

SPICE 2026



Ferron Transport in Ferroelectrics and its Potential Application in MESO Devices

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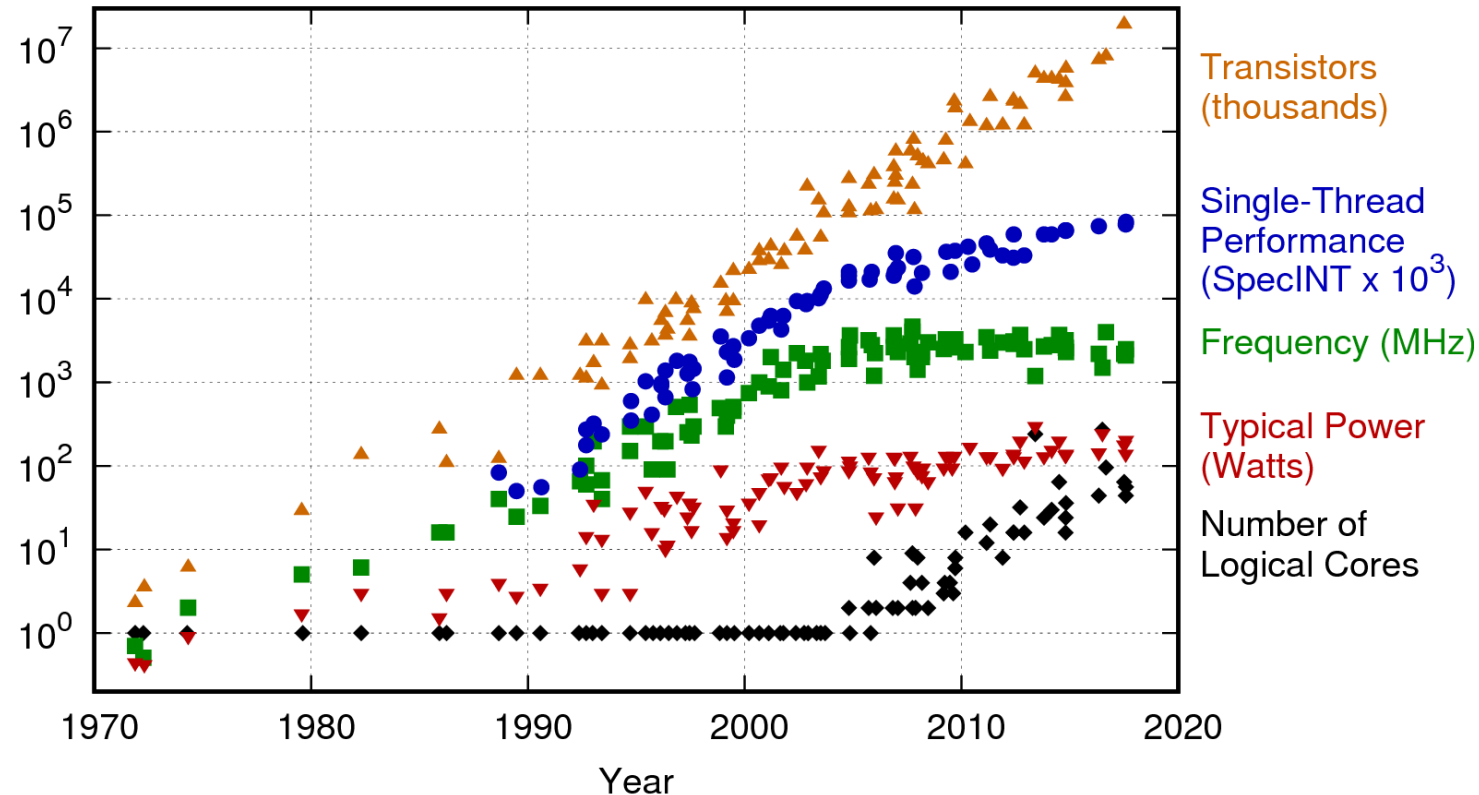
07/07/2026

From CMOS to MESO: Beyond Moore's Law

2

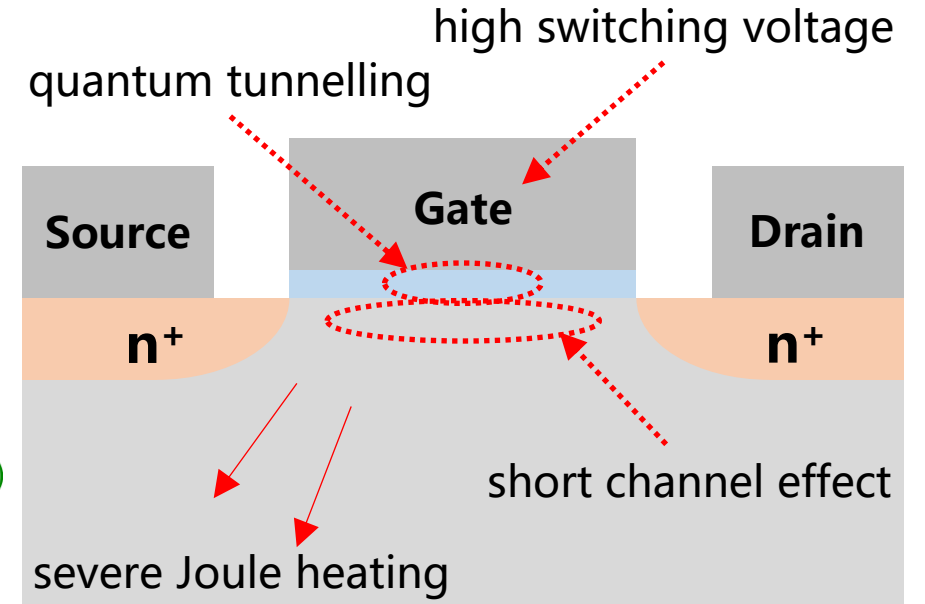
The decelerating Moore's law

42 Years of Microprocessor Trend Data



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2017 by K. Rupp

CMOS technical bottlenecks



Now hard to scale down!!

- ☹ *leakage current*
- ☹ *high switching voltage (~ 1 V)*
- ☹ *volatile*

Alternatives are needed!

1

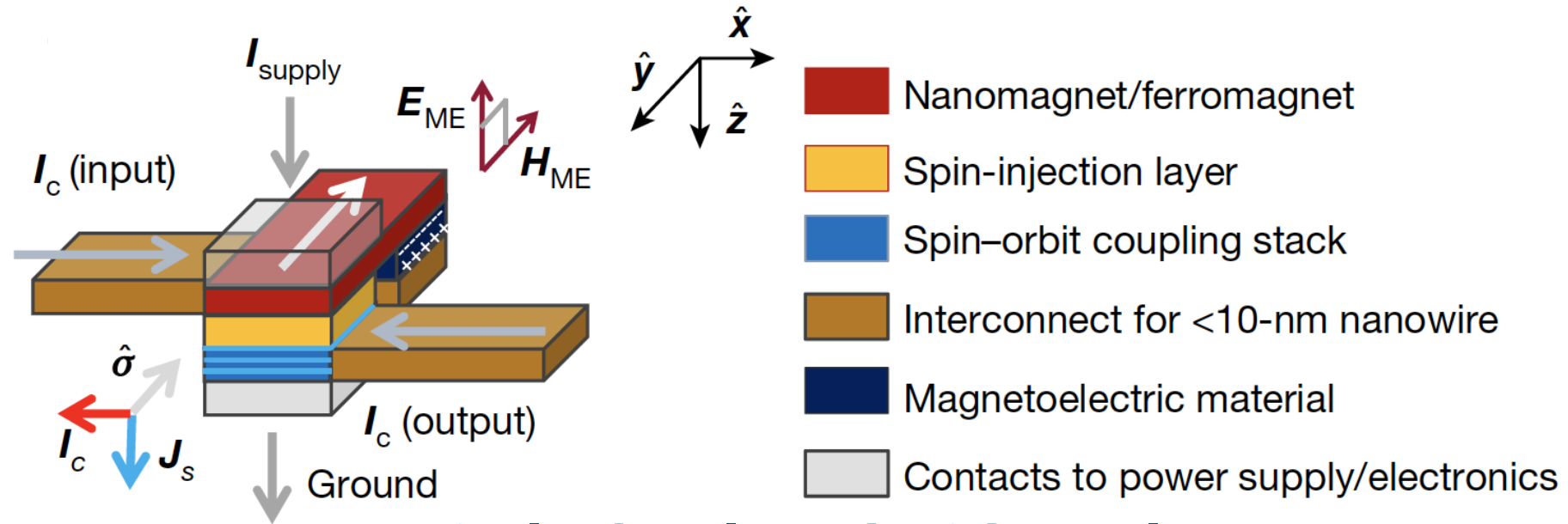
Magnon-mediated MESO Device

2

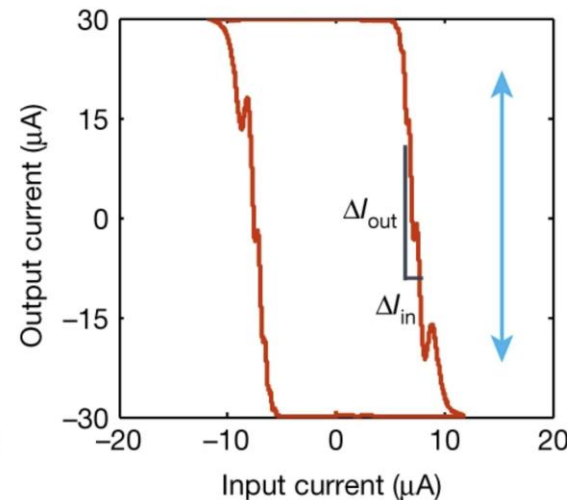
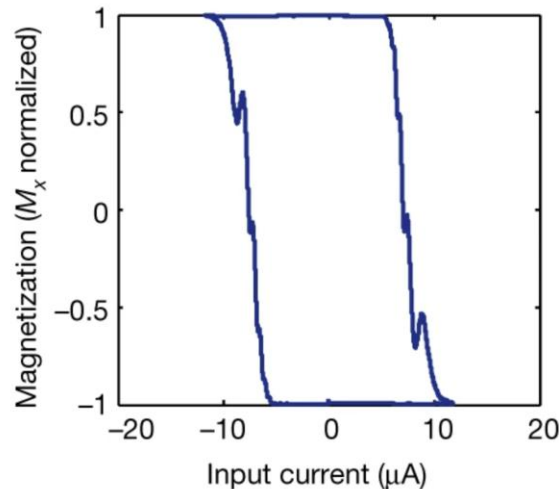
Ferron Transport for Potential MESO Applications

