# Spin transport in a semiconductor channel

## Condensed Matter Seminar, Korea University

**Hyun Cheol Koo**

*Center for Spintronics, Korea Institute of Science and Technology, Korea and*
*KU-KIST Graduate School of Converging Science and Technology, Korea University, Korea*

March 9, 2015

# Spintronics Group in KIST

Korea Institute of Science and Technology

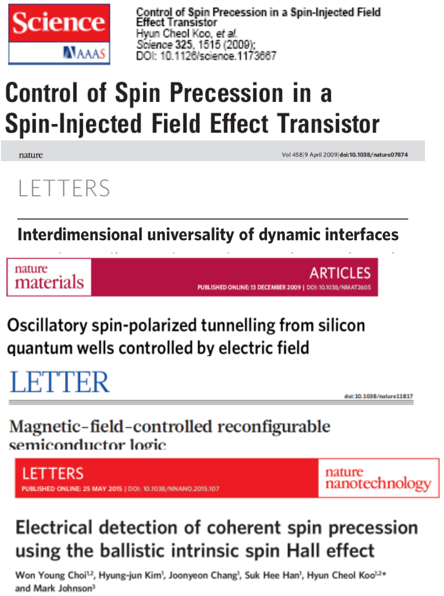
## 우수한 전문 인력

- 국내 최대의 스핀트로닉스 전문 연구조직
- 20여 년간 자성 관련 기술 연구로 풍부한 경험을 보유

**12 regular researchers,**
**25 postdocs & students**

## 탁월한 연구성과

- 스핀 제어 소자 분야의 NSC급 논문 등 질적 양적 성과 창출
- 차세대 스핀소자 분야의 다수의 핵심 특허 보유



Science AAAS

Control of Spin Precession in a Spin-Injected Field Effect Transistor
Hyun Cheol Koo, *et al.*
*Science* 325, 1515 (2009);
DOI: 10.1126/science.1173667

**Control of Spin Precession in a Spin-Injected Field Effect Transistor**

nature Vol 458|9 April 2009|**doi:10.1038/nature07874**

LETTERS

**Interdimensional universality of dynamic interfaces**

nature materials ARTICLES
PUBLISHED ONLINE: 13 DECEMBER 2009 | DOI: 10.1038/NMAT2605

**Oscillatory spin-polarized tunnelling from silicon quantum wells controlled by electric field**

LETTER doi:10.1038/nature11817

**Magnetic-field-controlled reconfigurable semiconductor logic**

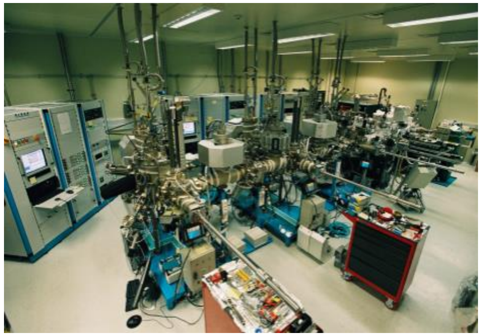
LETTERS nature nanotechnology
PUBLISHED ONLINE: 25 MAY 2015 | DOI: 10.1038/NNANO.2015.107

**Electrical detection of coherent spin precession using the ballistic intrinsic spin Hall effect**

Won Young Choi[1,2], Hyung-jun Kim[1], Joonyeon Chang[1], Suk Hee Han[1], Hyun Cheol Koo[1,2*] and Mark Johnson[3]

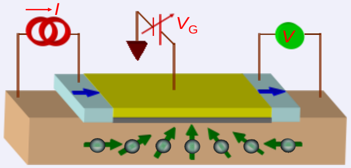
## 우수한 연구 인프라

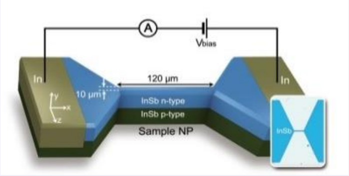
- Cluster MBE를 비롯한 스핀소재/소자용 전용 장비보유
- KIST Micro/Nano FAB과 직접 연계한 인프라 시스템 구축



# Research Fields

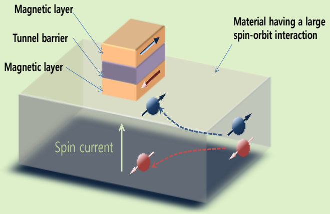
## Spin Transistor and logic device

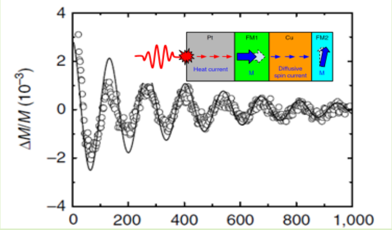




Science (2009), Nature (2013),
Nature Nanotech. (2015)

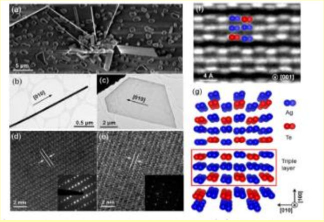
## Spin torque memory

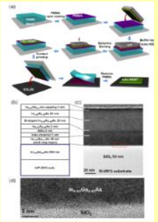




Nature (2009), Nature Comm. (2014), Nature
Physics (2015), Nano Letters (2016)

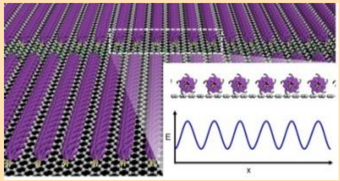
## New materials for spintronics

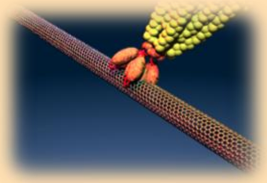




Nano Letters (2011, 2012), ACS Nano (2013),

## Bio-electronic material

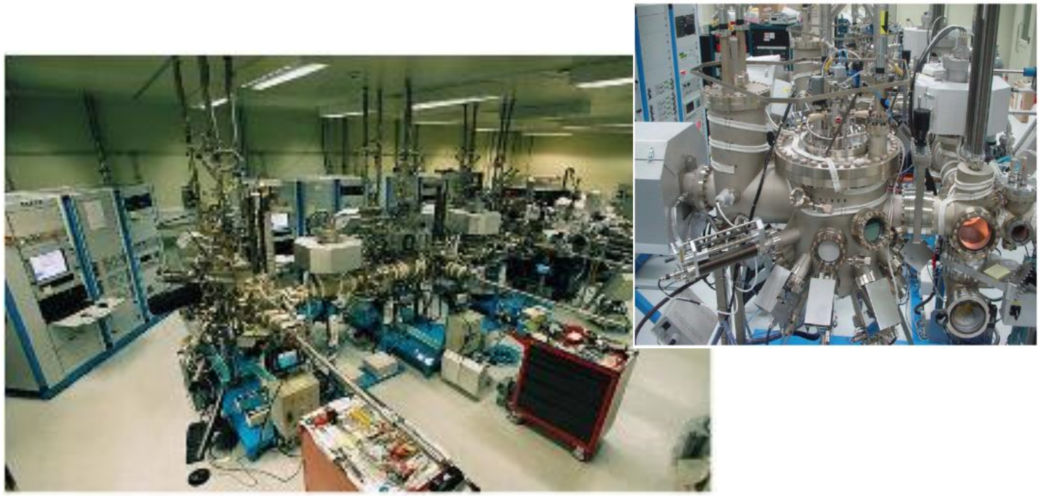




Advanced Materials (2015, 2016)

# Experimental Facilities

## Cluster MBE system



## Clean room facilities (495 m$^2$, 69 equipments)

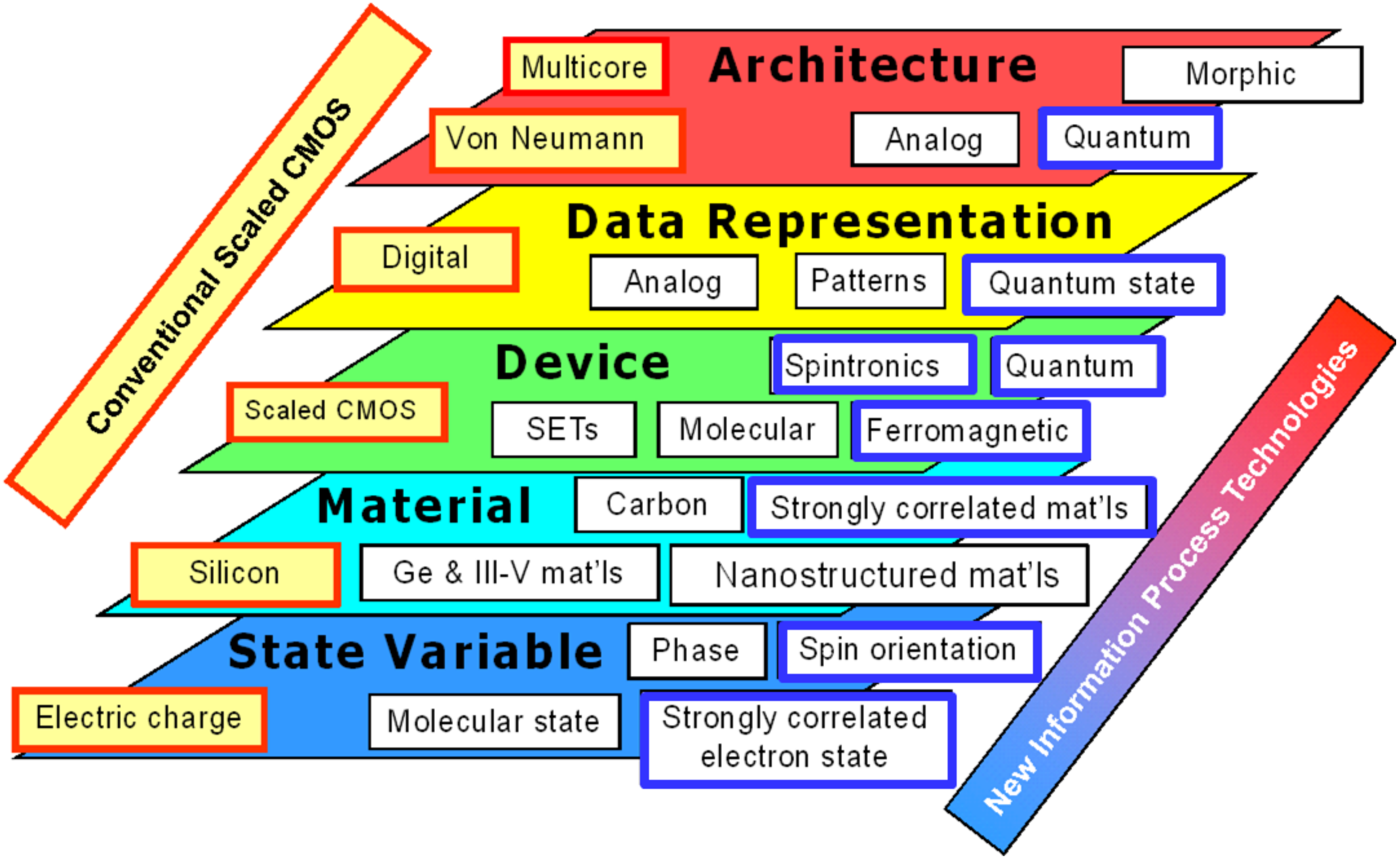
## E-beam lithography system

## Physical Property Measurement System

## Ion Beam /Plasma Etcher

# Why spintronics?

International Technology Roadmap for Semiconductors (2013)



Conventional Scaled CMOS

**Architecture**
Multicore
Von Neumann
Analog
Quantum
Morphic

**Data Representation**
Digital
Analog
Patterns
Quantum state

**Device**
Scaled CMOS
SETs
Molecular
Spintronics
Quantum
Ferromagnetic

**Material**
Silicon
Ge & III-V mat'ls
Carbon
Strongly correlated mat'ls
Nanostructured mat'ls

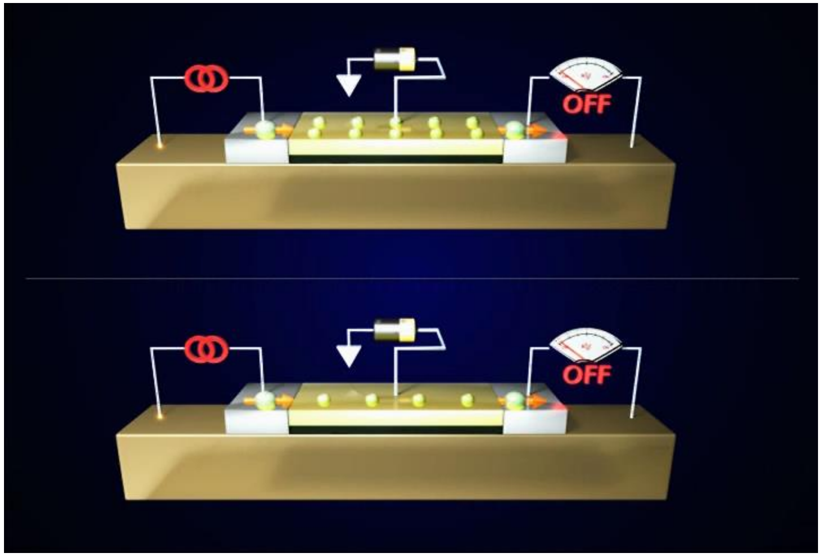
**State Variable**
Electric charge
Molecular state
Phase
Spin orientation
Strongly correlated electron state

New Information Process Technologies

☐ Spintronics-related field

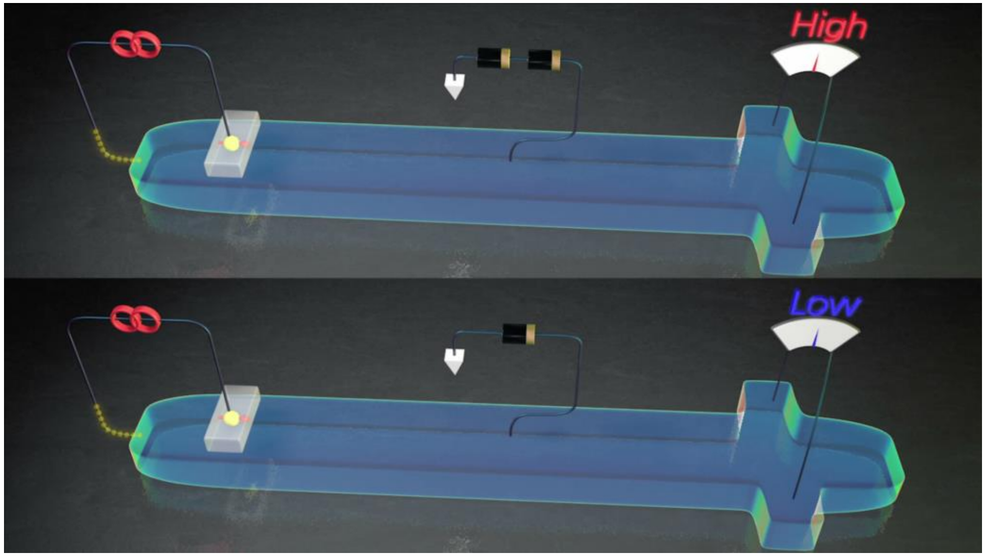
# Two fascinating devices in semiconductor spintroncis

## Spin-FET



(*Science* 2009)

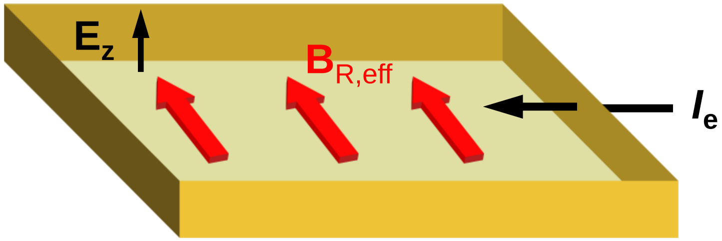
## Spin Hall Transistor



(*Nature Nanotechnology* 2015)

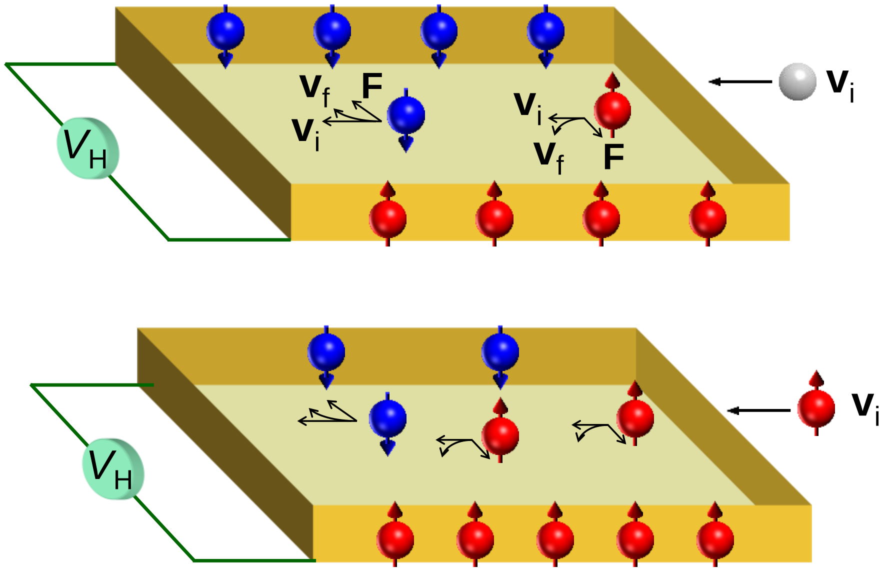
# Main Physics

**Rashba effect:** When the perpendicular electric field exists, the flow of electrons induces the effective magnetic field.



