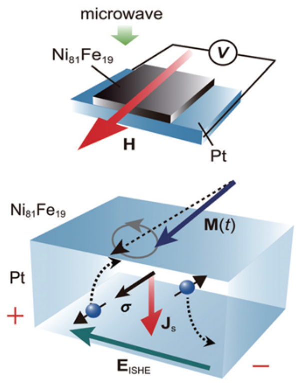
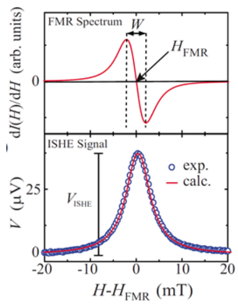
Spin pumping detected by the ISHE





Saitoh *et al.* (2006)
Ando *et al.* (2011)

Spin pumping and inverse spin Hall effect

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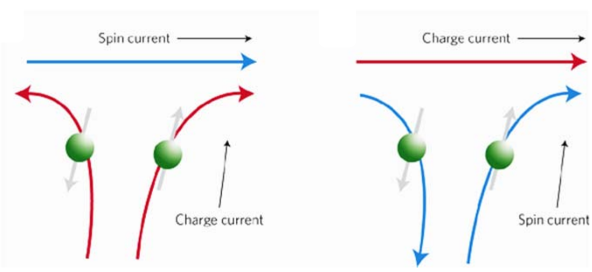
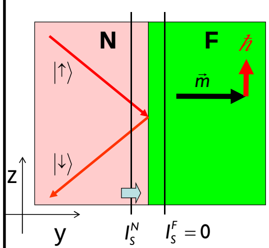
Spin Hall effects



direct SHE

inverse SHE
(Onsager)

Current-induced spin-transfer torque



$$\vec T = \vec I_s^N$$

$$= \left(\hat z \,\mathrm{Re}\, g^{\uparrow\downarrow} - \hat x \,\mathrm{Im}\, g^{\uparrow\downarrow}\right) \frac{\mu_N^\uparrow - \mu_N^\downarrow}{4\pi}$$

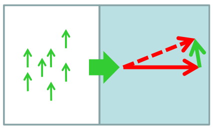
$$g^{\uparrow\downarrow} = N - \sum_{nm}^{\epsilon_F} r_{nm}^\uparrow \left(r_{nm}^\downarrow\right)^*$$

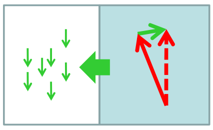
spin-mixing conductance

$$\mu_N^\uparrow - \mu_N^\downarrow$$

spin accumulation

Spin torque and spin pumping



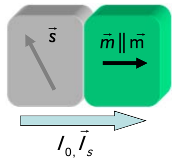


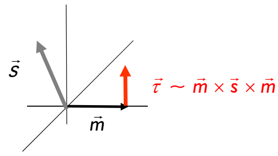
Onsager reciprocals

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

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

Dynamics of bilayers





Landau-Lifshitz-Gilbert equation with additional torque term:

$$\frac{\partial\vec{m}}{\partial t} = -\gamma\vec{m}\times\vec{H} + \alpha_0\vec{m}\times\frac{\partial\vec{m}}{\partial t} + \frac{\hbar\gamma}{4\pi M_s}\vec{m}\times\left(\vec{I}_s^{\,pump} + \vec{I}_s^{\,back}\right)\times\vec{m}$$

$$= -\gamma\vec{m}\times\vec{H} + \left(\alpha_0 + \frac{\hbar\gamma}{4\pi M_s}g_{\uparrow\downarrow}\right)\vec{m}\times\frac{\partial\vec{m}}{\partial t} + \frac{\hbar\gamma}{4\pi M_s}g_{\uparrow\downarrow}\vec{m}\times\vec{s}\times\vec{m}$$

