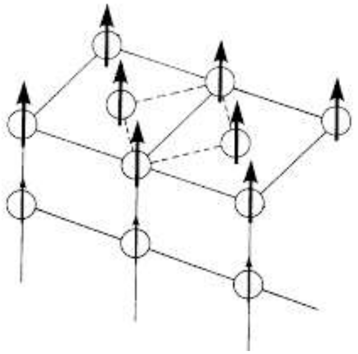
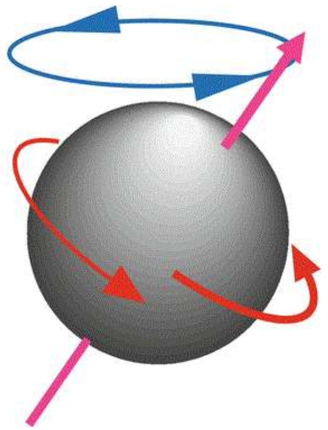


Characterization of Single Crystalline FeV thin Films on GaAs Substrate by Ferromagnetic Resonance

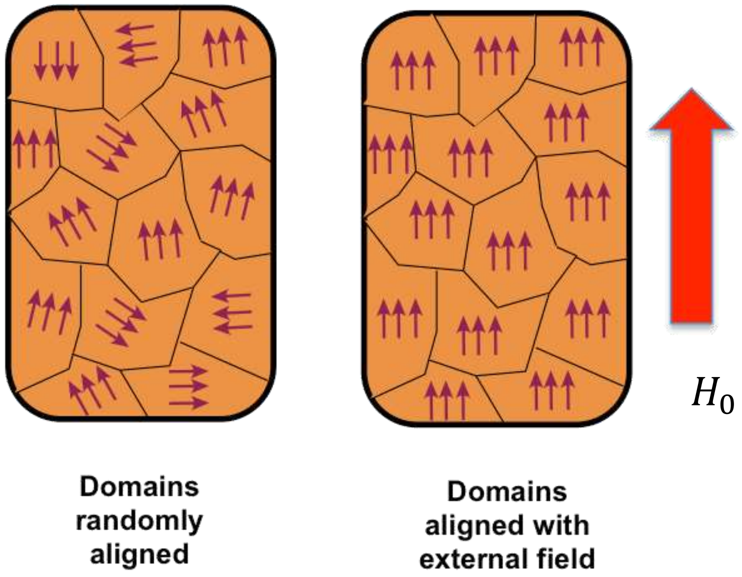


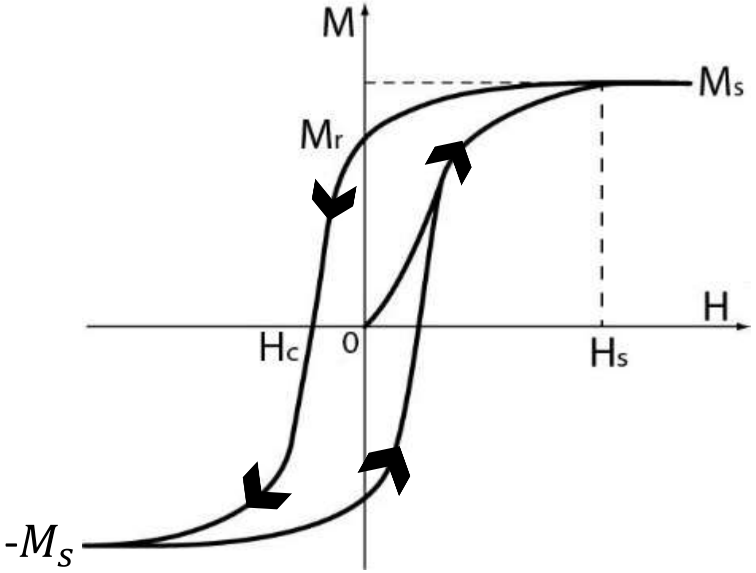
Student Name - G.D.K. De Silva
Supervisor - Matthieu Bailleul

Objectives

- ❖ Acquire experience of the Ferromagnetic Resonance (FMR) method and experimental setup.
- ❖ Understand the magnetic state of Fe and FeV thin films (20 nm) grow on GaAs substrate.

Ferromagnetic Materials





Hysteresis Curve

- ❖ If no magnetic field is applied, Each Domain align in different directions

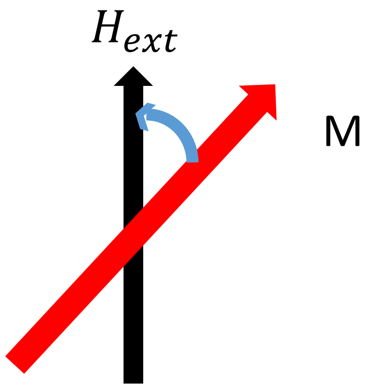
- ❖ If an external magnetic field is applied, domains align to the magnetic field

Magnetization (M) - The density of magnetic moments in a magnetic material

$$M = \frac{\sum m_i}{V}$$

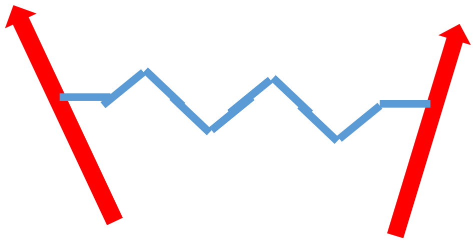
Saturation Magnetization (M_s) - maximum magnetic moment per unit volume for a magnetic material

Magnetic Energies



❖ Zeeman Energy

The interaction of the magnetization M with an **external magnetic field** H_{ext}.

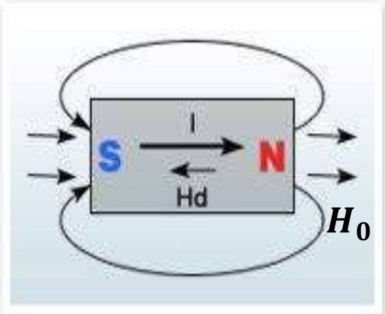


❖ Exchange Energy

Interaction Energy between **two Spins**

❖ Demagnetizing Field Energy

This is given by the **dipolar interaction** between magnetic moments in the material. This interaction creates a field that opposes the magnetization.



❖ Cubic Anisotropy Energy

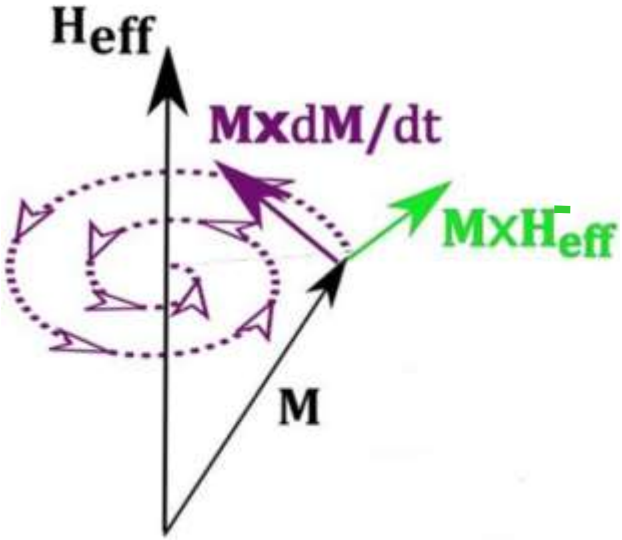
Energy that depends on **orientation of the magnetization** with respect to the lattice symmetry direction of the material

$$\mu_0 \overrightarrow{H_{eff}} = \overrightarrow{\nabla_{\vec{M}}} \varepsilon_T$$

$$\vec{H}_{eff} = \vec{H}_{Ze} + \vec{H}_{Ex} + \vec{H}_{de} + \vec{H}_{ku}$$

Magnetization Dynamics

Landau Lifshitz Gilbert equation

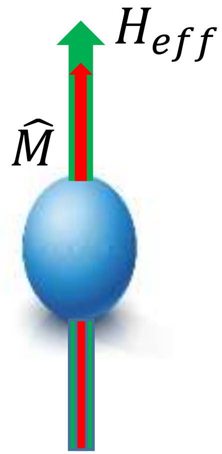


$$\frac{dM}{dt} = -\gamma M \times \mu_o H_{eff} + \alpha M \times \frac{dM}{dt}$$

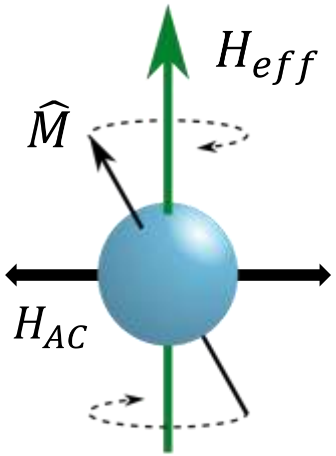
Steady State Precession

Dissipation Damping

$$f = \frac{\gamma \mu_0}{2\pi} \sqrt{(H_0 + H_x)(H_0 + H_y)}$$



- At equilibrium, magnetization will align with Effective magnetic field.



- Applying a transversal alternating magnetic field H_{AC} will drive the precession of magnetization M.

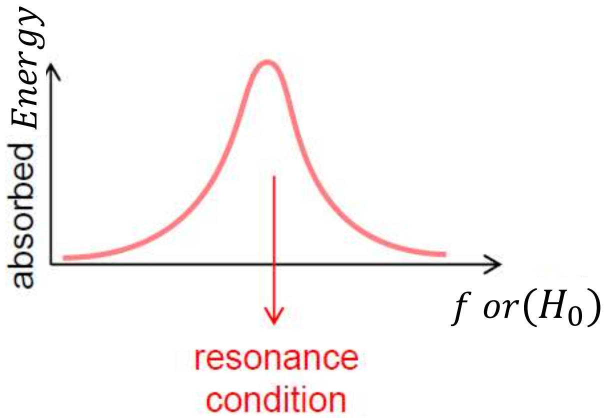
Ferromagnetic Resonance (FMR)

- Experimentally, the magnetization precession is driven by an external electromagnetic Wave (oscillating magnetic field)

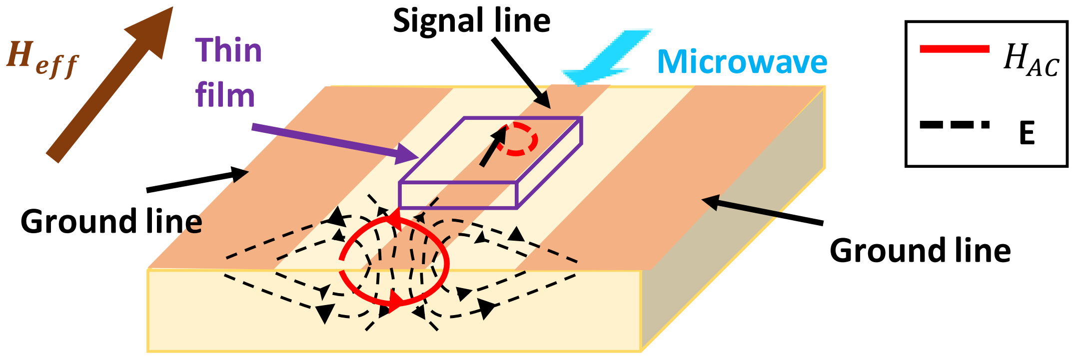
- The Magnetic material absorbs energy from the microwave leading to the magnetization precession.

