

SPIN-TORQUE-INDUCED FERROMAGNETIC RESONANCE

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奈米物理與新興量子物質特論課程

2018/11/29

OUTLINE

◆ Introduction and motivation

- Spintronics
- Spin transfer torque
- Previous works on ST-FMR
- Topological insulator
- ST-FMR with magnetic insulator

◆ Experimental

- Thin film growth
- Device fabrication for ST-FMR

◆ Analysis and discussion

- STM surface characterization
- ST-FMR on Py/TI
- ST-FMR on Pt/YIG

OUTLINE

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- Spintronics
- Spin transfer torque
- FMR
- Previous works on ST-FMR
- Topological insulator
- ST-FMR with magnetic insulator

◆ Experimental

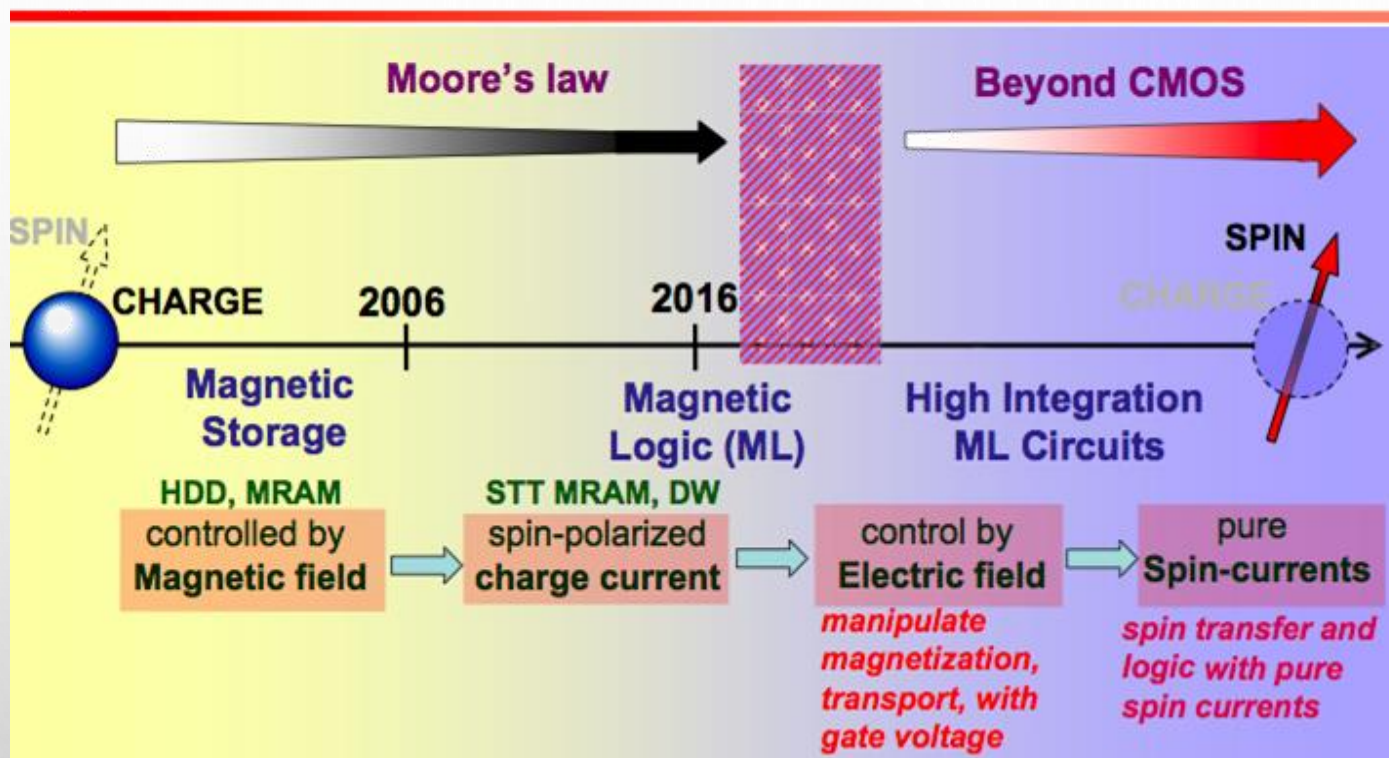
- Thin film growth
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◆ Analysis and discussion

- STM surface characterization
- ST-FMR on Py/TI
- ST-FMR on Pt/YIG

SPINTRONICS

Tentative roadmap



- ✓ Power dissipation
- ✓ Scaling
- ✓ High processing speed
- ✓ Non-volatility

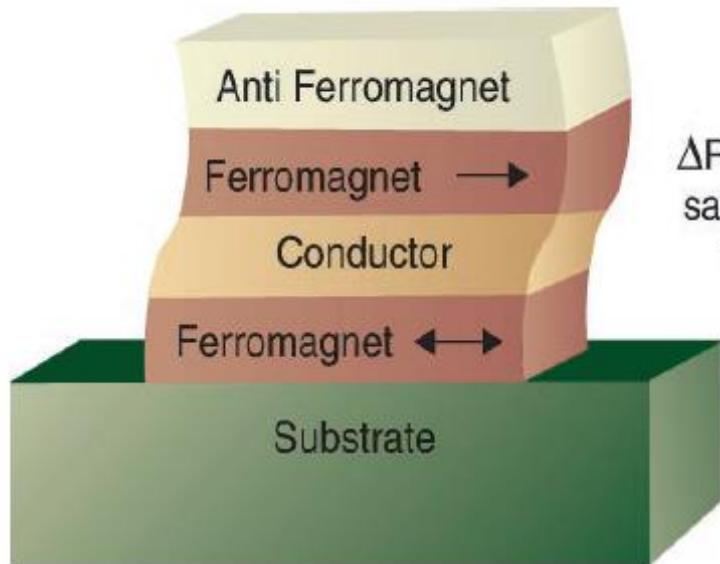
SPINTRONICS



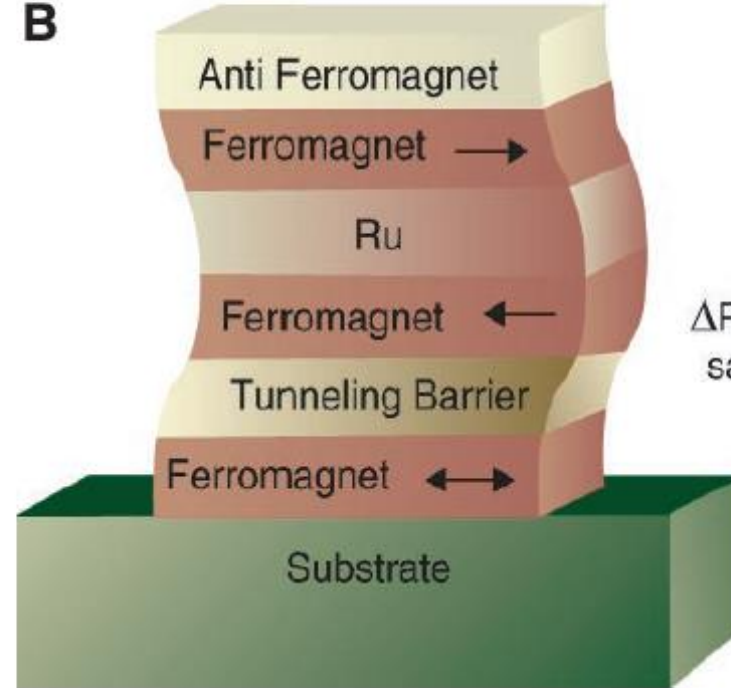
The robots sent into Fukushima have “died” due to high amounts of leaked radioactive materials.

◆ Radiation-resistant device

Most modern electronic circuitry relies on controlling **electronic charge** within a circuit, but this control **can easily be disrupted in the presence of radiation.**

A

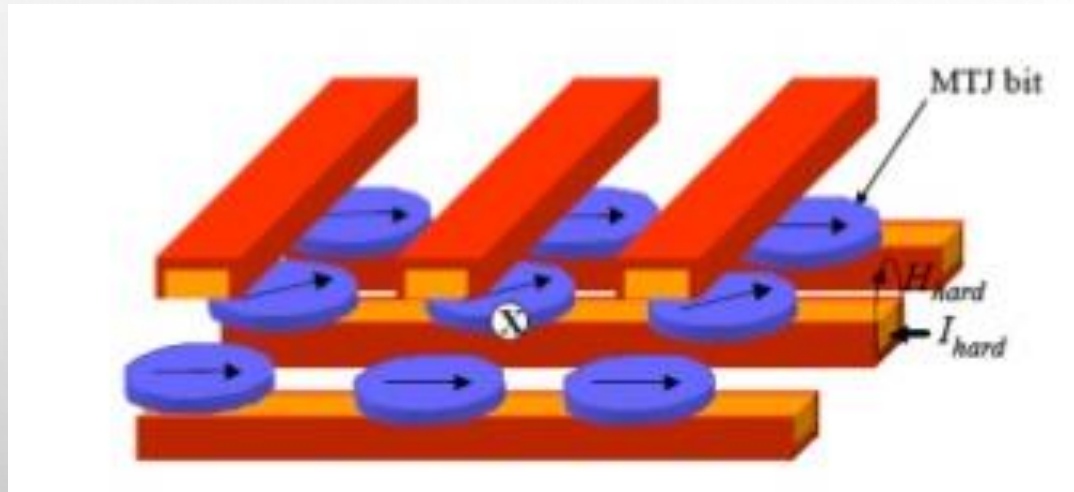
$\Delta R/R$ -5%-10%
saturation field
10-30 Oe

B

$\Delta R/R$ -20%-50%
saturation field
10-30 Oe

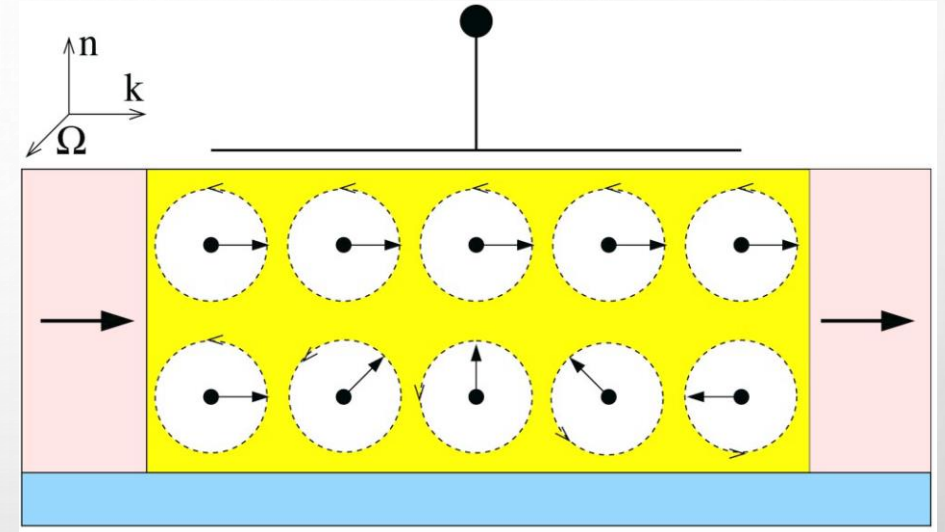
Fig. 1. Spin-dependent transport structures. **(A)** Spin valve. **(B)** Magnetic tunnel junction.

Spintronics



Magnetoresistive Random Access Memory

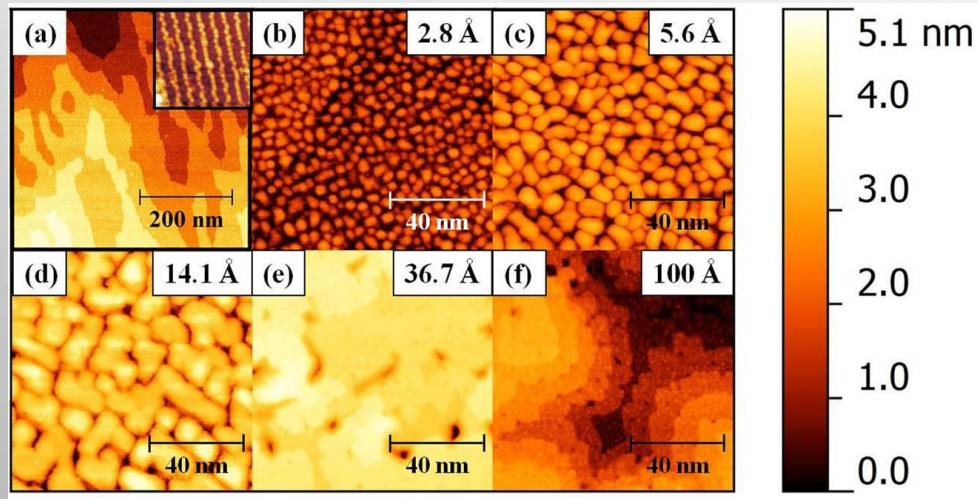
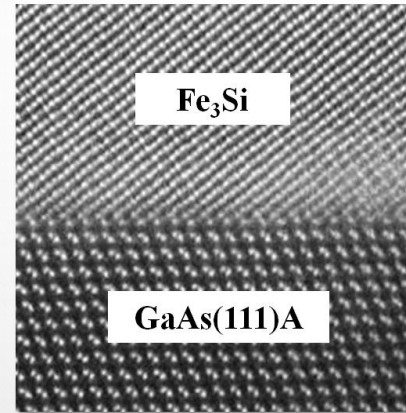
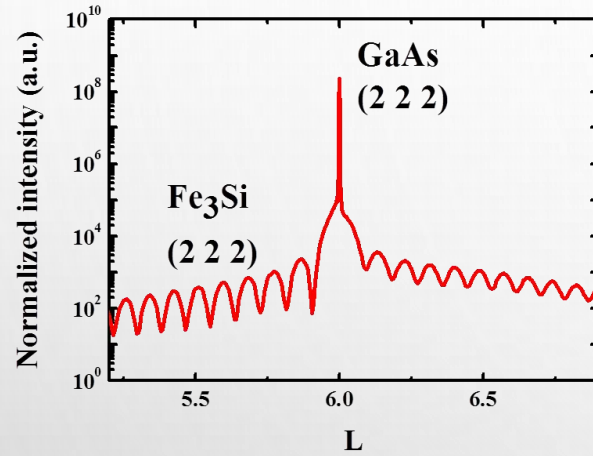
MRAM => STT-MRAM



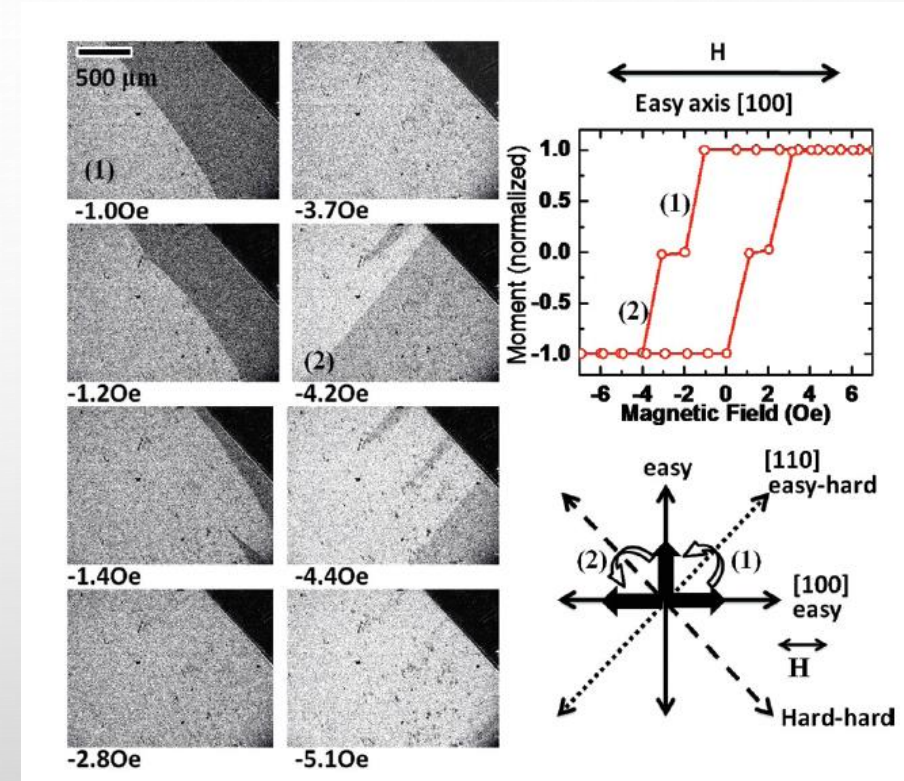
The Scheme of the Datta-Das spin field effect transistor (SFET).

Spintronics

FM/SM heterostructure

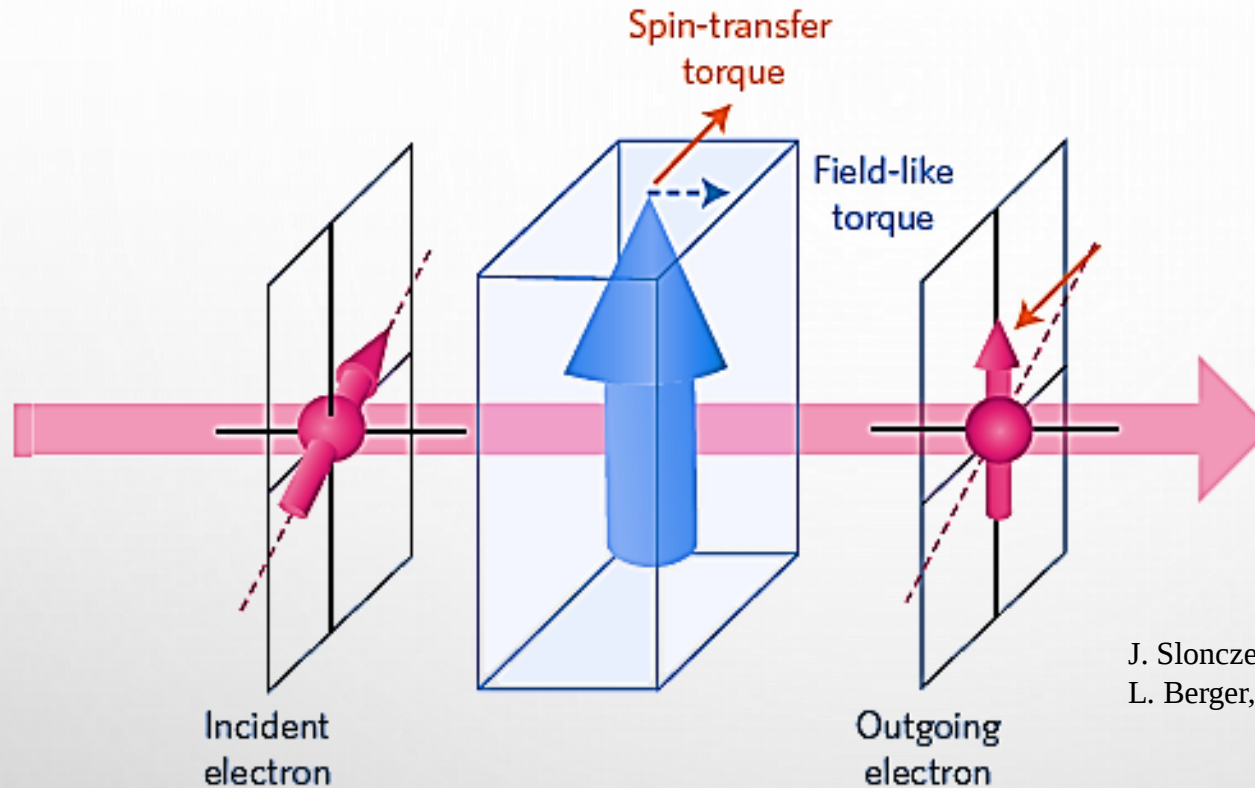


Observation of Magnetic Domain



Applications: Spin injection, Spin LED, Spin pumping

SPIN TRANSFER TORQUE



J. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996).
L. Berger, Phys. Rev. B **33**, 1572 (1996).

Applications:

**Efficiency of
magnetization switching**

STT-MRAM
Domain wall logic device

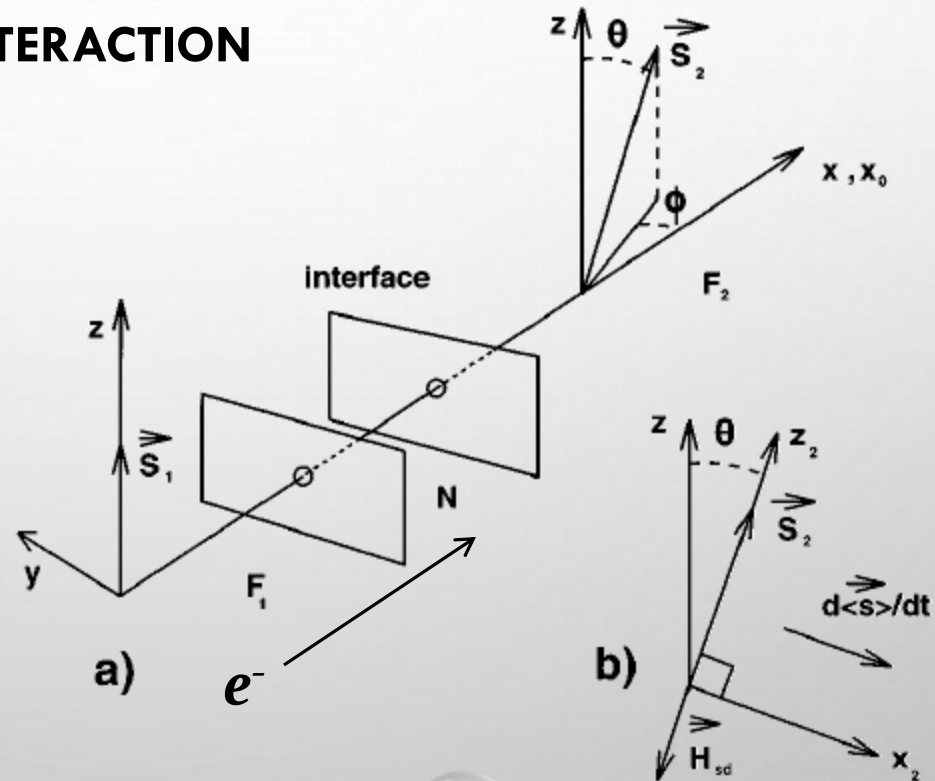
**Driving persistent
oscillations of magnetization**

Spin-transfer-torque- induced FMR

SPIN TRANSFER TORQUE

- 4S (ITINERANT)-3D (LOCALIZED) S-D INTERACTION

$$-J_{sd} \hat{\mathbf{S}} \cdot \vec{\mathbf{S}}(\vec{\mathbf{r}})$$



L. Berger, *Phys. Rev. B* **54**, 9353 (1996)

Ya. B. Bazaliy, B.A. Jones, and S.C. Zhang, *Phys. Rev. B* **57**, R3213 (1998)

Spin Polarization of Conduction Electrons Due to *s-d* Exchange Interaction

Kei YOSIDA and Ayao OKIJI

*Institute for Solid State Physics, University of Tokyo
Azabu, Tokyo*

(Received June 7, 1965)

Spin polarization of the conduction electron due to the *s-d* exchange interaction with a localized spin

