Pure spin pumping in 2D van der Waals materials

Karen Sobnath[1], Mehrdad Rahimi[1], Linsai Chen[1,2], Philippe Lafarge[1], Maria Luisa Della Rocca[1],

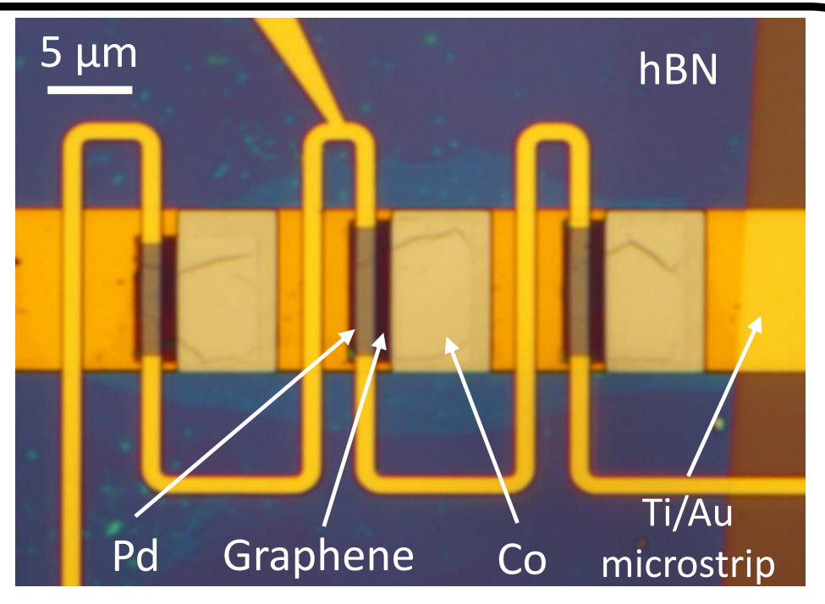
Bruno Dlubak[3], Clément Barraud[1] and François Mallet[1,4]

[1] Laboratoire Matériaux et Phénomènes Quantiques, Université Paris Cité, CNRS-UMR 7162, 75013 Paris, France
[2] ITODYS, Université Paris Cité, CNRS-UMR 7086, 75013 Paris, France
[3] Unité mixte de physique, CNRS, Thales, Université Paris Ssclay, 91767 Palaiseau, France
[4] Sorbonne Université, UFR925, 75005 Paris, France

Abstract

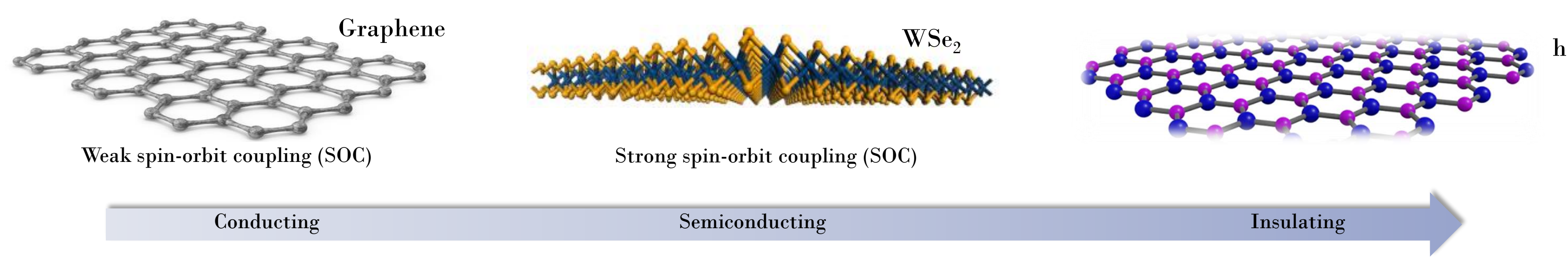
Pure spin current are carried by magnons, the quantum of excitation of a ferromagnet
Potential applications → for spintronics as information carrier with low energy consumption and dissipation
→ for novel quantum technologies as magnons can couple strongly to photons and phonons

Ferromagnetic resonance (FMR) is a powerful technique to study magnon damping. The absorption linewidth measured by FMR gives accurate information about magnetic anisotropies and interfacial interactions in ferromagnetic thin films. In this work, we investigate the influence of a Co thin film grown on various bidimensional (2D) materials on the gilbert damping and the effective magnetization. Our results reinforce the importance to consider the different damping mechanisms into play in order to characterize precisely the spin pumping in FM/2D material systems.