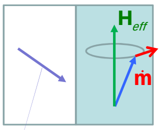
spin pumping backflow torque

Onsager reciprocity

LLG equation

$$\begin{pmatrix} M_s V\dot{\mathbf{m}} \\ \mathbf{I}_N^{(s)} \end{pmatrix} = \begin{pmatrix} \boxed{\tilde{L}^{(mm)}} & \tilde{L}^{(ms)} \\ \tilde{L}^{(sm)} & \boxed{\tilde{L}^{(ss)}} \end{pmatrix} \begin{pmatrix} \mathbf{H}_{\mathrm{eff}} \\ \mathbf{V}_N^{(s)} \end{pmatrix}$$

spin conductance



$e\mathbf{V}_N^{(s)} = \mathbf{s}(\mu_\uparrow - \mu_\downarrow)$

$\boxed{L_{ij}^{(sm)}(\mathbf{m})} = \boxed{L_{ji}^{(ms)}(-\mathbf{m})}$ $\sim g^{\uparrow\downarrow}$ spin mixing conductance

spin pumping

spin transfer torque

Brataas et al. (2011)

Sources and sinks of spin currents

F

N

$\tau_{sf} \to \infty$
e.g. Cu

$$\frac{\partial\vec{m}}{\partial t} = -\vec{m}\times\gamma\vec{H} + \alpha_0\vec{m}\times\frac{\partial\vec{m}}{\partial t}$$

intrinsic bulk damping

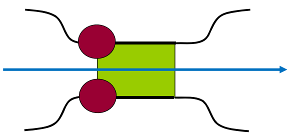
$\tau_{sf} \to 0$
e.g. Pt

$$\frac{\partial\vec{m}}{\partial t} = -\vec{m}\times\gamma\vec{H} + \left(\alpha_0 + \frac{\hbar\gamma}{4\pi M_s}g_{\uparrow\downarrow}\right)\vec{m}\times\frac{\partial\vec{m}}{\partial t}$$

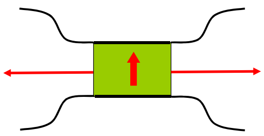
enhanced damping

Spin vs. charge pumping

Pumping (Büttiker, Brouwer): Current flows without applied bias, but due to time-dependent modulation of scattering matrix.



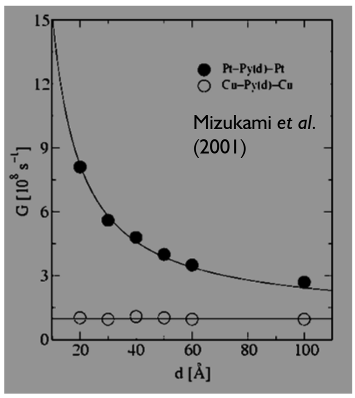
charge pumping



spin pumping

$$\vec{I}_{pump}^{\,F\to N} = \frac{\hbar}{4\pi}g_{\uparrow\downarrow}\vec{m}\times\frac{d\vec{m}}{dt}$$

Py|Pt mixing conductance



$G = \gamma M_s \alpha$

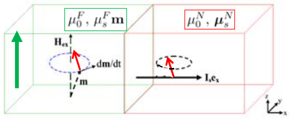
$$G(d) = G_0 + \frac{(g_L\mu_B)^2}{e^2}\frac{G_r^{\uparrow\downarrow}}{Ad}$$

$g_L = 2.1$ $G_0 = 10^8\,Hz$

Py|Pt:

$$\frac{G_r^{\uparrow\downarrow}}{A} = 1.0\cdot10^{15}\,\Omega^{-1}m^{-2}$$

Backflow



$$\mathbf{I}_s^{\mathrm{p}} = \frac{\hbar}{4\pi}\left(\mathrm{Re}g^{\uparrow\downarrow}\mathbf{m}\times\frac{d\mathbf{m}}{dt} + \mathrm{Im}g^{\uparrow\downarrow}\frac{d\mathbf{m}}{dt}\right)$$

pumping current

$$I_c = \frac{eg}{2h}[2(\mu_0^F - \mu_0^N) + p(\mu_s^F - \mathbf{m}\cdot\boldsymbol{\mu}_s^N)],$$
$$\mathbf{I}_s^{\mathrm{b}} = \frac{g}{8\pi}[2p(\mu_0^F - \mu_0^N) + \mu_s^F - \mathbf{m}\cdot\boldsymbol{\mu}_s^N]\mathbf{m} - \frac{\mathrm{Re}g^{\uparrow\downarrow}}{4\pi}\mathbf{m}\times\boldsymbol{\mu}_s^N\times\mathbf{m} - \frac{\mathrm{Im}g^{\uparrow\downarrow}}{4\pi}\boldsymbol{\mu}_s^N\times\mathbf{m}$$

