Charge and Spin Currents in Hybrid Structures

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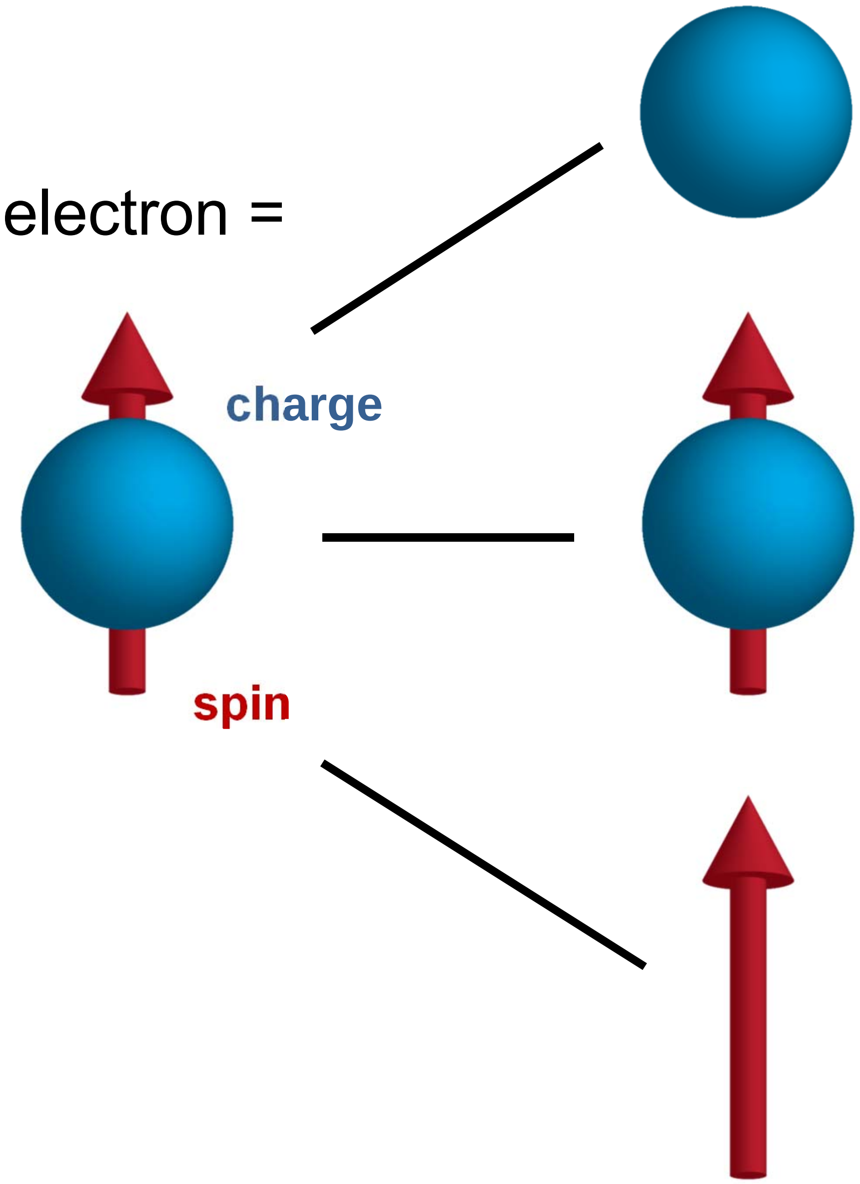
TU Delft

Financial support: Deutsche Forschungsgemeinschaft via
SPP 1538 “SpinCAT” (GO 944/4) and
Excellence Cluster NanoSystems Initiative Munich

Spin electronics = electronics with a spin ?



electronics:

… ONLY charge

… charge currents
in electrical conductors

- charge current sources
- charge current detectors
- charge amplification

Intel Core i7

magneto-electronics:

… charge AND spin

… spin-polarized currents
in electrical conductors

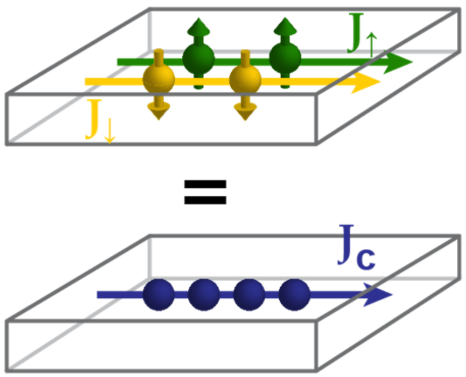
spin-tronics:

… ONLY spin

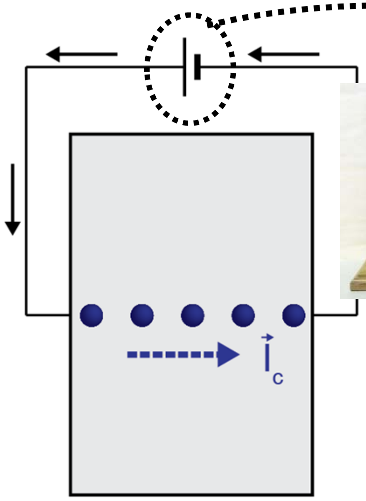
… spin currents
in “angular momentum conductors”

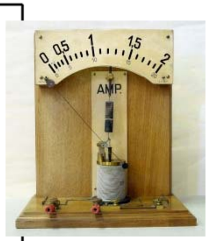
spin currents ?
spin current sources ?
spin current detectors ?
spin current gain ?

From charge currents to spin currents


Pure Charge Current

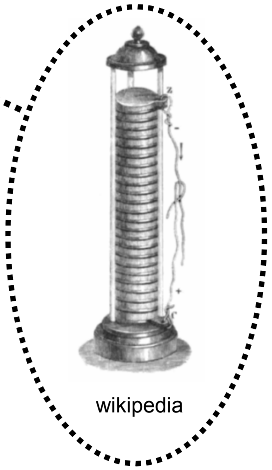
$$J_c = J_\uparrow + J_\downarrow$$



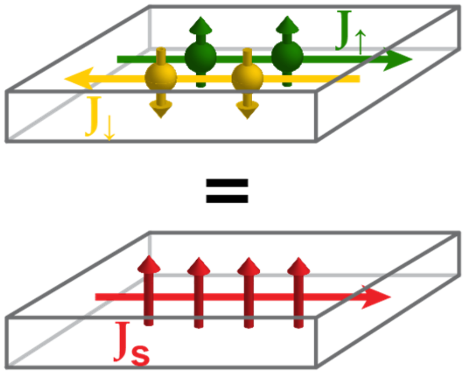


Schulhistorische Sammlung, Bremerhaven

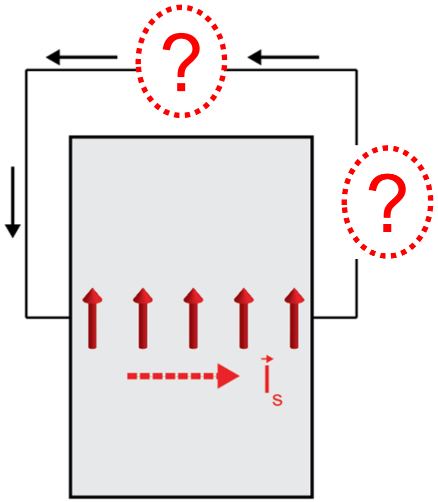
Ørsted

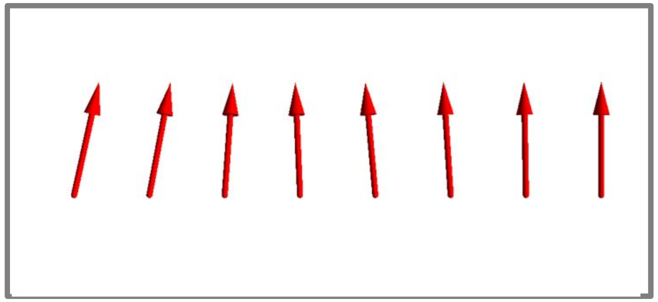

wikipedia

Volta


Pure Spin Current

$$J_s = \frac{\hbar/2}{q}(J_\uparrow - J_\downarrow)$$

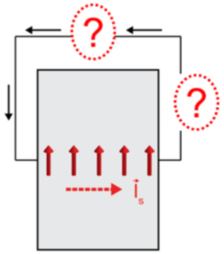




J_S can also flow in electrical insulators, as a magnon (spin) current !

spin current detection

Spin current meter: The spin Hall effect (SHE)



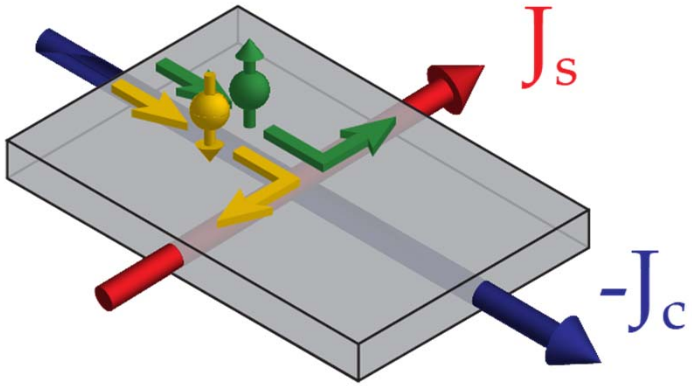
Spin Hall effect

spin-orbit coupling

spin Hall angle α_{SHE} parameterizes charge ↔ spin conversion efficiency

direct spin Hall effect (SHE)

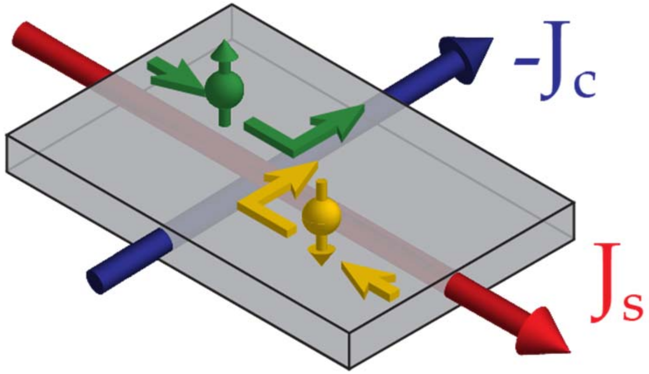
$$\mathbf{J}_{\text{s}}^{\text{SHE}} = \alpha_{\text{SHE}} \frac{\hbar}{2e} \left[\mathbf{J}_{\text{c}} \times \mathbf{s} \right]$$



charge current → spin current

inverse spin Hall effect (ISHE)

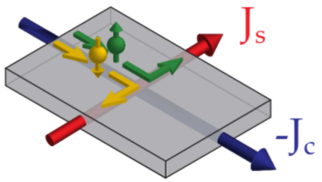
$$\mathbf{J}_{\text{c}}^{\text{ISHE}} = \alpha_{\text{SHE}} \frac{2e}{\hbar} \left[\mathbf{J}_{\text{s}} \times \mathbf{s} \right]$$

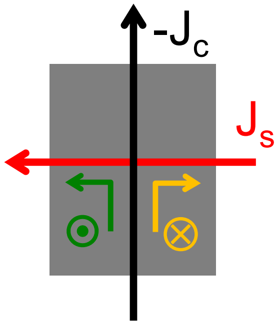


spin current → charge current

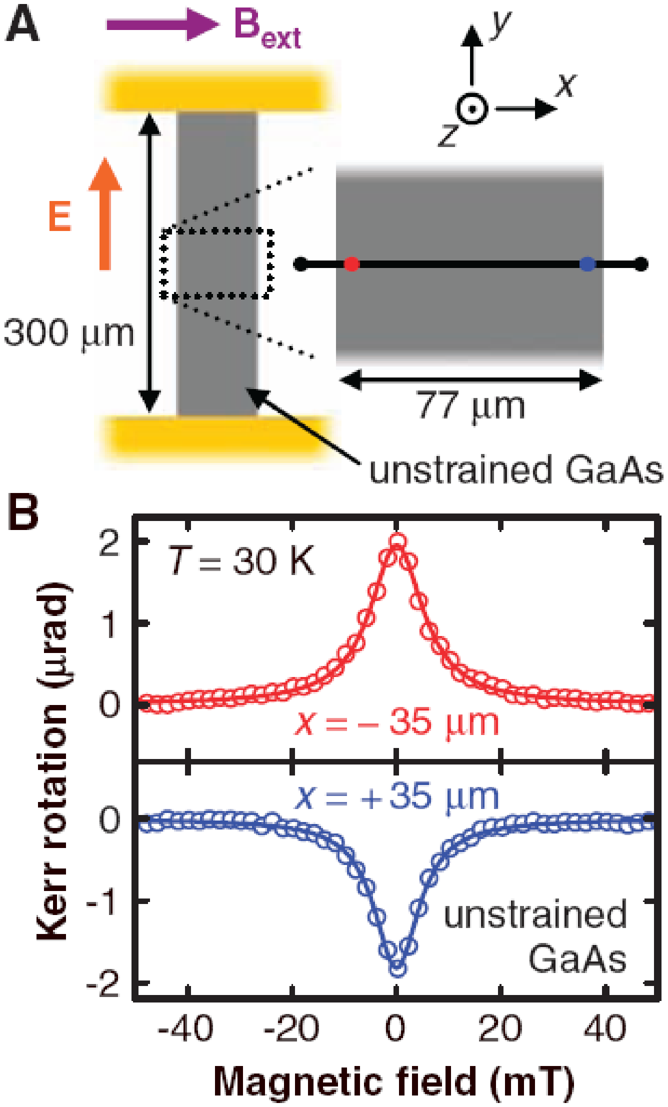
Direct Spin Hall Effect in GaAs

Kato *et al.*, Science **306**, 1910 (2004).

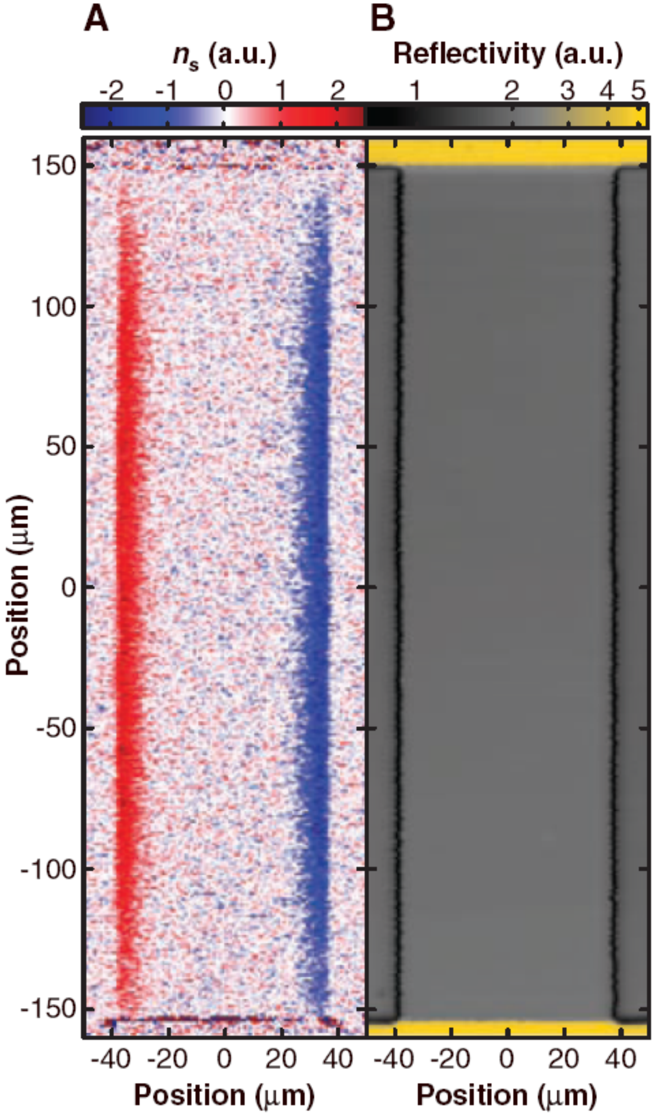




$$\mathbf{J}_s = \alpha_{\mathrm{SHE}}\frac{\hbar}{2e}[\mathbf{J}_c \times \mathbf{s}]$$



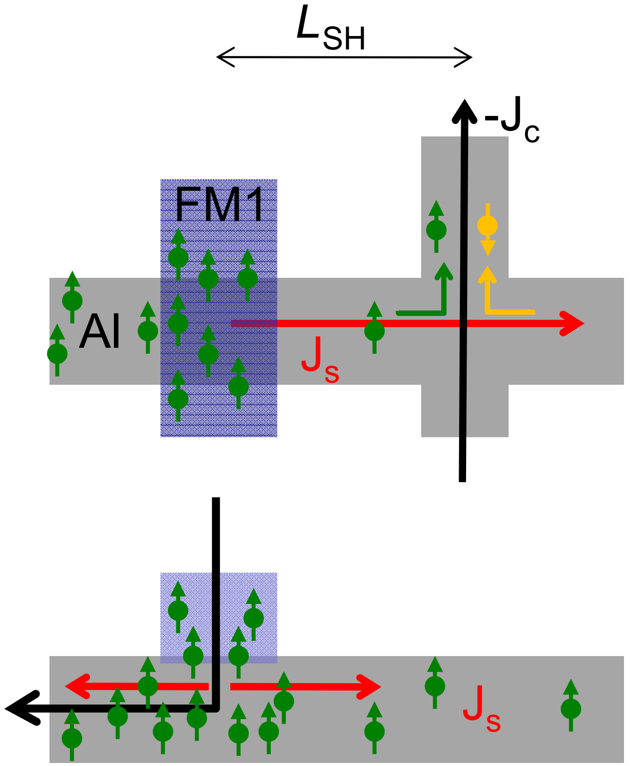
Kerr microscopy

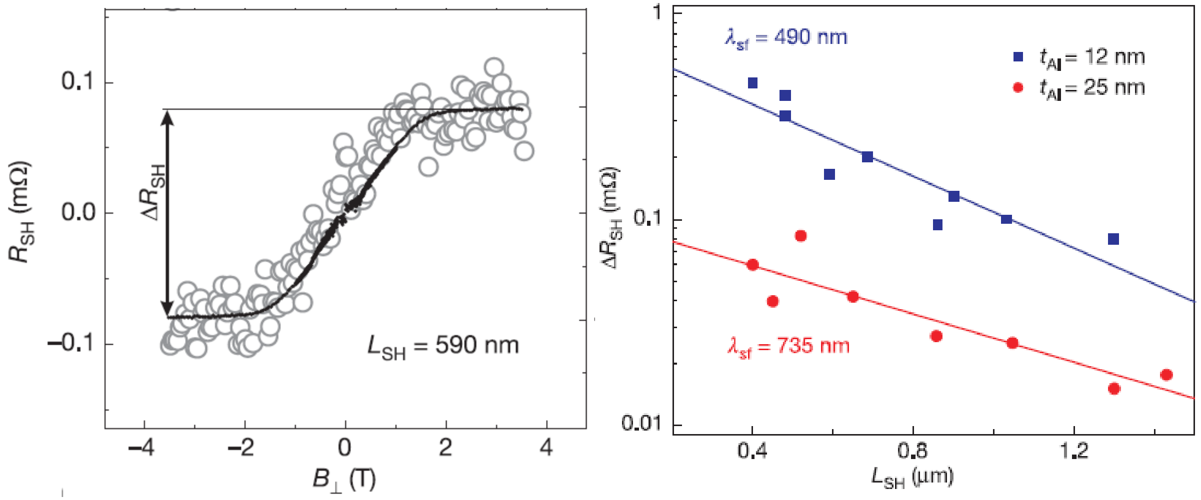


iSHE in Metallic F/N Nanostructures

Valenzuela & Tinkham, Nature **442**, 176 (2006).

$$\mathbf{J}_{\mathrm{c}}^{\mathrm{ISHE}} = \alpha_{\mathrm{SHE}} \frac{2e}{\hbar}\left[\mathbf{J}_{\mathrm{s}} \times \mathbf{s}\right]$$





detection of spin current
via inverse spin Hall effect

take away:
SHE enables “simple” experimental
spin current detection
(… given the spin Hall angle α_{SHE} and
the spin diffusion length λ_{SF} are known !)

Valenzuela & Tinkham, Nature **442**, 176 (2006).
Mosendz *et al.*, Phys. Rev. Lett. **104**, 046601 (2010).
Liu *et al.*, Science **336**, 555 (2012).
Niimi *et al.*, Phys. Rev. Lett. **109**, 156602 (2012).
…and many more …

Gold : α_{SHE}=0.0016
Platinum : α_{SHE}=0.013 … **0.11** (0.16)
Bi, Bi/Ag, Ta : α_{SHE}=0.1 … **0.3**

Open issues #1

take away:

SHE enables “simple” experimental spin current detection

(… given the spin Hall angle α_{SHE} and the spin diffusion length λ_{SF} are known !)

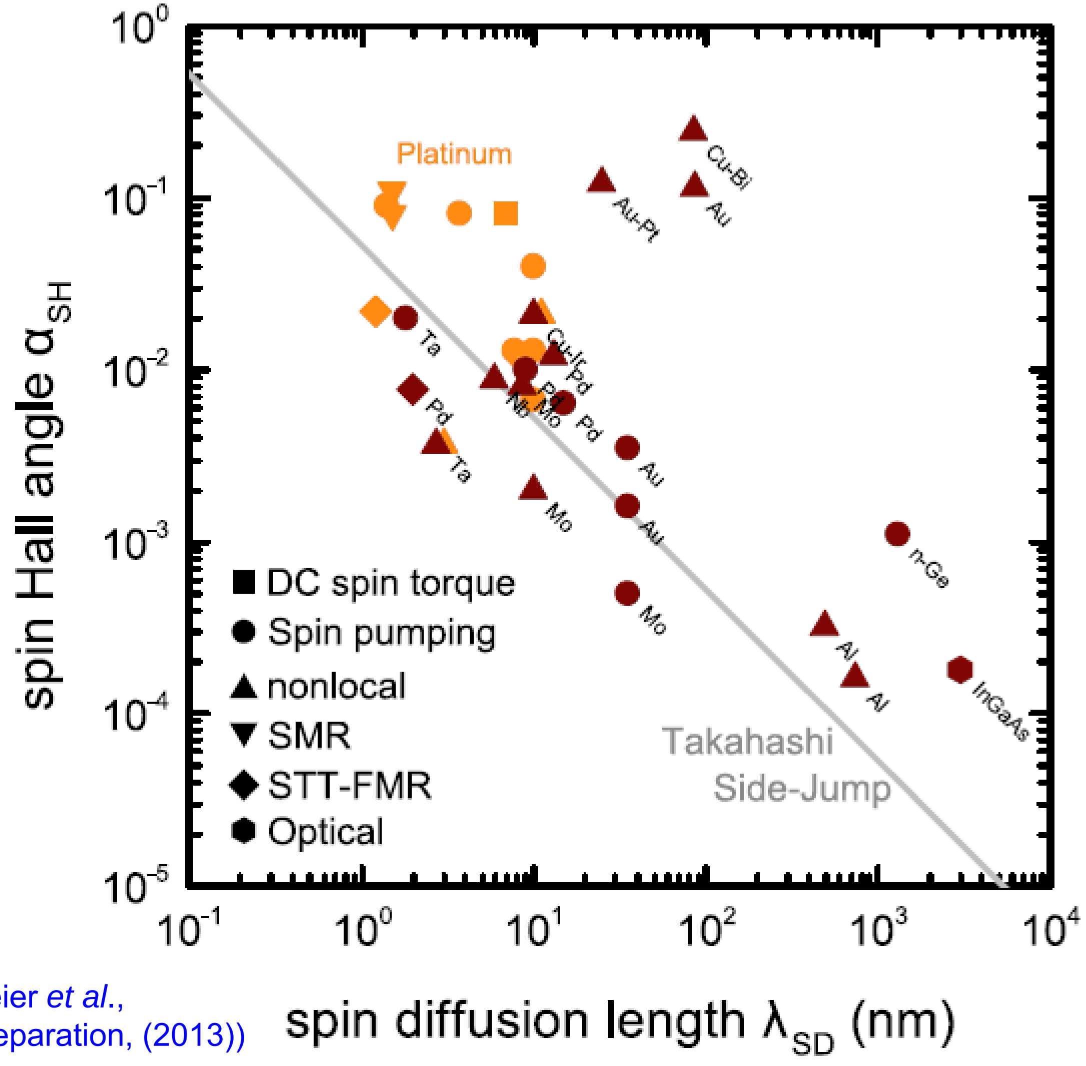
Open issues:

- magnitude and sign of α_{SHE}
- magnitude of λ_{SF}
- is it possible to tune α_{SHE} independently from λ_{SF} ??
- desirable for experiment: large α_{SHE} AND large λ_{SF} (cf. “$\sigma = n \mu e$”)

→ what are the relevant spin transport parameters ?

→ calculations of all relevant spin transport parameters (not only α_{SHE}) required !

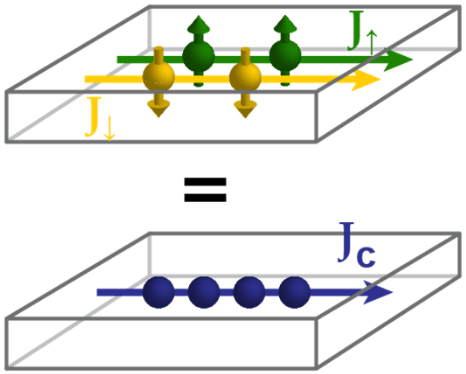
→ Neumann principle in single-crystalline Pt ?



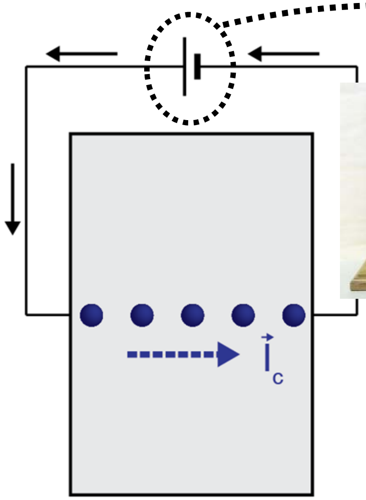
Schreier *et al.*,
(in preparation, (2013))

From charge currents to spin currents

Pure Charge Current



$$J_c = J_\uparrow + J_\downarrow$$



Schulhistorische Sammlung,
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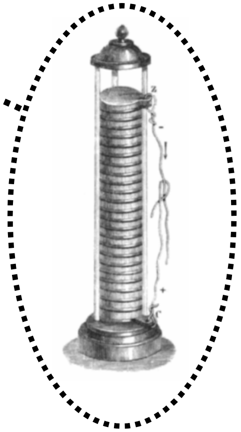
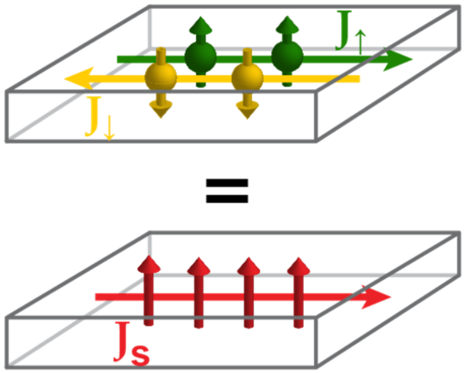
Ørsted



Volta

Pure Spin Current



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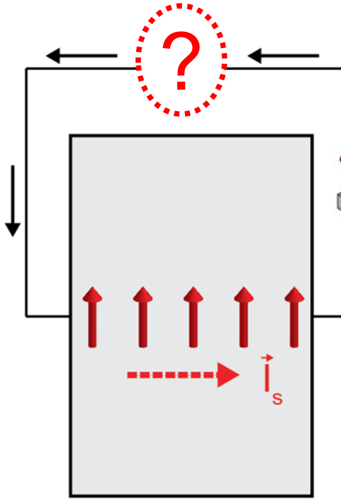
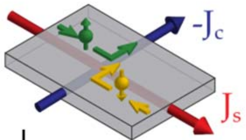


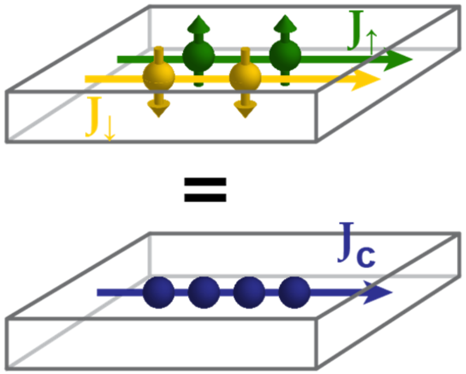


ISHE

Hirsch
(1999)

From charge currents to spin currents

Pure Charge Current



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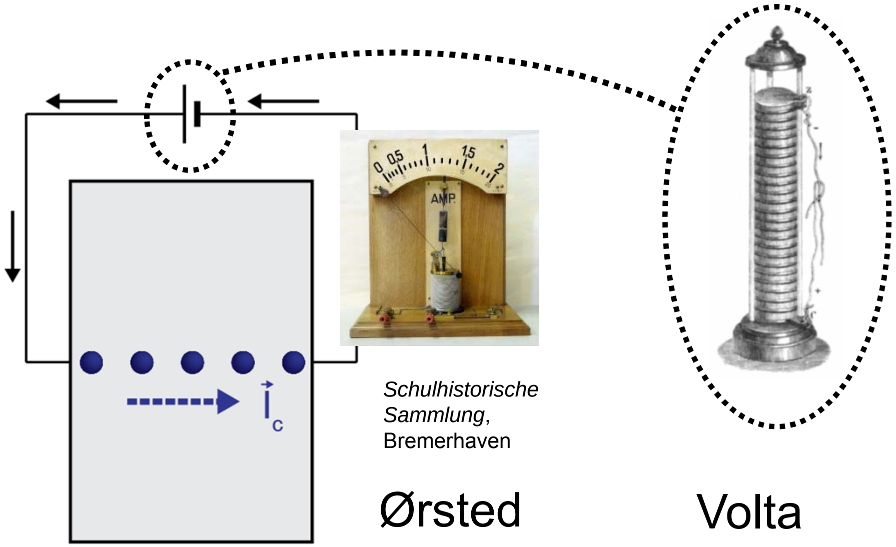
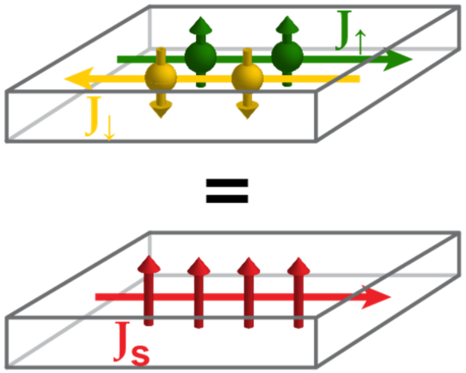


