

Spin torques and spin transport in antiferromagnets

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www.klaeui-lab.de

- AFM spin-orbit effects: spin-orbit torques
- Spin-orbit torques in ferro- and synthetic antiferromagnets for skyrmion motion
- Development of antiferromagnetic materials & engineering spin structures
- Spin Seebeck effect in ferri- and antiferromagnets
- Spin Transport in AFMs



Mathias Kläui

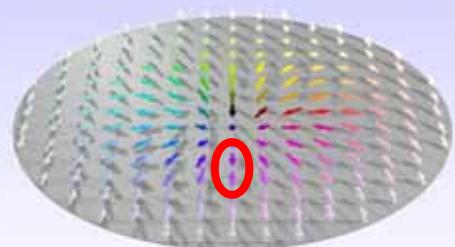
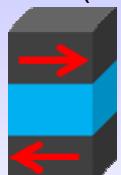
SPICE Workshop 30.09.2016

1. Types of antiferromagnetically coupled systems

Advantages using AFMs for spintronics:

- Not susceptible to stray fields*, no dipolar interaction
- Possibly ultra-fast dynamics (limited by magnon velocity)

1. Synthetic AFMs



2. Antiferromagnets

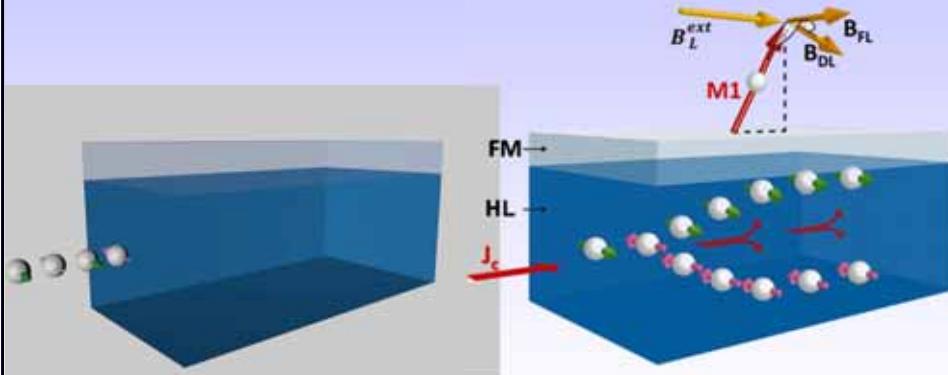


3. Ferrimagnets at the compensation point

*not fully true: O. Gomonay, MK, J. Sinova, arxiv:1608.05967 (APL in press)

2. Spin – orbit torques - Theory

Spin-orbit Torque Origin 1 - Spin Hall Effect (SHE):



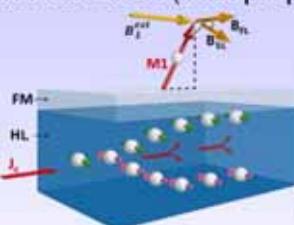
- In a heavy metal charge current generates spin current due to SHE¹
→ spin accumulation diffuses into the ferromagnet → measured by THz²
- These spins exert new damping-like and field-like **spin orbit torques**³

¹J. Sinova et al., RMP **87**, 1213 (2015); ²T. Seifert, MK et al., Nat. Phot. **10**, 483 (2016); ³K. Hals et al., Nat. **9**, 86 (2014);

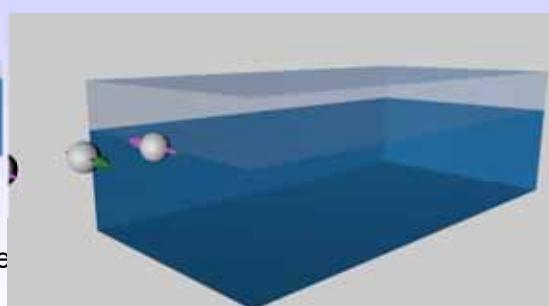
2. Spin – orbit torques - Theory

Spin-orbit Torque Origins:

- Origin 1:
Spin Hall Effect (bulk property)



- Origin 2:
Inverse Spin Galvanic Effect
(interface property)



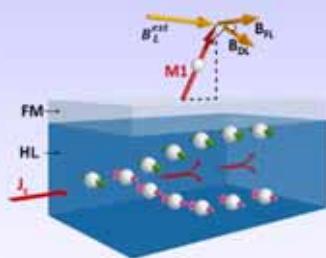
- Additionally the Inverse Spin Galvanic Effect generates a non-equilibrium spin density for electrons flowing at the interface.¹
- → interaction by exchange manipulates magnetization → SOTs!

¹K. Shen et al., Phys. Rev. Lett. **112**, 096601 (2014); V. m. Edelstein, Sol. State Comm. **73**, 233 (1990)

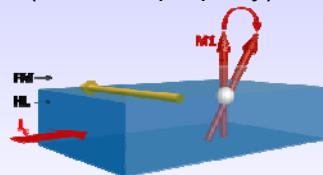
2. Spin – orbit torques - Theory

Spin-orbit Torque Origins:

- Origin 1:
Spin Hall Effect (bulk property)



- Origin 2:
Inverse spin-galvanic / Rashba-Edelstein Effect (interface property)



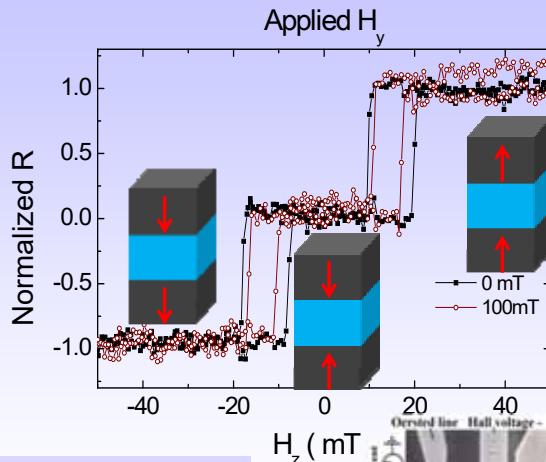
- Further bulk torques can occur in bulk inversion asymmetric systems.
- Different methods to measure the spin-orbit torques:
Second Harmonic Detection¹, Current-Field-equivalence and spin torque FMR², Spin Structure Dynamics³, etc.

