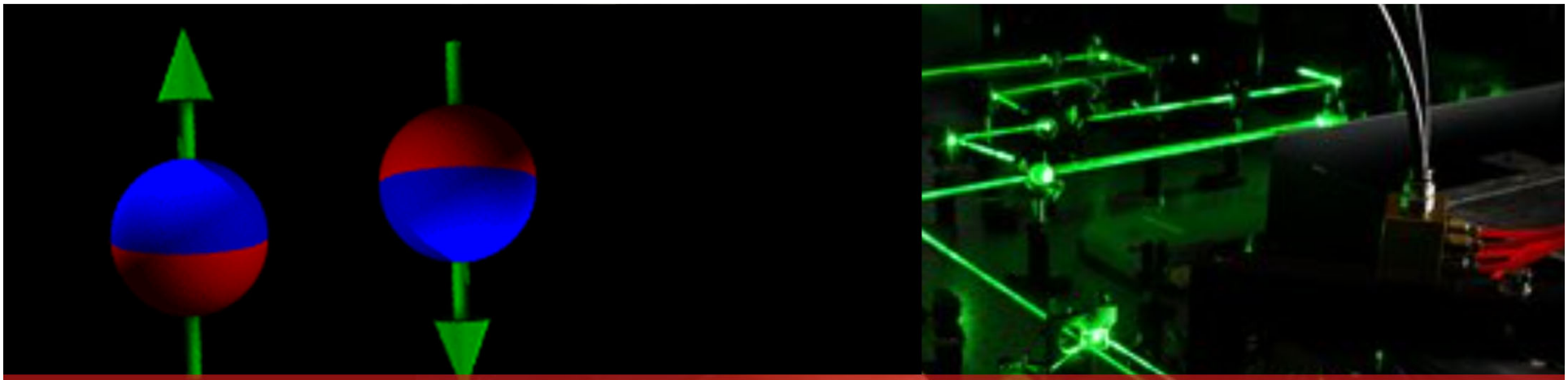
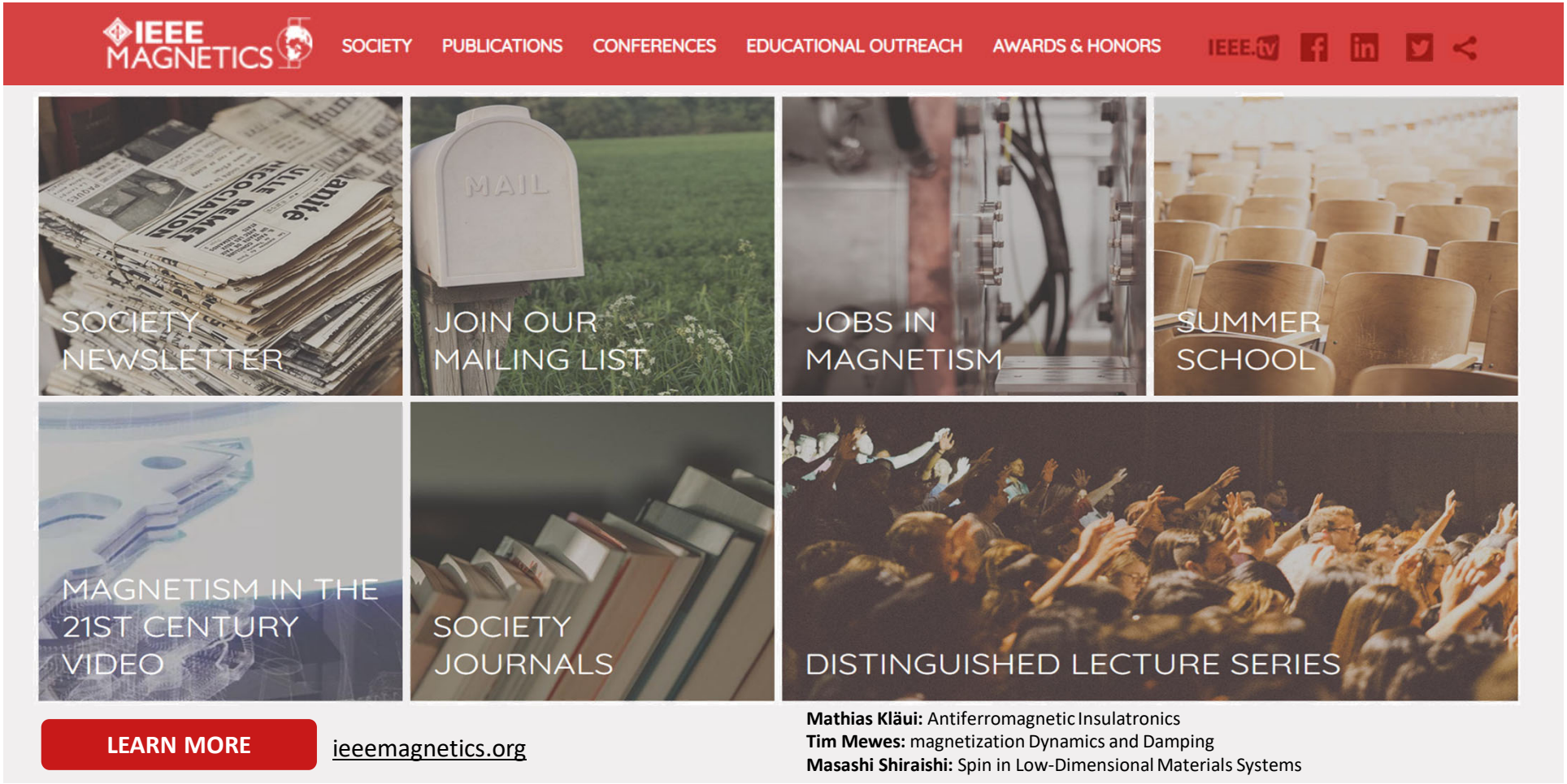


Femto-magnetism meets spintronics – *Towards integrated magneto-photonics*

Bert Koopmans, Eindhoven University of Technology

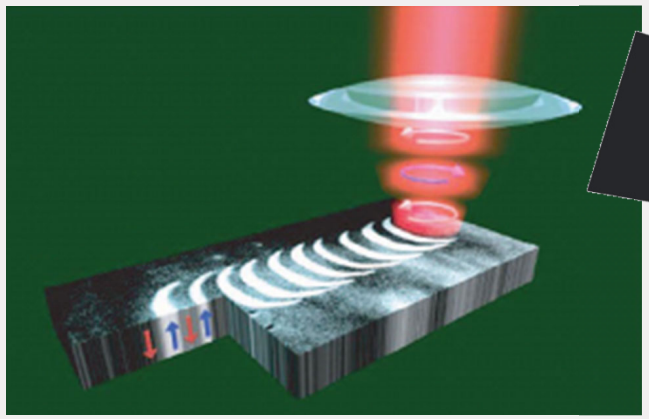
IEEE Magnetic Society DL online lecture – SPICE-SPIN+X Seminar, Mainz, December 2021



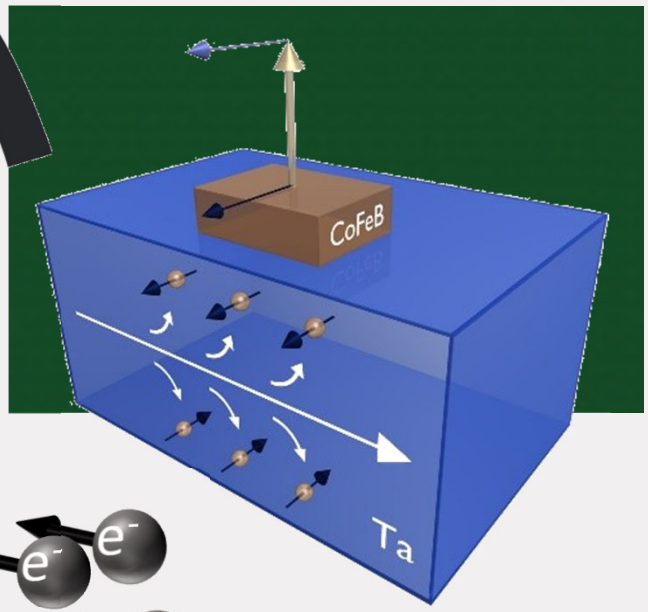
Mathias Kläui: Antiferromagnetic Insulatronics
Tim Mewes: magnetization Dynamics and Damping
Masashi Shiraishi: Spin in Low-Dimensional Materials Systems

Femto-magnetism *meets* Spintronics

Stanciu, Kimel, Rasing et al. PRL 2007



Hybrid concepts



Conservation & transfer
of angular momentum

Hellman et al. Rev. Mod. Phys. 2017

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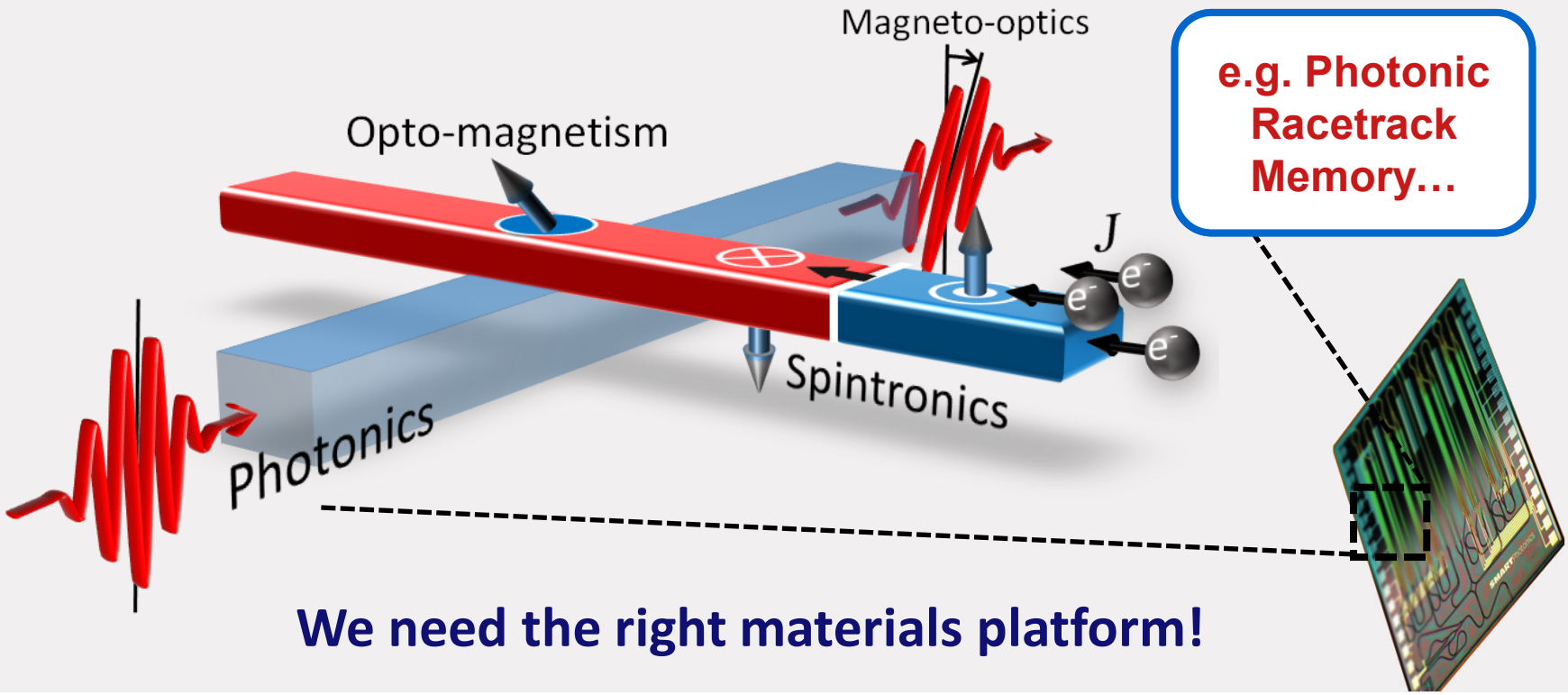
Towards Integrated Magneto-Photonics



We need the right materials platform!

