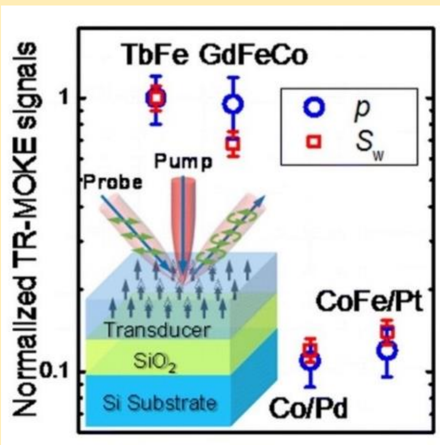
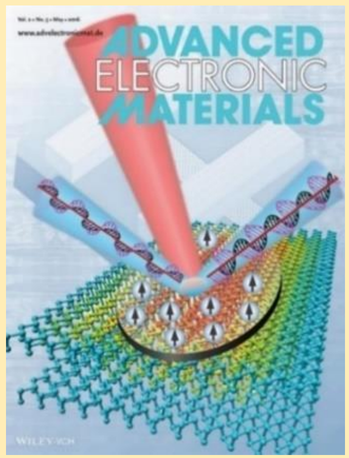
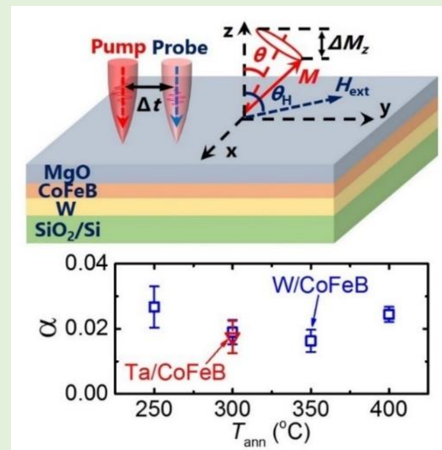
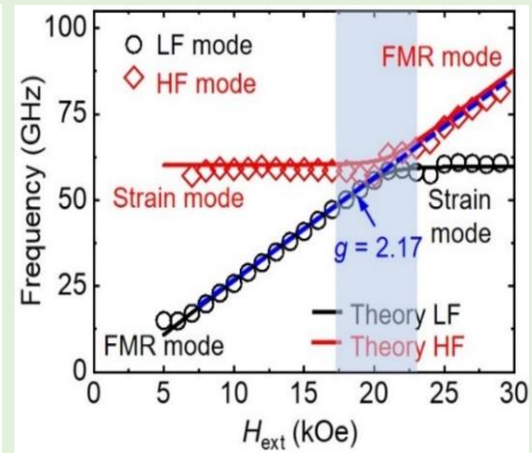
Time-Resolved Magneto-Optical Kerr Effect (TR-MOKE) for Thermal Characterization and Magnetic Dynamics





Thermal Characterization





Magnetization Dynamics

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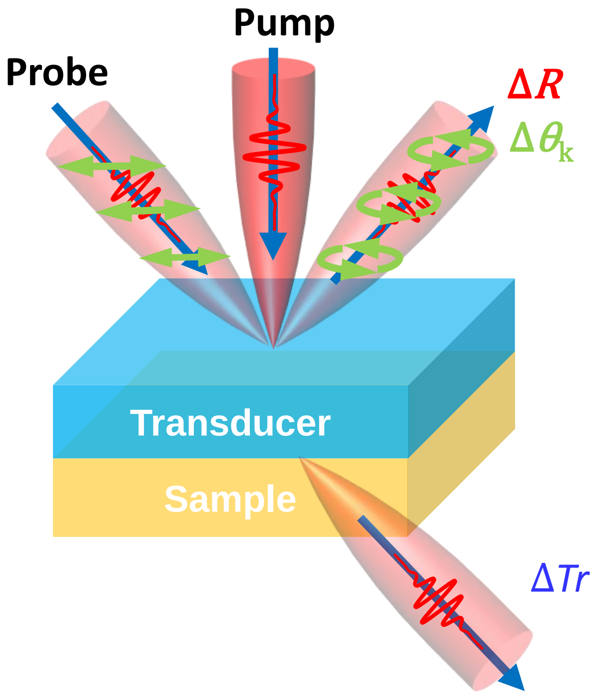
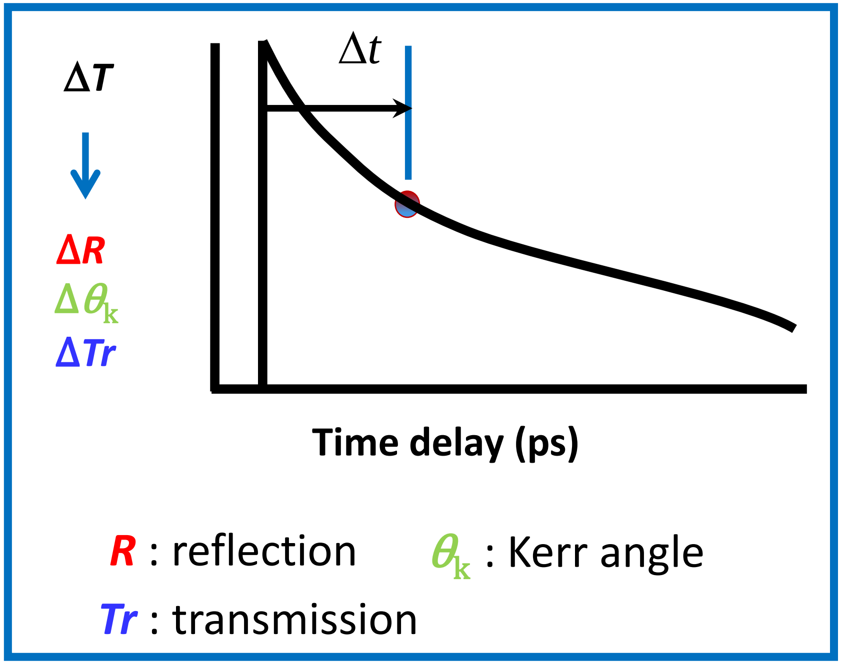
ITCC & ITES 2024 Conference
Oct. 27-30, 2024
Charlottesvile, VA, USA