- The energy absorption will be maximum when:

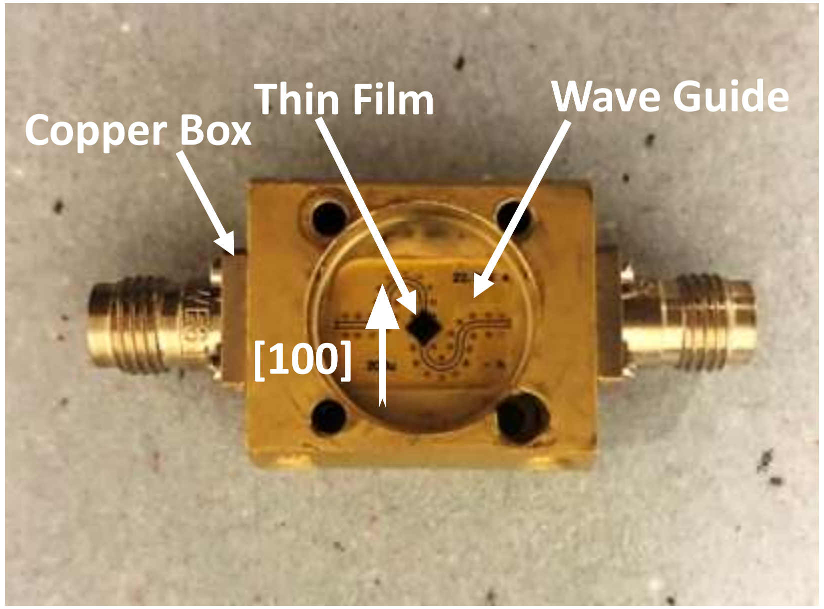
  The frequency of the excitation wave = resonance frequency of the magnetization.



$$f = f_{res}(H_0)$$

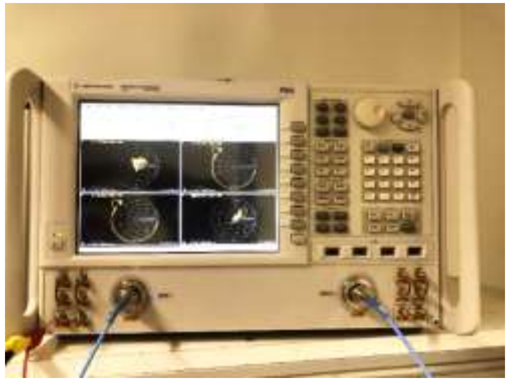


Coplanar Waveguide

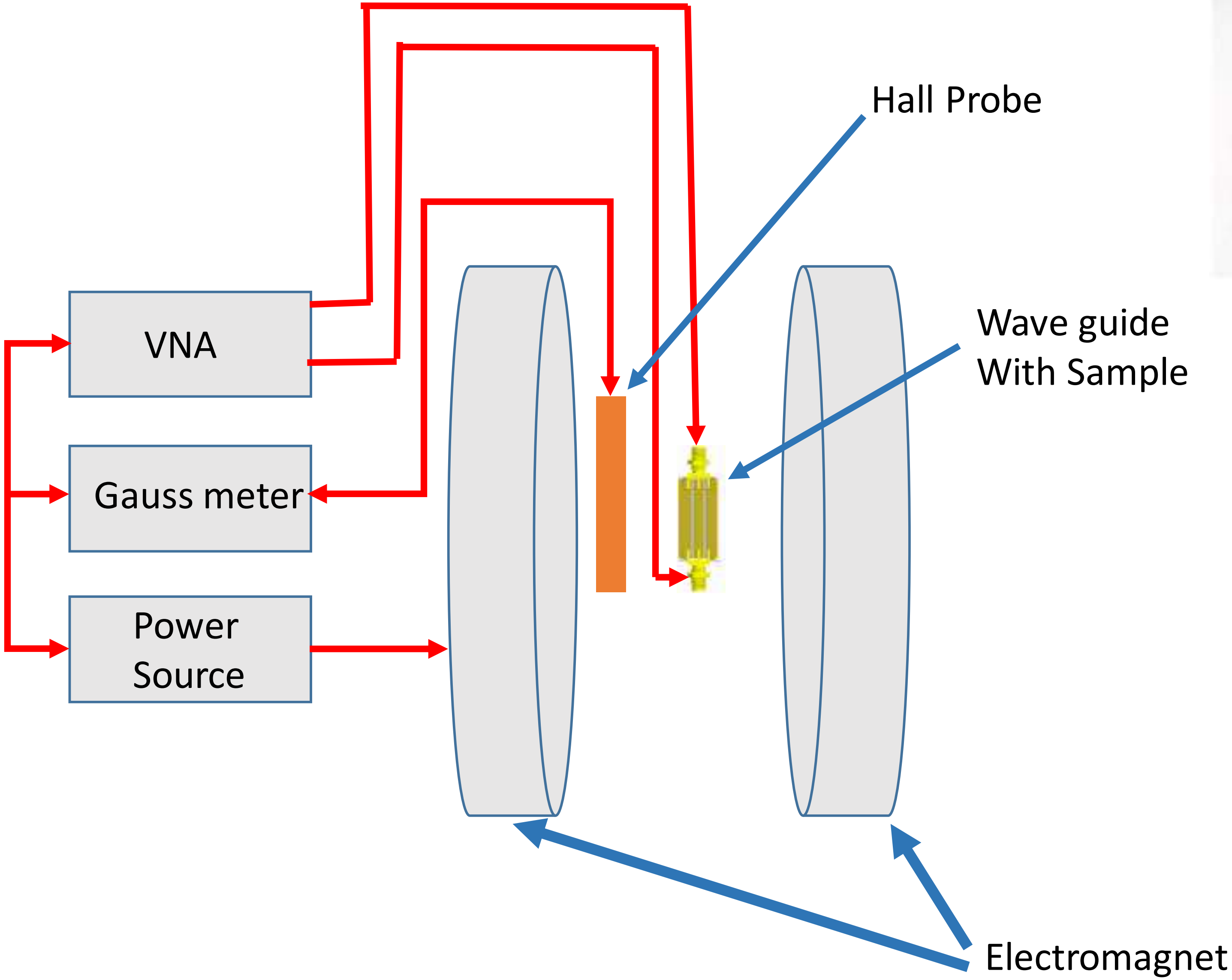


Coplanar Waveguide (inside the Copper Box) with a thin film on it.

Experimental Setup



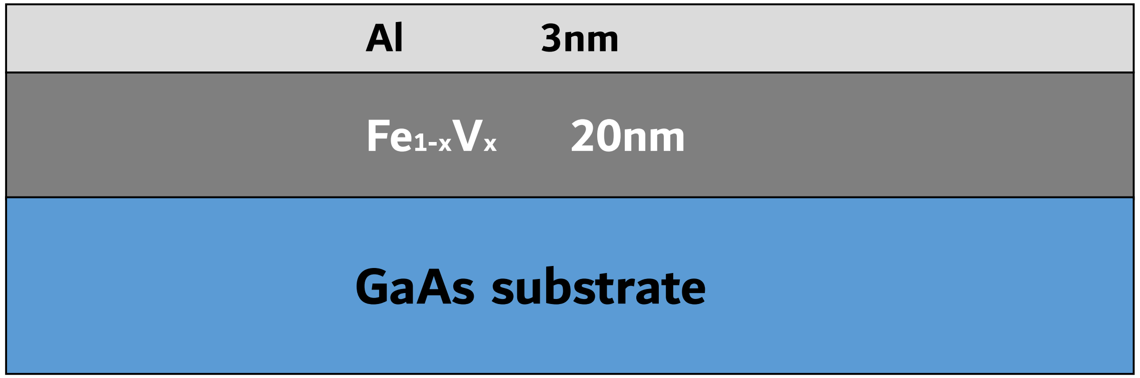
VNA (Vector Network Analyzer)



$Fe_{1-x}V_x$ Thin Films (single Crystalline)

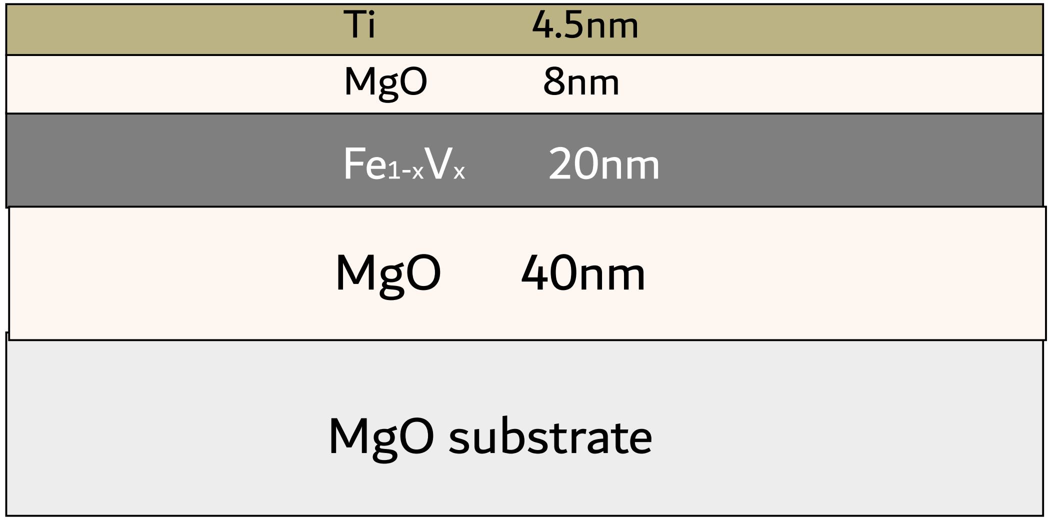
Grown by Molecular Beam Epitaxy (MBE)

by Matthias Kronseder



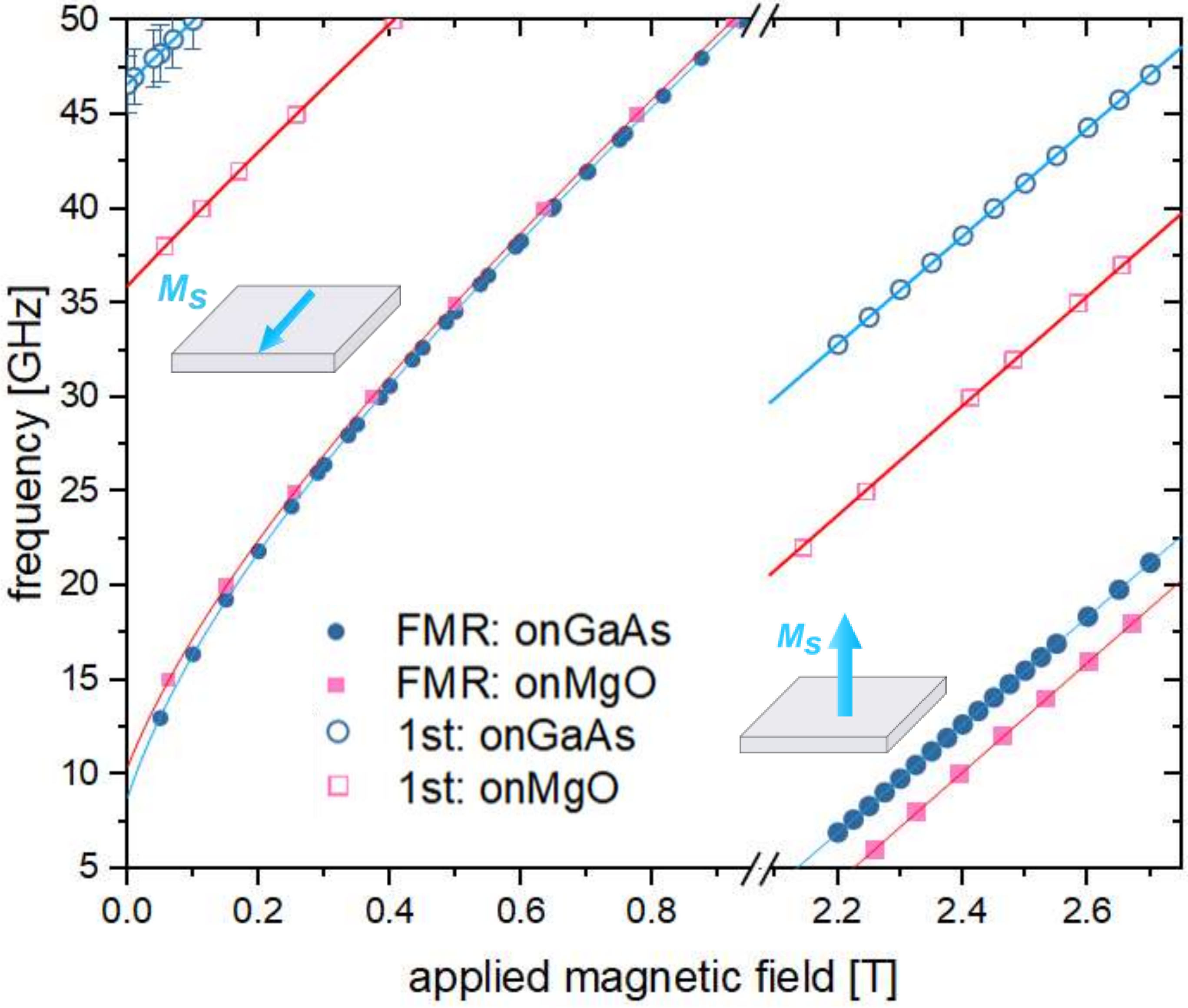
Films under study

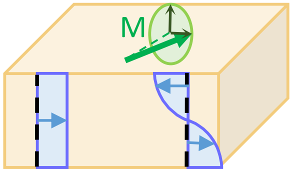
by David Halley (IPCMS)