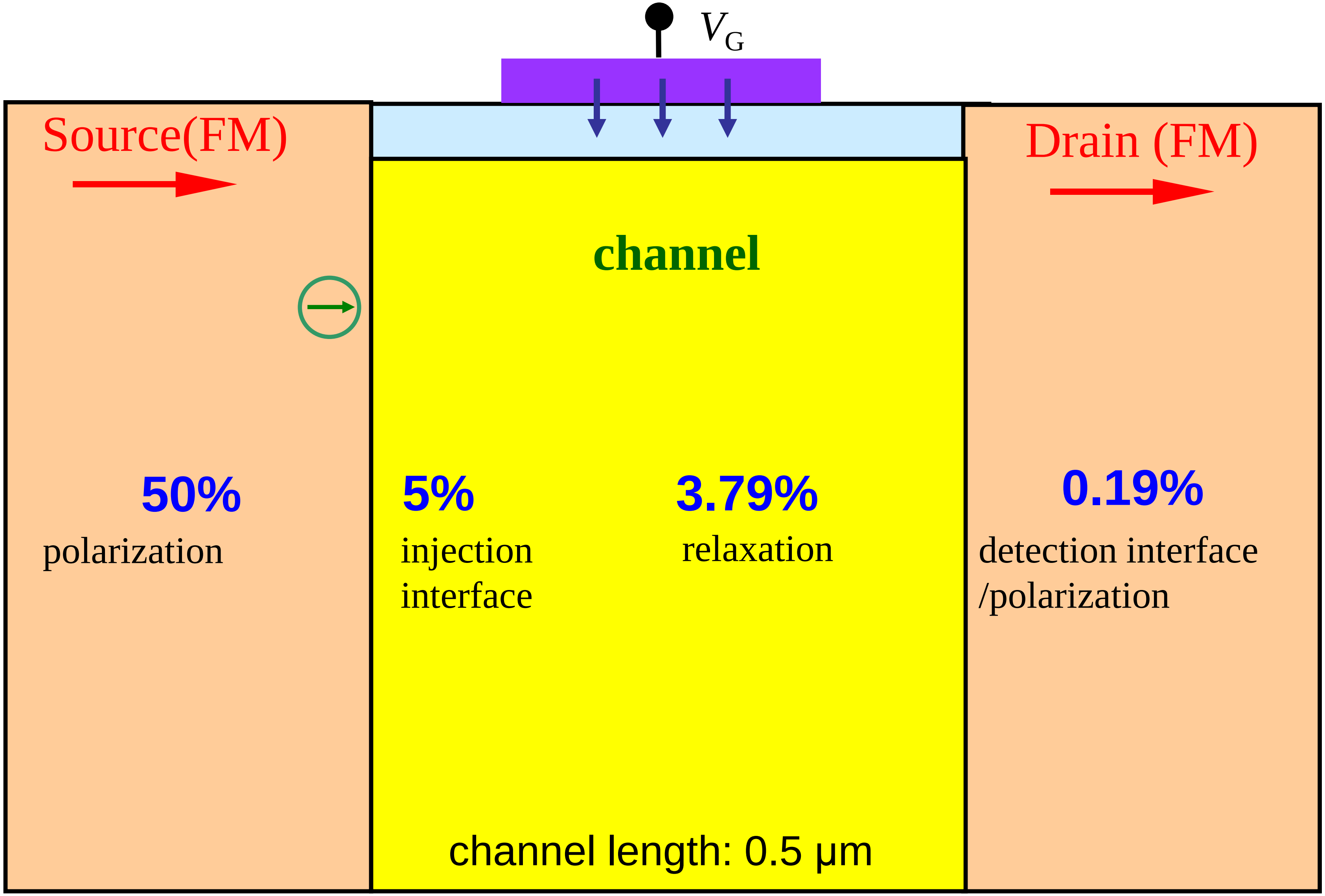
→ Gate control of spin orientation

**Spin Hall effect:** The direction of the carrier deviation depends on the spin orientation.



→ Realization of spin-charge conversion

# Difficulties for developing spin transistor



$V_G$

Source(FM)

Drain (FM)

**channel**

**50%**
polarization

**5%**
injection
interface

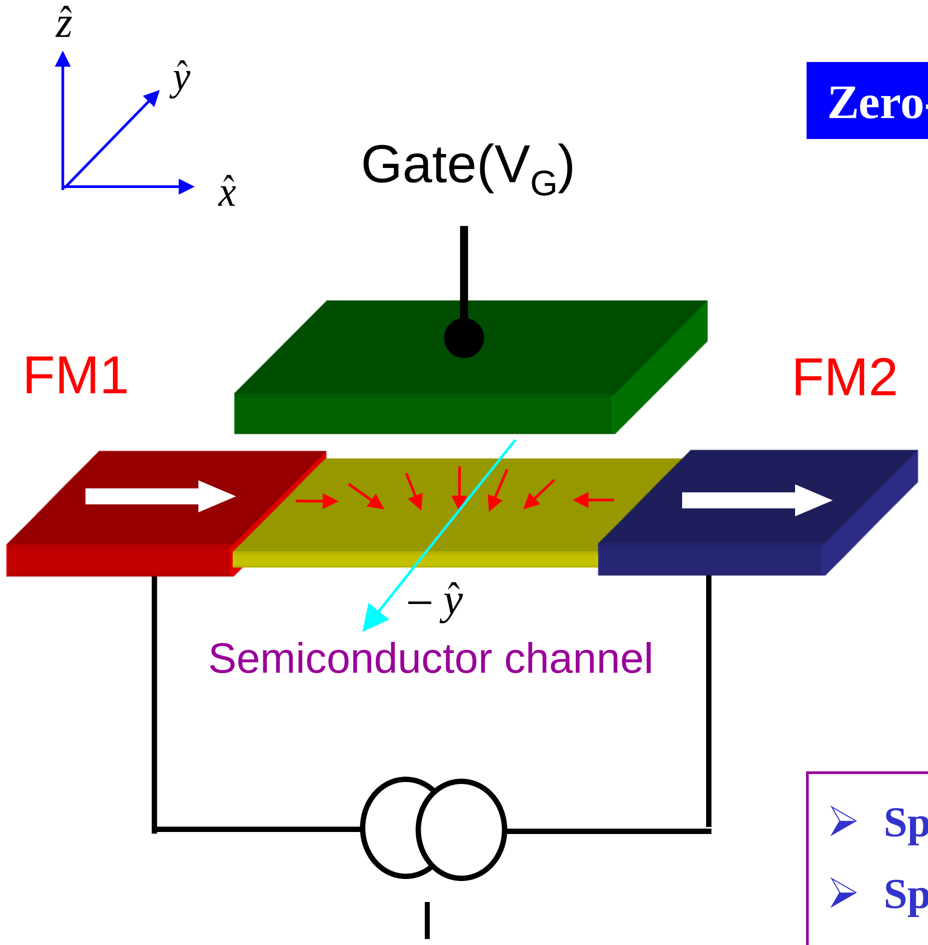
**3.79%**
relaxation

**0.19%**
detection interface
/polarization

channel length: 0.5 μm

# Spin transport channel

# Spin field effect transistor (spin-FET)



Datta and Das, APL 1990

**Zero-field spin splitting (Rashba Hamiltonian)**

$$H_R = \alpha \, (\vec{\sigma} \times \vec{k}) \cdot \hat{z}$$

**Spin precession angle for the electron traveling the channel length *L***

$$\Delta\theta = \frac{2m\alpha L}{\hbar^2}$$

- **Spin injection from FM1**
- **Spin precession by Rashba spin-orbit interaction.**
- **Spin detection at FM2 after Δθ – precession**

# Material : InAs quantum well structure

**InAs (2 nm)**

**$In_{0.52}Al_{0.48}As$ (20 nm)**

**$In_{0.53}Ga_{0.47}As$ (13.5 nm)**

**InAs quantum well (2 nm)**

**$In_{0.53}Ga_{0.47}As$ (2.5 nm)**

**$In_{0.52}Al_{0.48}As$ (6 nm)**

**n+ $In_{0.52}Al_{0.48}As$ (7 nm) , n= 4 x $10^{18}$ /$cm^3$**

**$In_{0.52}Al_{0.48}As$ (buffer)**

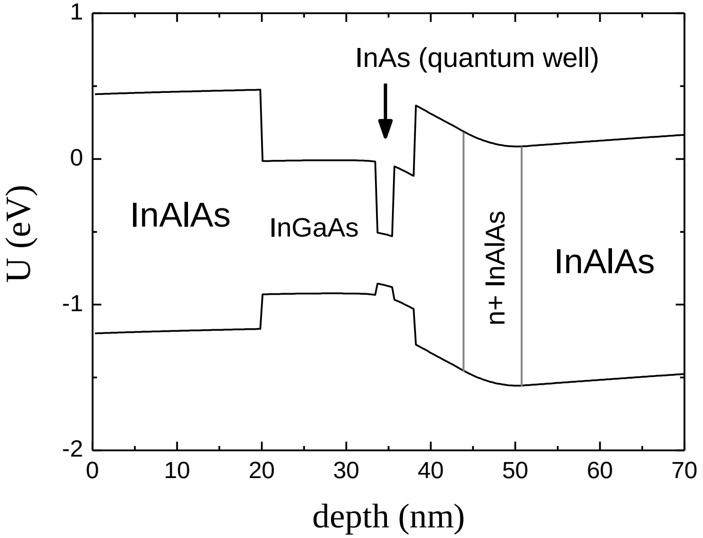
**Semi-insulated InP(100)**

| Temperature (K) | Carrier Density ($\times 10^{12}$ $cm^{-2}$) | Mobility ($cm^2$/Vsec) | Sheet resistance ($\Omega$) |
|---|---|---|---|
| 300 | ~2 | ~10000 | ~250 |
| 1.8 | ~2 | ~60000 | ~45 |

Large spin-orbit interaction parameter : $\alpha \approx 1.0 \times 10^{-11}$ eVm ($T$ = 1.8 K)

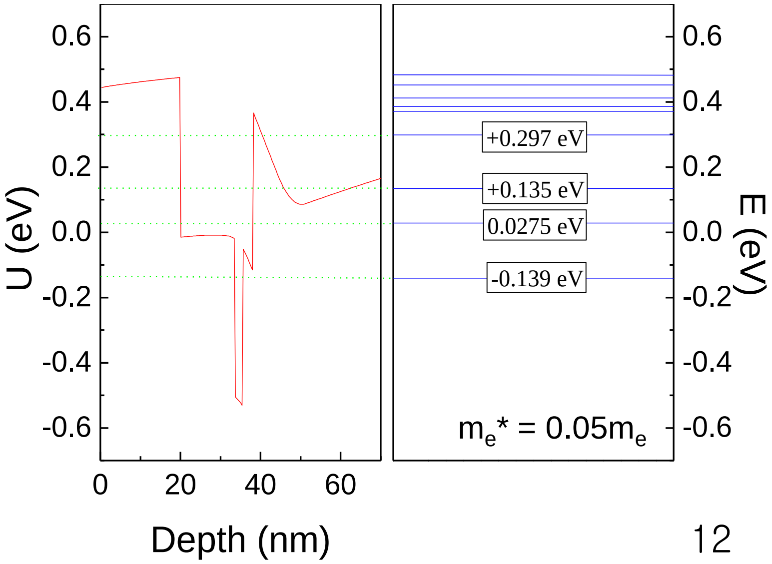
# Energy band profile of the InAs quantum well

| |
|---|
| InAs (2nm) |
| $In_{0.52}Al_{0.48}As$ (20 nm) |
| $In_{0.53}Ga_{0.47}As$ (13.5 nm) |
| InAs QW (2nm) |
| $In_{0.53}Ga_{0.47}As$ (2.5 nm) |
| $In_{0.52}Al_{0.48}As$ (6 nm) |
| n+ $In_{0.52}Al_{0.48}As$ (7 nm) |
| $In_{0.52}Al_{0.48}As$ (300 nm) |
| InP substrate |



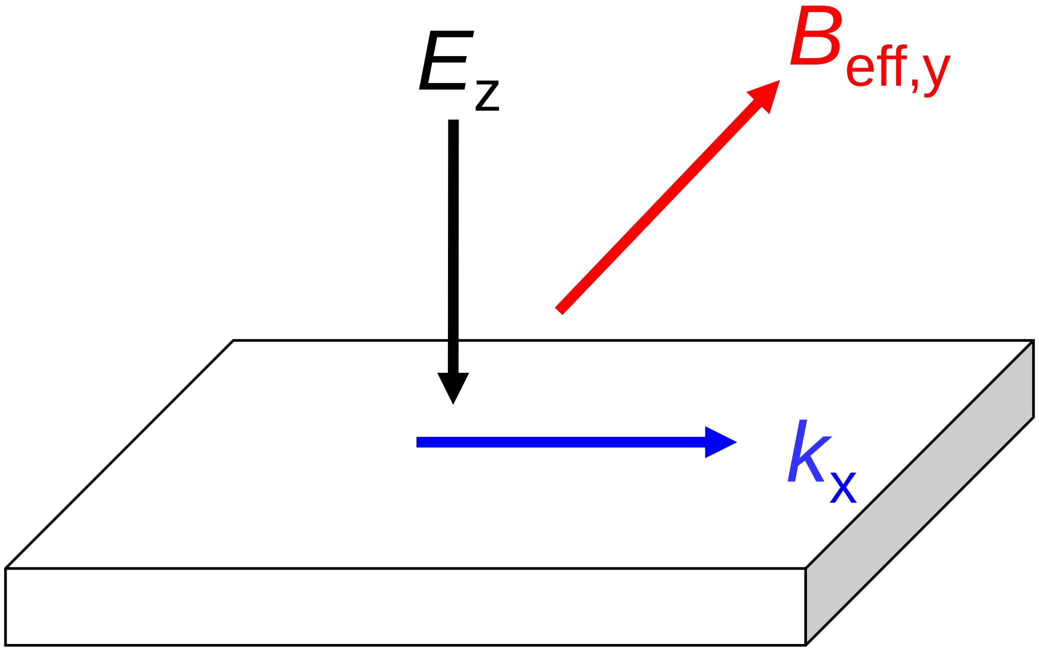
Only one quantum level exists below the Fermi energy.