Ultrafast all-optical pump-probe system in various configurations





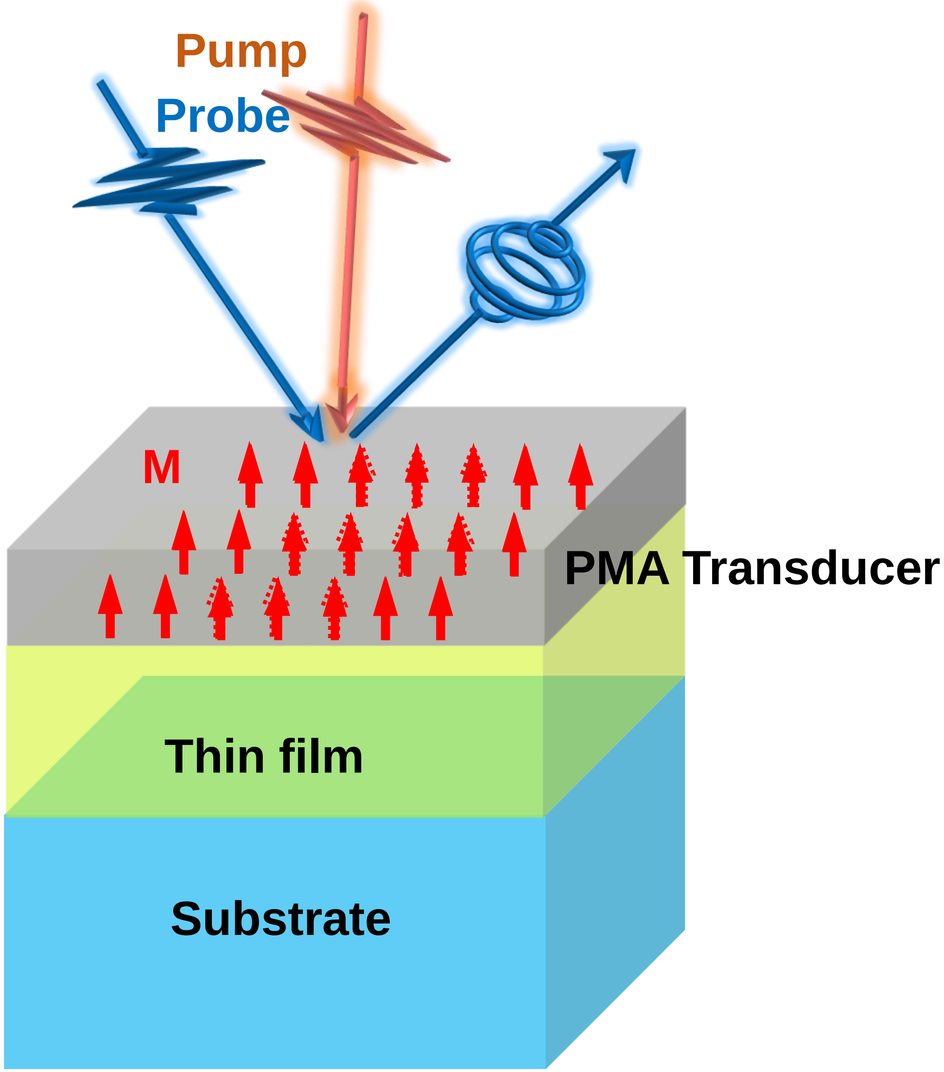
Various configurations

- $\Delta T \sim \Delta R$: time-domain thermoreflectance (TDTR)
- $\Delta T \sim \Delta \theta_k$: time-resolved magneto-optical Kerr effect (TR-MOKE)
- $\Delta T \sim \Delta Tr$: transient absorption (TA)

Zhu, Wu, Lattery, Zheng, Wang, Nanosc. Microsc. Therm. Eng., 21, 177-198 (2017);
Lattery, Zhu, Huang, Wang, Invited IOP Book Chapter (2020); Huang et al., ACS AEM, 3, 119-127 (2021).

TR-MOKE signal related to temperature rise

Sample with the perpendicular magnetic transducer



TR-MOKE signal:

$$S \propto R \frac{d\theta_k}{dT} \Delta T$$

Thermo-magneto-optical coefficient

$$= R \frac{d\theta_k}{dM} \frac{dM}{dT} \Delta T$$

PMA: perpendicular magnetic anisotropy

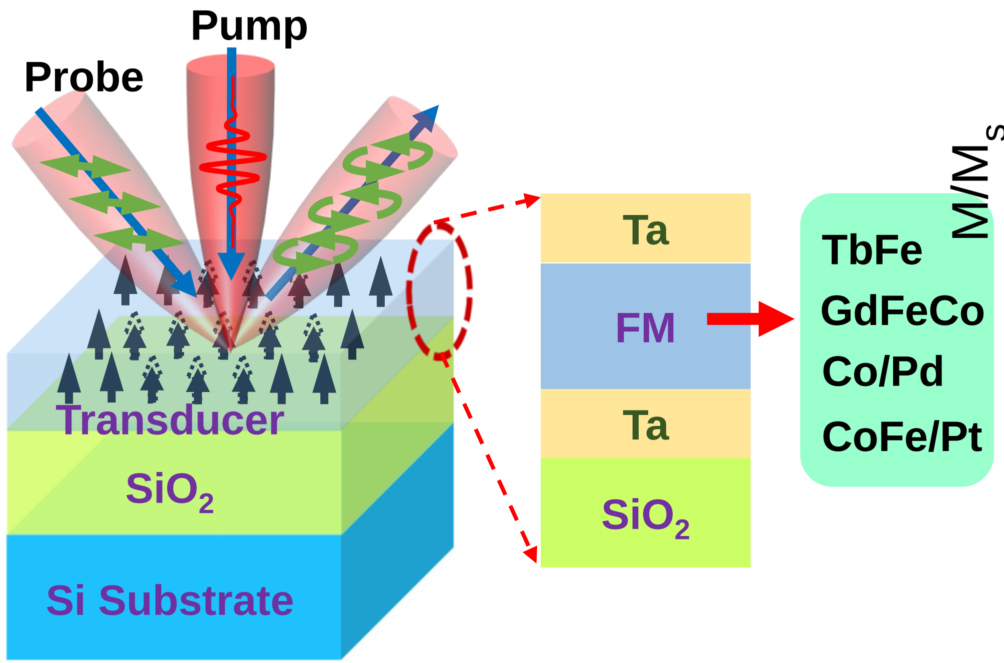
M*:* magnetization

$\boldsymbol{\theta_k}$**:** *Kerr* rotation

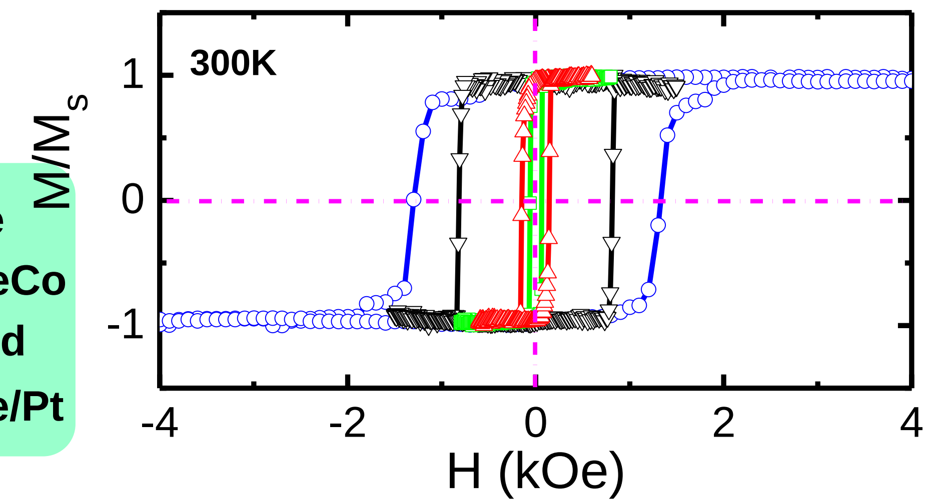
R**:** reflectivity

T: temperature

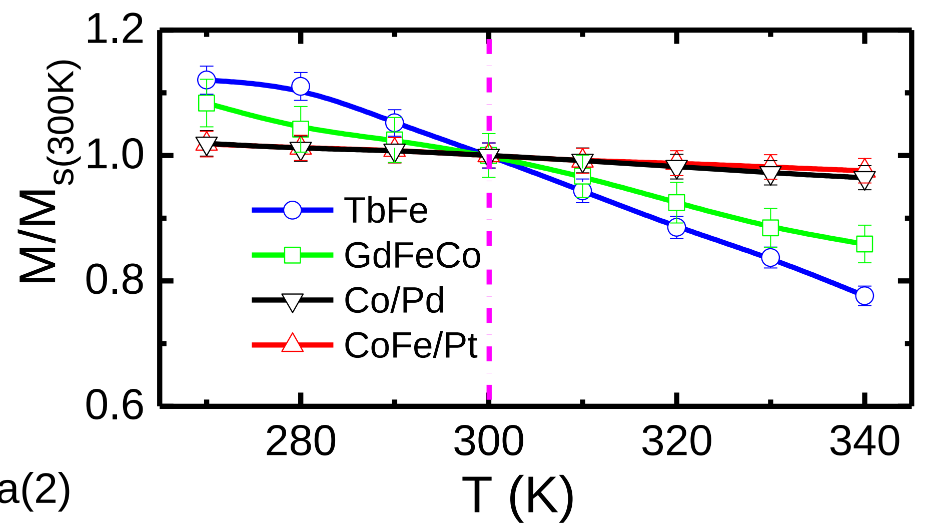
Magnetic transducers



Magnetic hysteresis loops



Compositions



Transducer structures in (nm):

TbFe: Ta(1.5)/$Tb_{36.8}Fe_{63.2}$(7)/Ta(3)

GdFeCo: Ta(4)/$Gd_{28}Fe_{63}Co_9$(20)/Ta(4)

Co/Pd: Ta(3)/Pd(3)/[Co(0.4)/Pd(0.7)]×5/Ta(2)

CoFe/Pt: Ta(2)/Pt(2)/[$Co_{90}Fe_{10}$(0.4)/Pt(0.7)]×5/Ta(2)

Zhu & Lattery et al., J. Phys. Chem. Lett., 7, 2328-2332 (2016).