Magnetoelectric Spin-orbit (MESO) Device

4



Jointly developed with Intel

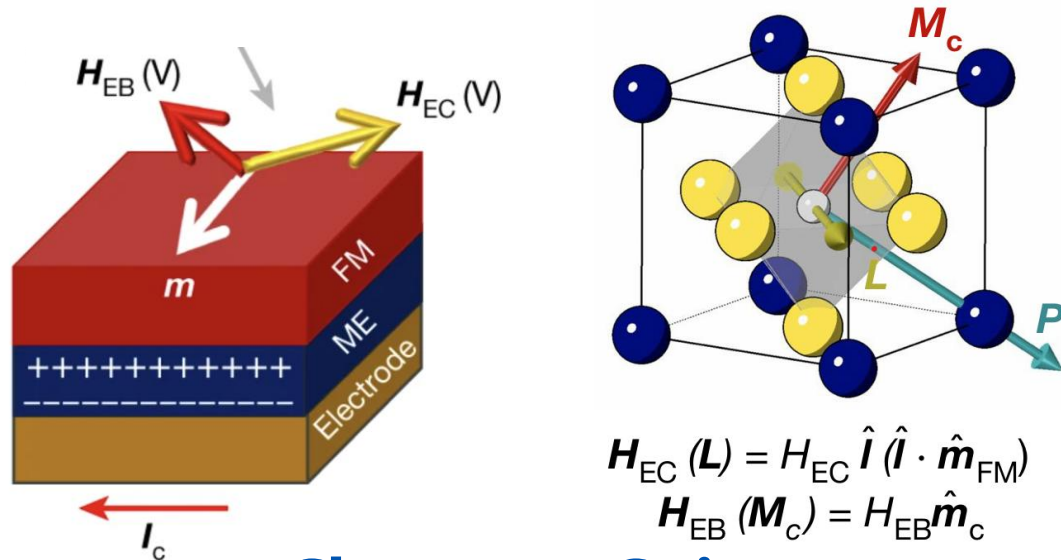
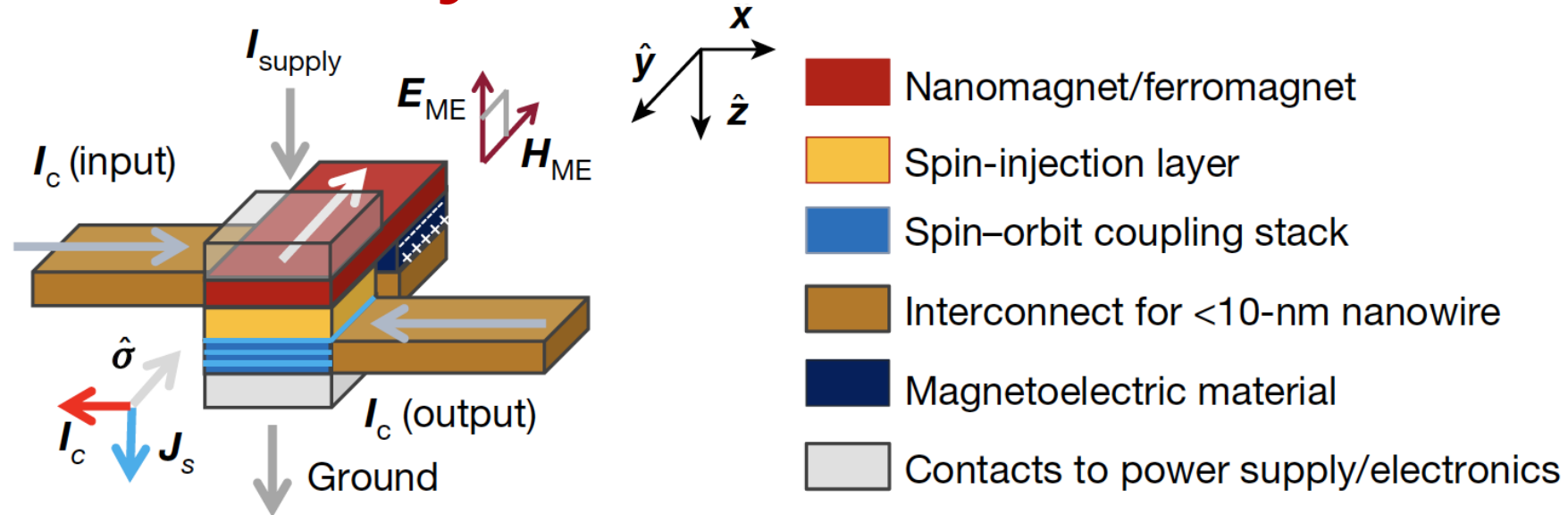


- ☺ *low switching energy (1-10 aJ)*
- ☺ *low switching voltage (0.1 V)*
- ☺ *non-volatile*

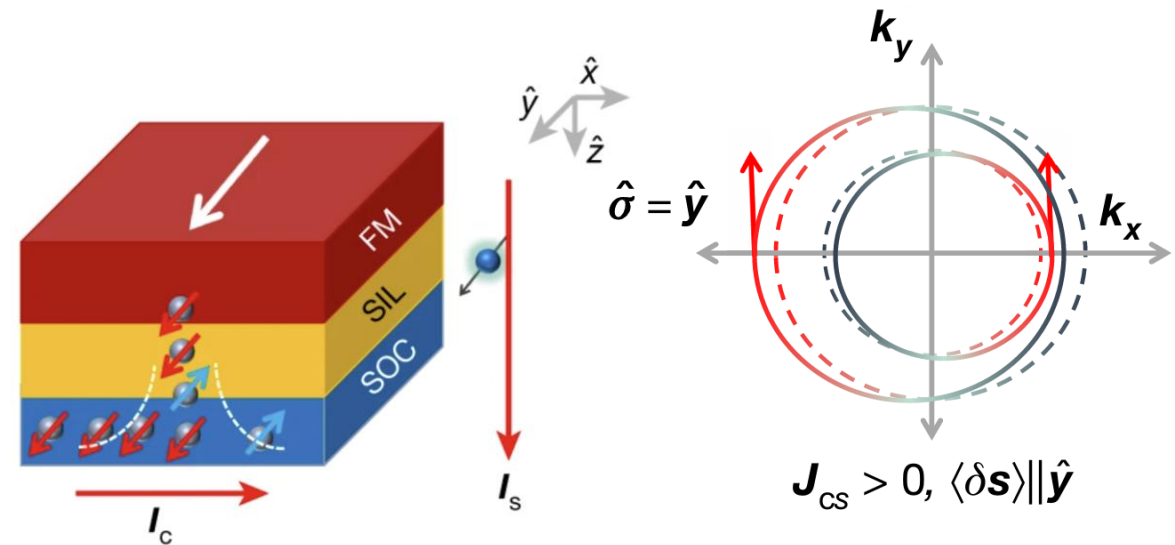
S. Manipatruni, R. Ramesh. *et al. Nature* **565**, 35–42 (2019)
J. Wang, *et al. Science* **299**, 1719 (2003)

