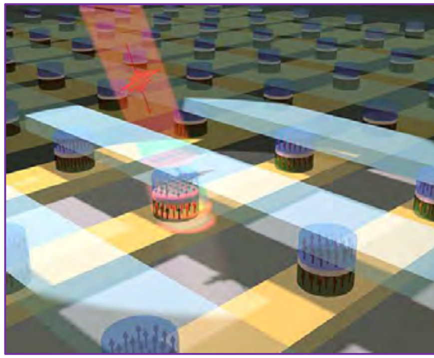
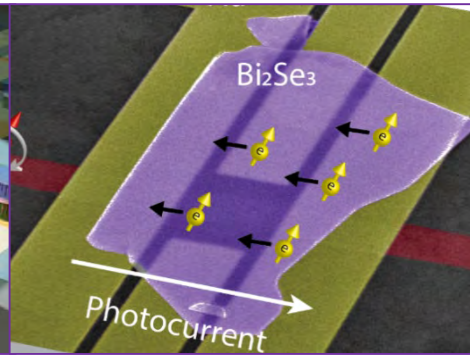
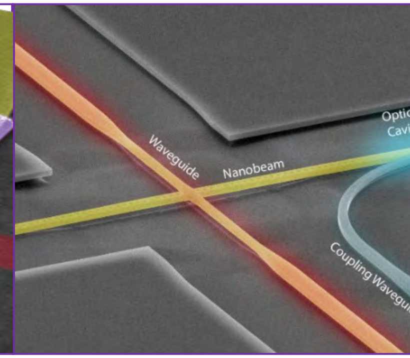
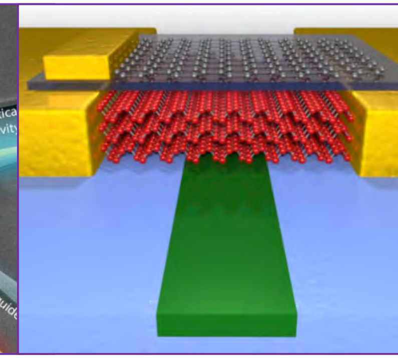
Ultrafast All-Optical Switching of <u>Magnetic Tunnel Junctions</u> With Sub-Picosecond <u>Infrared</u> Laser Pulses









Jun-Yang Chen, Li He, Jian-Ping Wang

Department of Electrical and Computer Engineering

University of Minnesota, Twin Cities

<u>Mo Li</u>

Department of Electrical and Computer Engineering

Department of Physics

University of Washington, Seattle

Ultrafast Spintronics: from Fundamentals to Technology

SPICE, Mainz

Oct. 24th, 2018

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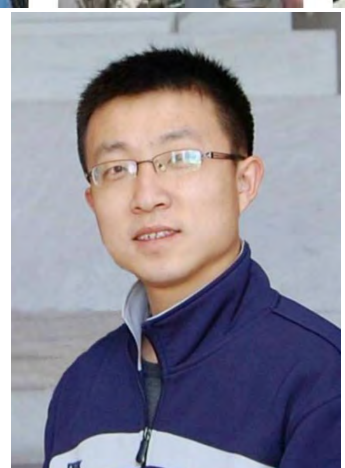
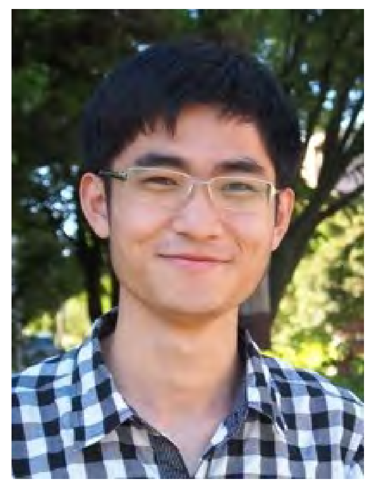
UNIVERSITY OF NOTRE DAME

Jian-Ping Wang



Junyang Chen



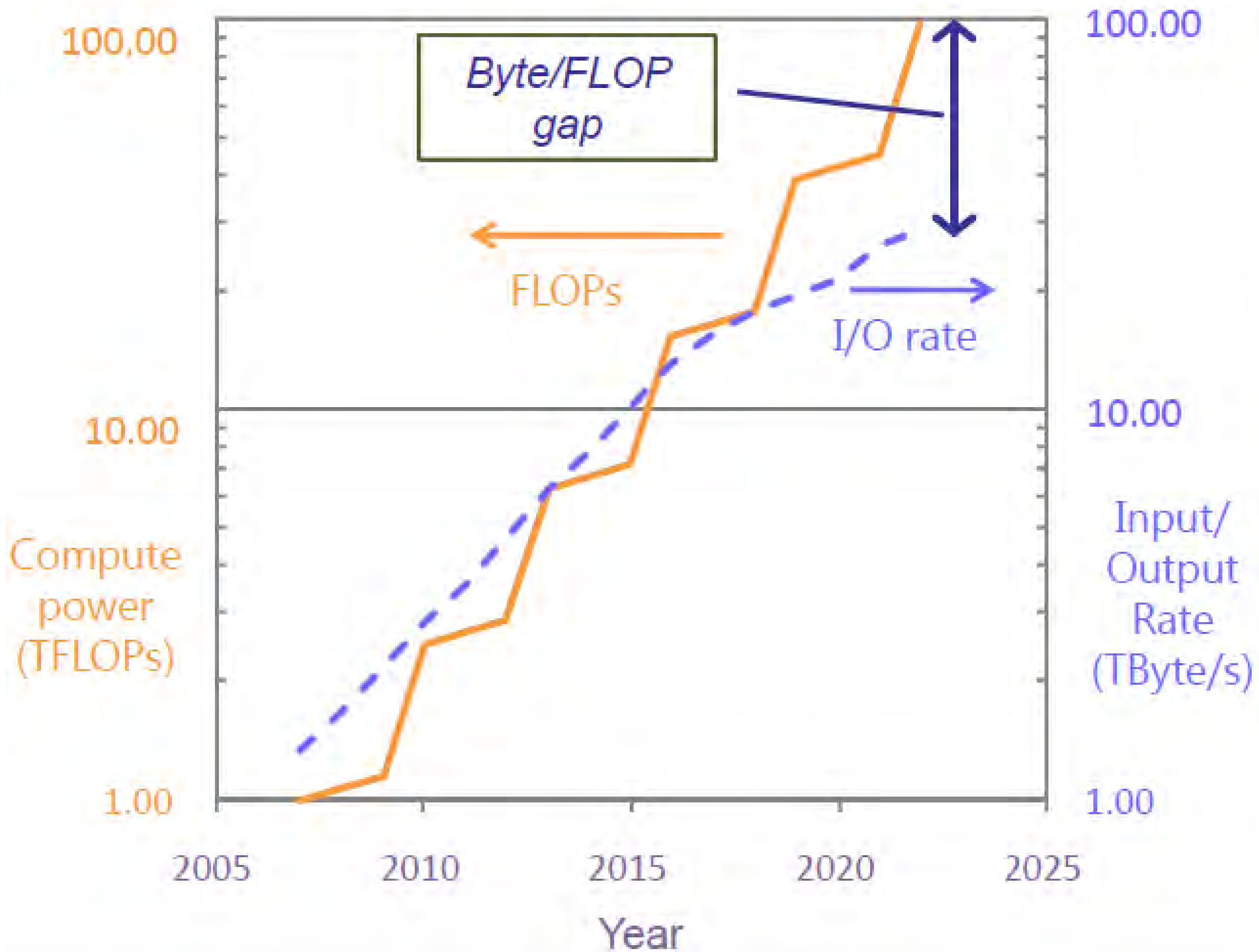
Li He

SRC

DARPA

Interconnect is the bottleneck in computation

ITRS Projected Chip Performance (scaled from 2007 chip)



I/O rate cannot keep up with computation power

D. Miller, Proc. Of IEEE (2009)

Need for Optical Interconnect

Interconnect is the central issue of information processing and computation
Two major bottlenecks:

- **Energy**
  - Energy consumption in computation is dominated by the interconnect energy on chip (logic: ~0.1-1pJ/bit)
  - A dominant energy dissipation in computation is charging and discharging the capacitances of interconnect wires (interconnect: ~1pJ/bit assuming 1cm distance)
- **Density**
  - Physical density of interconnects is already at the limit of electrical approaches
- **Bandwidth**
  - I/O interconnect rate lag behind the computation capability of chip (ideally 1 byte per FLOP)

<u>Optical interconnect is the only viable physical solution</u>

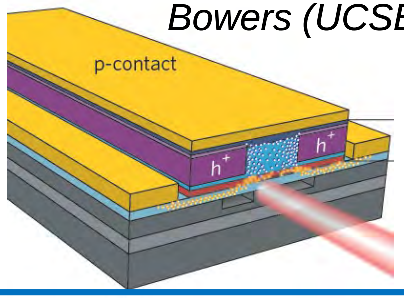
- **Energy**
  - Optical communication only need to charge the photodetector and transistor, not the interconnect line
- **Density**
  - (Dense) Wavelength Division Multiplexing: 40-80 channels per waveguide (1 μm pitch), equivalently 12.5~25 nm channel pitch >10 Gb/s

D. Miller, Proc. Of IEEE (2009)

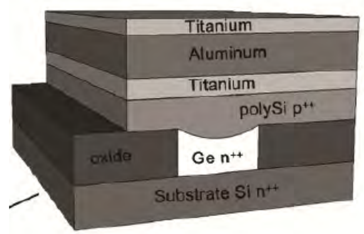
Status Quo of CMOS (silicon) integrated photonics

Laser

- Off-chip: fiber butt coupling, grating coupler
- On-chip: III-V, Ge, Q-dots



Bowers (UCSB)

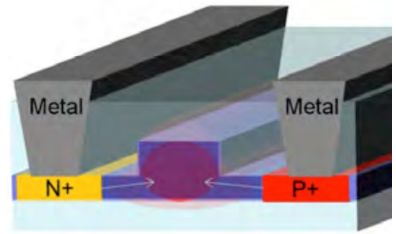


Kimerling (MIT)

Modulator

- Silicon: carrier injection/depletion
- III-V: FKE, QCSE
- Graphene

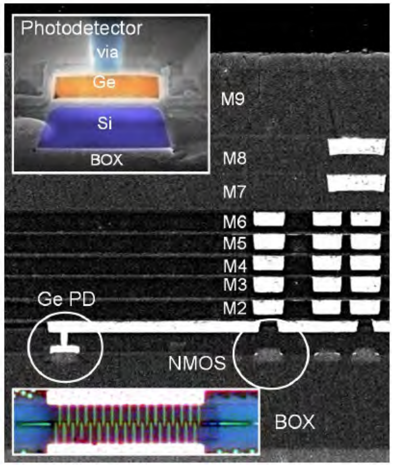
Reed(2010)



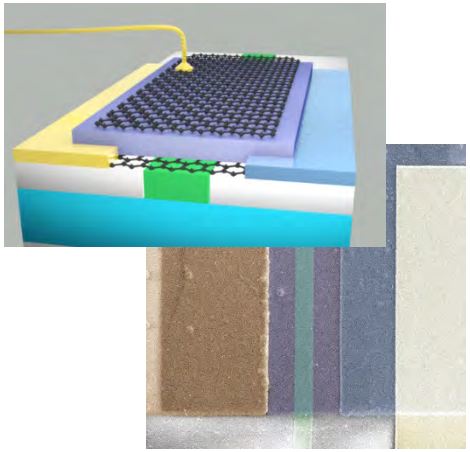
Assefa, IBM (2012)

Photodetector

- Ge, GeSi
- Graphene

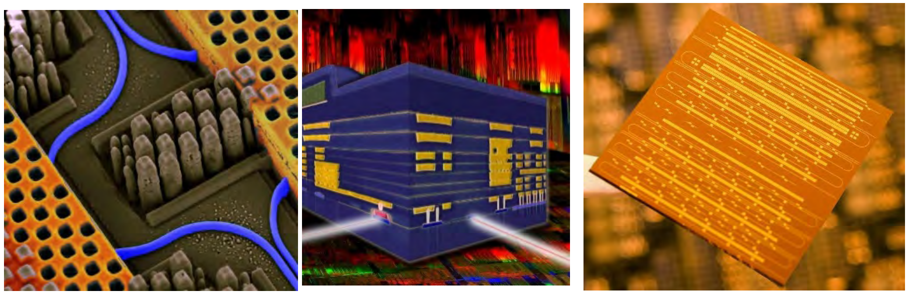


Assefa, IBM (2012)



Youngblood, UMN (2014)

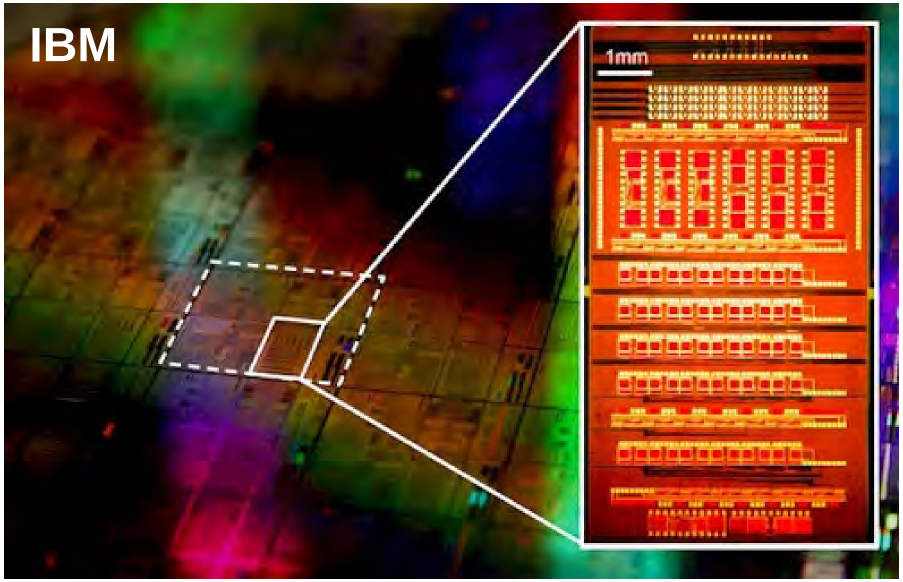
Waveguide (and integration)