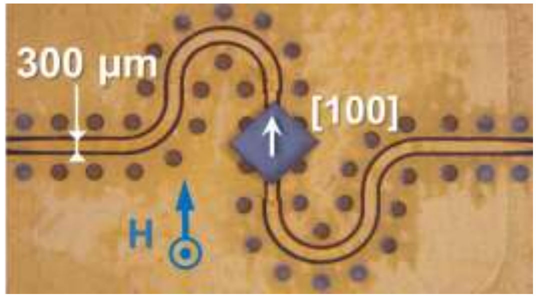


Reference Films

Fe: FMR







$$f = \frac{\gamma \mu_0}{2\pi} \sqrt{(H_0 + H_x)(H_0 + H_y)}$$

(In Plane)

$$f = \frac{\gamma \mu_0}{2\pi} (H_0 - H_Z)$$

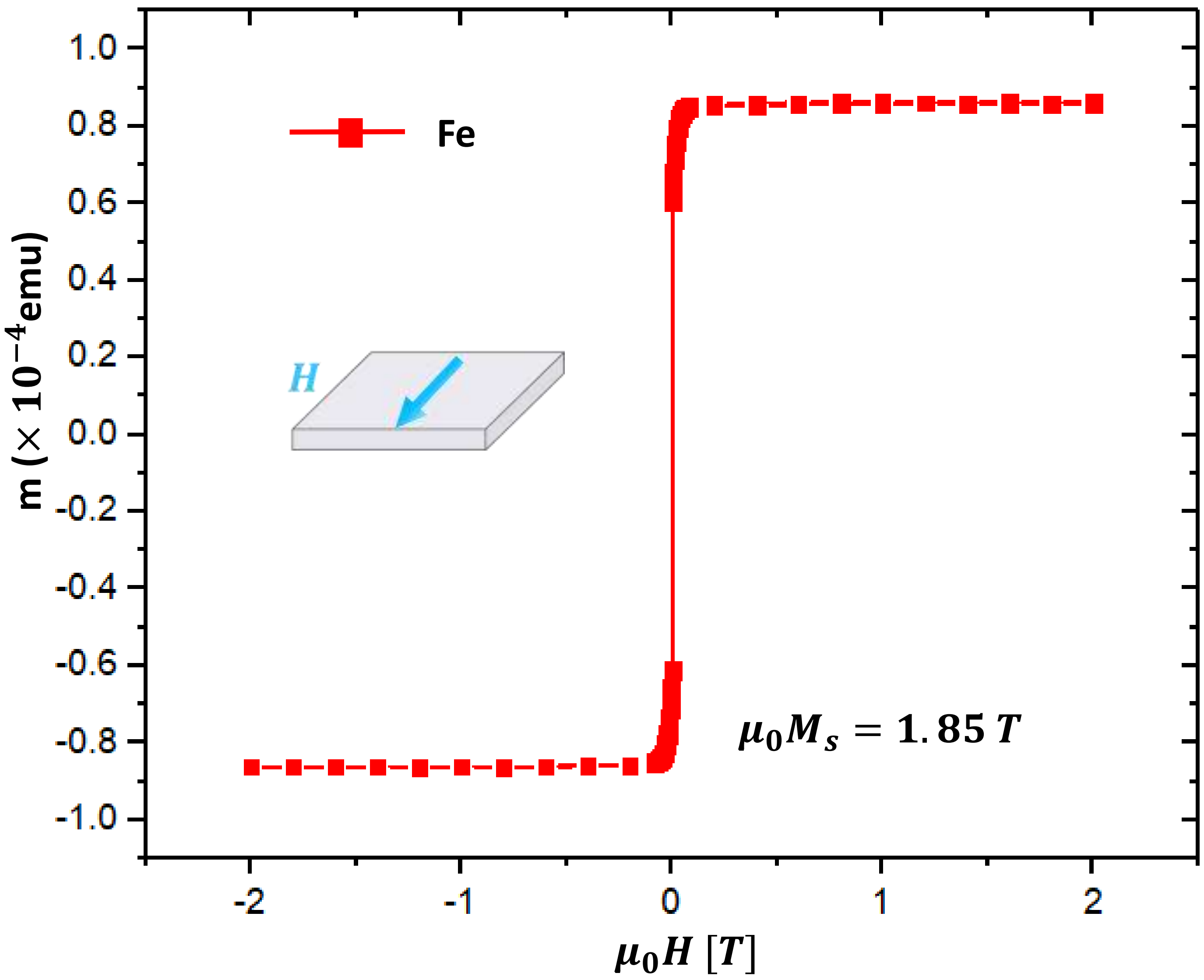
(Out Plane)

		on MgO (Reference)	on GaAs (Measured)	
H_x →	H_K [T]	0.06	0.04	↓
H_y →	M_{eff} [T]	2.07	2.07	-
H_y, H_z →	H_{ex}[T]	0.55	0.85*	↑

- Equal effective magnetization and increased exchange field* suggest a thickness smaller than expected: 16 nm

$$H_{ex} \; \alpha \; \frac{1}{M_s t^2}$$

Fe: SQUID (by Jerome Robert)

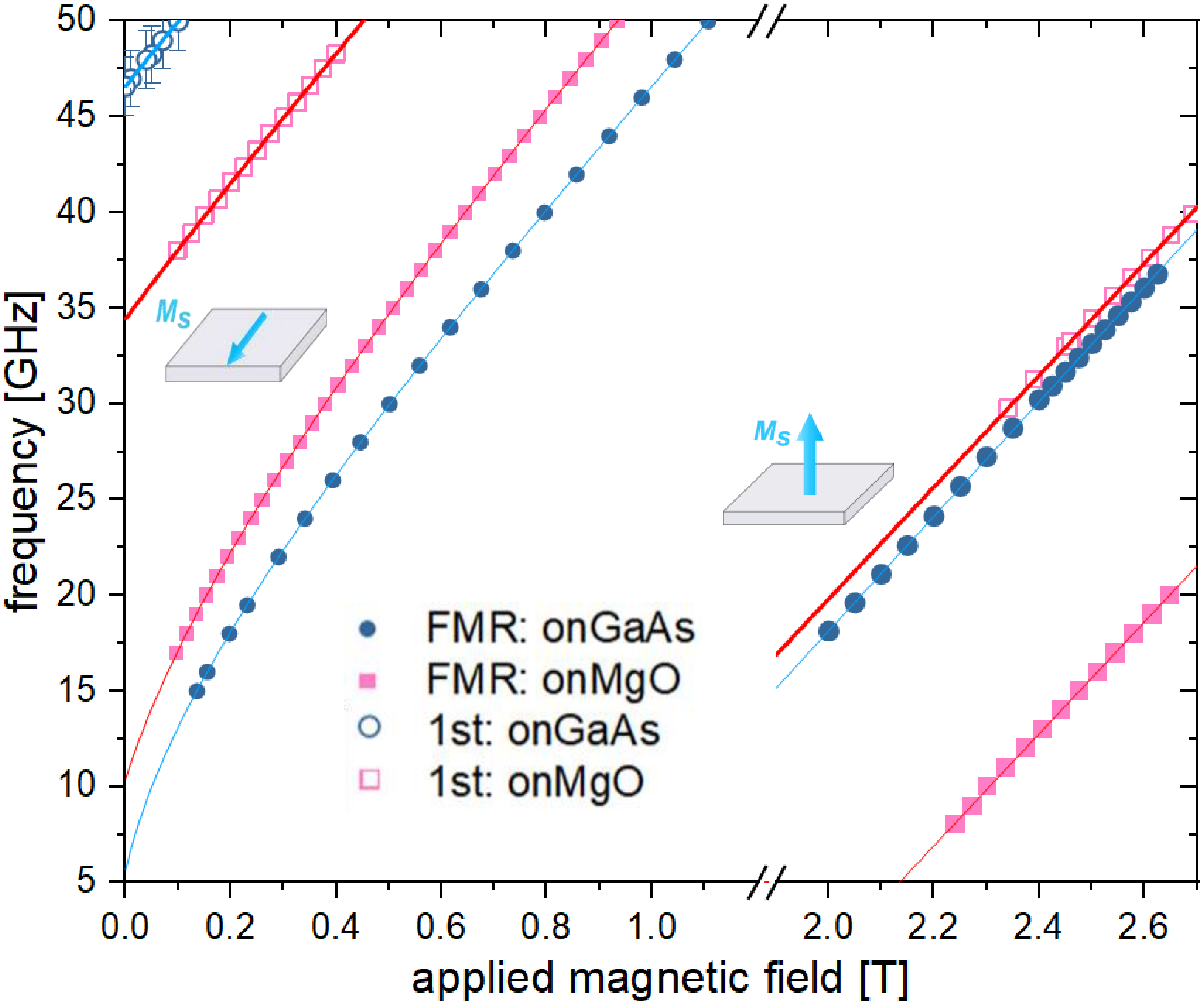


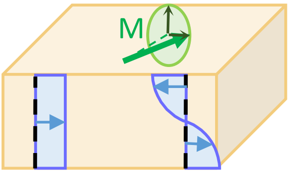
- Thickness =20 nm is assumed for the calculation of M.
- **Expected M_s: 2.15 T**