MESO Device: Physical Mechanism

5



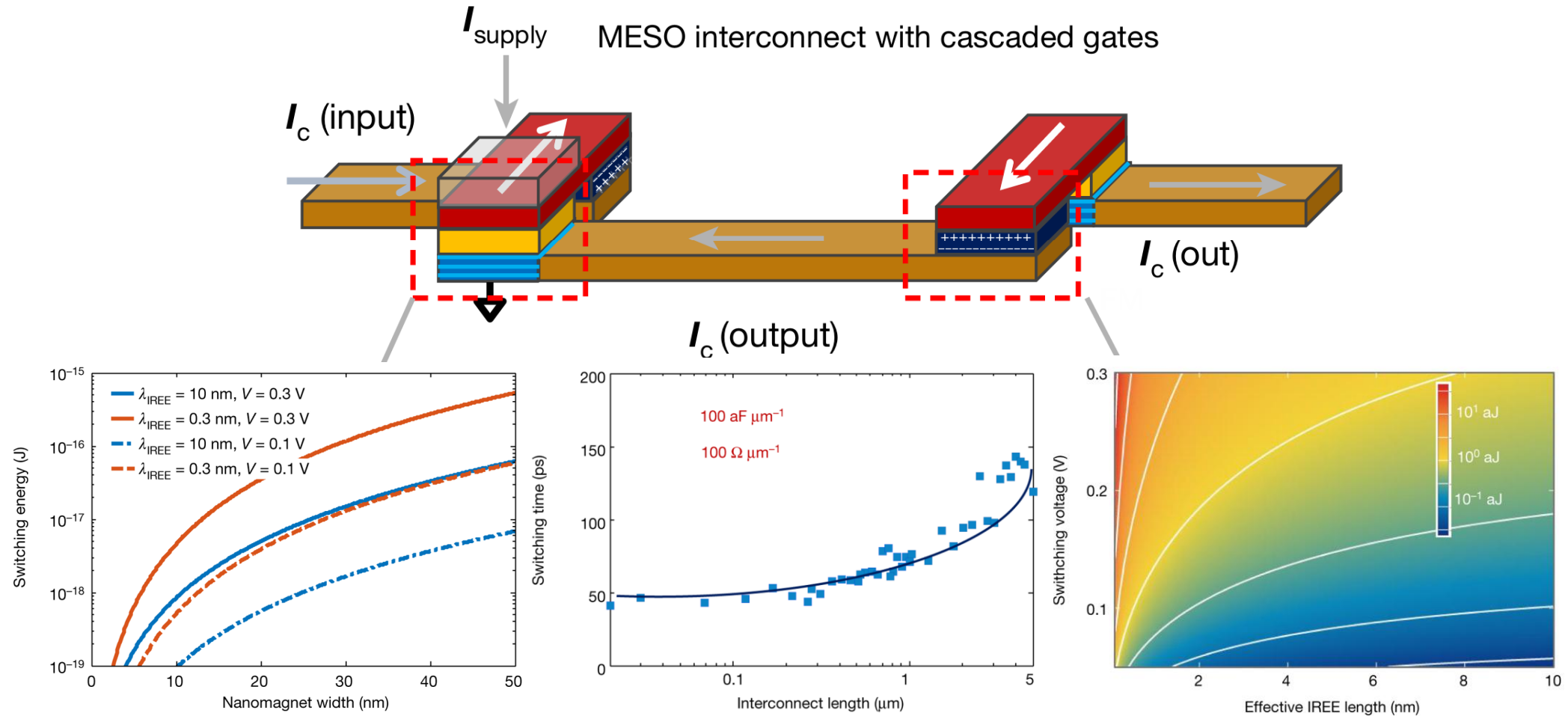
Charge $\rightarrow$ Spin



Spin $\rightarrow$ Charge

MESO Logic: Advantages

6

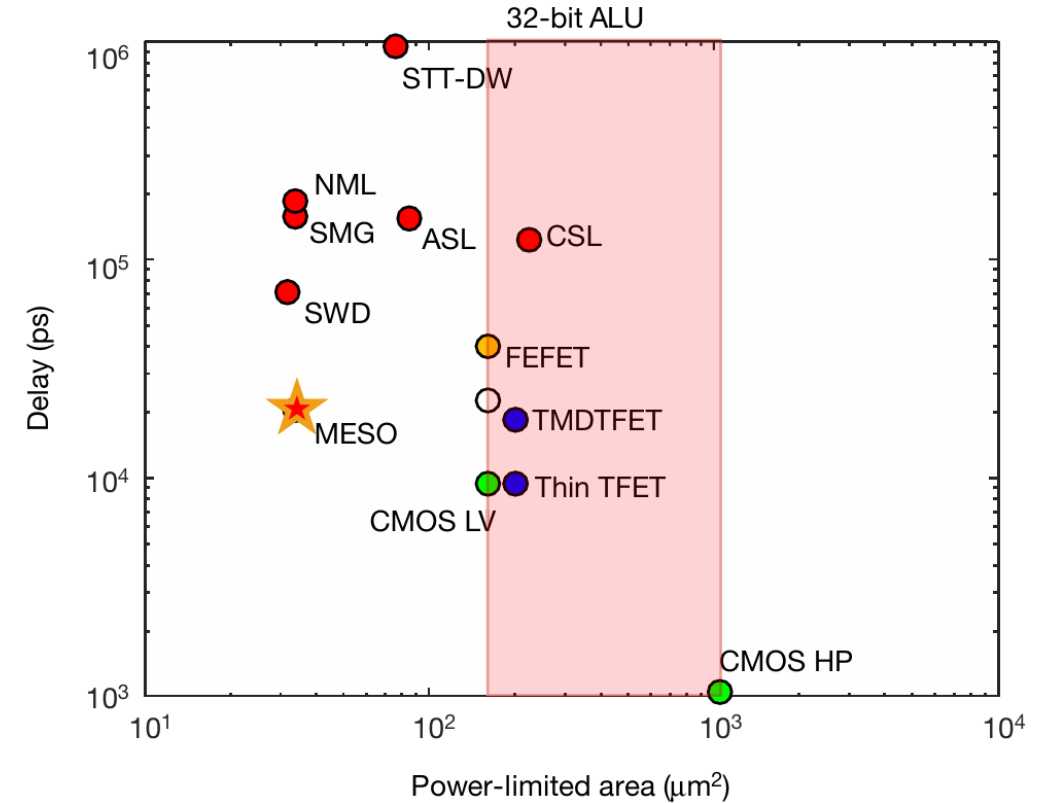
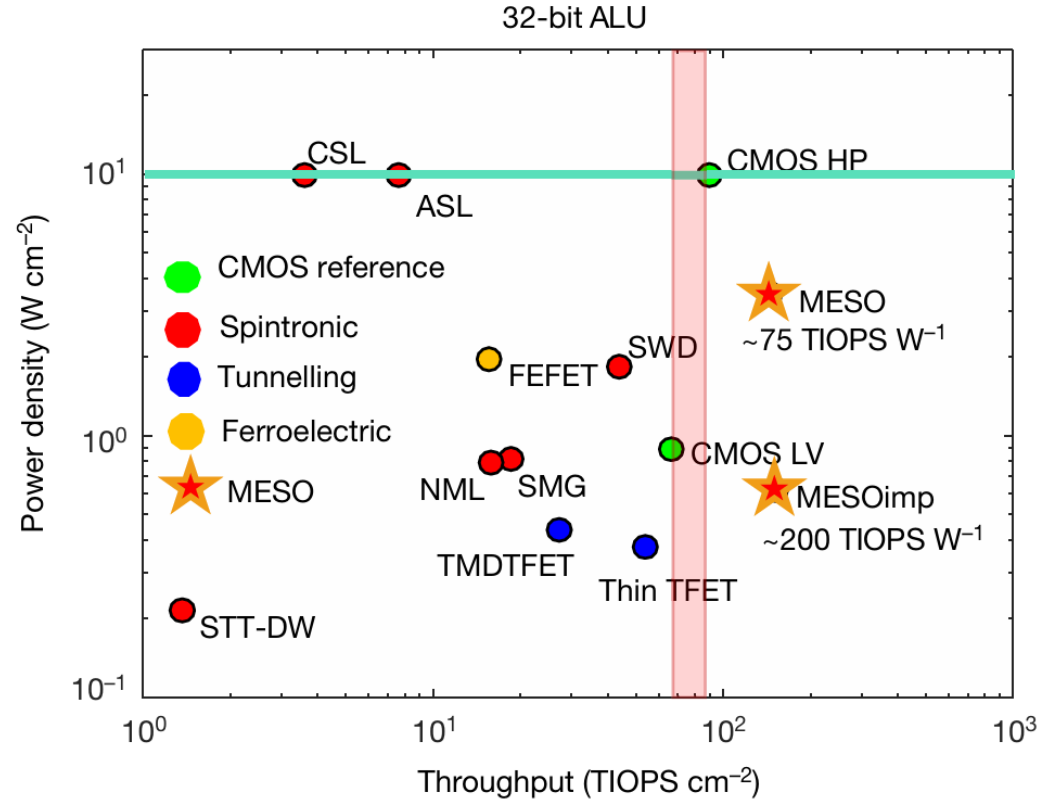


☺ *suitable for series connection*

☺ *low switching energy, switching time and switching voltage*

MESO Logic: Advantages

7



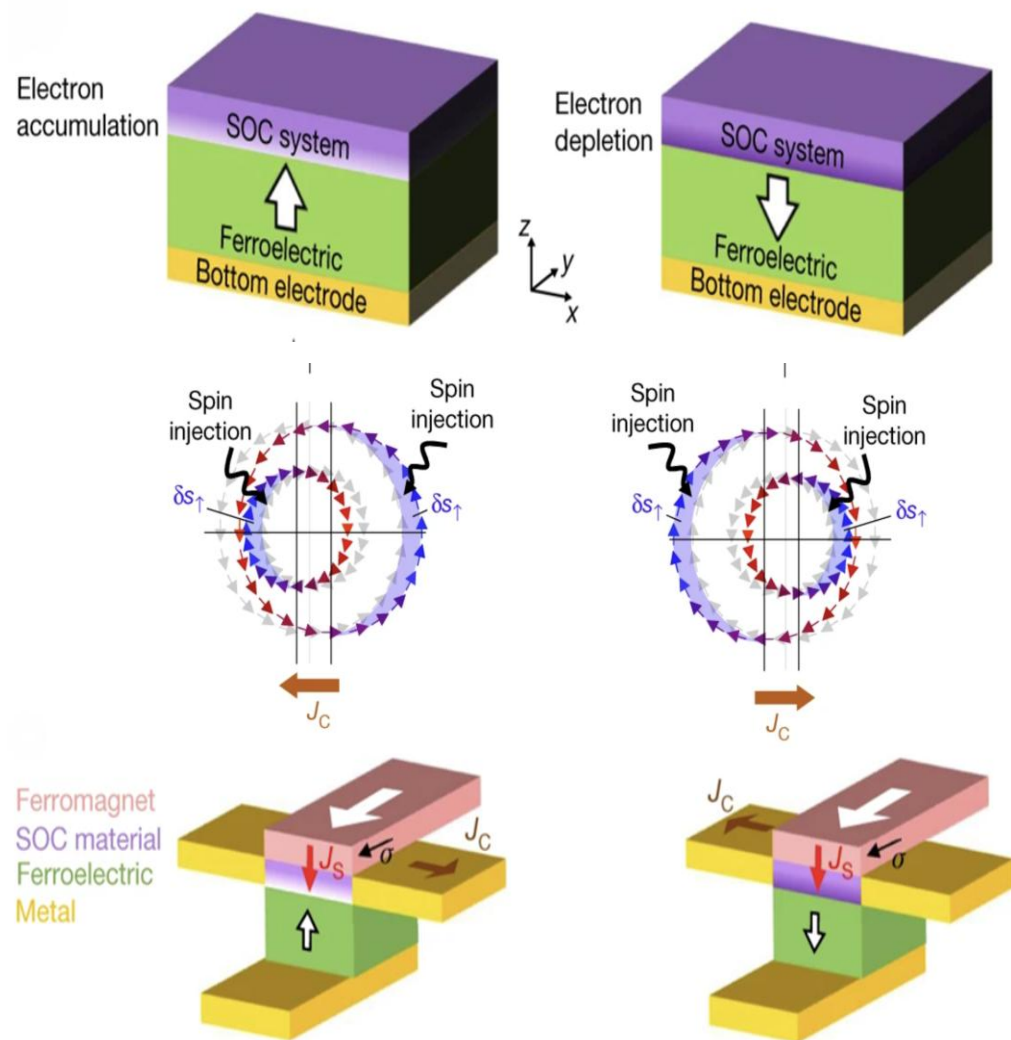
Compared to mainstream logic circuits:

☺ *higher performance*

☺ *lower power consumption*

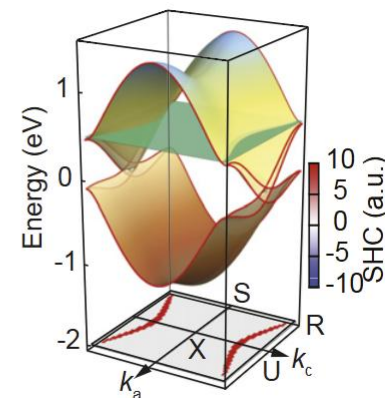
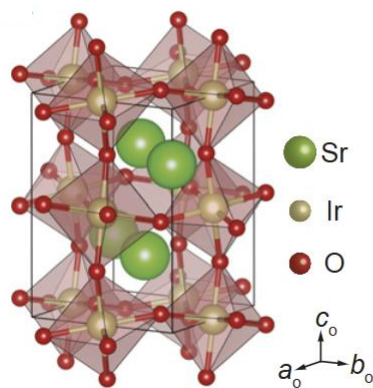
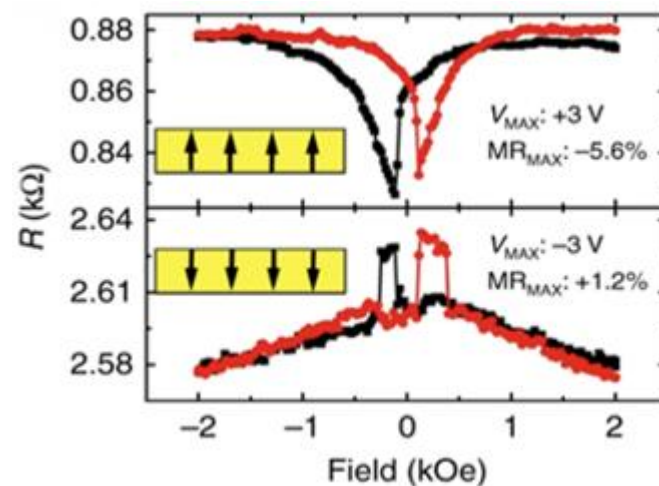
☺ *low delay time*