Schulhistorische Sammlung,
Bremerhaven

Ørsted

Volta

Pure Spin Current



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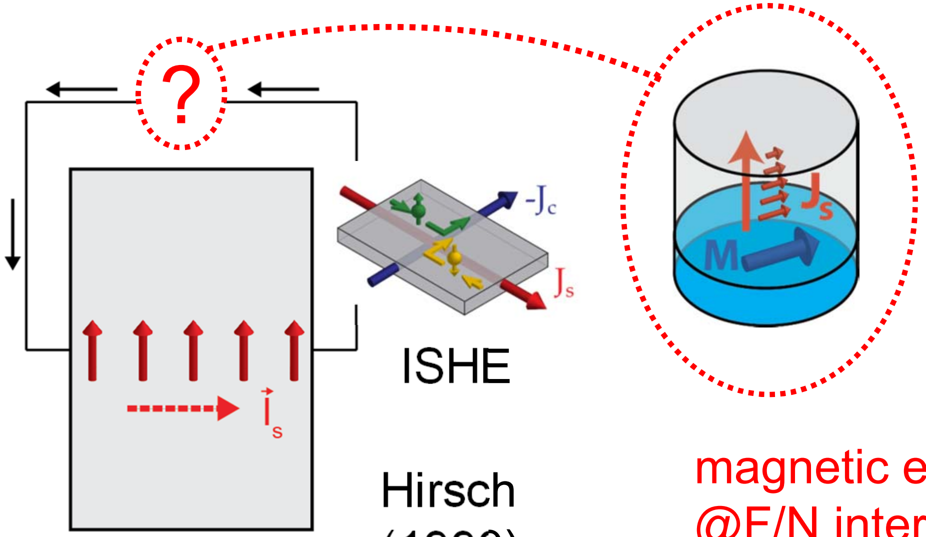


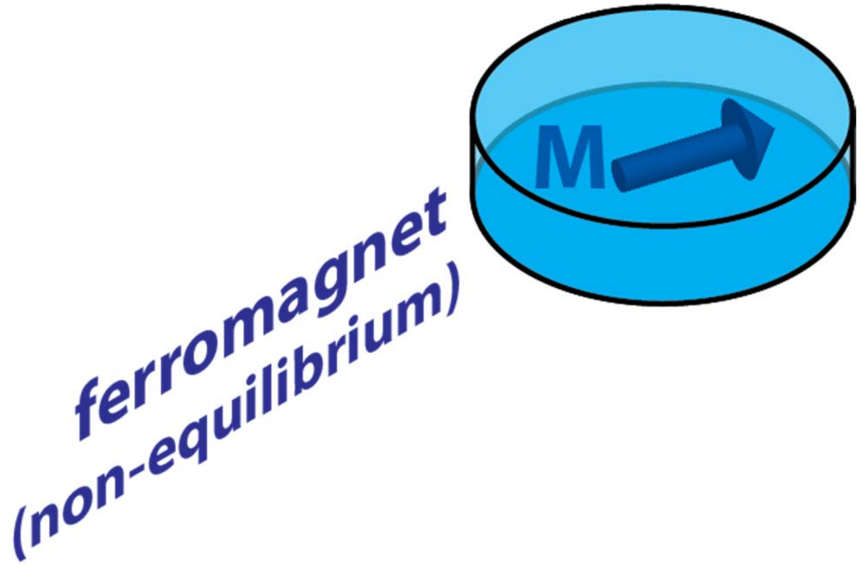
ISHE

Hirsch
(1999)

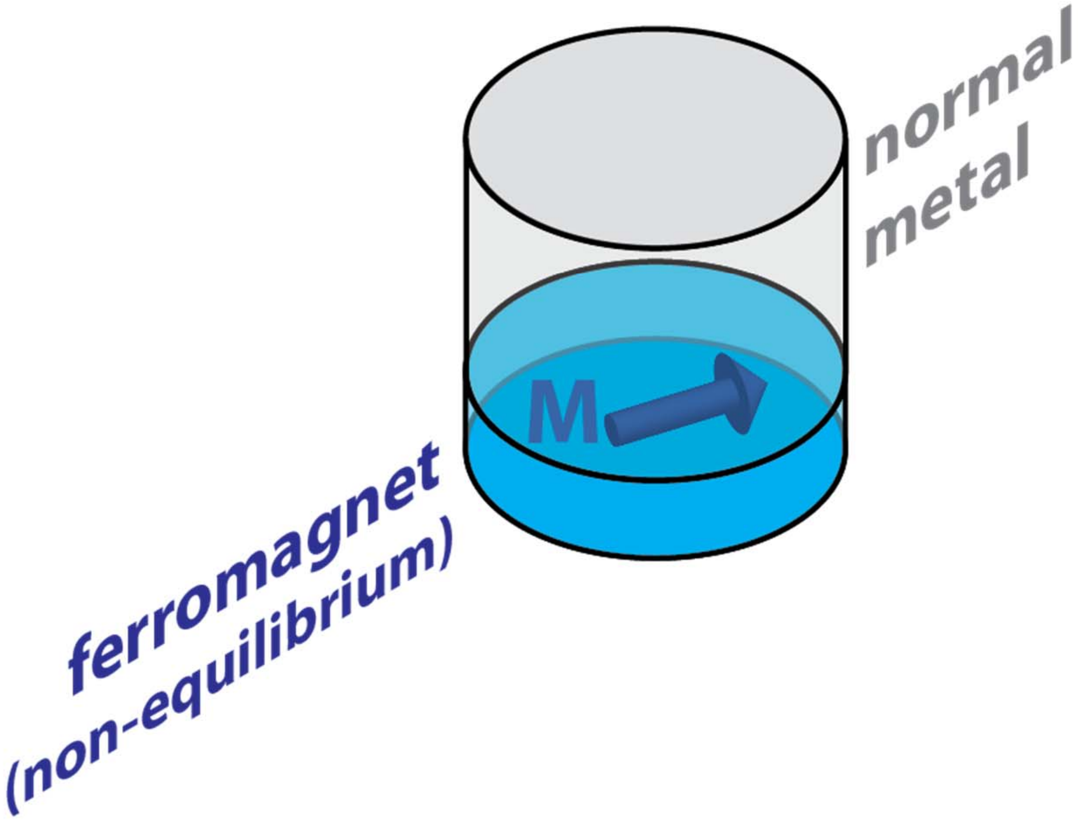
magnetic excitations
@F/N interface

spin current generation

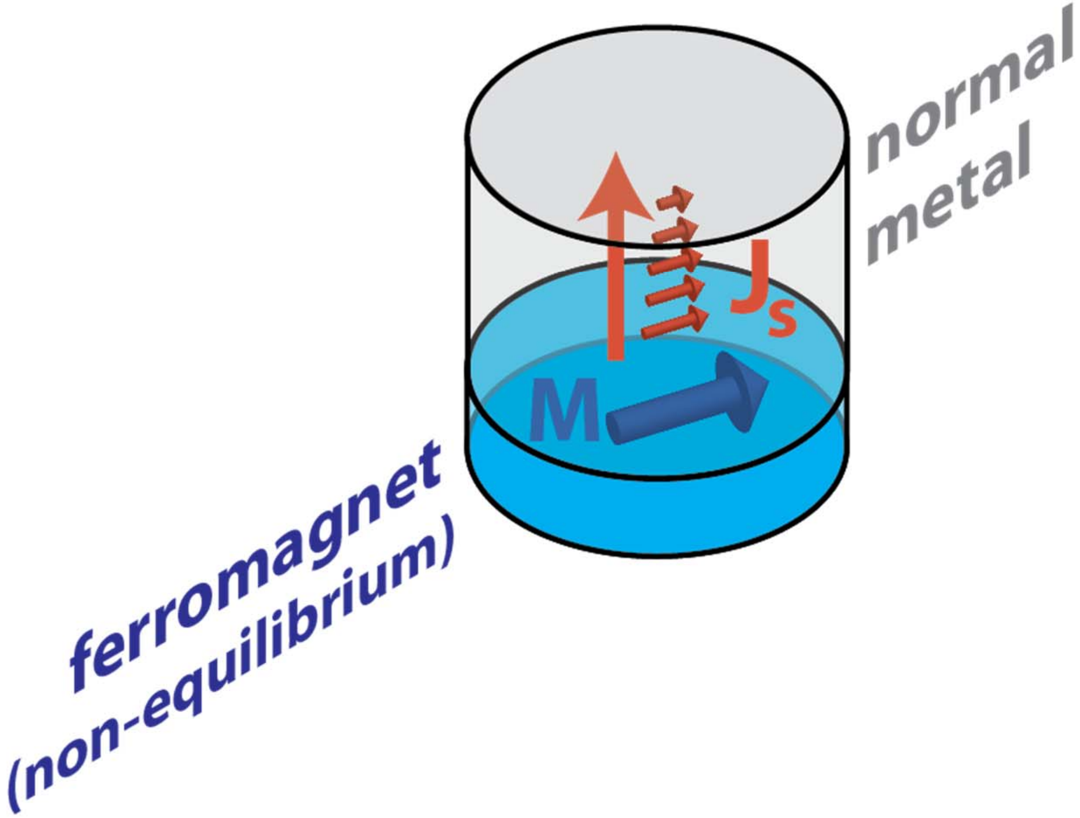
Spin currents in hybrid structures



Spin currents in hybrid structures



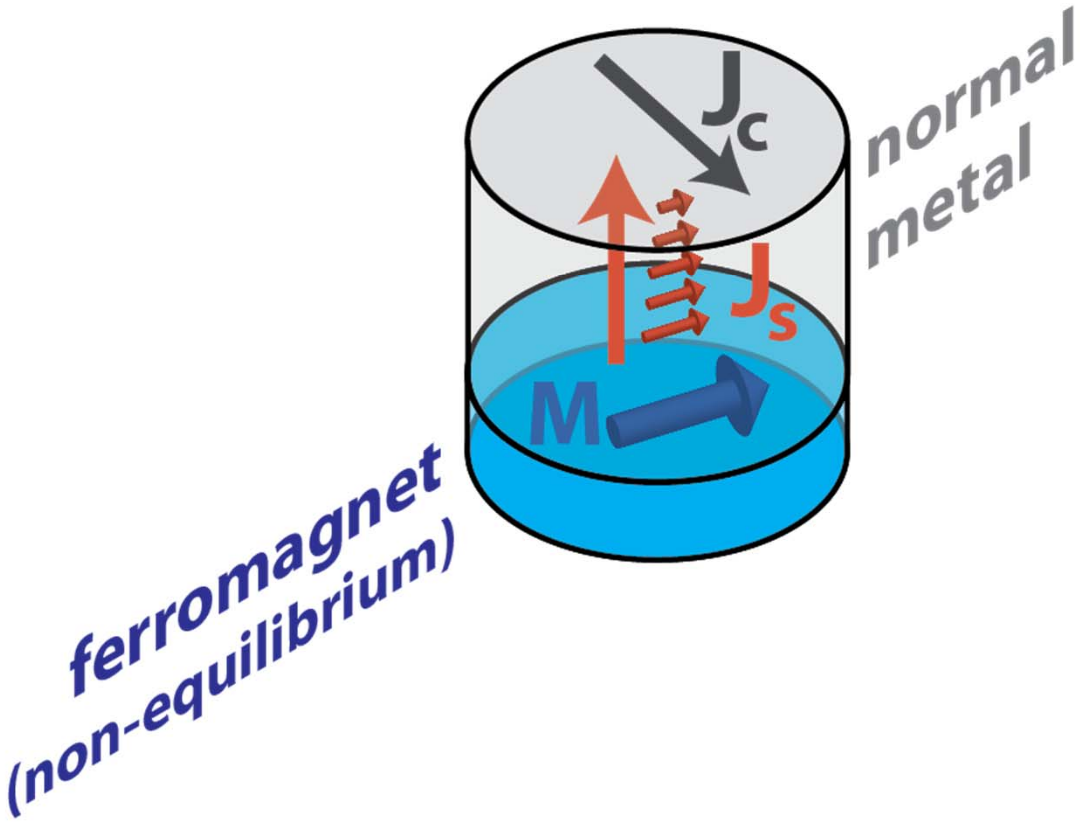
Spin currents in hybrid structures



Spin currents in hybrid structures

spin current generation

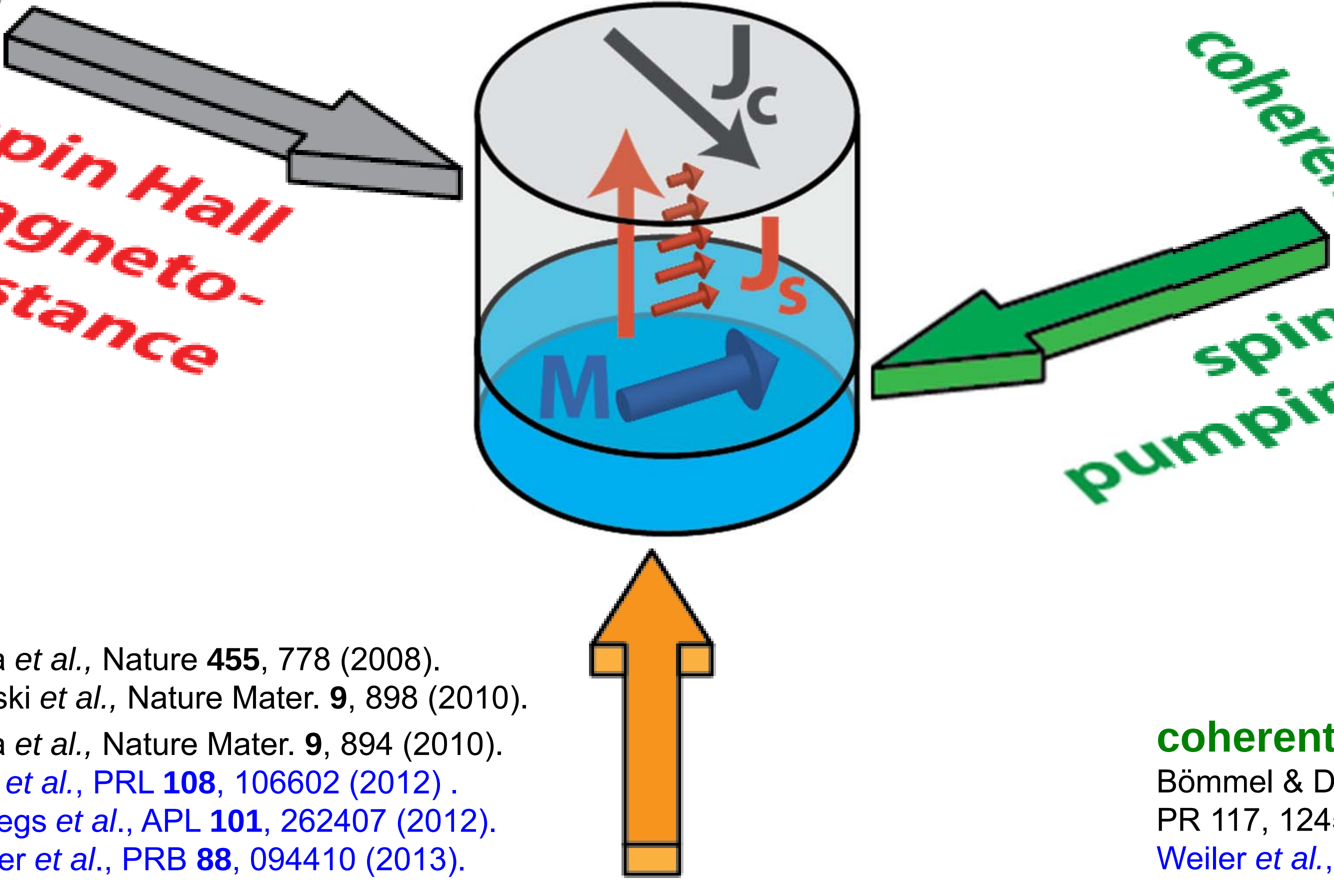
(with charge current detection)



Spin currents in hybrid structures

Nakayama *et al.*, PRL **110**, 206601 (2013).
Althammer *et al.*, PRB **87**, 224401 (2013).
Vlietstra *et al.*, PRB **87**, 184421 (2013).
Hahn *et al.*, PRB **87**,174417 (2013).
Chen *et al.*, PRB **87**, 144411 (2013).
Huang *et al.*, PRL**109**, 107204 (2012).
Weiler *et al.*, PRL **108**, 106602 (2012) .

Tserkovnyak *et al.*, PRL **88**, 117601 (2002).
Saitoh *et al.*, APL **88**, 182509 (2006).
Mosendz *et al.*, PRL **104**, 046601 (2010).
Czeschka *et al.*, PRL **107**, 046601 (2011).



charge current

spin Hall magneto-resistance

coherent photons

spin pumping

Uchida *et al.*, Nature **455**, 778 (2008).
Jaworski *et al.*, Nature Mater. **9**, 898 (2010).
Uchida *et al.*, Nature Mater. **9**, 894 (2010).
Weiler *et al.*, PRL **108**, 106602 (2012) .
Gepraegs *et al.*, APL **101**, 262407 (2012).
Schreier *et al.*, PRB **88**, 094410 (2013).

thermal phonons

spin Seebeck effect

coherent phonons:
Bömmel & Dransfeld,
PR 117, 1245 (1960).
Weiler *et al.*,
PRL **106**, 117601 (2011).
PRL **108**, 176601 (2012).

Spin currents in hybrid structures

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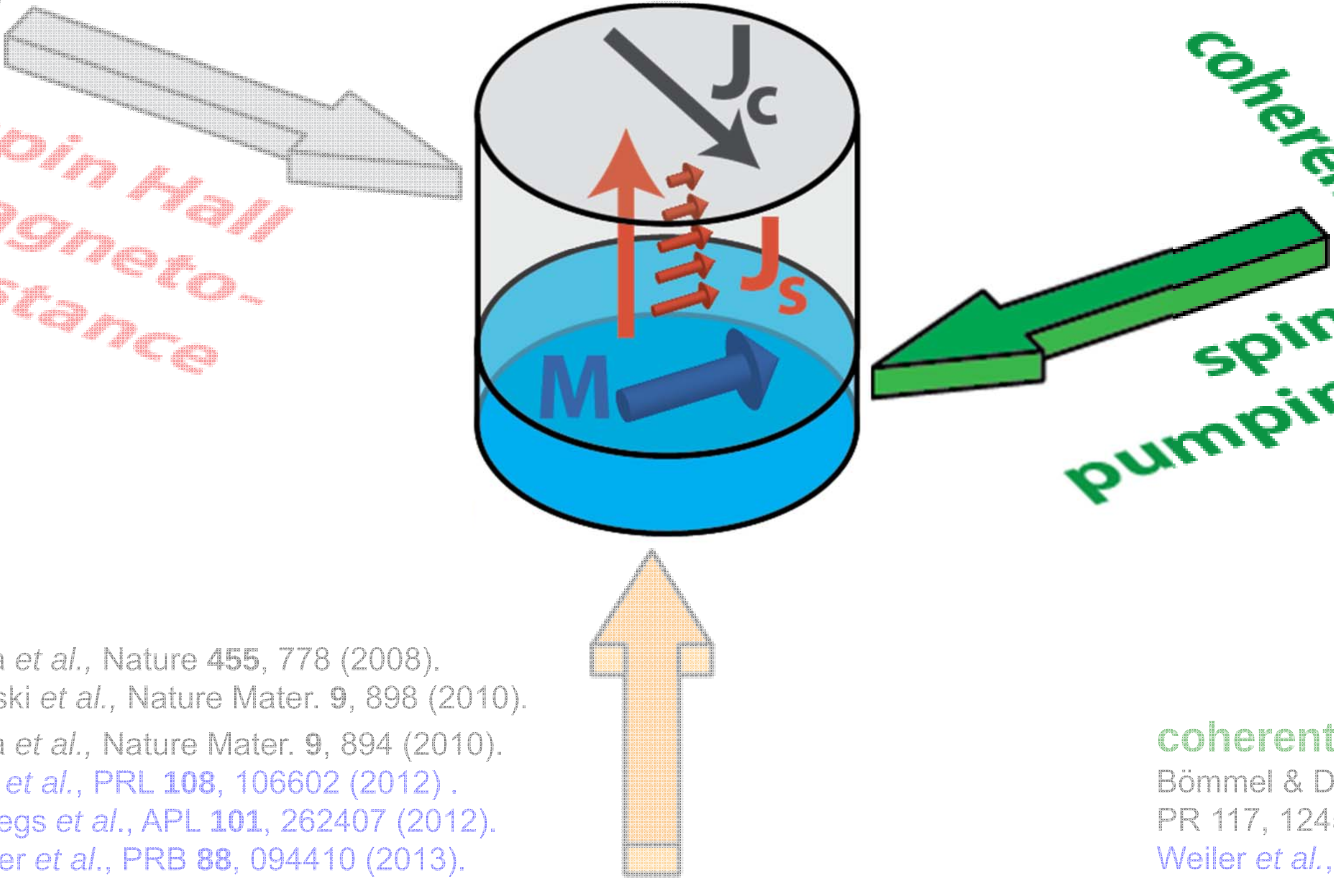

charge current

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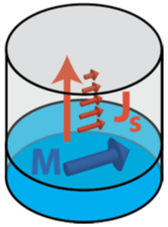
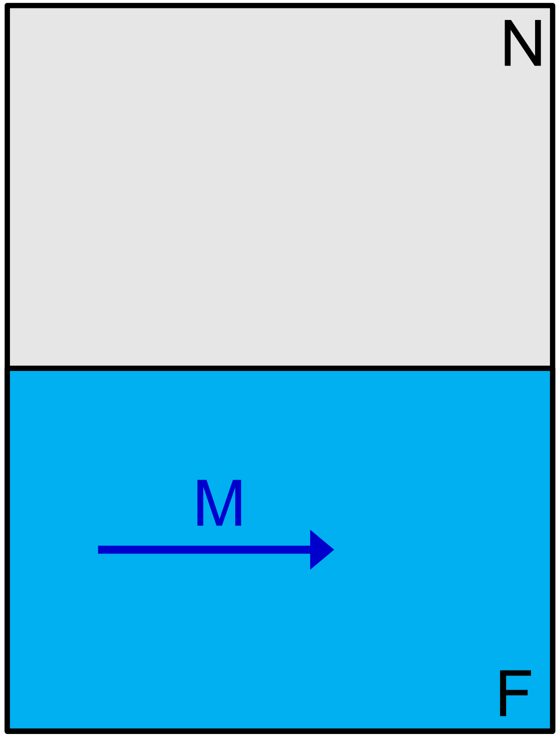
F/N + microwave photons = spin battery

suggested by Tserkovnyak, Brataas & Bauer, PRL (2002)





Tserkovnyak, Phys. Rev. Lett. **88**, 117601 (2002).
Brataas, Phys. Rev. B **66**, 060404 (2002).
Tserkovnyak, Phys. Rev. B **66**, 224403 (2002).

F/N + microwave photons = spin battery

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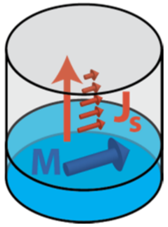
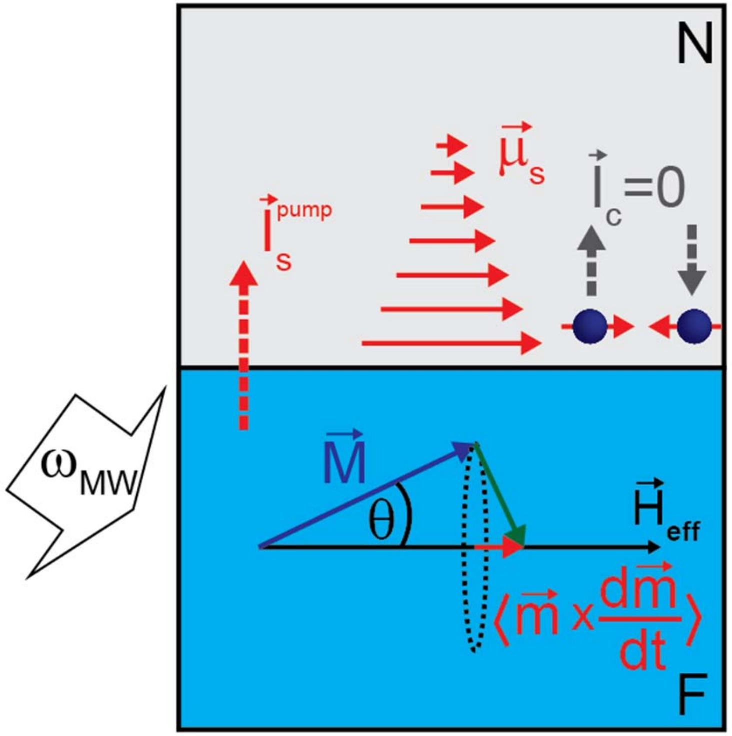




- ferromagnet / normal metal hybrid
- microwave induces magnetization precession
- magnetization can relax
  via the **emission of a spin current**
  into the adjacent N layer

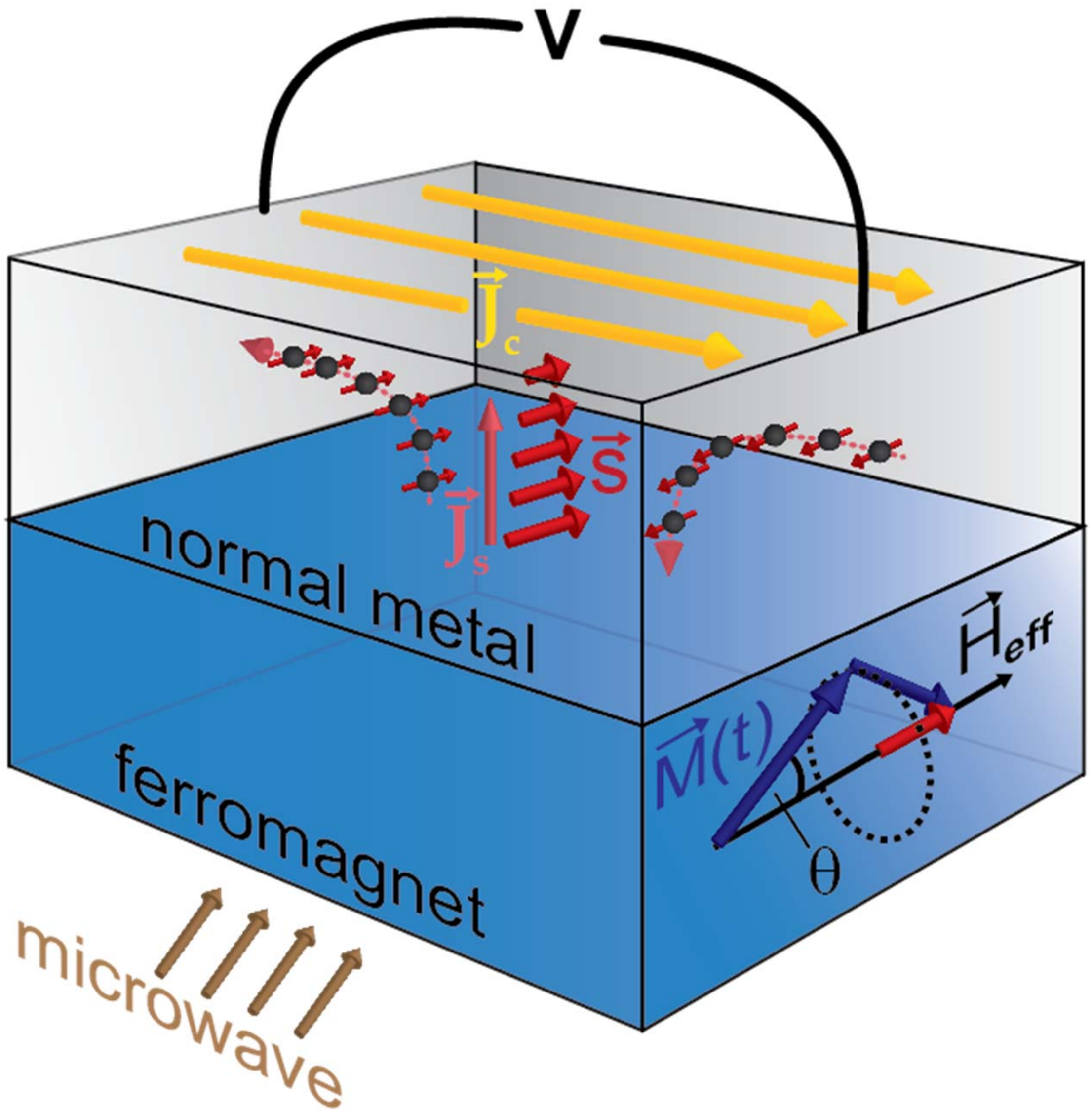
→ spin pumping

pure spin current

$$J_s^{\text{pump, circ}} = \frac{\hbar}{2}\nu_{\text{MW}} \text{Re}(g^{\uparrow\downarrow}) \sin^2 \Theta$$

Tserkovnyak, Phys. Rev. Lett. **88**, 117601 (2002).
Brataas, Phys. Rev. B **66**, 060404 (2002).
Tserkovnyak, Phys. Rev. B **66**, 224403 (2002).

