# Damping in FINEMET films capped by Pt: the role of SOC

Spin currents
Spin pumping
Rashba SO coupling
Ferromagnetic resonance
Gilbert damping (low damping)
Capping Pt layer
FM/NM interface
Spin Hall effect –DSHE & ISHE

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SWISS
CONTRIBUTION

MIKON, Kraków 2016.05.11

# SPIN CURRENT $J_S$

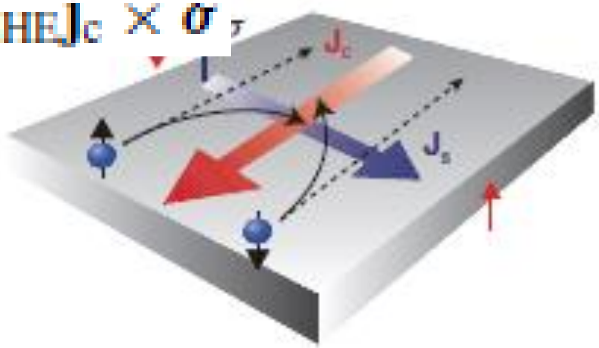
**Two definitions:**

$$j_s^{\mathrm{eff}} = -\frac{\hbar}{2e^2}\frac{1}{\rho}\nabla\mu_s \qquad [\mathrm{J/m^2}]$$

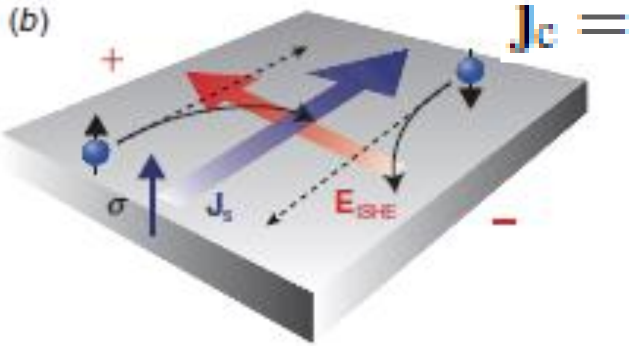
$$j_s = -\frac{1}{e\rho}\nabla\mu_s = -\frac{1}{e}\frac{\ell_{\mathrm{sf}}}{r_s}\nabla\mu_s \qquad [\mathrm{A/m^2}]$$