Co/graphene/hBN heterostructure for spin current injection via spin pumping and detection via Inverse Spin Hall Effect.

van der Waals materials for spintronics



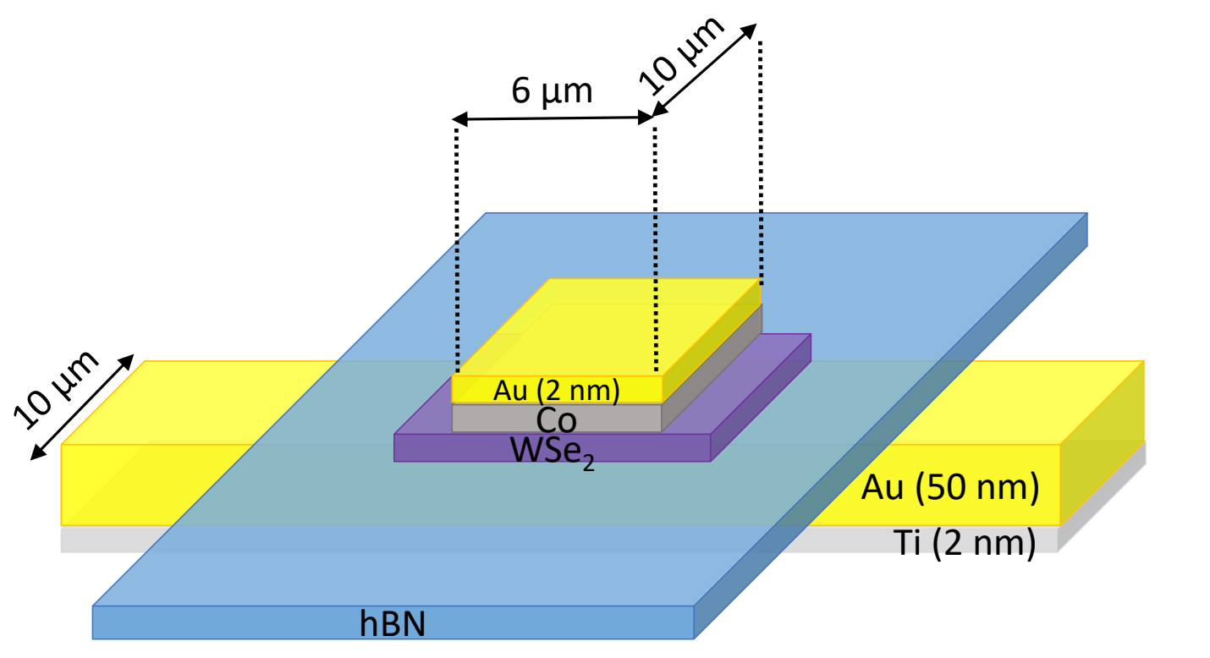
- <u>Advantages :</u>
  - Atomic control of the thickness
  - Wide landscape of emergent phenomena (spin-valley locking…)
  - Proximity effects in heterostructures

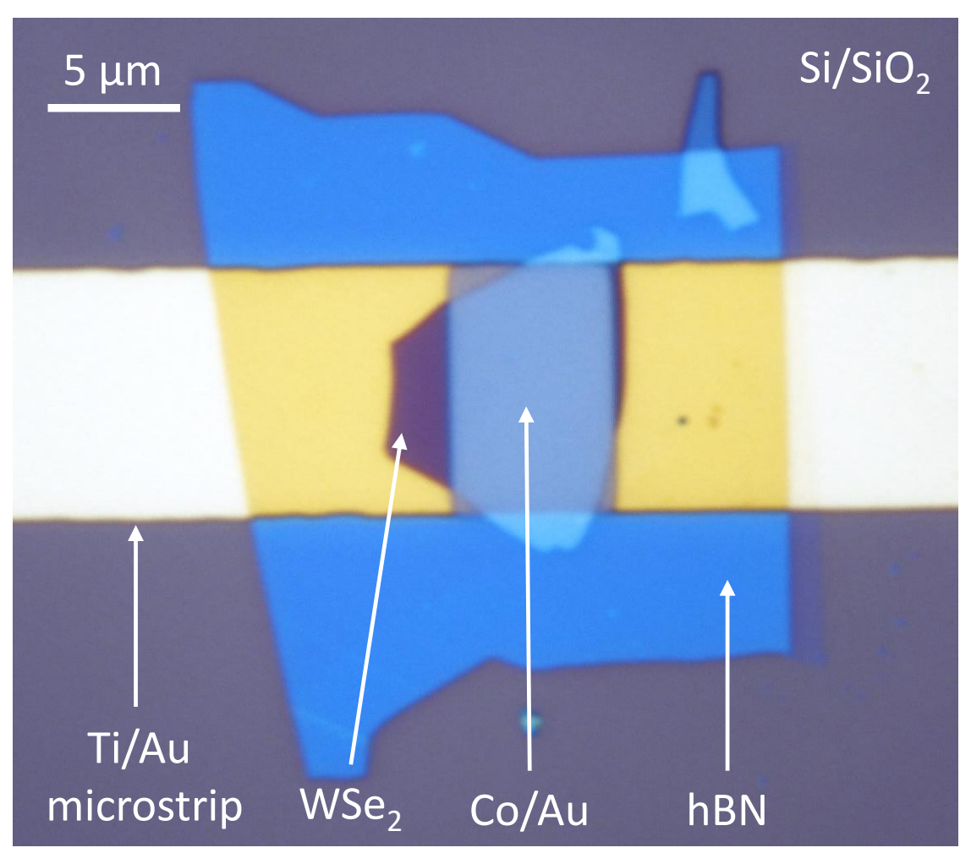
*L. L. Tao and E. Y. Tsymbal, Phys. Rev. B **100**, 161110 (2019)*
*Y. Saito et al., Nature Phys **12**, 144–149 (2016)*

