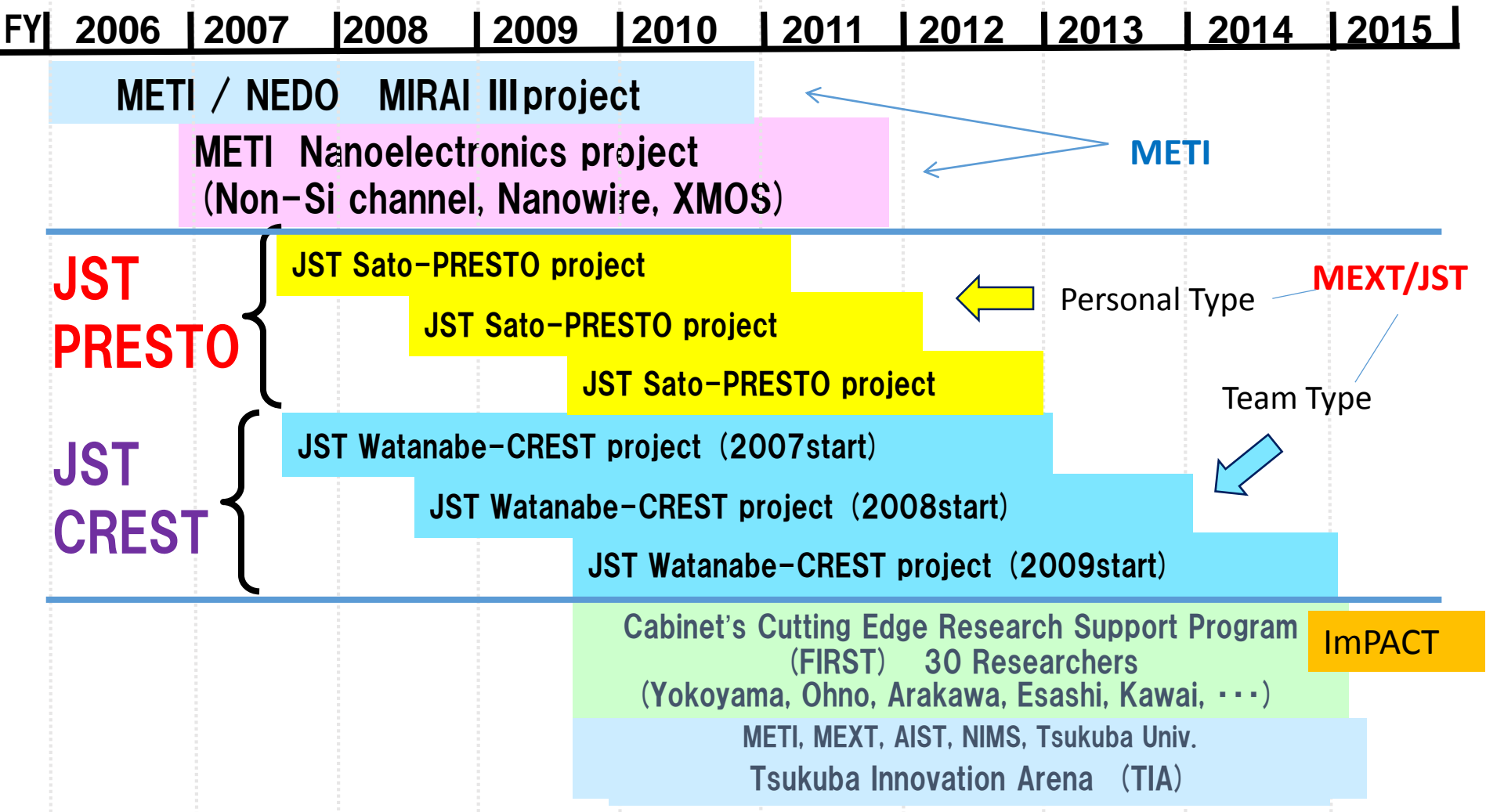
# Three ways to overcome the limit

- 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

# 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





# Scope of Sato 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
  - Molecular and organic electronics
  - Semiconductor nano-electronics
  - Wide-gap semiconductors

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

# Organization



**Supervisor**



**Office**

**Research Manager  
Administrative Manager**

**JST Staffs**

**Advisors**



Yuji Awano



Hiroshi Okamoto



Shunri Oda



Kazuhiro Kudo



Akiko Gomyo



Kazuhiro Komori



Koki Takanashi



Katsumi Tanigaki



Yasushi Nonishi



Akira Fujimaki



Mutsuko Hatano

**33 Researchers**

**phase (1): 11, phase (2): 10, phase (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

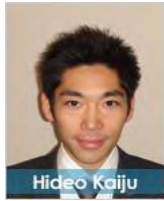
For Comparison: Case of Watanabe-CREST

Duration Max 5.5 years

Budget 150-500 M Yen (1.5-5 M Euro) per team

Teams: 18

# Fields



## Spin



## Charge



## Light

# Materials

## Oxides



## Dielctrics



## Semiconductors



## Organics



## Nano Carbon



## Superconducto



## Metals



# Research Themes

(1<sup>st</sup> phase 2007 start) 11 themes

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

spintronics

wide-gap

semiconductor

molecules/organics

others

## (2<sup>nd</sup> phase: 2008 start) 10 themes

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

spintronics

wide-gap

semiconductor

molecules/organics

others

## (3<sup>rd</sup> phase: 2009 start) 12 themes

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

spintronics

wide-gap

semiconductor

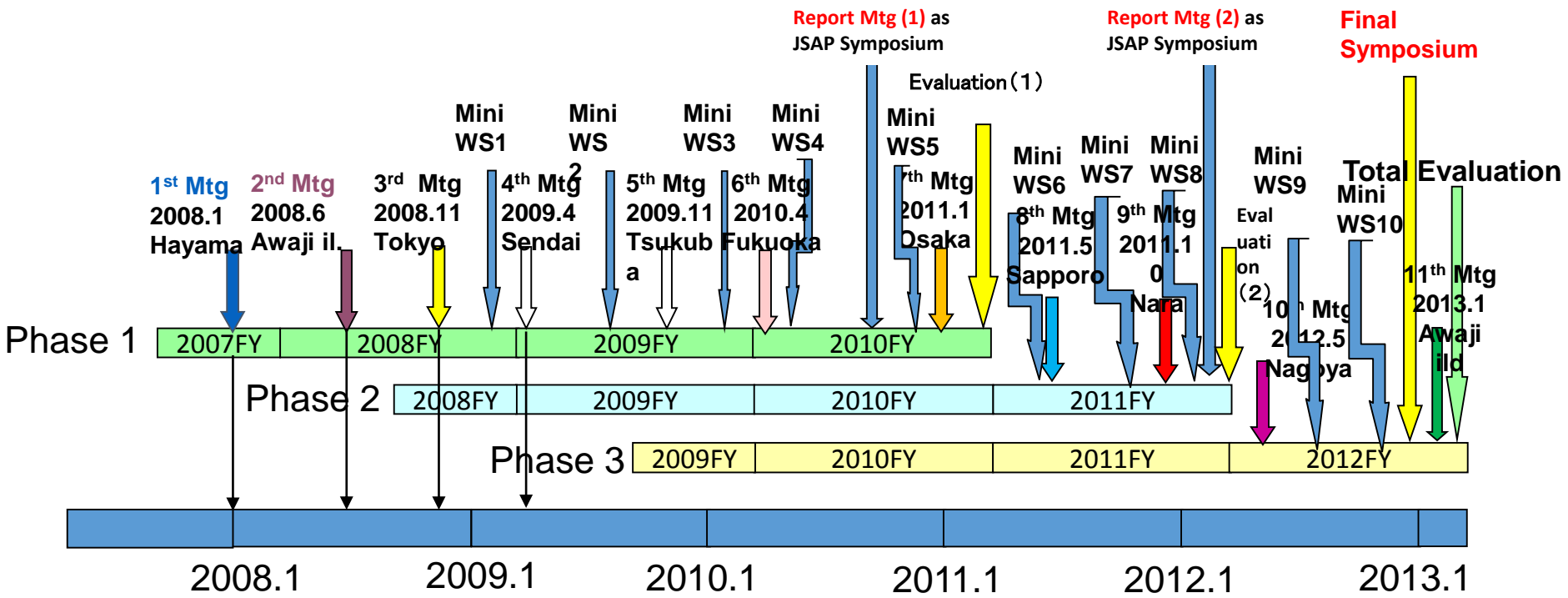
molecules/organics

others



# 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





Jiagling River

Products of the Research Project

Achievements

Molecular and organic electronics  
Spintronics devices and materials  
Semiconductor nanoelectronics  
Wide-gap semiconductors

Achievements



Spintronics devices and materials

# Spintronics devices and materials

1. E. Saitoh succeeded in transferring DC signal through *insulator* by using spin current. He discovered *Spin Seebeck* effect by using thermal spin current
2. S. Murakami proposed unified theory of spin and heat and predicted high thermoelectric performance in *topological insulators*
3. S. Shiraishi succeeded in spin injection to single sheet of *graphene*
4. K. Hamaya succeeded in spin injection to *nondegenerate silicon* leading to gate voltage control of spin injection
5. T. Fukumura succeeded in controlling magnetic properties by gate-voltage in *room temperature ferromagnetic semiconductor*  $\text{TiO}_2:\text{Co}$
6. Y. Takahashi developed *Heusler alloy*  $\text{Co}_2\text{Mn}(\text{Ga},\text{Ge})$  with the highest degree of spin polarization

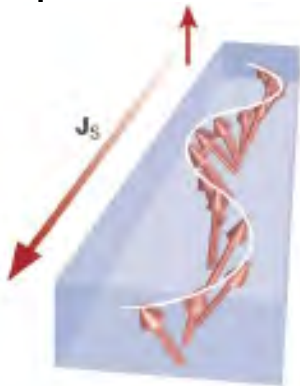
# Spintronics based on spin currents and spin-photon coupling in dielectrics



By utilizing the strong interaction between a spin current and an electric field in **dielectric materials**, the spin-wave spin currents will realize the coherent and **low-loss information transmission** which can be controlled in terms of light and/or an electric field



Realization of **Ultimate Spintronics** using pure Spin Current detached from electric current



Spin current is a wave of magnetization in ferromagnet, which is capable of transferring Spin Current (Flow of Spin Angular Moment)

## Eiji Saitoh (Tohoku Univ)

### Representative Papers

Nature **464**, 262-266 (2010).

Nature materials **9**, 894-897 (2010).

Nature materials **10**, 655 -659 (2011).

### Awards

Sir Martin Wood Prize

JSPS Award

Japan Academy Prize

Japan IBM Science Prize

### Promotion

Lecturer Keio U → Prof Tohoku U

### Special Comment

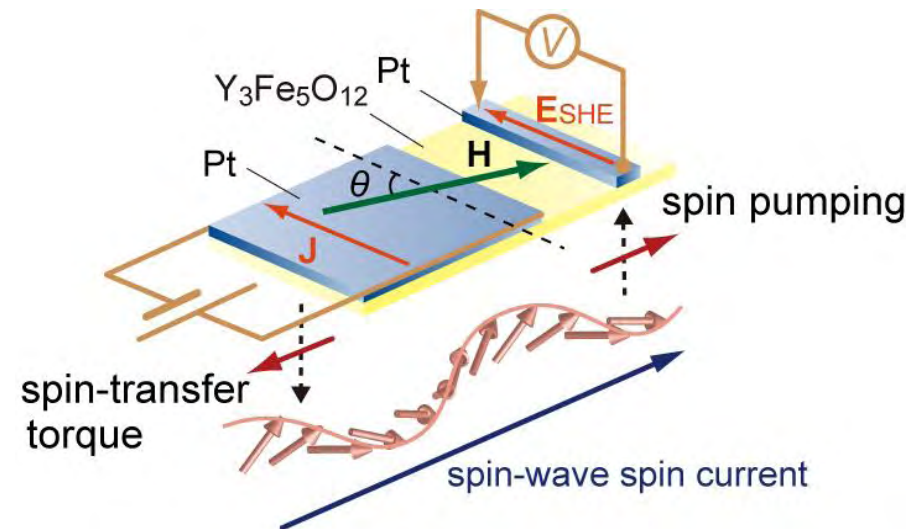
Editor of a Book "Spintronics for Next-Generation Innovative Devices" (John Wiley)

### Outreach

Press Lecture, JST News

# A magnetic insulator transmits electrical signals via spin waves

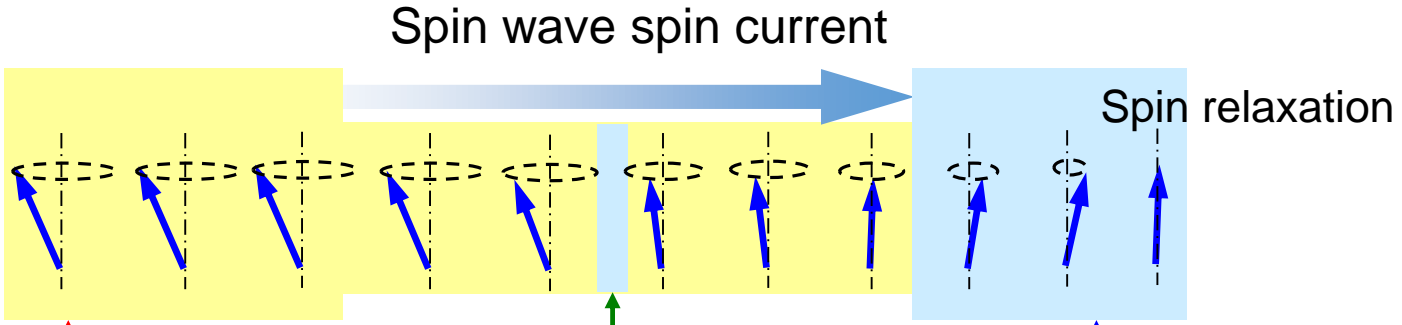
- Saito succeeded in transmitting electric signals through YIG using spin waves (pure spin current) in the insulator.
- The spin Hall effect, which converts the charge current to a spin current, and its inverse forms the basis for a proof of principle. (cited in *Physic Today*)



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)

Contribution to Scientific Progress

*Excitation, modulation and detection of spin wave spin current*



Excitation

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

Modulation

- electric field + SO

Detection

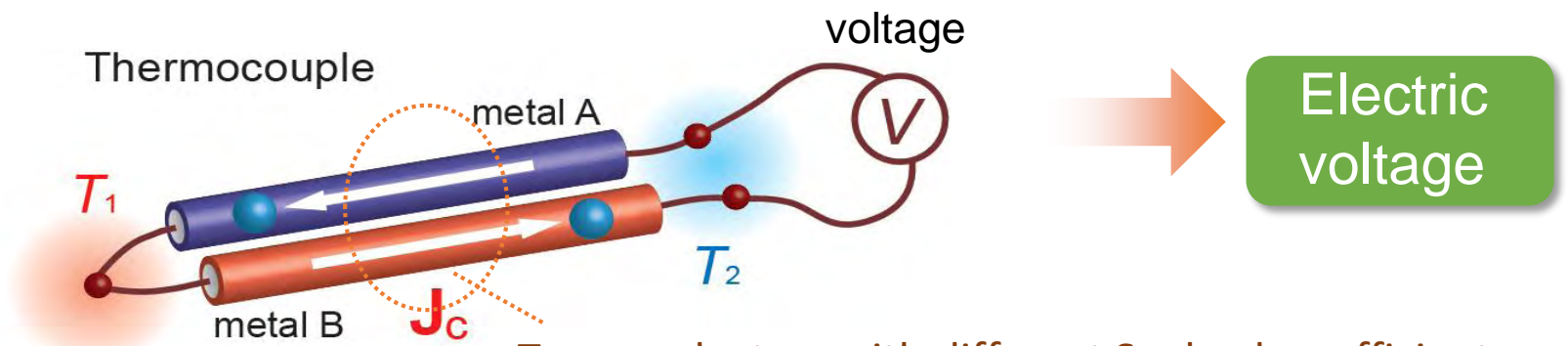
- spin torque meter
- Faraday effect
- electrical detection (ISHE)

**Dielectrics**

- application of electric field
- strong interaction with photon

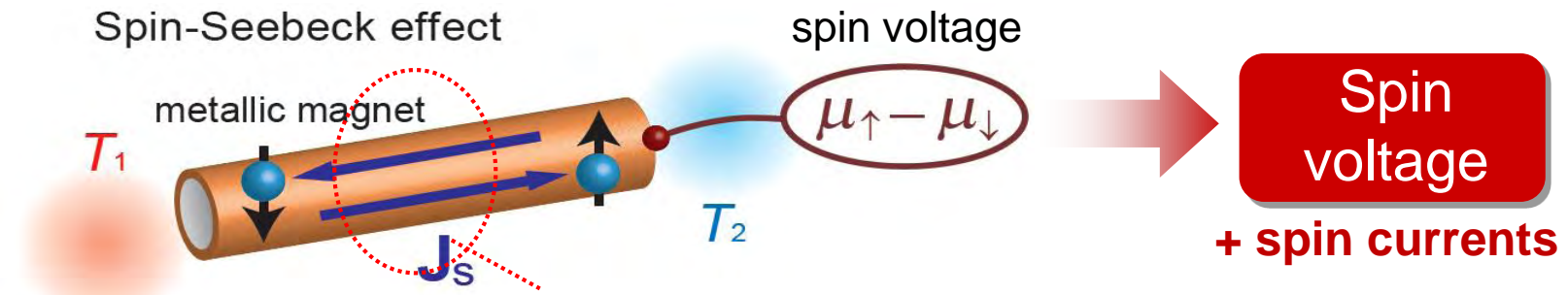


# Seebeck and "spin-Seebeck" effects



Two conductors with different Seebeck coefficients

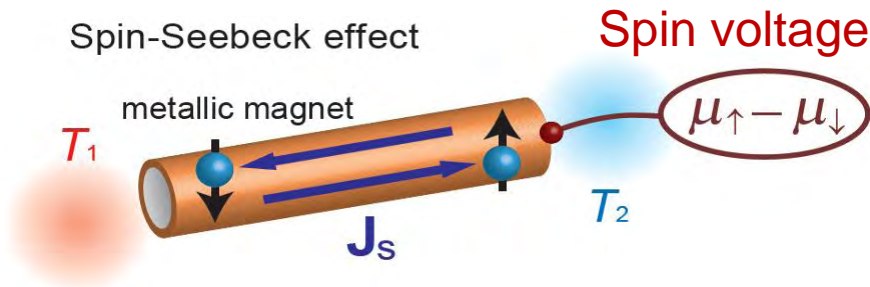
depending on the density of electrons



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

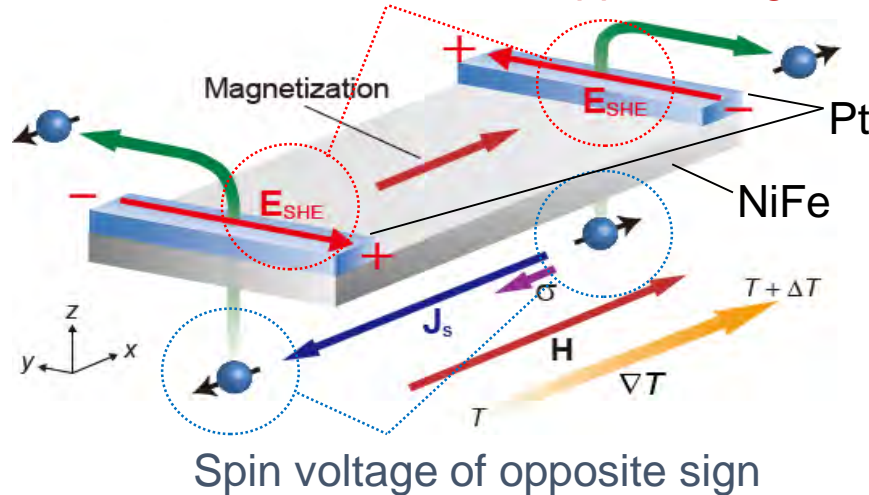


# Observation of spin-Seebeck effect

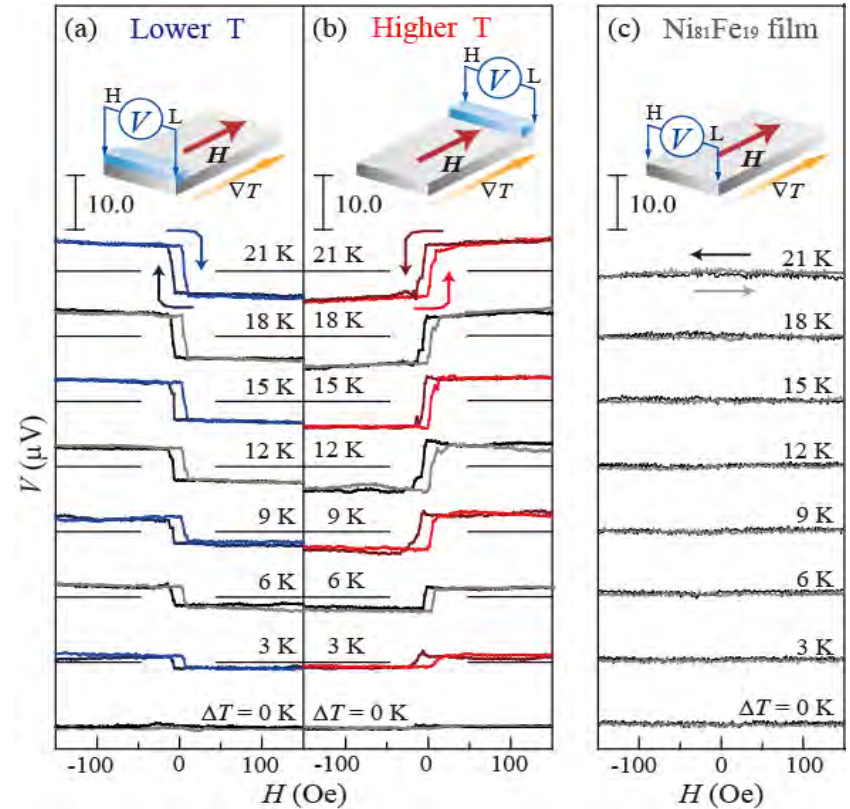


using the inverse spin-Hall effect (ISHE)

electromotive force of opposite signs



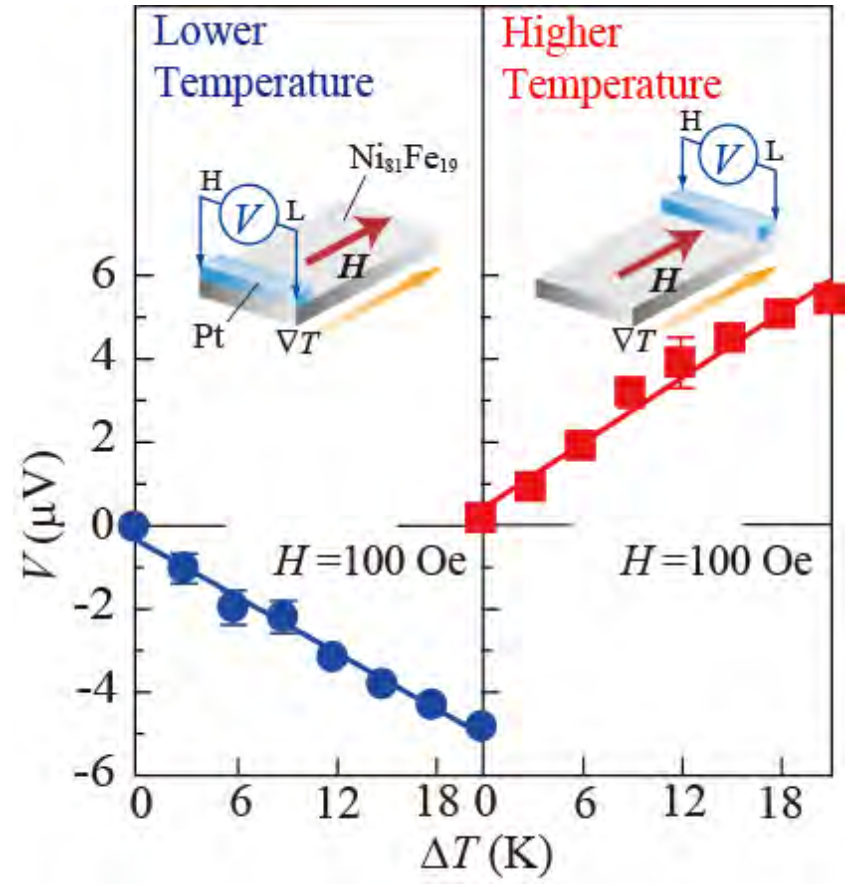
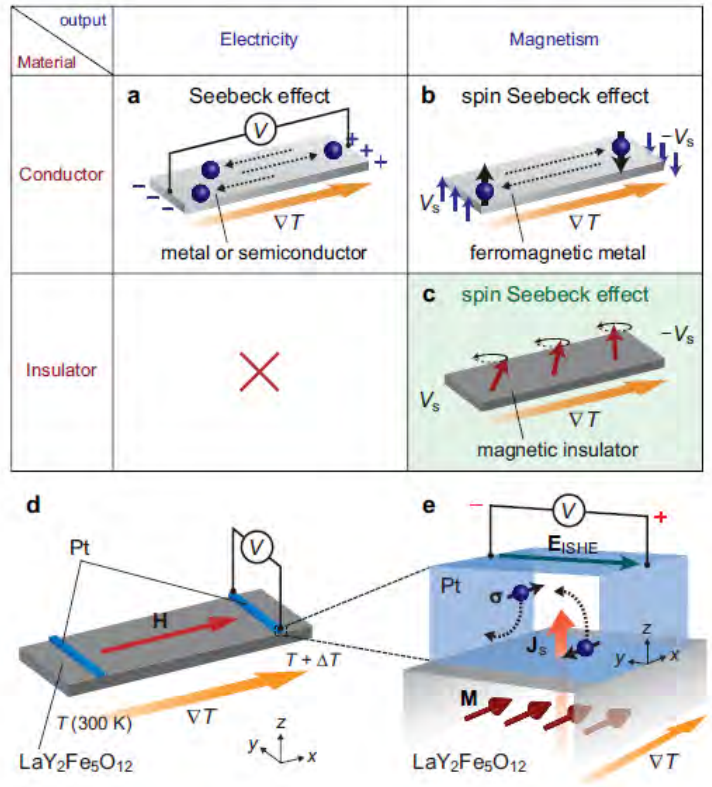
Magnetic field dependence of  $V$



ISHE voltage induced by the spin-Seebeck effect

# Spin Seebeck insulator

- Saito succeeded in observing spin Seebeck effect in insulating  $\text{LaY}_2\text{Fe}_5\text{O}_{12}$



# Theory of spin current and heat current



Shuichi Murakami

- 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**

**Shuichi Murakami**  
(Tokyo Inst Tech)

## Papers

- PR B **81**,161302(R), (2010).
- APL **97**,073108 (2010).
- PRL**106**,197202(2011).

