Light- and microwave-induced spin current and spin-to-charge conversion in magnetic quantum material heterostructures

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UNIVERSITY OF DELAWARE

CENTER FOR HYBRID, ACTIVE, AND RESPONSIVE MATERIALS
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October 11, 2023

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Acknowledgment

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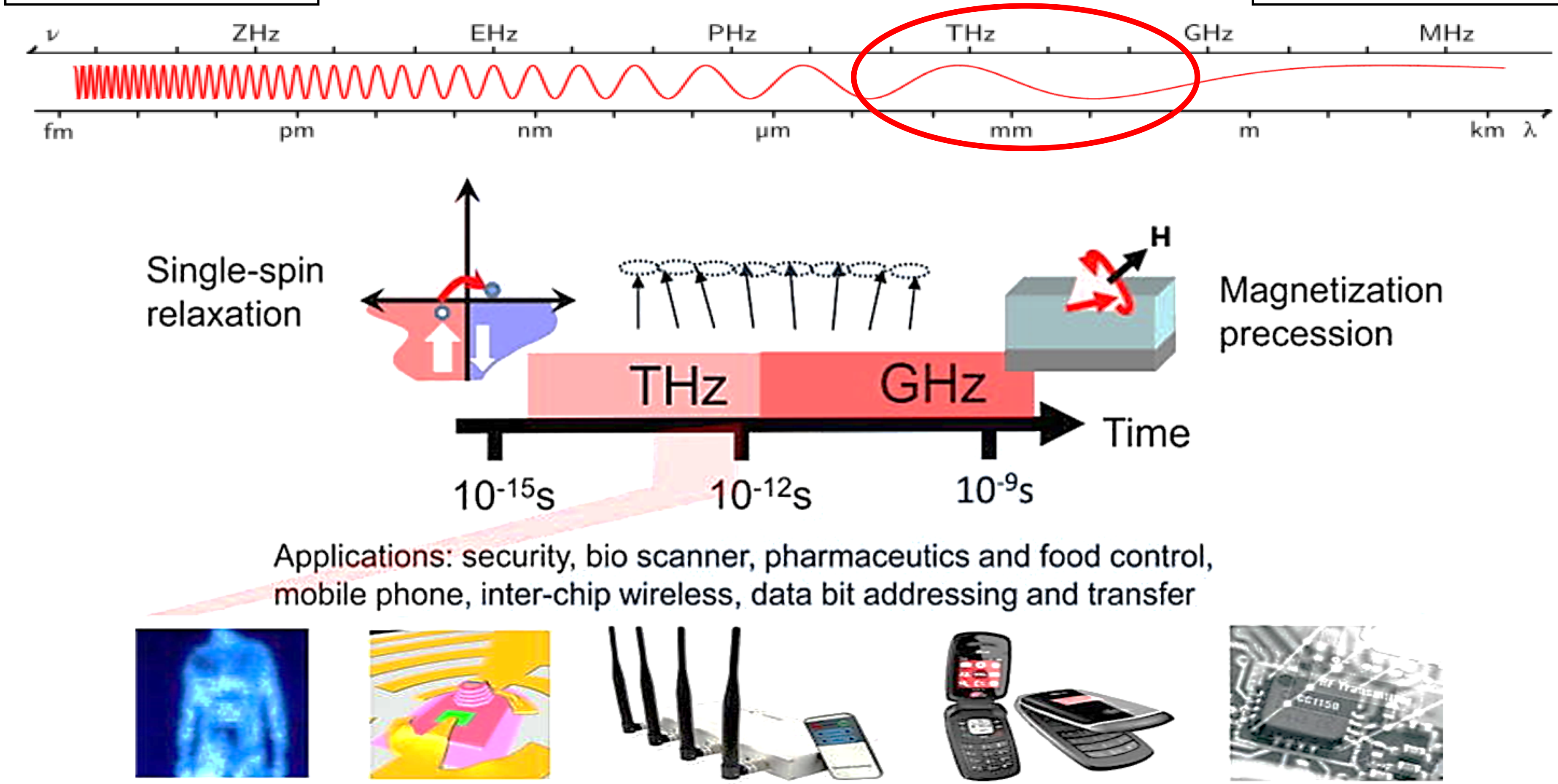
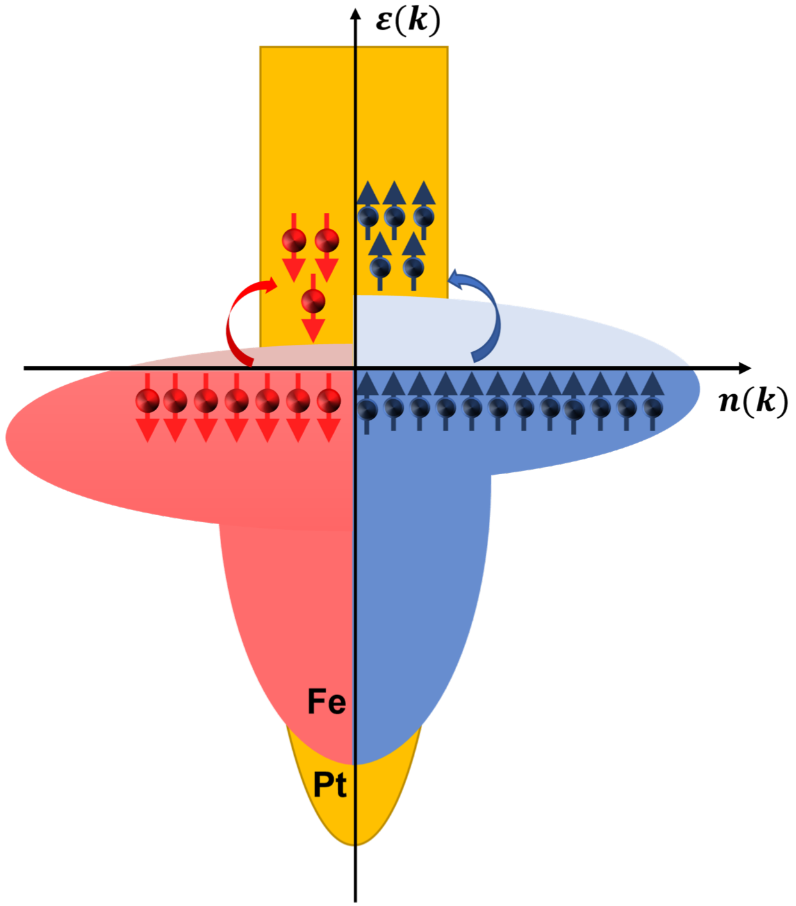
Terahertz technologies

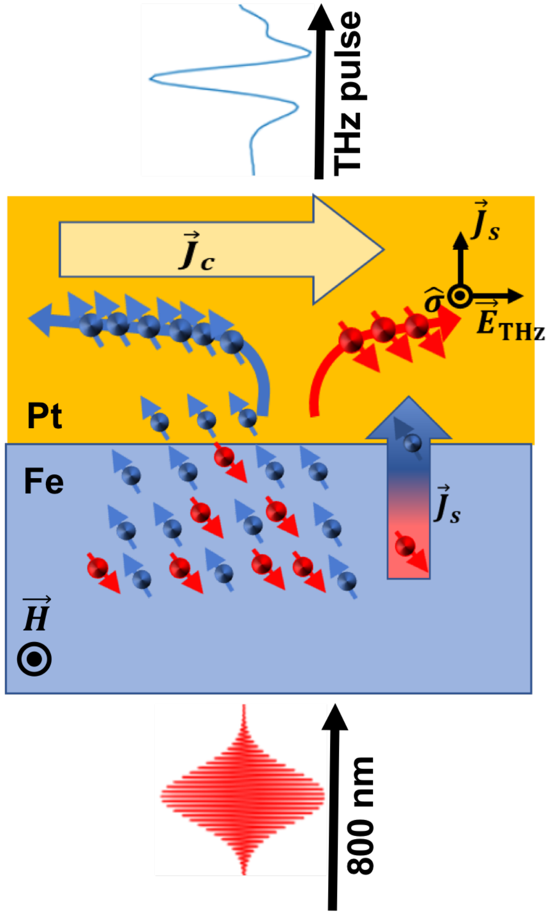
PHOTONICS **ELECTRONICS**



Miao et al., Rep. Prog. Phys. **74**, 036501 (2011)

Spintronic terahertz emitter





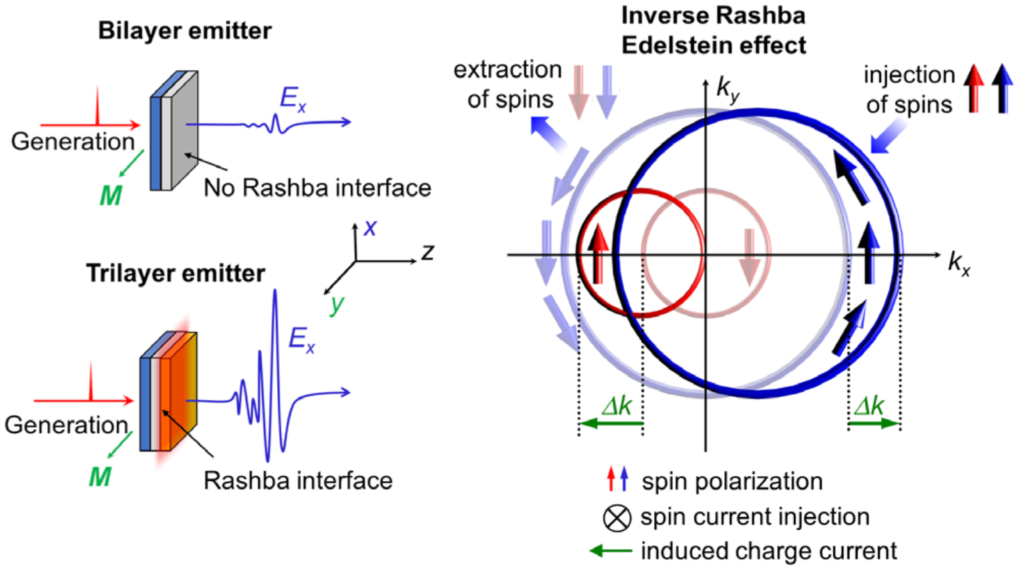
Femtosecond laser pulse excitation
↓
Ultrafast spin-current
↓
Inverse spin Hall effect
↓
THz transients

