Spin pumping and spin transport in magnetic metal and insulator heterostructures

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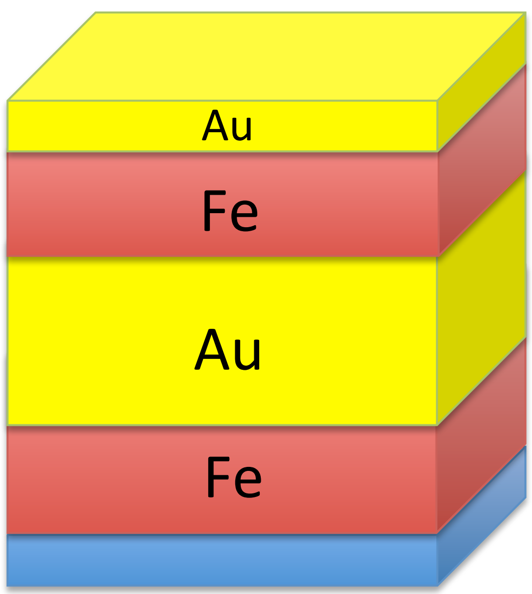
Why use spin currents?

We can eliminate circumvent these problems:

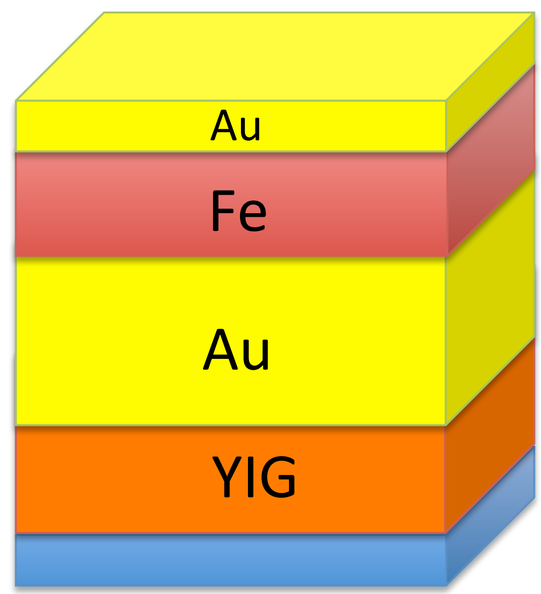
- Joule Heating
- Circuit Capacitance
- Electron migration

Outline:

- Introduce spin pumping
- Spin transport in Au
- Spin pumping from magnetic insulator (if time)



Magnetic metal

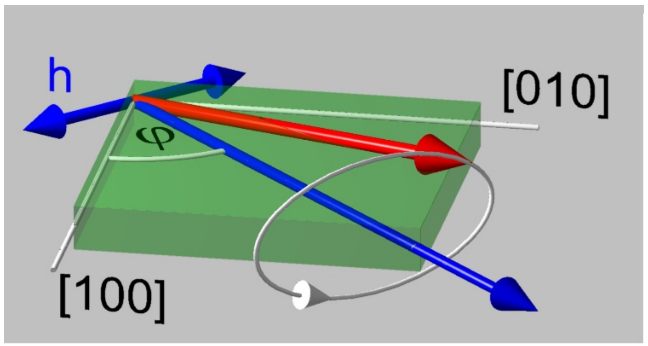


Magnetic insulator

Ferromagnetic Resonance (FMR)

Anritsu signal generator: 1-70 GHz

electromagnet: 2.8 T



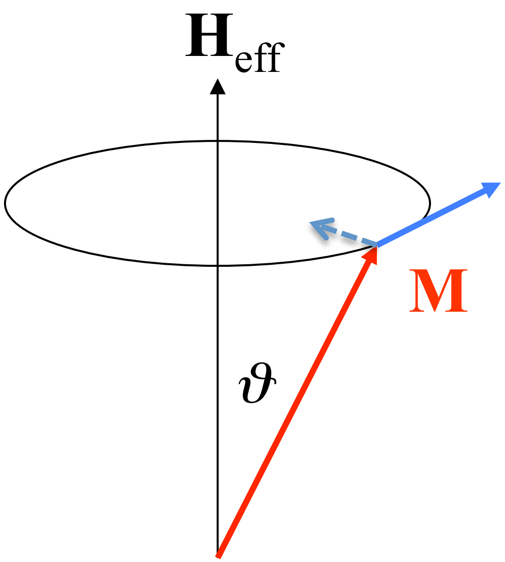
Spin Dynamics (LLG)

Landau Lifshitz Gilbert

$$\frac{\partial \vec{M}}{\partial t} = -\gamma \left[\vec{M} \times \vec{H}_{\text{eff}}\right] + \alpha \left[\vec{M} \times \frac{\partial \vec{n}}{\partial t}\right] \qquad \vec{n} = \frac{\vec{M}}{M_s}$$