FE-controlled SOC in 2D Gas

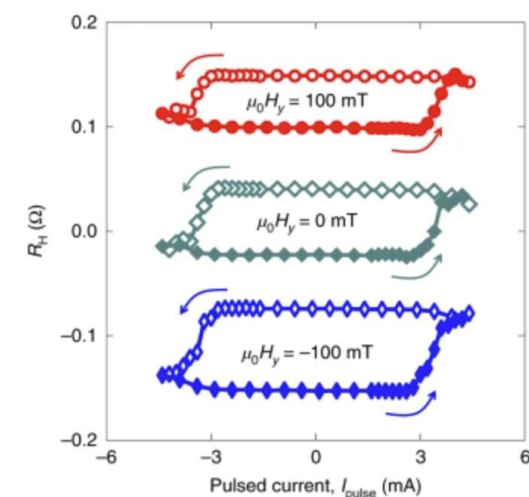
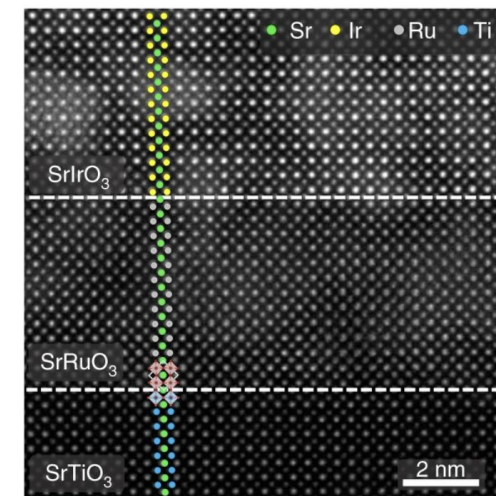


P. Noël. *et al. Nature* **580**, 483 (2020).

FE-controlled SOC in oxides



All-oxide SOT switching

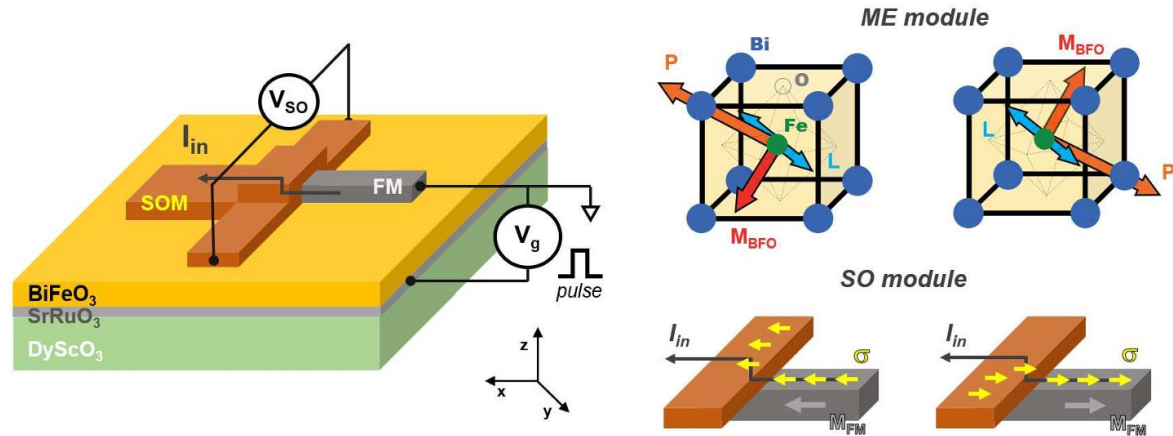


L. Liu. *et al. Nat. Nanotech.* **14**, 939 (2019).

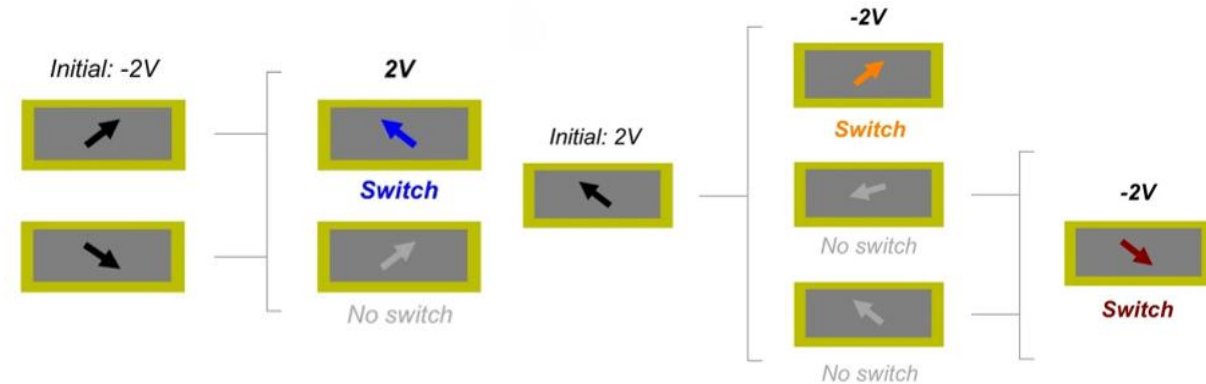
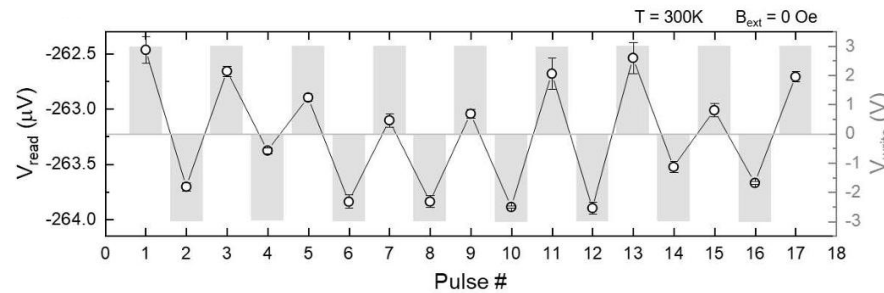
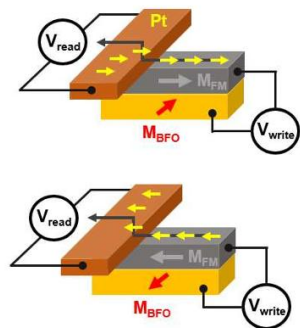
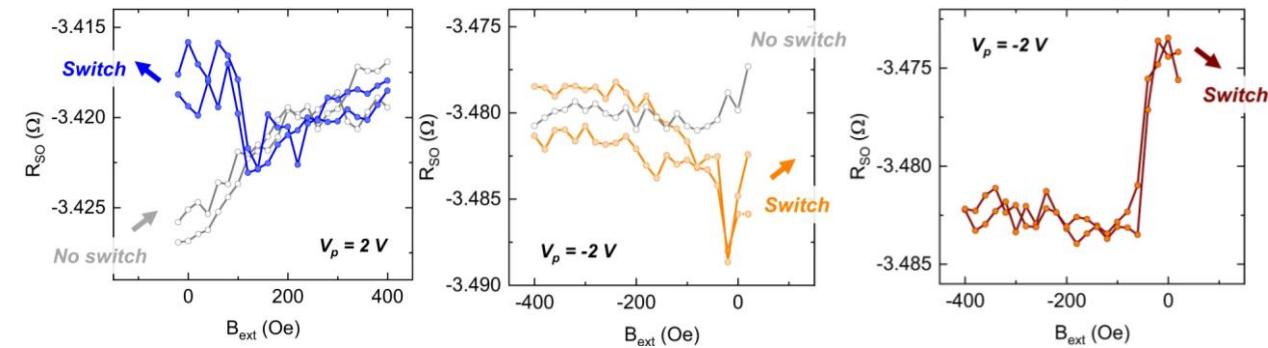
T. Nan. *et al. PNAS* **116**, 16186 (2019).

M. Fang. *et al. Nat. Commun.* **11**, 2627 (2020).

Fully Integrated MESO Device



Voltage-based writing and reading in MESO nanodevices

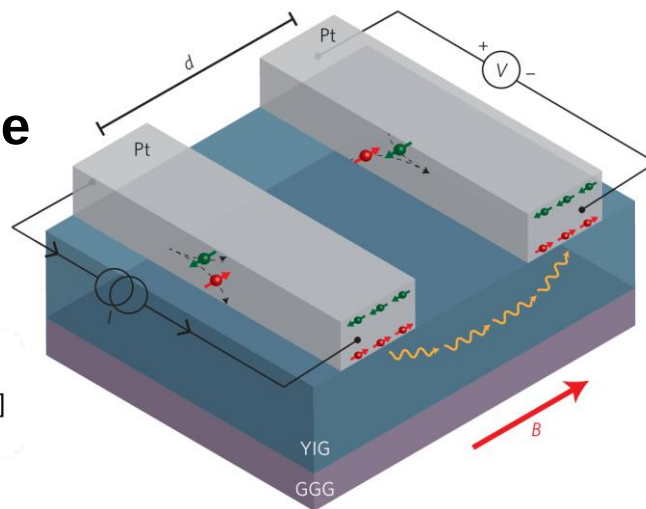
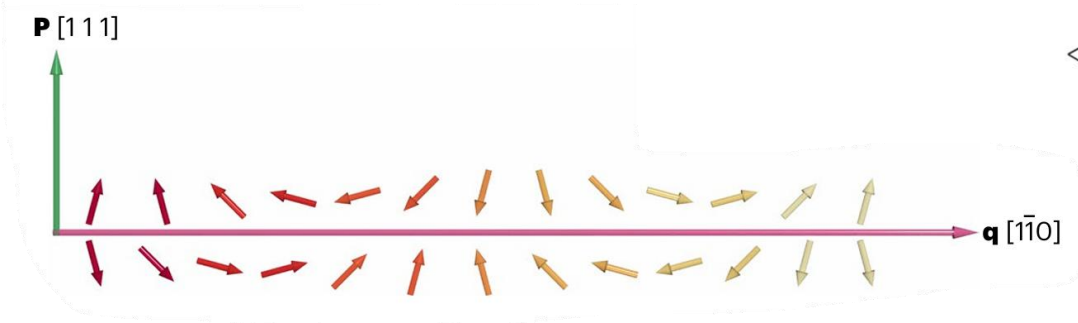