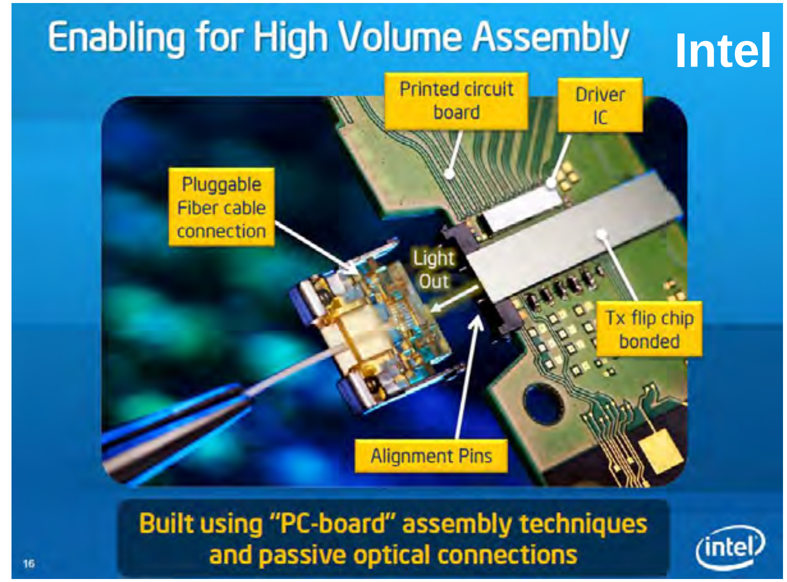


Intel (2010), IBM (2012)

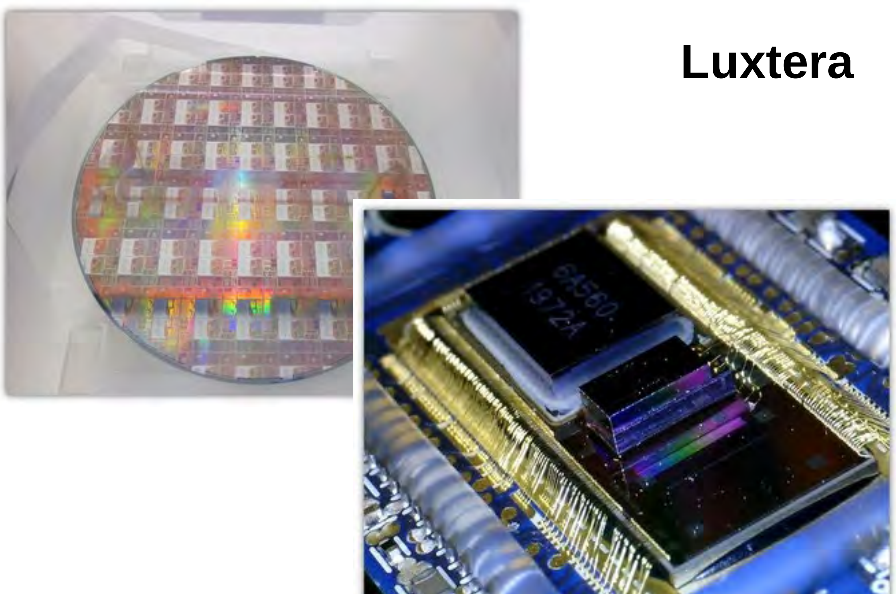
- 50 Gbps data link (Intel 2010)
- 90nm CMOS Integrated Nanophotonics: 25 Gbps WDM transceivers (IBM 2012)

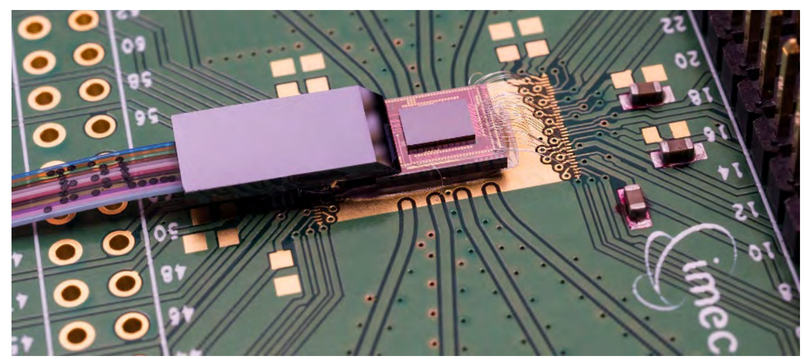
Silicon Photonics for 50-100 Gb/s Links





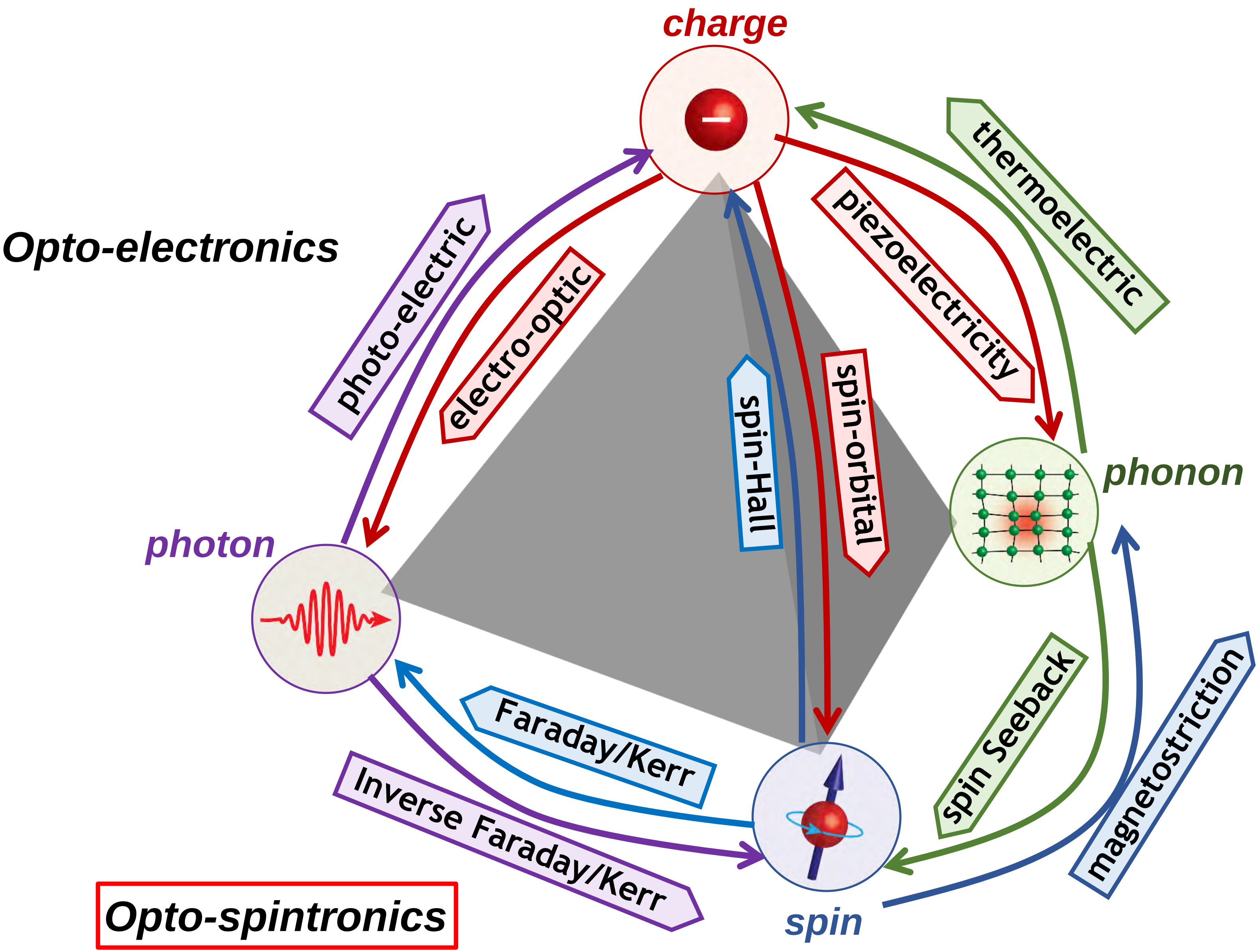
Luxtera





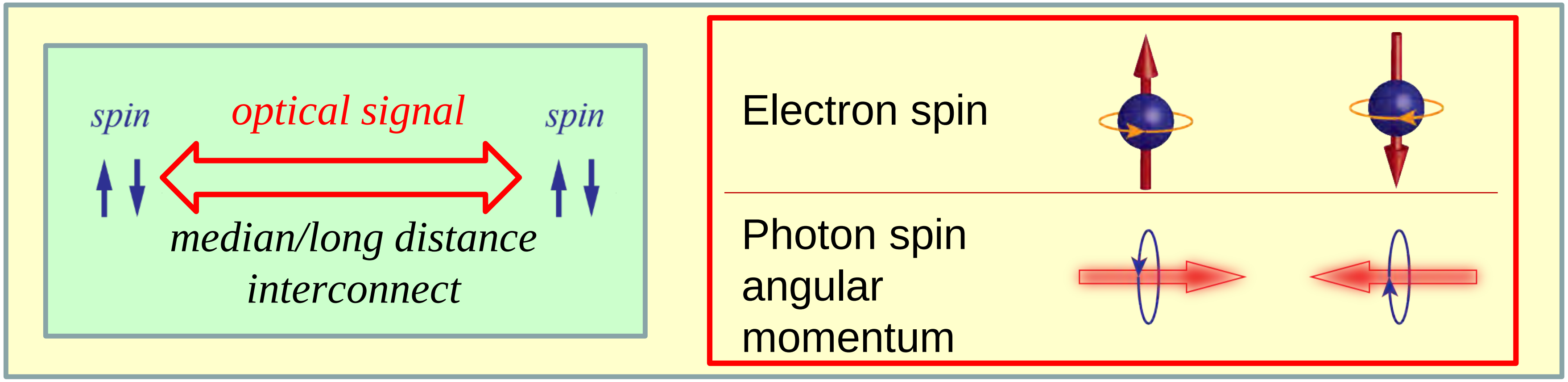
IMEC

From Opto-electronics to Opto-spintronics



Spin optical conversion for optical interconnnect

- Leveraging the state-of-the-art development of silicon photonics, this project aims to building integrated optical interconnect for spin computation.

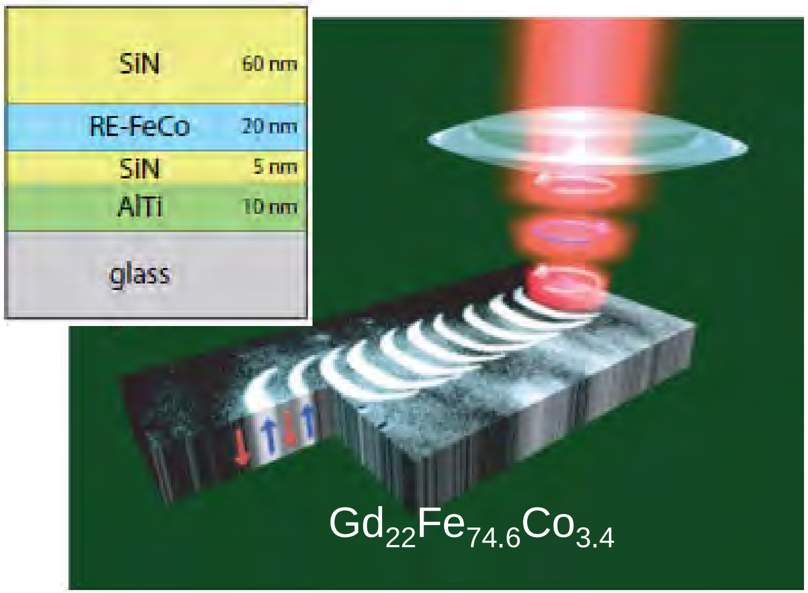


Addressing the following challenges:

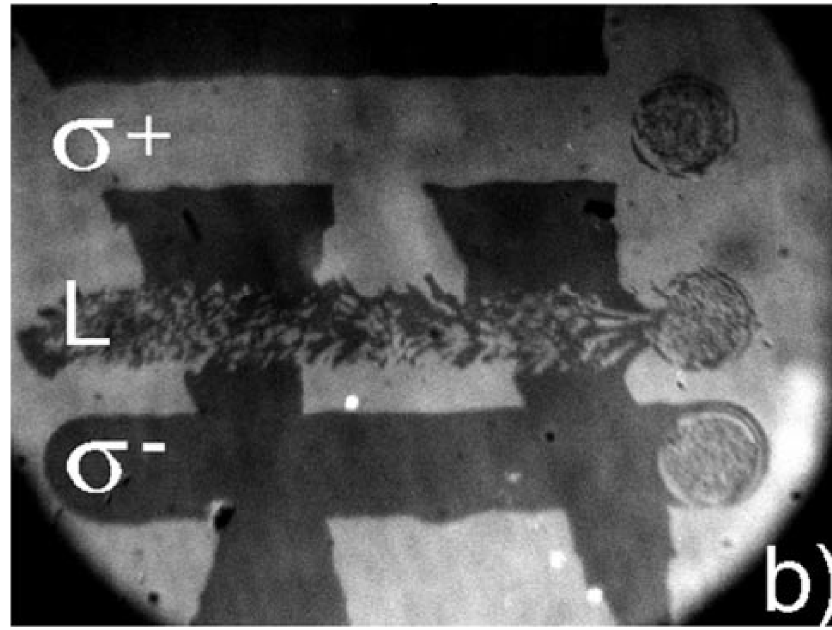
- Long distance direct communication of spin bits
- Ultrafast (sub-picosecond) optical switching of magnetization
- Large-scale integration of spintronics with silicon photonics

<u>Mission</u>: To build integrated optical interconnect for long range direct communication of spin information to address the energy, bandwidth and energy issues in spin-based and hybrid computation systems.