Bulk damping is noise in spin orbit (s-o) interaction

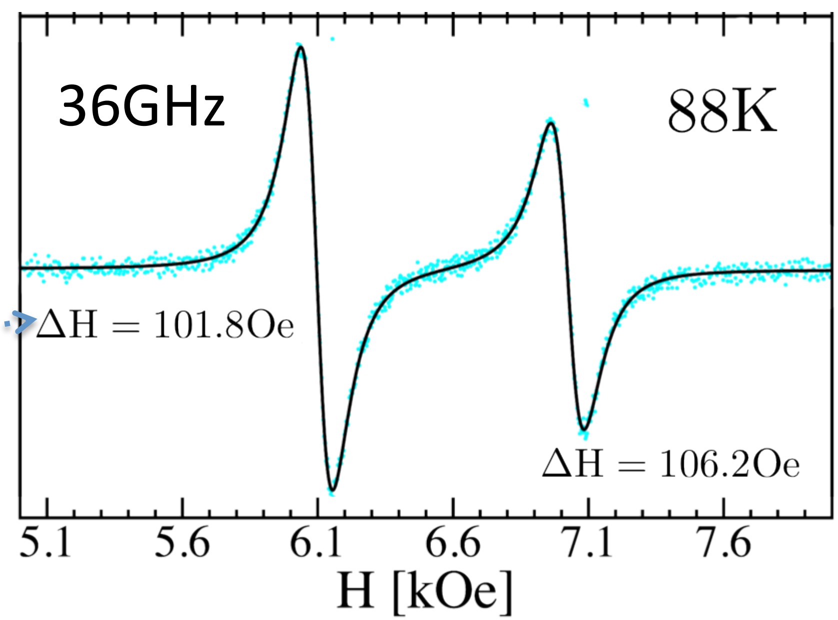
Interface damping is spin pumping



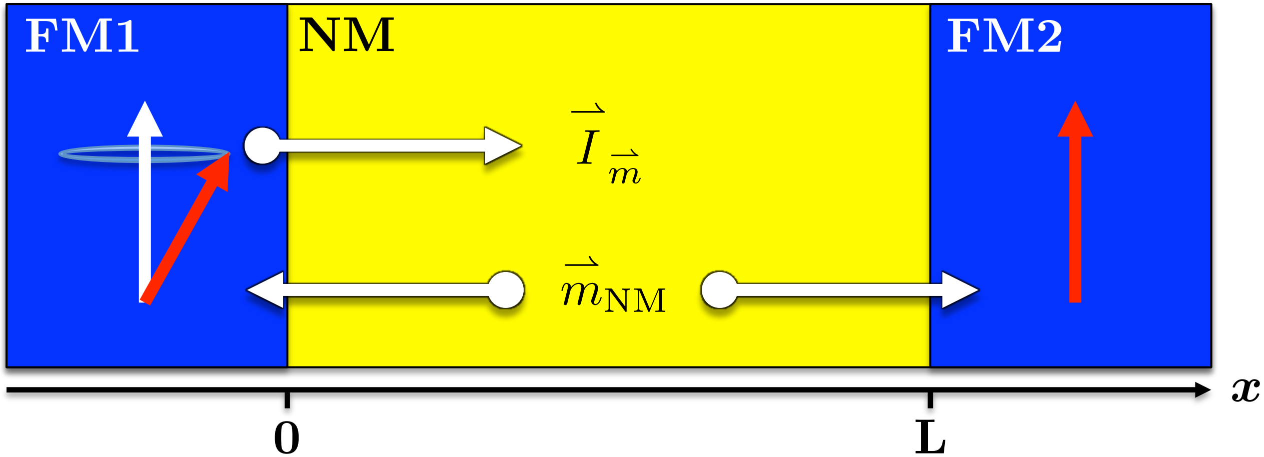
FMR linewidth:

$$\Delta H = \alpha \frac{\omega}{\gamma}$$

$$\alpha = \frac{G}{\gamma M_s}$$



Spin Pumping



$$\vec{m} = \frac{-g\mu_B}{\hbar}\vec{S}$$

Spin current arises from the time retarded response to interlayer exchange coupling
The spin current can be expressed as an accumulated magnetic moment (/area)

$$\vec{I}_{\vec{m}} = \frac{-g\mu_B}{4\pi \mathrm{M}_s} \mathrm{Re}\left[g_{\uparrow\downarrow}\right]\left[\vec{M} \times \frac{\partial \hat{n}}{\partial t}\right] \otimes \hat{x} \qquad \frac{\partial \vec{M}}{\partial t} = \frac{1}{d_{\mathrm{FM}}}\frac{\partial \vec{m}}{\partial t}$$

Spin mixing conductance for metals

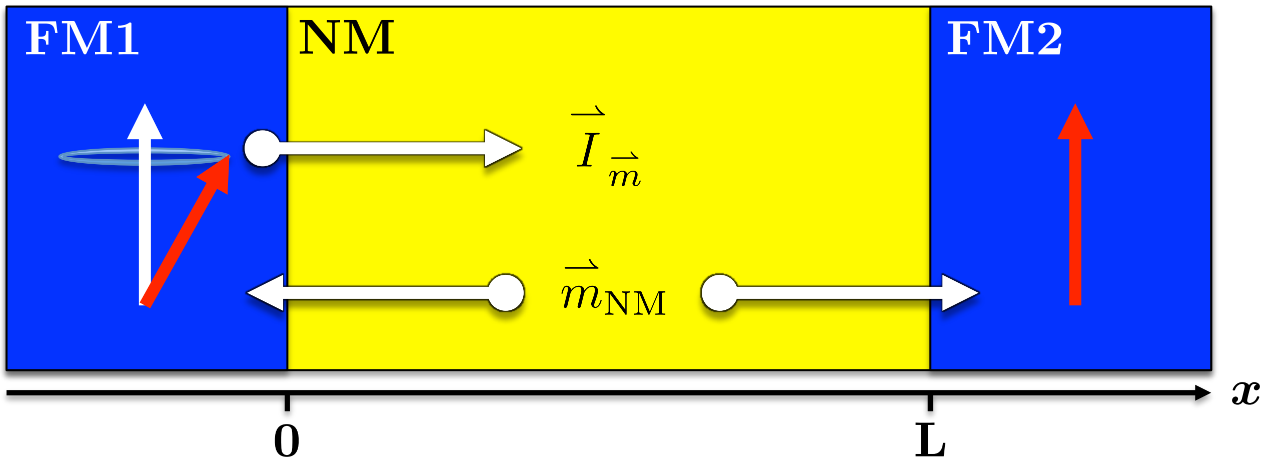
$$\mathrm{Re}\left[g_{\uparrow\downarrow}\right] = \frac{1}{2}\sum_n \left[|r_{\uparrow,n} - r_{\downarrow,n}|^2 + |t_{\uparrow,n} - t_{\downarrow,n}|^2\right]$$

$$|r_{\uparrow(\downarrow),n}|^2 + |t_{\uparrow(\downarrow),n}|^2 = 1 \qquad r_{\uparrow,n}r^*_{\downarrow,n} + t_{\uparrow,n}t^*_{\downarrow,n} \simeq 0$$

$$g_{\uparrow\downarrow} = \sum_n \left[1 - \mathrm{Re}\left[r_{\uparrow,n}r^*_{\downarrow,n} + t_{\uparrow,n}t^*_{\downarrow,n}\right]\right] \approx \frac{{k_F}^2}{4\pi} \sim N^{2/3}$$

Density of electrons per spin direction in NM

Spin Pumping



$$\delta_{\rm sd} = v_F\sqrt{\frac{\tau_{\rm sf}\tau_m}{3}}$$

$$D = \frac{{v_F}^2\tau_m}{3}$$

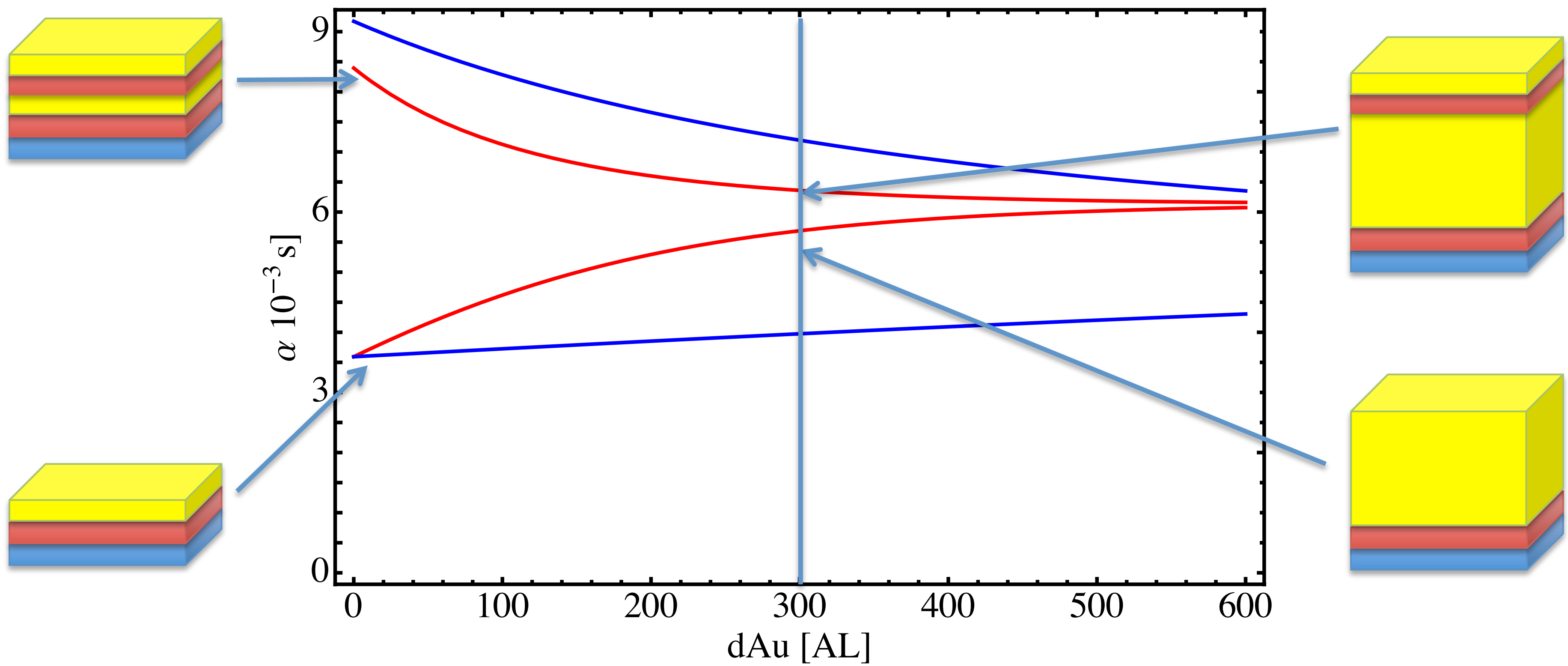
The accumulated magnetic moment then diffuses away from then interface