No magneto-intersubband scattering

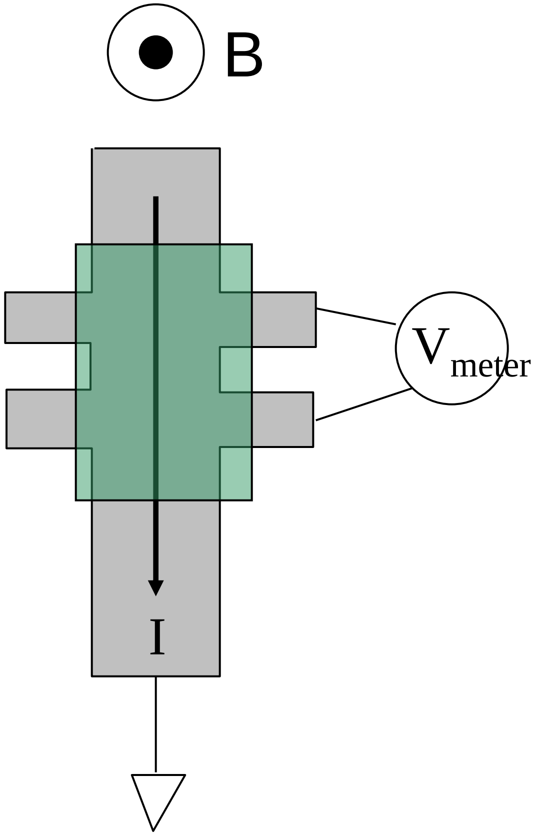


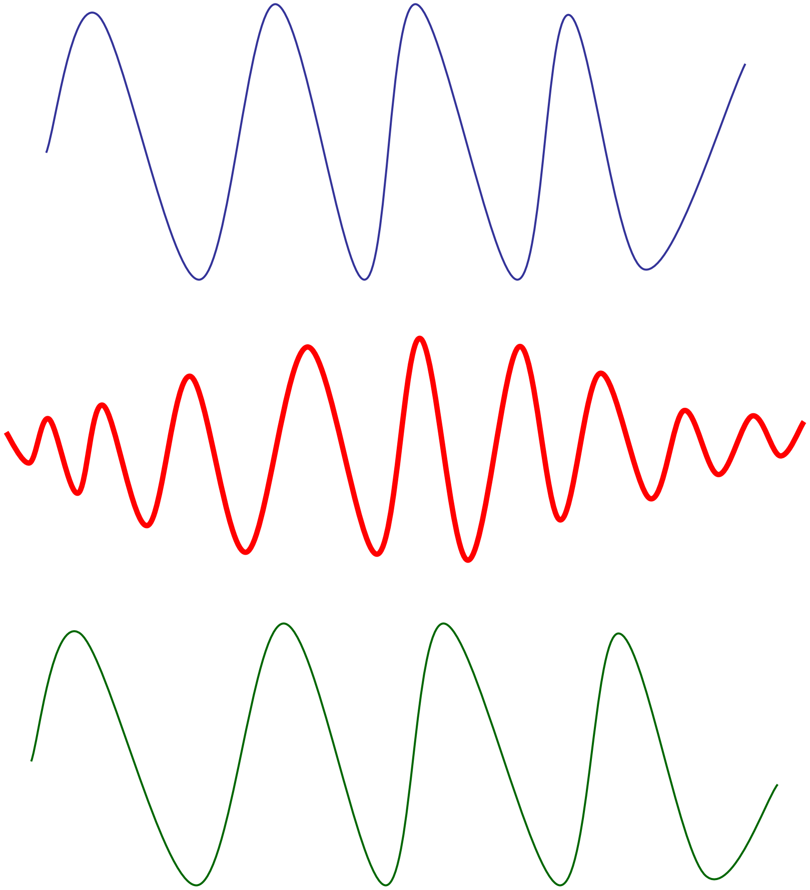
# Spin-orbit interaction (Rashba effect)

: When the perpendicular electric field ($E_z$) exists, the flow of electrons ($k_x$) in two-dimensional electron gas (2-DEG) produces unbalanced population of spin up and down electrons due to the effective magnetic field ($B_y$) induced by so-called Rashba effect.



# Shubnikov-de Haas (SdH) Oscillation





# Shubnikov-de Haas oscillations in our InAs

## Shubnikov-de Haas oscillation

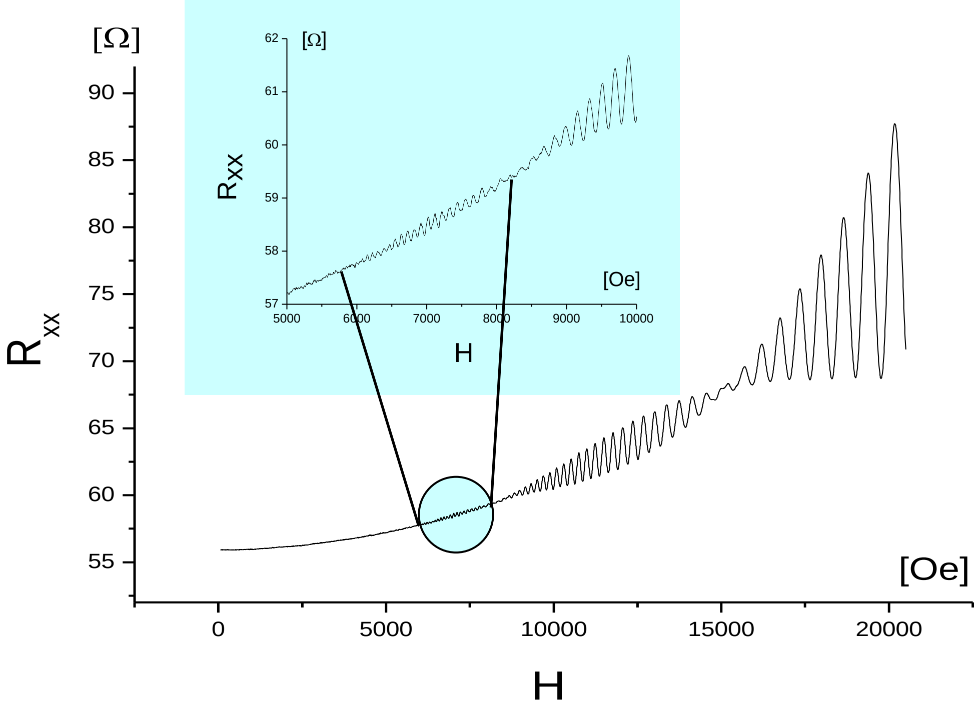
$$\boxed{\Delta\left(\frac{1}{B}\right) = \frac{2e}{h}\frac{1}{n_{2D}}}$$

$$n_{2D} = n_{\uparrow} + n_{\downarrow}$$

## Zero-field spin splitting

→ Beating pattern in $R_{xx}$

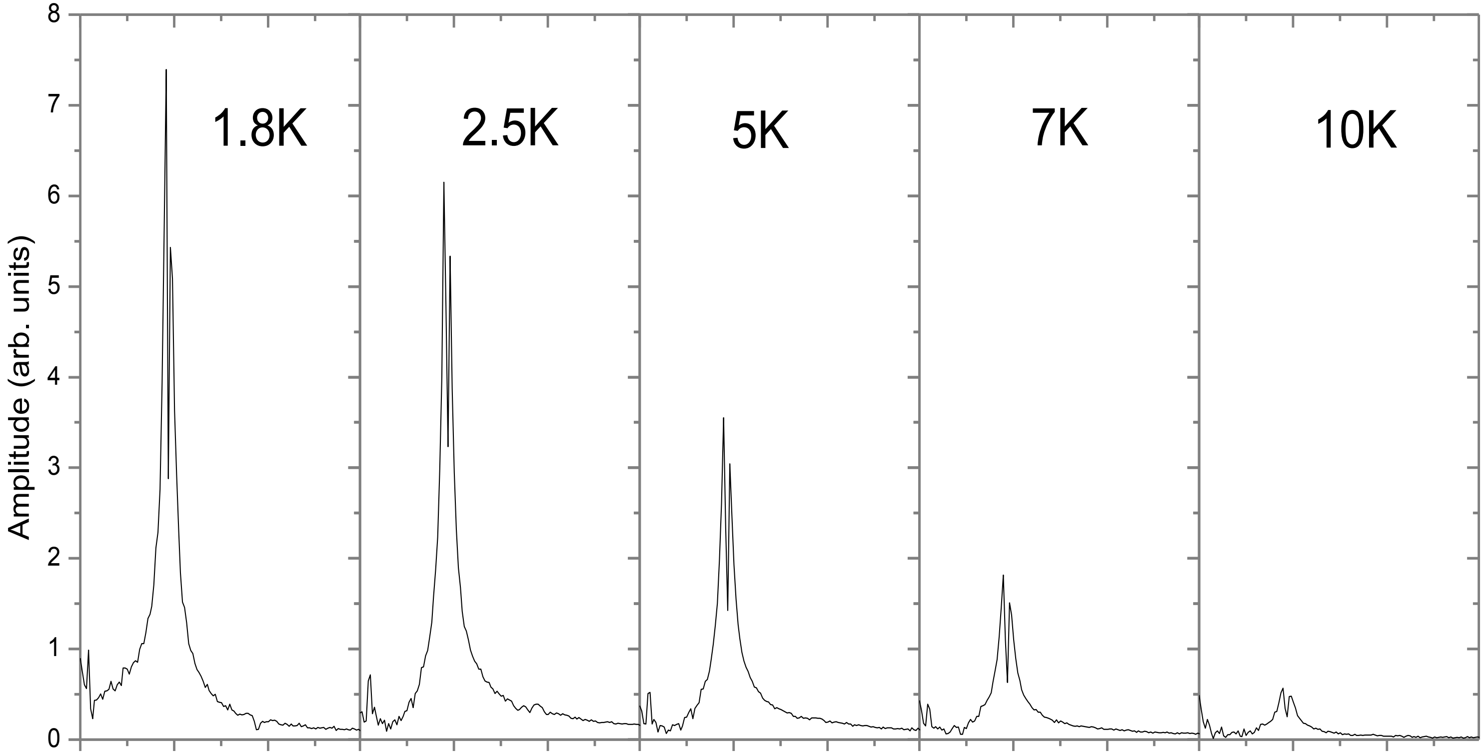
$$\boxed{n_{\uparrow} - n_{\downarrow} = \frac{e}{h}\frac{1}{\Delta(1/B)_{beat}}}$$



$$\Delta E = \frac{\pi\,\hbar^2}{m^*}\,(n_{\uparrow} - n_{\downarrow})$$

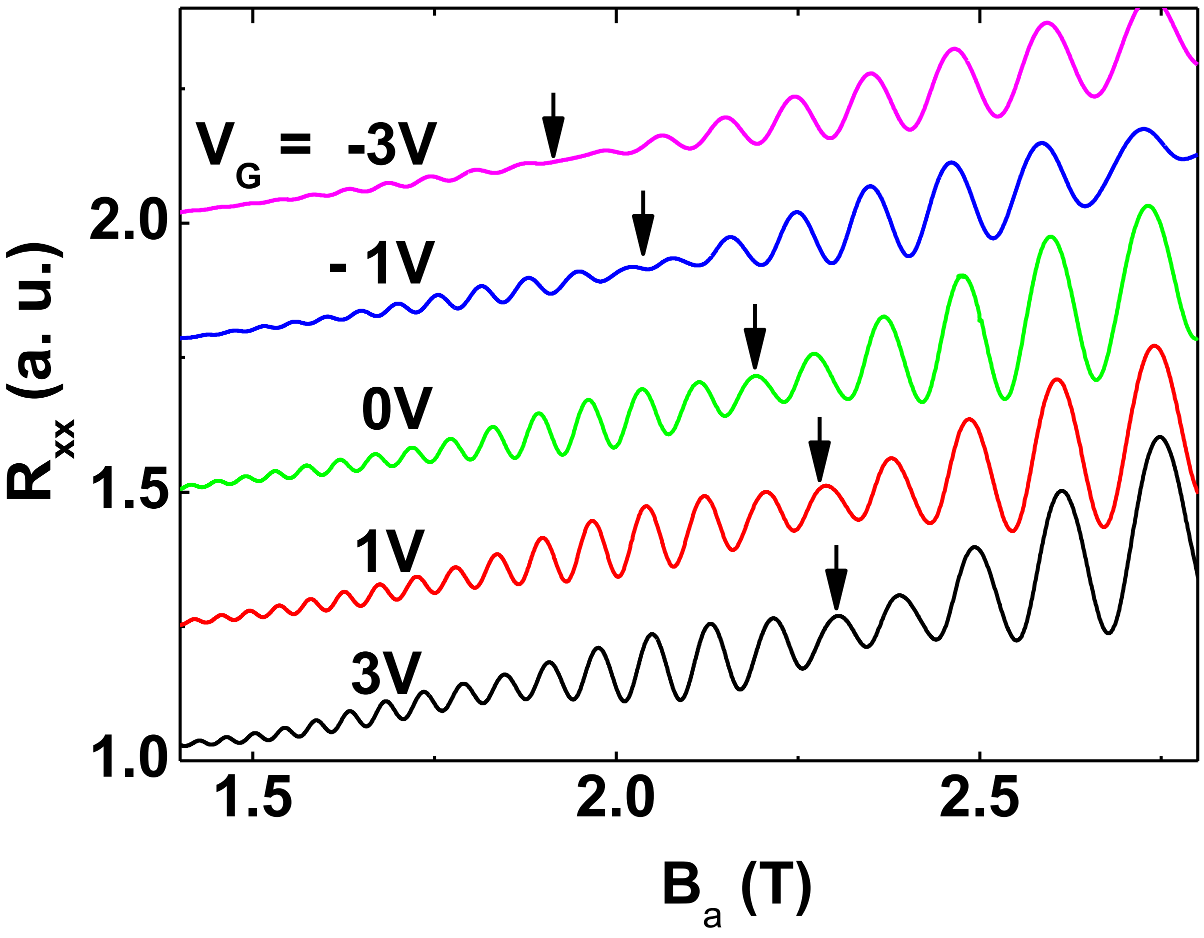
Using the observed ΔE, $\alpha = \Delta E/(2k_F) = \Delta E\,/\,(2\pi\, n_{2D})^{0.5}$

# Temperature dependence of SdH measurement



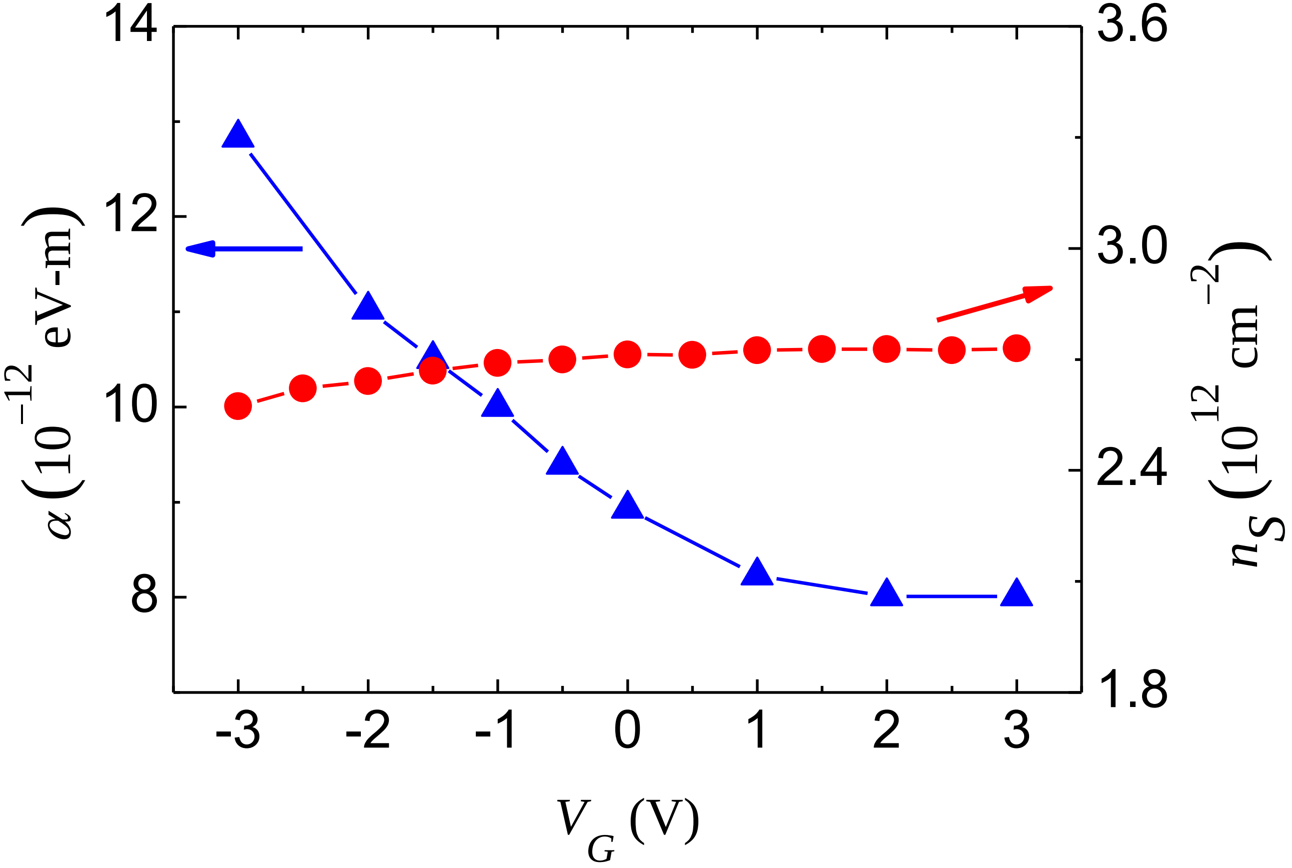
Major two peaks are not intermixing term between 1st and 2nd sub-band.