All-optical switching (AOS) with femtosecond laser pulses in ferrimagnetic GdFeCo



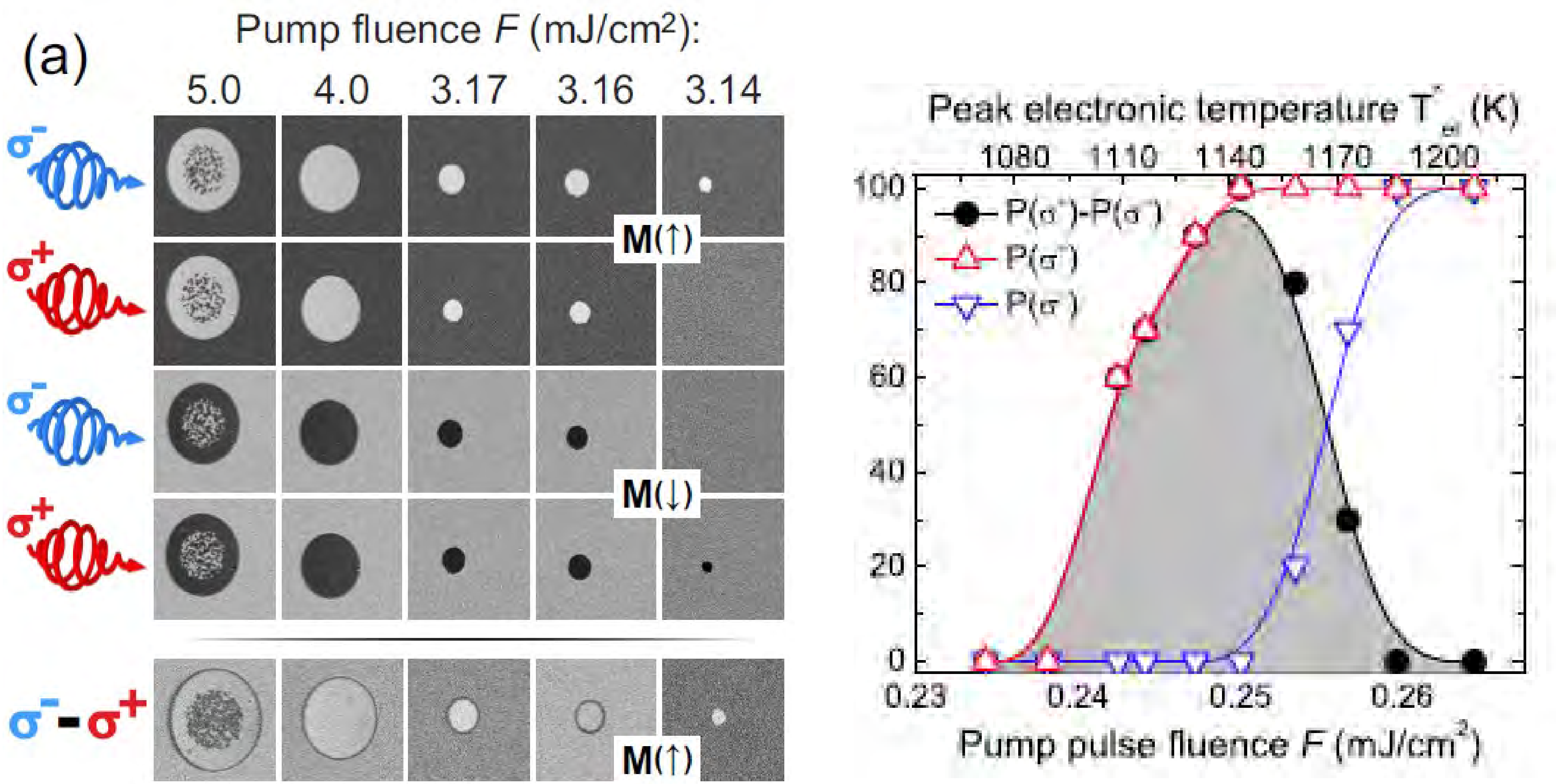
Rasing/Kimel group
Radboud University, Nijmegen



Stanciu et al., *Phys. Rev. Lett.* **99**, 047601 (2007).

- Sweeping femtosecond (40 fs) laser pulses can reverse magnetization without magnetic field
- Switching is deterministic and helicity dependent
- A critical range of fluence between ~2-5 mJ/cm^2, below which, no switching, above which, thermal demagnetization

Sub-picosecond all-optical switching (AOS) in ferrimagnetic materials

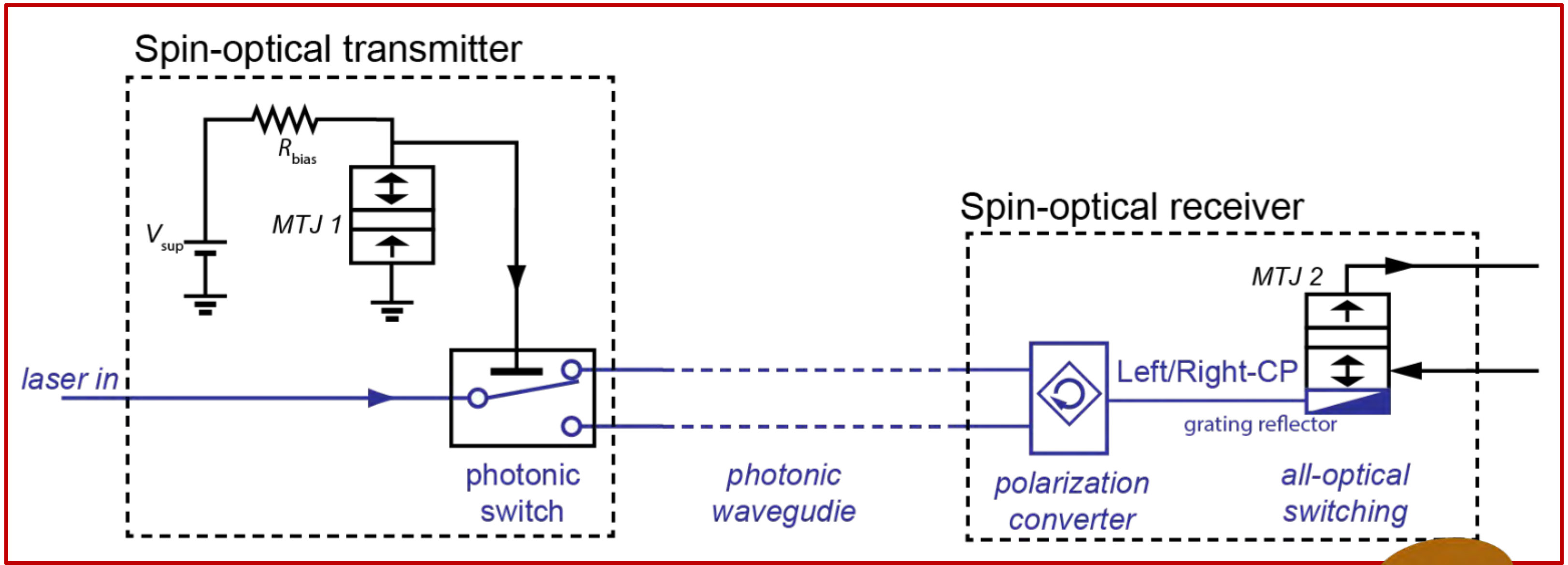


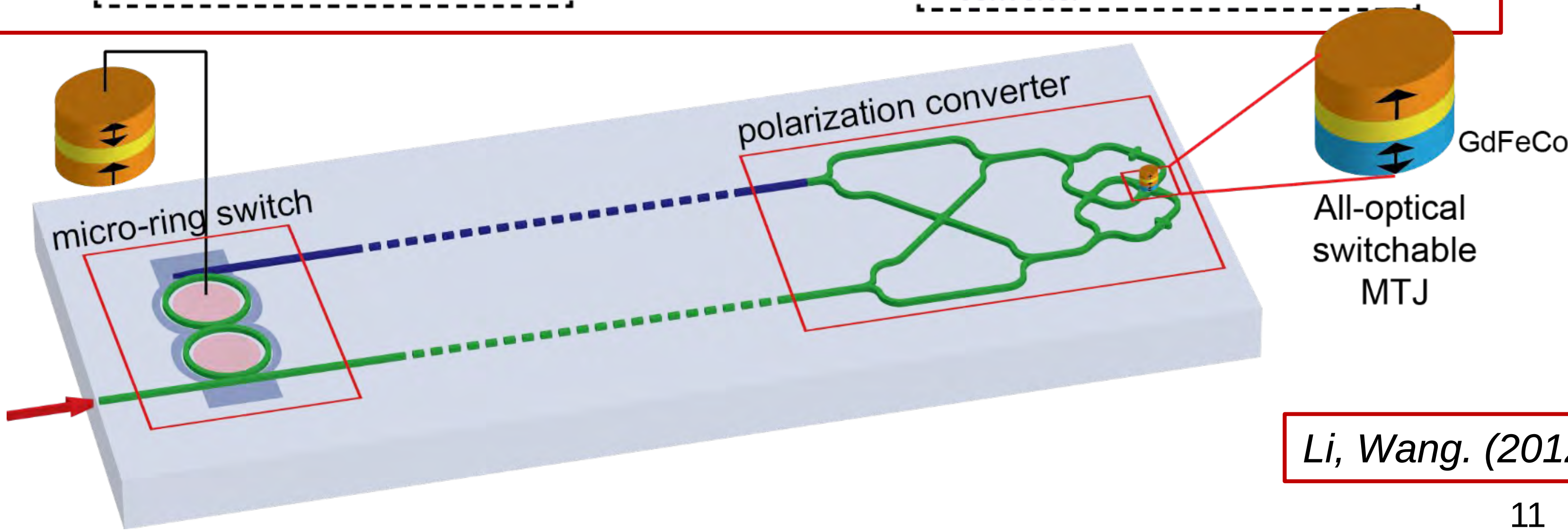
Rasing/Kimel group, Radboud University, Nijmegen

- Single laser pulse switching
- A pulse fluence window, within which deterministic, helicity dependent switching occurs. Above the window, helicity independent switching.

Scheme of Spin-Optical Interconnect

1. Spin bits is encoded into the pathways (two) of optical pulses through an 1x2 optical switch.
2. Linear polarized optical pulses are converted to left or right circular polarized pulses.
3. Circular polarized optical pulses switch the spin (and MR) states of a MTJ

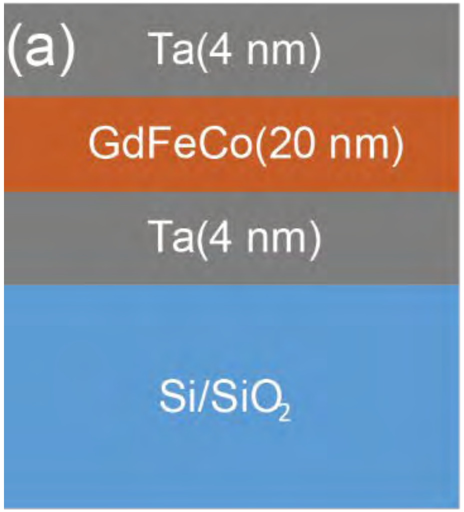


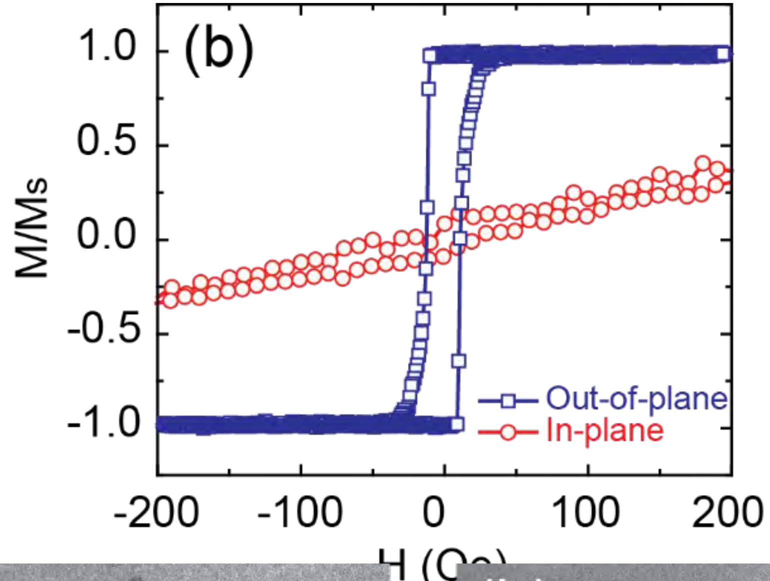


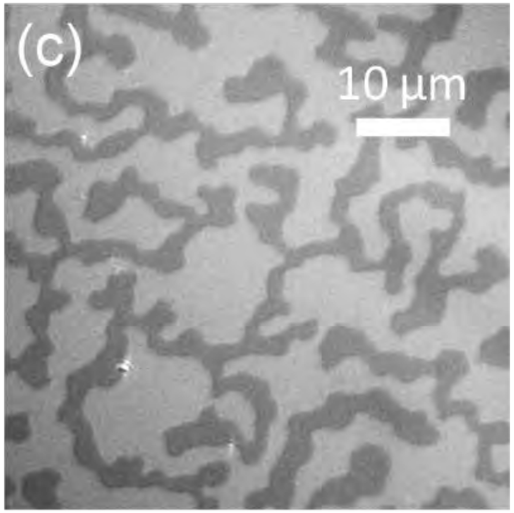
Li, Wang. (2012)

