Spin-Torque-Induced Ferromagnetic Resonance

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奈米物理與新興量子物質特論課程

2019/11/28

Outline

- **Introduction and motivation**
  - Spintronics
  - Spin transfer torque
  - Spin orbit 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

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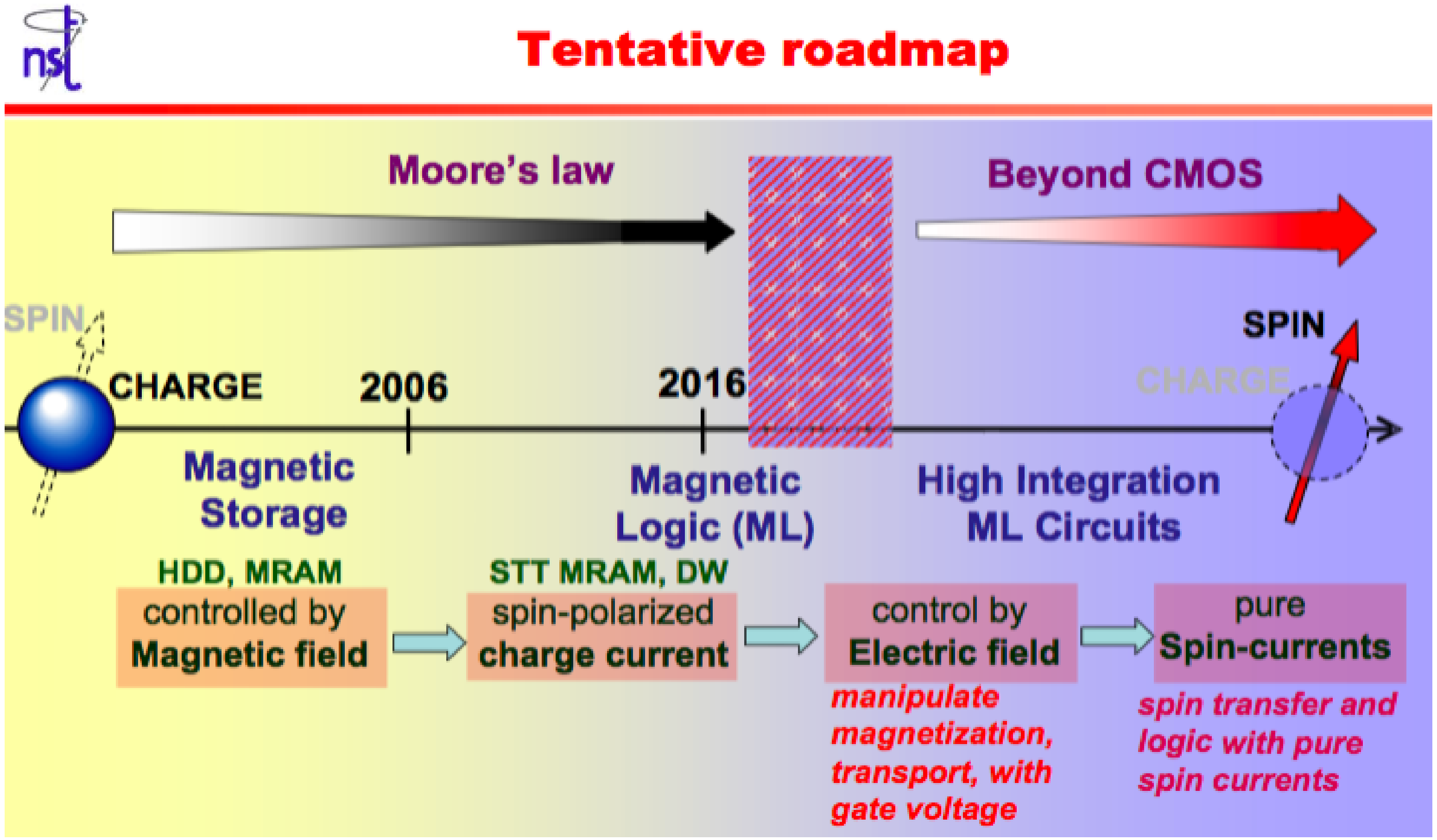
Spintronics



- ✓ 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.**

Spintronics

Magnetoresistance (MR) effect

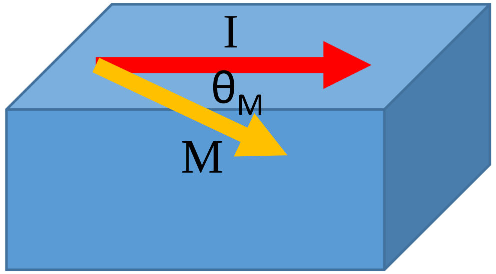
In a normal metal
$\vec{B}$ affects electrons with Lorentz force => R increase => ordinary MR

In a ferromagnetic metal
MR is strongly related to the direction of the magnetization $\vec{M}$.
=> anisotropic magnetoresistance (**AMR**)

$$\mathrm{AMR} = \frac{\rho_{||} - \rho_{\perp}}{\rho_0}$$

$\rho_{||}$: **M || I**
$\rho_{\perp}$: **M ⊥ I**

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



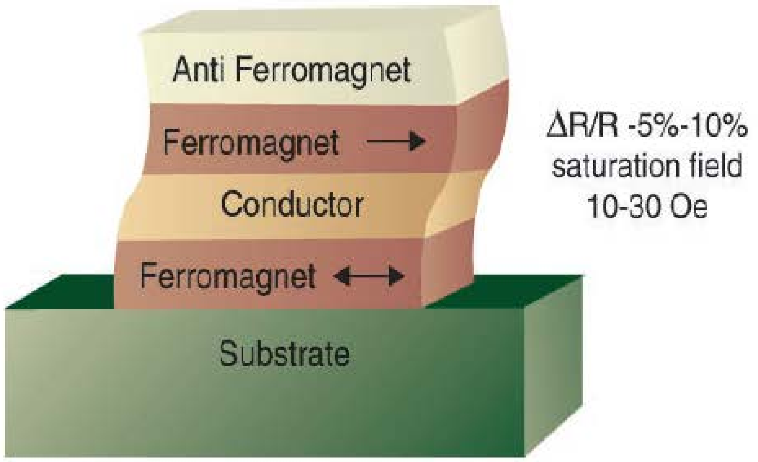
=> This phenomenon is related to the effect of spin–orbit coupling (SOC).

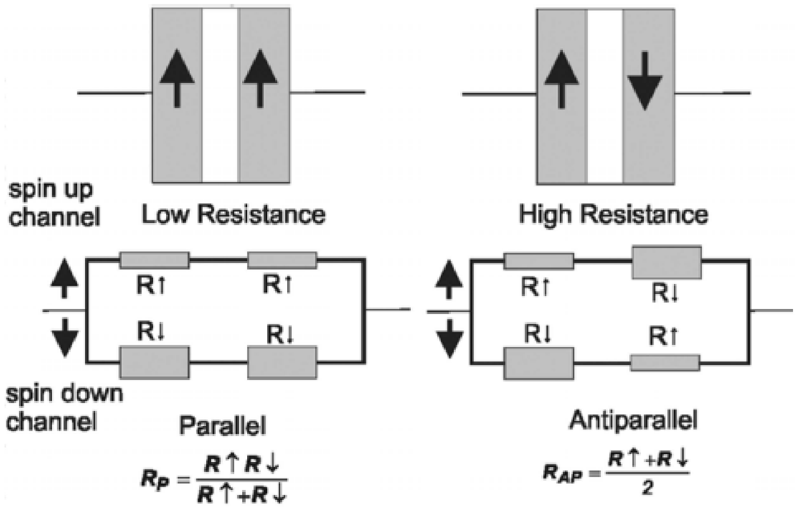
McGuire T, Potter R L 1975 IEEE Trans. Magn. **11** 1018

Spintronics

Magnetoresistance (MR) effect

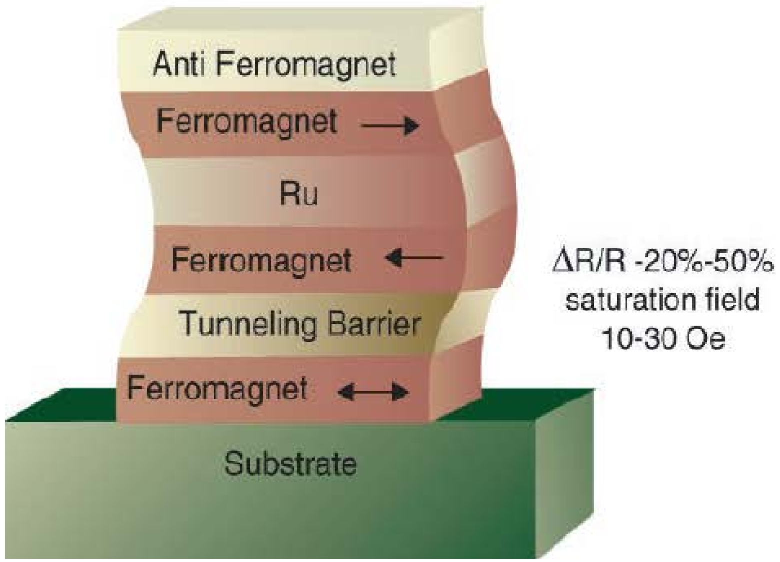
GMR





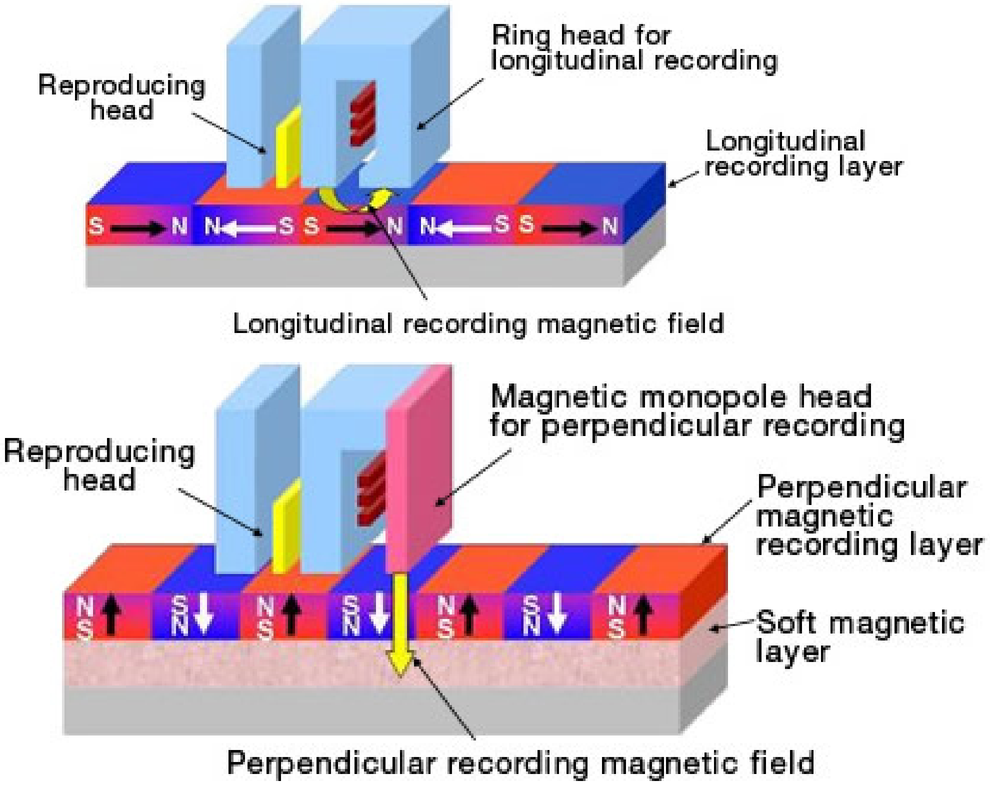
$$\mathrm{GMR} = \frac{R_{\mathrm{AP}} - R_{\mathrm{P}}}{R_{\mathrm{P}}}.$$

TMR

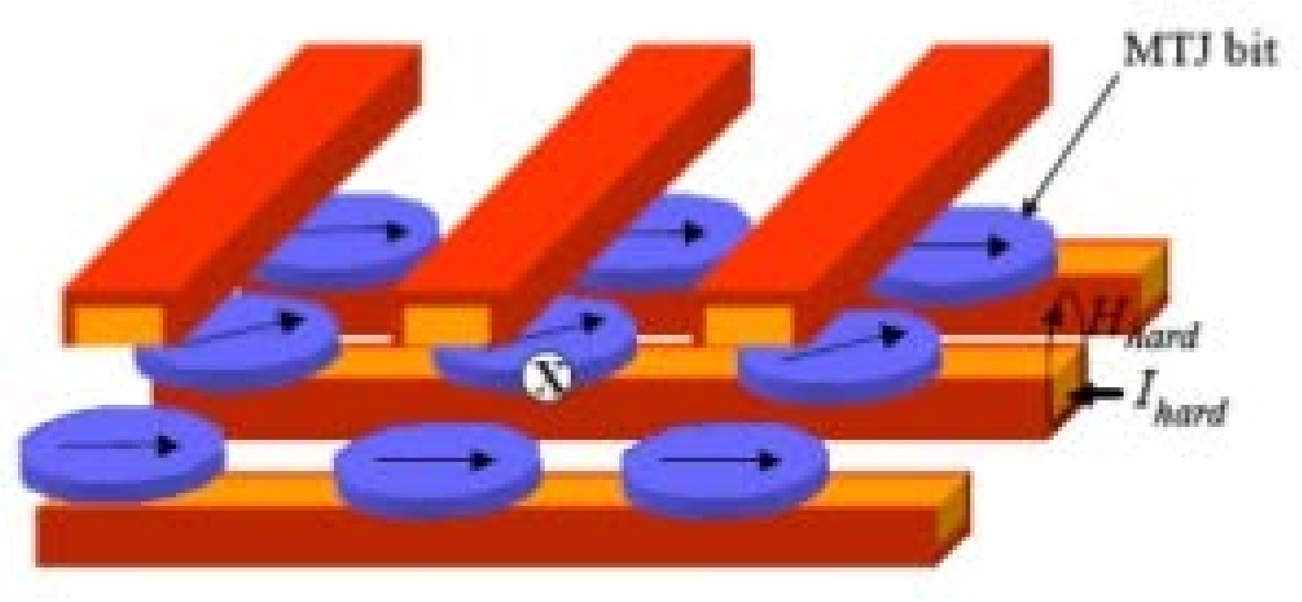


Spintronics

Applications

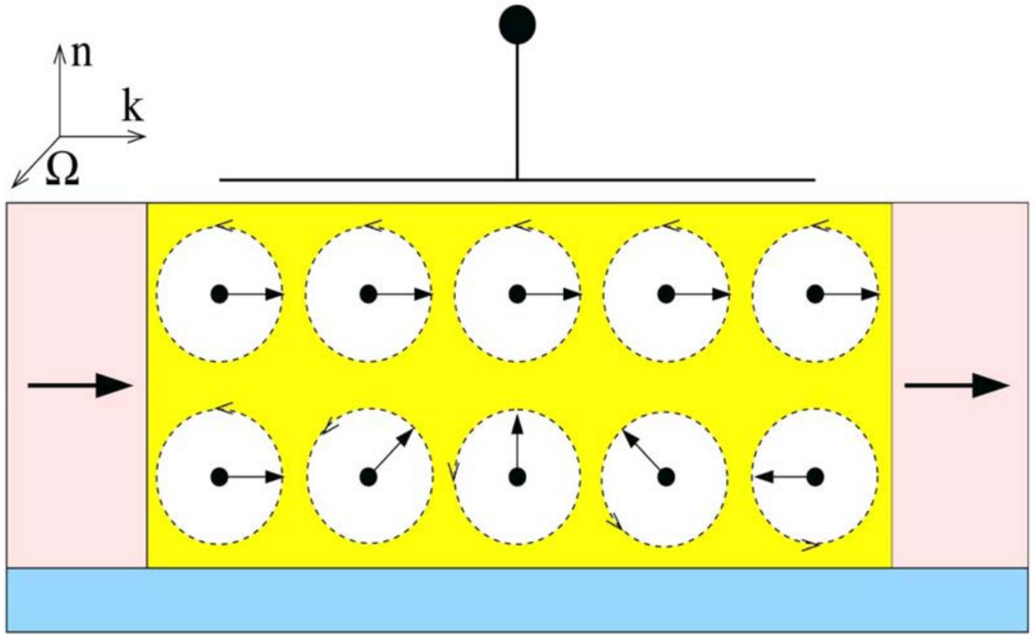


hard disk drive (HDD)



Magnetoresistive Random Access Memory
MRAM => STT-MRAM

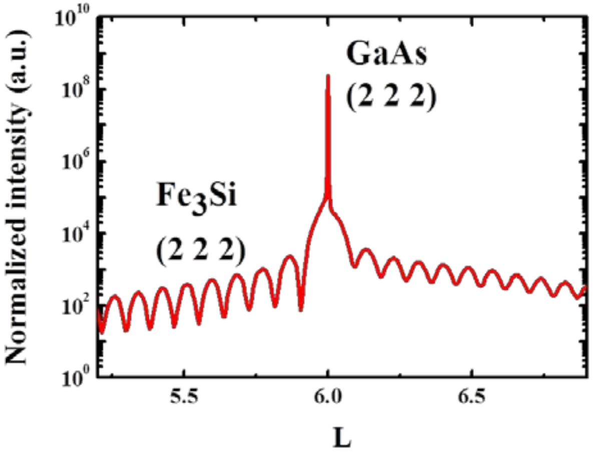
Applications

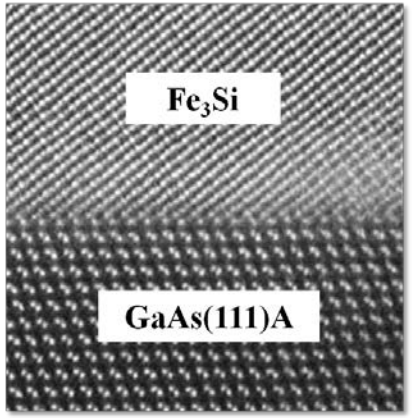


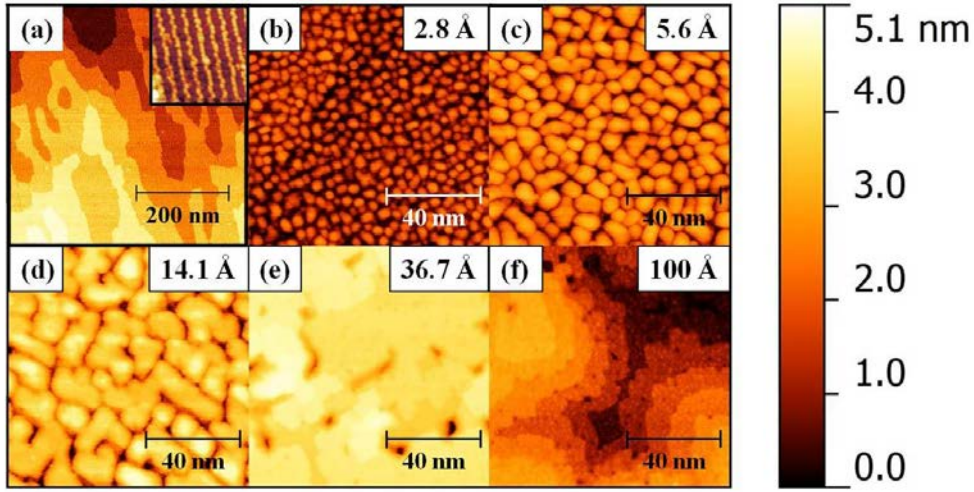
The Scheme of the Datta-Das spin field effect transistor (SFET).

Spintronics

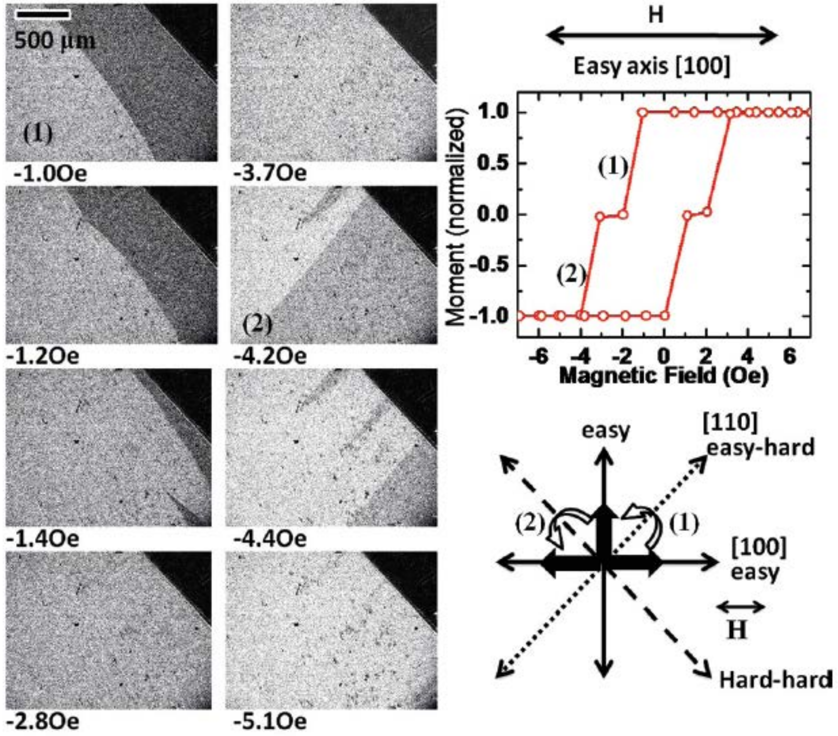
FM/SM heterostructure





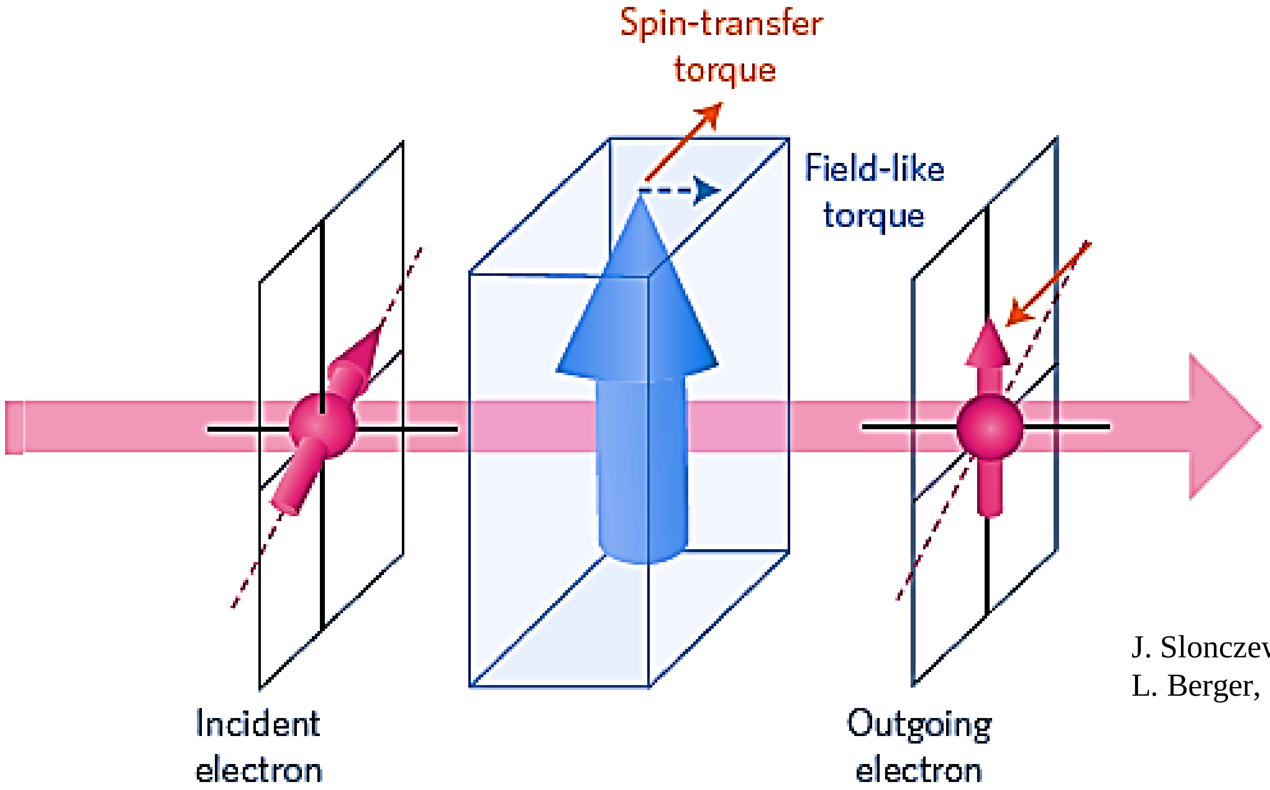


Observation of Magnetic Domain



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

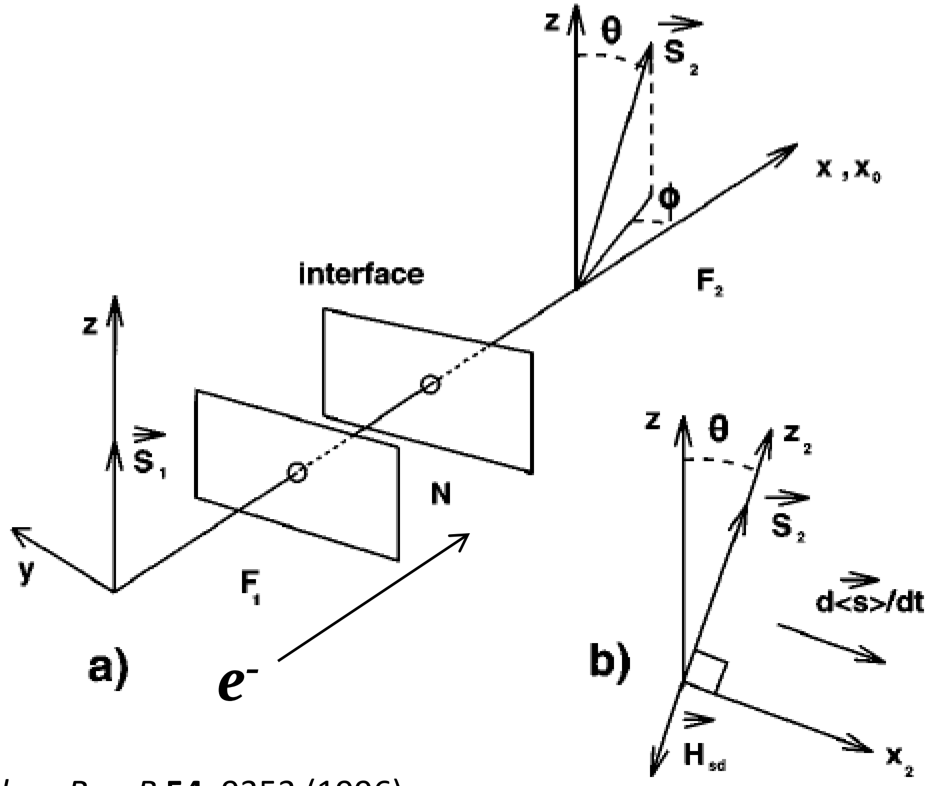
Driving persistent oscillations of magnetization