¹U. Pi et al., APL **97**, 162507 ('10); K. Garello et al., Nature Nano **8**, 587 (2013); M. Hayashi et al., PRB **89**, 144425 (2014)

²L. Liu et al., PRL **109**, 96602 ('12); Skinner et al., Nature Com. **6**:6730 ('15); T. Schulz, MK et al., APL **107**, 122404 ('15);

³K. Ryu et al., Nat. Nano. **8**, 527 ('13); S. Emori et al., Nat. Mat. **12**, 611 ('13); R. LoConte, MK et al., PRB **91**, 144433 ('15)

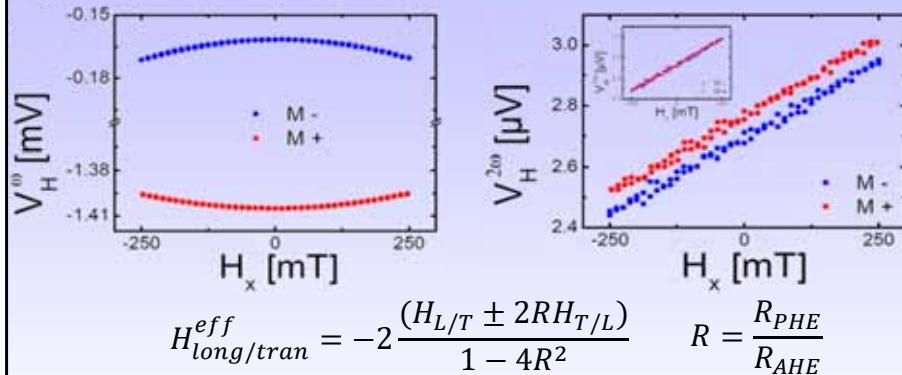
3. Spin – orbit torques in synthetic antiferromagnets



- Antiferromagnetically coupled multilayers have shown to yield fast DW motion.¹
- With 22 Å spacer the two FM layers couple antiferromagnetically.

¹S. Yang et al., Nature Nano. **10**, 221 (2015)
S. Gider et al., Science **281**, 797 (1998)

3. Spin – orbit torques in synthetic antiferromagnets



- Determine the transverse and longitudinal effective fields (field-like and damping-like torque by using the second harmonic measurement technique.¹

¹U. Pi et al., APL **97**, 162507 ('10); K. Garello et al., Nat. Nano. **8**, 587 ('13); M. Hayashi et al., PRB **89**, 144425 ('14)

3. Spin – orbit torques in synthetic antiferromagnets

Structure (nm)	Longitudinal Field (mT/10 ¹¹ Am ⁻²)	Transverse Field (mT/10 ¹¹ Am ⁻²)
Ta(4)/Co ₄₀ Fe ₄₀ B ₂₀ (1)/MgO(1.6)	3.5	-
Ta(3)/Co ₄₀ Fe ₄₀ B ₂₀ (0.9)/MgO(2)	2.4	4.5
Ta(1.5)/Co ₄₀ Fe ₄₀ B ₂₀ (1)/MgO(1.6)	1.3	4.7
Pt(3)/Co(0.6)/AlO _x (1.6)	6.9	4
Ta(4)/Ru(20)/[Co(0.7)/Pd(0.2)] ₂₂ /Ta(4)	11.7	50
Ta(2.5)/[Pt(2)/Co(0.9)] ₈ /Pt(2)/Ta(2)	7	1.3
Synthetic AFM	11	2.3

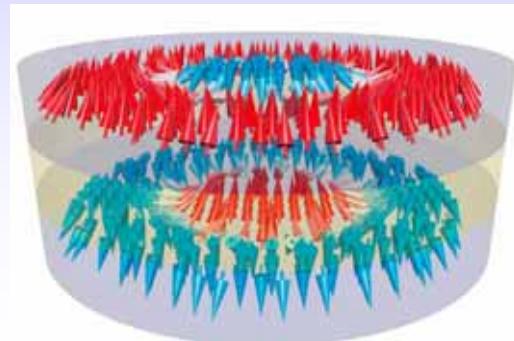
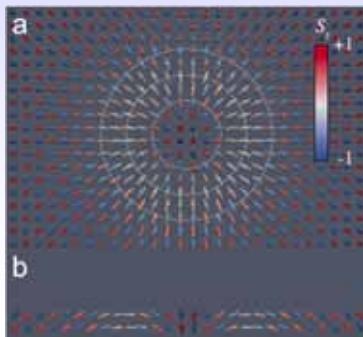
Kim et. al. Nat. Mater. **12**, 240 (2013)
Huang et. al. arXiv: 1510.00836 (2015)

Liu et. al. Science **336**, 555 (2012)
Garello et. al. Nat. Nanotech. **8**, 587 (2013)
Jamali et. al. Phys. Rev. Lett. **111**, 246602 (2013)

- Measurement of the longitudinal field (damping-like torque, which leads to Néel domain wall motion) shows a large value.
- Origin & dependence on coupling under investigation.