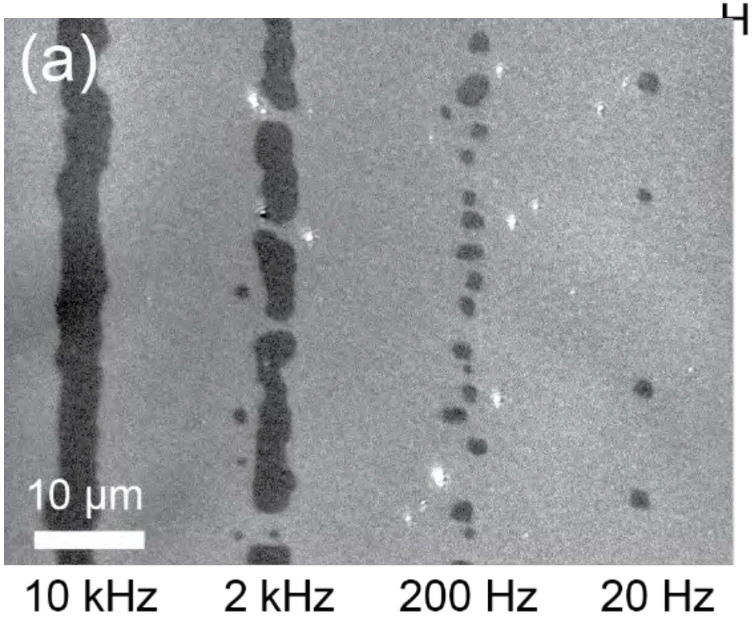
Irreversible AOS in $Gd_{0.3}(Fe_{90}Co_{10})_{0.7}$

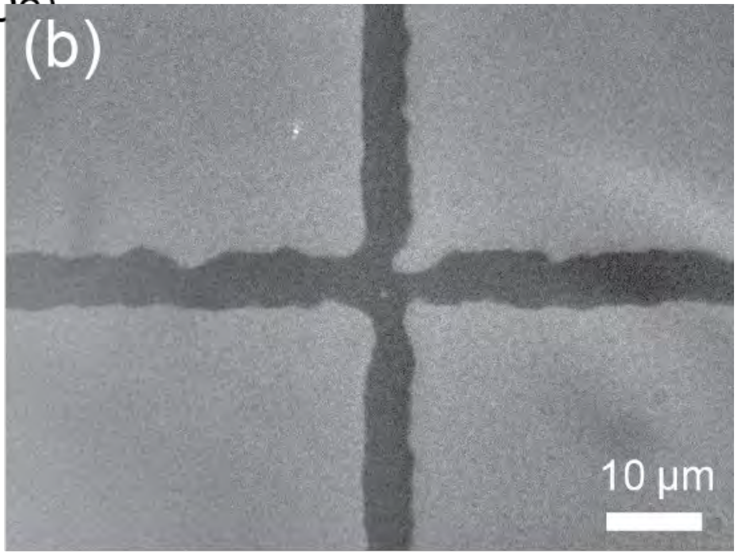
Li, et. al. App. Phys. Lett. (2015)



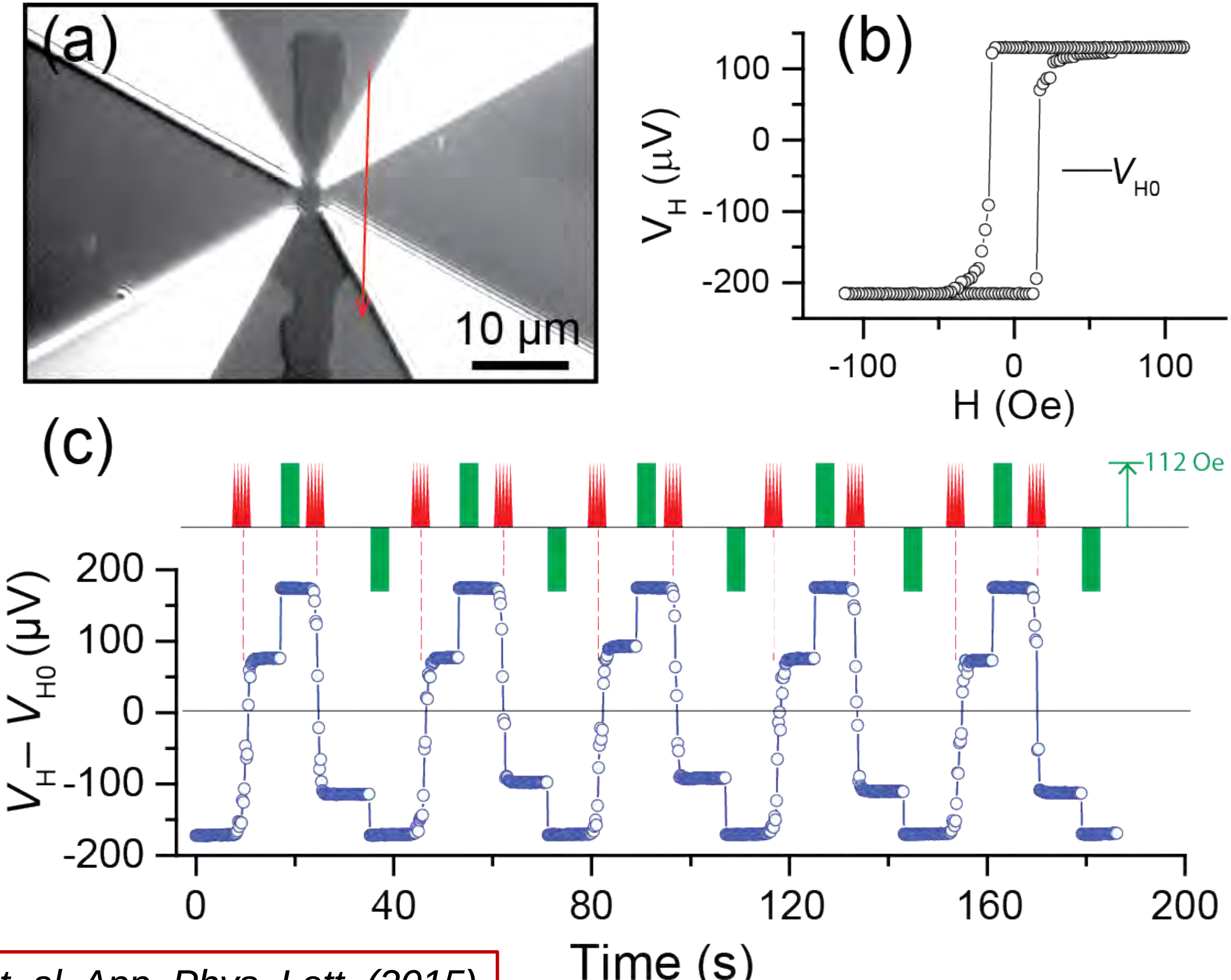








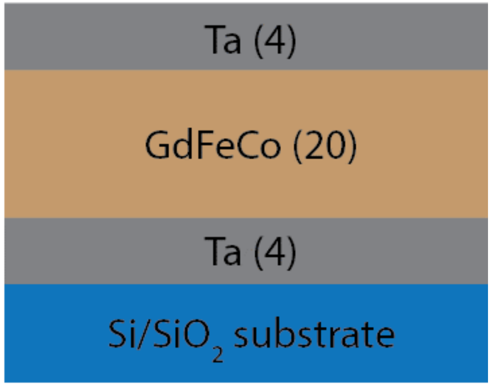
AHE readout of accumulative, partial switching

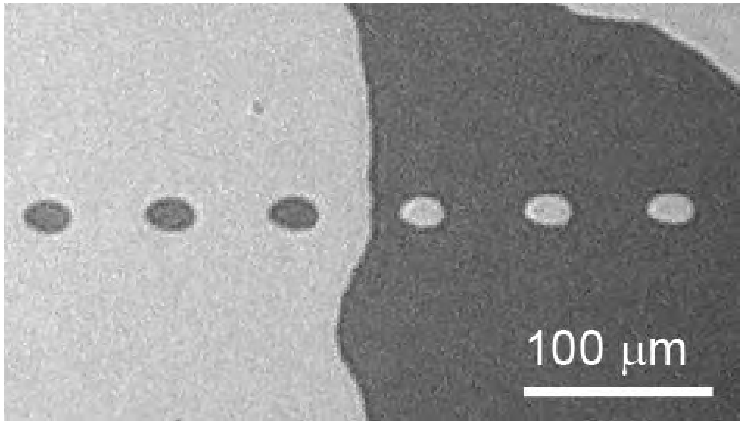


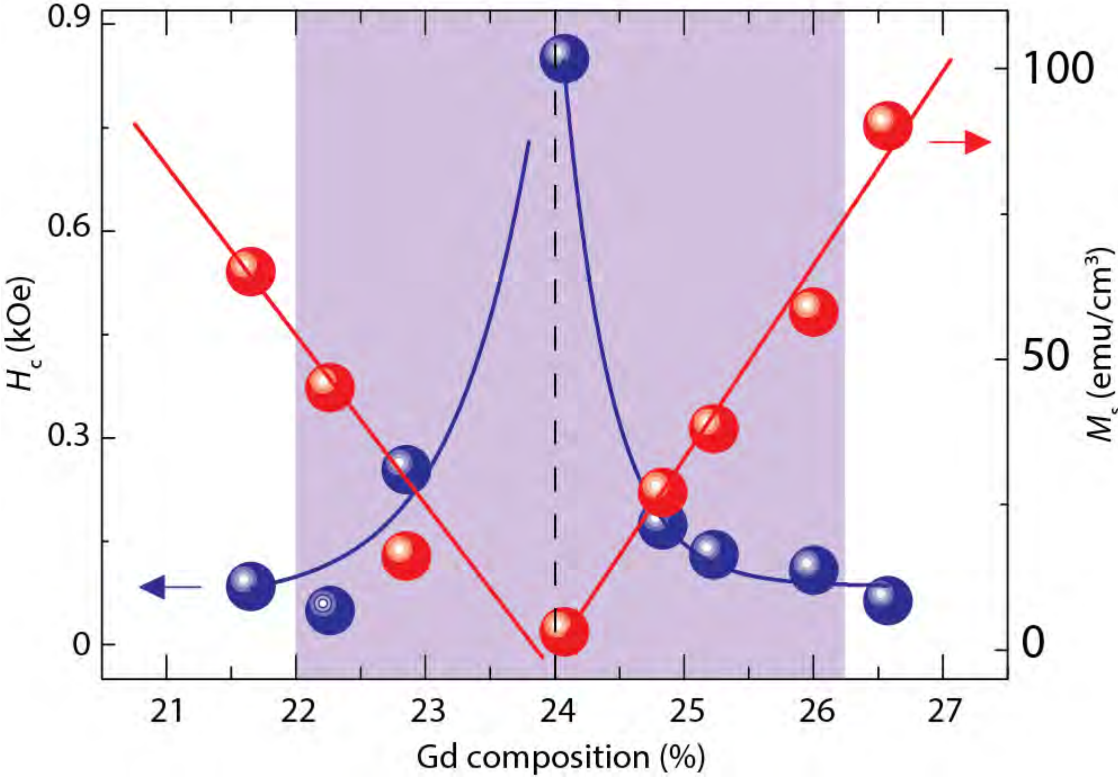
Li, et. al. App. Phys. Lett. (2015)

Switching magnetization with single <u>infrared</u> laser pulses

Chen, et. al. Phys. Rev. Appl. 7, 021001 (2017)