## Award

- Honda Memorial Award
- MEXT Minister's Award
- Sir Martin Wood Award
- IBM Science Award
- ISPS Award

## Ootreach

Comercial Magazine

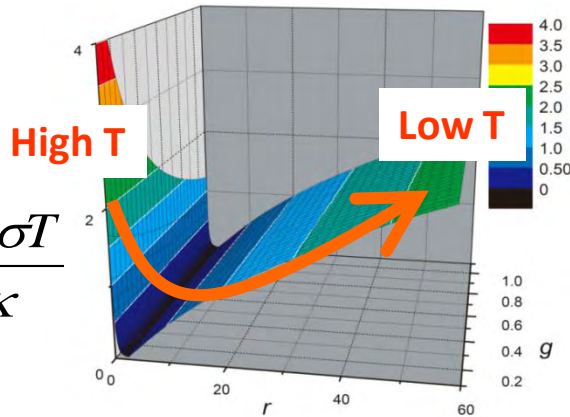
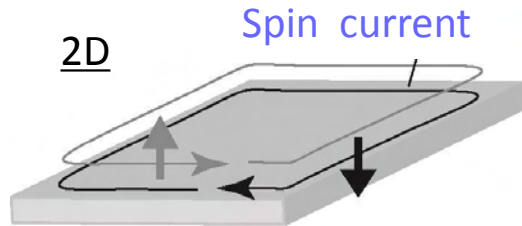
## Expectation

QSH systems can be good thermoelectric.

- \* suppress phonon conduction, keeping electron conduction
- \* Low-dimensional states (edge states, surface states)
- \* Similar materials involved ( $\text{Bi}_{1-x}\text{Sb}_x$ ,  $\text{Bi}_2\text{Se}_3$  etc.)

## Result

- Lower low 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



$r$  = "bulk/edge"

$g$  = "phonon/bulk"

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

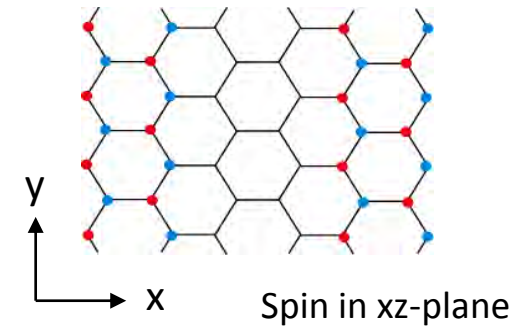
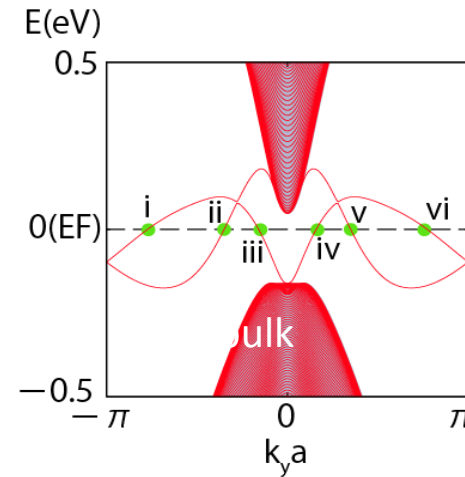
### Zigzag edge

|       | $S_x$  | $S_y$  | $S_z$  |
|-------|--------|--------|--------|
| 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

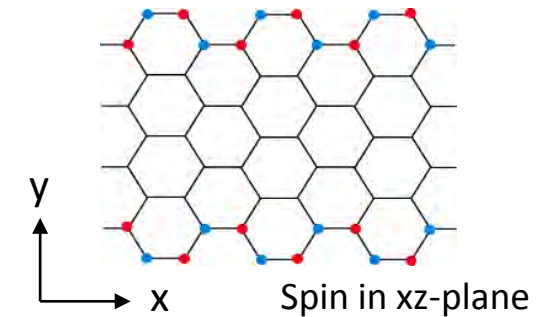
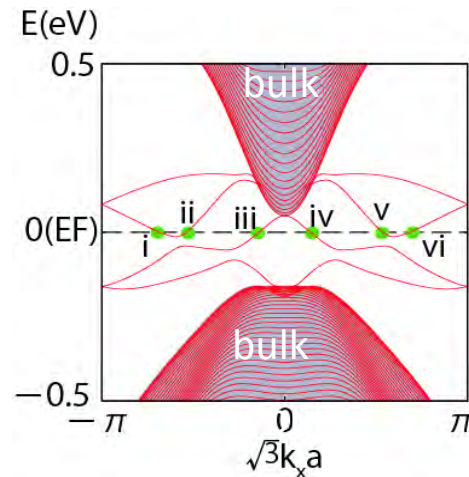
|       | $S_x$  | $S_y$  | $S_z$  |
|-------|--------|--------|--------|
| i-U   | 0.763  | 0.000  | -0.010 |
| i-L   | -0.763 | -0.000 | 0.010  |
| ii-U  | 0.395  | 0.000  | -0.237 |
| ii-L  | -0.395 | -0.000 | 0.237  |
| iii-U | 0.250  | -0.000 | -0.395 |
| iii-L | -0.250 | 0.000  | 0.395  |
| iv-U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

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



Odd number of Kramers pairs of edge states

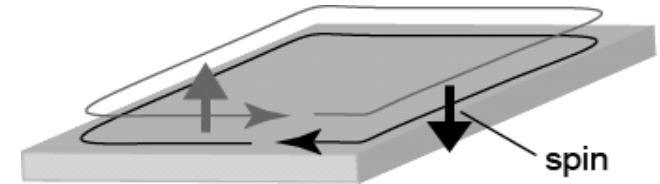
**Quantum spin Hall state**



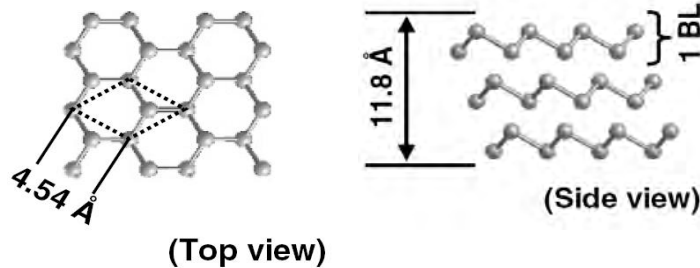
## Theoretical Approach

### Quantum Spin Hall Effect in Bismuth

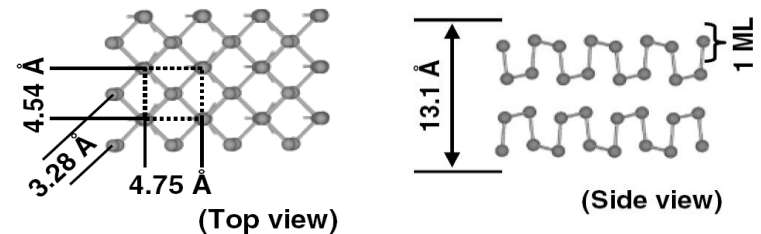
- Bulk Bi show no gap, while edge is gapless.
- **Bi ultra thin film (topological insulator)**



(111) 1-bilayer = quantum spin Hall phase



{012} 2-monolayer = insulating phase



- **Thermoelectric figure of merit**

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

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.

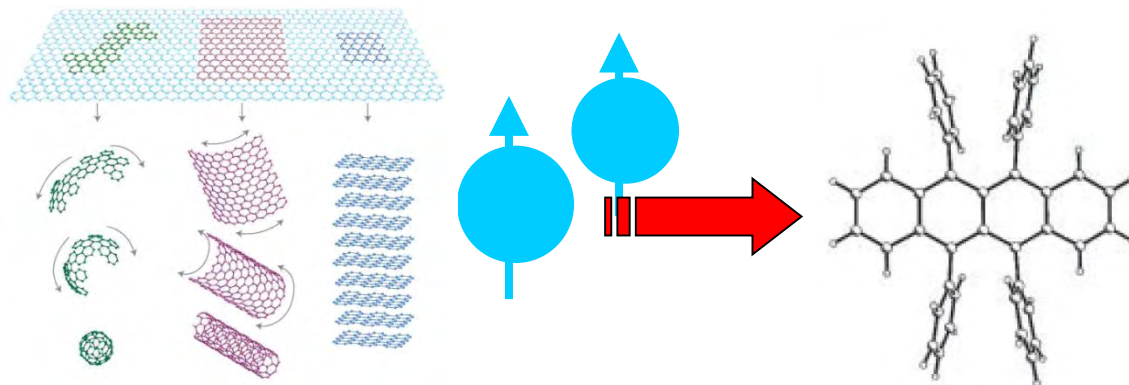
Wada, Murakami: "Well-localized edge states in two-dimensional topological insulator: bismuth film", APS March Meeting 2010(2010), Oregon, USA (2010/3/15).



# Spin current control in molecules

The purpose of this project is establishing and driving molecular spintronics, which is regarded to be one of the most potential research field, by observation of spin injection and control of spin current in molecules.

Objectives: Molecular semiconductors including nanocarbons such as graphene and fullerene, single crystalline organic semiconductor such as rubrene



## Masashi Shiraishi (Kyoto Univ)

### Papers

Adv. Func.Mat. **22**,3845(2012).  
Appl.Phys.Lett. **99**,043505  
(2011).

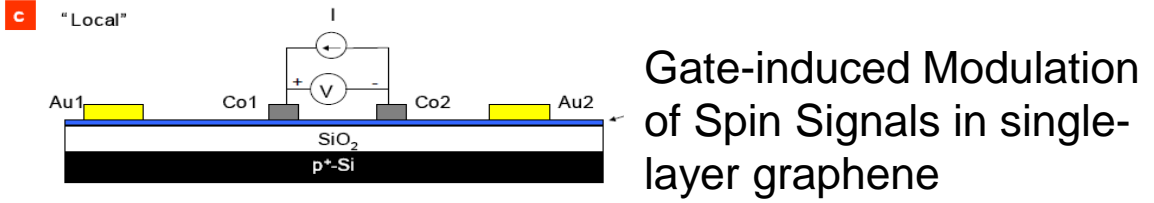
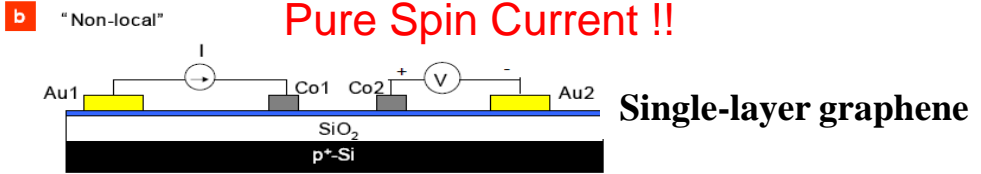
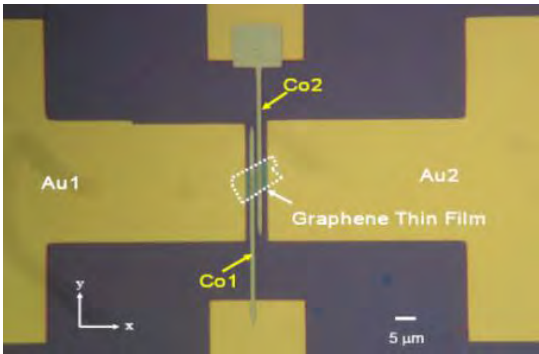
### Award

JSAP Paper Award

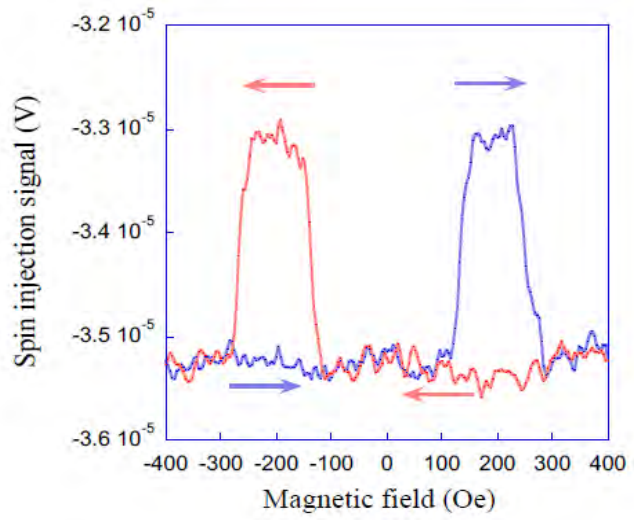
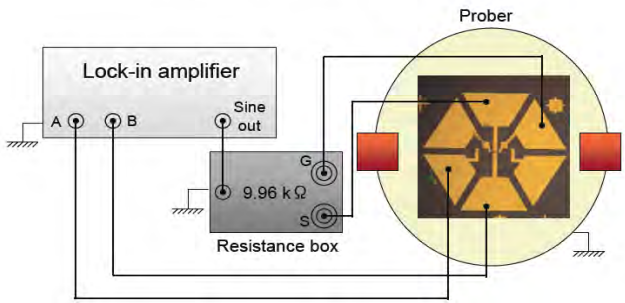
### Outreach

JST News

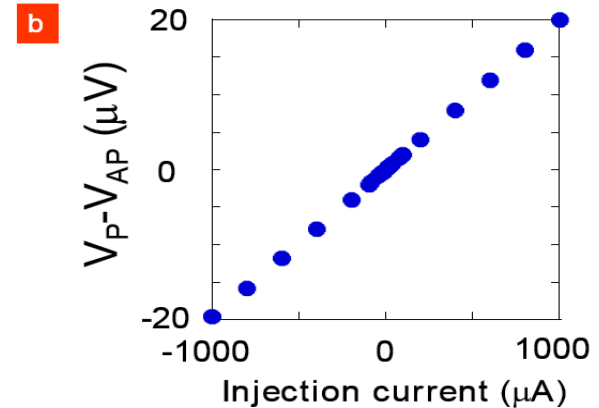
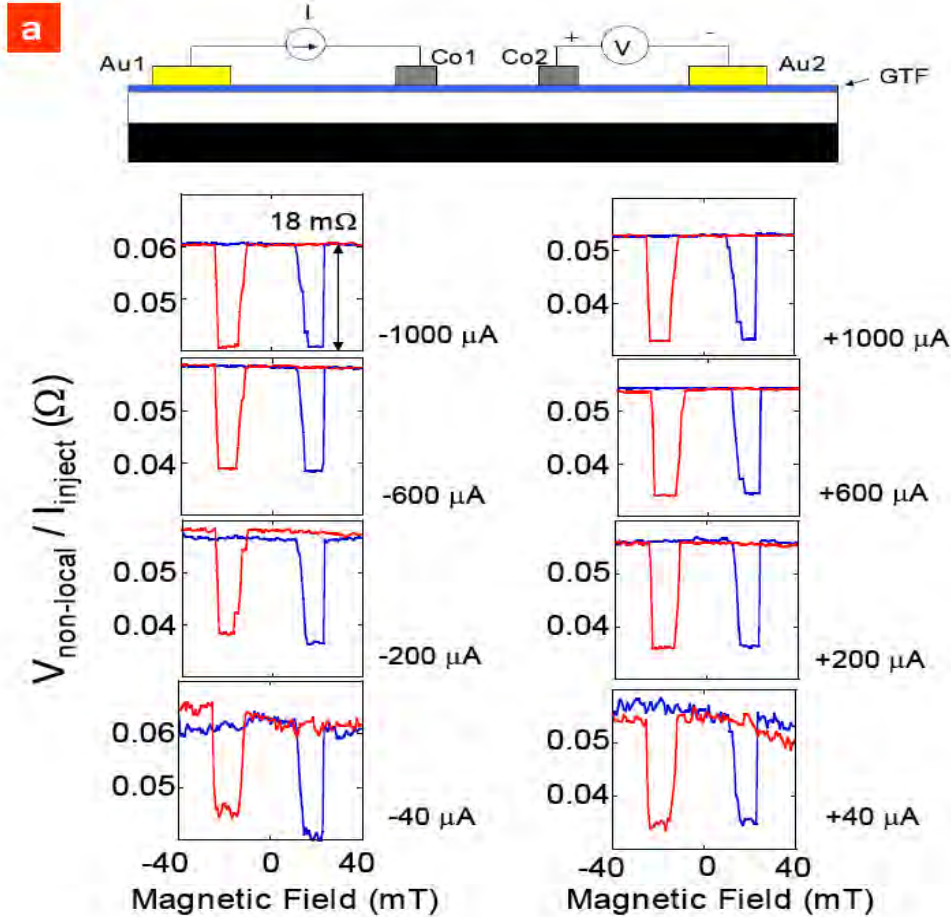
# Graphene Spintronics



Non-local measurement (Experimental setup)

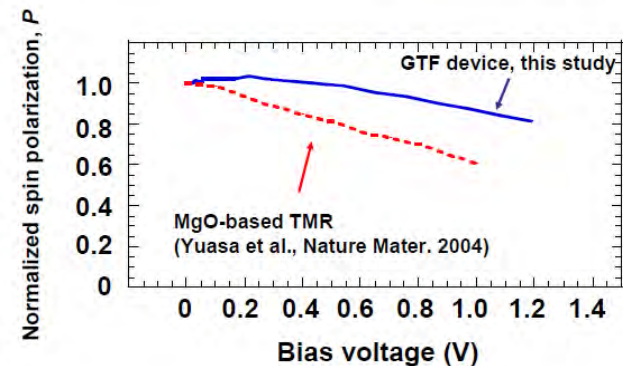


# Graphene Spintronics



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

Spin polarization is CONSTANT.



*Better  
robustness  
than that in  
MgO-TMR*

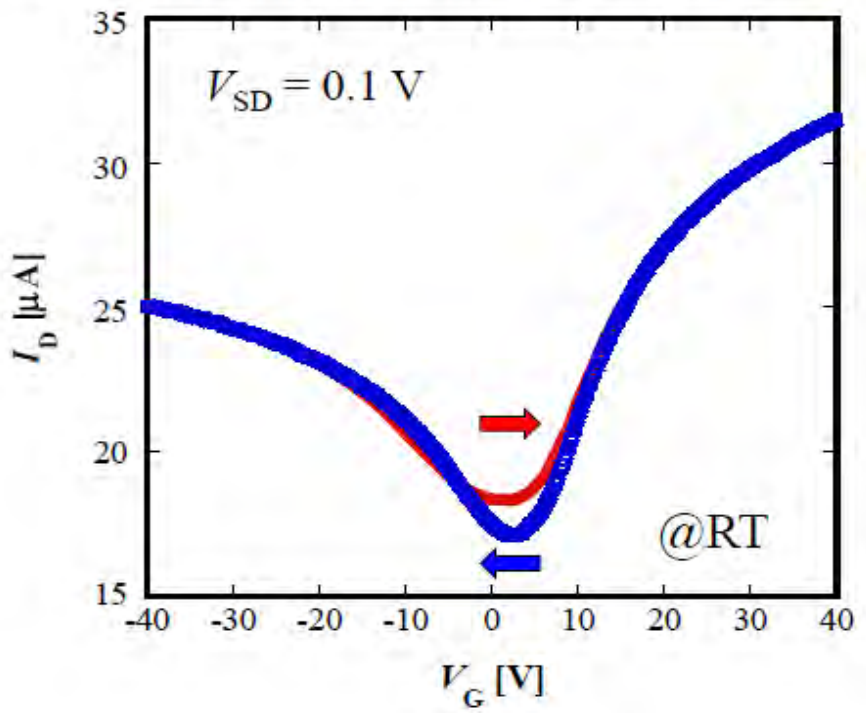
M. Ohishi, M. Shiraishi et al., JJAP 46, L605 (2007).  
 M. Shiraishi et al., Adv. Func. Mat., 19, 3711 (2009).  
 M. Shiraishi et al., Appl. Phys. Express 2, 123004 (2009).