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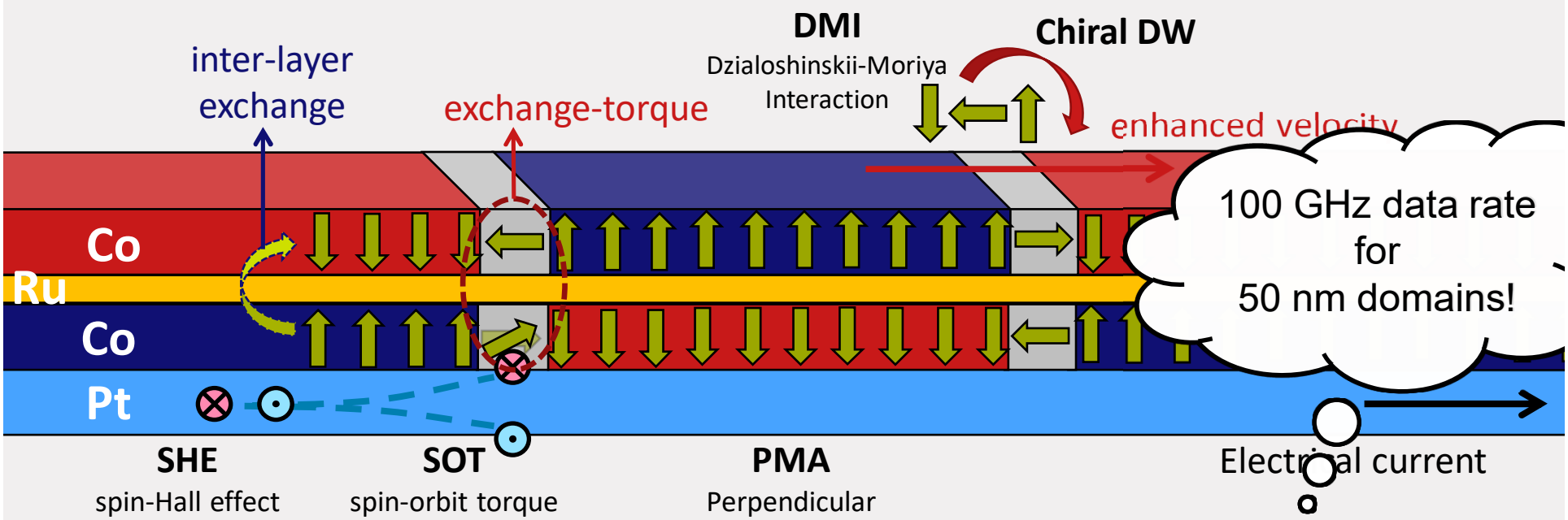
Spin-Orbit effects in synthetic AntiFerromagnets



v > 500 m/s if $M_1 \sim -M_2$

Co/Ni/Co/Ru/Co/Ni/Co: Yang, Parkin *et al.*, Nature Comms. 2015

v > 5000 m/s in CoGd!

Cai *et al.*, Nature Electr. 2020

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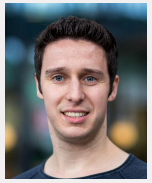
Acknowledgements

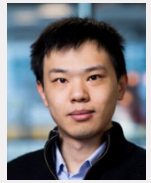

Youri van Hees


Maarten Beens

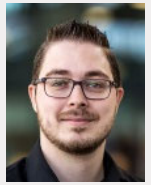

Mark Peeters


Anni Cao


Ece Demirer


Luding Wang


Pingzhi Li


Tom Lichtenberg


Mark Lalieu

For the optics & fs dynamics


Marielle Meijer

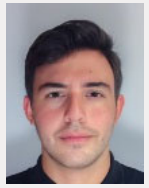

Juriaan Lucassen


Casper Schippers


Fanny Ummelen


Jianing Li


Michal Grzybowski


Tunc Ciftci

For related work

TU/e, Eindhoven: Reinoud Lavrijsen, Henk Swagten, Rembert Duine, and Jos van der Tol
Universite Lorraine, Nancy: Stephane Mangin, Gregory Malinowski, Quentin Remy, and team members
Beihang University, Beijing: Weisheng Zhao and team members
All partners in the EEX (NWO), COST network, Magnefi ITN and COMRAD ITN

Outline

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- All-Optical Switching (AOS) of magnetization
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Towards integrated magneto-photonics

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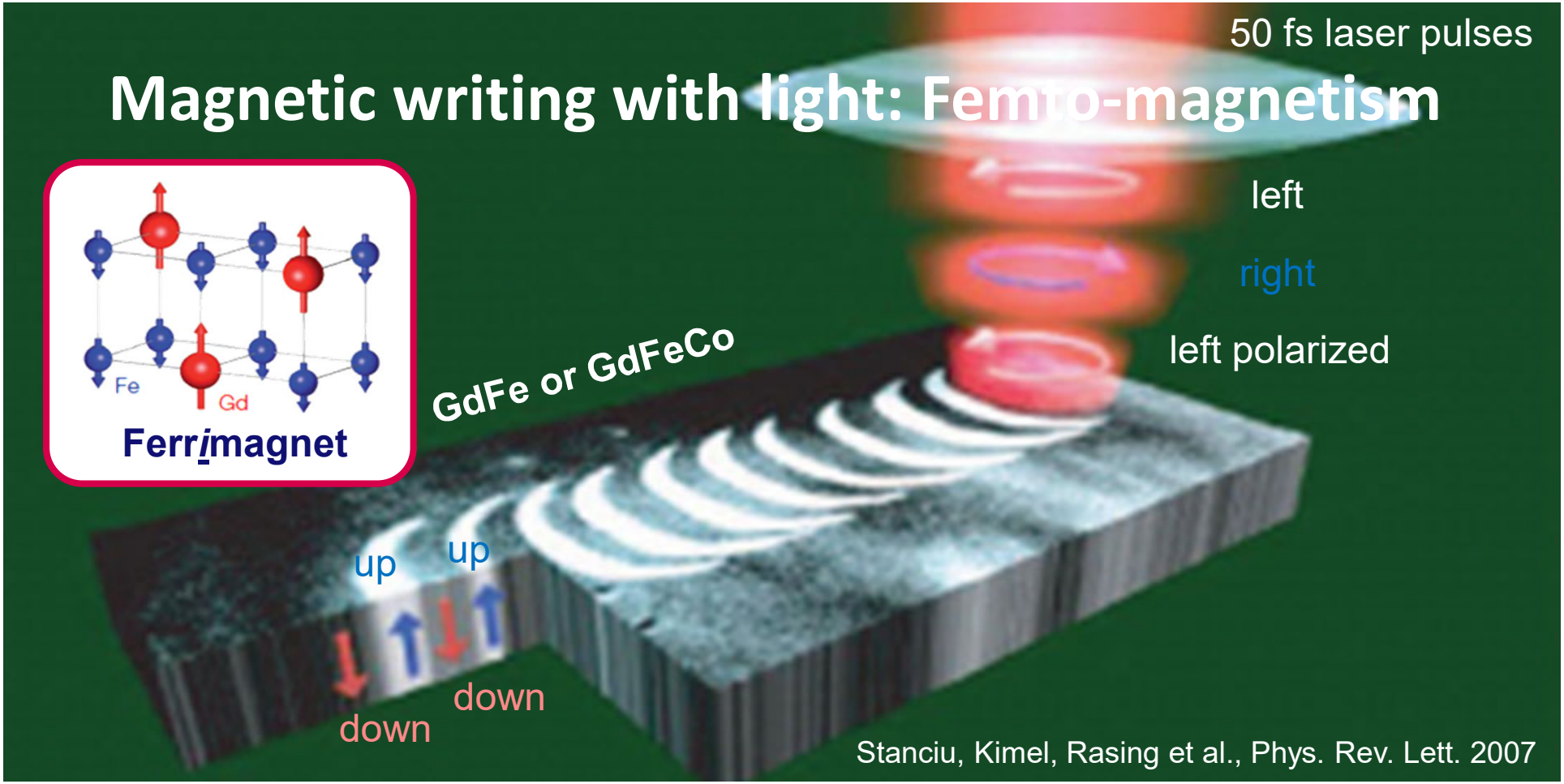
- First steps towards magneto-photonic integrated circuits

Magnetic writing with light: Femto-magnetism



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Magnetic writing with light: Femto-magnetism

Toggle mechanism (linearly polarized!)