Spin pumping with spin current detection



microwave + DC magnetic field

↓ FMR

magnetization precession

↓ spin pumping

spin current

$$J_S = \frac{\hbar}{2}\nu_{MW}\,\mathrm{Re}\left(g^{\uparrow\downarrow}\right)\sin^2\Theta$$

↓ inverse spin Hall effect

charge current J_c

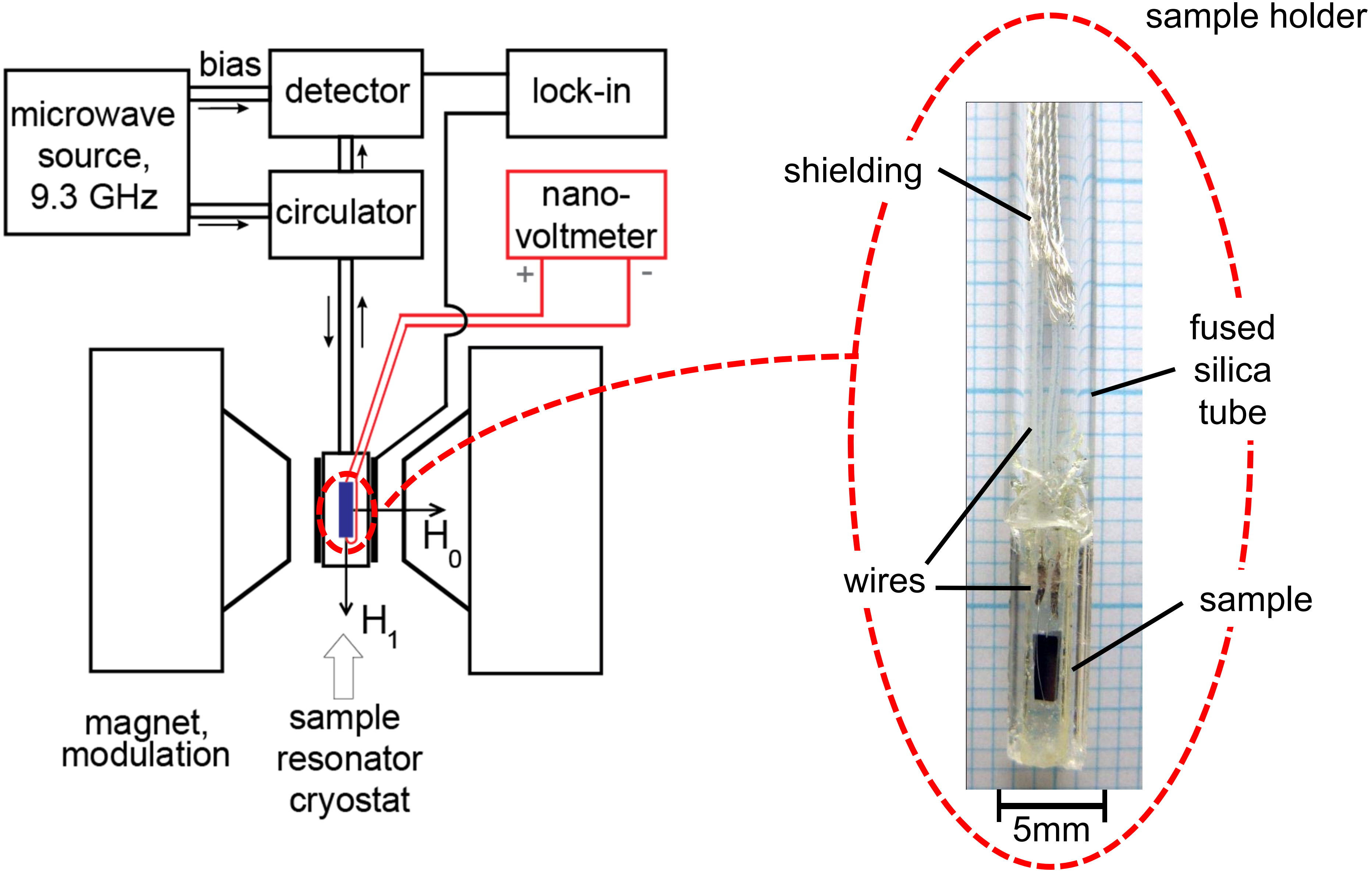
$$\vec{J}_C^{\mathrm{ISHE}} = \alpha_{SH}(2e/\hbar)\left[\vec{J}_S \times \hat{s}\right]$$

↓ open circuit

voltage drop V

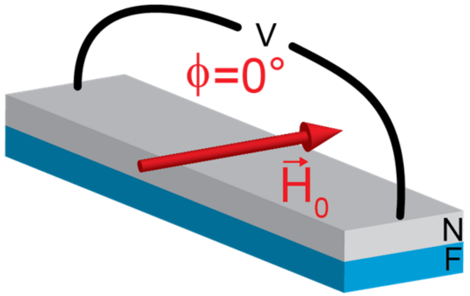
Tserkovnyak *et al.*, Phys. Rev. Lett. **88**, 117601 (2002). Saitoh *et al.*, Appl. Phys. Lett. **88**, 182509 (2006)

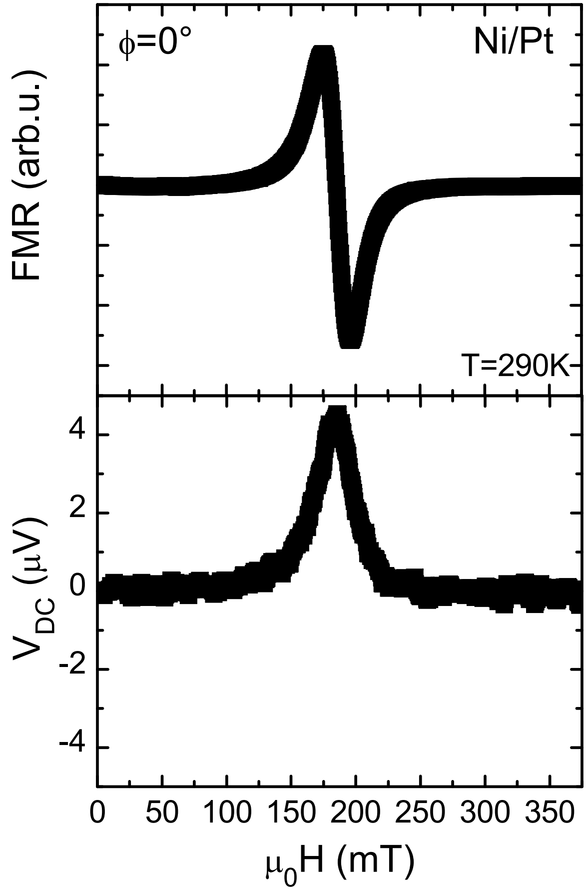
Measurement setup



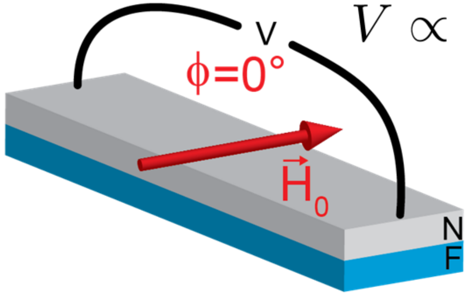
Typical sample dimensions L × W × t = 3mm × 1mm × (10nm/10nm)

Ni/Pt

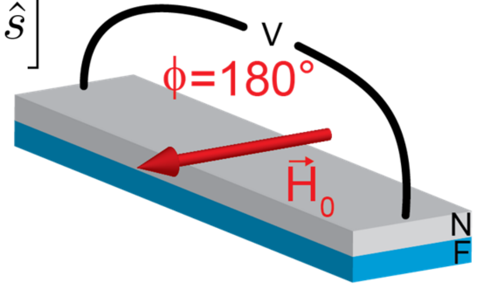

V
ϕ=0°
H0
N
F

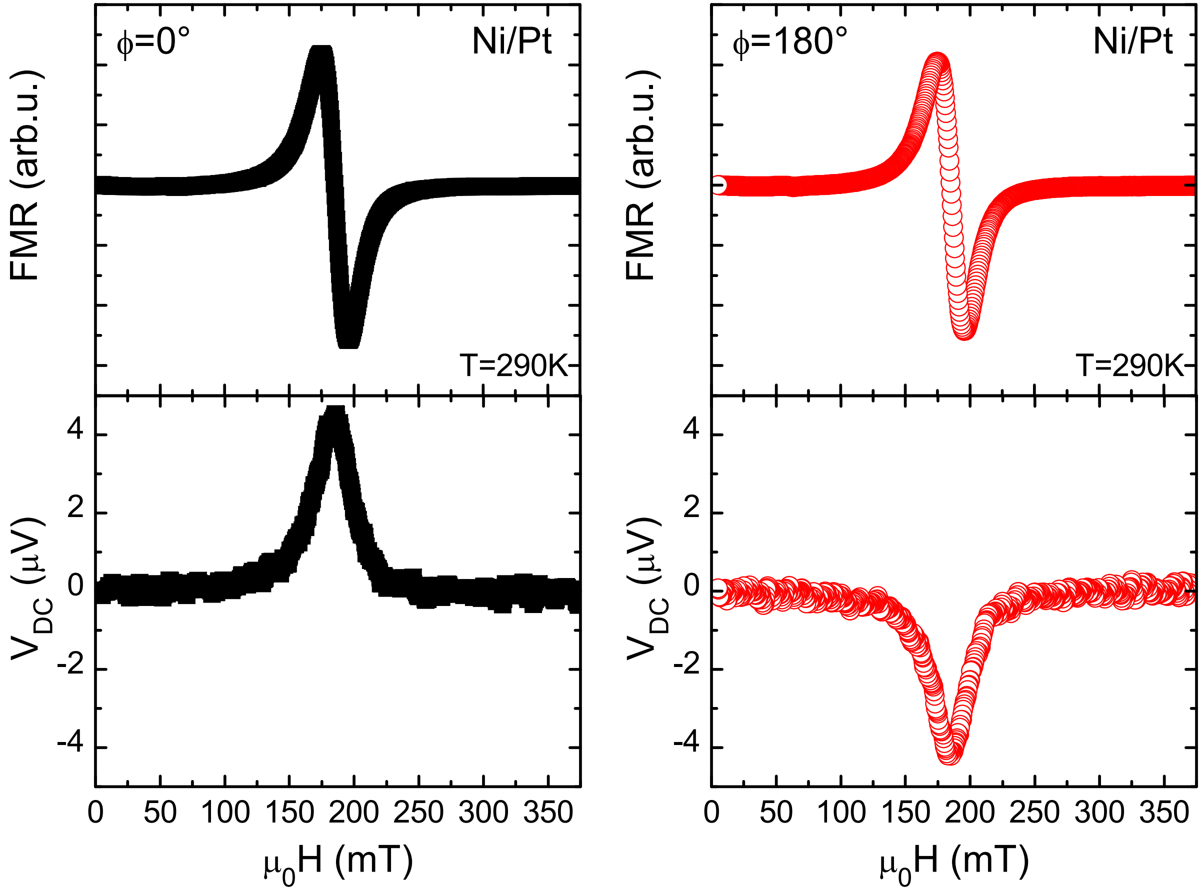

ϕ=0°
Ni/Pt
T=290K
FMR (arb.u.)
VDC (μV)
4
2
0
-2
-4
0
50
100
150
200
250
300
350
μ0H (mT)

Ni/Pt



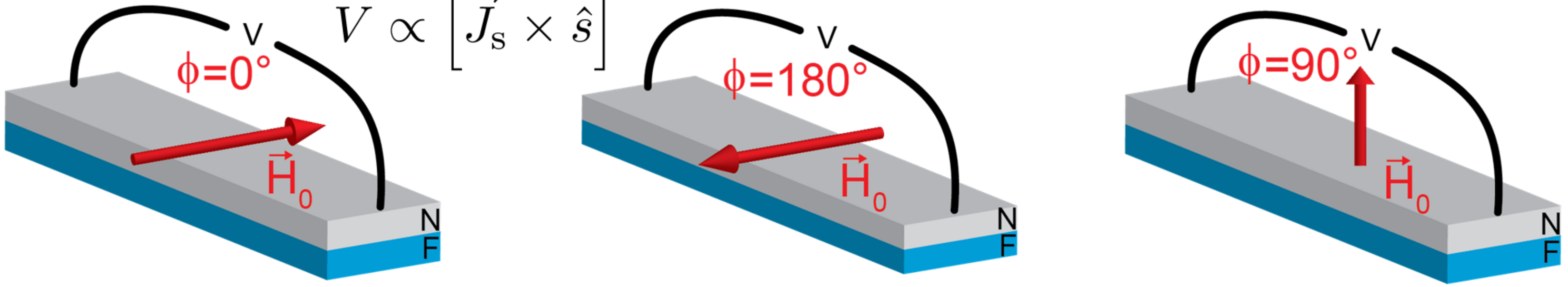
$$V \propto \left[\vec{J}_\mathrm{s} \times \hat{s}\right]$$

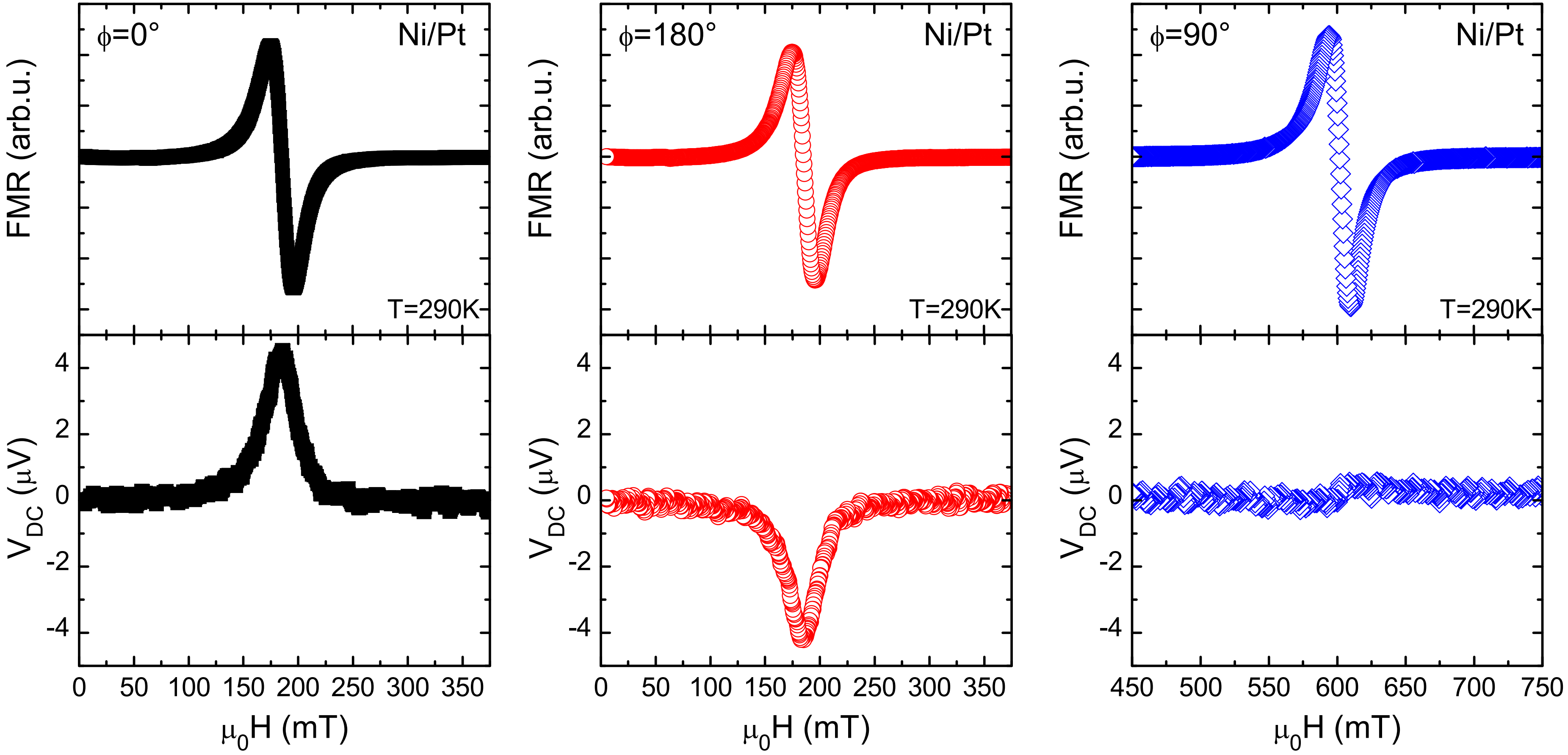




Ni/Pt

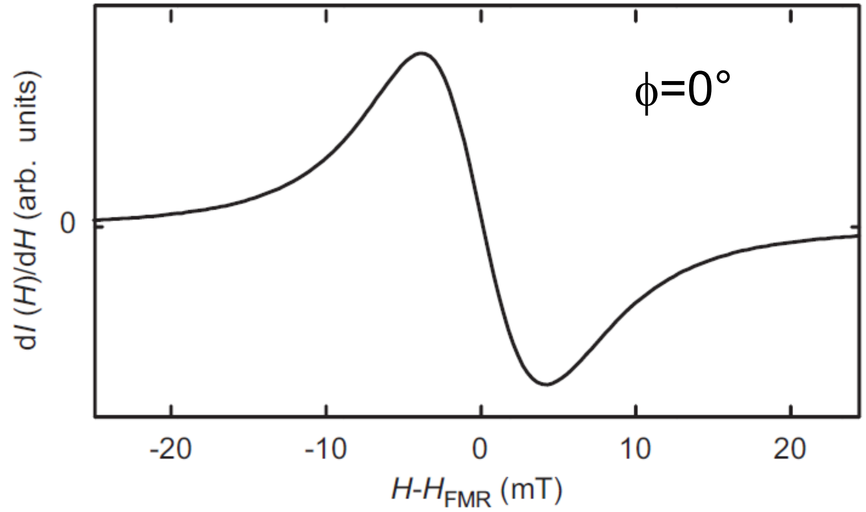
$$V \propto \left[\vec{J}_s \times \hat{s}\right]$$

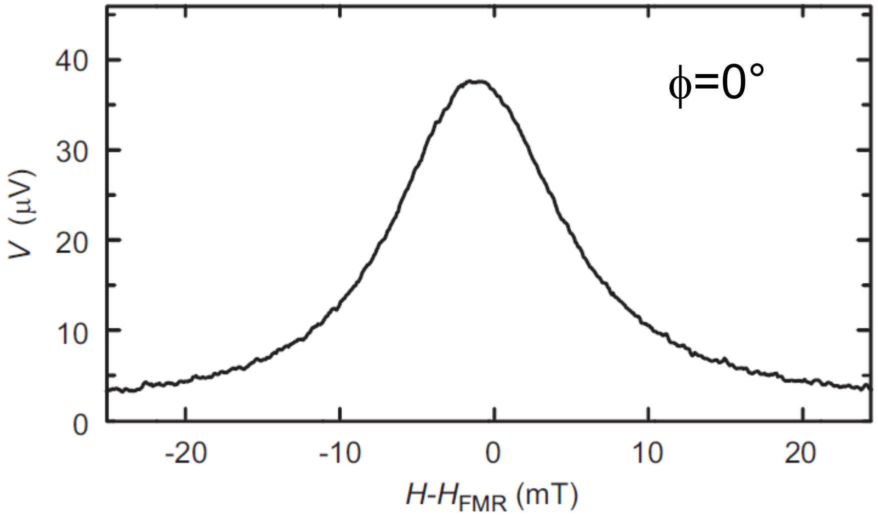


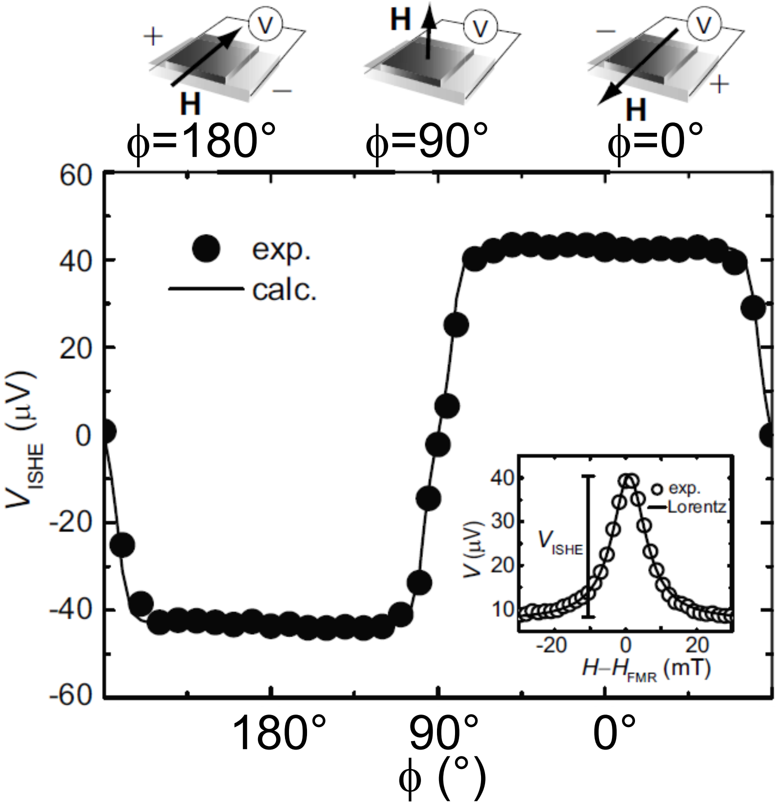


Experiments pioneered by the Saitoh group

$Ni_{81}Fe_{19}/Pt$







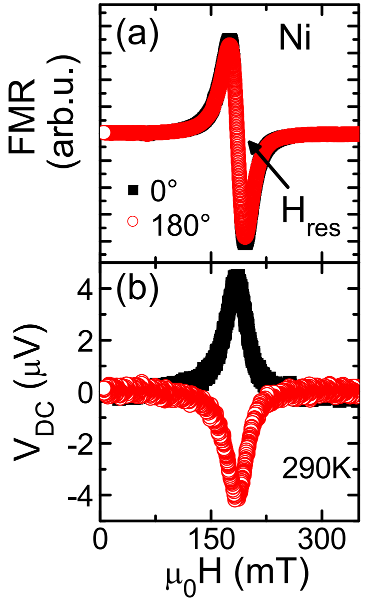
Experiments for 3d metals:

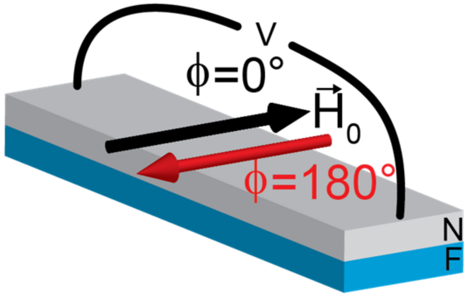
$Ni_{81}Fe_{19}$, Ni , Fe

Saitoh *et al.*, Appl. Phys. Lett. **88**, 182509 (2006)
Ando *et al.*, Phys. Rev. Lett. **101**, 036601 (2008)
Ando *et al.*, JMMM **322**,1422 (2010)

Egan *et al.*, J. Appl. Phys. **34**, 1477 (1963)
Juretschke, J. Appl. Phys. **31**, 1401 (1960)

Different materials





- works for many different F/platinum bilayers
- same sign of V_{DC} for $\phi=0°$ for all bilayers
- not MW rectification
  [MW-induced
  $J_c(t) \times m(t) \rightarrow V_{DC}$]
  but **spin pumping**!

Quantitative Analysis

spin mixing conductance

magnetization
precession cone

$$V_{\mathrm{ISH,\,res}} = \frac{-e\left[\alpha_{\mathrm{SH}}\lambda_{\mathrm{SD}}\tanh\frac{t_{\mathrm{N}}}{2\lambda_{\mathrm{SD}}}\right]P\,g_{\uparrow\downarrow}}{\sigma_{\mathrm{F}}t_{\mathrm{F}}+\sigma_{\mathrm{N}}t_{\mathrm{N}}}\,L\,\upsilon_{\mathrm{MW}}\sin^2\Theta_{\mathrm{res}}$$

$\equiv C$=const.
determined by
platinum only

determined by resistance
measurements:

$$\sigma_{\mathrm{F}}t_{\mathrm{F}}+\sigma_{\mathrm{N}}t_{\mathrm{N}} = \frac{L}{Rw}$$

microwave
frequency

$$\Rightarrow \boxed{\frac{V_{\mathrm{ISH,\,res}}}{\upsilon_{\mathrm{MW}}PRw} = e\,C\,g^{\uparrow\downarrow}\sin^2\Theta_{\mathrm{res}}}$$

Theory: $g^{\uparrow\downarrow} \cong$ const.

⇒ scaling !?

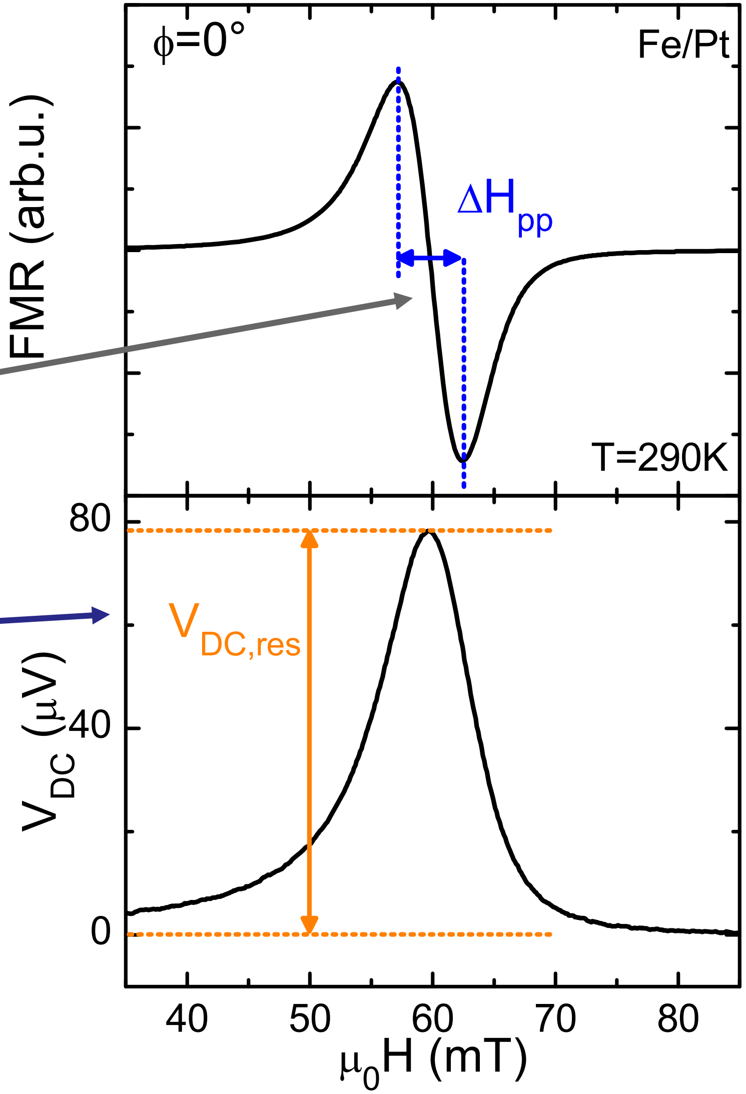
Mosendz *et al.*, Phys. Rev. Lett. **104**, 046601 (2010)

DC Voltage From Spin Pumping

$$\Theta_{\mathrm{res}} = \frac{2h_{\mathrm{MW}}}{\sqrt{3}\,\Delta H_{\mathrm{pp}}}$$

$$\boxed{\frac{V_{\text{ISH, res}}}{v_{\mathrm{MW}} P R w} = e\, C\, g^{\uparrow\downarrow} \sin^2 \Theta_{\mathrm{res}}}$$

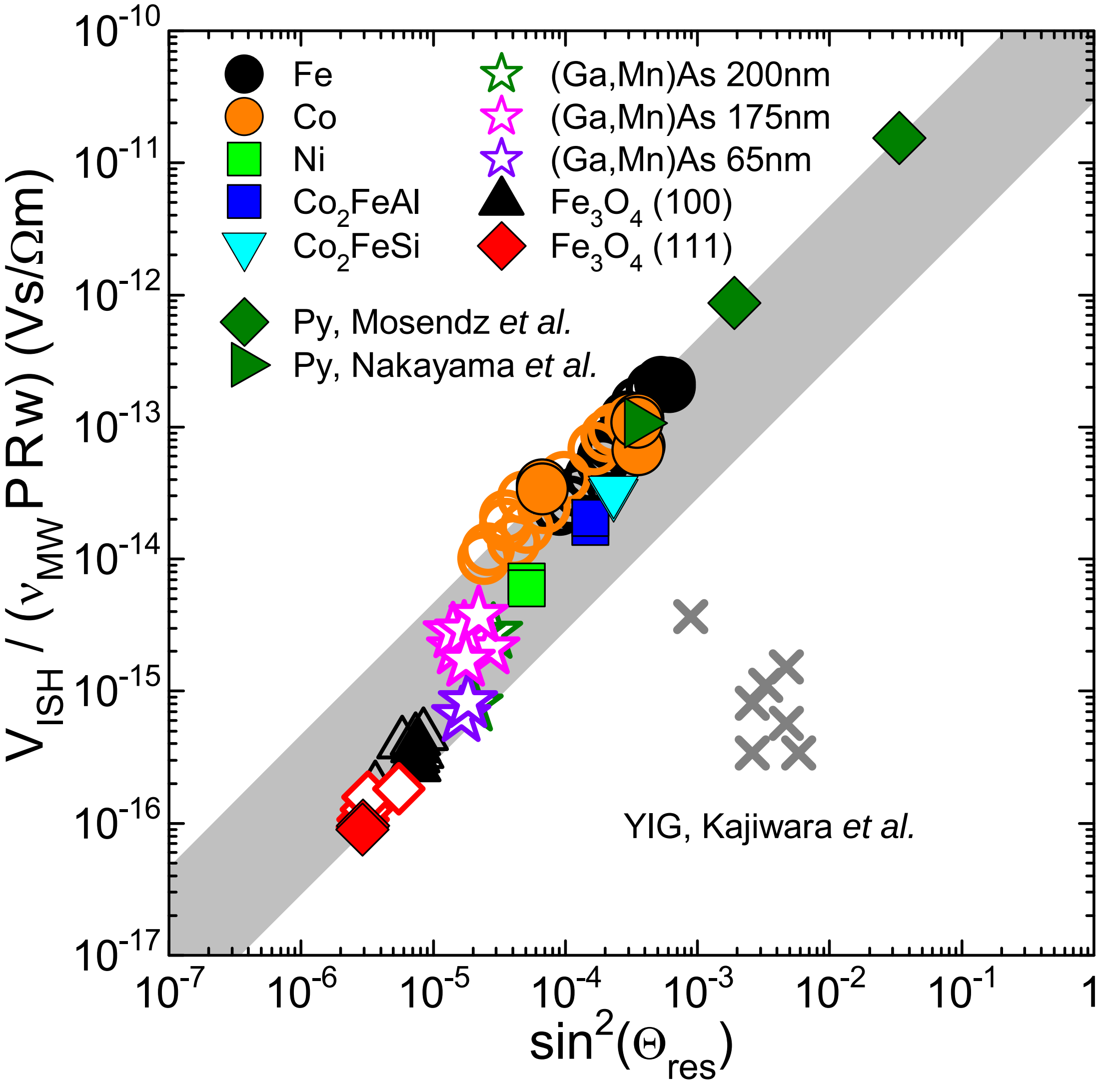
$$V_{\mathrm{ISH,res}} = V_{\mathrm{DC,res}}$$