**Spin Hall angle**

$$\mathbf{j}_s = \theta_{\mathrm{SHE}}\mathbf{j}_c \times \boldsymbol{\sigma}$$



$$\mathbf{j}_c = \theta_{\mathrm{SHE}}\mathbf{j}_s \times \boldsymbol{\sigma}$$

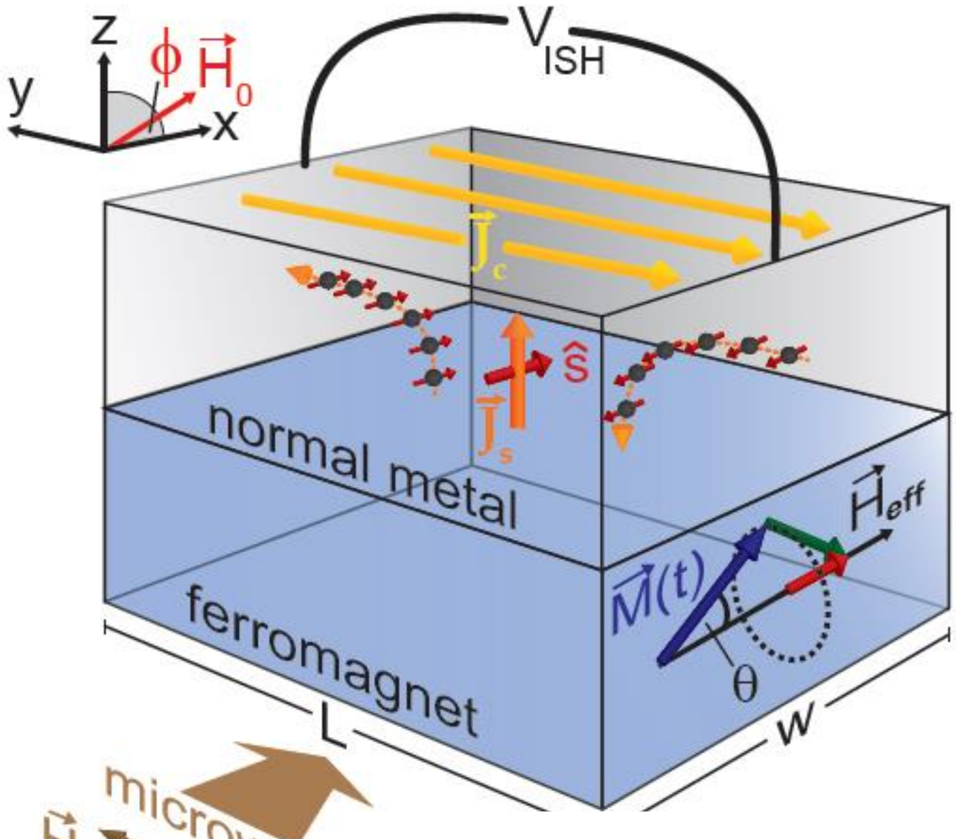


**GENERATION of SC (DSHE)**

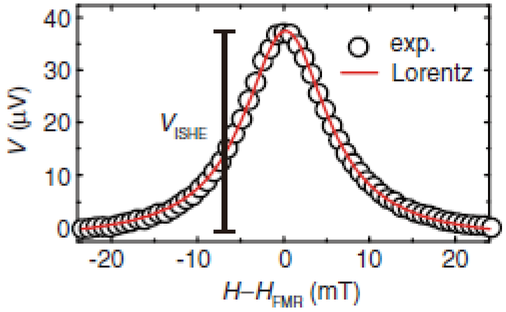
**DETECTION of SC (ISHE)**

Czeschka

# SPIN PUMPING & DETECTION of SPIN CURRENT

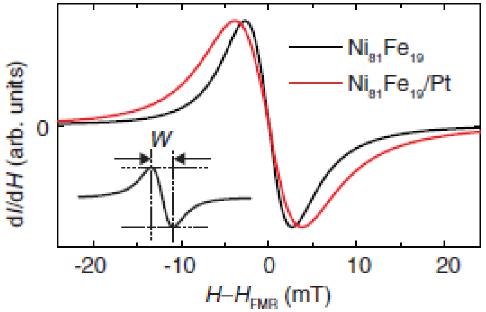


Franz Dominik Czeschka



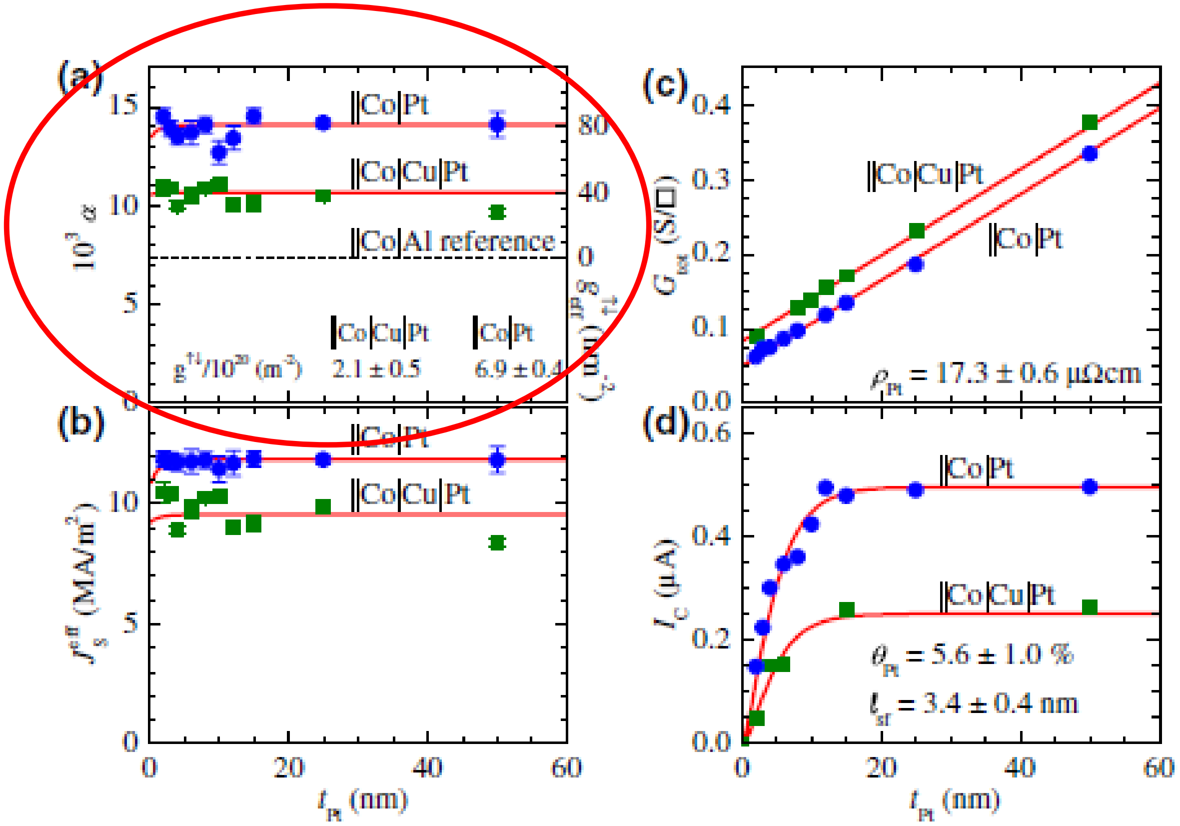
**? at interface**

$$\Delta\alpha_{\mathrm{SHE}} = \left(\frac{\gamma}{2\pi f M_s V_F}\right) J_s.$$



$$\mathbf{j}^s = \frac{\hbar}{4\pi}\left(g_r \mathbf{m} \times \frac{d\mathbf{m}}{dt} - g_i \frac{d\mathbf{m}}{dt}\right).$$

# SPIN-MEMORY LOSS



PRL 112, 106602 (2014)

Main conclusion:
spin-memory loss at interface
induces a strong spin current depolarization

# SP in the presence of SO coupling

Conventional theory without SO: reflecton (Tserkovniak)

$$\mathbf{j}^s = \frac{\hbar}{4\pi}\left(g_r \mathbf{m}\times\frac{d\mathbf{m}}{dt} - g_i\frac{d\mathbf{m}}{dt}\right). \qquad g \equiv g_r + i g_i = \sum(1 - r_\uparrow r_\downarrow^*)$$

Conventional theory: ~~influence of disorder at interface~~

~~influence of SOC~~ (spin-memory loss)

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SOC: effect Rashba $V(\mathbf{r}) = \alpha_R \delta(z)(\hat{\mathbf{k}}\times\hat{\mathbf{z}})\cdot\boldsymbol{\sigma}$ Rashba!