Magnon: New media for MESO

10

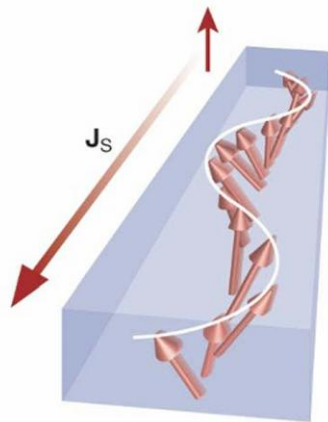
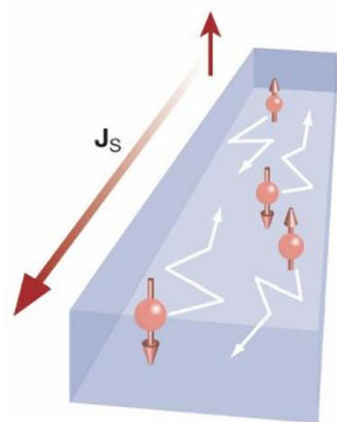
Definition

collective excitations of the spin structure



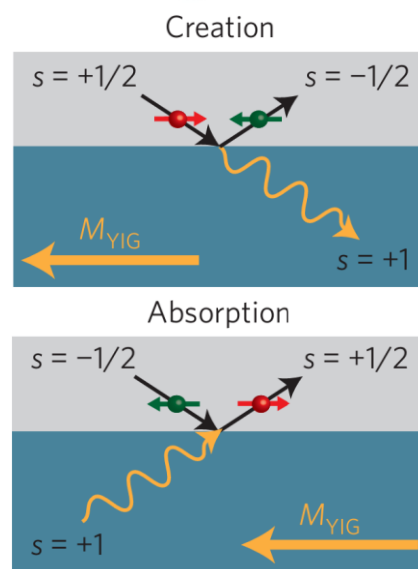
Spin-polarized current

Magnons

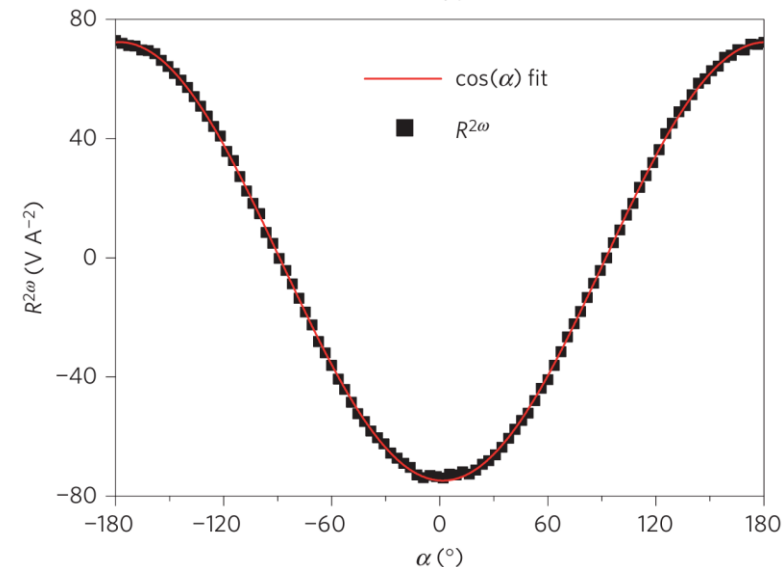
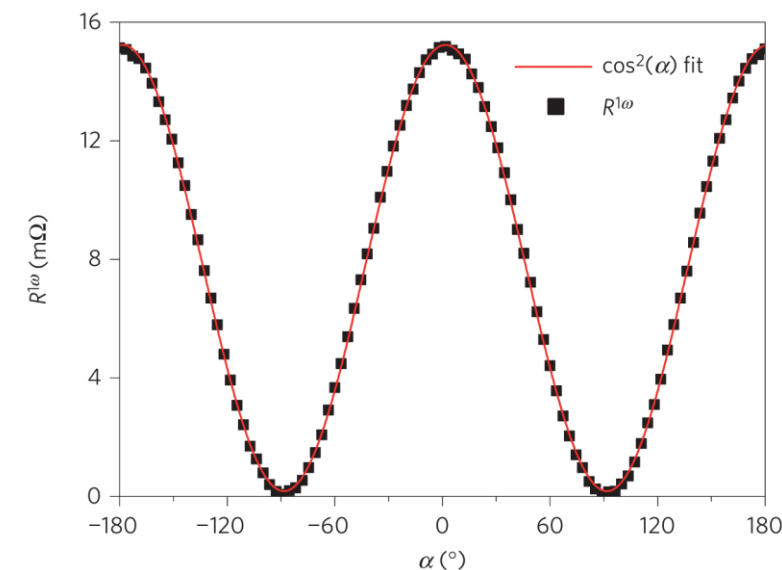


☹ Joule heat

☺ Dissipationless



Spin transport in magnetic insulator

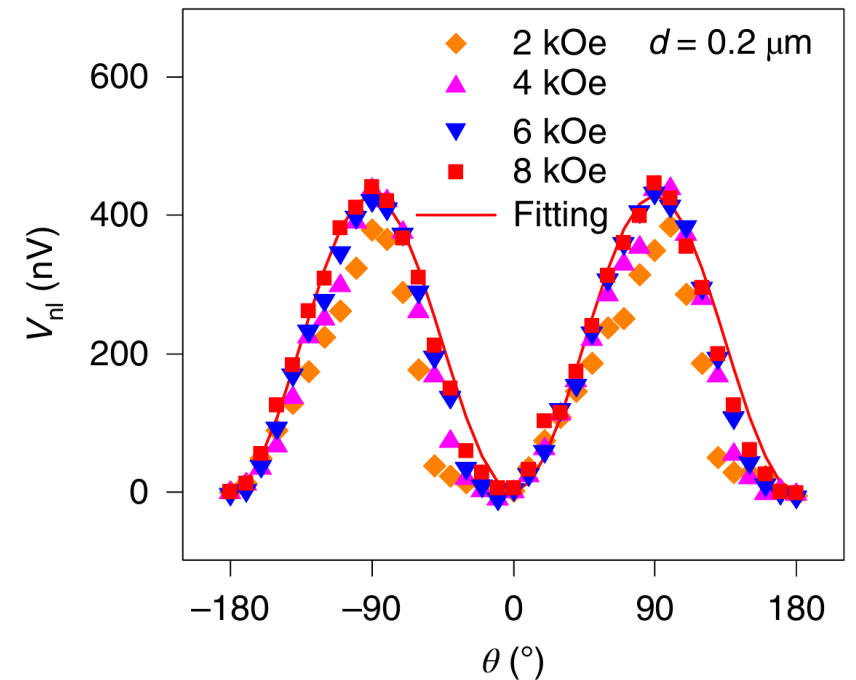
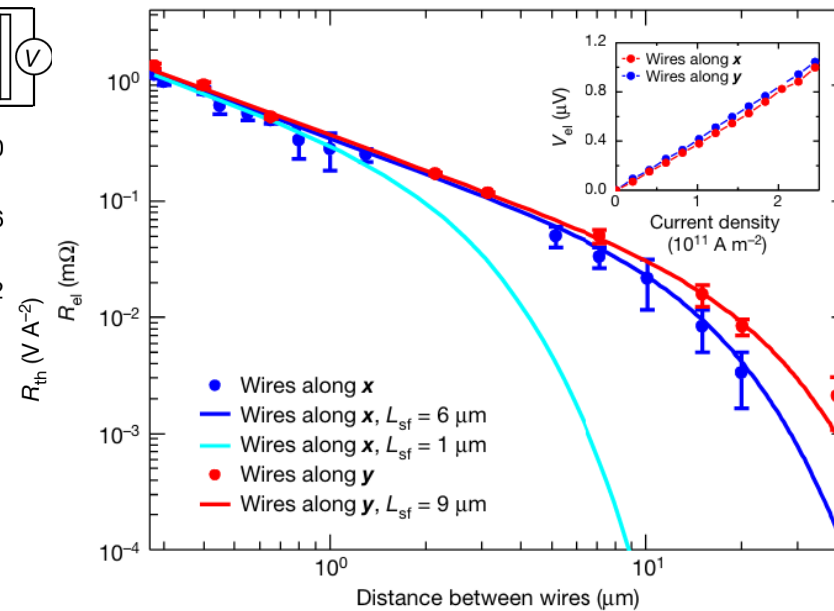
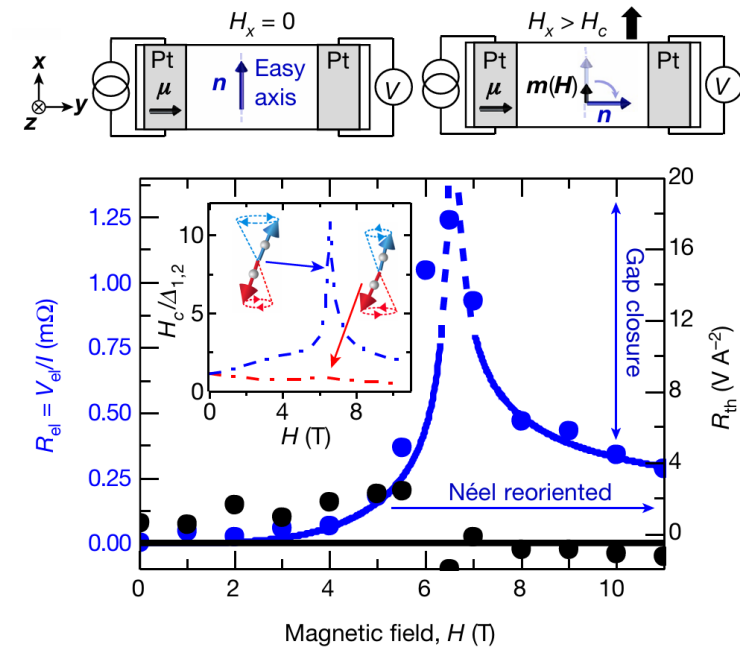
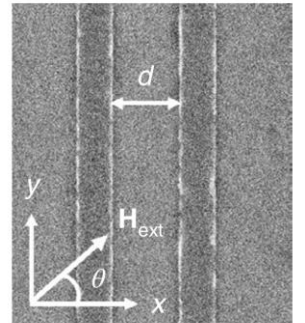
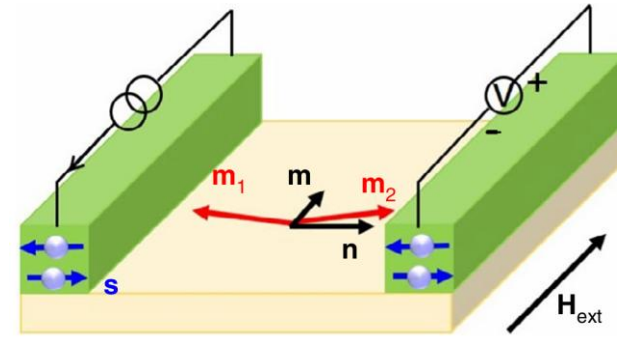
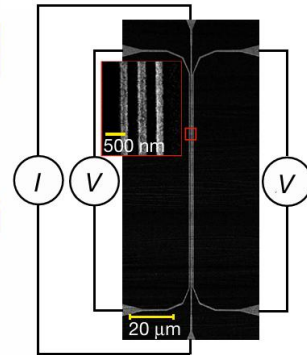
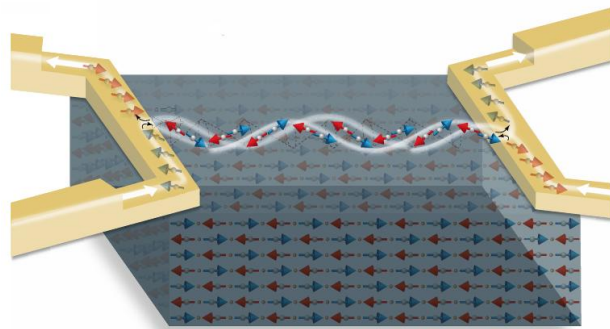