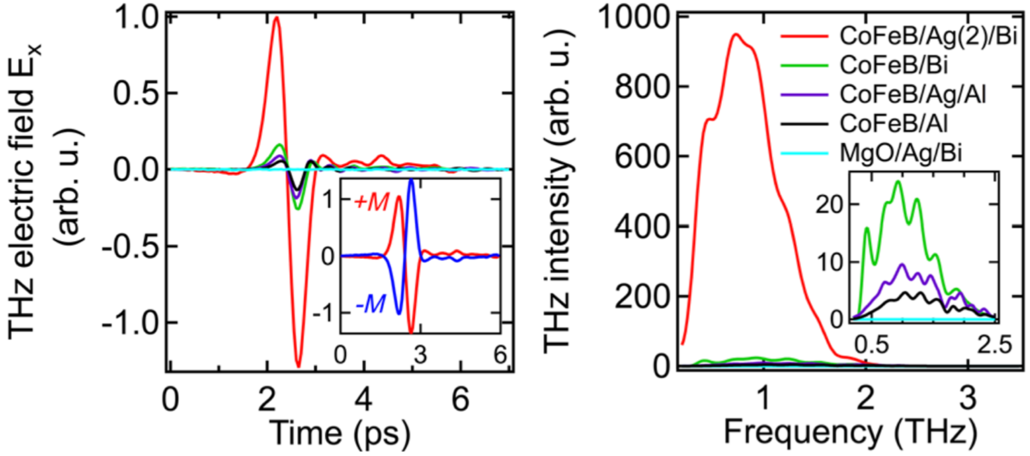
- **High signal strength**
- **Broadband**
- **Inexpensive and easy to fabricate**

Inverse spin Hall effect: $\vec{J}_c \propto \theta_{SH}\vec{J}_s \times \vec{\sigma}$

Wu, …, MBJ et al., J. Appl. Phys. **130**, 091101 (2021)

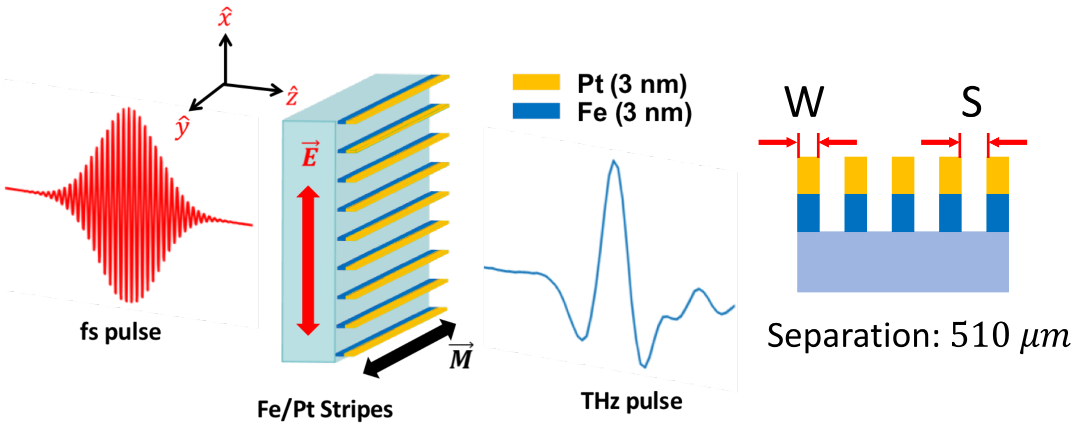
Control of THz emission by spin-charge current conversion at Rashba interfaces

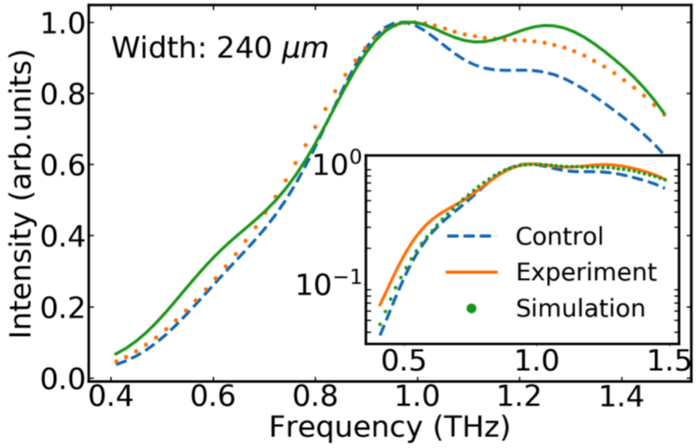




MBJ et al., Phys. Rev. Lett. **120**, 207207 (2018)

Modification of THz emission using microfabricated spintronic emitters





Wu, …, MBJ et al., J. Appl. Phys. **128**, 103902 (2020)

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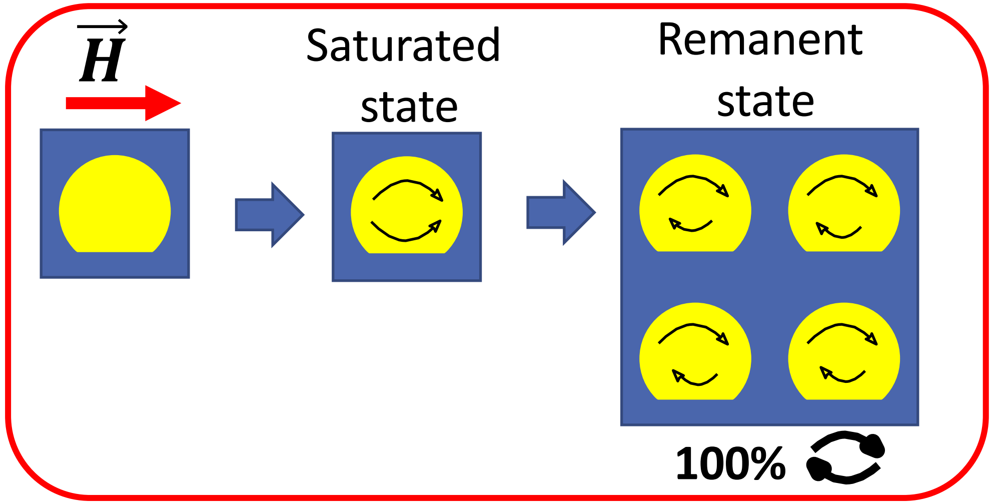
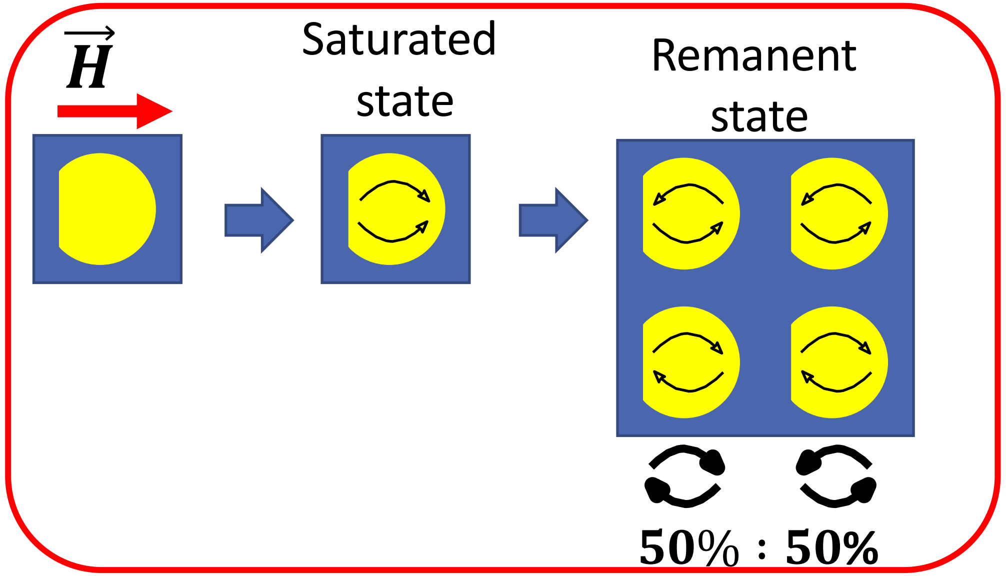
In collaboration with Haidan Wen and Rich Schaller, Argonne National Laboratory.