Magnetic transducers prepared by Prof. Jian-Ping Wang at UMN/ECE.

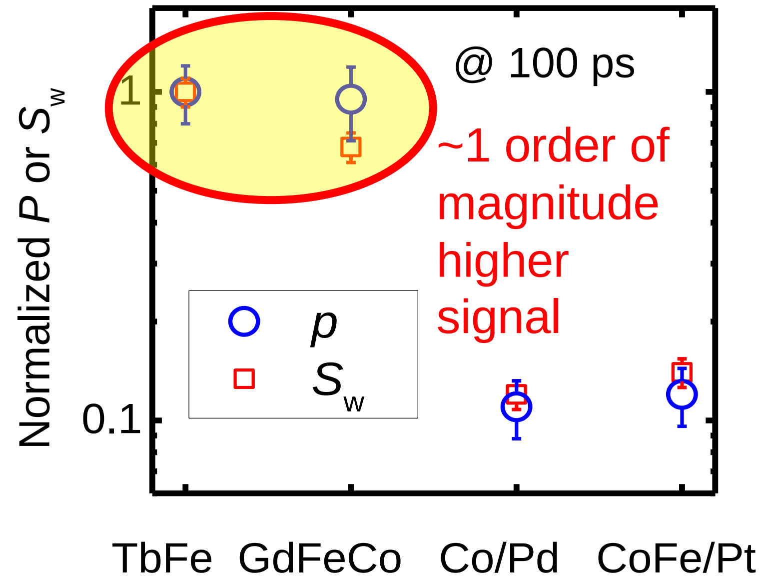
Thermo-magneto-optical performance of transducers

$$S_{\mathrm{w}} = \sqrt{V_{\mathrm{in}}^2 + V_{\mathrm{out}}^2}\left(\pi w_0^2\right) / \left(P_{\mathrm{pump}} P_{\mathrm{probe}}\right)$$

Figure of merit

Thermo-magneto-optical coefficient

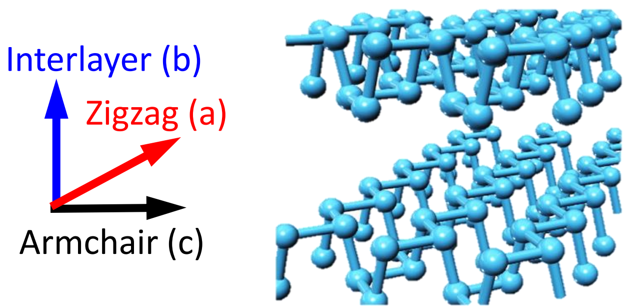
$$p = R\theta_{\mathrm{ks}} \frac{dM / M_{\mathrm{s}}}{dT} \Delta T = R \frac{d\theta_{\mathrm{k}}}{dT} \Delta T$$

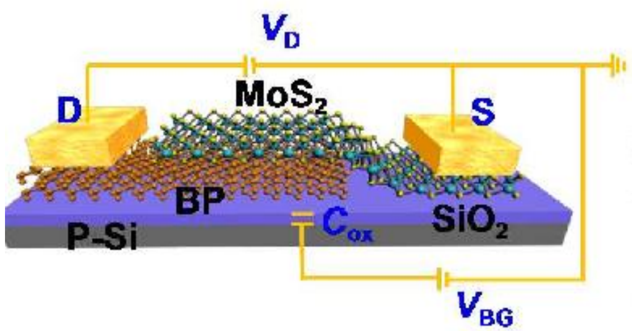


	Thickness	$M_{s(300\ K)}$	T_c	$\frac{dM/M_s}{dT}$	θ_{ks}	$\frac{d\theta_k}{dT}$	R	ΔT
	(nm)	(emu.cm^{-3})	(K)	(10^{-4} K^{-1})	(deg)	(10^{-4} deg K^{-1})		(K)
TbFe	11.5±0.5	420±15	385	-54±10	0.22±0.03	19	0.41±0.05	26±3
GdFeCo	28.0±1	100±5	540	-28±5	0.53±0.03	14	0.59±0.05	14±1
Co/Pd	13.5±0.5	460±20	804	-8.0±0.3	0.15±0.03	1.2	0.53±0.05	21±2
CoFe/Pt	11.5±0.5	420±16	780	-8.5±0.3	0.18±0.03	1.5	0.54±0.05	18±2

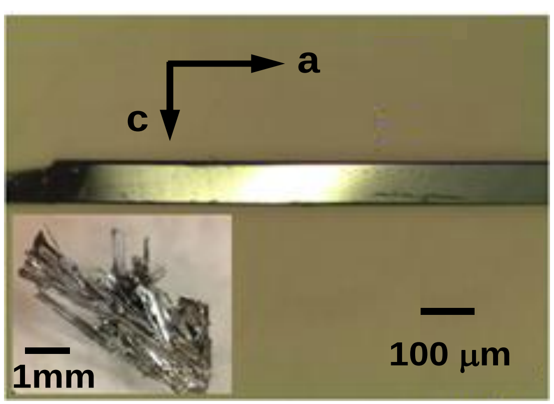
Zhu & Lattery et al., J. Phys. Chem. Lett., 7, 2328-2332 (2016).

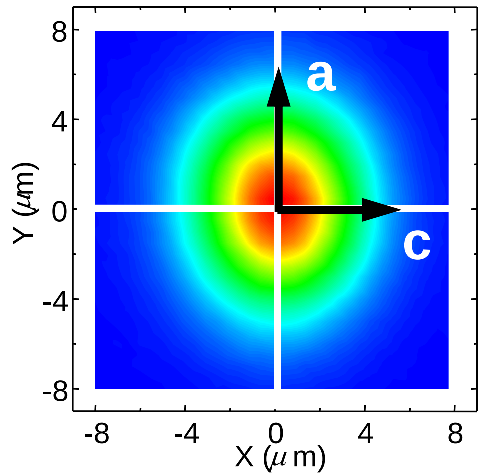
Engineering materials: anisotropic thermal transport in BP





Wonder materials: field-effect transistors

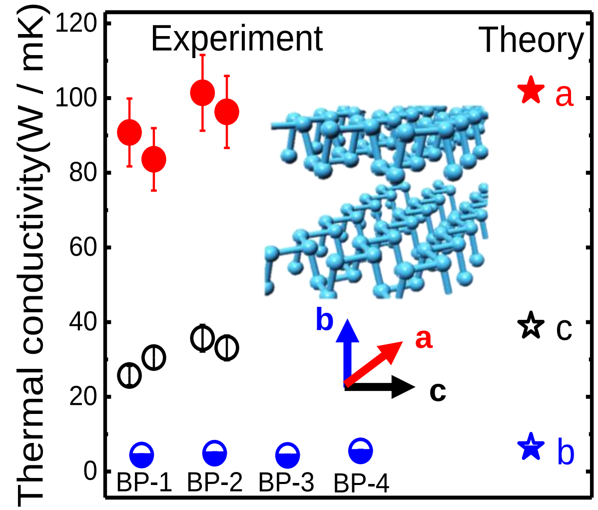


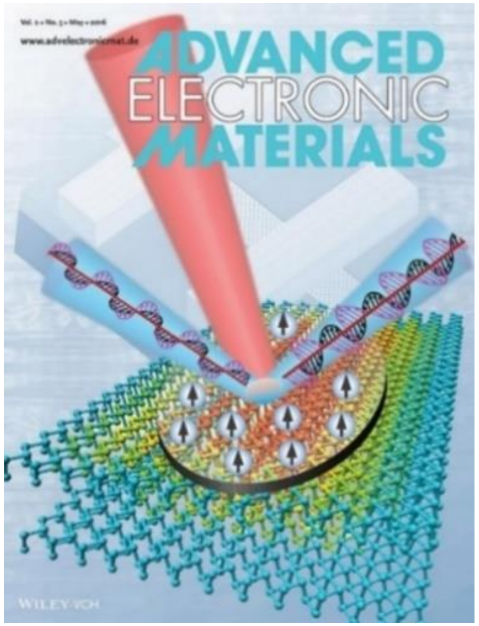


2D in-plane thermal contour

Transducer: ~27 nm TbFe
~17 W/m-K

Major finding: successfully resolved the 3D anisotropic thermal conductivity tensor of black phosphorus (BP). Excellent agreement between 1st-principles calculations and **TR-MOKE** measured 3D thermal conductivity tensor