$$\vec{I}_{\vec{m}} = \frac{-g\mu_B}{4\pi M_s}{\rm Re}\left[g_{\uparrow\downarrow}\right]\left[\vec{M}\times\frac{\partial\hat{n}}{\partial t}\right]\otimes\hat{x}$$

$$\frac{\partial\vec{m}_{\rm NM}}{\partial t} = D\frac{\partial^2\vec{m}_{\rm NM}}{\partial x^2} - \frac{1}{\tau_{\rm sf}}\vec{m}_{\rm NM}$$

Boundary	FM1/NM	FM1/NM/FM2
$x=0$	$\vec{I}_{\vec{m}} - \frac{1}{2}v_F\vec{m}_{\rm NM} = -D\frac{\partial\vec{m}_{\rm NM}}{\partial x}$	
$x=L$	$\frac{\partial\vec{m}_{\rm NM}}{\partial x}=0$	$-D\frac{\partial\vec{m}_{\rm NM}}{\partial x} = \frac{1}{2}v_F\vec{m}_{\rm NM}$

Spin Pumping Theory



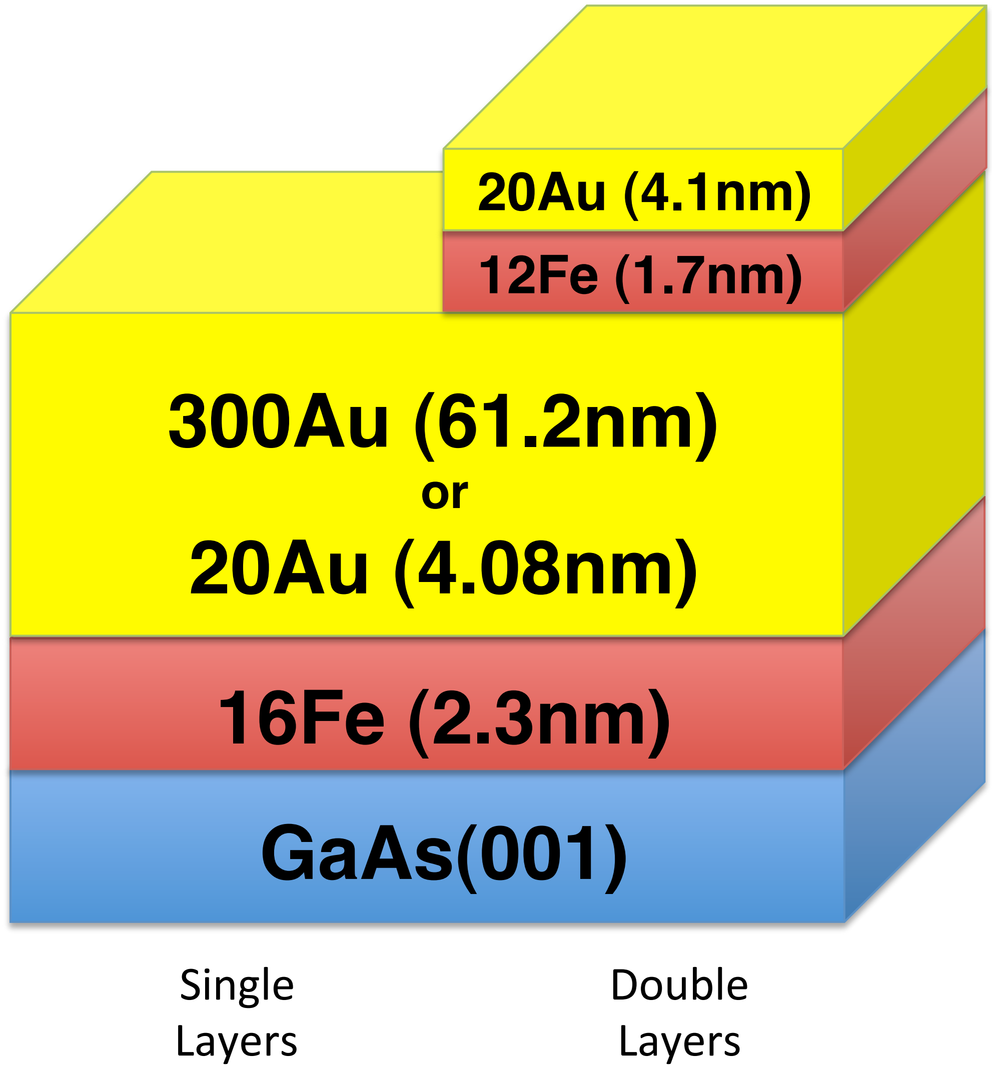
$F_b = F(d_{FM}, 4\pi M_S, g_{\uparrow\downarrow}, g, \mu_B)$