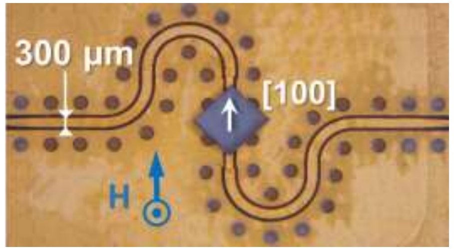
$$M_s = \frac{\sum m_i}{V}$$

- Thickness smaller than expected? 17 nm

FeV: FMR







f= $\frac{\gamma\mu_0}{2\pi}\sqrt{(H_0 + H_x)(H_0 + H_y)}$

(In Plane)

f= $\frac{\gamma\mu_0}{2\pi}(H_0 - H_Z)$

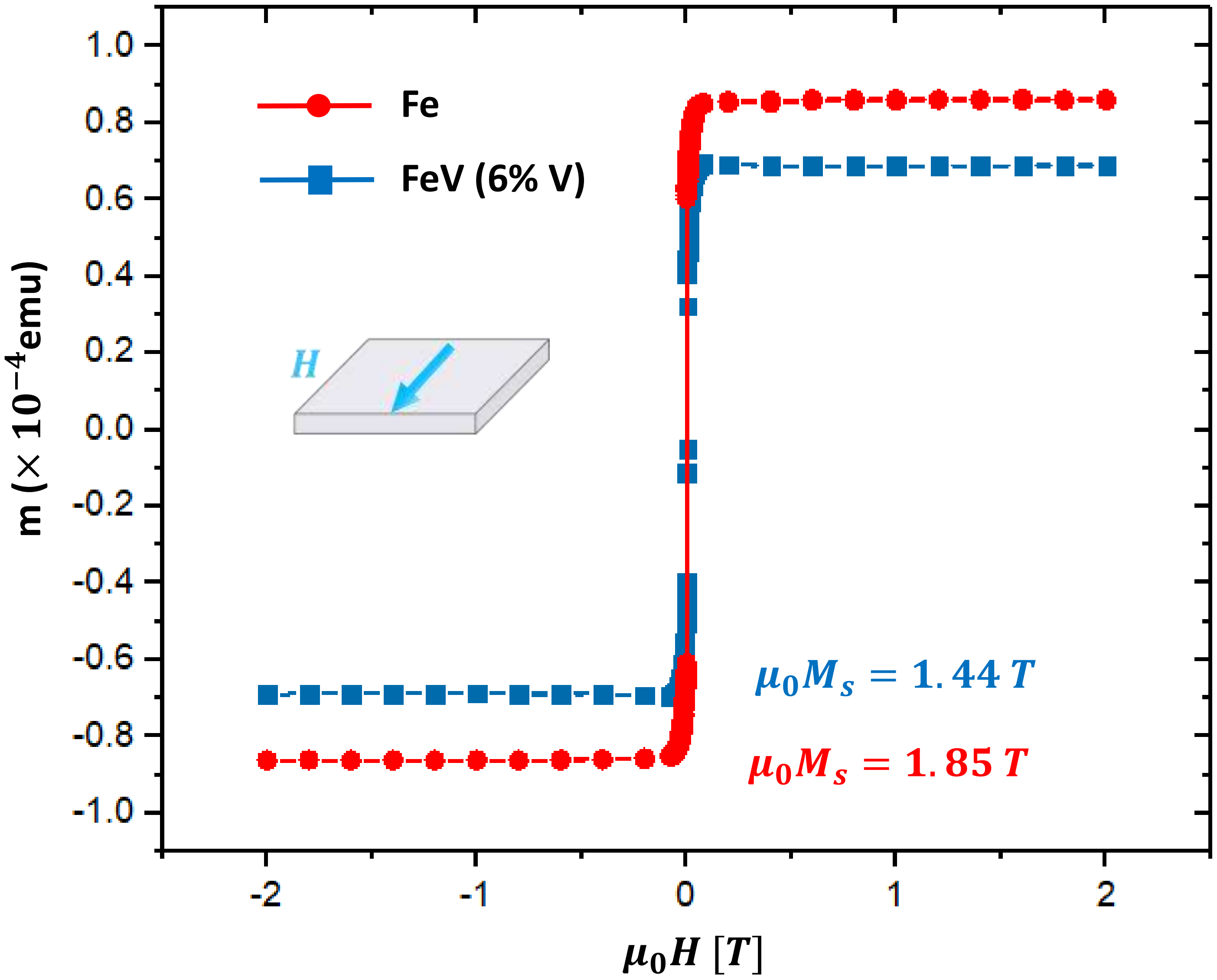
(Out Plane)

		on MgO (Reference)	on GaAs (Measured)	
H_x →	$\mathbf{H_K}$ [T]	0.06	0.03	↓
H_y →	$\mathbf{M_{eff}}$ [T]	1.99	1.48	↓
H_y, H_z →	$\mathbf{H_{ex}}$[T]	0.53	0.85*	↑

- Smaller effective magnetization and increased exchange field* suggest:
  - Lower Ms.(Saturation Magnetization)
  - Or/And thickness smaller than expected: 16 nm

$$H_{ex} \; \alpha \; \frac{1}{M_s t^2}$$

FeV (6% V): SQUID (by Jerome Robert)



- Thickness=20 nm is assumed for the calculation of M.
- **Expected Ms: 1.95 T**

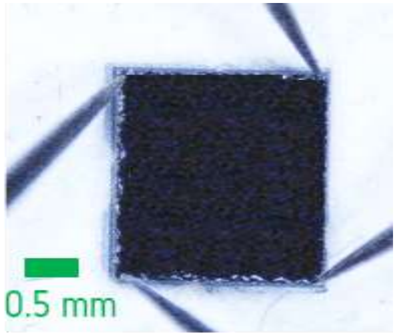
  [Devolder, Appl. Phys. Lett. 103, 242410 (2013)]

$$M_s = \frac{\sum m_i}{V}$$

1) Thickness smaller than expected? 15 nm?
2) V concentration higher than targeted? 20-24%?

Resistivity

Room Temperature Van der Pauw measurements,



For Fe,

sample	resistivity [μΩ cm]		
	MgO (Reference)	GaAs (Measured)	
MC211111C_e4	11.4 – 13.3	16.4	↑

- Actual Thickness = 15 nm ?

For FeV (6%)

sample	resistivity [μΩ cm]		
	MgO (Reference)	GaAs (Measured)	
MC211116A_a1	25	54.2	↑

- Actual Thickness = 9 nm ?

=> Increased concentration of impurities. (Higher than 6%)

Conclusions

For Fe;

1. All measurements agree with an actual thickness < 20 nm.

2. Decrease of cubic anisotropy: An indication of impurities in the film?

For FeV;

1. In this case, a smaller thickness may not be the only explanation.

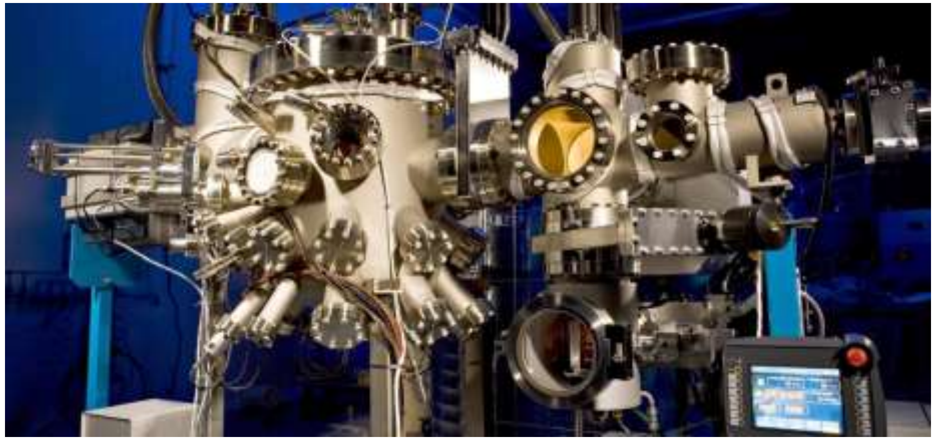
2. Measurements also suggest an M_s smaller than expected:
   $\Rightarrow$ Larger concentration of V impurities.

- **So this characterization gave clues to that the samples where not in the required condition. Therefore, the characterization continued to understand the origin of the problems**
- **Now we know the films are actually 17-18 nm thick, and the V concentration is higher than expected (9.5 – 12 %). Also there is some oxygen inside.**
- **By considering all these things, growth condition need to be checked and Al capping layer should be also improved.**

THANK YOU

Backups

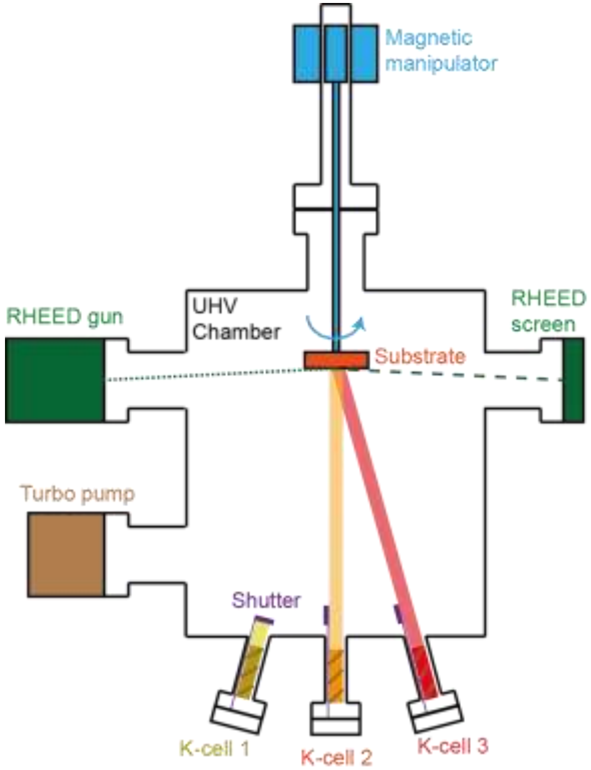
MBE (Molecular Beam Epitaxy)



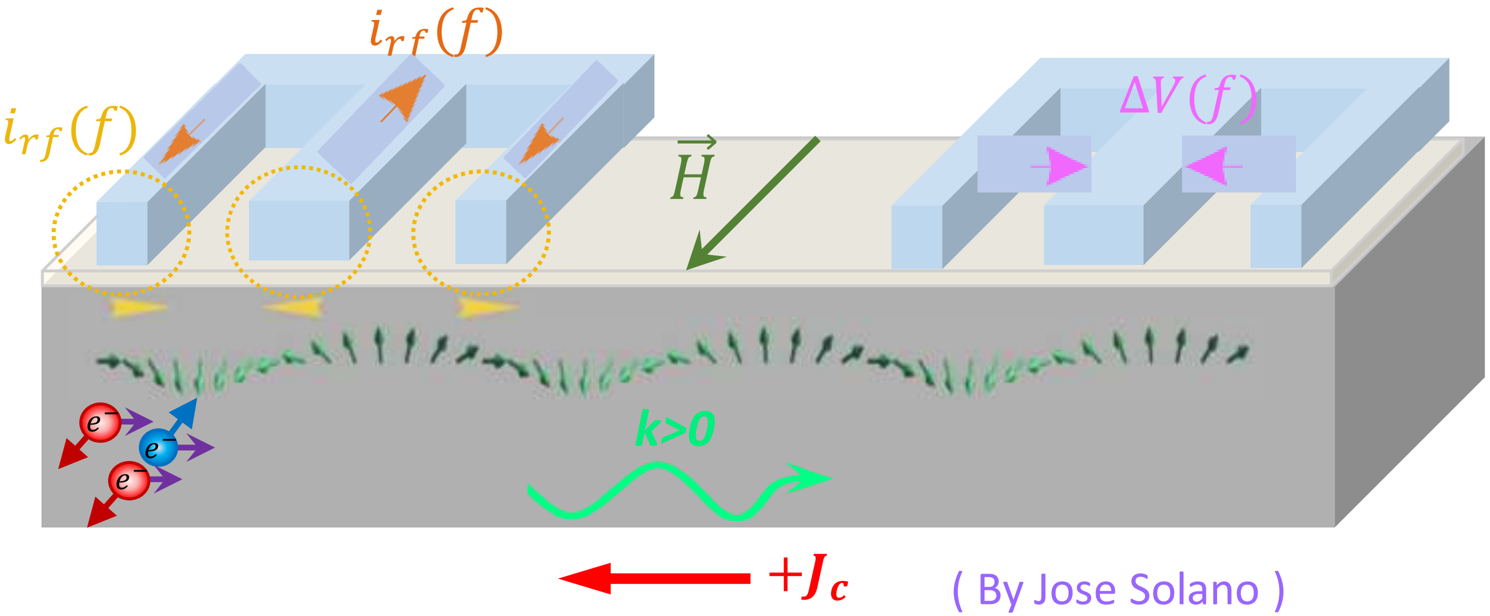
- MBE has evolved in to one of the most widely used techniques for producing epitaxial layers of metals, insulators and superconductors as well.

- it consists essentially of atoms or clusters of atoms, which are produced by heating up a solid source.

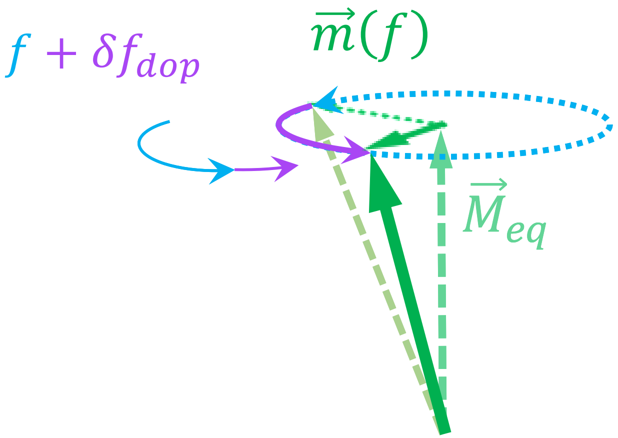
- They then migrate in an UHV environment and impinge on a hot substrate surface, where they can diffuse and eventually incorporate in to the growing film.