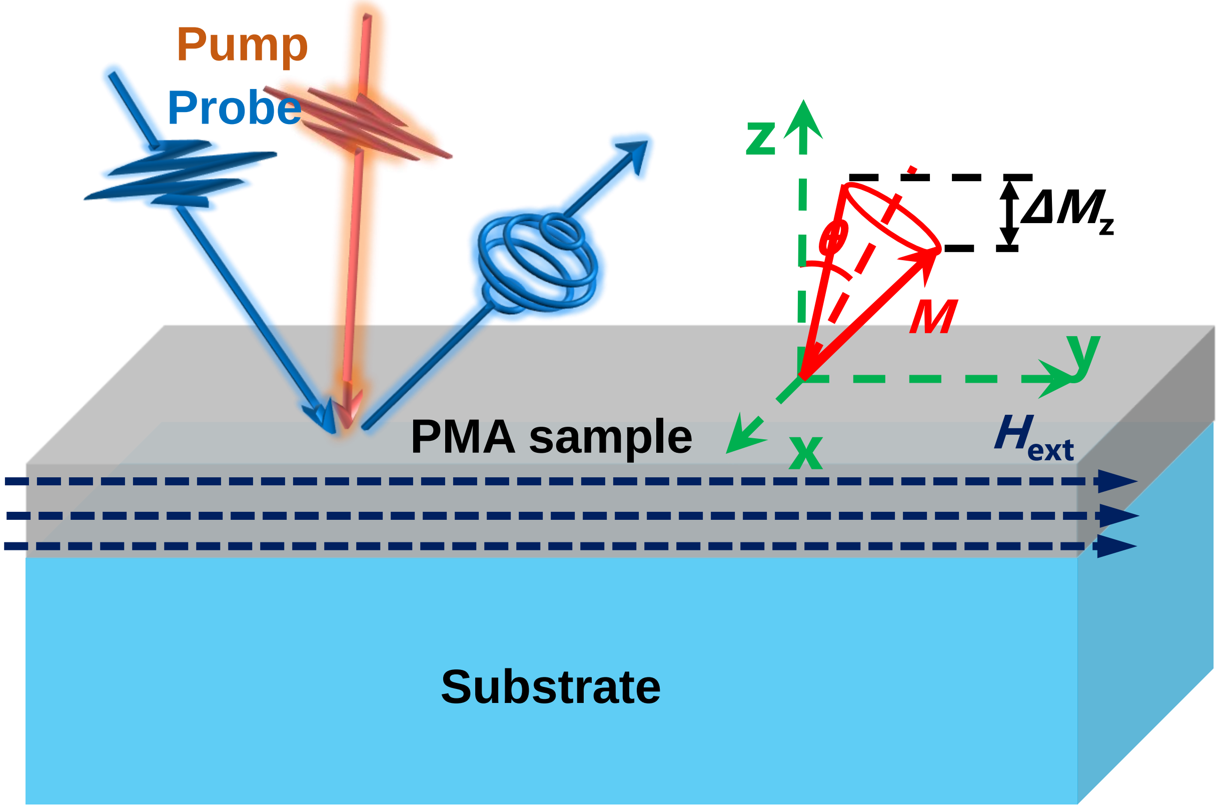
BP samples provided by Prof. Steve Campbell at UMN and Prof. Xu Du at SBU;
First-principles simulations performed by Prof. Ronggui Yang at UCB.

Zhu et al., Adv. Electron. Mater., 2, 1600040 (2016, cover image).

TR-MOKE signal related to magnetization

Pump-probe configuration

Reflected probe beam signals: $S \propto \Delta M_z$



M: magnetization

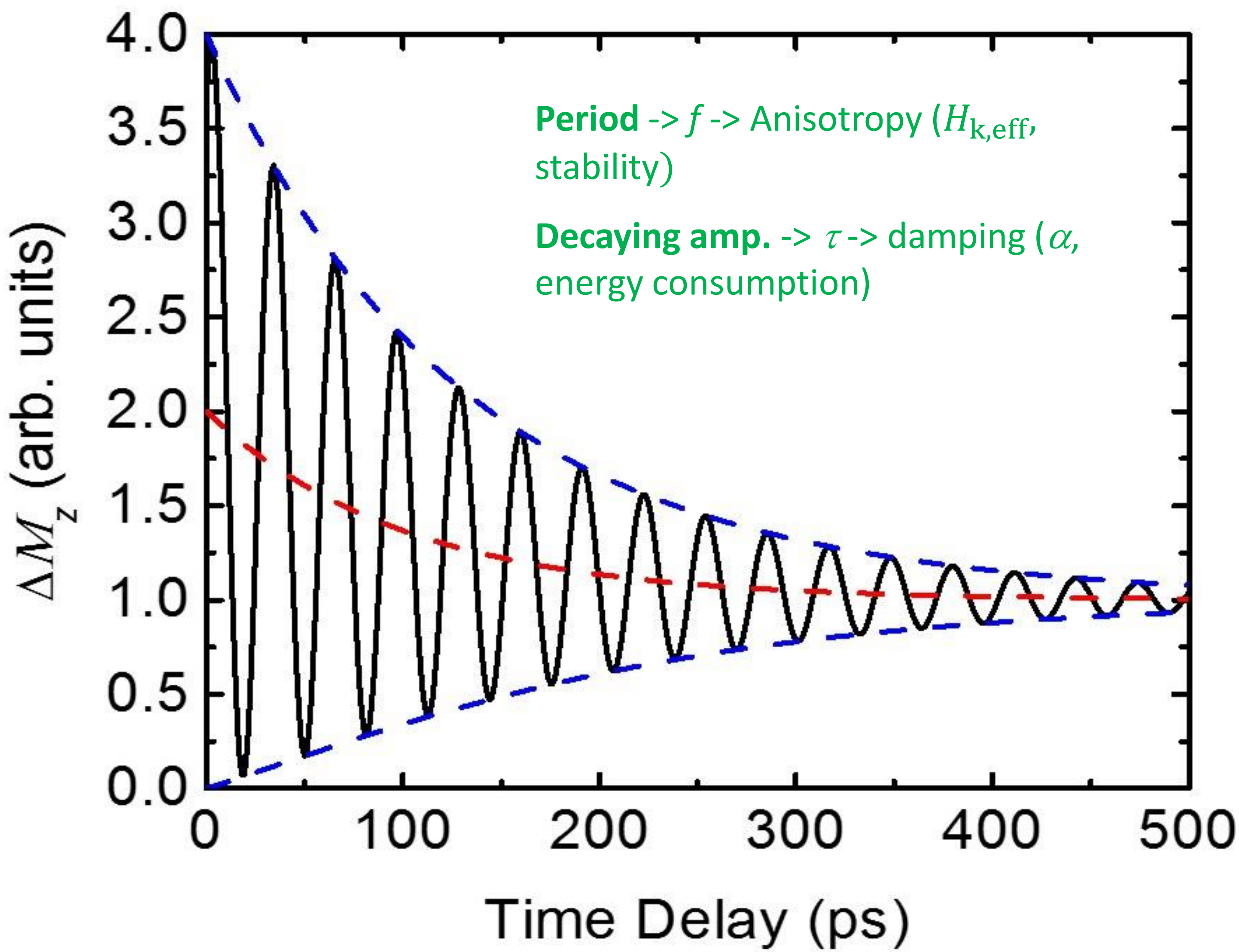
ΔM_z: variation of the *z* component of the magnetization