# Gate voltage dependence of SdH oscillations



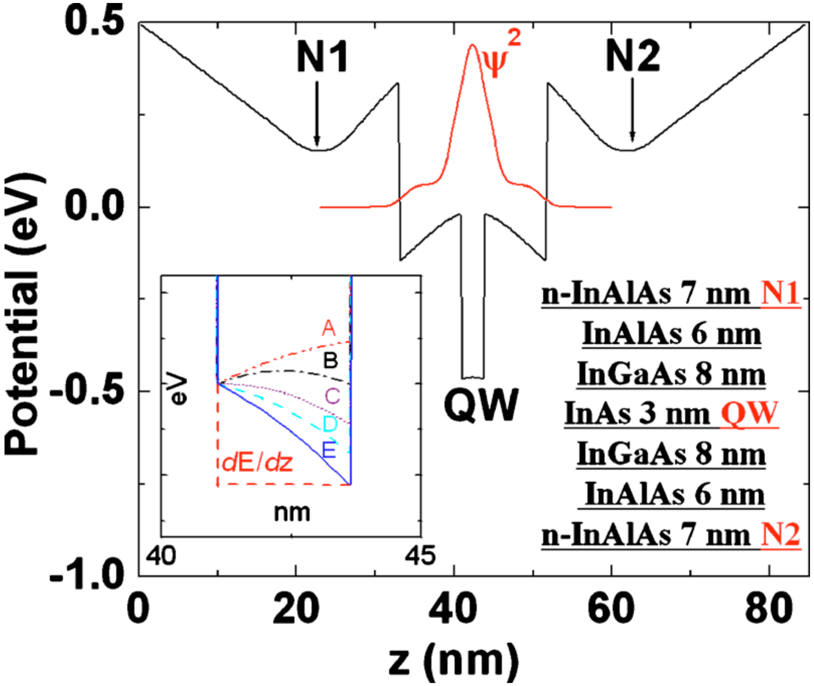
H. C. Koo *et al. Science* 325,1515 (2009)

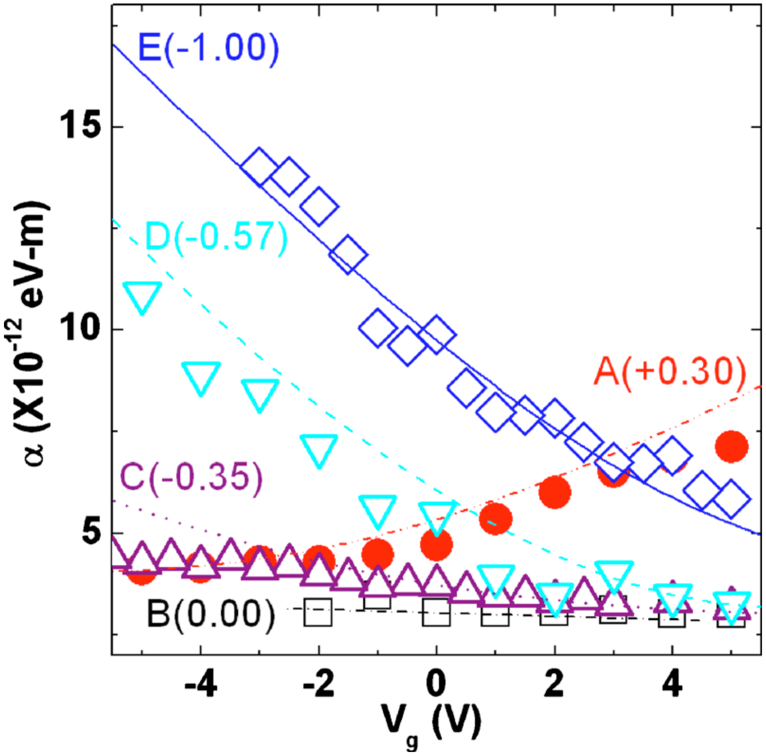
# Gate voltage dependence of $\alpha$ and carrier density



H. C. Koo *et al. Science* 325,1515 (2009)

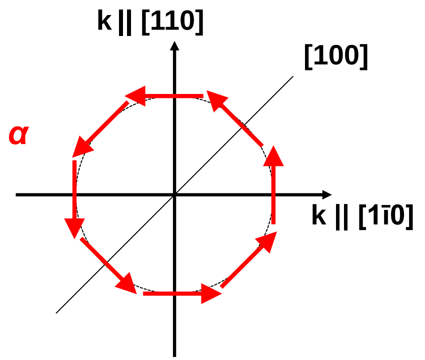
# Rashba constant control using doping levels

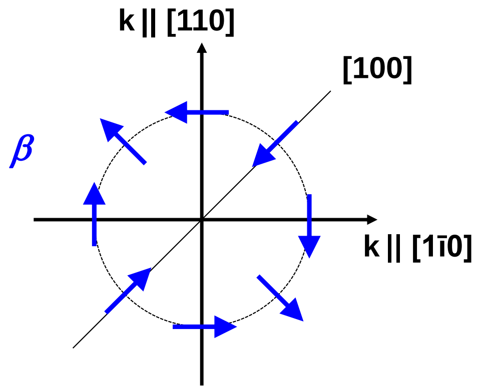




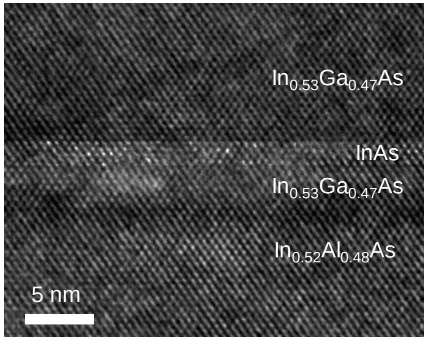
K.-H. Kim *et al. Appl. Phys. Lett.* 97,012504 (2010)

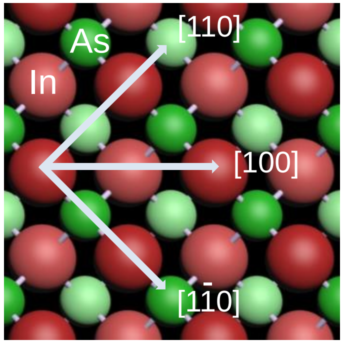
# Crystal direction dependence of Rashba (α) and Dresselhaus (β) effects

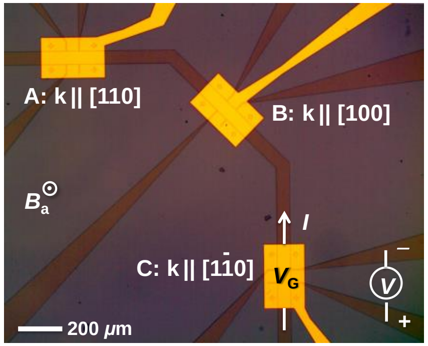




| |
|---|
| **InAs 2 nm** |
| **$\mathrm{In_{0.52}Al_{0.48}As}$ 20 nm** |
| **$\mathrm{In_{0.53}Ga_{0.47}As}$ 13.5 nm** |
| **InAs (Quantum Well) 2 nm** |
| **$\mathrm{In_{0.53}Ga_{0.47}As}$ 2.5 nm** |
| **$\mathrm{In_{0.52}Al_{0.48}As}$ 6 nm** |
| **$n$+ $\mathrm{In_{0.52}Al_{0.48}As}$ 7 nm ($n = 4\times10^{18}$)** |
| **$\mathrm{In_{0.52}Al_{0.48}As}$ 300nm** |
| **Semi-insulating InP(001) sub** |