$$\sigma = (\rho J / 2N) \langle S_z \rangle$$

$\langle S_z \rangle$: expectation value of localized spin in the ground state

ρ : density of the conduction electrons at the Fermi surface

J : Ferromagnetic interaction factor

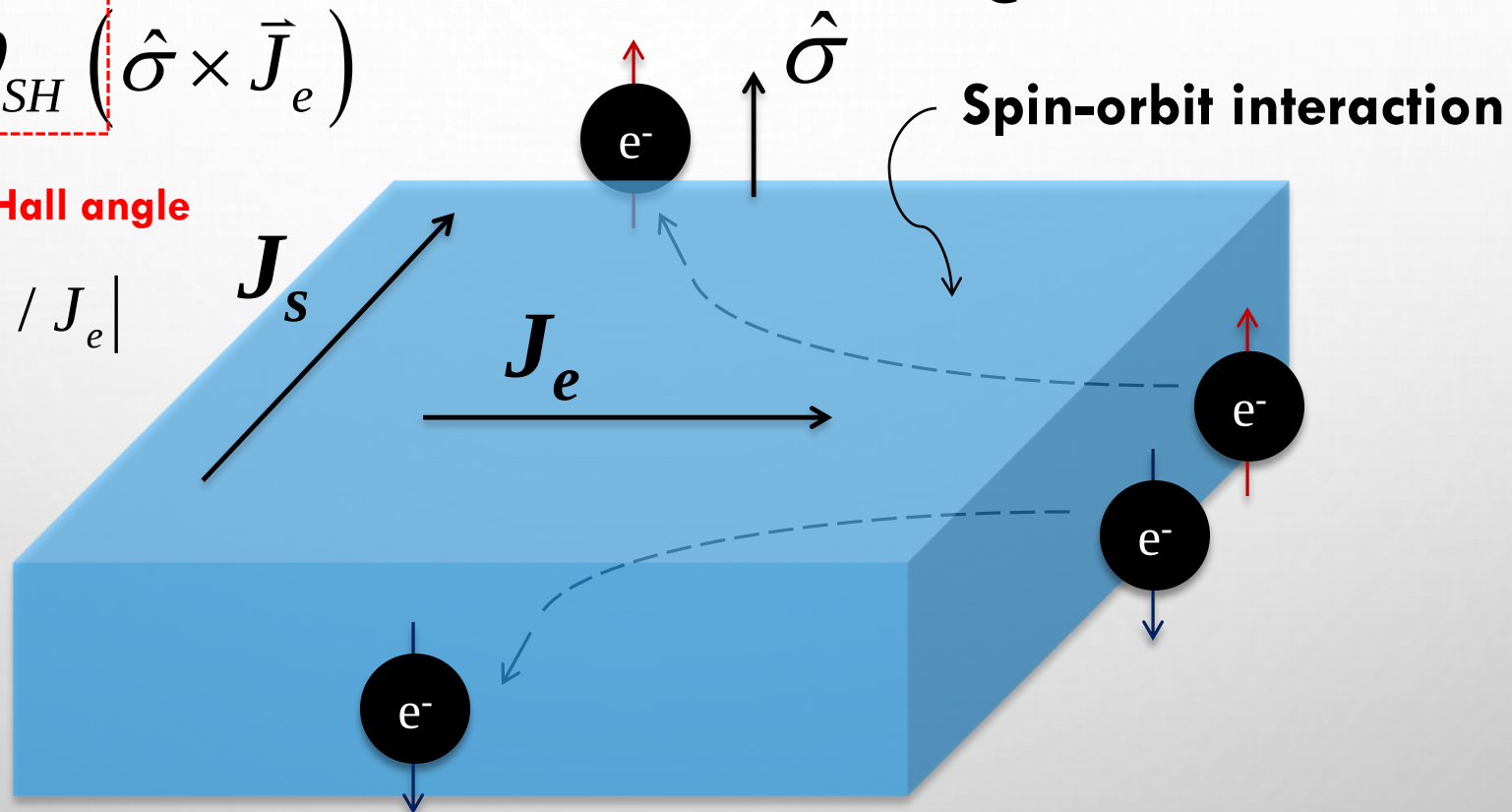
SPIN ORBIT TORQUE

The spin Hall effect

$$\vec{J}_S = \theta_{SH} (\hat{\sigma} \times \vec{J}_e)$$

The spin Hall angle

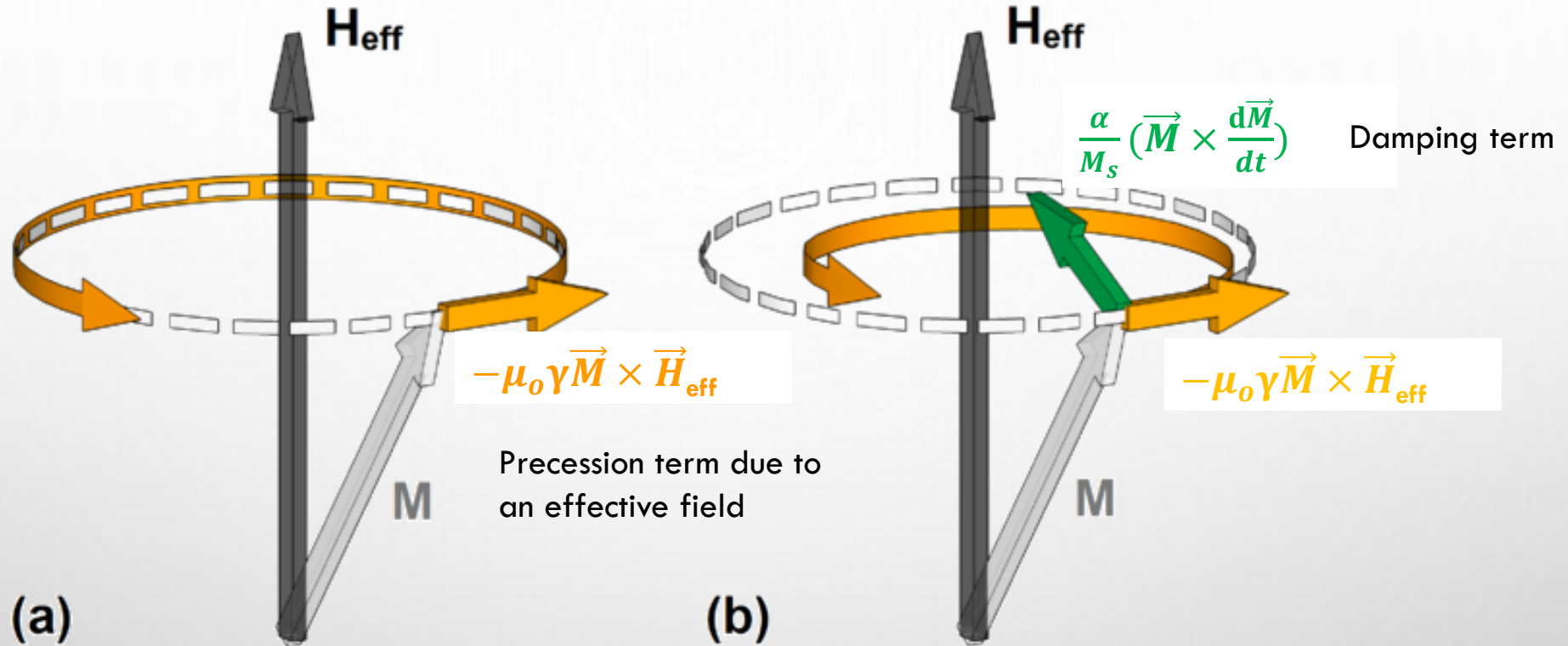
$$|\theta_{SH}| = |J_s / J_e|$$



M. I. Dyakonov and V. I. Perel, *JETP* **13** 467 (1971)

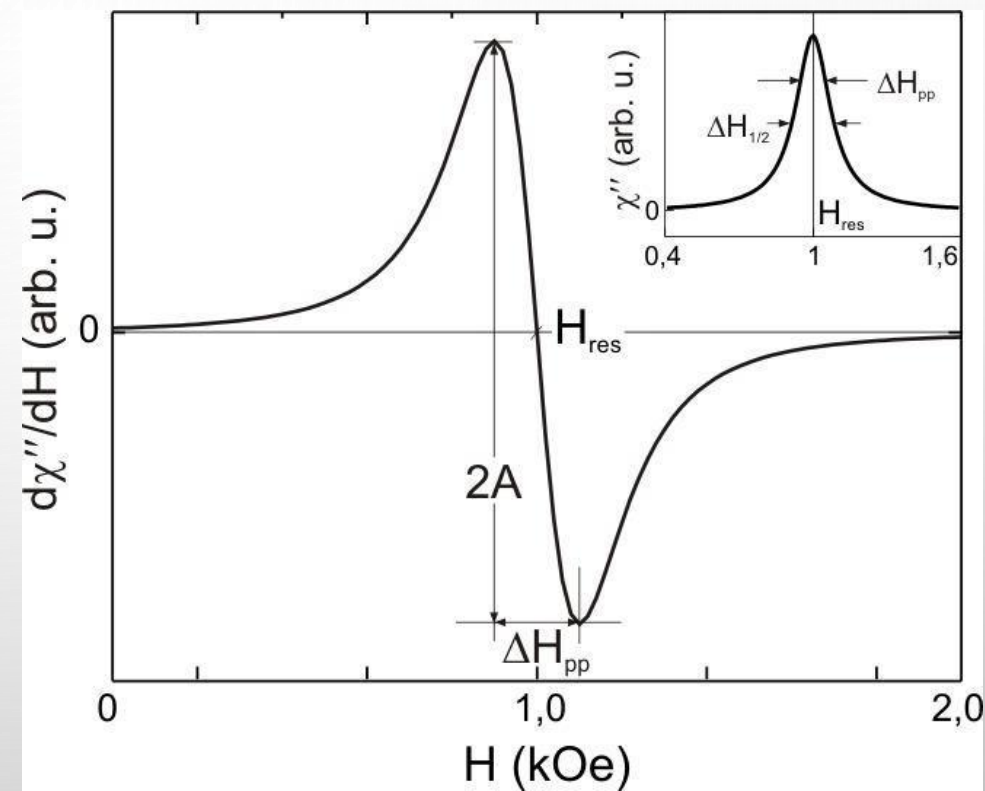
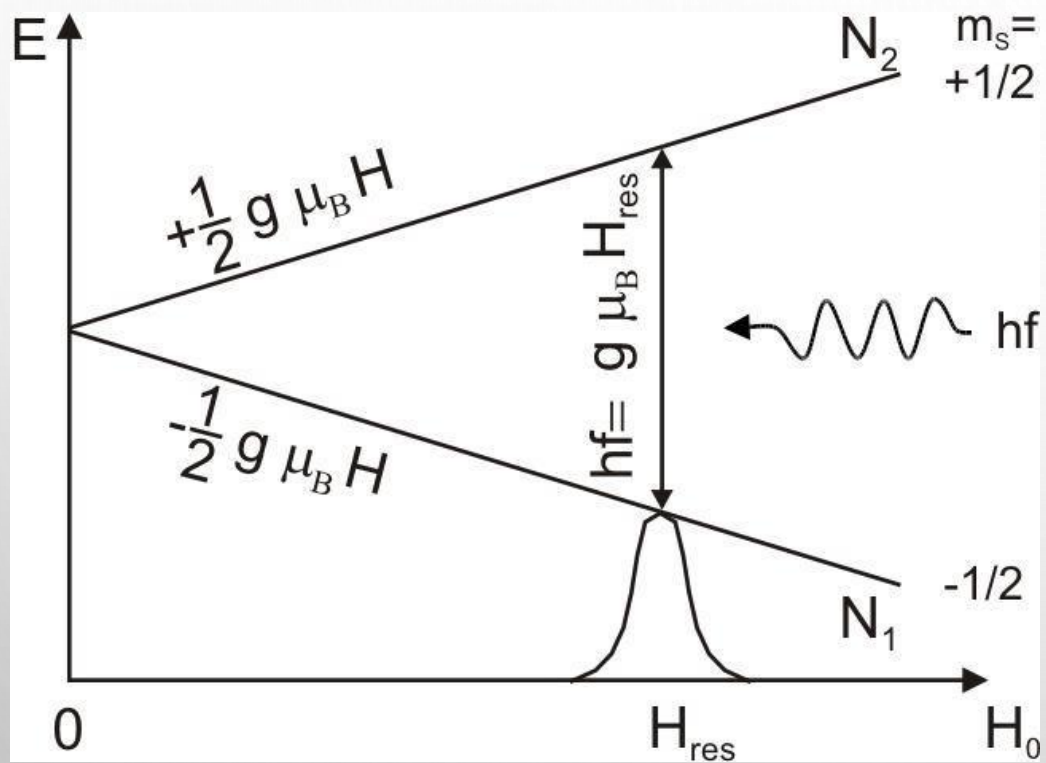
J. E. Hirsch, *Phys. Rev. Lett.* **83** 1834 (1999)

FERROMAGNETIC RESONANCE

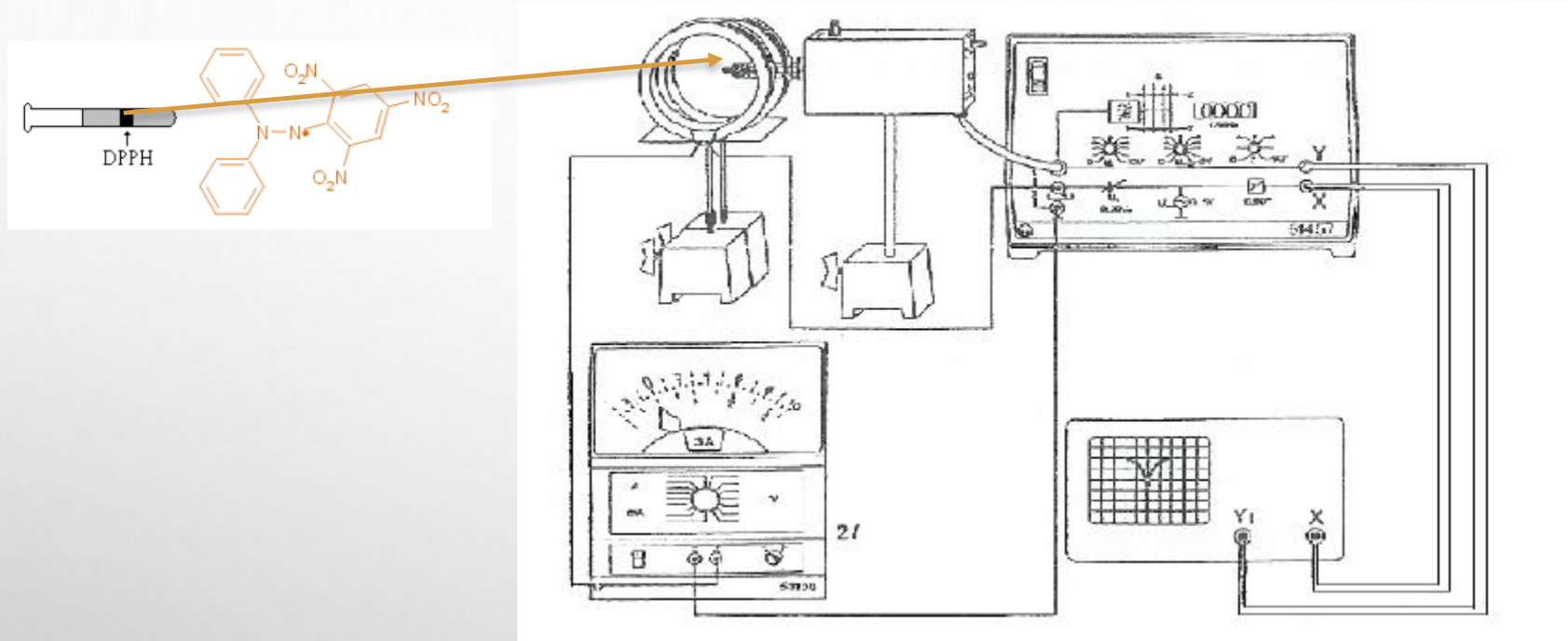


$$\frac{d\vec{M}}{dt} = -\mu_0\gamma\vec{M} \times \vec{H} + \frac{\alpha}{M_s}(\vec{M} \times \frac{d\vec{M}}{dt})$$

Ferromagnetic resonance

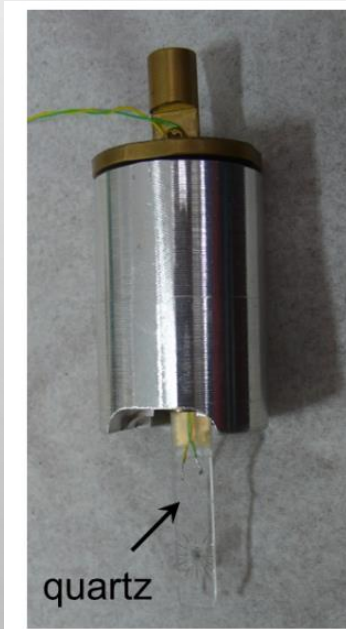
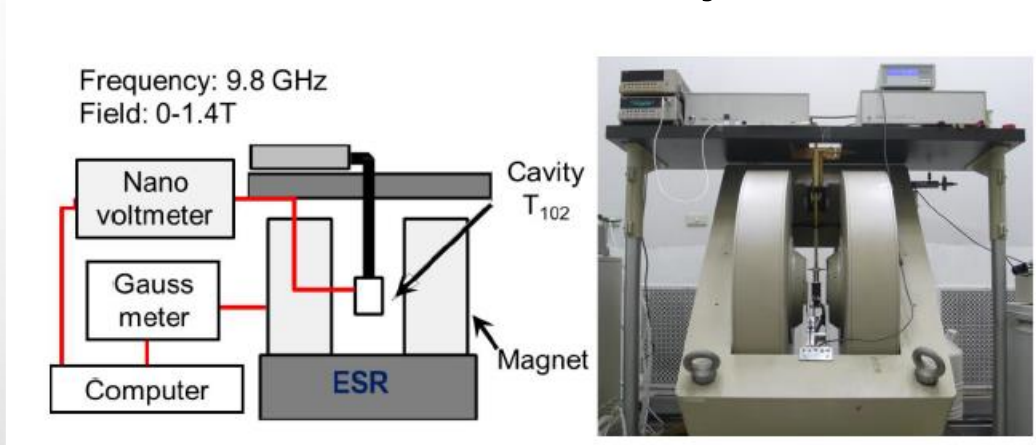


STILL REMEMBER THE ESR MEASUREMENT?

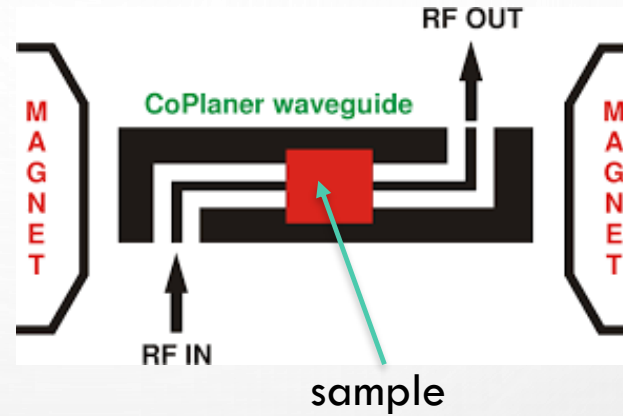


FERROMAGNETIC RESONANCE SETUP

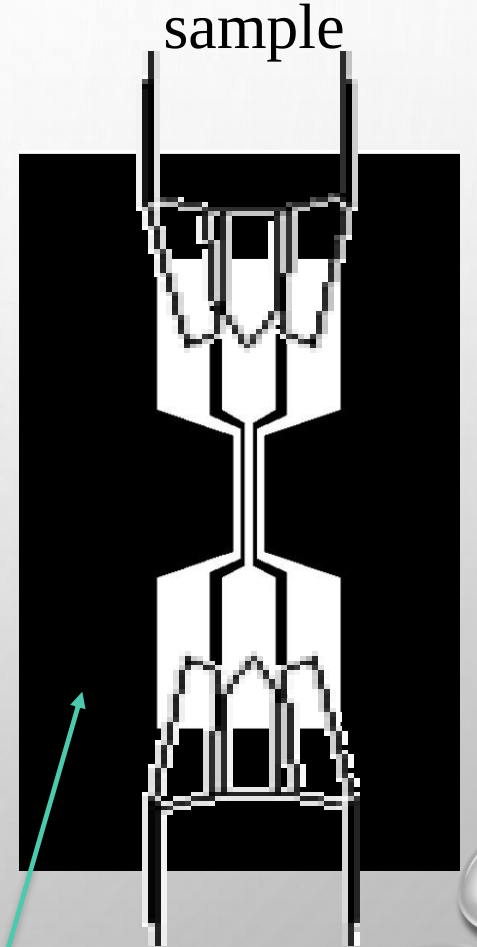
FMR with cavity

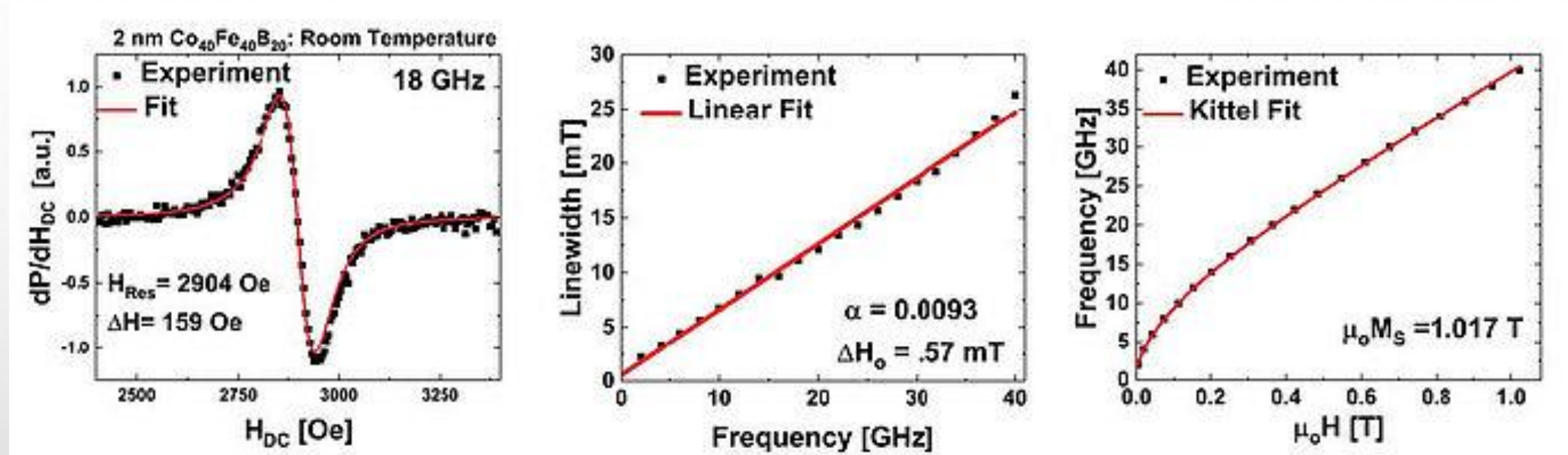


Flip-chip type FMR



Micro-CoPlaner
waveguide patterned on
sample



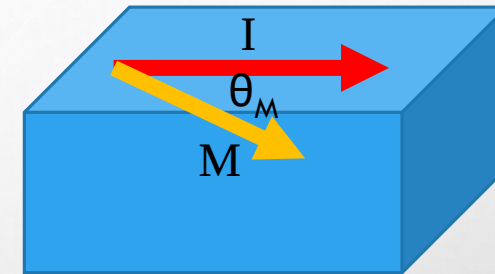
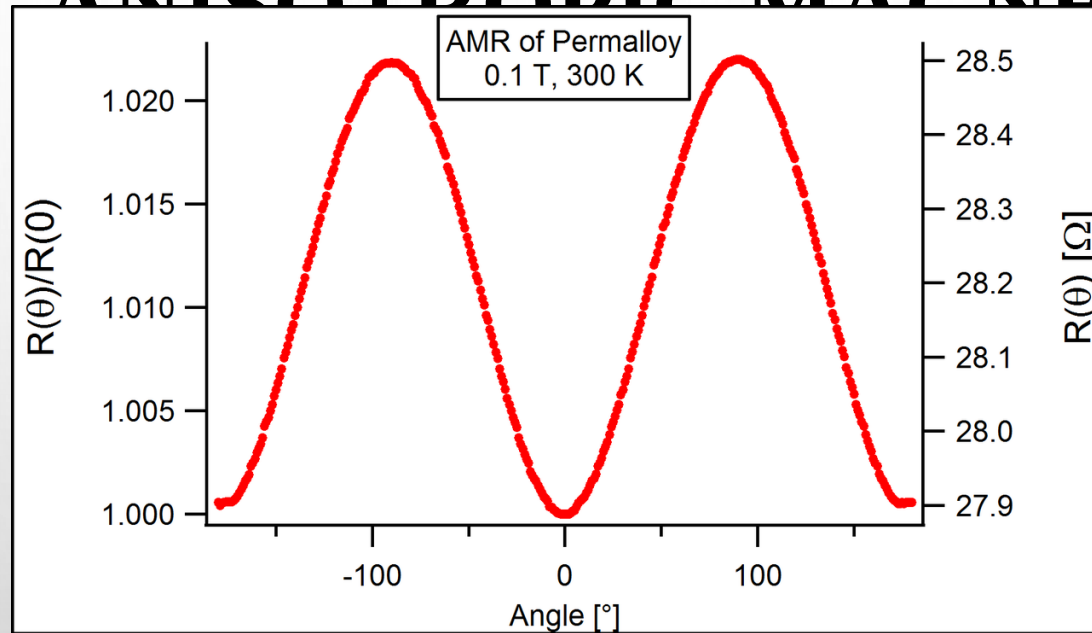


$$\frac{dP}{dH} = A \frac{\Delta H (H_{\text{ex}} - H_{\text{res}})}{(H_{\text{ex}} - H_{\text{res}})^2 + \Delta H^2}$$

$$\Delta H = \Delta H_0 + \frac{4\pi\alpha f_r}{\gamma}$$

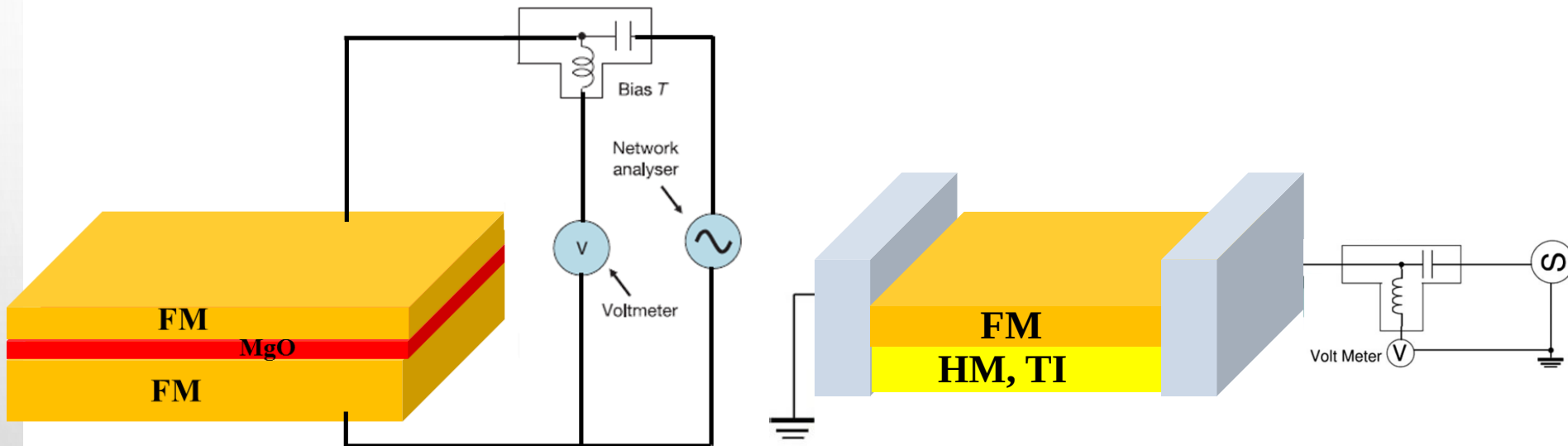
$$f_r = \frac{\gamma}{2\pi} \sqrt{H_0 (H_0 + 4\pi M_{\text{eff}})}$$

ANISOTROPIC MAGNETIC RESISTANCE



$$\rho = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp}) \cos^2 \theta_M$$

Previous ST-FMR researches



Tulapurkar et al., Nature **438**, 339 (2005)
Sankey et al., Nature Physics **4**, 67 (2008)

**Spin-torque diode effect in
MTJ structure**



Liu. et al. PRL **106**, 036601 (2011)
Pai et al. APL **101**, 122404 (2012)

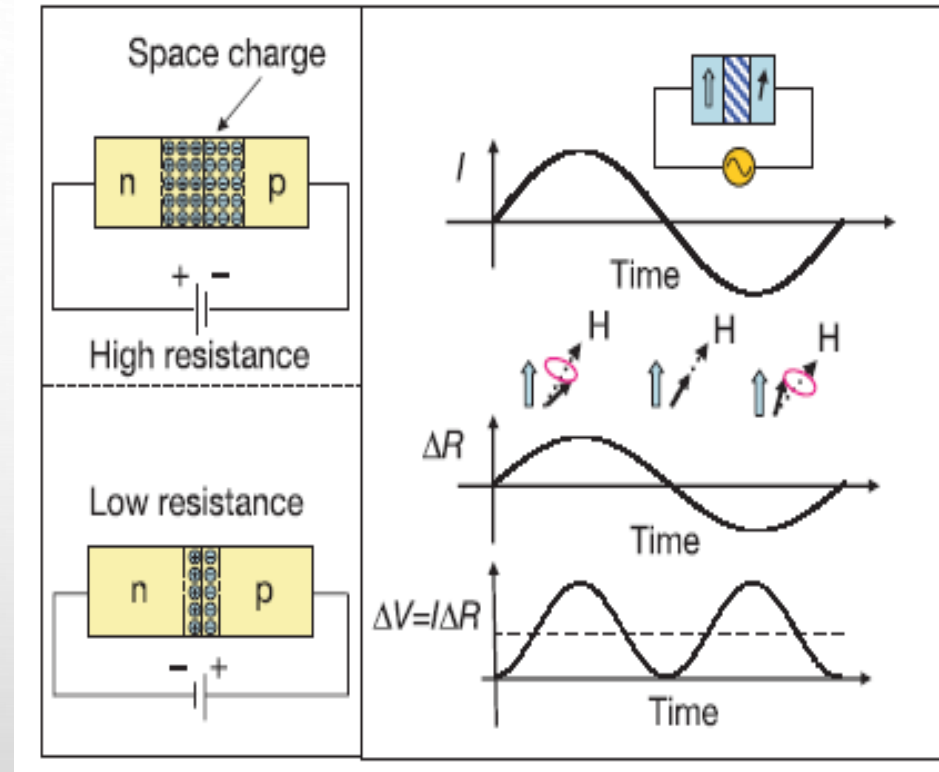
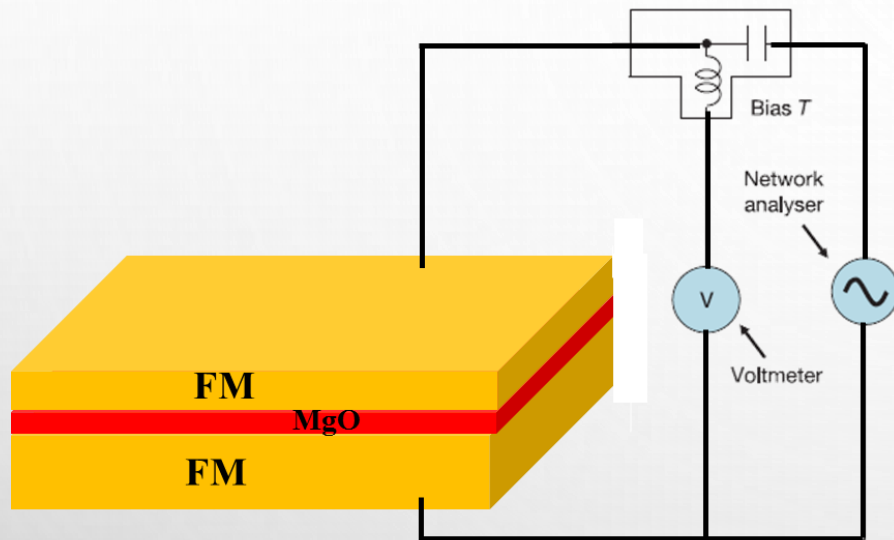
**Heavy metals/FM
Bilayer structure**