H_{ext}: external applied magnetic field

θ: equilibrium direction of spin precession

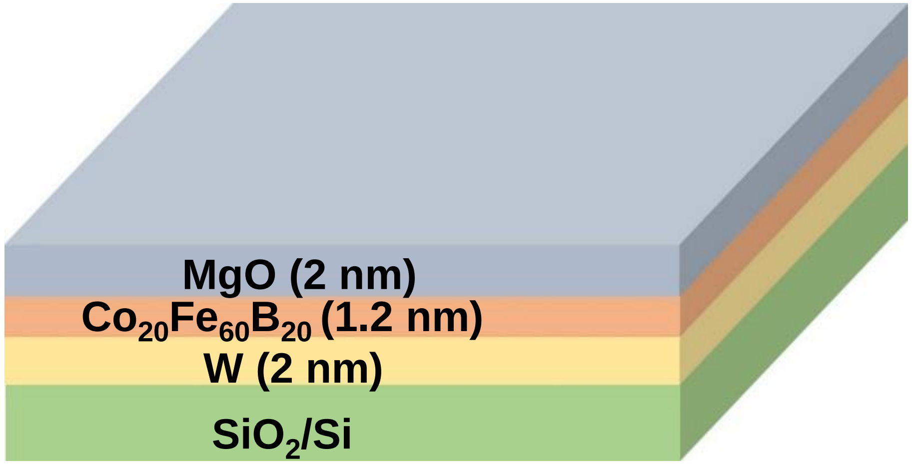
Dynamic view of spin precession

We measure the change in M_z (ΔM_z) as a function of time delay through MOKE.



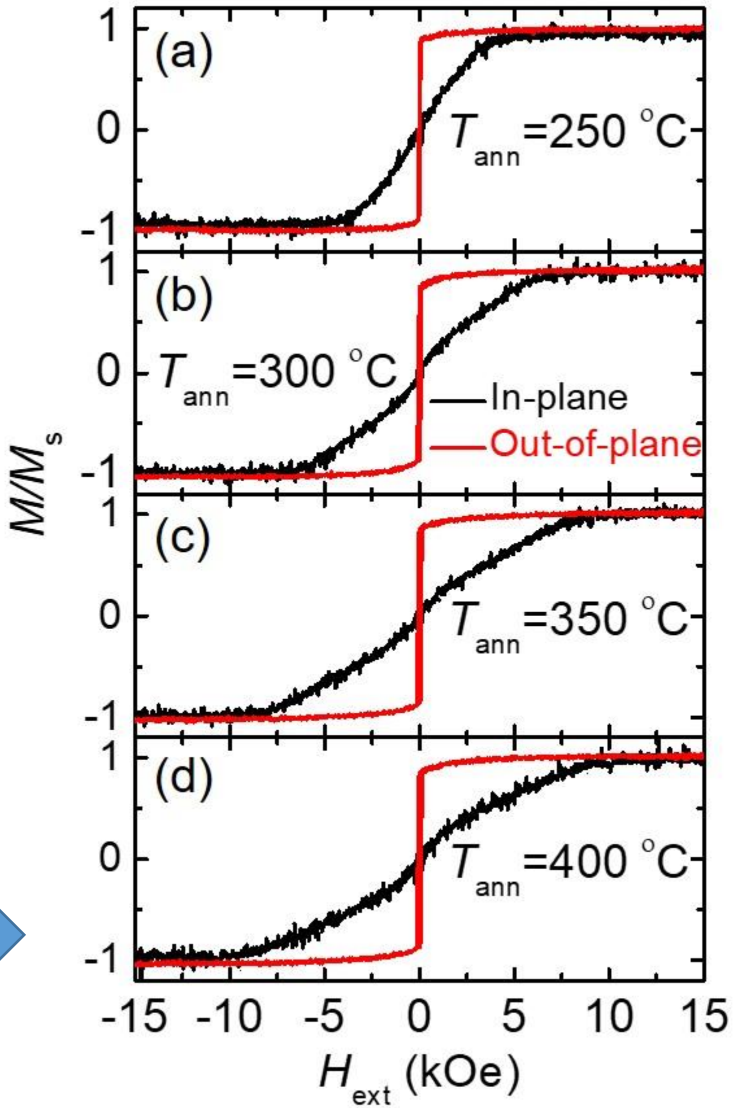
CoFeB with perpendicular magnetic anisotropy (PMA)

Goal: to understand the seed layer effect to make CoFeB-based PMA thin films with high thermal stability and low damping