$F_{sd} = F(\tau_{sf}, \tau_m, d_{NM}, v_F) \times F_b$

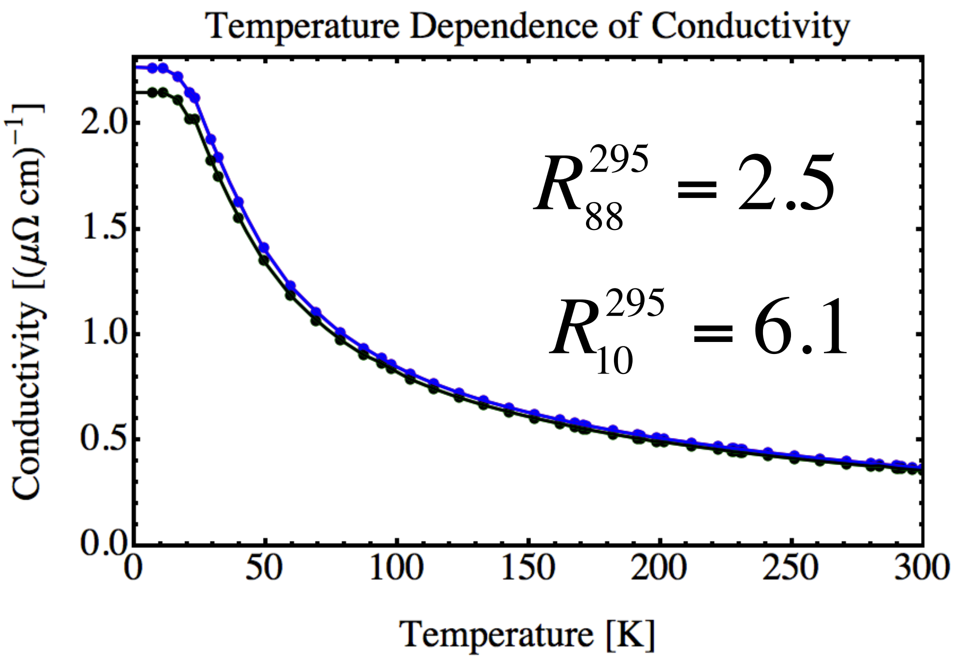
τ_{sf} is only unknown parameter

Sample Growth by MBE

- GaAs(001) Template
  - Atomic H etching
  - 650eV Ar^+ sputtering (continuous rotation)
  - 4x6 reconstruction RHEED monitored
- 16Fe and 12Fe have different FMR fields
- At 16Fe FMR, 16Fe acts as spin pump and 12Fe acts as spin sink



Charge Transport



- Van der Pauw measurements
  - 10K-300K

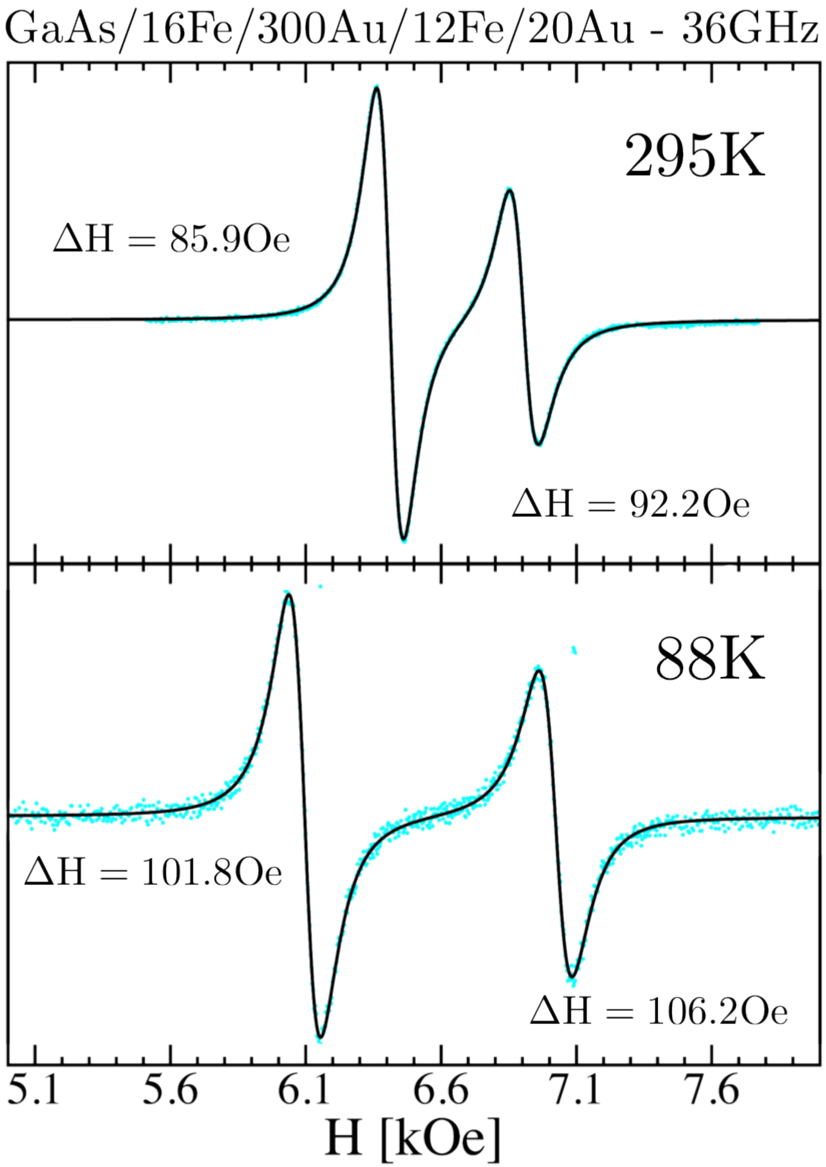
$$\tau_m = \frac{\sigma \mathrm{m}_e}{\mathrm{ne}^2}$$

- Contribution due to bulk phonon and interface scattering
- Using Mathiassen's Rule:

$$\frac{1}{\tau_m} = \frac{1}{\tau_p} + \frac{1}{\tau_i}$$

- Interface scattering contribution independent of temperature

Ferromagnetic Resonance

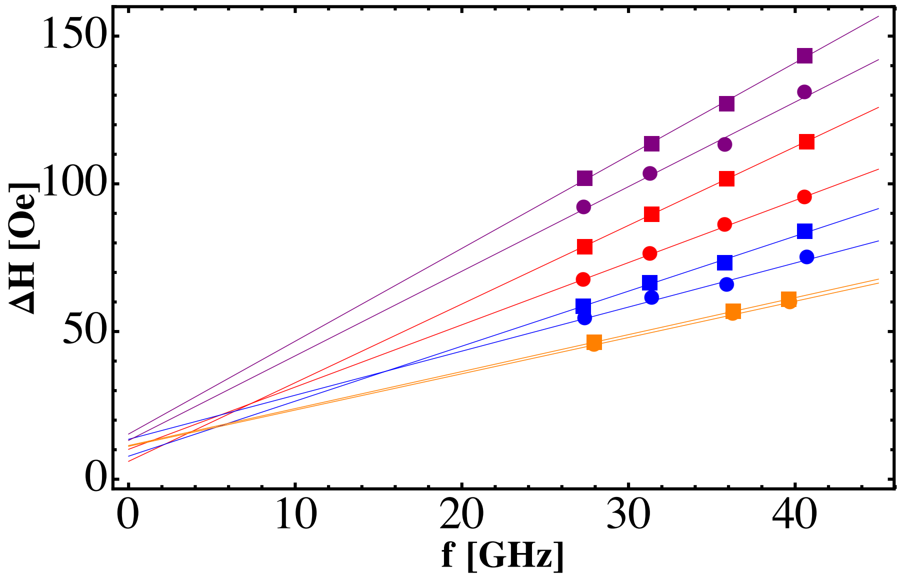


- FMR followed Gilbert damping phenomenology:

$$\Delta \mathrm{H}(\omega) = \alpha \frac{\omega}{\gamma} + \Delta \mathrm{H}(0)$$