*Y. Zhang et al., Nature **613**, 268-273 (2023)*
*T. S. Ghiasi et al., Nano Lett. **17**, 7528-7532 (2017)*
*Y. K. Luo et al., NanoLett. **17**, 3877 (2017)*

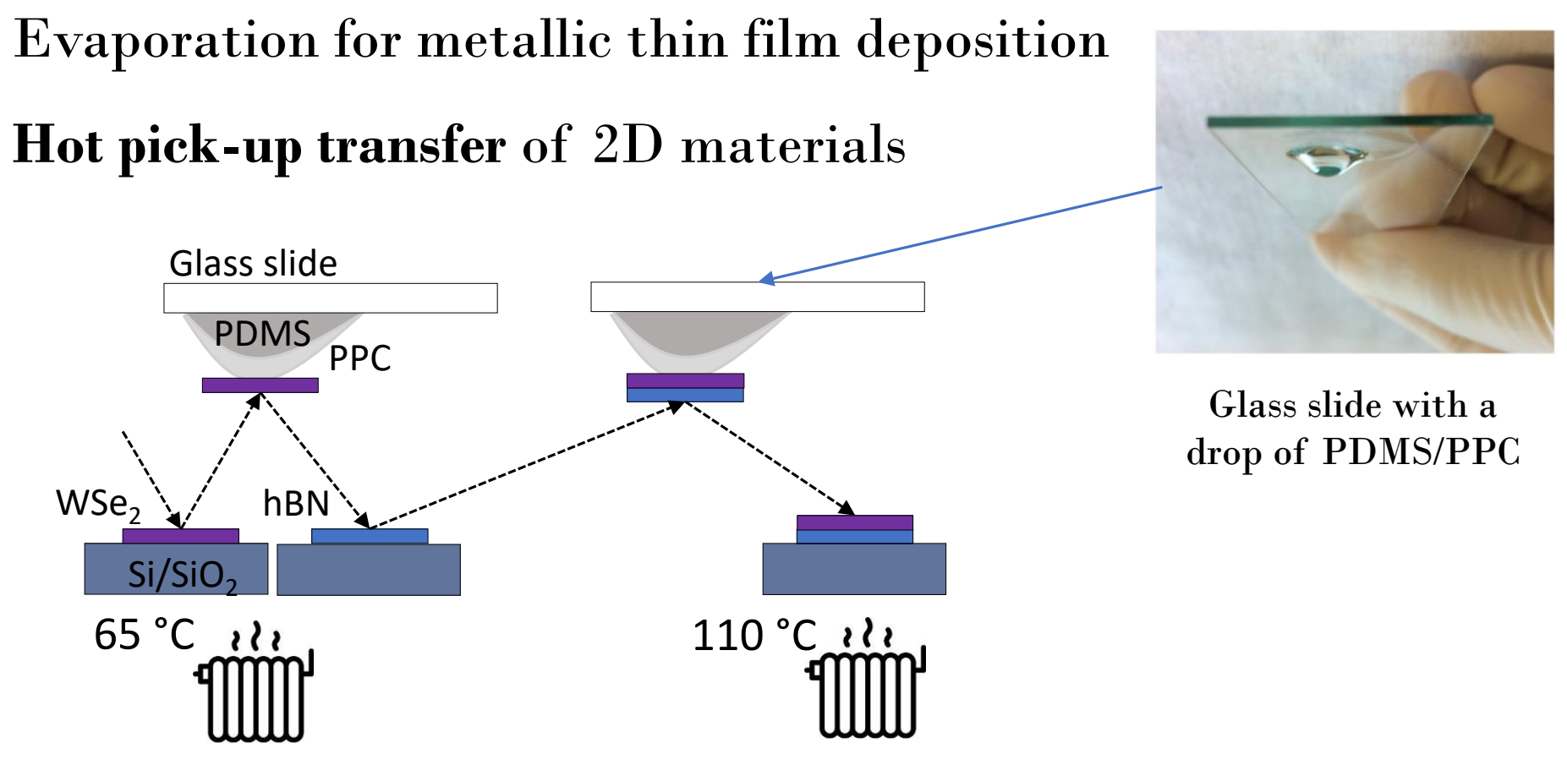
Device fabrication and characterizations

An on-chip microstrip waveguide has been designed to generate RF excitation of the ferromagnet and to measure the absorbed FMR signal transmitted through it.