4. Skyrmions in synthetic AFMs

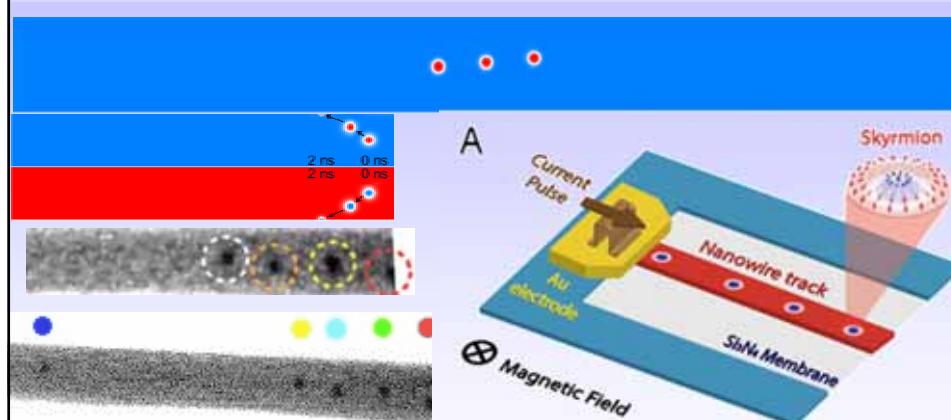
- Skyrmions can be stabilized due to DMI in Heisenberg – type in antiferromagnets
and
in synthetic antiferromagnets.



J. Barker and O. Tretiakov, PRL 116, 147203 (2016);

X. Zhang et al., Nature Comm. 7, 10294 (2016)

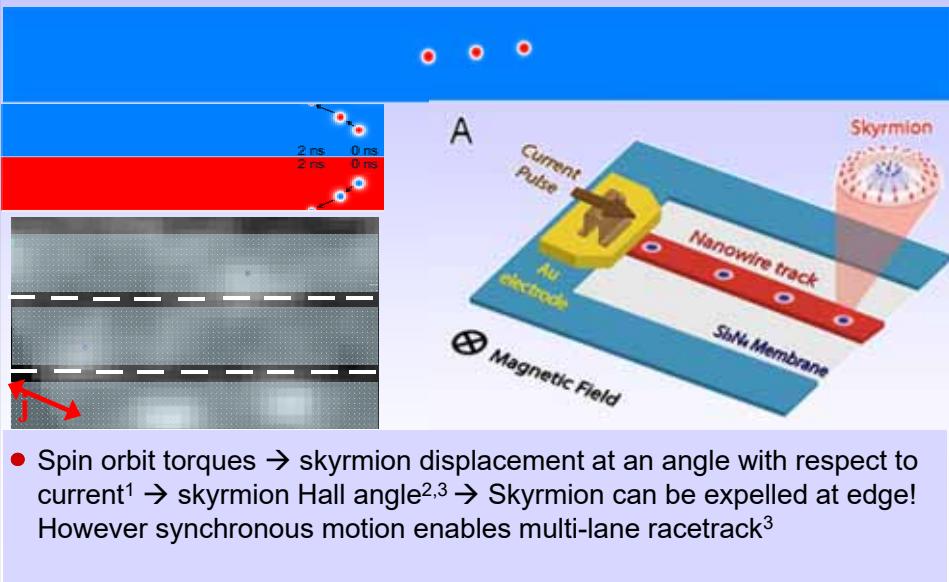
4. Spin – orbit torques in synthetic antiferromagnets



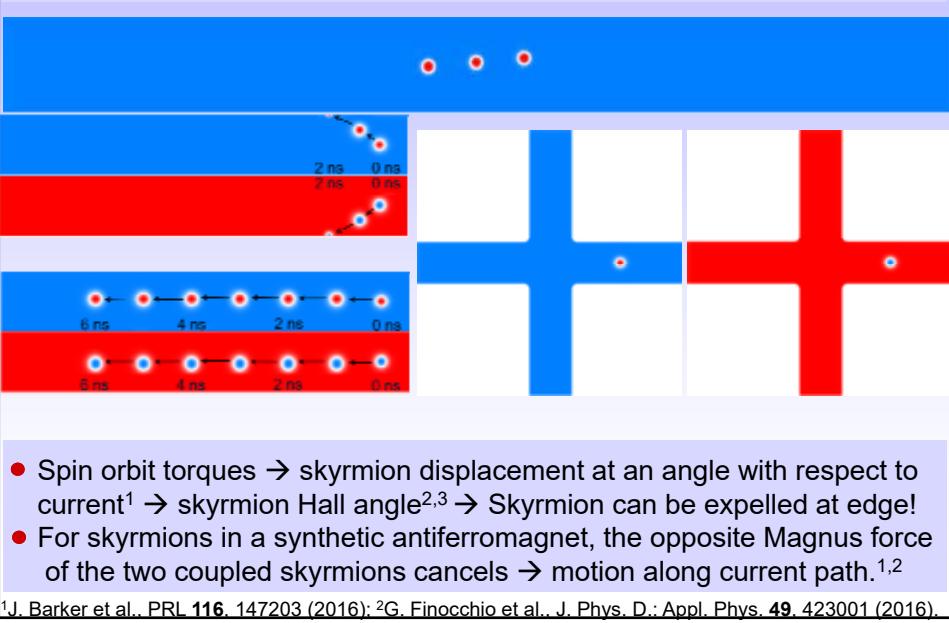
- Spin orbit torques → skyrmion displacement at an angle with respect to current¹ → skyrmion Hall angle^{2,3} → Skyrmion can be expelled at edge!