Spin-transfer-torque- induced FMR

Spin transfer torque

- 4s (itinerant)-3d (localized) *s*-d interaction

$$-J_{sd}\hat{s}\cdot\vec{S}\left(\vec{r}\right)$$



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 transfer torque

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

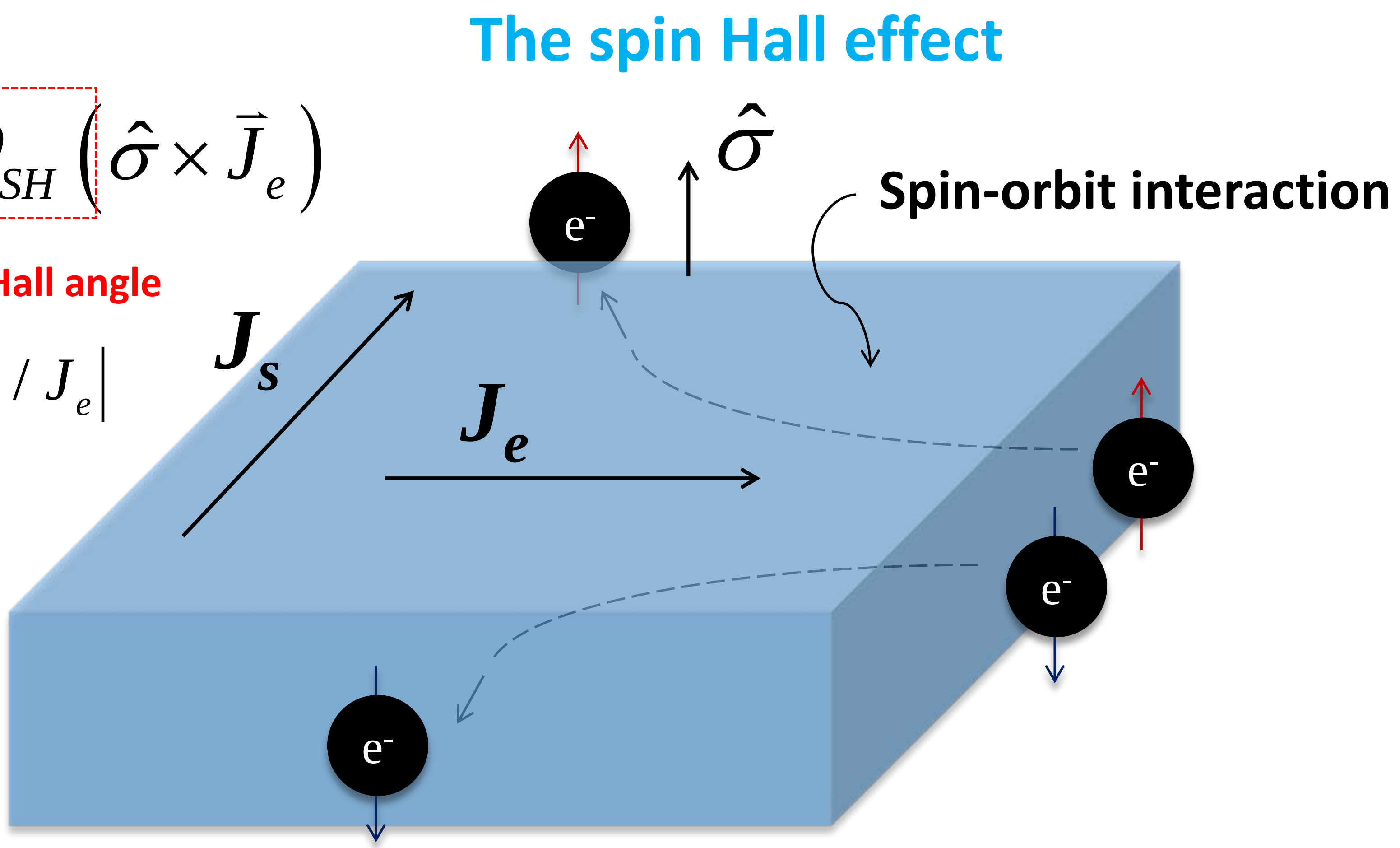
J: Ferromagnetic interaction factor

Spin orbit torque

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

The spin Hall angle

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

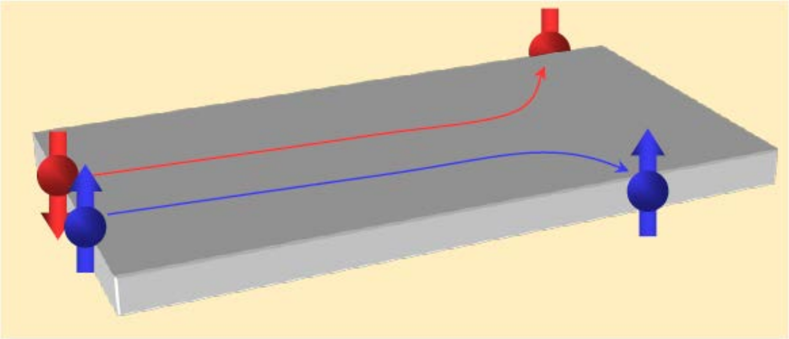


M. I. Dyakonov and V. I. Perel, *JETP* **13** 467 (1971)

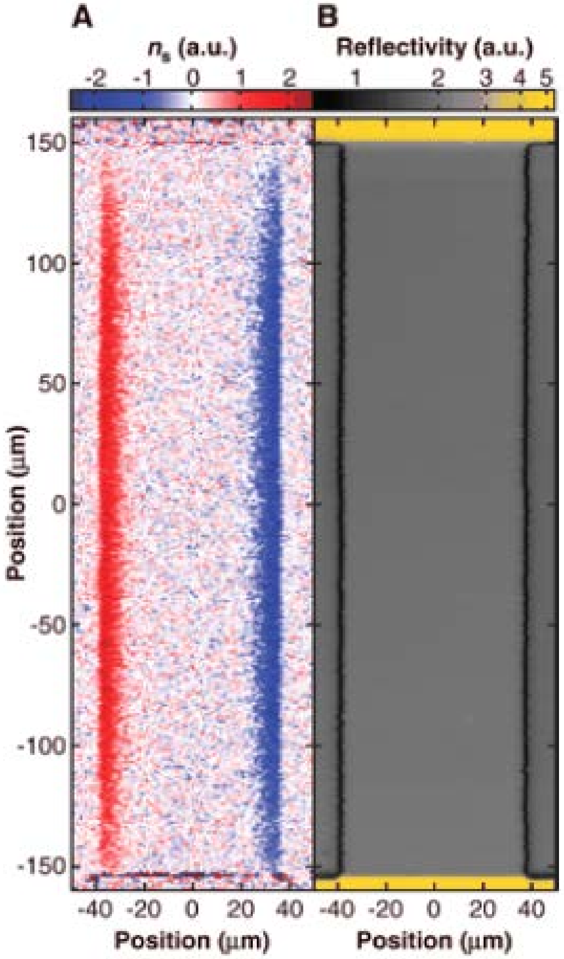
J. E. Hirsch, *Phys. Rev. Lett.* **83** 1834 (1999)

Spin orbit torque

The spin Hall effect

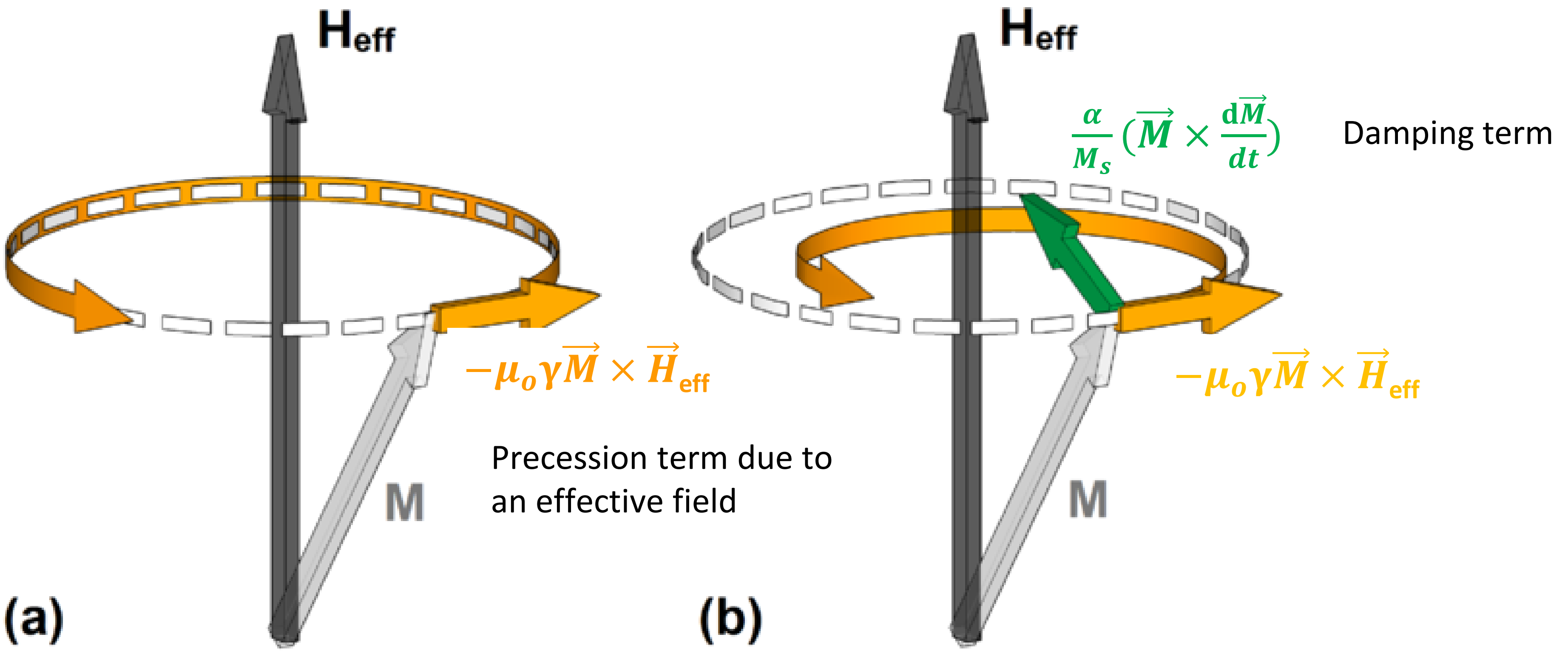


Spin-dependent scattering gives rise to transverse spin imbalance of charge currents



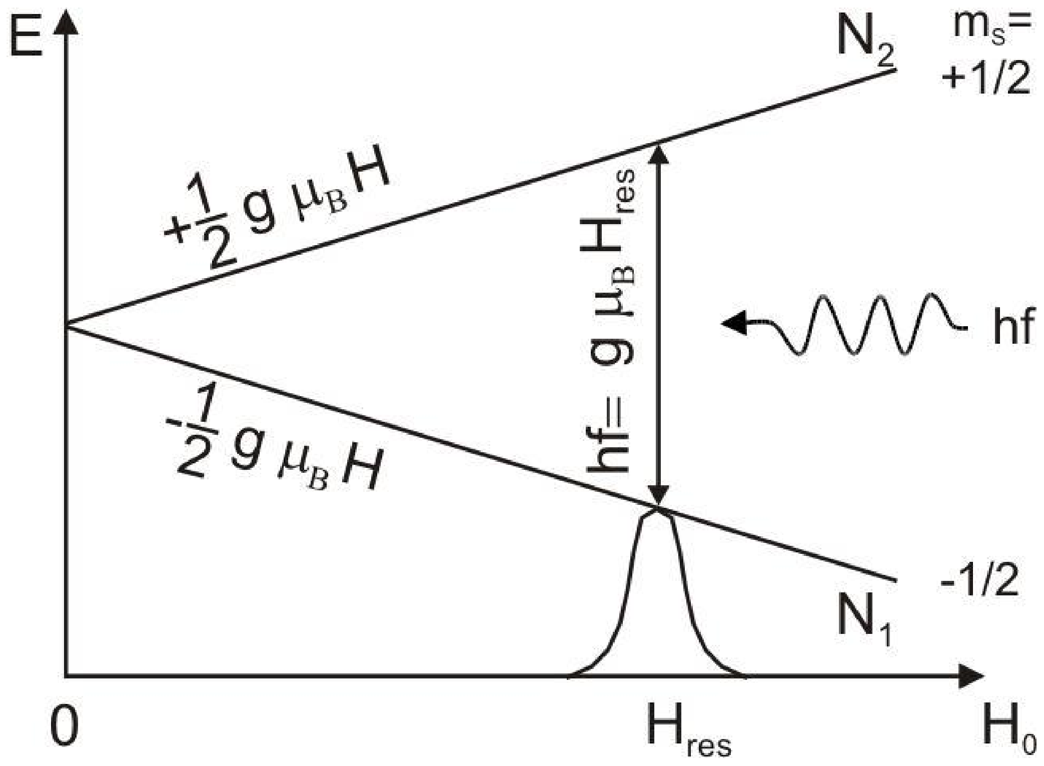
Direct observation in GaAs with optical detection (Kerr effect)

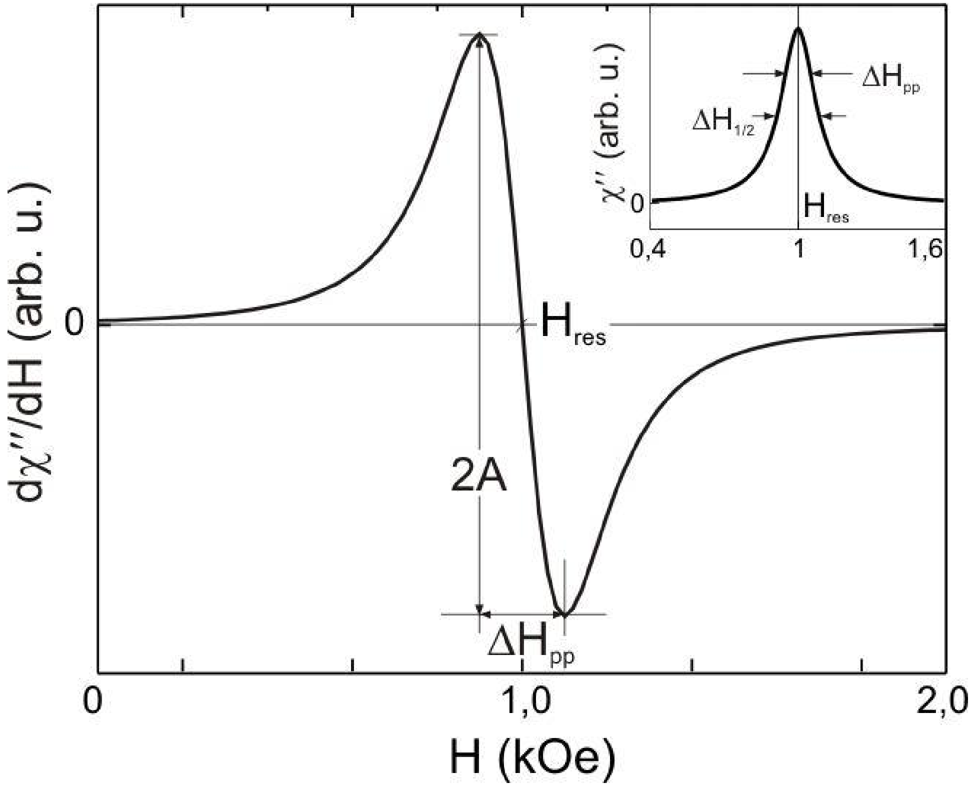
Ferromagnetic resonance



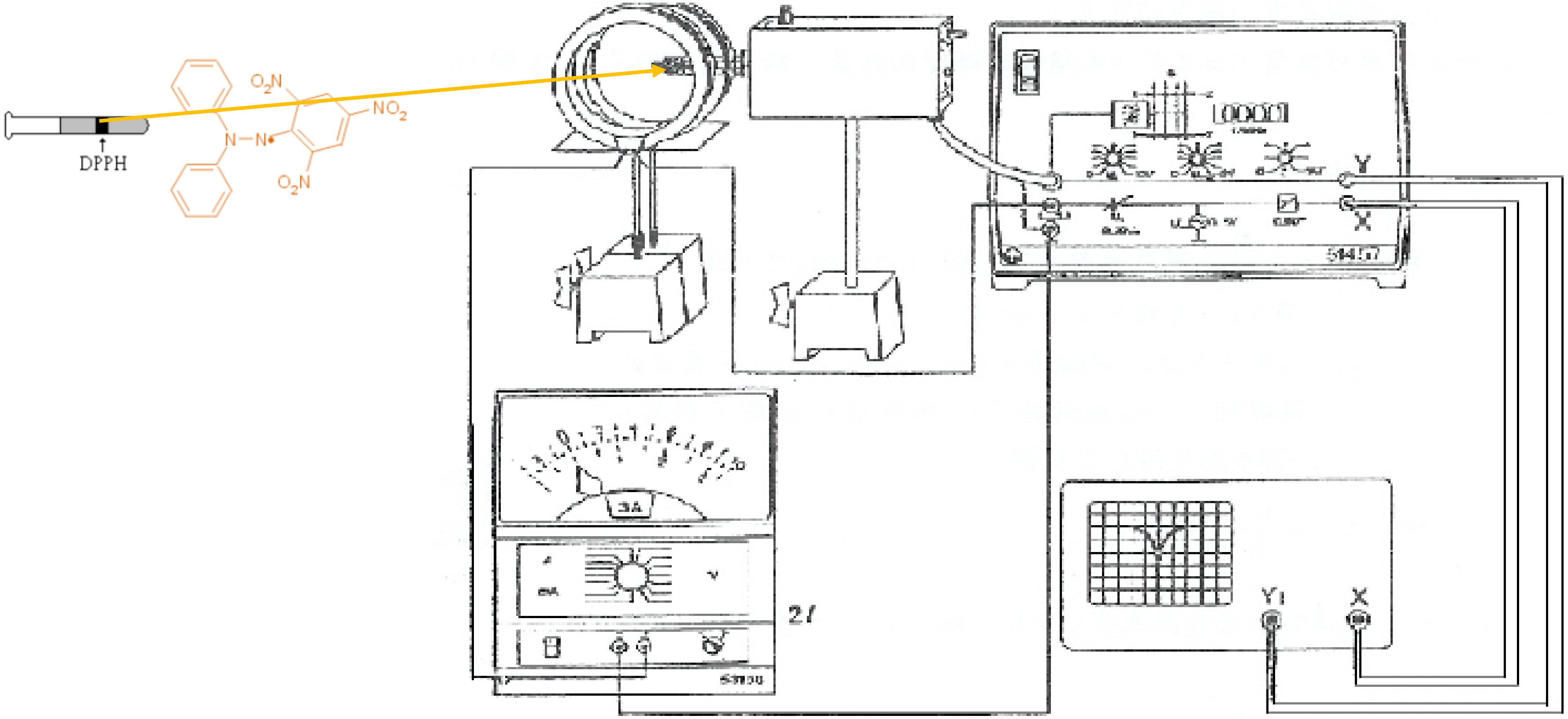
$$\frac{d\vec{M}}{dt} = -\mu_o \gamma \vec{M} \times \vec{H} + \frac{\alpha}{M_s}(\vec{M} \times \frac{d\vec{M}}{dt})$$

Ferromagnetic resonance



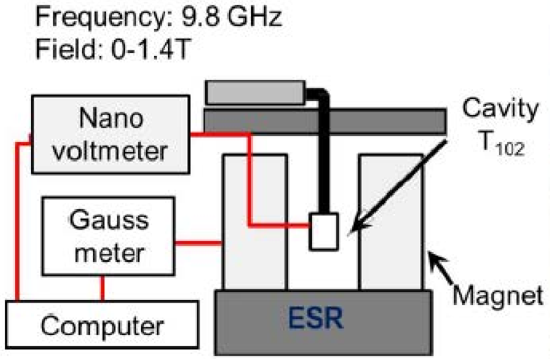


Still remember the ESR measurement?

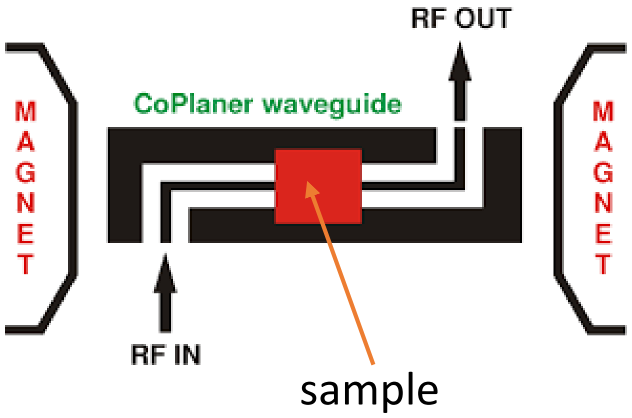


Ferromagnetic resonance experimental setup

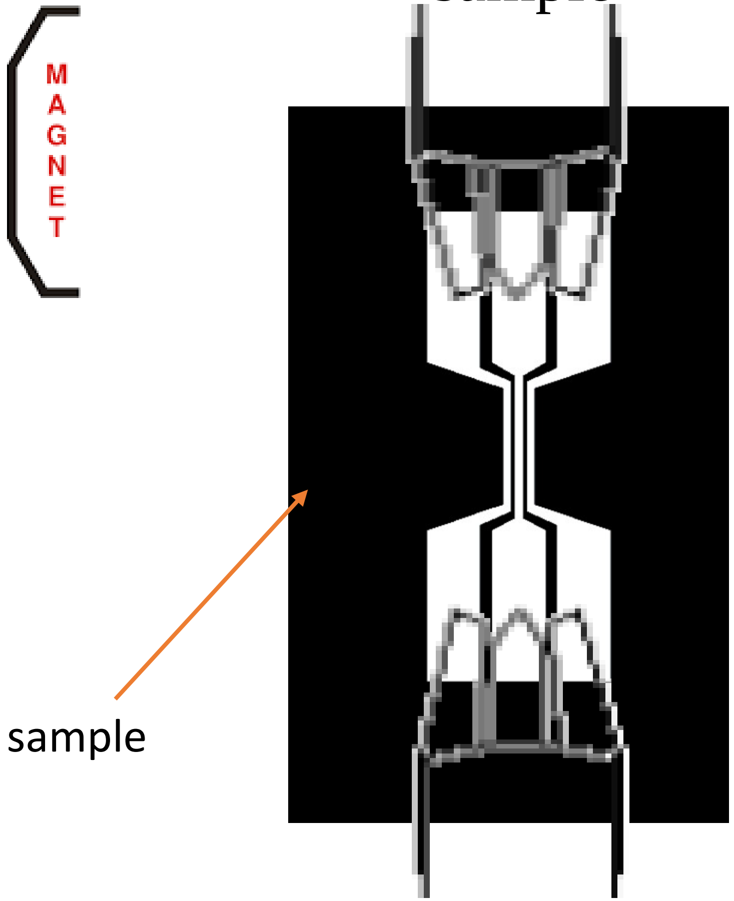
FMR with cavity



Flip-chip type FMR

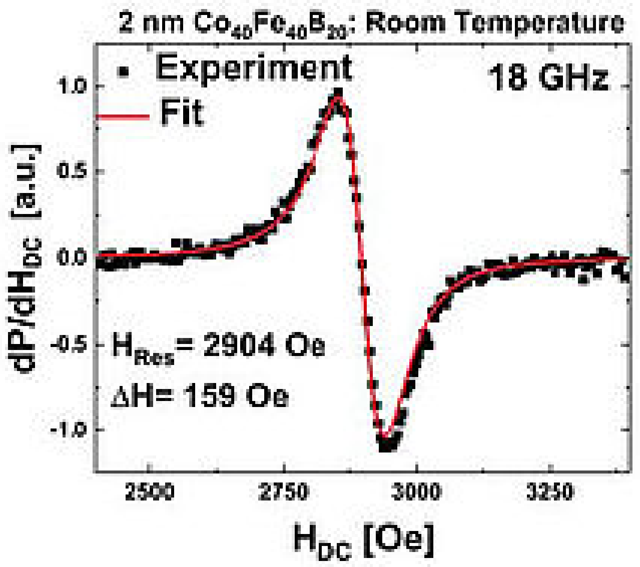


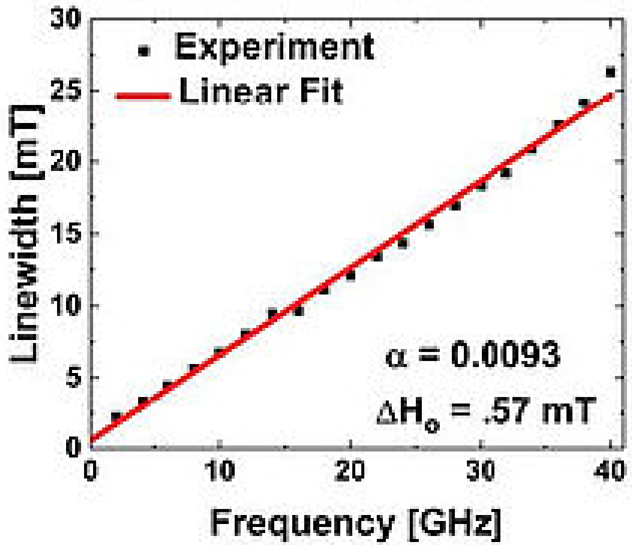
Micro-Coplaner waveguide patterned on sample

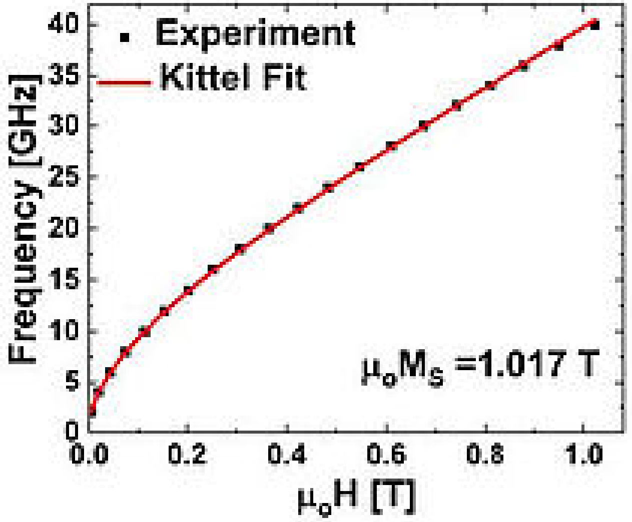


Ferromagnetic resonance

Analysis of the resonance signal





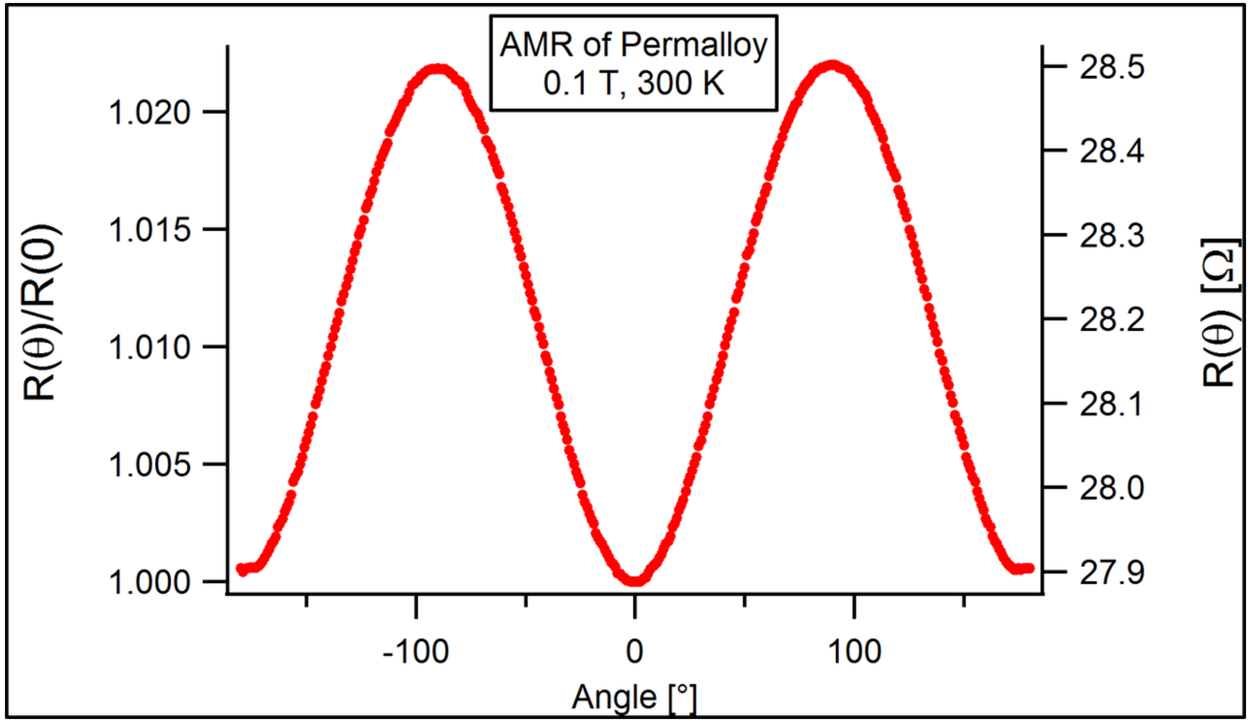


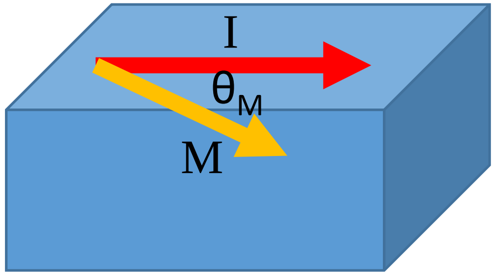
$$\frac{dP}{dH} = A\frac{\Delta \mathrm{H}(\mathrm{H_{ex}} - \mathrm{H_{res}})}{(\mathrm{H_{ex}} - \mathrm{H_{res}})^2 + \Delta \mathrm{H}^2}$$