backflow current

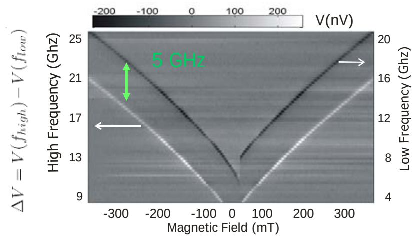
$$i\omega\boldsymbol{\mu}_s^N(\mathbf{r},\omega) = D_N\frac{\partial^2\boldsymbol{\mu}_s^N(\mathbf{r},\omega)}{\partial x^2} - \frac{\boldsymbol{\mu}_s^N(\mathbf{r},\omega)}{\tau_{sf}^N}$$

spin diffusion equation (normal metal)

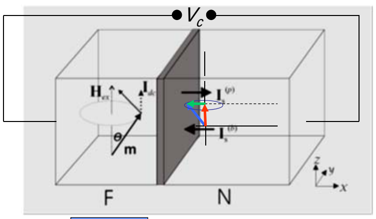
$$\partial\boldsymbol{\mu}_s^N(\mathbf{r},t)/\partial x|_{x=0} = -2\mathbf{I}_s(x=0,t)/(\hbar\nu A D_N)$$

boundary condition

Costache *et al.* (2006)



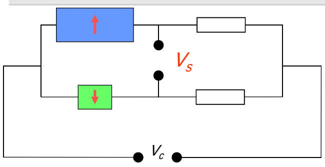
Spin battery



$\vec{s} = \vec{s}_{\parallel} + \vec{s}_{\perp}(t)$

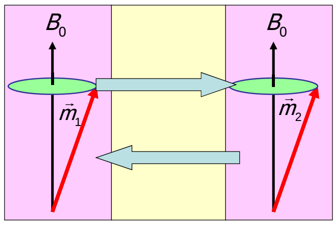
$\langle \vec{s}_{\perp}(t) \rangle = 0$

$|\vec{s}_{\parallel}| = eV_s$



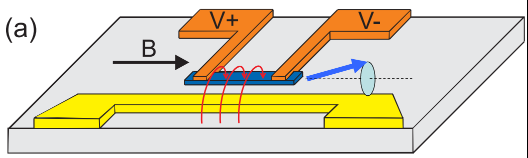
V_c voltage signal over bilayer in the presence of spin-flip in the ferromagnet

Dynamic coupling

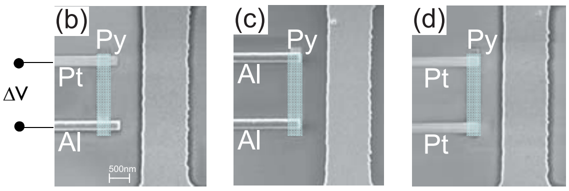


- semiclassical
- limited by spin-flip diffusion length

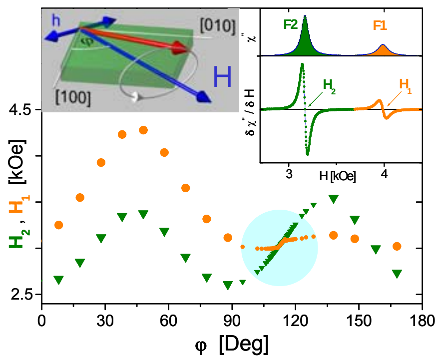
Costache *et al.* (2006)

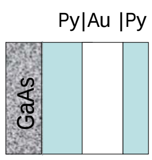


$\theta \cong 5°$ (from AMR)

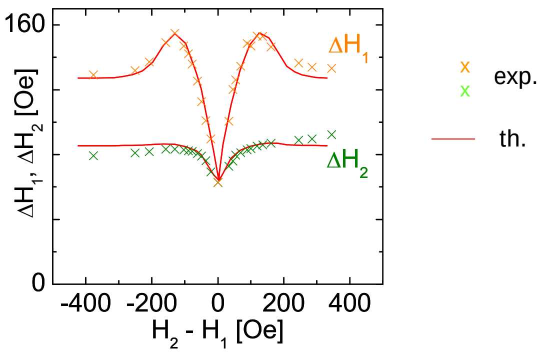


FMR spectra of spin valves (Heinrich *et al.*, 2002)