Mellink et al. Nature **511**, 449 (2014)
Wang et al. PRL **114**, 257202 (2015)

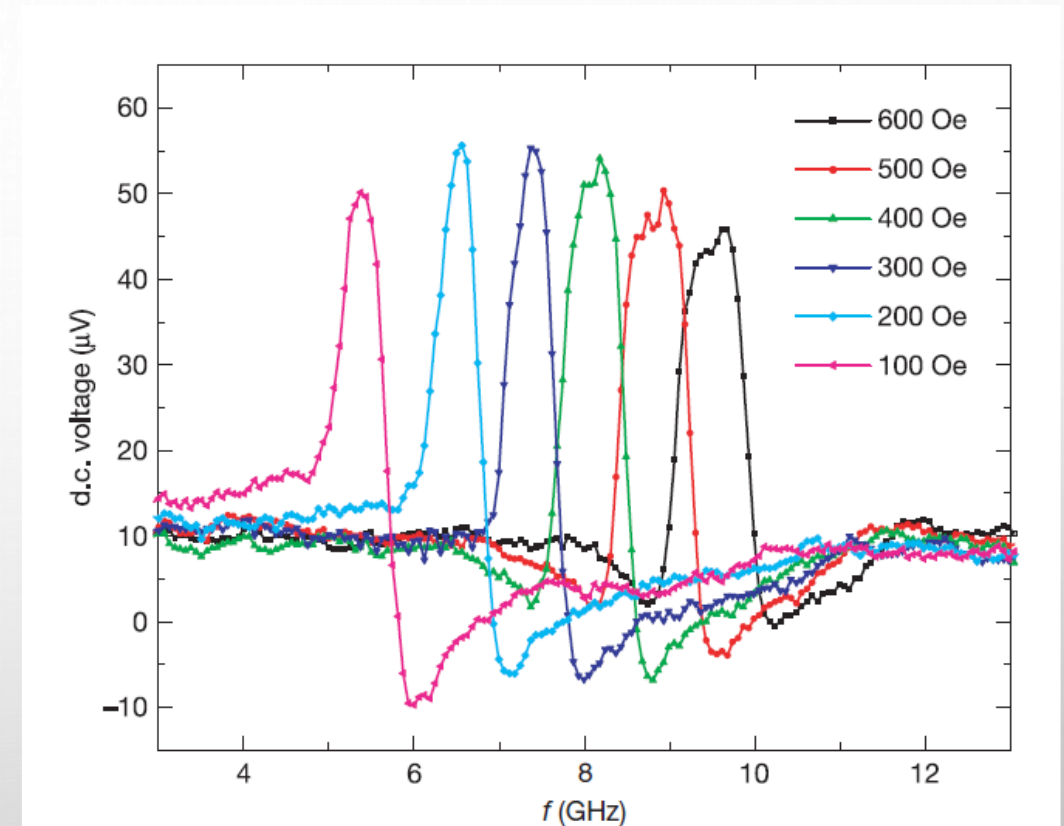
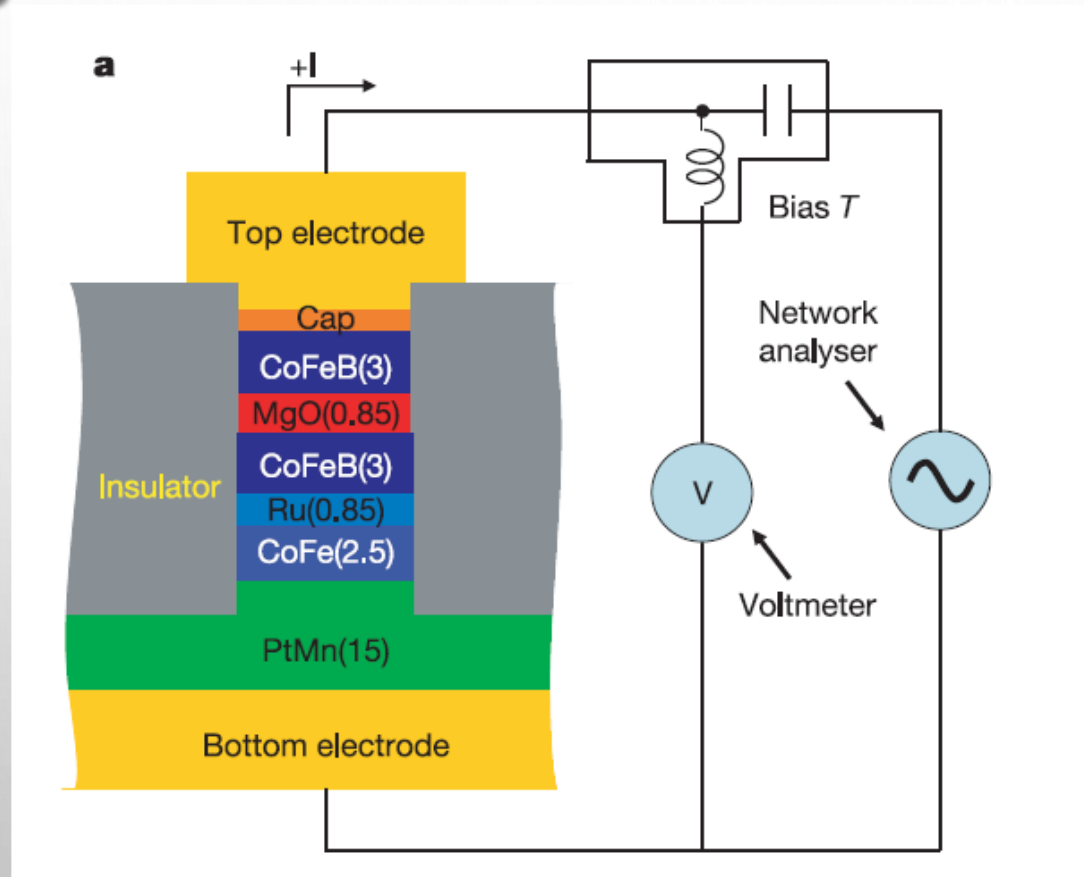
Topological insulators/FM

SPIN-TORQUE DIODE EFFECT IN MTJ STRUCTURE



Source of Spin transfer torque:
current polarized by the fixed FM layer

Tulapurkar et al., Nature **438**, 339 (2005)



This behavior is markedly different from that of a conventional semiconductor diode²³, and could form the basis of a nanometre-scale radio-frequency detector in telecommunication circuits.

PHYSICAL REVIEW B **75**, 014430 (2007)

**Current-driven ferromagnetic resonance, mechanical torques, and rotary motion
in magnetic nanostructures**

Measurement of the spin-transfer-torque vector in magnetic tunnel junctions

JACK C. SANKEY¹, YONG-TAO CUI¹, JONATHAN Z. SUN², JOHN C. SŁONCZEWSKI^{2*},
ROBERT A. BUHRMAN¹ AND DANIEL C. RALPH^{1†}

¹Cornell University, Ithaca, New York 14853, USA

²IBM T. J. Watson Research Center, Yorktown Heights, New York 10598, USA

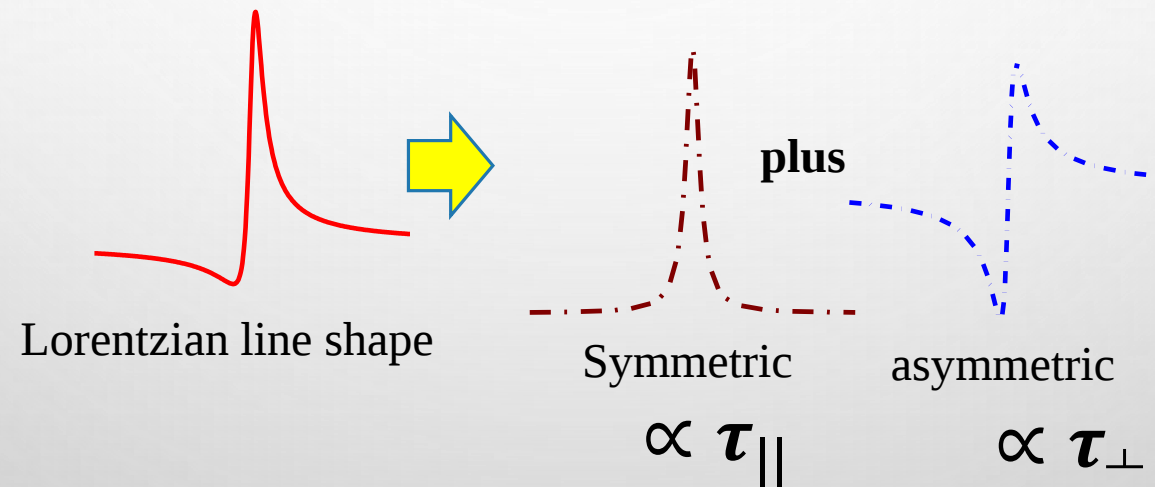
*IBM RSM Emeritus

†e-mail: ralph@ccmr.cornell.edu

**Supplementary Material for: “Measurement of the Spin-Transfer-
Torque Vector in Magnetic Tunnel Junctions”**

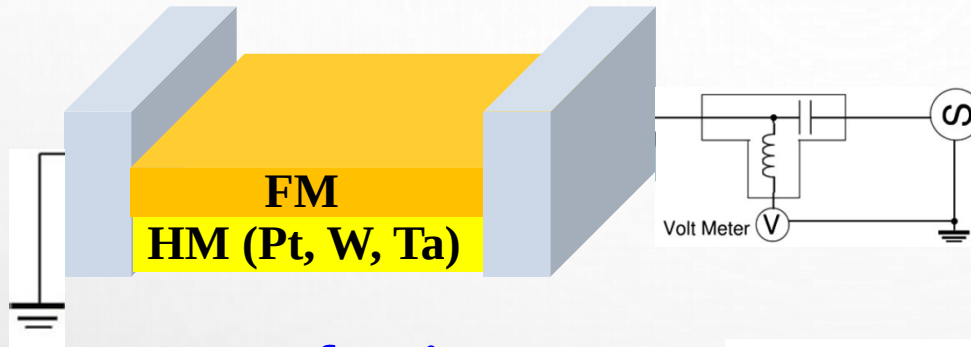
ASYMMETRIC AND SYMMETRIC LINE SHAPE ANALYSIS

$$\begin{aligned} \frac{d\hat{M}}{dt} &= -\gamma\hat{M} \times \vec{H}_{\text{eff}} + \alpha_0\hat{M} \times \frac{d\hat{M}}{dt} + \frac{\gamma\hbar J_s}{2eM_s d_F} (\hat{m} \times \hat{\sigma} \times \hat{m}) - \gamma\hat{M} \times \vec{H}_{\text{rf}} \\ &= -\gamma\hat{M} \times \vec{H}_{\text{eff}} + \alpha_0\hat{M} \times \frac{d\hat{M}}{dt} + \gamma\left[\tau_{||} \frac{\hat{M} \times (\hat{x} \times \hat{M})}{|\hat{x} \times \hat{M}|} + \tau_{\perp} \frac{\hat{x} \times \hat{M}}{|\hat{x} \times \hat{M}|}\right] \end{aligned}$$



ST-FMR on bi-layer structures

STT=>SOT

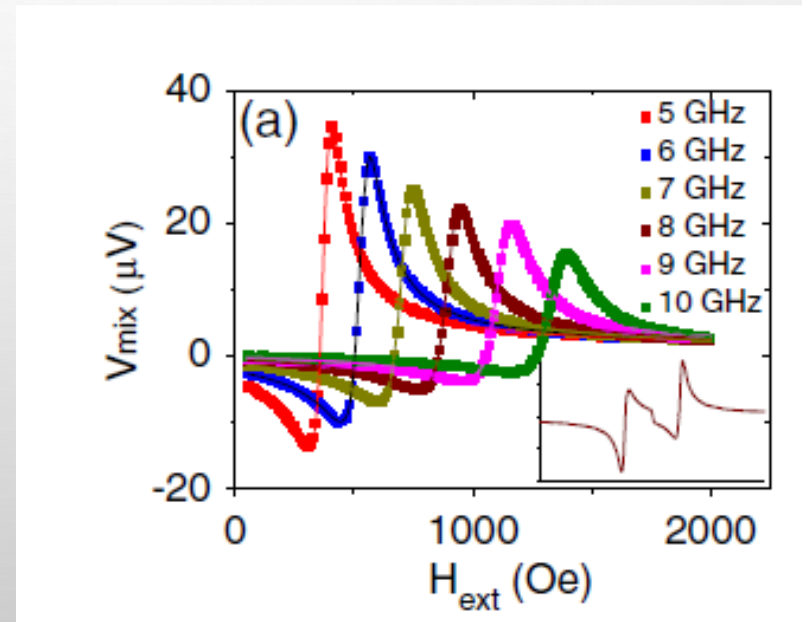


Liu. et al. PRL **106**, 036601 (2011)

Pai et al. APL **101**, 122404 (2012)

Source of Spin torque:

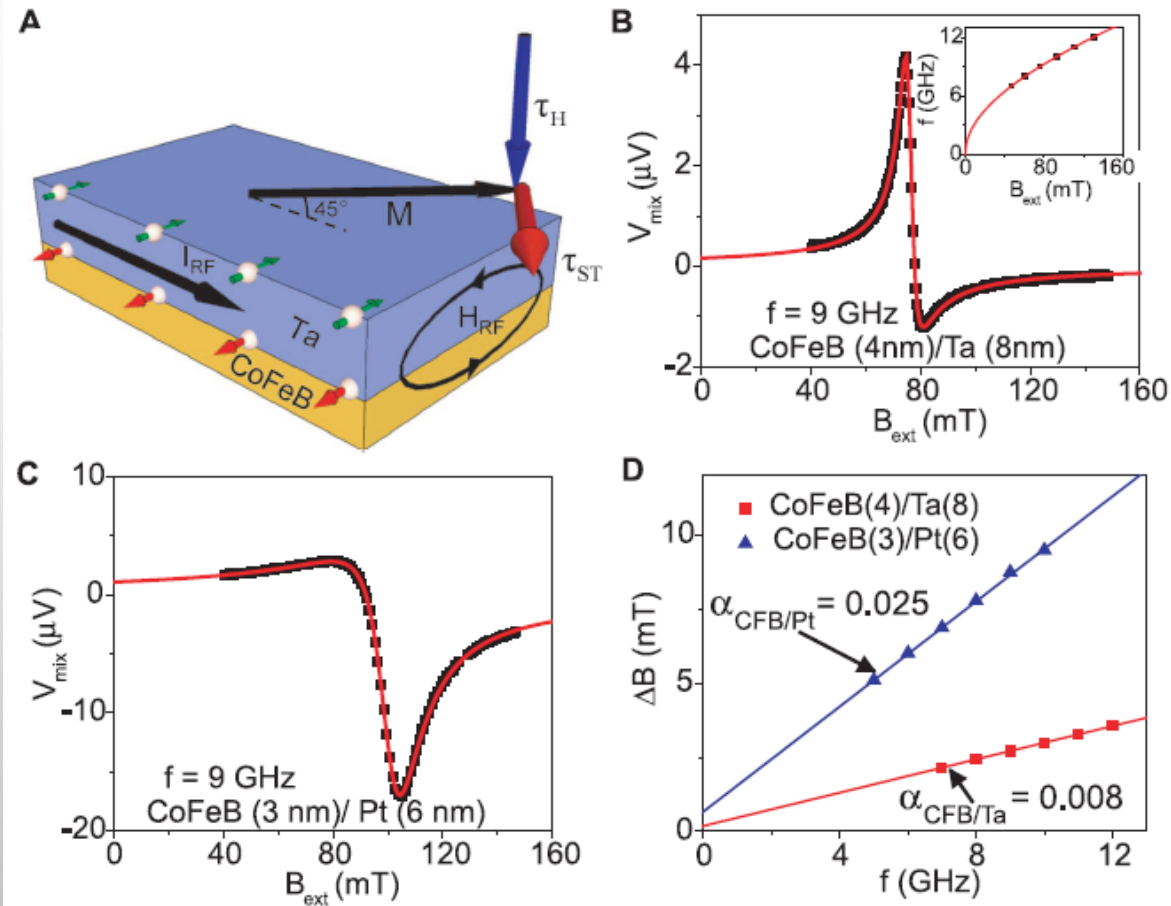
SHE



Spin-Torque Switching with the Giant Spin Hall Effect of Tantalum

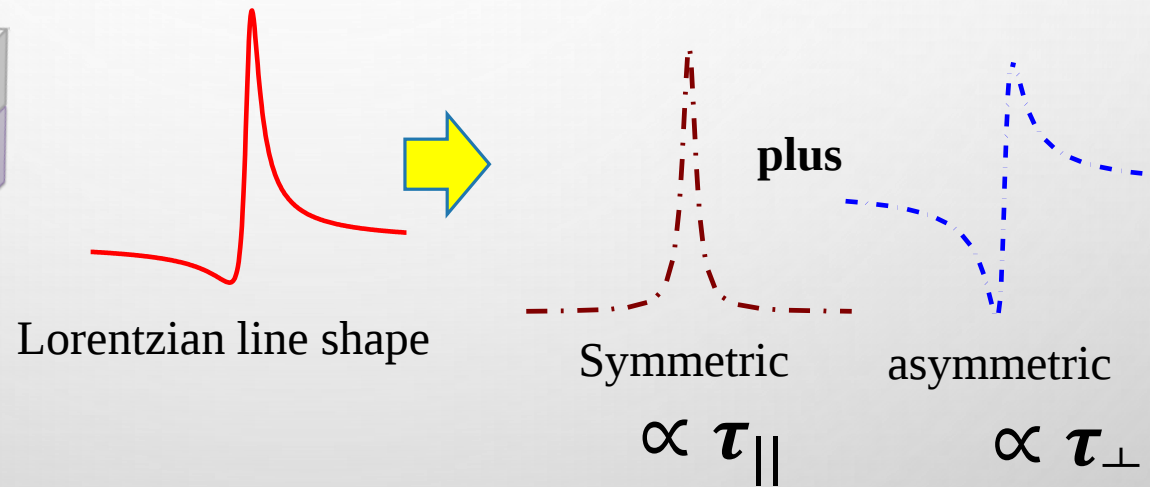
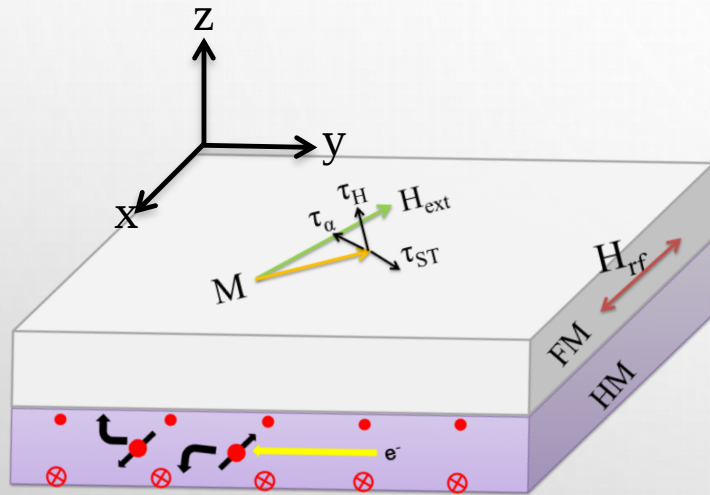
Luqiao Liu,^{1*} Chi-Feng Pai,^{1*} Y. Li,¹ H. W. Tseng,¹ D. C. Ralph,^{1,2} R. A. Buhrman^{1†}

SCIENCE VOL 336



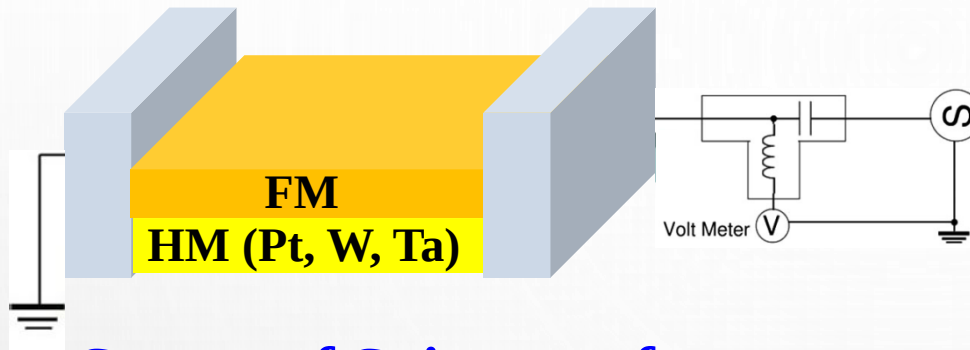
ASYMMETRIC AND SYMMETRIC LINE SHAPE ANALYSIS

$$\begin{aligned}\frac{d\hat{M}}{dt} &= -\gamma\hat{M} \times \vec{H}_{\text{eff}} + \alpha_0\hat{M} \times \frac{d\hat{M}}{dt} + \frac{\gamma\hbar J_s}{2eM_s d_F} (\hat{m} \times \hat{\sigma} \times \hat{m}) - \gamma\hat{M} \times \vec{H}_{\text{rf}} \\ &= -\gamma\hat{M} \times \vec{H}_{\text{eff}} + \alpha_0\hat{M} \times \frac{d\hat{M}}{dt} + \gamma\left[\tau_{\parallel} \frac{\hat{M} \times (\hat{x} \times \hat{M})}{|\hat{x} \times \hat{M}|} + \tau_{\perp} \frac{\hat{x} \times \hat{M}}{|\hat{x} \times \hat{M}|}\right]\end{aligned}$$



spin-orbit torque ratio $\theta_{\parallel} = J_s/J_c = V_S/V_A(e\mu_0 M_S t d/\hbar)[1+(4\pi M_{\text{eff}}/H_{\text{ext}})]^{1/2}$

ST-FMR on bi-layer structures

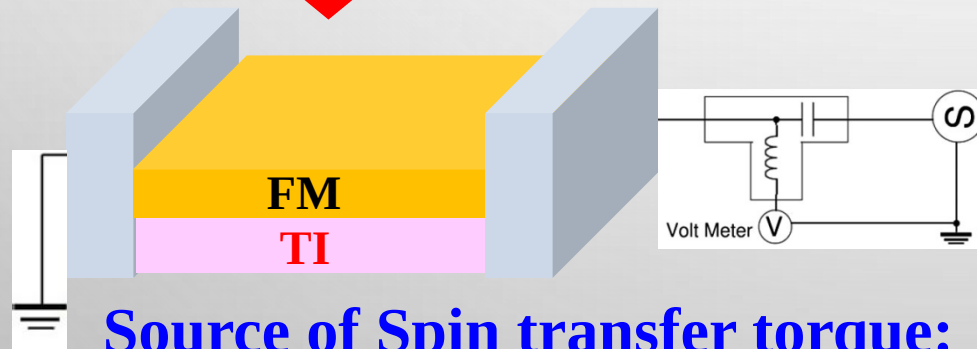


Liu. et al. PRL **106**, 036601 (2011)

Pai et al. APL **101**, 122404 (2012)

Source of Spin transfer torque:

SHE



Source of Spin transfer torque:

SHE, TI surface state

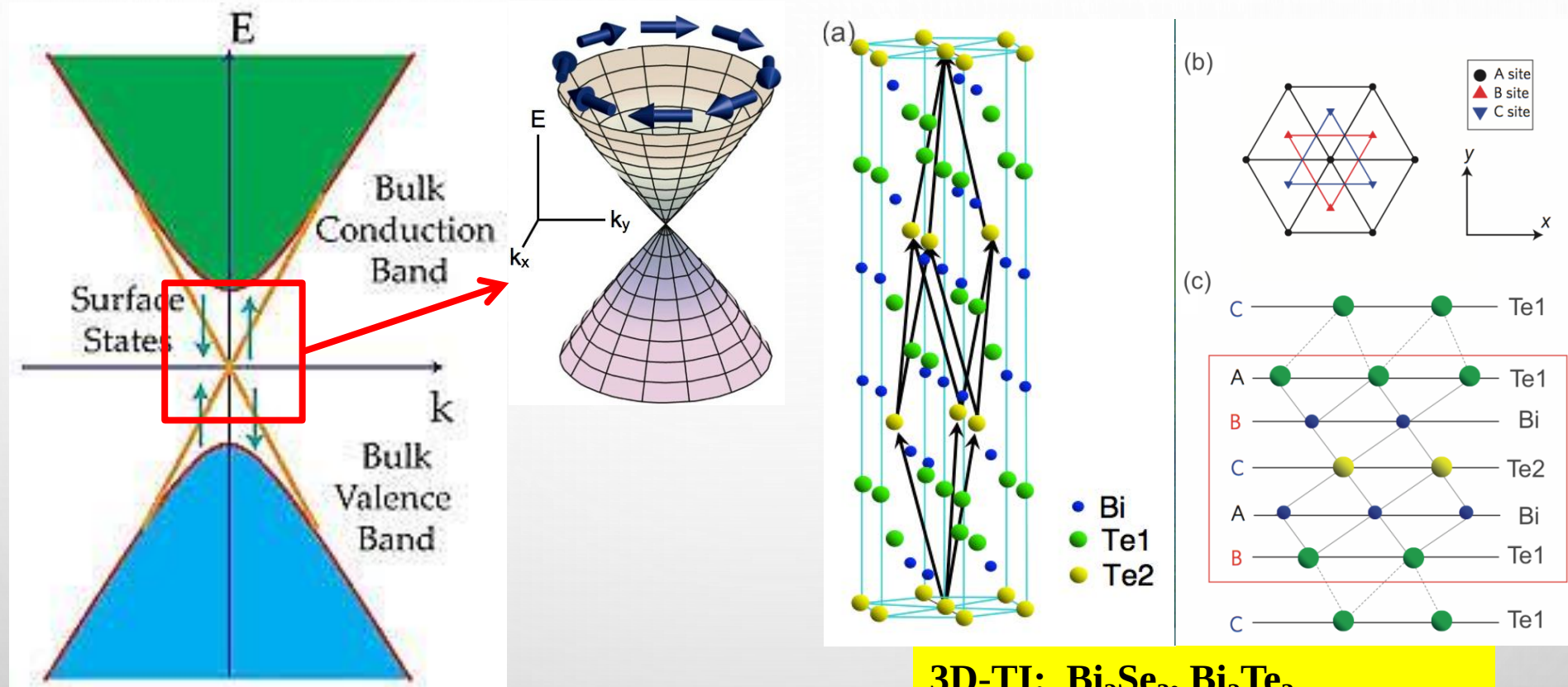
An oscillation of sample resistance due to the **anisotropic magnetoresistance** of FM.