¹S. Woo, MK et al., Nature Mater. 15, 401 (2016); ²W. Jiang et al., DOI:10.1038/nphys3883; ³K. Litzius, MK et al., arxiv:1608.07216

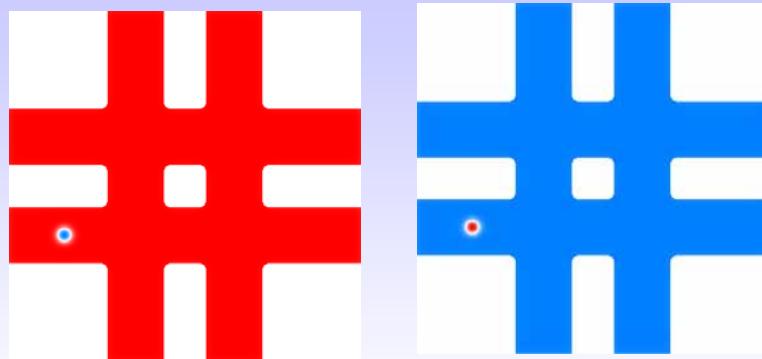
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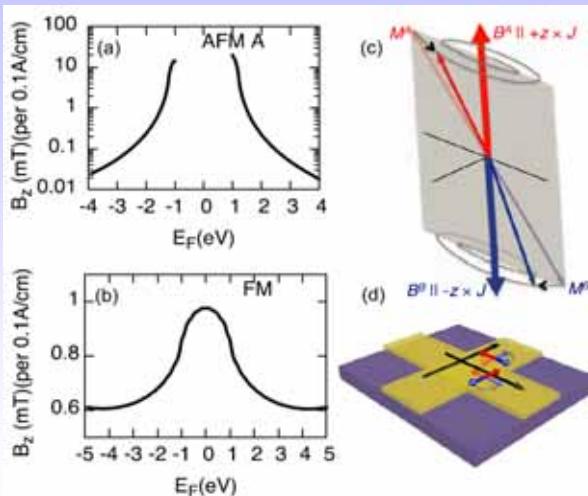
4. Spin – orbit torques in synthetic antiferromagnets



- Spin orbit torques \rightarrow skyrmion displacement at an angle with respect to current¹ \rightarrow skyrmion Hall angle^{2,3} \rightarrow Skyrmion can be expelled at edge!
- For skyrmions in a synthetic antiferromagnet, the opposite Magnus force of the two coupled skyrmions cancels \rightarrow motion along current path.^{1,2}

¹J. Barker et al., PRL **116**, 147203 (2016); ²G. Finocchio et al., J. Phys. D.: Appl. Phys. **49**, 423001 (2016).

5. Development of materials to study spin – orbit effects



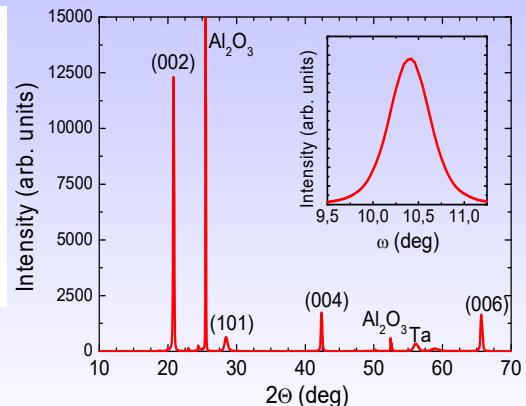
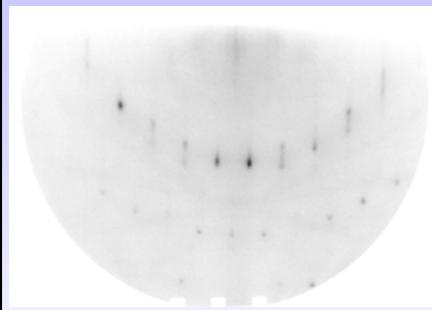
J. Zelezny,
T. Jungwirth,
J. Sinova et al.,
PRL **113**, 157201
(2014)



A. Sapozhnik
with H. Elmers, H. Zabel, M. Jourdan

- Prediction of spin orbit torques acting on the Néel order in AFM Mn₂Au (opposite on the two sub-lattices)¹ \rightarrow manipulation of magnetization using electric currents.

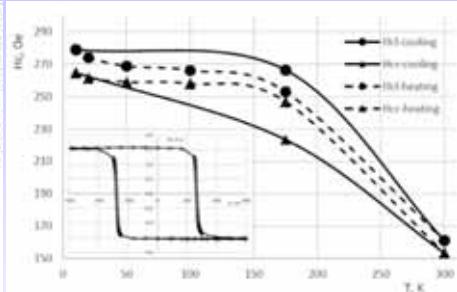
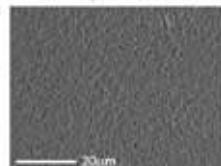
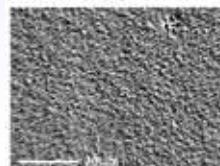
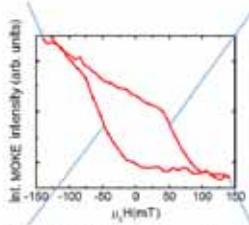
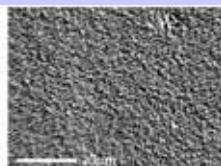
5. Development of materials to study spin – orbit effects



- Growth of Mn_2Au : RF sputtering of epitaxial Mn_2Au (001) thin films on Al_2O_3
Introduction of a Ta layer to induce interfacial spin-orbit effects:
 $\text{Al}_2\text{O}_3/\text{Ta}/\text{Mn}_2\text{Au}$ (001)
- XRD shows: high degree of crystallographic ordering.

M. Jourdan, MK et al., J. Phys. D: Appl. Phys. **48**, 385001 (2015)

5. Development of materials to study spin – orbit effects



- Mn_2Au is an antiferromagnet with a high Curie temperature ($>1000\text{K}$)¹.
- Only small exchange bias is observed for Fe/ Mn_2Au & field cooling from 375K .
- Large coercivity exchange points to exchange bias. Close to the coercivity of Fe, small domains are visible indicating imprinting of AFM domains into the FM via uncompensated spins.