Controlling polarization by remanent magnetization - concept



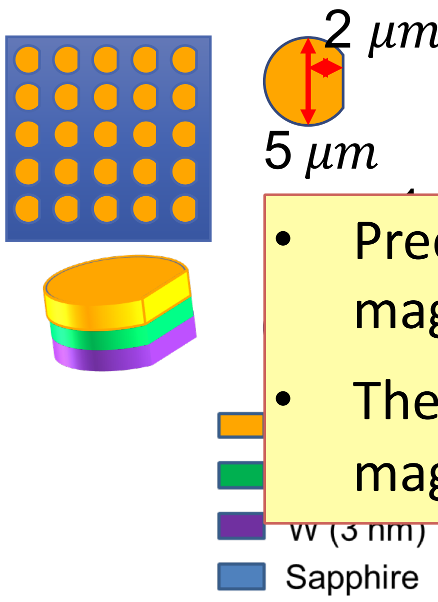
Same chirality

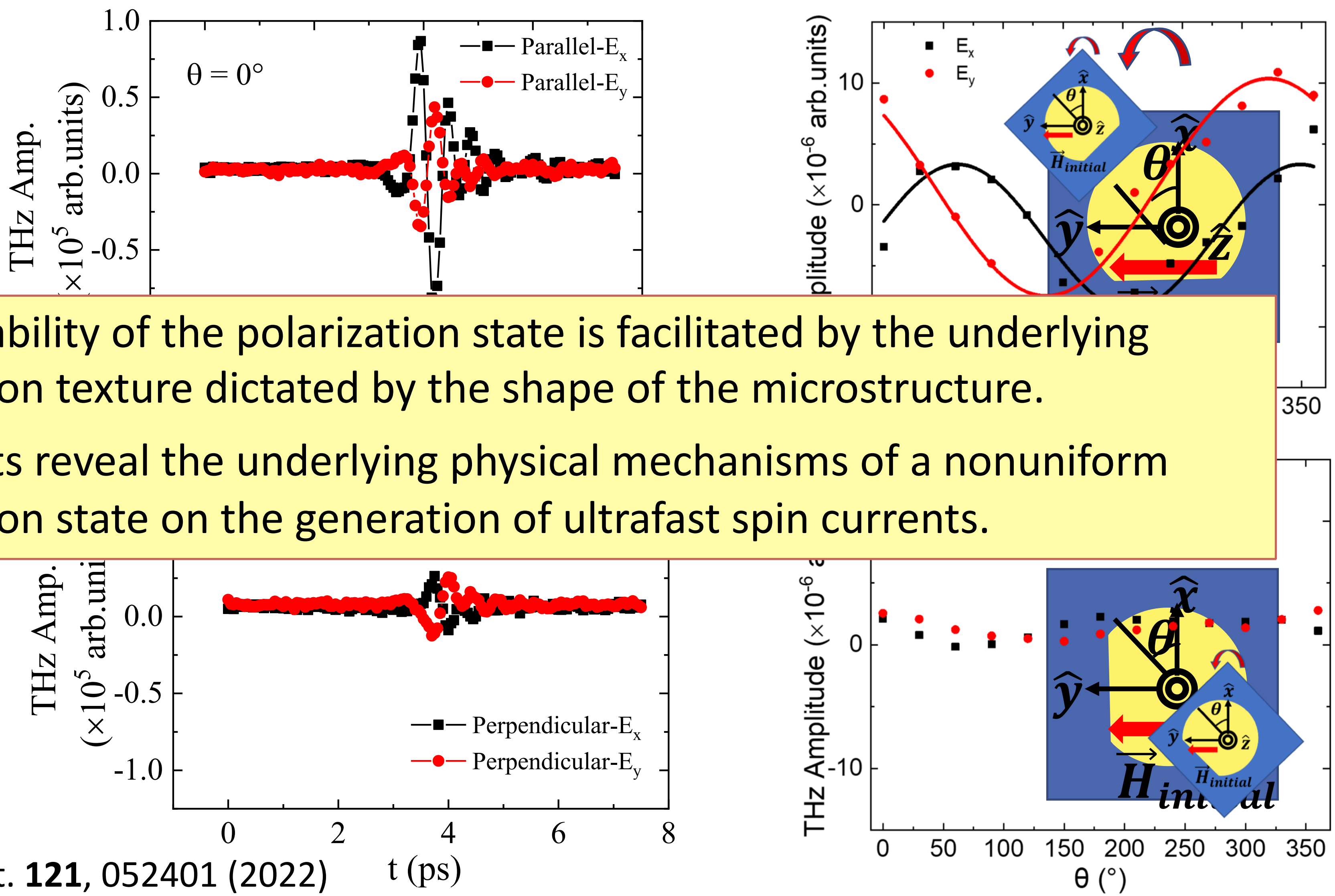


Random chirality

Wu, …, MBJ et al., Appl. Phys. Lett. **121**, 052401 (2022)

Controlling polarization by remanent magnetization - realization





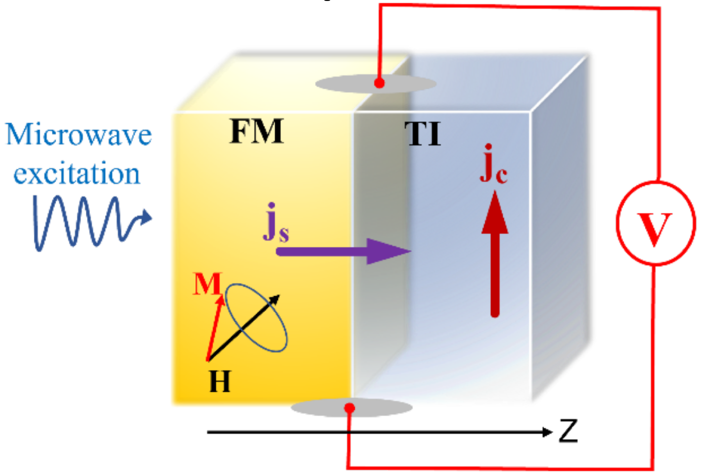
- Precise tunability of the polarization state is facilitated by the underlying magnetization texture dictated by the shape of the microstructure.
- These results reveal the underlying physical mechanisms of a nonuniform magnetization state on the generation of ultrafast spin currents.

Wu, …, MBJ et al., Appl. Phys. Lett. **121**, 052401 (2022)

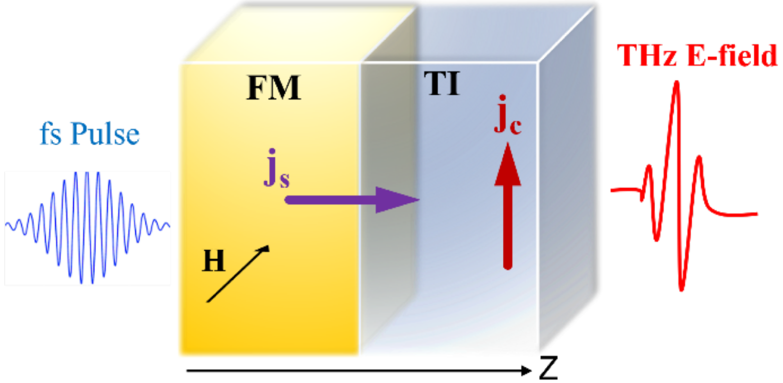
In collaboration with Haidan Wen and Rich Schaller, Argonne National Laboratory.

Outline: Spin current injection across FM/ TI interfaces

GHz inverse spin Hall effect experiment



THz emission inverse spin Hall effect experiment



Ferromagnet/ 3D topological insulator heterostructures grown by DC magnetron sputtering:

- Sapphire(substrate)//$Fe_{78}Ga_{13}B_9$(**FeGaB**)/$Bi_{85}Sb_{15}$(**BiSb**)/MgO(capping)
  - Amorphous FeGaB
  - BiSb with (001) texture

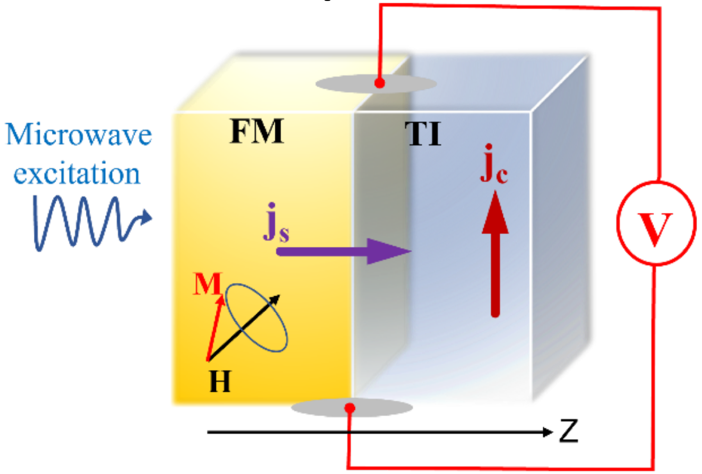
→ Phys. Rev. Materials **5**, 124410 (2021)

- $MgAl_2O_4$(substrate)// $Fe_{75}Co_{25}$(**FeCo**) / Bi_2Te_3(**BiTe**)/Al(capping)
  - Epitaxial FeCo with body-centered cubic (bcc) structure
  - Polycrystalline BiTe

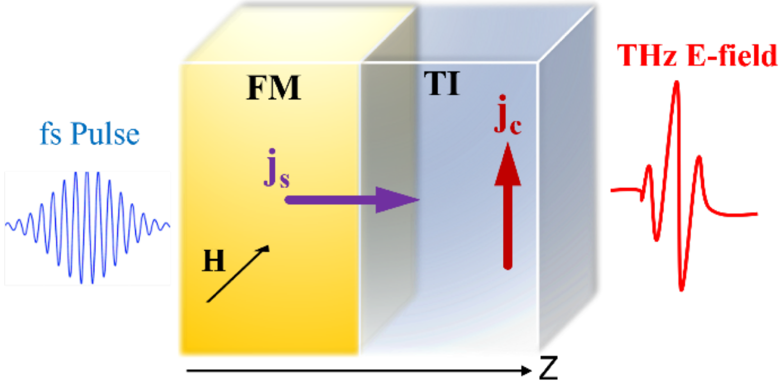
→ Appl. Phys. Lett. **122**, 072403 (2023)

Outline: Spin current injection across FM/ TI interfaces

GHz inverse spin Hall effect experiment



THz emission inverse spin Hall effect experiment



Ferromagnet/ 3D topological insulator heterostructures grown by DC magnetron sputtering:

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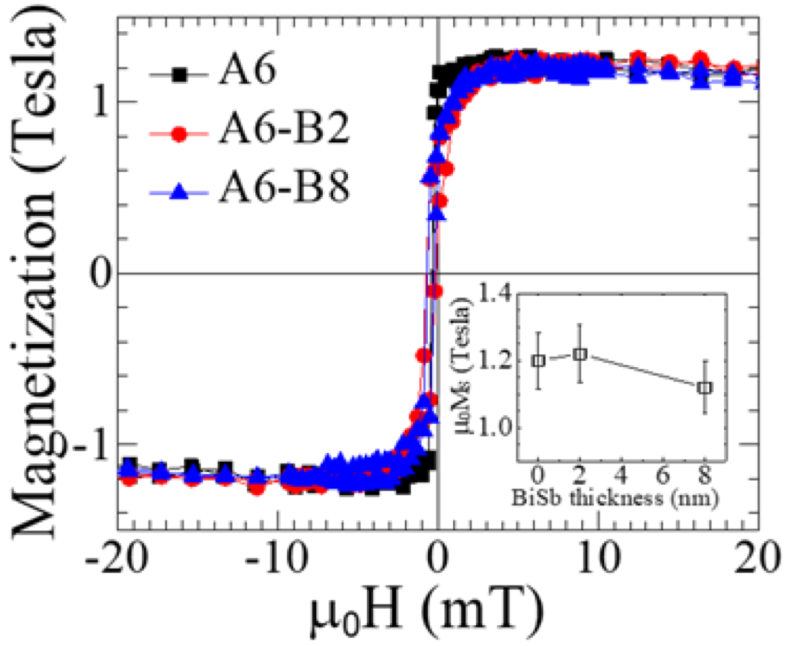
  - Polycrystalline BiTe

Bilayer thin film growth and characterization

DC magnetron sputtering: $\mathbf{Fe_{78}Ga_{13}B_9}$ and $\mathbf{Bi_{85}Sb_{15}}$
Thickness FeGaB: 6 nm, BiSb: 0, 1, 2, 4, 6, 8, 10, 15, 20 nm
We refer FeGaB(6)/BiSb(2) as A6-B2.