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

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

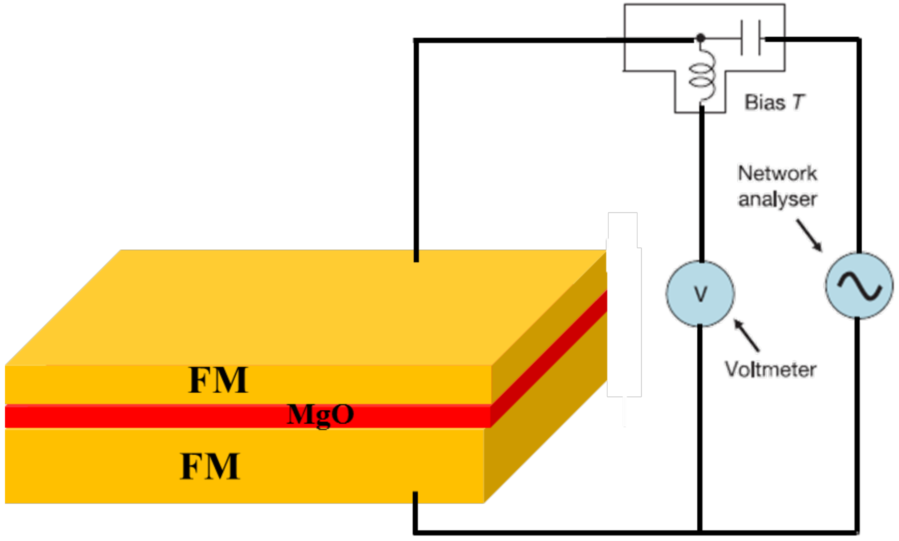
Anisotropic magnetic resistance (AMR)

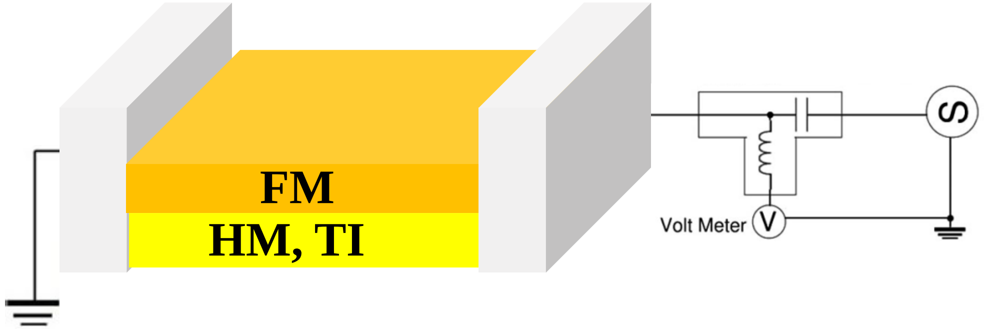




$$\rho = \rho_{\perp} + (\rho_{//} - \rho_{\perp}) \cos^2 \theta_M$$

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

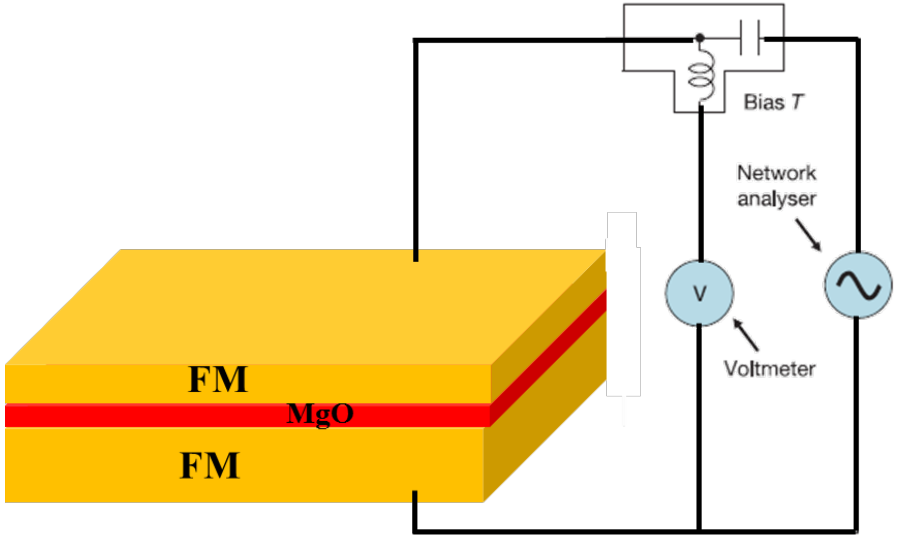
Liu. *et al*., PRL **106**, 036601 (2011)
Pai *et al*., APL **101**, 122404 (2012)

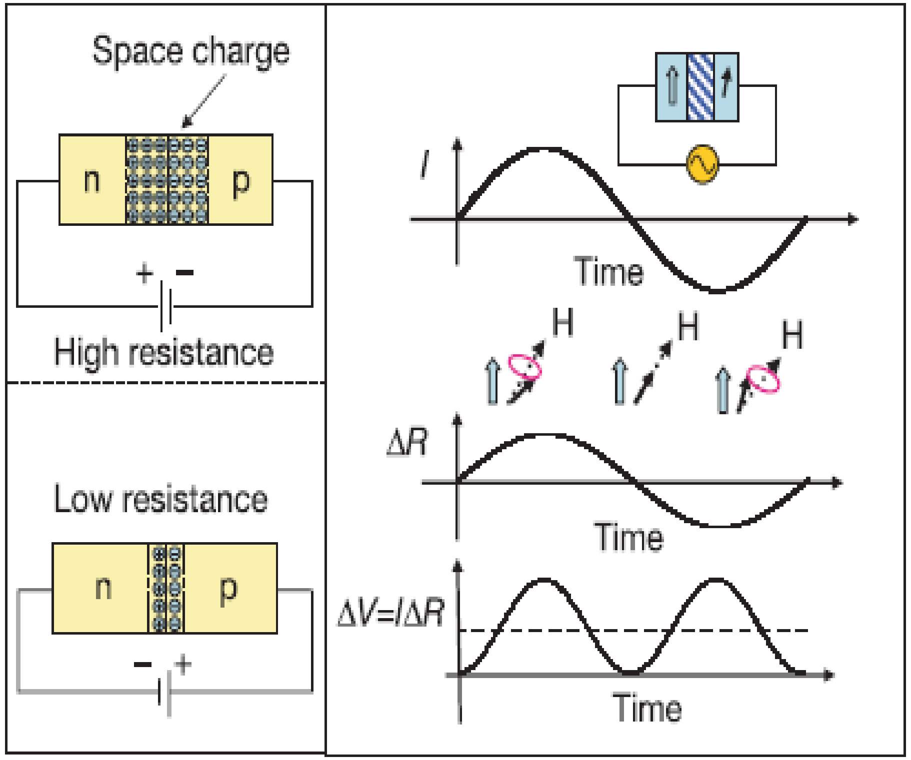
Heavy metals/FM Bilayer structure

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

Topological insulators/FM

Spin-torque diode effect in MTJ structure

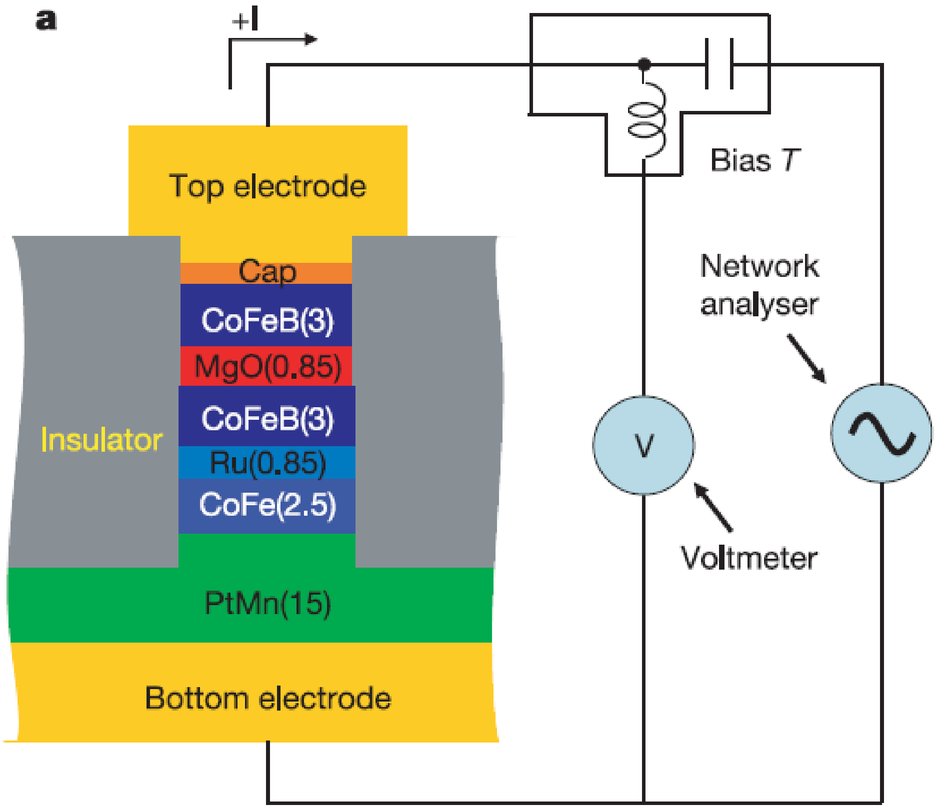


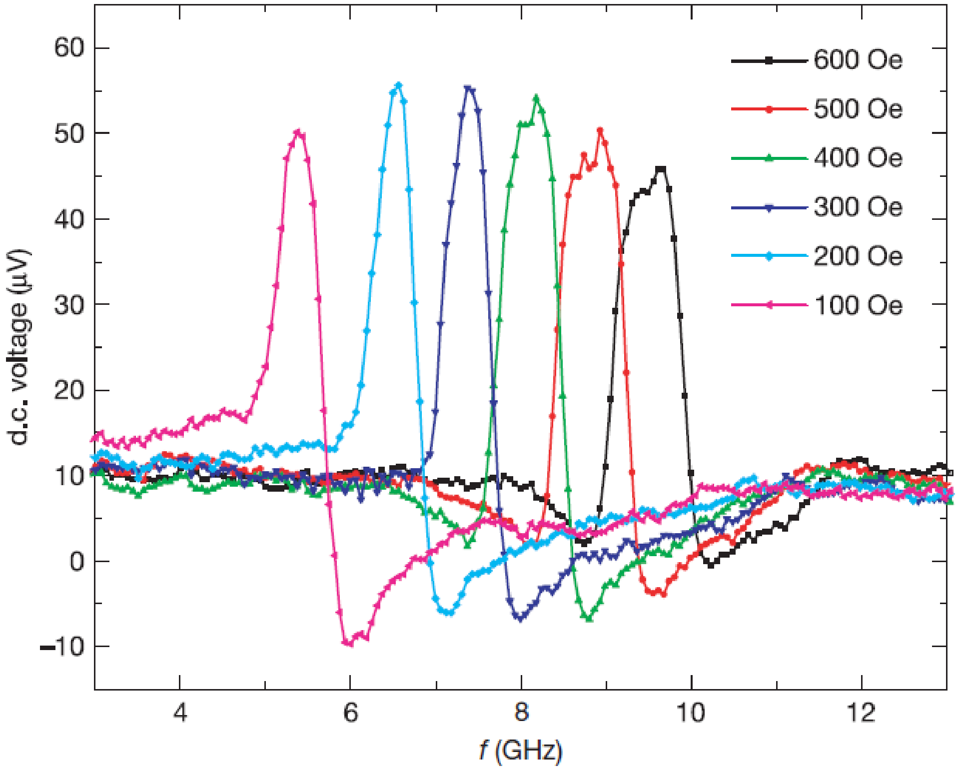


Source of Spin transfer torque:

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 diode, and could form the basis of a nanometre-scale radio-frequency detector in telecommunication circuits.

Line shape analysis

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. SANKEY[1], YONG-TAO CUI[1], JONATHAN Z. SUN[2], JOHN C. SLONCZEWSKI[2]*, ROBERT A. BUHRMAN[1] AND DANIEL C. RALPH[1†]

[1]Cornell University, Ithaca, New York 14853, USA
[2]IBM 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"

Quantitative measurement of voltage dependence of spin-transfer torque in MgO-based magnetic tunnel junctions

HITOSHI KUBOTA[1]*, AKIO FUKUSHIMA[1], KAY YAKUSHIJI[1], TARO NAGAHAMA[1], SHINJI YUASA[1], KOJI ANDO[1], HIROKI MAEHARA[2], YOSHINORI NAGAMINE[2], KOJI TSUNEKAWA[2], DAVID D. DJAYAPRAWIRA[2], NAOKI WATANABE[2] AND YOSHISHIGE SUZUKI[1,3]

[1]National Institute of Advanced Industrial Science and Technology (AIST), Nanoelectronics Research Institute (NeRI), Tsukuba, Ibaraki 305-8568, Japan
[2]Electron Device Division, Canon ANELVA Corporation, Fuchu, Tokyo 183-8508, Japan
[3]Graduate School of Engineering Science, Osaka University, Toyonaka, Osaka 560-8531, Japan
*e-mail: hit-kubota@aist.go.jp

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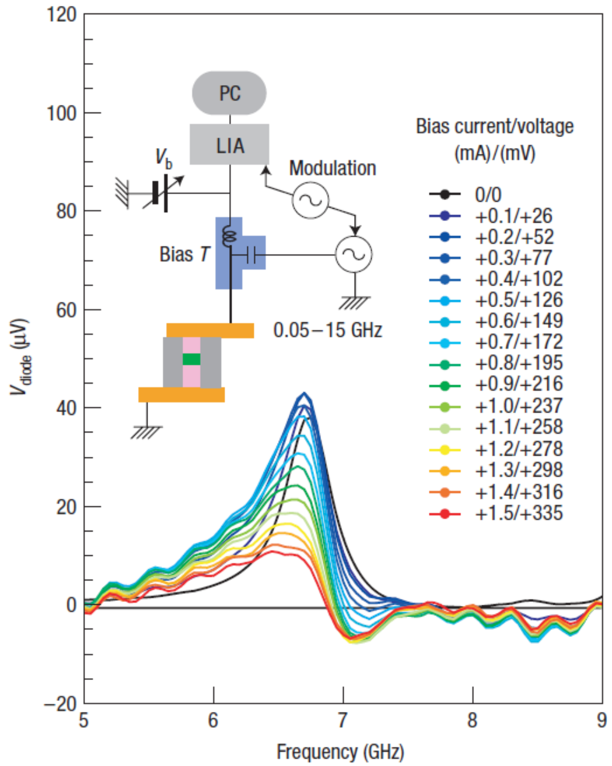

Measurement of the spin-transfer-torque vector in magnetic tunnel junctions

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*IBM RSM Emeritus
†e-mail: ralph@ccmr.cornell.edu

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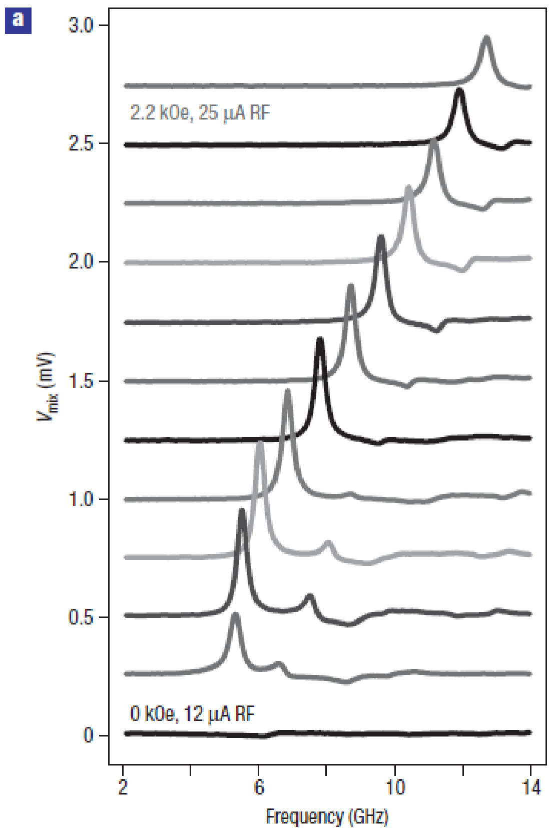
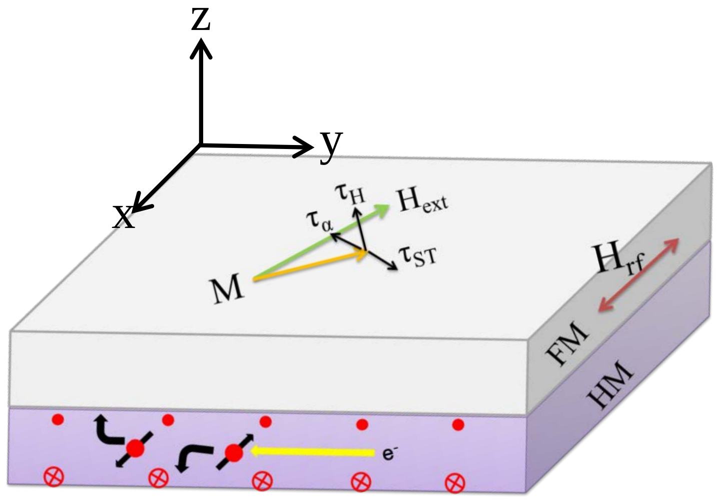


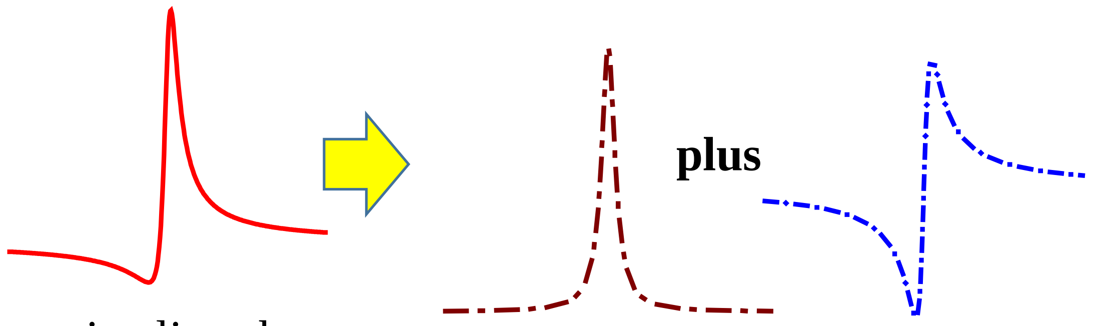
$$\langle V_{mix}\rangle = \frac{1}{4}\frac{\partial^2 V}{\partial I^2} I_{RF}^2 + \frac{1}{2}\frac{\partial^2 V}{\partial\theta\partial I}\frac{\hbar\gamma\sin\theta}{4eM_s \mathrm{Vol}\,\sigma} \times I_{RF}^2(\zeta_\parallel S(\omega) - \zeta_\perp \Omega_\perp A(\omega)).$$

Asymmetric and symmetric line shape analysis

$$\frac{d\hat{M}}{dt} = -\gamma\hat{M}\times\vec{H}_{eff} + \alpha_0\hat{M}\times\frac{d\hat{M}}{dt} + \frac{\gamma\hbar J_s}{2eM_s d_F}(\hat{m}\times\hat{\sigma}\times\hat{m}) - \gamma\hat{M}\times\vec{H}_{rf}$$

$$= -\gamma\hat{M}\times\vec{H}_{eff} + \alpha_0\hat{M}\times\frac{d\hat{M}}{dt} + \gamma[\tau_{||}\frac{\hat{M}\times(\hat{x}\times\hat{M})}{|\hat{x}\times\hat{M}|} + \tau_{\perp}\frac{\hat{x}\times\hat{M}}{|\hat{x}\times\hat{M}|}]$$





Lorentzian line shape

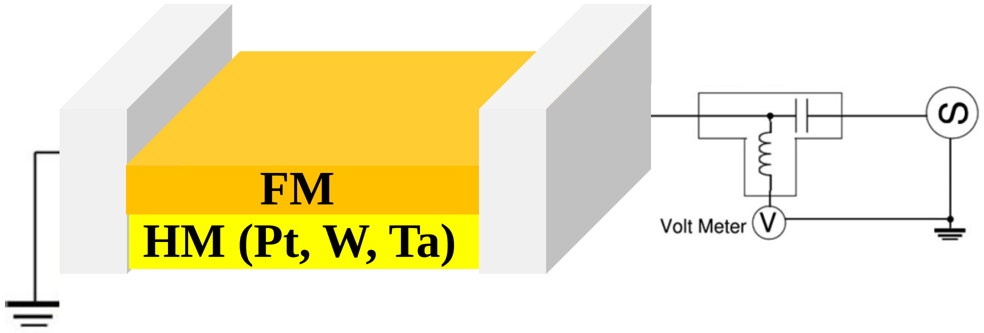
Symmetric $\propto \tau_{||}$

asymmetric $\propto \tau_{\perp}$

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

ST-FMR on bi-layer structures

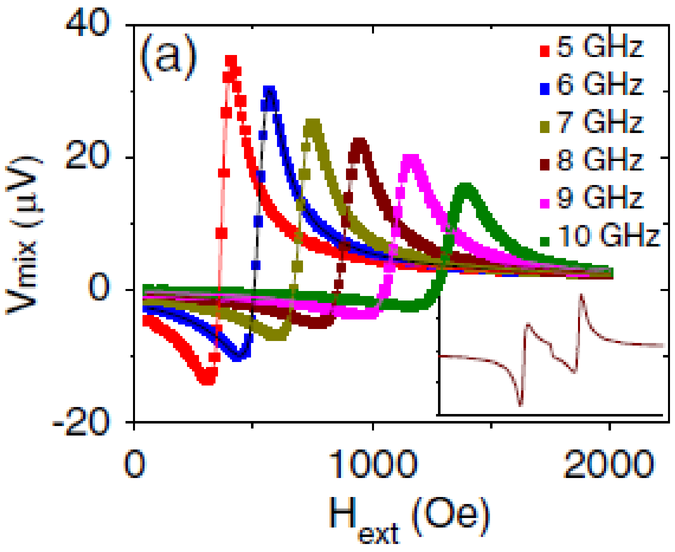
STT=>SOT



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

Source of Spin torque:

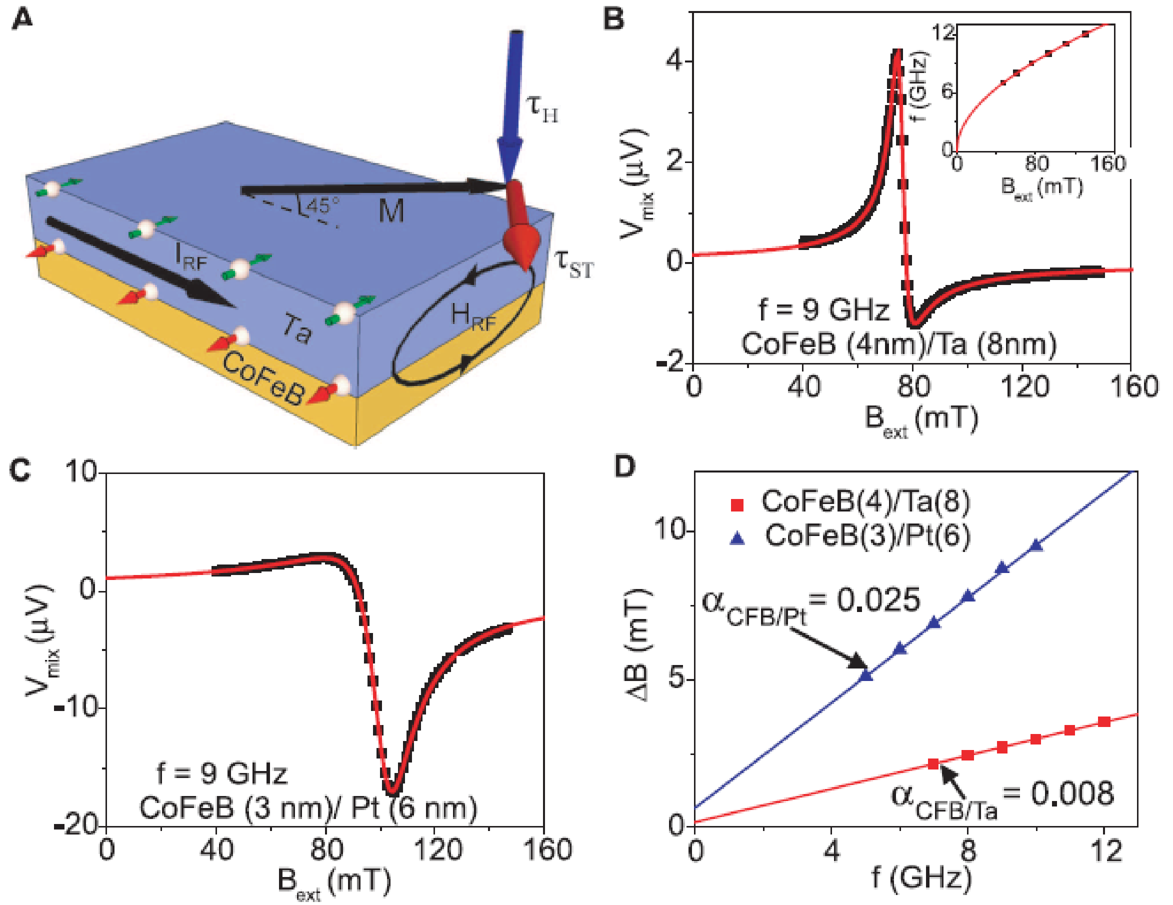
SHE



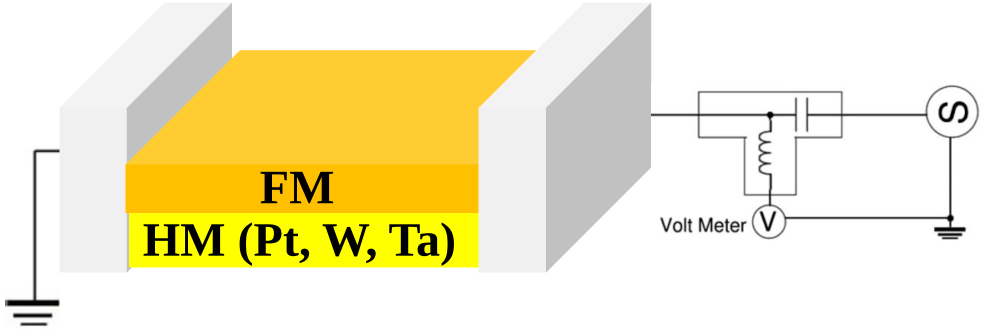
Spin-Torque Switching with the Giant Spin Hall Effect of Tantalum