Scaling behavior of spin pumping

$$\frac{V_{\mathrm{ISH,\,res}}}{\upsilon_{\mathrm{MW}} P R w} = e\, C\, g^{\uparrow\downarrow} \sin^2 \Theta_{\mathrm{res}}$$

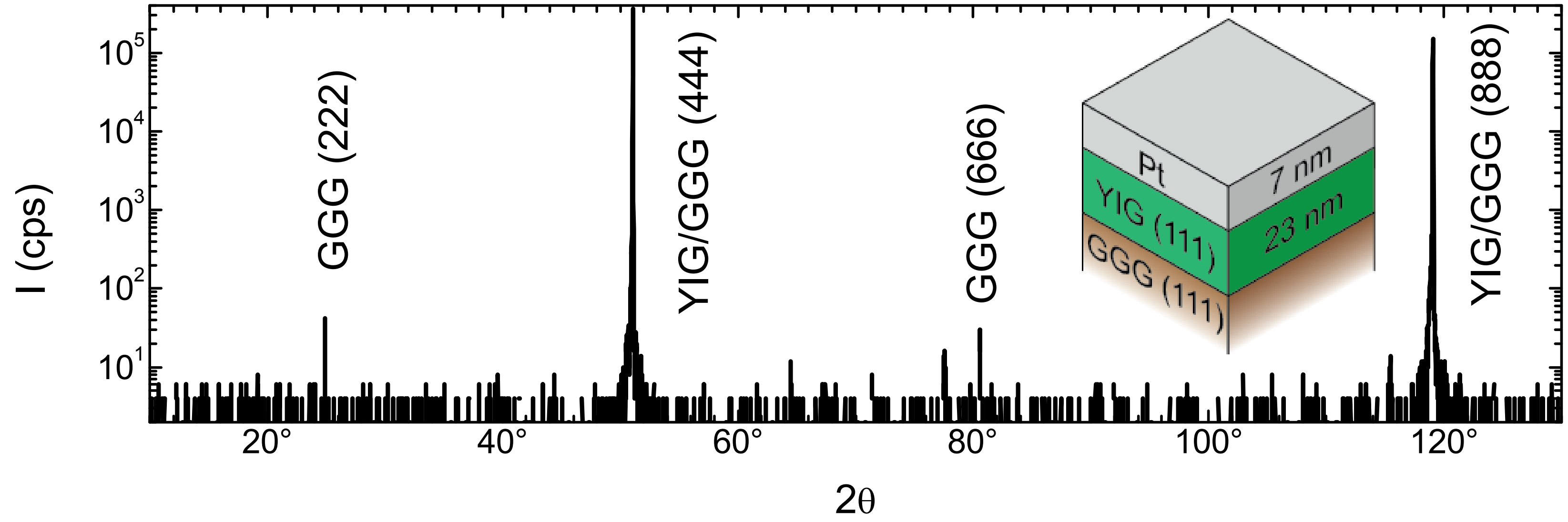
Theory quantitatively describes the experimental data.
(well… except for YIG=$Y_3Fe_5O_{12}$)

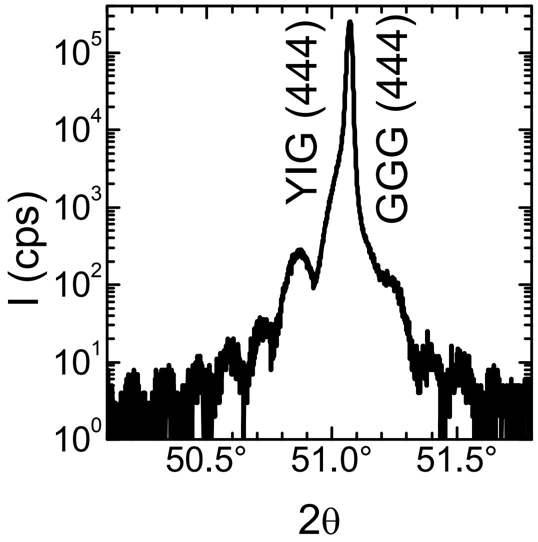


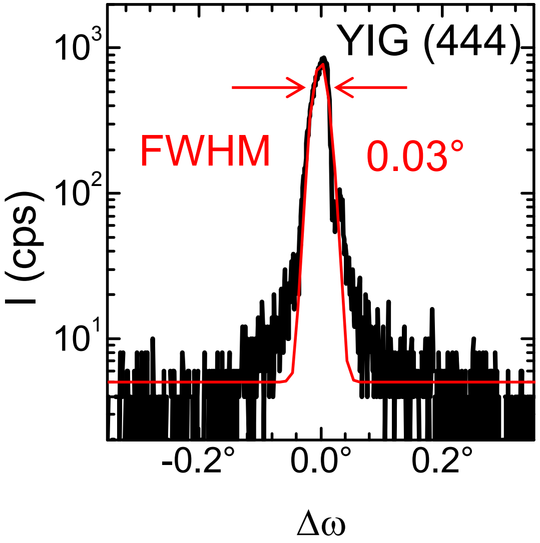
Kajiwara *et al.*, Nature **464**, 262 (2010).
Mosendz *et al.*, Phys. Rev. Lett. **104**, 046601 (2010).
Nakayama *et al.*, IEEE Trans. Magn. **46**, 2202 (2010).

Czeschka et al. Phys. Rev. Lett. **107**, 046601 (2011).

YIG/Pt hybrids grown at WMI (Pt deposited in-situ!)

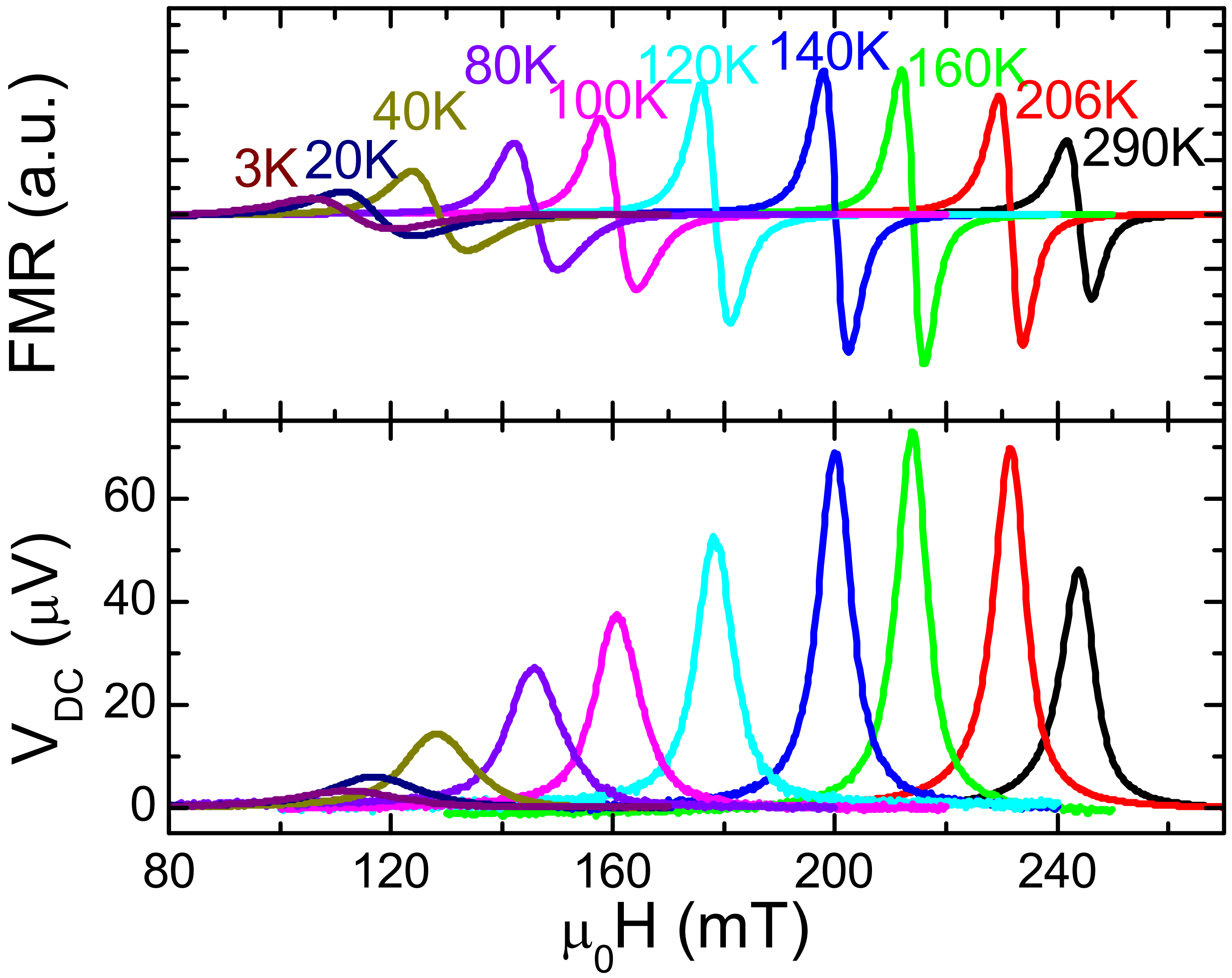


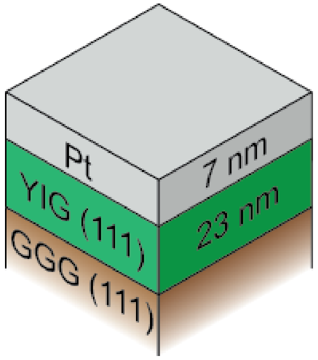




state-of-the-art samples

Spin pumping in YIG/Pt

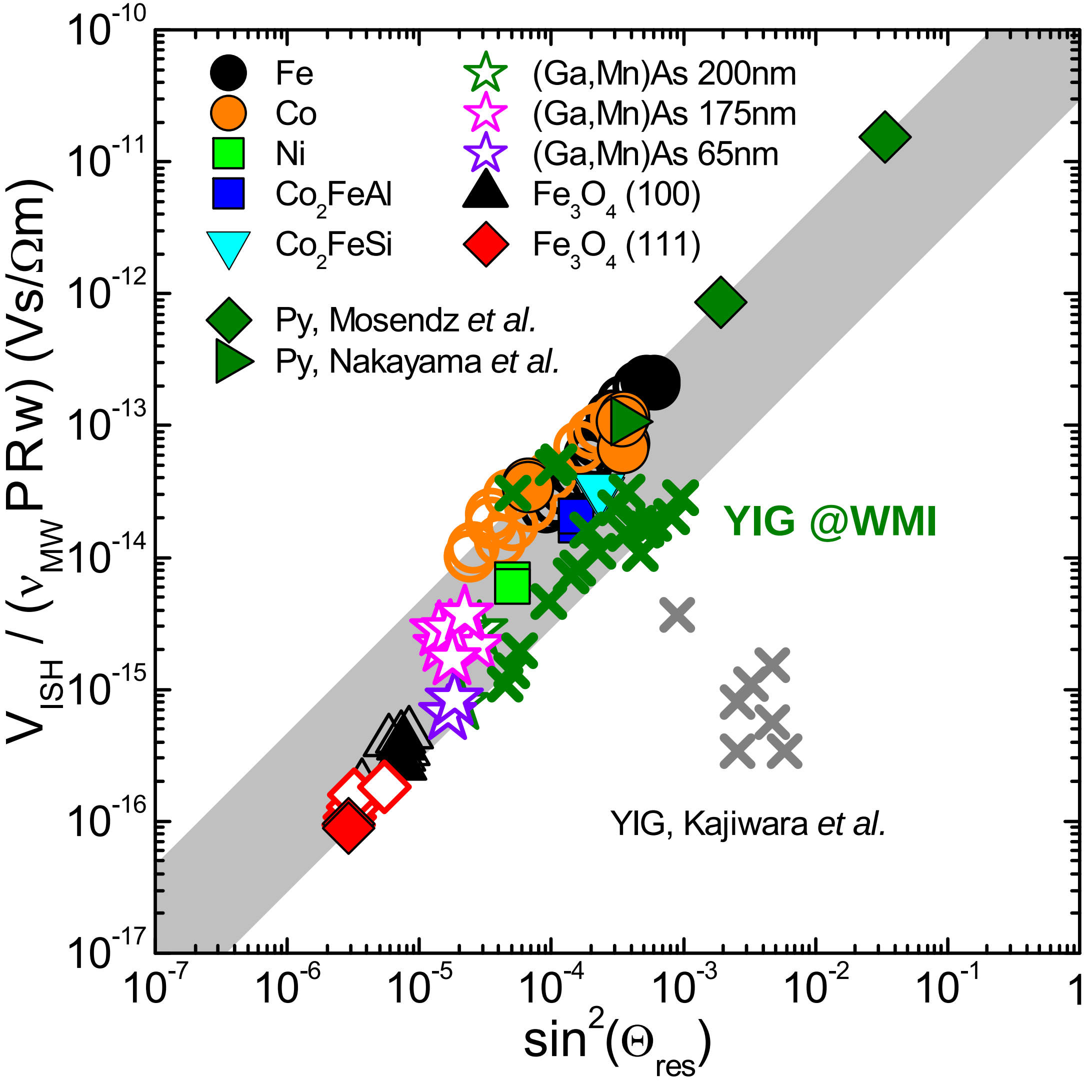




Spin pumping scaling

$$\frac{V_{\mathrm{ISH,\,res}}}{\upsilon_{\mathrm{MW}} P R w} = e\,C\,g^{\uparrow\downarrow} \sin^2 \Theta_{\mathrm{res}}$$

Theory quantitatively ✓
describes the experimental
data…
in FM metals
and in FM insulators



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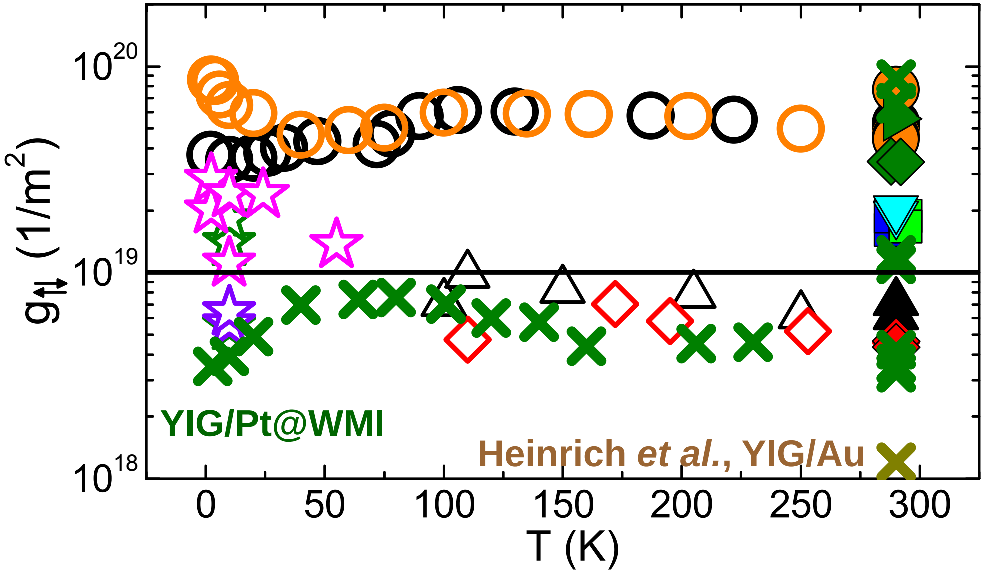
Czeschka *et al.*, Phys. Rev. Lett. **107**, 046601 (2011).
Weiler *et al.*, arXiv 1306.5012 (2013) (PRL, accepted)

Spin-Mixing Conductance of F/Pt hybrid structures

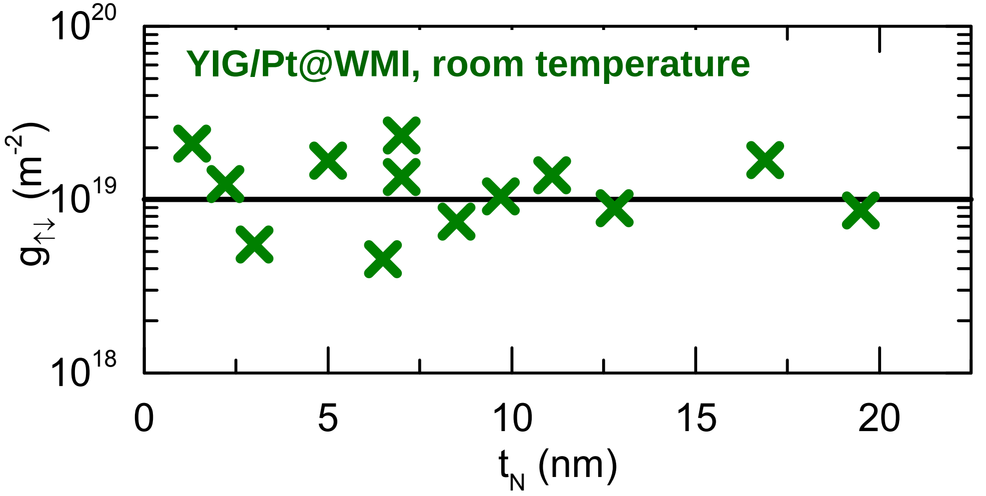
$$g^{\uparrow\downarrow} = \frac{V_{\mathrm{ISH,\,res}}}{e\,C\,v_{\mathrm{MW}} P R\,w\,\sin^2\Theta_{\mathrm{res}}}$$

using
α_{SH}=0.013 and λ_{SD}=10nm :

Mosendz *et al.*, Phys. Rev. Lett. **104**, 046601 (2010).
Heinrich *et al.*, Phys. Rev. Lett. **107**, 066604 (2011).
Vilela-Leão *et al.*, Appl. Phys. Lett. **99**, 102505 (2011).



using
α_{SH}=0.11 and λ_{SD}=1.5nm :
(and taking into account backflow)
… consistent with damping expts.!

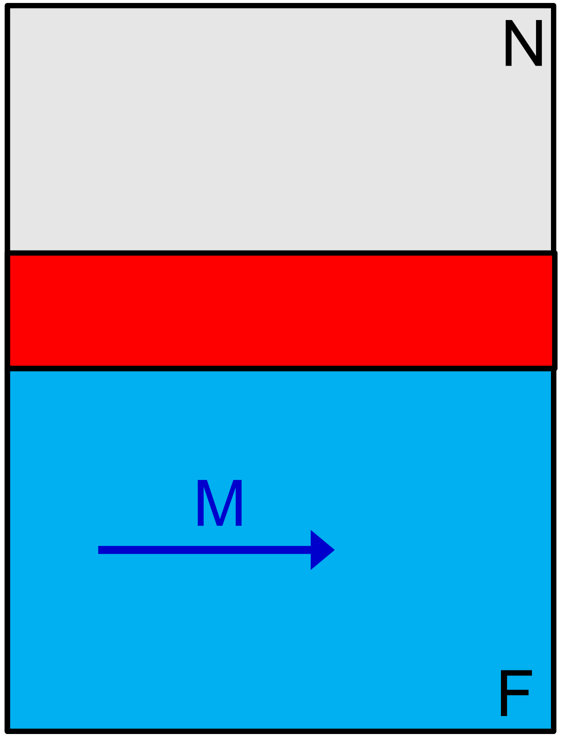


Weiler *et al.*, arXiv 1306.5012 (2013) (PRL, accepted)
Weiler *et al.*, in Solid State Physics Vol. 64, chapter 5,
A. Hoffmann and M. Wu, eds., (Elsevier, 2014)

take away:
spin pumping from FM metals ***and*** FM insulators with similar efficiency

Open issues #2

take away:
spin pumping from FM metals ***and*** FM insulators with similar efficiency



Open issues:

- spin polarized (proximitized) interface layer
  present in FM metal/Pt
  absent in YIG/Pt (?)
  [but cf. Lu *et al.*, PRL**110**, 147207 (2013)]

→ spin pumping and spin currents in F1 / F2 / N
(e.g., Co / proximitized Pt / Pt)
understand "spin current circuits"

→ spin pumping and spin currents in F / N1 / N2
(e.g., Co / Cu / Pt ,
or YIG / Cu / Pt)

Open issues #3

take away:
spin pumping from FM metals ***and*** FM insulators with similar efficiency

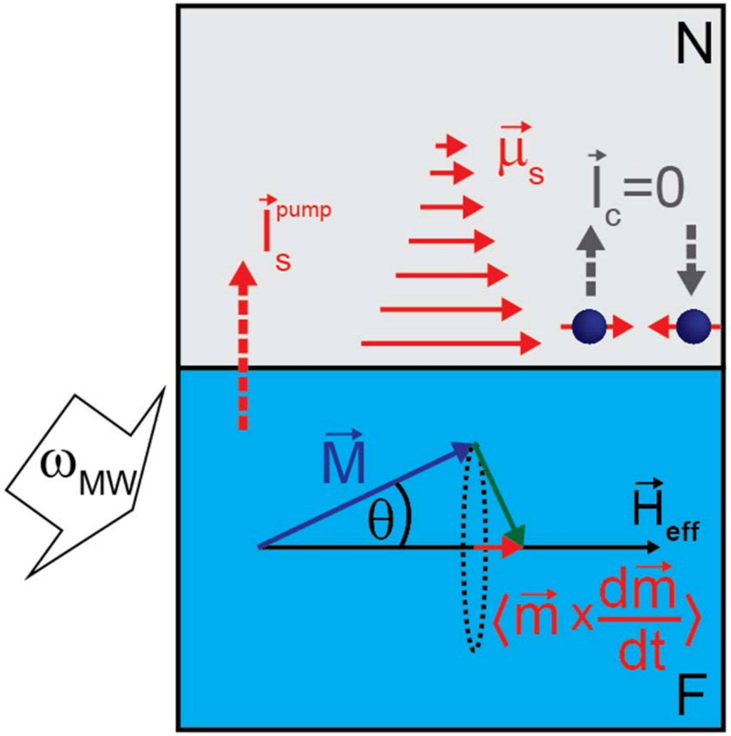
Open issues:

- Spin pumping ⇔ longitudinal relaxation
  (T1 process, spin -lattice)

→ spin pumping from T2 processes ?
(spin-spin relaxation / dephasing)

→ relevant time scales for SP ?
(this might require microscopic understanding
of magnetization damping first …)

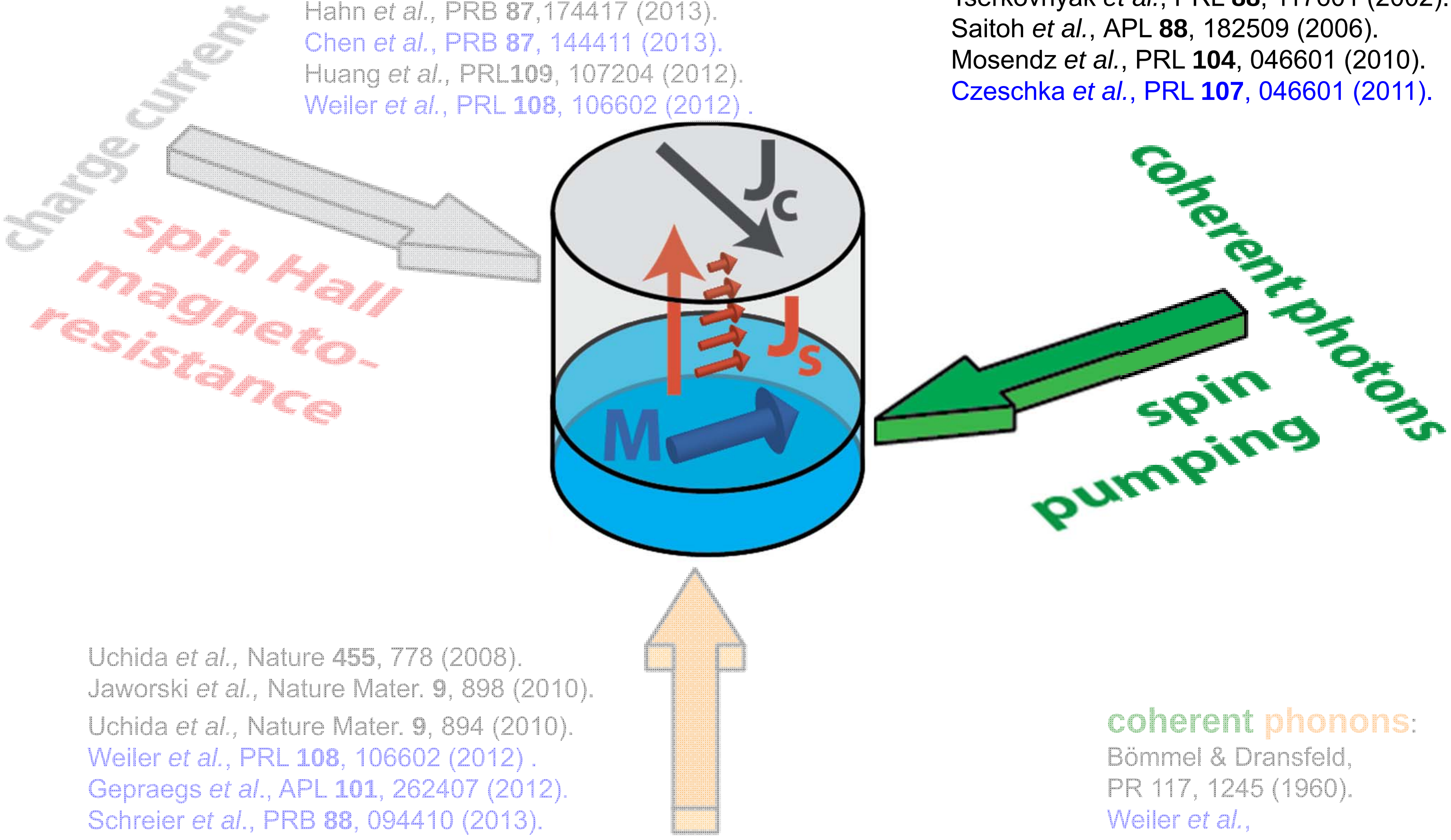
→ relevant length scales for SP ?
magnon wavelength ?
what about interface roughness ?



Spin currents in hybrid structures

Nakayama *et al.*, PRL **110**, 206601 (2013).
Althammer *et al.*, PRB **87**, 224401 (2013).
Vlietstra *et al.*, PRB **87**, 184421 (2013).
Hahn *et al.*, PRB **87**,174417 (2013).
Chen *et al.*, PRB **87**, 144411 (2013).
Huang *et al.*, PRL**109**, 107204 (2012).
Weiler *et al.*, PRL **108**, 106602 (2012) .

Tserkovnyak *et al.*, PRL **88**, 117601 (2002).
Saitoh *et al.*, APL **88**, 182509 (2006).
Mosendz *et al.*, PRL **104**, 046601 (2010).
Czeschka *et al.*, PRL **107**, 046601 (2011).



charge current

spin Hall magneto-resistance

coherent photons

spin pumping

Uchida *et al.*, Nature **455**, 778 (2008).
Jaworski *et al.*, Nature Mater. **9**, 898 (2010).
Uchida *et al.*, Nature Mater. **9**, 894 (2010).
Weiler *et al.*, PRL **108**, 106602 (2012) .
Gepraegs *et al.*, APL **101**, 262407 (2012).
Schreier *et al.*, PRB **88**, 094410 (2013).

thermal phonons

spin Seebeck effect

coherent phonons:
Bömmel & Dransfeld,
PR 117, 1245 (1960).
Weiler *et al.*,
PRL **106**, 117601 (2011).
PRL **108**, 176601 (2012).