Ostler *et al.*, Nature Comms. 2012

up

Helicity dependence just due to circular dichroism

Khorsand *et al.*, Phys. Rev. Lett. 2012

Stanciu, Kimel, Kasing et al., Phys. Rev. Lett. 2007

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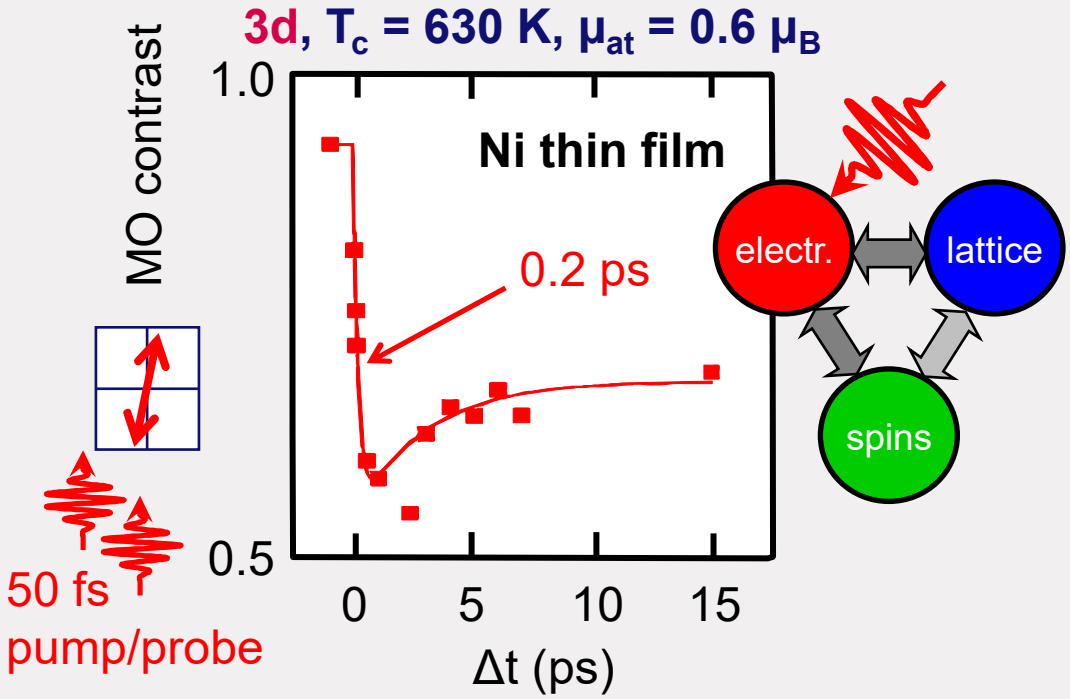
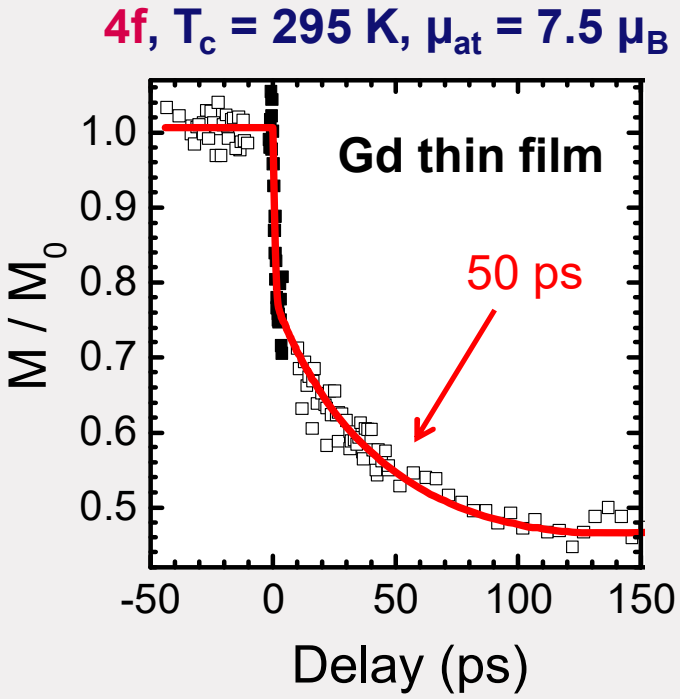
Femtosecond demagnetization

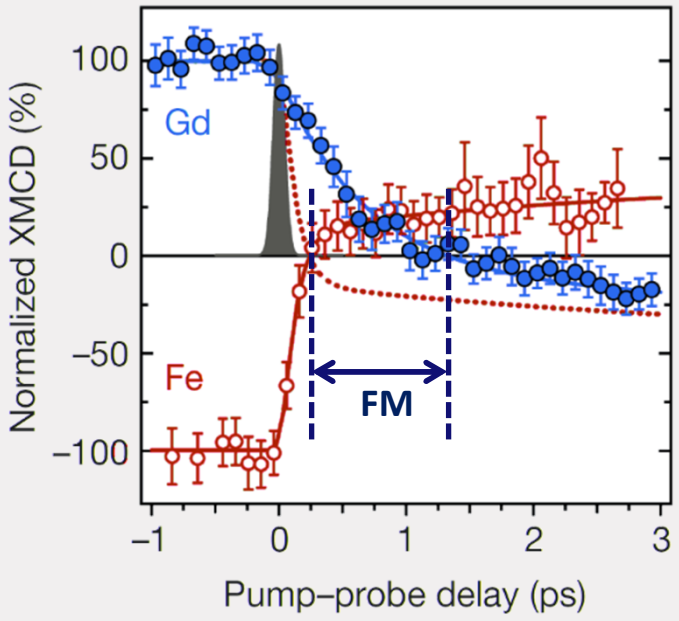




Beaurepaire, Bigot *et al.*, Phys. Rev. Lett. 76, 4250 (1996)

Wietstruk, Weinelt, Bovensiepen *et al.*, Phys. Rev. Lett. (2011)

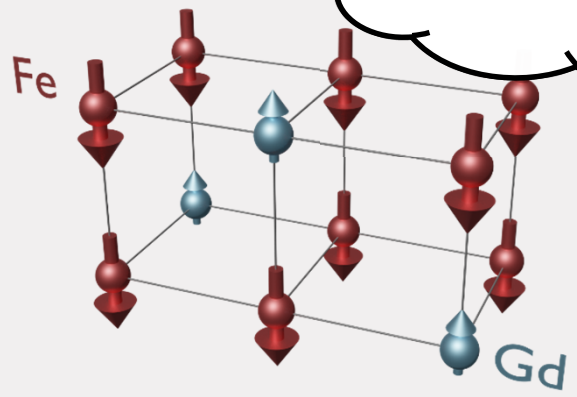
Detailed insight in AOS from fs-XMCD

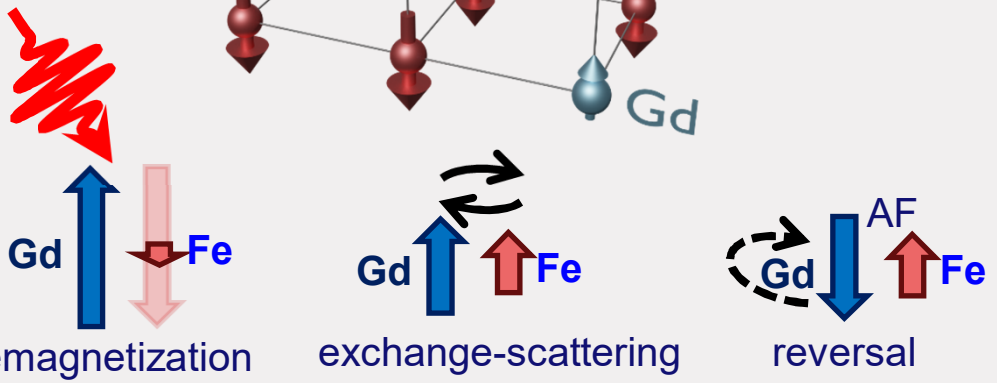


Radu, Dürr *et al.*, Nature (2011)

Ferrimagnetic GdFe

Composition near "compensation" needed





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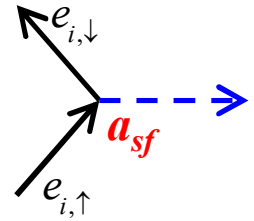
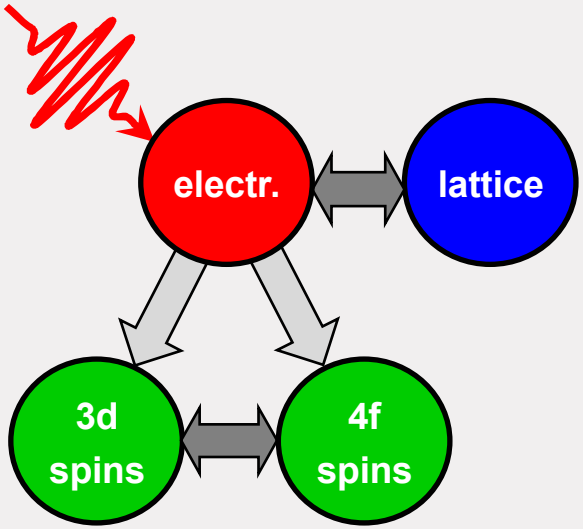
The Microscopic 3-Temperature Model for AOS

$$H = H_e + H_p + H_s + H_{ee} + H_{ep} + H_{ep-s} \xrightarrow{\text{Golden rule}} \text{rate equations}$$

Magnetic thermalization

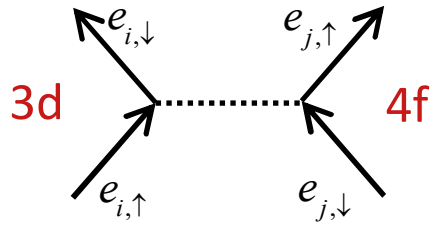


Elliott-Yafet spin flip



$S = \frac{1}{2}$ $S = \frac{7}{2}$ *)

Inter-sub-lattce spin transfer



Nearest-neighbor exchange

Schellekens *at al.* PRB(R) (2013),
Beens *et al.* PRB(R) (2019)

*) or $S = \frac{1}{2}$

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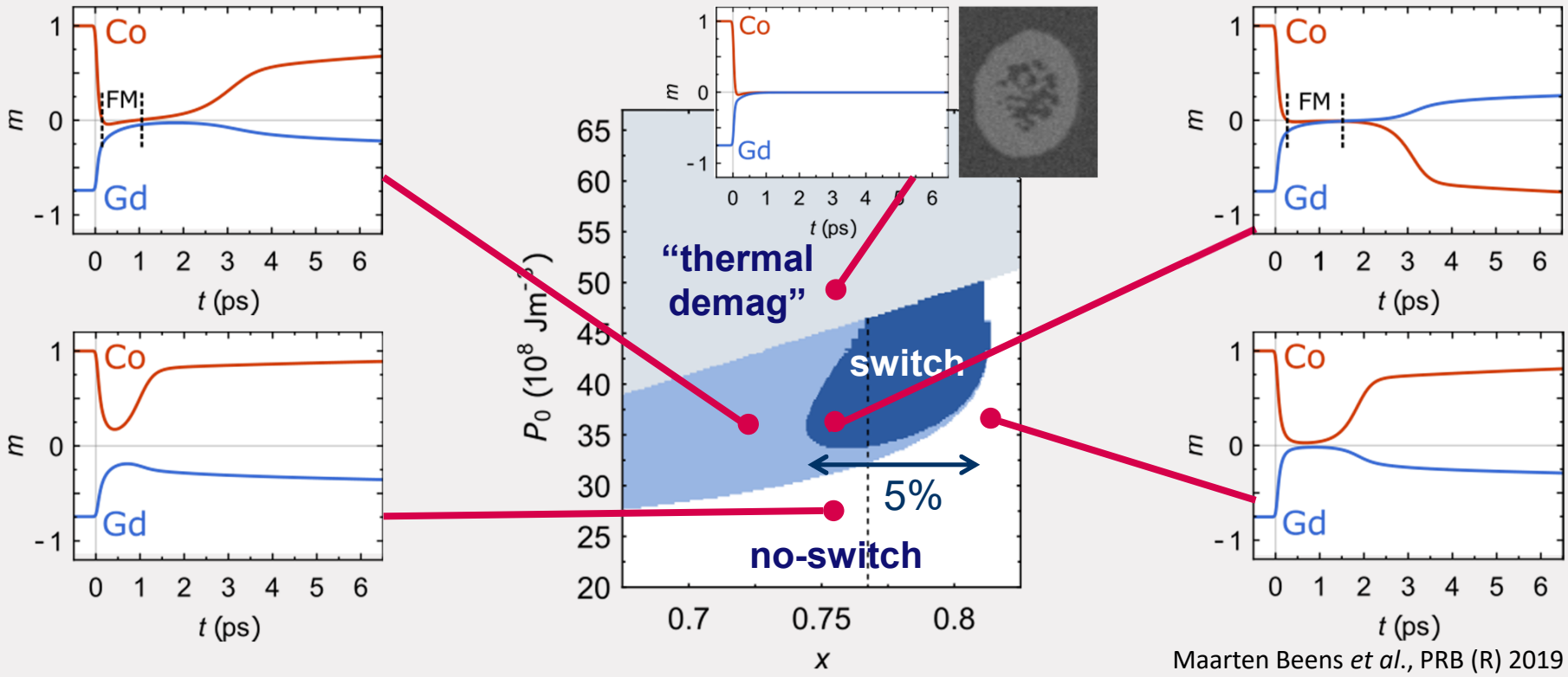
Understanding its behavior (M3TM), $Gd_{1-x}Co_x$