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



ST-FMR on FM/TI bi-layer structures



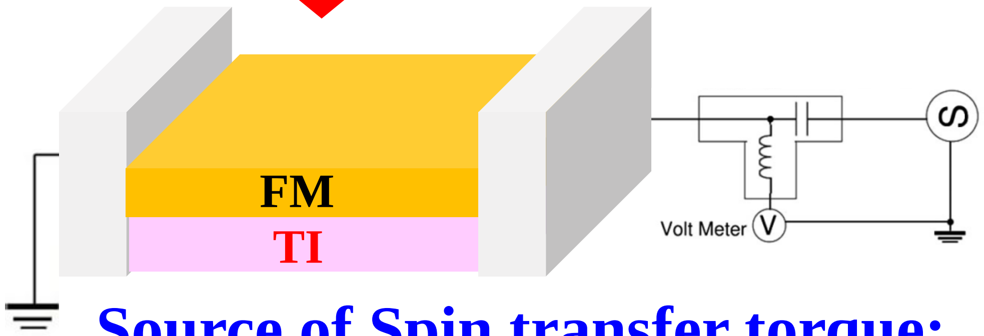
Liu. et al. PRL **106**, 036601 (2011)
Pai et al. APL **101**, 122404 (2012)

Source of Spin transfer torque:

SHE

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

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

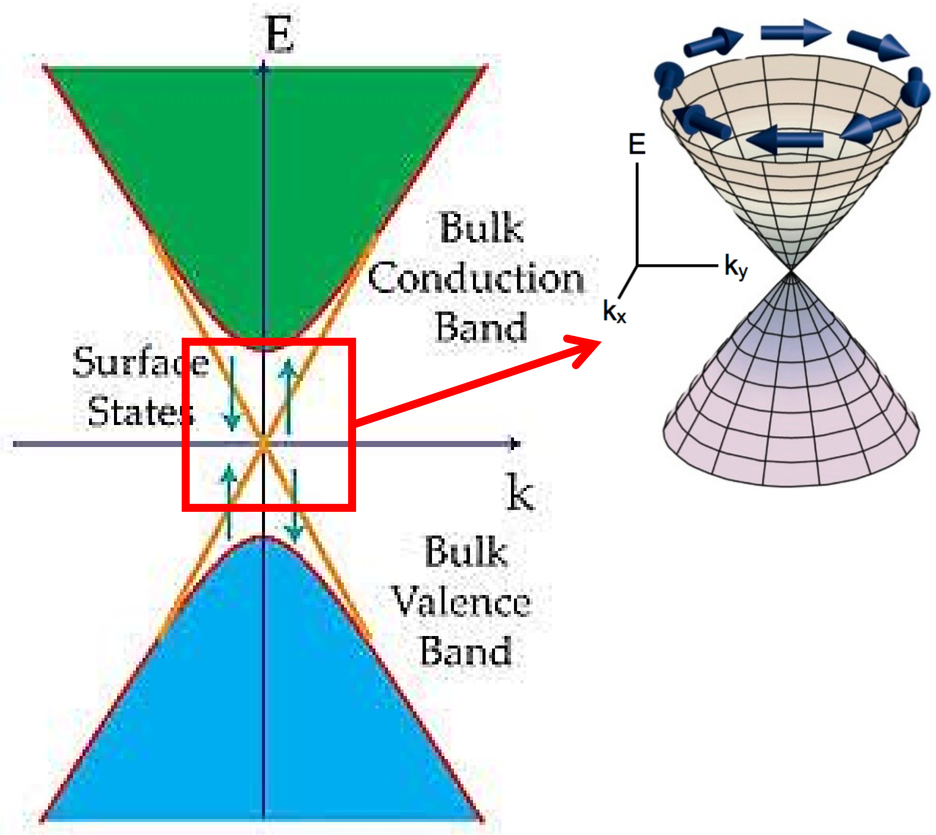


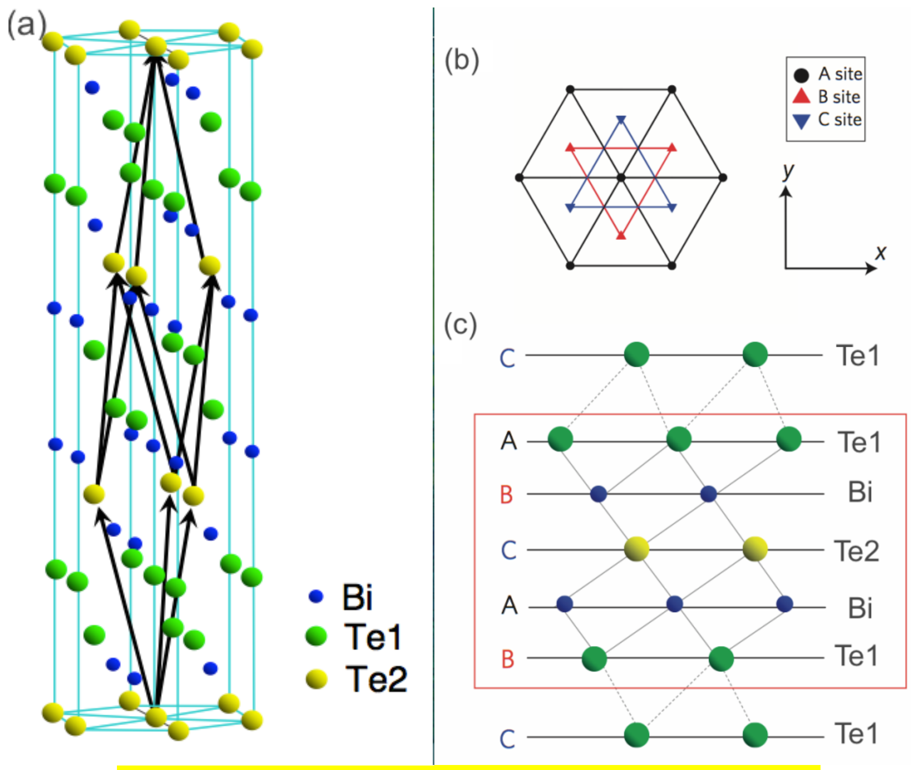
Mellink et al. Nature **511**, 449 (2014)
Wang et al. PRL **114**, 257202 (2015)

Source of Spin transfer torque:

SHE, TI surface state

Topological insulator





3D-TI: Bi_2Se_3, Bi_2Te_3

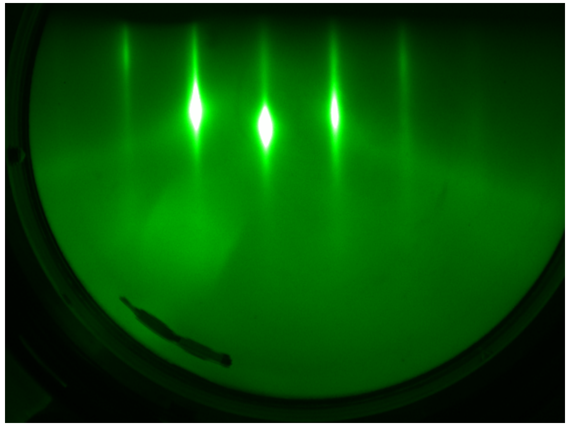
- Strong spin orbit coupling

- Spin-momentum locking

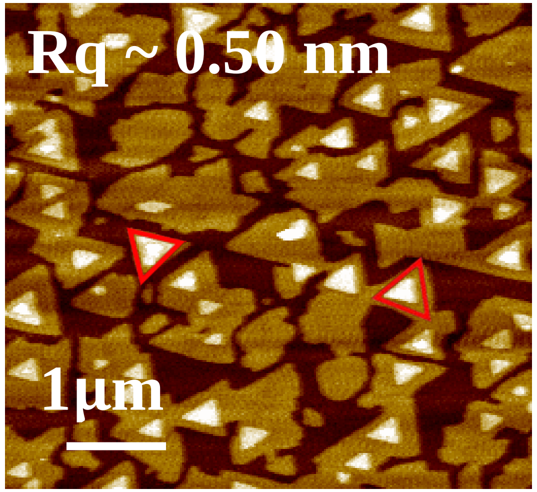
TI surface state ➡ **High spin–charge conversion**

Bi_2Se_3, Bi_2Te_3 $BiSb_xTe_{1-x}$ Films grown by MBE

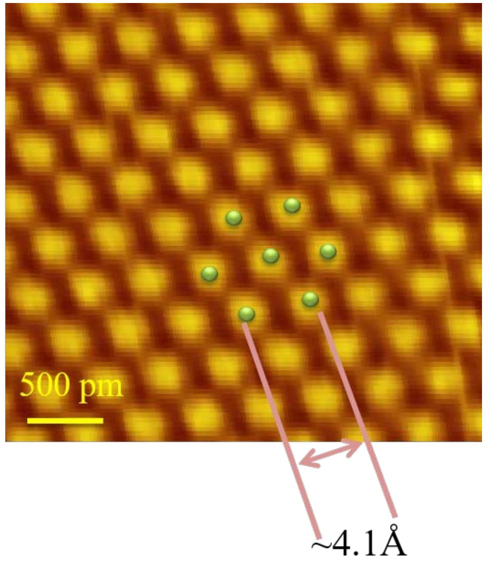
RHEED



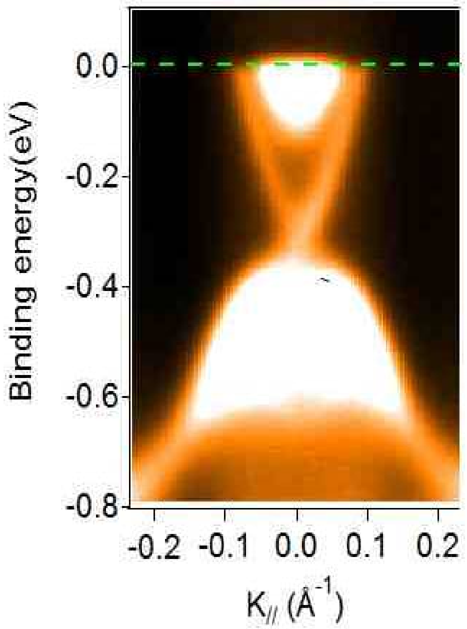
AFM

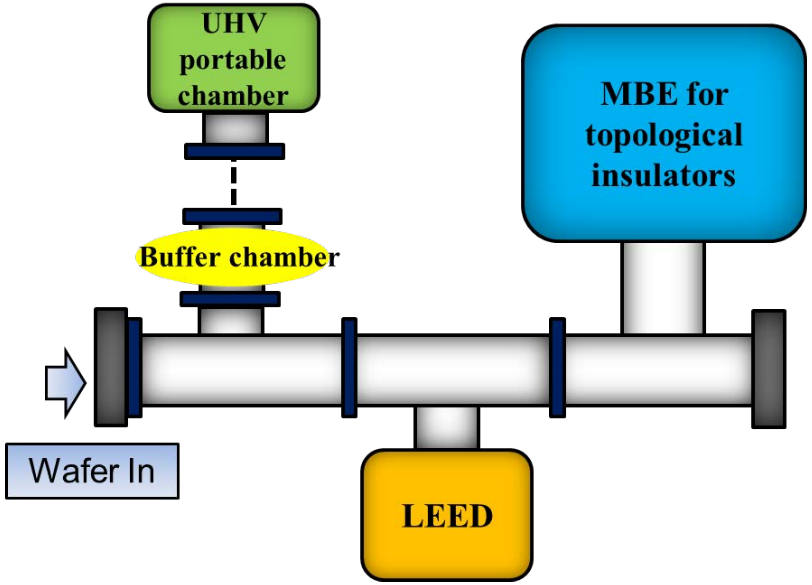


STM

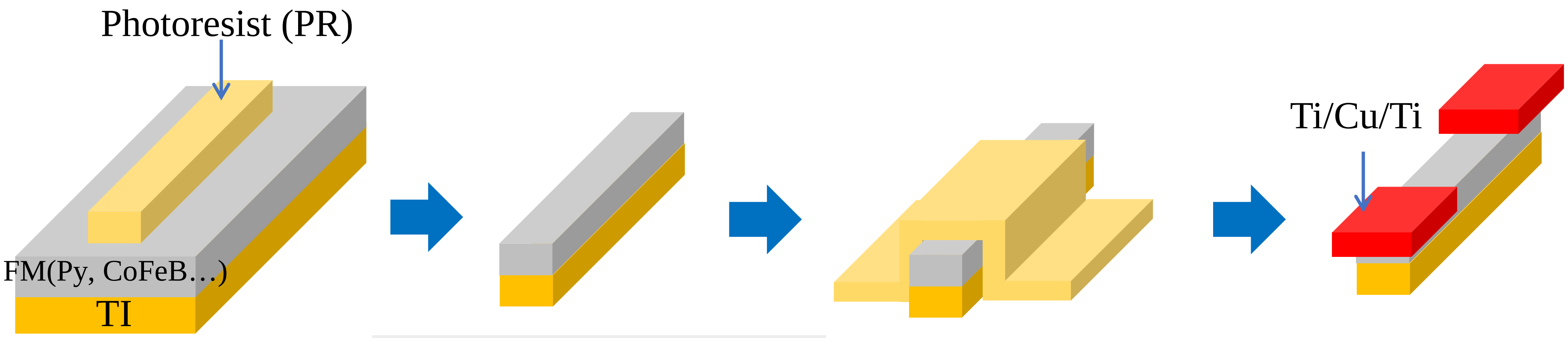


ARPES





Device fabrication for ST-FMR experiment



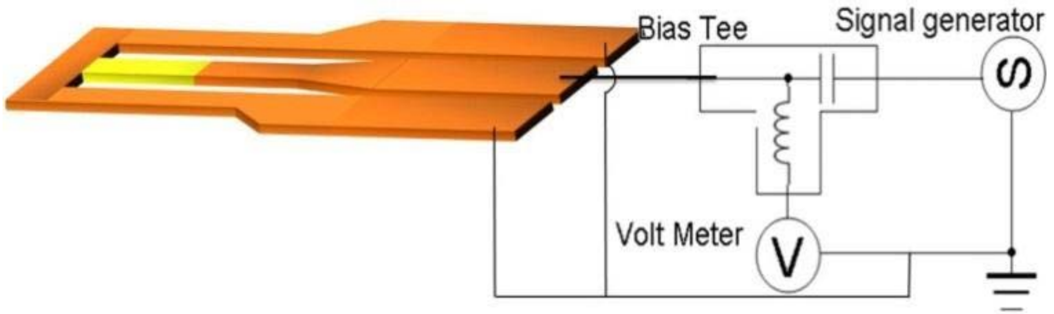
Define the sample shape at “dark” area

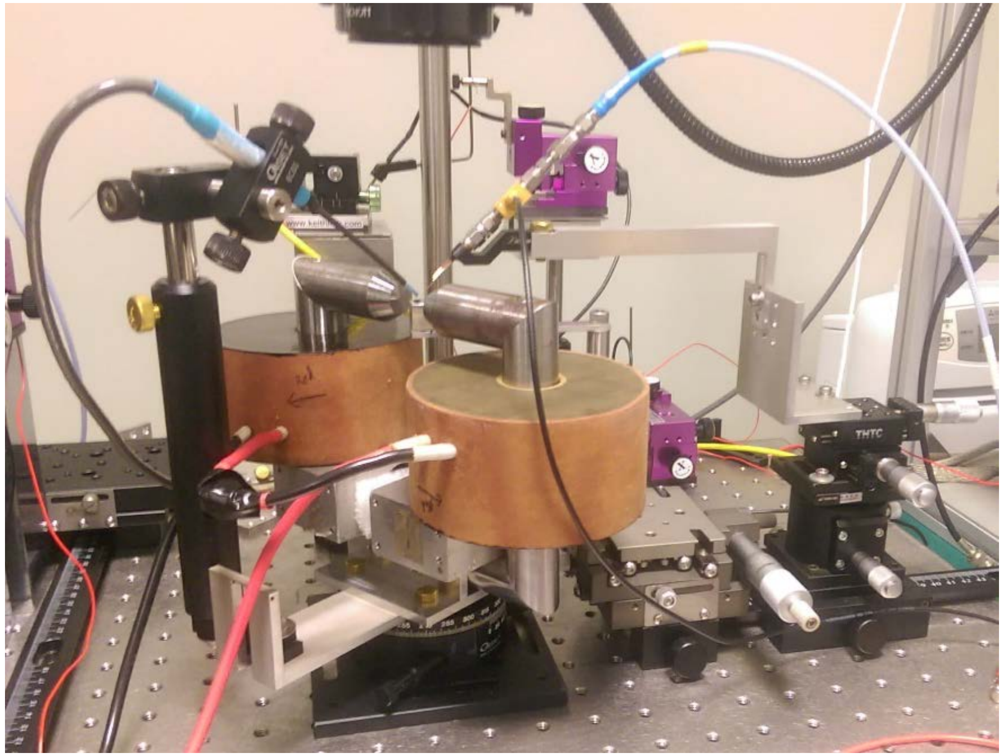
Etched with ion beam bombardment and PR removed with solvent

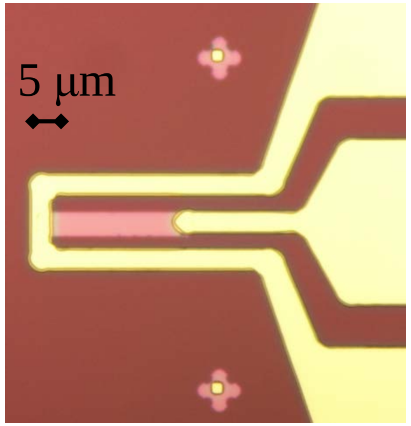
Define the contacts at “clear” area

Metal deposition and lift-off process

ST-FMR experimental setup

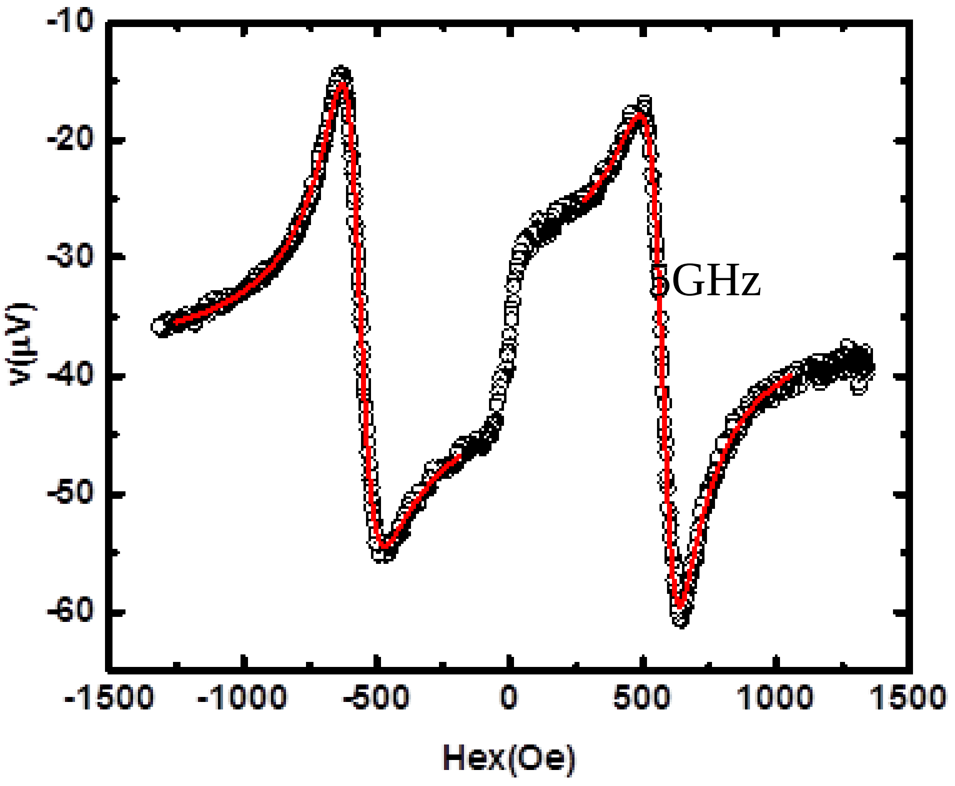


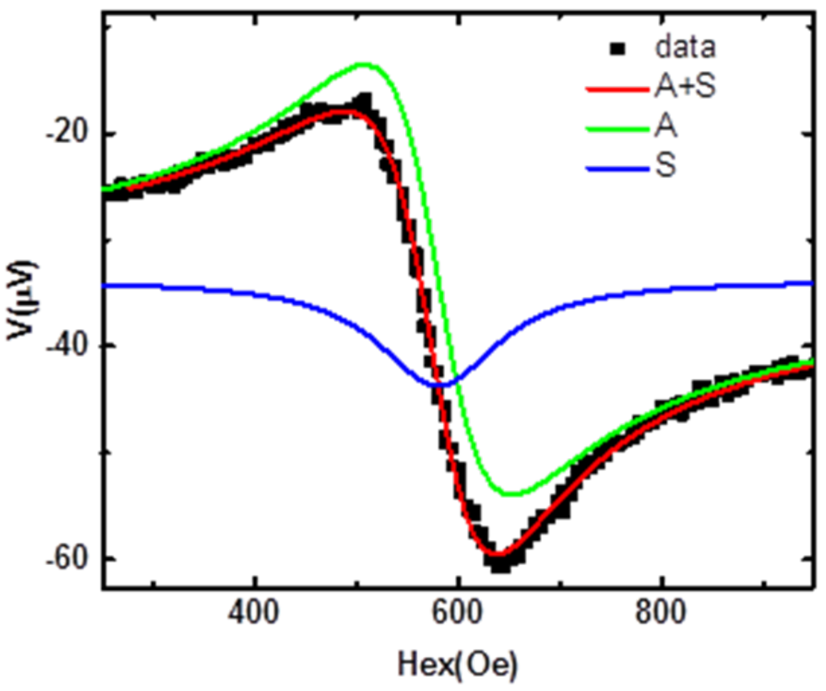




ST-FMR device

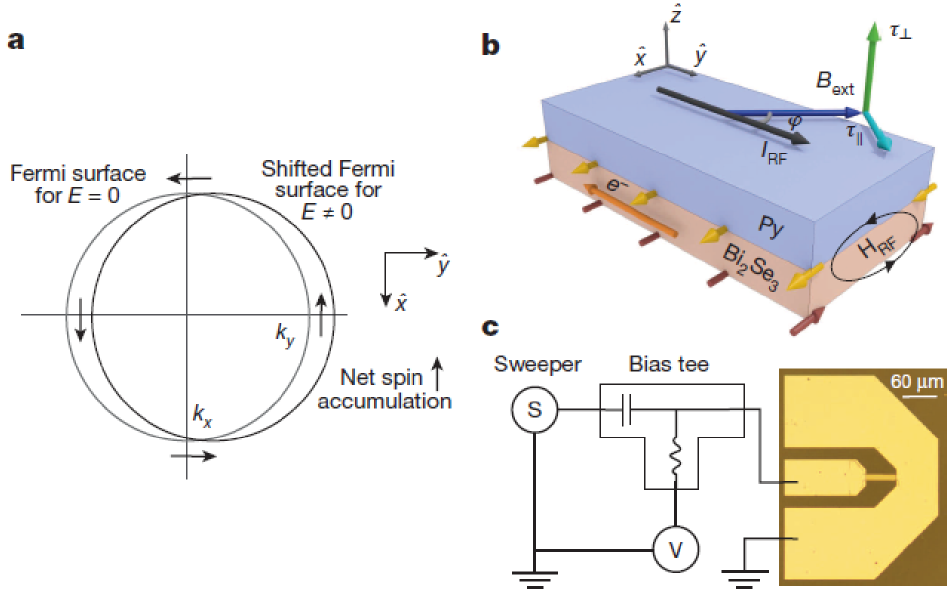
Line curve analysis

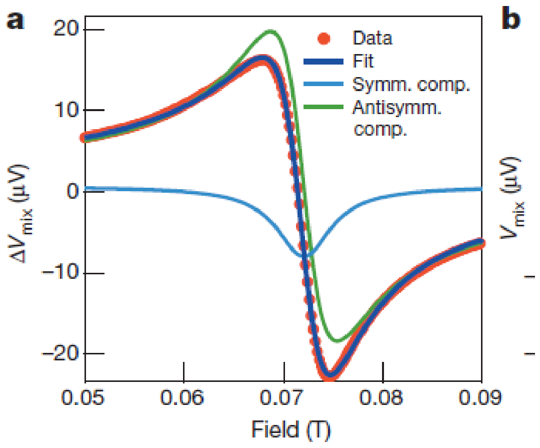




Spin-transfer torque generated by a topological insulator

A. R. Mellnik[1], J. S. Lee[2], A. Richardella[2], J. L. Grab[1], P. J. Mintun[1], M. H. Fischer[1,3], A. Vaezi[1], A. Manchon[4], E.-A. Kim[1], N. Samarth[2] & D. C. Ralph[1,5]

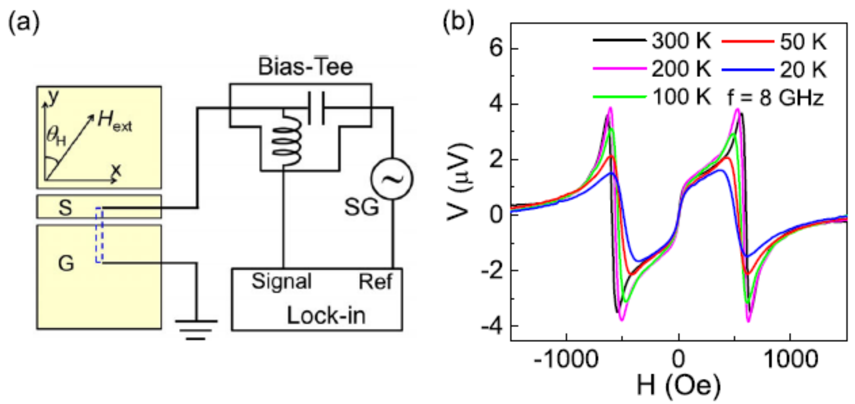




PRL 114, 257202 (2015) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2015

Topological Surface States Originated Spin-Orbit Torques in Bi_2Se_3

Yi Wang,[1] Praveen Deorani,[1] Karan Banerjee,[1] Nikesh Koirala,[2] Matthew Brahlek,[2] Seongshik Oh,[2] and Hyunsoo Yang[1,*]
[1]*Department of Electrical and Computer Engineering, National University of Singapore, 117576 Singapore, Singapore*
[2]*Department 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)

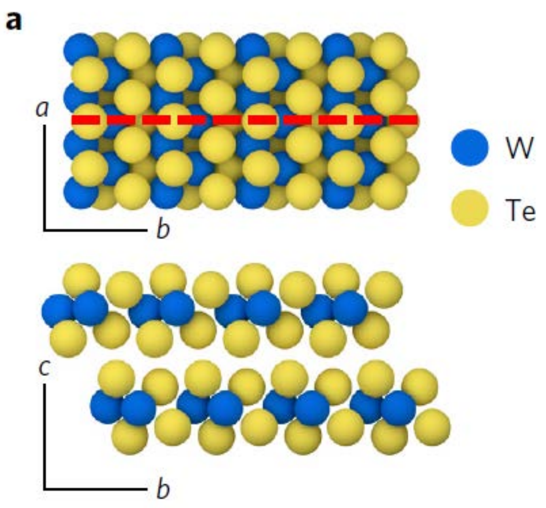


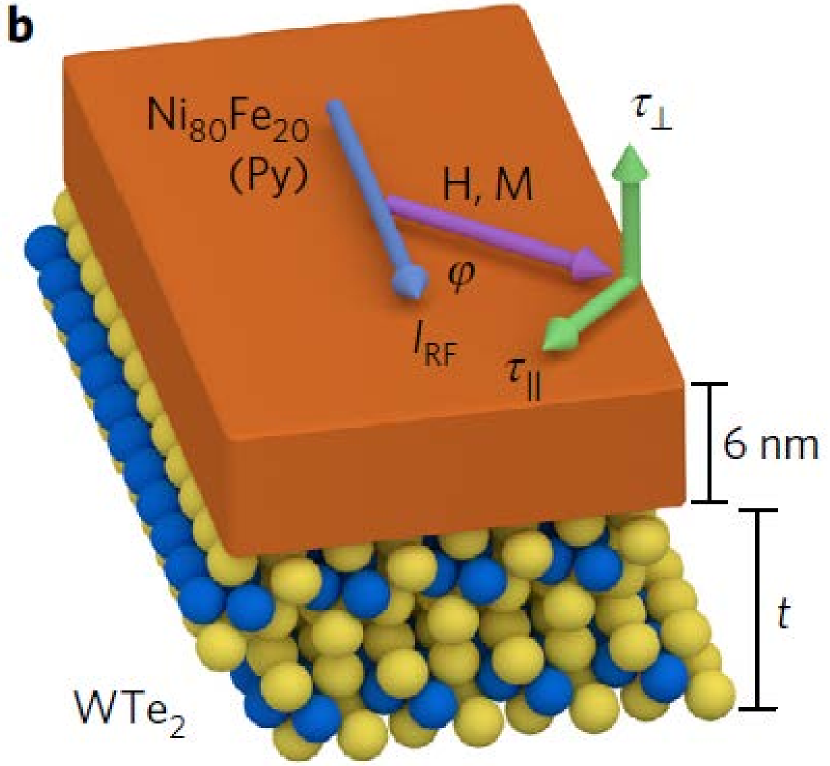
ST-FMR on FM/TMD bi-layer structures

ARTICLES
PUBLISHED ONLINE: 7 NOVEMBER 2016 | DOI: 10.1038/NPHYS3933
nature physics