$$\mathbf{j}_z(z>0) = \frac{\hbar\Gamma^0}{4\pi}\frac{J_{\mathrm{ex}}^2}{J_{\mathrm{ex}}^2+\Delta^2}N(z)A_N\cdot\left(\mathbf{m}\times\frac{d\mathbf{m}}{dt}\right),$$

$\eta$ – Rashba factor

$\Gamma$o – SP across interf. without disorder

$\xi$ –back-flow factor

Chen, Zhang PRL 114 (2015)

# SP in the presence of SO coupling

**(THEORY)**

$\Gamma^0$ ~ 7 nm$^{-2}$

$\alpha_R$ ~ 0.03 - 0.3 eV nm

$k_F$ ~ 11 nm$^{-1}$

$E_F$ ~ 9 eV

$\lambda_{\mathrm{sd}}$ ~ 8 nm spin diffusion length

$l_m$ ~ 5 nm mean free path

$\eta = (\alpha_R k_F / E_F)^2$ of 0.1- 0.2 Rashba

$\xi = (3/2)(\Gamma^0 / k_F^2)(\lambda_{\mathrm{sd}} / l_m) \times \coth(t_N / \lambda_{\mathrm{sd}})$ of 0.1 – 0.2 back-flow factor

increase in $\alpha$ due to SP

$$\boxed{\alpha_{\parallel} \propto \frac{1 + 6\eta\xi}{1 + \xi} + \frac{\eta}{2(1 + \xi)^2}}$$

Chen, Zhang PRL 114 (2015)

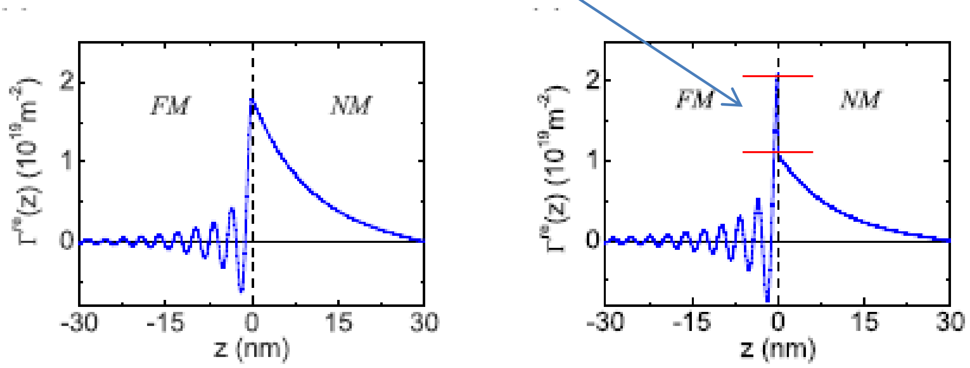
# SP in the presence of SO coupling

**(THEORY)**

Theory:

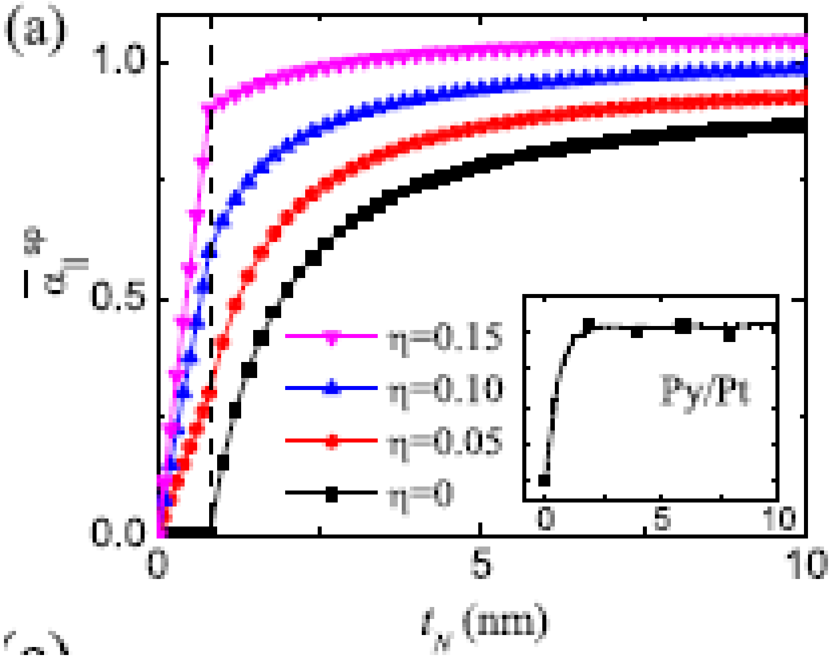
- spin-pumping formalism in the presence of SOC
- origin of spin-memory loss