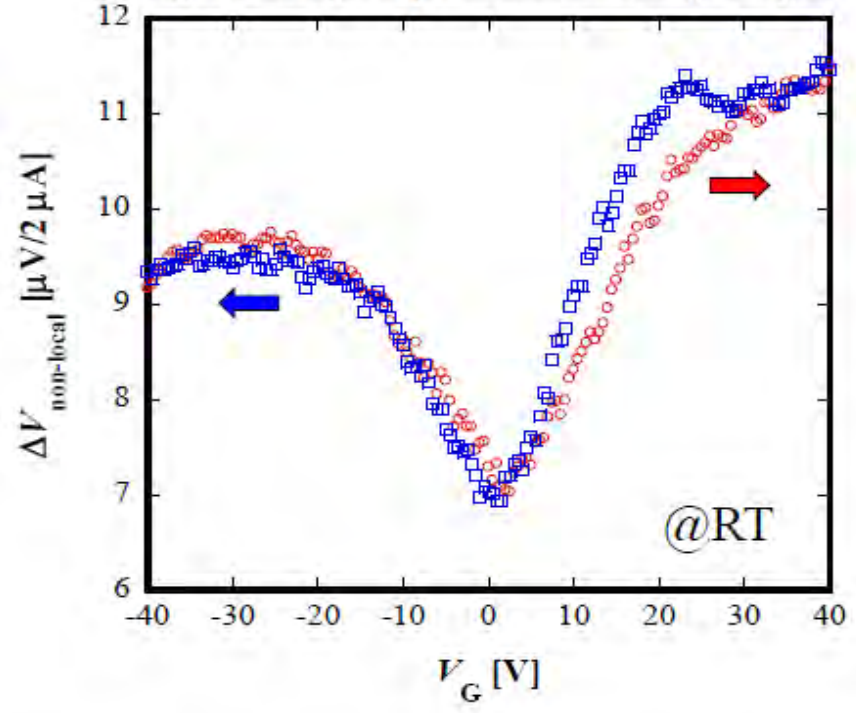
# Gate Voltage Control of Spin Current in Graphene

(Transistor with a Single Layer Graphene)

FET characteristics between Co electrodes



A gate voltage dependence of the spin signal





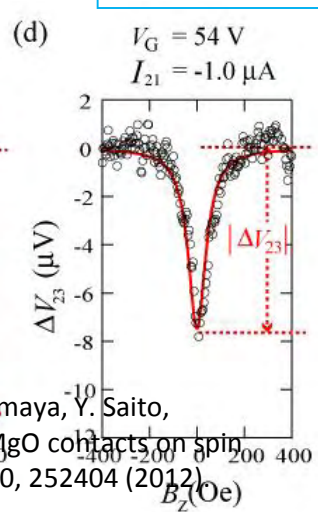
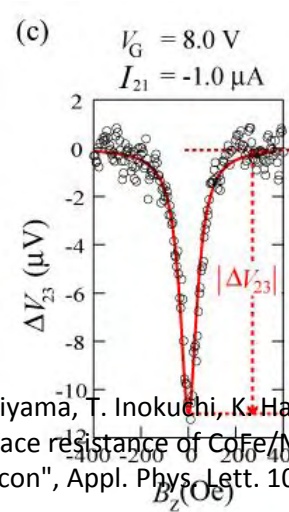
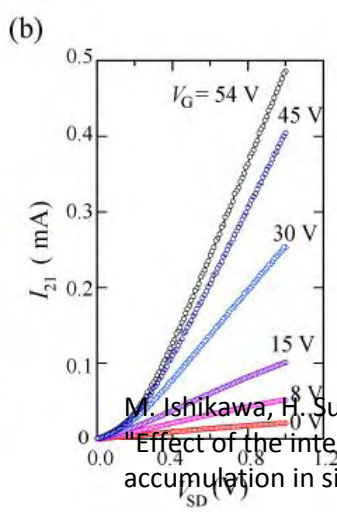
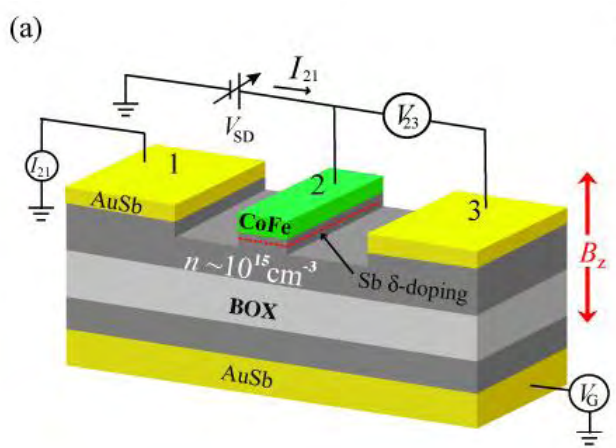
# Silicon Spintronics

- 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 successfully utilized low-doped Si for spintronics application.

**Kohei hamaya**  
**(Osaka Univ)**

Papers  
 APL **99**,132511(2011).  
 APL **97**,192501(2010)  
 APL **94**,182105 (2009).

Awards  
 Funai Award  
 Ando Memorial Award  
 MEXT Minister's Award

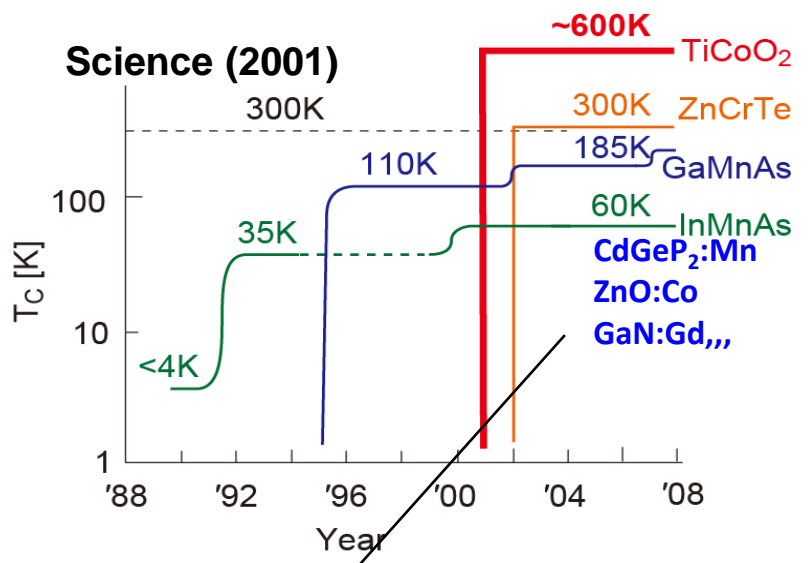


M. Ishikawa, H. Sugiyama, T. Inokuchi, K. Hamaya, Y. Saito,  
 "Effect of the interface resistance of CoFe/MgO contacts on spin accumulation in silicon", Appl. Phys. Lett. 100, 252404 (2012)



# High $T_C$ FM semiconductor: Co-doped $TiO_2$

Extraordinary high  $T_C$



TiO<sub>2</sub>:Co Room temperature FM semiconductor

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)

Tomoteru Fukumura (Univ Tokyo)

Papers  
 APL **94**,102515 (2009).  
 AAPL**95**, 032109 (2009).  
 Science **332**,1065 (2011).

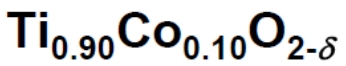
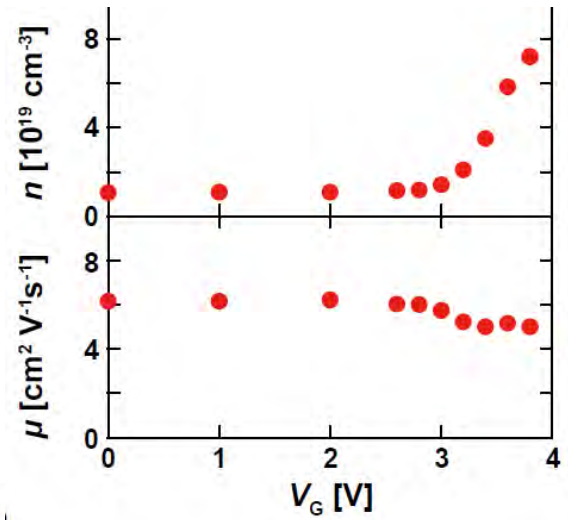
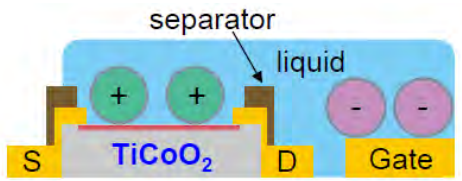
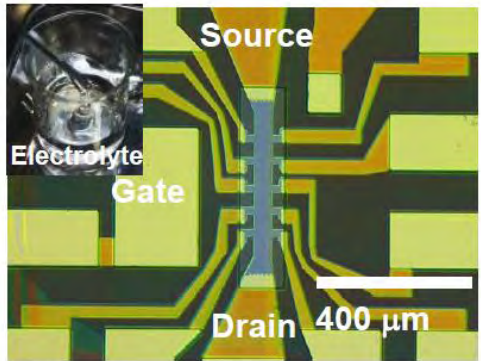
Award  
 JSPS Award  
 Outreach  
 Press Lecture

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

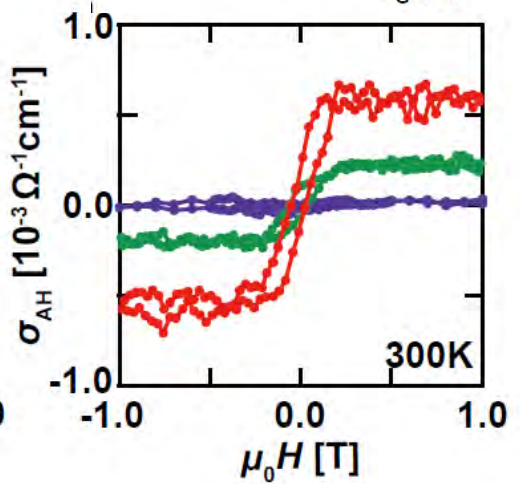
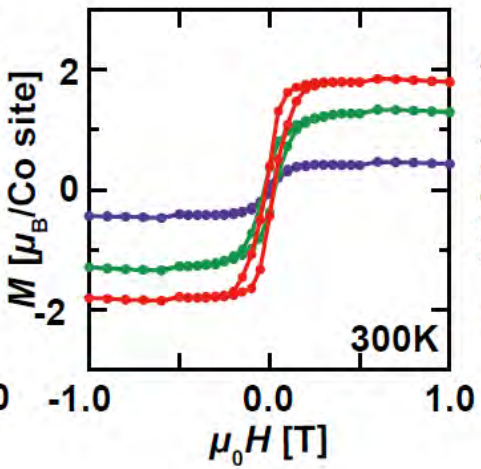
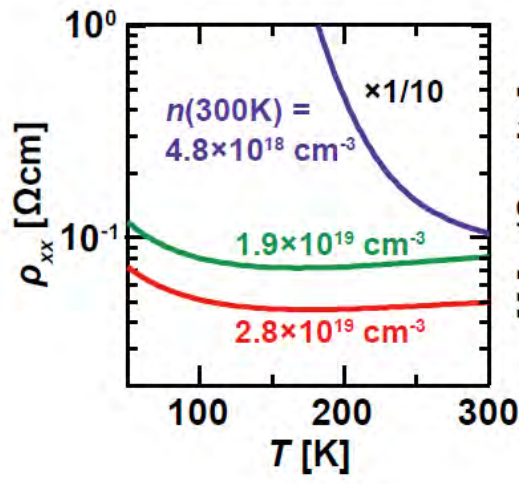
Zn<sub>1-x</sub>TM<sub>x</sub>O combinatorial library

| IIIB      |          | IVB      |          | VB        |         | VIB       |         | VIIB   |       | — VIII B — |   | IB |   | IIB |   |
|-----------|----------|----------|----------|-----------|---------|-----------|---------|--------|-------|------------|---|----|---|-----|---|
| 21        | 2        | 22       | 2        | 23        | 2       | 24        | 2       | 25     | 2     | 26         | 2 | 27 | 2 | 28  | 2 |
| 8         | 8        | 8        | 8        | 8         | 8       | 8         | 8       | 8      | 8     | 8          | 8 | 8  | 8 | 8   | 8 |
| Sc        | Ti       | V        | Cr       | Mn        | Fe      | Co        | Ni      | Cu     | Zn    |            |   |    |   |     |   |
| Scandium  | Titanium | Vanadium | Chromium | Manganese | Iron    | Cobalt    | Nickel  | Copper | Zinc  |            |   |    |   |     |   |
| 44.955910 | 47.867   | 50.9415  | 51.9961  | 54.938049 | 55.8457 | 58.933200 | 58.6934 | 63.546 | 65.39 |            |   |    |   |     |   |

# Carrier control of magnetism in $\text{TiO}_2\text{:Co}$ by gate voltage



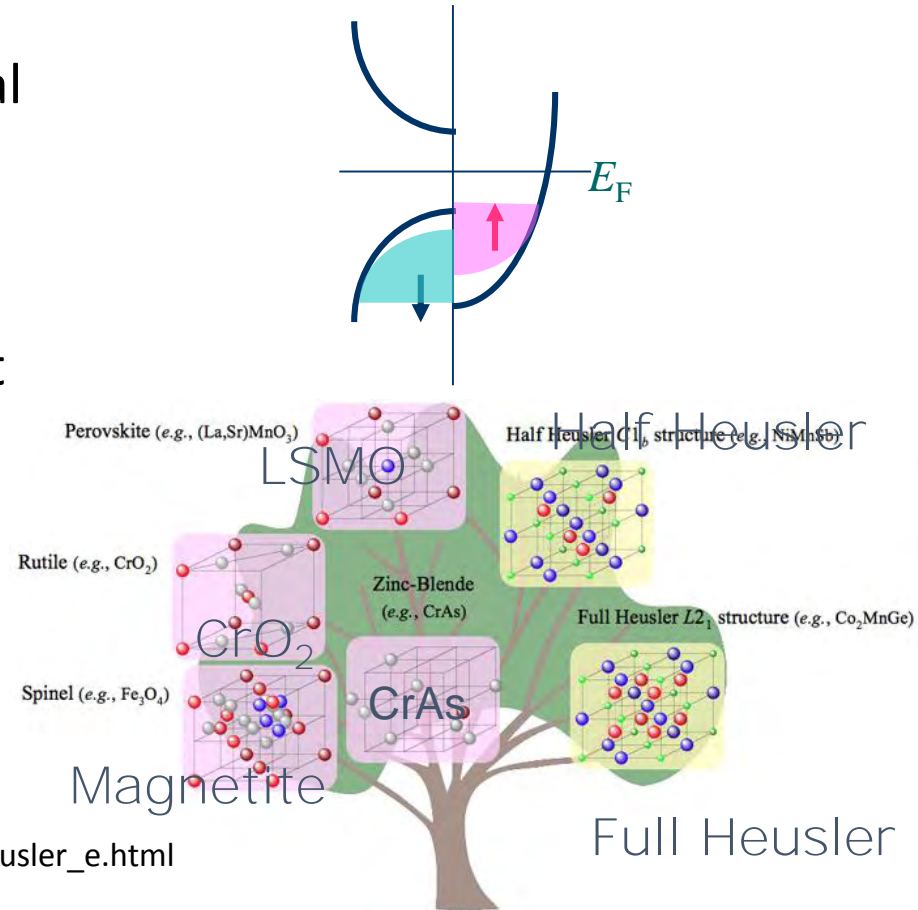
**PM insulator → FM metal**



# Half metal electrodes for MTJ

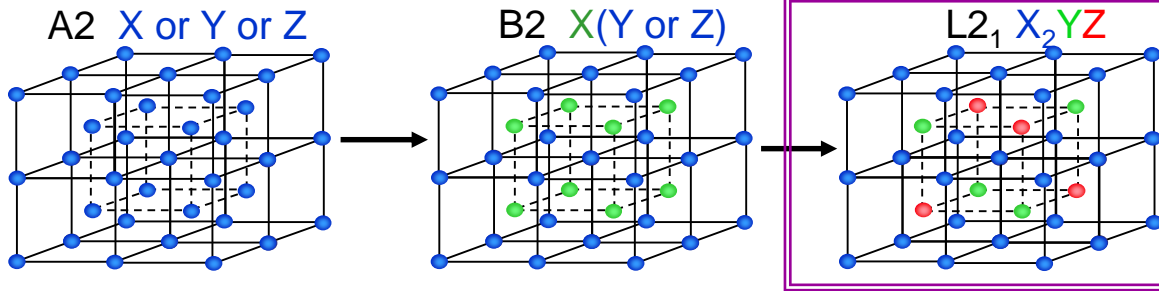
- Half metal is a magnetic material in which electronic state for  $\uparrow$  spin is metallic while that for  $\downarrow$  spin is semiconducting.
- Therefore the electronic state at the Fermi level is fully spin-polarized in half metals.
- Heusler compounds, LSMO ( $\text{La}_{1-x}\text{Sr}_x\text{MnO}_3$ ), magnetite ( $\text{Fe}_3\text{O}_4$ ), chromium oxide ( $\text{CrO}_2$ ) are candidates of half metals.

[http://www.riken.go.jp/lab-www/nanomag/research/heusler\\_e.html](http://www.riken.go.jp/lab-www/nanomag/research/heusler_e.html)



# Alloy search for RT half-metal

Co based Heusler alloy,  $X_2YZ$



High  $T_c$   
Theoretical  $P=1$

However,  
Experimental  $P$  is low



**Yukiko Takahashi**  
(NIMS)

Papers

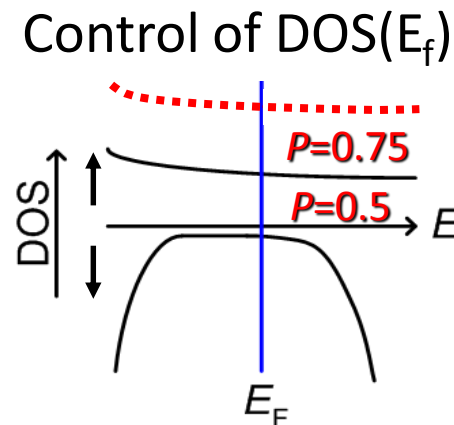
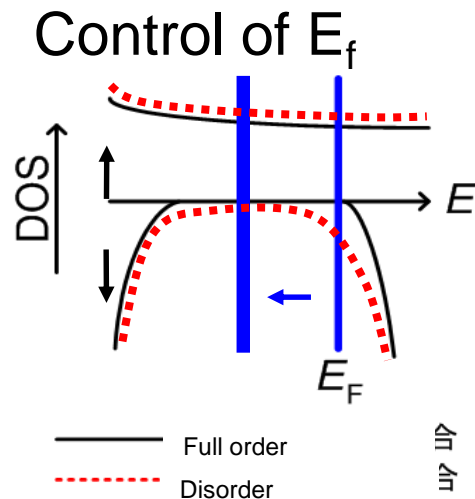
APL **98**, 152501 (2011).  
APEX **3**, 023002 (2010)

Awards

Honda Memorial Award  
MEXT Minister's Award

Outreach

JST News



## Search of high spin-polarization half metals using PCARS

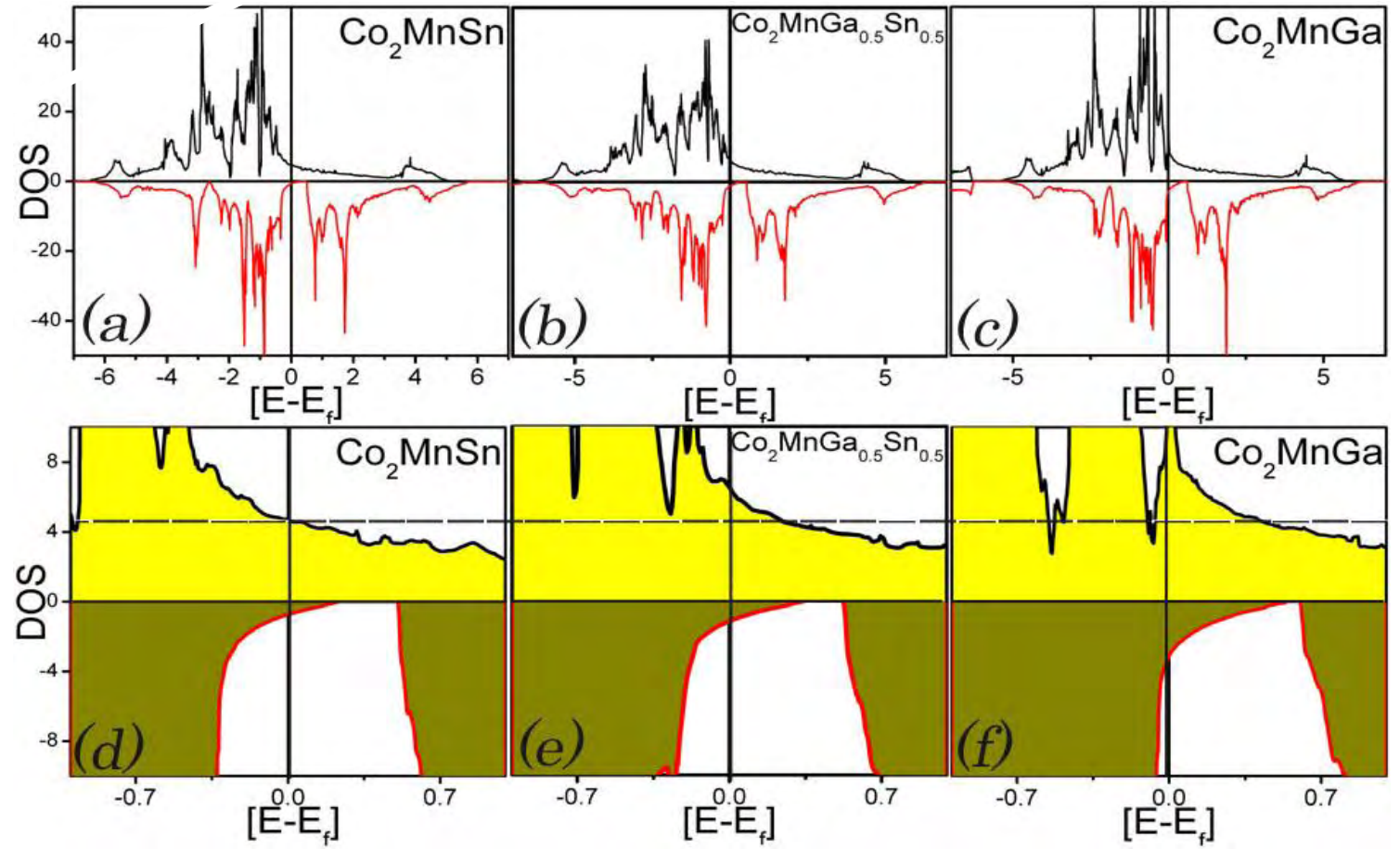
- Aiming at high performance GMR devices Takahashi has investigated as many as 32 full Heusler alloys and found 74% spin polarization in CoMnGeGa alloy.

| Metals and binary                 | P  | Ref. |
|-----------------------------------|----|------|
| Fe                                | 46 |      |
| Co                                | 45 |      |
| FeCo                              | 50 |      |
| Co <sub>75</sub> Fe <sub>25</sub> | 58 |      |
| B2-FeCo                           | 60 |      |
| [Co/Pd] <sub>n</sub>              | 60 |      |

| Ternary alloys       | P  | Ref. |
|----------------------|----|------|
| Co <sub>2</sub> MnSi | 56 |      |
| Co <sub>2</sub> MnGe | 58 |      |
| Co <sub>2</sub> MnSn | 60 |      |
| Co <sub>2</sub> MnAl | 60 |      |
| Co <sub>2</sub> MnGa | 60 |      |
| Co <sub>2</sub> CrAl | 62 |      |
| Co <sub>2</sub> FeAl | 59 |      |
| Co <sub>2</sub> FeSi | 60 |      |
| Co <sub>2</sub> FeGa | 58 |      |
| Co <sub>2</sub> CrGa | 61 |      |
| Co <sub>2</sub> TiSn | 57 |      |
| Co <sub>2</sub> VAl  | 48 |      |
| Fe <sub>2</sub> VAl  | 56 |      |