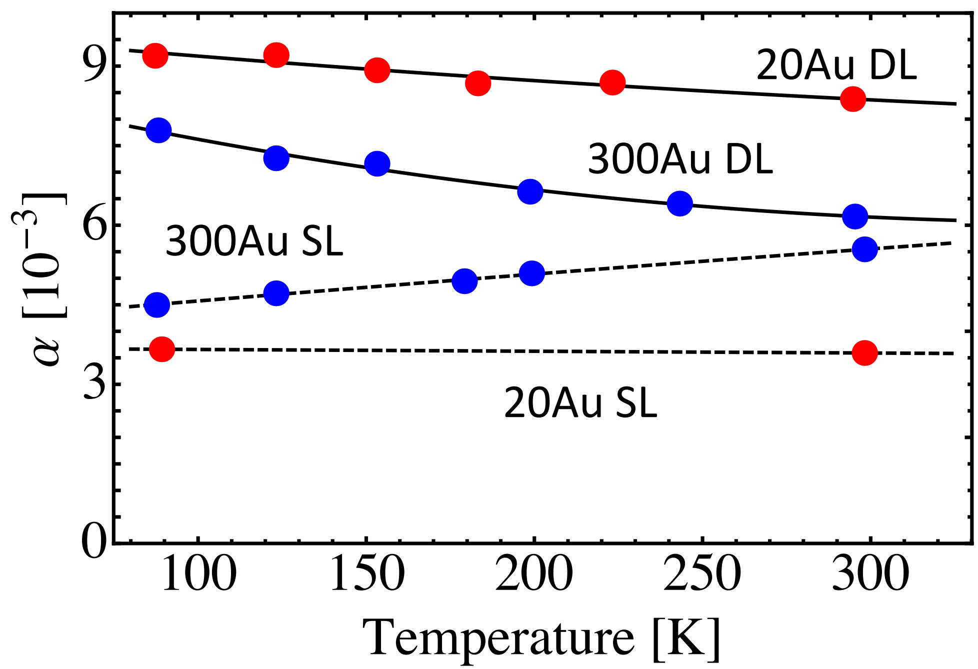
- Enhanced Gilbert damping due to spin pumping is an interface effect
- Spin momentum accumulates at the Fe/Au interface

Gilbert Damping

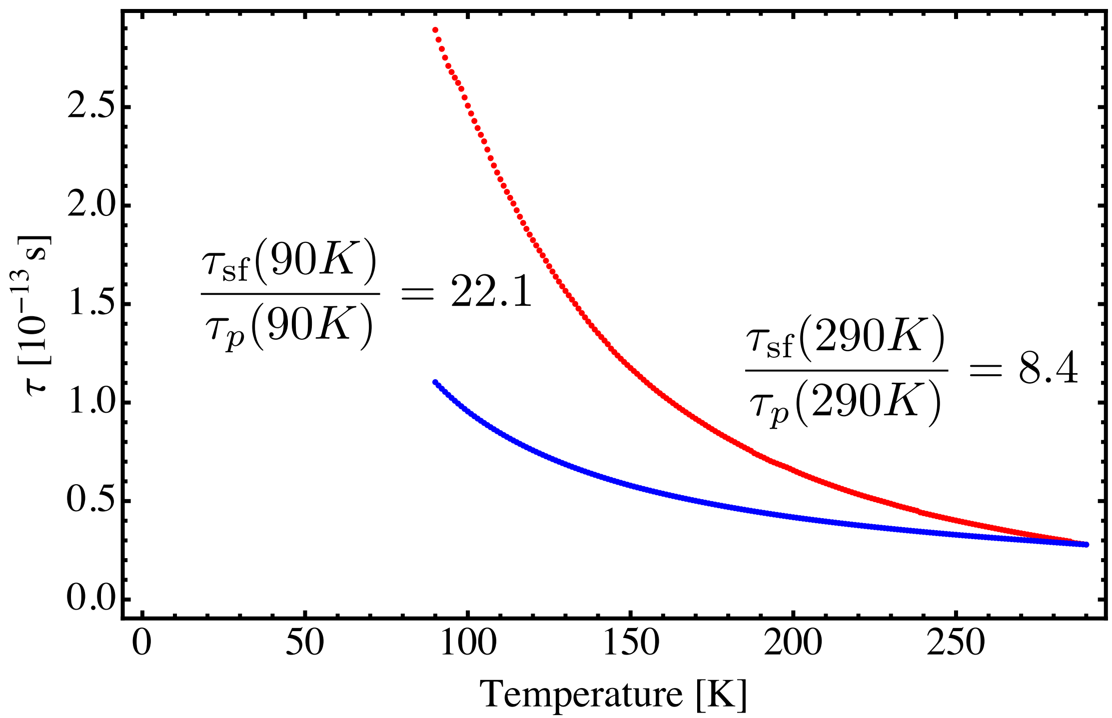


	#	Sample	α	offset
● (red circle)	1	300Au DL 295K	6.164×10^{-3}	10.13
■ (red square)	2	300Au DL 87K	7.789×10^{-3}	6.055
● (blue circle)	3	300Au SL 295K	4.365×10^{-3}	13.52
■ (blue square)	4	300Au SL 88K	5.448×10^{-3}	7.801
● (orange circle)	5	20Au SL 295K	3.591×10^{-3}	11.14
■ (orange square)	6	20Au SL 89K	3.661×10^{-3}	11.41
● (purple circle)	7	20Au DL 295K	8.378×10^{-3}	13.13
■ (purple square)	8	20Au DL 87K	9.192×10^{-3}	15.29

- α_{sp} greatest in ballistic limit for double layer
- α_{sp} increases with decreasing temperature for double layers
- α_{sp} decreases with decreasing temperature for single layers



Relaxation parameters



- τ_{sf} increases faster than τ_{p} as temperature decreases
- τ_{i} very weakly dependent on temperature

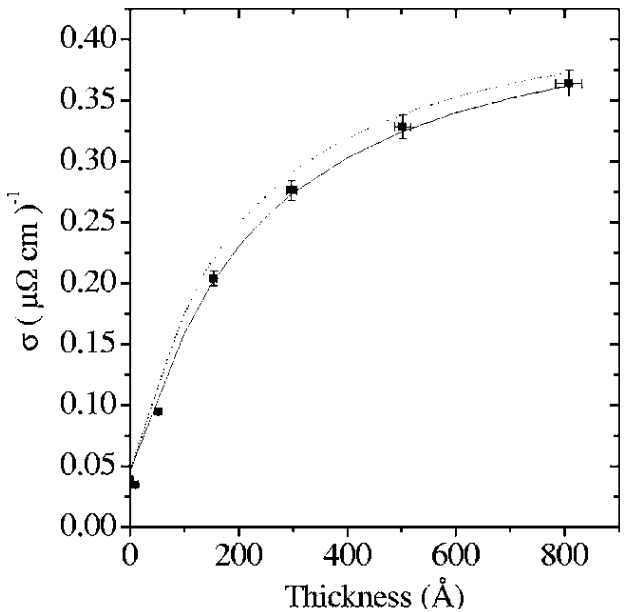
Spin flip scattering dominated by phonon processes

Combined influence of temperature dependent spin flip scattering at interfaces and bulk phonon scattering?