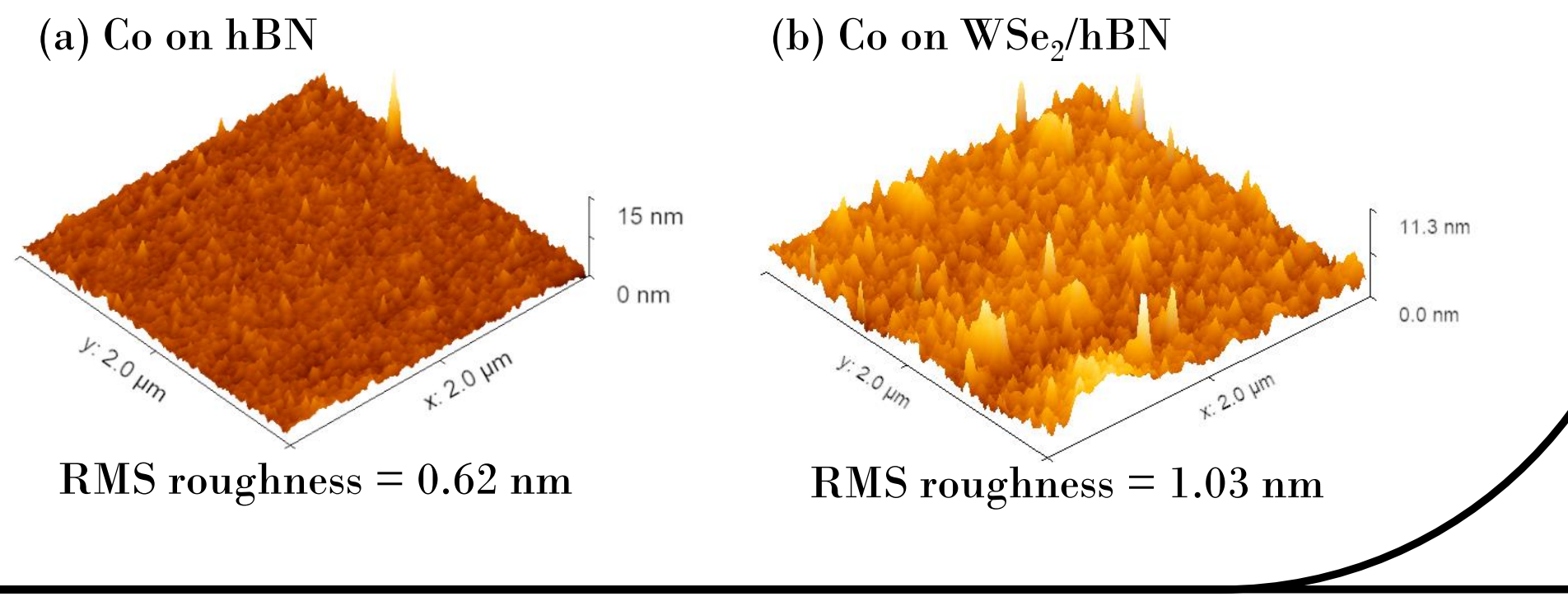
- <u>Fabrication techniques</u>
  - Optical and e-beam lithography
  - Evaporation for metallic thin film deposition
  - **Hot pick-up transfer** of 2D materials