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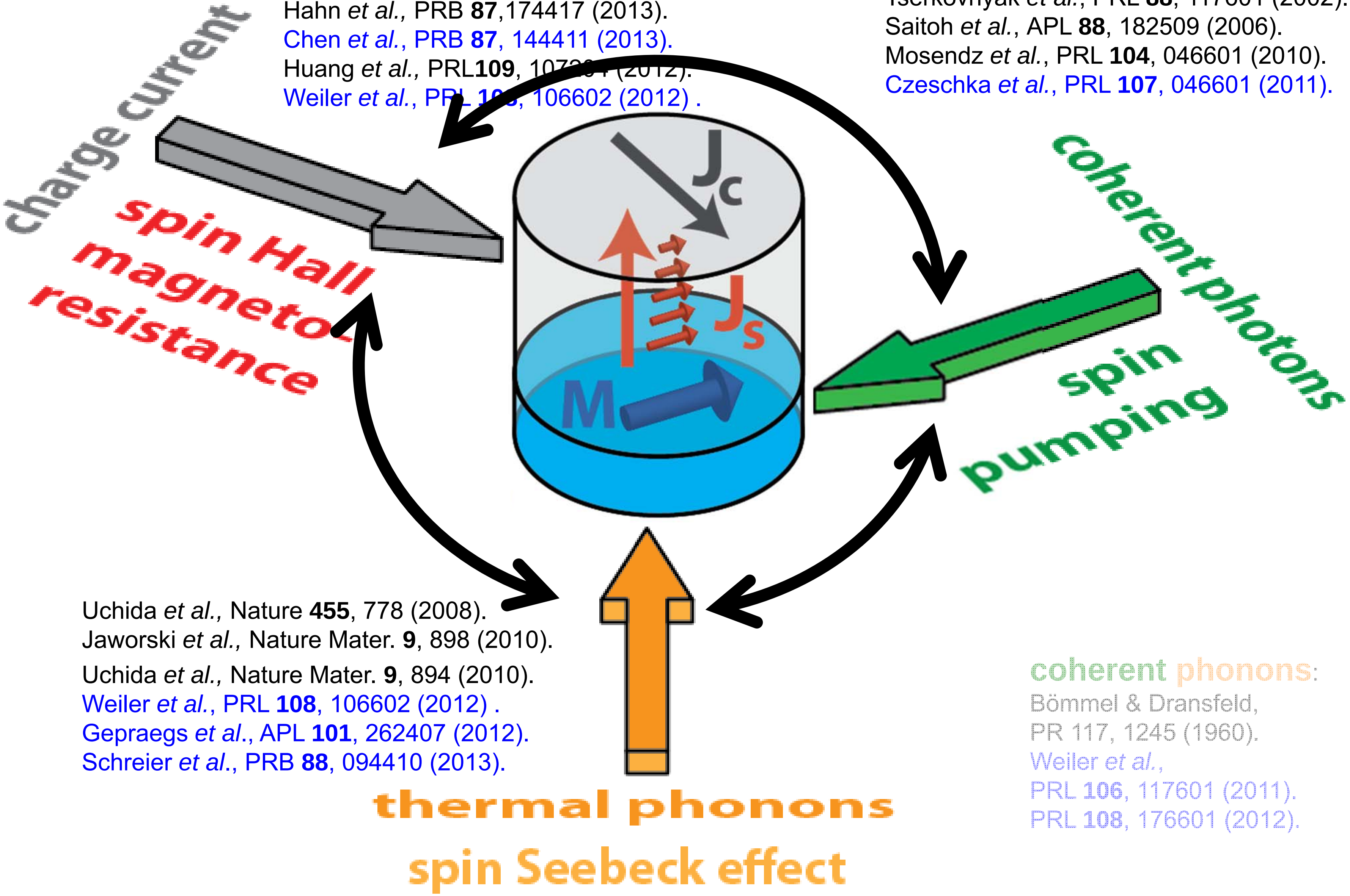

charge current
spin Hall magnetoresistance

coherent photons
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quantitative test of the spin mixing conductance concept

("spin Ohm's law")

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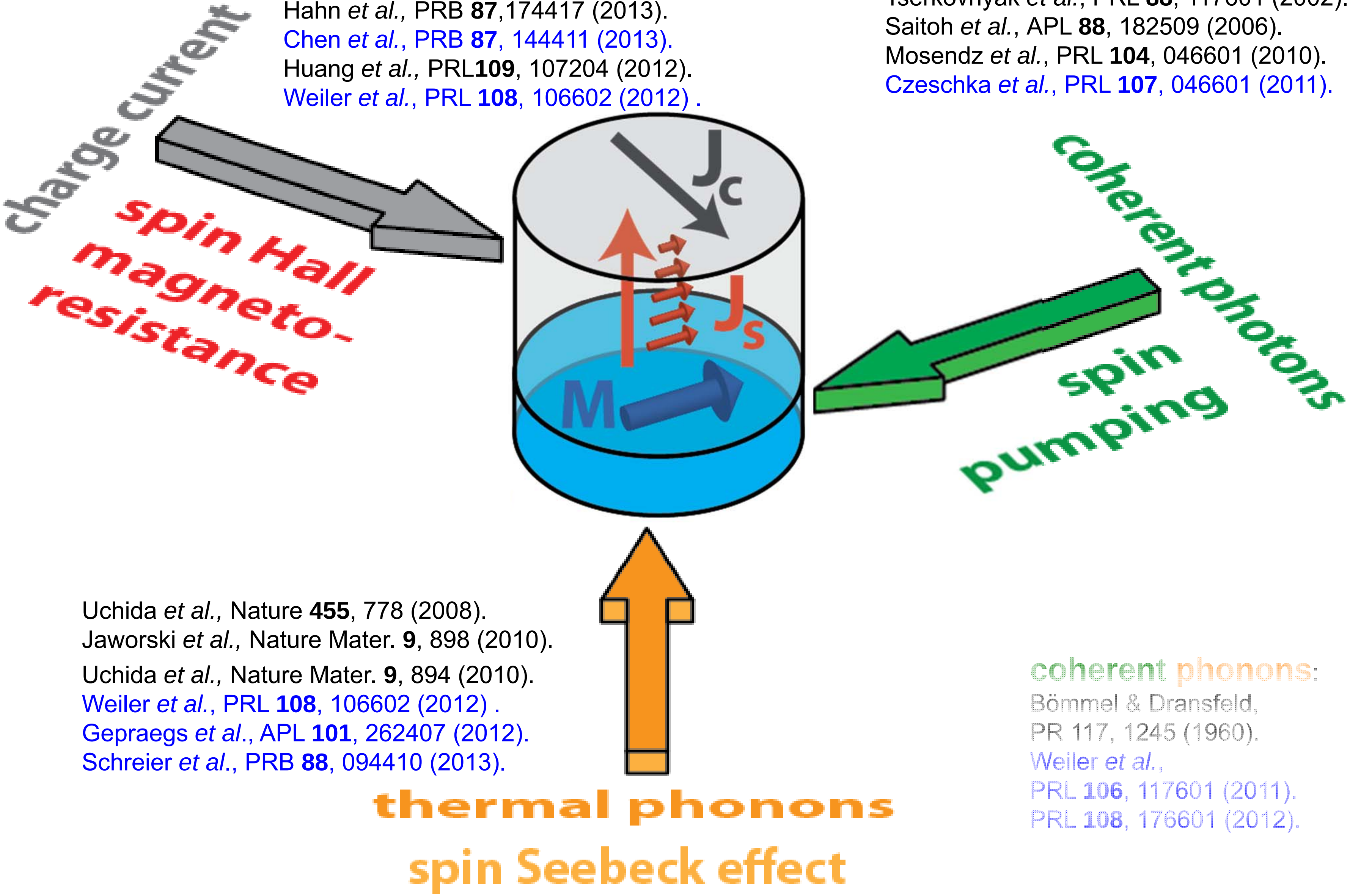

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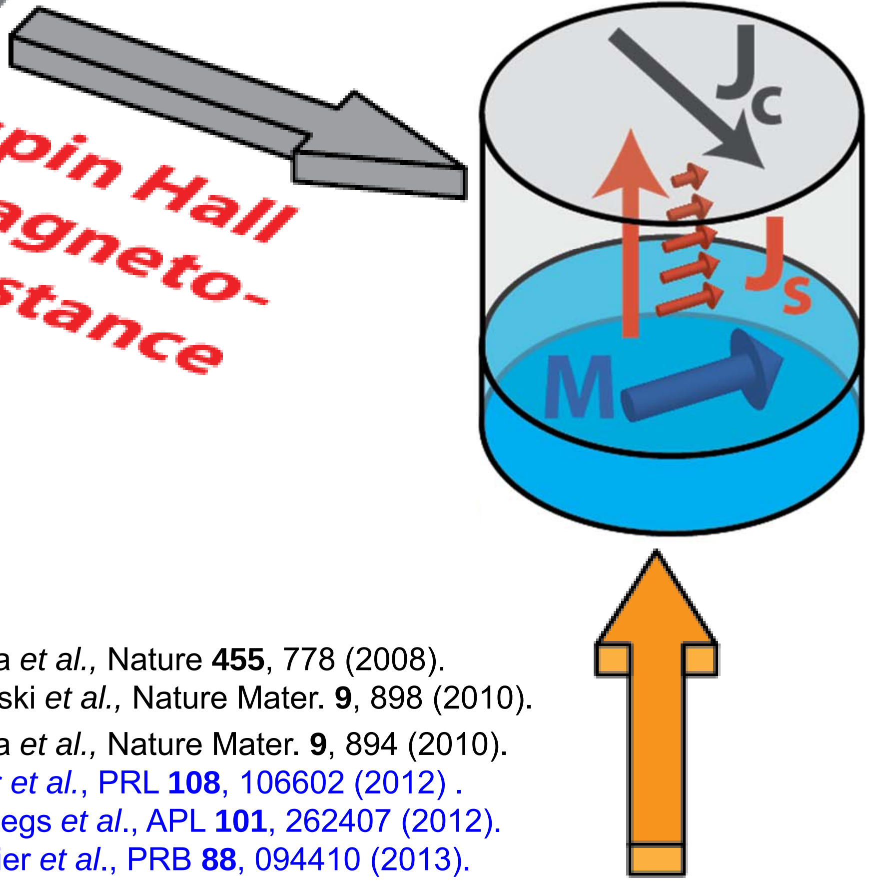
charge current

spin Hall magneto-resistance



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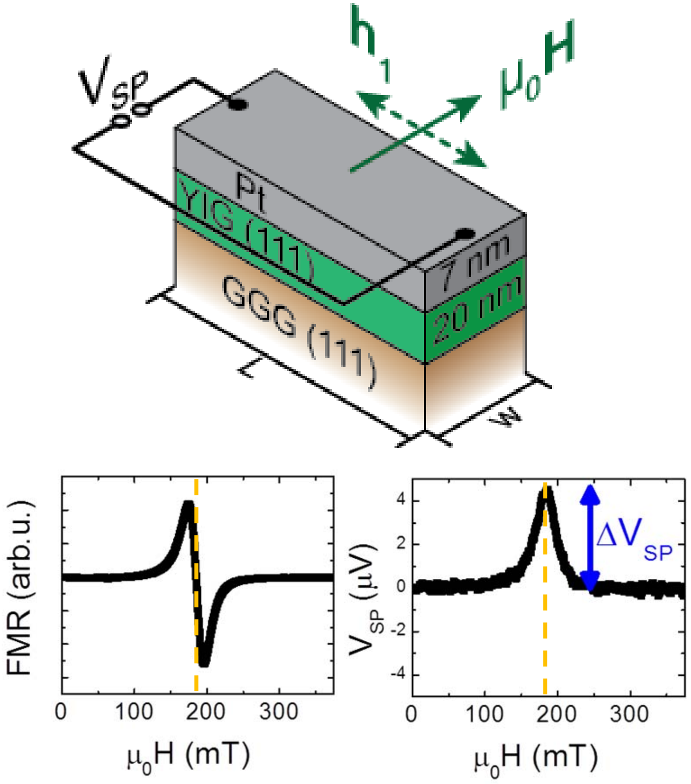

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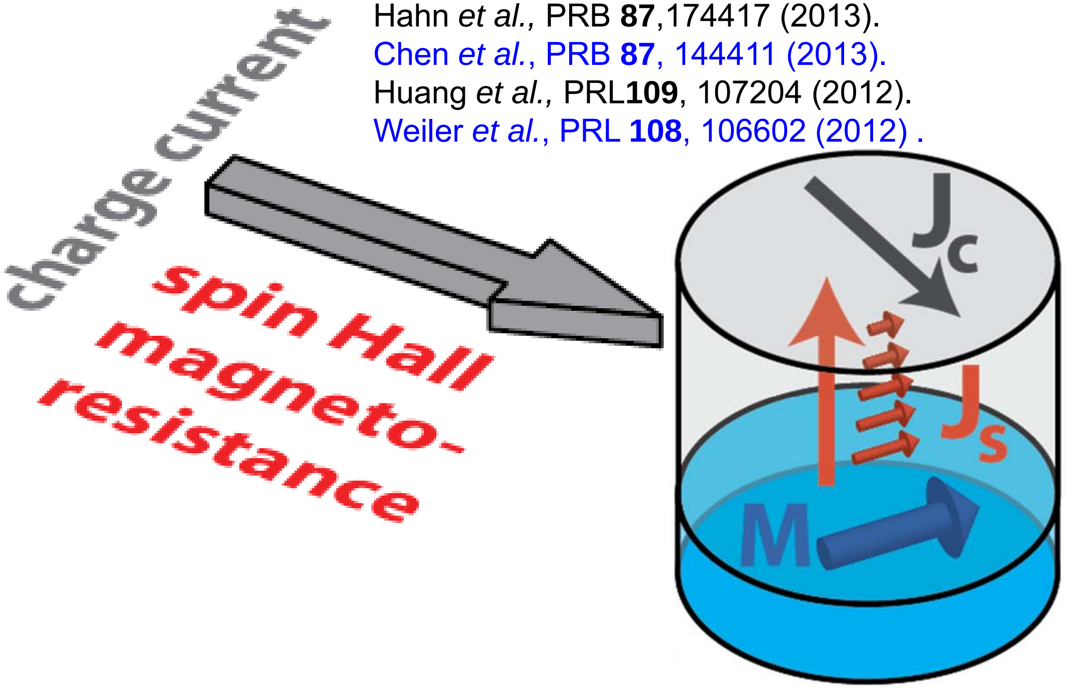
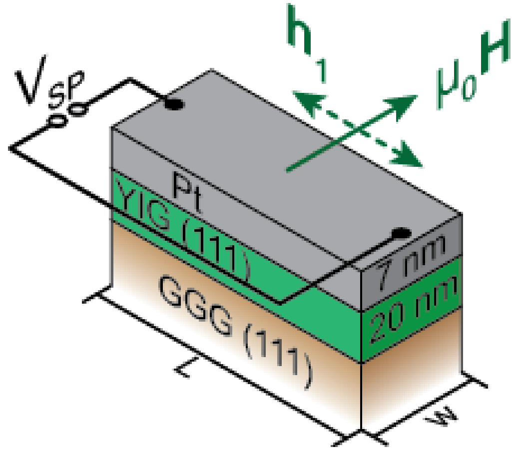
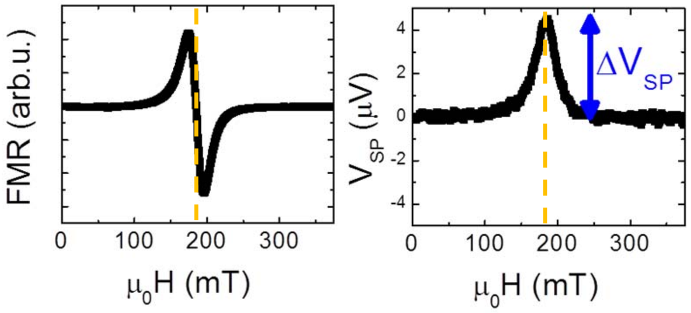
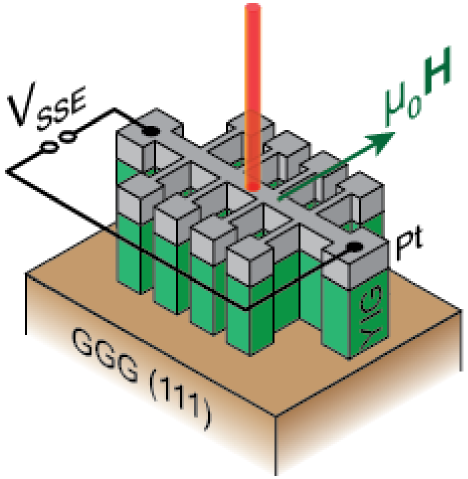
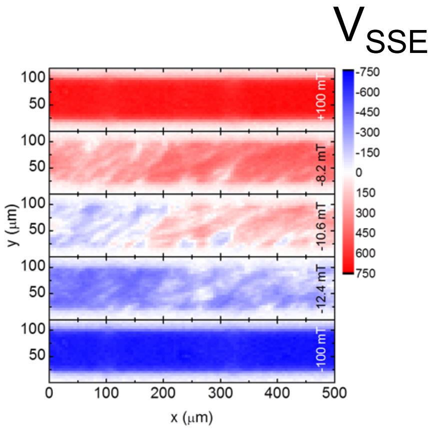
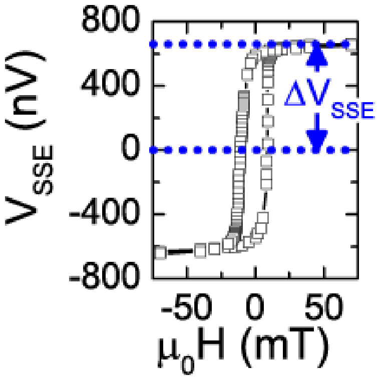




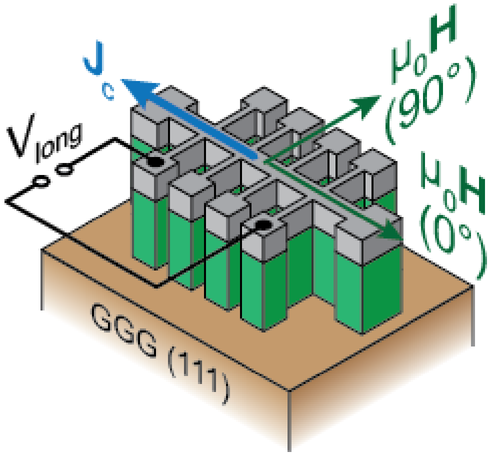


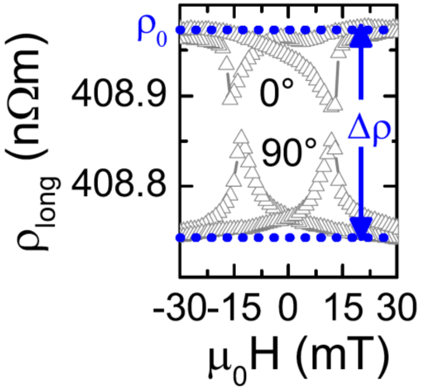


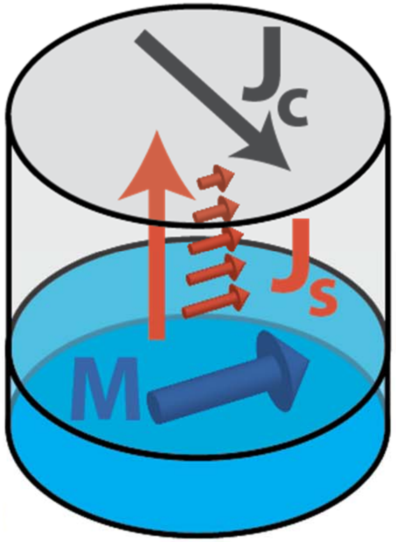


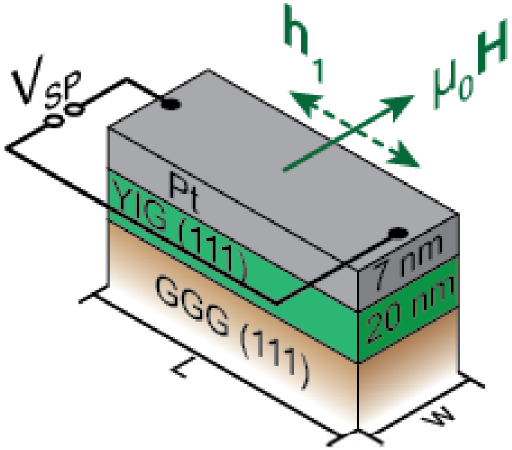


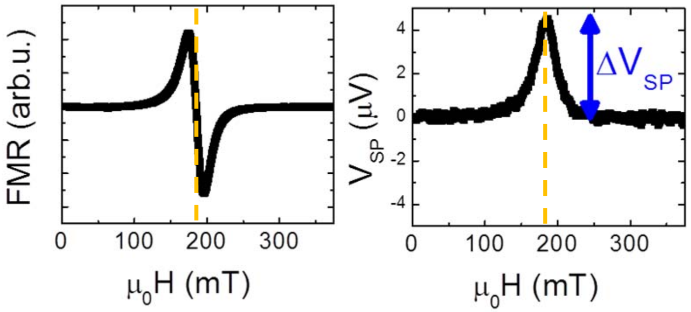
Spin currents in hybrid structures

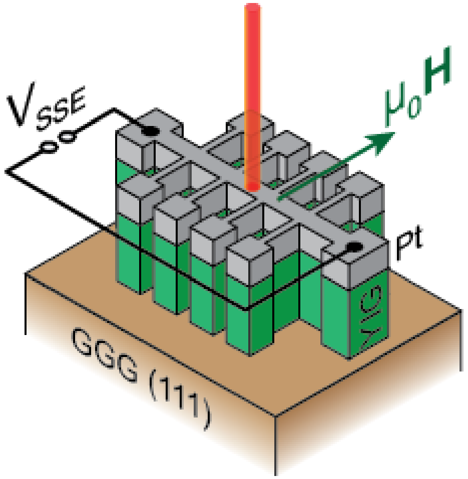


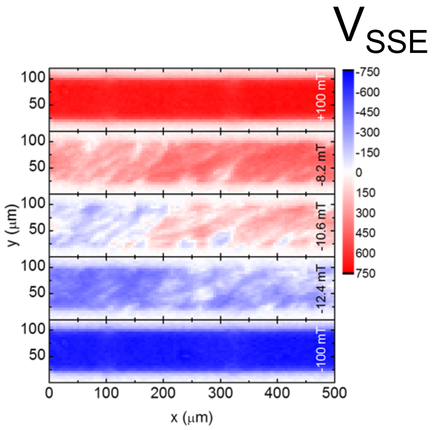


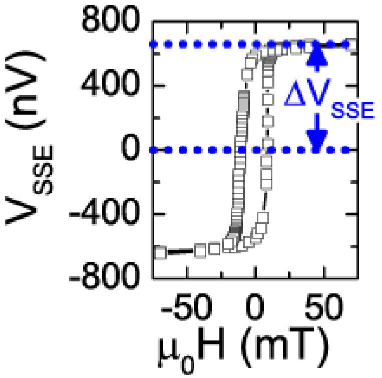












Tserkovnyak *et al.*, PRL **88**, 117601 (2002).
Xiao *et al.*, PRB **81**, 214418 (2010).
Jiao & Bauer, PRL **110**, 217602 (2013).
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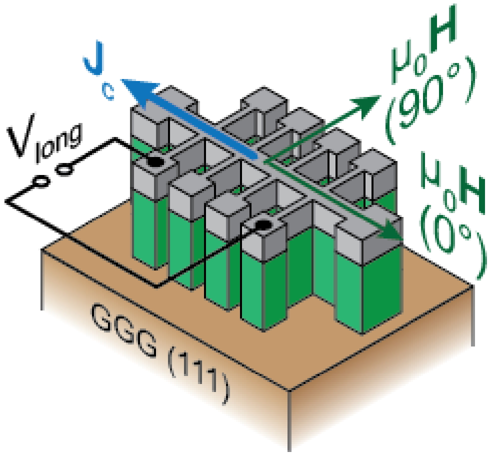
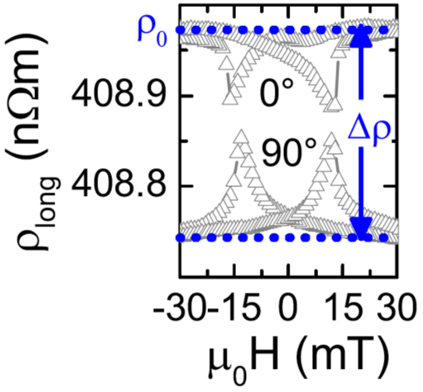
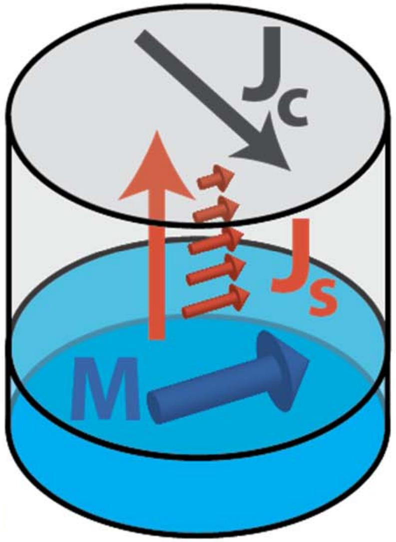
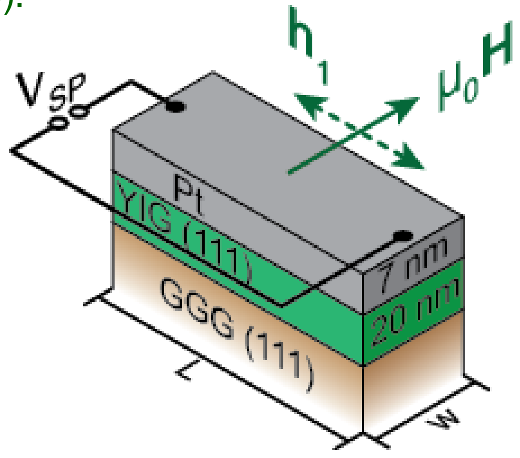
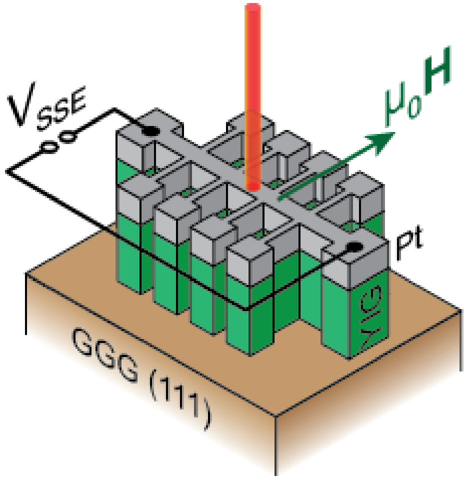


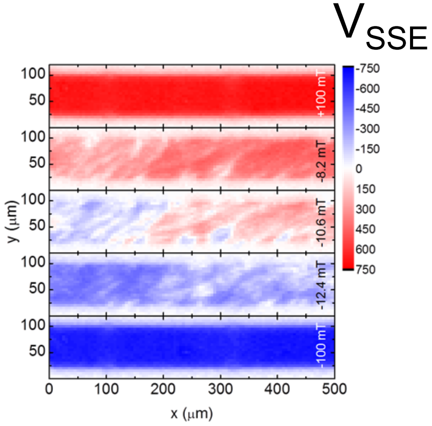


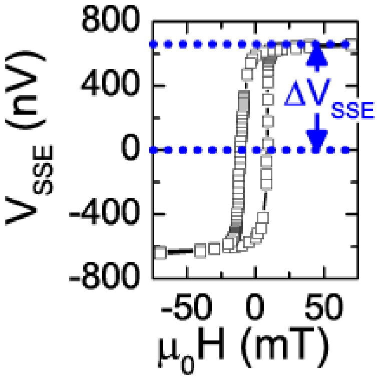




$$J_s^{SP} = \frac{g_{\uparrow\downarrow}}{2\pi}\frac{1}{2}h\nu P\sin^2\Theta$$







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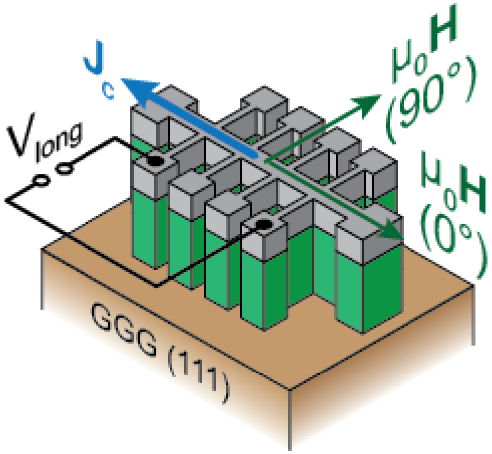
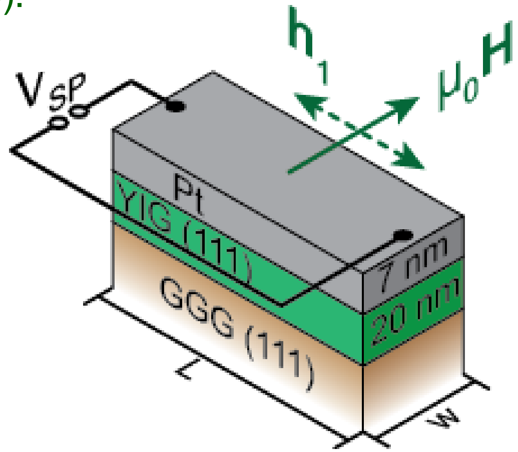
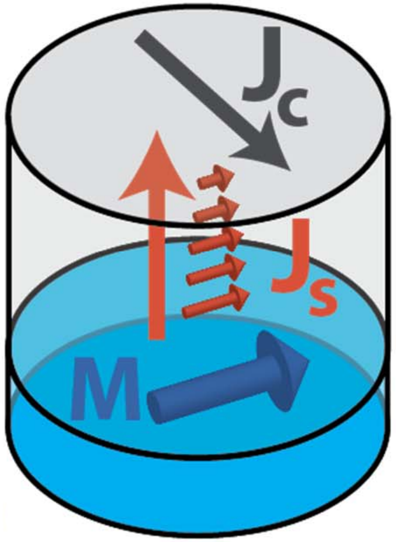
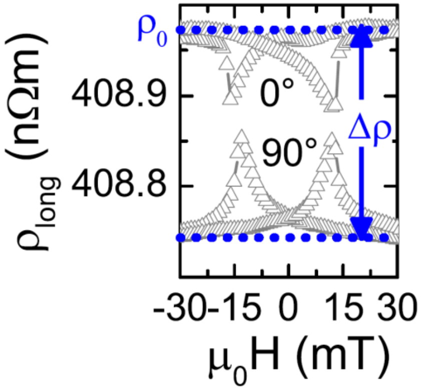
Jiao & Bauer, PRL **110**, 217602 (2013).
Chen *et al.*, PRB **87**, 144411 (2013).