Application – Spin Wave Doppler Shift



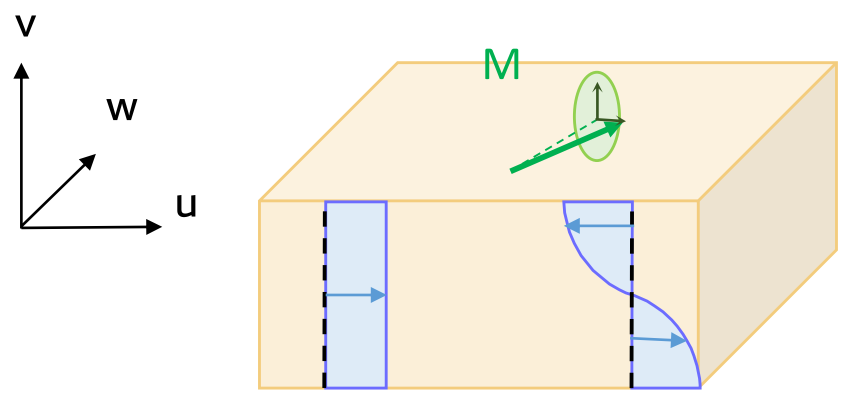
(By Jose Solano)



$$\frac{\partial \vec{M}}{\partial t} = -\gamma \mu_o \vec{M} \times \vec{H} - u \frac{d\vec{M}}{dx}$$

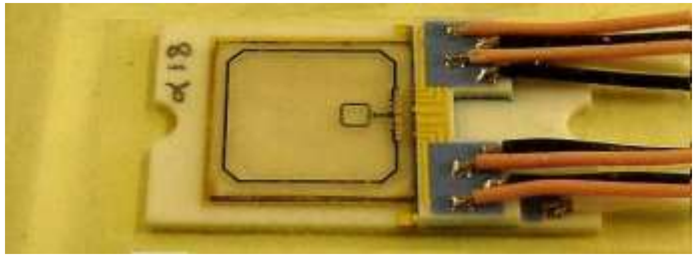
- Two antennas on top of the sample, exiting with respective magnetic fields.
- in magnetic materials, there is an unbalance between spin up and spin down electron densities. (two current models)
- That create an effective magnetic moment.
- That effective magnetic moment interact with the spin waves and produce a frequency shift.
- This shift depends on sign of the current or propagation direction of the spin wave.
- This effect doesn't change the magnitude of the magnetization. Only modifies its frequency.

Spin Wave Modes

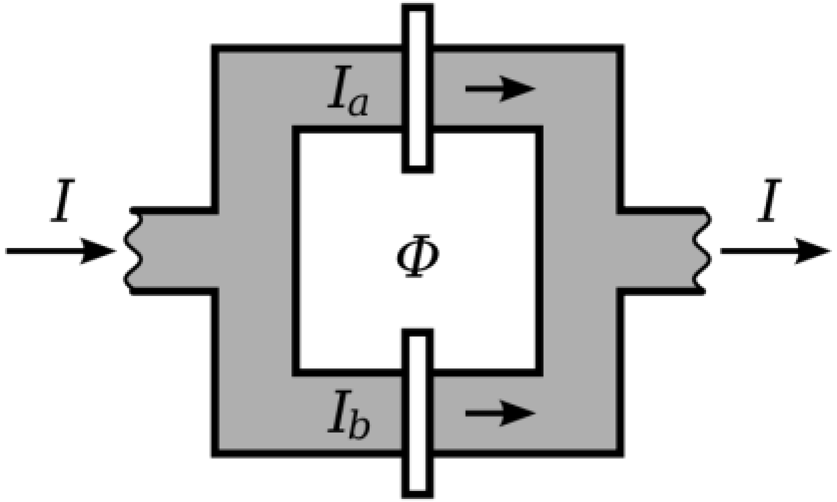


- They are thickness modes. Because of constrain thickness.
- Confinement of the magnetization oscillations leads to a discretization of the energy levels of the spin waves (spin wave modes become distinguishable)

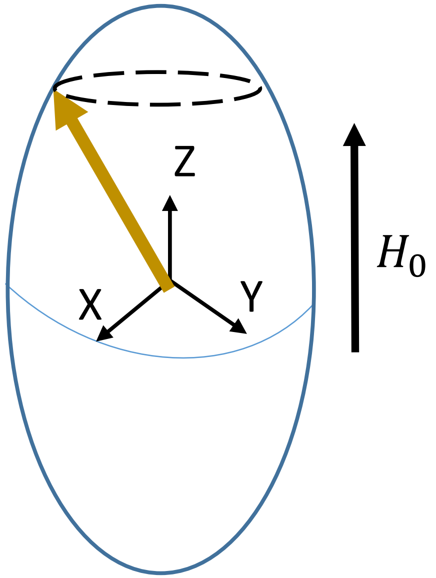
SQUID (superconducting quantum interference device)



- The most sensitive magnetic flux detector is the superconducting quantum interference device SQUID.
- Contains two Josephson junctions (insulators) between two super conducting Wires.
- Classically, current not conducting through this.
- But in quantum mechanical limit, there is a probability for tunneling.
- It depends on temperature and amount of magnetic moments.



Derivation of resonance frequency Equations



$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \boldsymbol{\mu_o H_{eff}}$$

Landau Lifshitz equation

$$\vec{h} = \overline{\chi_k}^{-1}\vec{m} = \frac{1}{\gamma\mu_0 M_s}\begin{pmatrix} \omega_x & -i\omega \\ i\omega & \omega_y \end{pmatrix}\vec{m}$$

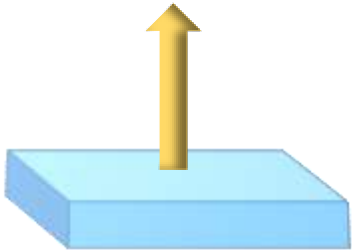
$$\omega_x = \gamma\mu_0(H_0 + (N_x - N_z)M_s) \qquad \omega_y = \gamma\mu_0(H_0 + (N_y - N_z)M_s)$$

$$\boxed{\omega = \sqrt{\omega_x\omega_y}}$$

Kittel Formula

$$\omega_{res} = \gamma\mu_0\{[(H_0 + (N_x - N_z)M_s)\gamma\mu_0(H_0 + (N_y - N_z)M_s)]\}^{1/2}$$

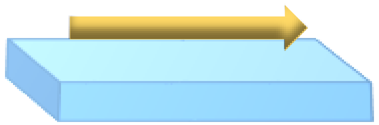
Out Plane



$$N_x = N_y = 0 \qquad N_Z = 1$$

$$\boxed{\omega = \gamma\mu_0(H_0 - M_s)}$$

In Plane

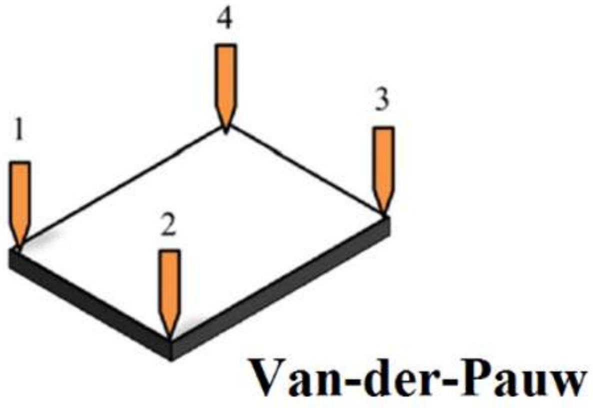


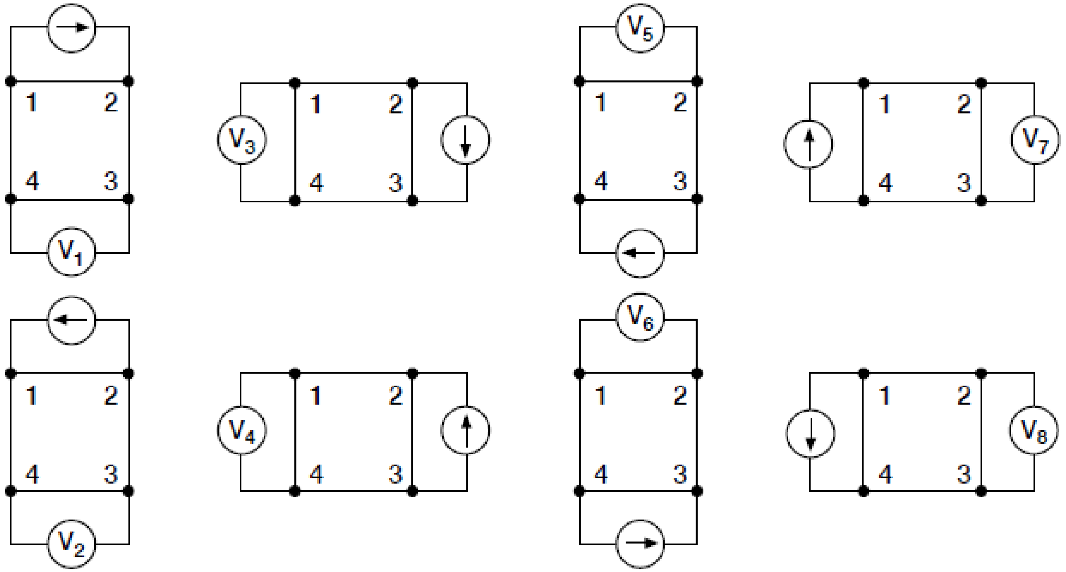
$$N_y = N_z = 0 \qquad N_x = 1$$

$$\boxed{\omega = \gamma\mu_0\sqrt{H_0(H_0 + M_s)}}$$

Van der Pauw Resistivity Measurement Method

- The van der Pauw method involves applying a current and measuring voltage using four small contacts on the perimeter of a flat, arbitrarily shaped sample of uniform thickness





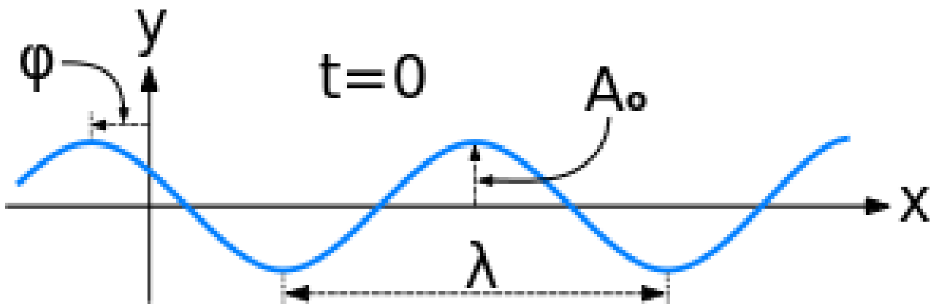
$$\rho_A = \frac{\pi}{ln2} f_A t_s \frac{(V_1 - V_2 + V_3 - V_4)}{4I}$$

$$\rho_B = \frac{\pi}{ln2} f_B t_s \frac{(V_5 - V_6 + V_7 - V_8)}{4I}$$

$$\rho_{AVG} = \frac{\rho_A + \rho_B}{2}$$

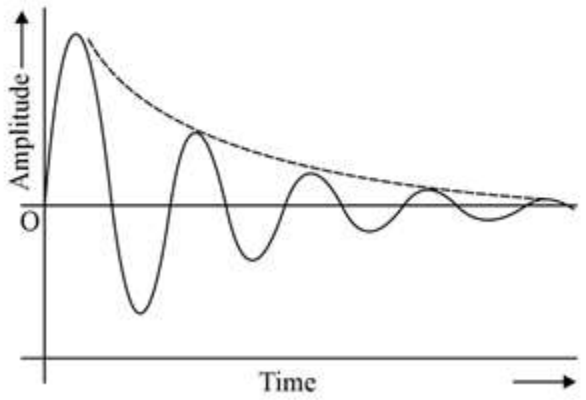
$* \, f_A , f_B = Geometrical\ Factors\ (Based\ on\ sample\ geometry)$
(f_A =f_B=1 for perfect symmetry)