L. Cornelissen. *et al. Nat. Phys.* **11**, 1022–1026 (2015).

Y. Kajiwara, E. Saitoh. *et al. Nature* **464**, 262–266 (2010).

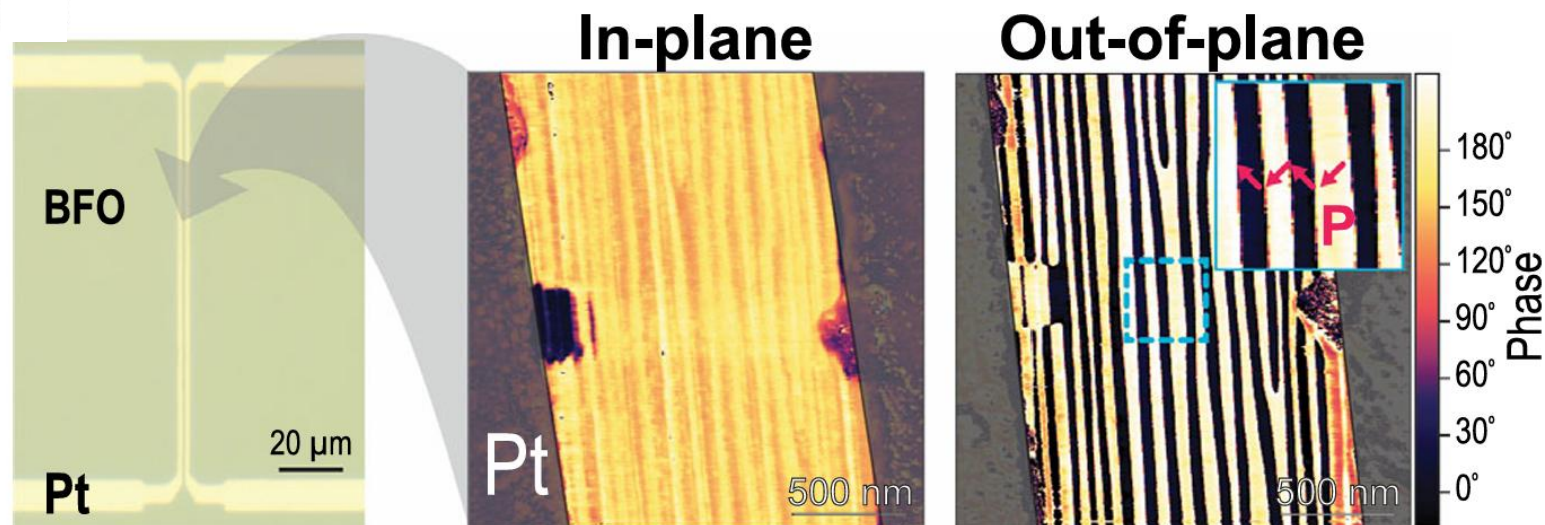
Magnon: Transport in Antiferromagnets

11

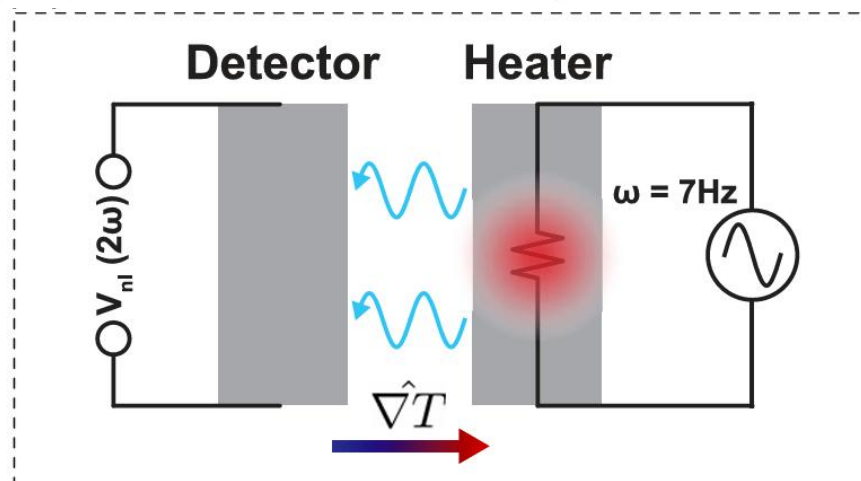


Magnon-mediated MESO Device

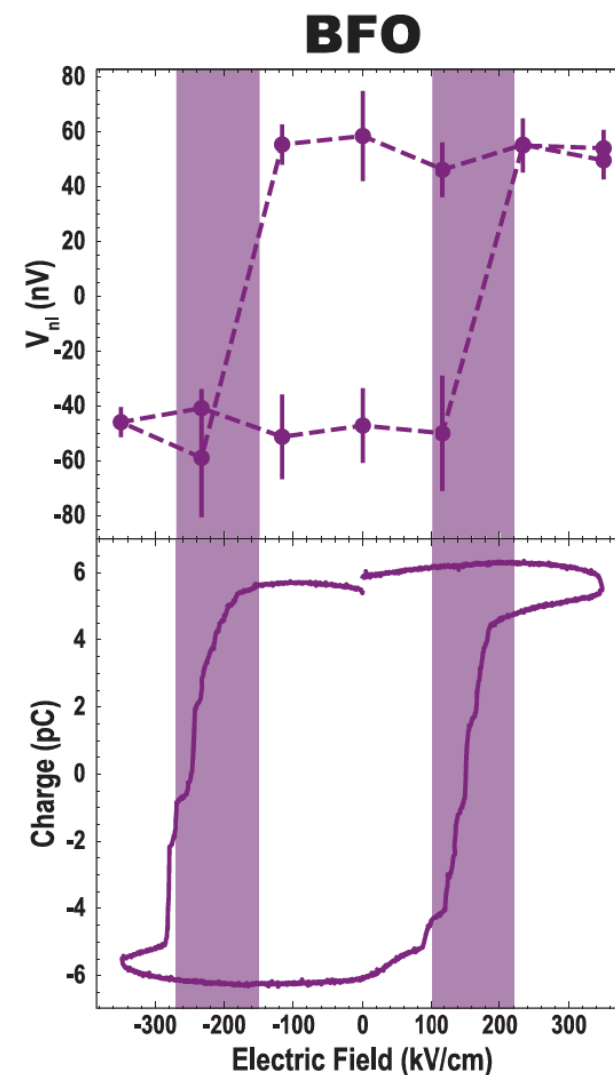
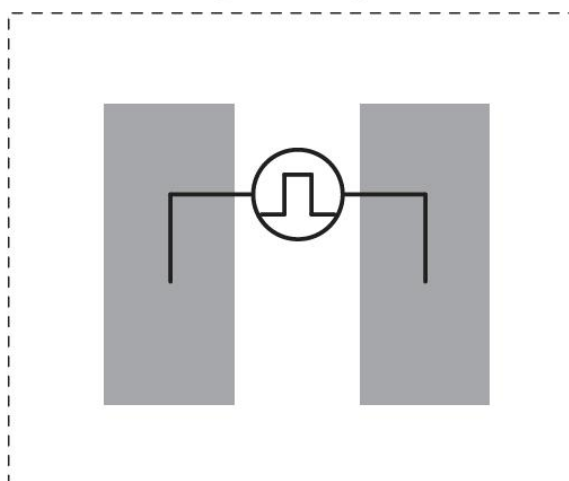
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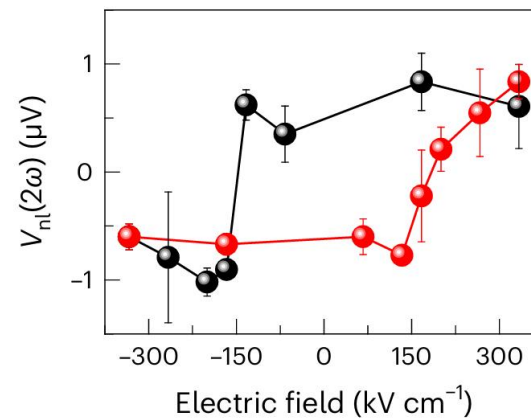
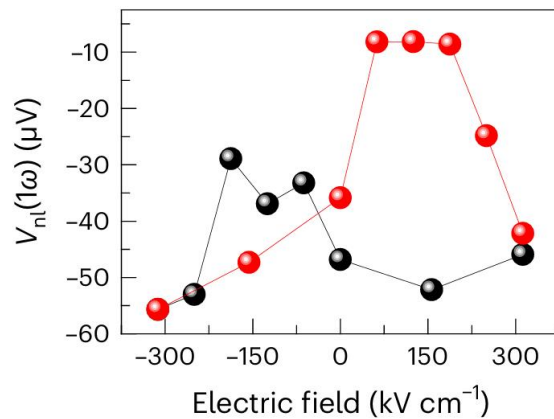
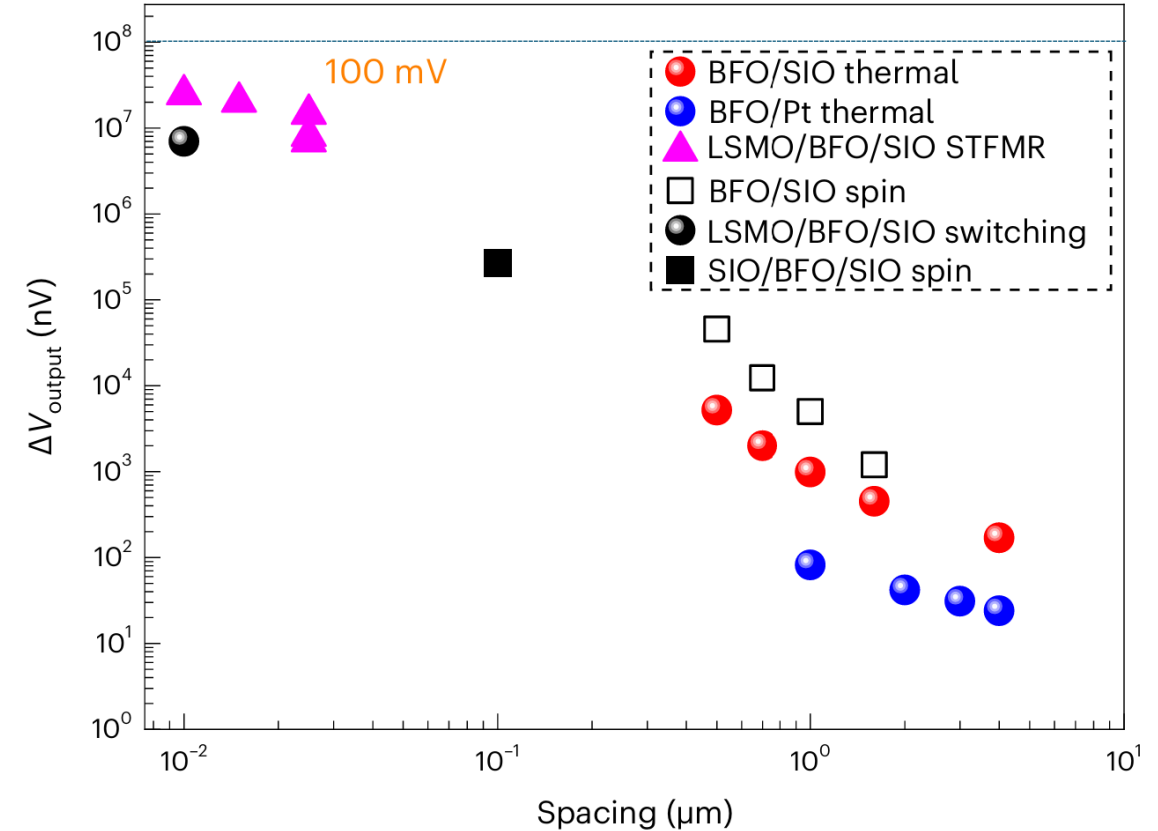
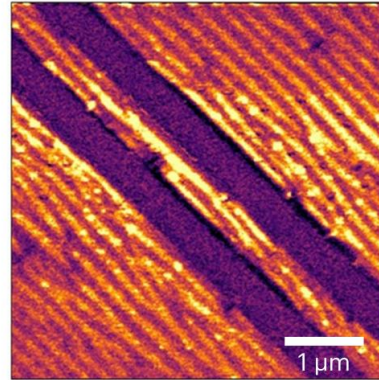
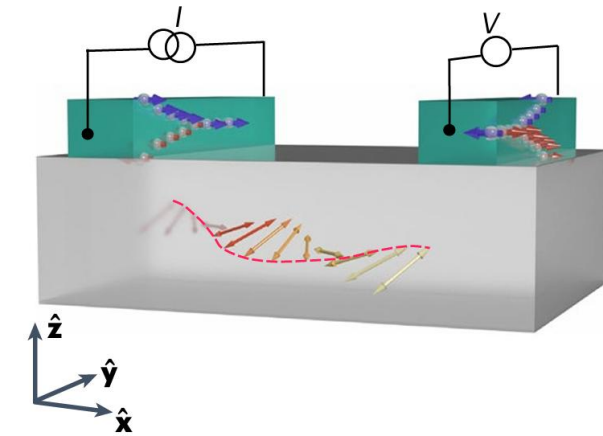
Measurement Configuration