spin-memory loss
or mixing conductance jump



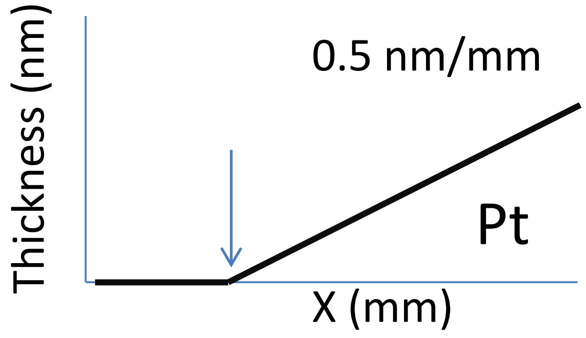
without SO

with SO

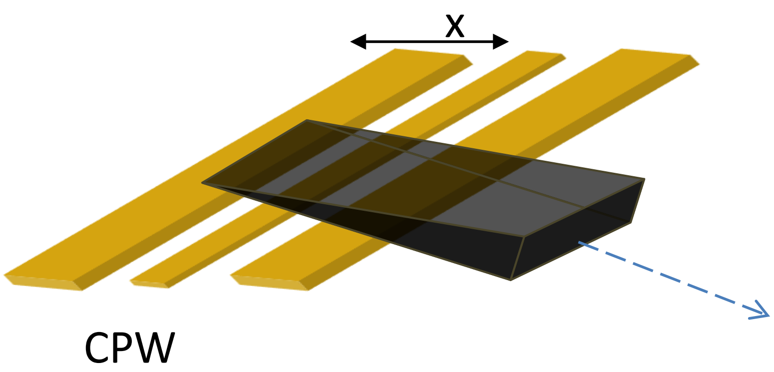


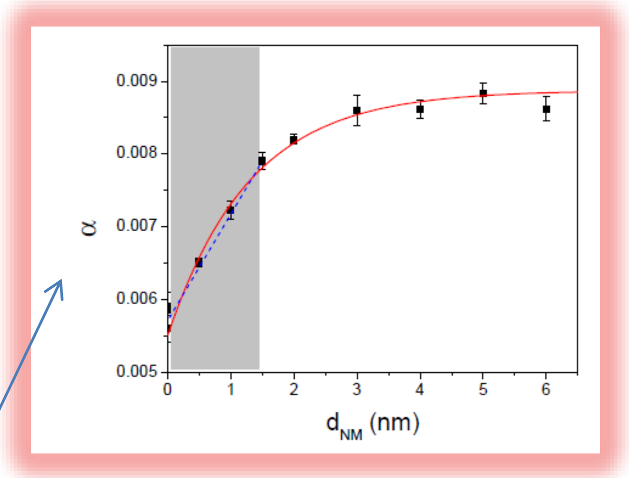
Chen, ZhangPRL 114 (2015)