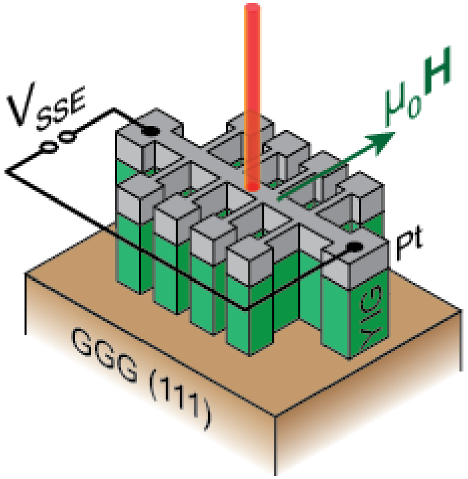




$$J_s^{SP} = \frac{g_{\uparrow\downarrow}}{2\pi}\frac{1}{2}h\nu P\sin^2\Theta$$

$$J_s^{SP} = \frac{g_{\uparrow\downarrow}}{2\pi}\ E^{SP}$$

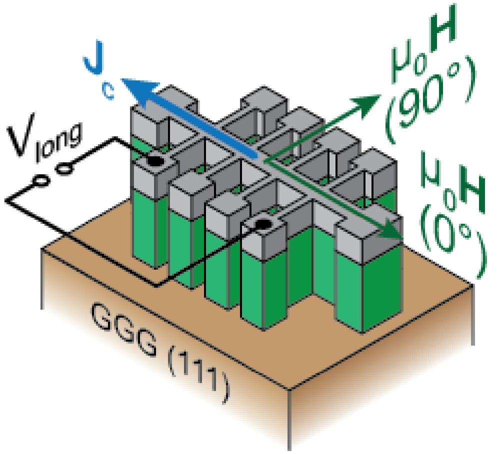
$$E^{SP} = \tfrac{1}{2}h\nu P\sin^2\Theta$$



$$J_s^{SSE} = \frac{g_{\uparrow\downarrow}}{2\pi}\ E^{SSE}$$

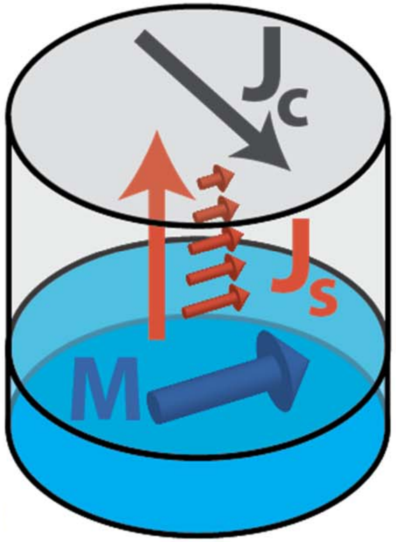
$$E^{SSE} = \frac{\gamma}{M_s V_a/\hbar}k_B\Delta T$$

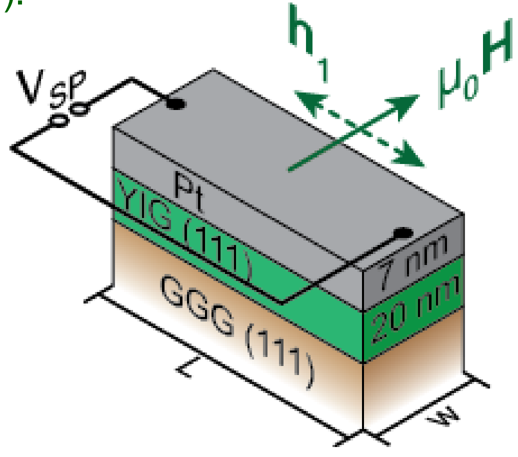
Tserkovnyak *et al.*, PRL **88**, 117601 (2002).
Xiao *et al.*, PRB **81**, 214418 (2010).
Jiao & Bauer, PRL **110**, 217602 (2013).
Chen *et al.*, PRB **87**, 144411 (2013).



$$J_s^{\mathrm{SMR}} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SMR}}$$

$$E^{\mathrm{SMR}} = 2e\,\alpha_{\mathrm{SH}}\rho_{\mathrm{Pt}}J_c \times \lambda_{\mathrm{SD}}\tanh\frac{t_{\mathrm{Pt}}}{2\lambda_{\mathrm{SD}}}\eta$$

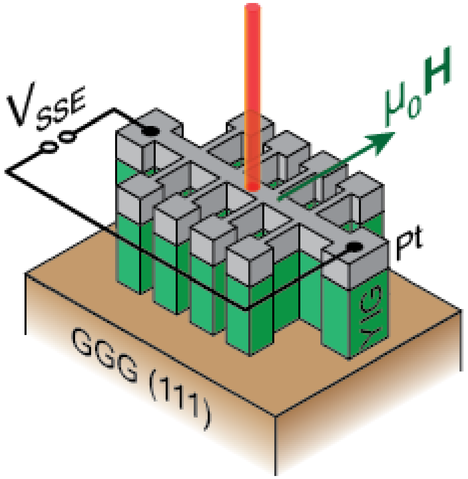




$$J_s^{\mathrm{SP}} = \frac{g_{\uparrow\downarrow}}{2\pi}\frac{1}{2}h\nu P\sin^2\Theta$$

$$J_s^{\mathrm{SP}} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SP}}$$

$$E^{\mathrm{SP}} = \tfrac{1}{2}h\nu P\sin^2\Theta$$

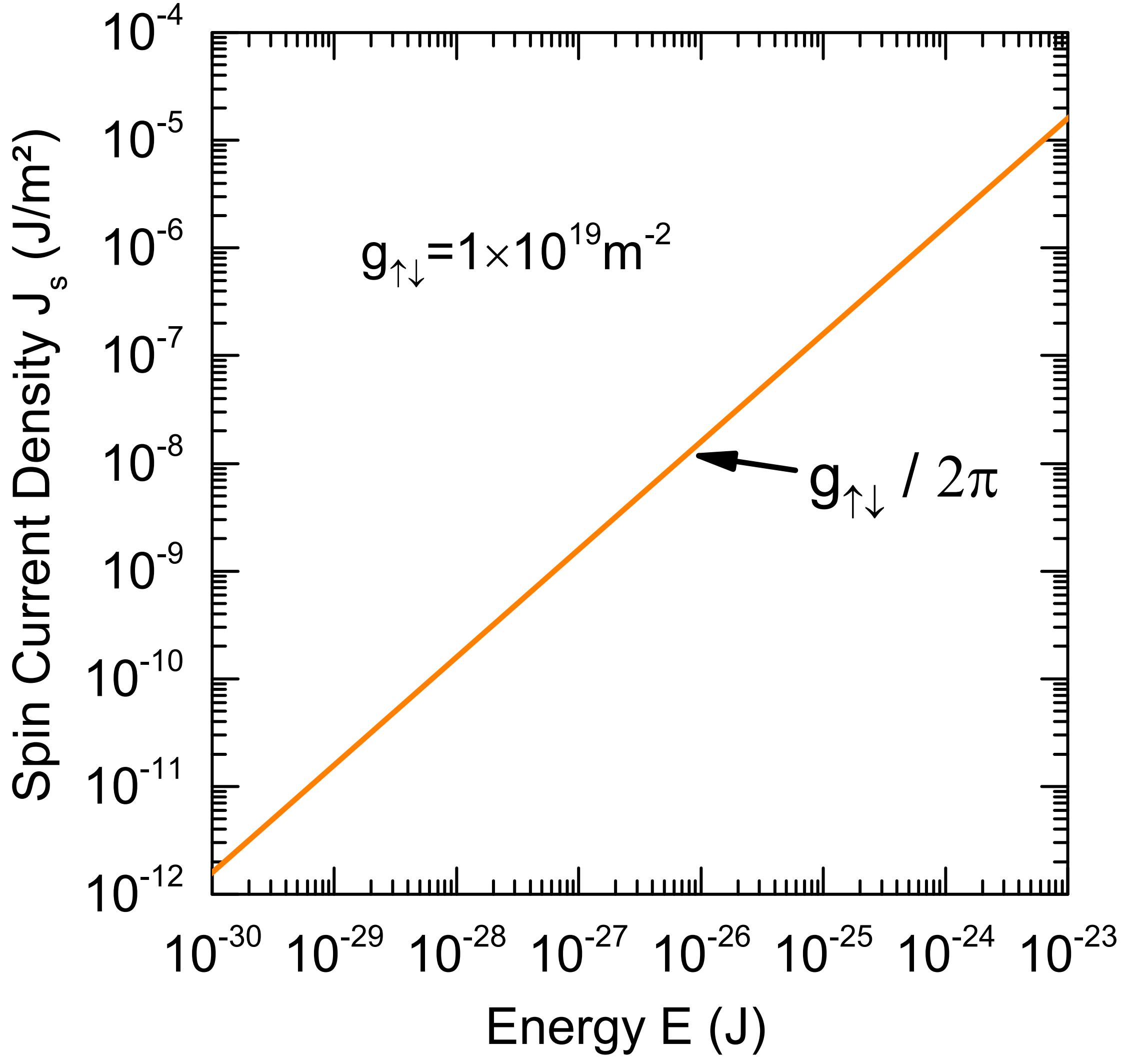


$$J_s^{\mathrm{SSE}} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SSE}}$$

$$E^{\mathrm{SSE}} = \frac{\gamma}{M_s V_a/\hbar} k_B \Delta T$$

Spin current scaling: $g_{\uparrow\downarrow}$ concept

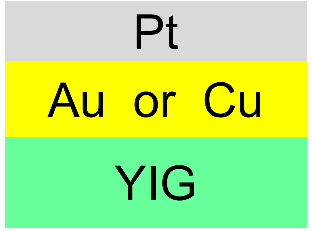
$$J = \frac{g_{\uparrow\downarrow}}{2\pi} E$$



Sample	ρ_{Pt} (nΩm)
GGG/YIG(50)/Pt(7)	409.4
GGG/YIG(54)/Pt(7)	406.5
GGG/YIG(53)/Pt(2.5)	719
GGG/YIG(65)/Pt(6.6)	582.6
GGG/YIG(46)/Pt(3.5)	306.6
GGG/YIG(69)/Pt(2.7)	453.6
GGG/YIG(58)/Pt(2.2)	761.7
GGG/YIG(57)/Pt(1.3)	1089.9
GGG/YIG(61)/Pt(11.1)	334.5
GGG/YIG(52)/Pt(16.9)	339.2
GGG/YIG(53)/Pt(8.5)	348.3
YAG/YIG(59)/Pt(6.8)	487.7
YAG/YIG(64)/Pt(3)	622.2
YAG/YIG(61)/Pt(19.5)	361.3
YAG/YIG(63)/Pt(6.5)	412
YAG/YIG(60)/Pt(9.7)	429
YAG/YIG(60)/Pt(12.8)	434.9
YAG/YIG(50)/Pt(3)	513

Pt

YIG



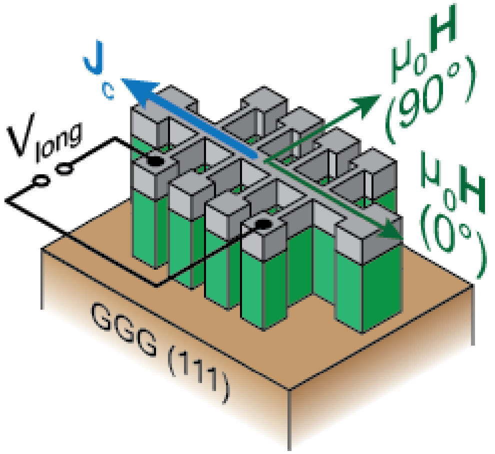
Pt

Au or Cu

YIG

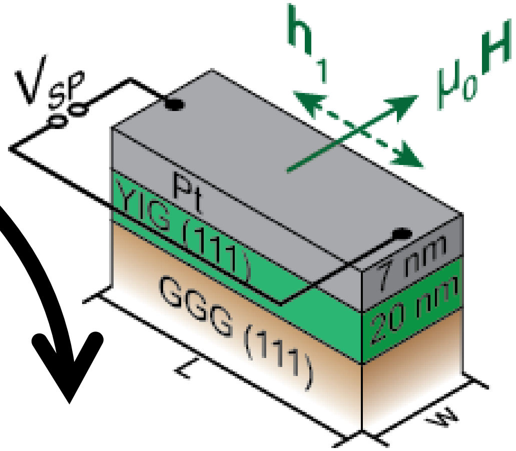
Sample	ρ_{Pt} (nΩm)
GGG/YIG(31)/Cu(8.8)/Pt(7.3)	410
GGG/YIG(20)/Au(7)/Pt(7)	400
GGG/YIG(20)/Cu(9)/Pt(7)	400
YAG/YIG(55)/Au(9.2)/Pt(9)	370
YAG/YIG(45)/Au(9.4)/Pt(2.9)	860

Tserkovnyak *et al.*, PRL **88**, 117601 (2002).
Xiao *et al.*, PRB **81**, 214418 (2010).
Jiao & Bauer, PRL **110**, 217602 (2013).
Chen *et al.*, PRB **87**, 144411 (2013).



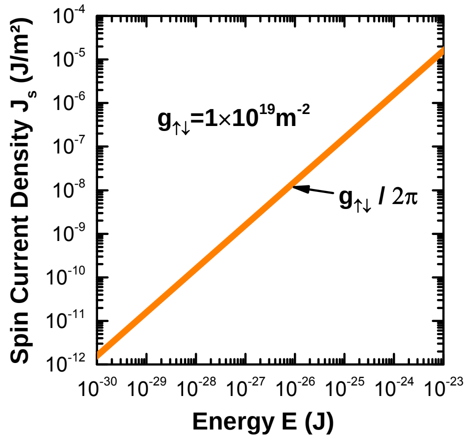
$$J_s^{\mathrm{SMR}} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SMR}}$$

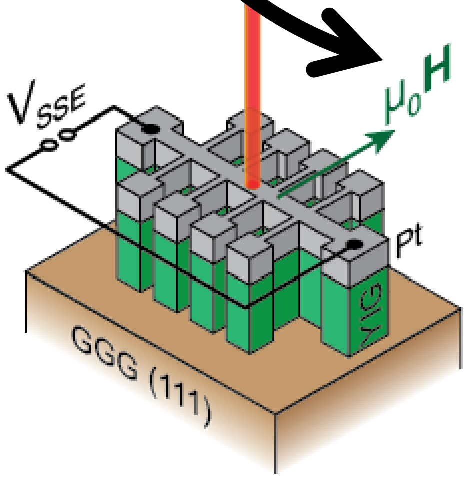
$$E^{\mathrm{SMR}} = 2e\,\alpha_{\mathrm{SH}}\rho_{\mathrm{Pt}}J_c \times \lambda_{\mathrm{SD}} \tanh \frac{t_{\mathrm{Pt}}}{2\lambda_{\mathrm{SD}}}\eta$$



$$J_s^{\mathrm{SP}} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SP}} = \frac{g_{\uparrow\downarrow}}{2\pi}\frac{1}{2} h\nu P \sin^2\Theta$$

$$E^{\mathrm{SP}} = \tfrac{1}{2} h\nu P \sin^2\Theta$$

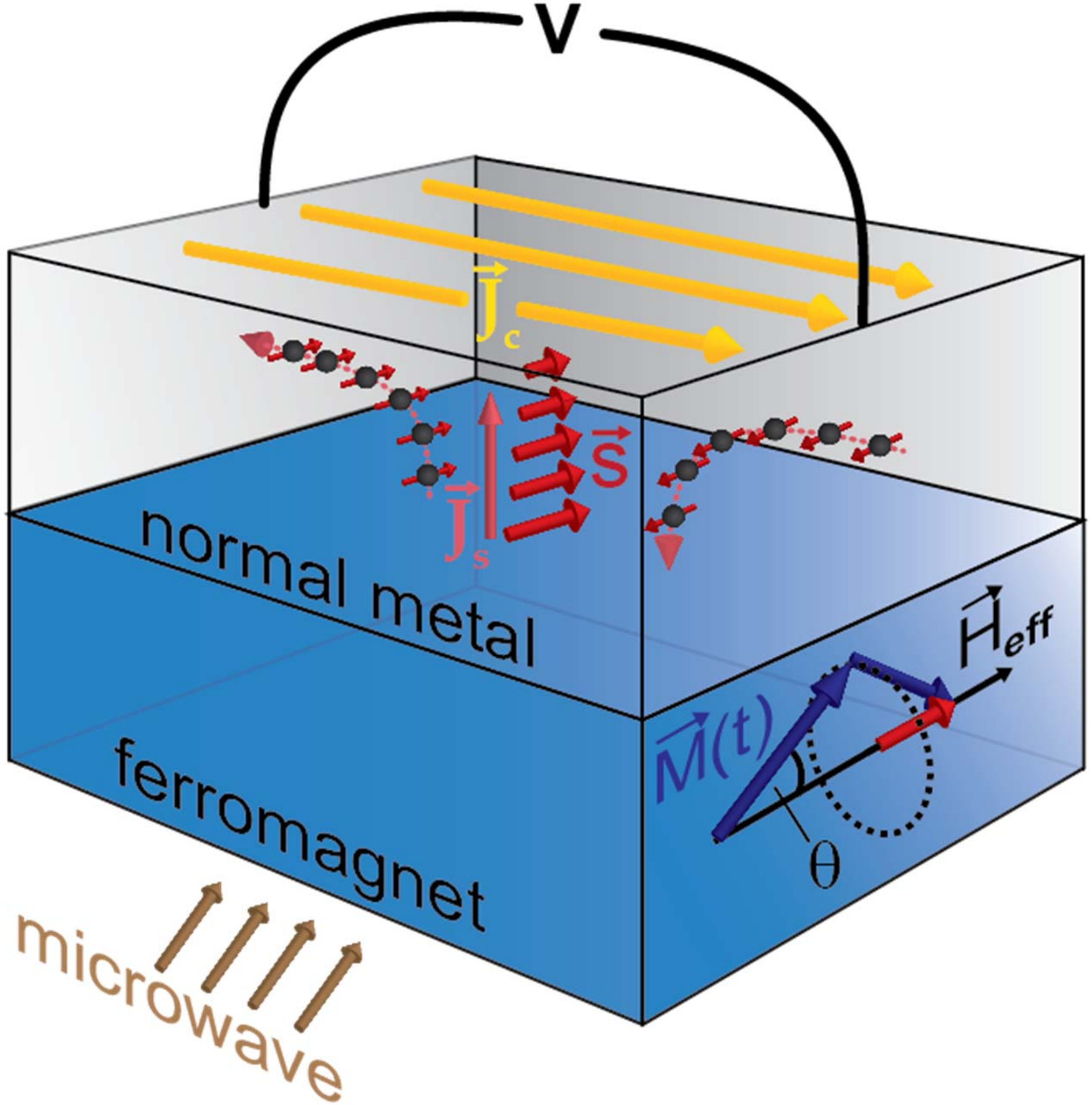


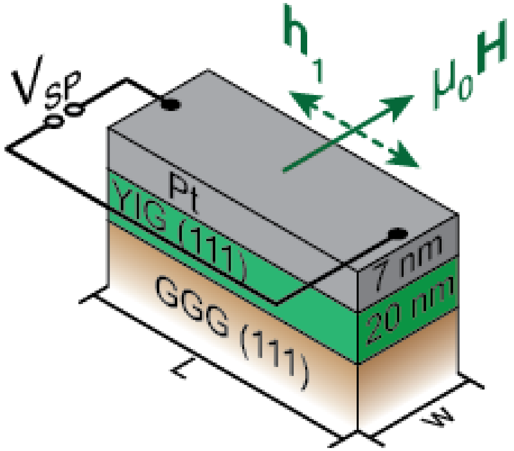


$$J_s^{\mathrm{SSE}} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SSE}}$$

$$E^{\mathrm{SSE}} = \frac{\gamma}{M_s V_a/\hbar} k_B \Delta T$$

Spin pumping (with spin current detection)



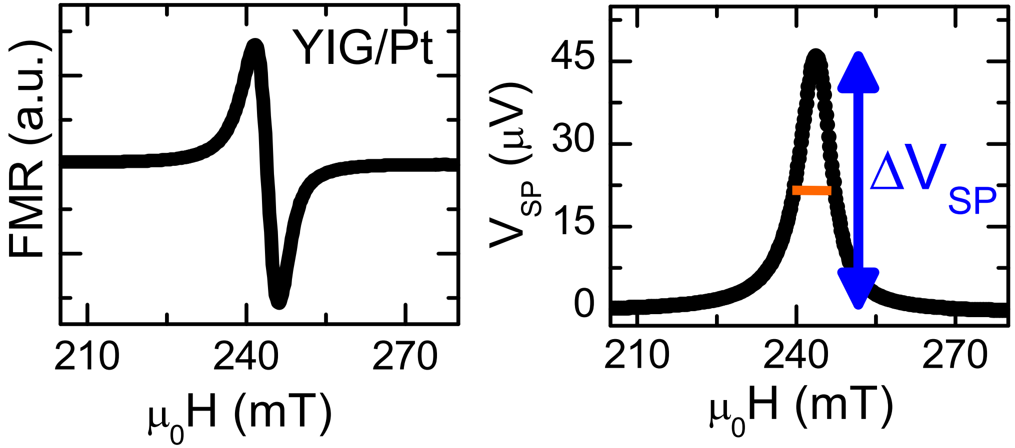


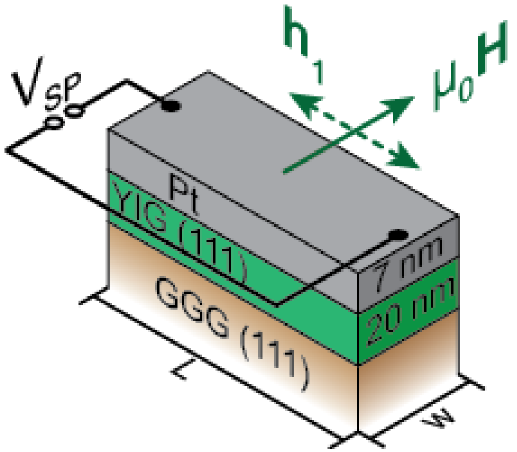
$$J_s^{SP} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{SP} = \frac{g_{\uparrow\downarrow}}{2\pi} \frac{1}{2} h\nu P \sin^2 \Theta$$

$$E^{SP} = \tfrac{1}{2} h\nu P \sin^2 \Theta$$

Tserkovnyak *et al.*, Phys. Rev. Lett. **88**, 117601 (2002). Saitoh *et al.*, Appl. Phys. Lett. **88**, 182509 (2006)

Spin pumping (with spin current detection)





$$E^{\mathrm{SP}} = \tfrac{1}{2} h\nu P \sin^2\Theta$$

… Θ from width of resonance line

$$J_s^{\mathrm{SP}} = \frac{1}{C\eta L}\Delta V_{\mathrm{SP}}$$

… ΔV_{SP} measured

… C and η calculated, with α_{SH} and λ_{SD}

$$C = \frac{2e}{\hbar}\alpha_{\mathrm{SH}}\lambda_{\mathrm{SD}} \tanh\left(\frac{t_{\mathrm{Pt}}}{2\lambda_{\mathrm{SD}}}\right)\frac{\rho_{\mathrm{Pt}}}{t_{\mathrm{Pt}}}$$

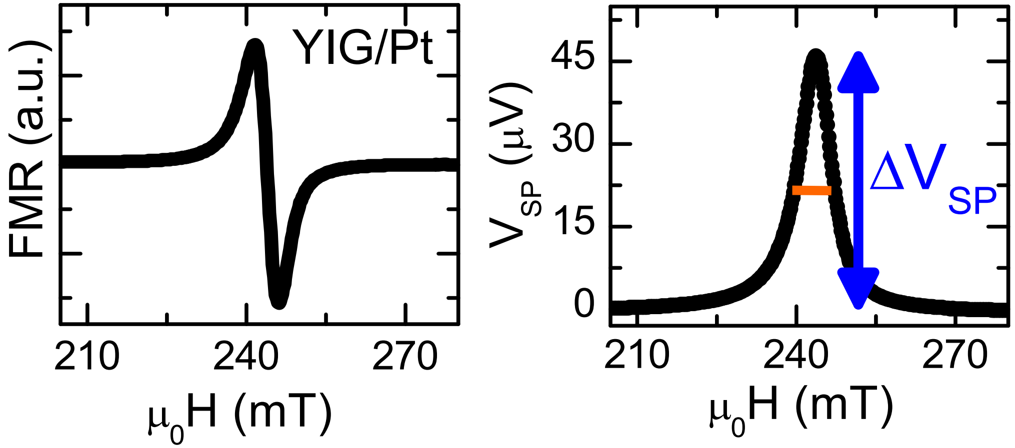
$$\eta = \left[1 + 2g_{\uparrow\downarrow}\rho_{\mathrm{Pt}}\lambda_{\mathrm{SD}}\frac{e^2}{h}\coth\frac{t_{\mathrm{Pt}}}{\lambda_{\mathrm{SD}}}\right]^{-1}$$

$$\begin{aligned} J_s^{\mathrm{SP}} &= \frac{g_{\uparrow\downarrow}}{2\pi}E^{\mathrm{SP}} \\ &= \frac{g_{\uparrow\downarrow}}{2\pi}\frac{1}{2}h\nu P\sin^2\Theta \end{aligned}$$

$$E^{\mathrm{SP}} = \tfrac{1}{2} h\nu P \sin^2\Theta$$

Tserkovnyak *et al.*, PRL **88**, 117601 (2002).
Xiao *et al.*, PRB **81**, 214418 (2010).
Czeschka *et al.*, PRL **107**, 046601 (2011).
Chen *et al.*, PRB **87**, 144411 (2013).
Jiao & Bauer, PRL 110, 217602 (2013).

Spin pumping (with spin current detection)



$$E^{\mathrm{SP}} = \tfrac{1}{2} h\nu P \sin^2\Theta$$

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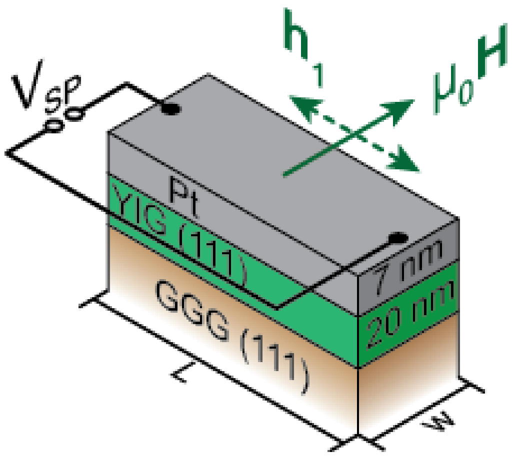
$$\eta = \left[1 + 2g_{\uparrow\downarrow}\rho_{\mathrm{Pt}}\lambda_{\mathrm{SD}}\frac{e^2}{h}\coth\frac{t_{\mathrm{Pt}}}{\lambda_{\mathrm{SD}}}\right]^{-1}$$



$$\begin{aligned} J_s^{\mathrm{SP}} &= \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SP}} \\ &= \frac{g_{\uparrow\downarrow}}{2\pi}\frac{1}{2} h\nu P \sin^2\Theta \end{aligned}$$

$$E^{\mathrm{SP}} = \tfrac{1}{2} h\nu P \sin^2\Theta$$

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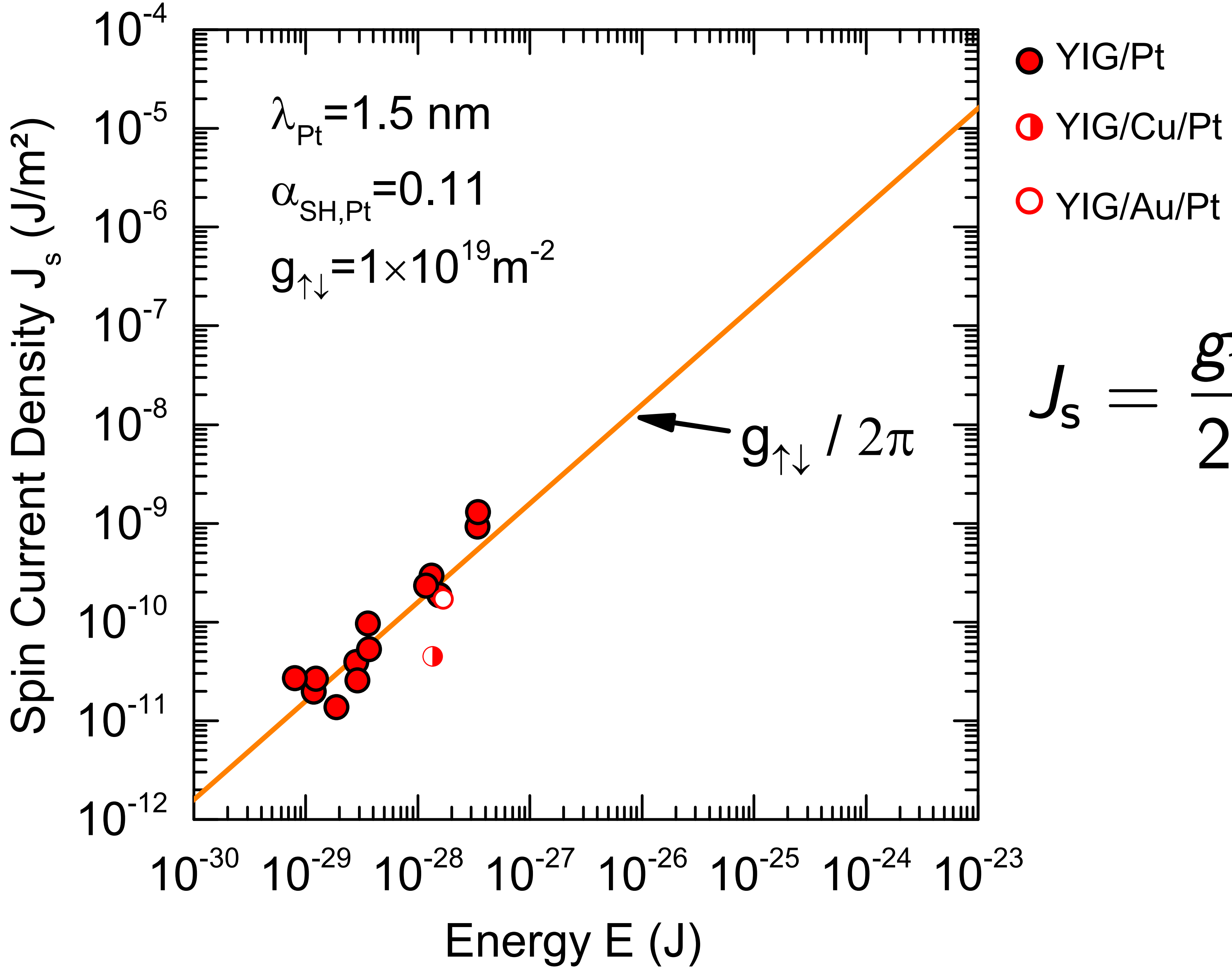
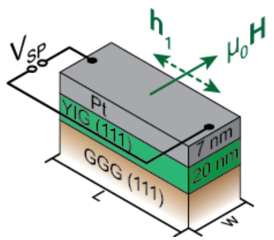
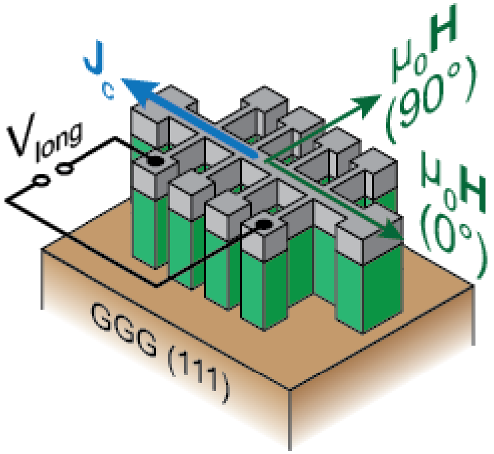
Spin current scaling = $g_{\uparrow\downarrow}$ concept