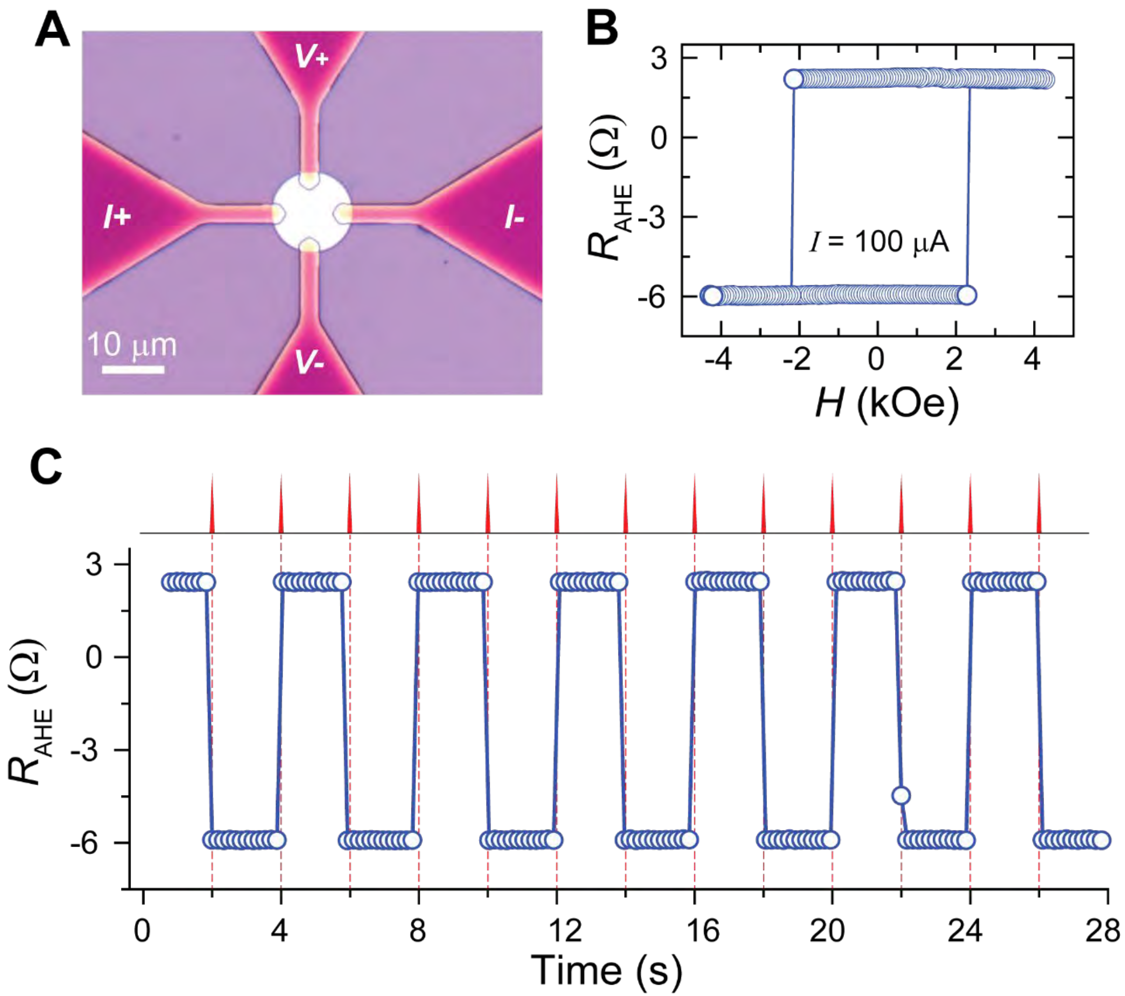




- Single 0.5 ps infrared laser pulse switching of GdFeCo film
- Switching is independent on laser polarization

GdFeCo is a robust system for optical switching. Switching is by single shot of laser pulse, not cumulative of multiple pulses

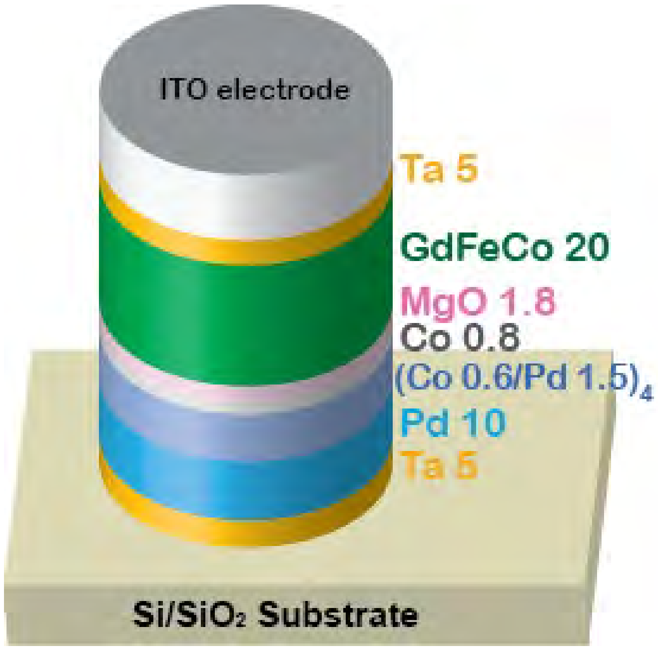
Magnetoelectric readout with Anomalous Hall resistance

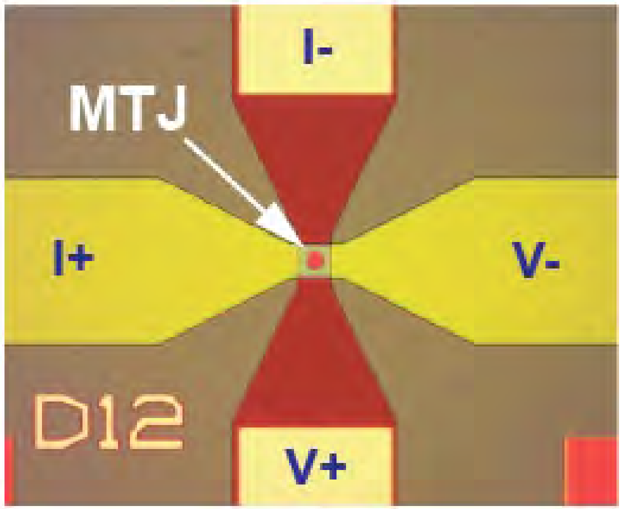


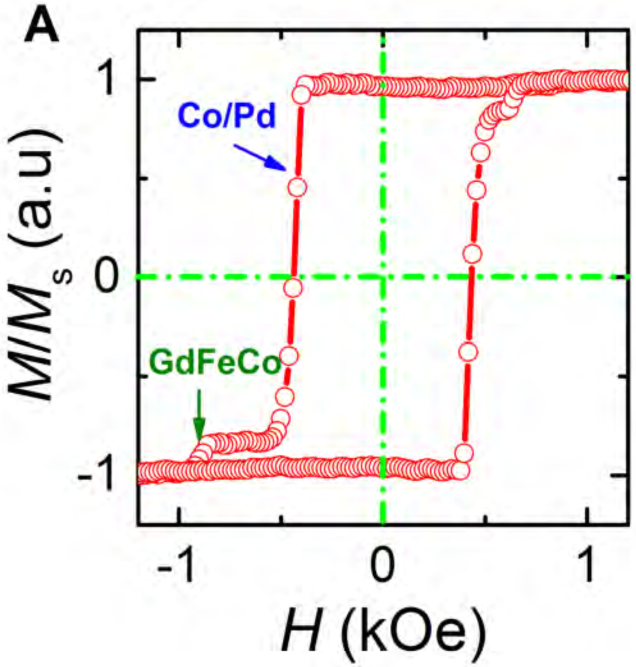
Chen, et. al. Phys. Rev. Appl. 7, 021001 (2017)

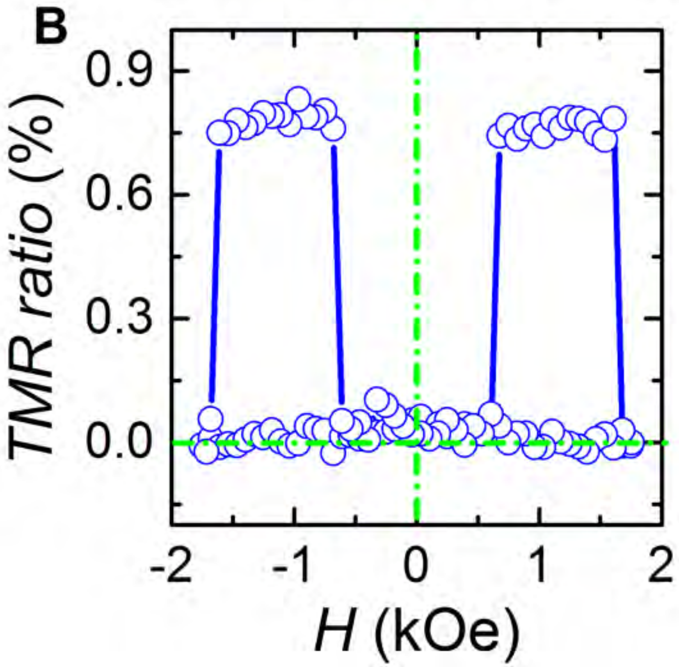
- Readout optical switching in real time by measuring Hall resistance.
- **Optical switching of the GdFeCo pillar is complete by comparing with the magnetic field measurement.**

GdFeCo/MgO/CoPd MTJ



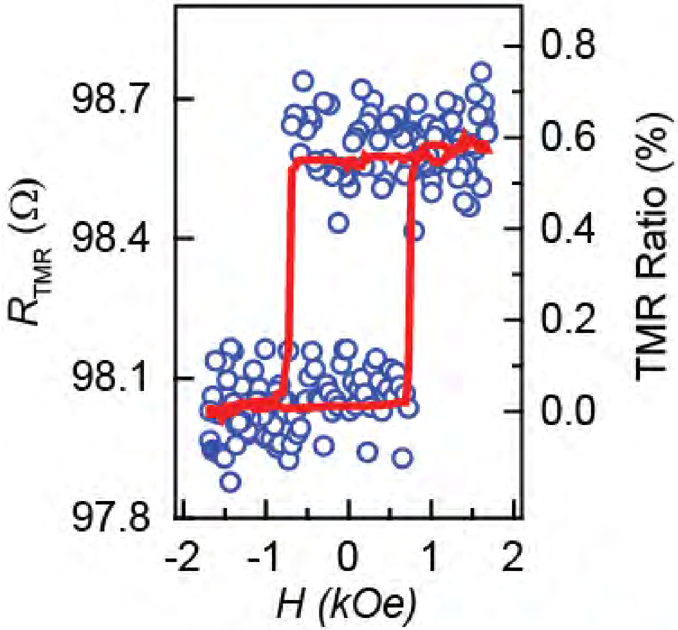


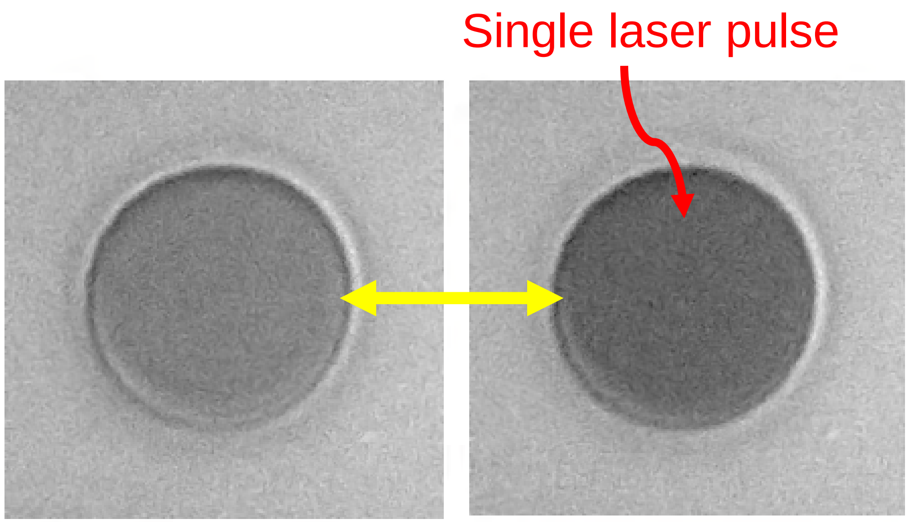


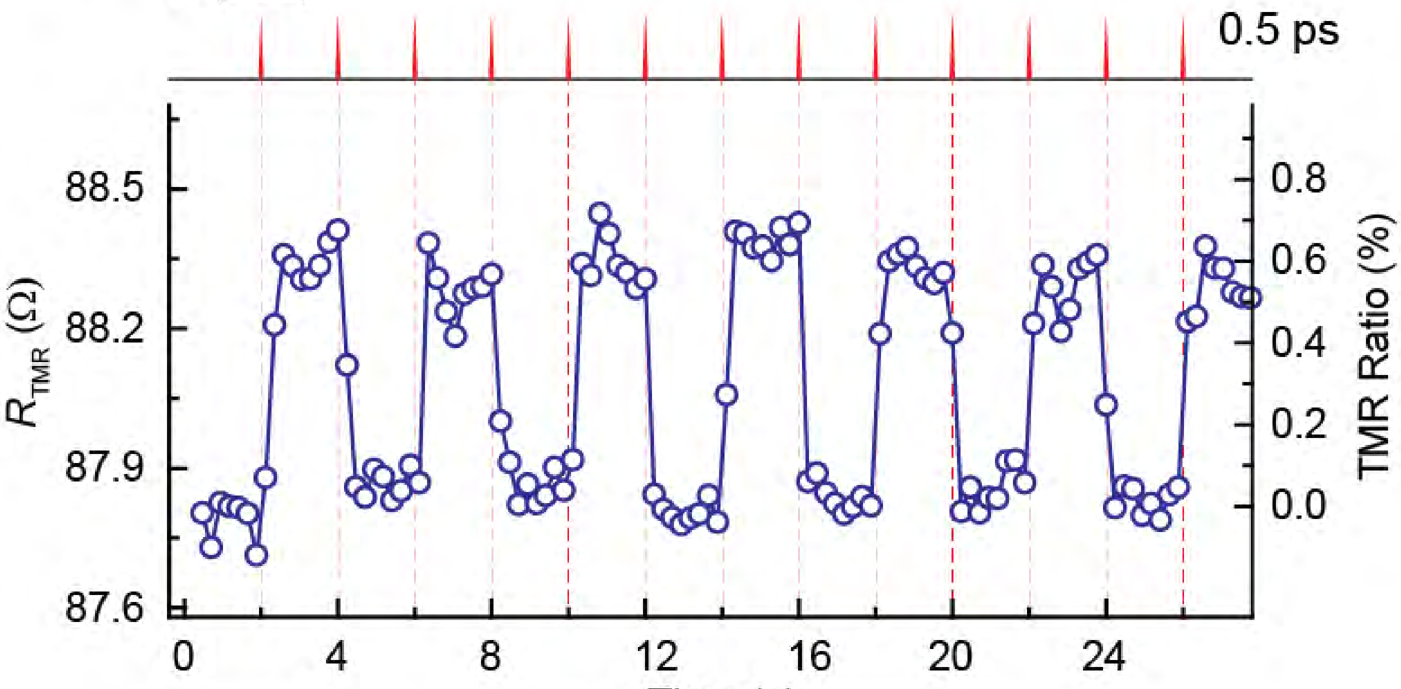


Chen, et. al. Phys. Rev. Appl. 7, 021001 (2017)