Glass slide with a drop of PDMS/PPC

*F. Pizzocchero et al., Nat. Comm. **7**, 11894 (2016)*

- <u>Co surface topography measured by **atomic force microscopy** (AFM)</u>



(a) Co on hBN — RMS roughness = 0.62 nm

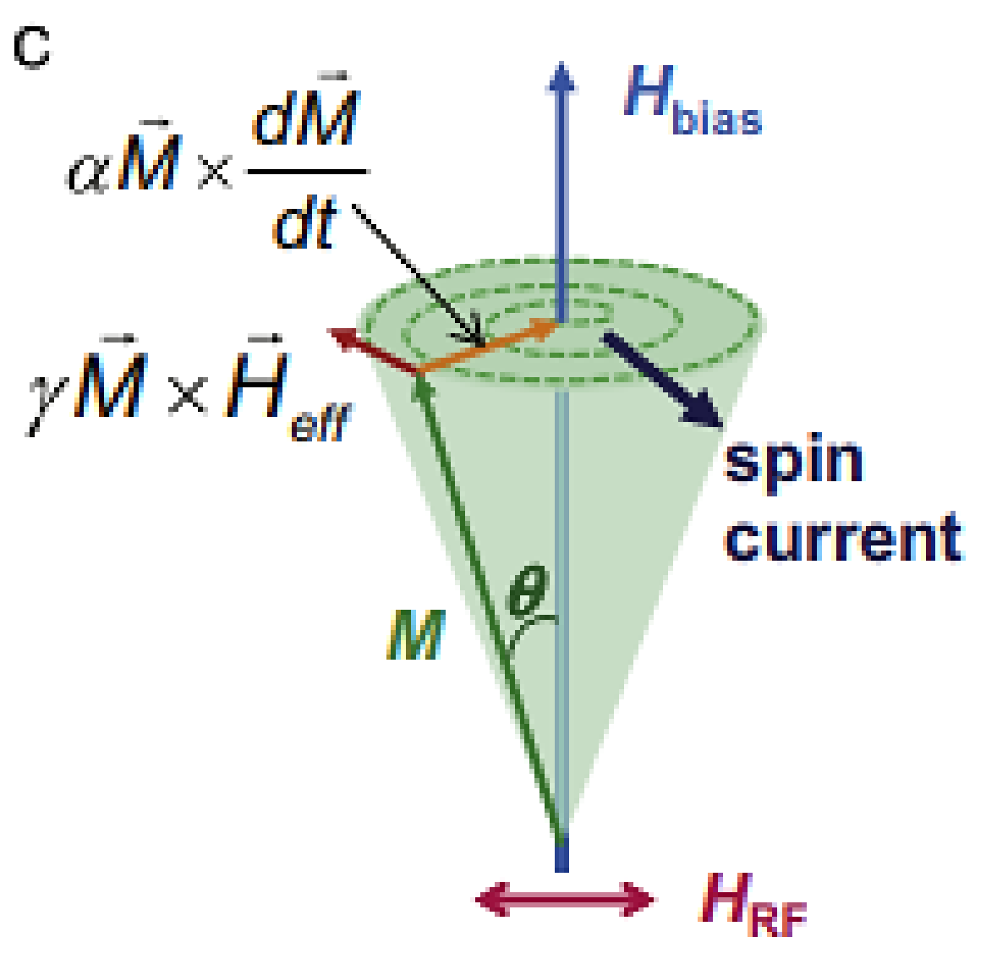
(b) Co on WSe$_2$/hBN — RMS roughness = 1.03 nm

Magnetization dynamics

- <u>Landau-Liftshitz Gilbert equation (LLG)</u>

$$\frac{d\boldsymbol{M}}{dT} = \underbrace{-\gamma(\boldsymbol{M}\times\boldsymbol{H}_{\boldsymbol{eff}})}_{\text{Precessionnal motion}} + \underbrace{\frac{\alpha}{M_s}\left(\boldsymbol{M}\times\frac{d\boldsymbol{M}}{dt}\right)}_{\text{Damping}}$$

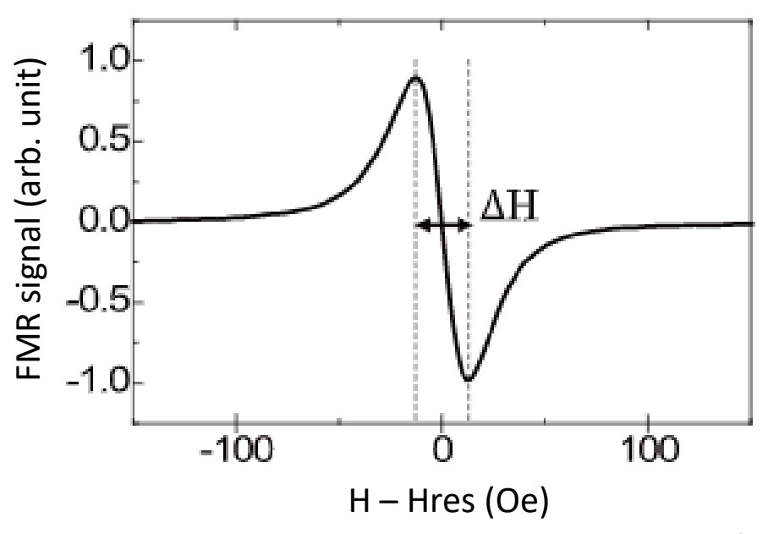
$\boldsymbol{M}$: Magnetization vector
γ : Gyromagnetic ratio
$\boldsymbol{H_{eff}}$: Effective field
α : Gilbert damping parameter
Ms : Saturation magnetization