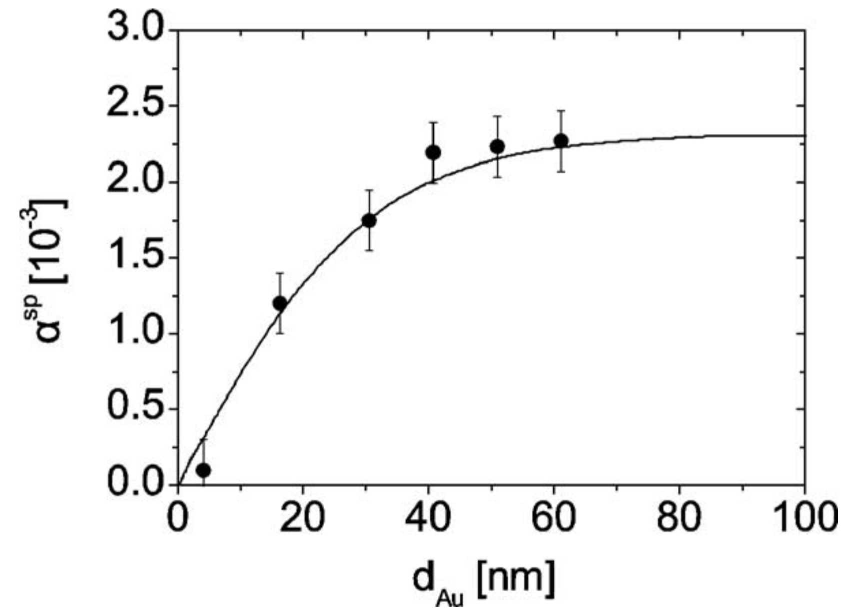
or

Multi-phonon scattering that does not contribute strongly to resistivity?

Previous Studies



T. Monchesky et. al. Phys.Rev.B. **71** (2005)



B. Kardasz et. al. J.Appl.Phys. **103** (2008)

From 80-5nm thickness of Au τ_i increases by a factor of 12

τ_{sf} only increases by a factor of 1.5

τ_{sf} can only weakly be dependent on interface scattering

Temperature dependence of τ_{sf} governed by multi-phonon scattering

Spin pumping at YIG/Au interface

recently new ideas and systems being developed for generation
of pure spin currents for driving Spin Transfer Torque (STT) devices

John Slonczewski has shown higher spin efficiency can be achieved by thermal gradients
using **Magnetic Insulator (MI)/NM** heterostructures

J. Slonczewski, PRB **82**, 054403 (2010)

new emerging field
spincoloritronics

Arne Brataas and Gerrit Bauer have shown that the spin pumping generation
is determined at MI/NM interfaces by spin mixing conductance

?????what is $g_{\uparrow\downarrow}$ at the YIG/Au interface ????

Spin mixing conductance in magnetic insulators

$$g^{\uparrow\downarrow} = \frac{1}{2}\sum_n \left(| r_n^{\uparrow} - r_n^{\downarrow} |^2 + | t_n^{\uparrow} - t_n^{\downarrow} |^2 \right)$$

$$t_n^{\uparrow\downarrow} = 0 \qquad r_n^{\uparrow\downarrow} = 1 \times e^{i\varphi_n^{\uparrow\downarrow}}$$

$$g_{\uparrow\downarrow} = \sum_n \left(1 - \cos(\varphi_n^{\uparrow} - \varphi_n^{\downarrow}) \right)$$

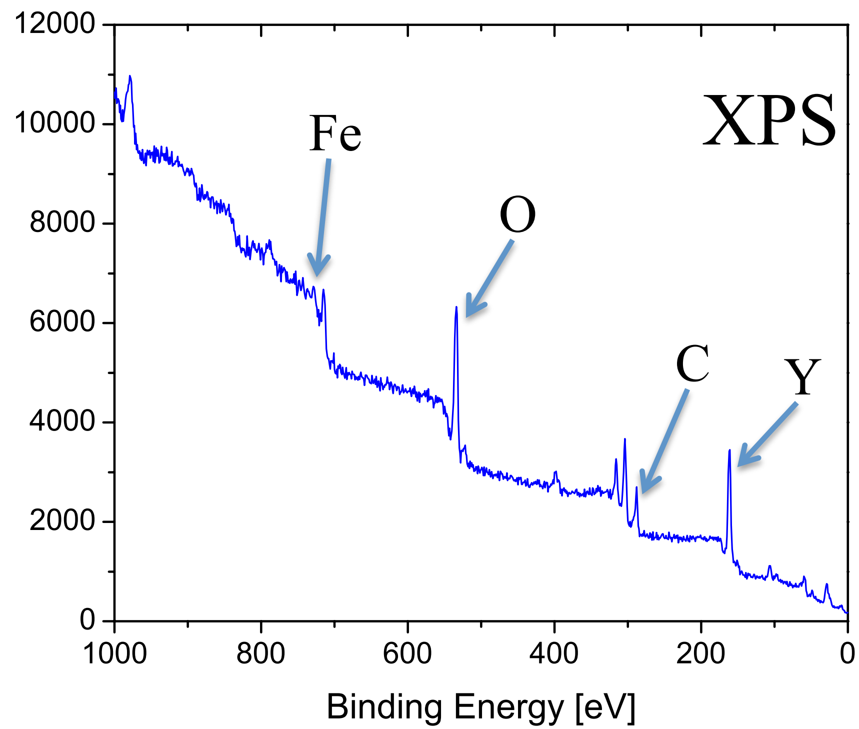
B. Heinrich et al. PRL, **107**, 066604 (2011)

C. Burrowes et al. APL , **100**, 092403 (2012)

YIG surface chemistry

YIG: $Y_3Fe_2(FeO_4)_3$

- Grown on (111) $Gd_3Ga_5O_{12}$ substrate by PLD at 700C and 0.1Torr O_2
- Thickness d=9nm (low angle XRD)
- $4\pi Ms$=1.31kG(SQUID), g=2.027 (FMR)
- Surface roughness 0.5nm (AFM)



Element Ratio	Measured	Expected
Y/Fe	1.9	0.6
O/Fe	8.1	2.4
O/y	4.3	4.0

→

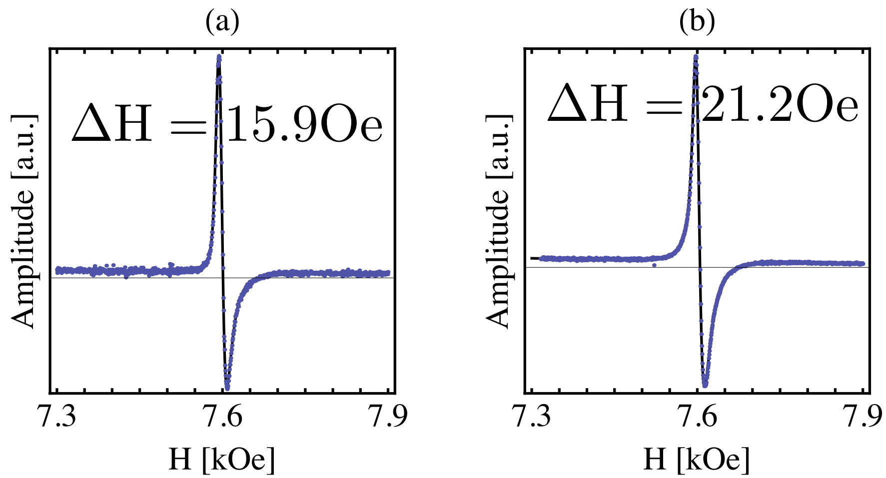
As prepared YIG has **surface deficiency of Fe**