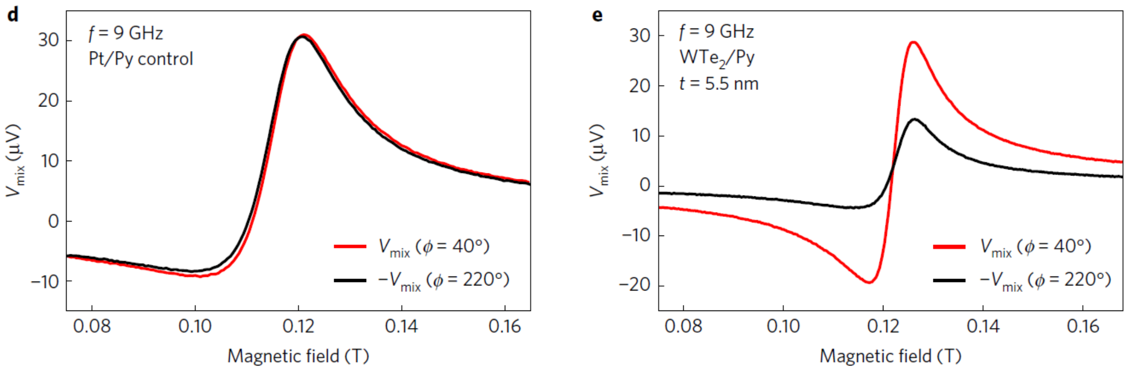
Control of spin–orbit torques through crystal symmetry in WTe_2/ferromagnet bilayers

D. MacNeill[1†], G. M. Stiehl[1†], M. H. D. Guimaraes[1,2], R. A. Buhrman[3], J. Park[2,4] and D. C. Ralph[1,2*]

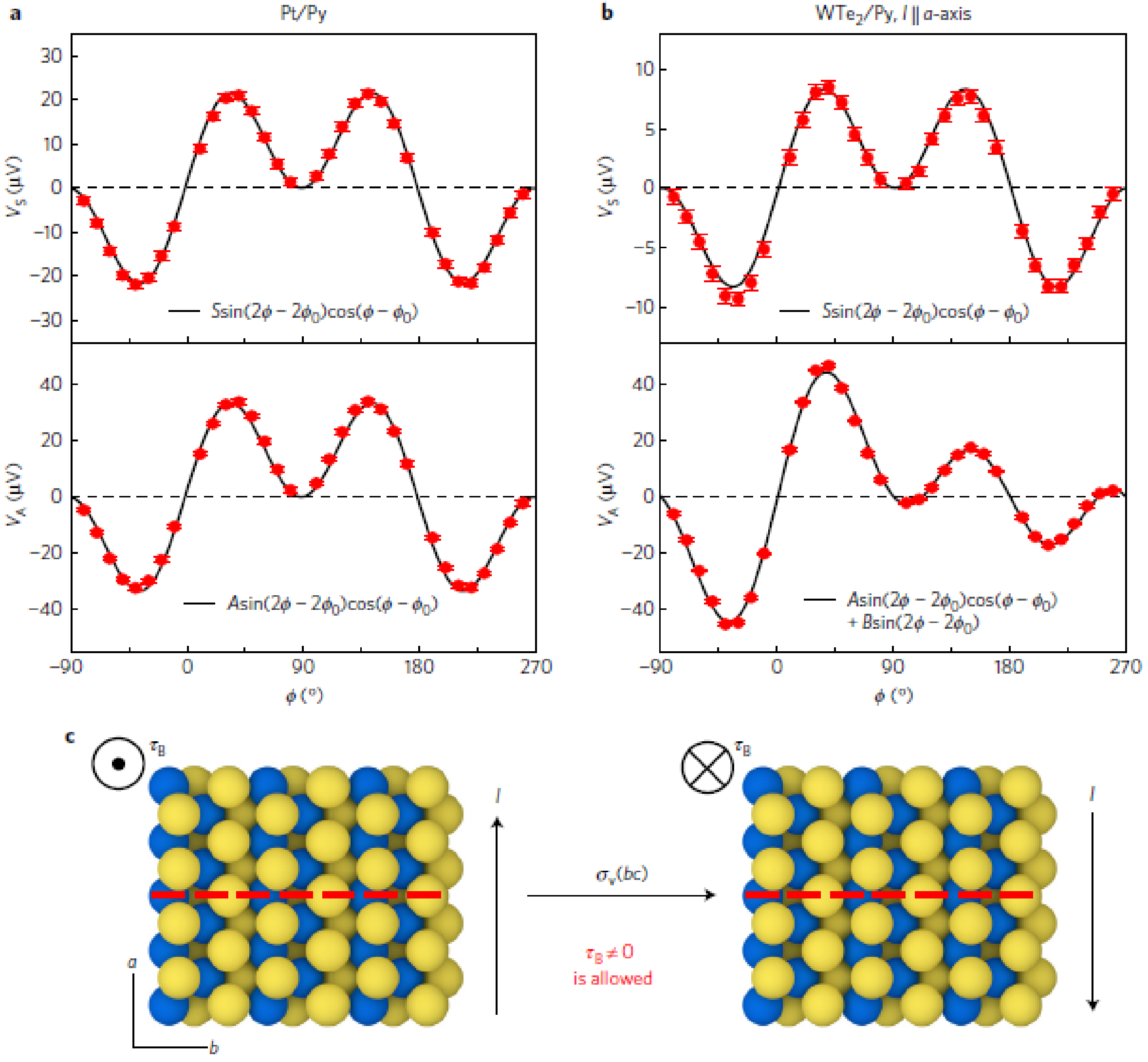




The surface possesses mirror symmetry with respect to the *bc* plane (dashed line), but not with respect to the *ac* plane, and therefore it is also not symmetric relative to a 180° rotation about the *c*-axis.



d
f = 9 GHz
Pt/Py control
V_{mix} (μV)
V_{mix} (ϕ = 40°)
$-V_{mix}$ (ϕ = 220°)
Magnetic field (T)
e
f = 9 GHz
WTe_2/Py
t = 5.5 nm
V_{mix} (μV)
V_{mix} (ϕ = 40°)
$-V_{mix}$ (ϕ = 220°)
Magnetic field (T)



a
Pt/Py
V_S (μV)
$S\sin(2\phi - 2\phi_0)\cos(\phi - \phi_0)$
V_A (μV)
$A\sin(2\phi - 2\phi_0)\cos(\phi - \phi_0)$
ϕ (°)
b
WTe_2/Py, I ∥ a-axis
V_S (μV)
$S\sin(2\phi - 2\phi_0)\cos(\phi - \phi_0)$
V_A (μV)
$A\sin(2\phi - 2\phi_0)\cos(\phi - \phi_0)$
$+ B\sin(2\phi - 2\phi_0)$
ϕ (°)
c
τ_B
I
$\sigma_v(bc)$
$\tau_B \neq 0$
is allowed
a
b

$$V_S = -\frac{I_{RF}}{2}\left(\frac{dR}{d\phi}\right)\frac{1}{\alpha_G\gamma(2B_0+\mu_0 M_{eff})}\tau_\parallel$$

$$V_A = -\frac{I_{RF}}{2}\left(\frac{dR}{d\phi}\right)\frac{\sqrt{1+\mu_0 M_{eff}/B_0}}{\alpha_G\gamma(2B_0+\mu_0 M_{eff})}\tau_\perp$$

$$\tau_\parallel(\phi) = \tau_S\cos(\phi)$$

$$\tau_\perp(\phi) = \tau_A\cos(\phi) + \tau_B$$

$$dR/d\phi \propto \sin(2\phi).$$

$$V_A(\phi) = A\cos(\phi)\sin(2\phi) + B\sin(2\phi)$$

It is consistent with predictions[35] that broken lateral mirror symmetry can allow an out-of-plane torque of the form $\boldsymbol{\tau}_{AD} \propto \hat{\mathbf{m}} \times (\hat{\mathbf{m}} \times \hat{\mathbf{c}})$. That an out-of-plane antidamping-like torque with the form of τ_B could exist has also been discussed in an analysis of the allowed symmetries for S–O torques in GaMnAs /Fe samples[24], but this torque has not previously been identified in experiment.

APL MATERIALS **4**, 032302 (2016)

Research Update: Spin transfer torques in permalloy on monolayer MoS_2

Wei Zhang,[1,a] Joseph Sklenar,[1,2,a] Bo Hsu,[3] Wanjun Jiang,[1]
Matthias B. Jungfleisch,[1] Jiao Xiao,[3] Frank Y. Fradin,[1] Yaohua Liu,[4]
John E. Pearson,[1] John B. Ketterson,[2] Zheng Yang,[3,b] and Axel Hoffmann[1,c]

[1]*Materials Science Division, Argonne National Laboratory, Lemont, Illinois 60439, USA*
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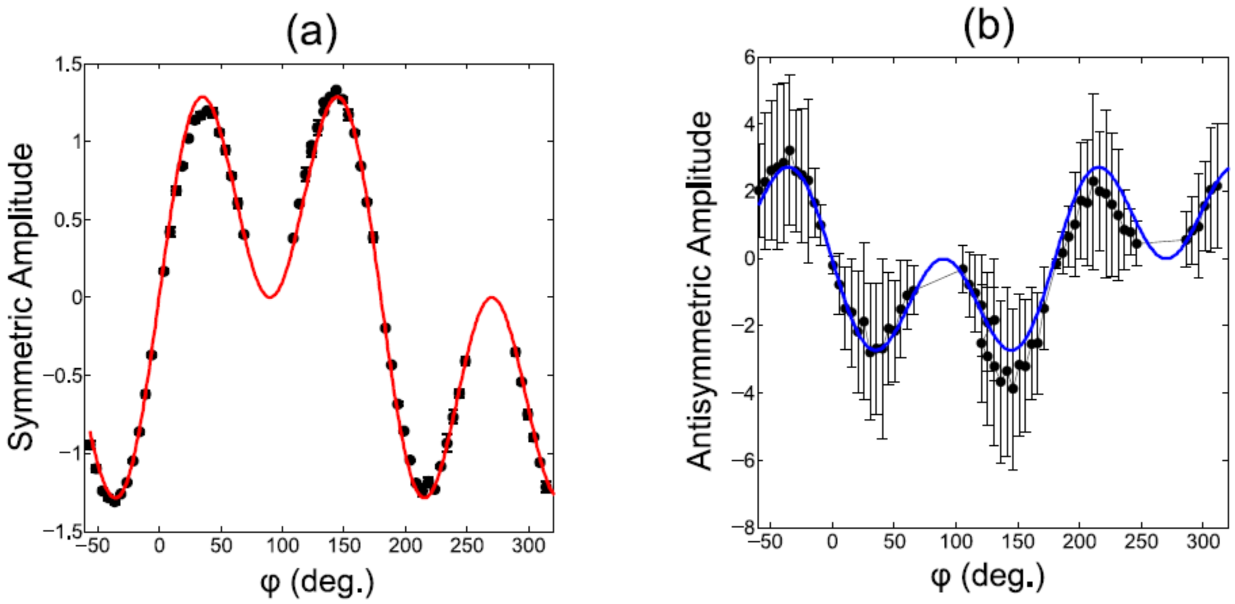
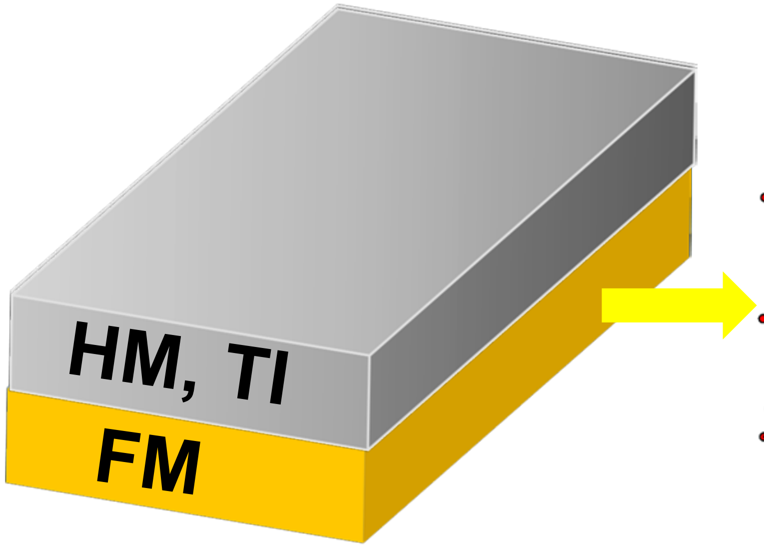
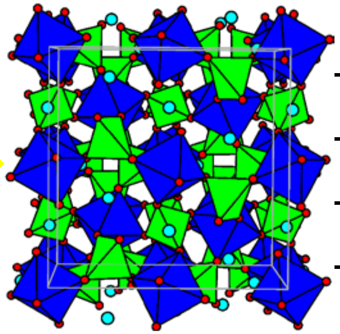
(Received 1 December 2015; accepted 17 February 2016; published online 3 March 2016)



ST-FMR on HM/FI

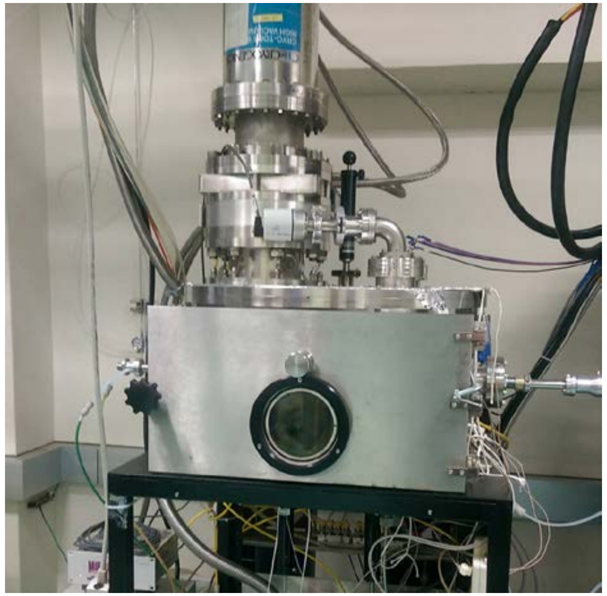




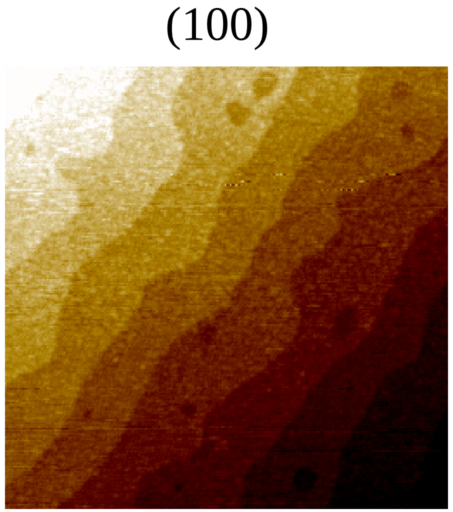
$Y_3Fe'_2(Fe''O_4)_3$

- Extremely small damping(α~10^{-4})
- Electrically insulating
- Long-range spin wave transmission
- Chemically stable surface

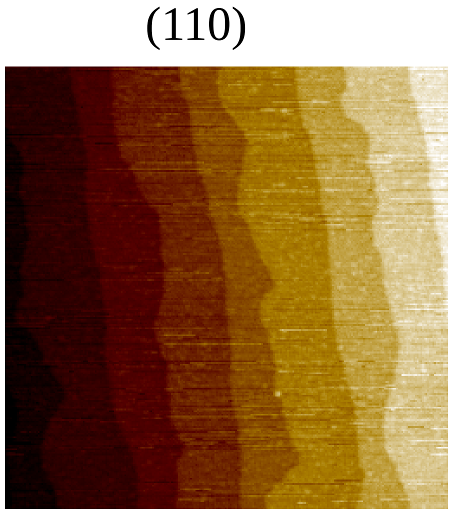
Ferrimagnetic insulator YIG



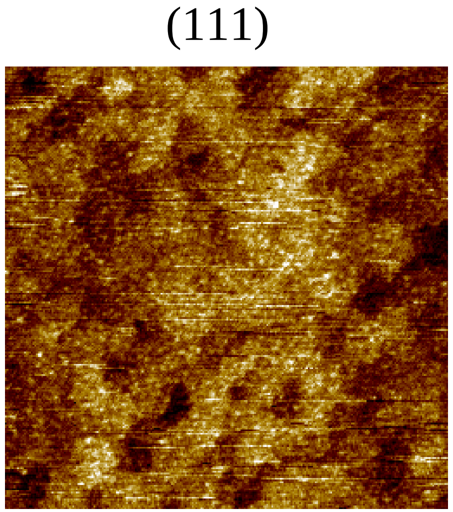
Sputtering YIG on GGG



Rq: 1.1Å



Rq: 0.85Å

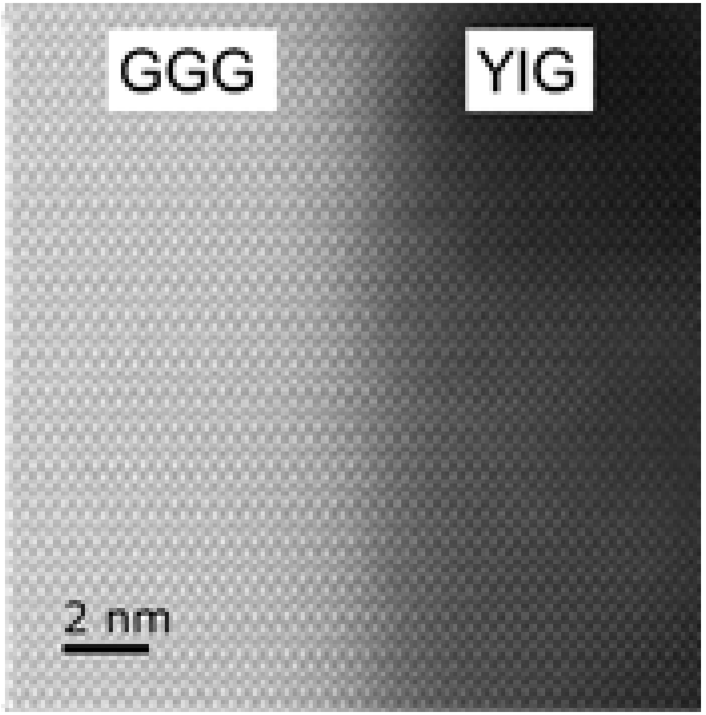


Rq: 1.7Å

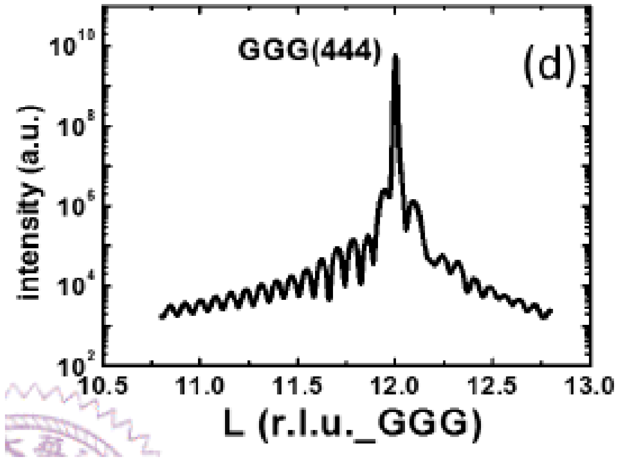
AFM surface morphology

Sample preparation

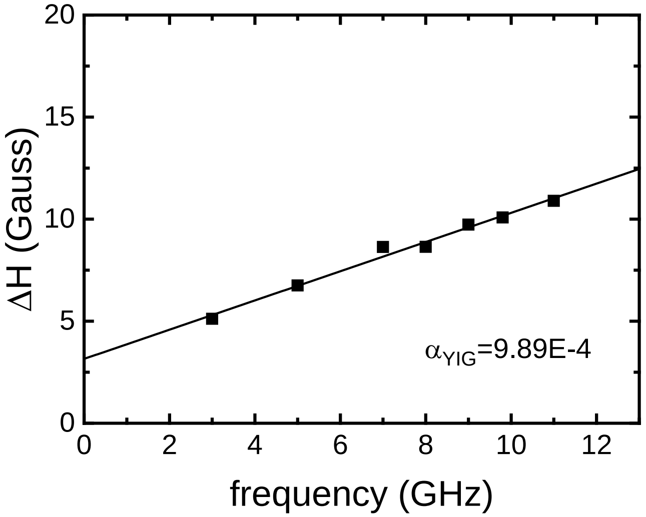
$Y_3Fe_5O_{12}$/GGG grown in sputtering chamber



TEM



XRD



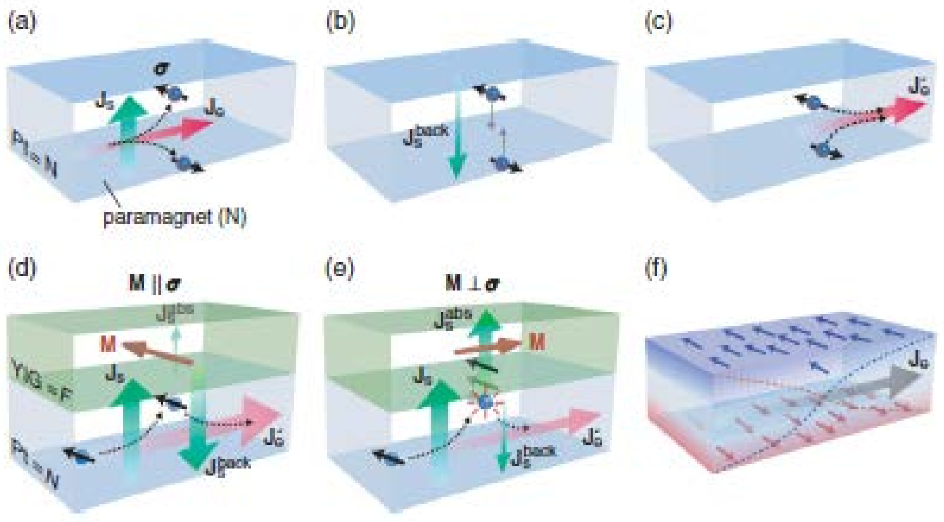
FMR

ST-FMR on Pt/YIG

RF current no longer pass through the FM layer.

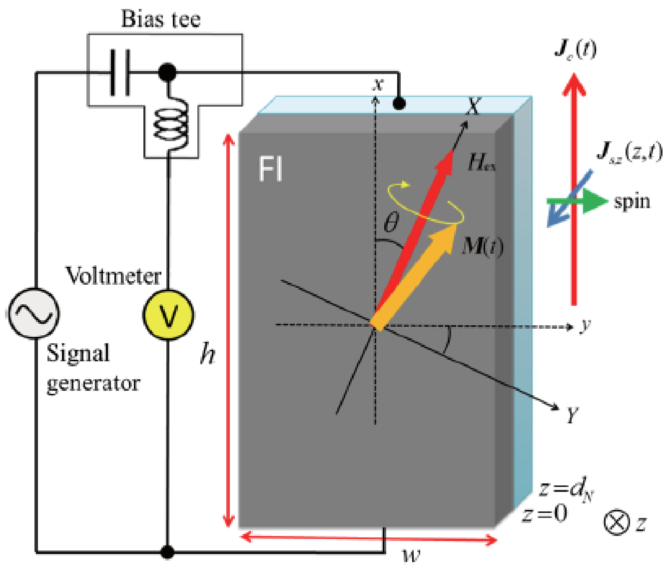
New theoretical model based on SMR should be applied.