$\boldsymbol{T_{ann}}$: post-annealing temperature
250, 300, 350, and 400°C

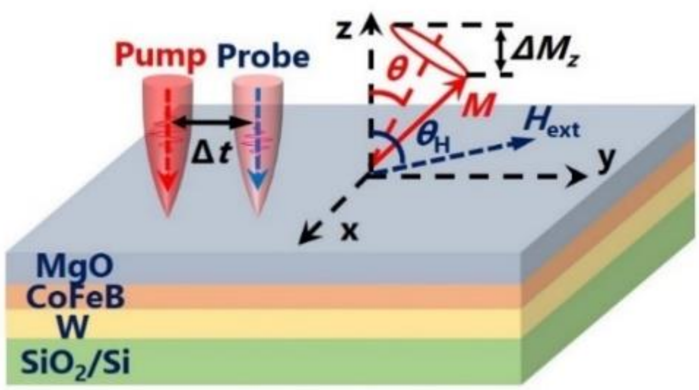
Hysteresis loop from VSM measurements

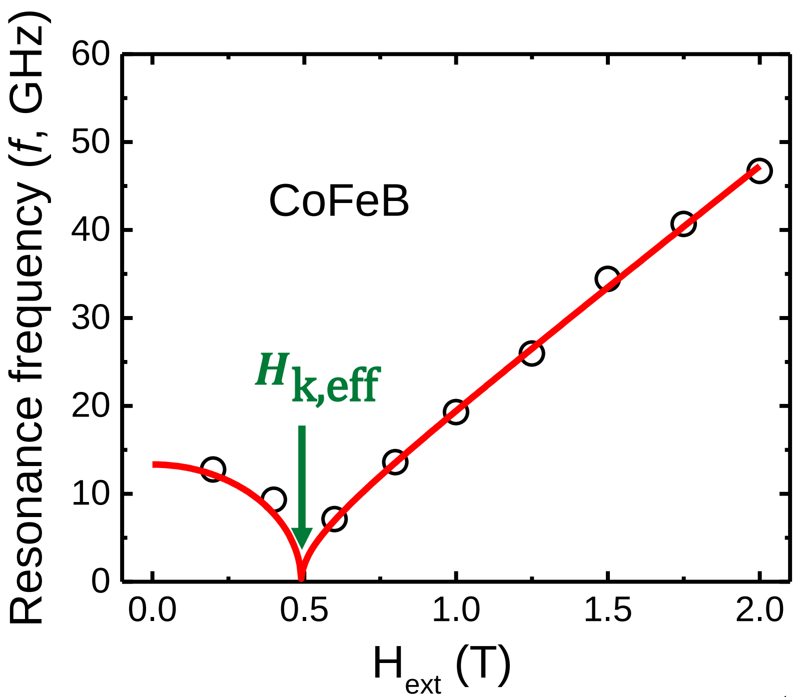


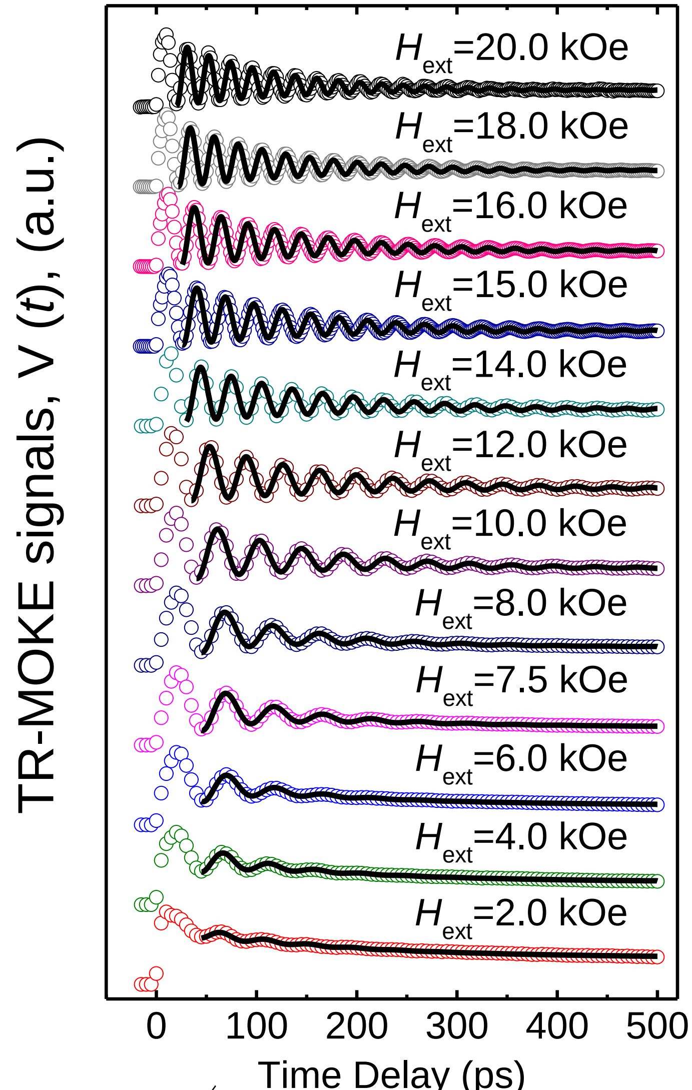
Lattery et al., Sci. Rep., 8, 13395 (2018).

Spin precession frequency – CoFeB (PMA)

$Si/SiO_2/\ W(7\ nm)/Co_{20}Fe_{60}B_{20}(1.2\ nm)/MgO(2\ nm)/Ta(3\ nm)$



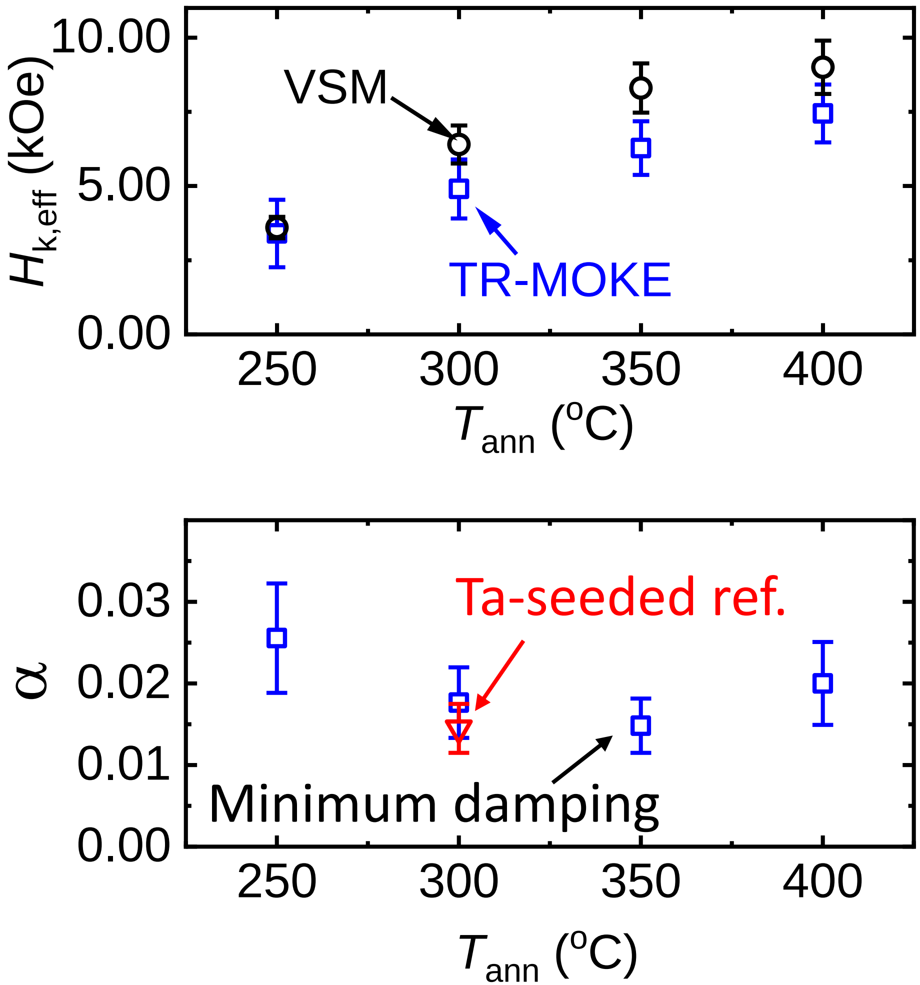




$$V(t) = A + Be^{-t/C} + D\sin(2\pi f t + \varphi)e^{-t/\tau}$$

Lattery et al., Sci. Rep., 8, 13395 (2018).

PMA CoFeB with low damping and high thermal stability



Reference (Ta-seeded, losing PMA properties after post-annealed at 350°C)

Ta(7 nm)/$Co_{20}Fe_{60}B_{20}$(1.2 nm)/MgO(2 nm)/Ta(3 nm)

Benefits:

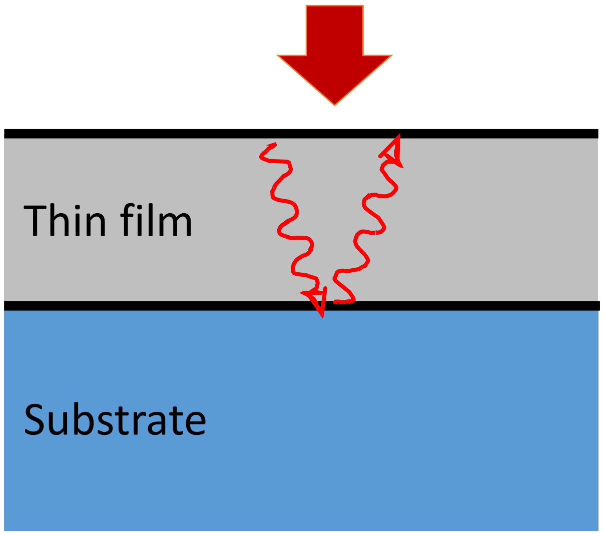
1. Higher magnetic anisotropy ($H_{k,eff}$) -> Maintaining good PMA properties after post-annealed at 400 °C -> Enhanced thermal stability