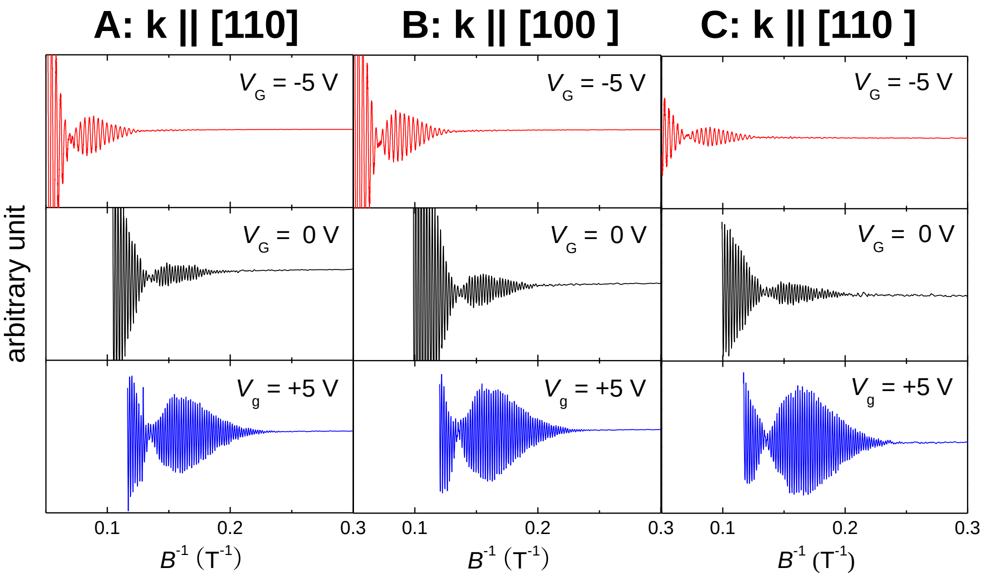


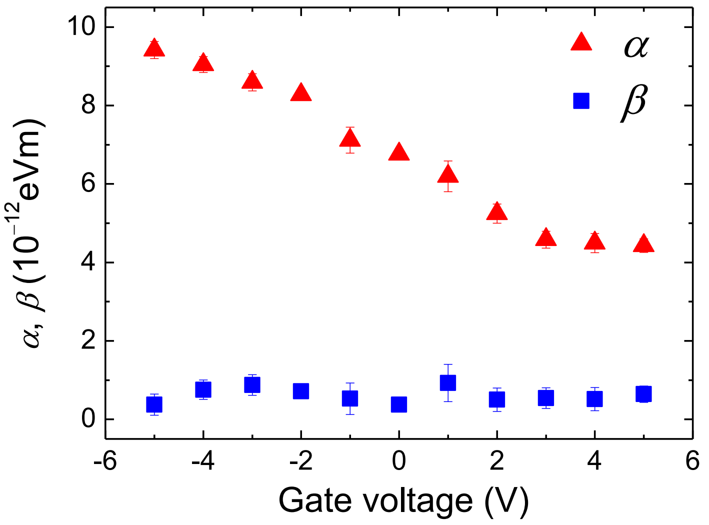




Y. H. Park *et al. Appl. Phys. Lett.* 103, 252407 (2013)

# Separation of Rashba and Dresselhaus term

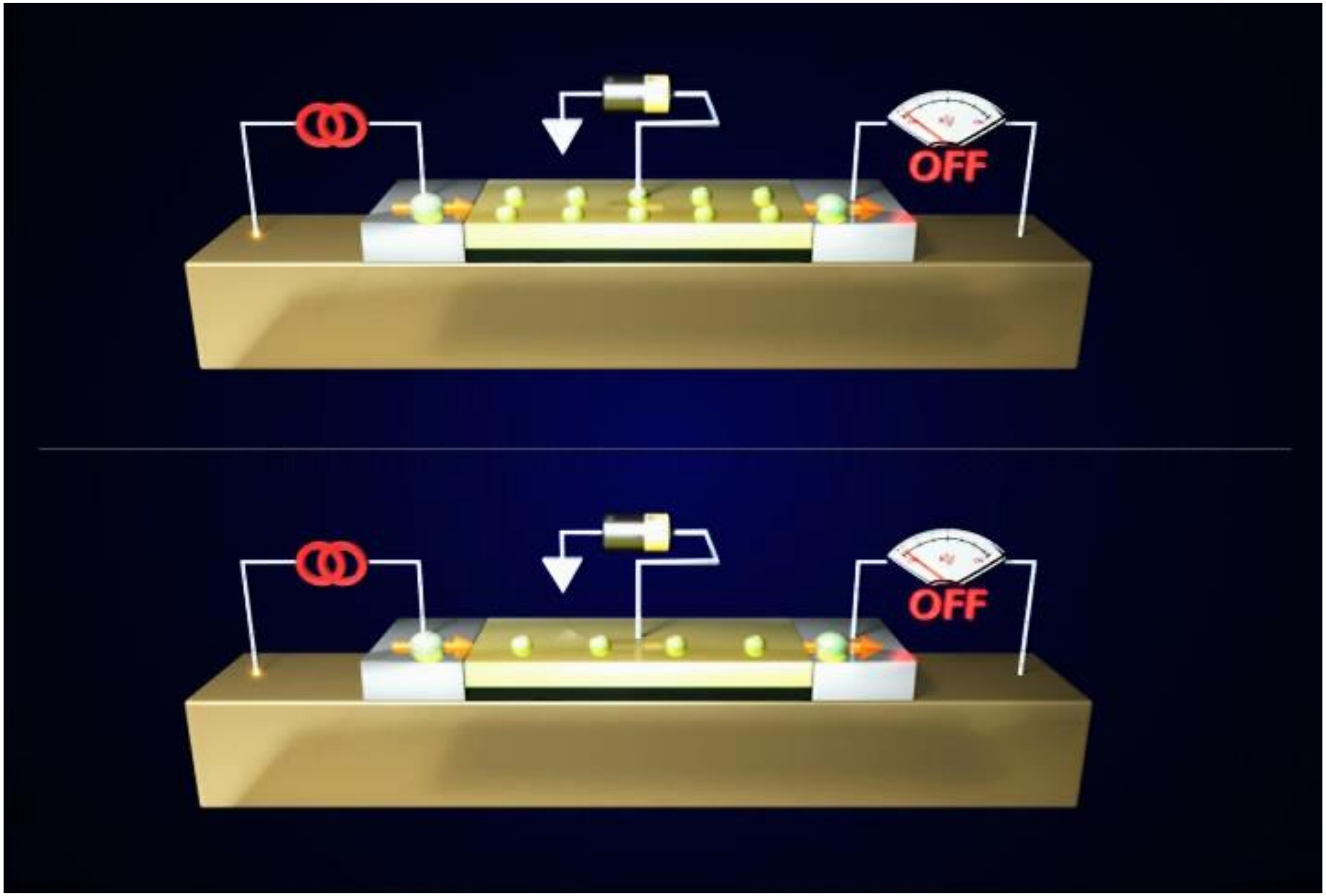




Y. H. Park *et al. Appl. Phys. Lett.* 103, 252407 (2013)

# Spin-FET operation

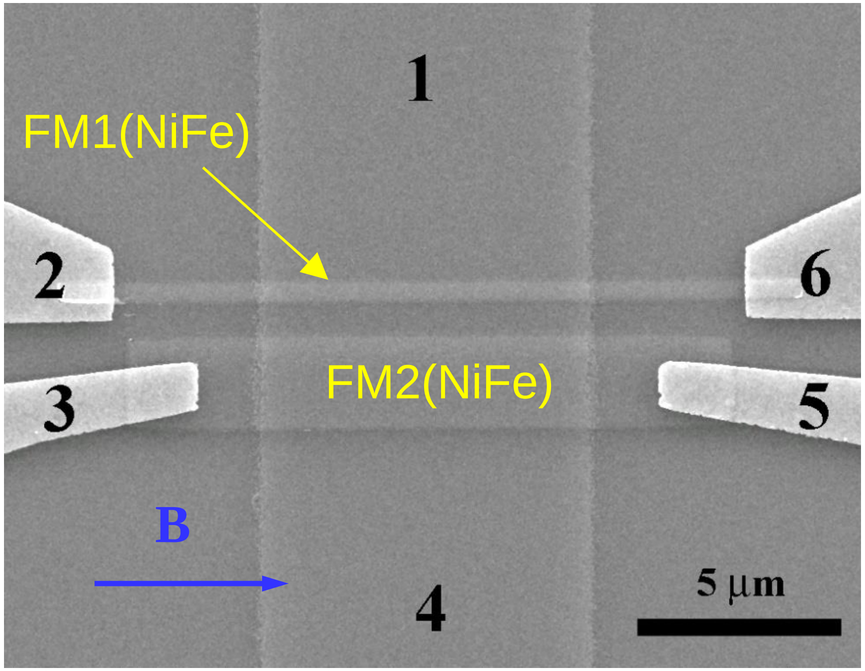
# Spin-FET



H. C. Koo *et al.*

# Semiconductor spin-valve : NiFe/(InAs-2DEG)/NiFe

Korea Institute of Science and Technology

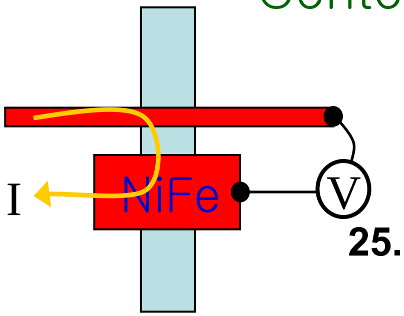


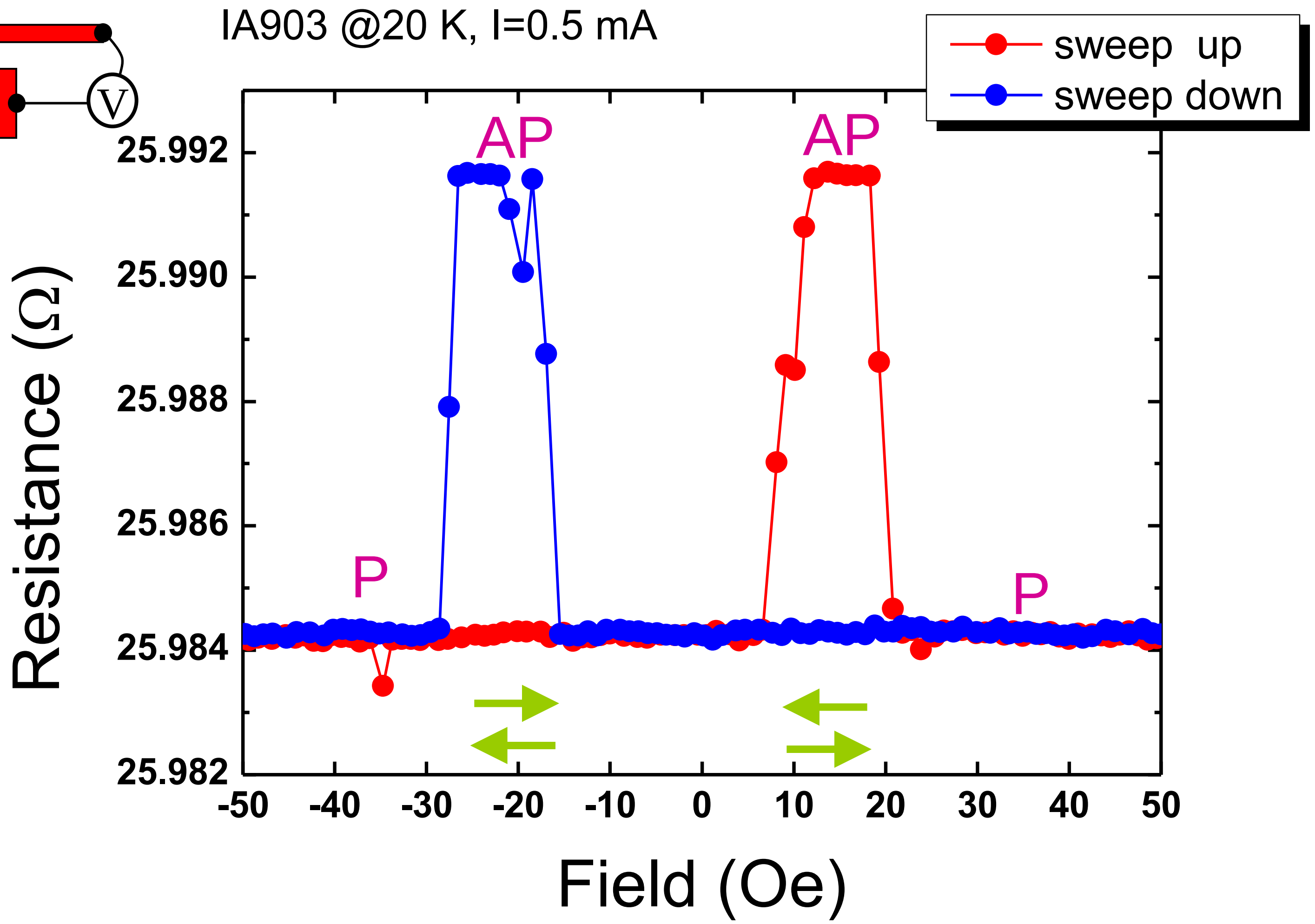
Local measurement
(Spin-valve effect)

Non-local measurement
(Spin accumulation)

# Local spin valve measurement at *T* = 20 K

Center-to-center distance between FM1 and FM2 = 2.2 μm

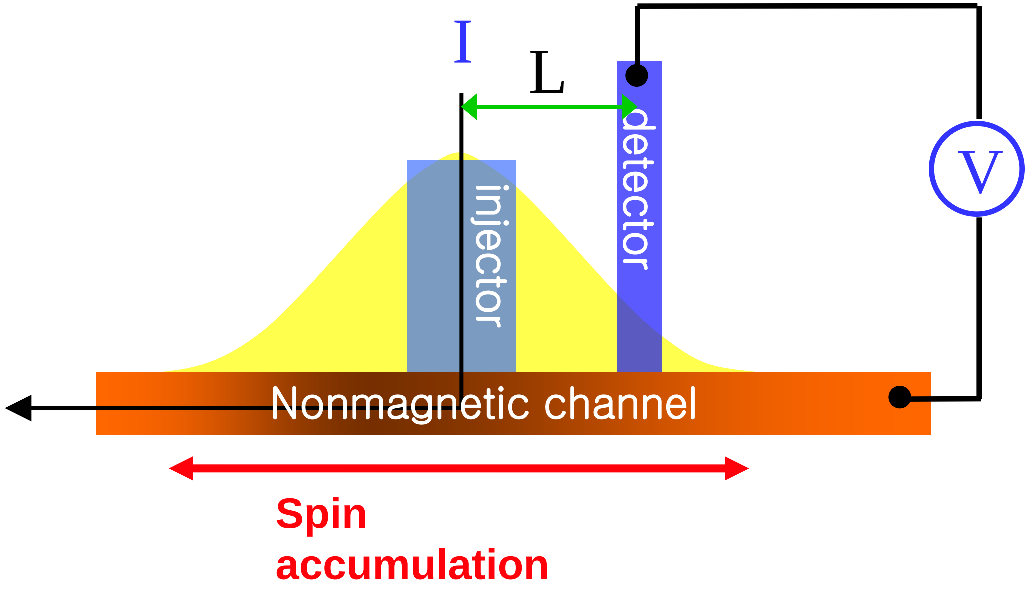




H. C. Koo *et al. Appl. Phys. Lett.* 90,022101 (2007)

# Non-local measurement

## Ferromagnetic injector and detector



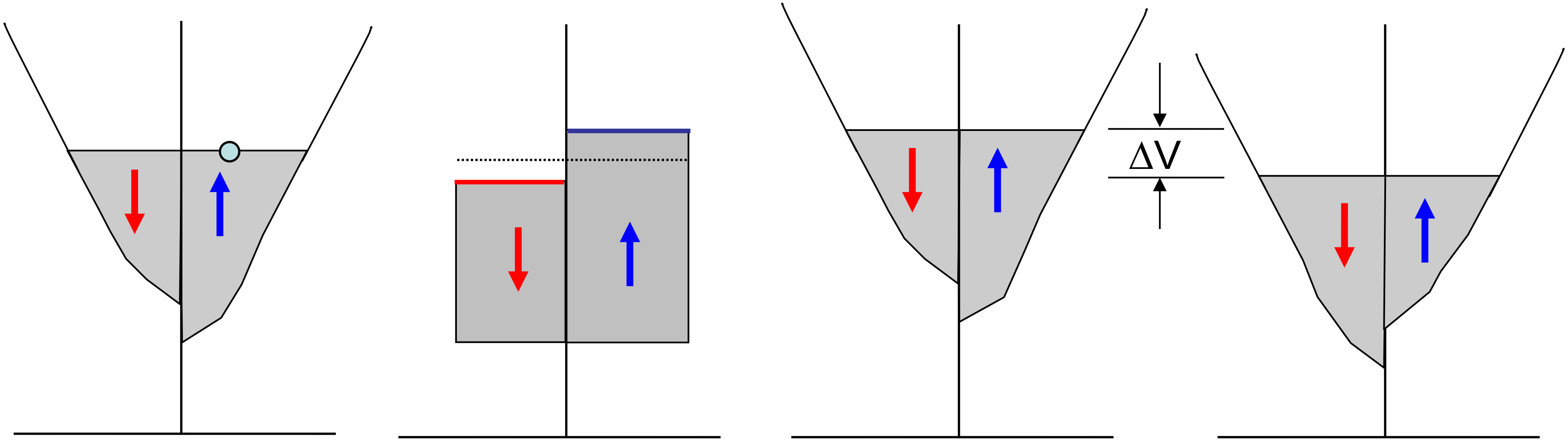
$$\frac{\mu}{I} = R_{spin} = \frac{\eta_1\eta_2\rho\lambda_s}{A} e^{-L/\lambda_s}$$

$$= \frac{\eta_1\eta_2 R_t\lambda_s}{W} e^{-L/\lambda_s} \quad \text{(for 2 DEG)}$$

$\mathbf{R}_t$ : sheet resistance
$\lambda_s$ : spin diffusion length

Johnson and Silsbee, Phys. Rev. B **37**, 5312 (1988)
Johnson, J. Appl. Phys. 75, 6714 (1994)
Zutic et al., Rev. Mod. Phys. **76**, 323 (2004)

# Mechanism of non-local signal



FM1

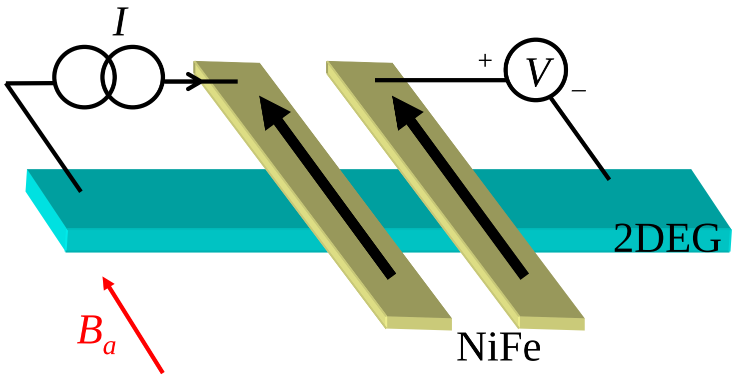
Channel

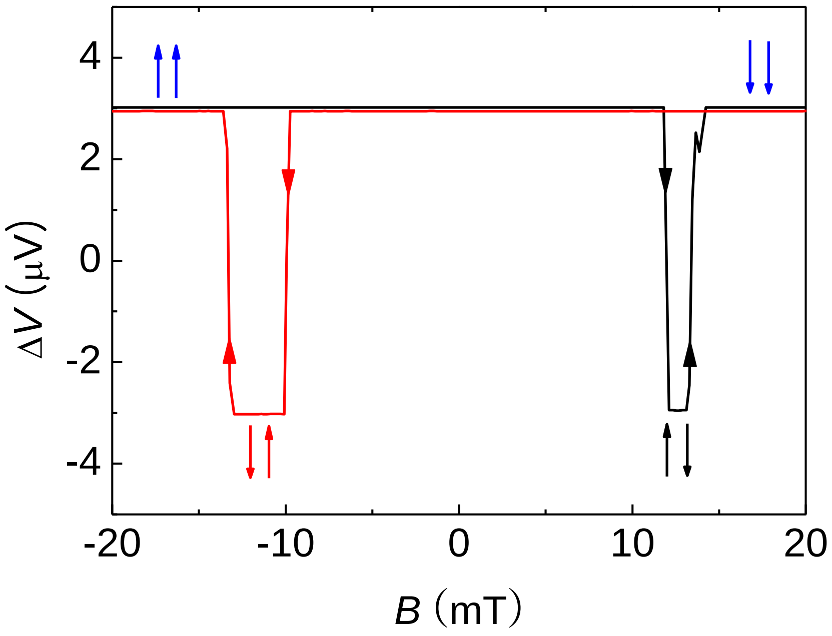
FM2
parallel

FM2
anti-parallel

# Non-local measurement of spin injection

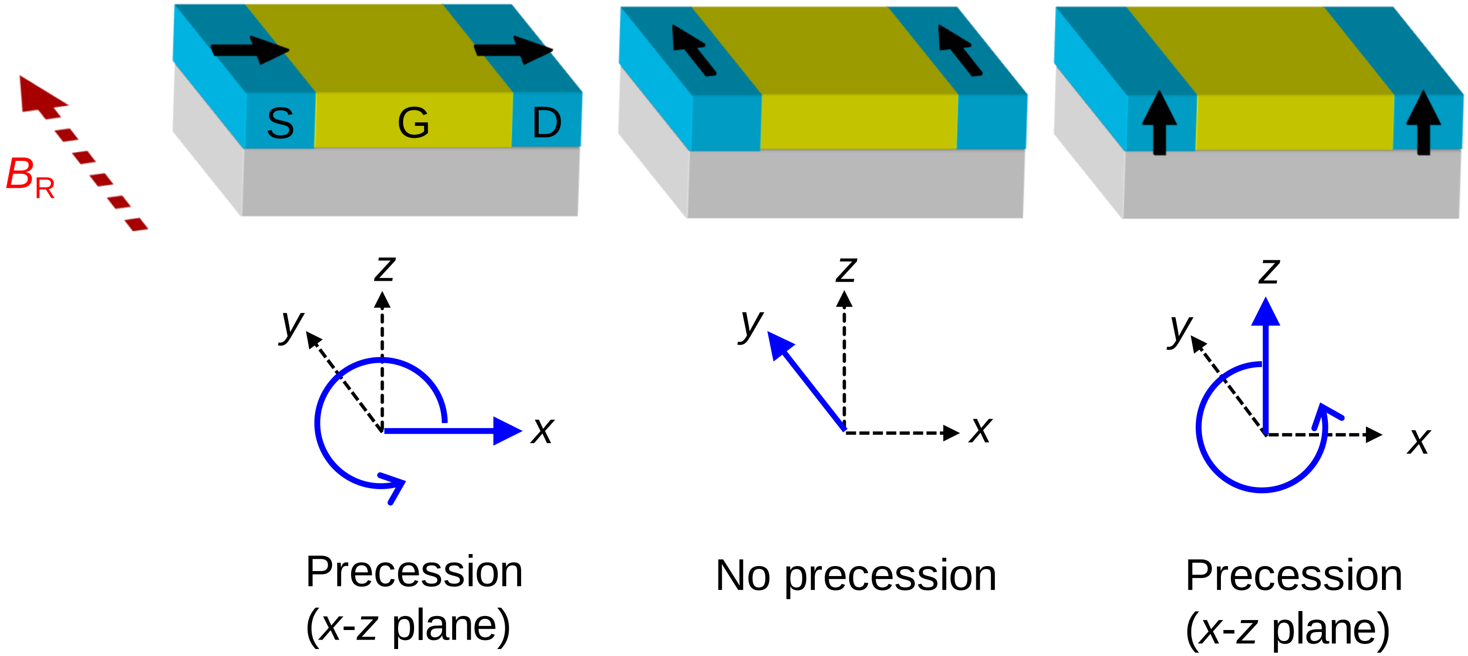
A clear spin valve signal by non-local measurement is observed at 1.8K.