Maarten Beens *et al.*, PRB (R) 2019

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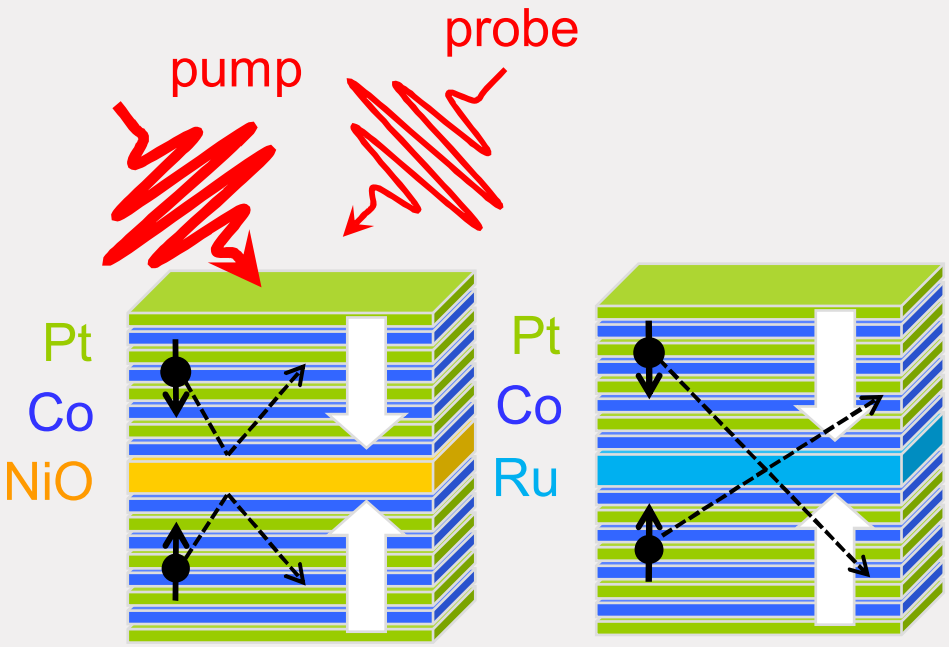
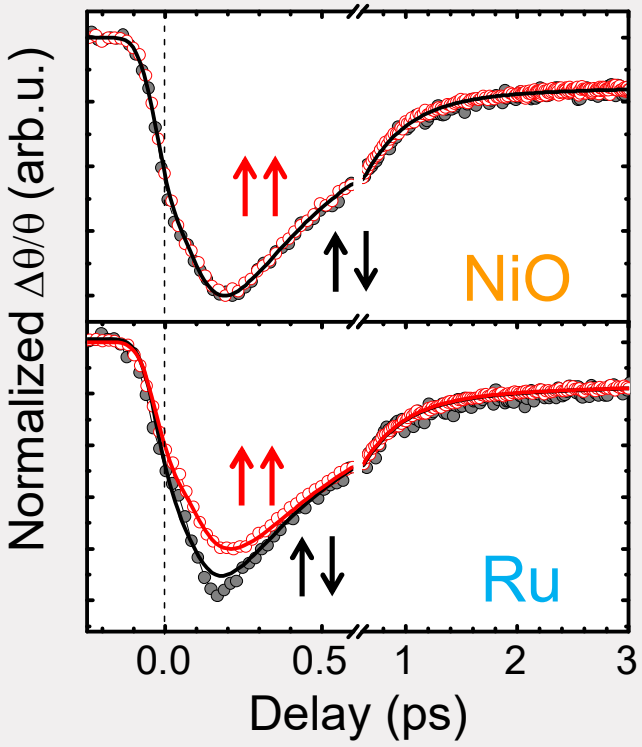
Fs laser-induced nonlocal spin transfer





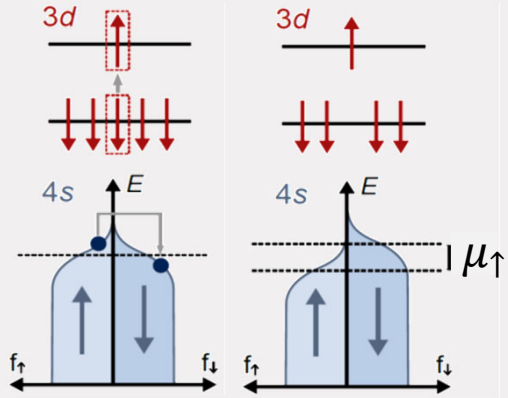
Malinowski *et al*., Nature Physics (2008)

See also:

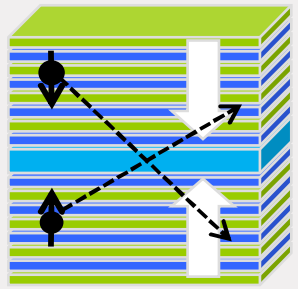
Rudolf *et al*., Nat. Comms. 2011
Melnikov, Bovensiepen *et al*., PRL 2011
Choi, Cahill *et al*., Nat. Comms. 2014
Hofherr, Aeschlimann, *et al*., PRL 2017

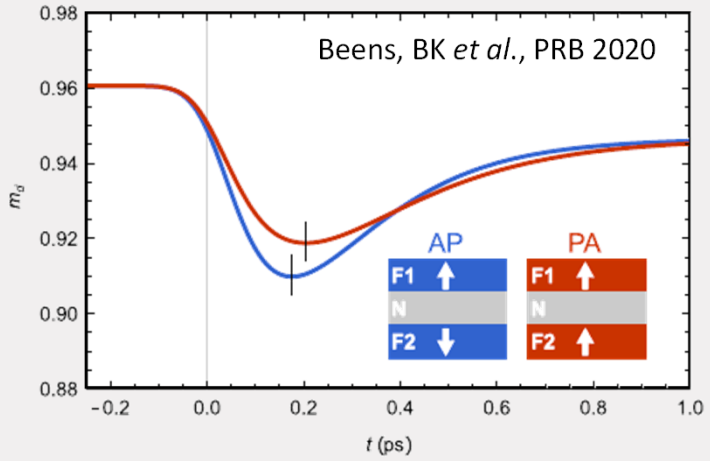
Models for Optical spin current generation

1. **Balistic injection optical spin pol.**
2. **Super-diffusive transport, spin filtering**
   Battiato, Oppeneer et al., PRL 2010
3. **Spin-dependent Seebeck effect**
   Choi et al., Nat. Phys. 2015
4. **s-d model – "dM/dt"**



$\mu_\uparrow - \mu_\downarrow \rightarrow J_s$





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See also: Choi *et al.*, Nat. Comms. 2014
Tveten *et al.*, PRB 2015

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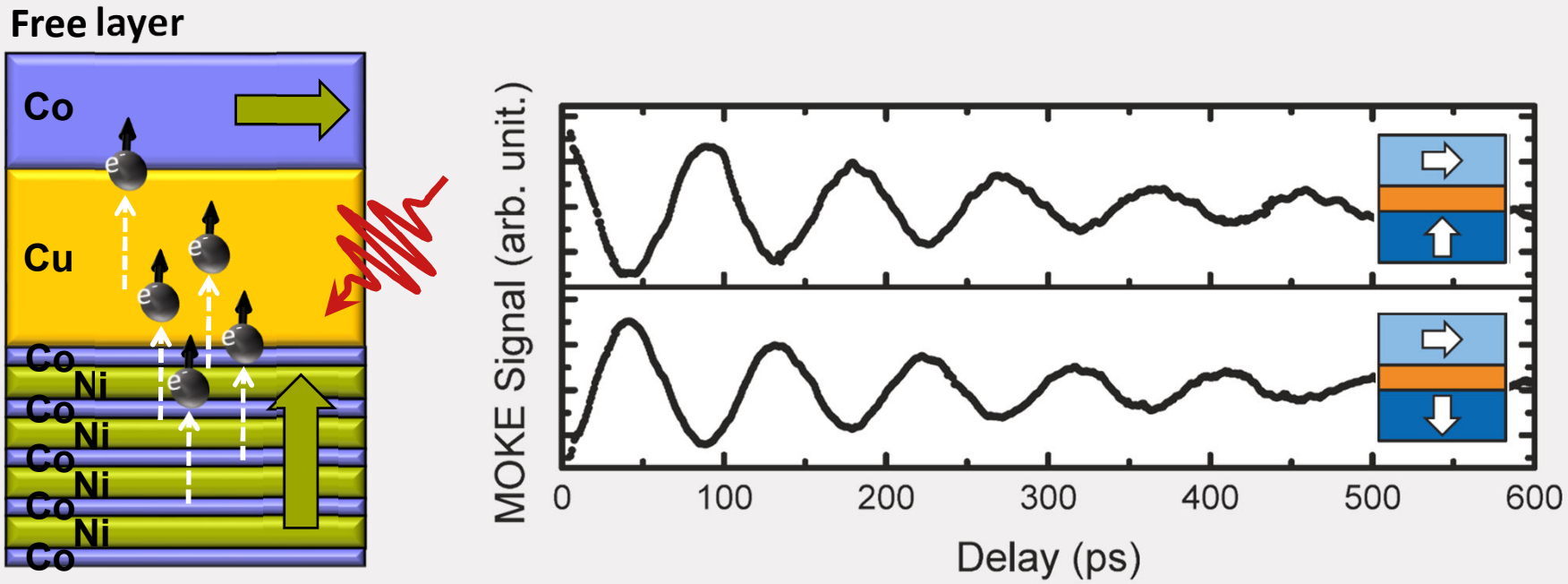
Experimental demonstration optical STT



Schellekens *et al.*, Nature Comm. (2014)

Mark Lalieu, PhD Thesis (2019)

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See also: Choi *et al.*, Nat. Comms. 2014
Razdolski, Melnikov *et al.*, Nat. Comms. 2017