Common for even thick PLD prepared YIG

Spin pumping from YIG

9nmYIG

9nm YIG/**6.1**nm Au/4.3nm Fe/6.1nm Au

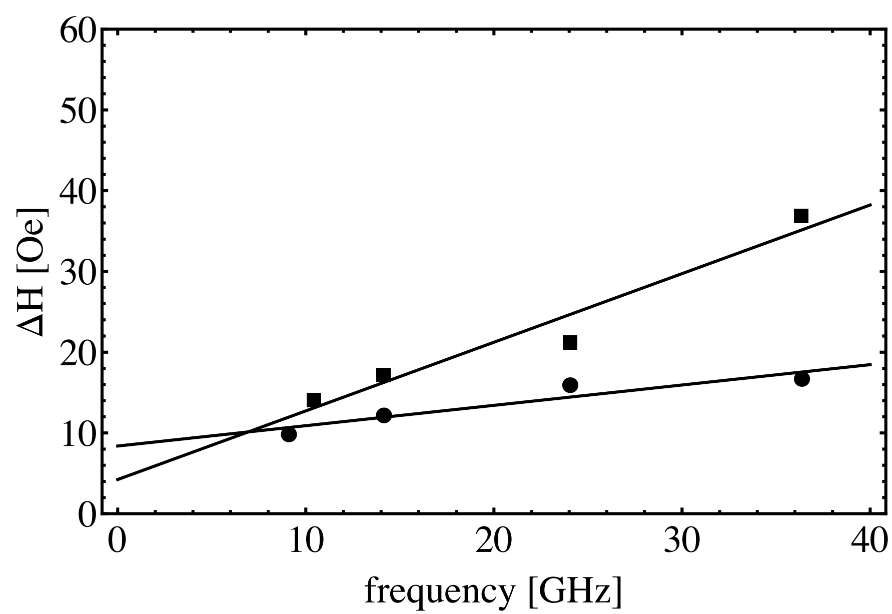


Transfer of angular momentum to Fe layer is seen as loss of angular momentum in YIG layer

Damping!

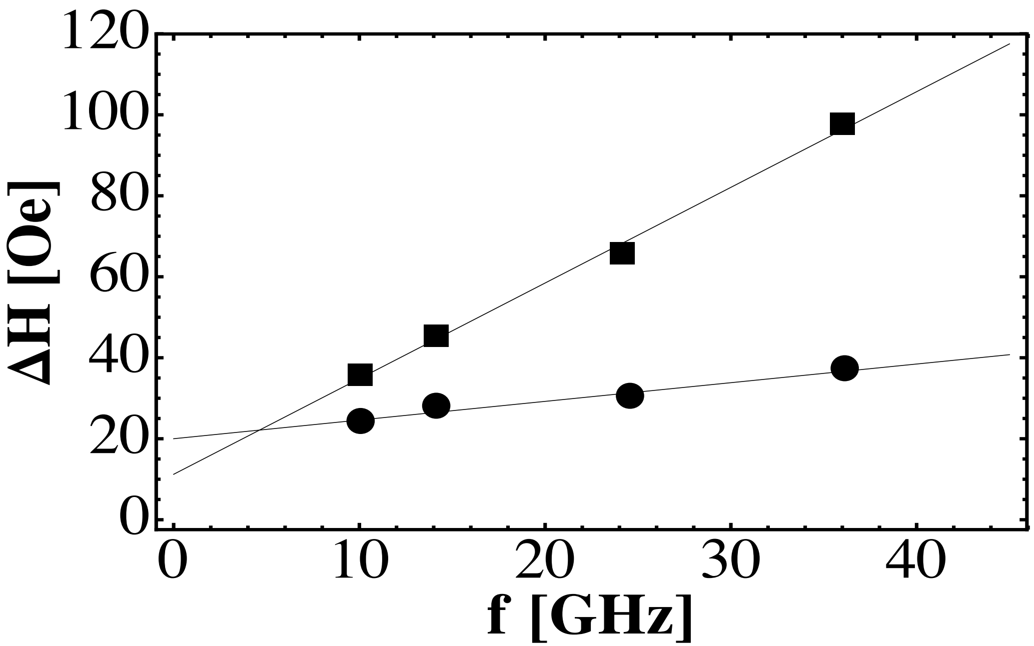
$$g_{\uparrow\downarrow} \cong 1.3 \times 10^{14}\, cm^{-2}$$

12% efficiency compared to Fe



Evaluating $g_{\uparrow\downarrow}$ in Ar+ etched YIG

Low angle Ar+ etched
10minutes
0.8kV, 400° C



9YIG(etched)/6.1Au/4.3Fe/6.1Au

$$\alpha = 0.0069$$

9YIG(etched)/6.1Au

$$\alpha = 0.0014$$

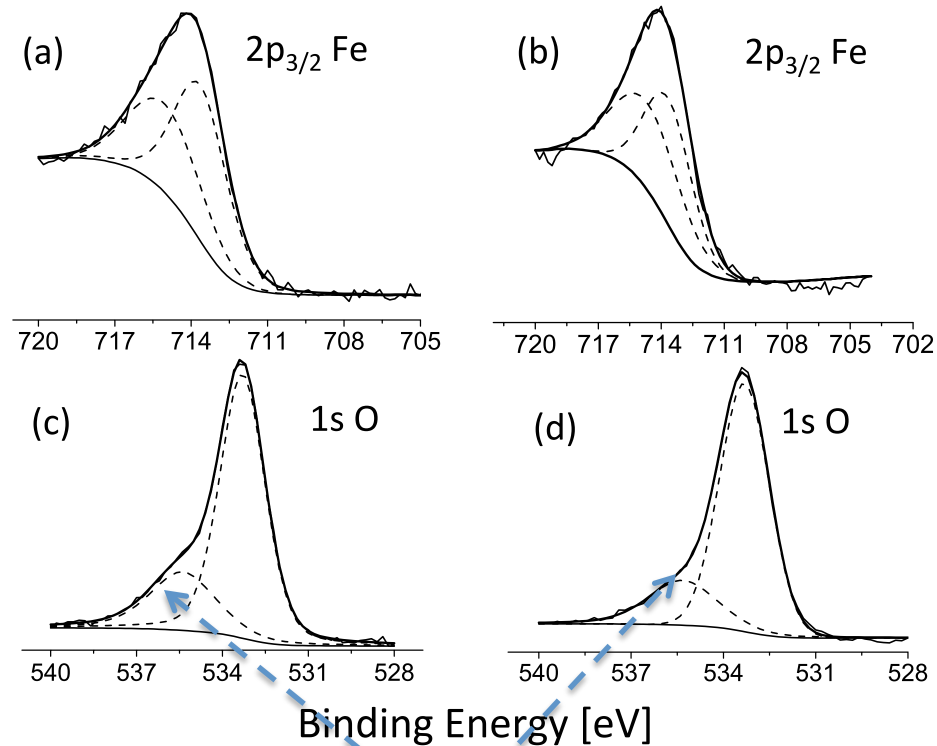
$$g_{\uparrow\downarrow} = 5.1 \times 10^{14}\, cm^{-2}$$