$$\rho = \rho_{\perp} + (\rho_{\parallel} - \rho_{\perp}) \cos^2 \theta_M$$

Mellink et al. Nature **511**, 449 (2014)

Wang et al. PRL **114**, 257202 (2015)

TOPOLOGICAL INSULATOR



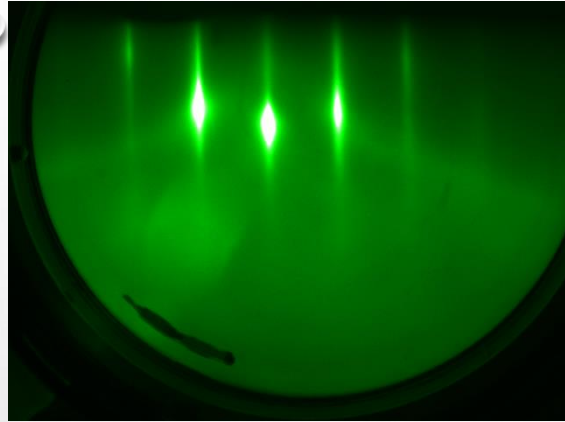
- Strong spin orbit coupling
 - Spin-momentum locking
- TI surface state



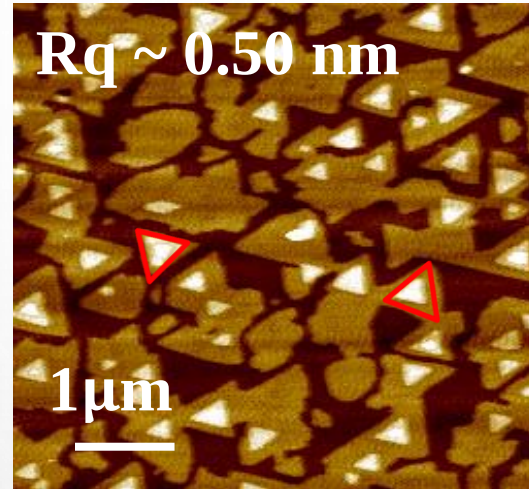
High spin-charge conversion

Bi₂Se₃, Bi₂Te₃, BiSb_xTe_{1-x} FILMS ON Al₂O₃ BY MBE

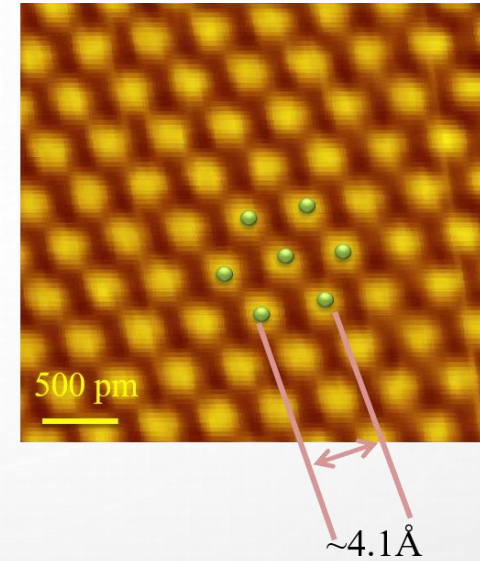
RHEED



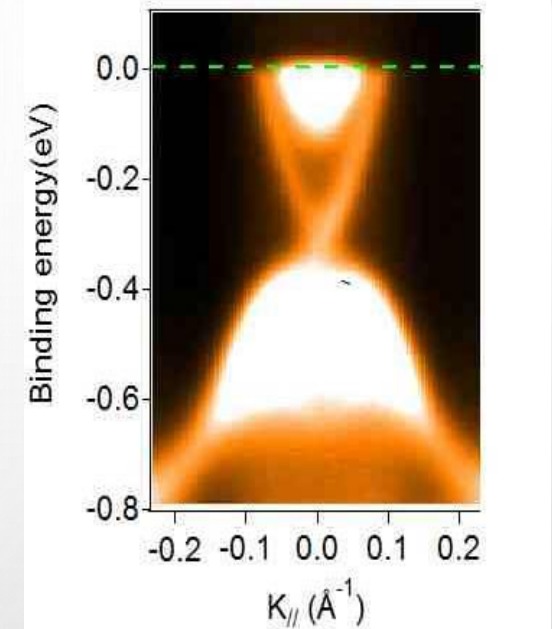
AFM



STM

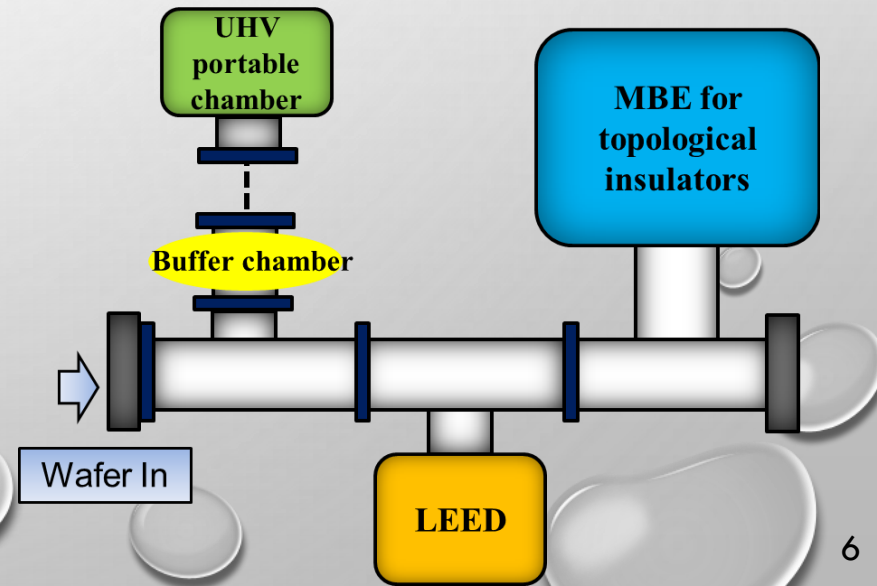
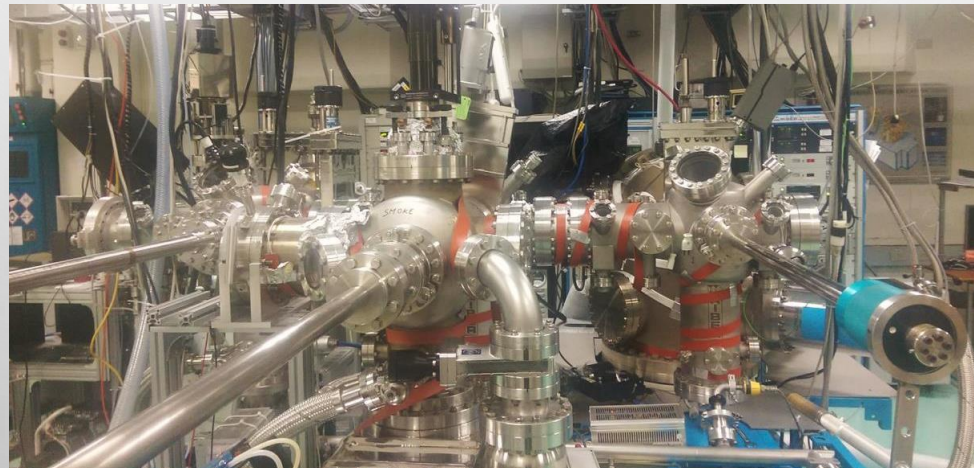


ARPES



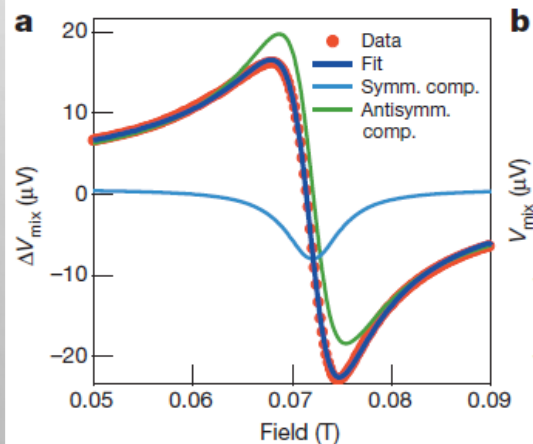
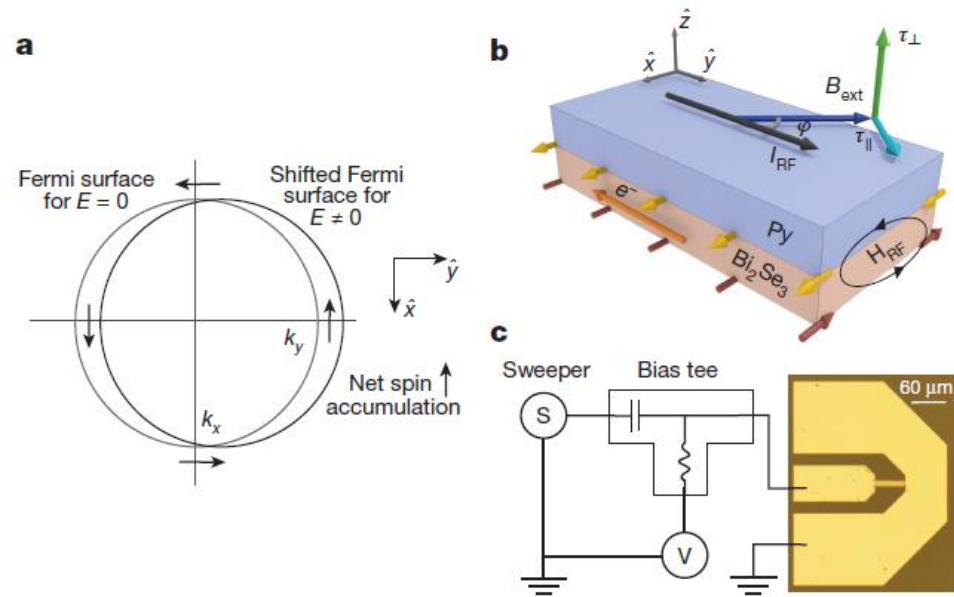
Bi₂Se₃

Al₂O₃



Spin-transfer torque generated by a topological insulator

A. R. Melnik¹, J. S. Lee², A. Richardella², J. L. Grab¹, P. J. Mintun¹, M. H. Fischer^{1,3}, A. Vaezi¹, A. Manchon⁴, E.-A. Kim¹, N. Samarth² & D. C. Ralph^{1,5}



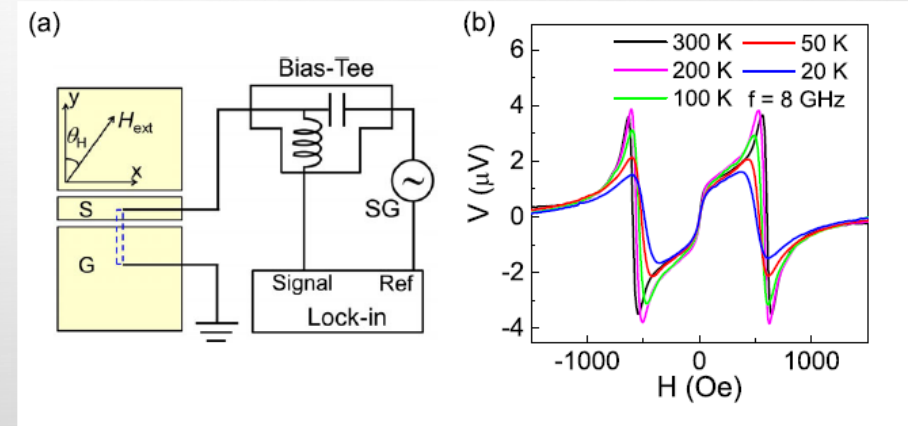
PRL **114**, 257202 (2015)

PHYSICAL REVIEW LETTERS

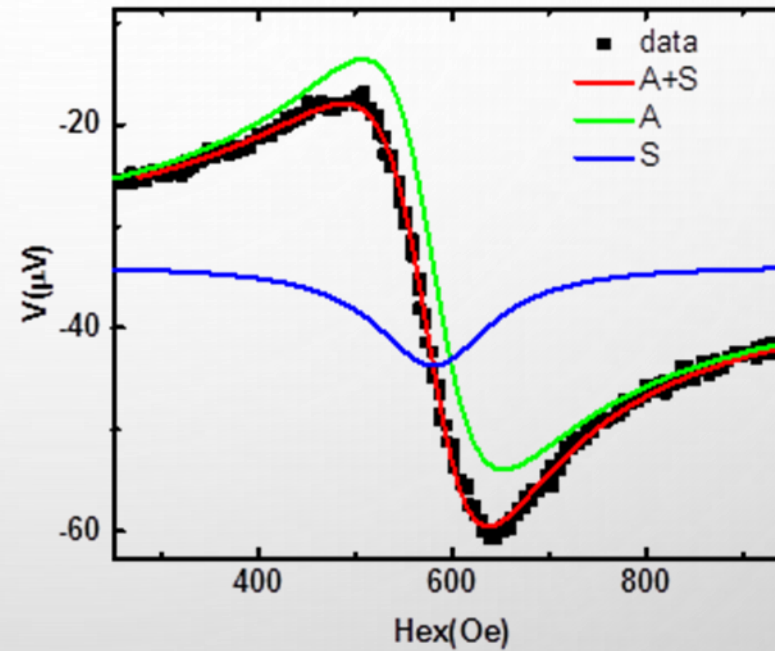
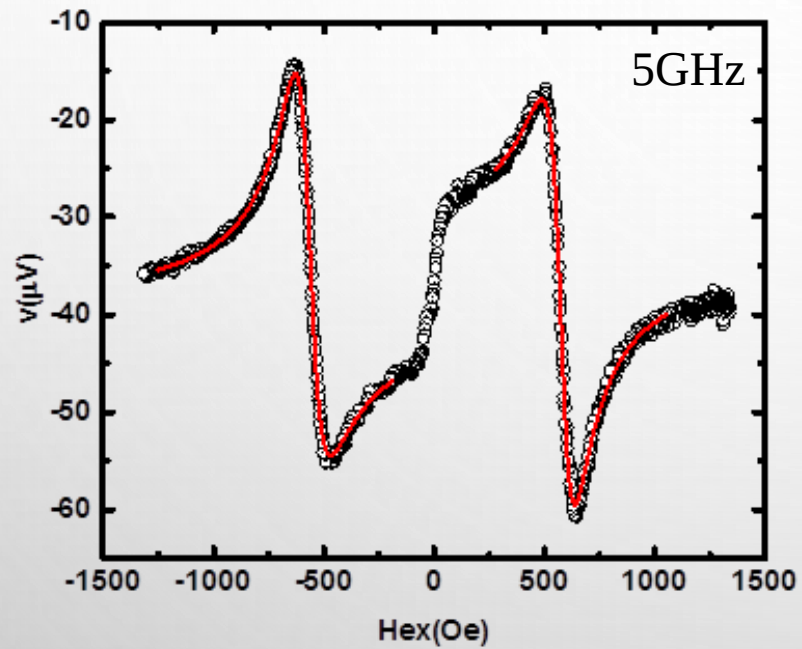
week ending
26 JUNE 2015

Topological Surface States Originated Spin-Orbit Torques in Bi₂Se₃

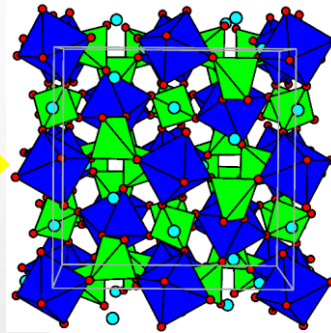
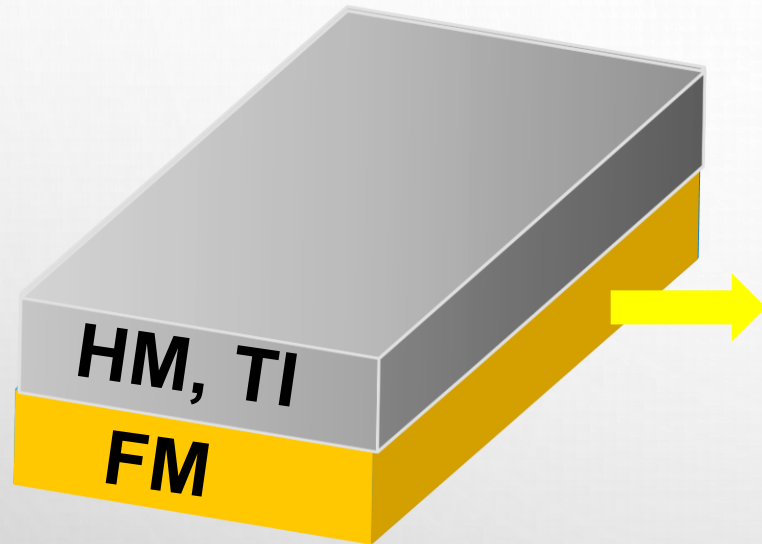
Yi Wang,¹ Praveen Deorani,¹ Karan Banerjee,¹ Nikesh Koirala,² Matthew Brahlek,² Seongshik Oh,² and Hyunsoo Yang^{1,*}
¹Department of Electrical and Computer Engineering, National University of Singapore, 117576 Singapore, Singapore
²Department of Physics and Astronomy, Rutgers, The State University of New Jersey, Piscataway, New Jersey 08854, USA
 (Received 4 February 2015; revised manuscript received 27 April 2015; published 24 June 2015)



LINE CURVE ANALYSIS

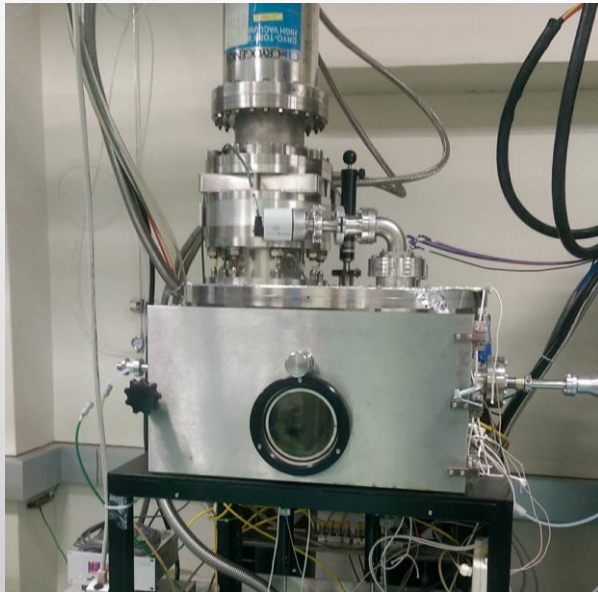


ST-FMR on HM/FI



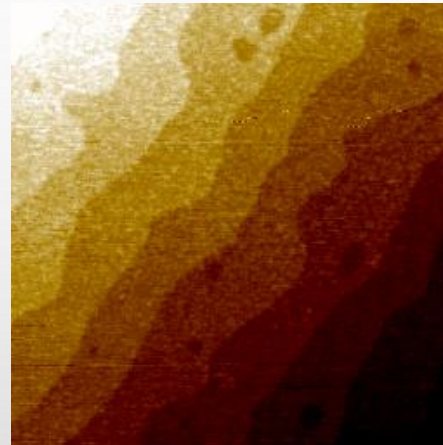
- Extremely small damping ($\alpha \sim 10^{-4}$)
- Electrically insulating
- Long-range spin wave transmission
- Chemically stable surface

FERRIMAGNETIC INSULATOR YIG



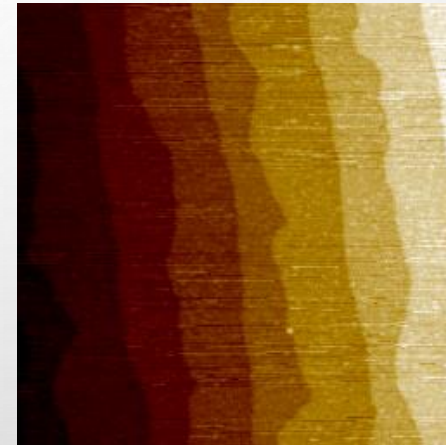
Sputtering YIG on GGG

(100)



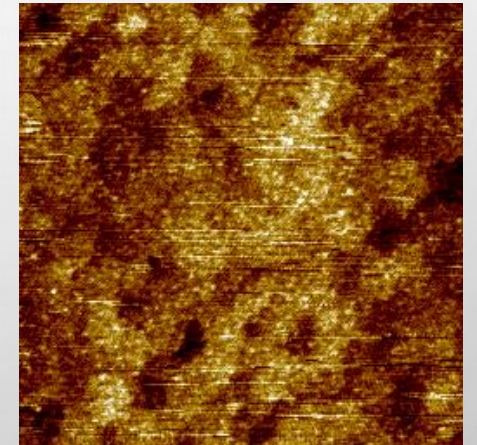
Rq: 1.1Å

(110)



Rq: 0.85Å

(111)

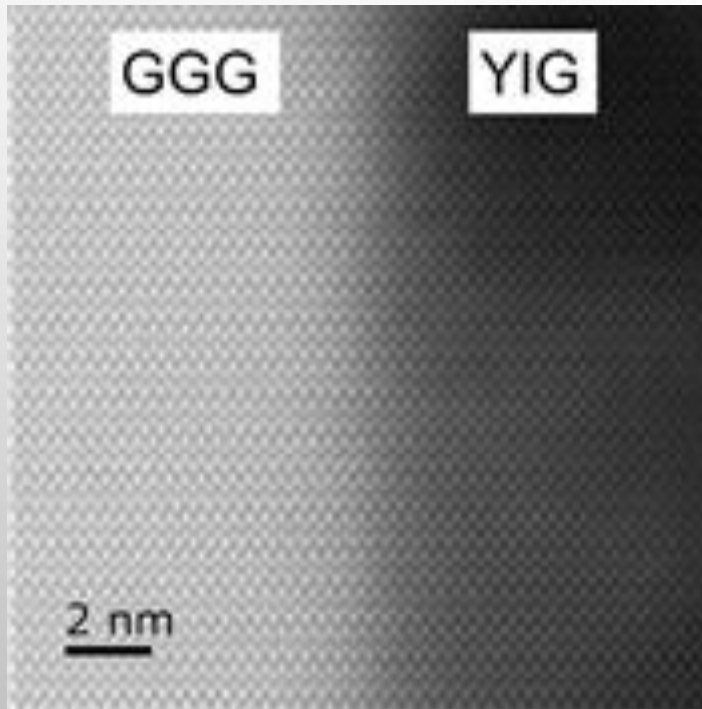


Rq: 1.7Å

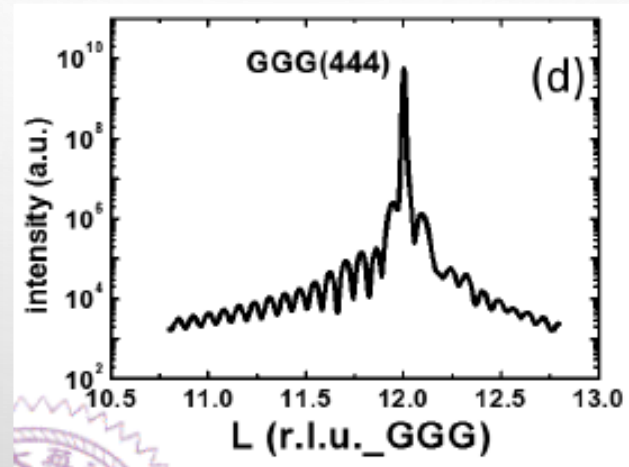
AFM surface morphology

Sample preparation

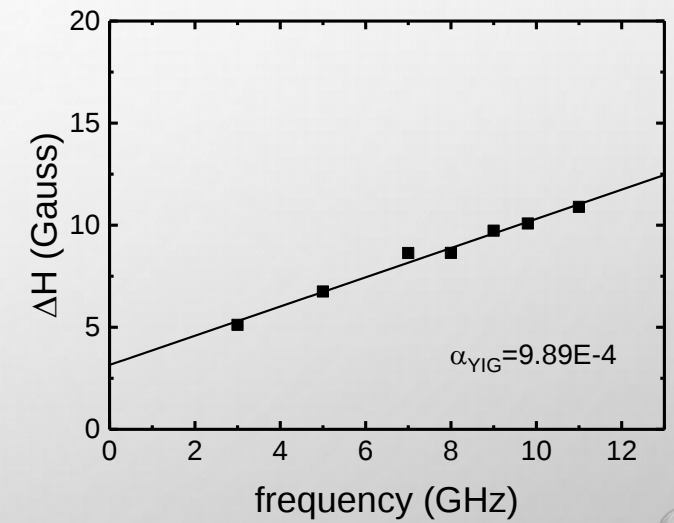
$\text{Y}_3\text{Fe}_5\text{O}_{12}/\text{GGG}$ grown in sputtering chamber