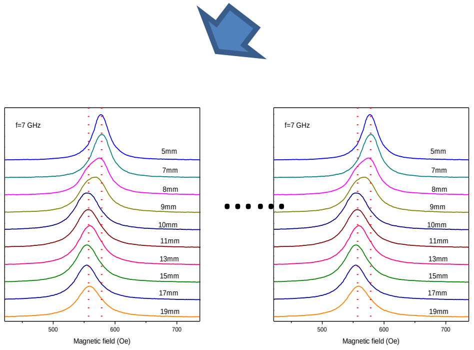
# EXPERIMENT with CPW



Finemet thin film
with wedged Pt
capping layer

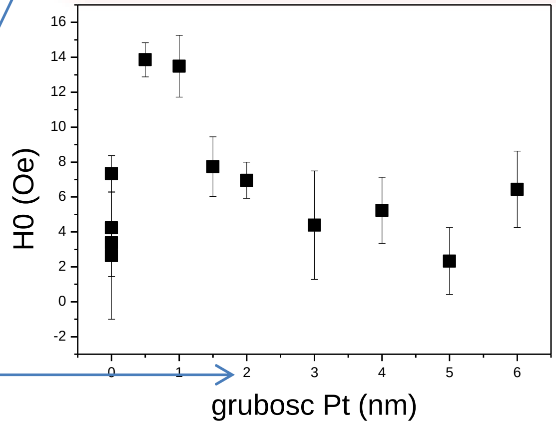




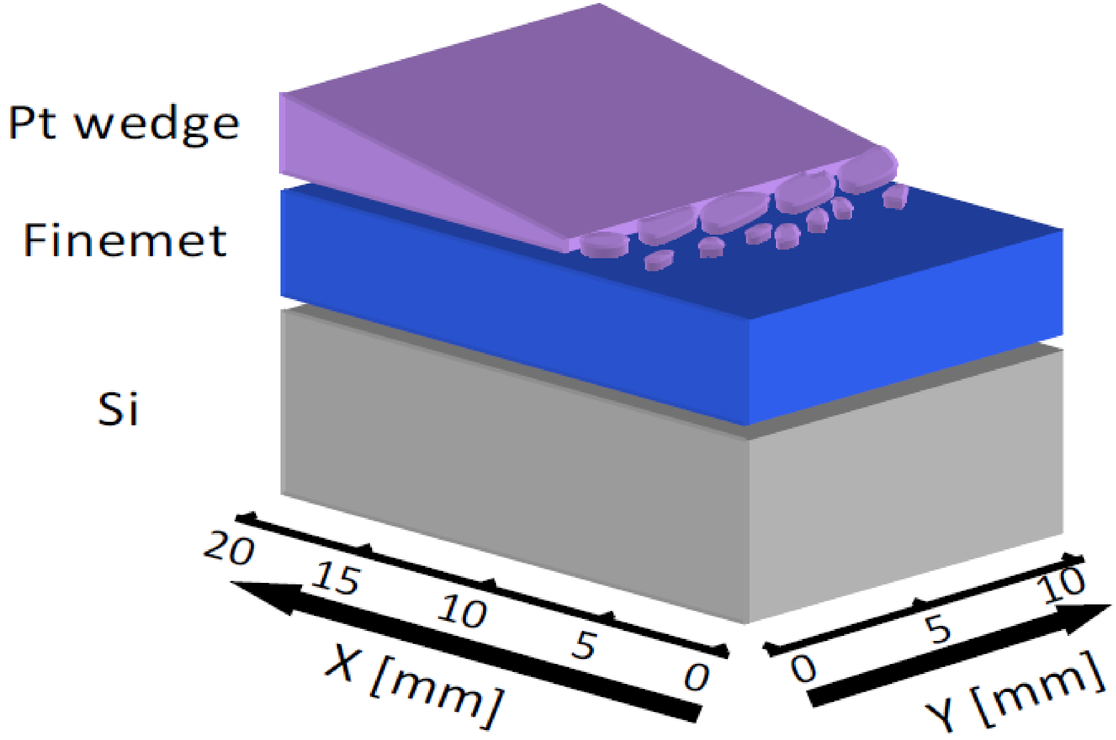


f: 3 -20 GHz

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



# STRUCTURE of Finemet-Al with a Pt wedge

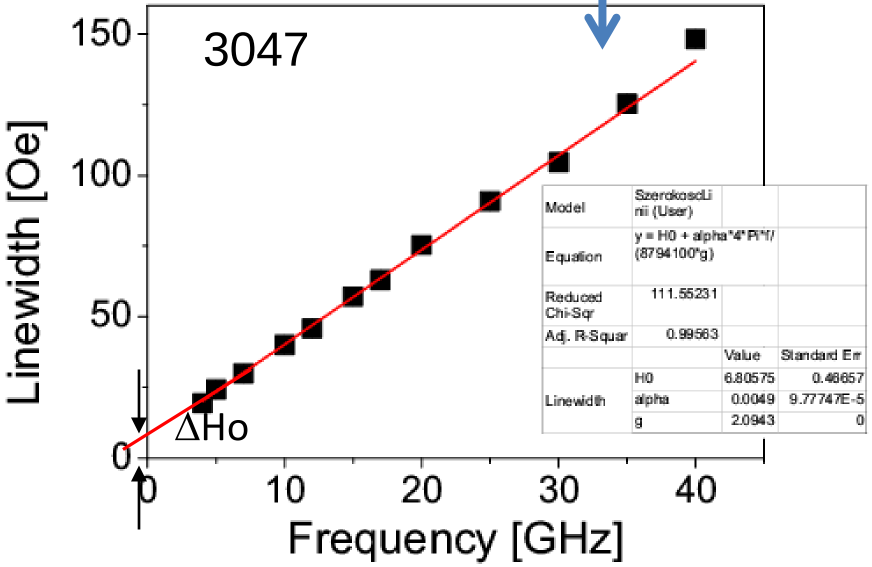


# **Why Finemet+Al. ?** …. $Fe_{66.5}Cu_1Nb_3Si_{13.5}B_9Al_7$

Essential issue for FM: damping as low as possible

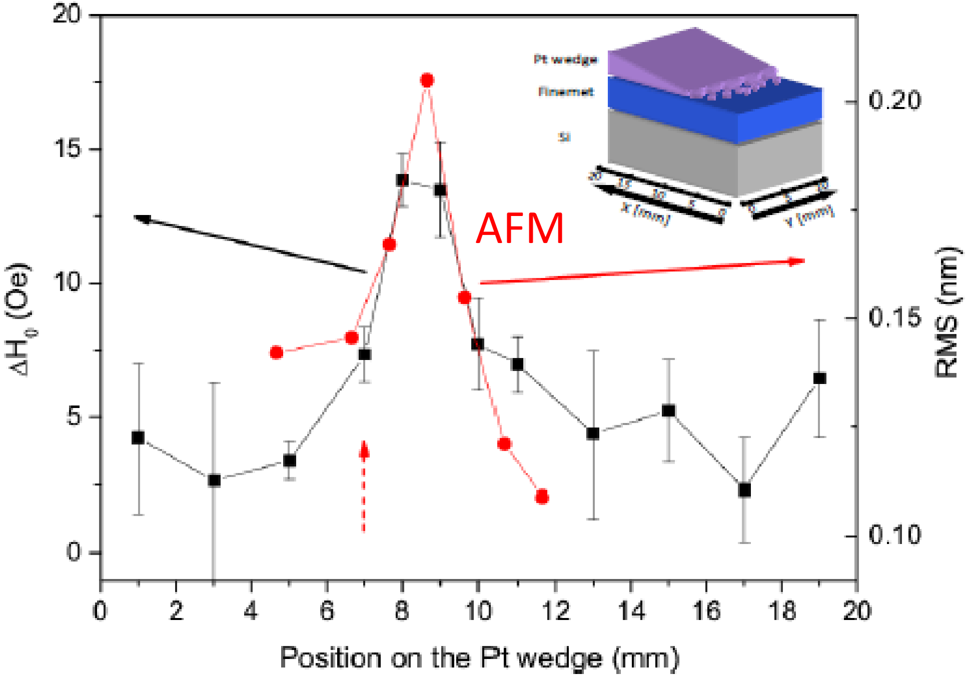
- Permalloy – widely used $\alpha = 8\times10^{-3}$ & $\Delta H_o = 10$ Oe
- CoFeB – low damping $\alpha = 4\times10^{-3}$ but $\Delta H_o = 10 - 20$ Oe
- **FINEMET + Al** * - $\alpha = 4\text{-}5\times10^{-3}$ & $\Delta H_o = 3 - 7$ Oe !
- **epi – YIG** ** - $\alpha = 5\times10^{-4}$ & $\Delta H_o = 2 - 8$ Oe