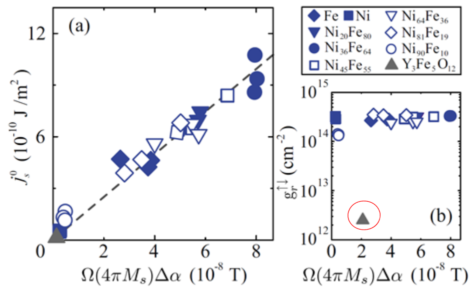




Spin valve FMR (Heinrich *et al.*, 2002)

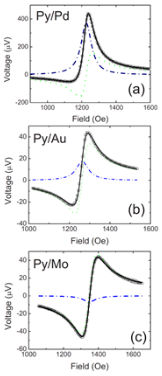


Spin mixing conductance

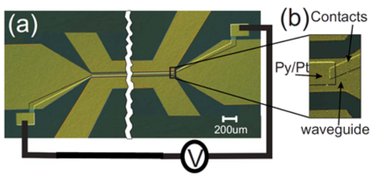


Yoshino *et al.* (2011)

Spin Hall angle in Py|N

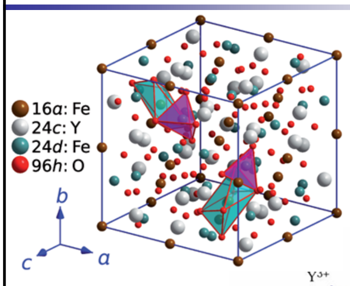


Mosendz *et al.* (2011)



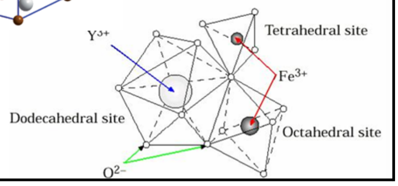
Normal metal	λ_{sd} (nm)	σ_N $1/(\Omega\ \mathrm{m})$	γ
Pt	10 ± 2	$(2.4\pm0.2)\times10^6$	0.013 ± 0.002
Pd	15 ± 4	$(4.0\pm0.2)\times10^6$	0.0064 ± 0.001
Au	35 ± 3	$(2.52\pm0.13)\times10^7$	0.0035 ± 0.0003
Mo	35 ± 3	$(4.66\pm0.23)\times10^6$	-0.0005 ± 0.0001

YIG: Yttrium Iron Garnet

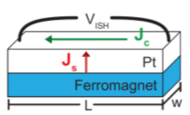


- 80 atoms/primitive unit cell
- ferrimagnetic insulator
- Curie temperature 550 K
- Gilbert damping $\alpha\sim10^{-4}$–10^{-5}

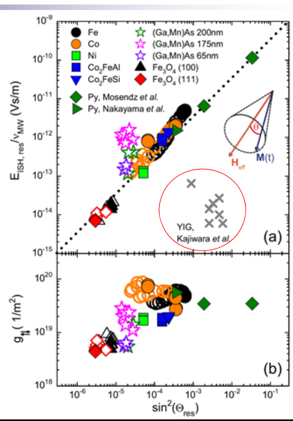
$Y_3Fe_2(FeO_4)_3$



Spin mixing conductance

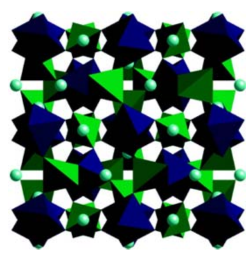


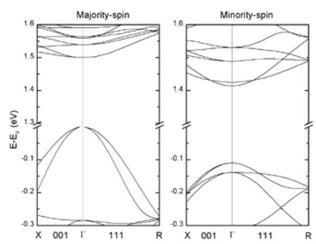
Scaling as a function of μ-wave intensity



Czeschka *et al.* (2011)