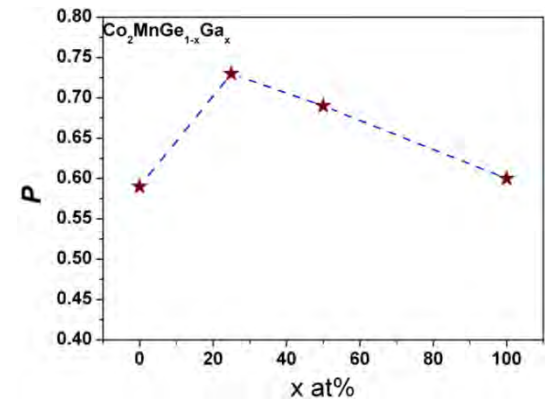
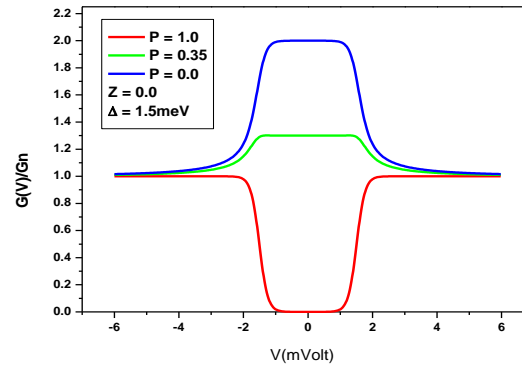
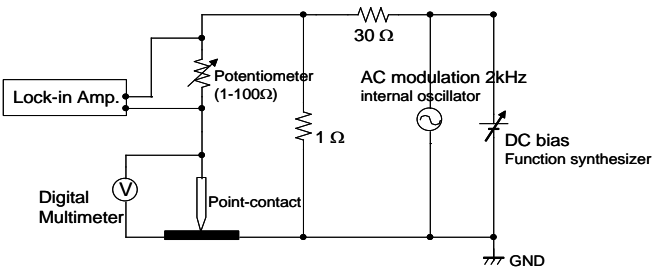
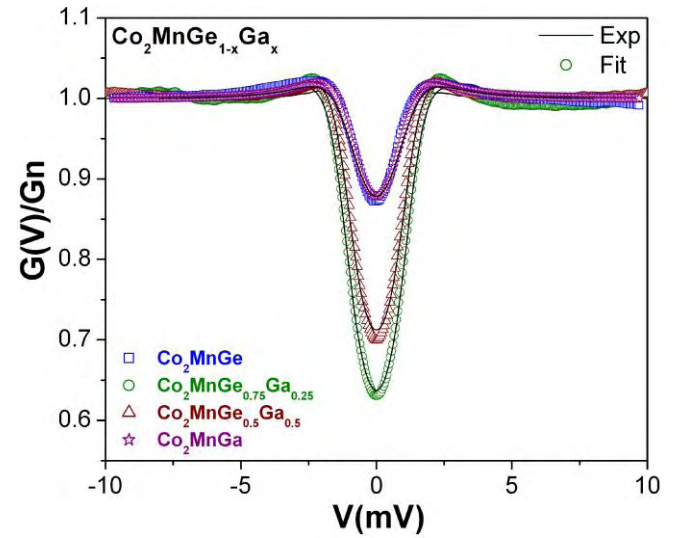
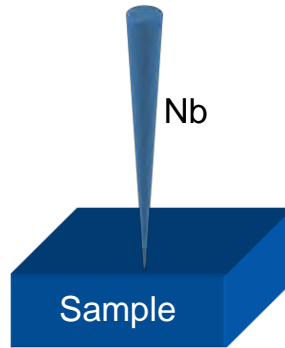
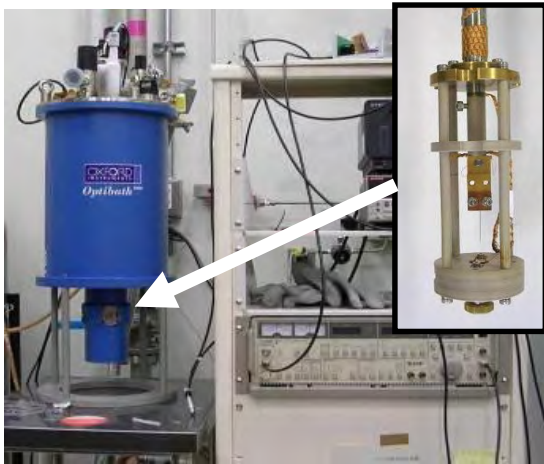
| Quaternary alloys  | P  | Ref. |
|--|----|------|
| Co <sub>2</sub> Mn(Ge <sub>0.75</sub> Ga <sub>0.25</sub> ) | 74 |      |
| Co <sub>2</sub> Mn(Ga <sub>0.5</sub> Sn <sub>0.5</sub> )   | 72 |      |
| Co <sub>2</sub> Fe(Si <sub>0.75</sub> Ge <sub>0.25</sub> ) | 70 |      |
| Co <sub>2</sub> FeGa <sub>0.5</sub> Ge <sub>0.5</sub>      | 68 |      |
| Co <sub>2</sub> (Cr <sub>0.02</sub> Fe <sub>0.98</sub> )Ga | 67 |      |
| Co <sub>2</sub> MnGeSn                                     | 67 |      |
| Co <sub>2</sub> (Mn <sub>0.95</sub> Fe <sub>0.05</sub> )Sn | 65 |      |
| (CoFe) <sub>2</sub> MnGe                                   | 65 |      |
| Co <sub>2</sub> (Mn <sub>0.5</sub> Fe <sub>0.5</sub> )Ga   | 65 |      |
| Co <sub>2</sub> (Cr <sub>0.02</sub> Fe <sub>0.98</sub> )Si | 65 |      |
| Co <sub>2</sub> MnTiSn                                     | 64 |      |
| Co <sub>2</sub> MnAl <sub>0.5</sub> Sn <sub>0.5</sub>      | 63 |      |
| Co <sub>2</sub> MnGa <sub>x</sub> Si <sub>1-x</sub>        | 63 |      |
| Co <sub>2</sub> FeAlGa                                     | 63 |      |
| Co <sub>2</sub> MnSiGe                                     | 63 |      |
| Co <sub>2</sub> (Mn <sub>0.5</sub> Fe <sub>0.5</sub> )Si   | 61 |      |
| Co <sub>2</sub> Mn(Al <sub>0.5</sub> Si <sub>0.5</sub> )   | 60 |      |
| Co <sub>2</sub> FeGa <sub>0.5</sub> Si <sub>0.5</sub>      | 60 |      |
| Co <sub>2</sub> Fe(Al <sub>0.5</sub> Si <sub>0.5</sub> )   | 60 |      |

# Search of Heusler alloys following band calculation





# Point contact Andreev reflection (PCAR)



**Co<sub>2</sub>MnGe<sub>0.75</sub>Ga<sub>0.25</sub> shows highest P**

# 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 Radboud Univ. group, ultrafast magnetization switching (less than ps) was accomplished in the vicinity of the compensation point of MO-recording media.

## Arata Tsukamoto (Nihon Univ)

### Paper

J. Appl. Phys. **109**, 07D302 (2011).

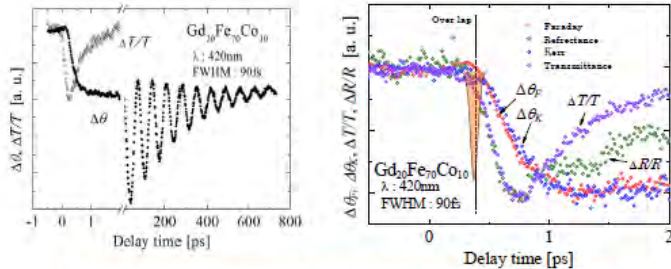
Nature **472**, 205 (2011).

Phys.Rev.Lett.**103**, 117201 (2009)

### Award

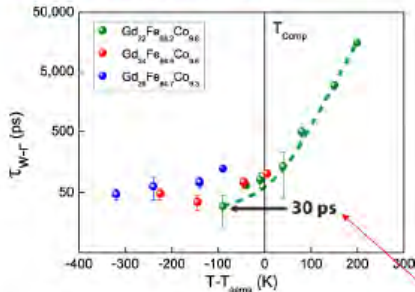
MORIS2009 Best poster Awards

# Analysis of light-induced ultrafast magnetization reversal



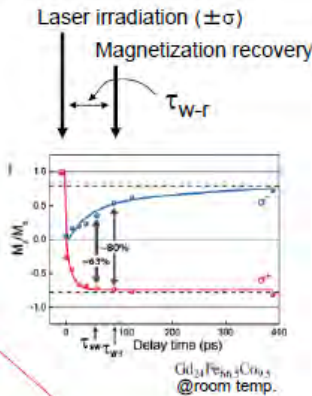
The magnetization modified monotonically reaches to a temporal state within 1ps

## 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.

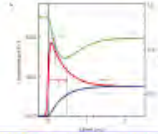
Fastest write-read event demonstrated for magnetic recording so far.



## Classification of ultrafast dynamics

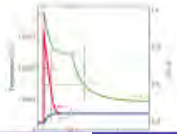
### Type I material

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

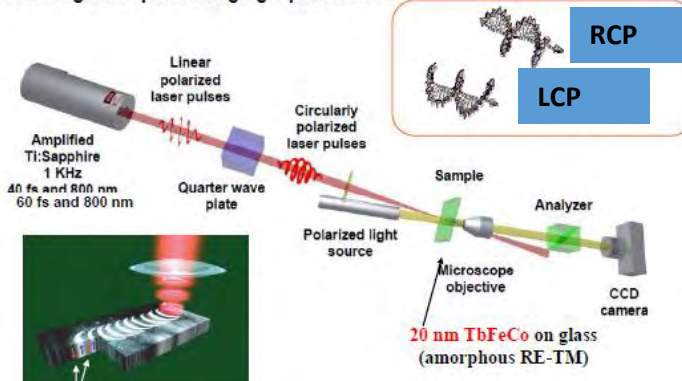


### Type II material

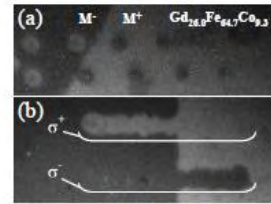
- Weaker magnetic coupling
- 2step demagnetizations very fast (first picosecond) slower demagnetization
- Ga, TbFe



## Static magneto-optical imaging + pulsed laser

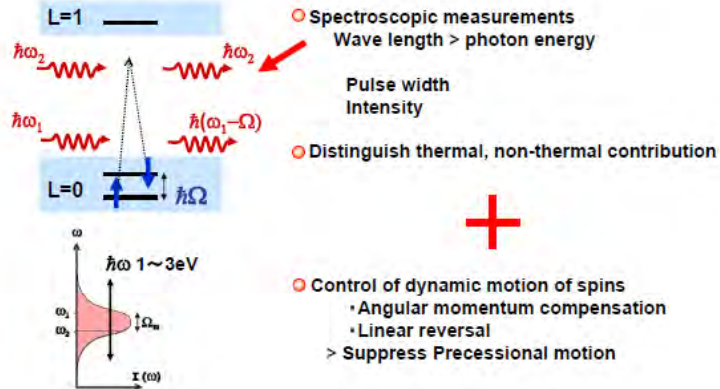


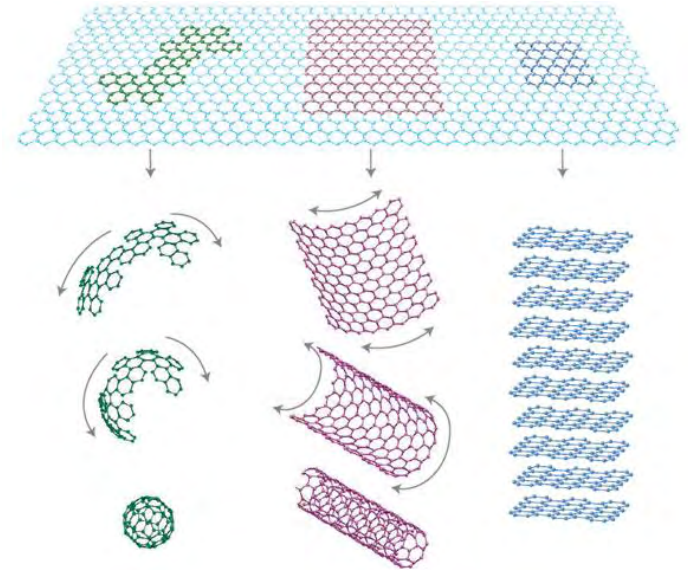
### Magnetization direction



Light-induced ultrafast magnetic recording

## Origin of photo induced magnetization phenomena





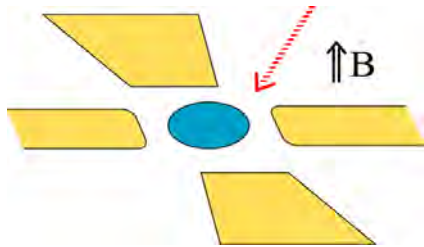
# Molecules and Organics

# Molecules and Organics

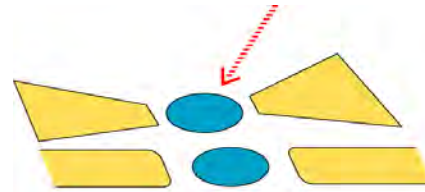
1. K. Machda fabricated nano structured graphene to find single electron and quantum effect
2. H. Yamamoto fabricated organic FET with high field effect mobility using *voltage controlled Mott-transition*. He also succeeded in *electrical control of superconductivity* in organic material
3. S. Noda succeeded in growing single *graphene sheet on insulating substrate* by metal-free process
4. J. Nishinaga succeeded in *delta-doping of C<sub>60</sub> in GaAs* thin film during MBE growth

# Graphene Quantum Dot

## Ultra high sensitivity THz detector



- Single electron transistor + quantum Hall effect



- Parallel double q-dot



Tomoki Machida

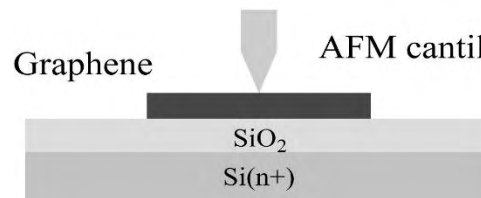
**Tomoki Machida**  
**(Univ Tokyo)**

### Papers

- Phys. Rev. Lett. **109**, 036601 (2012).
- J. Mag. Mag. Mater. **324**, 849 (2012).
- Nano Letters **11**, 4542 (2011)

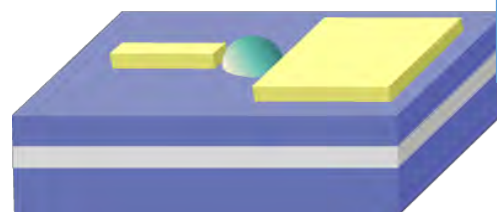
## Room temperature SET

- Local anode oxidation using AFM

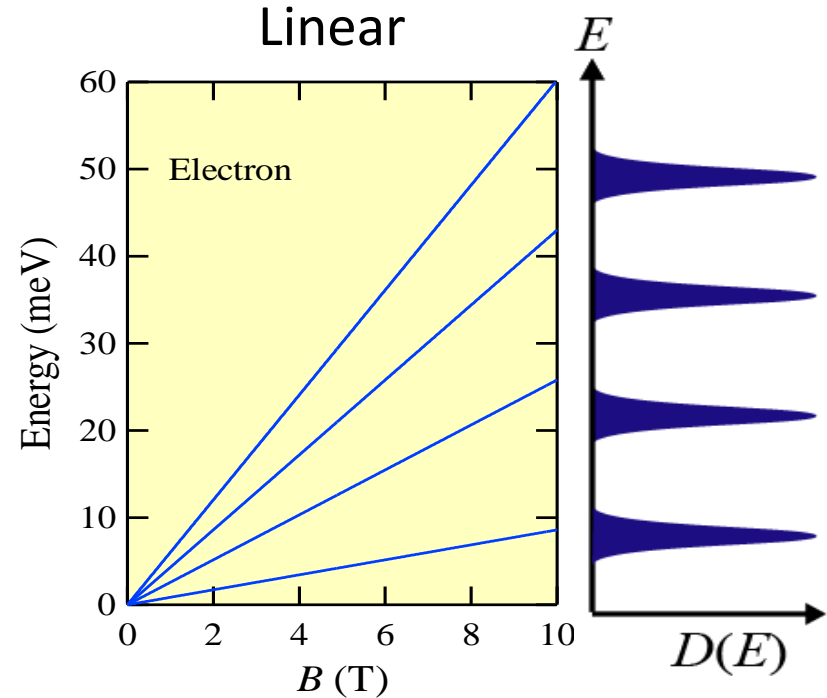
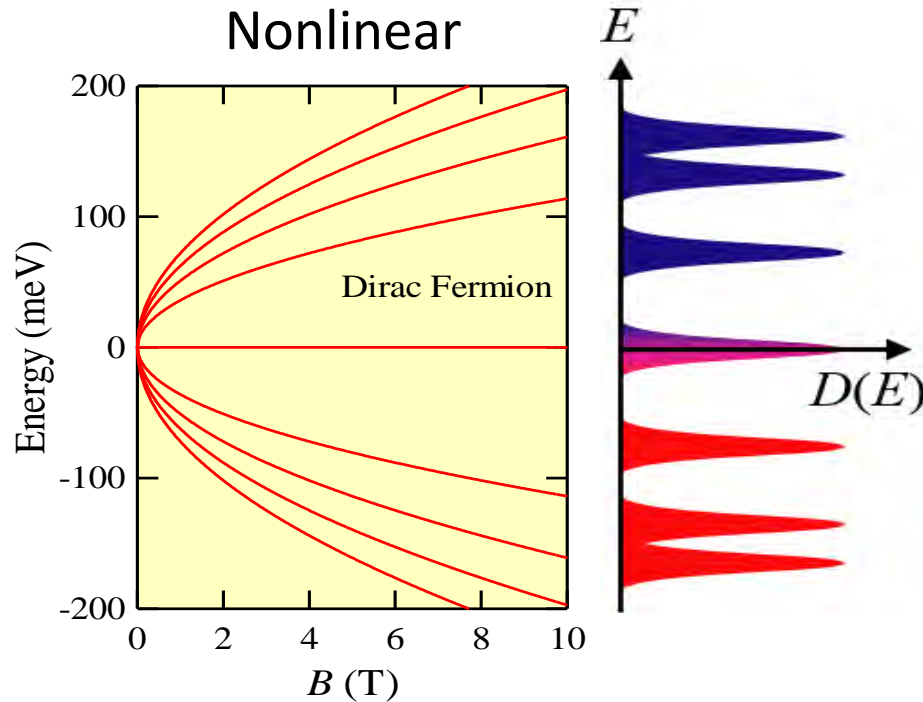


## Q-dot spin valve

- FM electrode + Graphene Q-dot



# Landau quantization: Dirac Fermion v.s. electron



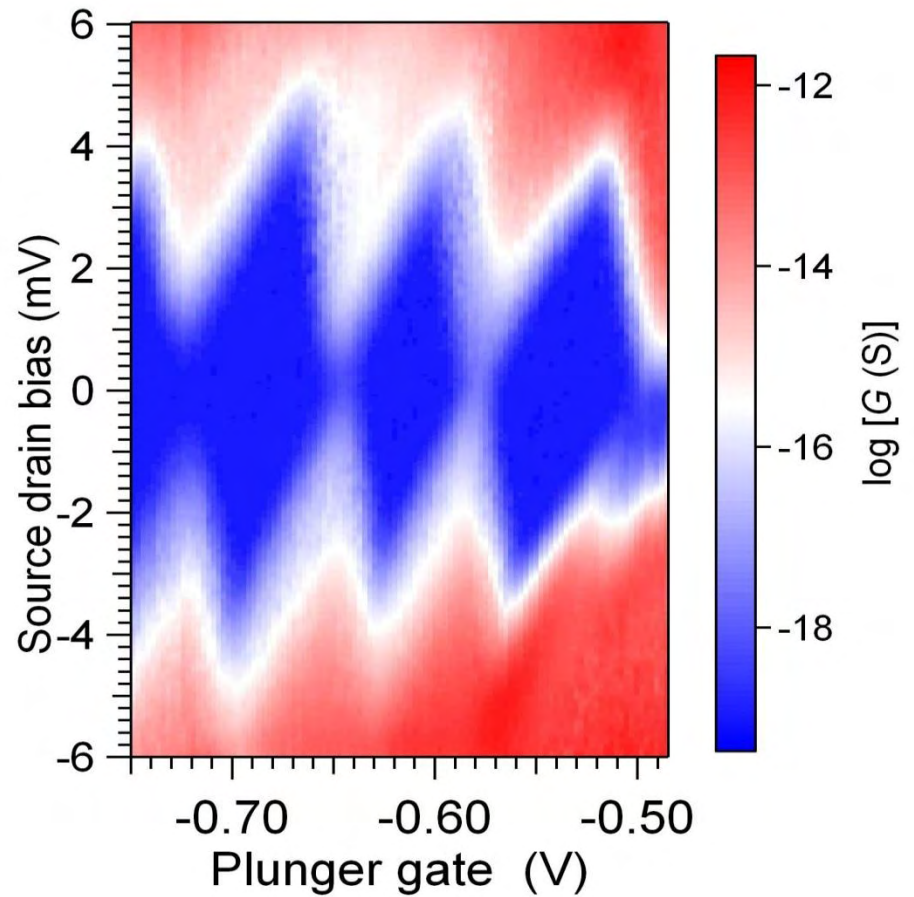
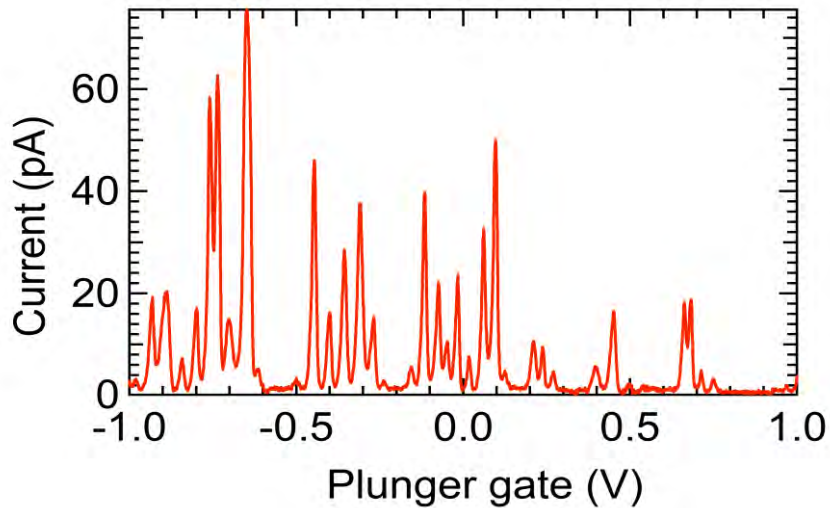
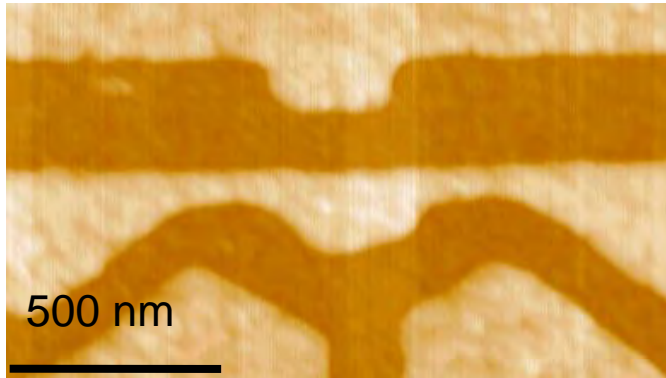
$$E_n = \tilde{c} \sqrt{2|n|\hbar e B} \quad \gg$$

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

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

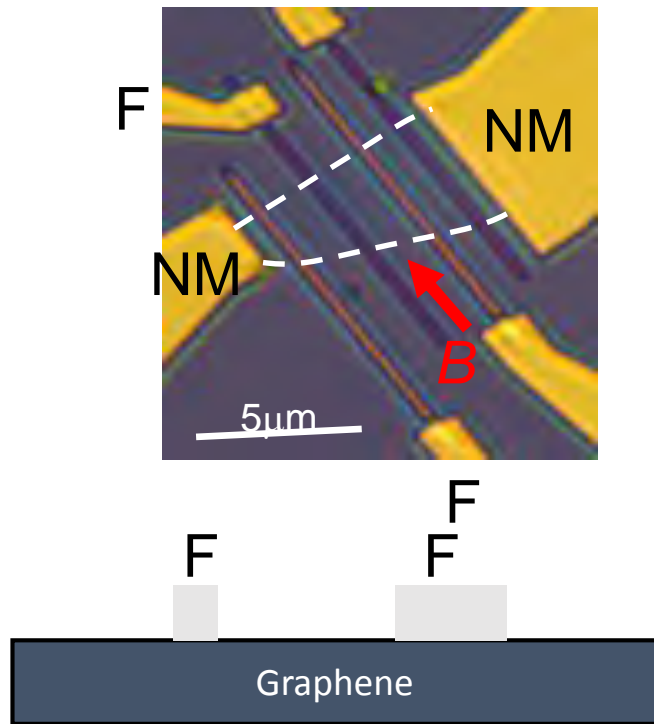
$$\sigma_{xy} = \frac{4e^2}{h} \left( n + \frac{1}{2} \right)$$

# Graphene single QD

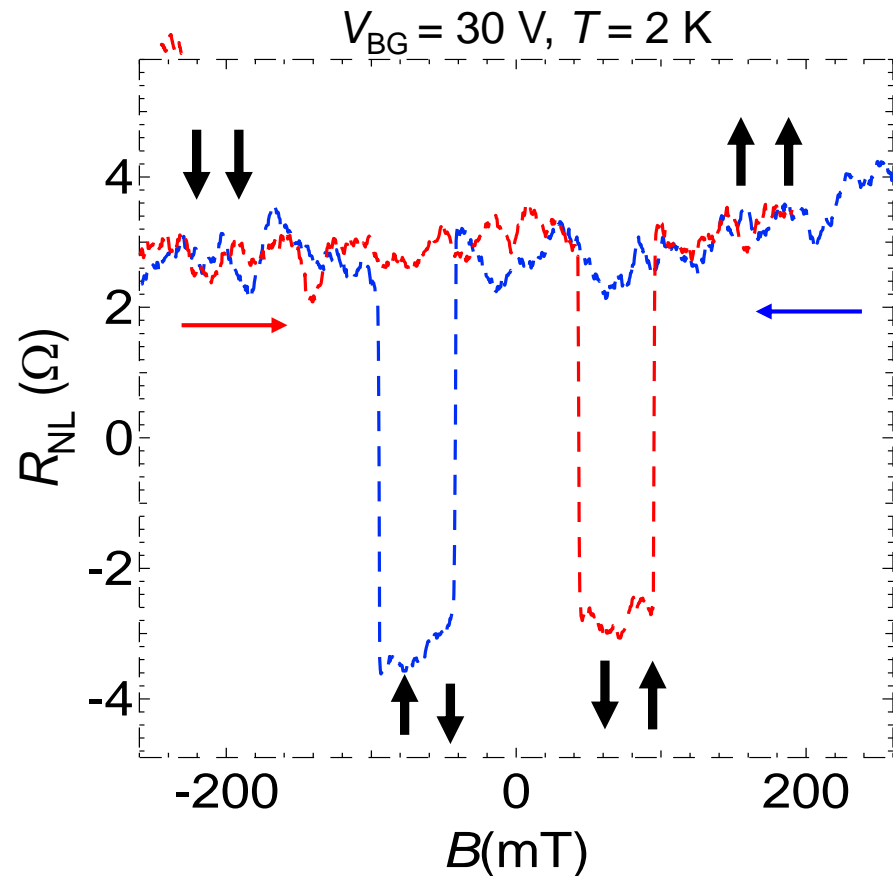




# Nonlocal Magnetoresistance



FM/Graphene/FM  
Spin valve



Without barrier

# Development of novel organic devices based on electronic correlation

---

Functions peculiar to Strongly correlated material is applied to organic electronics, aiming at high efficiency flexible devices