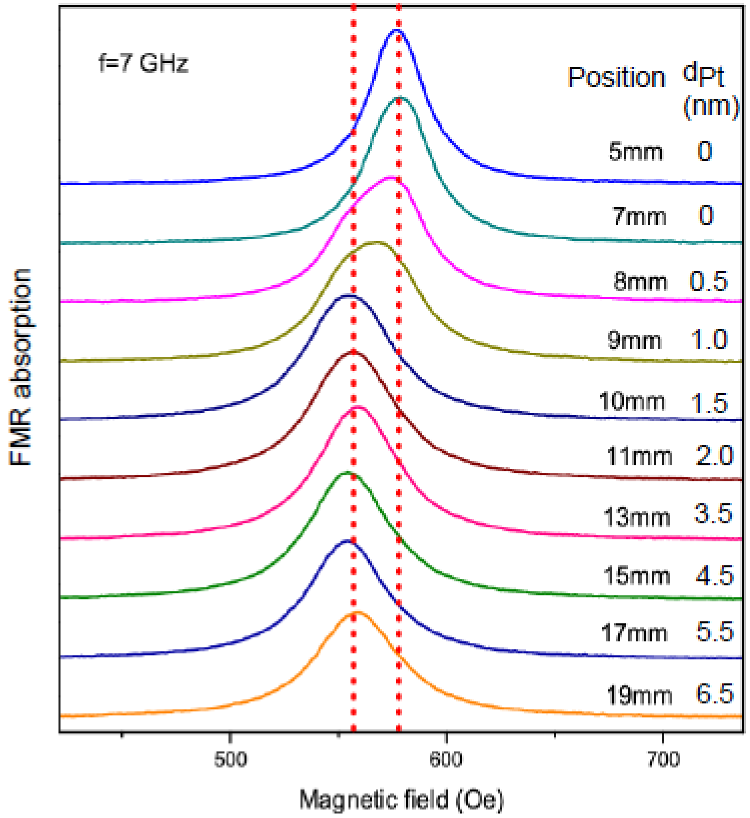
$$\Delta H = \Delta H_0 + \frac{4\pi f \alpha}{\gamma}.$$



| | | | |
|---|---|---|---|
| Model | SzerokoscLinii (User) | | |
| Equation | y = H0 + alpha*4*Pi*f/(8794100*g) | | |
| Reduced Chi-Sqr | 111.55231 | | |
| Adj. R-Squar | 0.99563 | | |
| | | Value | Standard Err |
| Linewidth | H0 | 6.80575 | 0.46657 |
| | alpha | 0.0049 | 9.77747E-5 |
| | g | 2.0943 | 0 |

# Finemet-Al with a Pt wedge



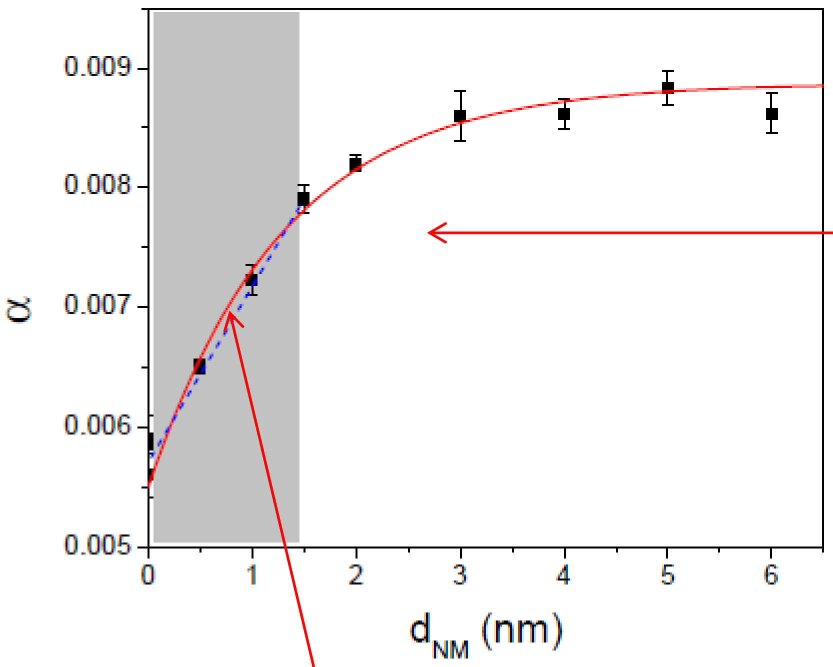


Low roughness with maximum for discontinuous Pt

Hr modulation

Maximum in $\Delta$H corresponds to maximum in RMS

# SPIN PUMPING in Finemet-Al capped with Pt



$$\alpha = \alpha_0 + \frac{g\mu_B}{4\pi M_S}\frac{g_{\mathrm{eff}}^{\uparrow\downarrow}}{d_{\mathrm{Al-F}}}\left(1-\exp\left(-\frac{2d_{\mathrm{Pt}}}{\lambda_{sf}}\right)\right)$$

