Material-dependent spin caloritronics

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Ke Xia, Xingtao Jia, Kai Liu

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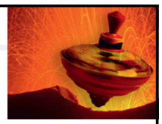
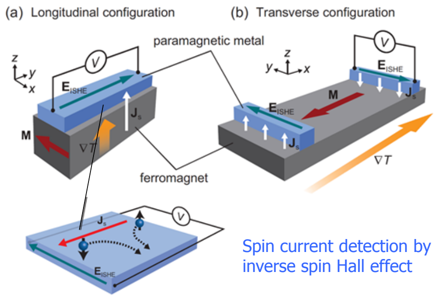


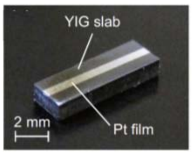
Spin Seebeck effect in magnetic insulators



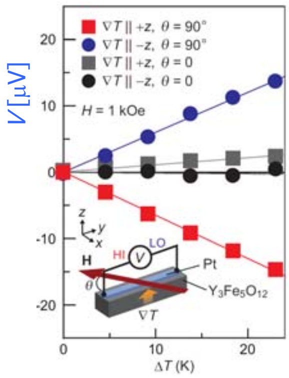
Spin current detection by inverse spin Hall effect

Experiments: Uchida *et al.* (**2010**/2011),
Theory: **Xiao *et al.* (2010)**,
Adachi *et al.* (2010), Ohe *et al.* (2011)

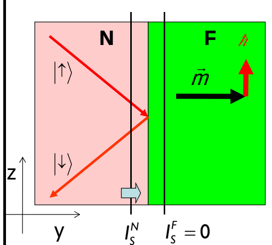
Experiment



Uchida *et al.* (2010/2011)



Current-induced spin-transfer torque



$$\vec T = \vec I_S^N$$

$$= \left(\hat z \,\mathrm{Re}\, g^{\uparrow\downarrow} - \hat x \,\mathrm{Im}\, g^{\uparrow\downarrow}\right) \frac{\mu_N^{\uparrow} - \mu_N^{\downarrow}}{2}$$

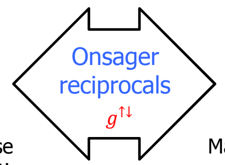
$$g^{\uparrow\downarrow} = N - \sum_{nm}^{\varepsilon_F} r_{nm}^{\uparrow} \left(r_{nm}^{\downarrow}\right)^*$$

spin-mixing conductance

$\mu_N^{\uparrow} - \mu_N^{\downarrow}$

spin accumulation

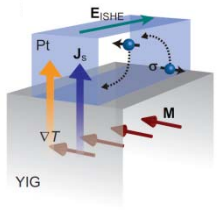
Spin torque and spin pumping



Spin currents cause magnetization motion (spin transfer torque, Slonczewski, 1996).

Magnetization motion causes spin currents (spin pumping, Tserkovnyak, 2002).

Theory by Xiao *et al.* (2010)



$$\boxed{J_s = J_s^{\text{pump}} - J_s^{\text{J-N noise}}}$$

Foros *et al.* (2005)

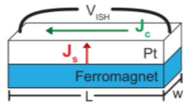
spin mixing conductance

local non-equilibrium

$$J_s = \frac{\gamma \hbar k_B g_r^{\uparrow\downarrow}}{2\pi M_s V_{coh}} \left(T_F^M - T_N^e \right)$$

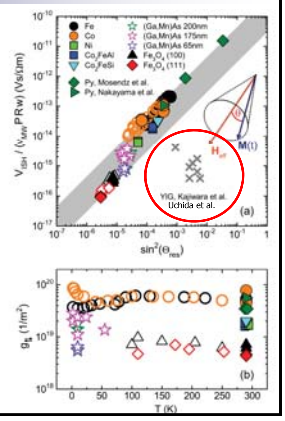
coherence volume near to contact

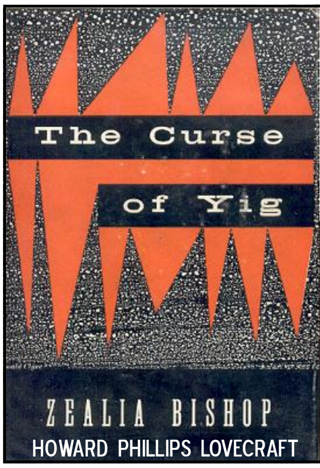
FMR spin pumping experiments



Scaling as a function of μ-wave intensity

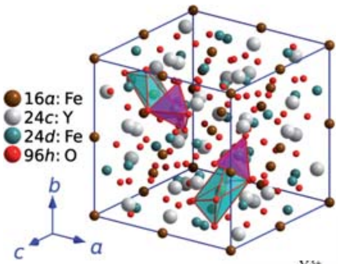
Czeschka *et al.* (2011)