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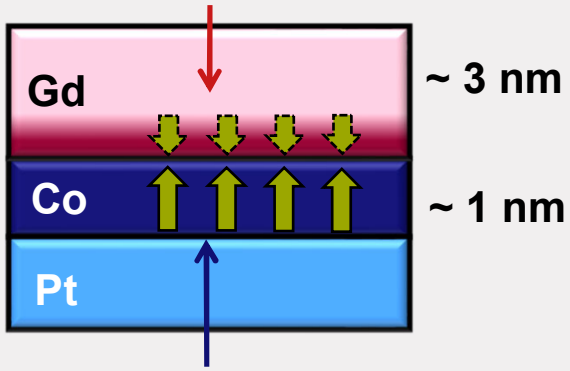
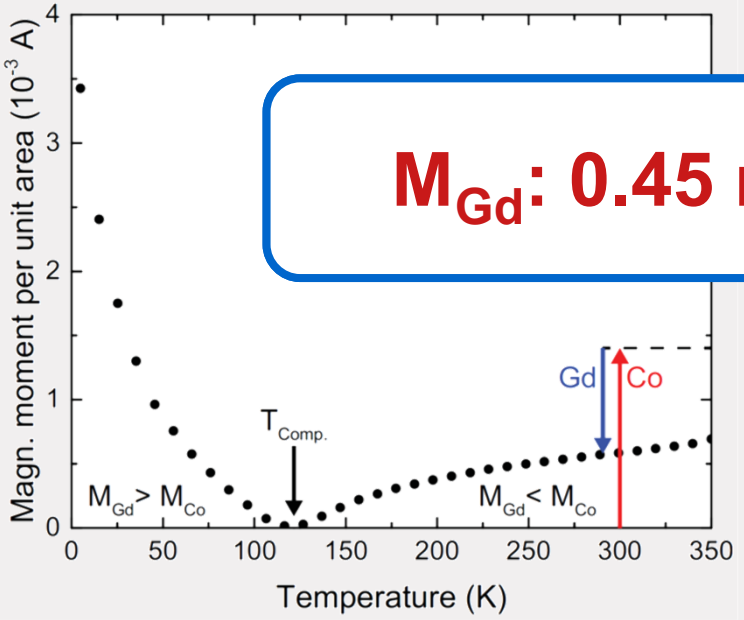
Pt/Co/Gd: Synthetic ferrimagnet

Proximity induced FM @ RT



Strong spin-orbit (DMI & SHE)



M_{Gd}: 0.45 nm

VSM SQUID

→ 0.45 nm FM Gd @ RT

→ $M_{sat,Gd}$ = 1.8 MA/m (bulk: 2.1 MA/m)

Mark Lalieu, Reinoud Lavrijsen, *et al.*, Phys. Rev. B 96, 220411 (Rapid) 2017

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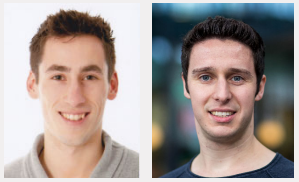
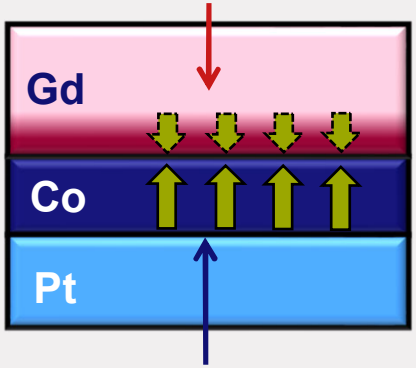
Pt/Co/Gd: Single-pulse switching

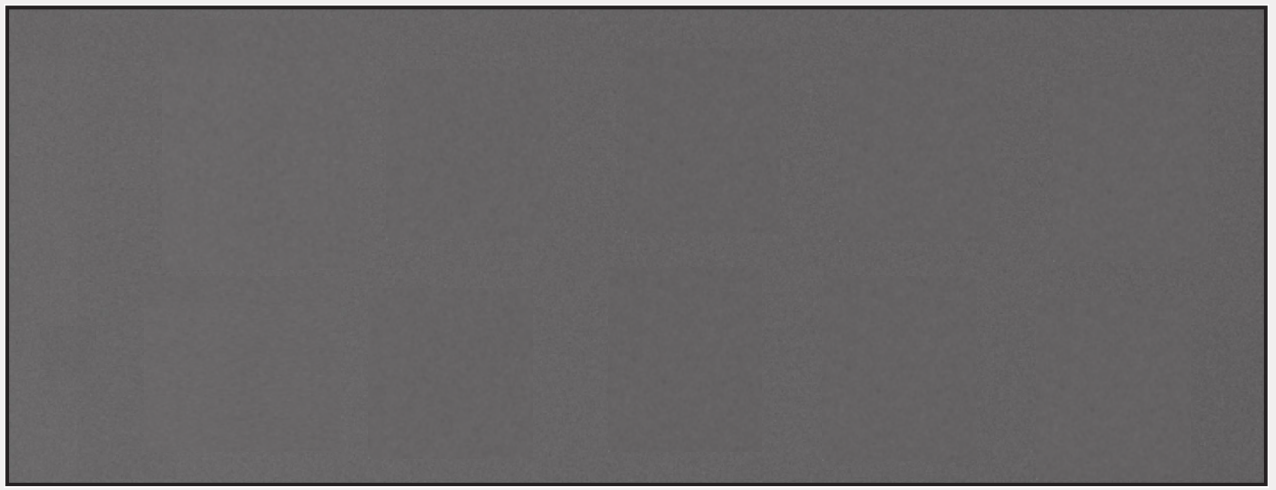


Proximity induced FM @ RT



Strong spin-orbit (DMI & SHE)

Magneto-optical microscopy

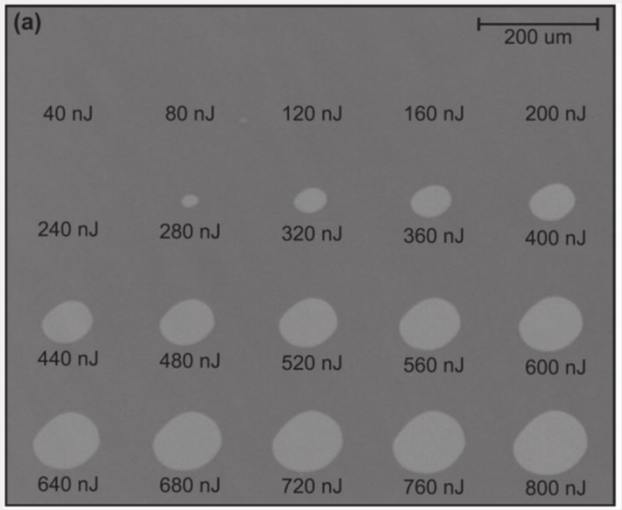


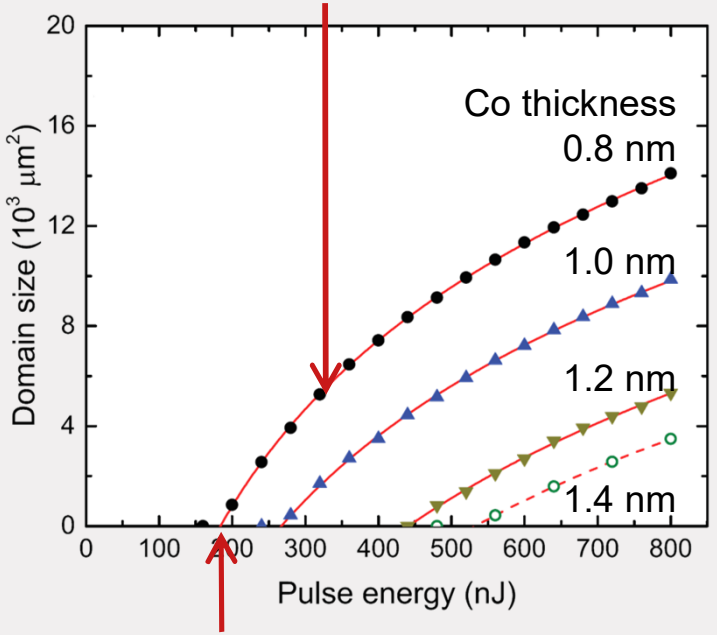
> 10^8 successful switches @ 100 kHz

Mark Lalieu, Reinoud Lavrijsen, *et al.*, Nature Comms. 2019
Mark Lalieu, Mark Peeters, *et al.*, PRB (R) 2017

Super robust and Ultra-efficient

Fit assuming fixed threshold temperature





50 fJ for 50 x 50 nm^2

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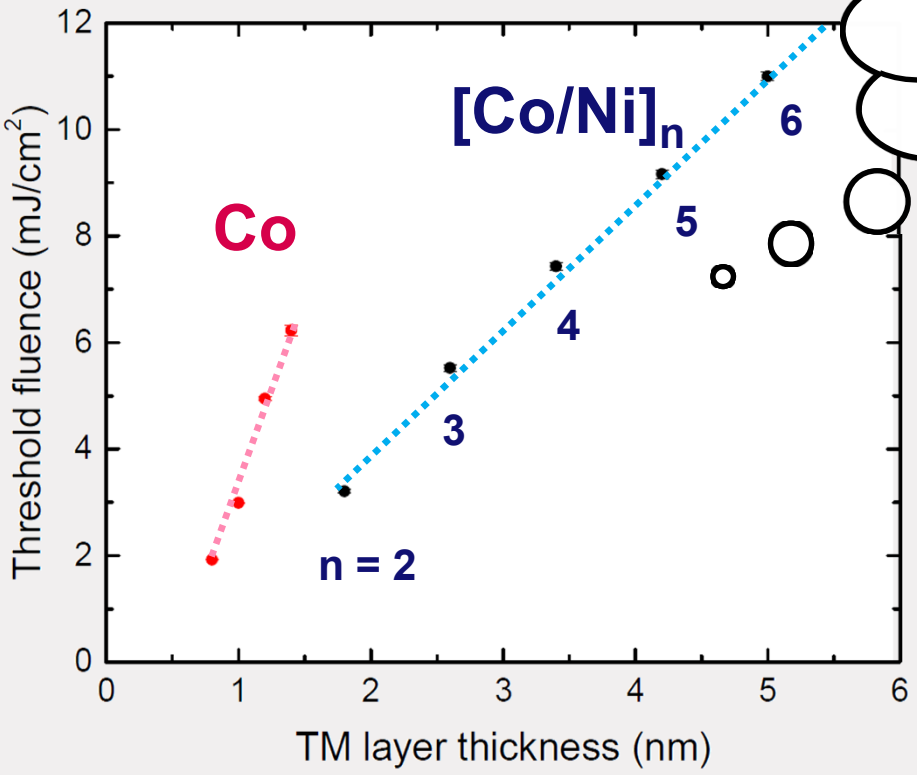
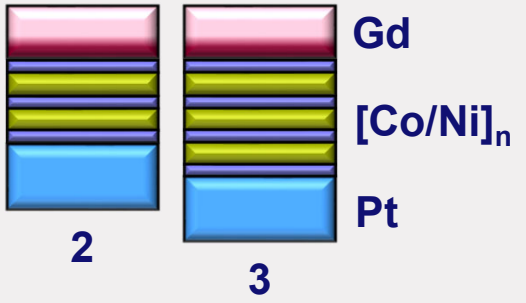
Surprise: Switching far from compe