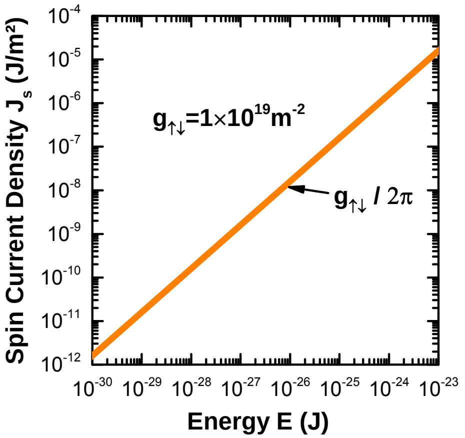


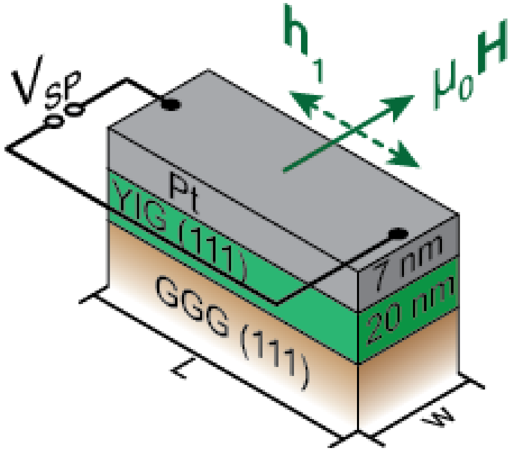
$$J_s = \frac{g_{\uparrow\downarrow}}{2\pi} E$$



$$J_s^{\mathrm{SMR}} = \frac{g_{\uparrow\downarrow}}{2\pi}\,E^{\mathrm{SMR}}$$

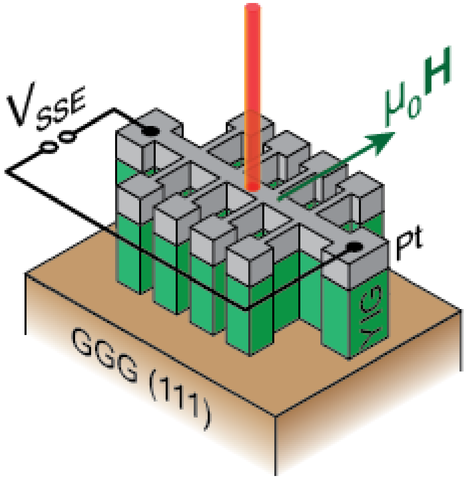
$$E^{\mathrm{SMR}} = 2e\,\alpha_{\mathrm{SH}}\rho_{\mathrm{Pt}}J_c \times \lambda_{\mathrm{SD}}\tanh\frac{t_{\mathrm{Pt}}}{2\lambda_{\mathrm{SD}}}\eta$$





$$J_s^{\mathrm{SP}} = \frac{g_{\uparrow\downarrow}}{2\pi}\,E^{\mathrm{SP}} = \frac{g_{\uparrow\downarrow}}{2\pi}\frac{1}{2}h\nu P\sin^2\Theta$$

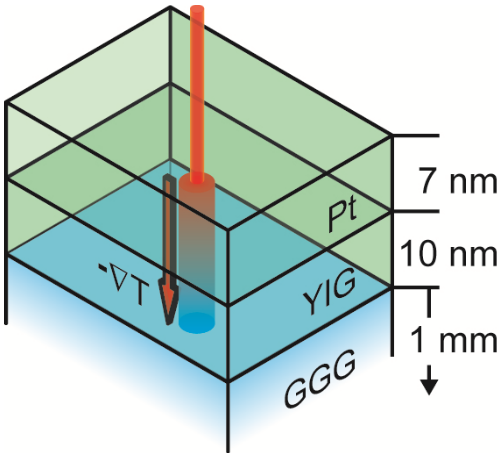
$$E^{\mathrm{SP}} = \tfrac{1}{2}h\nu P\sin^2\Theta$$

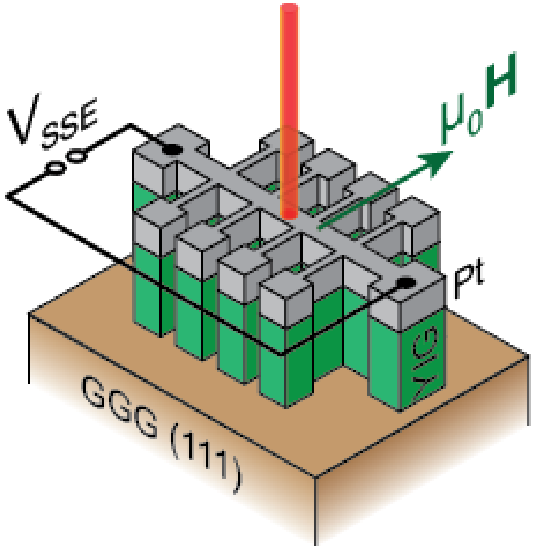


$$J_s^{\mathrm{SSE}} = \frac{g_{\uparrow\downarrow}}{2\pi}\,E^{\mathrm{SSE}}$$

$$E^{\mathrm{SSE}} = \frac{\gamma}{M_s V_a/\hbar}k_{\mathrm{B}}\Delta T$$

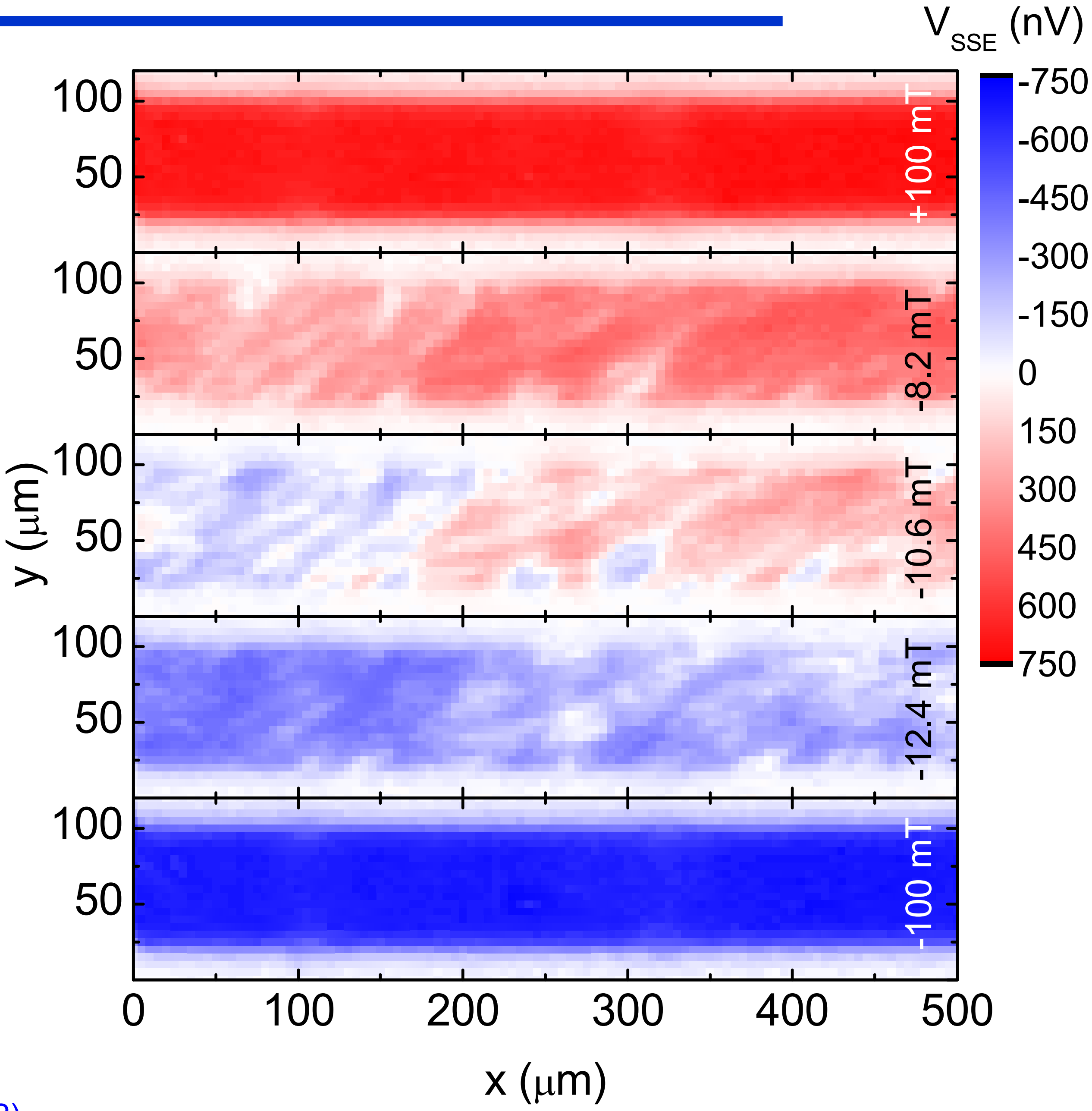
Spin Seebeck effect in YIG/Pt





$$\mathbf{E}_{\mathrm{SSE}} = -\Sigma_{\mathrm{SSE}}\,\mathbf{m}\times\nabla T$$

Weiler *et al.*, PRL **108**, 106602 (2012).

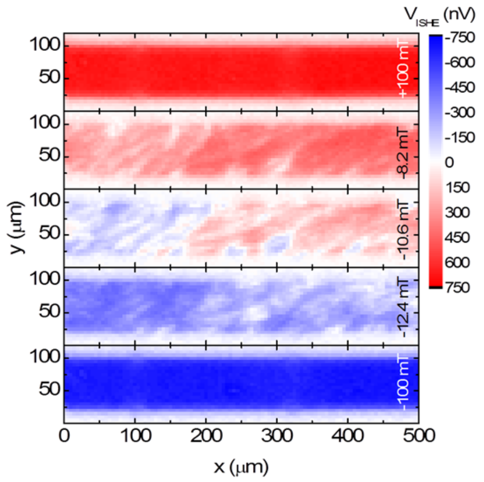


Spin Seebeck effect in YIG/Pt

$$E^{\mathrm{SSE}} = \frac{\gamma}{M_s V_a/\hbar} k_B \Delta T$$

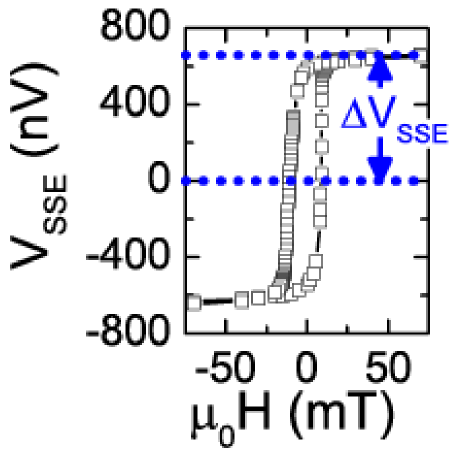
… $\Delta T = T_{\text{electrons,Pt}} - T_{\text{magnons,YIG}}$, calculated

$$\ldots \quad V_a = \frac{2}{3\zeta(5/2)} \left(\frac{4\pi D}{k_B T}\right)^{3/2} \approx (1.38\,\mathrm{nm})^3$$



Schreier *et al.*, PRB **88**, 094410 (2013).

$$J_s^{\mathrm{SSE}} = \frac{1}{C\eta} \frac{2w}{a^2\pi} \Delta V_{\mathrm{SSE}}$$



… *w* = Hall bar width, *a* = laser spot radius

… *C* and η calculated, see spin pumping

… ΔV_{SSE} measured

$$J_s^{\mathrm{SSE}} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SSE}}$$

$$C = \frac{2e}{\hbar} \alpha_{\mathrm{SH}} \lambda_{\mathrm{SD}} \tanh\left(\frac{t_{\mathrm{Pt}}}{2\lambda_{\mathrm{SD}}}\right) \frac{\rho_{\mathrm{Pt}}}{t_{\mathrm{Pt}}}$$

$$\eta = \left[1 + 2 g_{\uparrow\downarrow} \rho_{\mathrm{Pt}} \lambda_{\mathrm{SD}} \frac{e^2}{h} \coth \frac{t_{\mathrm{Pt}}}{\lambda_{\mathrm{SD}}}\right]^{-1}$$

Tserkovnyak *et al.*, PRL **88**, 117601 (2002).
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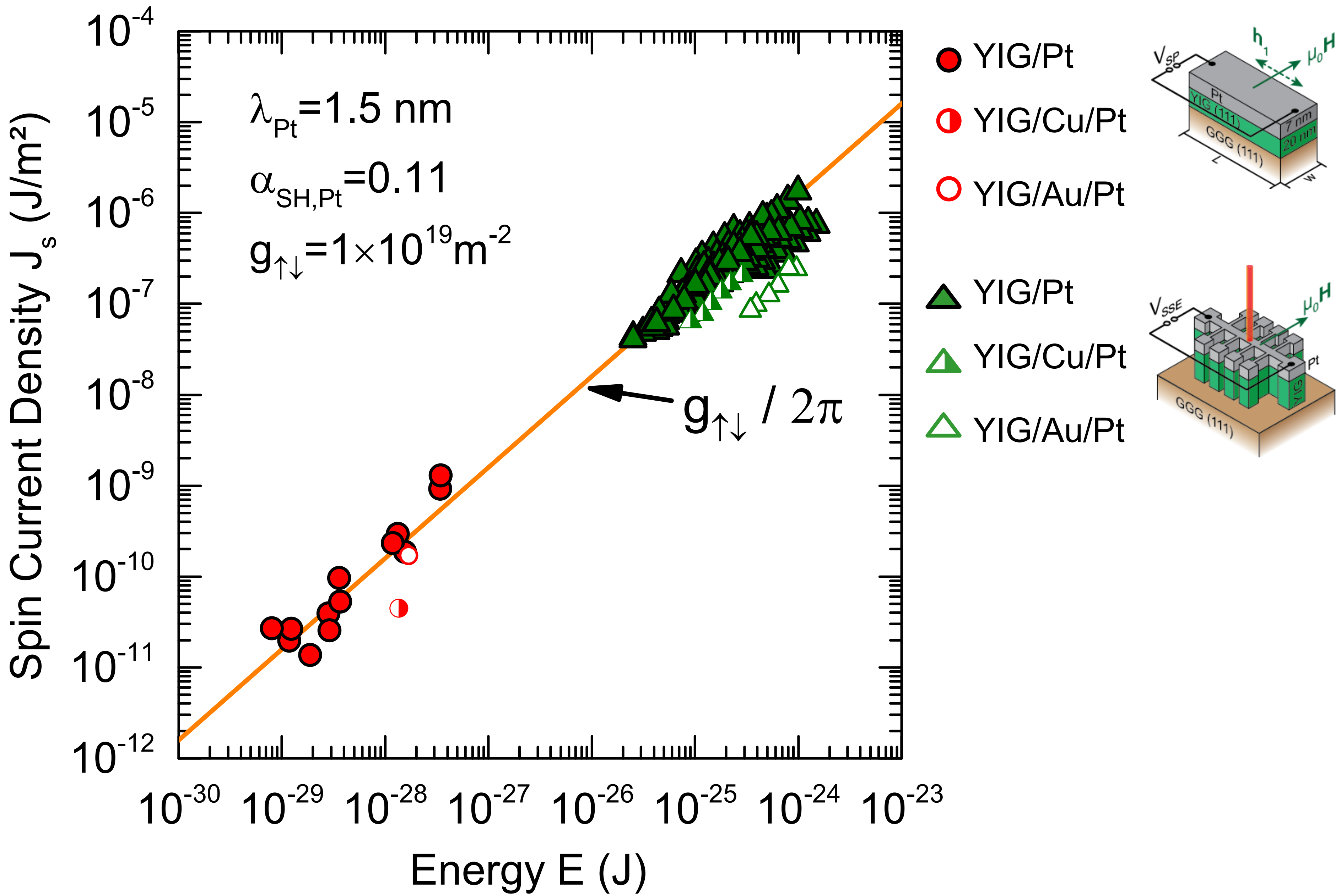
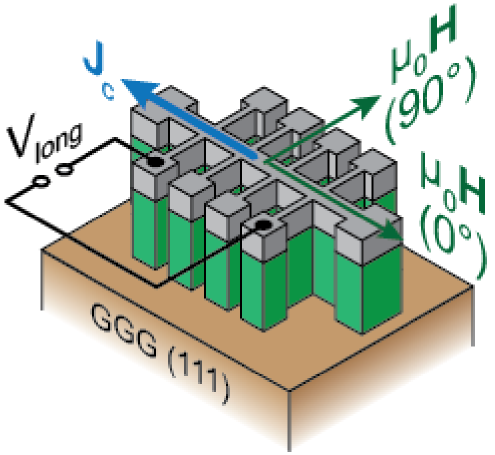
Weiler *et al.*, PRL **108**, 106602 (2012).

Spin current scaling: the $g_{\uparrow\downarrow}$ concept





$$J_s^{\mathrm{SMR}} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SMR}}$$

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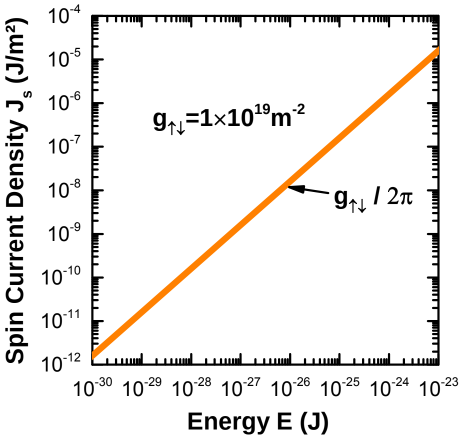
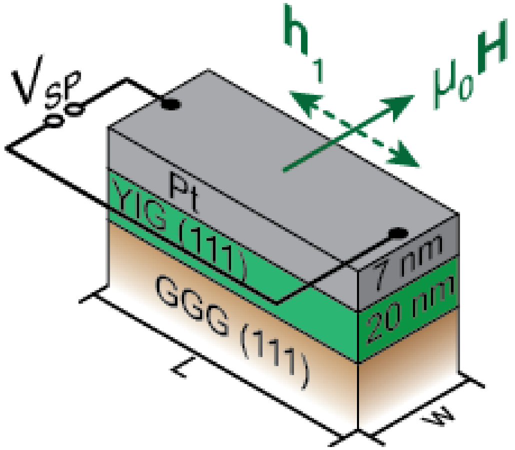
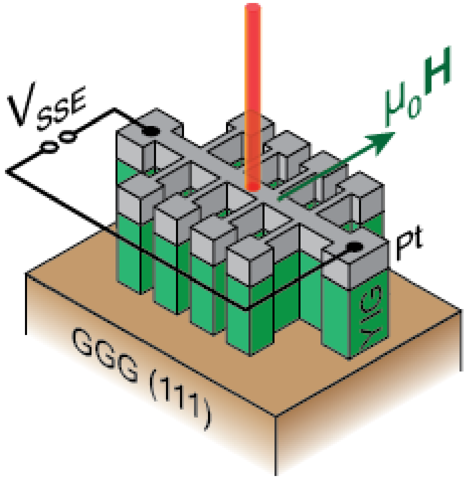




$$J_s^{\mathrm{SP}} = \frac{g_{\uparrow\downarrow}}{2\pi}\frac{1}{2}h\nu P \sin^2\Theta$$

$$J_s^{\mathrm{SP}} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SP}}$$

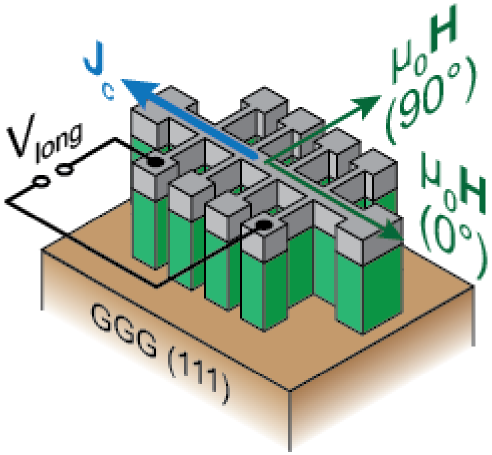
$$E^{\mathrm{SP}} = \tfrac{1}{2}h\nu P \sin^2\Theta$$

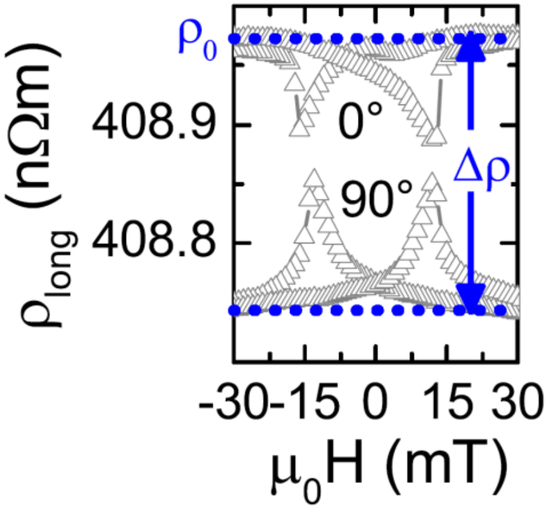


$$J_s^{\mathrm{SSE}} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SSE}}$$

$$E^{\mathrm{SSE}} = \frac{\gamma}{M_s V_a/\hbar} k_B \Delta T$$

Magnetoresistance of YIG/Pt hybrids

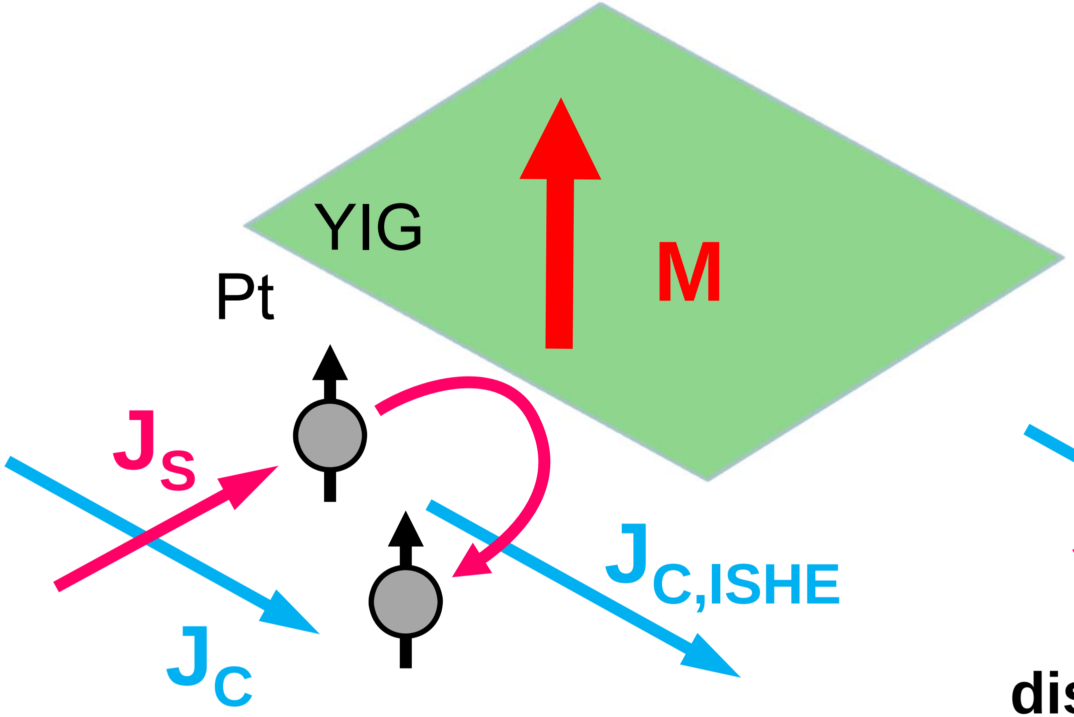


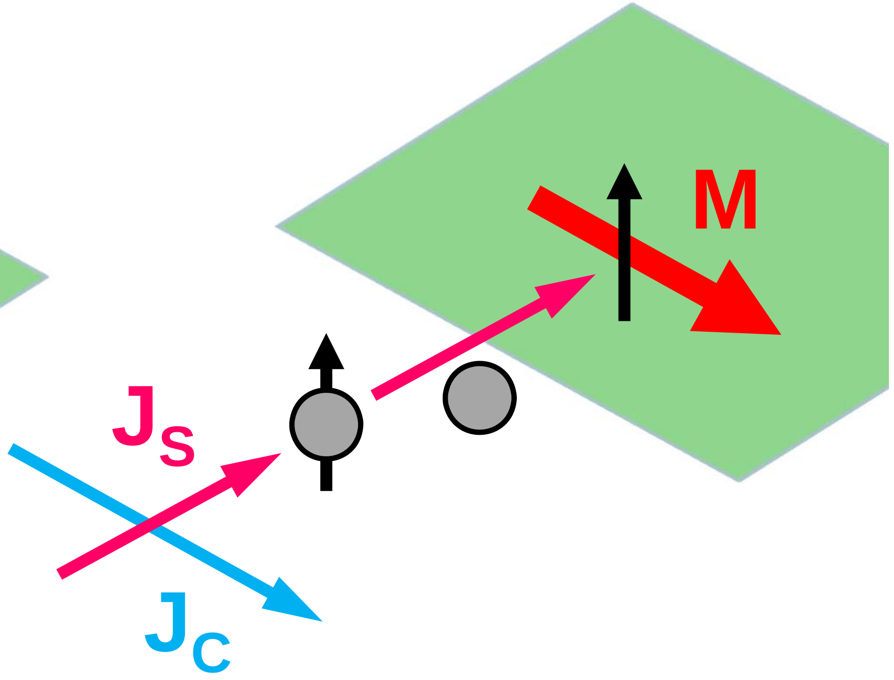


Chen *et al.*,
PRB **87**, 144411 (2013).

Nakayama *et al.*,
PRL **110**, 206601 (2013).

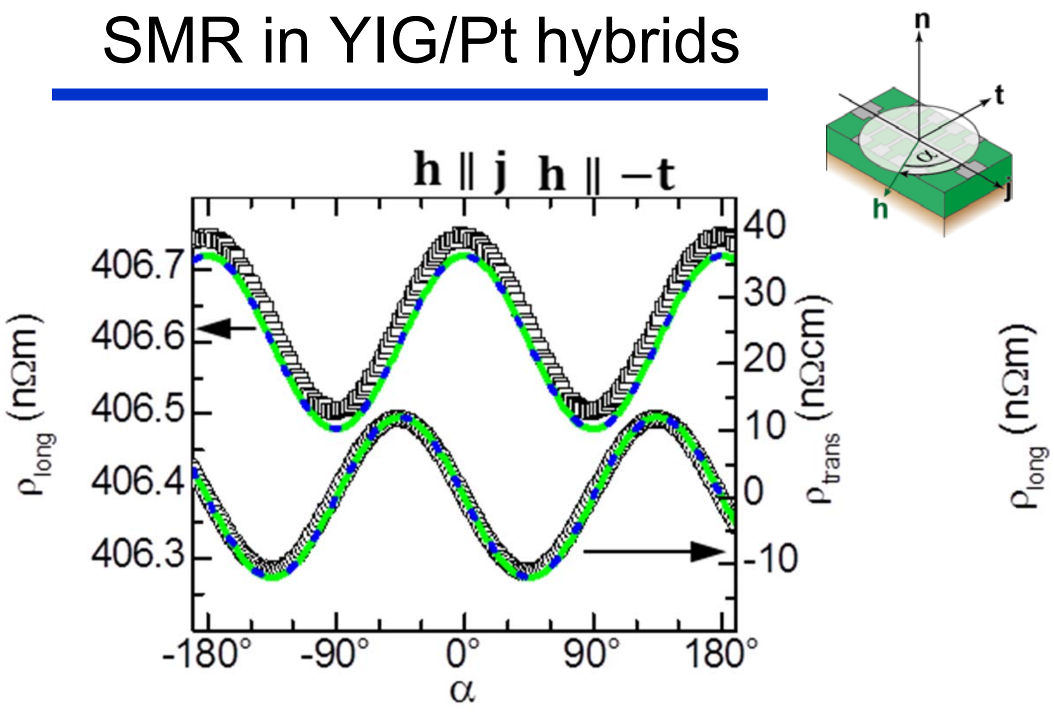
Althammer *et al.*,
PRB **87**, 224401 (2013).