¹V. Barthem et al., Nat. Comm. **4**, 2892 (2013) M. Jourdan, MK et al., J. Phys. D: Appl. Phys. **48**, 385001 (2015)

5. Spin-flop in Mn₂Au

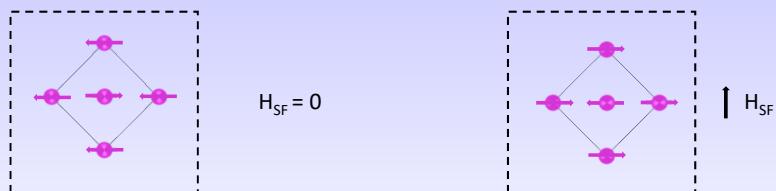
Two AFM domains with different orientation of moments



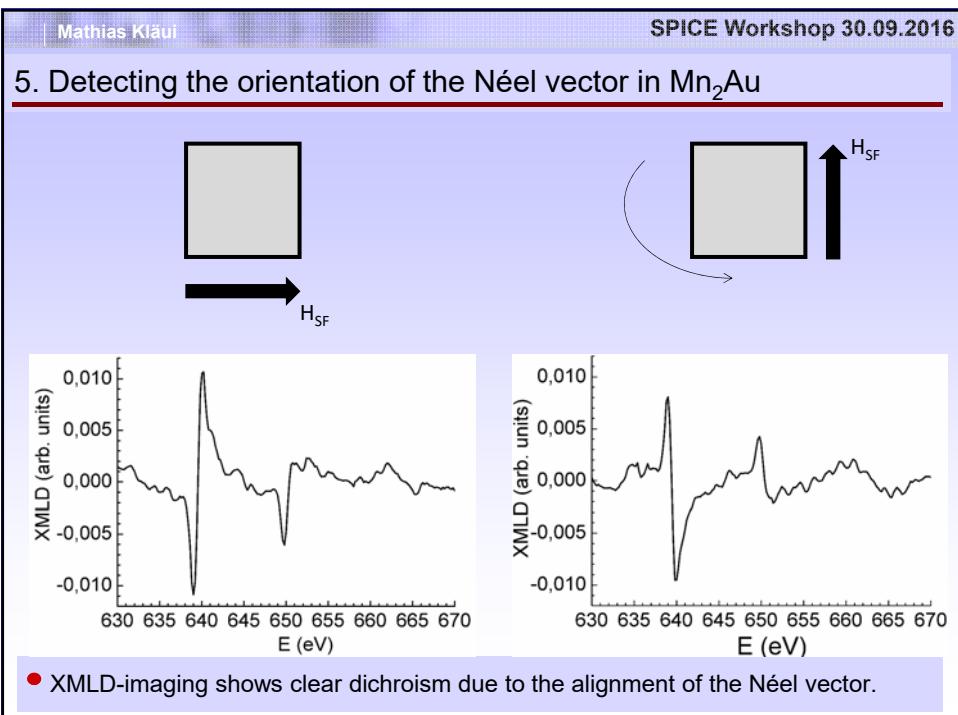
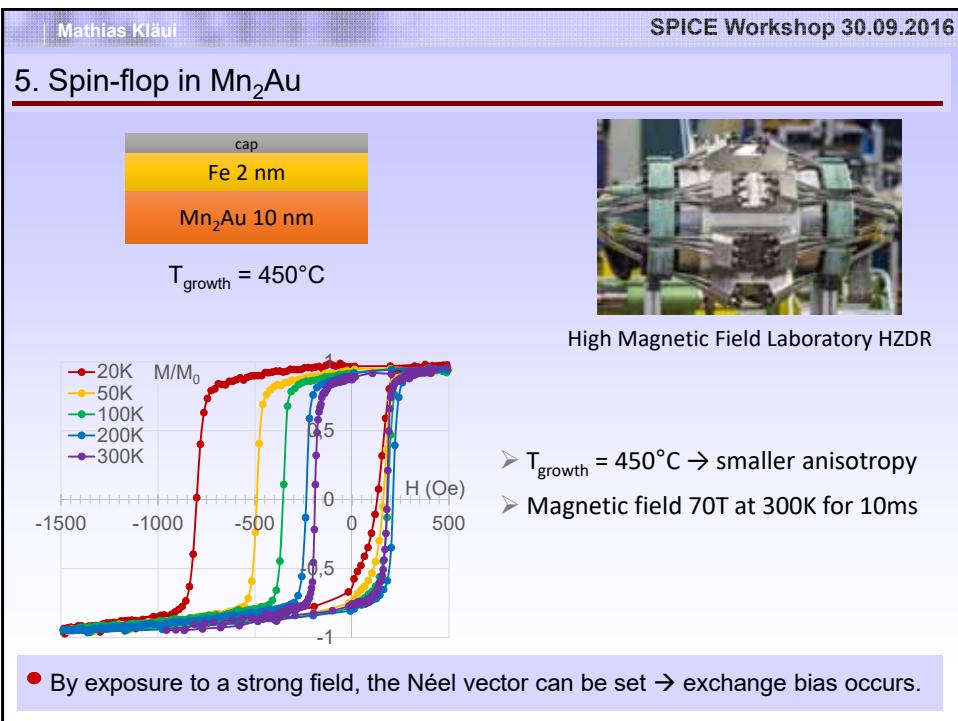
- Switching from one easy axis to the other upon applying a high magnetic field
- Moments preserve their initial orientation
- By applying a strong field, a spin-flop transition can be induced and the Néel vector aligns perpendicularly to the field direction