Spin Hall magnetoresistance (SMR)



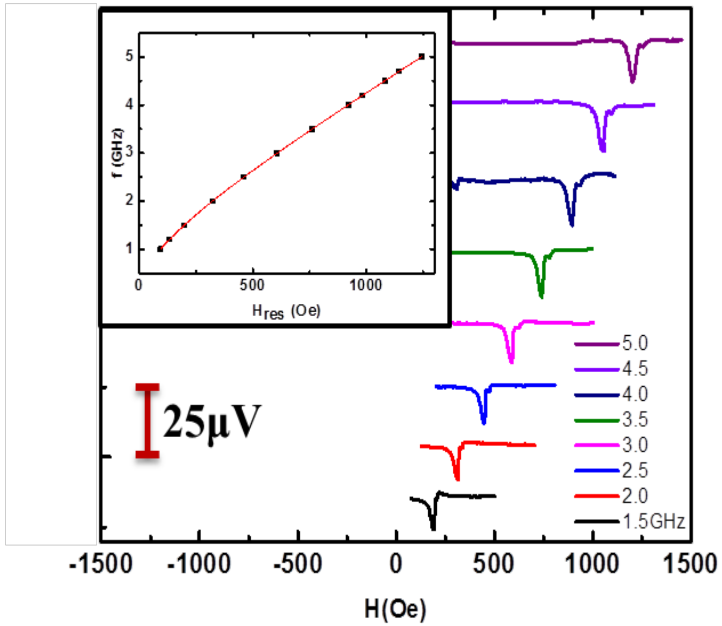
Nakayama et al., Phys. Rev. Lett. **110**, 206601 (2013)

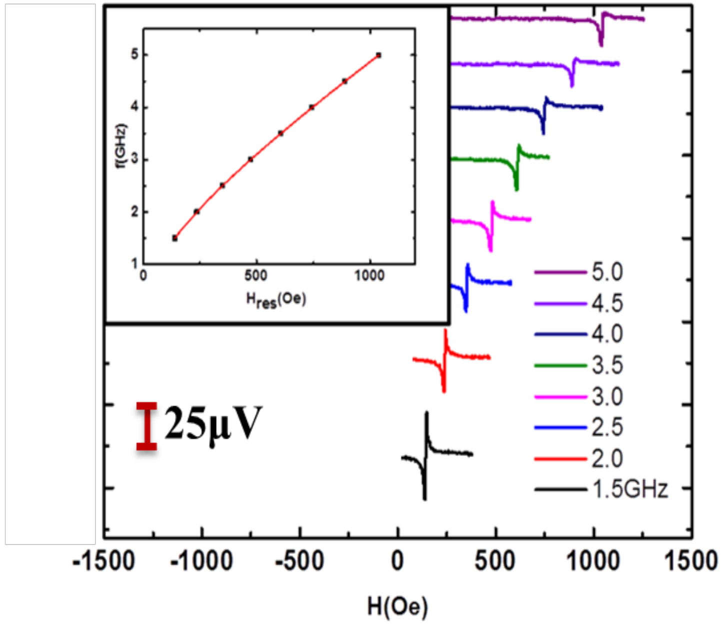
Current-induced spin torque resonance of magnetic insulators



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

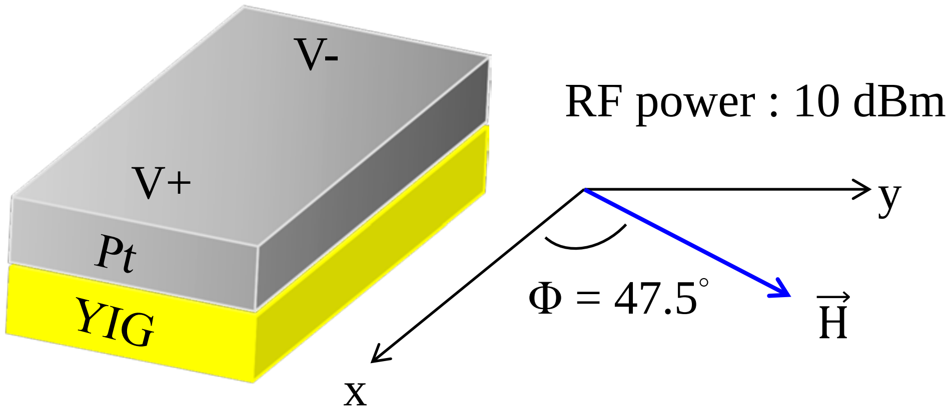
ST-FMR on Pt/YIG





A	Pt (5 nm)
	YIG (50 nm)

B	Pt (16 nm)
	YIG (50 nm)



Theoretical calculation

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

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

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

$$V_{mix} = VSM_R + V_{SP}$$

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

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 Gi Gr.
δ : phase shift between rf current and Oersted field inside YIG

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

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

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

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

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

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

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

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

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

$r = d_N/\lambda,$

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

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

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

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

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

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

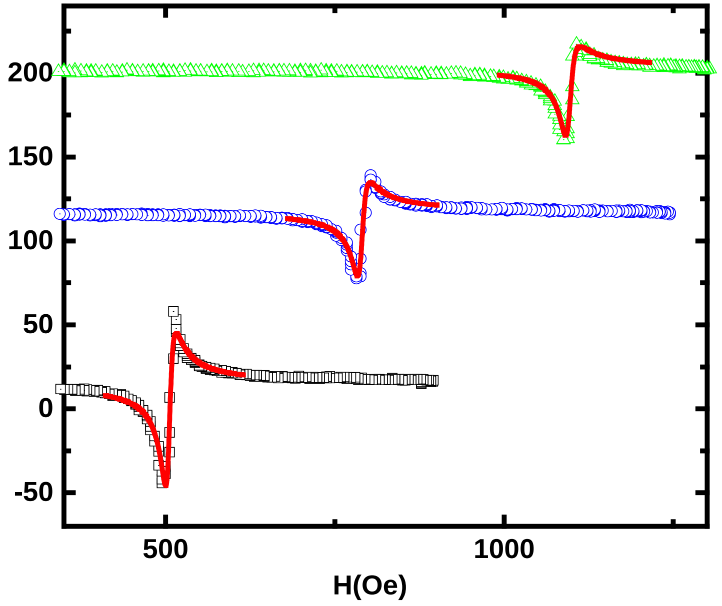
$\widetilde{\Delta H} = \Delta H/2\pi M_S,$

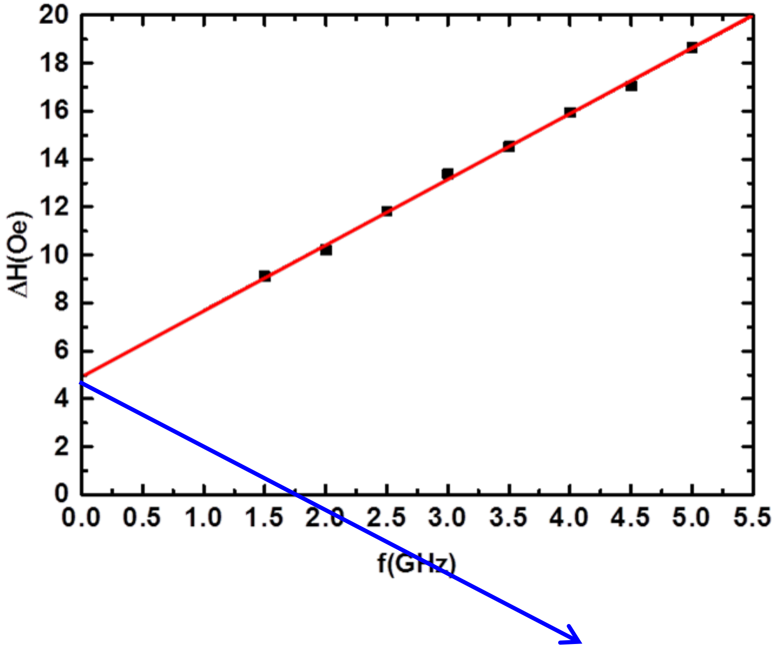
$C = \tilde{\omega}_a/\sqrt{1+\tilde{\omega}_a^2},$

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

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

Line width analysis





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

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

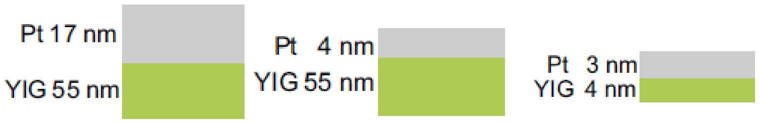
An inhomogeneous broadening factor was observed!

Thermal effect in the Pt/YIG film during ST-FMR measurement

Heating-induced ΔH_{0}, α_{SSE}

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

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



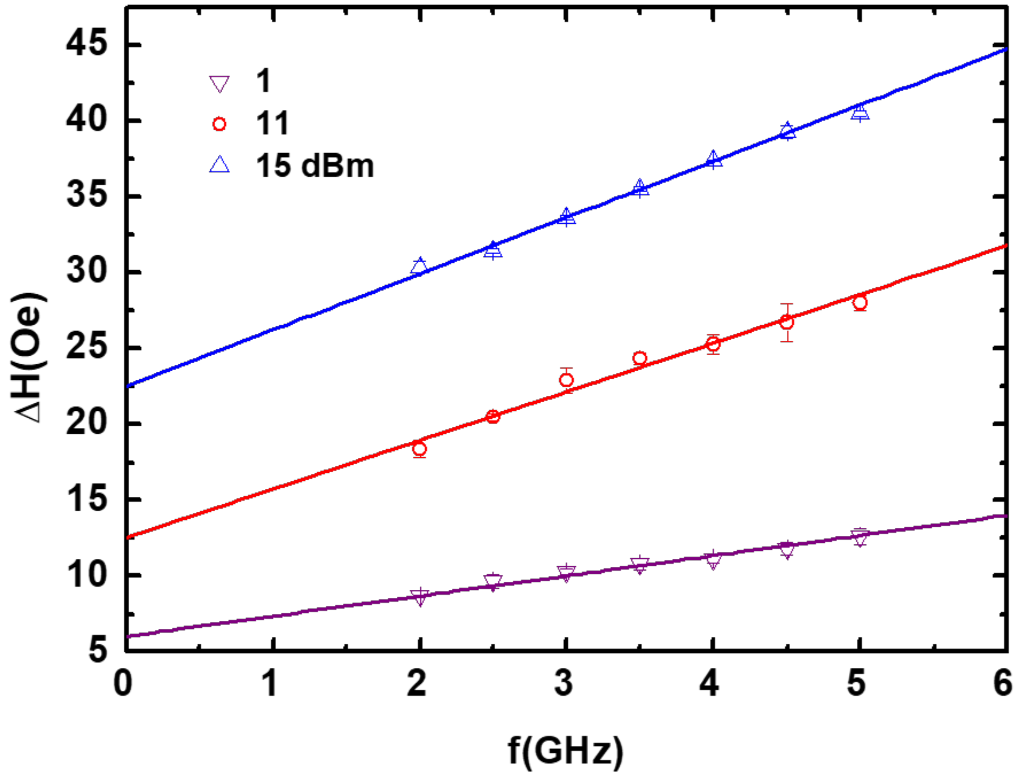
Fitting results yield α_0 = 0.01, 0.015, 0.04

2. Inconsistent fitting results of frequency-independent parameters.

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

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

η should be frequency independent based on SMR theory.



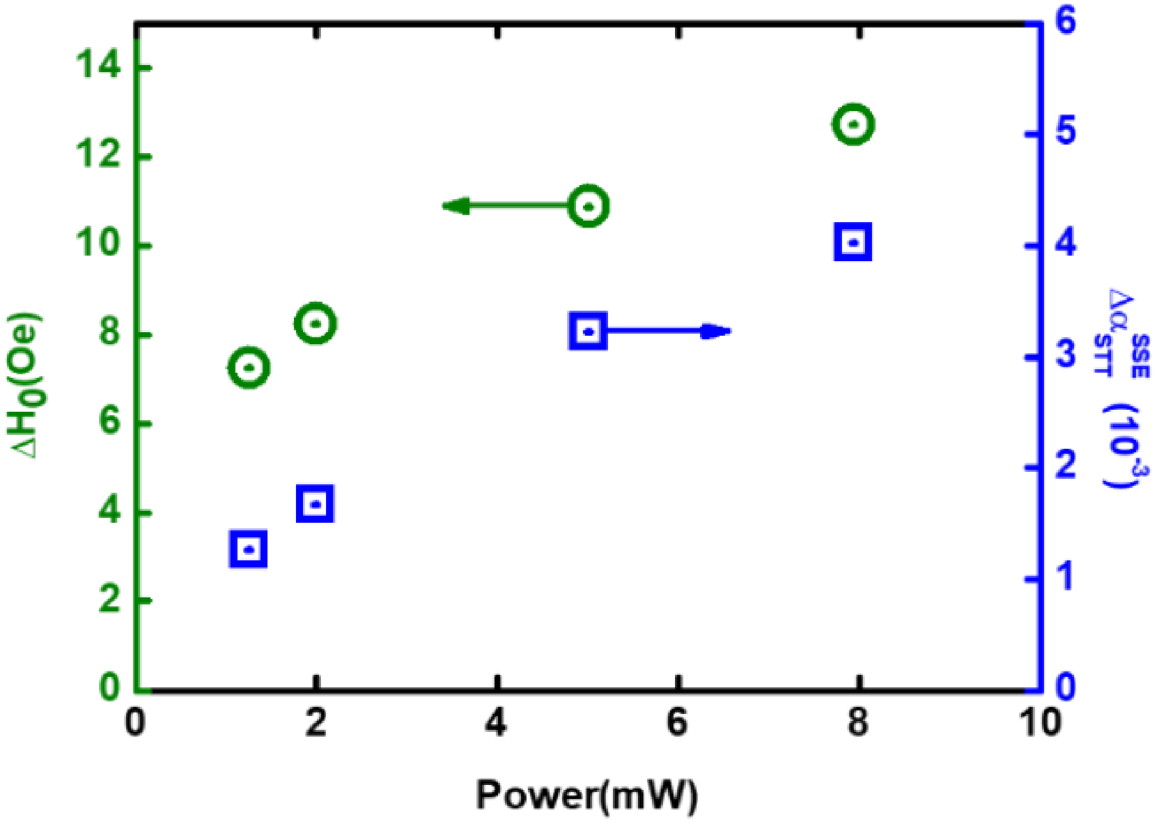
3. Fitting results of the slope will vary with applied power, suggesting another damping term induced by thermal effect.

Thermal effect in the Pt/YIG film during ST-FMR measurement

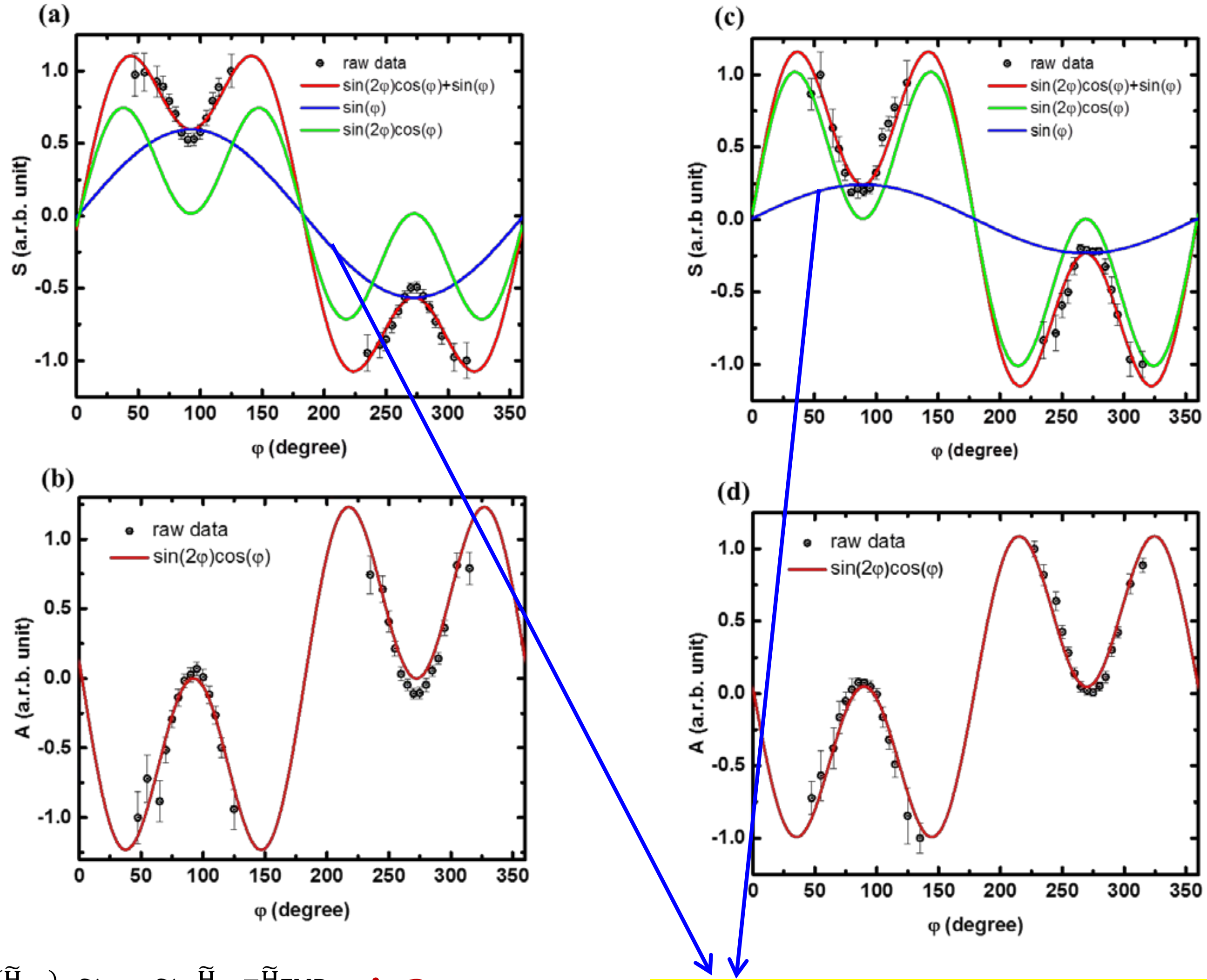
heat-induced spin torque

$$\Delta H = [(\alpha_0 + \beta \coth(r/2) \mathrm{Re}(\eta) + \Delta\alpha_{STT}^{SSE})/\gamma]\ \omega_a + \Delta H_0$$

Power dependent factors in
the linewidth analysis



In-plane angular dependency

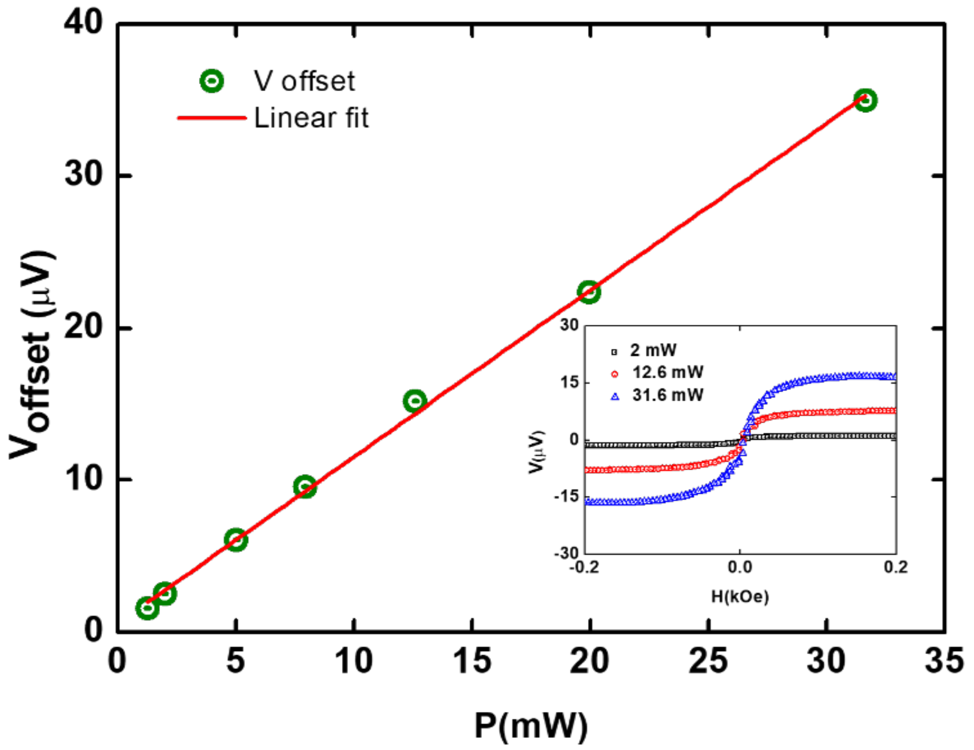


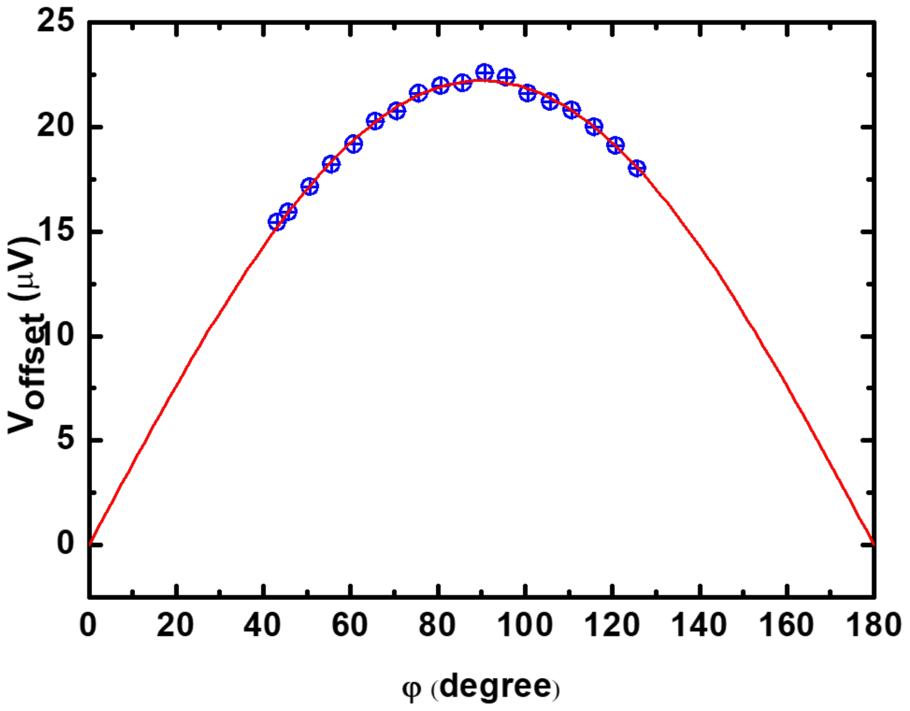
$$V_{SMR} = \frac{h\Delta\rho_1 J_c^0}{4}\frac{F_S(\tilde{H}_{ex})}{\Delta\tilde{H}}\left(\tilde{Y}_i^c + \tilde{Y}_r^c\frac{\tilde{H}_{ex}-\tilde{H}_{FMR}}{\Delta\tilde{H}}\right) \mathbf{\sin 2\varphi \cos\varphi}$$

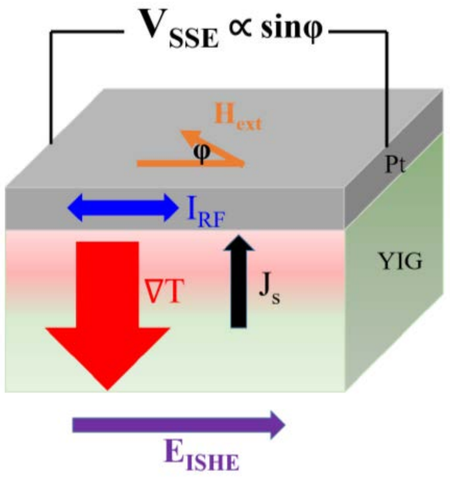
$$V_{SP} = \frac{h\rho J_r^P}{4}\frac{F_S(\tilde{H}_{ex})}{\Delta\tilde{H}^2}\left(\tilde{Z}_i^c\tilde{Y}_r^c - \tilde{Z}_r^c\tilde{Y}_i^c\right) \mathbf{\sin 2\varphi \cos\varphi}$$

An extra sin(φ) component of symmetric part was observed

Heating induced V_{offset} during M switching process







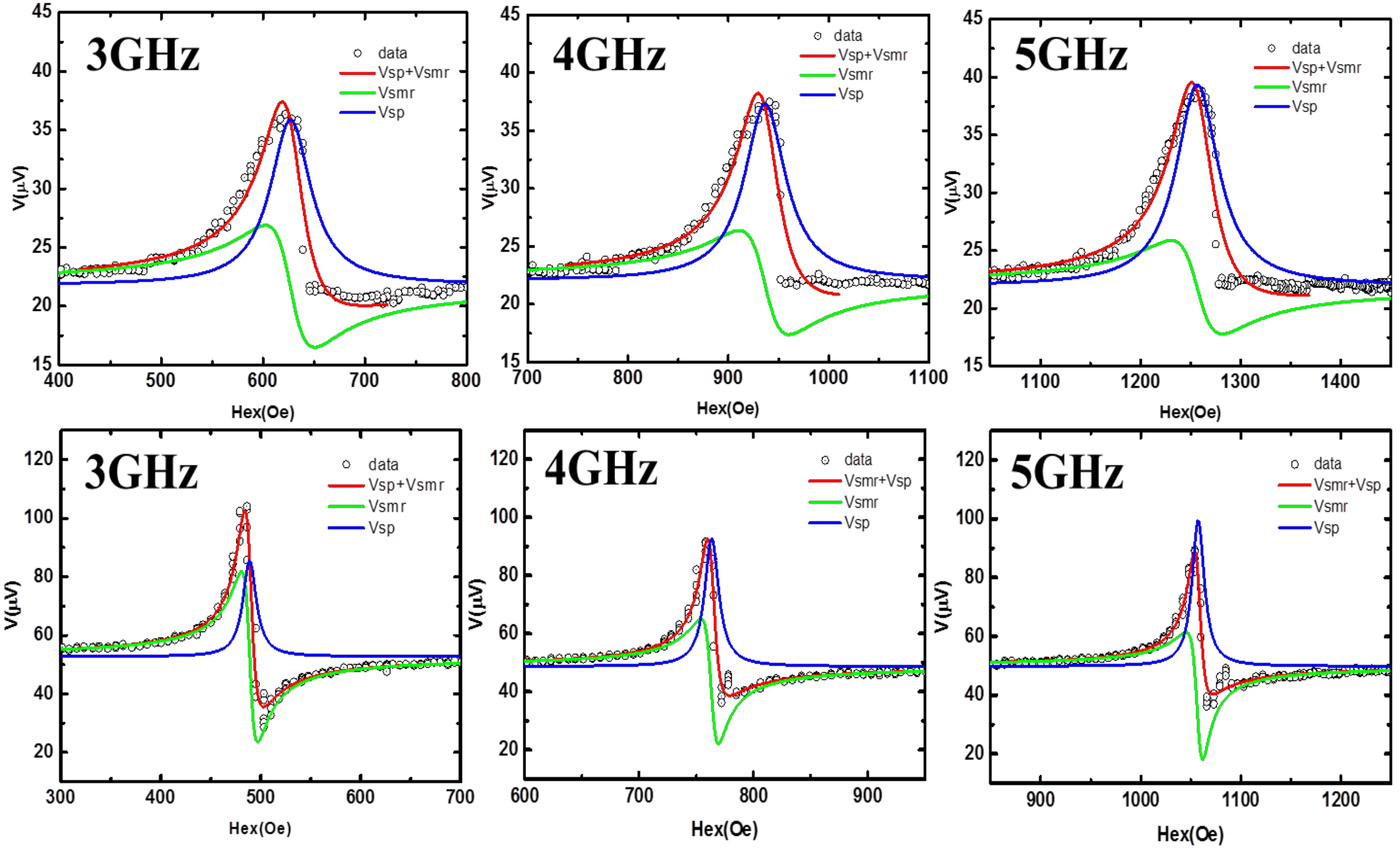
T. Kikkawa et al., Phys. Rev Lett **110**, 067207 (2013)

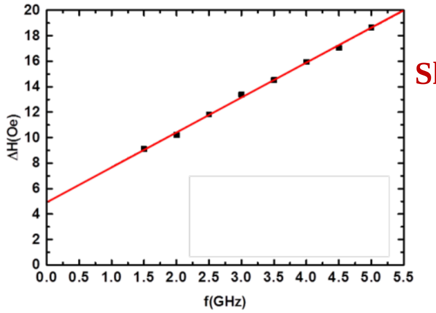
Longitudinal spin Seebeck effect (LSEE)

Curve fitting with theoretical model

Sample A

Sample B





Slope ➡

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

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

Assumption: G_r 1order larger than G_i

Gr:

Sample A: $1.5\times10^{14}\ \Omega^{-1}m^{-2}$

Sample B: $1.9\times10^{14}\ \Omega^{-1}m^{-2}$

Curve fitting with theoretical model

Sample A	**3GHz**	**4GHz**	**5GHz**
J_C (A/m^2)	$2.52(\pm0.11)\times10^{11}$	$2.24(\pm0.08)\times10^{11}$	$2.20(\pm0.06)\times10^{11}$
θ_{SH}	0.058 ± 0.004	0.064 ± 0.003	0.063 ± 0.003

Sample B	**3GHz**	**4GHz**	**5GHz**
J_C	$1.40\pm(0.03)\times10^{11}$	$1.30(\pm0.04)\times10^{11}$	$1.09(\pm0.04)\times10^{11}$
θ_{SH}	0.110 ± 0.003	0.104 ± 0.004	0.126 ± 0.006

Summary

- We examined 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 sinφ symmetric component.