TEM

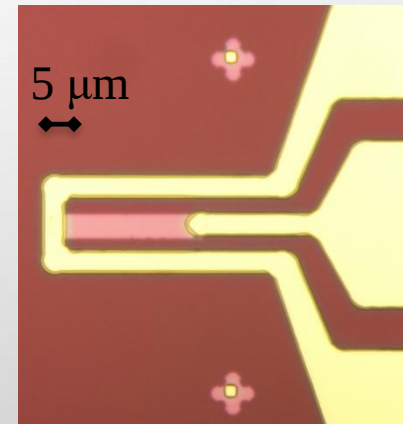
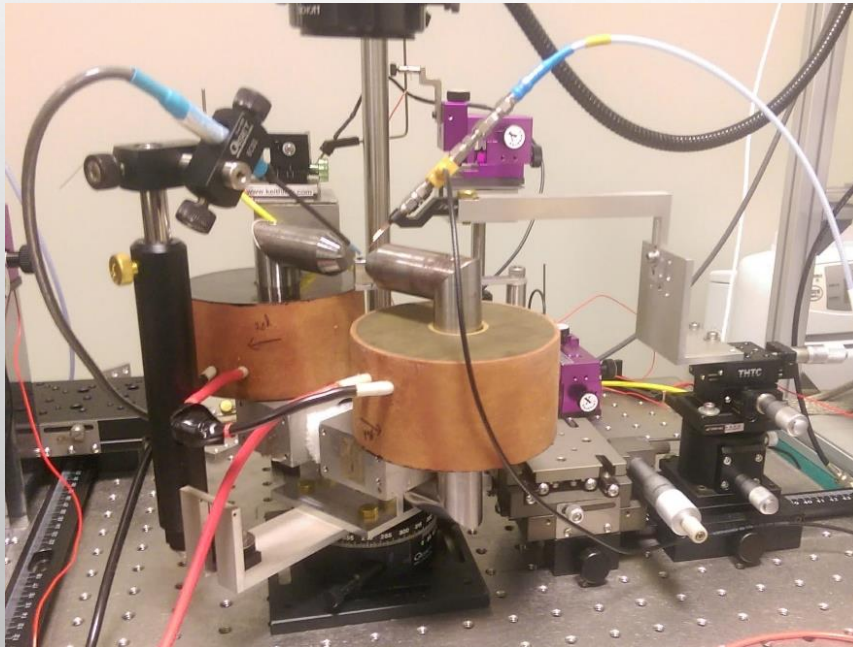
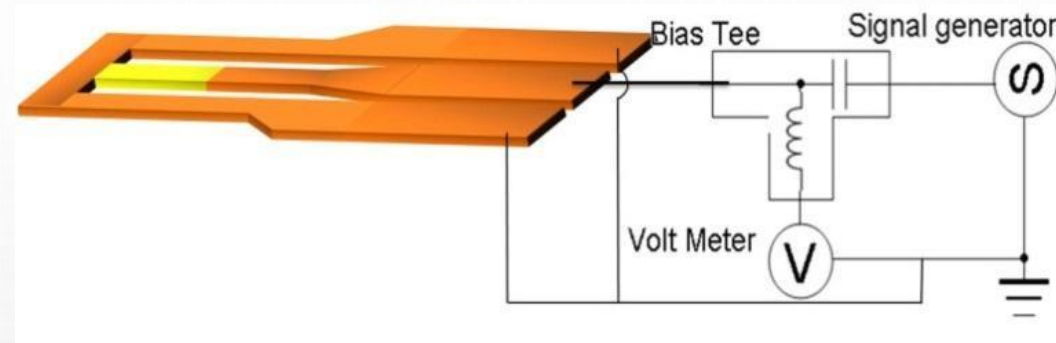


XRD



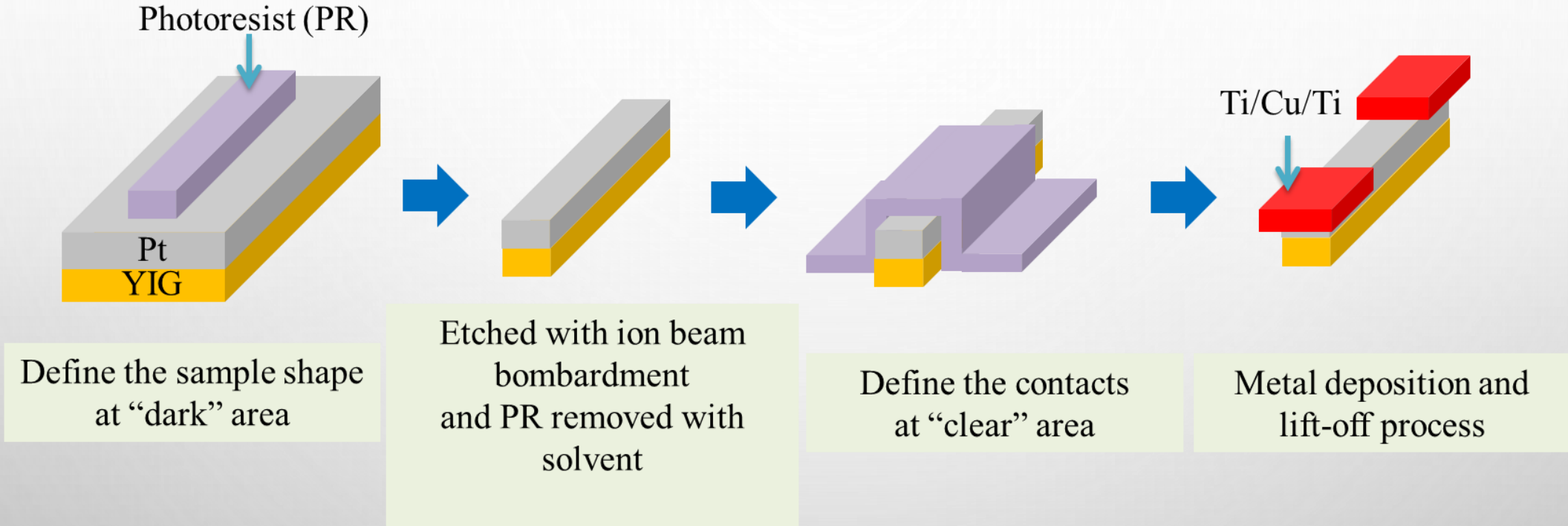
FMR

Device fabrication for ST-FMR experiment



ST-FMR device

FABRICATION PROCESS



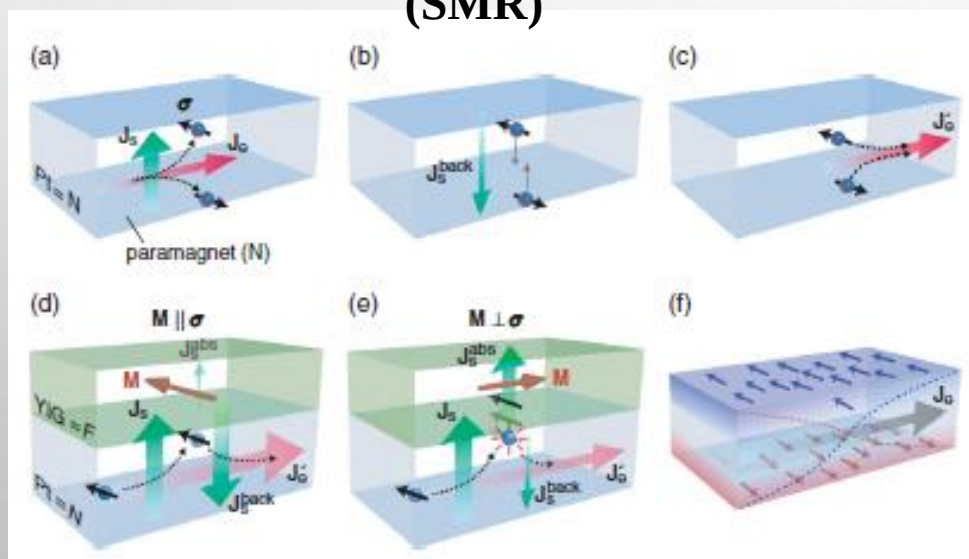
ST-FMR ON PT/YIG

RF current no longer pass through the FM layer.



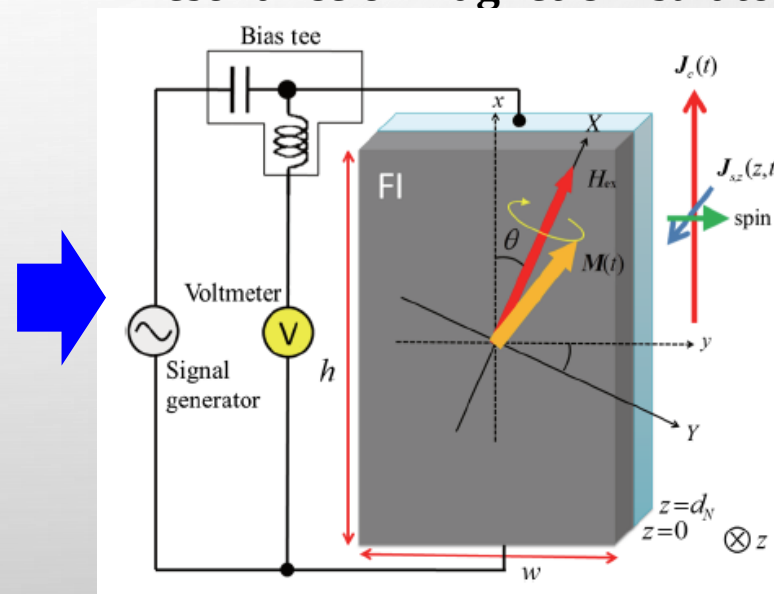
New theoretical model based on SMR should be applied.

Spin Hall magnetoresistance (SMR)



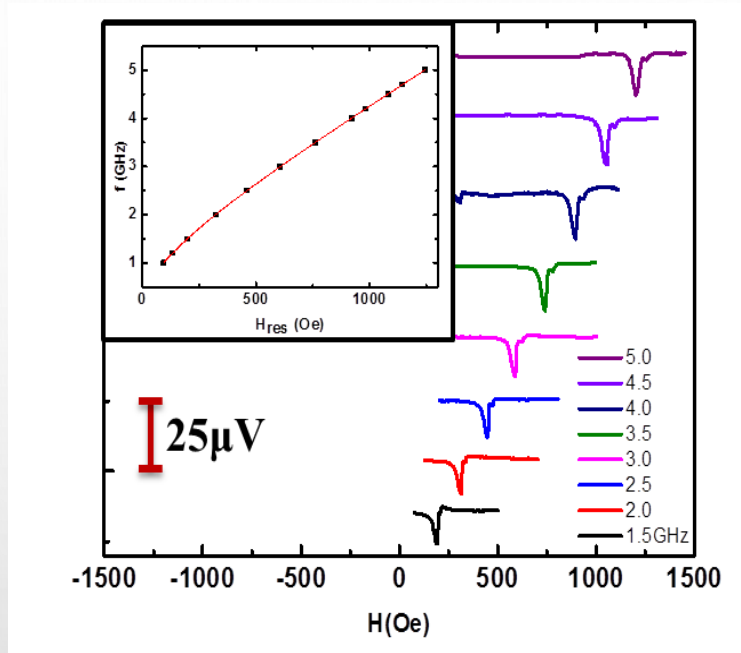
Nakayama et al., Phys. Rev. Lett. **110**, 206601 (2013)

Current-induced spin torque resonance of magnetic insulators

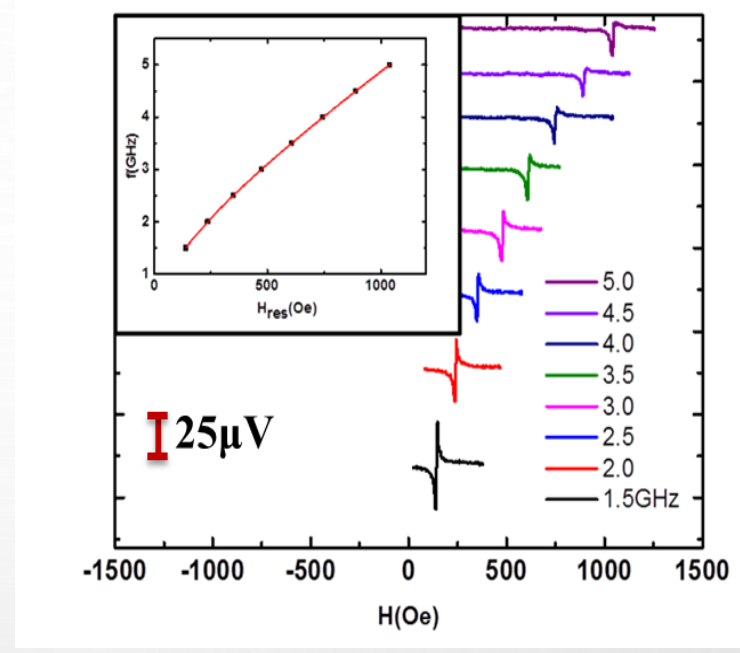


Chiba et al., J. Appl. Phys. **117**, 17C715 (2015)

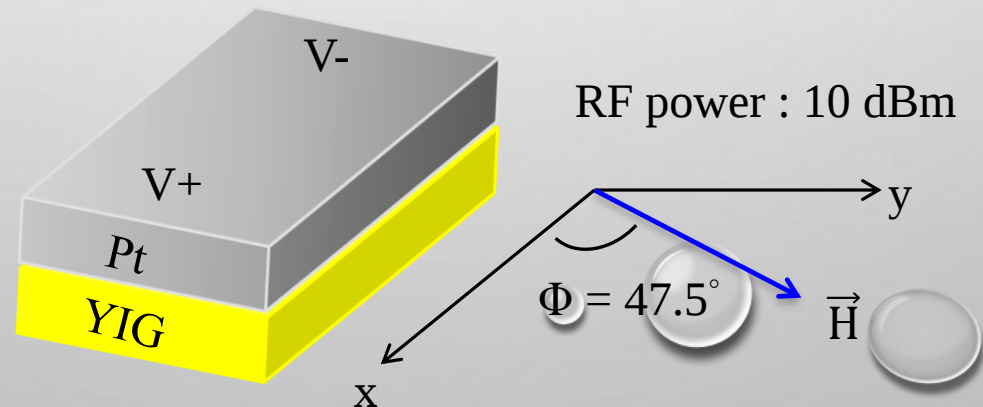
ST-FMR ON PT/YIG



A Pt (5 nm)
YIG (50 nm)



B Pt (16 nm)
YIG (50 nm)



THEORETICAL CALCULATION

$$V_{\text{SMR}} = \frac{h\Delta\rho_1 J_c^0 F_S(\tilde{H}_{\text{ex}})}{4 \frac{\Delta H}{\tilde{H}}} (\tilde{Y}_i^c + \tilde{Y}_r^c \frac{\tilde{H}_{\text{ex}} - \tilde{H}_{\text{FMR}}}{\tilde{H}}) \cos\varphi \sin 2\varphi$$

$$V_{\text{SP}} = \frac{h\rho J_r^P F_S(\tilde{H}_{\text{ex}})}{4 \frac{\Delta H}{\tilde{H}^2}} (\tilde{Z}_i^c \tilde{Y}_r^c - \tilde{Z}_r^c \tilde{Y}_i^c) \cos\varphi \sin 2\varphi$$

Chiba et al., J. Appl. Phys. **117**, 17C715 (2015)

$$V_{\text{mix}} = V_{\text{SMR}} + V_{\text{SP}}$$

$$= S \frac{\Delta H^2}{(H_{\text{ex}} - H_{\text{res}})^2 + \Delta H^2} + A \frac{\Delta H (H_{\text{ex}} - H_{\text{res}})}{(H_{\text{ex}} - H_{\text{res}})^2 + \Delta H^2}$$

h: sample length,
 ω_a : resonant frequency,
 d_N : Pt thickness,
 λ : spin diffusion length,
 γ : gyromagnetic ratio
 α_0 : intrinsic damping constant of YIG.
 ρ : resistivity of Pt,
 d_F : thickness of YIG,
 M_s : magnetization of YIG.
 $G_{r(i)}$: Real (Imaginary) part of spin mixing conductance,
 η : spin diffusion efficiency described in the SMR theory, a complex function of G_i G_r .
 δ : phase shift between rf current and Oersted field inside YIG

$$F_S(\tilde{H}_{\text{ex}}) = \frac{\tilde{H}^2}{(\tilde{H}_{\text{ex}} - \tilde{H}_{\text{FMR}})^2 + \tilde{H}^2}$$

$$Y_i^c = C[H_r + \alpha(H_{\text{ac}} \cos\delta + H_i)] + C_+ H_{\text{ac}} \sin\delta,$$

$$Y_r^c = C_+(H_{\text{ac}} \cos\delta + H_i) - C\alpha H_{\text{ac}} \sin\delta,$$

$$Z_i^c = C[\alpha H_r - (H_{\text{ac}} \cos\delta + H_i)],$$

$$Z_r^c = C_- H_r + C H_{\text{ac}} \sin\delta,$$

$$J_r^P = \frac{\hbar\omega_a}{2ed_N\rho} \theta_{\text{SH}} \text{Re}(\eta),$$

$$\eta = (1 - \frac{1}{\cosh(d_N/\lambda)}) \frac{\tilde{g}_r(1+\tilde{g}_r) + \tilde{g}_i^2 + i\tilde{g}_i}{(1+\tilde{g}_r)^2 + \tilde{g}_i},$$

$$\tilde{g}_{r(i)} = 2\lambda\rho G_{r(i)} \coth(d_N/\lambda),$$

$$\alpha = \frac{\alpha_0 + \beta \coth(r/2) \text{Re}(\eta)}{1 - \beta \coth(r/2) \text{Im}(\eta)},$$

$$r = d_N/\lambda,$$

$$\beta = \gamma\hbar^2/4\lambda\rho e^2 M_s d_F,$$

$$\tilde{\gamma} = \gamma/(1 - \beta \coth(r/2) \text{Im}(\eta)),$$

$$\Delta\rho_1 = \rho\theta_{\text{SH}}^2 (2\lambda/d_N) \text{Re}(\eta/2),$$

$$H_{r(i)} = \frac{\hbar}{2eM_s d_F} \theta_{\text{SH}} J_c^0 \text{Re}(\text{Im})\eta,$$

$$H_{\text{ac}} = 2\pi J_c^0 d_N/c,$$

$$\Delta H = \alpha\omega_a/\tilde{\gamma},$$

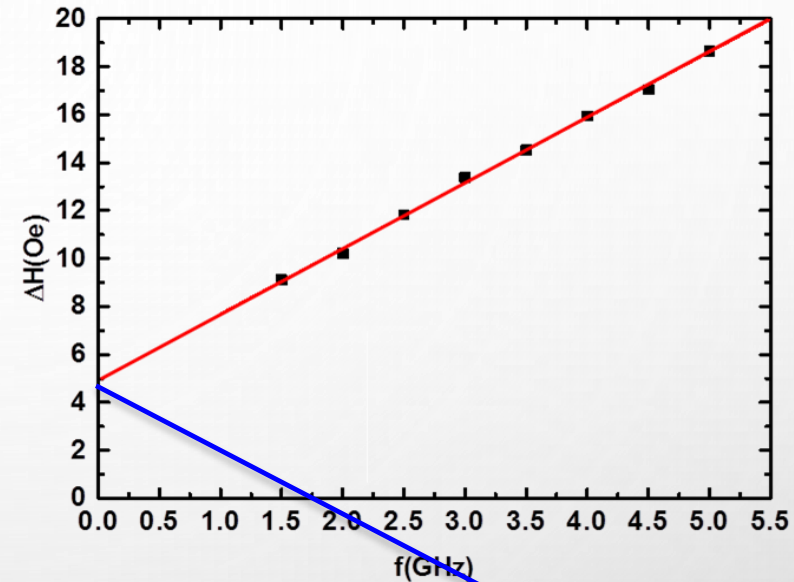
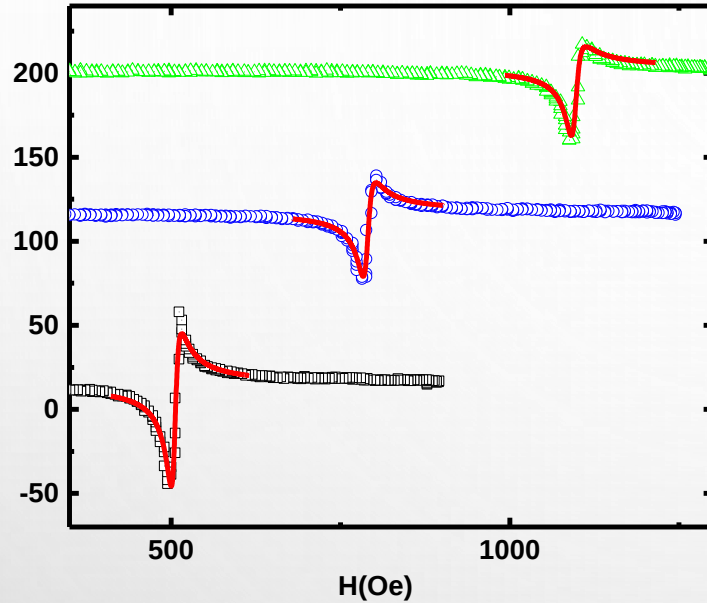
$$\tilde{H} = \Delta H/2\pi M_s,$$

$$C = \tilde{\omega}_a/\sqrt{1 + \tilde{\omega}_a^2},$$

$$C_{\pm} = 1 \pm 1/\sqrt{1 + \tilde{\omega}_a^2},$$

$$\tilde{\omega}_a = \omega_a/2\pi M_s \gamma$$

Line width analysis



$$V_{\text{mix}} = S \frac{\Delta H^2}{(H_{\text{ex}} - H_{\text{res}})^2 + \Delta H^2} + A \frac{\Delta H (H_{\text{ex}} - H_{\text{res}})}{(H_{\text{ex}} - H_{\text{res}})^2 + \Delta H^2}$$

$$\Delta H = \alpha \omega_a / \tilde{\gamma} + \Delta H_0$$

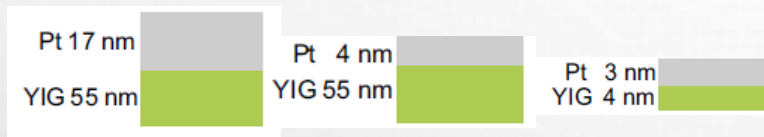
An inhomogeneous broadening factor was observed!

WHY ΔH_0 IS IMPORTANT IN THE ANALYSIS?

Neglecting ΔH_0 can lead to

1. Overestimation of damping coefficient α or spin mixing conductance (Real part) G_r .

Schreier et al. Phys. Rev. B **92**, 144411 (2015)



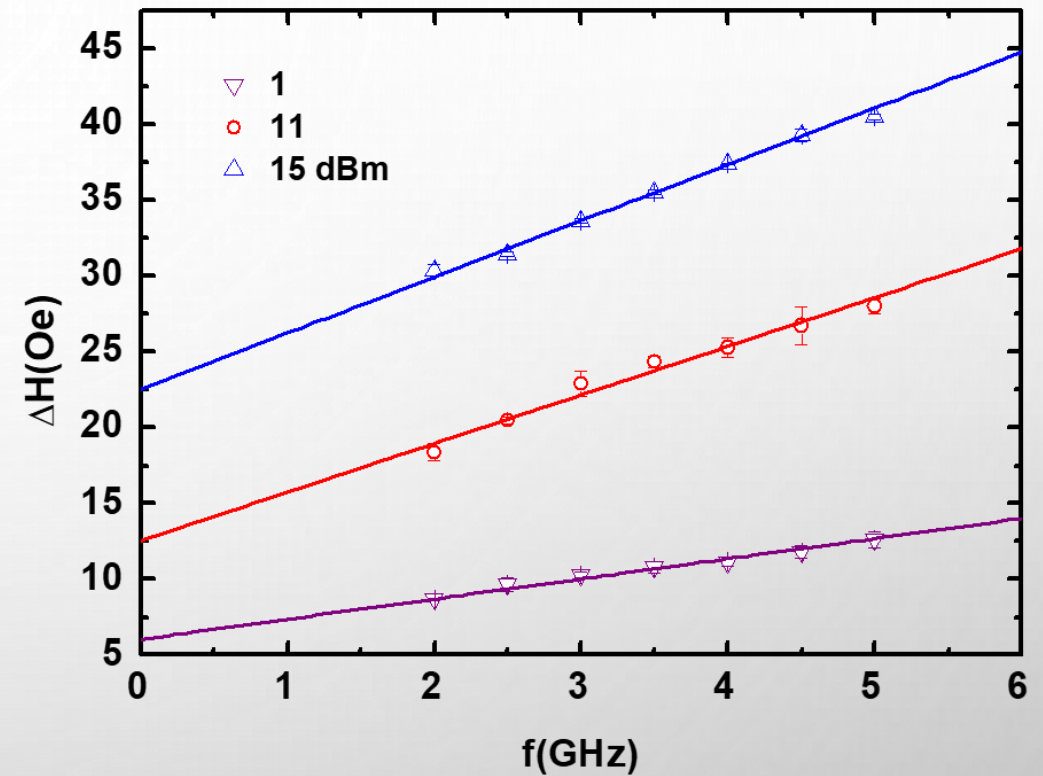
Fitting results yield $\alpha_0 = 0.01, 0.015, 0.04$

2. Inconsistent fitting results of frequency-independent parameters.

$$\Delta H = \alpha \omega_a / \tilde{\gamma}$$

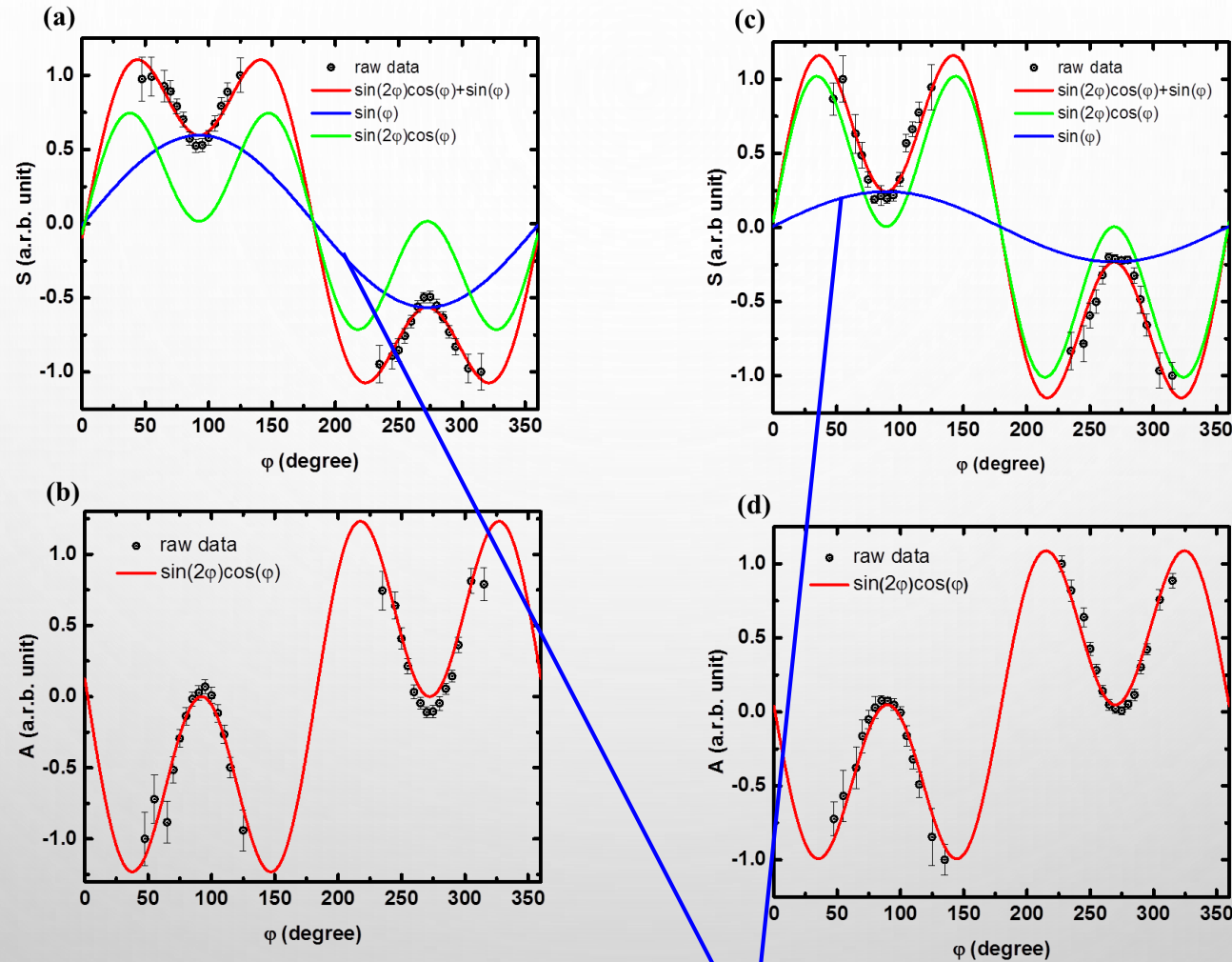
$$\frac{\alpha}{\tilde{\gamma}} = \frac{\alpha_0 + \beta \coth(r/2) \text{Re}(\eta)}{\gamma}$$

η should be frequency independent based on SMR theory.