5. Spin-flop in Mn₂Au

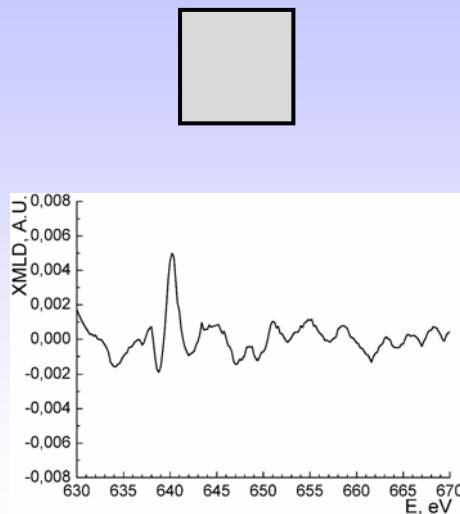
Two AFM domains with different orientation of moments



- Switching from one easy axis to the other upon applying a high magnetic field
- Moments preserve their initial orientation
- By applying a strong field, a spin-flop transition can be induced and the Néel vector aligns perpendicularly to the field direction.
- For the Néel vector perpendicular to the field, only small transient canting occurs.

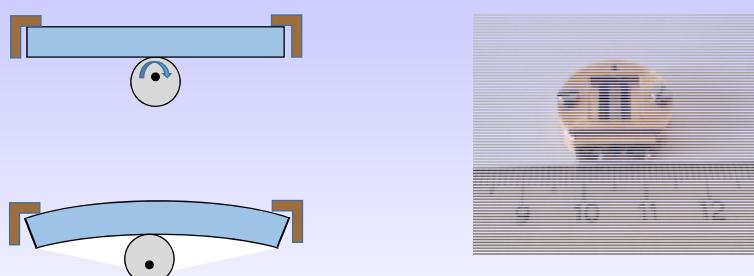


5. Detecting the orientation of the Néel vector in Mn_2Au



- Reference sample – same structure not exposed to strong field shows no XMCD!

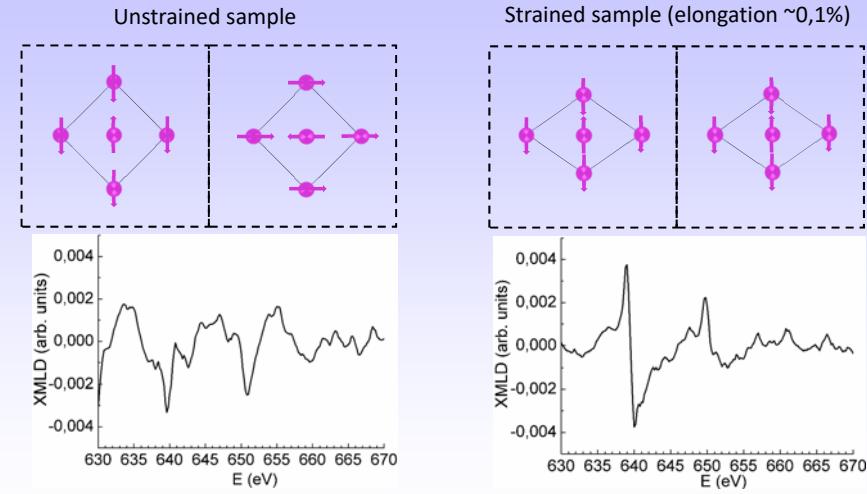
5. Engineering the spin structure of Mn_2Au by strain



- Compatibility with UHV conditions
- Controllable value of strain
- Monitoring of strain with a strain gauge

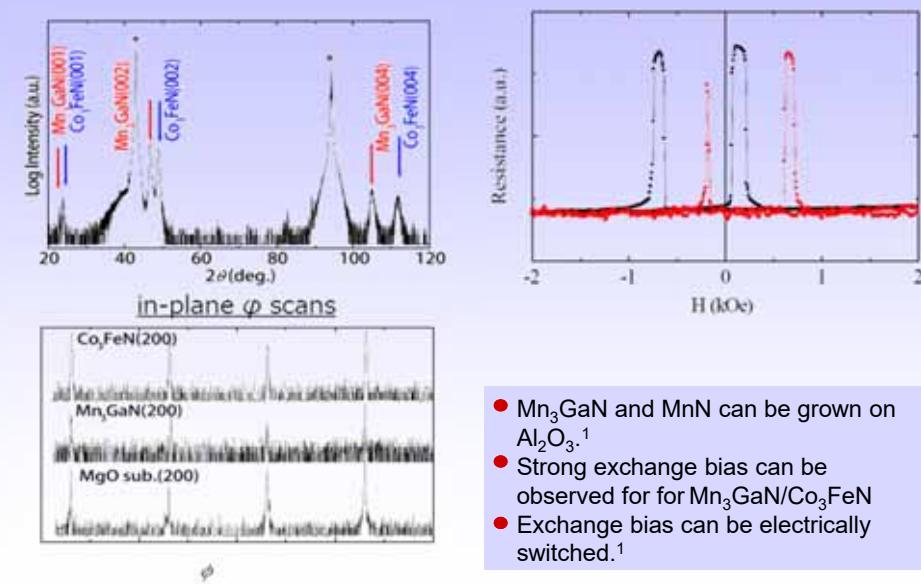
- Expected strain-induced uniaxial anisotropy → apply strain to the sample!

5. Engineering the spin structure of Mn_2Au by strain



- Application of strain (0,1%) leads to alignment of Néel vector visible from XMLD!
- Spin structure can be controlled by strain → preparation of desired spin state!