Realization of two types of “Phase transition transistors using organic materials

- Mott-FET
- Superconducting FET



## Hiroshi Yamamoto (IMR)

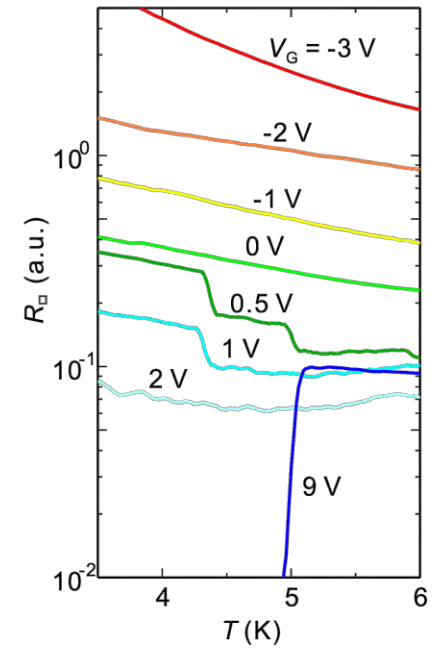
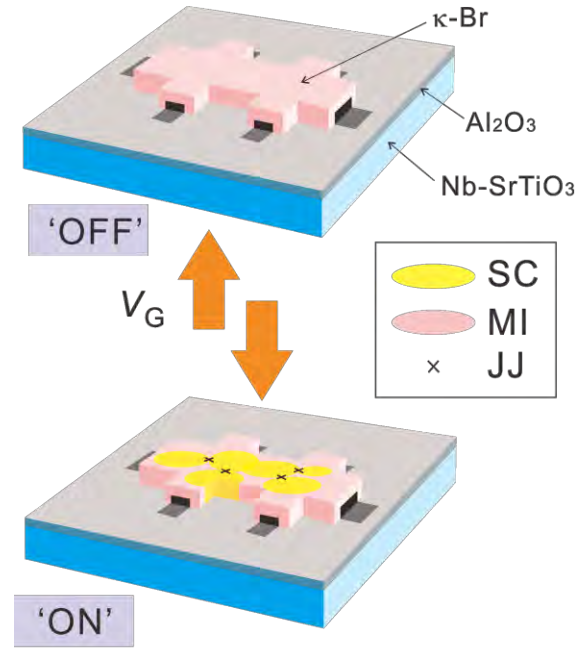
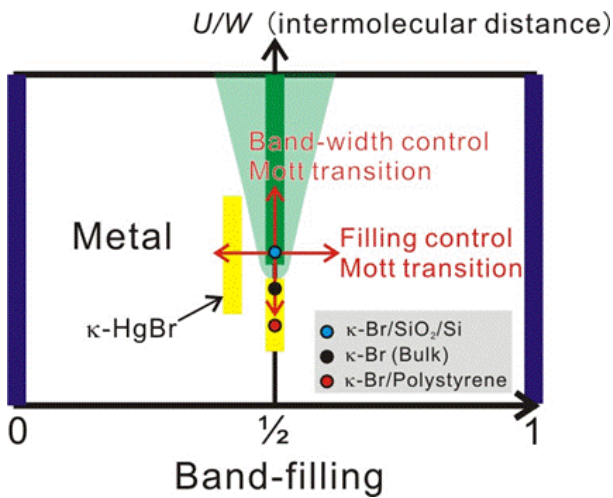
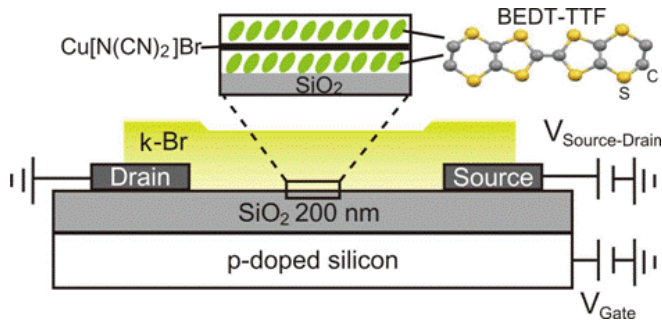
### PaperS

Phys. Rev. **B 84**, 125129 (2011).  
Nature Commun. **3**, 1089 (2012).  
Inorg. Chem. **51**, 11645 (2012).

### Outreach

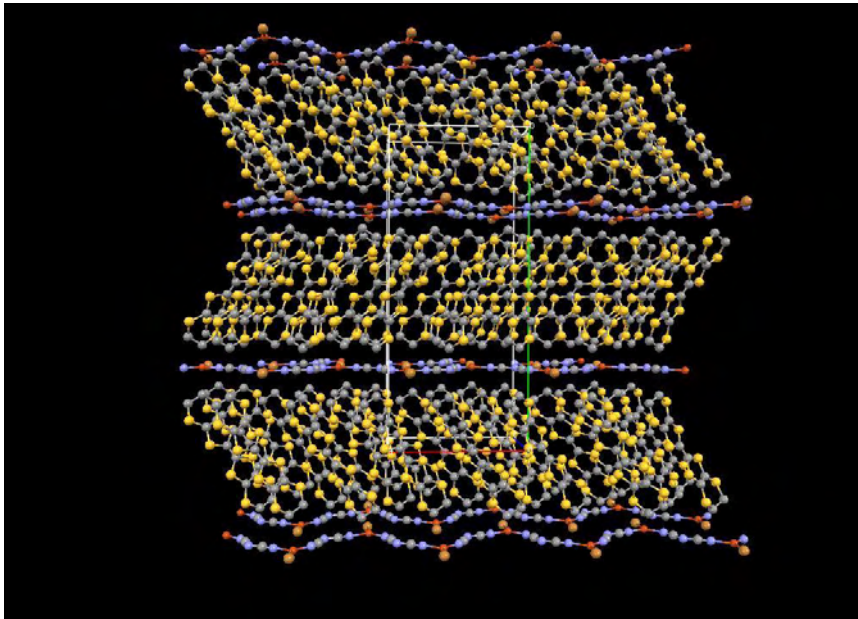
Review paper for JSAP

# Dramatic change btw on and off states by gate control

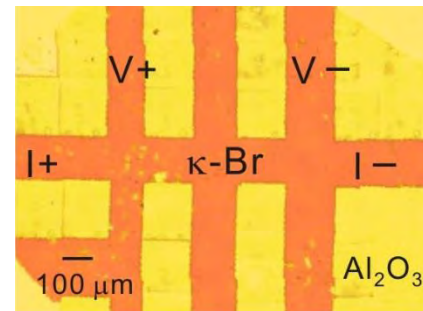
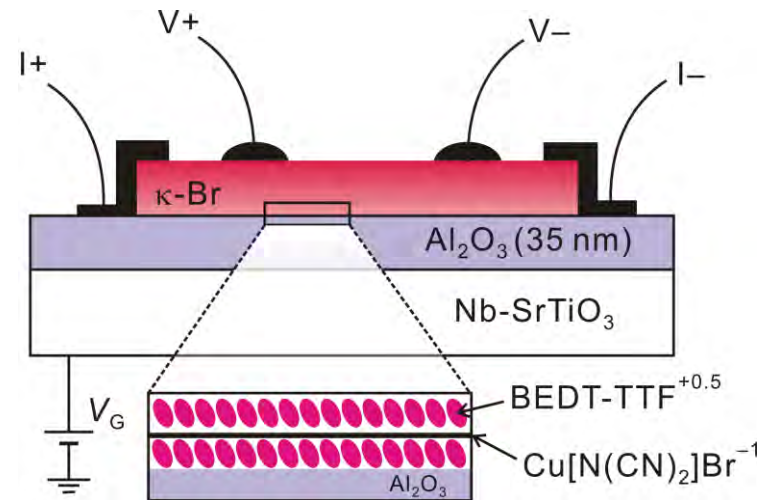


Gate-controlled Josephson junction switching

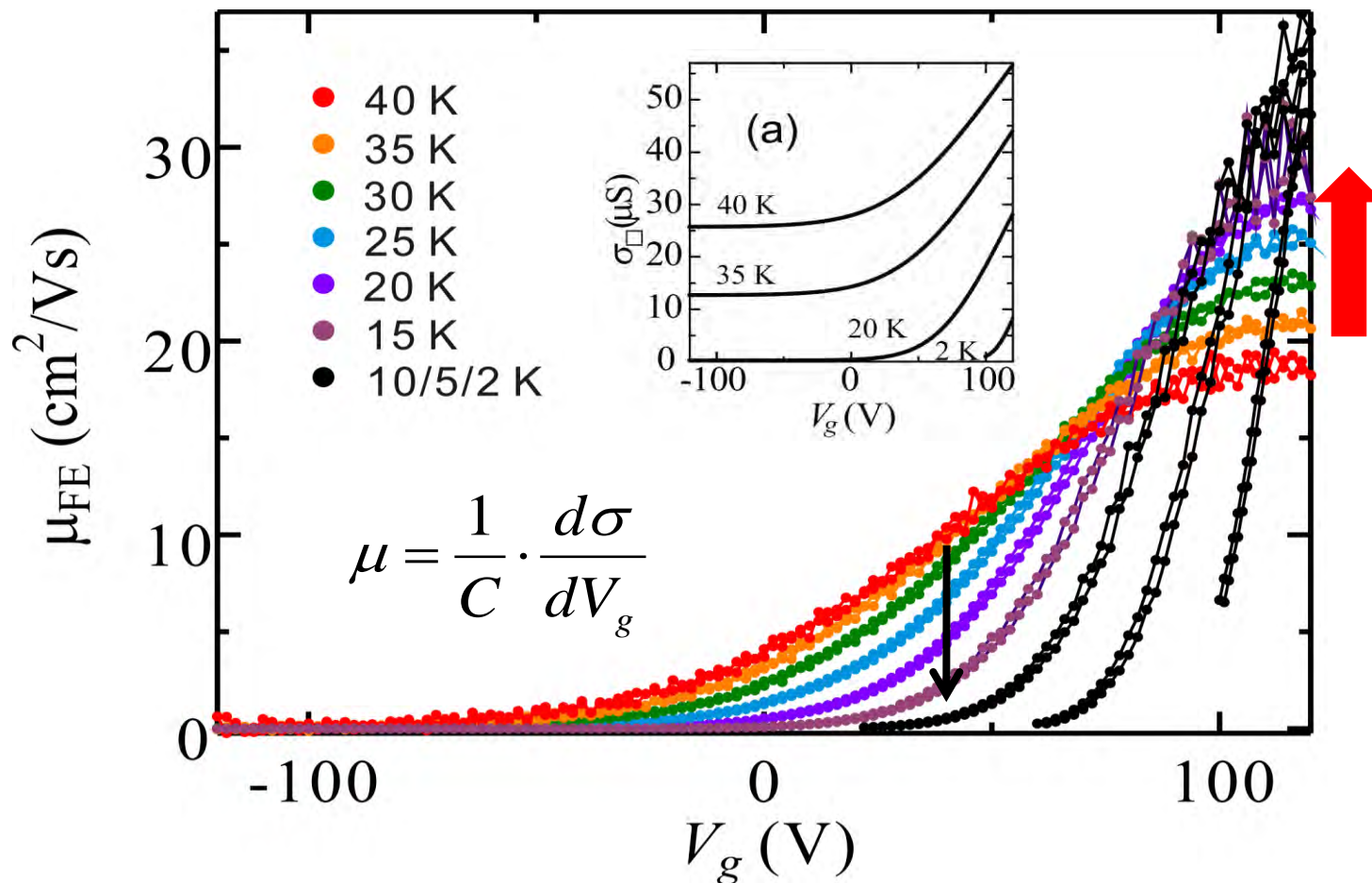
# Organic FET structure



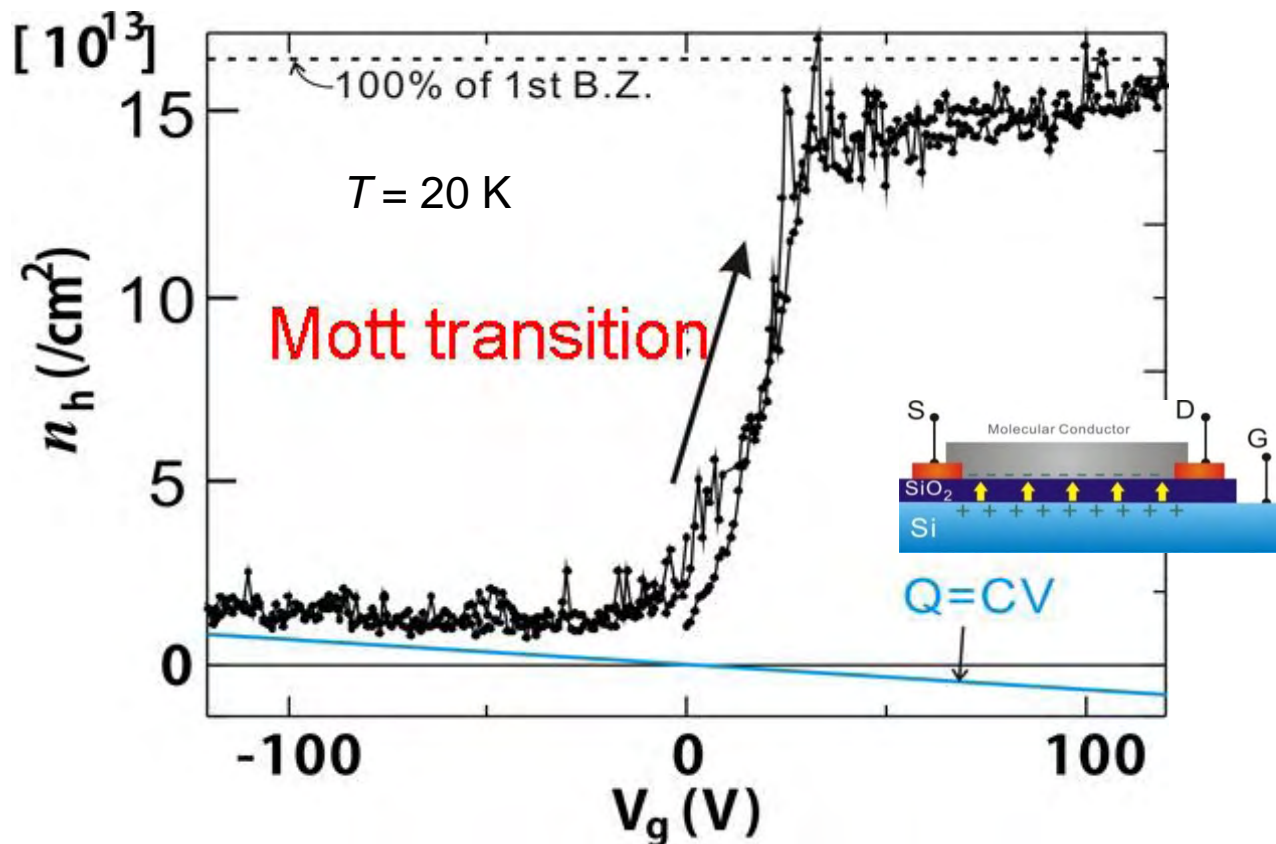
$\kappa$ -Br ( $\text{Cu}[\text{N}(\text{CN})_2\text{Br}^{-1}]$ ) crystal structure



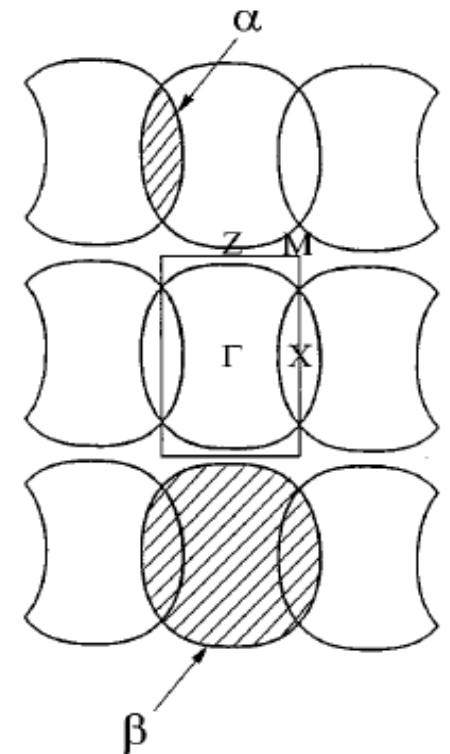
# Temperature dependence of carrier mobility



# Gate-voltage dependence of carrier concentration



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



Calculated Fermi surface of  $\kappa$ -Br

Achievements

Semiconductor Nanoelectronics

# Semiconductor nanoelectronics

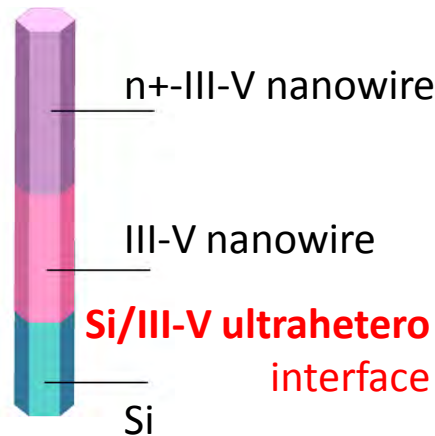
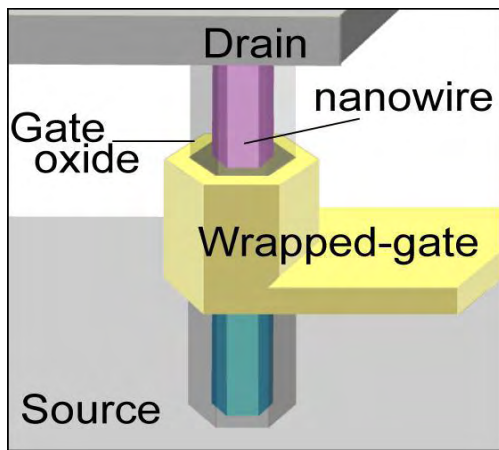
1. K.Tomioka successfully fabricated *InAs nanowire/Si tunnel-FET* with record SS (subthreshold slope) of **21mV/dec** much smaller than theoretical limit of 60
2. N.Fukata succeeded in characterization of *small amount of dopant in nanowire* Si using EPR and Raman spectroscopy
3. M.Takenaka developed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



# Control of Si/III-V super-heterointerface and development of nanowire-based tunneling FETs



The goal of this project to fabricate steep-slope nanowire-based FET by controlling Si/III-V heterojunctions without misfit dislocations, which can be achieved with nano-heteroepitaxial methods.



## Katsuhiko Tomioka (Hokkaido Univ/JST)

### Papers

Appl.Phys.Lett., **98**, 083114 (2011)  
Nature **488**, 189 (2012)  
IEEE VLSI Technol. 2012 Tech. Dig. 47 (2012)

### Award

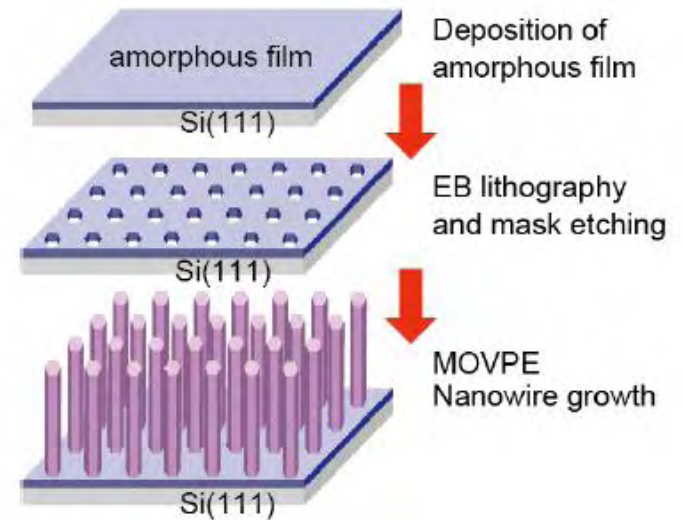
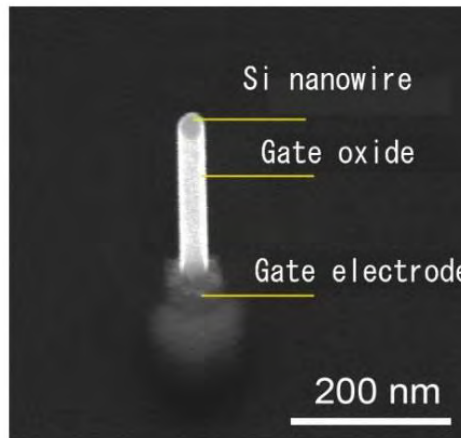
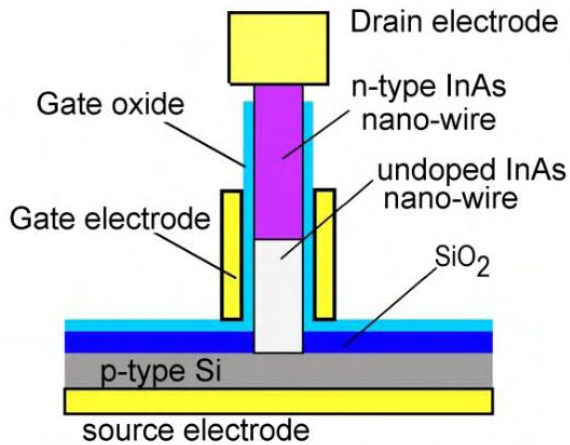
JSAP Presentation Award

### Outreach

Press Lecture, JST News, Science News

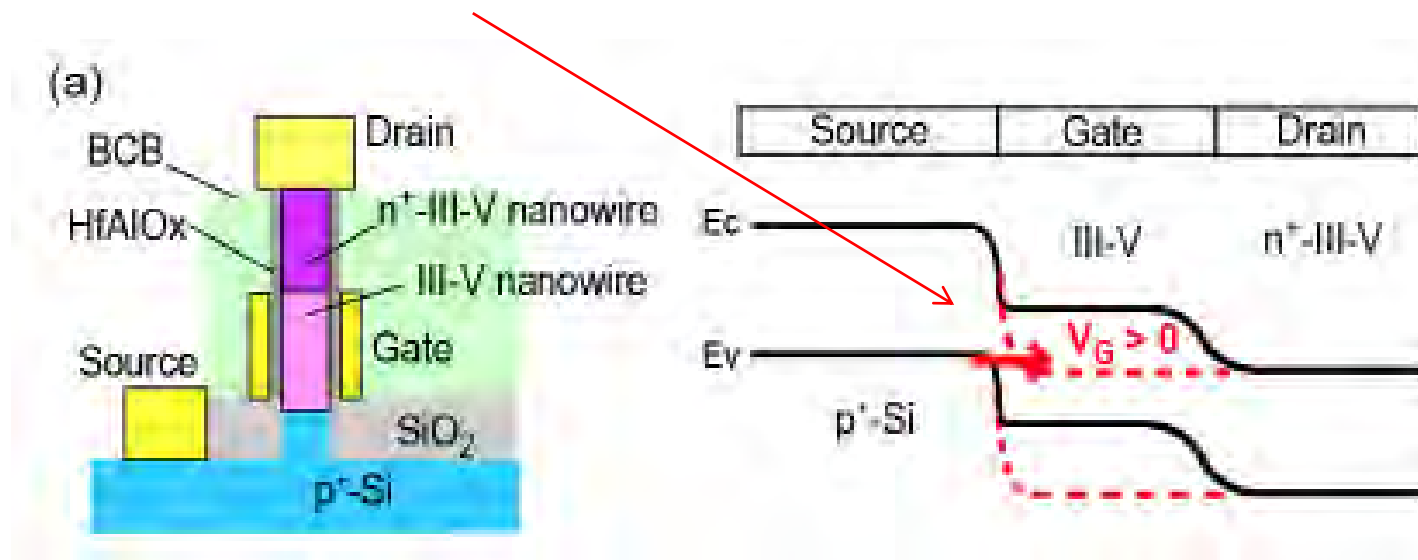
# InAs nanowire Tunnel FET

- Tomioka succeeded in fabricating a Tunnel FET using InAs nanowire on Si substrate by MOVPE through holes fabricated on SiO<sub>2</sub> insulator by electron beam lithography.