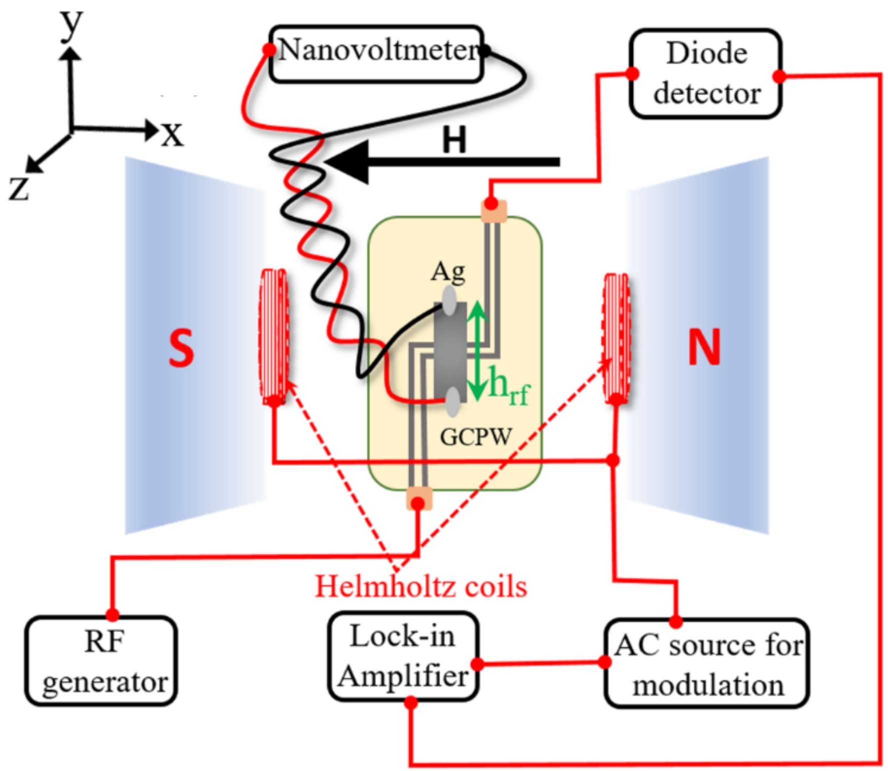
- Similar saturation magnetization M_s of 1.2 ± 0.14 T for bilayer with different thickness of BiSb
- Small coercivity field of $\mu_0 H \leq 2mT$ indicating a soft magnetic character of the FeGaB films with in-plane magnetization

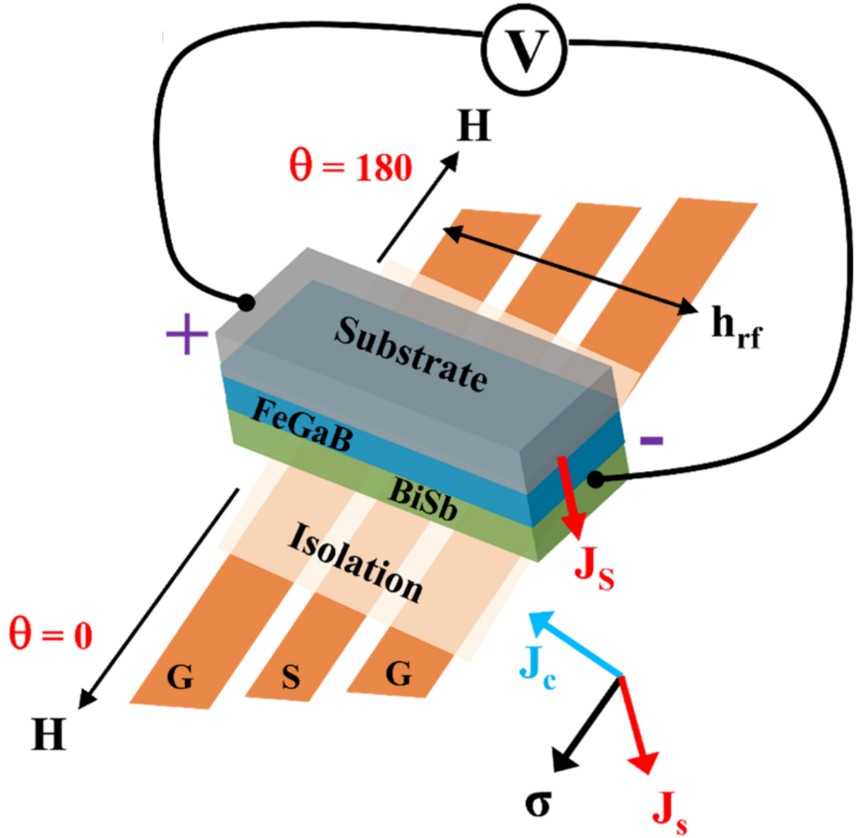
The deposition of BiSb on top of FeGaB does not affect the magnetization significantly

Sharma, Wu, …, MBJ et al., Phys. Rev. Materials **5**, 124410 (2021)

Experimental setup for combined FMR/ISHE

Ferromagnetic resonance (FMR): Gilbert damping α → spin-mixing conductance $g^{\downarrow\uparrow}$
Inverse spin-Hall effect (ISHE): spin-to-charge current conversion → spin-Hall angle θ_{SH} and spin-diffusion length λ_{SD} of BiSb

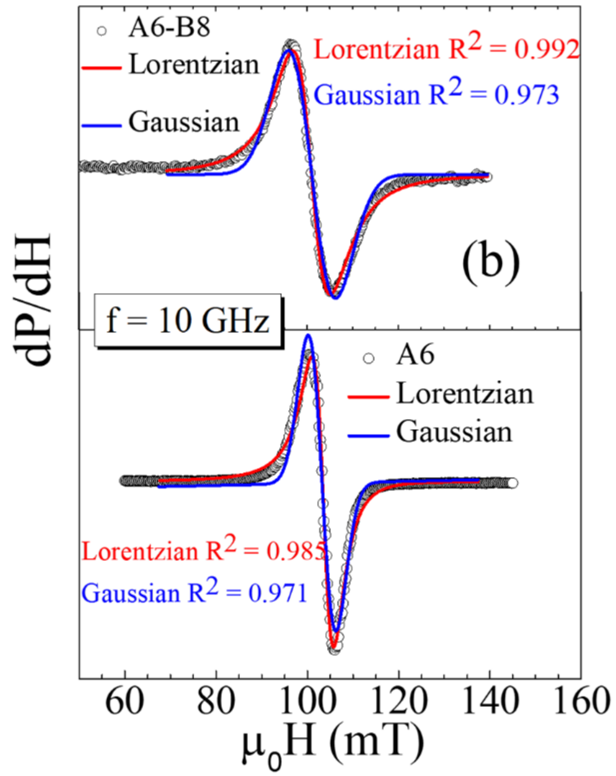




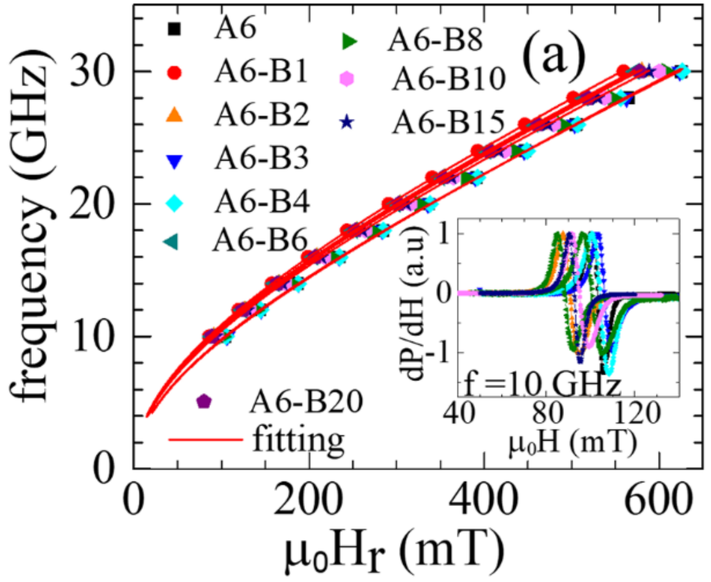
Sharma, Wu, …, MBJ et al., Phys. Rev. Materials **5**, 124410 (2021)

Ferromagnetic resonance (FMR)

Differential absorption



High degree of magnetic homogeneity of FeGaB film



H_r, ΔH

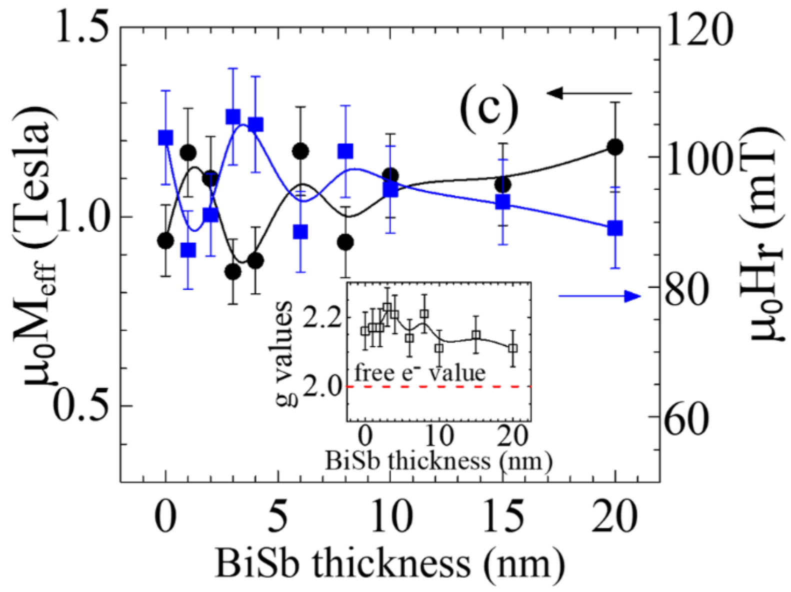
$$\frac{dP}{dH} = K_1 \frac{4\Delta H(H-H_r)}{[4(H-H_r)^2+(\Delta H)^2]^2} - K_2 \frac{(\Delta H)^2 - 4(H-H_r)^2}{[4(H-H_r)^2+(\Delta H)^2]^2}$$