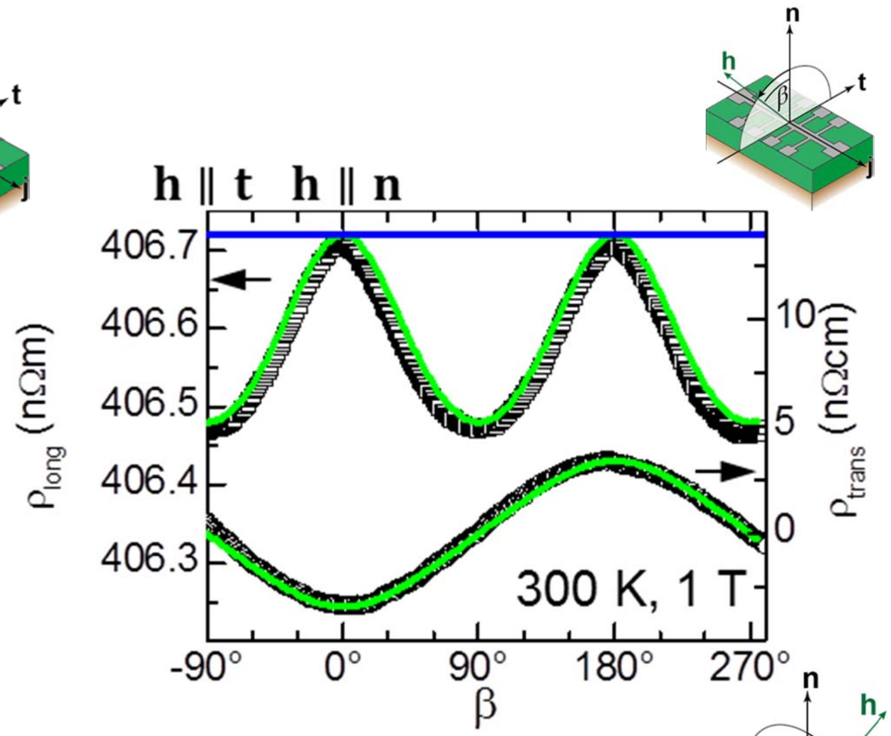


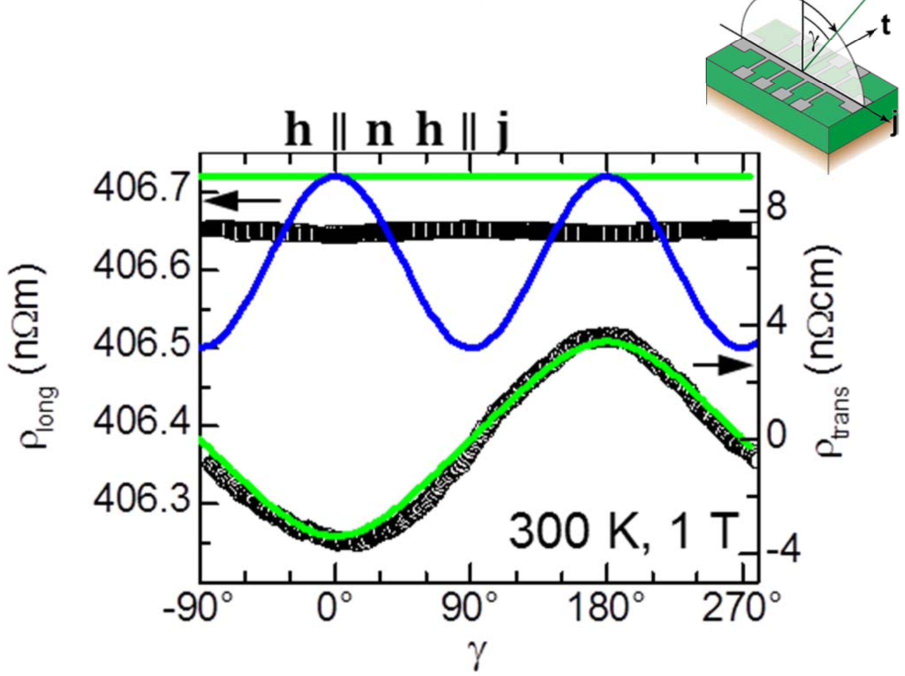


dissipation ⇒ larger resistance

SMR in YIG/Pt hybrids







Spin-Hall Magnetoresistance (SMR):

$$\rho_{\mathrm{long}} = \rho_0 - \rho_1\, \mathbf{m}_{\mathrm{t}}{}^2$$

$$\rho_{\mathrm{trans}} = \rho_2 \mathbf{m}_{\mathrm{n}} + \rho_1 \mathbf{m}_{\mathrm{j}} \mathbf{m}_{\mathrm{t}}$$

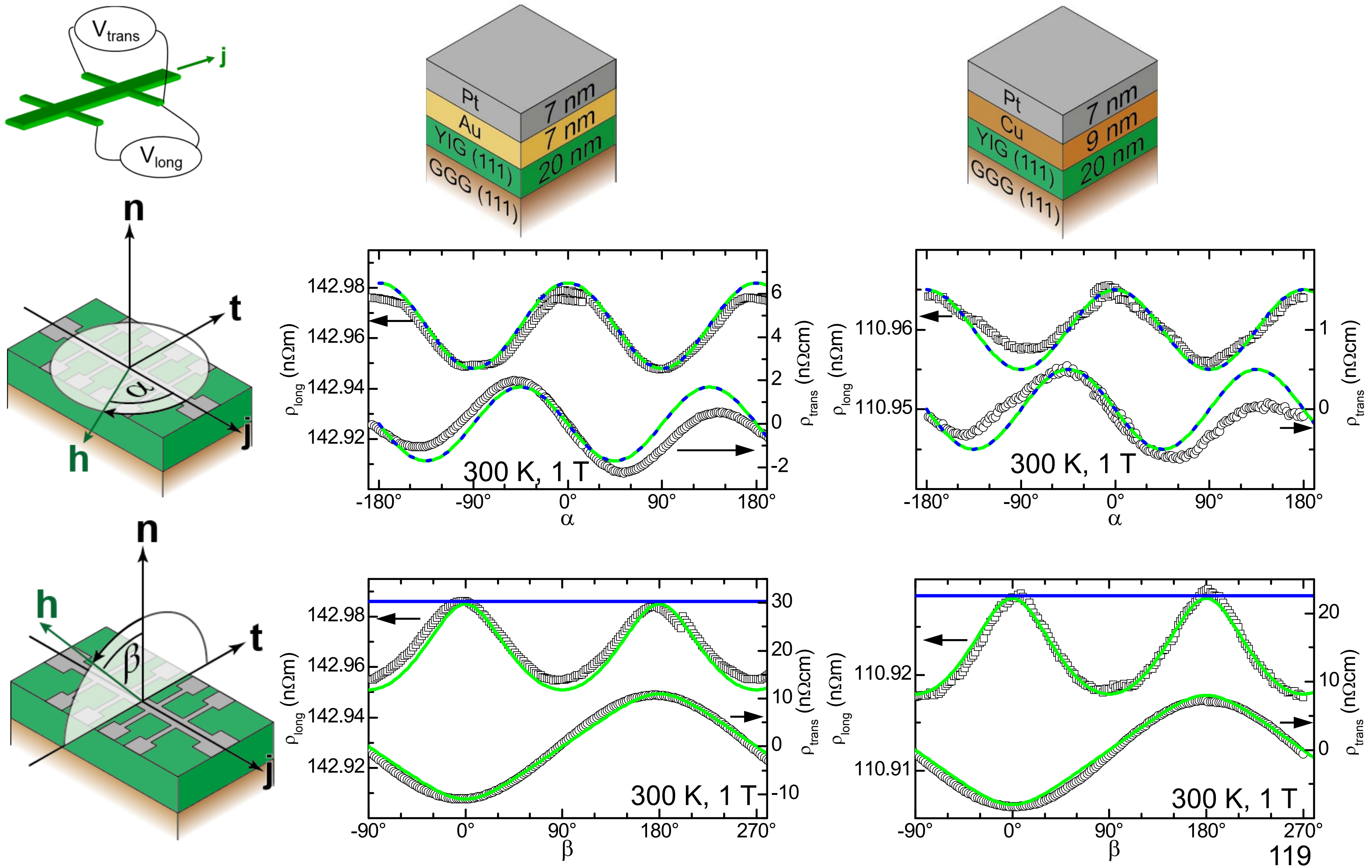
conventional polycrystalline AMR:

$$\rho_{\mathrm{long}} = \rho_0 + \Delta\rho\, \mathbf{m}_{\mathrm{j}}{}^2$$

$$\rho_{\mathrm{trans}} = \rho_2 \mathbf{m}_{\mathrm{n}} + \Delta\rho \mathbf{m}_{\mathrm{j}} \mathbf{m}_{\mathrm{t}}$$

⇒ **angular dependence**
unambiguously identifies SMR

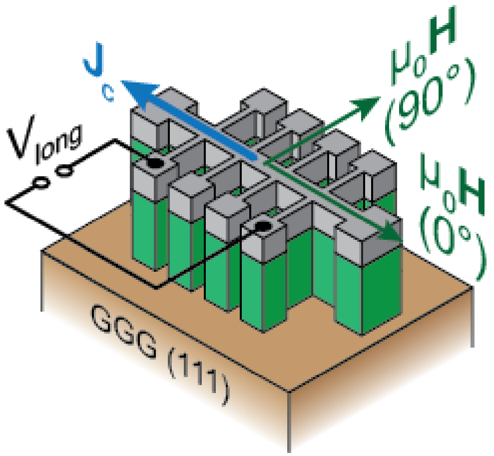
SMR in YIG/NM/Pt hybrids

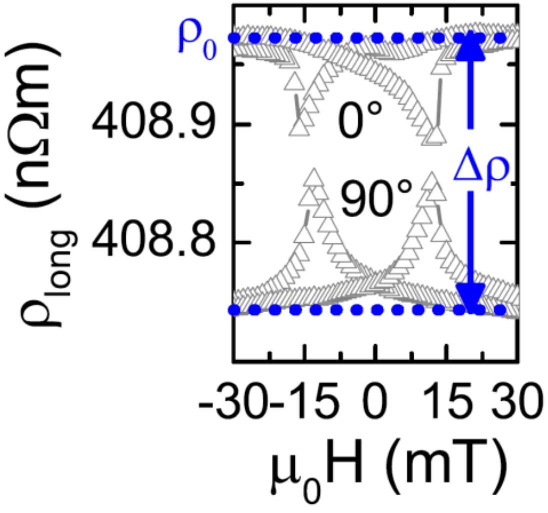


⇒ **spin current physics !**

not static proximity effect [cf. Huang *et al.*, PRL **109**, 107204 (2012).]

Magnetoresistance of YIG/Pt hybrids

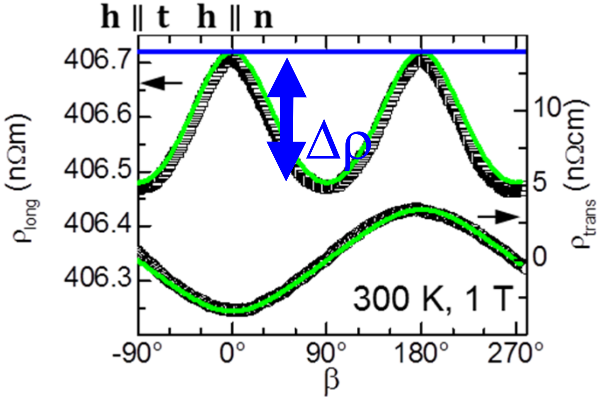




Chen *et al.*,
PRB **87**, 144411 (2013).

Nakayama *et al.*,
PRL **110**, 206601 (2013).

Althammer *et al.*,
PRB **87**, 224401 (2013).

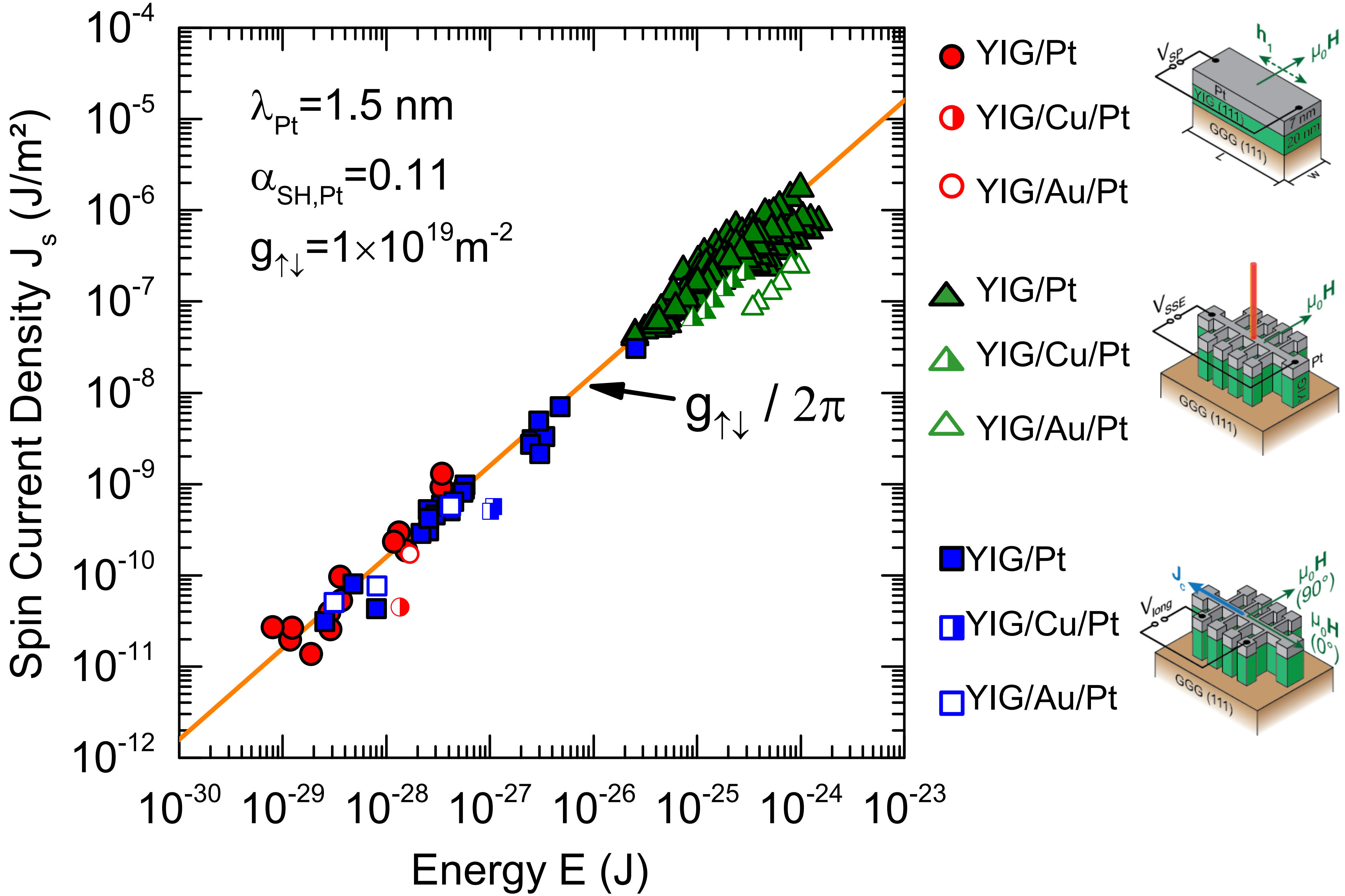


$$J_s^{\mathrm{SMR}} = \frac{g_{\uparrow\downarrow}}{2\pi} E^{\mathrm{SMR}}$$

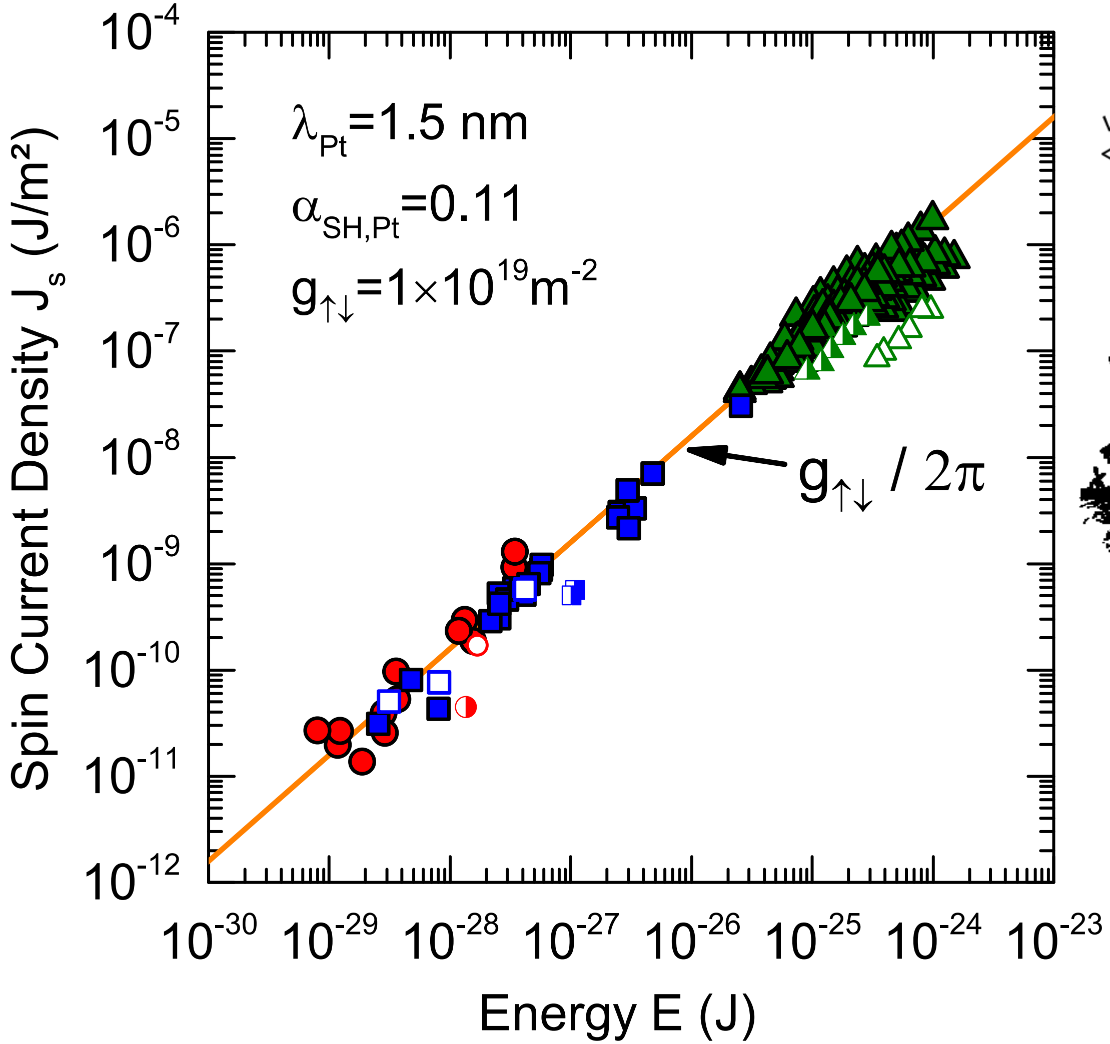
$$E^{\mathrm{SMR}} = \left(2e\,\alpha_{\mathrm{SH}}\rho_{\mathrm{Pt}}\lambda_{\mathrm{SD}}\tanh\frac{t_{\mathrm{Pt}}}{2\lambda_{\mathrm{SD}}}\eta\right) J_c$$

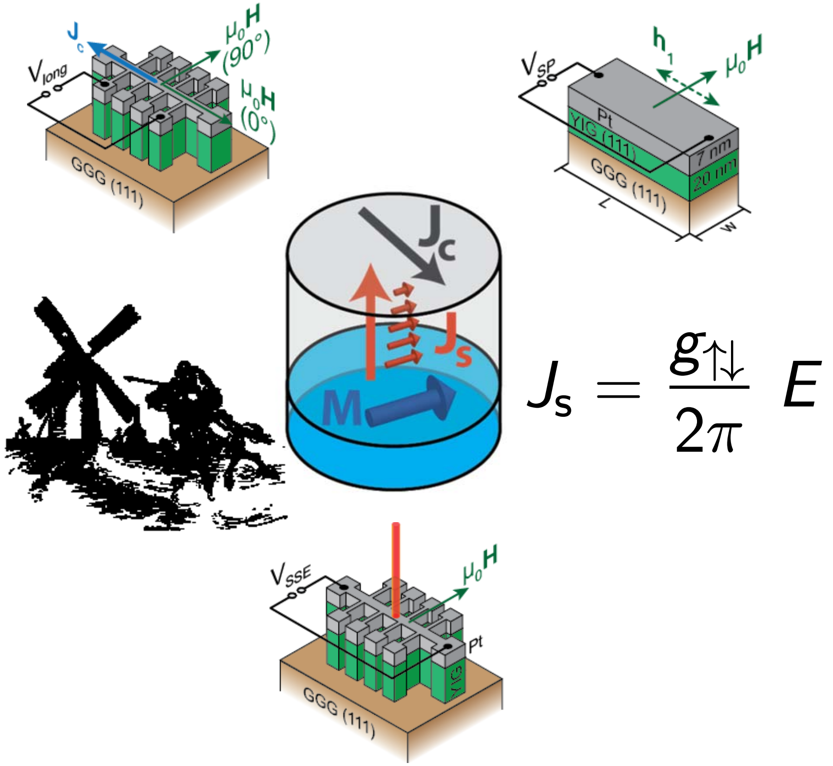
$$J_s^{\mathrm{SMR}} = \frac{\hbar t_{\mathrm{Pt}} J_c}{\alpha_{\mathrm{SH}} e\lambda_{\mathrm{SD}}\tanh\frac{t_{\mathrm{Pt}}}{2\lambda_{\mathrm{SD}}}}\frac{\Delta\rho}{\rho_0}$$

Spin current scaling: the $g_{\uparrow\downarrow}$ concept



Spin current scaling: the $g_{\uparrow\downarrow}$ concept



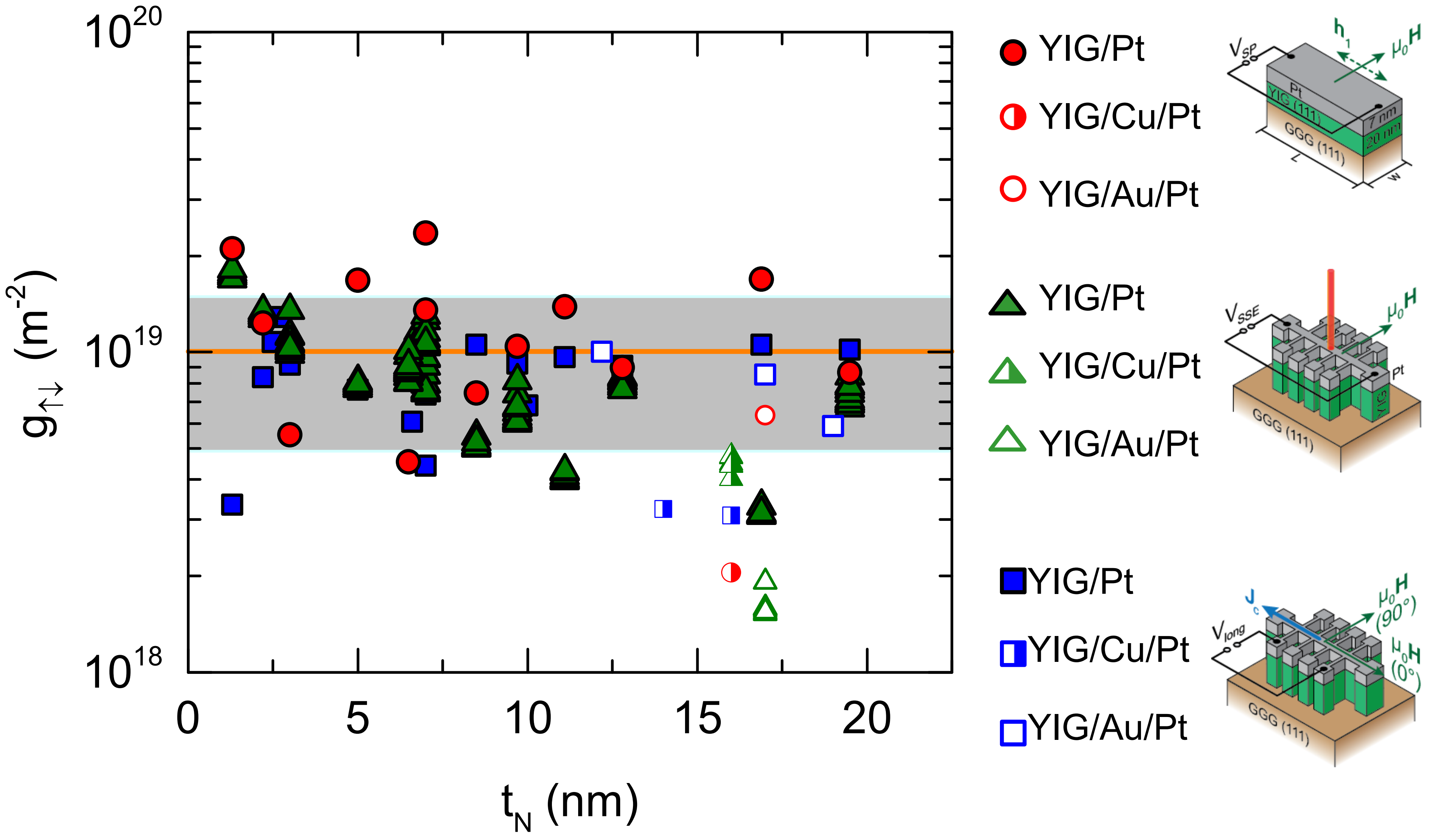


$$J_s = \frac{g_{\uparrow\downarrow}}{2\pi} E$$

take away:
spin-current-based modeling
(“$g_{\uparrow\downarrow}$ concept”) yields
consistent description

Weiler *et al.*, arXiv 1306.5012 (2013).
(Phys. Rev. Lett., accepted)

Spin current scaling: the $g_{\uparrow\downarrow}$ concept



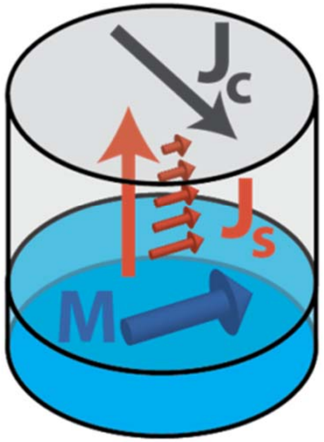
Weiler *et al.*, arXiv 1306.5012 (2013).
(Phys. Rev. Lett., accepted)

Open issues #4

take away:
spin-current-based modeling (“$g_{\uparrow\downarrow}$ concept”) yields consistent description

Open issues:

- “diffusive spin transport” limit ?
  (λ_{SD} = 1.5 nm < charge transport mean free path ??)
- spin currents in multilayers (**“spin current circuits”**)



→ is the “experimental λ_{SD}“ really a/the spin diffusion length ?

→ ballistic spin transport vs. diffusive spin transport

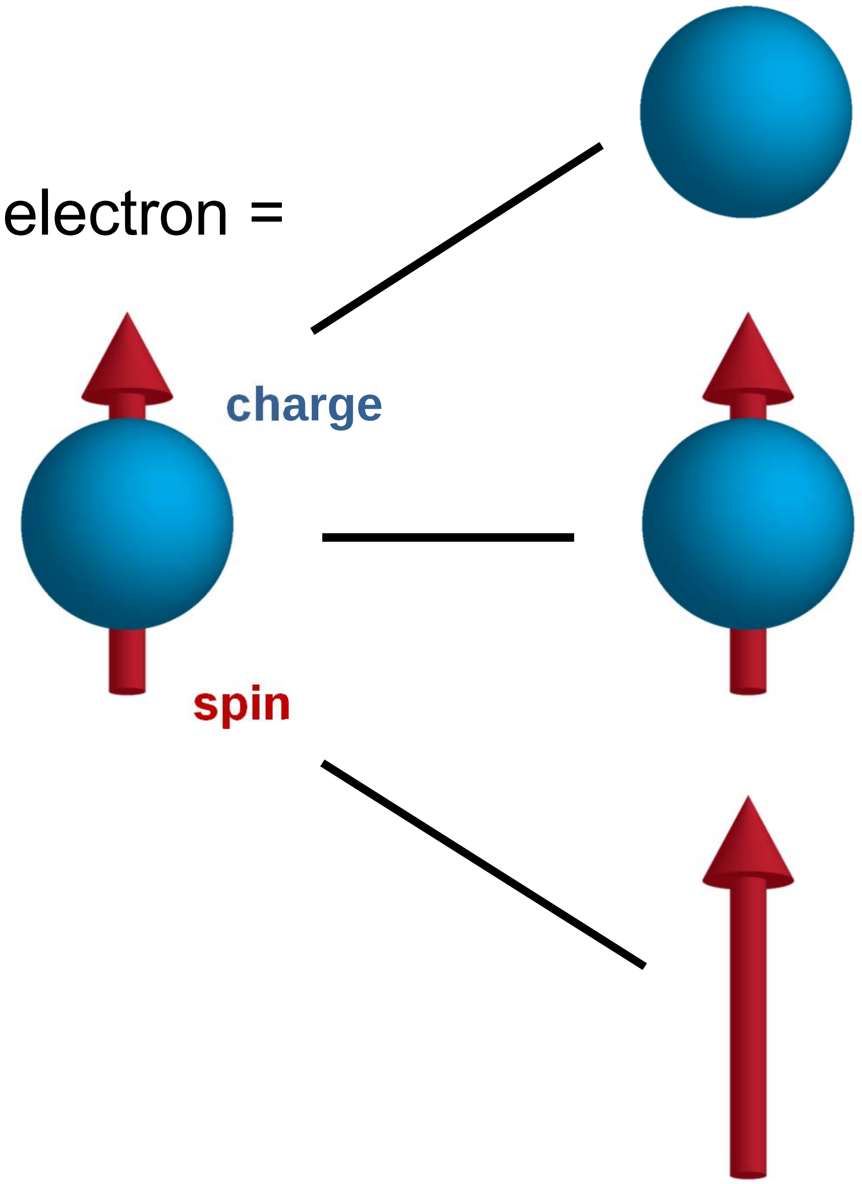
→ pure spin currents in multilayers or “spin current circuits” ?
(F / N1 / N2 ; F1 / F2 / N ; F1 / N1 / F2 / N2 ; etc. …)

→ surface corrugations, intermixing, …

→ spin Hall effect and spin transport in crystalline or anisotropic media
SHE and Neumann principle in single crystalline metals
SHE and spin Hall angle in two spin channel model ?
SHE and spin Hall angle in a ferromagnetic metal ?

→ Maxwells equations for spin transport
(spin transport not only addendum to charge transport …)

Spin electronics = electronics with a spin ?



electronics:
… ONLY charge
… charge currents
in electrical conductors

- charge current sources
- charge current detectors
- charge amplification

Intel Core i7

magneto-electronics:
… charge AND spin
… spin-polarized currents
in electrical conductors

spin-tronics:
… ONLY spin
… spin currents
in “angular momentum conductors”

consistent charge and spin transport equations ?

voltmeter for spin ?