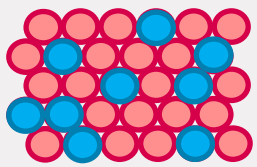


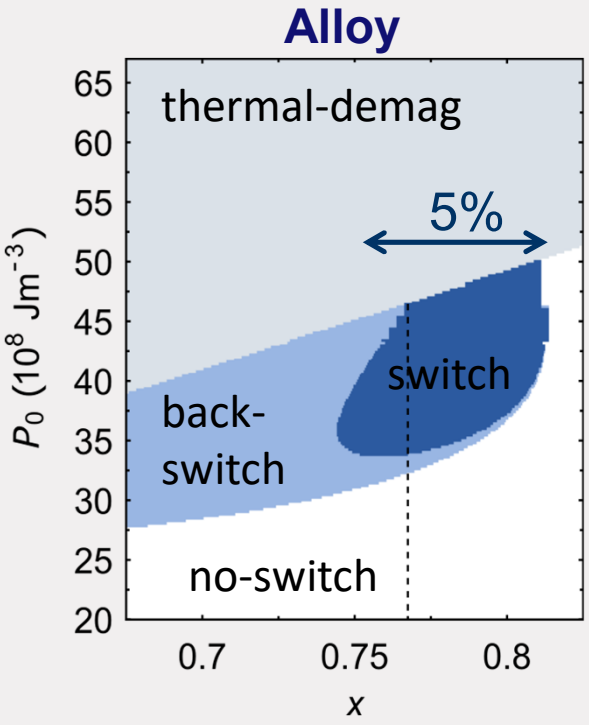
Alloys:
Composition near "compensation" needed

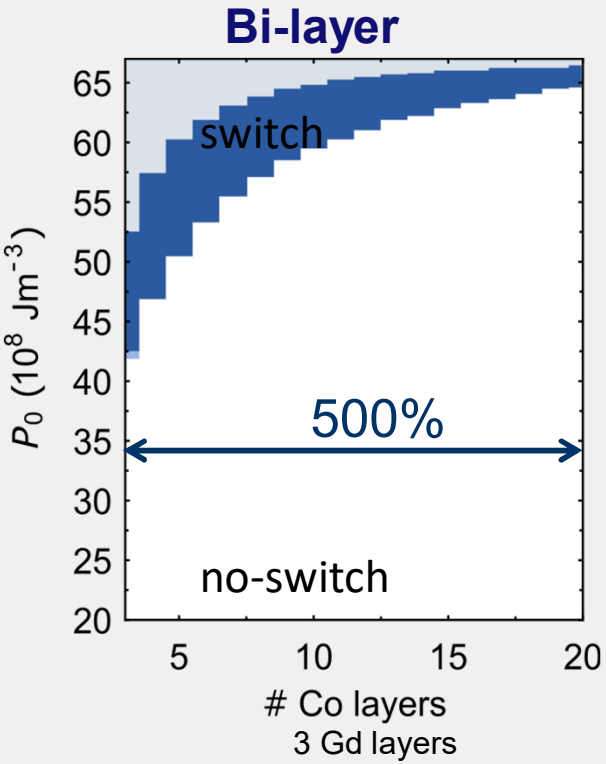


Beens, Lalieu *et al.*, PRB (R) 2019

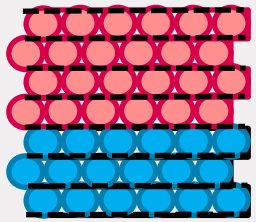
Understanding its behavior (M3TM)







Maarten Beens *et al.*,
PRB (R) 2019



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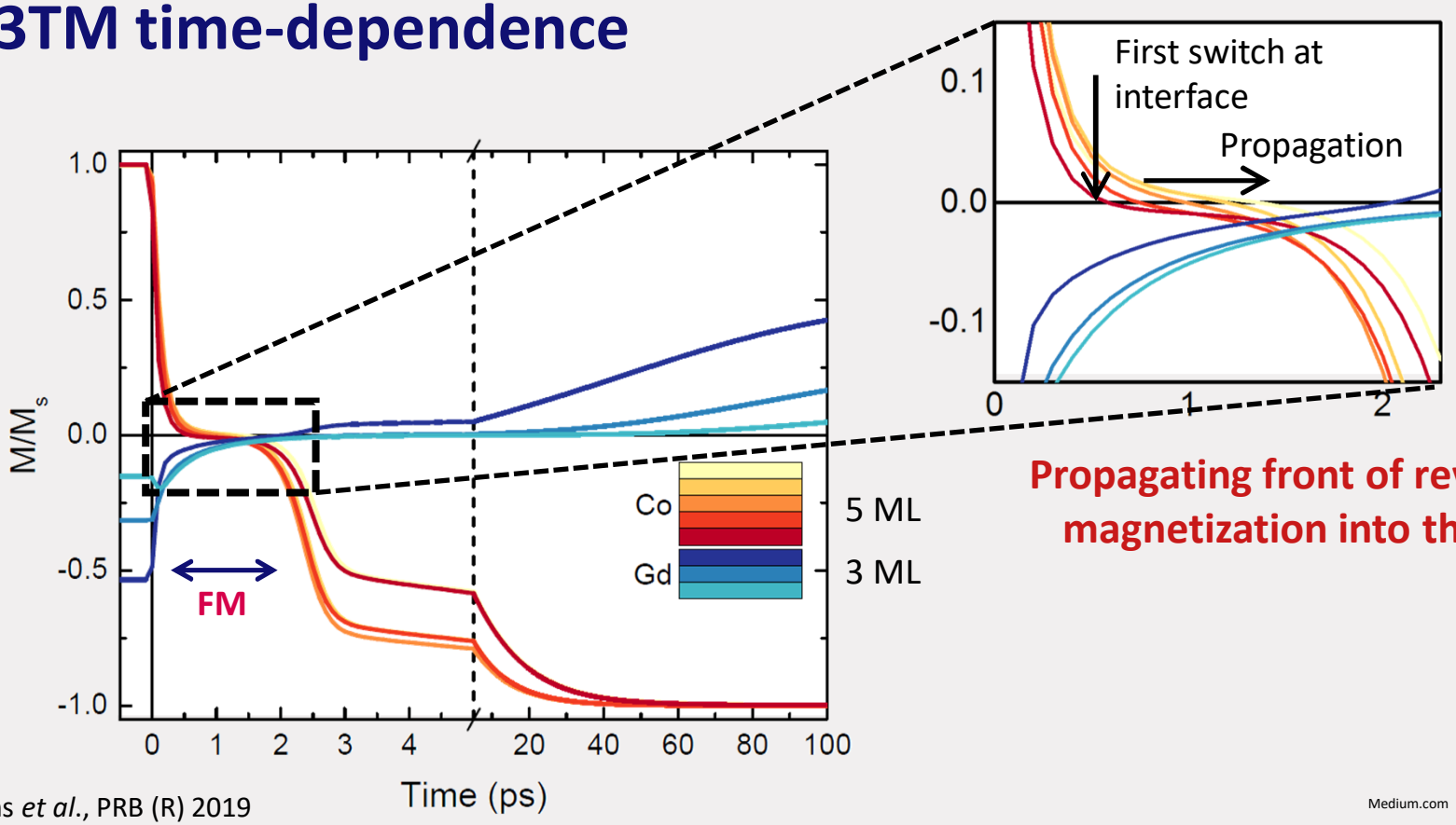
M3TM time-dependence



Propagating front of reversed magnetization into the Co

Maarten Beens *et al.*, PRB (R) 2019

Medium.com

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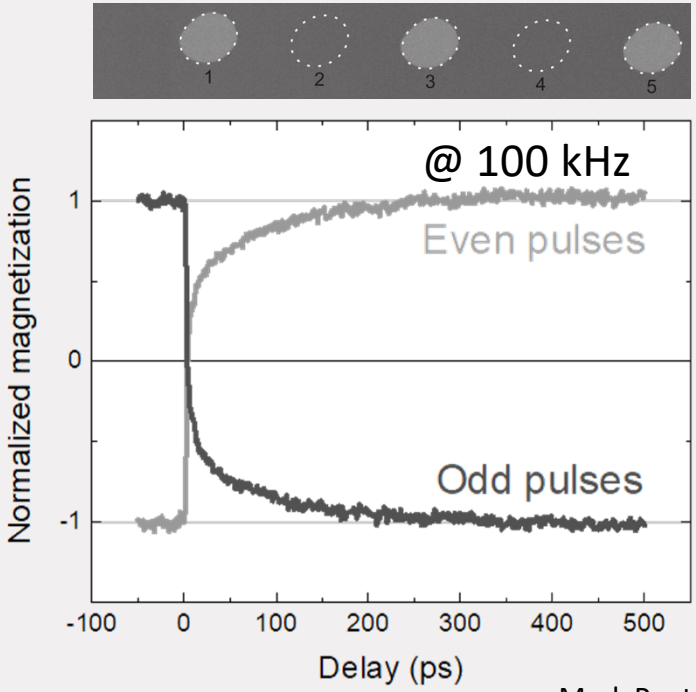
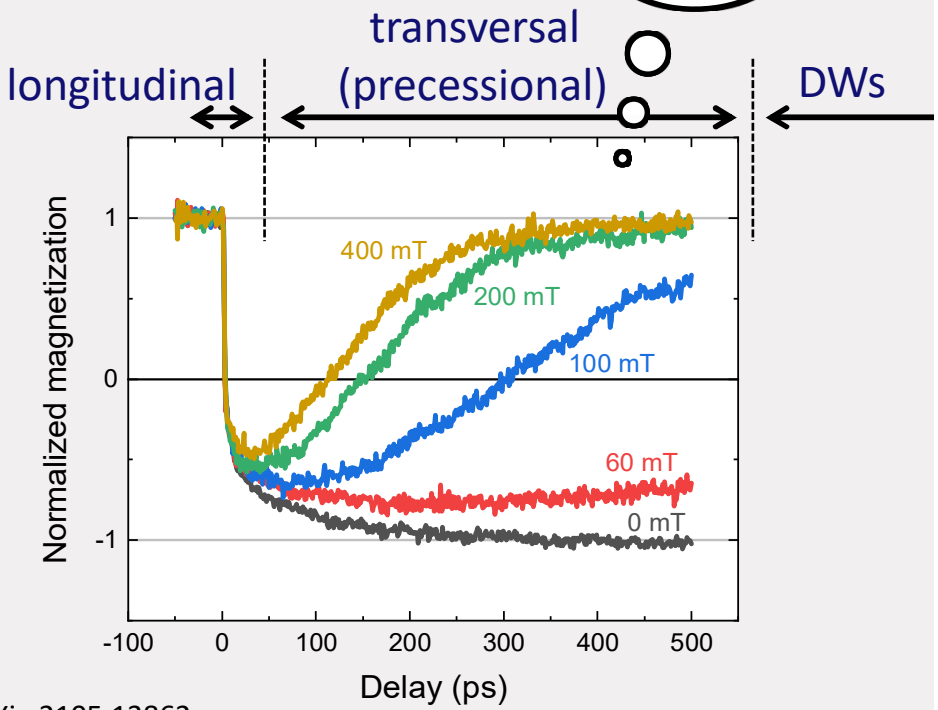
Time-resolved insight