H. C. Koo *et al. Science* 325,1515 (2009)

# Magnetization direction dependence of spin precession



Precession
($x$-$z$ plane)

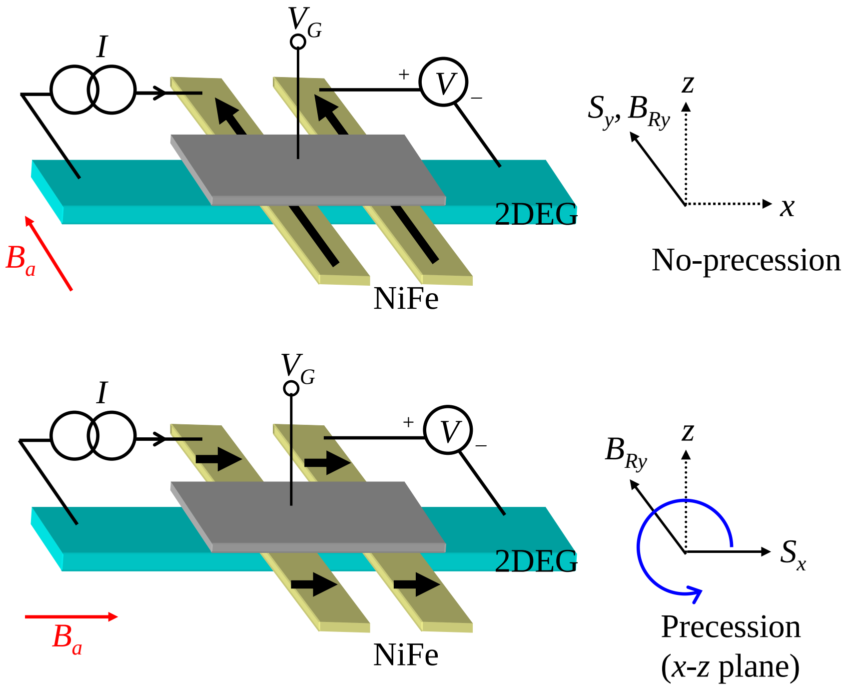
No precession

Precession
($x$-$z$ plane)

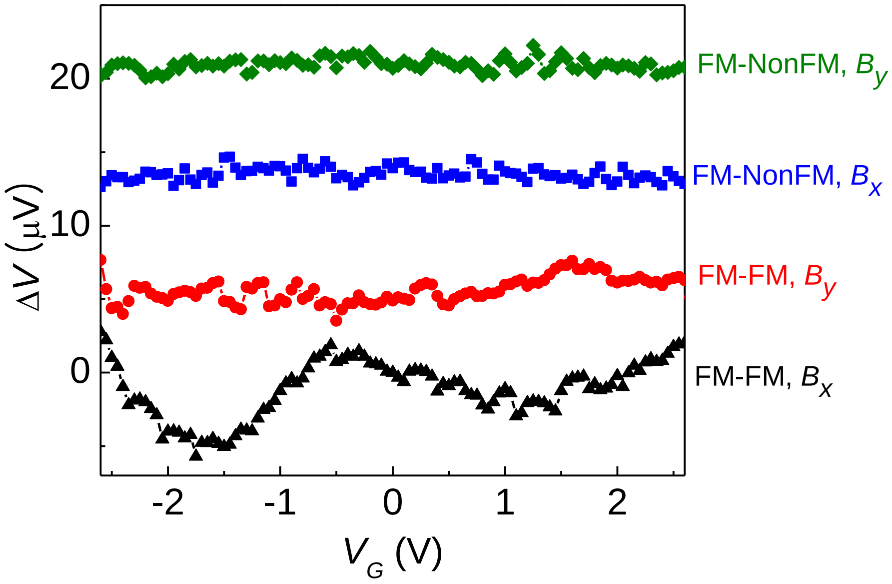
Magnetization of FM should be aligned in either $x$ or $z$ direction.

# Gate control of spin precession

## Magnetization configuration

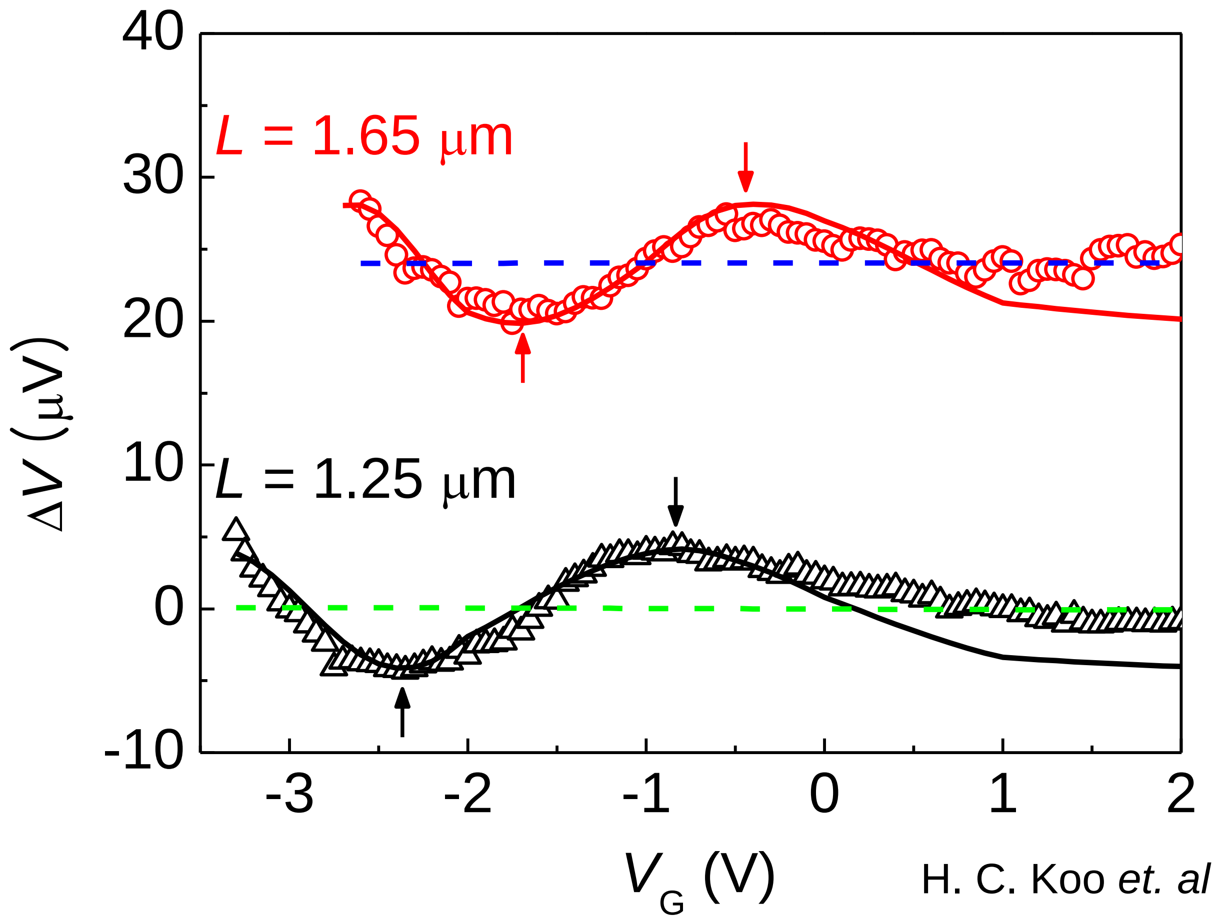


## Measurement at 1.8K



H. C. Koo *et al.* *Science* 325,1515 (2009)

# Fitting of Spin FET signals



Solid line : Ballistic

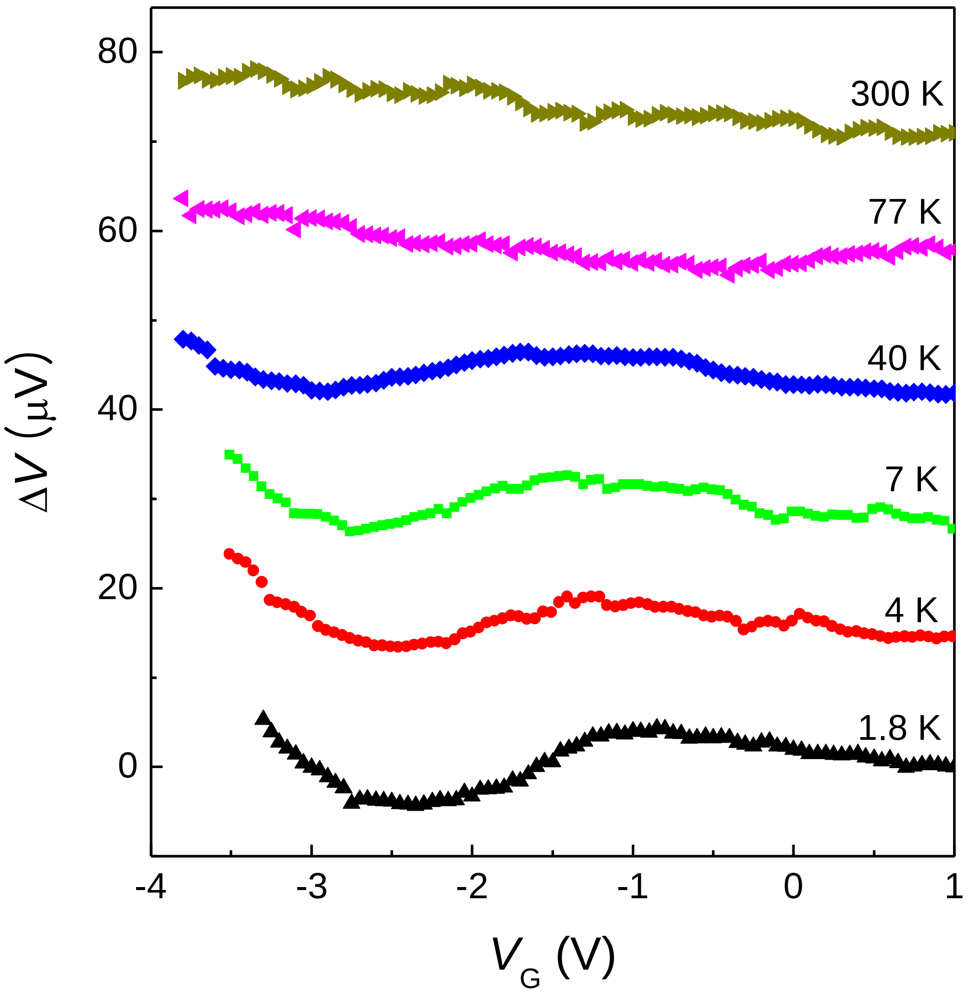
Dashed line : Diffusive

H. C. Koo *et. al. Science* 325,1515 (2009)

Period of oscillation signal when $L$ =1.65 μm : ~ 2.5 V

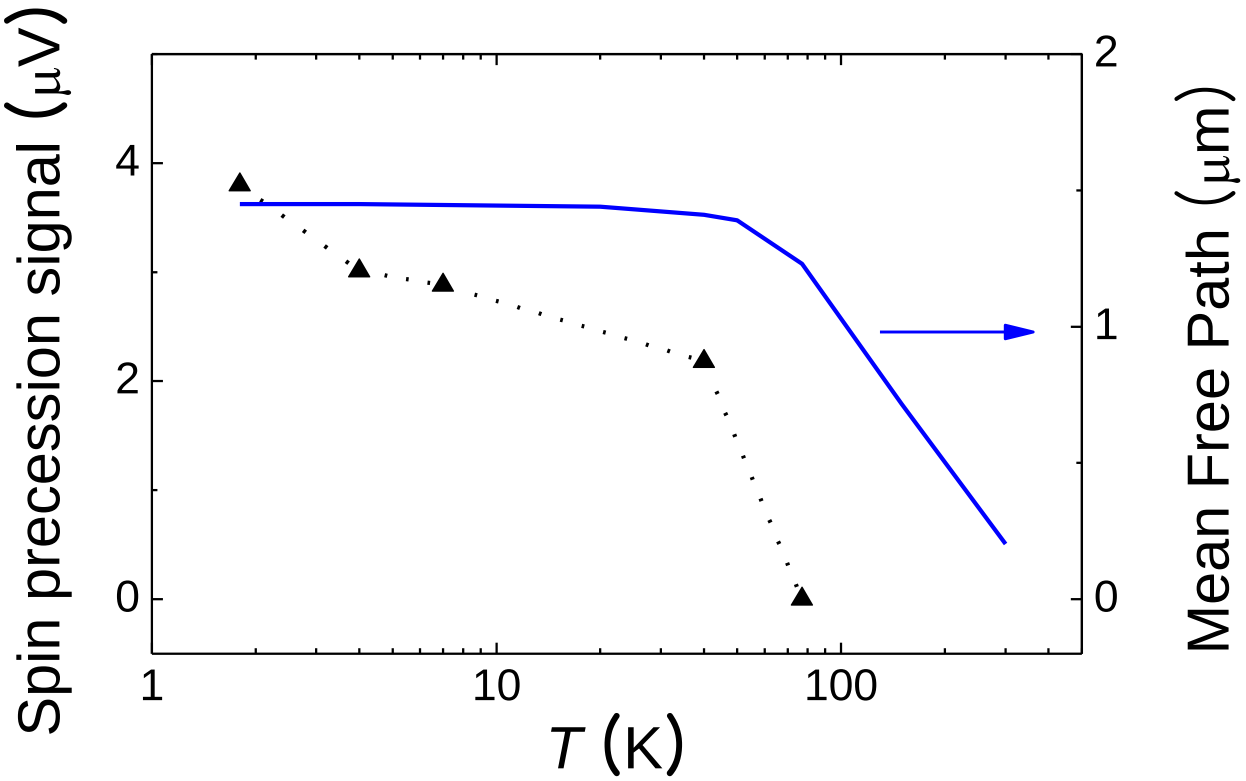
when $L$ =1.25 μm : ~3 V

# Temperature dependence of spin precession signal



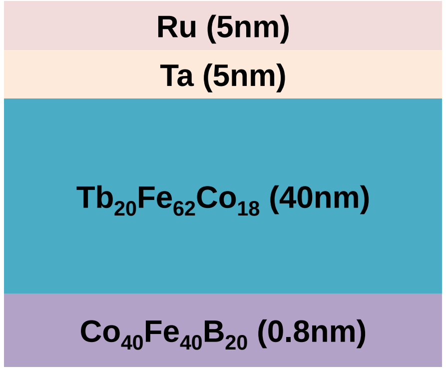
H. C. Koo *et al.* *Science* 325,1515 (2009)

# Spin precession signal and mean free path



H. C. Koo *et al. J. Phys. D: Appl. Phys.* (2011)

# Spin precession signal with a perpendicular magnetization

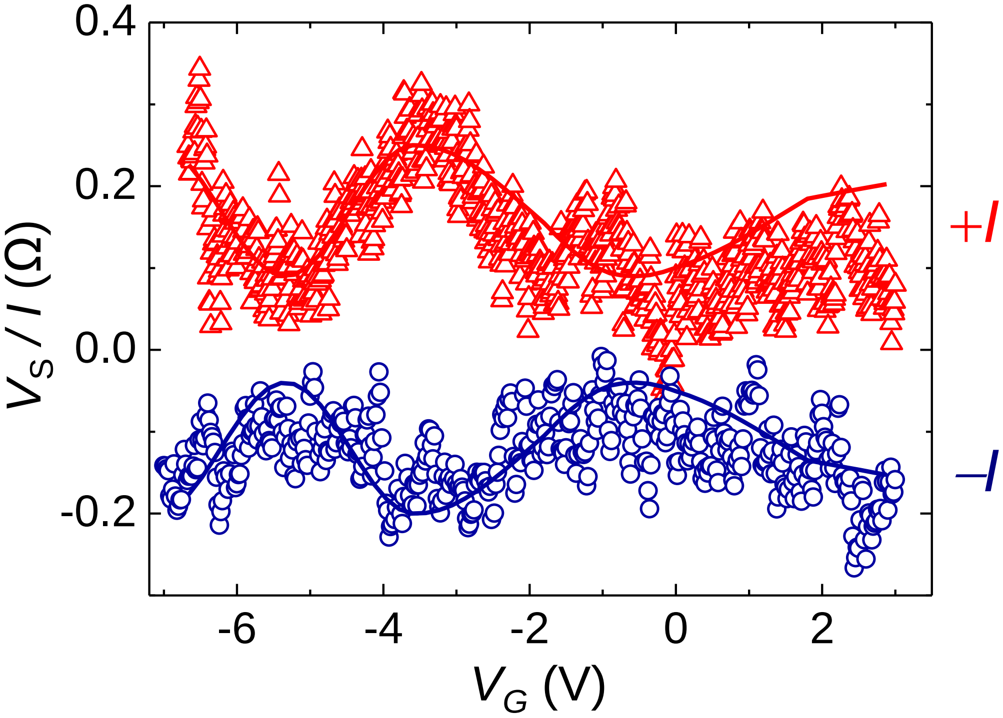


Ru (5nm)