Pulsing Configuration



Spin Hall injection + Electric field control + Inverse spin Hall reading

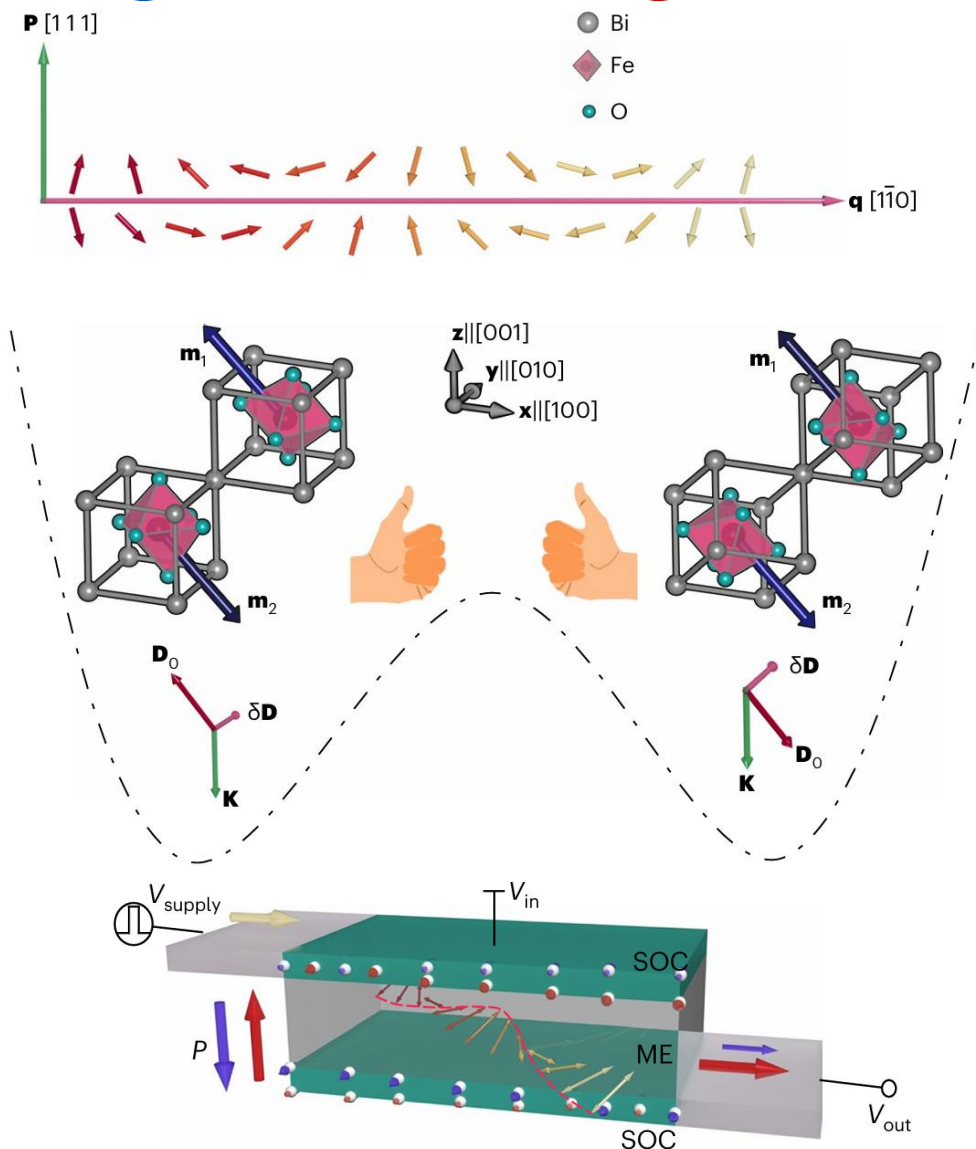


**Magnon transport
in multiferroic BiFeO_3**

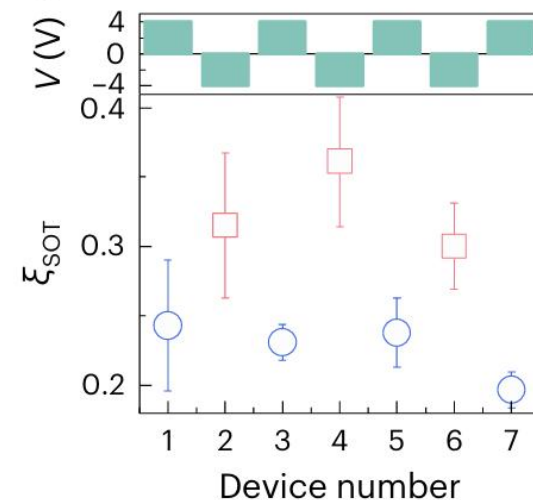
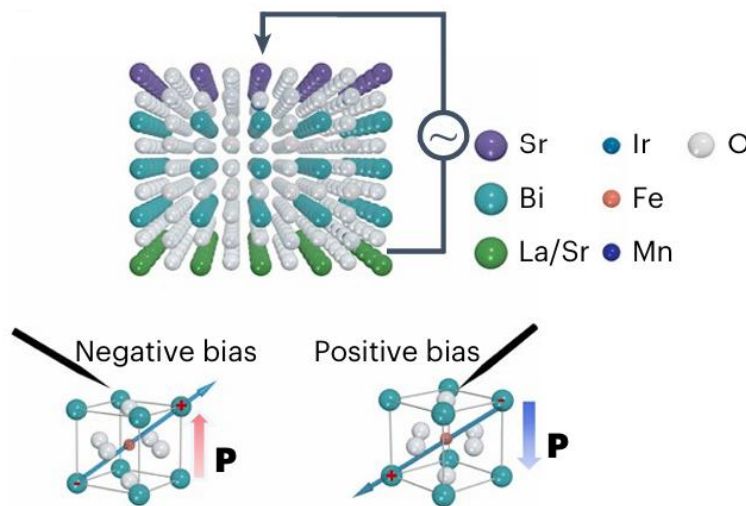
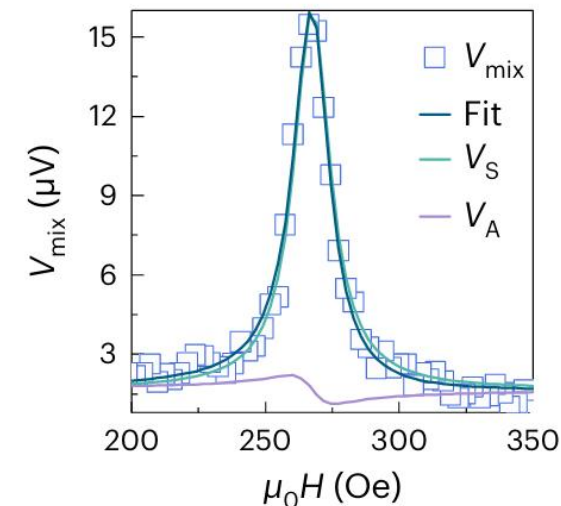
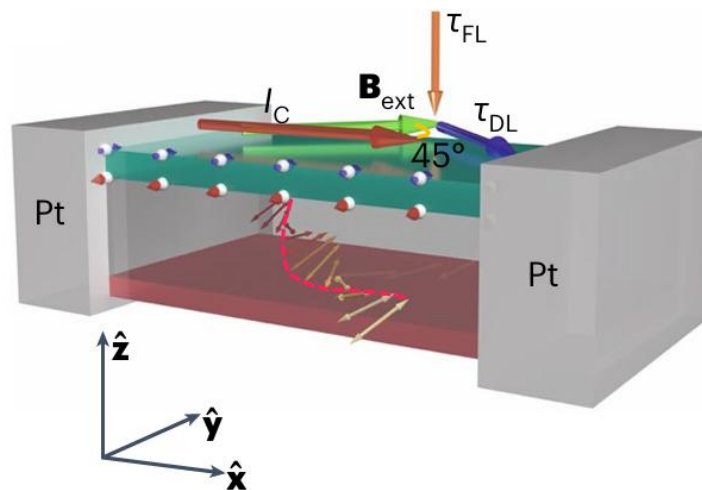
$\lambda \sim 0.17 \mu\text{m}$ (first harmonic)
 $\lambda \sim 0.25 \mu\text{m}$ (second harmonic)