- <u>Ferromagnetic resonance (FMR)</u>

$$\frac{dP}{dH} = K \times \frac{4\times\Delta H\times(H-H_{res})}{(4\times(H-H_{res})^2+\Delta H^2)^2} + \Delta K\times\frac{\Delta H^2 - 4\times(H-H_{res})^2}{(4\times(H-H_{res})^2+\Delta H^2)^2}$$

ΔH : Half-width at half maximum
H_{res} : Resonnance field
H : External magnetic field



- <u>Kittel's equation</u>

$$f_{RF} = \frac{\gamma\mu_0}{2\pi}\sqrt{H_{res}(H_{res}+4\pi M_{eff})}$$

μ_0 : vacuum permeability

- <u>Frequency dependent linewidth</u>

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

ΔH_0 : Frequency independent inhomogeneous linewidth

- <u>Gilbert damping</u>

$$\alpha = \alpha_{int} + \alpha_{SP} + \alpha_{TMS}$$

Intrinsic damping
Spin pumping
Two-magnon scattering (TMS)

$$\alpha_{SP} \propto \frac{g_{\uparrow\downarrow}}{t_{Co}}$$

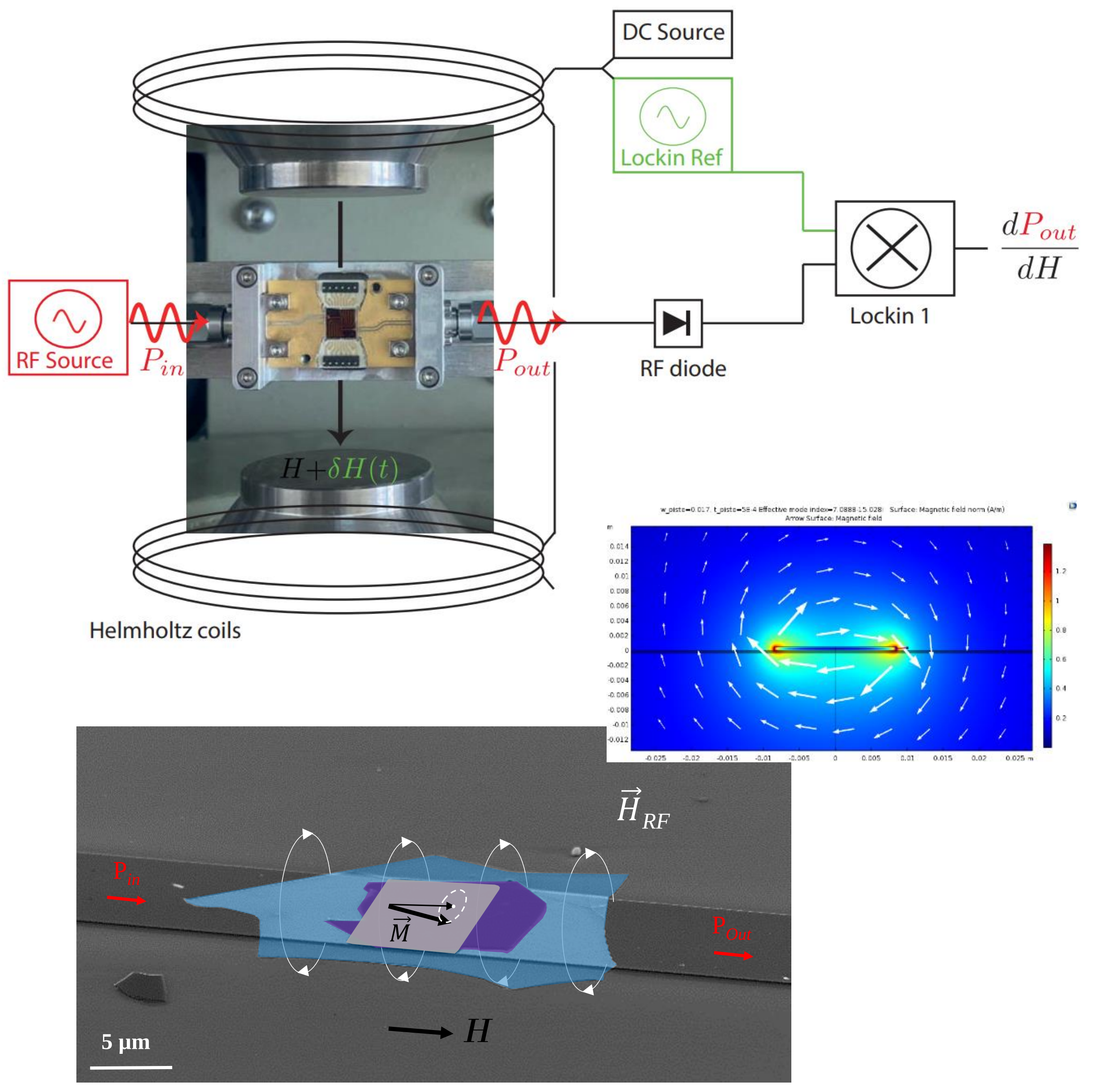
$g_{\uparrow\downarrow}$: effective spin mixing conductance

$$\alpha_{\mathrm{TMS}} \propto H_u^2 \times P \qquad \mathrm{H_u} \propto \frac{1}{t_{Co}}$$