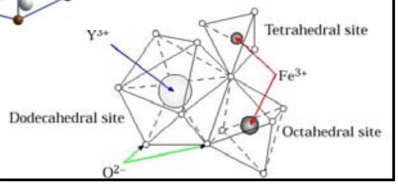
YIG (the Father of Serpents), a Great Old One of the Cthulhu Mythos

YIG: Yttrium Iron Garnet



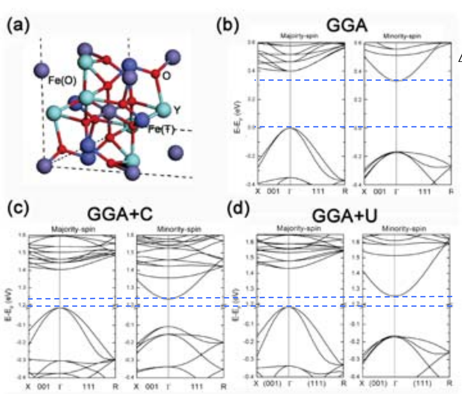
- 80 atoms/primitive unit cell
- ferrimagnetic insulator
- Curie temperature 550 K
- Gilbert damping $\alpha \sim 10^{-4}$–10^{-5}

$Y_3Fe_2(FeO_4)_3$



YIG band structure

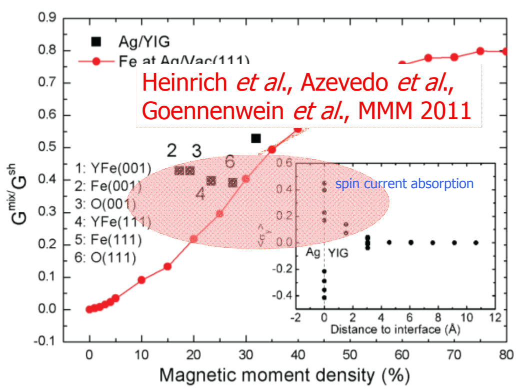
Jia *et al.*, EPL (2011)



$\Delta E_g^{GGA} = 0.33\,\text{eV}$

$\Delta E_g^{U} = 1.4\,\text{eV}$

Mixing conductance



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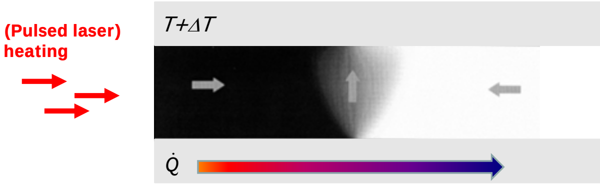
- Spin Seebeck effect in YIG|Pt
- Thermal spin transfer torques in magnetic tunnel junctions
- Shot noise in magnetic tunnel junctions

Thermal magnetization torques



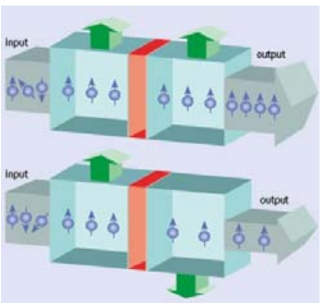
<u>Heat current induced magnetization dynamics</u>:

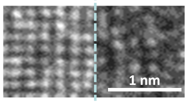
Theory:- spin valves: Hatami *et al.* (2007), Slonczewski (2010).
- domain walls: Kovalev & Tserkovnyak (2010,2011), Bauer *et al.* (2010) Hals *et al.* (2010), Hinzke & Nowak (2011), Yan & Wang (2011)
- tunnel junctions: **Jia *et al.*** (2011)

Experiment (spin valves): Yu *et al.* (2010).