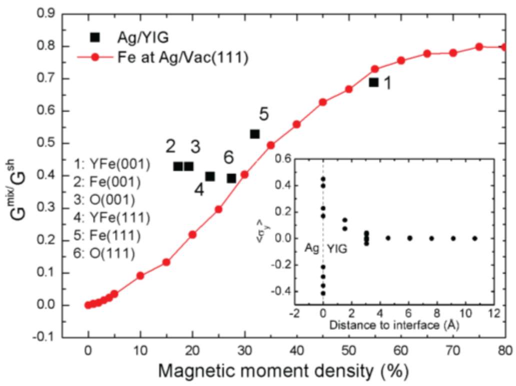
Electronic structure of YIG



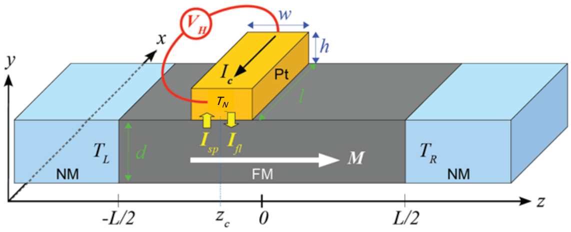


X. Jia *et al.*, arXiv:1103.3764

Mixing conductance (X. Jia *et al.*, arXiv:1103.3764)



Spin (magnon) Seebeck effect (J. Xiao et al., 2010)



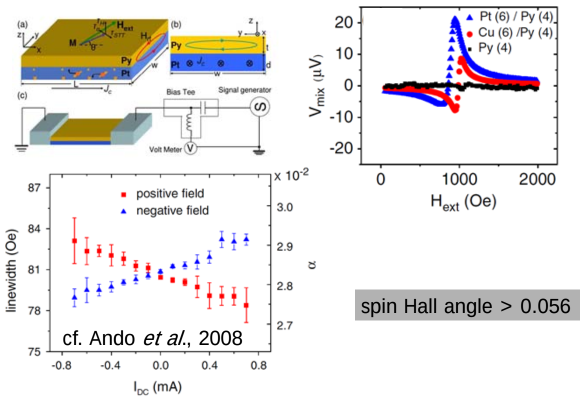
Mixing conductance

$$\langle I_z \rangle = \frac{\gamma \hbar g_r k_B}{2\pi M_s V}(T_F^m - T_N)$$

Magnon temperature distribution gives position dependence.

Volume of magnetization governs signal strength.

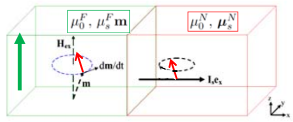
FMR by spin Hall effect Liu *et al.*, 2011



cf. Ando *et al.*, 2008

spin Hall angle > 0.056

Backflow issues (Hujun Jiao)



Pumping current:

DC component along z ($\sim\theta^2$)
AC component along x-y: AC spin Hall effect

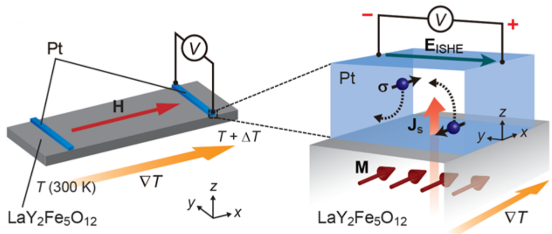
Non-linear back flow terms: $\boldsymbol{\mu}_s^N \cdot \mathbf{m}$ $\boldsymbol{\mu}_s^N \times \mathbf{m}$

Possibly significant depletion of DC spin accumulation by backflow in the AC channel.

Spin Seebeck effect

Experiments: Uchida *et al.* (2008/**2010**/2011), Jaworski *et al.* (2010/2011)

Theory: **Xiao *et al.* (2010)**, Adachi *et al.* (2010).



Conclusions

Results

- Evidence for spin pumping in magnetic heterostructures (enhanced damping, emf's, dynamical exchange interaction).
- Quantitative description of most experiments.
- Inverse spin Hall effect to measure spin Hall angles.

Issues

- Spin mixing conductance for magnetic insulators is not yet understood.
- Better description of dynamic back flow of spins is necessary.
- Inverse ac spin Hall effect?