Sub-picosecond switching of MTJ and TMR measurement

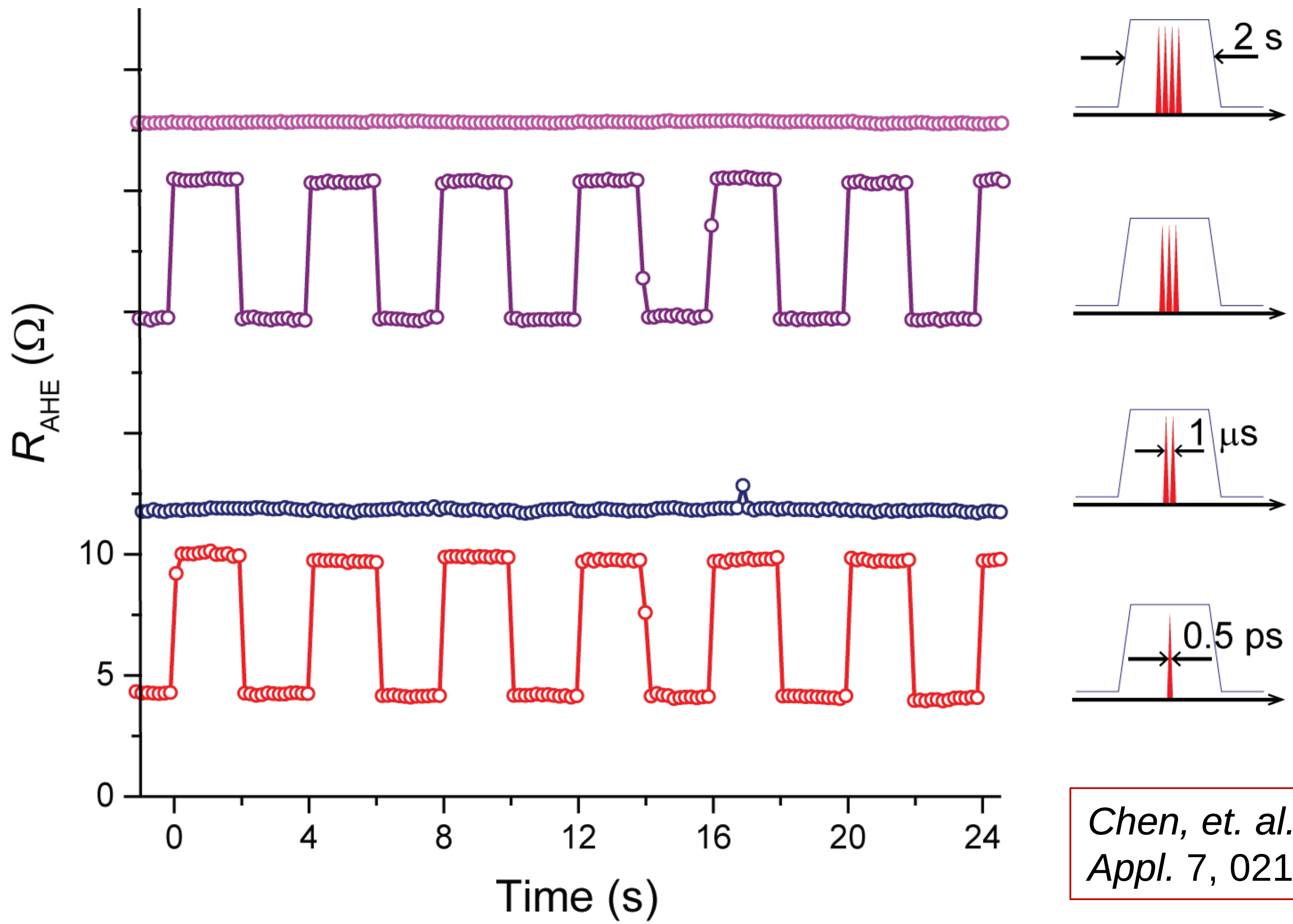






Chen, et. al. Phys. Rev. Appl. 7, 021001 (2017)

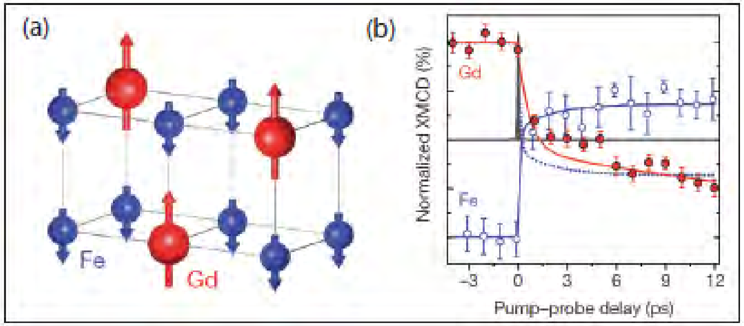
How fast can AOS be repeated?

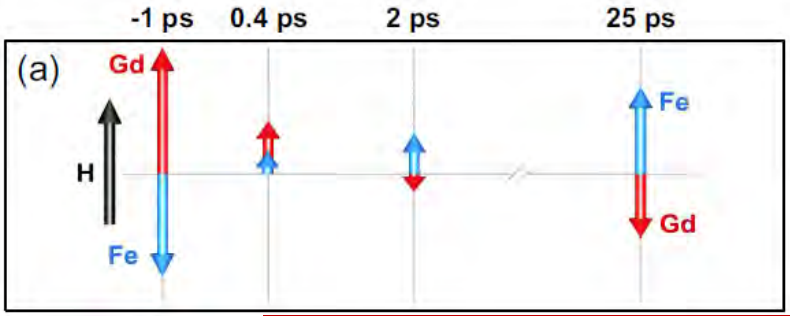


Chen, et. al. Phys. Rev. Appl. 7, 021001 (2017)

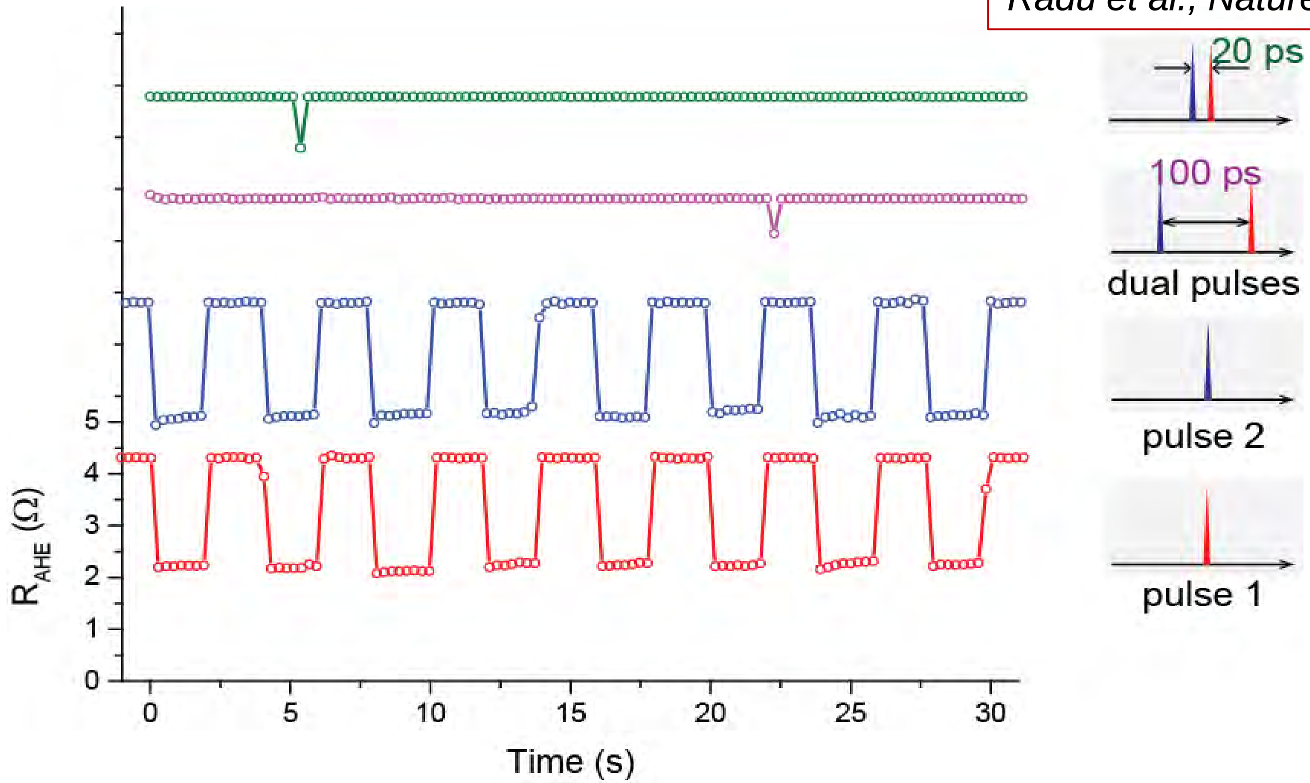
- **AOS repetition rate of 1MHz is demonstrated, limited by the laser repetition rate.**

What's ultimate repetition rate?



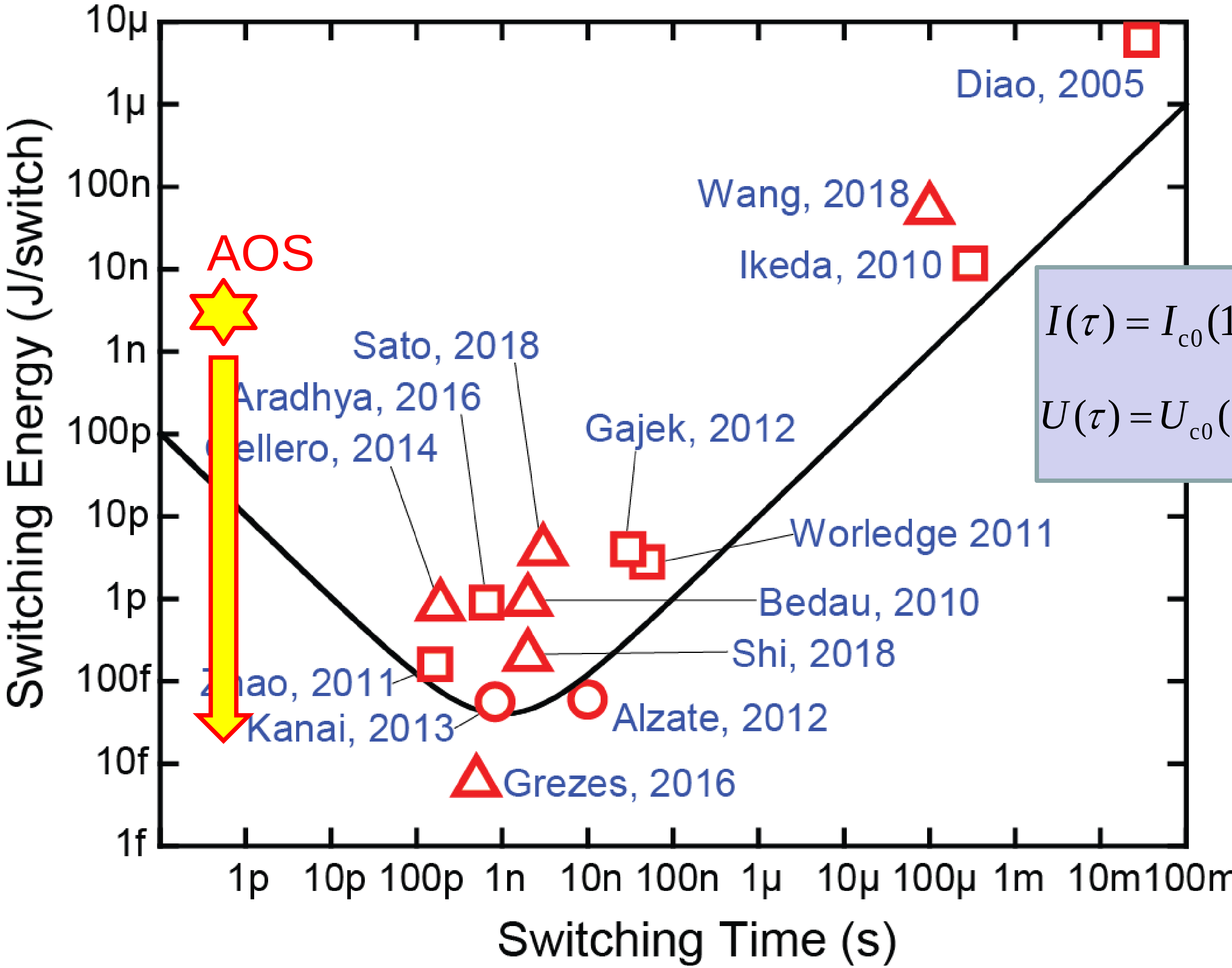


*Radu et al., Nature **472**, 2015 (2011)*



- **Second switching can be sooner than 20 ps before the system reaches equilibrium.**