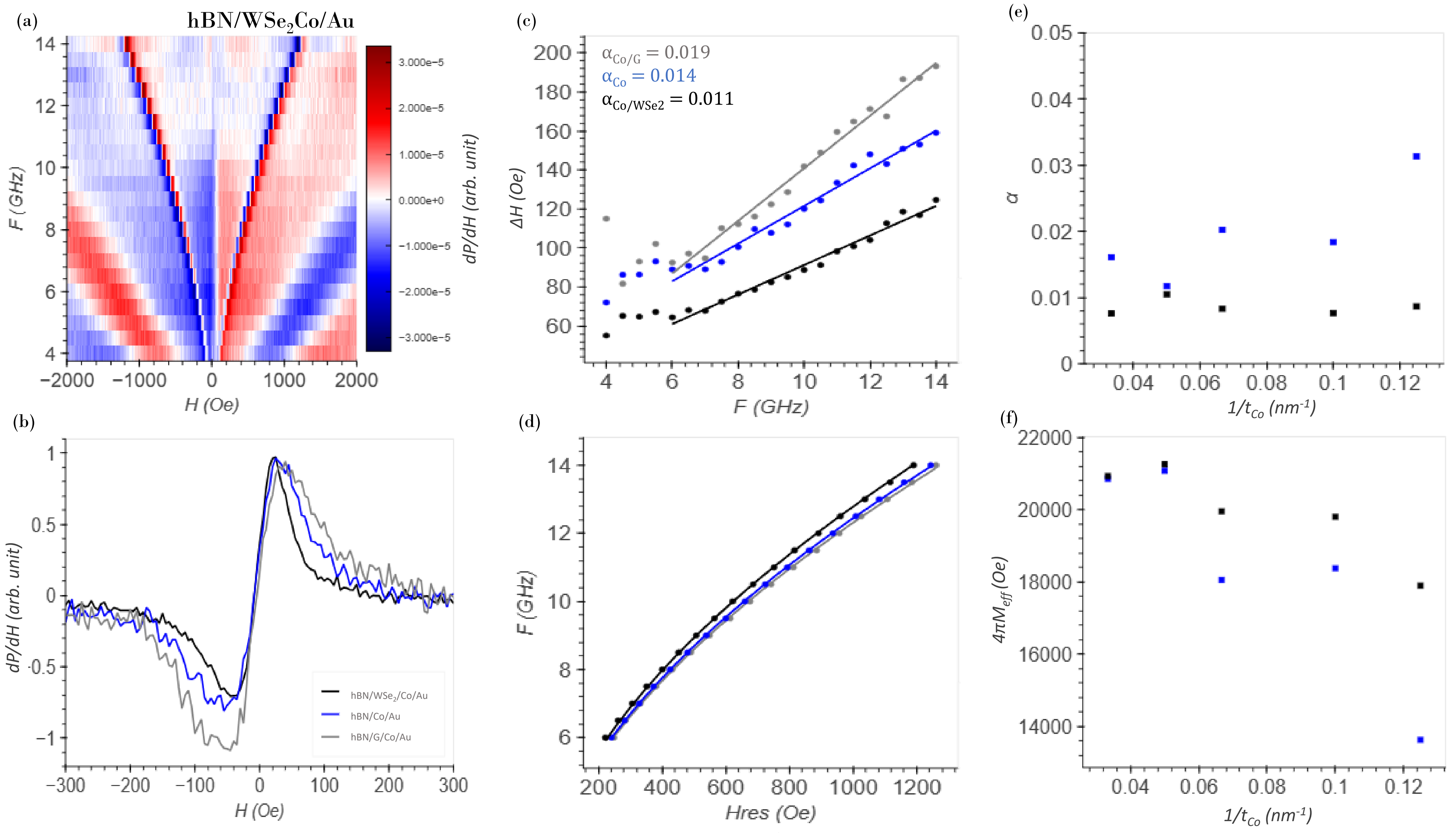
$\mathrm{H_u}$: Uniaxial anisotropy field
P : Surface defect fraction