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

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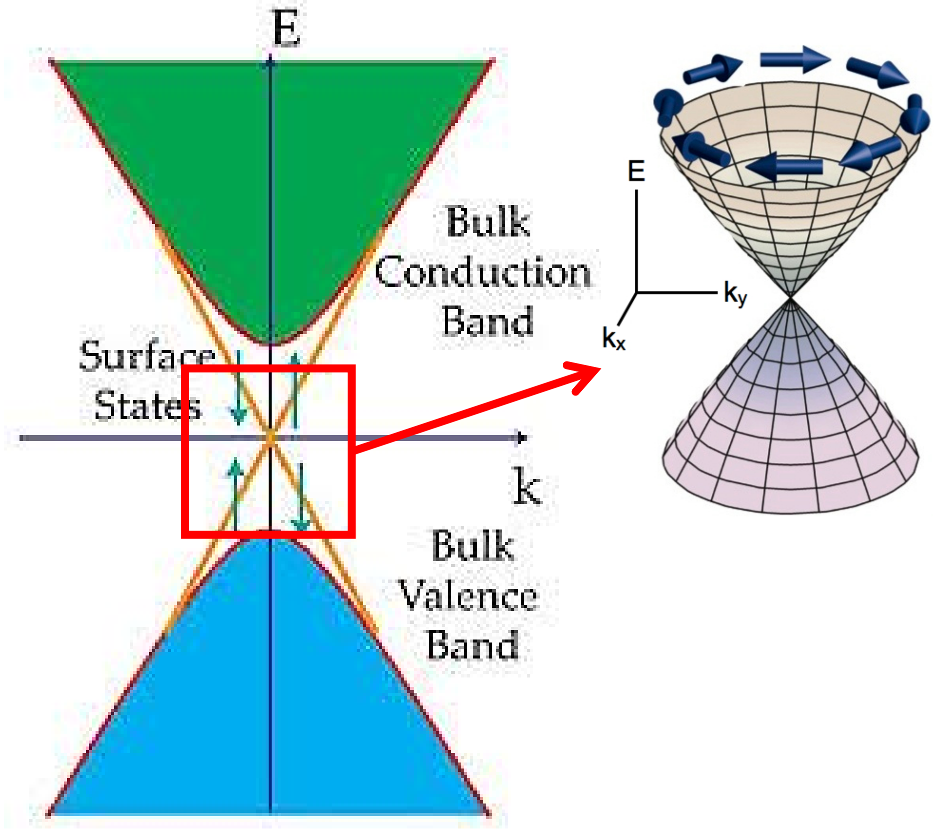
Outline

- **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**

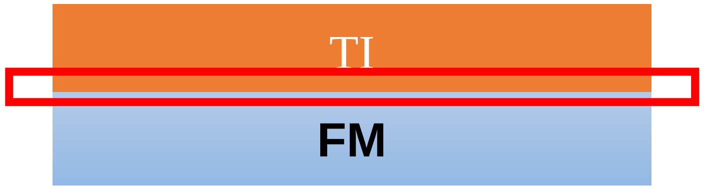
Application of spin momentum locked surface state



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

→ **High spin–charge conversion**

→ **magnetization switching (SOT-MRAM)**



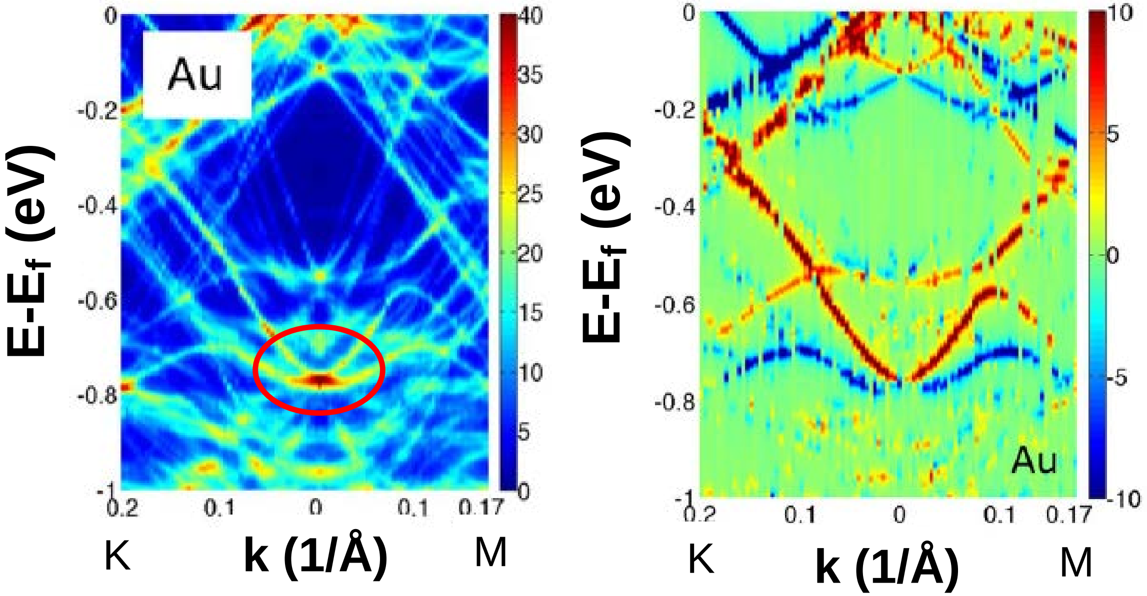
Does the strong interfacial exchange coupling modify the spin texture of the topological surface state, further influencing spin-to-charge conversion (SCC)?

Electronic property and chemistry of metals in contact with Bi_2Se_3

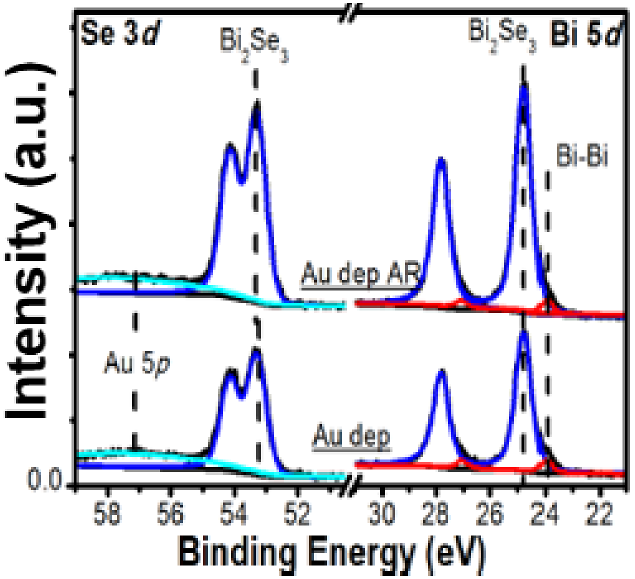
C. D. Spataru *et al.*, *Phys. Rev. B* **90**, 085115 (2014)

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

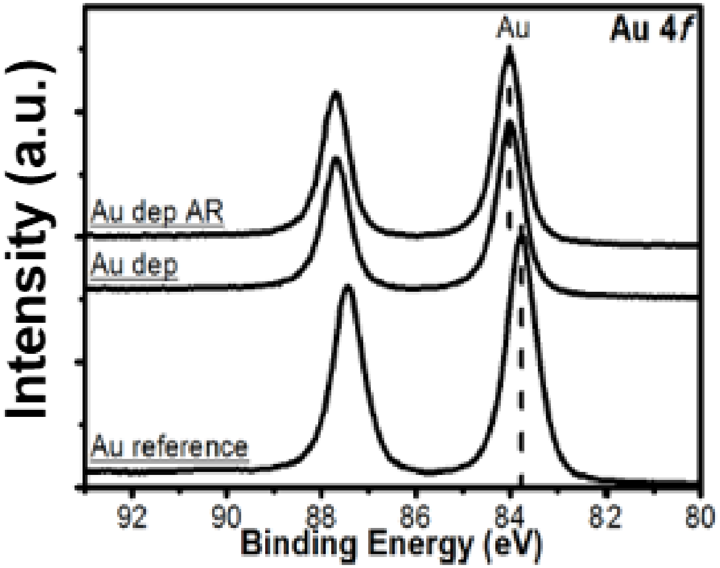
Calculated spectral function of Au/Bi_2Se_3

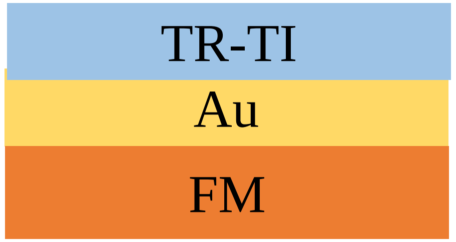


XPS result for Se 3*d* and Bi 5*d*



XPS result for Au 4*f*





- **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.

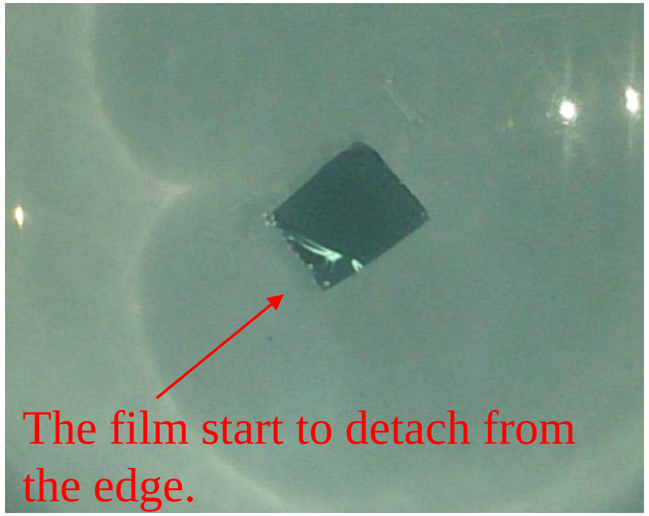
=>Thin film transferring

Transfer procedure

Peel-off

Floating the Bi_2Se_3/Al_2O_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 ^oC on a hot plate
(~ 5 min)

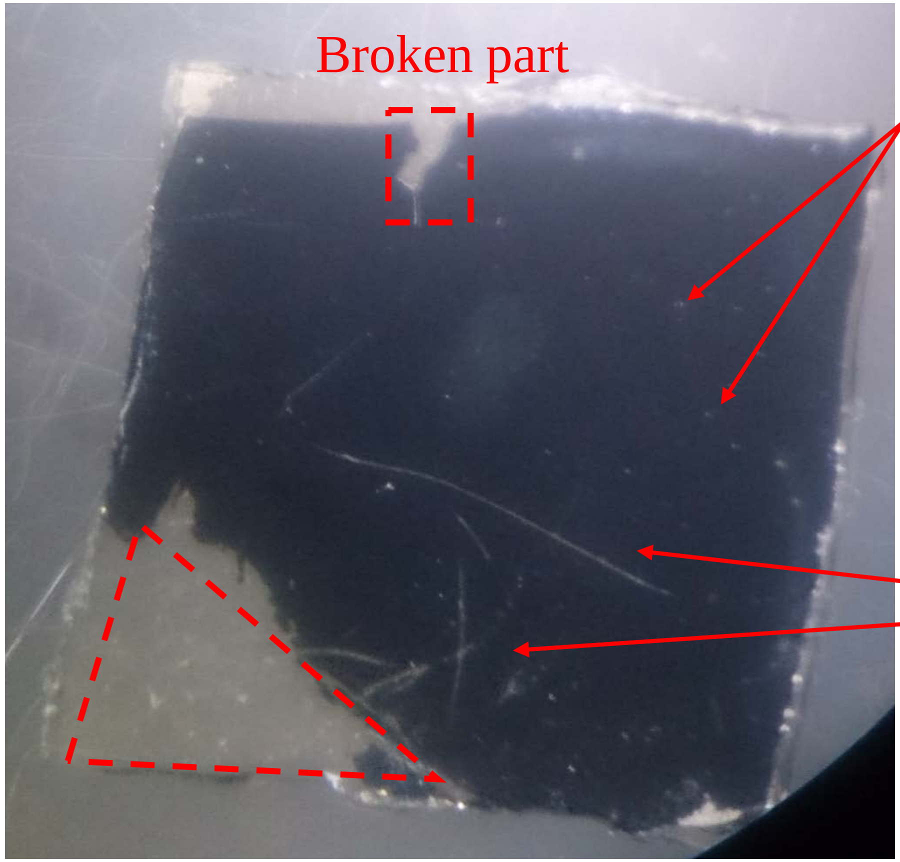
PMMA removal

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

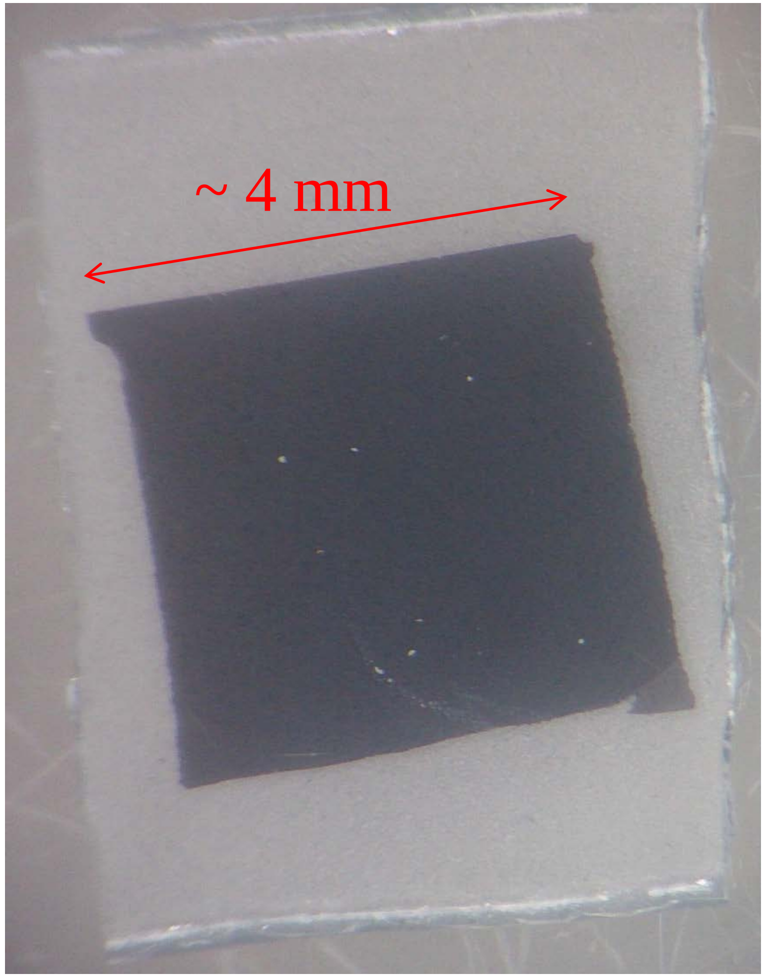
Improved transfer technique



Pinholes spreading throughout the film.

improvement

large cracks & wrinkles

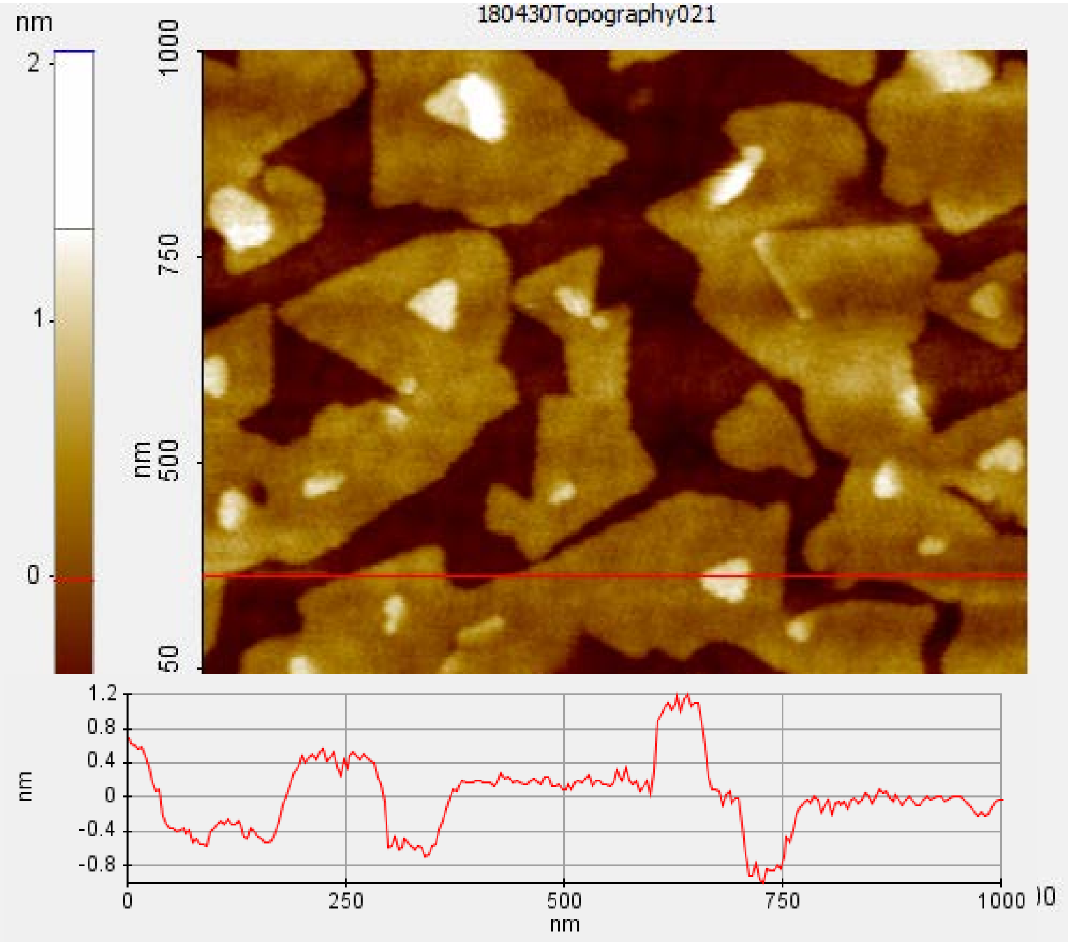


This part was not successfully peeled off, and remained on Al_2O_3.

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

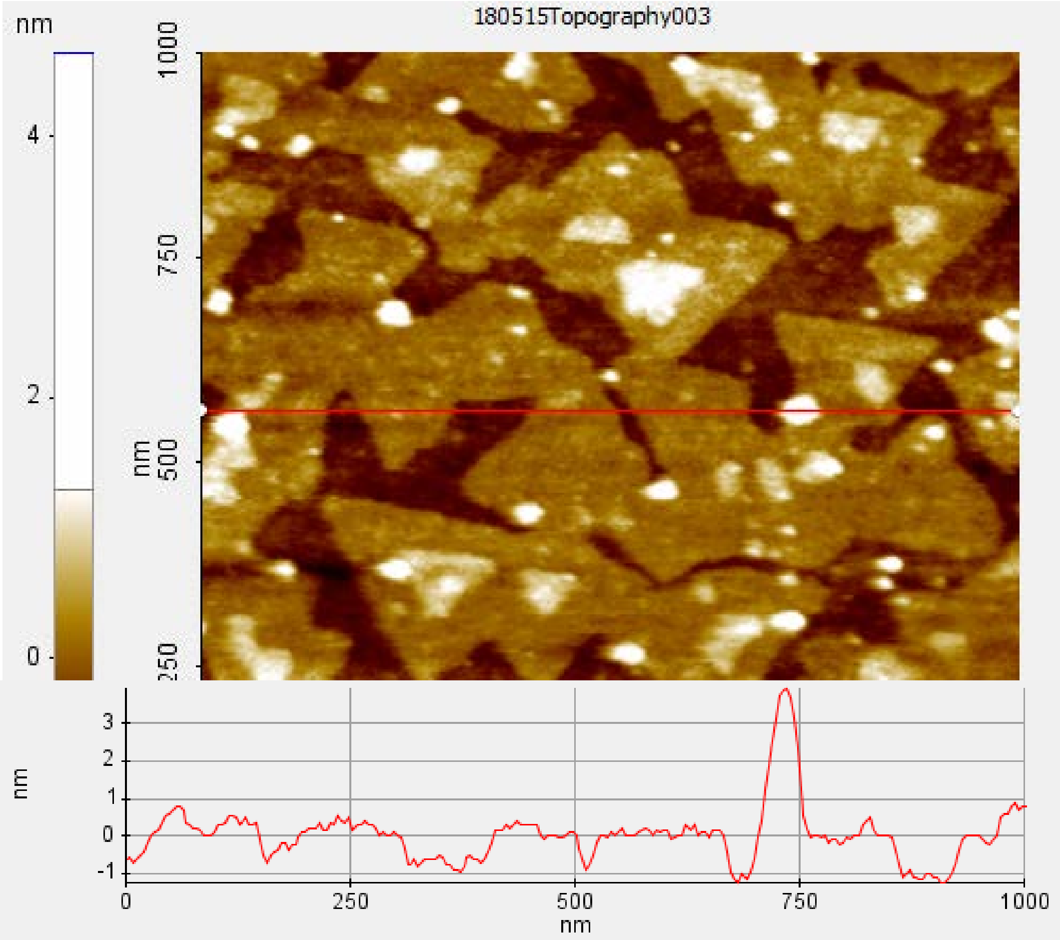
Surface morphology preserved (1 x 1 μm)

TI782: 9 nm Bi_2Se_3/sapphire



R_q = 0.46 nm

TR-Bi_2Se_3/sapphire

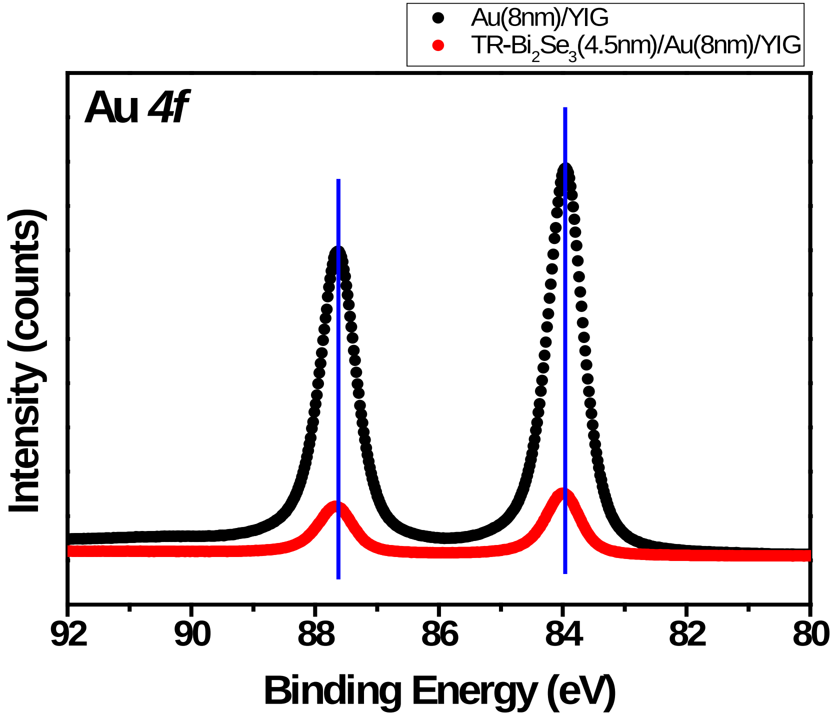


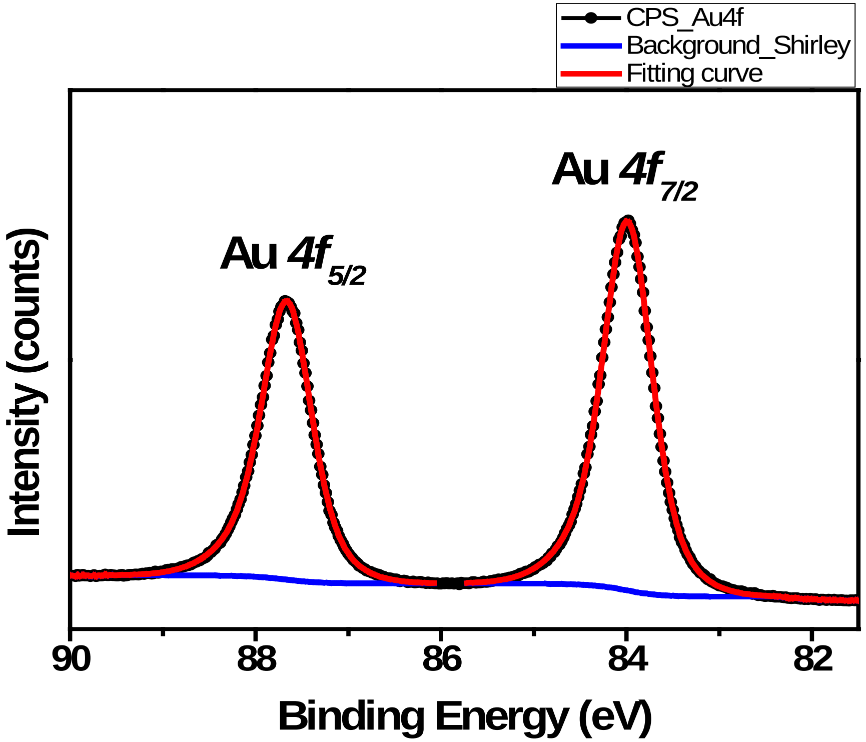
R_q = 0.55 nm

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

XPS characterization

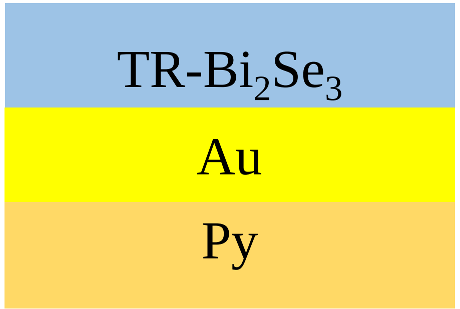
- There is **no substantial change in line shape** and **peak position** between Au 4f core-levels of Au/YIG and TR-Bi_2Se_3/Au/YIG.
- The **peak position of Au 4f is nearly consistent**, which indicates that there was **no severe interfacial interaction** between Bi_2Se_3 and Au after heated at 150^{o}C for 2min.

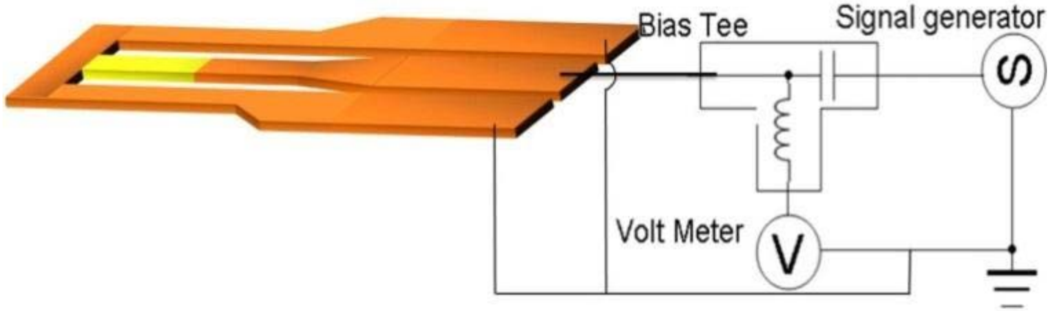


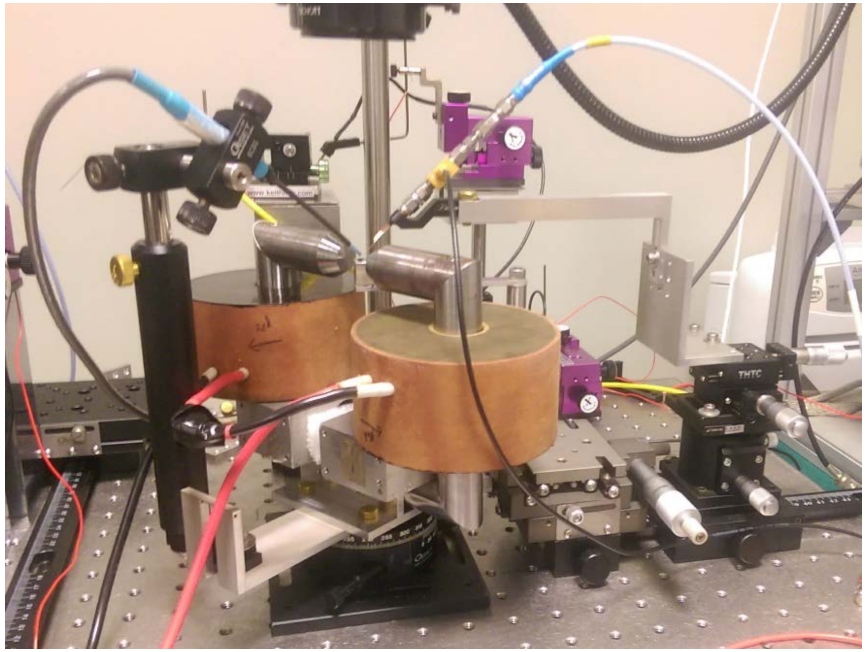


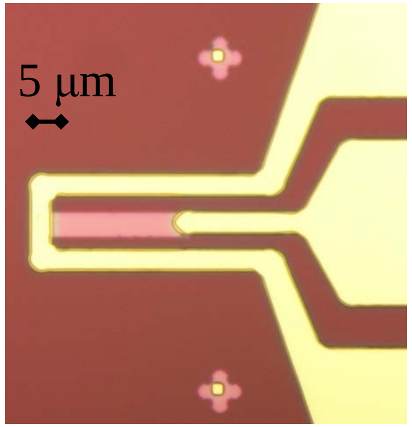
peak position	Au $4f_{7/2}$	Au $4f_{5/2}$
Au/YIG	83.943 eV	87.616 eV
TR-Bi_2Se_3/Au/YIG	83.960 eV	87.632 eV