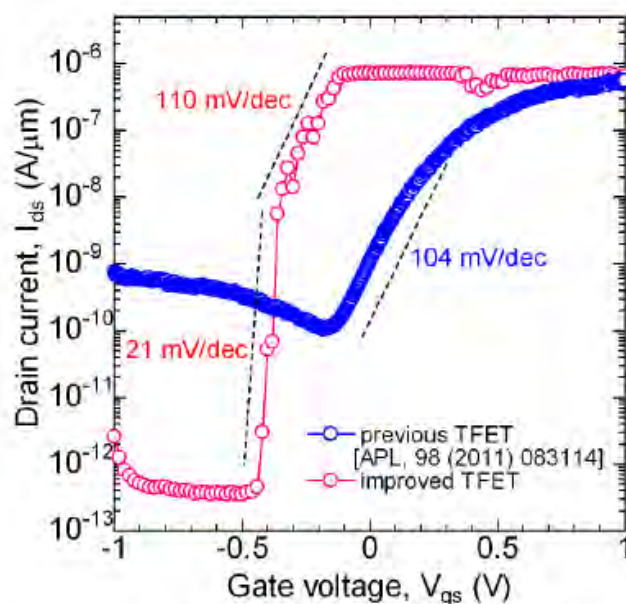
# How the InAs nanowire TFET works

- 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.

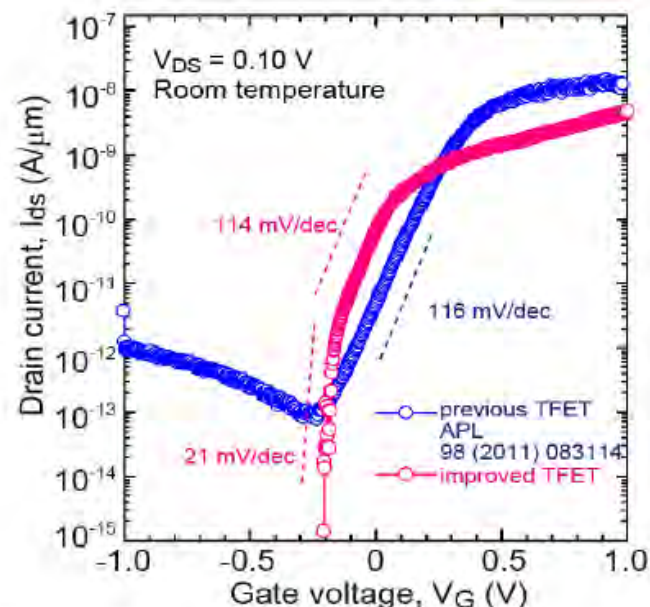


# InAs nanowire Tunnel FET

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



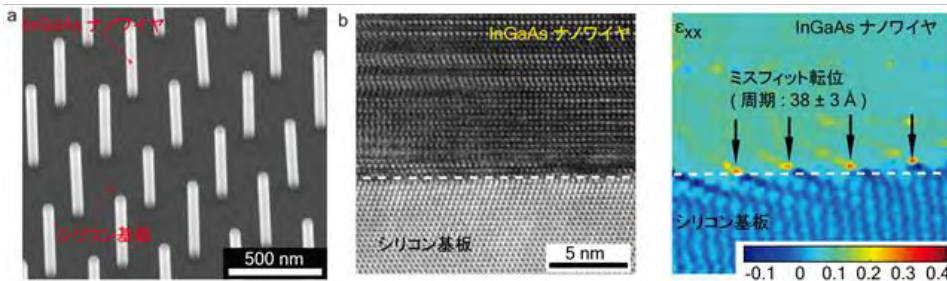
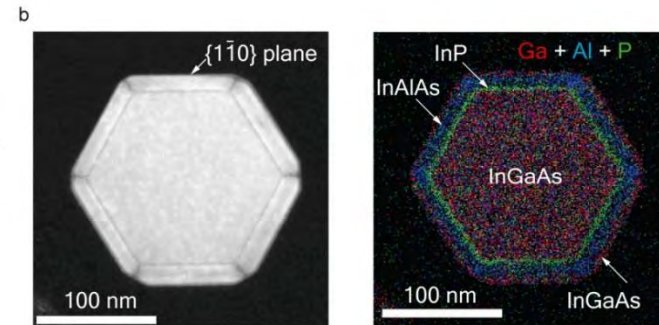
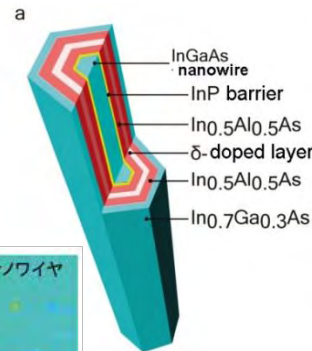
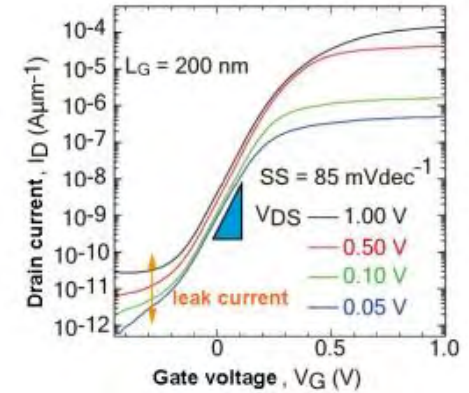
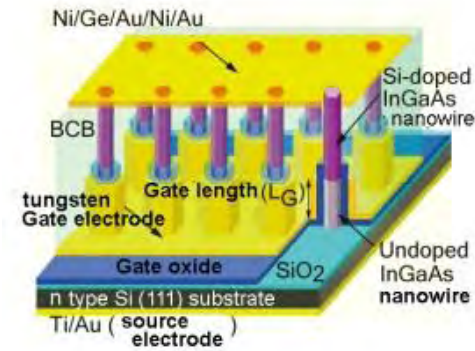
**Fig. 9** Experimental transfer characteristics of optimized TFET with a NW-diameter of 30 nm (red curve)  $V_{DS} = 1.00$  V.



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

# Nanowire FET with core-shell HEMT structure

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



# Development of semiconductor nanowires for the realization of vertical three-dimensional semiconductor devices



- 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.

## Naoki Fukata (NIMS)

### Papers

Adv. Mater. **21**, 2829 (2009).  
Nano Lett. **11**, 651 (2011).  
ACS NANO **6**, 8887 (2012).

### Award

MRS Poster Award

### Comment

Adopted as FIRST Program

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

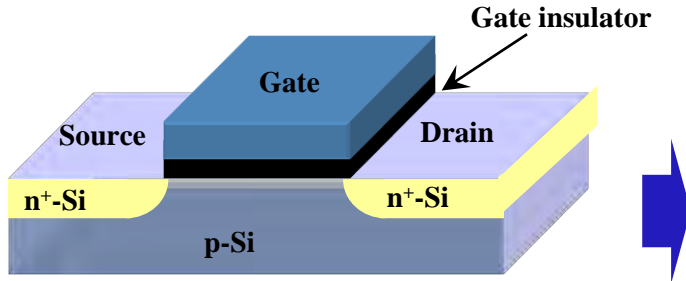
Transistor size scaling

**Limit of scaling ?**

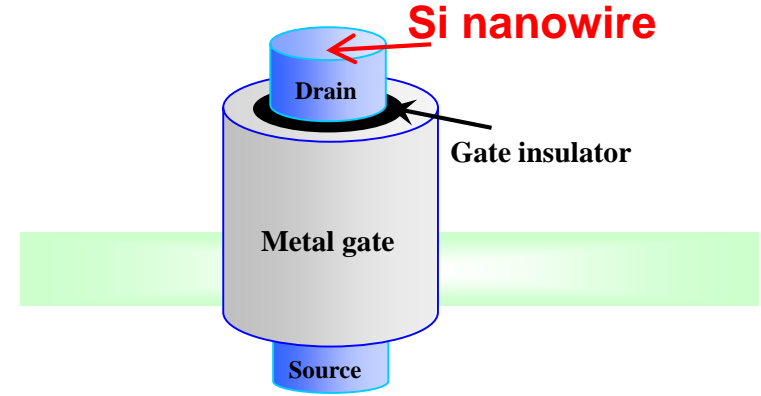


2-orders of magnitude reduction in transistor size in 30 years.

Present: Planar type



Next generation: Vertical type



**Vertical-type MOSFET using Si nanowires !**

**Miniaturization of FET**

↓

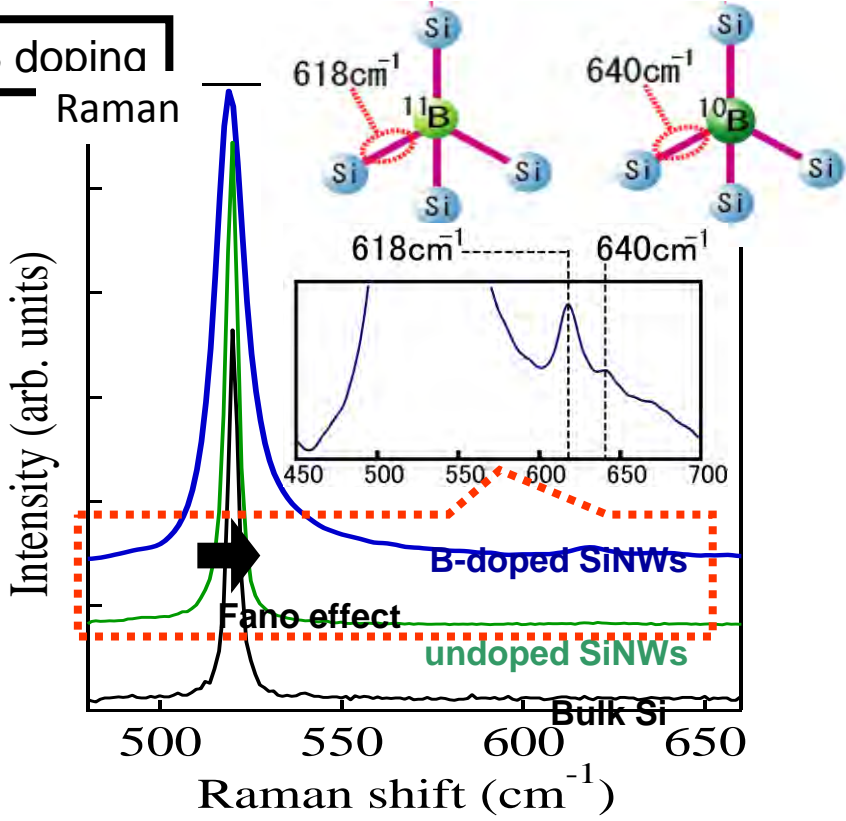
**Increase in power consumption & leak current**

↓

**Enhancement of the heating**

# Synthesis & Impurity doping in Si nanowires

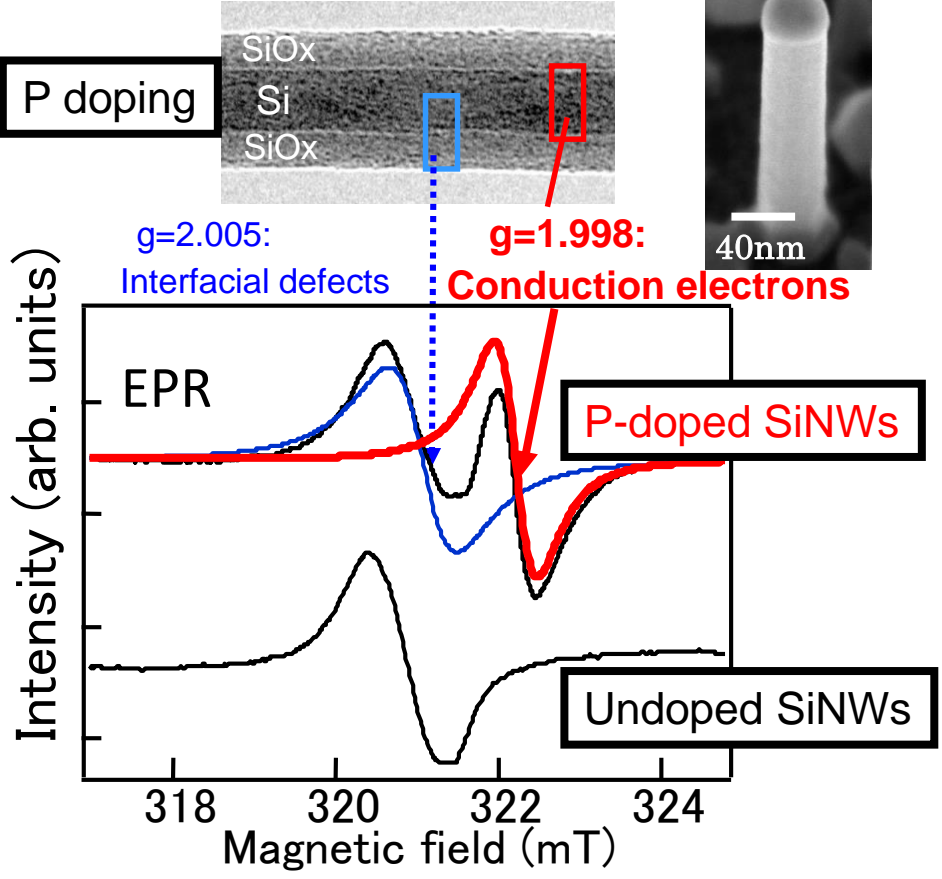
**B dopina**



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

**Formation of p-type SiNWs**

**P doping**



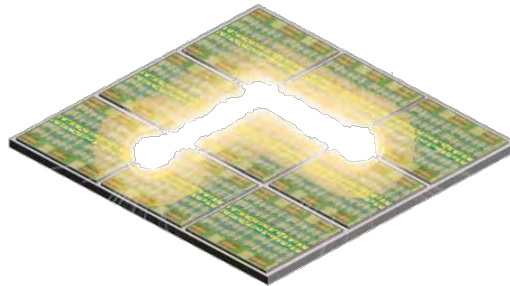
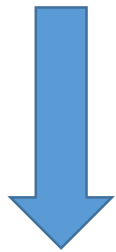
First observation of conduction electron signals in P-doped SiNWs

**Formation of n-type SiNWs**



# Ge Nano Electro-Optic LSI for intrachip optical interconnects

The target of this research is monolithical integration of Ge MOSFETs and Ge photodetectors on a Si substrate for ultrahigh performance LSI.



Fundamental technologies for one-chip super computers and photonic router chips will be established through this research.



**Mitsuru Takenaka**  
**(Univ Tokyo)**

## Representative papers

IEEE Electron. Dev. Lett. **21**,1092 (2010).

Jpn. J. Appl. Phys. **50**, 010105 (2011).

Optics Exp. Lett. **20**, 8718 (2012)

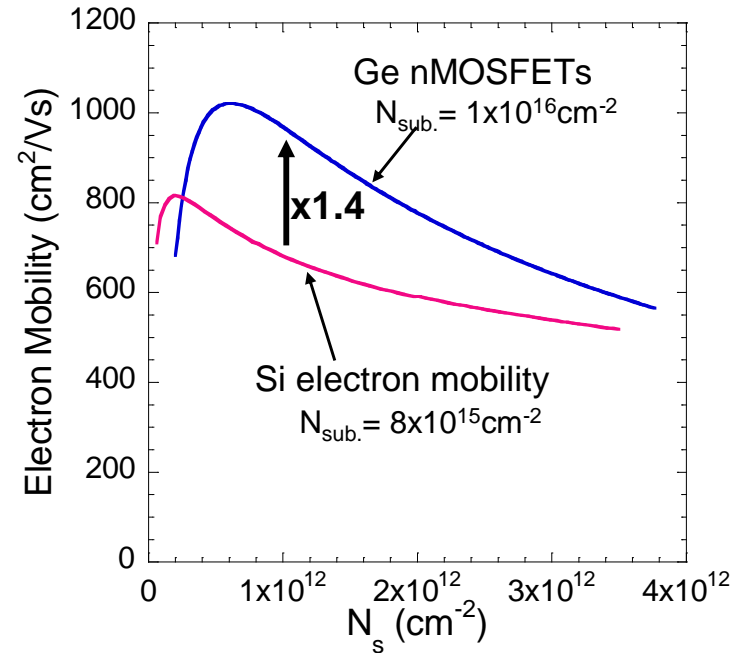
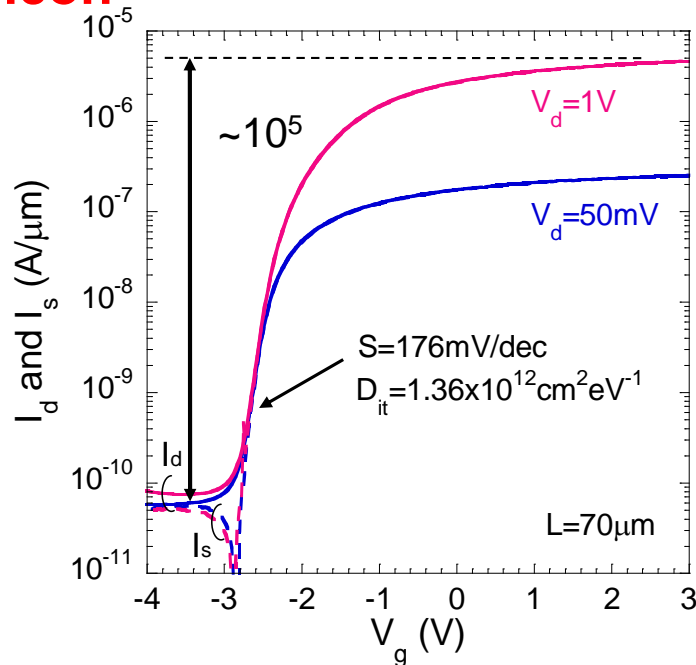
## Award

Silicon Technology Division Paper Award  
of JSAP

] 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.

# Toward Realization of Ge CMOS

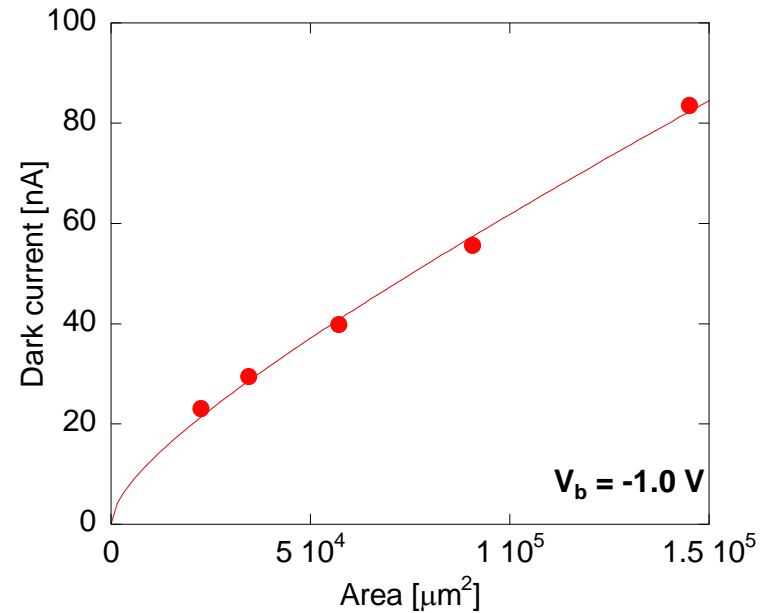
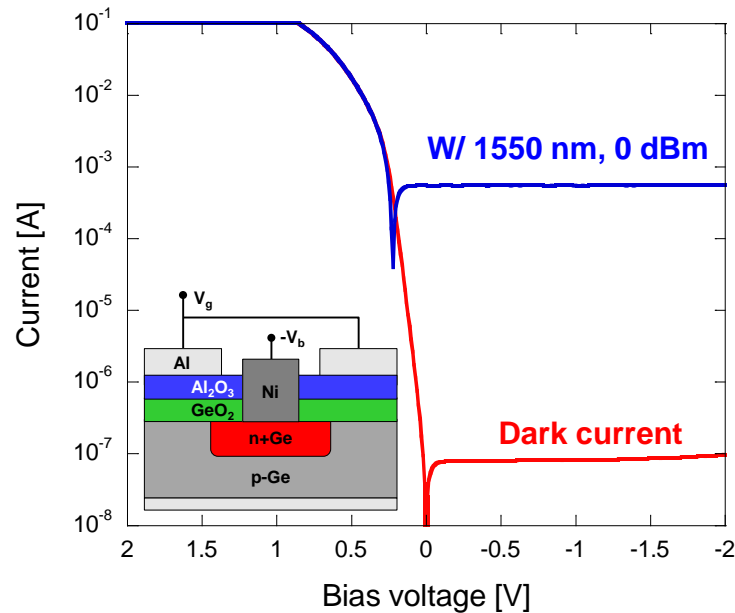
- Achievement of World Record on/off Value of  $10^5$
- First Verification of Record Effective Mobility higher than Silicon



**Electrical Characteristics and Effective Mobility in Ge n-MOS FET grown by vapor deposition technique**

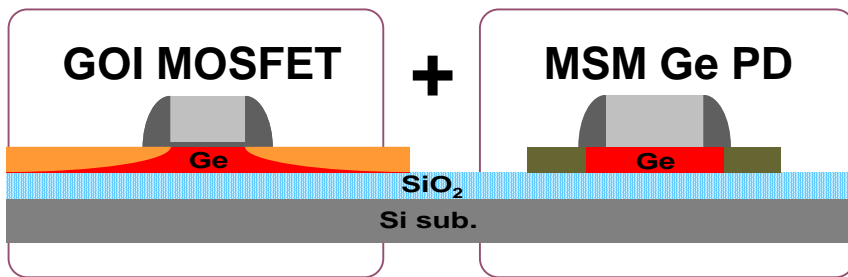
# Ge Photodetector

- Thermally oxidized  $\text{GeO}_2$  (Surface Passivation of Ge)
  - Vapor-phase doping (reduction of Junction leakage by 2 order of magnitude compared with ion-implantation)
- ↓
- First experimental demonstration that dark current of Ge PD can be reduced to less than 1 nA

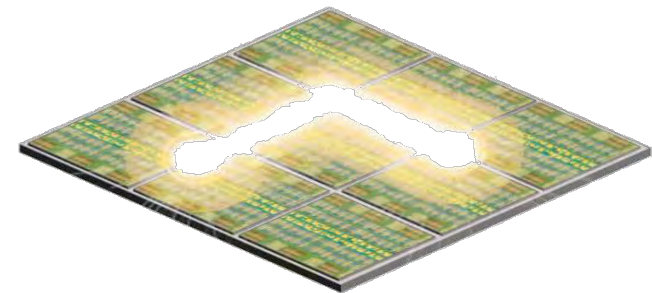


# Ge-based LSI with on-chip optical interconnects

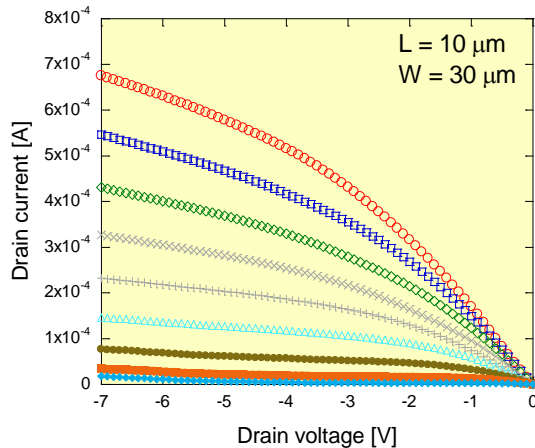
**Monolithic integration:**



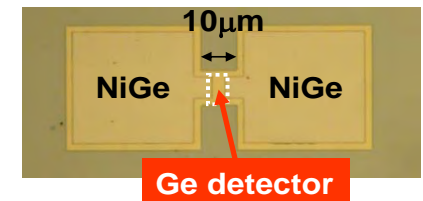
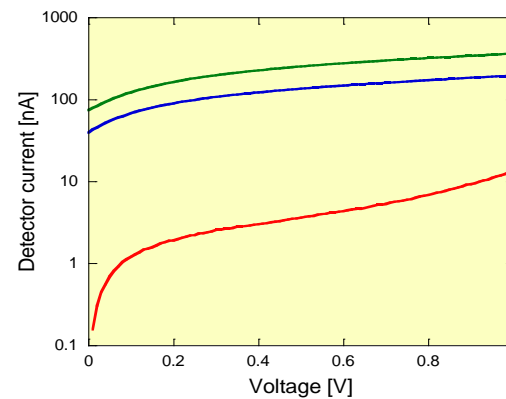
**Ge based LSI with on-chip optical interconnects**