Plane Waves



$$U(r,t) = Ae^{i(k.x - \omega t)}$$

$$U(r,t) = Acos(k.x - \omega t) + iAsin(k.x - \omega t)$$



$$U(r,t) = Ae^{-\lambda}e^{i(k.x - \omega t)}$$

Landau Lifshitz Equation

- There is no damping term
- Signal width is zero

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \mu_o \boldsymbol{H}_{eff}$$

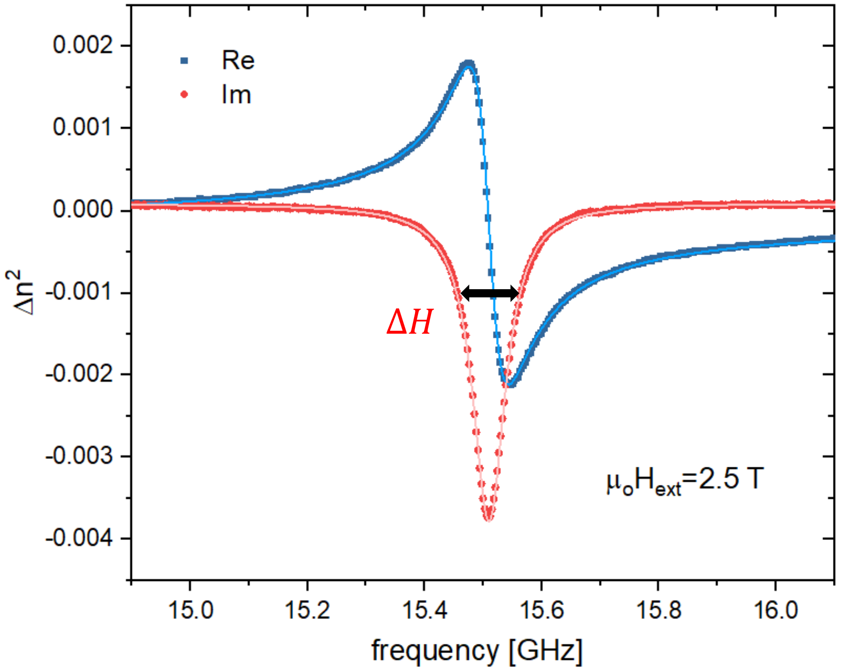
$$\omega = \gamma\mu_0(H_0 - M_s)$$

$$\omega = \gamma\mu_0\sqrt{H_0(H_0 + M_s)}$$

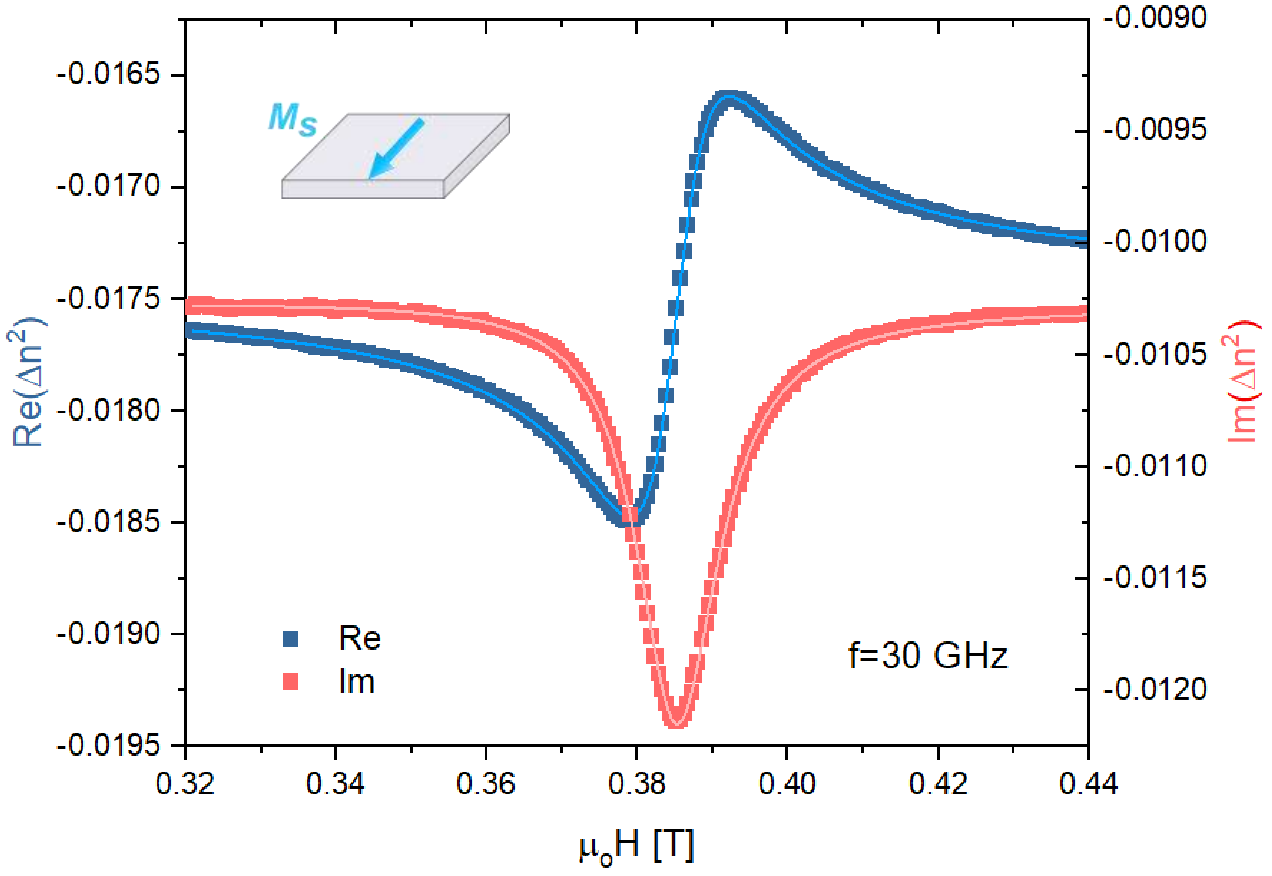
Landau Lifshitz Gilbert equation

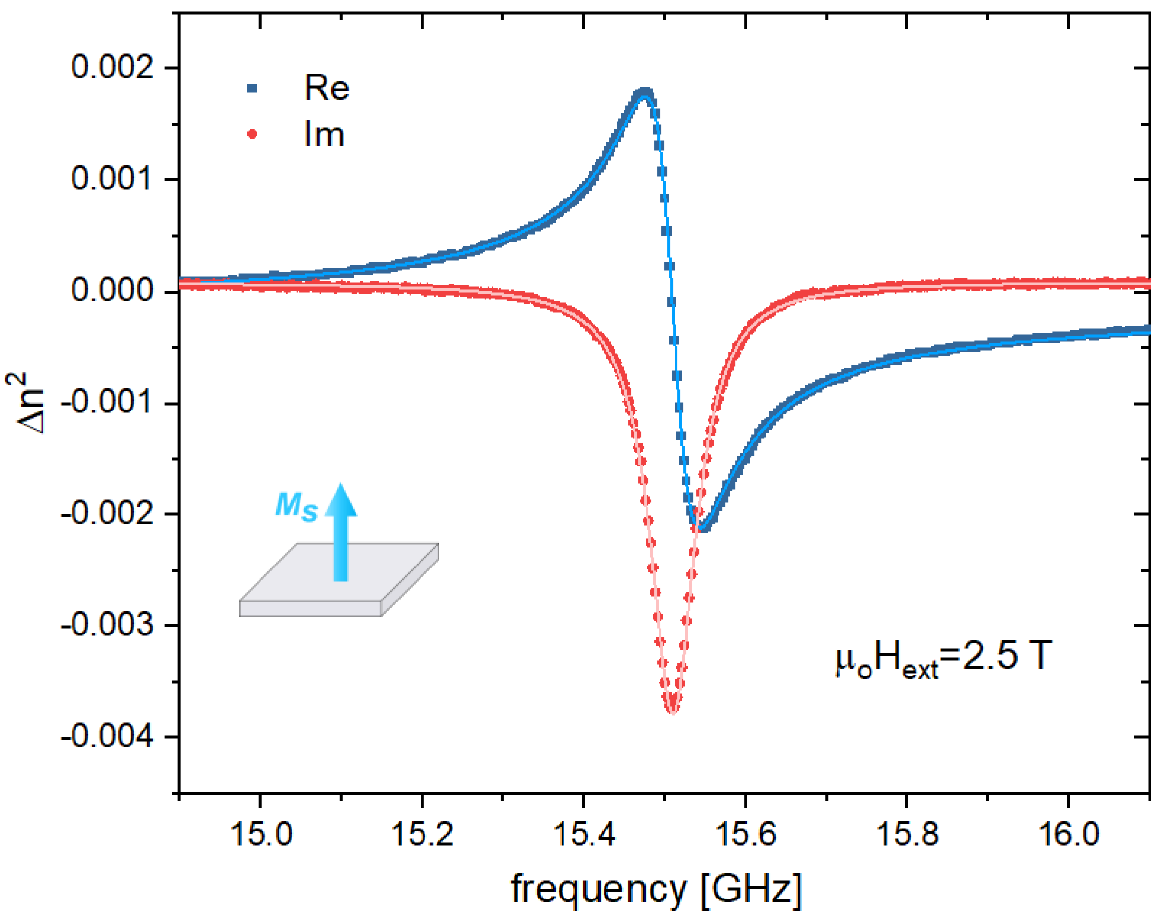
- The Damping term increase the width of the signal due to the dispersion of absorption.

$$\frac{d\boldsymbol{M}}{dt} = -\gamma \boldsymbol{M} \times \mu_o \boldsymbol{H}_{eff} + \alpha \boldsymbol{M} \times \frac{d\boldsymbol{M}}{dt}$$