3. Fitting results will vary with applied power.

IN-PLANE ANGULAR DEPENDENCY

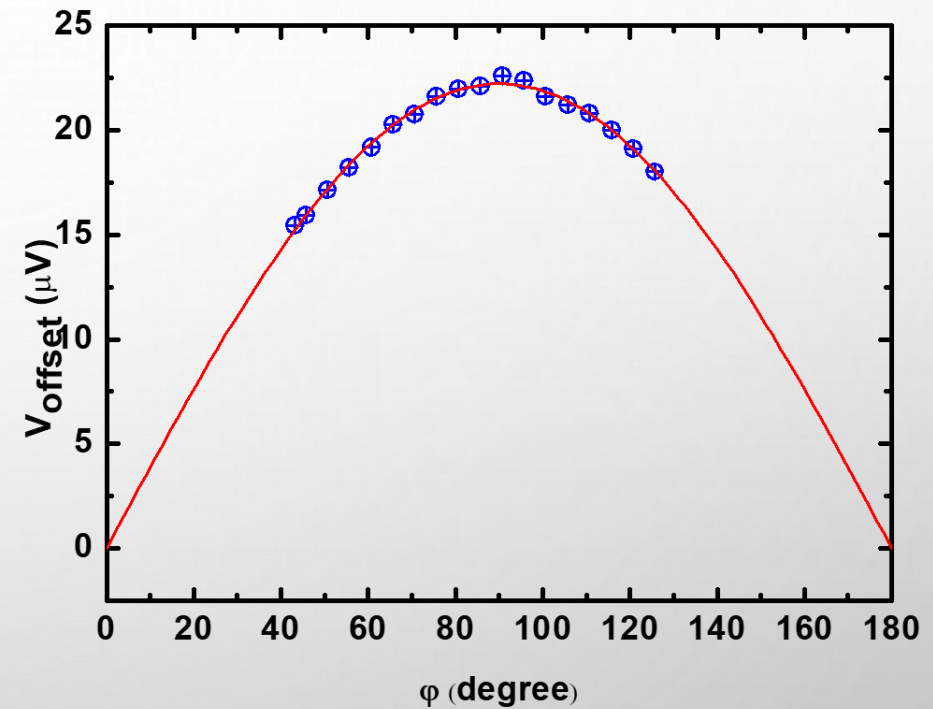
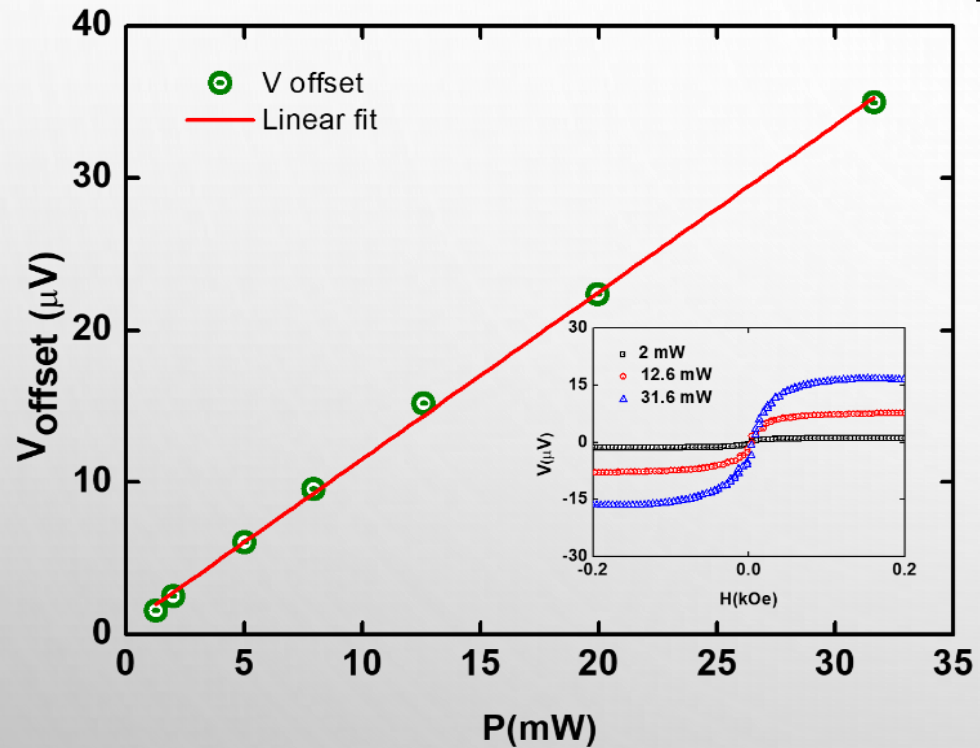


$$V_{\text{SMR}} = \frac{\hbar \Delta \rho_1 J_c^0}{4} \frac{F_S(\tilde{H}_{\text{ex}})}{\Delta \tilde{H}} (\tilde{Y}_i^c + \tilde{Y}_r^c \frac{\tilde{H}_{\text{ex}} - \tilde{H}_{\text{FMR}}}{\Delta \tilde{H}}) \sin 2\phi \cos \phi$$

$$V_{\text{SP}} = \frac{\hbar \rho J_F^P}{4} \frac{F_S(\tilde{H}_{\text{ex}})}{\Delta \tilde{H}^2} (\tilde{Z}_i^c \tilde{Y}_r^c - \tilde{Z}_r^c \tilde{Y}_i^c) \sin 2\phi \cos \phi$$

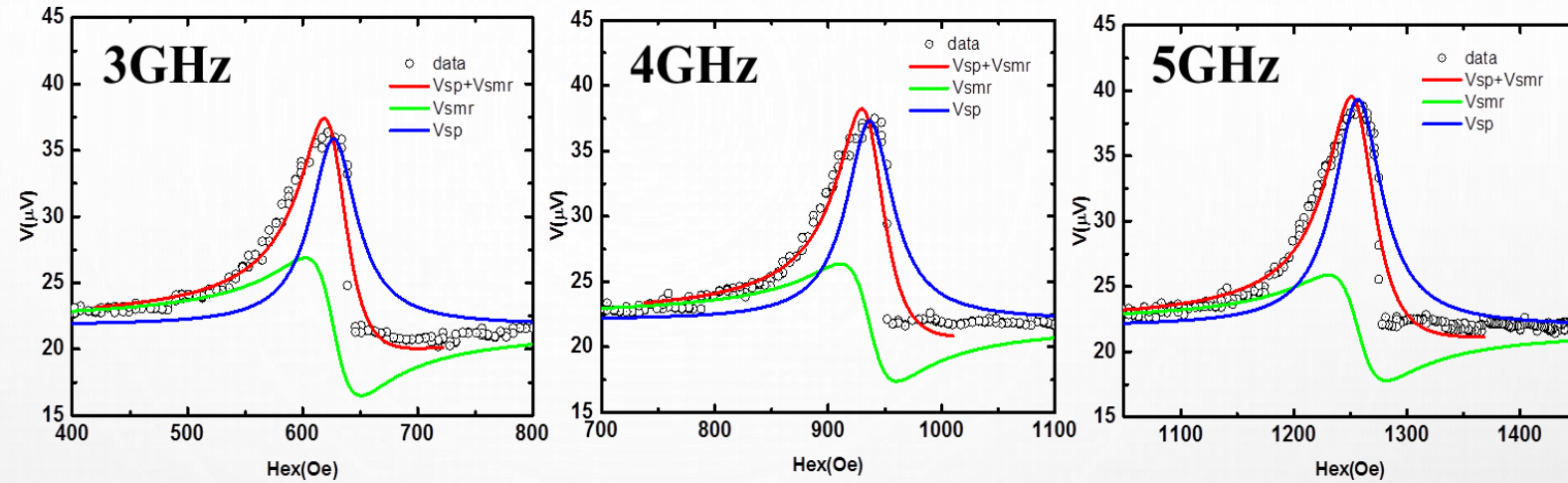
An extra $\sin(\phi)$ component of symmetric part was observed

HEATING INDUCED V_{OFFSET} DURING M SWITCHING PROCESS

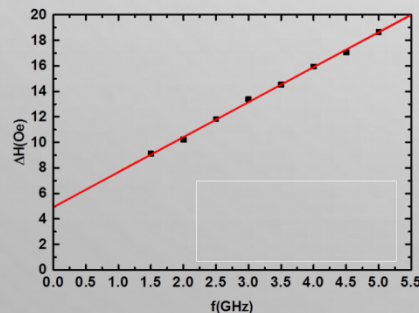
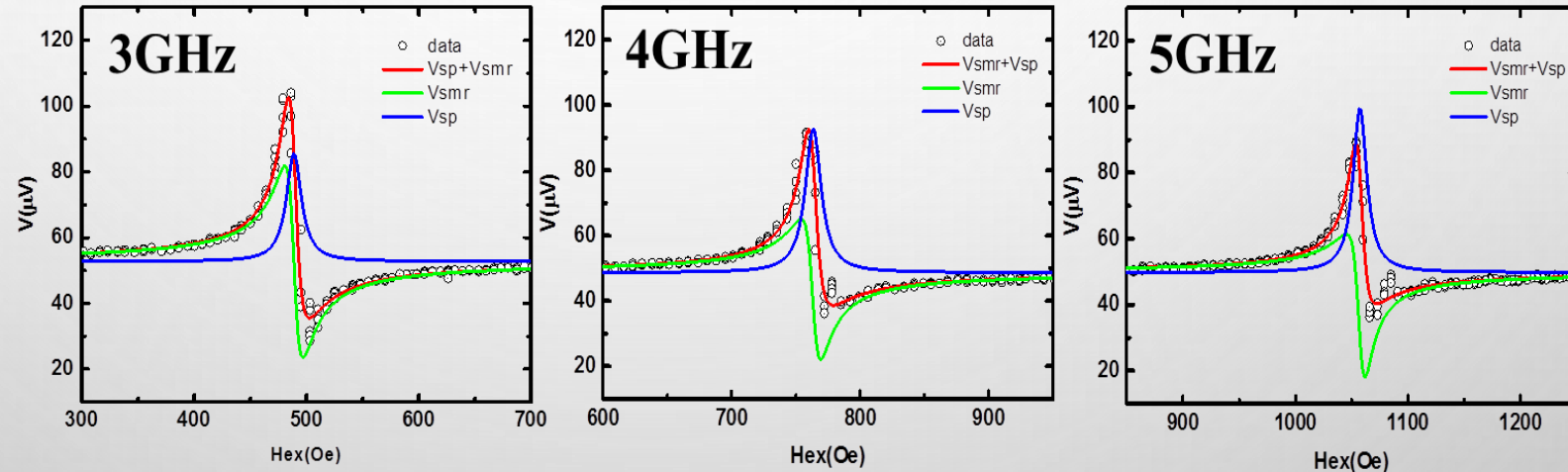


Curve fitting with theoretical model

Sample A



Sample B



Slope

$$\frac{\alpha}{\tilde{\gamma}} = \frac{\alpha_0 + \beta \coth(r/2) \operatorname{Re}(\eta)}{\gamma}$$

$$\eta = \left(1 - \frac{1}{\cosh(d_N/\lambda)}\right) \frac{\tilde{g}_r(1 + \tilde{g}_r) + \tilde{g}_i^2 + i\tilde{g}_i}{(1 + \tilde{g}_r)^2 + \tilde{g}_i}$$

Assumption: G_r 1order larger than G_i

Gr:

Sample A: $1.5 \times 10^{14} \Omega^{-1} \text{m}^{-2}$

Sample B: $1.9 \times 10^{14} \Omega^{-1} \text{m}^{-2}$

Curve fitting with theoretical model

Sample A	3GHz	4GHz	5GHz
J_C (A/m ²)	$2.52(\pm 0.11) \times 10^{11}$	$2.24(\pm 0.08) \times 10^{11}$	$2.20(\pm 0.06) \times 10^{11}$
θ_{SH}	0.058 ± 0.004	0.064 ± 0.003	0.063 ± 0.003
Sample B	3GHz	4GHz	5GHz
J_C	$1.40 \pm (0.03) \times 10^{11}$	$1.30(\pm 0.04) \times 10^{11}$	$1.09(\pm 0.04) \times 10^{11}$
θ_{SH}	0.110 ± 0.003	0.104 ± 0.004	0.126 ± 0.006

SUMMARY

- WE TESTIFIED THE THEORETICAL MODEL OF SMR-BASED ST-FMR MEASUREMENT.
- WE PROVIDE SOME MODIFICATIONS ON THE MODEL
 1. ADDING AN INHOMOGENEOUS FACTOR.
 2. FREQUENCY DEPENDENT MEASUREMENT.
 3. SUBTRACTING AN EXTRA $\sin\Phi$ SYMMETRIC COMPONENT.



Spin-Orbit torque ferromagnetic resonance in transferred-topological insulator/normal metal/ferromagnetic metal heterostructure

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Department of Physics, National Tsing-Hua University

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Department of Physics, National Taiwan University

L. J. Chang, S. F. Lee

Institute of Physics, Academia Sinica

Outline

- INTRODUCTION

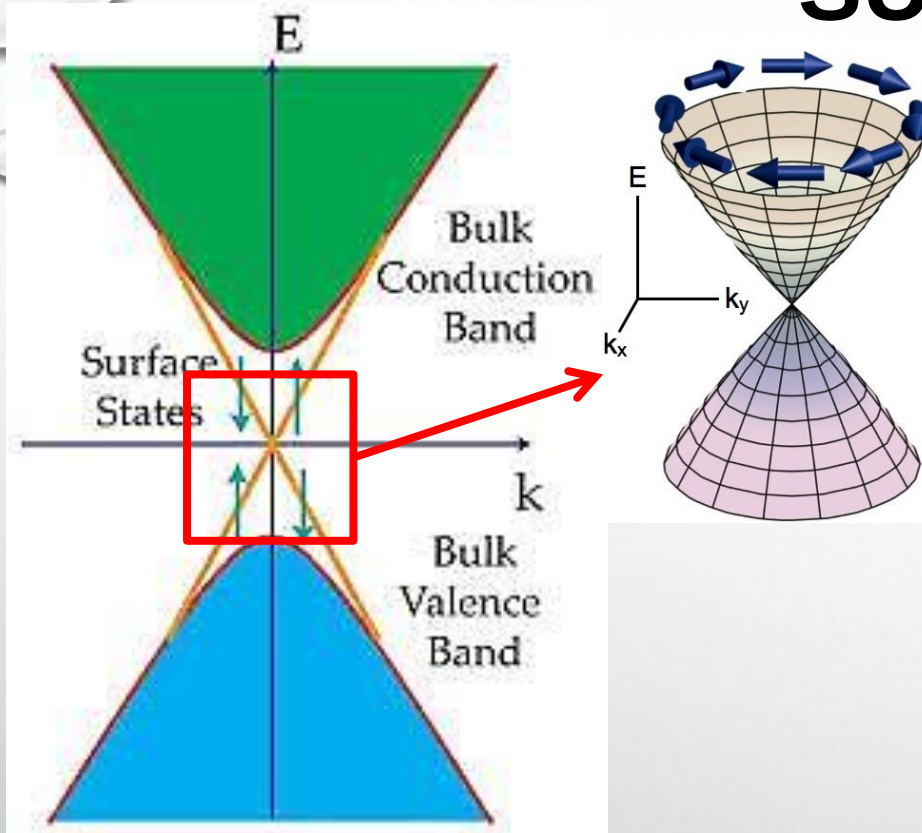
- ◆ TO DECOUPLE/REDUCE THE INTERFACIAL COUPLING BETWEEN TI AND FM

- RESULTS FOR TRANSFERRED (TR) Bi_2Se_3 FILMS

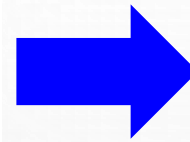
- ◆ SAMPLE TRANSFERRING AND CHARACTERIZATION
- ◆ SPIN-ORBIT TORQUE FMR

- SUMMARY AND FUTURE WORK

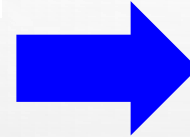
APPLICATION OF SPIN MOMENTUM LOCKED SURFACE STATE



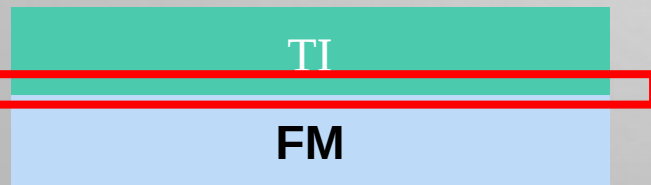
- Spin-momentum locked surface state
- Protected by time reversal symmetry (TRS)



High spin-charge conversion



magnetization switching (SOT-MRAM)

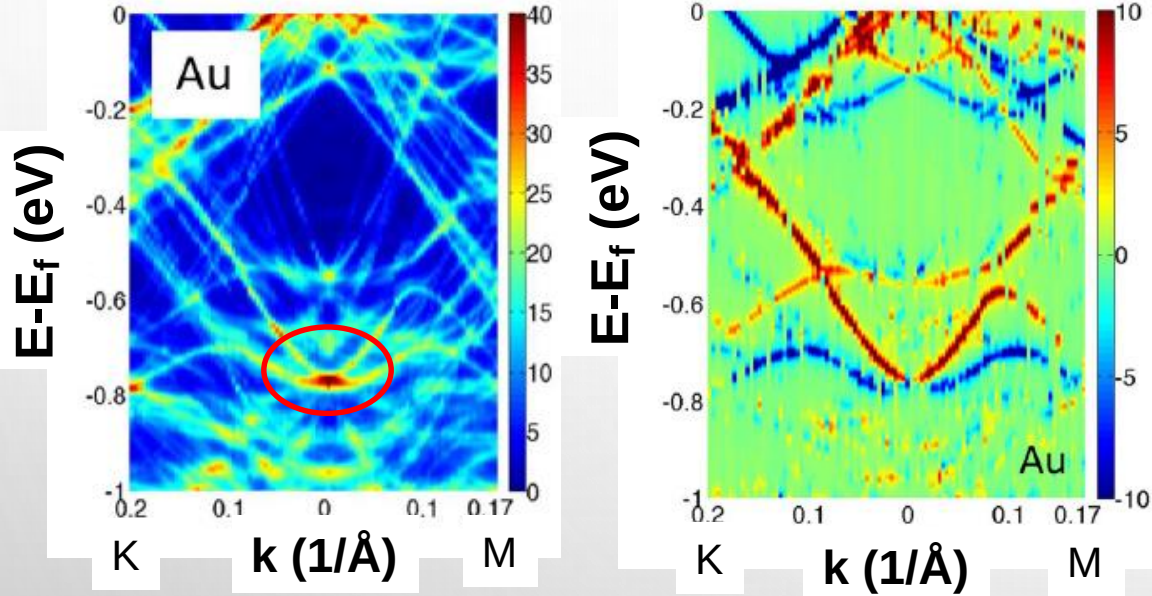


Does the strong interfacial exchange coupling modify the spin texture of the topological surface state, further influencing spin-to-charge conversion (SCC)?

Electronic property and chemistry of metals in contact with Bi_2Se_3

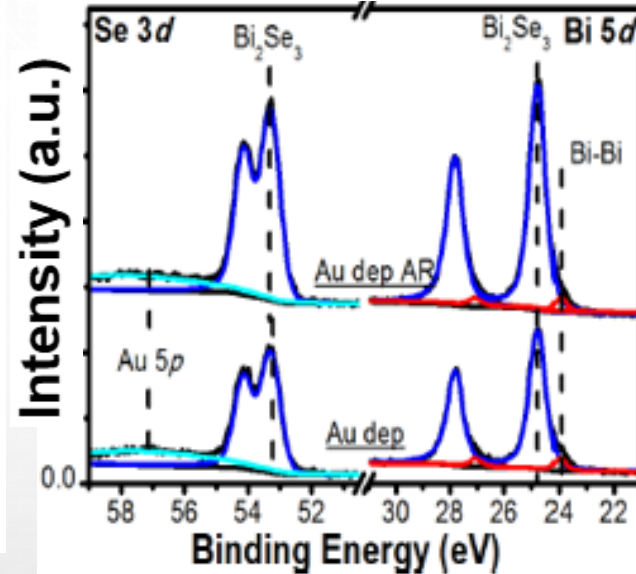
C. D. Spataru *et al.*, *Phys. Rev. B* **90**, 085115 (2014)

Calculated **spectral function of Au/ Bi_2Se_3**

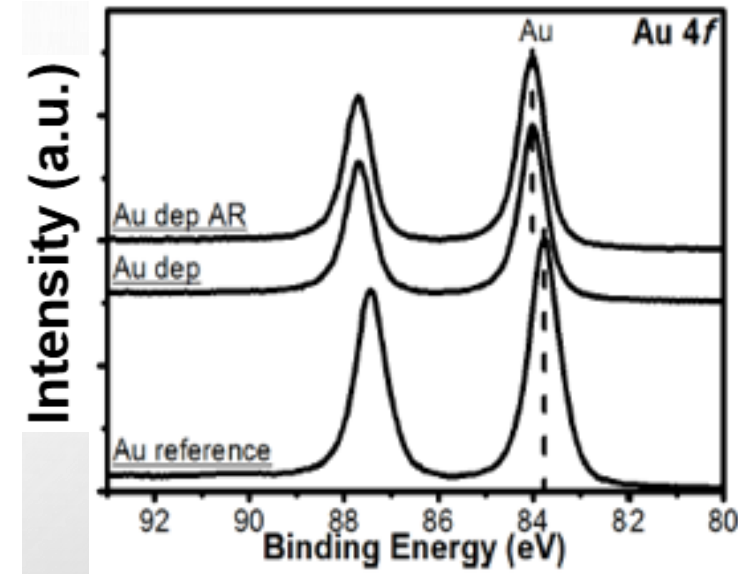


L. A. Walsh *et al.*, *J. Phys. Chem.* **121**, 23551–23563 (2017)

XPS result for **Se 3d and Bi 5d**



XPS result for **Au 4f**



- **Preservation of Dirac cone and the spin texture of TI**
 - **Chemically inert to TI**
- => **Au may serve as a promising interlayer**



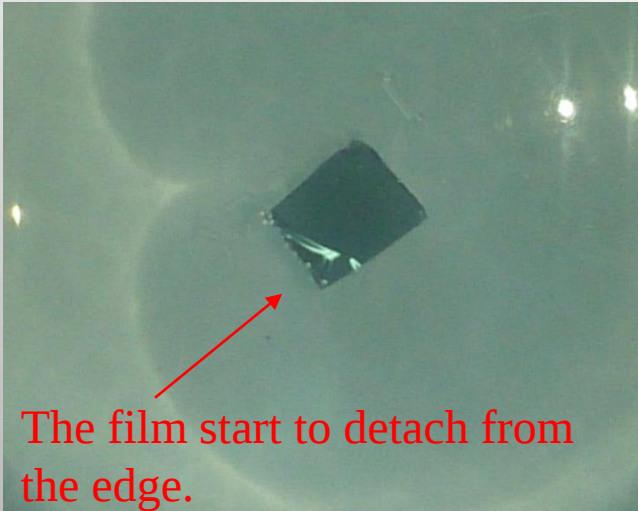
However, it is difficult to directly grow Bi_2Se_3 on Au/YIG.
=> **Thin film transferring**

TRANSFER PROCEDURE

Peel-off

Floating the $\text{Bi}_2\text{Se}_3/\text{Al}_2\text{O}_3$ film on BOE solution
(a few mins to several hrs)

This is the most uncertain step.
The difficulty of peel-off depends on samples.



Ideally, the film can be peeled off by itself without our poking or peeling.

Film transfer

Floating the Bi_2Se_3 film on water to rinse off BOE
(1 hr)

Transferring the film to target substrate

Drying the transferred film in the chemical hood
(1 hr)

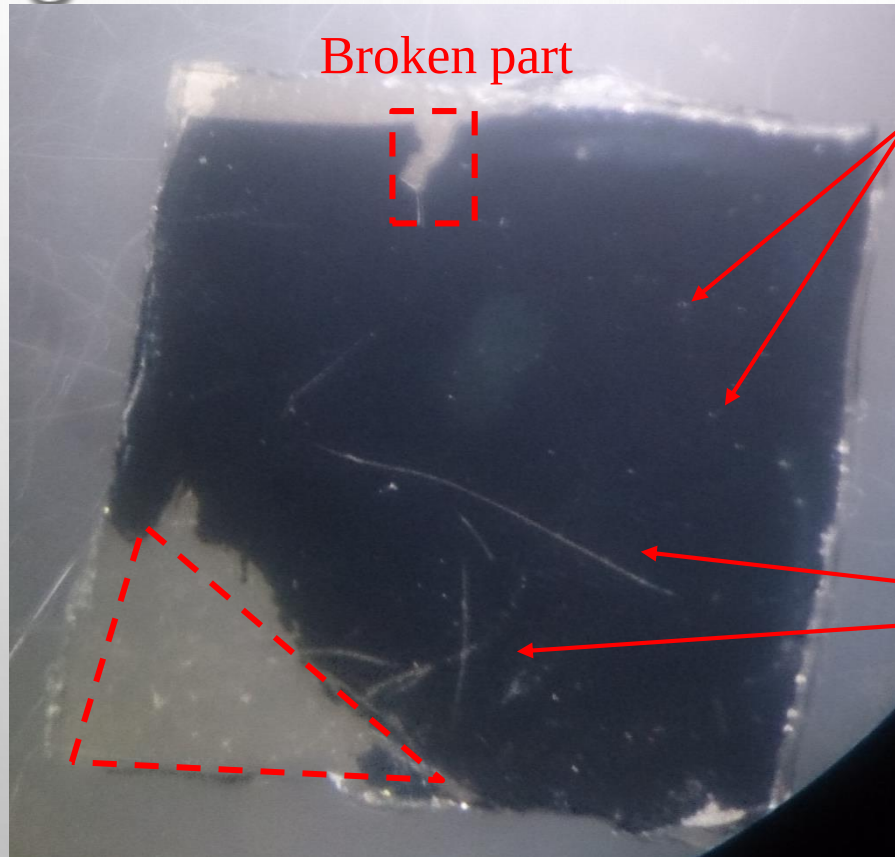
Heating the sample at 40 – 50 °C on a hot plate
(~ 5 min)

PMMA removal

Bathing the TR- Bi_2Se_3 in acetone
(1 hr)

Ultrasonically cleaning the sample:
1. Acetone x 3 (10 min x3)
2. IPA x 1 (10 min x 1)
3. Water rinse multiple times

IMPROVED TRANSFER TECHNIQUE



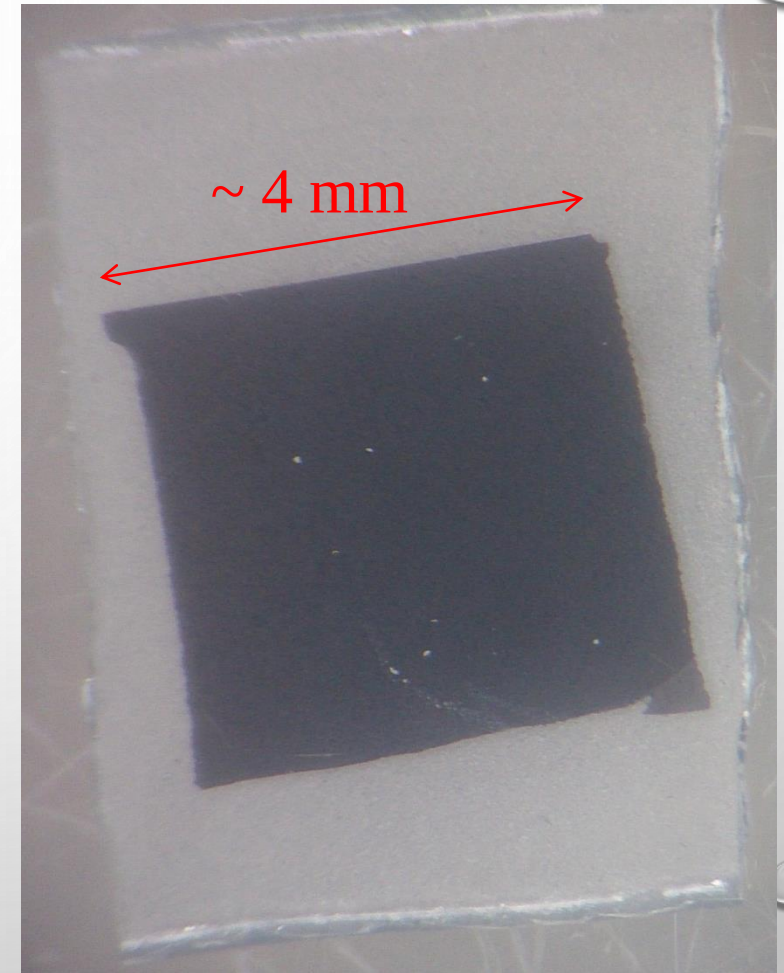
Broken part

Pinholes spreading
throughout the film.

improvement

large cracks & wrinkles

This part was not successfully
peeled off, and remained on Al_2O_3 .