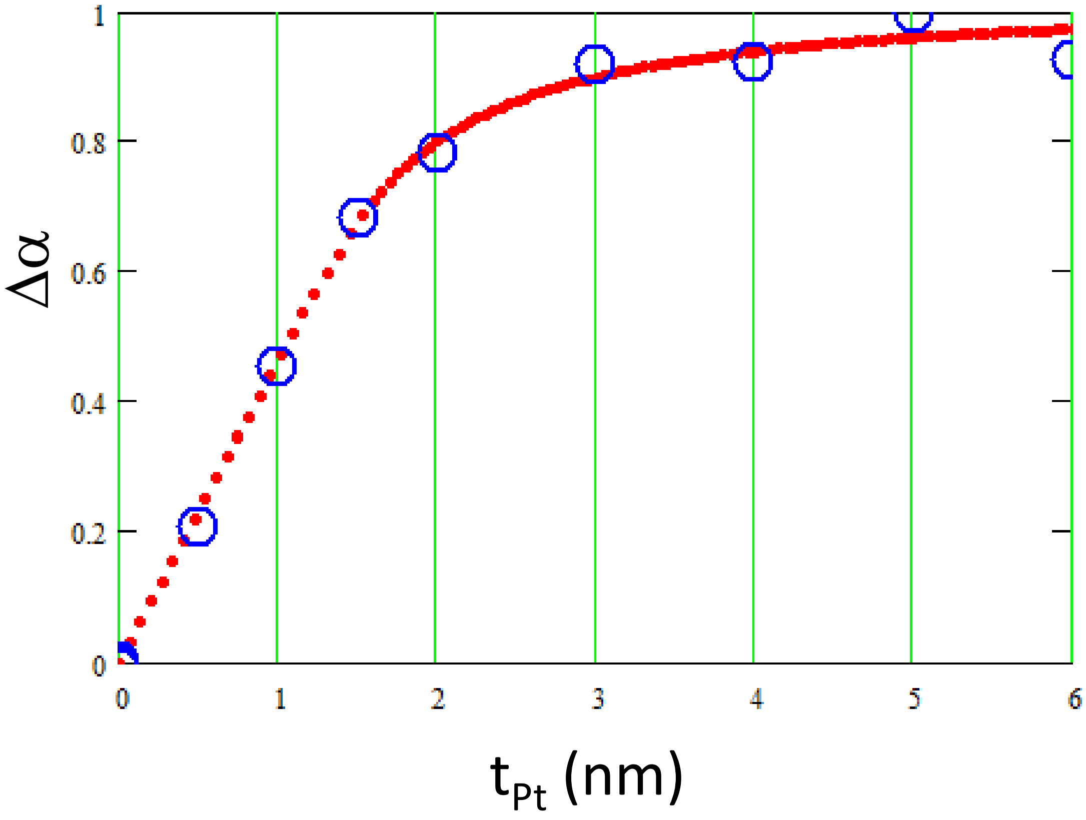
conventional theory

$g_{eff}$ = 5 $10^{15}$ $cm^{-2}$

$\lambda_{sf}$ = 2.5 nm

OK, but
this region
is ill defined

# CALCULATIONS of $\Delta\alpha$ within the framework of SOC



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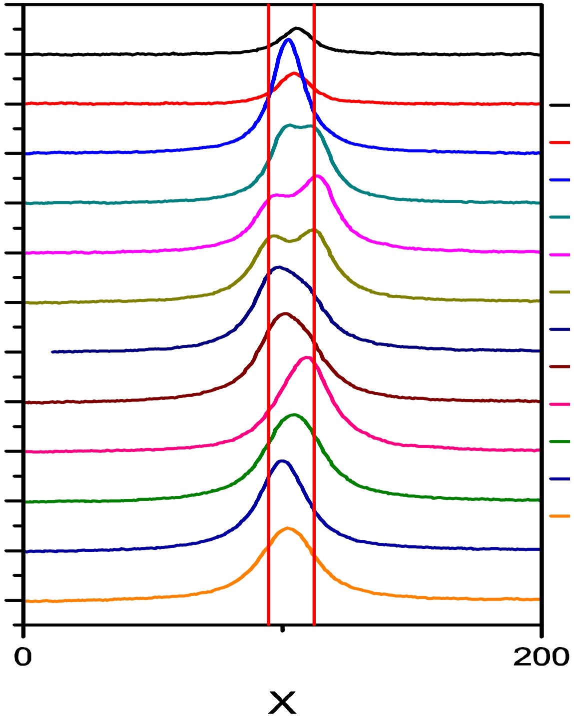
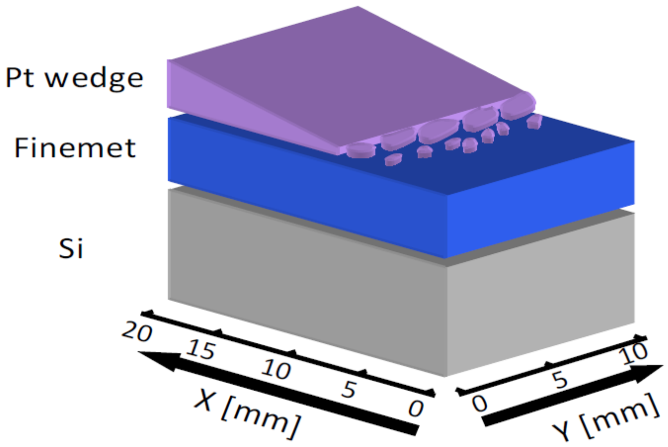
$\eta = (\alpha_R k_F / E_F)^2$ of 0.1- 0.2

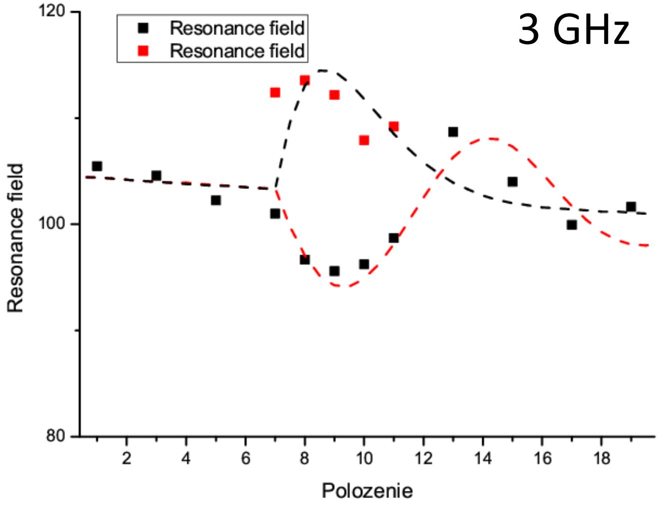
$\xi = (3/2)(\Gamma^0/k_F^2)(\lambda_{sd}/l_m) \times \coth(t_N/\lambda_{sd})$ of 0.1 – 0.2