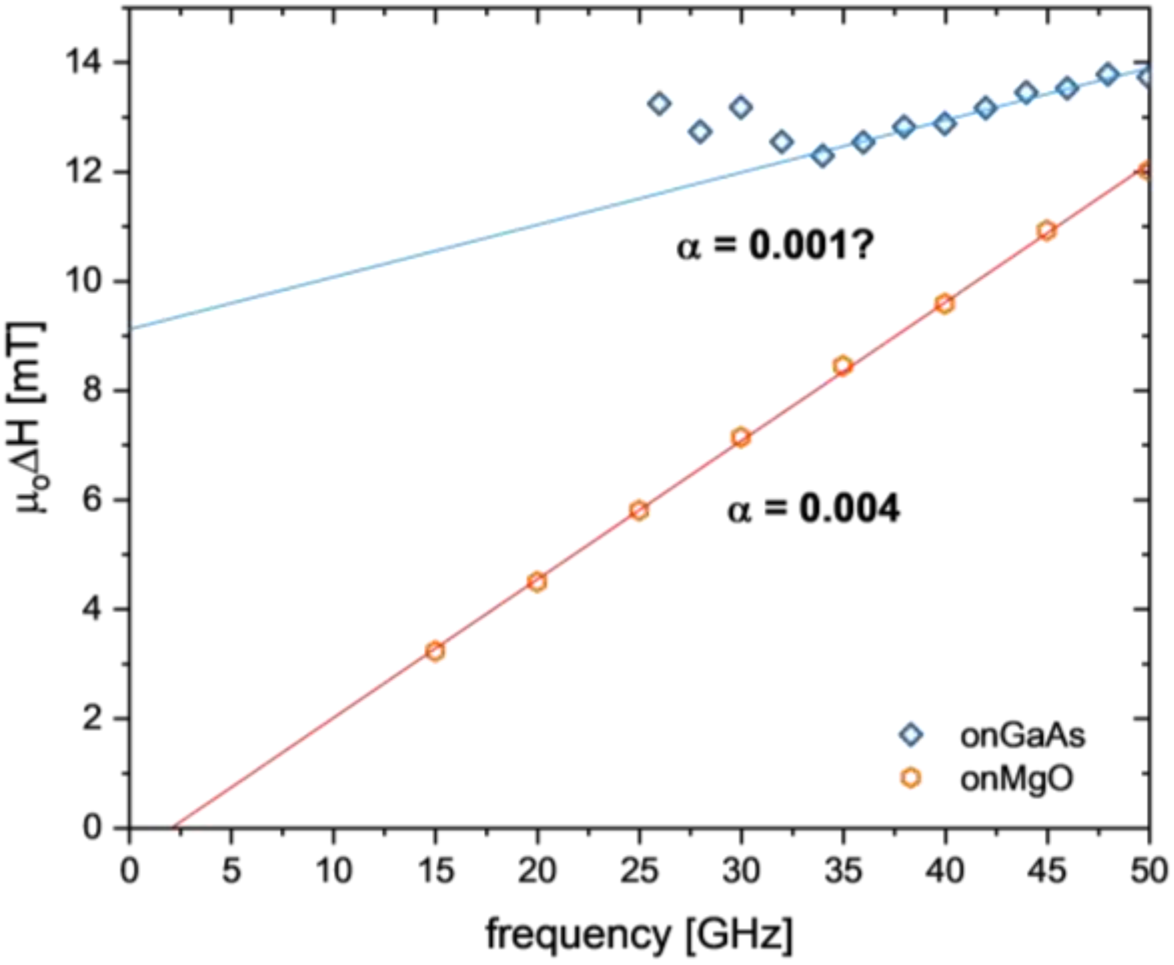


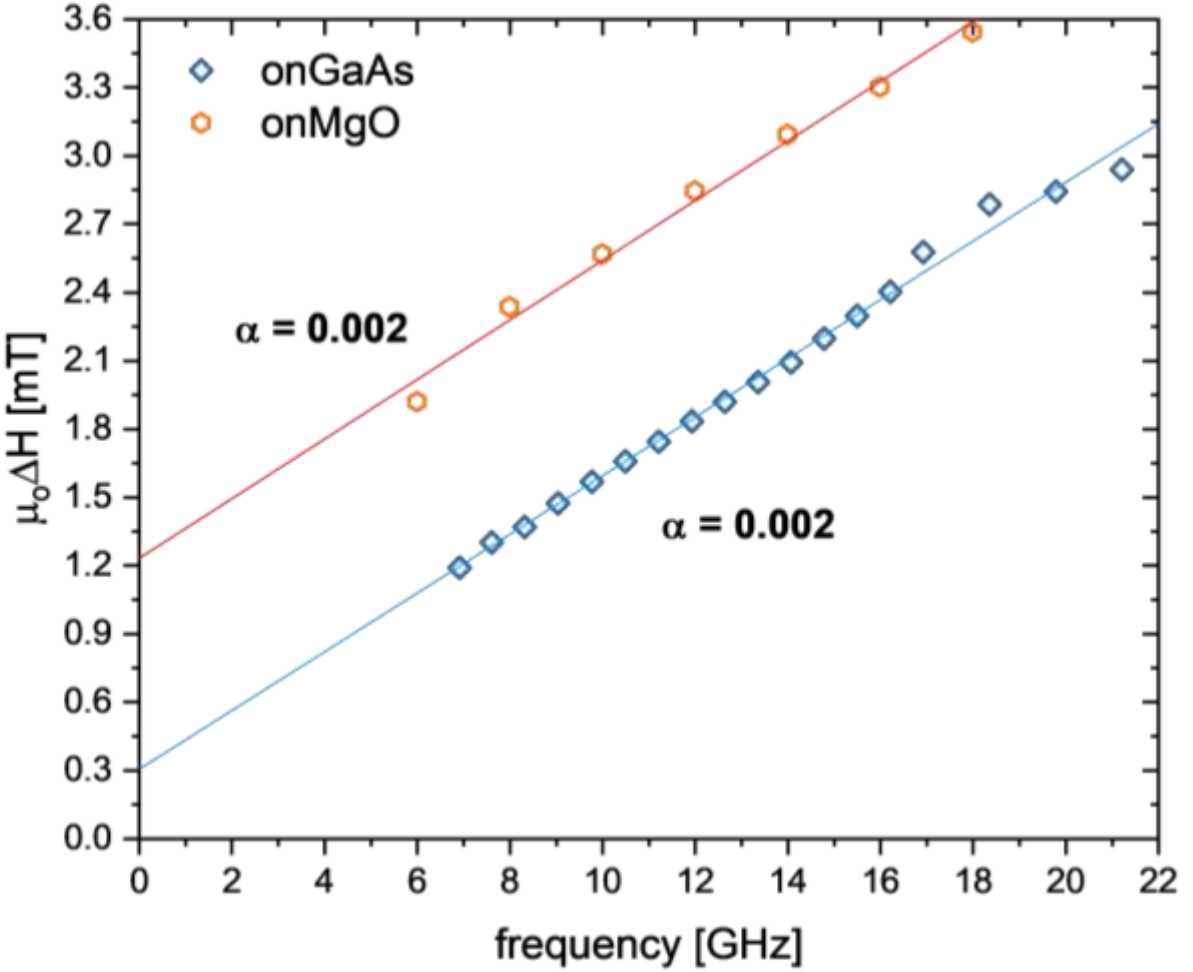
Resonance Peaks

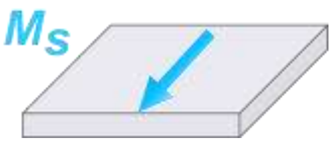




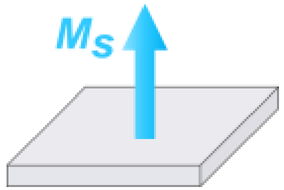
Fe : Linewidth





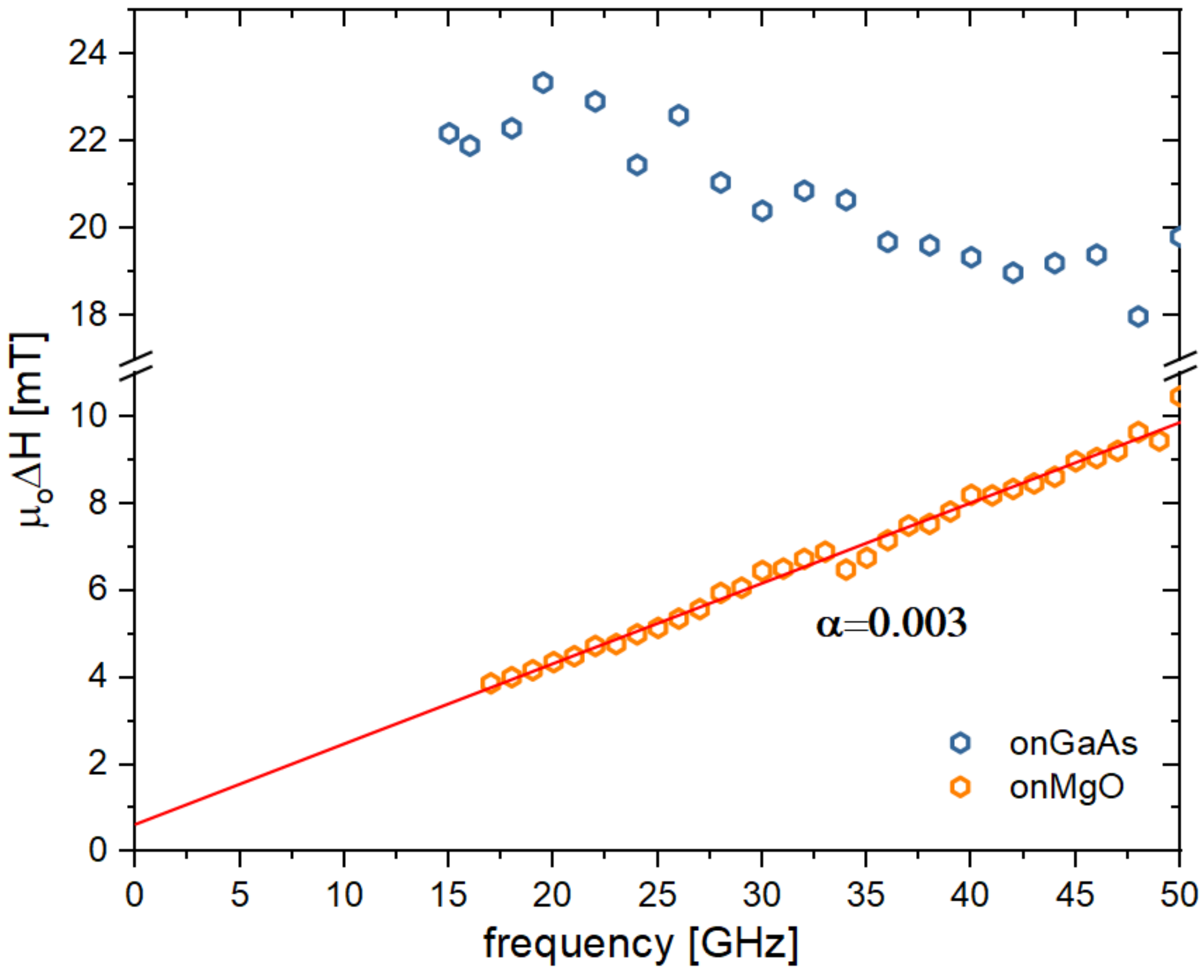


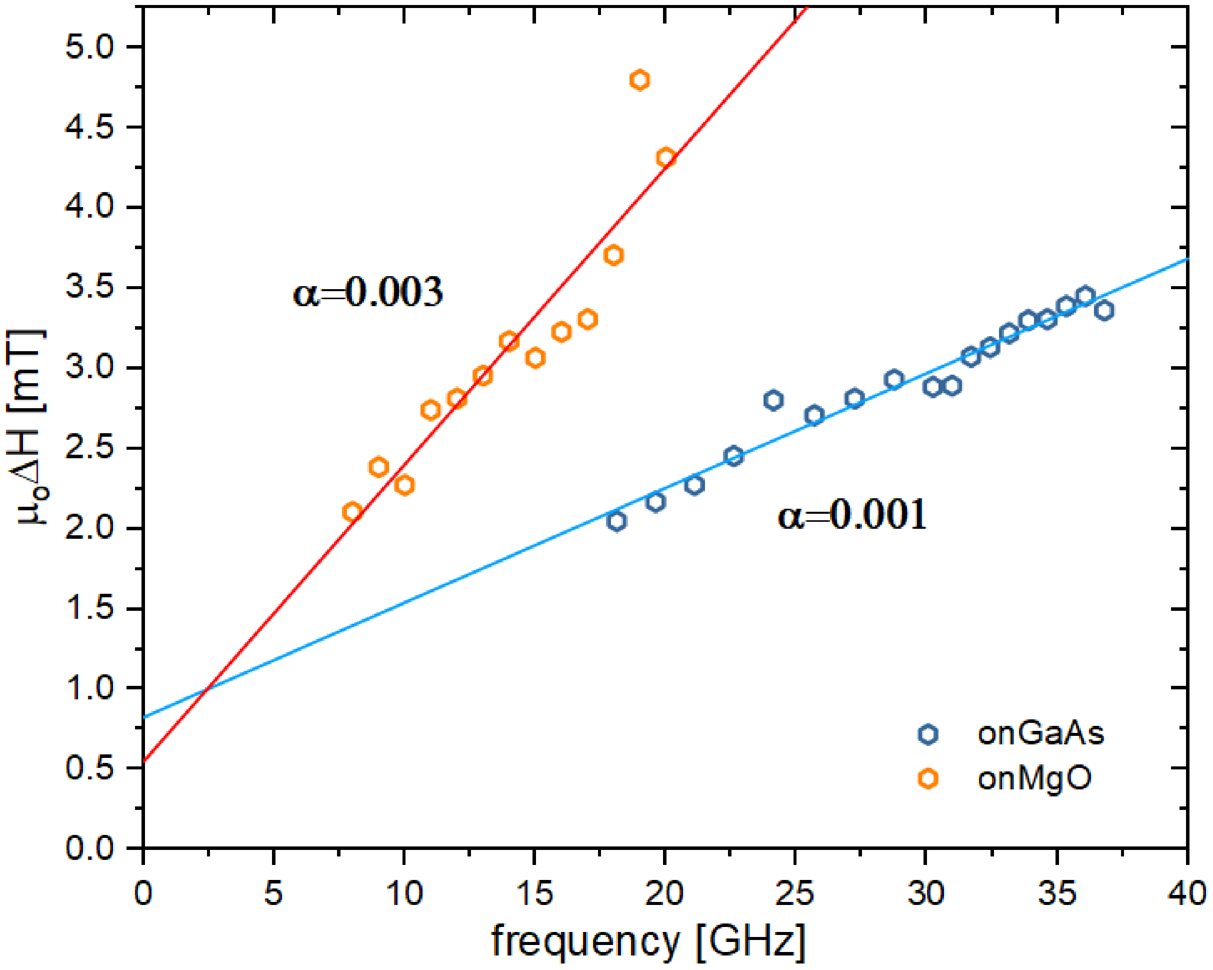
	MgO	*->*	*GaAs*
α	0.004	->	0.001?
ΔH_o	-0.5 mT	->	9 mT