70% of predicted
by first principles calculations
X. Jia et al. Europhysics Letters **96**, 17005 (2011)

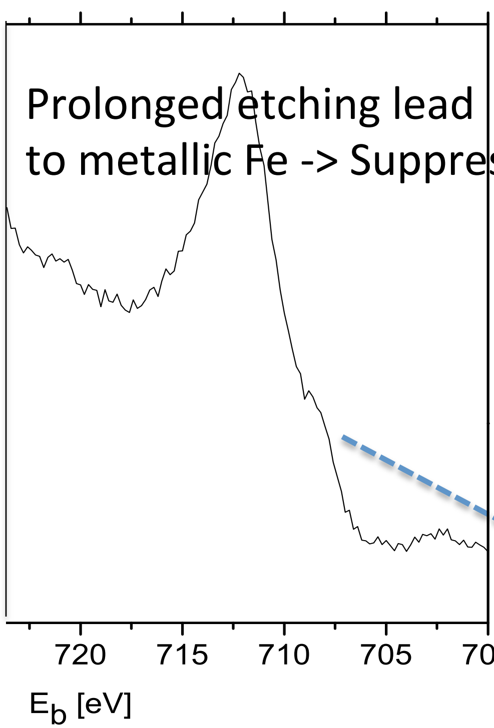
50% of Fe/Au

XPS on YIG

Fe $2p_{3/2}$	$E_B^1[eV]$	I_R^1	E_B^2 [eV]	I_R^2
untreated	713.6	0.6	715.0	0.4
etched	713.6	0.5	714.6	0.5
O 1s	**$E_B^1[eV]$**	**I_R^1**	**$E_B^2[eV]$**	**I_R^2**
untreated	533.3	0.75	535.4	0.25
etched	533.3	0.77	535.1	0.23



required change for increased $g_{\uparrow\downarrow}$



Prolonged etching lead to metallic Fe -> Suppresses pumping

metallic state of Fe decreases rapidly

$$g_{\uparrow\downarrow} \cong 3.7\times10^{14}\,cm^{-2}$$

spin pump/sink effect
can be used to
investigate the spin transport parameters in magnetic nanostructures

Conclusions:

spin pumping at YIG/Au is efficient
70% of theory calc. 50% of Fe/Au
evidence that a time retarded interlayer exchange coupling creates spin pumping

$$\frac{\hbar}{4\pi}\omega g_{\uparrow\downarrow}\sin^2\theta \qquad \frac{\hbar}{4\pi}g_{\uparrow\downarrow}\gamma\left(\frac{2k_B\left(T_{YIG}^m - T_{Au}\right)}{V_{coh}M_s}\right) \qquad \omega_{eff} = \gamma\left(\frac{2k_B\left(T_{YIG}^m - T_{Au}\right)}{V_{coh}M_s}\right)$$

J. Xiao et al. PRB **81**, 214418 (2010)

Efficiency of spin pumping comparison

		$\hbar$ nm^{-2}
Microwave driven: for f=10GHz and Θ=90^o		2x10^{10}
Thermal excitation: for ΔT=10 K , V_{coh}=2.7x10^3 nm^3	ω_{eff}=2x10^2 MHz	1.0x10^8
STT (60% polarization): for 2x10^6 Acm^{-2} :		2x10^{10}

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Conclusions

Temperature dependence of τ_{sf}

from 290K to 90K
τ_{sf} increases by factor of 10
τ_p increases by factor of 4
τ_i negligible dependence

Thickness dependence of τ_{sf}

from 80nm to 5nm
τ_{sf} increases by factor of 1.5
τ_p constant
τ_i increases by factor of 12

Temperature dependence of τ_{sf} governed by multi-phonon scattering

deposition of Fe on bare YIG
results in metallic state of Fe

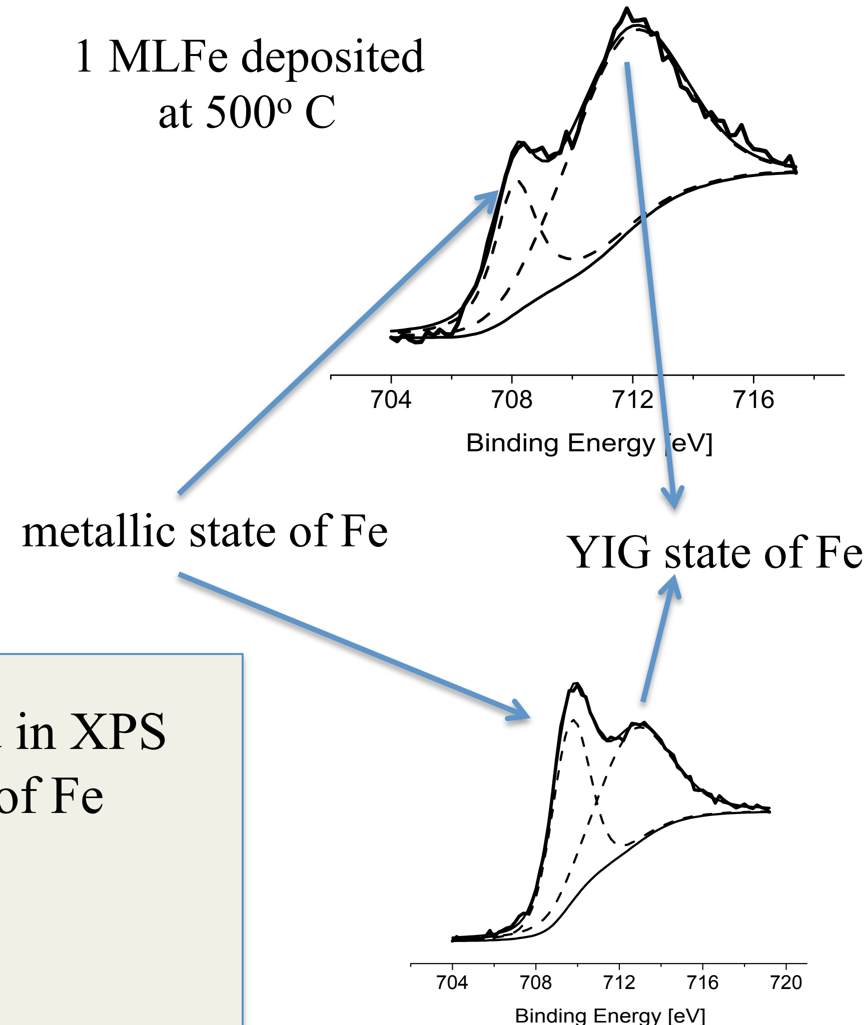
⬇

no spin pumping

YIG surface H atom etching showed in XPS
a strong presenceof metallic state of Fe

⬇

no spin pumping



spin current blockade by metallic Fe