Magnetic tunnel junctions

Fe (↑) | MgO | Fe (↑/↓)



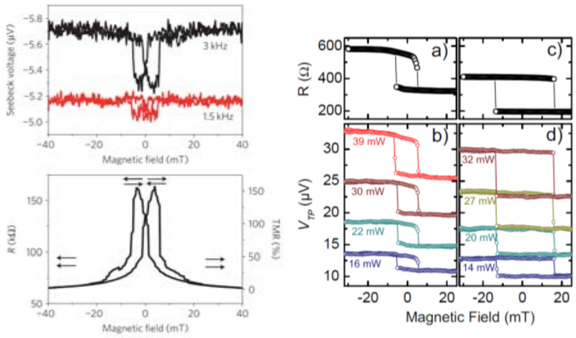


MgO CoFeB

$$\mathrm{TMR} = \frac{R_{AP} - R_P}{R_P}$$

$\leq 1000\%$

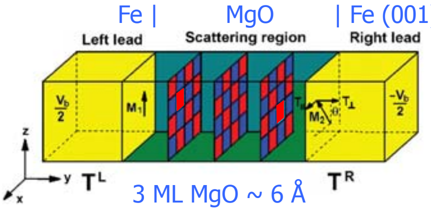
Walter *et al.* (2011); Liebing *et al.* (2011)



10 ML MgO 7 ML MgO

Sample configuration

Fe | MgO | Fe (001)



3 ML MgO ~ 6 Å

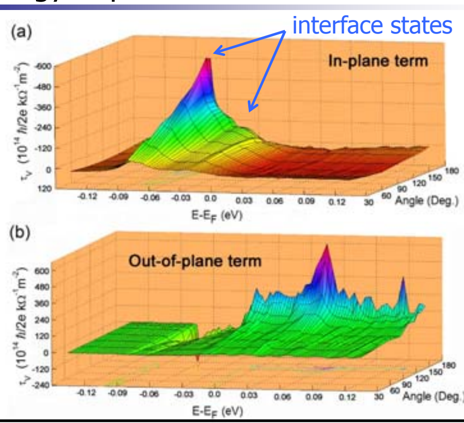
$$\mathbf{T}_{\Delta T} = \frac{1}{8\pi}\frac{\Delta T}{2T_0}\int d\epsilon(\epsilon - \epsilon_F)\cdot \mathbf{t}(\epsilon)\frac{\partial}{\partial \epsilon}f(\epsilon)$$

energy-dependent torkance

$$\boxed{\begin{aligned}\Delta T_c^{AP\to P}(300\,\mathrm{K}) &= 7\,\mathrm{K}\\ \Delta T_c^{P\to AP}(300\,\mathrm{K}) &= 60\,\mathrm{K}\end{aligned}}$$

Energy-dependent torkances

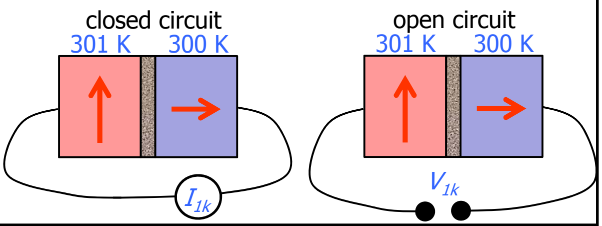
interface states



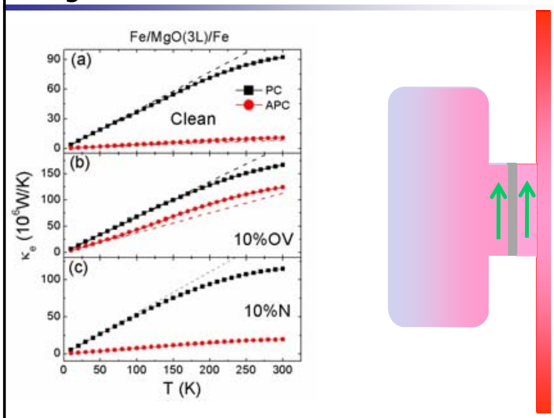
Numbers

n	τ_V (mJ/V/m^2)	T_{1K}* (nJm^{-2})	ΔV_{eq} (mV)	ΔV_{1K} (mV)	T_{1K}/I_{1K} ($\hbar/2e$)	T_V/I_V ($\hbar/2e$)
3	0.72	-195(-232)	-0.27	0.052	-0.94	0.21
5	0.082	-3.32(-5.33)	-0.040	0.025	-0.84	0.46
7	0.011	-0.24(-0.062)	-0.021	-0.0154	3.58	0.98

$^*1\ \mathrm{JV^{-1}m^{-2}} = 3 \cdot 10^{18} (\hbar/2)\mathrm{k\Omega^{-1}m^{-2}}$