*Y. Tserkovnyak, Phys. Rev. Lett. **88**, 117601 (2002)*
*S. Yoshii, Phys. Rev. B **106**, 174414 (2022)*

FMR measurements

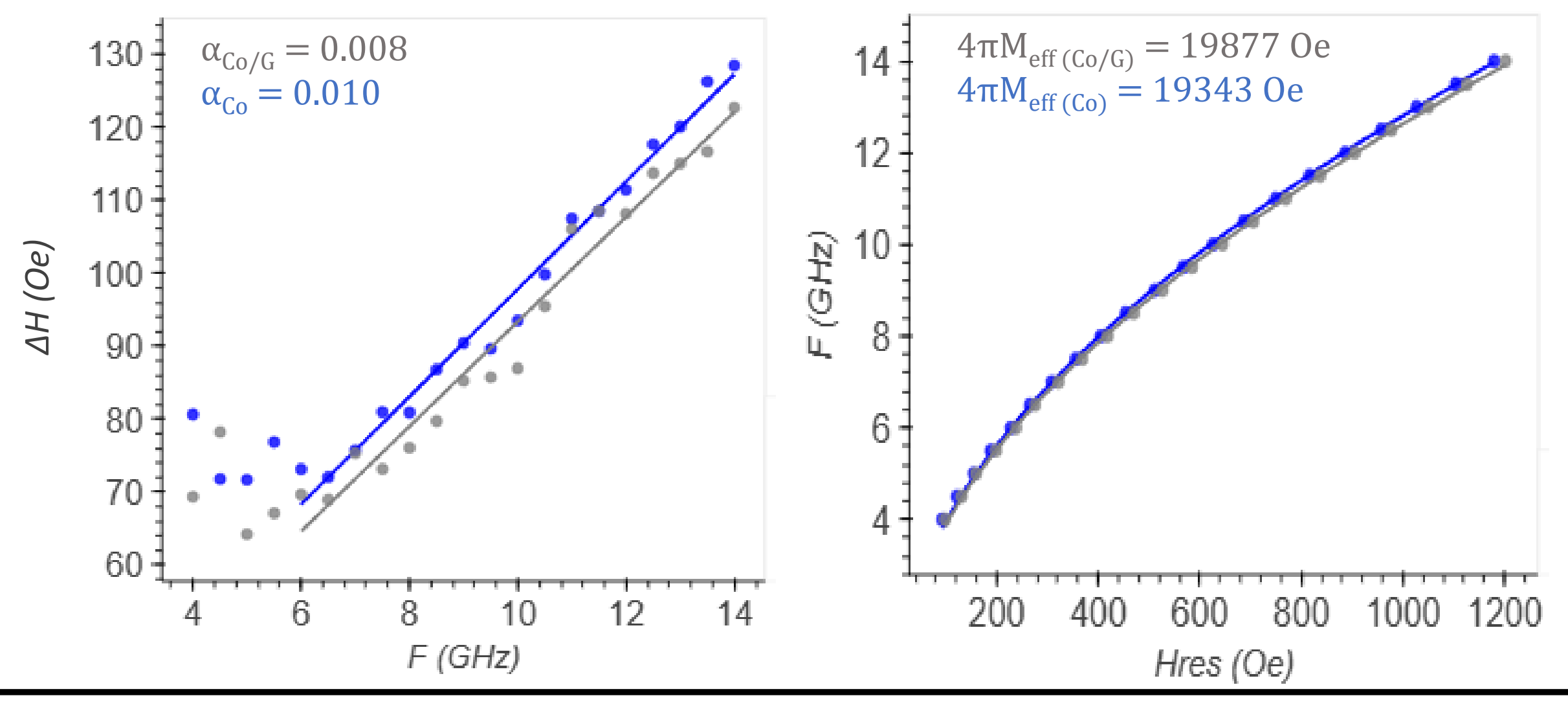


Scanning electron microscopy (SEM) image of a device composed of a Au/Co/WSe$_2$/hBN heterostructure (from top to bottom) deposited on top of an on-chip microstrip. On this sample, WSe$_2$ and hBN layers are 10 nm and 15 nm thick respectively.



Figures (a), (b), (c) and (d) shows results from a 15 nm thick evaporated Co film.

- <u>Sputtering of Co (work in progress …)</u>



On **graphene** : Magnon dissipation in ultrathin Cobalt is enhanced which is attributed to **spin pumping.**

On **WSe$_2$** : Magnon dissipation is greatly suppressed, and the bulk limit is recovered, which is attributed to the **suppression of surface magnetic anisotropy.**

Future plans

- Cross-sectional TEM
- Angle measurements
- Inverse spin Hall effect measurements
- Gate tunability
- Bi$_2$Se$_3$ (topological insulator)