Device fabrication for ST-FMR experiment



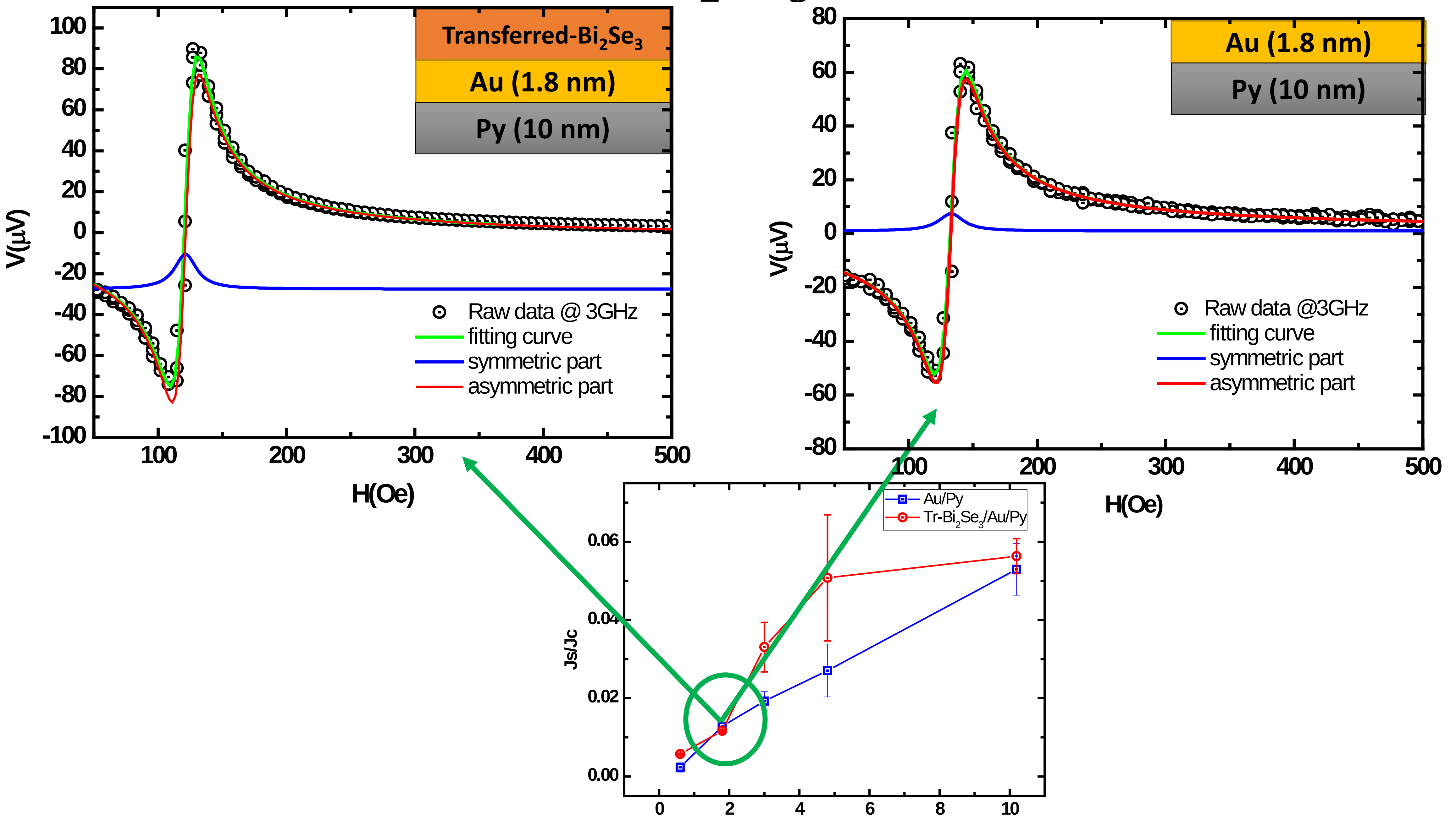




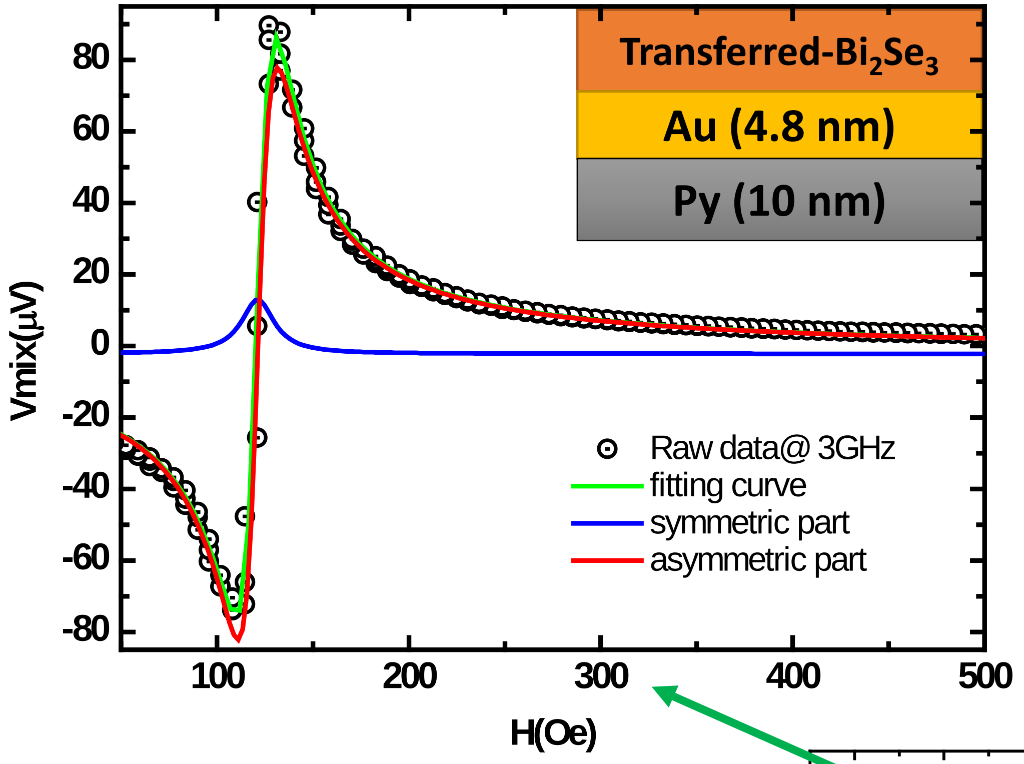


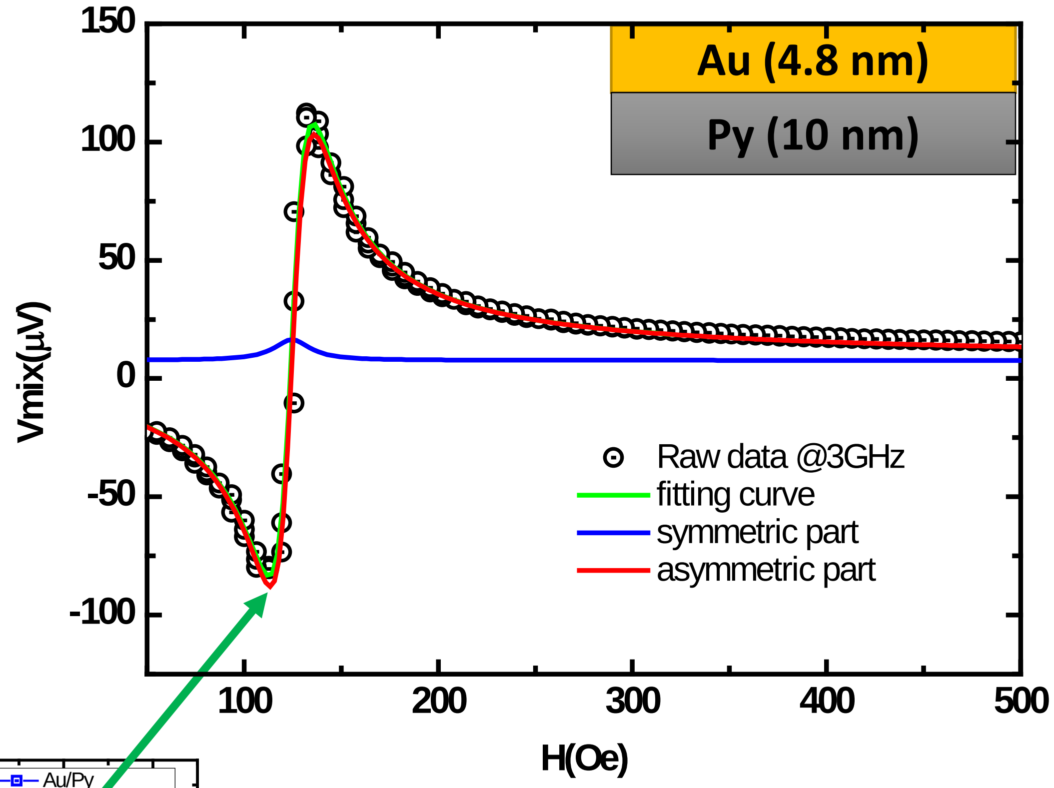
ST-FMR device

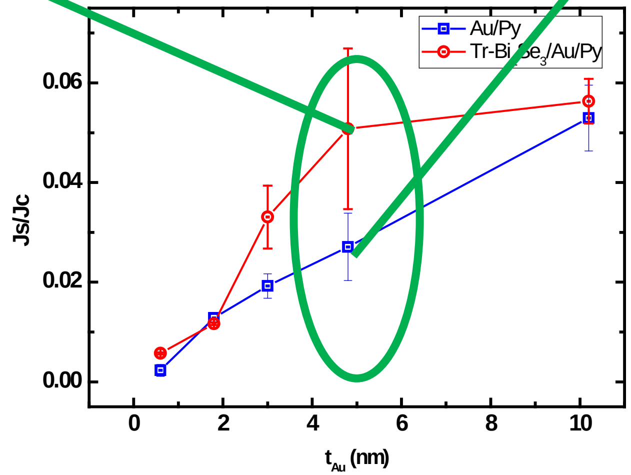
ST-FMR on TR-Bi_2Se_3/Au/Py before annealing



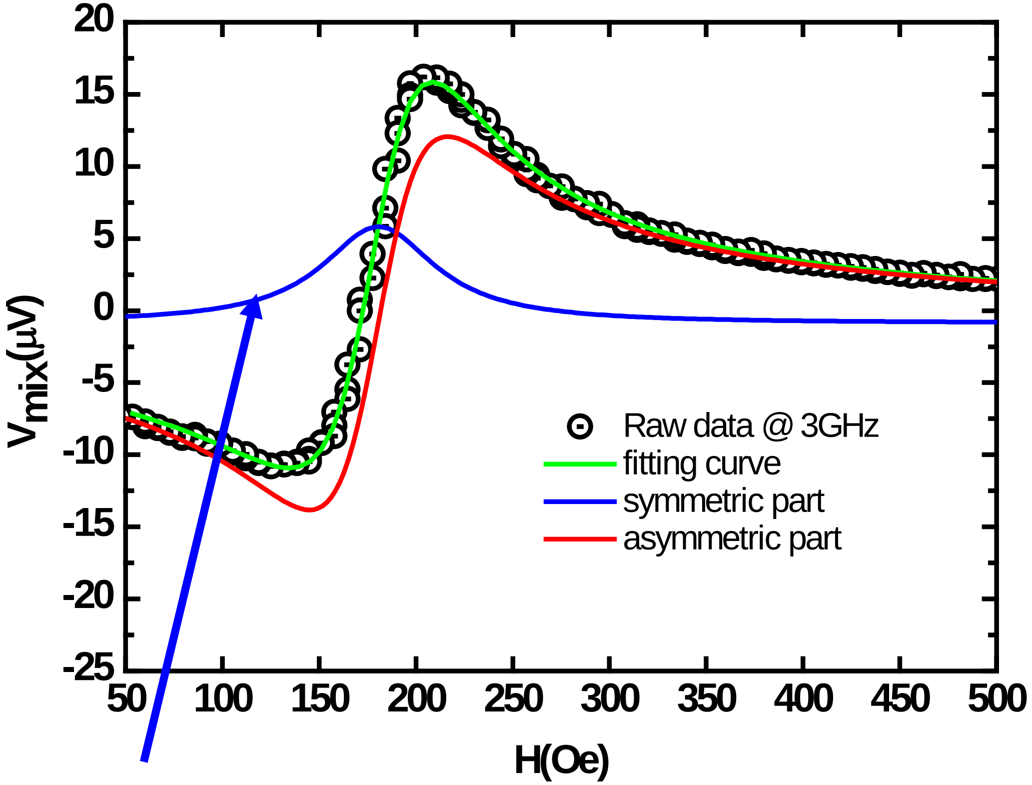
ST-FMR on TR-Bi_2Se_3/Au/Py before annealing

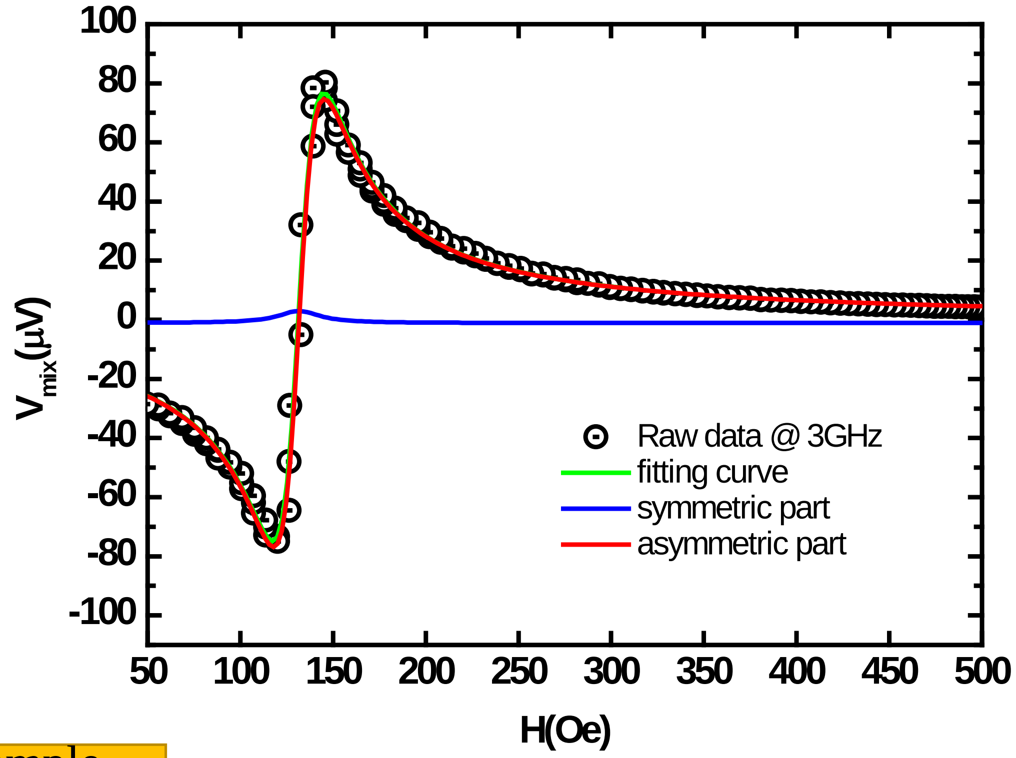




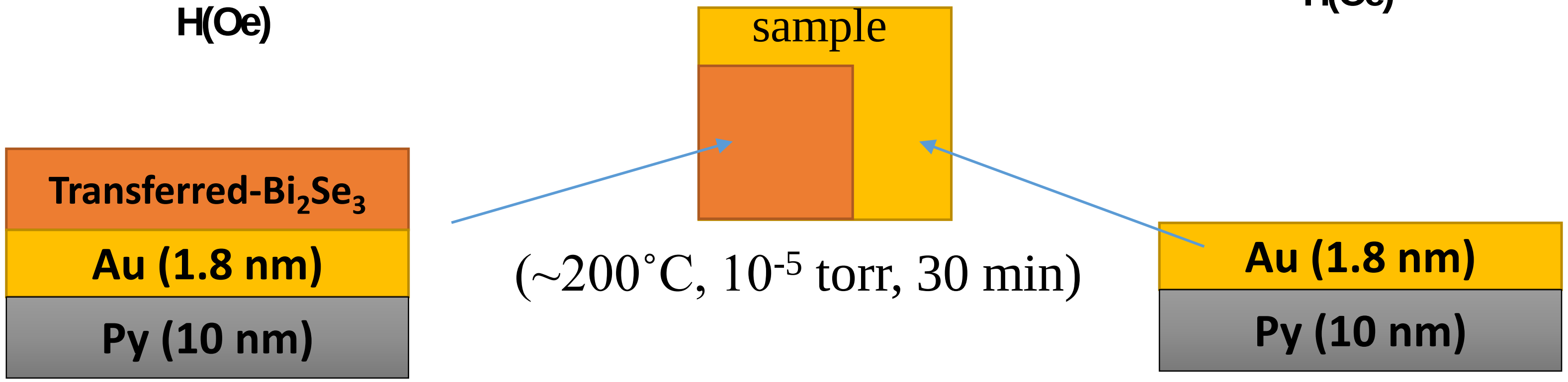


After annealing

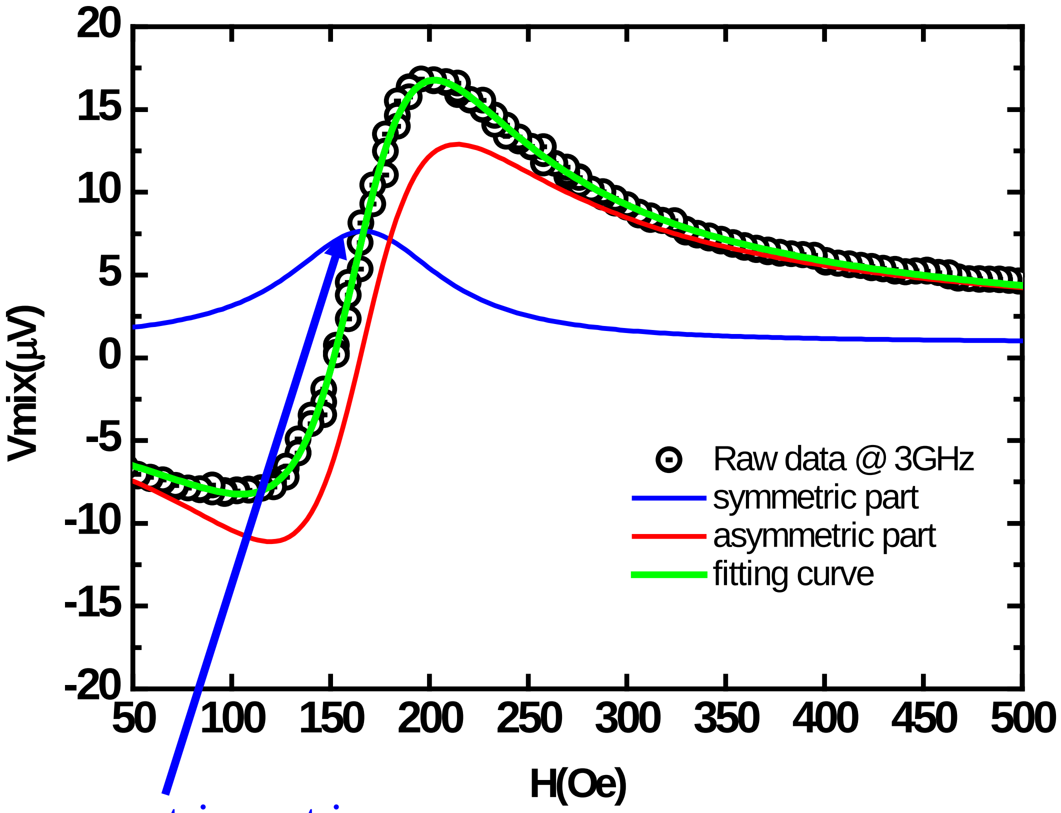




The symmetric part is drastically enhanced.



After annealing



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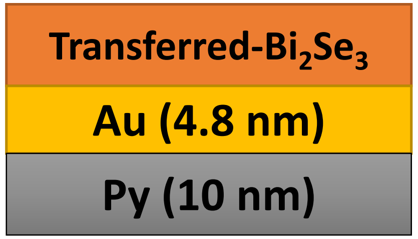
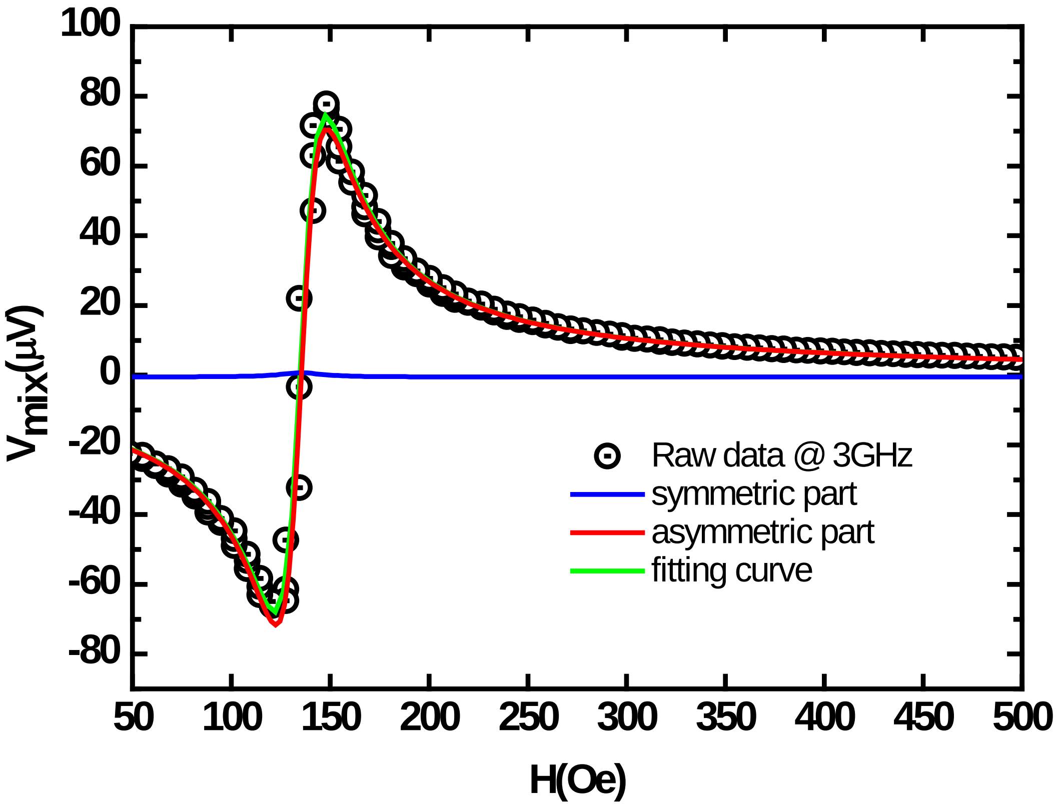
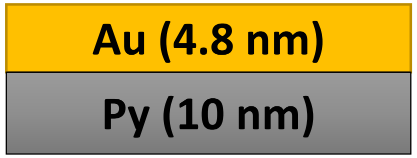
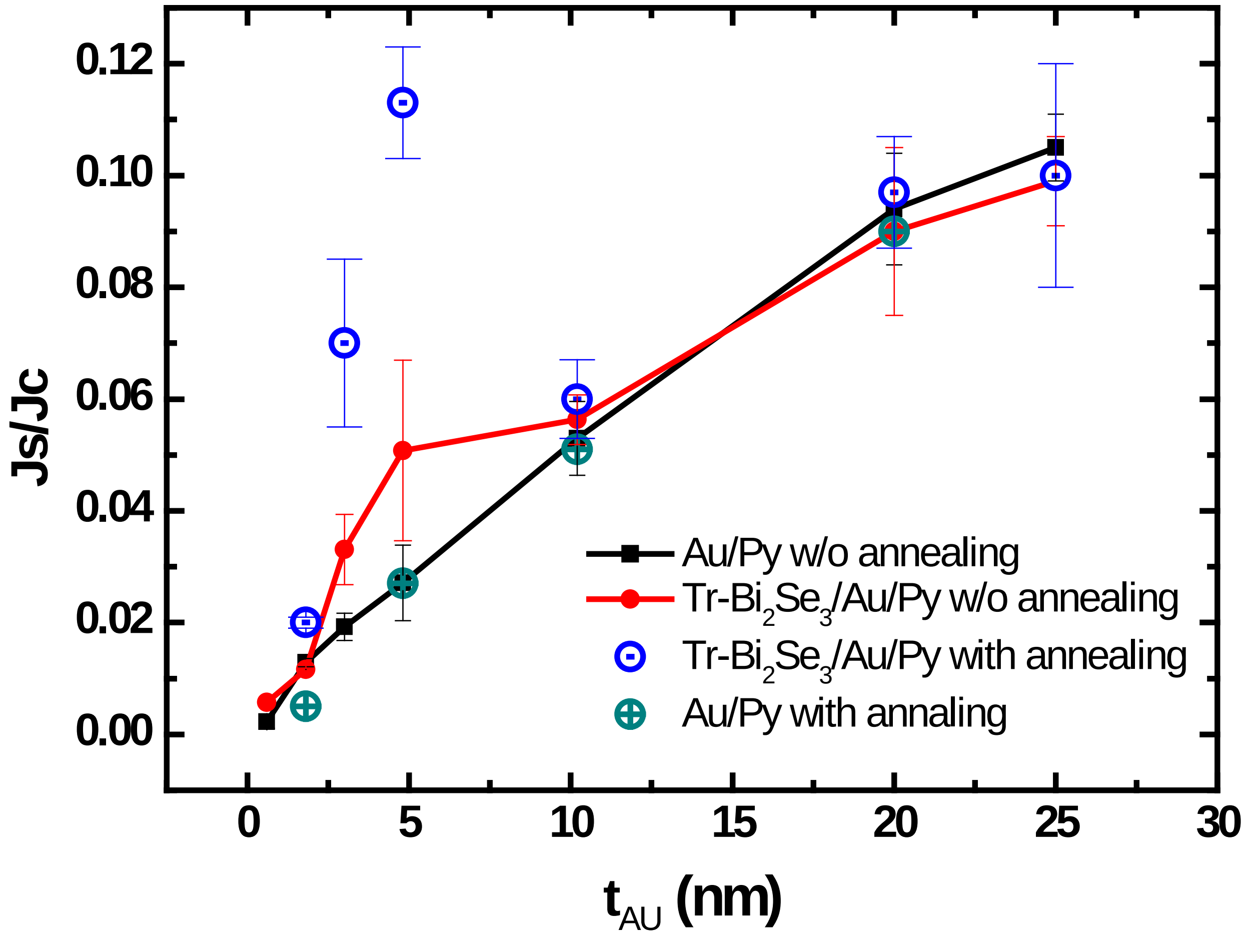
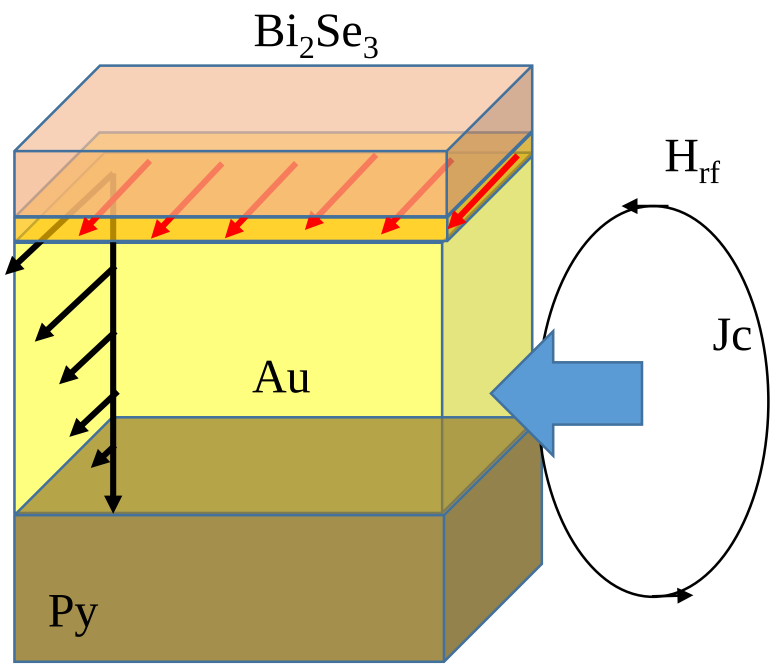






Au thickness dependent Js/Jc





Js/Jc shows larger enhancement after annealing at Au thickness 3-5 nm.

Summary

- After annealing at high vacuum, large enhancement of Js/Jc 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-Bi_2Se_3 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