Energy-time of switching a MTJ



$$I(\tau) = I_{c0}(1 + t_{c0}/\tau)$$

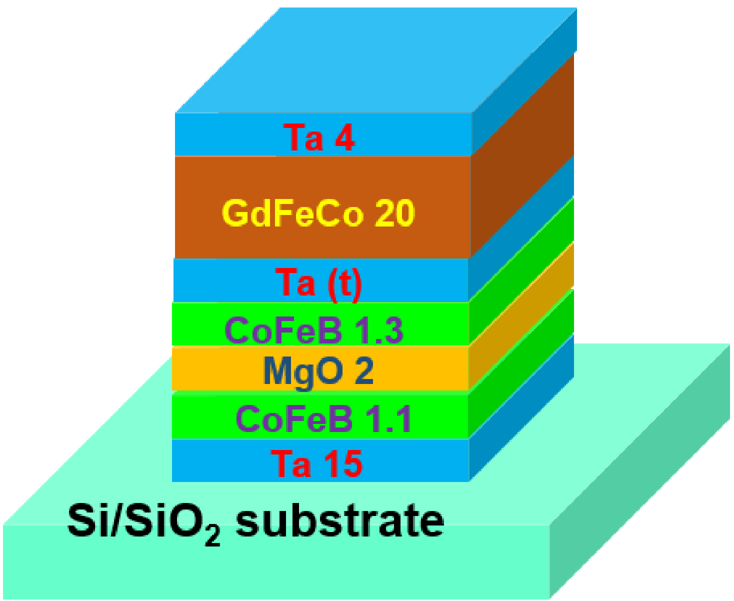
$$U(\tau) = U_{c0}\left(2 + \frac{\tau}{t_{c0}} + \frac{t_{c0}}{\tau}\right)$$

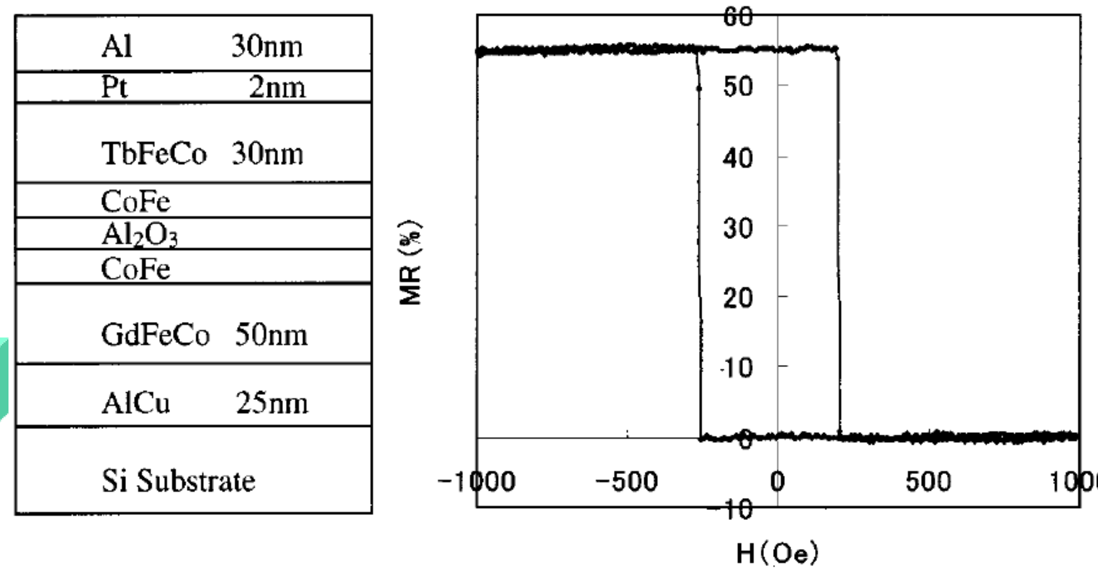
A. Kimel, M. Li (2018)

To Improve the TMR ratio of the MTJ

Add CoFe or CoFeB layers between GdFeCo and barrier layer can dramatically increase MR.

We aim to exchange couple CoFeB layer with the GdFeCo to increase TMR.





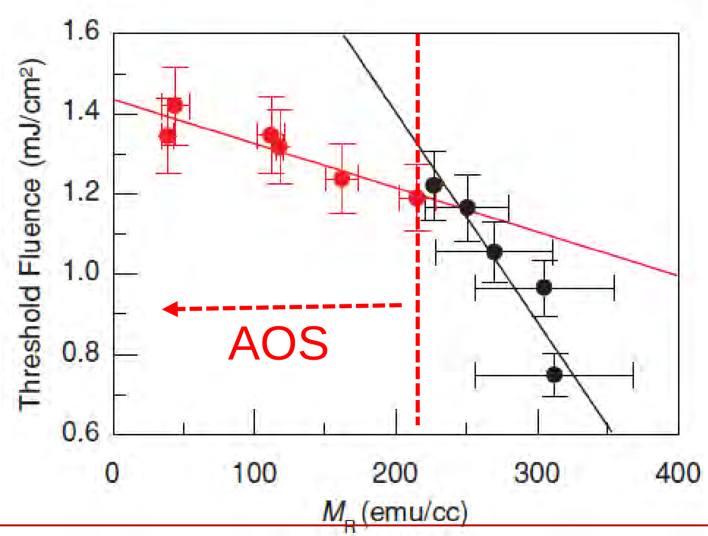
Nishimura et al., *J. App. Lett.* **91**, 5246 (2002).

No fundamental reason that the TMR of optically switchable MTJ cannot be higher.

Need to reduce optical energy requirement

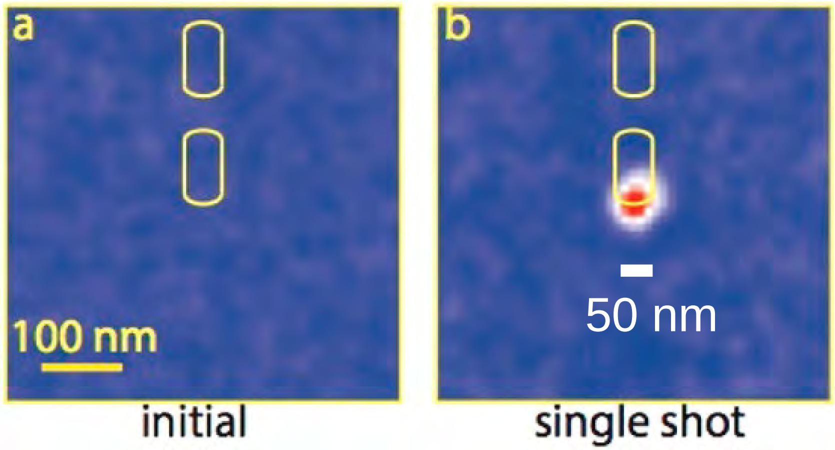
- Reduce the switching area to reduce required optical energy
- Increase optical absorption in the magnetic layer
- New materials may appear with much lower switching threshold

AOS requires a fluence of >1 mJ/cm^2



Hassdenteufel et al., *Adv. Mat.* **25**, 3122 (2013)

Use plasmonic antenna to create sub-diffraction limit switching spot

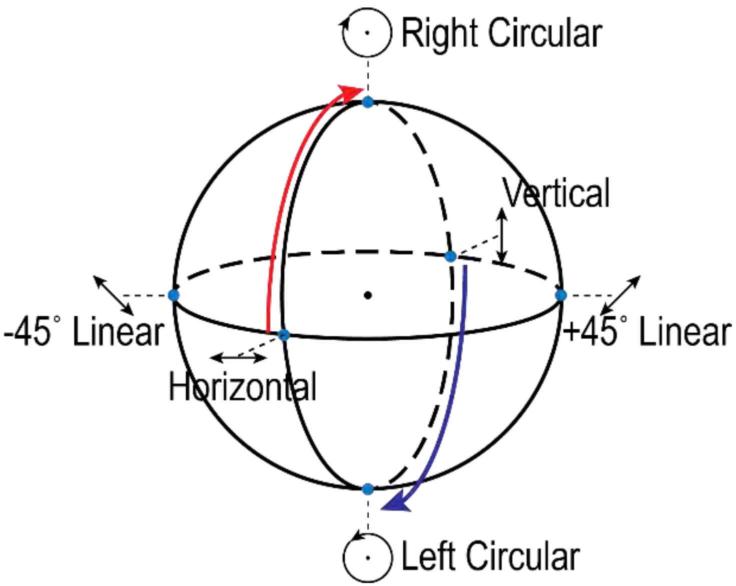


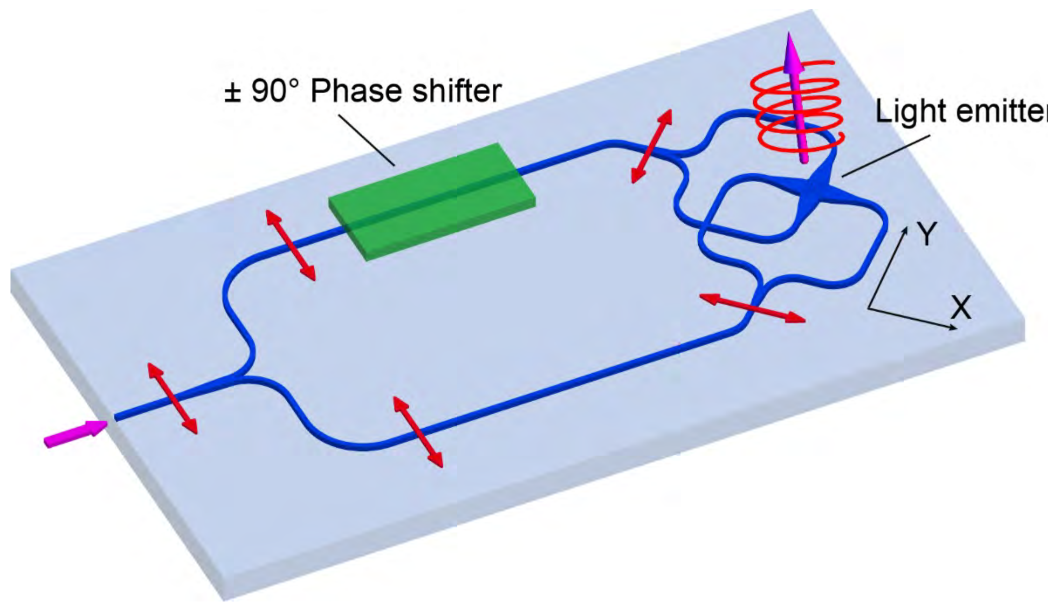
Liu et al., *Nano Lett.* **15**, 6862 (2015).

- **With 20nm diameter MTJ and using plasmonic nano-antenna, optical switching energy can be reduced to 3 fJ/bit.**
- **To be competitive in energy cost, need to combine the best of everything**

On-chip Synthesis of Circularly Polarized Light

- Scheme to synthesize circular polarization state from linear polarization eigenmode of integrated waveguides to circumvent the birefringence issue.