**GOI MOSFET**



**Ge PD**



# 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.

**Yasushi Takahashi**  
**(Osaka Pref Univ)**



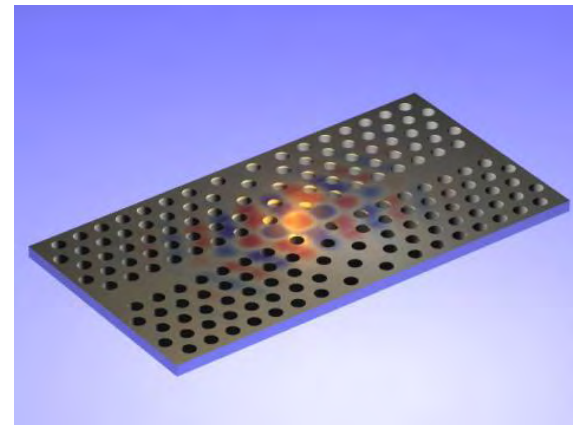
## Papers

Opt.Exp. **19**, 11916(2011)

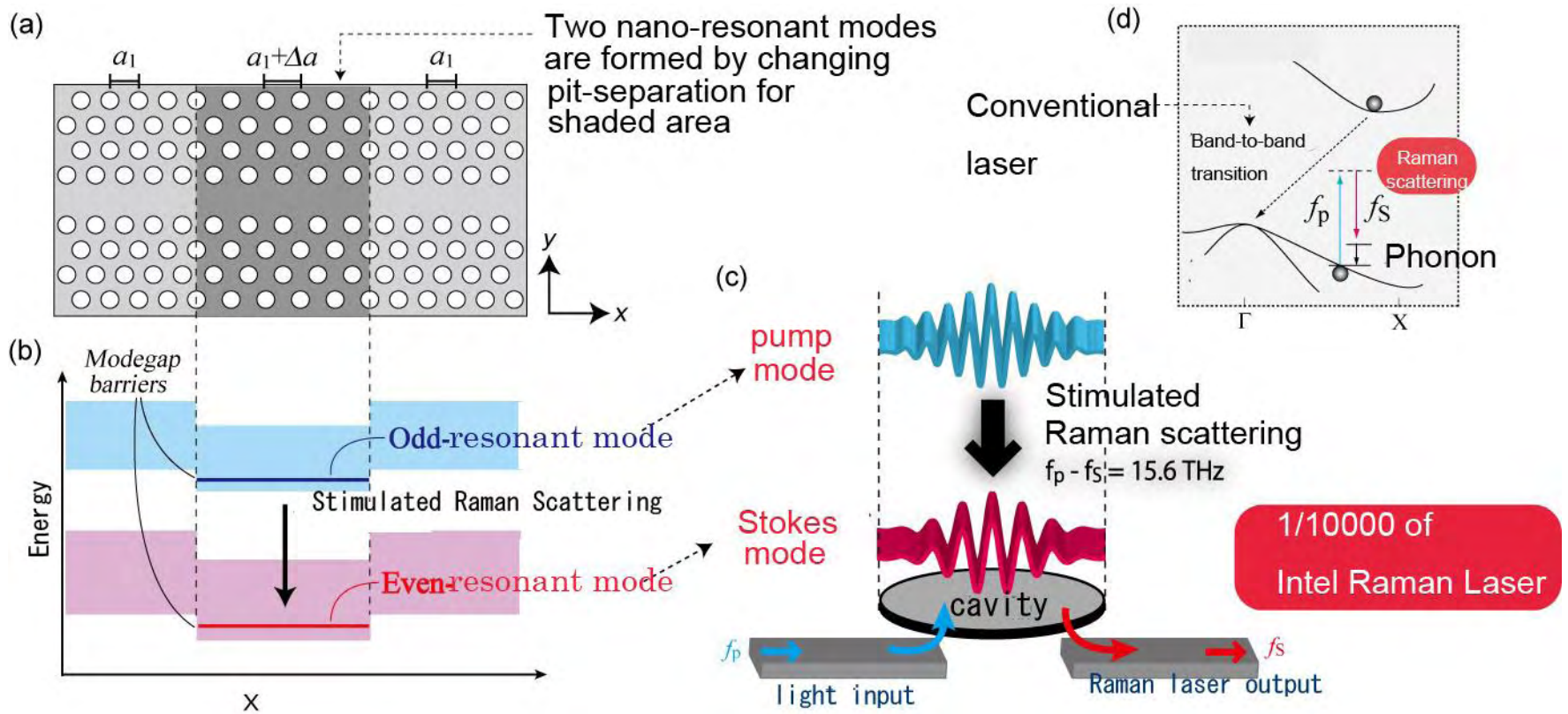
Nature Photonics **6**, 56 (2012)

Optics Express **20**, 22743 (2012)

Nature **498**, 470 (2013).

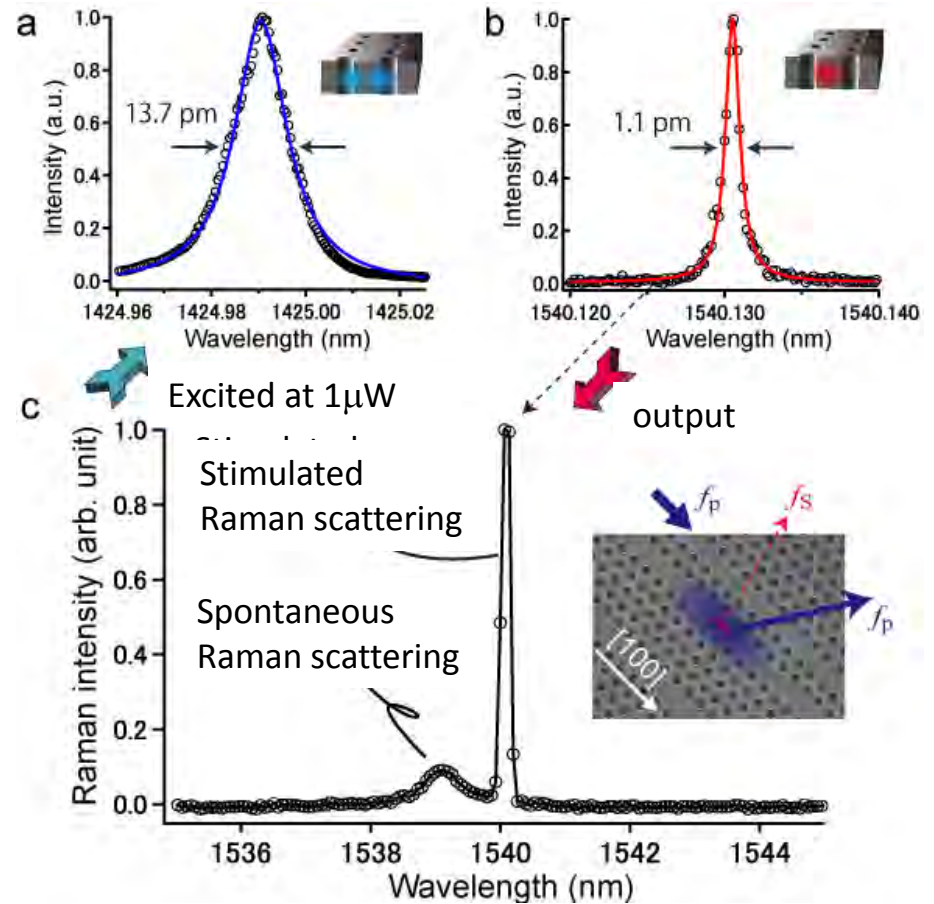


# Explanation of Silicon Raman Laser



# 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

# Research on **stochastic resonance** nanodevices and their integration for novel noise-robust information processing systems

Novel semiconductor nanodevices utilizing "stochastic resonance" and their integration are investigated to realize state-of-the-art electronics hardware for noise-robust information processing.



## Seiya Kasai (Hokkaido U)

### Paper

Appl.Phys.Lett. **96**,194102 (2010)

### Award

MNC2007 Outstanding

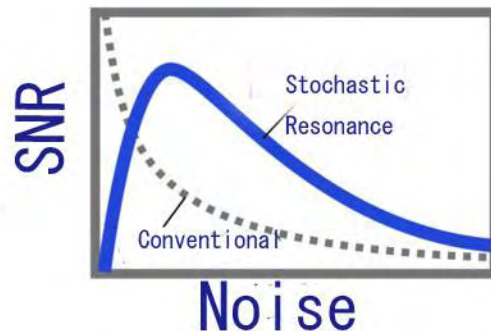
Paper Award

MNC2010 Outstanding

Paper Award

### Outreach

Science News

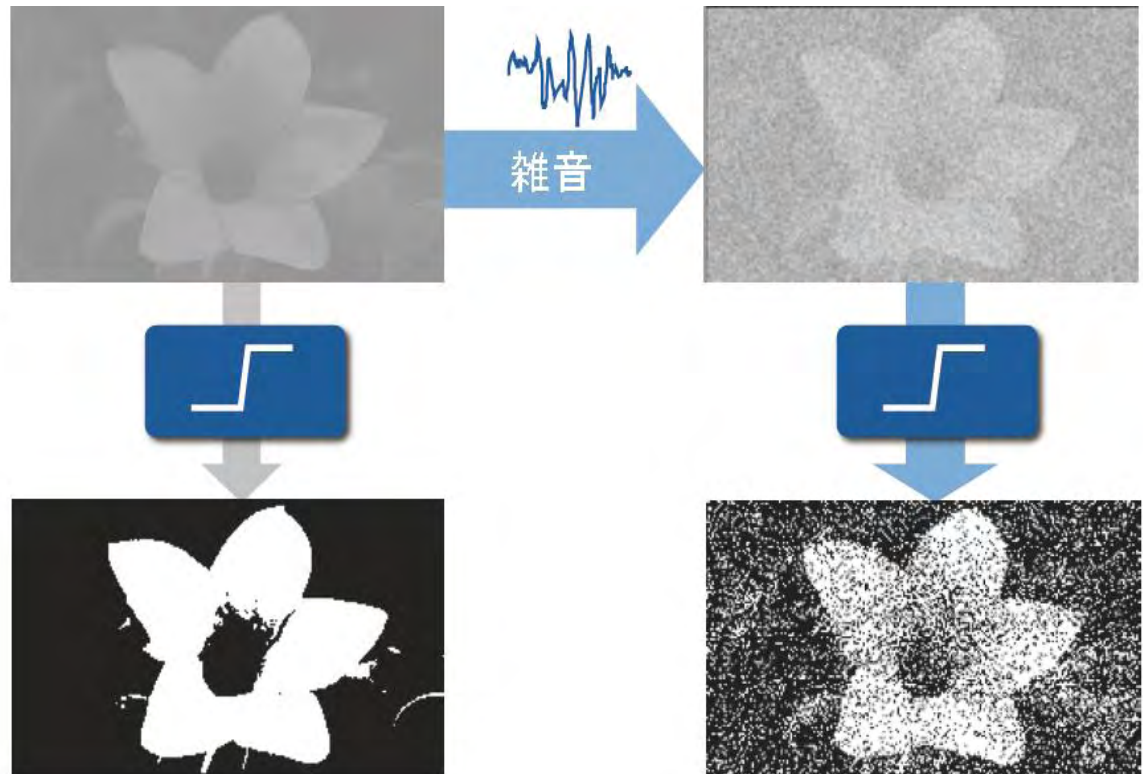




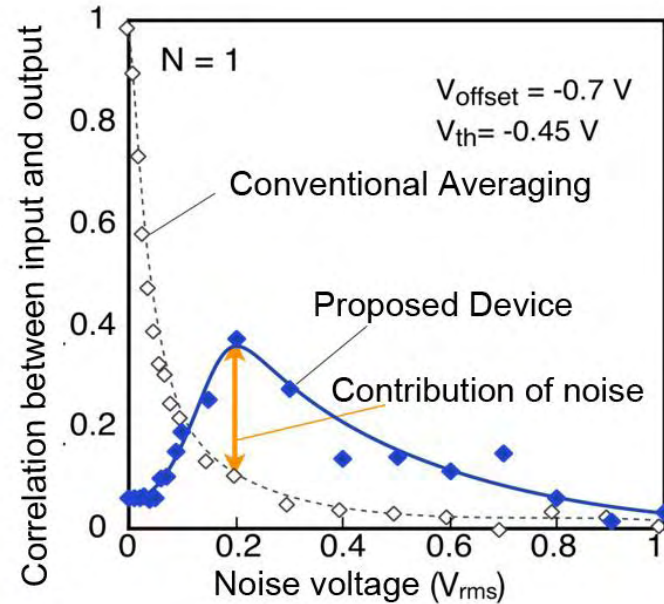
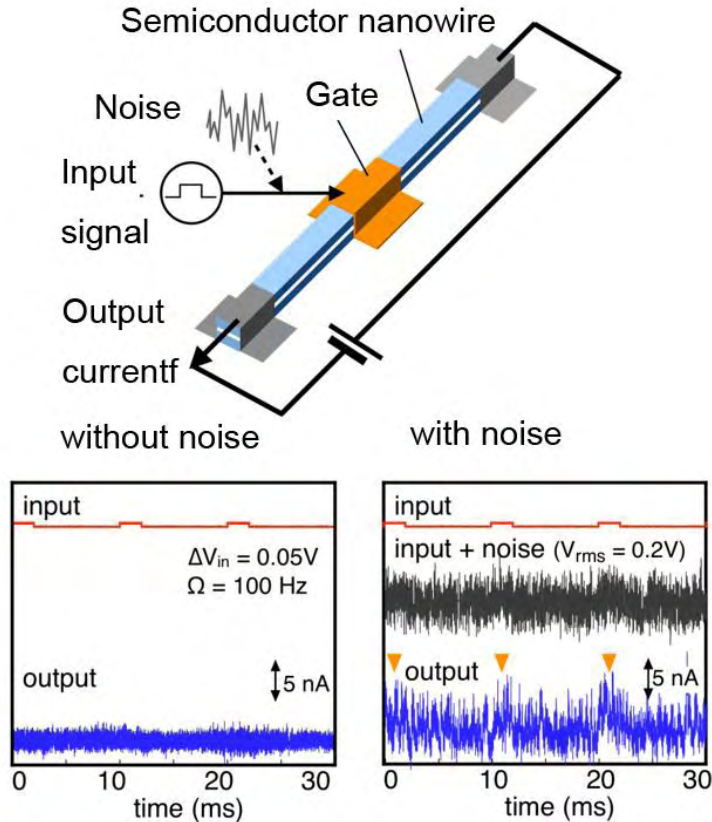
# Characteristic Feature of “Stochastic Resonance”

Middle level information is lost if simple filter is used.

Grey information is reproduced when stochastic resonance is applied.

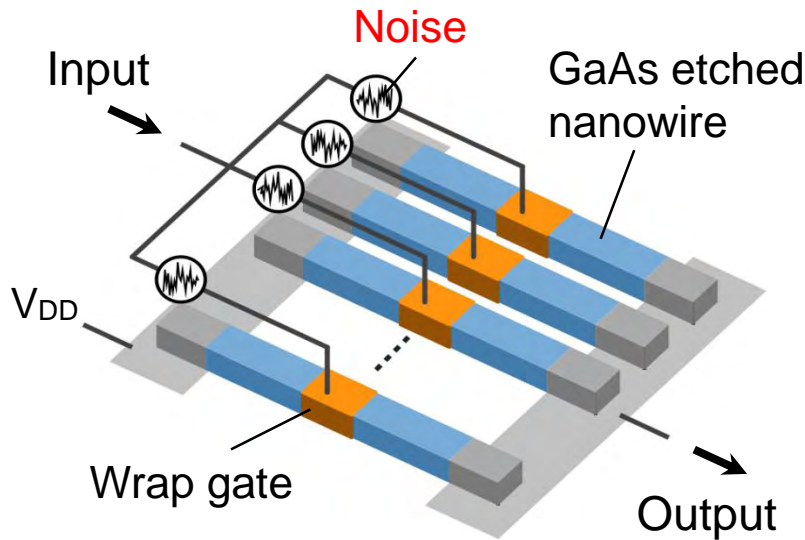


# Electronic introduction of stochastic resonance by using a nanowire transistor

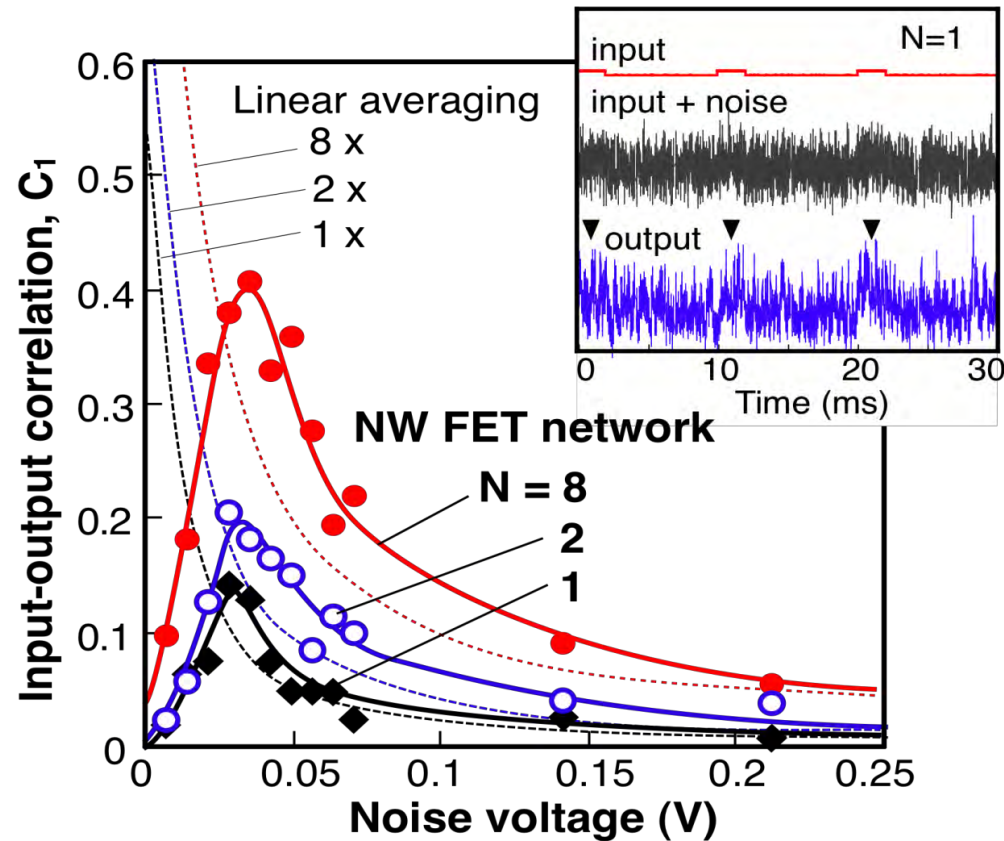


Parallel adder network of nanowire FETs proved enhancement of stochastic resonance

# Stochastic Resonance in Nanowire FET Network



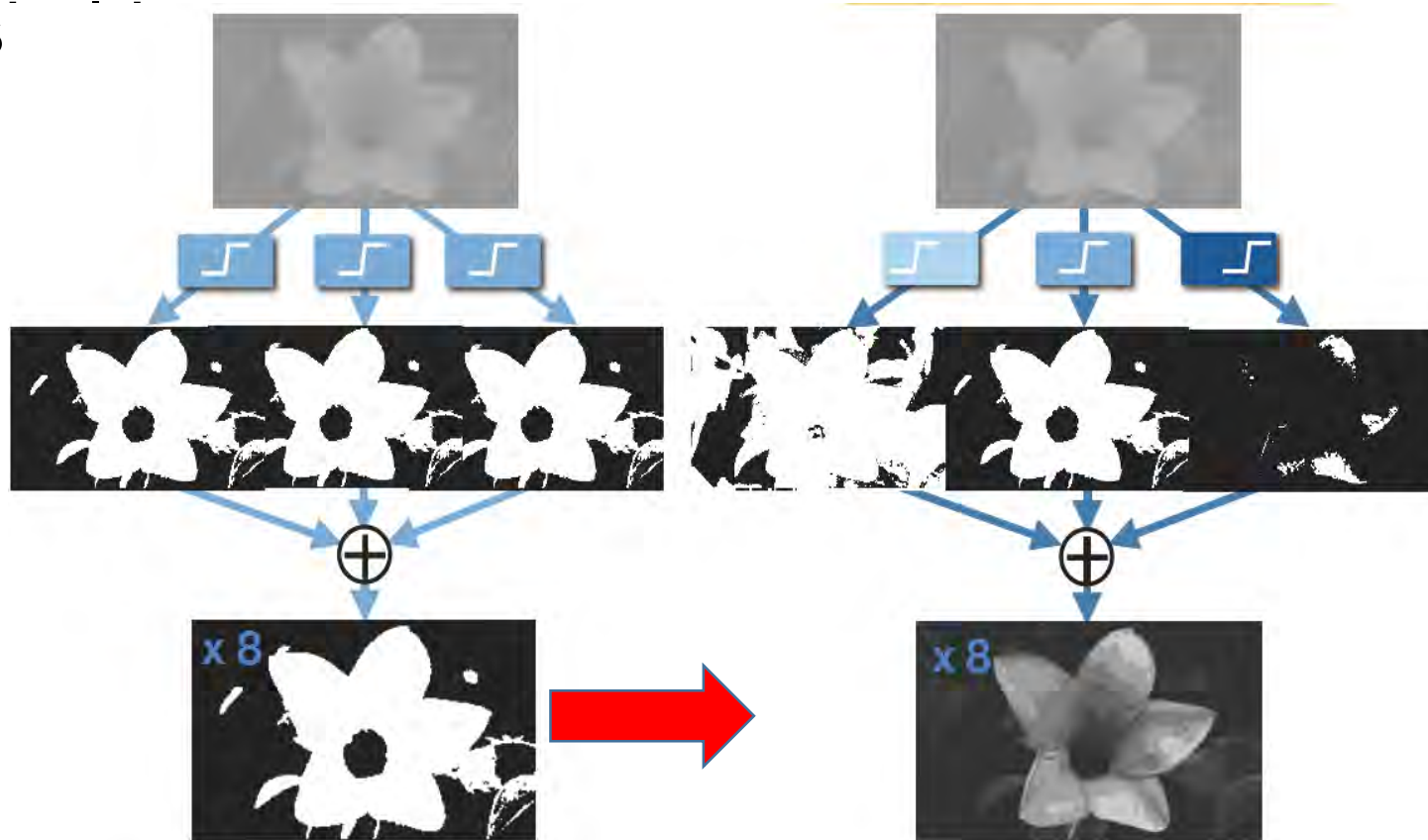
S.Kasai et al., Appl. Phys. Express 1, 083001 (2008)



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.