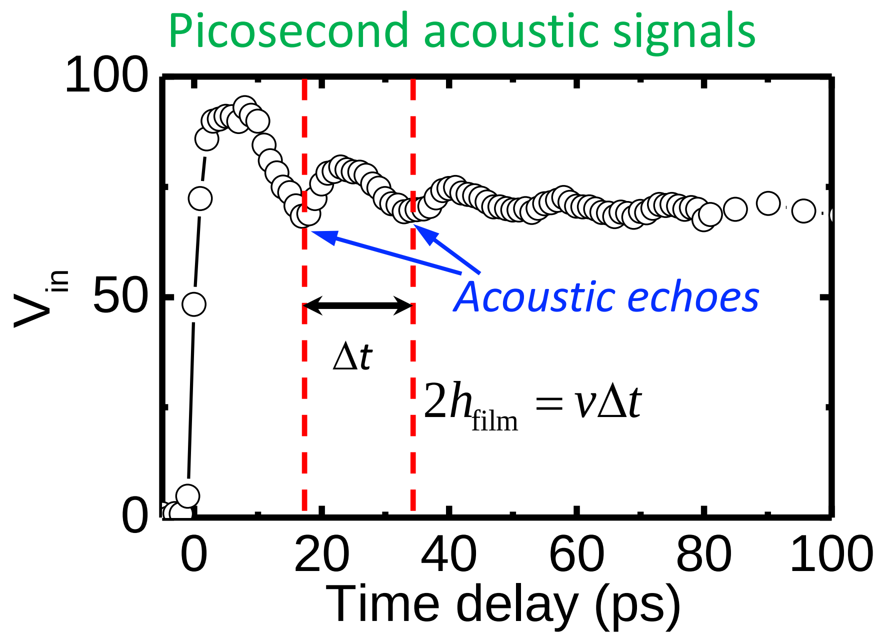
2. Lower damping (a) -> Smaller critical switching current -> Low power-consumption devices

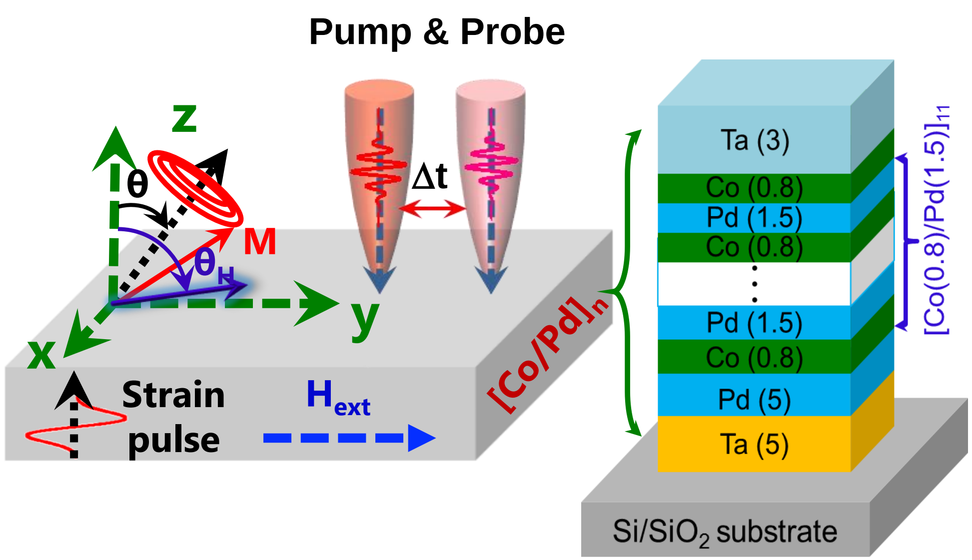
Min damping due to the competing effect as T_{ann} increases:
(1) Dead-layer growth (damping ↑); (2) Increased crystallization (damping ↓)

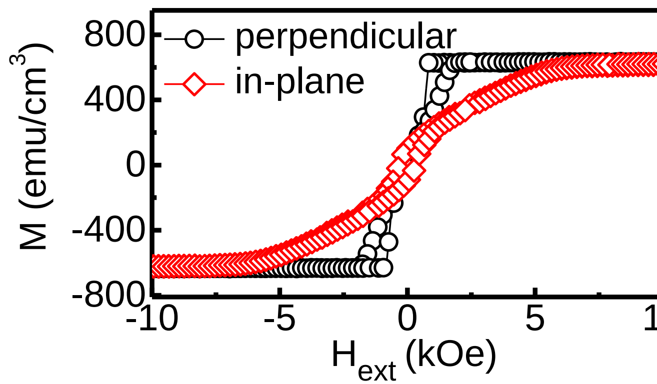
Lattery et al., Sci. Rep., 8, 13395 (2018).

Other complex magnetic structures: spin-strain coupling









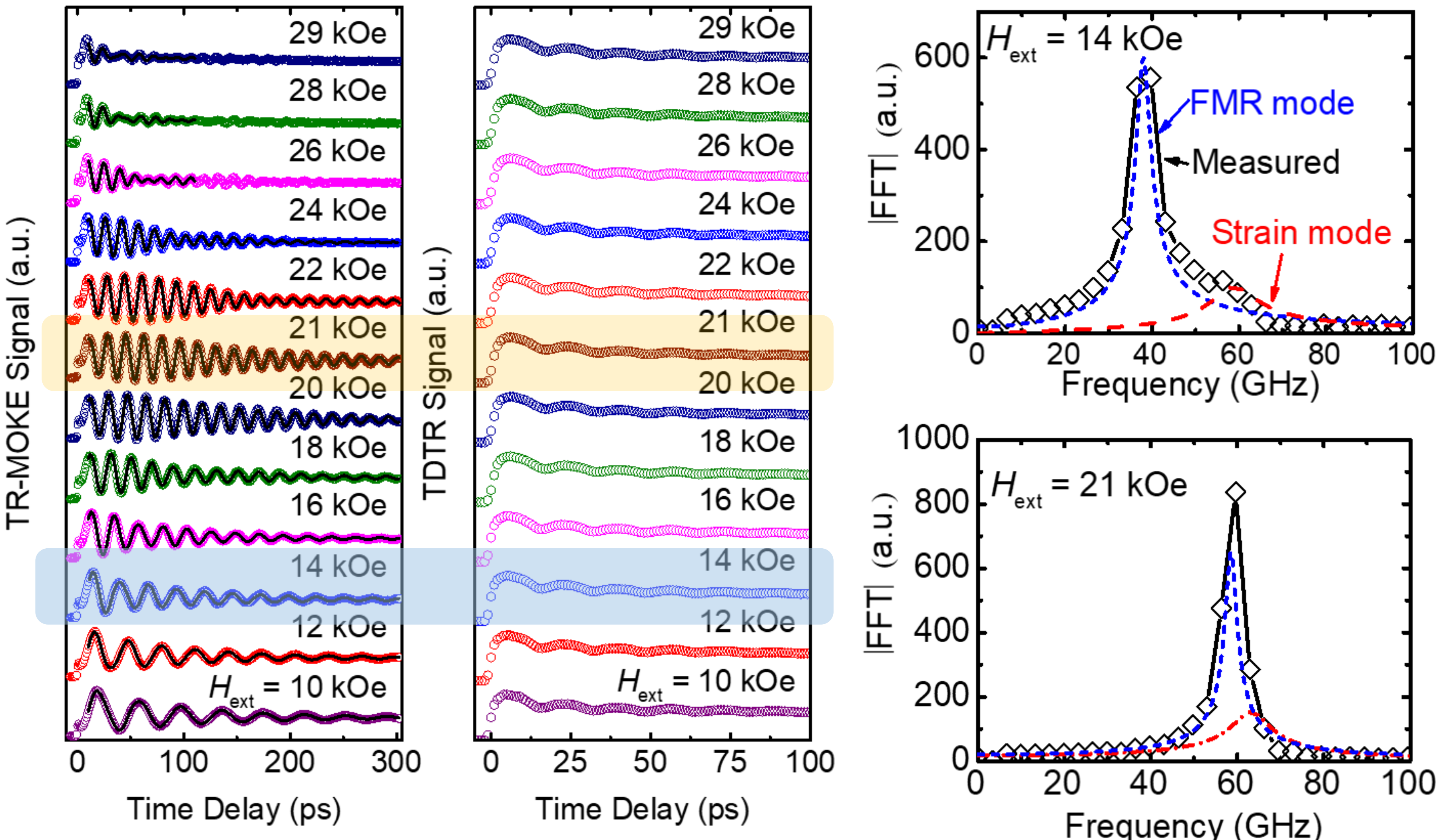
Extremely high strain frequency tunable by varying the film thickness (~ 60 GHz)

Zhu & Lattery et al. Science Advances, 6, eabb4606 (2020).