Magnetoheatresistance



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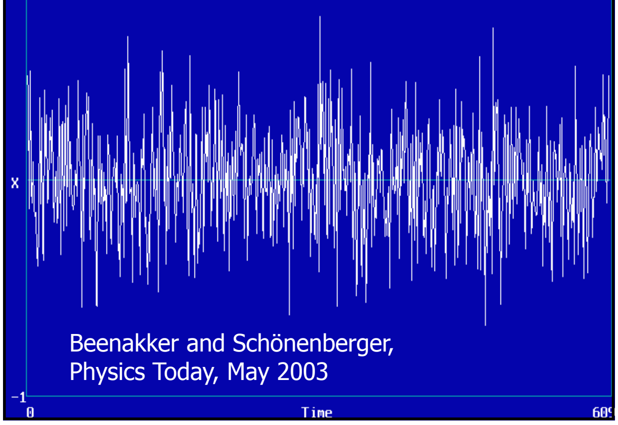
Q-Noise

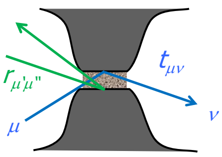


Beenakker and Schönenberger,
Physics Today, May 2003

Scattering theory

t matrix of transmission coefficients at the Fermi energy

T = t†t transmission matrix



$$\langle I \rangle = \frac{e}{h}\Delta\mu \mathrm{Tr}\{\mathbf{T}\}$$ Landauer-Büttiker formula

$$= \frac{e}{h}\Delta\mu \sum_{ns} T_{ns} = \frac{e}{h}\Delta\mu \int_0^1 \rho(T) T dT$$

$$\rho(T) = \sum_{ns} \delta(T - T_{ns})$$ distribution function of transmission matrix eigenvalues

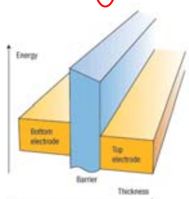
Electronic noise

$$\Delta I(t) = I(t) - \langle I \rangle \qquad P(\omega) = \int_{-\infty}^{+\infty} \langle \Delta I(0) \Delta I(t) \rangle e^{i\omega t} dt$$

Fano factor

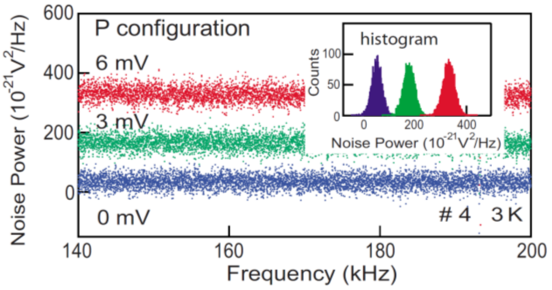
$$S = P(\omega \to 0) = \frac{2e}{h}|\Delta\mu| \int_0^1 \rho(T) T(1-T) dT \equiv 2eF\langle I \rangle$$

Common wisdom for tunnel junctions:



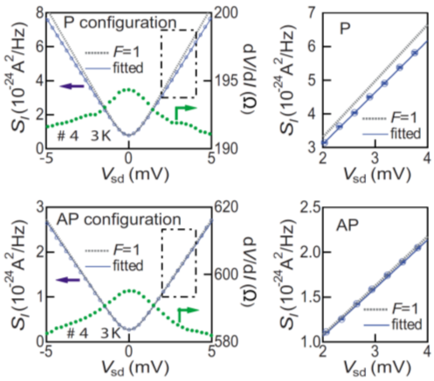
$$T_n \ll 1: S = \frac{2e}{h}|\Delta\mu| \int_0^1 \rho(T) T dT \equiv 2e\langle I \rangle \to F = 1$$

Noise in magnetic tunnel junctions



T. Arakawa *et al.* (2011)

Noisy magnetic tunnel junctions



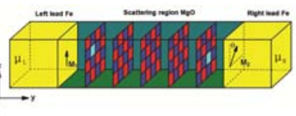
$S_I = 2eF\langle I\rangle$

Fano factor

Experiments Arakawa *et al.* (2011) @ 3K (10K)
d_{MgO} = 5 ML

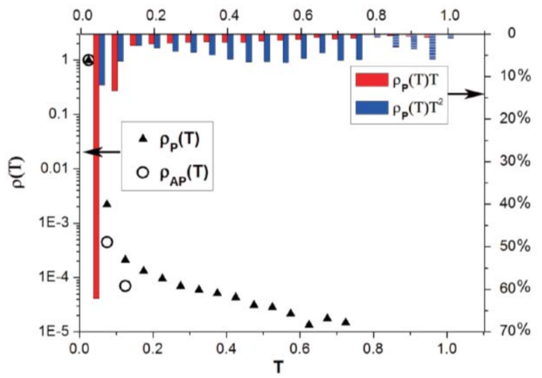
Sample Nos.	P	AP	MR ratio (%)
1	0.91 ± 0.01	0.97 ± 0.01	202.0
2	0.89 ± 0.01	0.97 ± 0.01	191.3
3	0.93 ± 0.01	0.99 ± 0.01	210.0
4	0.92 ± 0.01	0.98 ± 0.01	206.2