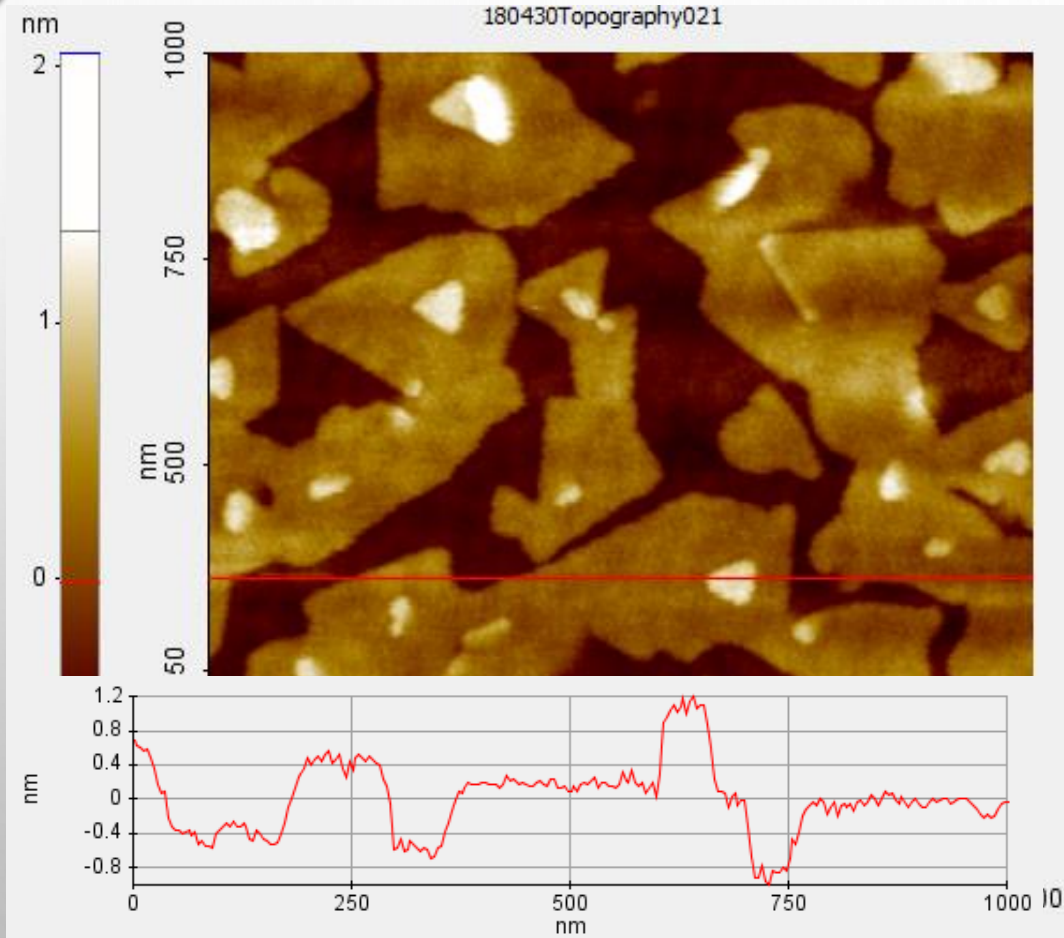


$\sim 4 \text{ mm}$

Bi_2Se_3 can be completely peeled off from Al_2O_3 .
Much less pinholes.
Very few wrinkles, ripples, and cracks.

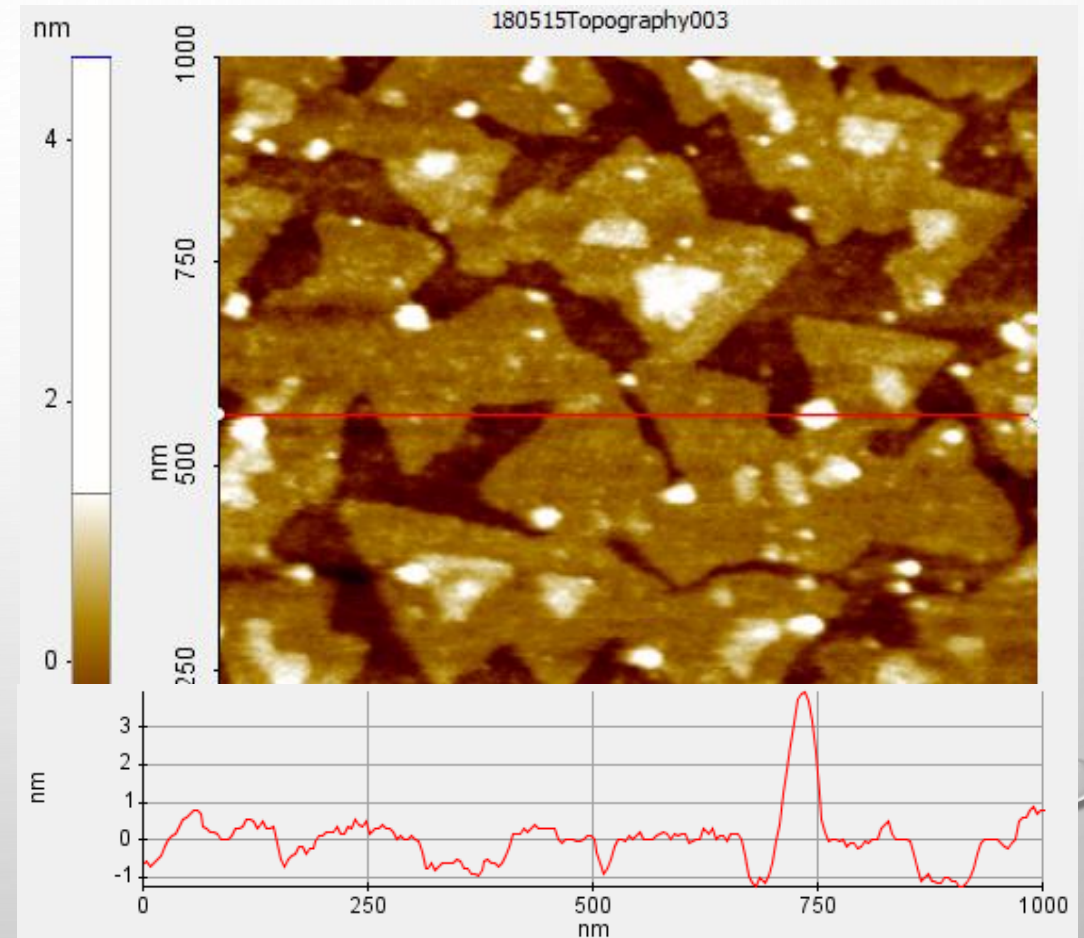
SURFACE MORPHOLOGY PRESERVED (1 X 1 MM)

TI782: 9 nm Bi_2Se_3 /sapphire



$$R_q = 0.46 \text{ nm}$$

TR- Bi_2Se_3 /sapphire

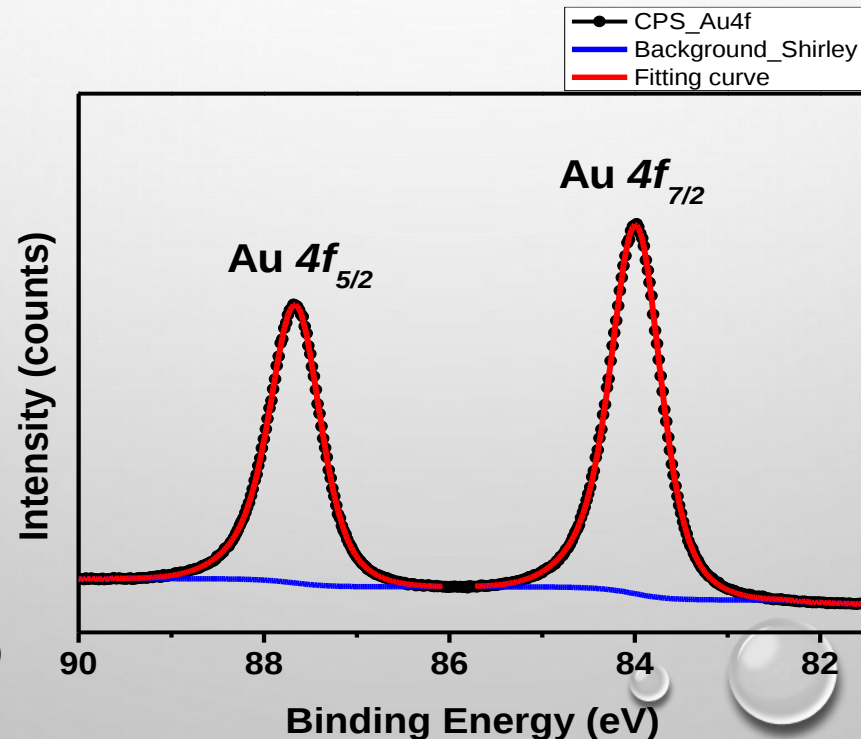
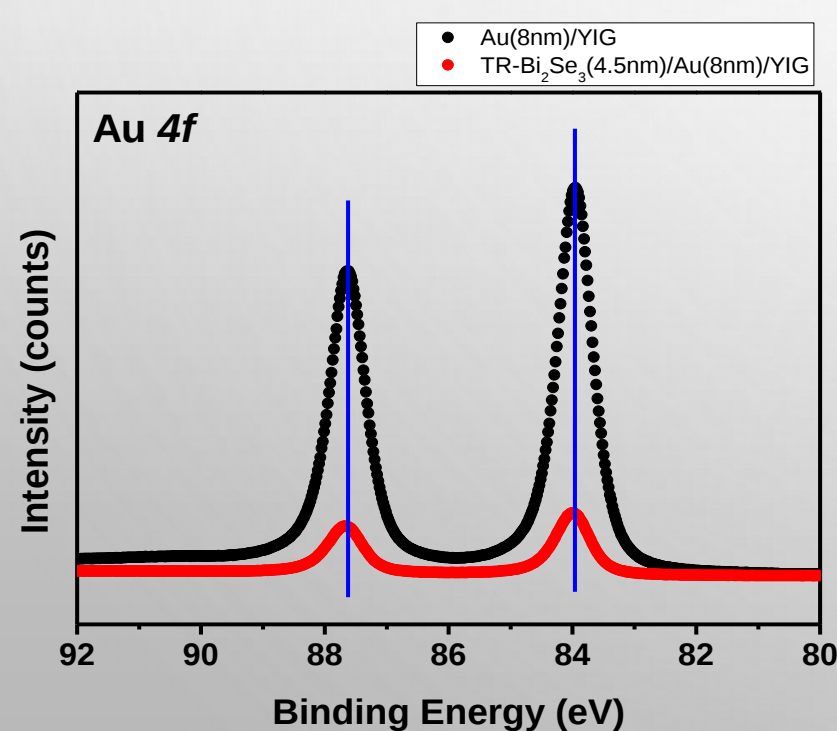


$$R_q = 0.55 \text{ nm}$$

The particles might be the residual PMMA, which is hard to completely remove.

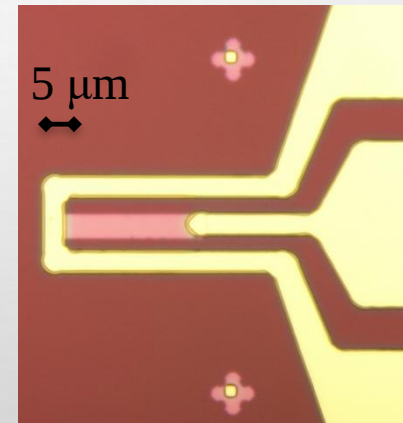
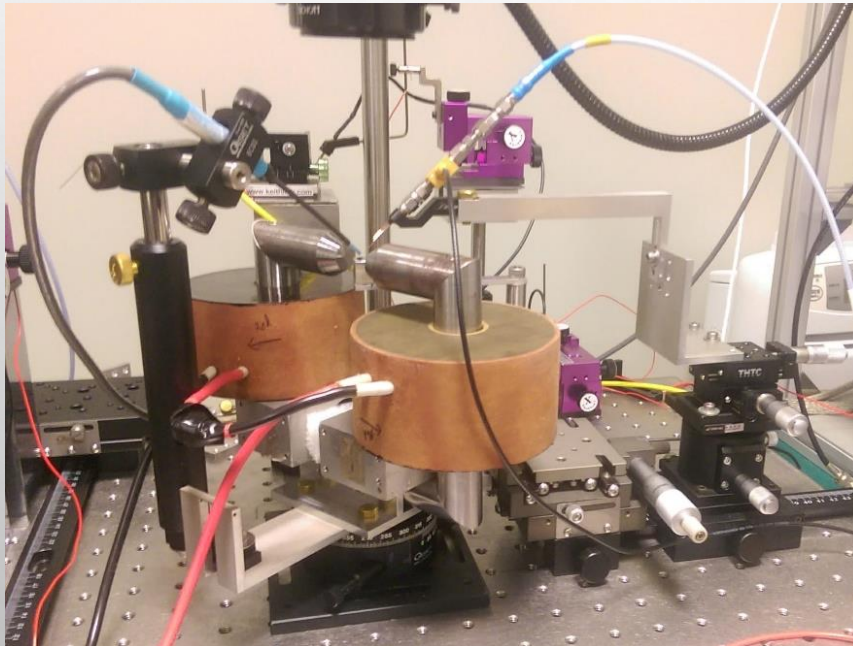
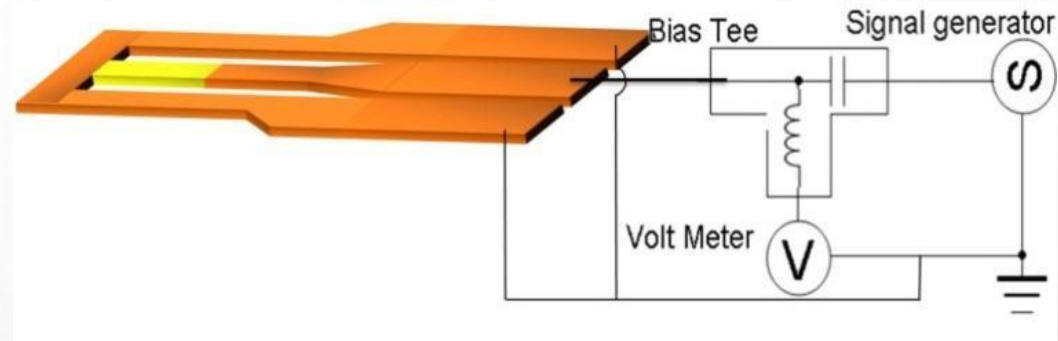
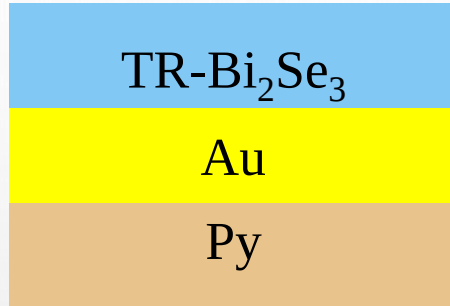
XPS characterization

- There is **no substantial change in line shape** and **peak position** between Au 4f core-levels of Au/YIG and TR-Bi₂Se₃/Au/YIG.
- The **peak position of Au 4f is nearly consistent**, which indicates that there was **no severe interfacial interaction** between Bi₂Se₃ and Au after heated at 150°C for 2min.



peak position	Au 4f _{7/2}	Au 4f _{5/2}
Au/YIG	83.943 eV	87.616 eV
TR-Bi ₂ Se ₃ /Au/YIG	83.960 eV	87.632 eV

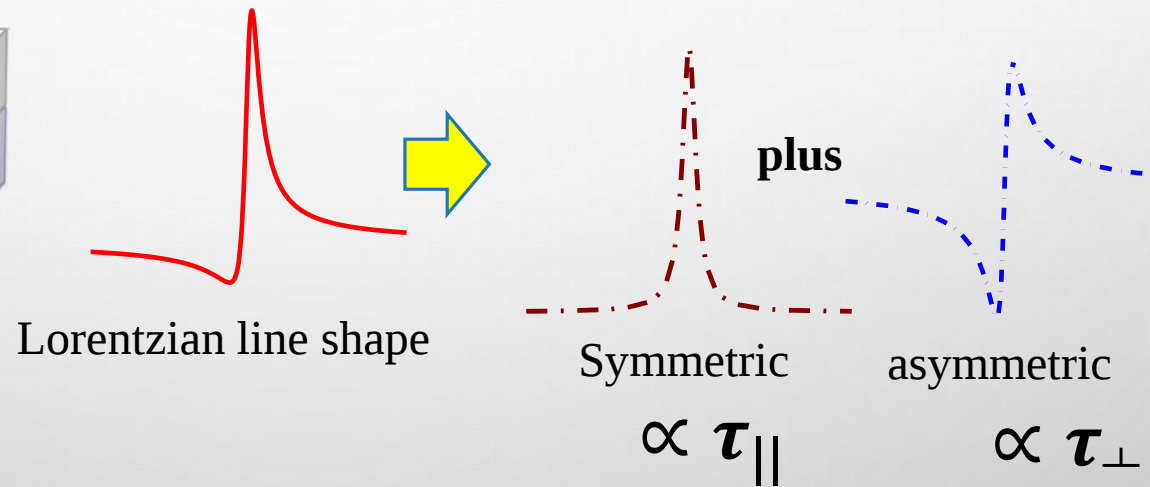
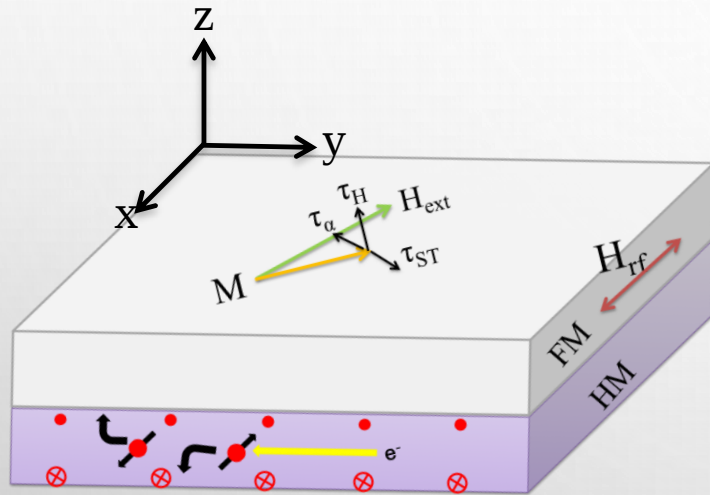
Device fabrication for ST-FMR experiment



ST-FMR device

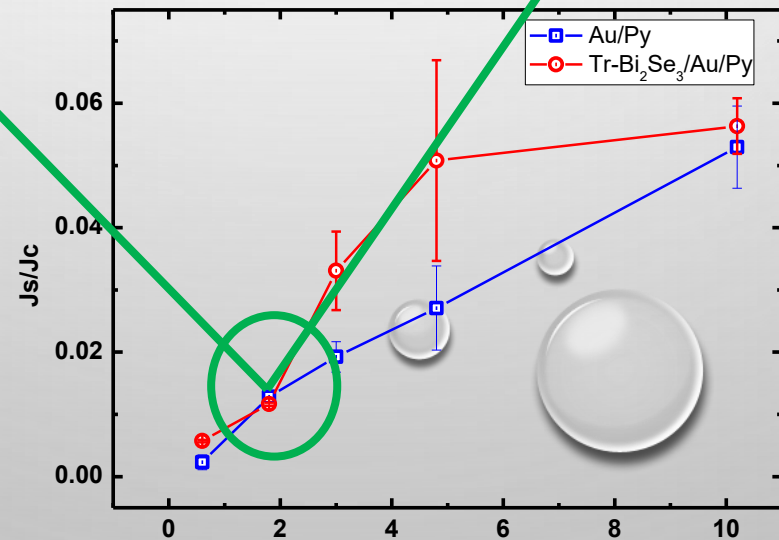
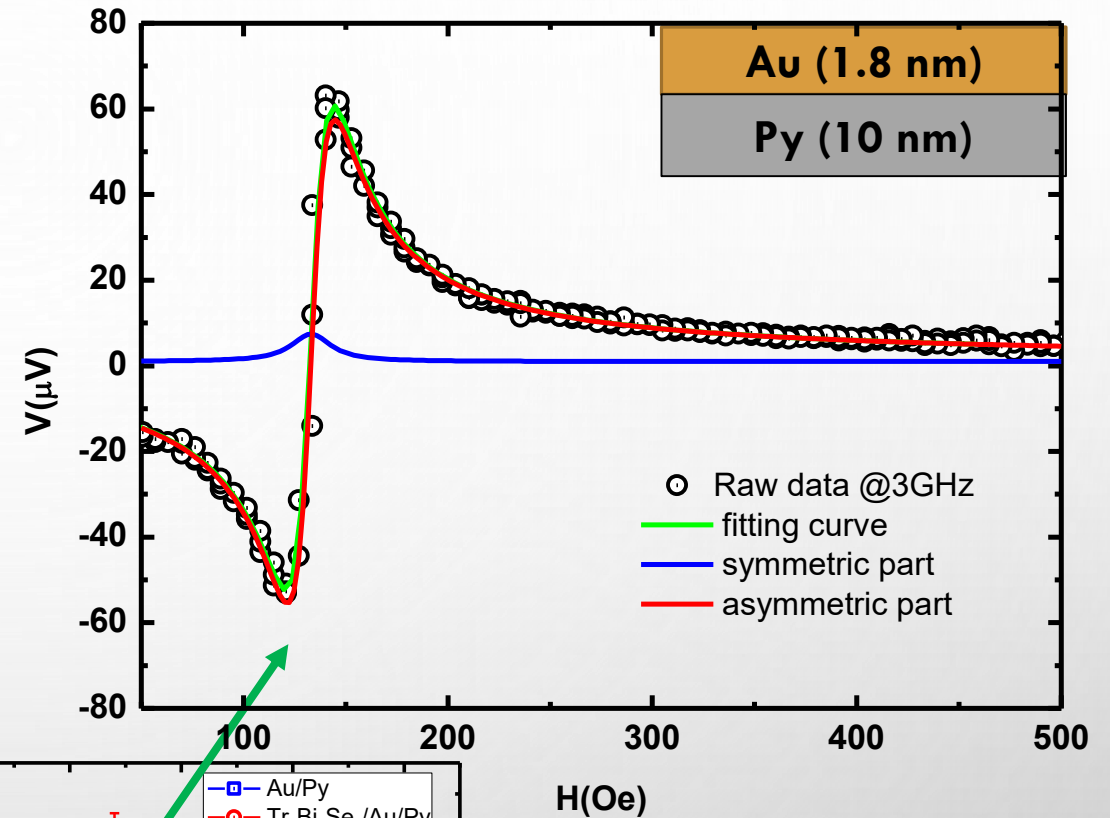
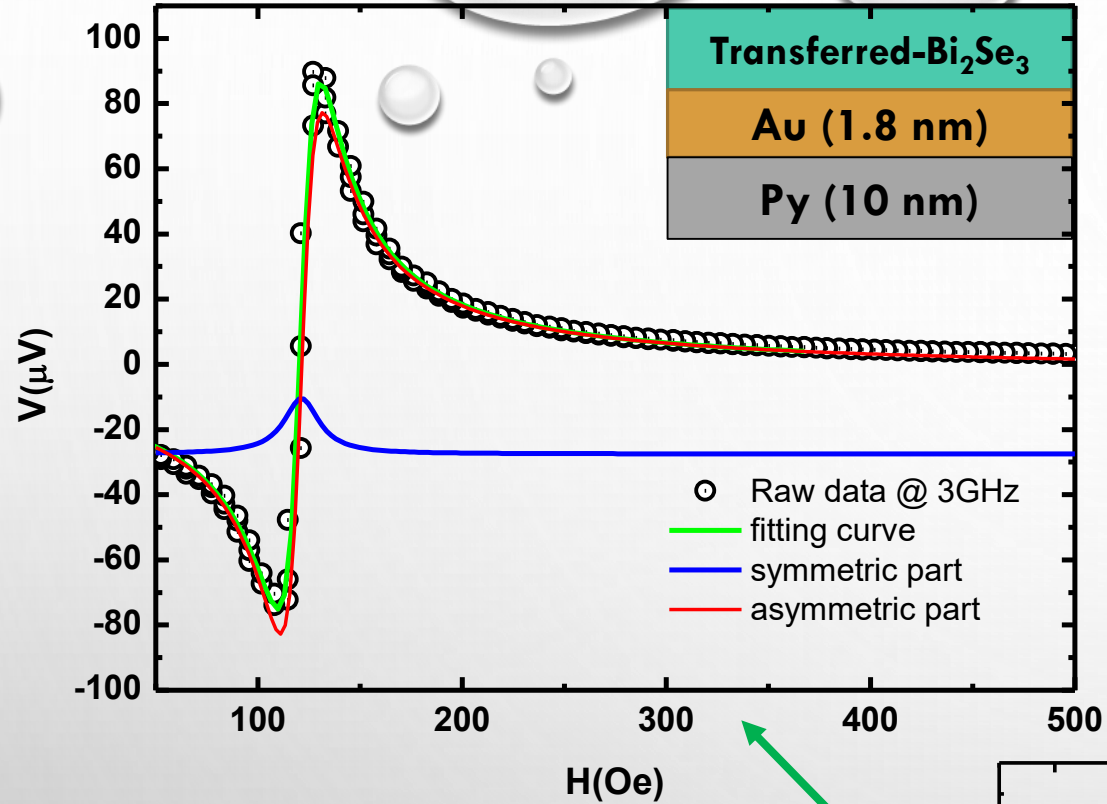
ASYMMETRIC AND SYMMETRIC LINE SHAPE ANALYSIS

$$\begin{aligned}\frac{d\hat{M}}{dt} &= -\gamma\hat{M} \times \vec{H}_{\text{eff}} + \alpha_0\hat{M} \times \frac{d\hat{M}}{dt} + \frac{\gamma\hbar J_s}{2eM_s d_F} (\hat{m} \times \hat{\sigma} \times \hat{m}) - \gamma\hat{M} \times \vec{H}_{\text{rf}} \\ &= -\gamma\hat{M} \times \vec{H}_{\text{eff}} + \alpha_0\hat{M} \times \frac{d\hat{M}}{dt} + \gamma\left[\tau_{\parallel} \frac{\hat{M} \times (\hat{x} \times \hat{M})}{|\hat{x} \times \hat{M}|} + \tau_{\perp} \frac{\hat{x} \times \hat{M}}{|\hat{x} \times \hat{M}|}\right]\end{aligned}$$