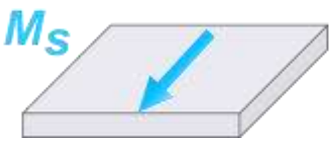


	MgO	*->*	*GaAs*
α	0.002	->	0.002
ΔH_o	1.2 mT	->	0.3 mT

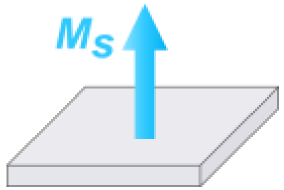
FeV : Linewidth





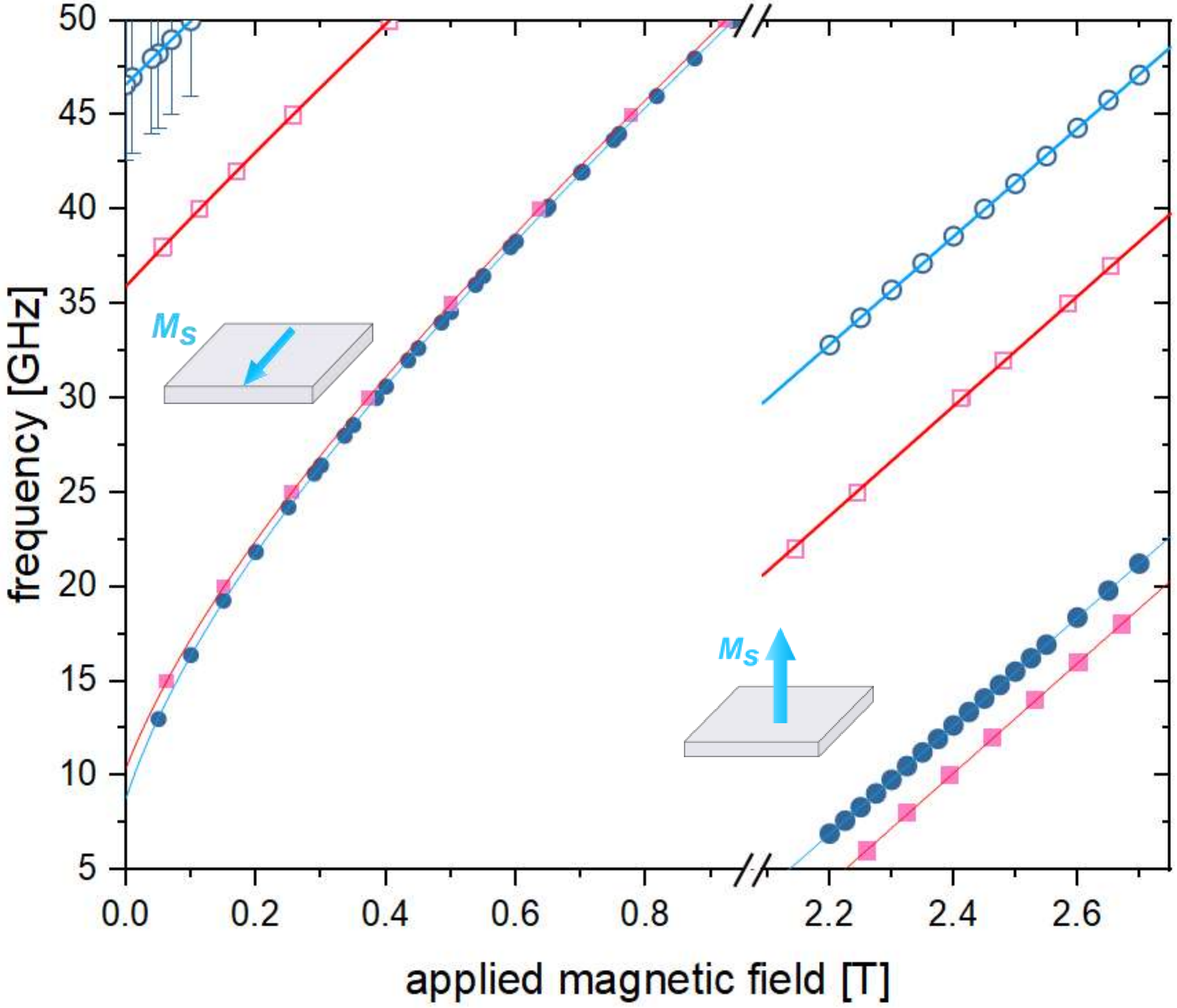


	MgO	***->***	***GaAs***
α	0.003	->	-
ΔH_o	0.6 mT	->	-



	MgO	***->***	***GaAs***
α	0.003	->	0.001
ΔH_o	0.5 mT	->	0.8 mT

Fe: FMR



	on MgO	on GaAs	
$\gamma[GHz.T^{-1}]$	29.1	28.6	↓
H_K [T]	0.06	0.04	↓
M_{eff} [T]	2.07	2.07	-
H_{ex}[T]	0.55	0.85*	↑
H_{ex}+ H_S [T]	0.67	0.91	↑

In Plane FMR: MgO -> GaAs

$H_x = H_K$ 0.06 T -> 0.04 T

$H_y = M_s + H_K - Hu - H_S$ 2.08 T -> 2.18 T

Out Plane FMR: MgO -> GaAs

$H_Z = M_s - H_K - Hu - H_S$ 2.05 T -> 1.96 T

In Plane :Second mode MgO -> GaAs

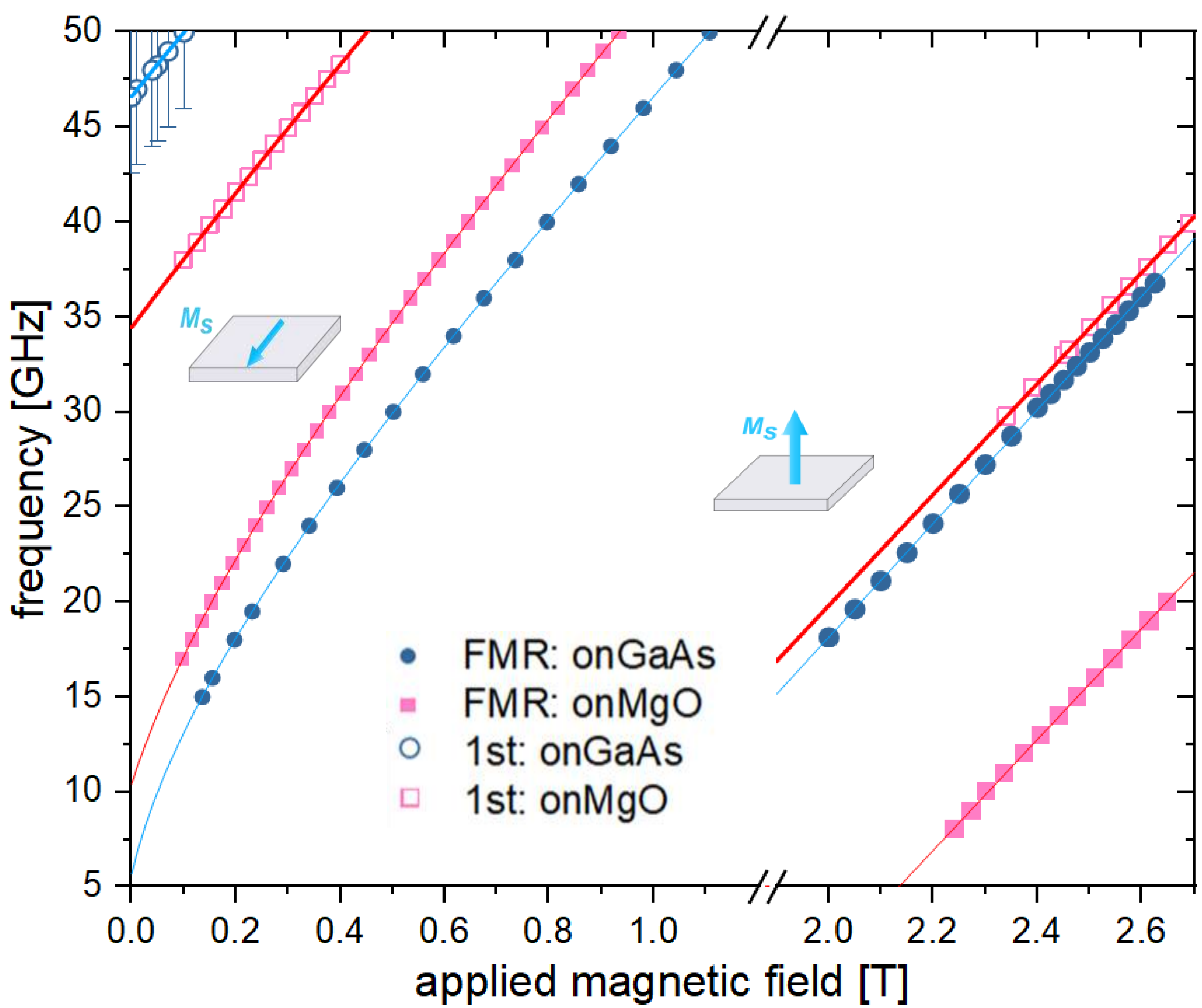
$H_K + H_{Ex}$ 0.61 T -> 0.89 T

$M_s + H_K - Hu - 2H_S + H_{Ex}$ 2.52 T -> 2.98 T

Out Plane :Second mode MgO -> GaAs

$M_s - H_K - Hu - 2H_S - H_{Ex}$ 1.38 T -> 1.05 T

FeV: FMR



	on MgO	on GaAs	
$\gamma\ [GHz.T^{-1}]$	29.2	29.3	-
H_K [T]	0.06	0.03	↓
M_{eff} [T]	1.99	1.48	↓
H_{ex} [T]	0.53	0.85*	↑

In Plane FMR: *MgO -> GaAs*

H_K 0.06 T -> 0.03 T

M_S+ H_K- Hu- H_S 2.02 T -> 1.57 T

Out Plane FMR: *MgO -> GaAs*

M_S- H_K- Hu − H_S 1.96 T -> 1.39 T

In Plane :Second mode *MgO -> GaAs*

H_K+H_{Ex} 0.59 T -> 0.89 T

M_S+ H_K- Hu- 2H_S +H_{Ex} 2.39 T -> 2.95 T

Out Plane :Second mode *MgO -> GaAs*

M_S- H_K- Hu- 2H_S −H_{Ex} 1.32 T -> -