# MODULATION of the resonance field (field-torque ?)

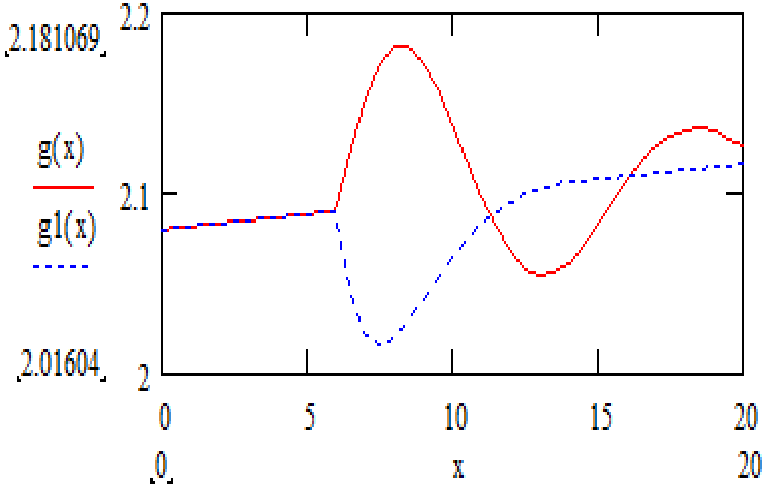




$$\mathbf{j}^s = \frac{\hbar}{4\pi}\left(g_r \mathbf{m} \times \frac{d\mathbf{m}}{dt} - \boxed{g_i \frac{d\mathbf{m}}{dt}}\right).$$

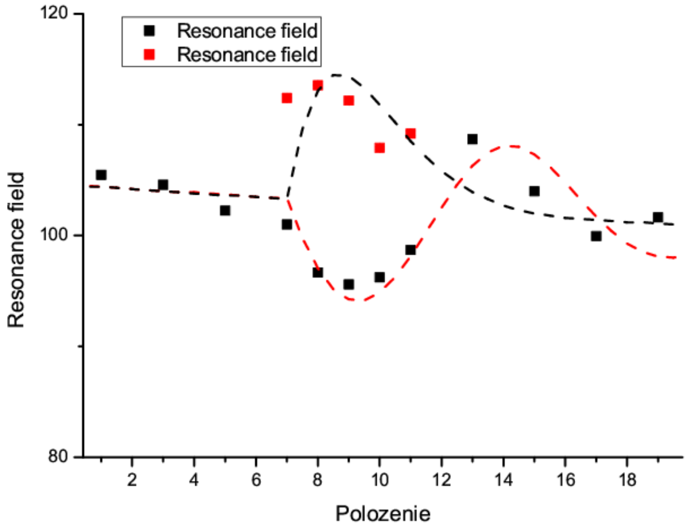


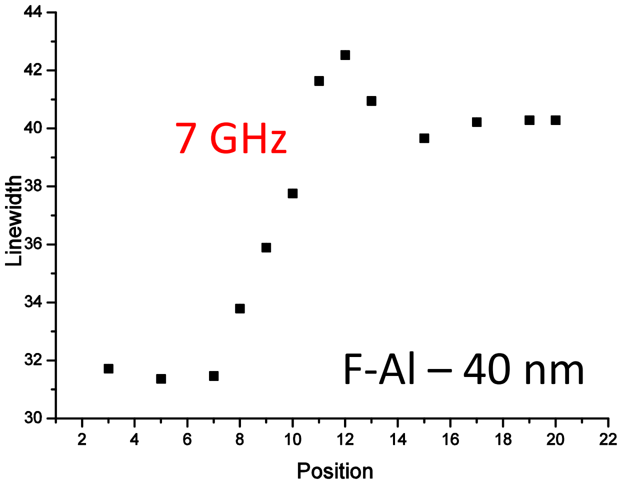
3 GHz



# CHANGES in α and modulation of resonance field

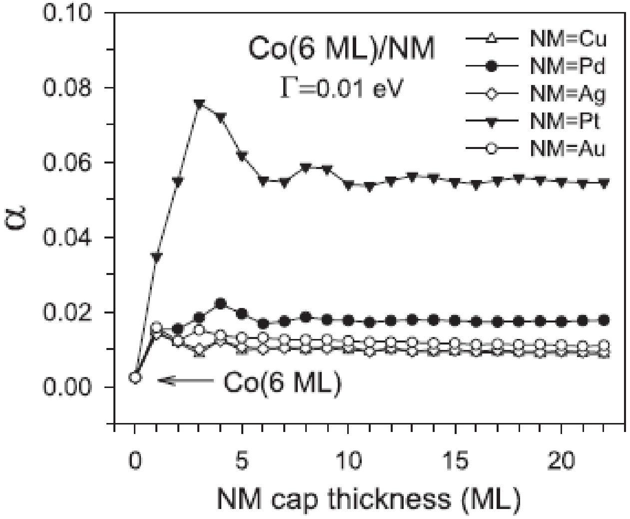
resonace field modulation





Theory

PHYSICAL REVIEW B **90**, 014420 (2014)



# SUMMARY

- Interface is discontinuous – Pt islands up to **1.5** nm
- SP needs the presence of **SO** at interfaces
- Experiment – **$\alpha$ vs. d(Pt)** – can be described assuming reasonable values of parameters for Pt (**$E_F$, $k_f$, $l_{sd}$, $l_m$** ..)
- Modulation of **Hr** – to be explained

Gościańska (Finemet, technology); H. Głowiński (experiment & analysis); A. Krysztofik (experiment); J. Barnas(theory); M. Cecot, (STT & ISHE)