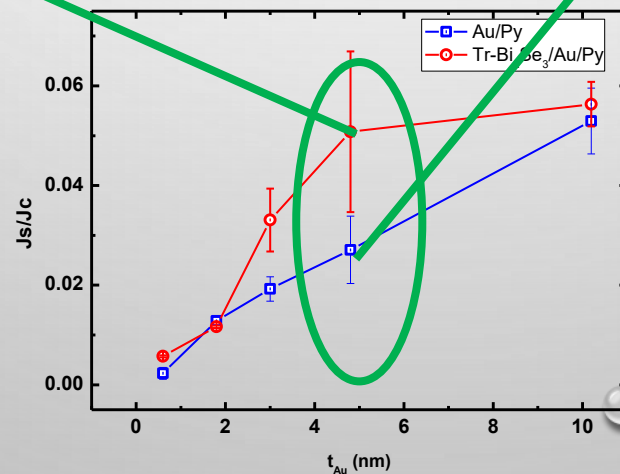
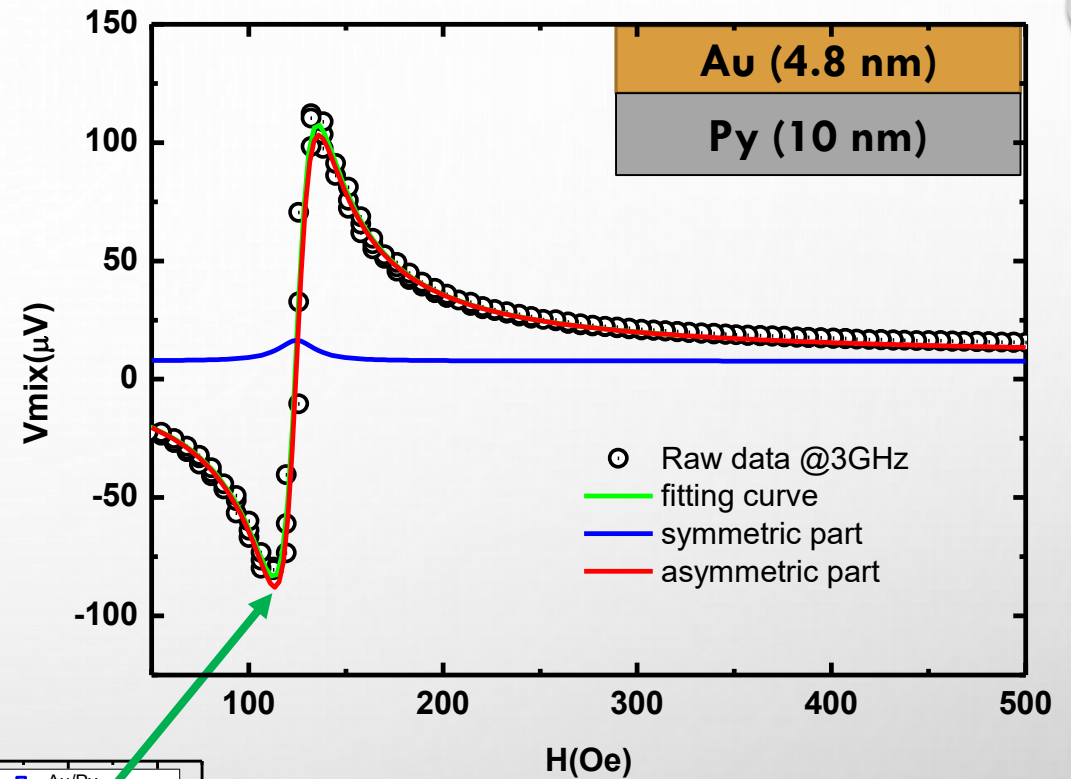
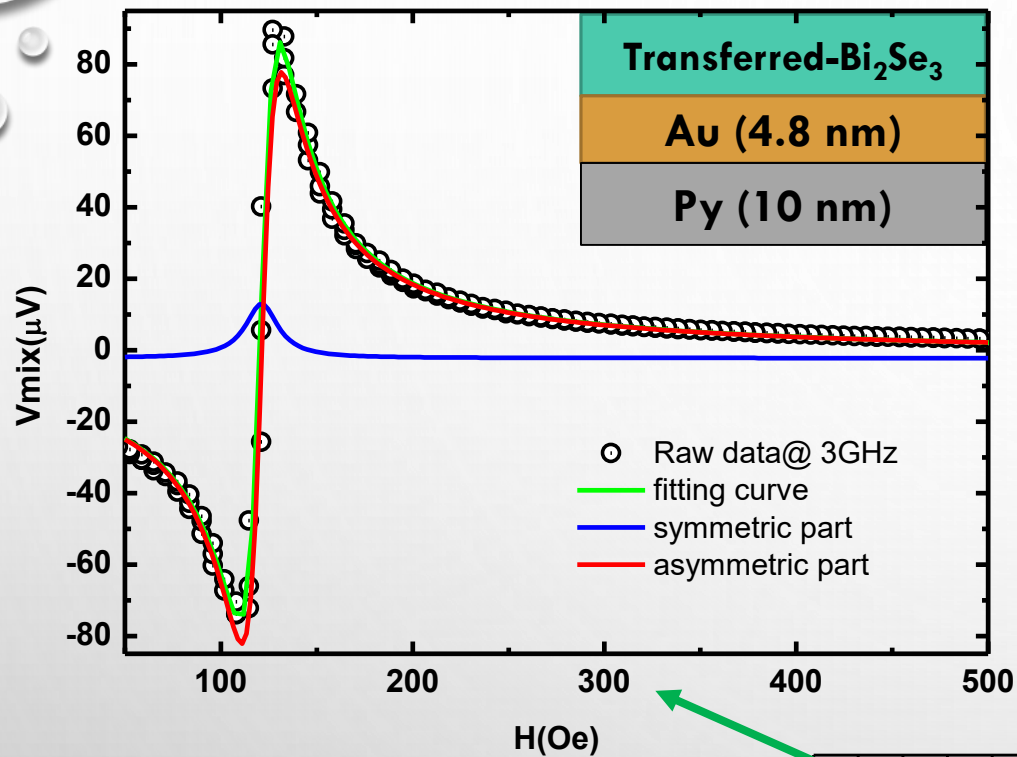


spin-orbit torque ratio $\theta_{\parallel} = J_s/J_c = V_S/V_A(e\mu_0 M_S t d/\hbar)[1+(4\pi M_{\text{eff}}/H_{\text{ext}})]^{1/2}$

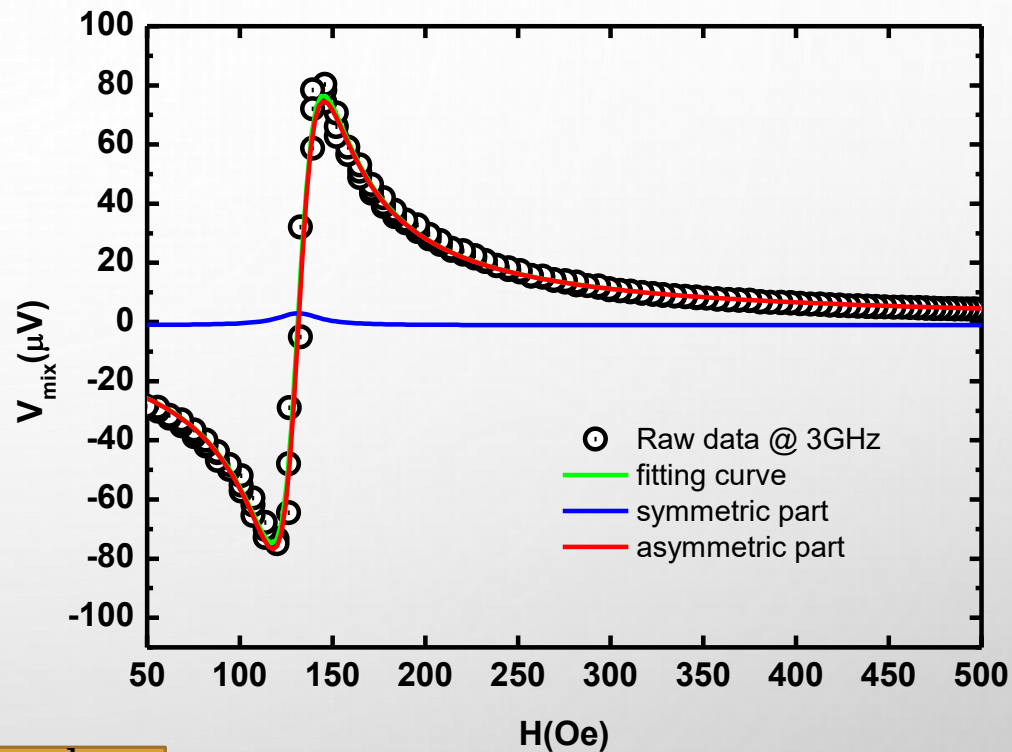
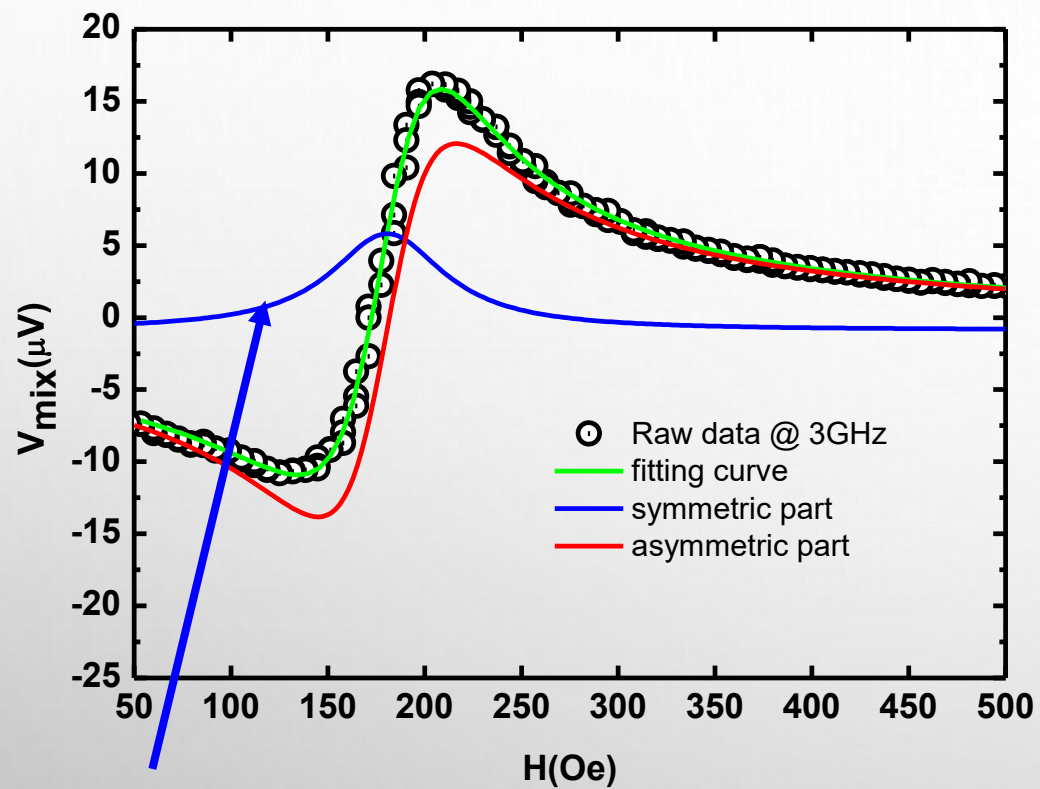
ST-FMR on TR-Bi₂Se₃/Au/Py before annealing



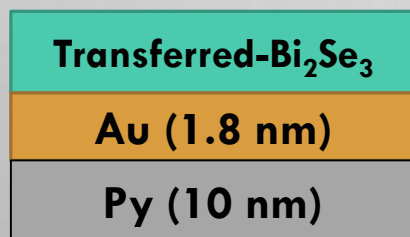
ST-FMR on TR-Bi₂Se₃/Au/Py before annealing



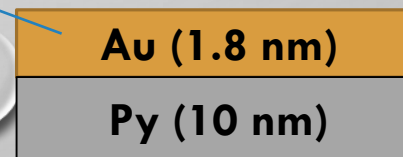
After annealing



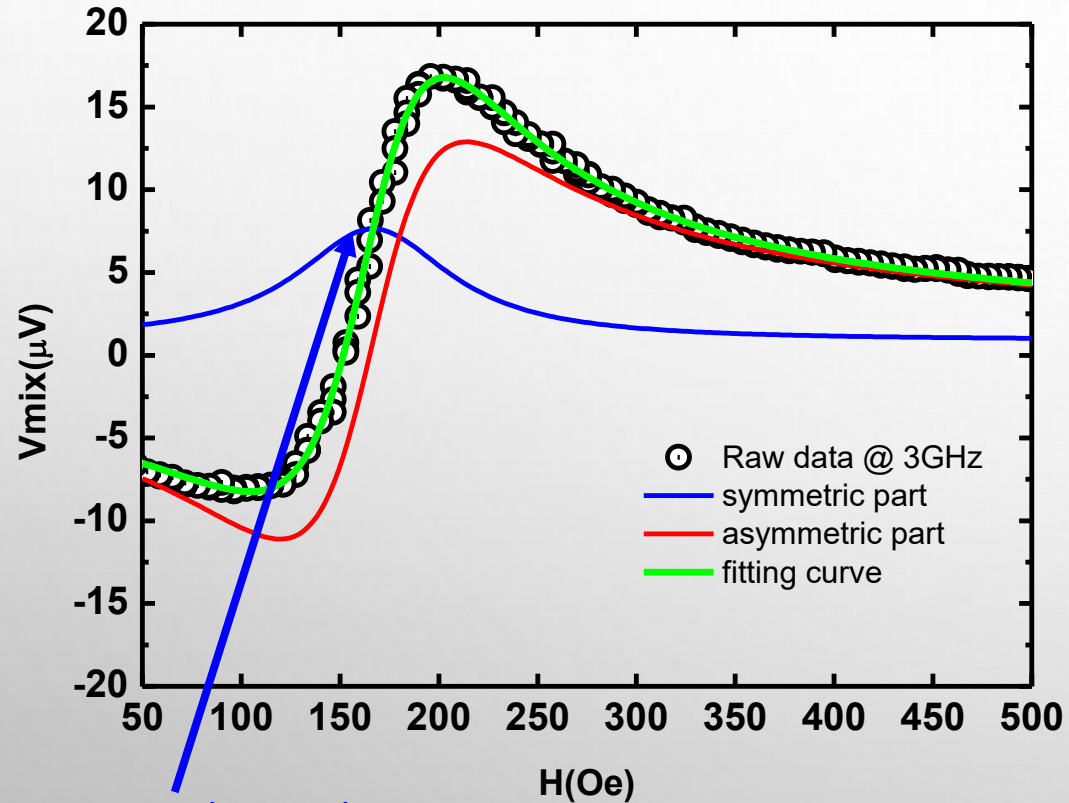
The symmetric part is drastically enhanced.



sample
($\sim 200^\circ\text{C}$, 10^{-5} torr, 30 min)

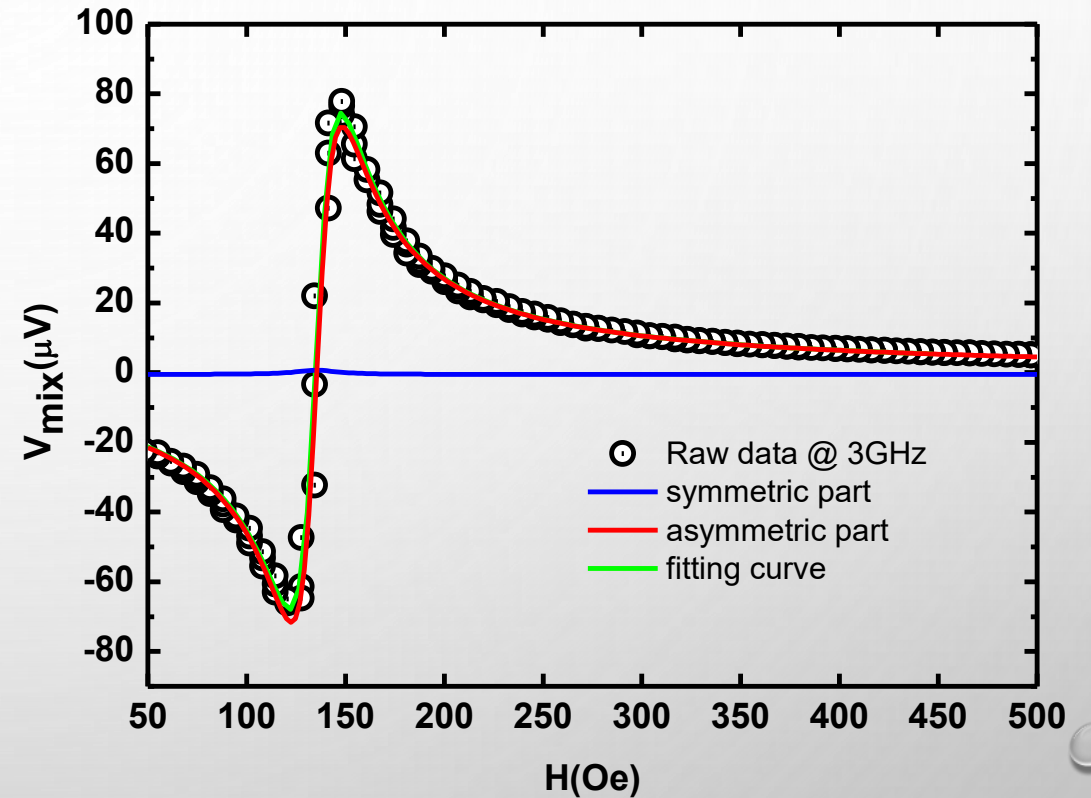


After annealing



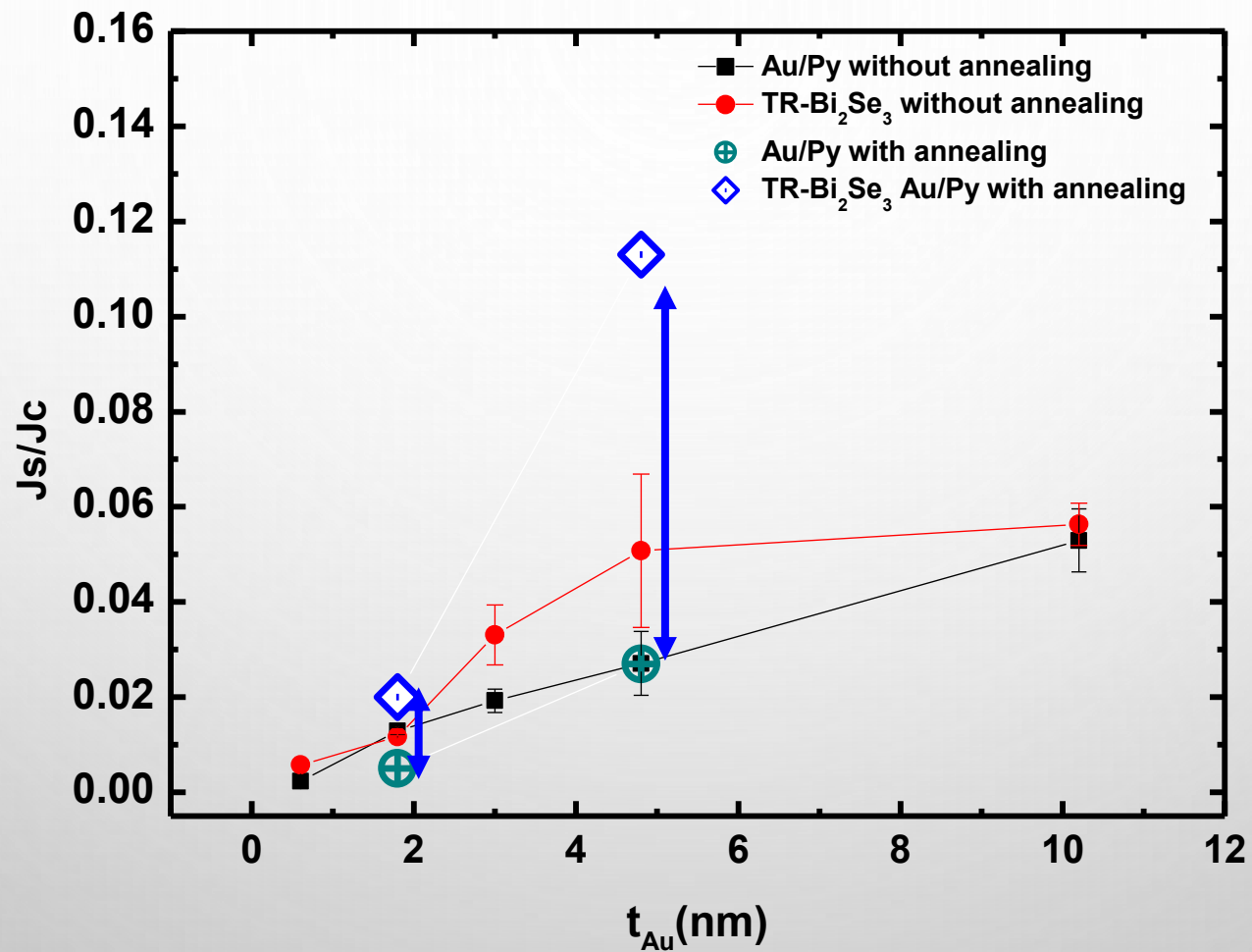
The symmetric part is drastically enhanced.

Transferred-Bi ₂ Se ₃
Au (4.8 nm)
Py (10 nm)

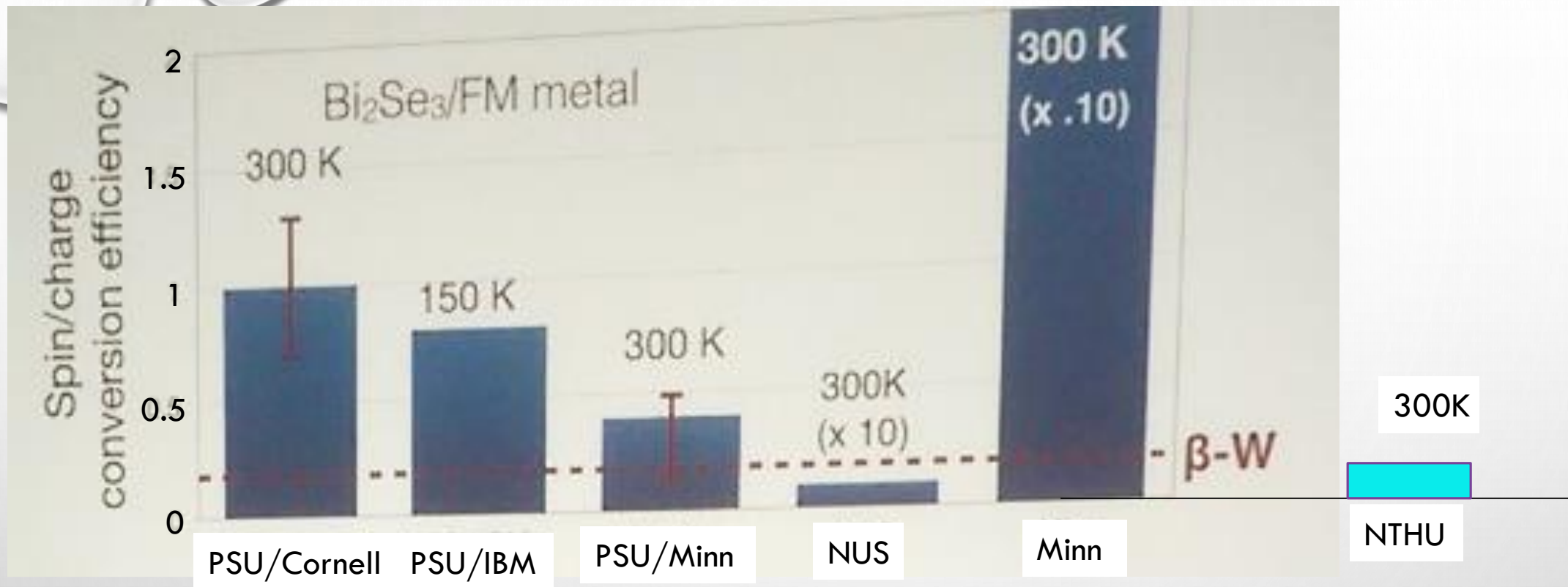


Au (4.8 nm)
Py (10 nm)

Comparison of Au thickness dependent J_s/J_c



J_s/J_c shows larger enhancement after annealing.



PSU/Cornell, Nature **511**, 499 (2014). (ST-FMR)

PSU/IBM, Phys. Rev. B **91**, 235437 (2015). (Spin-polarized tunnel junction)

PSU/Minn, Nano Letters **15**, 7125 (2015). (Spin pumping)

NUS, Phys. Rev. Lett. **114**, 257202 (2015). (ST-FMR)

Minn, Nature Materials (arXiv:1703.03822) (Switching)

SUMMARY

- AFTER ANNEALING AT HIGH VACUUM, LARGE ENHANCEMENT OF J_S/J_C WAS OBSERVED.
=> COULD BE DUE TO BETTER ADHESION BETWEEN TR-TI/AU
- HOWEVER, THE OBTAINED VALUE OF SPIN TORQUE RATIO IS NOT MUCH HIGHER THAN PREVIOUS WORK ON TI/FM

FUTURE WORK

- SO FAR WE HAVE ONLY USED TRANSFERRED-BI₂SE₃ THIN FILM WHICH IS QUITE BULK CONDUCTING.
=> USING BULK INSULATING BST FOR THE TRANSFERRING COULD INCREASE THE RATIO.
- SWITCHING MEASUREMENT OF TR-TI/AU/FM