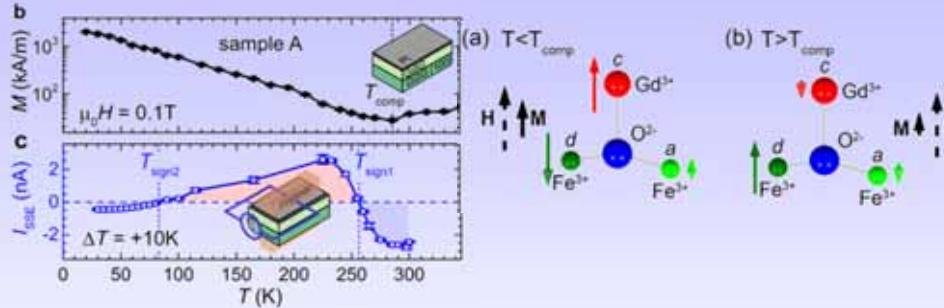
5. Development of other materials to study spin – orbit effects



- Mn_3GaN and MnN can be grown on Al_2O_3 .¹
- Strong exchange bias can be observed for Mn_3GaN/Co_3FeN
- Exchange bias can be electrically switched.¹

¹H. Sakakibara et al., JAP 117, 17D725 (2015); Collaboration T. Hajiri, H. Asano Nagoya University

6. Spin Transport in ferrimagnets and antiferromagnets



- Gadolinium Iron Garnet: Ferrimagnet with magnetic compensation point at $\sim 285\text{ K}$ ¹
First SSE sign change at high temp. close to magnetization compensation point.
- Second sign change at low temp $\sim 80\text{ K}$:
- Gd moment strongly increases at with temperatures and strongly is coupled to a site Fe \rightarrow at low temperatures Gd dominates the spin current signal
- \rightarrow Spin current does not simply mirror the total magnetization!

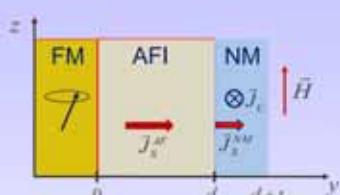
→ See poster by J. Cramer for details

¹Geprägs, Kehlberger, Barker, Ohnuma, Bauer, Saitoh, Gönnenwein, Kläui et al., Nature Comms. 7, 10452 (2016)

7. Spin transport in AFM insulators: spin pumping

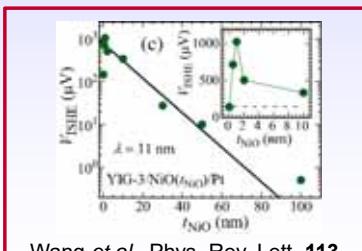
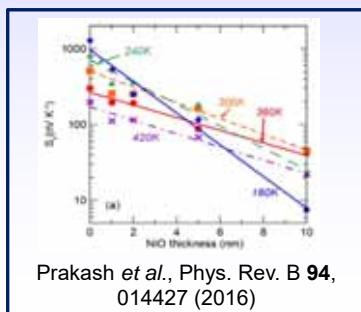
FMR/Thermal spin pumping from YIG into antiferromagnetic insulator (NiO, ...)

- Strong decay of signal for “thick” NiO, spin propagation length $\approx 10\text{ nm}$
- Significant signal enhancement in “thin” ($d_{\text{NiO}} \leq 2\text{ nm}$) NiO



Single crystalline YIG
No enhancement

Polycrystalline YIG
Enhancement

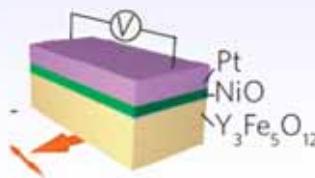
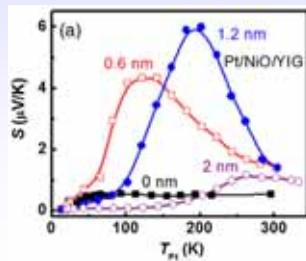
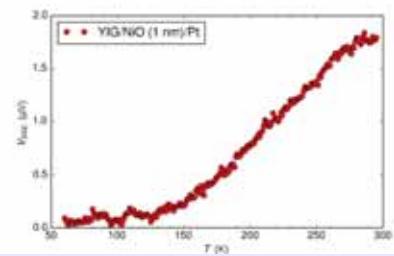


Lin et al., Phys. Rev. Lett. 116, 186601 (2016)

7. Spin transport in AFM insulators: thermal spin currents

FMR/Thermal spin pumping into antiferromagnetic insulator for varying temperature (NiO, CoO)

- Spin transmission enhancement at $T_c \approx T_{\text{Néel}}$
→ Spin fluctuations at phase transition
→ Enhanced spin conductivity¹
- Signal strongly suppressed at lower temperatures
→ Spin transport by incoherent, thermal magnons

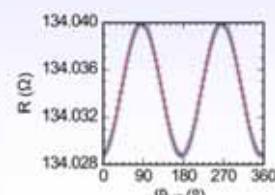
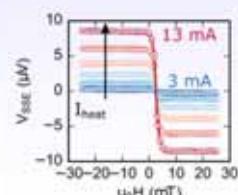
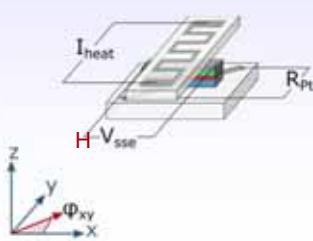


Lin *et al.*, Phys. Rev. Lett. **116**, 186601 (2016)

¹Okamoto *et al.*, Phys. Rev. B **93**, 064421 (2016) Qiu *et al.*, Nat. Comm. **7**, 12670 (2016)

7. Spin transmission in antiferromagnetic $\text{Ir}_{20}\text{Mn}_{80}$

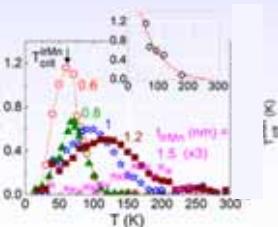
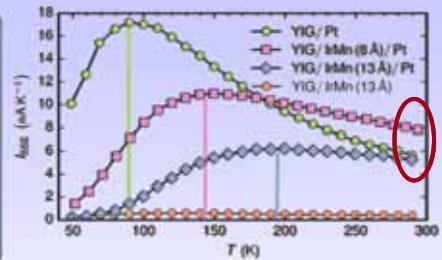
- Thus far, AFM spin transport dominantly studied in insulators
- Here: Temperature dependent spin transmission through **conducting** antiferromagnet $\text{Ir}_{20}\text{Mn}_{80}$ via
 - thermal spin currents generated by the SSE
 - spin Hall Magnetoresistance (SMR) measurements
 → Spin transport by conduction electrons or magnetic excitations?