K_1, K_2: symmetric & antisymmetric Lorentzian coefficients

$$f = \frac{\gamma}{2\pi}\mu_0\sqrt{H(H+M_{eff})}$$

$\gamma = \frac{g\mu_B}{h}$ and $\mu_0 M_{eff} = \mu_0(M_s - H_s)$

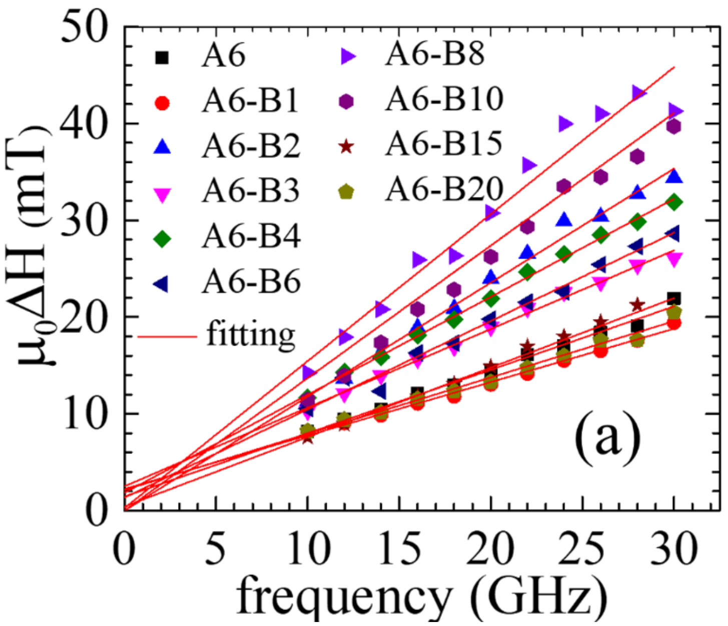
M_{eff}, Landé g-factor fitting parameters



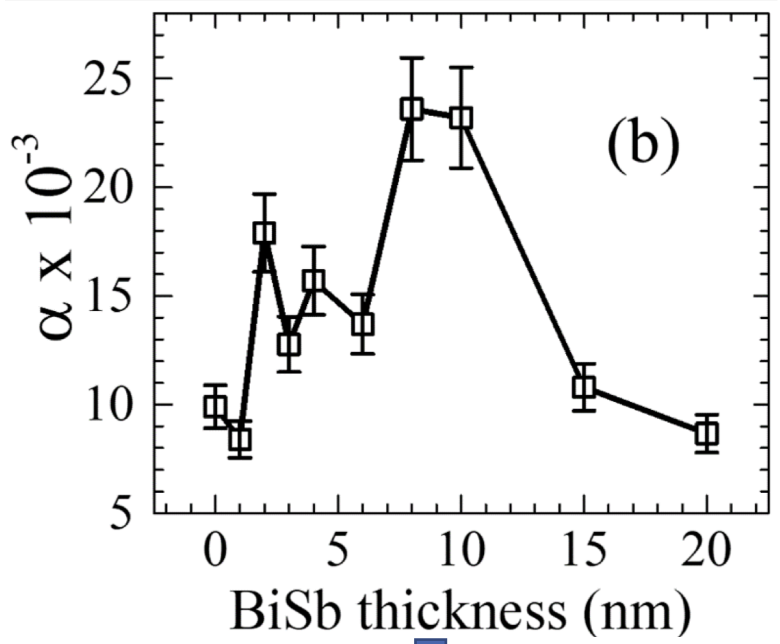
Small variation of $\mu_0 M_{eff}$ and $\mu_0 M_s$ suggests metallurgically clean interface with FeGaB layer

Sharma, Wu, …, MBJ et al., Phys. Rev. Materials **5**, 124410 (2021)

BiSb-thickness dependent variation of Gilbert damping



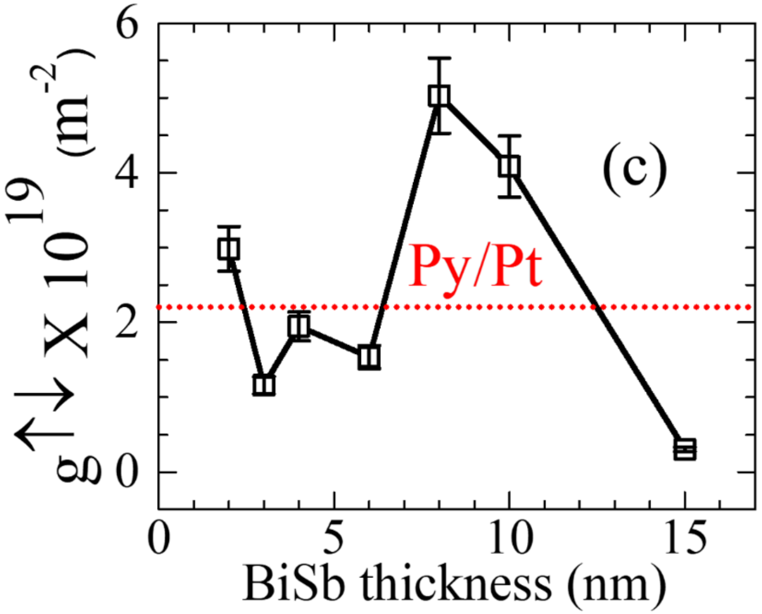
$$\Delta H = \Delta H_0 + \frac{4\pi\alpha}{\gamma} f$$



- FMR linewidth is enhanced in FeGaB/BiSb bilayer
- The rapid increase of α indicates efficient absorption of spin current in BiSb layer

Spin mixing conductance $g^{\downarrow\uparrow}$:

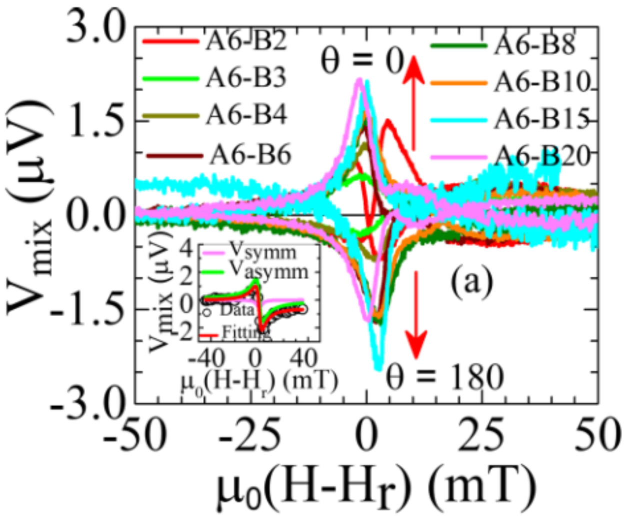
$$g^{\downarrow\uparrow} = \frac{4\pi M_s t_{FeGaB}}{g\mu_B}(\alpha_{FeGaB-BiSb} - \alpha_{FeGaB})$$



Topological surface state plays an important role!

Sharma, Wu, …, MBJ et al., Phys. Rev. Materials **5**, 124410 (2021)

Inverse spin Hall effect (ISHE) of BiSb



- Positive spin Hall angle of BiSb
- Opposite spin Hall angle for bare FeGaB compared to FeGaB/BiSb

$BiSb(8\,nm)\!:\ \theta_{SH} = 0.007 \pm 0.001$

$BiSb(10\,nm)\!:\ \theta_{SH} = 0.010 \pm 0.001$

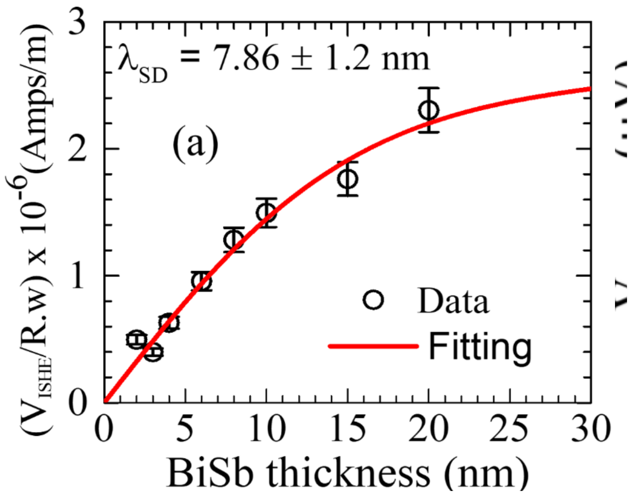
$$V_{mix} = K_s \frac{\delta H^2}{(H-H_r)^2 + \delta H^2} + K_{as} \frac{-2\delta H (H-H_r)}{(H-H_r)^2 + \delta H^2}$$

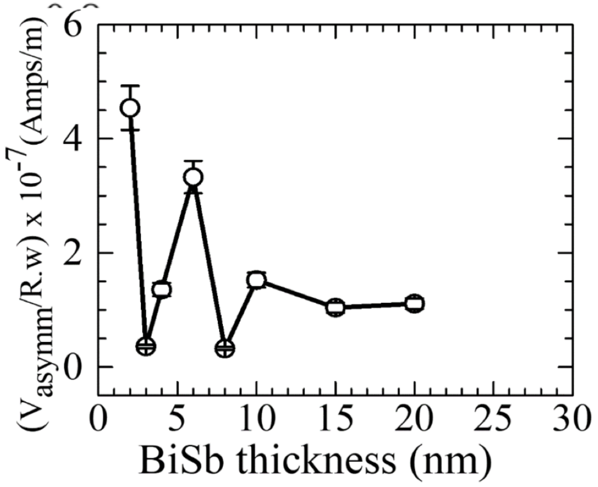
V_{symm}:

- Spin-pumping induced ISHE in BiSb
- Self-induced ISHE in FeGaB

V_{asymm}:

- Anisotropic magnetoresistance
- Anomalous Hall effect



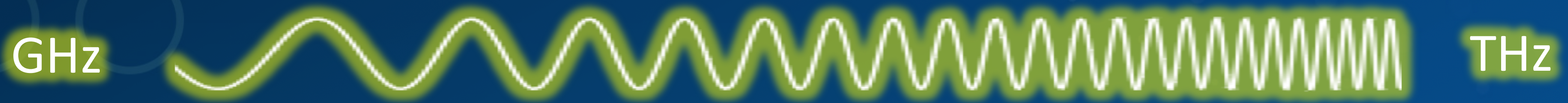


Damped-oscillator-like behavior due to opposite signs of AMR in FeGaB and BiSb

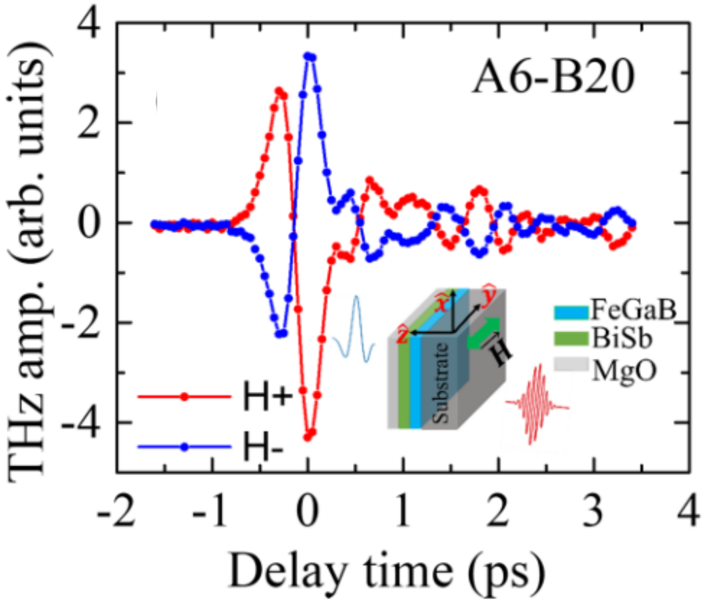
CENTER FOR HYBRID, ACTIVE, AND RESPONSIVE MATERIALS CHARM

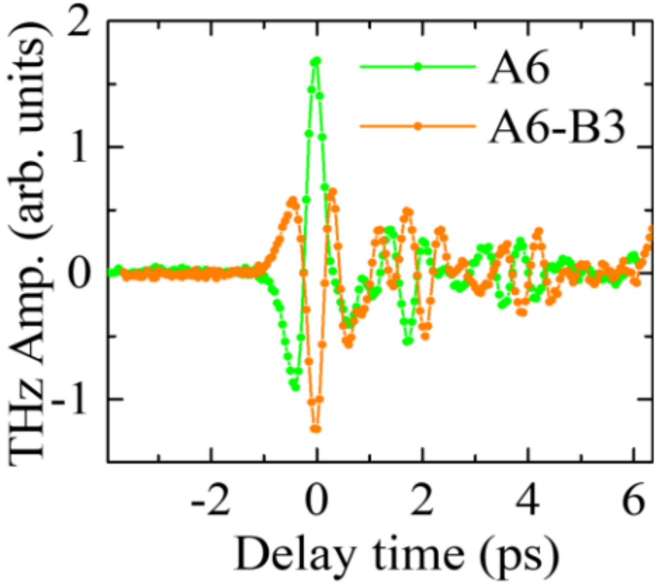
Budhani et al. AIP Adv. **11**, 55020 (2021)
Bajracharya et al., J. Phys. D: Appl. Phys. **55**, 075303 (2022)

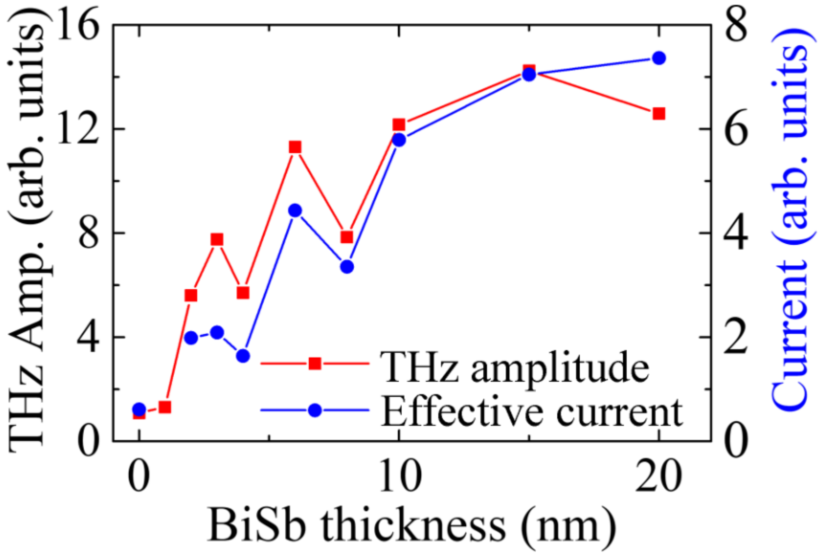
How do GHz dynamics translate to the THz range?



THz emission experiments







Signal inverted when reversing the magnetic field

→ Magnetic origin of the THz emission

Opposite sign of bare FeGaB and FeGaB/BiSB bilayer

→ SHA θ_{SH} of FeGaB and FeGaB/BiSb opposite

Effective current:

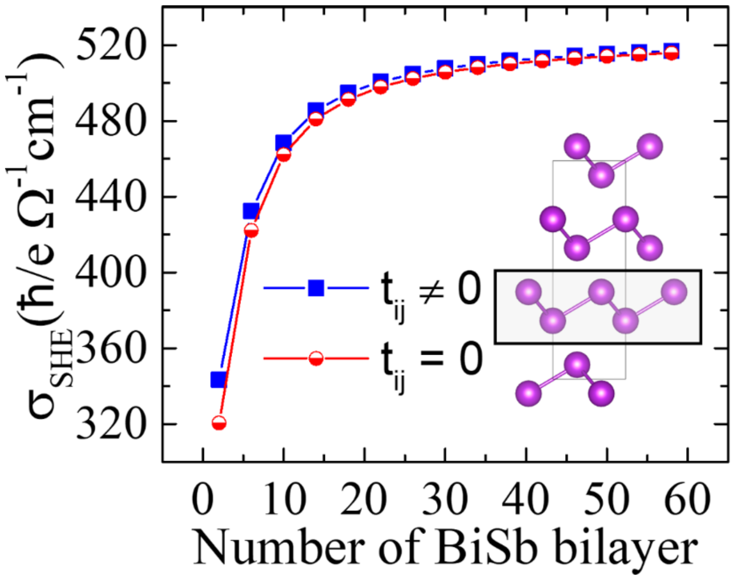
$$I_{eff} = \frac{E_{THz}}{R}$$

R: DC resistance of bilayer

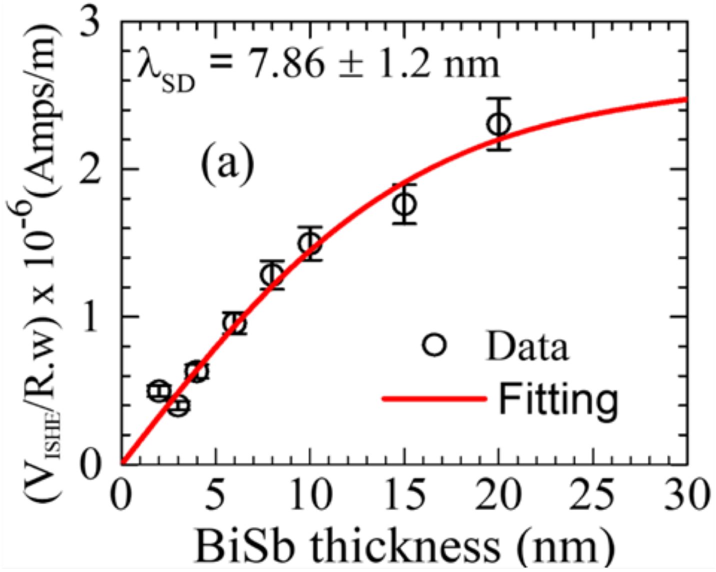
Experimental results of light and microwave driven spin pumping across FeGaB–BiSb interface in agreement.

Comparison to theory: Tight-binding model of BiSb

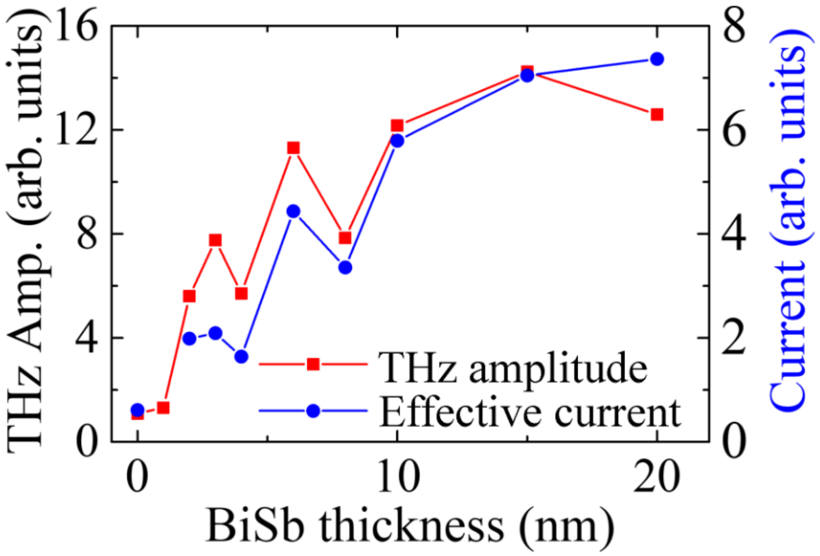
Model



Spin pumping/ISHE (GHz)



Ultrafast spin injection (THz)



$t_{ij} \neq 0$ and $t_{ij} = 0$ correspond to the case with with and without surface Rashba effect

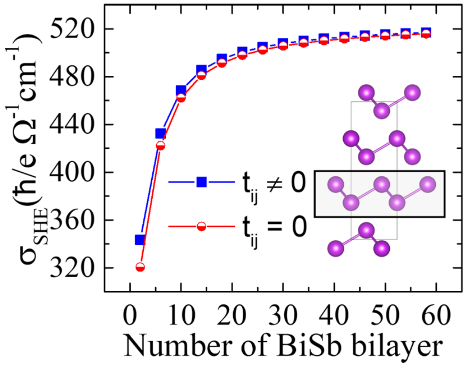
Increased BiSb thickness leads to an increase of spin-Hall conductivity σ_{SHE}, hence increasing the spin-to-charge conversion efficiency in GHz and THz experiments.