Ta (5nm)

$Tb_{20}Fe_{62}Co_{18}$ (40nm)

$Co_{40}Fe_{40}B_{20}$ (0.8nm)

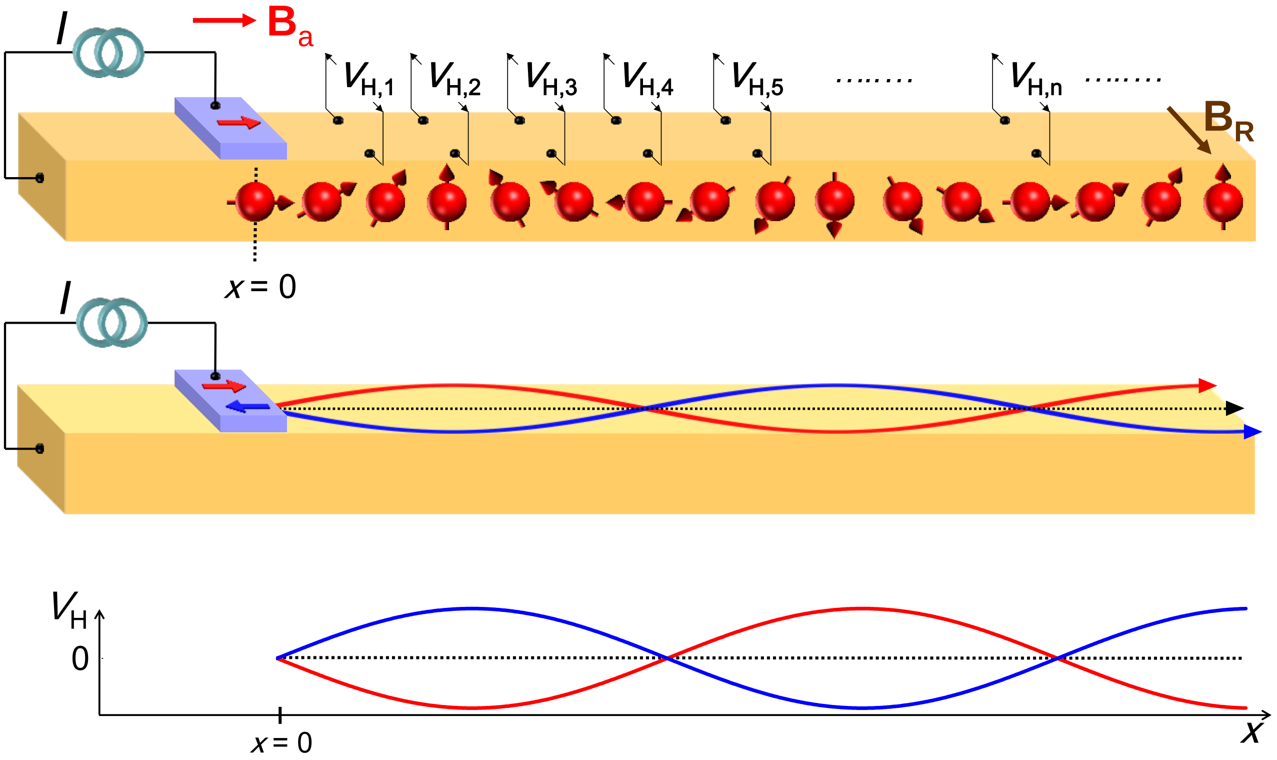


J. H. Kim *et al. J. of Magnetism and Magn. Mater.* (in press)

# Spin Hall effect in a semiconductor channel

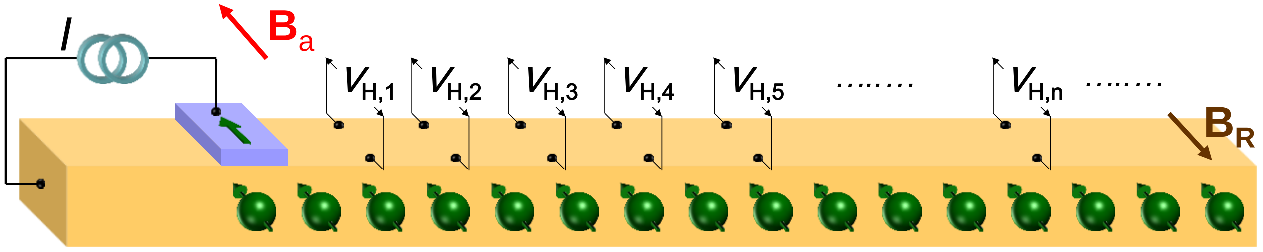
# Spin Hall Transistor

# Spin Hall effect and carrier movement



$B_a \perp B_R$ :

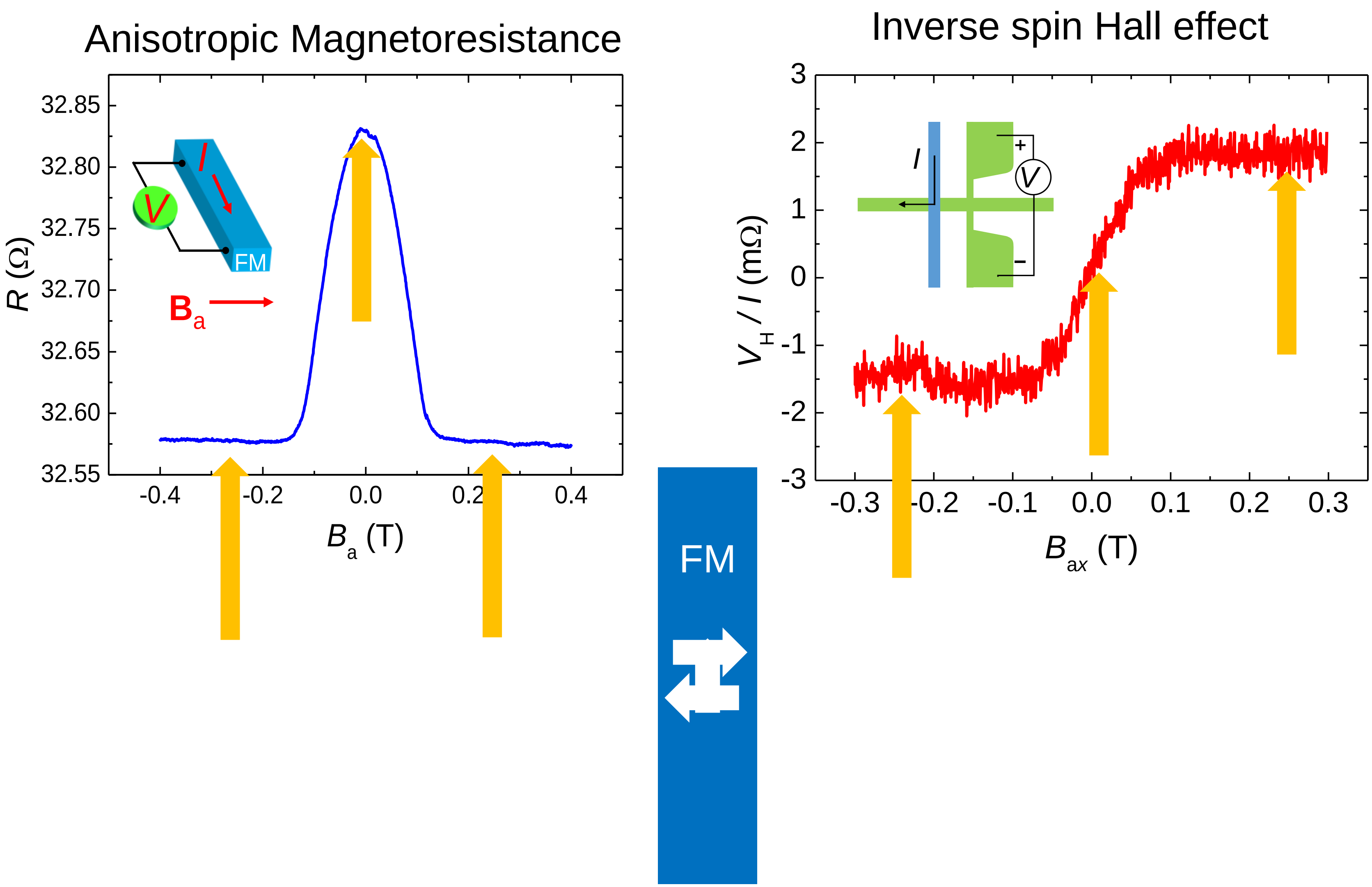
Spin precession



$B_a // B_R$ :

No Spin precession

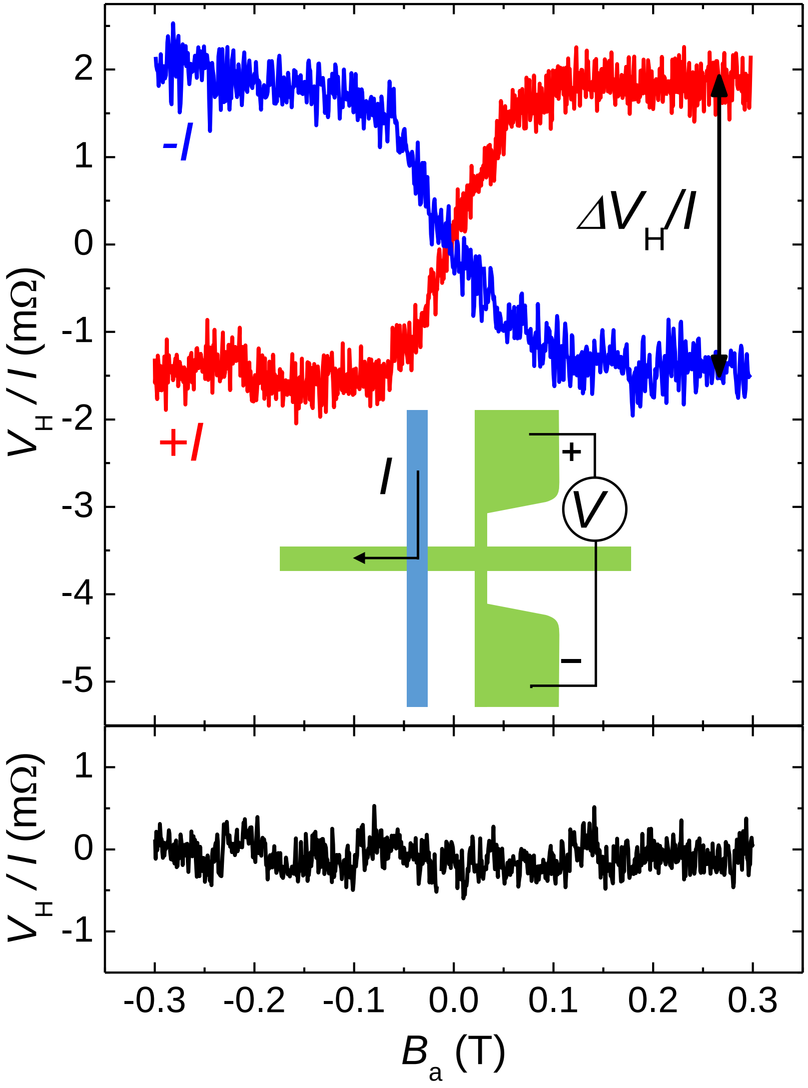
# Spin Hall voltage as a function of Magnetization direction



Anisotropic Magnetoresistance

Inverse spin Hall effect

# Inverse spin Hall effect



## $B_a \perp B_R$ :

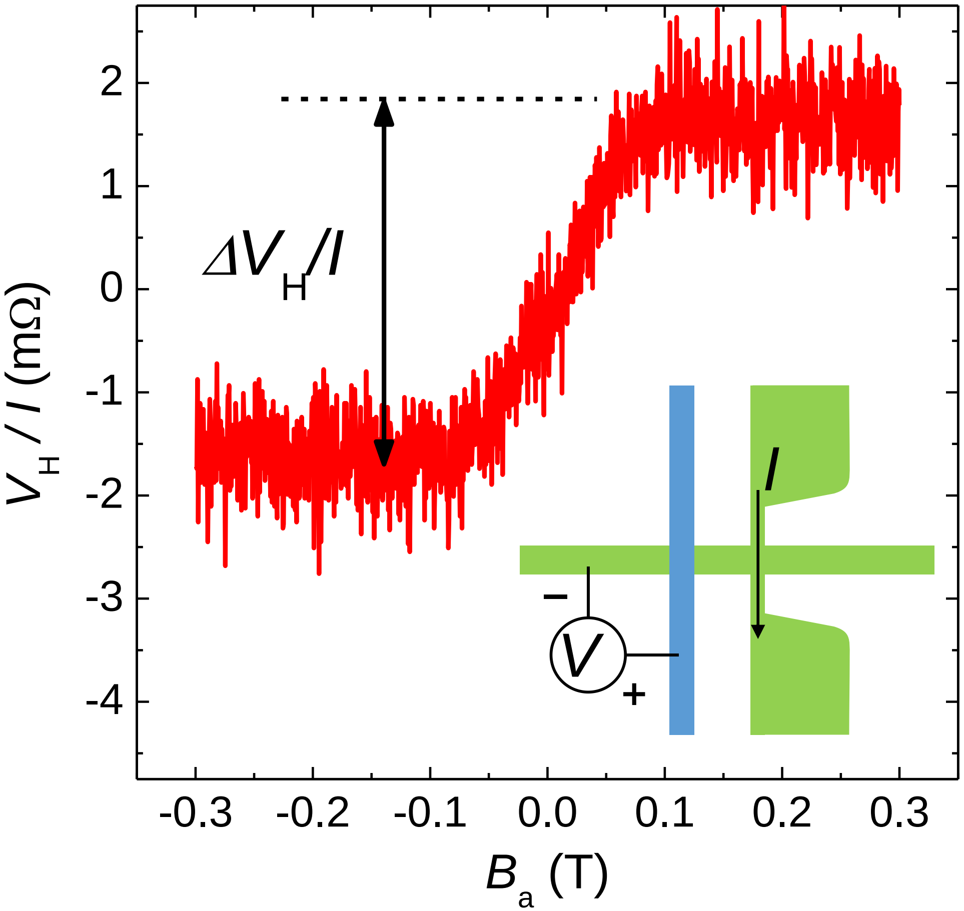
- We observed inverse spin Hall effect.
- The sign of spin Hall voltage is determined by the sign of *M* and *I*.