> 10^8 error free witches @ 100 kHz



0.1 T competing with 1000 T of exchange?



Mark Peeters, et al., arXiv:2105.13862

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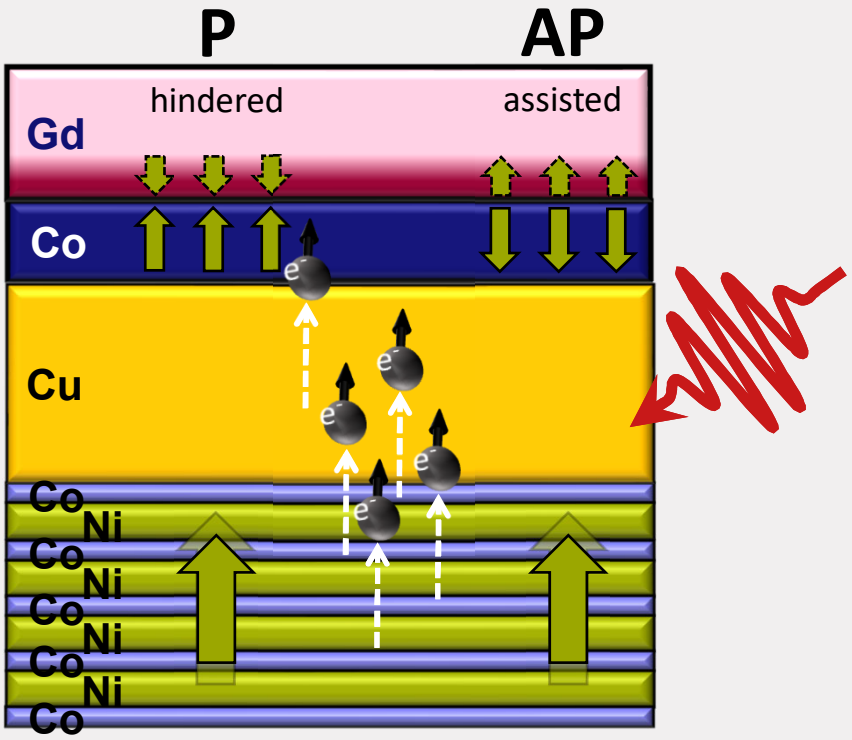
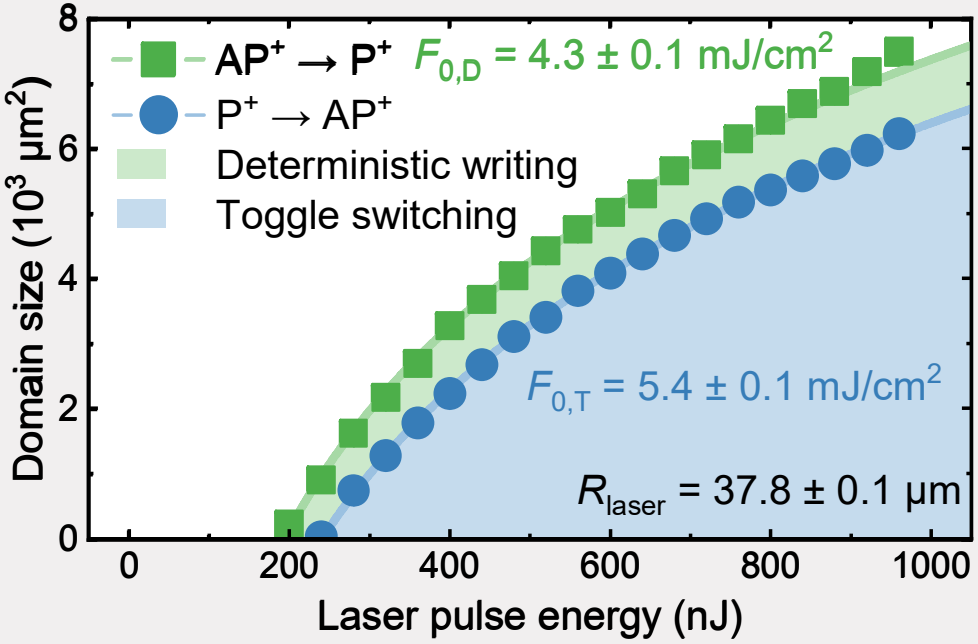
Back to AOS: local vs. non-local spin transfer





Youri van Hees *et al.*, Nature Comms. (2020)

See also Quentin Remy, Mangin *et al.*, Adv. Sci. (2020)

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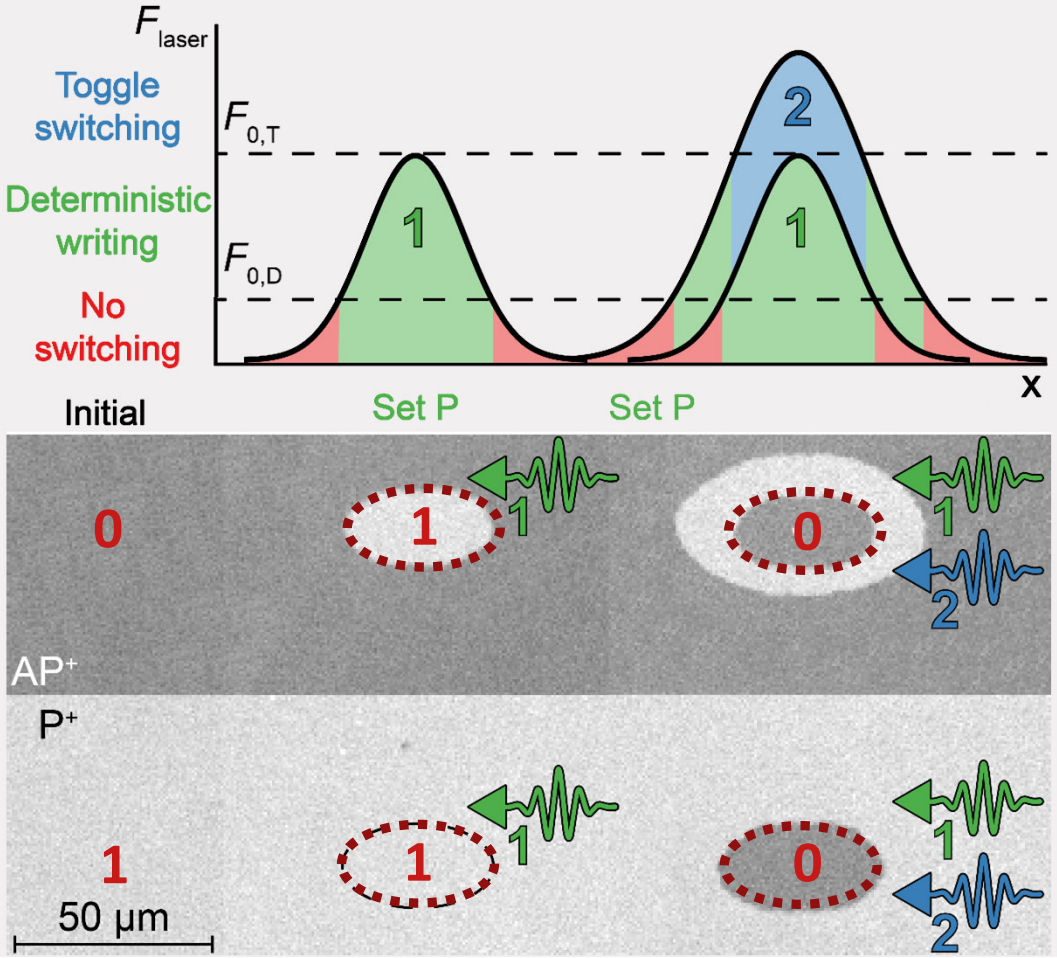
Deterministic writing

How to write a logic 0 or 1, rather than just toggle?



Youri van Hees *et al.*, Nature Comms. (2020)

Outline

Femto-magnetism meets spintronics

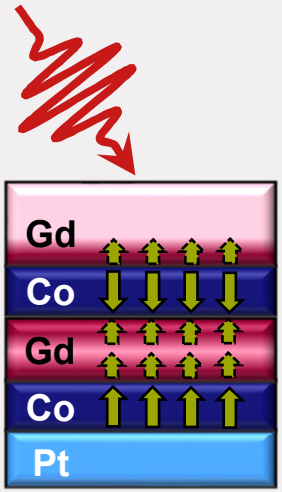
- All-Optical Switching (AOS) of magnetization
- Laser-induced spin transport
- The beauty of AOS in a “synthetic” anti-ferromagnet
- Spin-current enhanced AOS

Towards integrated magneto-photonics

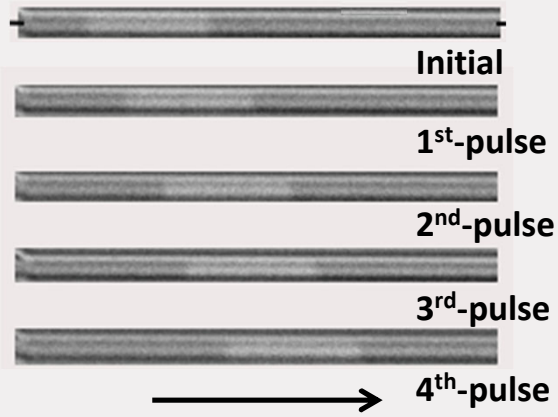
- Hybrid photonic/spintronic (AOS/DWM) functionality
- First steps towards magneto-photonic integrated circuits

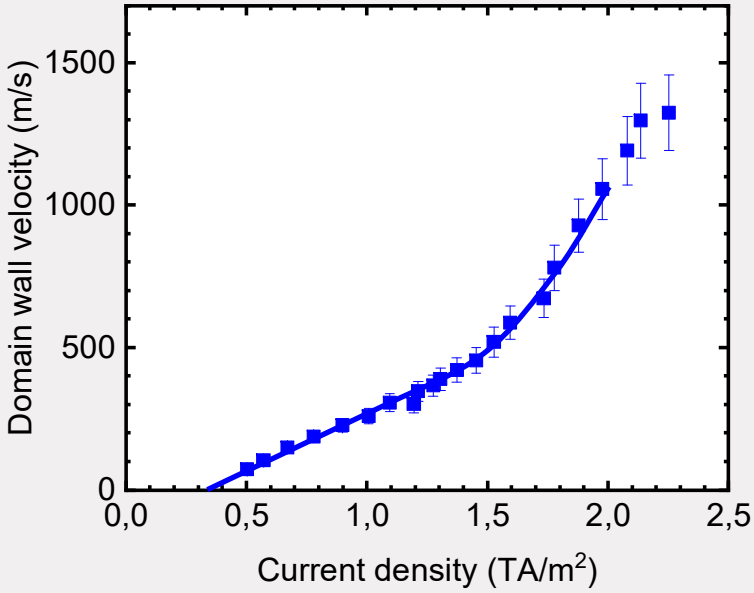
Current-driven domain wall motion in AOS stack

near angular momentum compensation: v > 2000 m/s



AOS verified!