Samples provided by Prof. Jian-Ping Wang at UMN/ECE.

Coupling between the strain mode & FMR mode

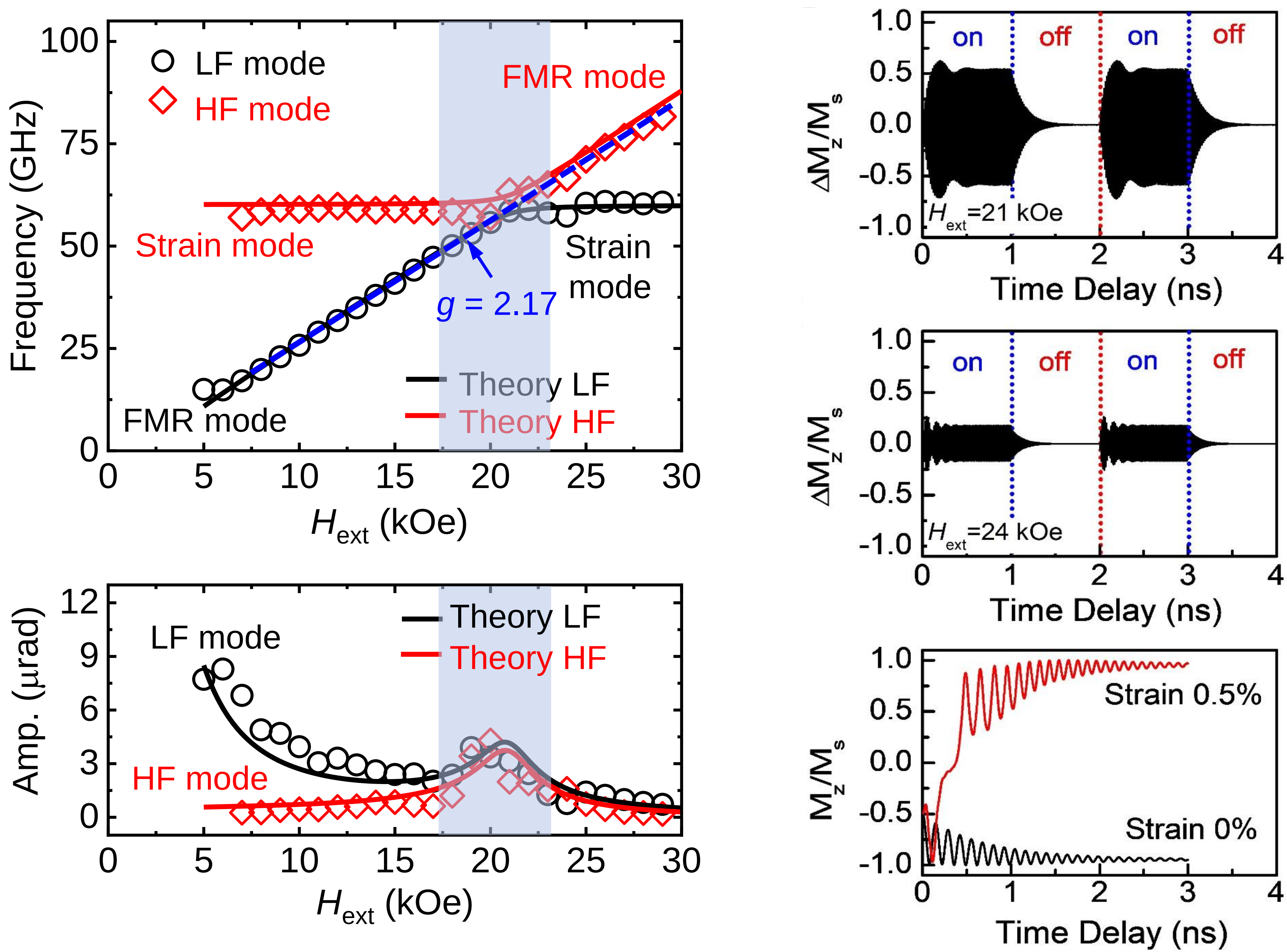
$[Co(0.8)/Pd(1.8)]_{11}$ multilayer (~ 38 nm)



TR-MOKE signals are field dependent

Picosecond acoustic signals are field independent

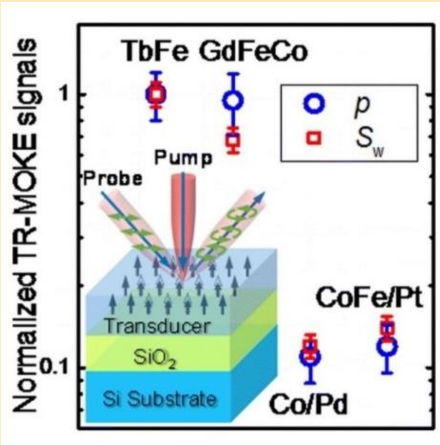
Stain-assisted ultrahigh frequency magnetic switching (~60 GHz)

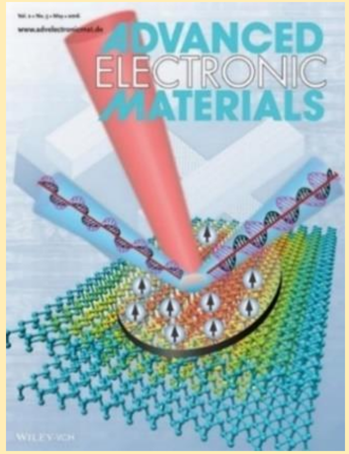


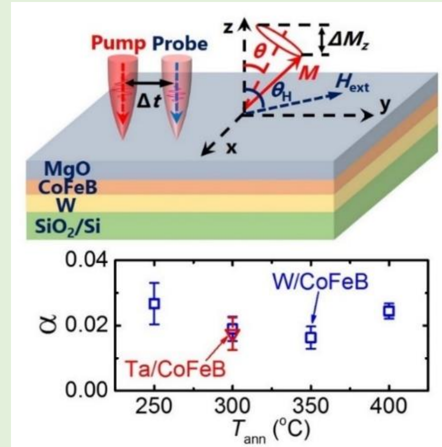
Zhu & Lattery et al. Science Advances, 6, eabb4606 (2020).

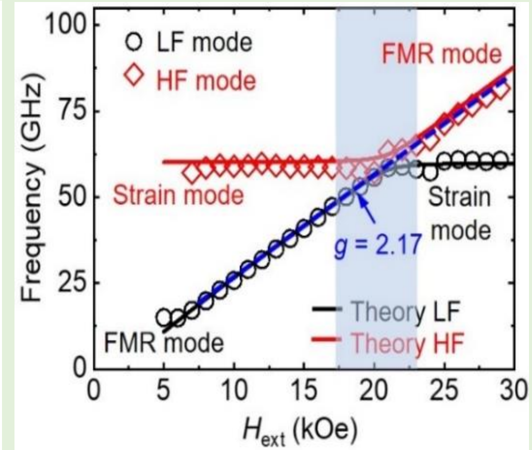
Simulation performed by Prof. Randall Victora at UMN/ECE.

Summary









- Ultrafast pump-probe technique offers a robust and high throughput way to study both the thermal properties and spin precession dynamics of materials, which are otherwise undetectable with conventional approaches;
- Metrology development is important to extend the instrument capabilities for more sensitive and accurate measurements of the transport properties of materials;
- The figure of merit for TR-MOKE characterization of thermal properties has been proposed, and the best magnetic transducer has been identified. The high-sensitivity thermal characterization of TR-MOKE has been demonstrated by studying the 3D anisotropic thermal conductivities of BP;
- The powerful capability of TR-MOKE has been demonstrated by studying the damping constant of magnetic materials (for both perpendicular and in-plane samples).