## $B_a$ // $B_R$ :

No Spin precession

W. Y. Choi *et al. Nature Nanotechnol.* *10*, 666 (2015)

# Direct spin Halll effect

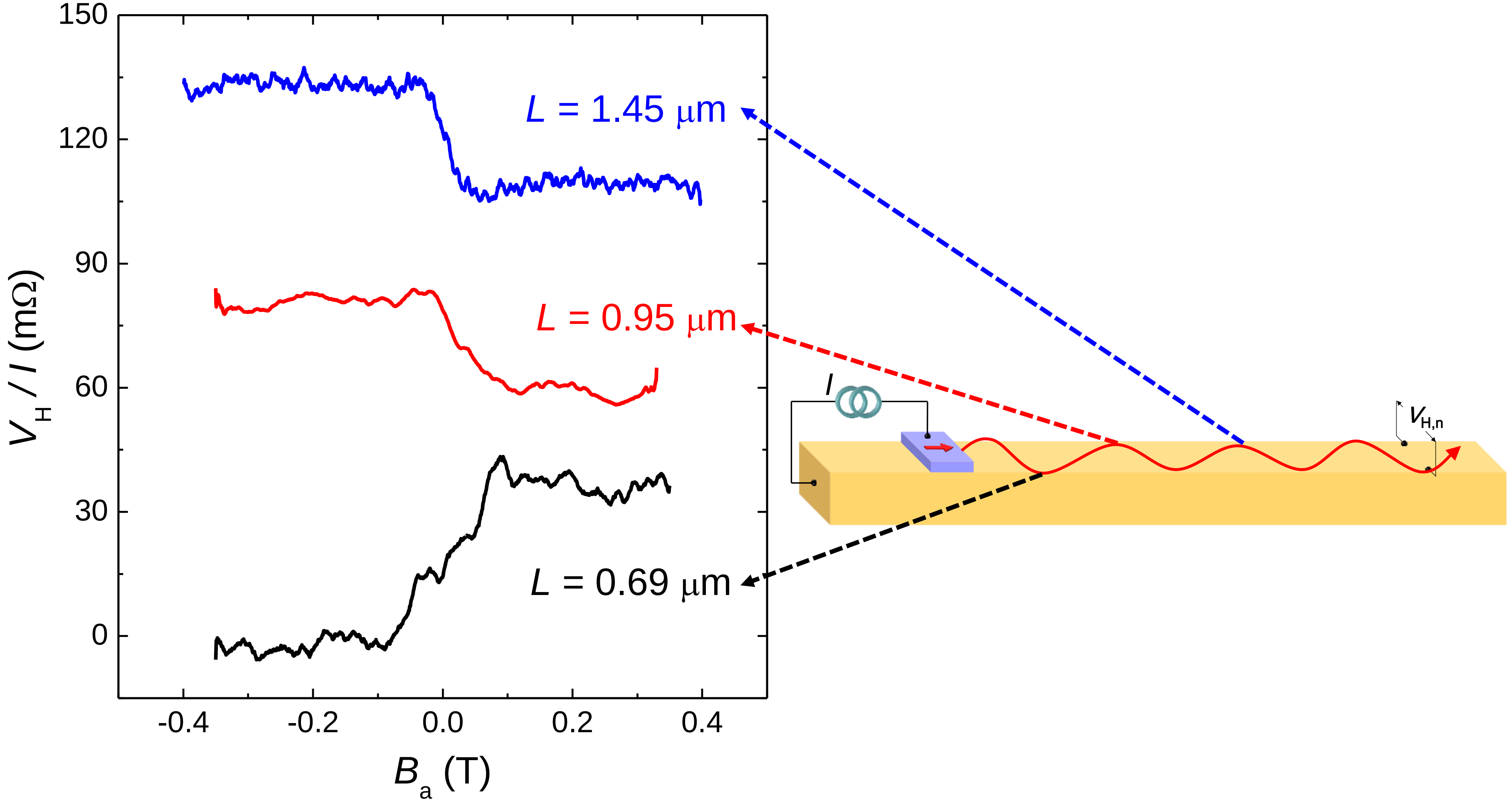


$B_a \perp B_R$ :

- We observed direct spin Hall effect.
- $\Delta V_{H,direct} = \Delta V_{H,inverse}$

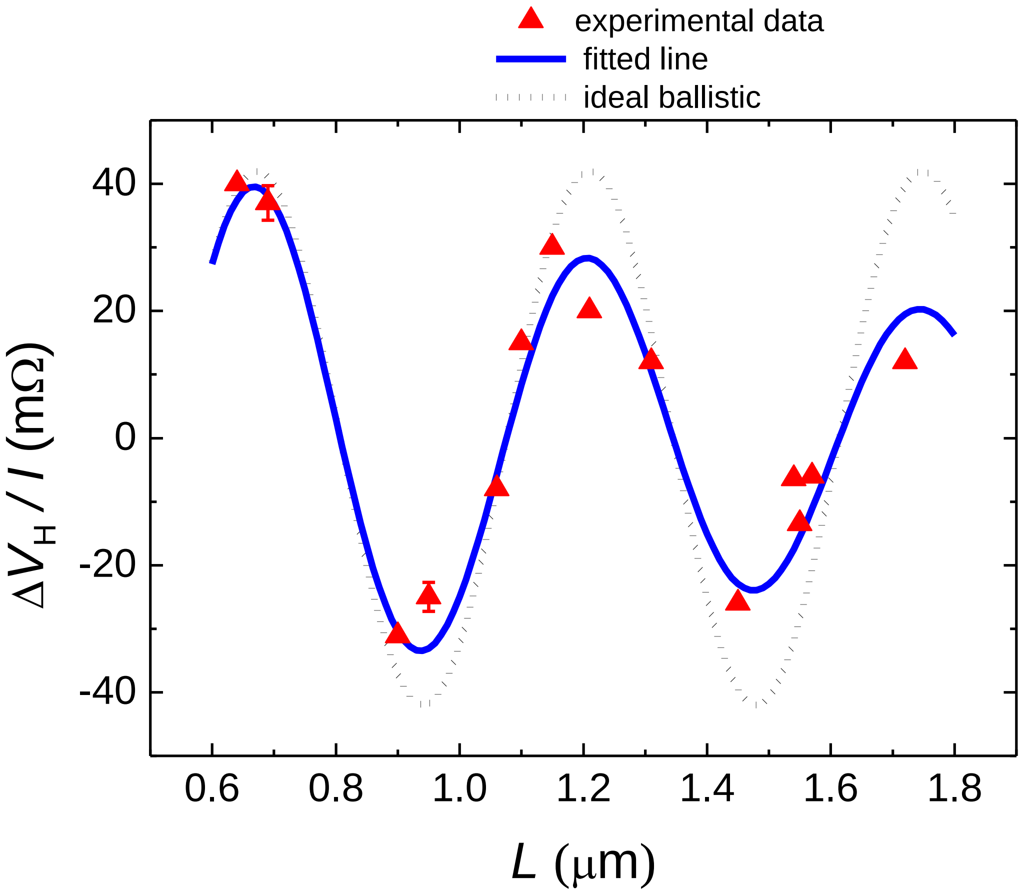
W. Y. Choi *et al. Nature Nanotechnol. 10*, 666 (2015)

# Spin Hall voltage for various lengths



W. Y. Choi *et al.* *Nature Nanotechnol.* 10, 666 (2015)

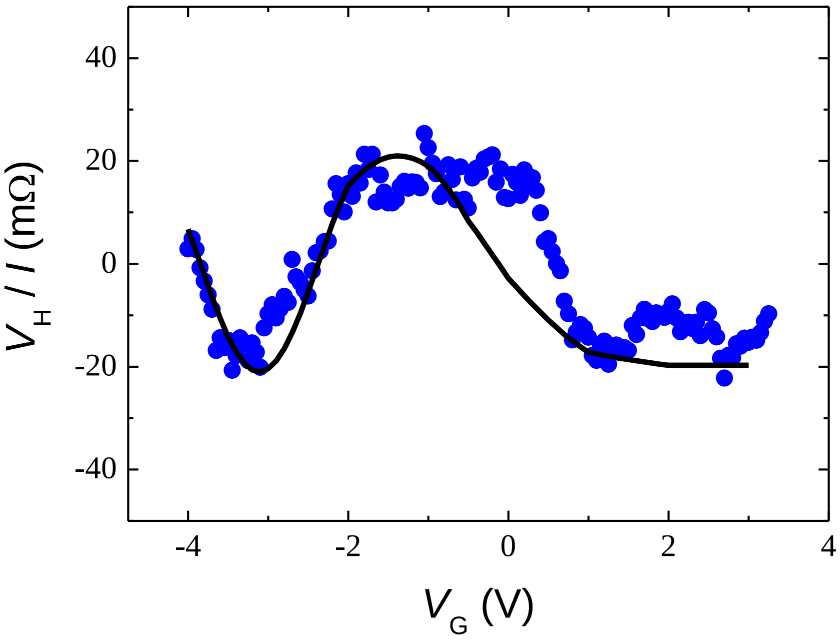
# Ballistic spin Hall effect

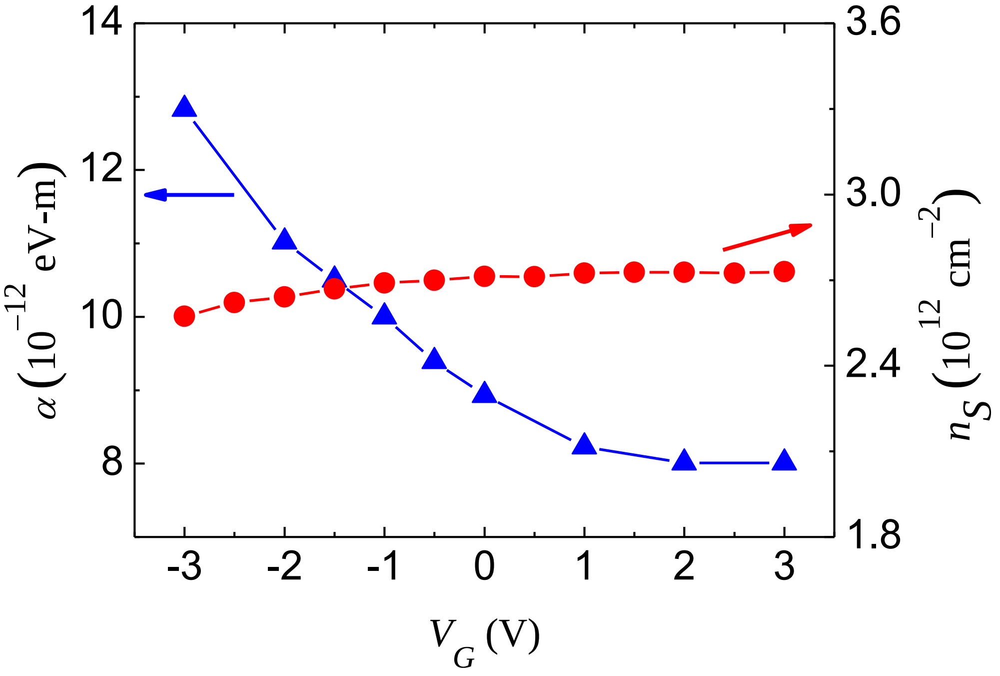


- The Datta–Das conductance oscillation are clearly seen.
- The solid line fit includes an exponential decay $e^{-L/l}$ governed by the mean free path of ballistic trajectories. ($l$ = 1.61 μm)

W. Y. Choi *et al. Nature Nanotechnol. 10*, 666 (2015)

# Gate control of spin Hall voltage

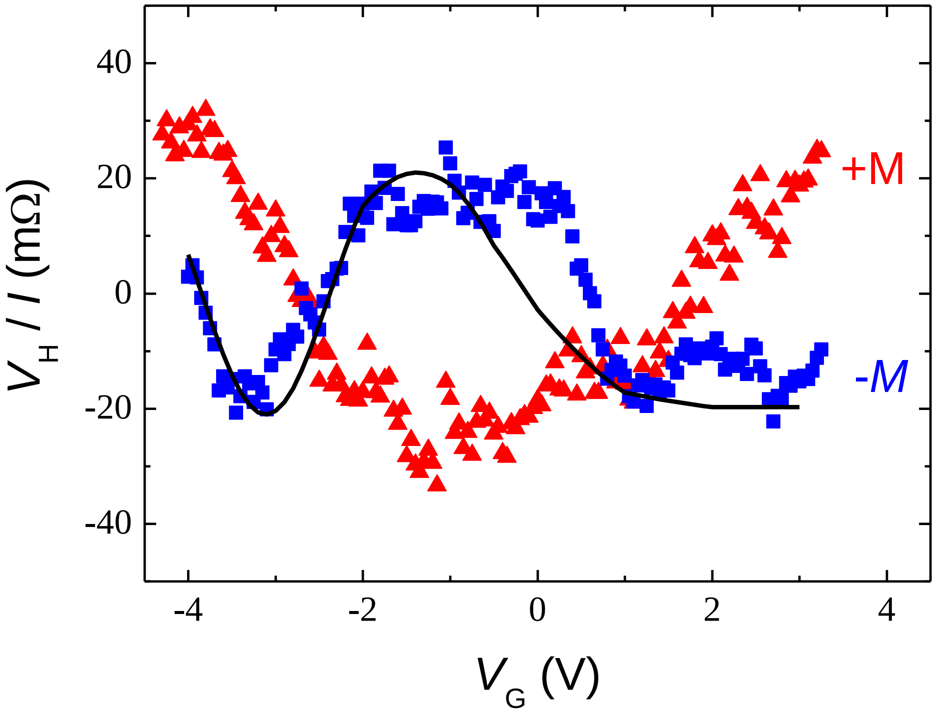




W. Y. Choi *et al. Nature Nanotechnol. 1*0, 666 (2015)

- Gate controlled spin Hall signal is nice matched with gate dependence of Rashba parameter.

# Gate control: application to complementary device



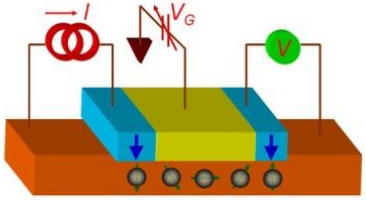
- When the *M* is reversed, the injected electrons have spins with opposite orientation and the sinusoidal trajectories are shifted in phase by 180°.
  → Complementary logic is possible.

# Summary

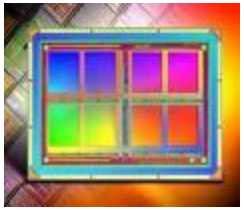
- All electric spin injection was achieved in an InAs quantum well layer.
- We determined the absolute values of the Rashba and Dresselhaus parameters separately.
- Spin-FET signal was detected in the quasi-ballistic regime.
- Ballistic spin Hall voltage in a semiconductor channel was observed using direct and inverse spin Hall effect.
- Spin Hall signal was modulated by the gate voltage.

# Future direction

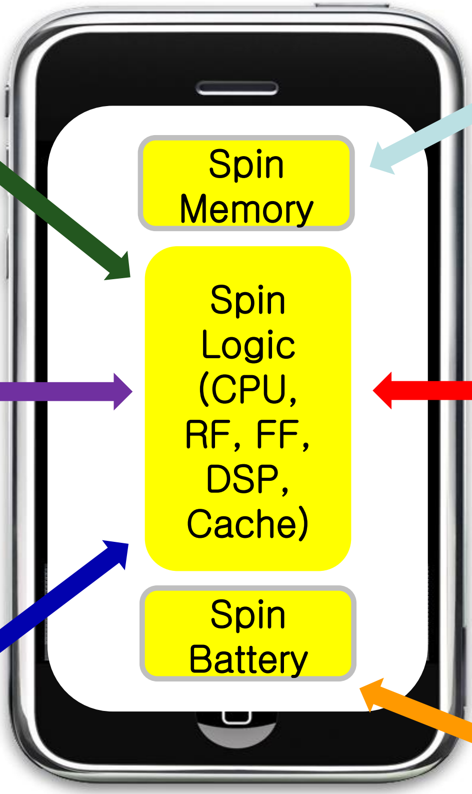
## : Total Solution of Mobile Electronics



**Spin transistor**



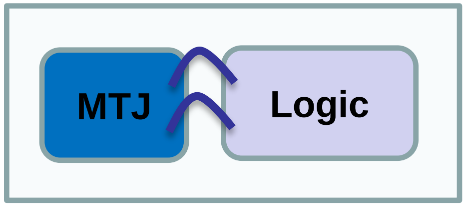
**High speed memodry**



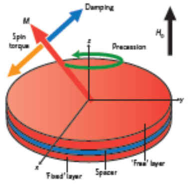
Spin Memory

Spin Logic (CPU, RF, FF, DSP, Cache)

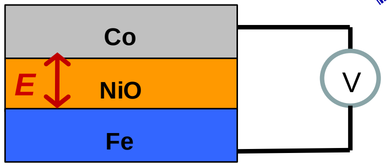
Spin Battery



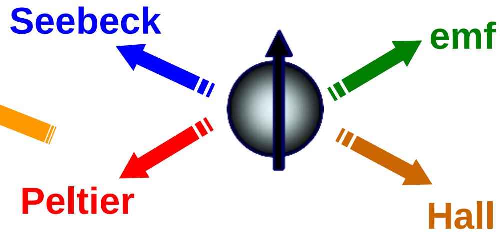
**Logic-in-Memory**



**Spin osicllator**



**Electric field controlled Magnetic device**



**Spin energy device**