First-principles theory
Liu *et al.*, arXiv:1111.268



Fano factor	3MgO	4MgO	5MgO	7MgO
P	0.64[0.65(2)]	0.91[0.69(4)]	0.97[0.87(4)]	1.00[0.99(1)]
AP	0.94[0.77(2)]	1.00[0.94(1)]	1.00[0.98(1)]	1.00[0.99(1)]
TMR	1320%[165%]	2400%[288%]	3580%[250%]	5600%[107%]

Distribution of transmission eigenvalues



Disorder dependence

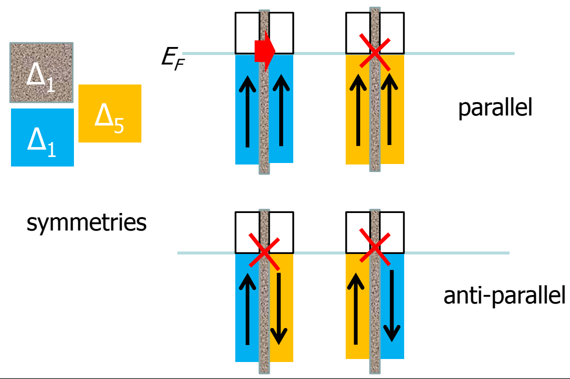
non-monotonous

Concentration	P		
	G(maj)	G(min)	Fano factor
0	68.00[68.50]	3.47[3.51]	0.97
4.69%	89(3)[94.5]	41(7)[33.6]	0.85(3)
5.56%	80(4)[91.0]	44(10)[29.2]	0.87(4)
6.25%	79(3)[85.5]	25(4)[26.9]	0.95(2)

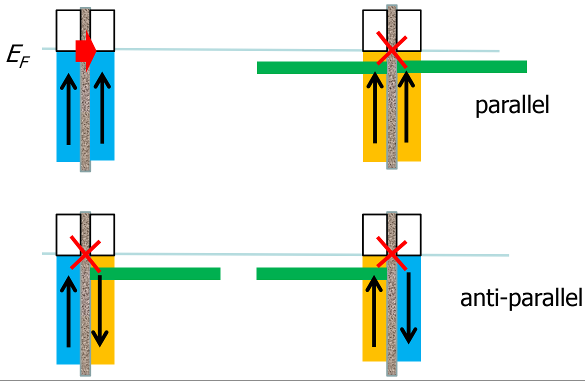
Concentration	AP	
	G	Fano factor
0	1.95[1.95]	1.00
4.69%	35(3)[32.8]	0.98(1)
5.56%	36(4)[37.5]	0.98(1)
6.25%	38(3)[41.0]	0.98(1)

[...] CPA

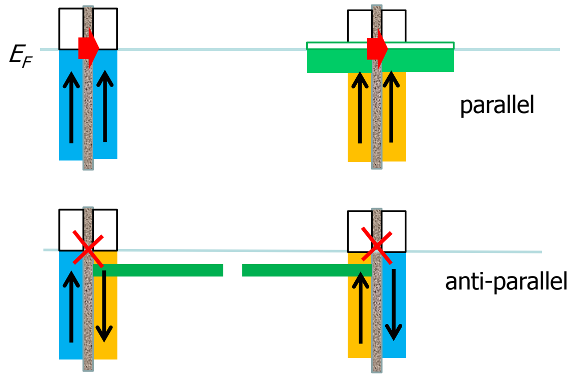
Without interface states



With interface states, thick junctions

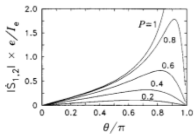


With interface states, thin junctions



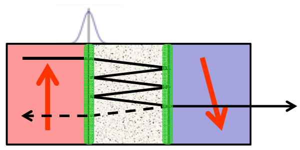
Skewness/enhancement of the torque

metallic spin valves
(Slonczewski, 1996)



spin accumulation
enhanced torque

thin tunnel junctions



multiple scattering
between interface
states

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