7. Spin transmission in $\text{Ir}_{20}\text{Mn}_{80}$: SSE

Temperature dependent SSE in $\text{YIG}/\text{Ir}_{20}\text{Mn}_{80}(\text{d})/\text{Pt}$

- Increased spin current in YIG/IrMn (8 \AA) / Pt → enhancement possible for metallic AFM!
- Low temperature SSE enhancement in YIG/Pt due to intrinsic YIG properties¹
- (Broad) Signal maximum at higher temperatures when $\text{Ir}_{20}\text{Mn}_{80}$ introduced
- Small signal for $\text{YIG}/\text{Ir}_{20}\text{Mn}_{80}/\text{MgO}$
→ Spin current mainly probed in Pt



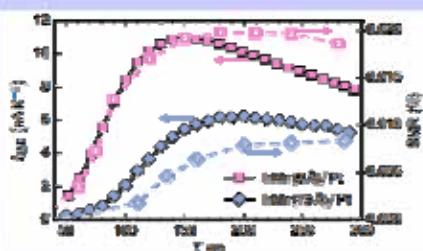
Frangou *et al.*, Phys Rev. Lett. **116**, 077203 (2016)

Spin pumping in $\text{NiFe}/\text{Cu}/\text{IrMn}/\text{Al}$

- Enhanced damping $\delta\alpha^p$ at critical temperature
- T^{IrMn} increases linearly with increasing IrMn thickness → Antiferromagnetic phase transition

¹Guo *et al.*, Phys Rev. X **6**, 031012 (2016)

7. Spin transmission in $\text{Ir}_{20}\text{Mn}_{80}$: SSE + SMR

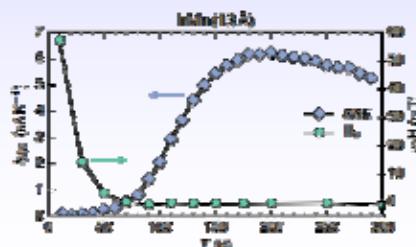


Comparison of SSE (closed) and SMR (open) temperature dependence in $\text{YIG}/\text{Ir}_{20}\text{Mn}_{80}(\text{d})/\text{Pt}$

- $R_{\text{Pt}} \ll R_{\text{IrMn}}$: Spin current generation via SHE mainly in Pt
- SSE and SMR reveal similar temperature dependence → Spin transport suppression

Correlation to magnetic properties of $\text{Ir}_{20}\text{Mn}_{80}$

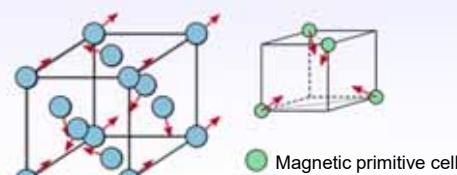
- No exchange bias in YIG ($4 \mu\text{m}$)/ $\text{Ir}_{20}\text{Mn}_{80}$
- Si/IrMn (13 \AA)/CoFe (2 nm)/MgO reference
→ Exchange bias observed until $T_{\text{block}} \approx 70 \text{ K}$
($T_{\text{block}} \leq T_{\text{neel}} \leq 2T_{\text{block}}$)
→ SSE strongly suppressed below T_{block}



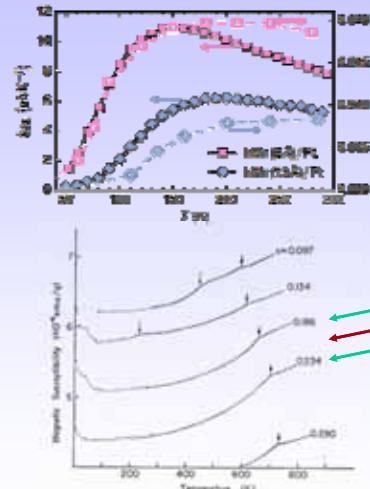
7. Spin transmission in $\text{Ir}_{20}\text{Mn}_{80}$: SSE + SMR

Origin of temperature dependence

- $\text{Ir}_{20}\text{Mn}_{80}$ condensates in chemically disordered γ -IrMn phase \rightarrow fcc, no preference for Ir, Mn
- 3Q spin density wave structure (non-collinear)
- No distinct maximum of magnetic susceptibility at $T_{\text{Néel}}$ observed (as e.g. CoO, ...)
- Spin fluctuation at $T_{\text{Néel}}$ not dominating!?
- Strong suppression at low temperatures resembles spin transport via thermal magnons



After Kohn *et al.*, Sci. Rep. **3**, 2412 (2013)



Yamaoka *et al.*, J. Phys. Soc. Jpn. **36**, 445 (1974)

1. Great people in my group:

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Summary:

- Spin-orbit effects such as DMI and spin-orbit torques can occur in antiferromagnetically coupled systems
- Strong spin-orbit torques in ferromagnets and synthetic AFMs for skyrmion motion.
- Antiferromagnetic materials with bulk spin-orbit torques are developed: spin structures in Mn_2Au are engineered by strain.
- Thermal spin currents can be transported in insulating and metallic antiferromagnets.