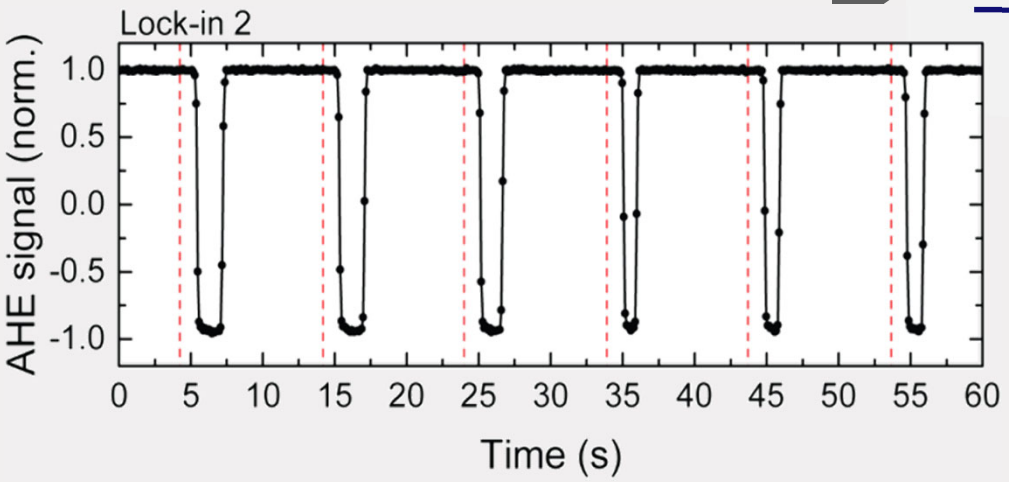


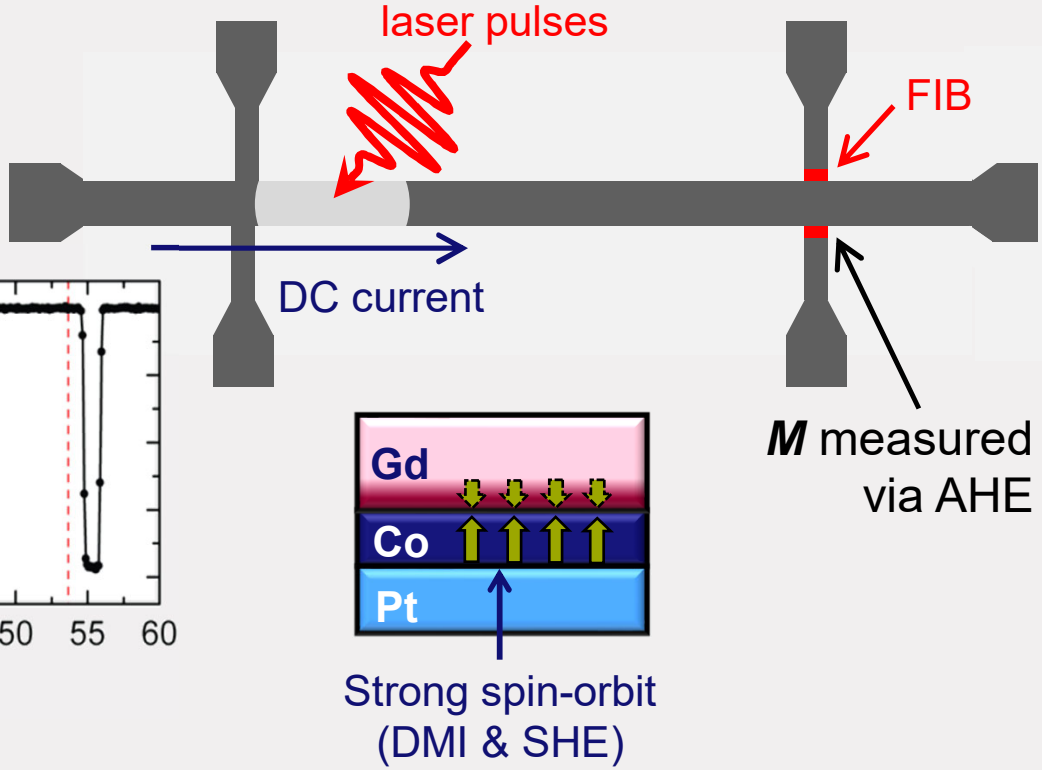
Si:B/Ta(4)/Pt(4)/Co(1.0)/Ru(0.9)/Pt(0.9)/Co(1)/Gd(3)/Pt(2)

Pingzhi Li & Thomas Kools, In progress

In line with Bläsing *et al.*, Nature Comms. 2018

Magneto-photonic memories





Mark Lalieu *et al.*, Nature Comms. 2019

Outlook: Integrated Magneto-Photonics

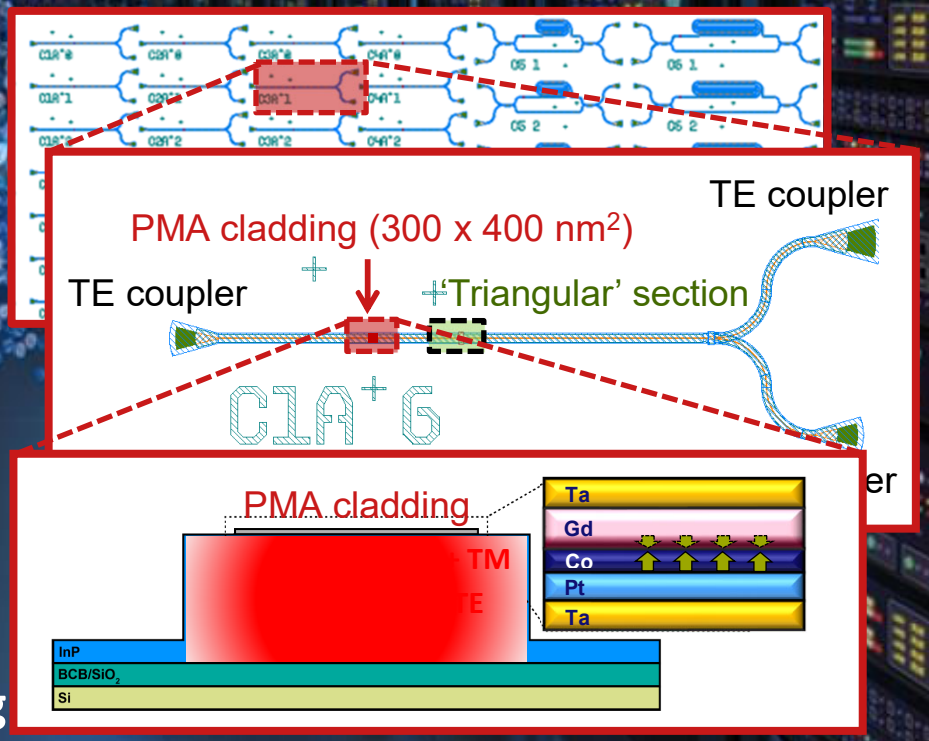
Institute for Photonic Integration

Materials · Devices · Systems


Ece Demirer


Sander Reiniers


Jos van der Tol (EE)



Writing

Reading using MO mode conversion

IEEE MAGNETICS

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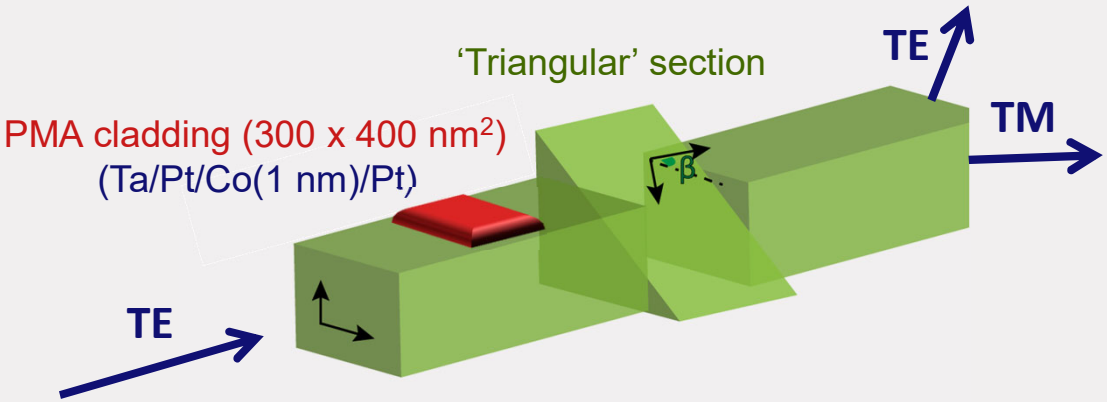
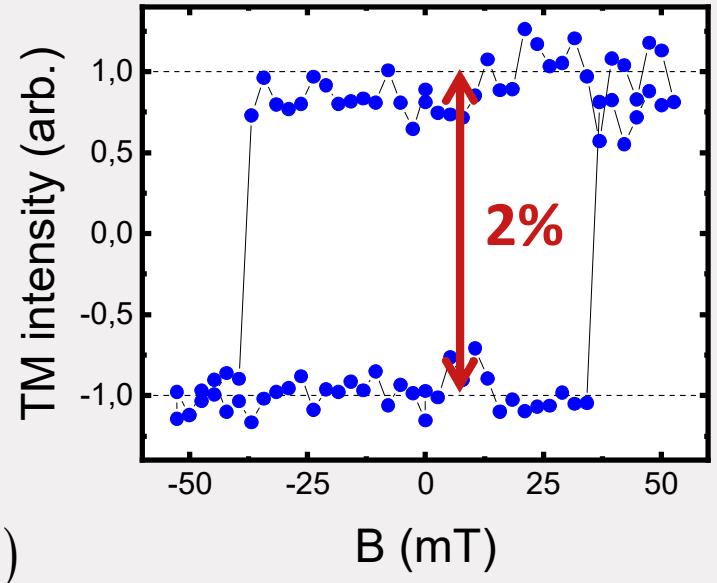
On-chip MO Mode Conversion



$$\begin{pmatrix} TE \\ TM \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \longrightarrow \begin{pmatrix} 1 \\ \pm(\theta + i\varepsilon) \end{pmatrix} \longrightarrow 1 \pm \mathrm{Re}\left(C(\theta + i\varepsilon)\right)$$



Ece Demirer, Yngwie Baron, *et al.*, Nature Comms. 2019

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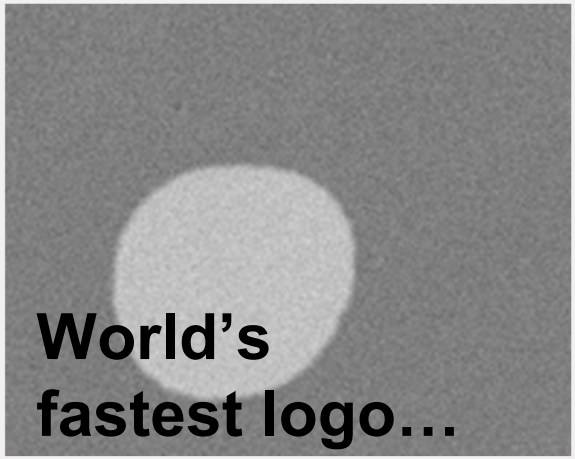
Take home message

- Converging of spintronics and fs magnetism rapidly progressing – interplay of all-optical switching and optical spin currents
- First step towards integrated magneto-photonics



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