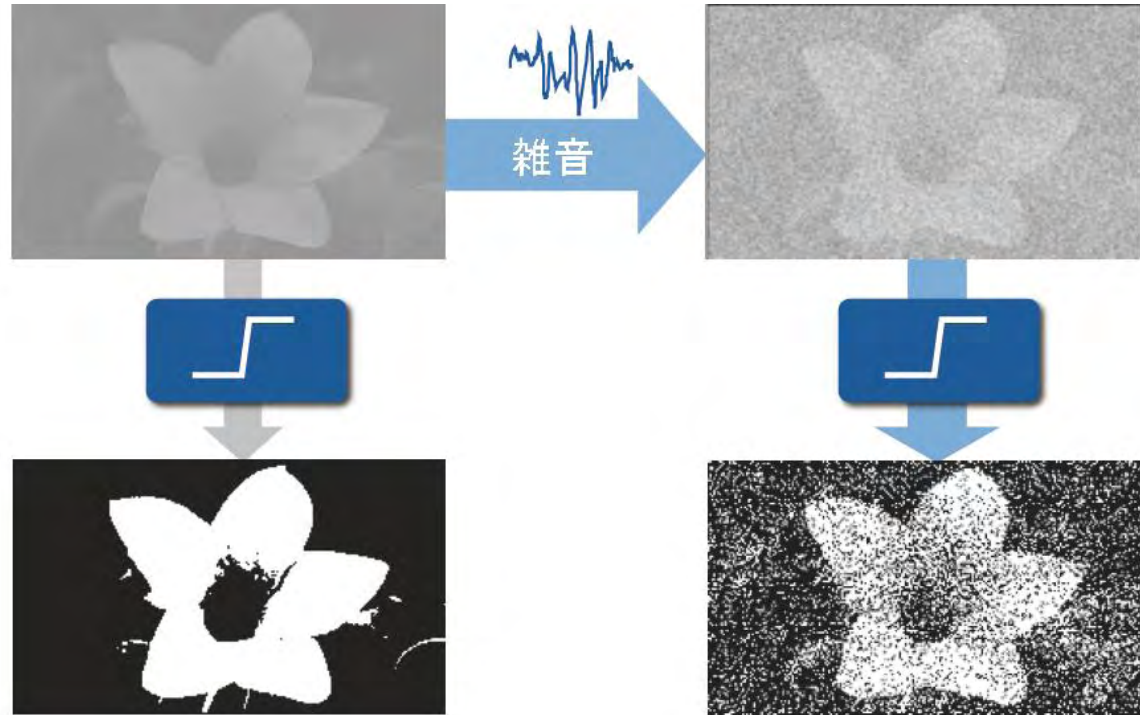
# Scatter of thres



しきい値のばらつきは入力信号の中心が大きくずれても  
応答曲線が変わらず、入力信号の変化に追従できる。  
先端集積回路の同一設計でのばらつきも利用できる。

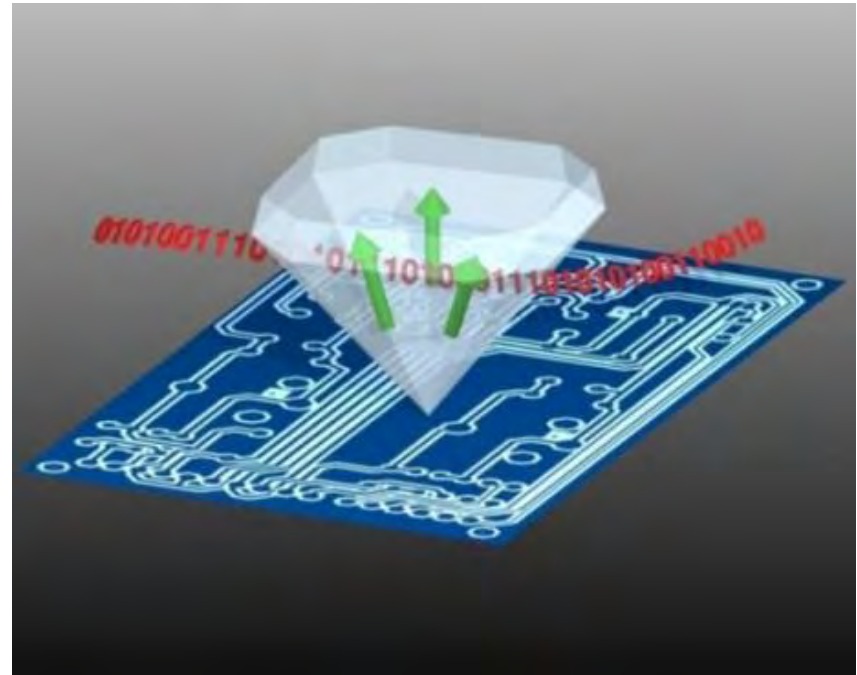
# Improvement of SNR by using noise

- Stochastic resonance improve grey scale reproduction



High contrast but  
lose grey scale

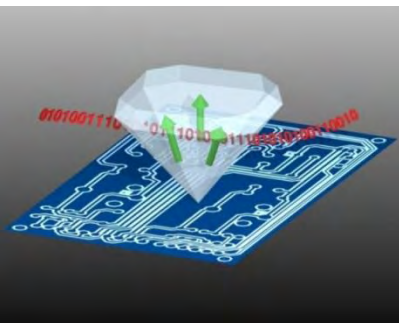
recover grey scale by  
addition of noise



# Wide Gap Semiconductors

# Wide-gap semiconductors

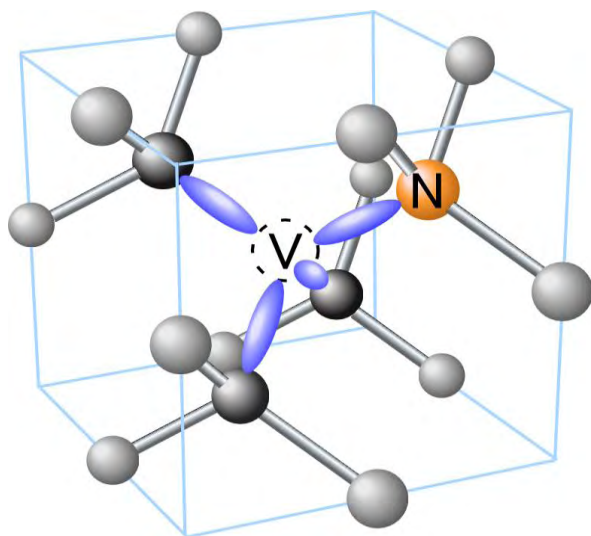
1. N.Mizuochi succeeded in **room temperature** operation of quantum information processing solid state device and current-induced **single photon source** by using *NV center in diamond p-i-n junction*
2. M.Higashiwaki succeeded in fabricating *Ga<sub>2</sub>O<sub>3</sub> – based device* for power electronics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



## Single NV center in diamond



NV center: ( $\text{NV}^-$ , 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

### Narikazu Mizuochi (Osaka Univ)

#### Papers

Nature Photonics, **6**, 299 (2012).  
Nature **478**, 221 (2011)  
Phys.Rev.**B80**,041201(R)  
(2009)

#### Awards

Marubun Research Award  
Nagase Award

#### Outreach

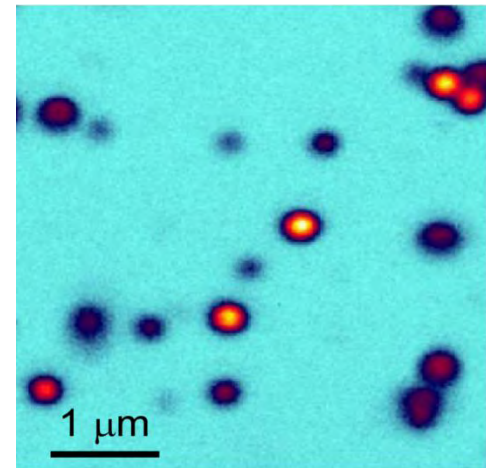
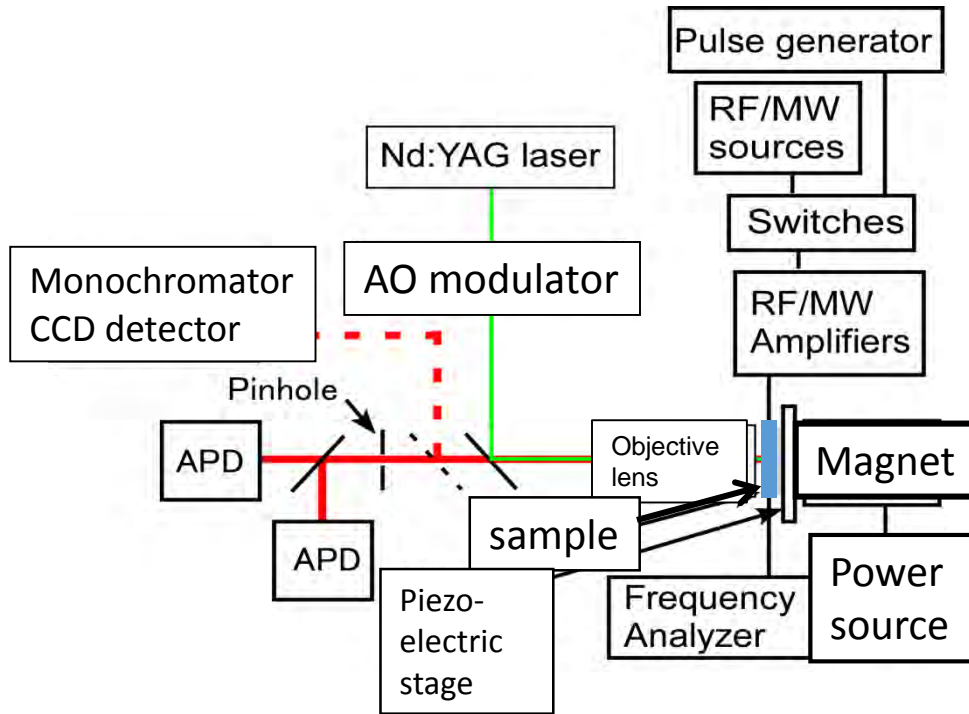
Press Lecture on diamond single  
photo source

Quantum information processing solid state device for  
**room temperature** operation

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

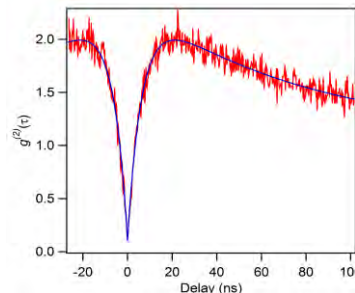


# Measurement Instruments for single NV center



Fluorescent image of single NV center by confocal laser microscope

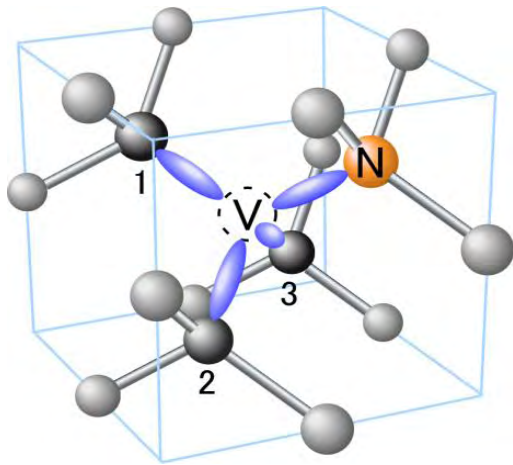
Anti-bunching measurement using Hanbury-Brown Twiss interferometer



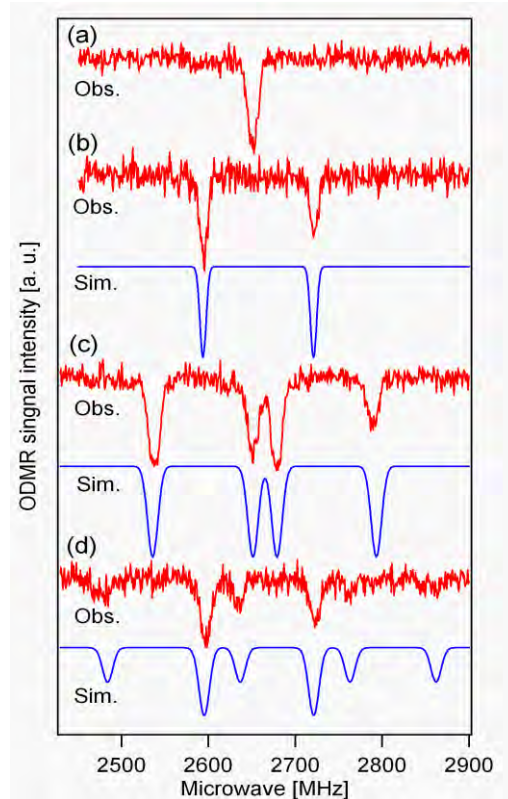
# Multiple quantum bit

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

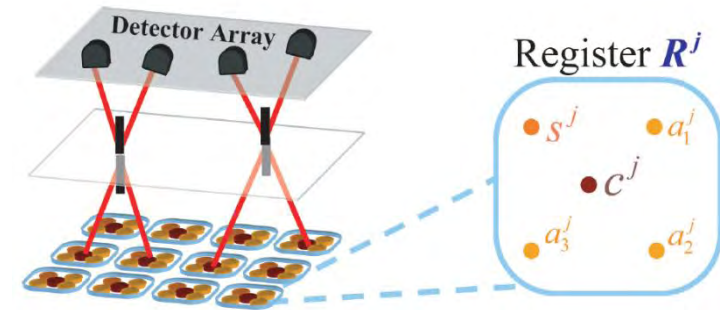
## $^{13}\text{C}$ -doped system



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)

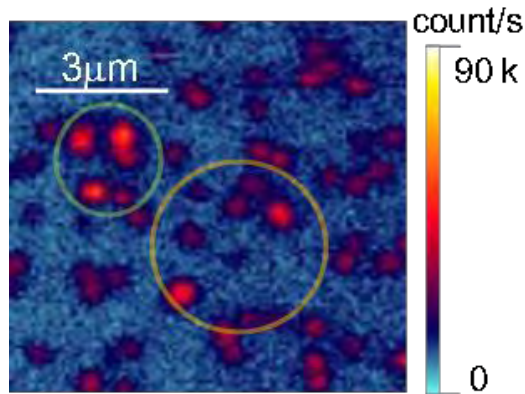


Jiang et al., PRA 76, 062323 (2007)

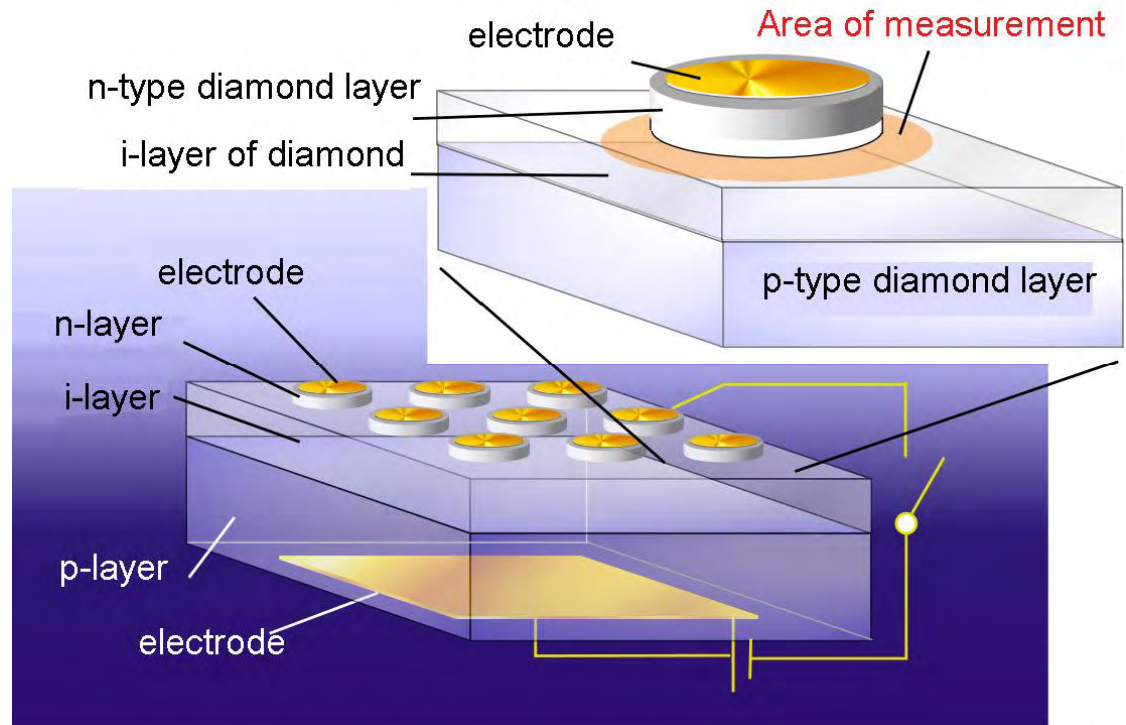
Experimental and simulated ODMR spectra of nearest neighbor carbon atoms assigned as consisting of (a)0, (b)1, (c)2, (d)3  $^{13}\text{C}$ -center(s)

# Room temperature single photon emission from NV<sup>0</sup> 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).

# Interfacial Control of Group III oxide/nitride hetero-structure

He focused attention on III-oxides as the strong candidates. He fabricated and analyzed ideal oxide/nitride composite structures aiming at not only improvements in device characteristics but also evolutions of widegap transistors.



## Masataka Higashiwaki (NICT)

### Papers

JAP **108**, 063719 (2010).

APL **97**, 222104 (2010)

APL. **100**, 013504 (2012).

### Special Comment

Patents on Ga<sub>2</sub>O<sub>3</sub> FET

### Group III nitrides

GaN, AlN, InN

### Group III oxides

Ga<sub>2</sub>O<sub>3</sub>, Al<sub>2</sub>O<sub>3</sub>, In<sub>2</sub>O<sub>3</sub>

AlGaN/GaN HFET

Ga<sub>2</sub>O<sub>3</sub> MESFET, MOSFET

### Transistors using hybrid structure of Group III oxide/nitride

GaN channel: AlO<sub>x</sub>/GaN MISFET, AlO<sub>x</sub>/AlN/GaN MIS-HFET

Ga<sub>2</sub>O<sub>3</sub> channel: AlN/Ga<sub>2</sub>O<sub>3</sub> HFET, AlN/Al<sub>2</sub>O<sub>3</sub>/Ga<sub>2</sub>O<sub>3</sub> HFET

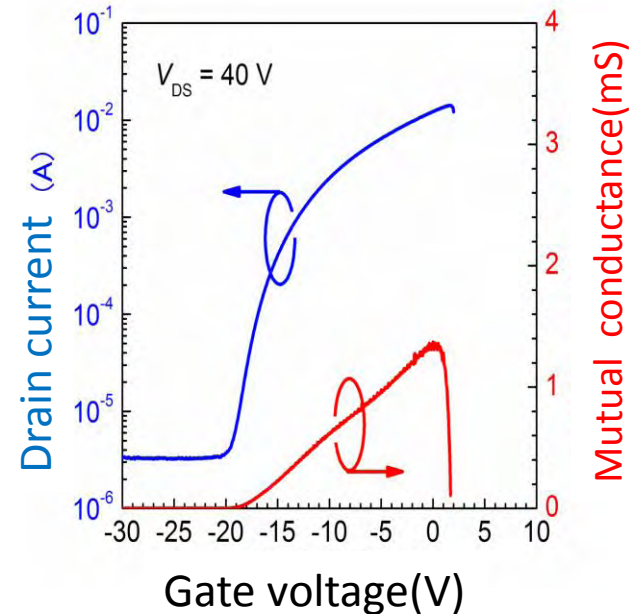
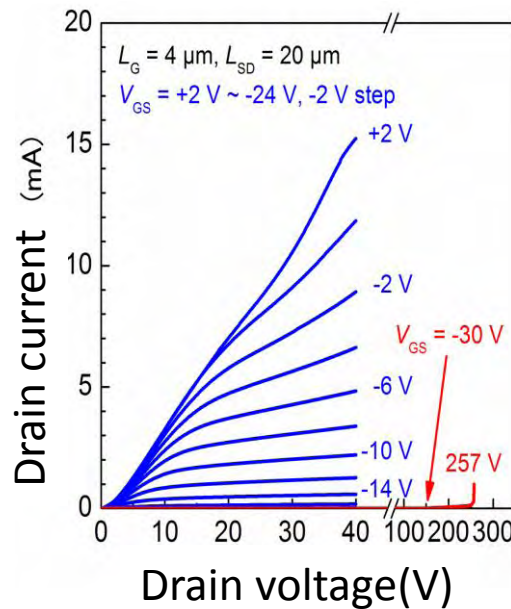
# Niride/Ga<sub>2</sub>O<sub>3</sub>Hybrid

First of MESFET with Ga<sub>2</sub>O<sub>3</sub> channel.

The device shows high performance as represented by high off-drain tolerance above 250V and high on/off ratio of 4 order of magnitudes.



High potentiality of Ga<sub>2</sub>O<sub>3</sub> for power-device application.



Performance of Ga<sub>2</sub>O<sub>3</sub> MESFET

(a) I-V characteristics

(b) Transfer characteristics

# 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<br>2007–2011 | 194        | 8         | 159         | 234        | 1        | 37        | 107           | 75         | 815                 | 26        | 5             |
| 2nd Phase<br>2008–2012 | 77         | 5         | 97          | 159        | 0        | 6         | 42            | 23         | 409                 | 10        | 2             |
| 3rd Phase<br>2009–2013 | 68         | 10        | 95          | 176        | 6        | 7         | 46            | 24         | 432                 | 16        | 9             |
| <b>Total</b>           | <b>339</b> | <b>23</b> | <b>351</b>  | <b>569</b> | <b>7</b> | <b>50</b> | <b>195</b>    | <b>122</b> | <b>1656</b>         | <b>52</b> | <b>16</b>     |

# Publications and Patents

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

# 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                                  |



## Products of the Research Project

# Outcomes

(1) Contribution to Scientific Progress, (2) Development to Practical Application, (3) Results for future innovation, (4) Promising challenging technology, (5) Nurture of future scientific leader

### (1) Contribution to Scientific Progress

- Eiji Saitoh: Establishment of Concept of Spin Current in Insulator, Discovery of Spin Seebeck Effect
- Masashi Shiraishi: First Verification of Injection of Pure Spin Current into Graphene, and Graphene-based GMR Device
- Tomoteru Fukumura: Realization of Voltage-Controlled Magnetization Change in  $\text{TiO}_2\text{:Co}$  Room-Temperature Ferromagnetic Semiconductor
- Kohei Hamaya: Establishment of Spin Injection to Nondegenerate Semiconductor Silicon

### (2) Development for Practical Application

- Mitsuru Takenaka : Monolithic Integration of Ge-Channel High Performance MOS Transistor and Ge-Photodetector
- Katsuhiro Tomioka : World Record SS-value of 21mV/dec in Tunnel FET using InAs Nanowires on Si
- Akira Tsukamoto: Elucidation of Ultra-High Speed Light-Induced Magnetization Reversal Mechanism for Next-Generation Magnetic Recording
- Tomoki Machida: High Sensitivity THz Detector Using Graphene Quantum Dot

### (3) Results for future innovation

- Norikazu Mizuochi: Single photon source for quantum information communication which can be operated at Room Temperature using NV center in Diamond LED
- Yasushi Takahashi: Realization of silicon Raman laser using extremely high Q value of photonic crystal
- Suguru Noda: Direct growth of metal-free graphene on quartz using novel etching deposition technique.

### (4) Promising challenging technology,

- Hiroshi Yamamoto: Realization of Phase-Transition Transistors using organic materials
- Yutaka Noguchi: Photosensitive SET (single electron transistor) action using nanogap and gold particle coated by organic molecules and pigments
- Jiro Nishinaga: Introduction of C60 molecules during GaAs growth without defect

### (5) Nurture of future scientific leader

Many scientific leaders have been nurtured from our project

- Six researchers got professorship
- Total of 55 awarded such as Japan Academy Prize, IBM Science Prize, Sir Martin Wood Prize, etc.
- Book of Spintronics edited by Eiji Saitoh and K. Sato is now in press.



# Are our achievements in accordance with the 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), TiO<sub>2</sub>-based room temperature ferromagnetic semiconductors (Fukumura), Heusler alloys with highest spin polarization (Y.Takahashi), Femtosecond 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?



# 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

# “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.

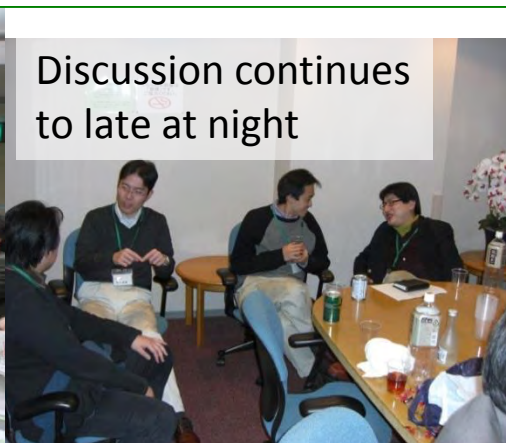


# Research Area Meetings

- 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



JST NEWS



## 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



Sketch at Guanyinqiao District