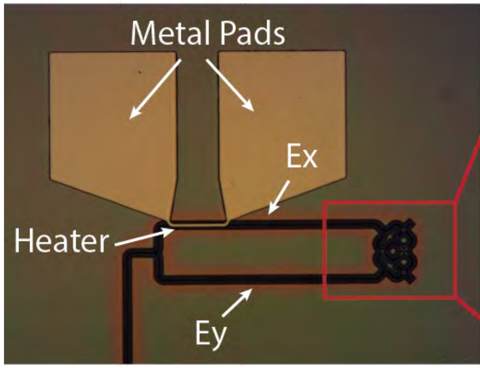




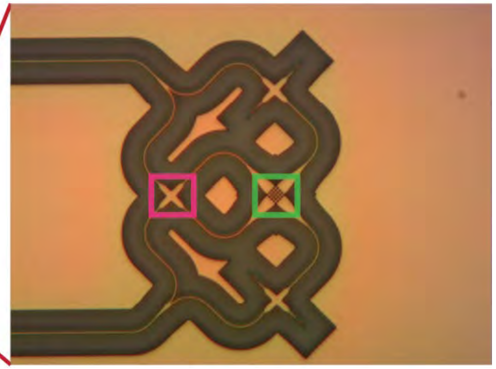
- **Circular polarized light can be deterministically synthesized from linearly polarized mode of a single-mode waveguide only at the spot it is needed (to optically switch).**

On-chip synthesis of Circularly Polarized Light

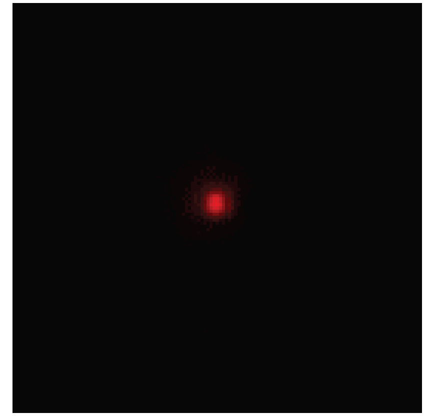
(a) Phase shifting heater

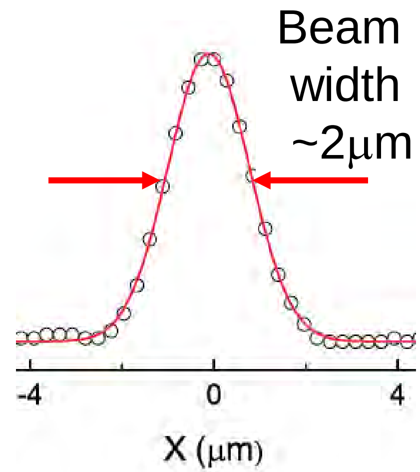


(b)

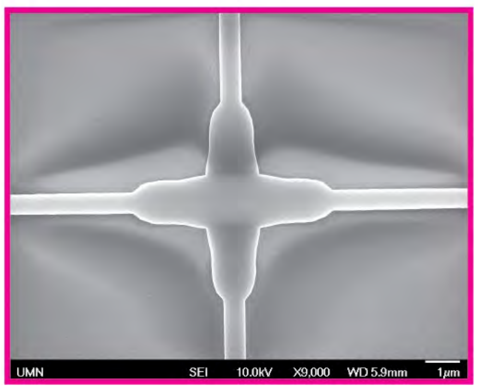


IR Camera Image

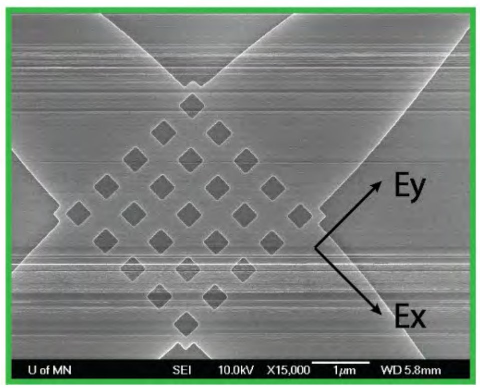




(c) Waveguide crossing

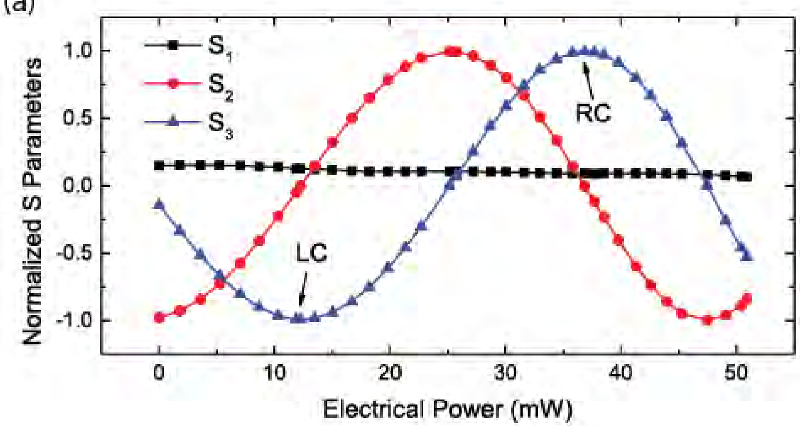


(d) 2D grating coupler



Measured Stokes Parameters

(a)

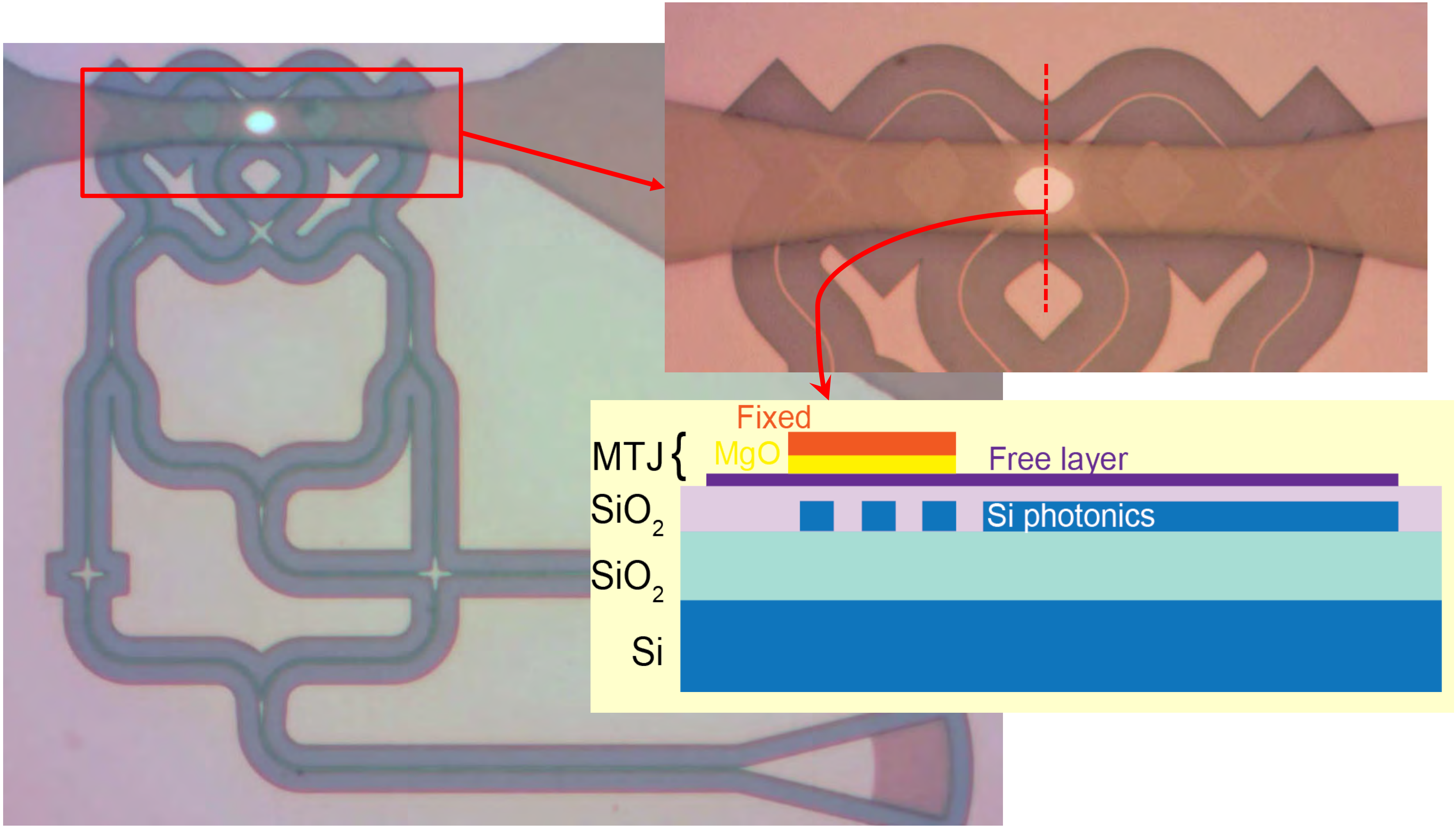


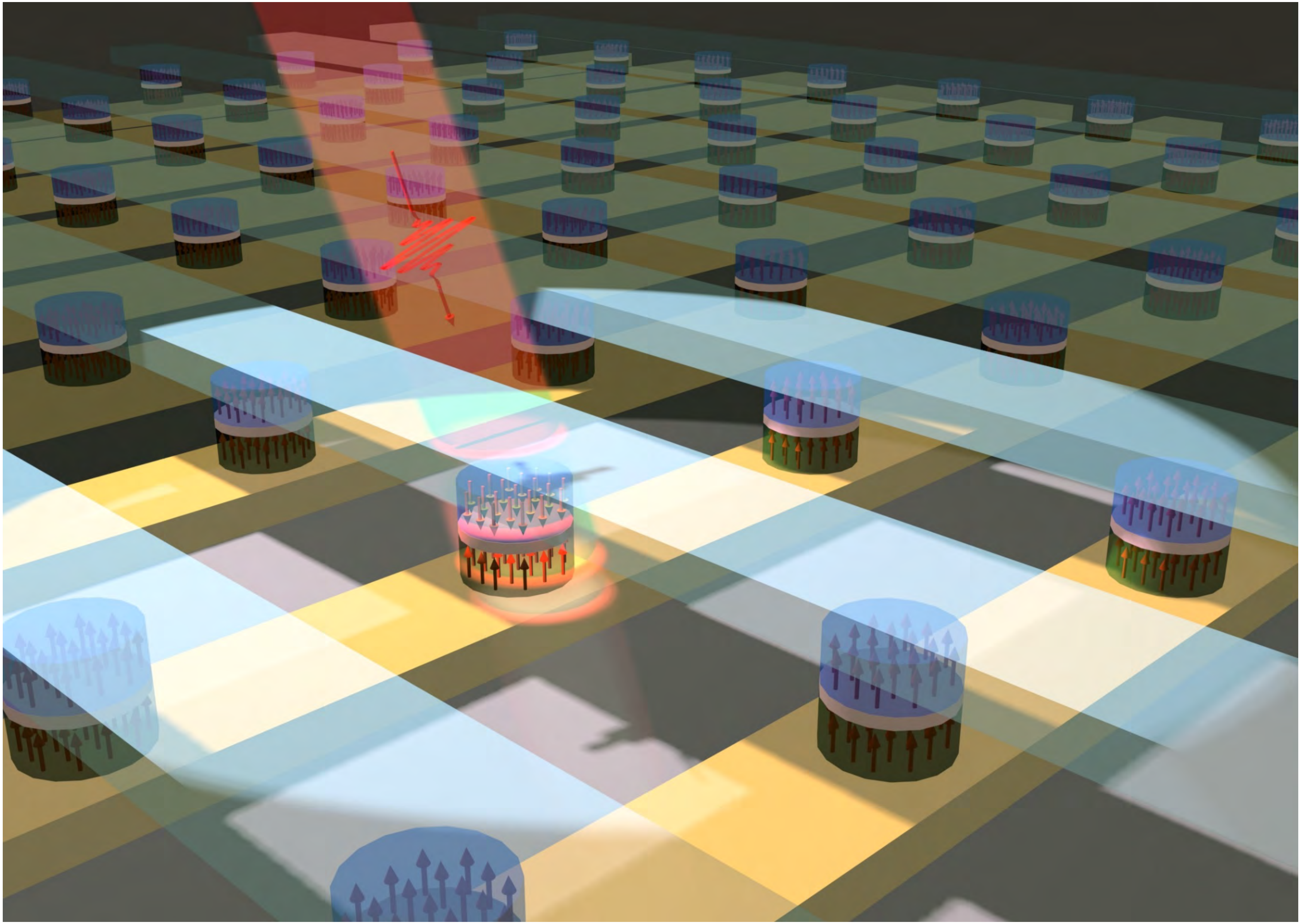
99% degree of circular polarization can be synthesized on-chip.

L. He, M. Li, Opt. Lett. ***39****, 2553 (2014)*

Integration with Silicon Photonics

MTJ on silicon photonics





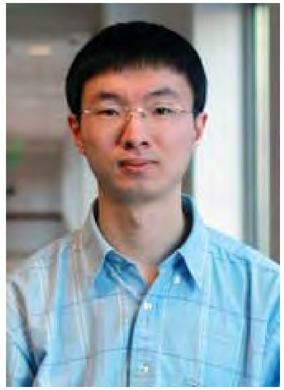
Summary and Outlook

- The demonstrated optically switchable MTJ is the first of its kind that convert optical signal directly to magnetic state.
- The picosecond switching time set a new record of switching spintronic devices.
- The device can be used as the receiver for spin-optical interconnect.
- The device is switchable by infrared light so compatible with silicon photonics and fiber optics for integration.
- The device is also an optical memory.

- **In addition to what we have proposed, there may be surprisingly new application of this novel opto-spintronic device.**

Group members, Collaborators and Sponsors

Prof. Jian-Ping Wang



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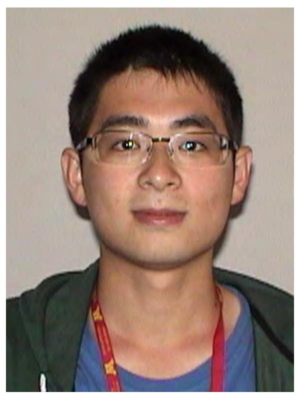

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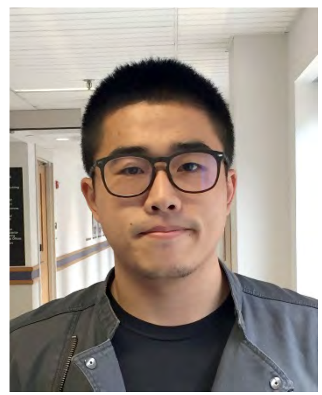

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