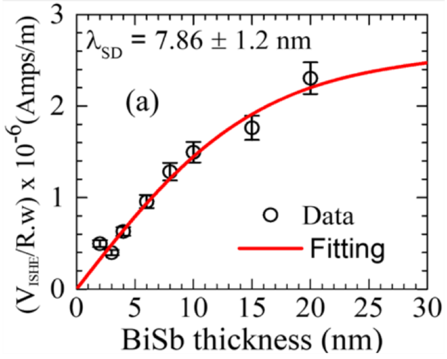
Modeling by To, Janotti, Bryant (UDCHARM)

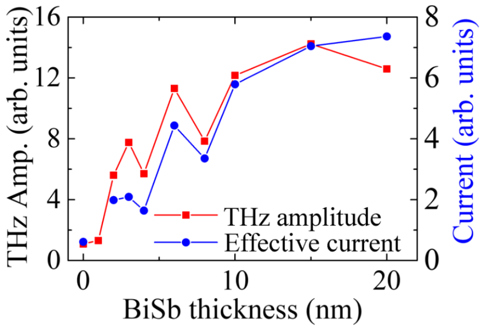
Sharma, Wu, …, MBJ et al., Phys. Rev. Materials **5**, 124410 (2021)

Take-home messages - Part 1

- Metallurgically clean interface between FeGaB and BiSb layer
- Unconventional thickness dependence of $g^{\downarrow\uparrow}$ in FeGaB/BiSb
- Spin-pumping-induced DC measurements enable separation of contributions from AMR and ISHE
- Spin Hall angle ($\theta_{SH} = 0.010$) and spin-diffusion length ($\lambda_{SD} = 7.86\,nm$) of BiSb determined
- Agreement between GHz, THz experiments & linear response theory based on Kubo-Bastin formula considering a tight-binding model







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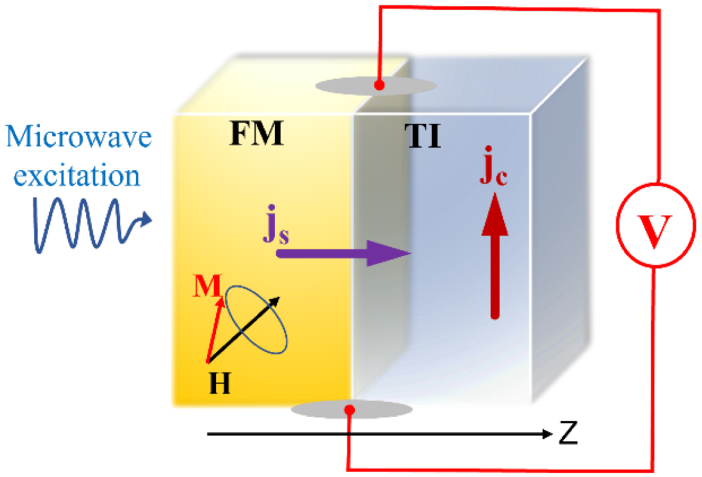
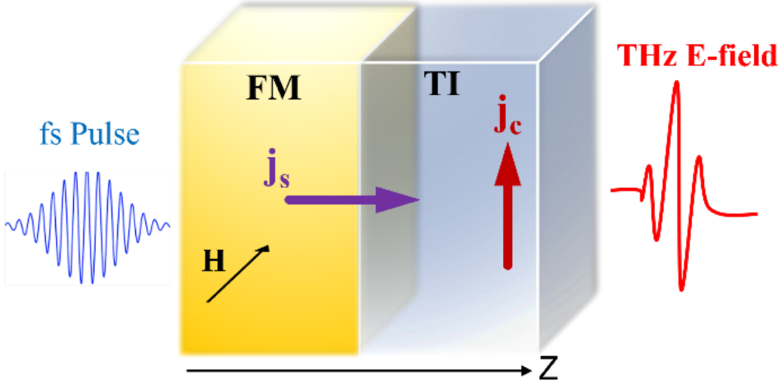
Sharma, Wu, …, MBJ et al., Phys. Rev. Materials **5**, 124410 (2021)

Outline: Spin current injection across FM/ TI interfaces

GHz inverse spin Hall experiment



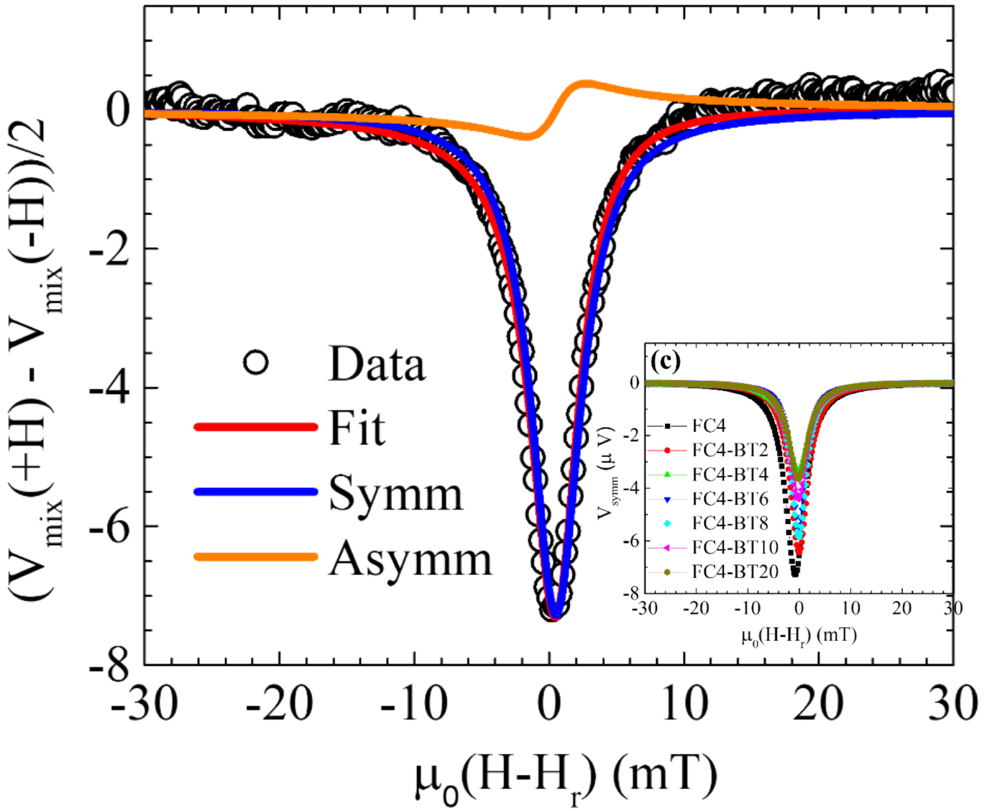
THz emission mediated by inverse spin Hall experiment

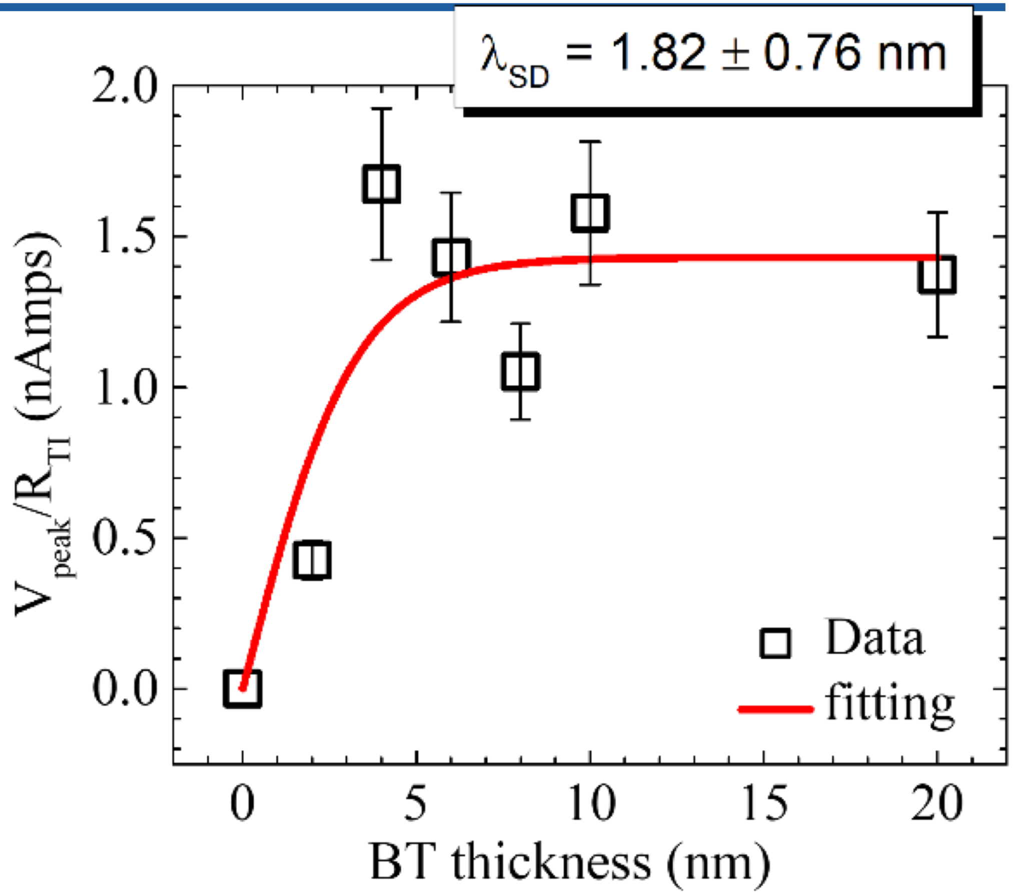


Materials of interest (ferromagnet/3D topological insulator) grown by DC magnetron sputtering:

- Sapphire(substrate)//$Fe_{78}Ga_{13}B_9$(FeGaB)/$Bi_{85}Sb_{15}$(BiSb)/MgO(capping)
    - Amorphous FeGaB
    - BiSb with (001) texture
- **$MgAl_2O_4$(substrate)// $Fe_{75}Co_{25}$(FeCo) / Bi_2Te_3(BiTe)/Al(capping)**
    - **Epitaxial FeCo with body-centered cubic (bcc) structure**
    - **Polycrystalline BiTe**

GHz – ISHE studies: FeCo/BiTe



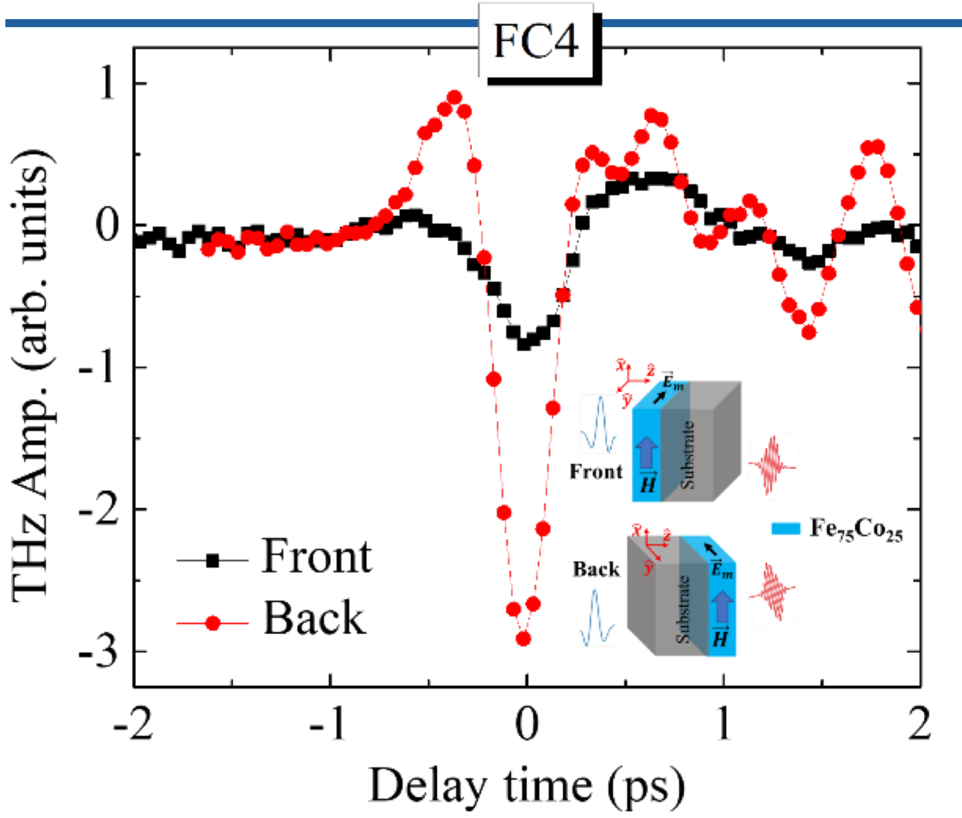


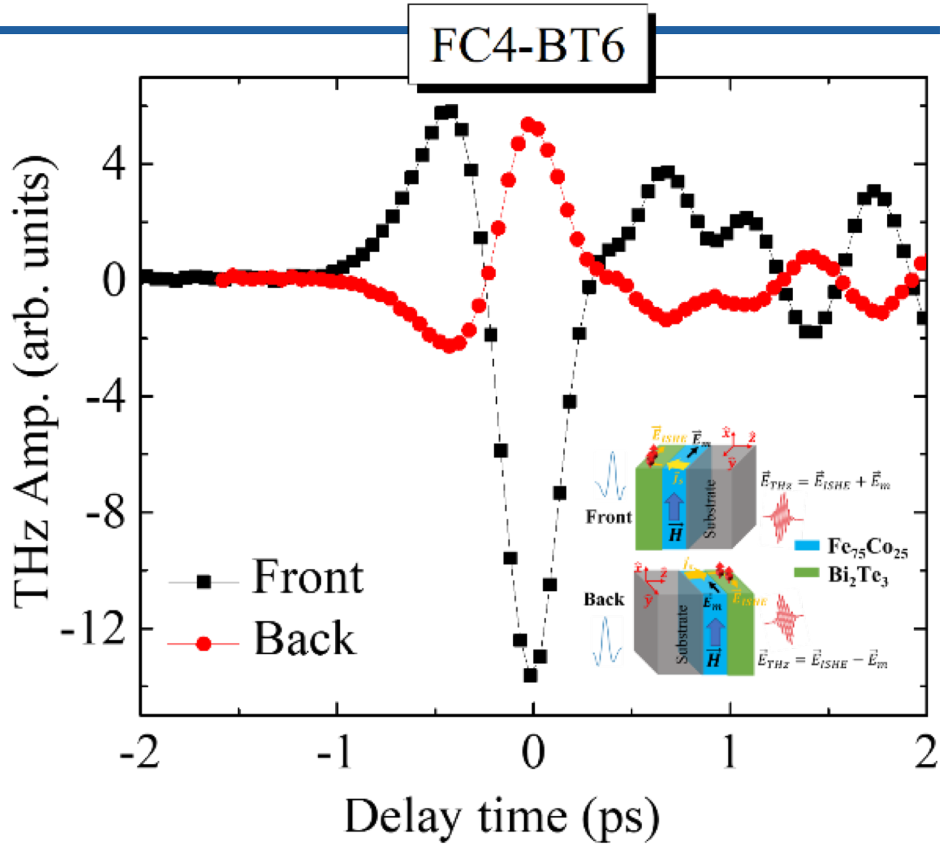
$$V_{mix} = K_s \frac{H^2}{(H-H_r)^2 + H^2} + K_{as} \frac{-2H(H-H_r)}{(H-H_r)^2 + H^2}$$

ISHE and rectification effects

Sharma, Wu, …, MBJ et. al.
Appl. Phys. Lett. **122**, 072403 (2023)

THz – ISHE studies: FeCo/BiTe





Magnetic dipole radiation + AMR/AHE + self-induced-ISHE

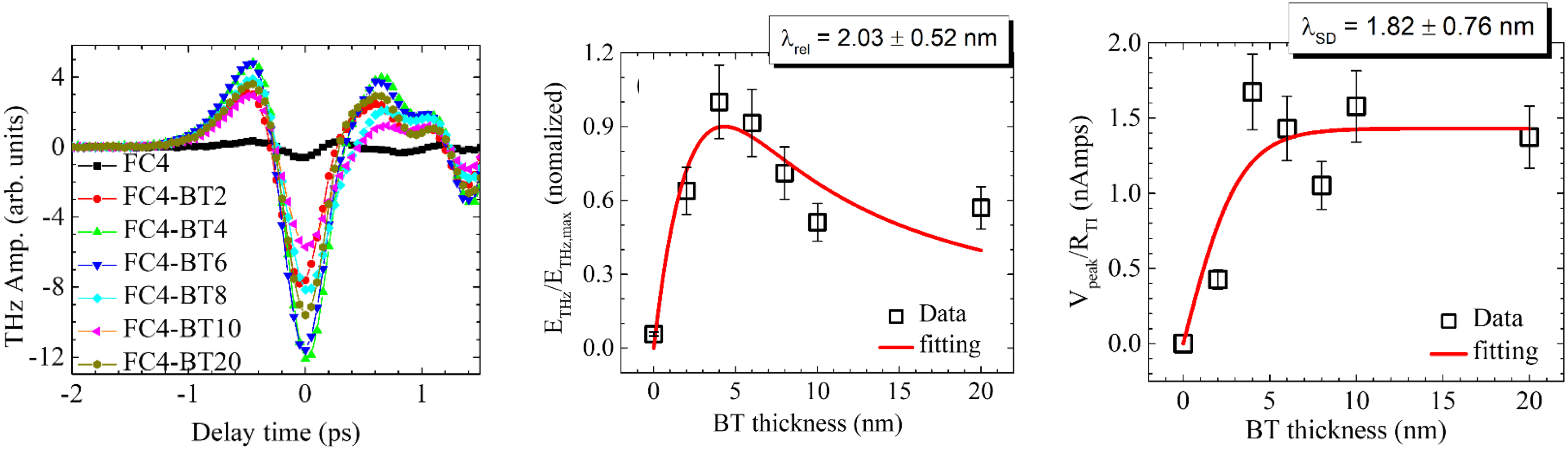
$$\vec{E}_m \sim \hat{n} \times \vec{m}$$

$$\vec{E}_{ISHE} \sim \frac{\partial J_c}{\partial t} \sim \frac{\partial(\theta_{ISHE} \cdot \vec{J}_S \times \hat{\sigma})}{\partial t}$$

ISHE in Bi_2Te_3 + Magnetic dipole radiation

Sharma, Wu, …, MBJ et. al.
Appl. Phys. Lett. **122**, 072403 (2023)

Spin-diffusion length - comparison



Spin diffusion lengths determined from experiments at different time scales in agreement.

Sharma, Wu, …, MBJ et. al.
Appl. Phys. Lett. **122**, 072403 (2023)

Take-home messages - Part 2

- Observation of spin pumping induced ISHE signal in FeCo/BiTe; additional contribution from high AMR of $Fe_{75}Co_{25}$ is revealed.
- Extracted spin-diffusion lengths obtained from the two experiments agree well despite the drastically different time scales.
- FMR-induced spin pumping and ultrafast spin-current injection are promising complementary tools to investigate inverse spin Hall effect.

$Fe_{78}Ga_{13}B_9/Bi_{85}Sb_{15}$ results:

Phys. Rev. Materials **5**, 124410 (2021)

$Fe_{75}Co_{25}/Bi_2Te_3$ results:

Appl. Phys. Lett. **122**, 072403 (2023)

National Science Foundation
MRSEC
Materials Research Science and Engineering Centers
Award Number DMR-2011824

Recent tutorial article on Principles of THz spintronics:
Wu et al., J. Appl. Phys. **130**, 091101 (2021)