Magnon: Voltage Controlled Spin Transport

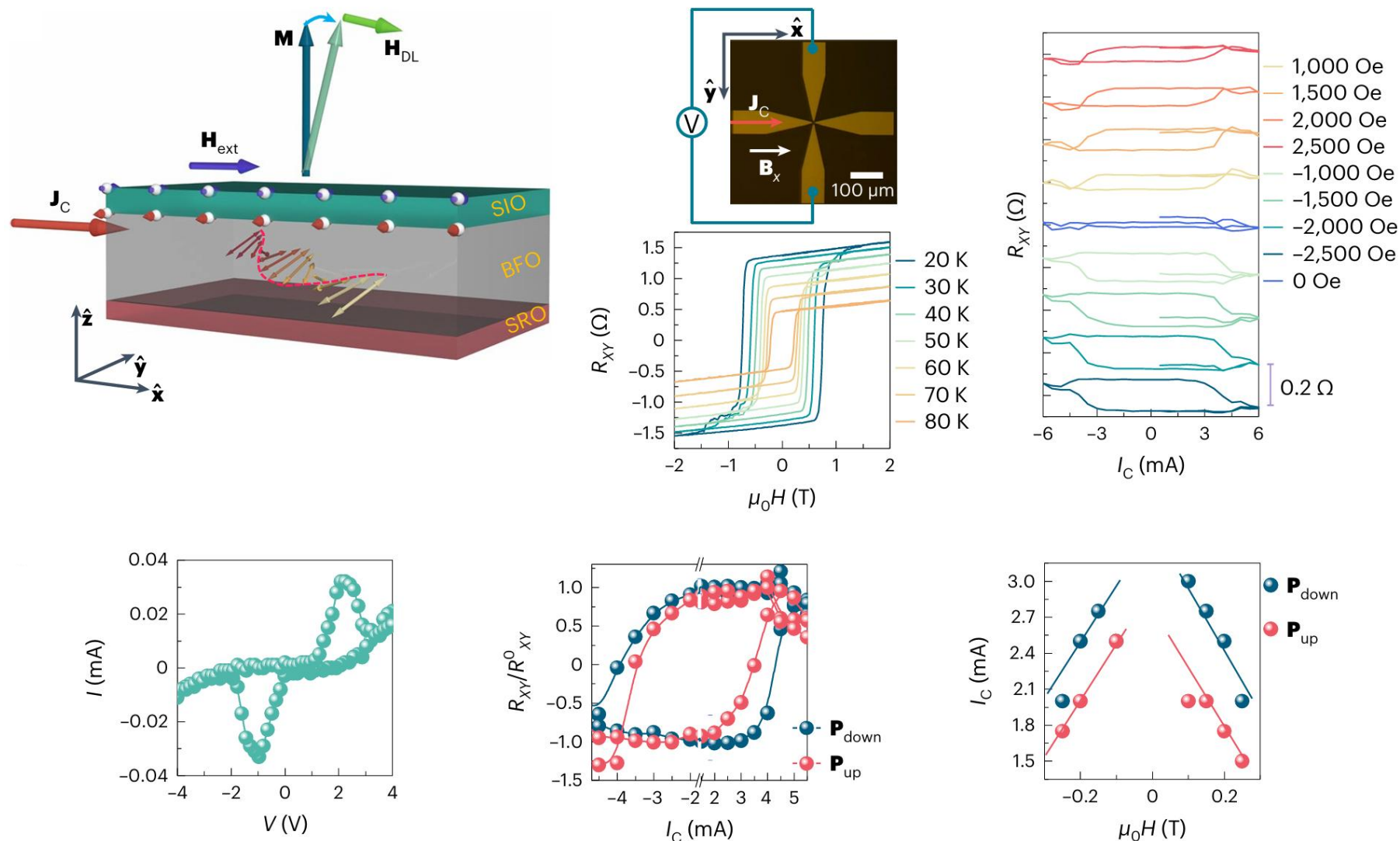
14



Chiral magnon transport

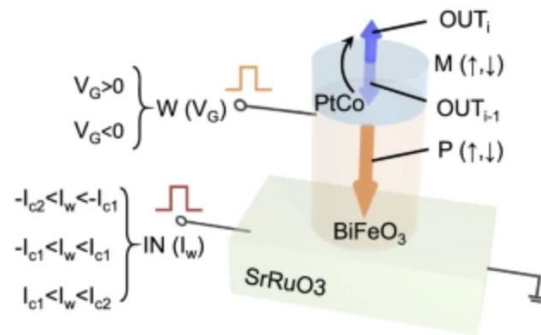
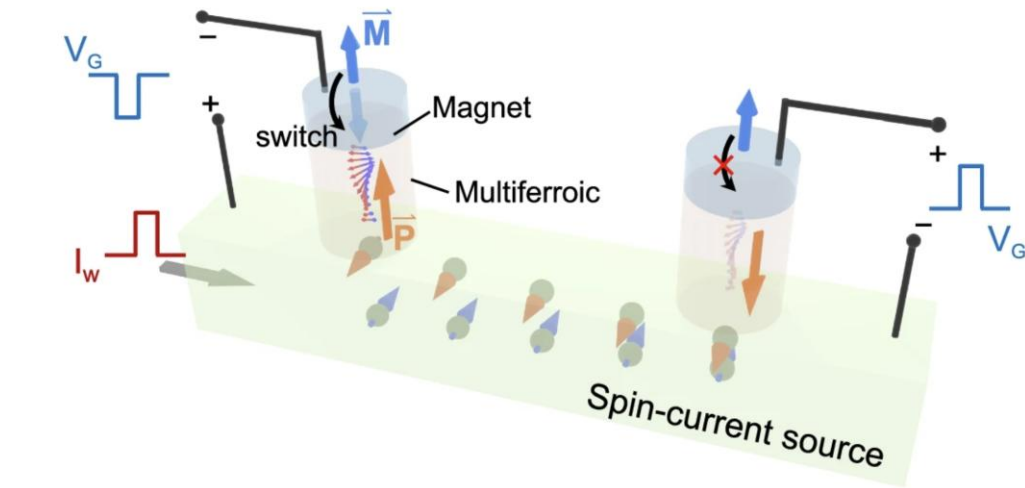


Polarization controlled spin transport



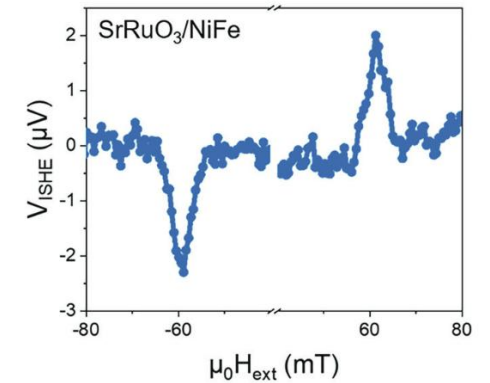
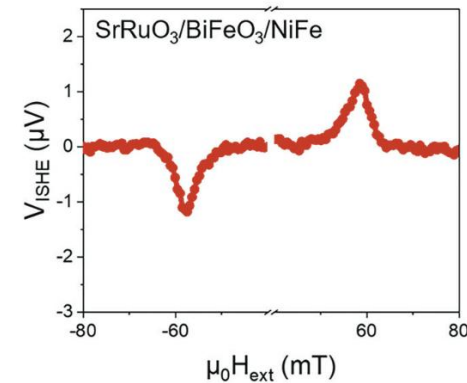
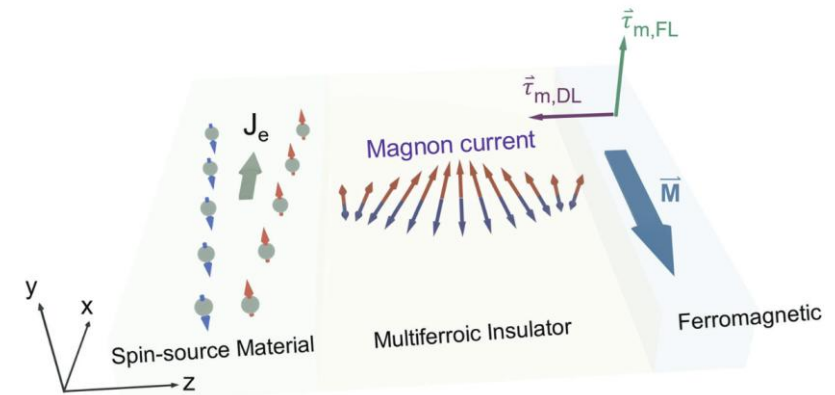
Polarization controlled magnetization switching

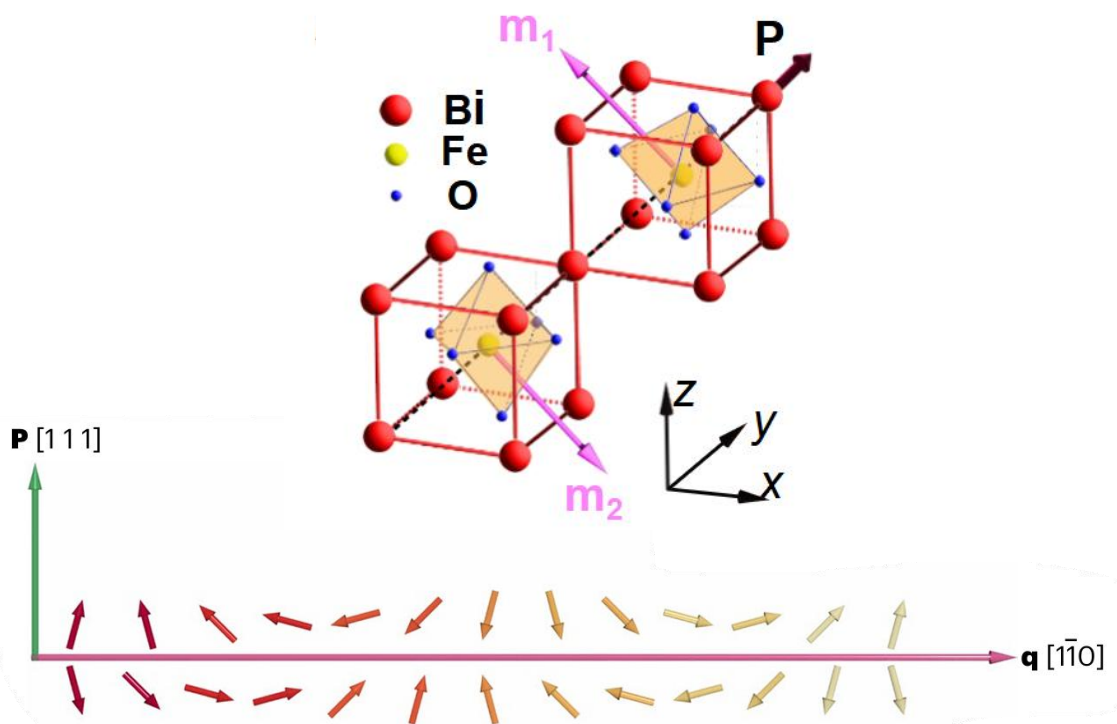
Reconfigurable logic-in-memory



Logic function	Initial state	Logic input		Output
	Out _{i-1}	Definition of IN	W	Out _i
IN AND W	0	0 ⇒ -I _{c1} < I _w < I _{c1}	0	0
	0	1 ⇒ -I _{c2} < I _w < -I _{c1}	1	1
IN XNOR W	1	0 ⇒ I _{c1} < I _w < I _{c2}	0	1
	0	1 ⇒ -I _{c2} < I _w < -I _{c1}	1	0

BFO magnon transport





Magnons in BiFeO₃

best for MESO now

- ☹ *low maximum amplitude*
- ☹ *lack of material candidates*



?

New quasiparticle

for further improvement of MESO

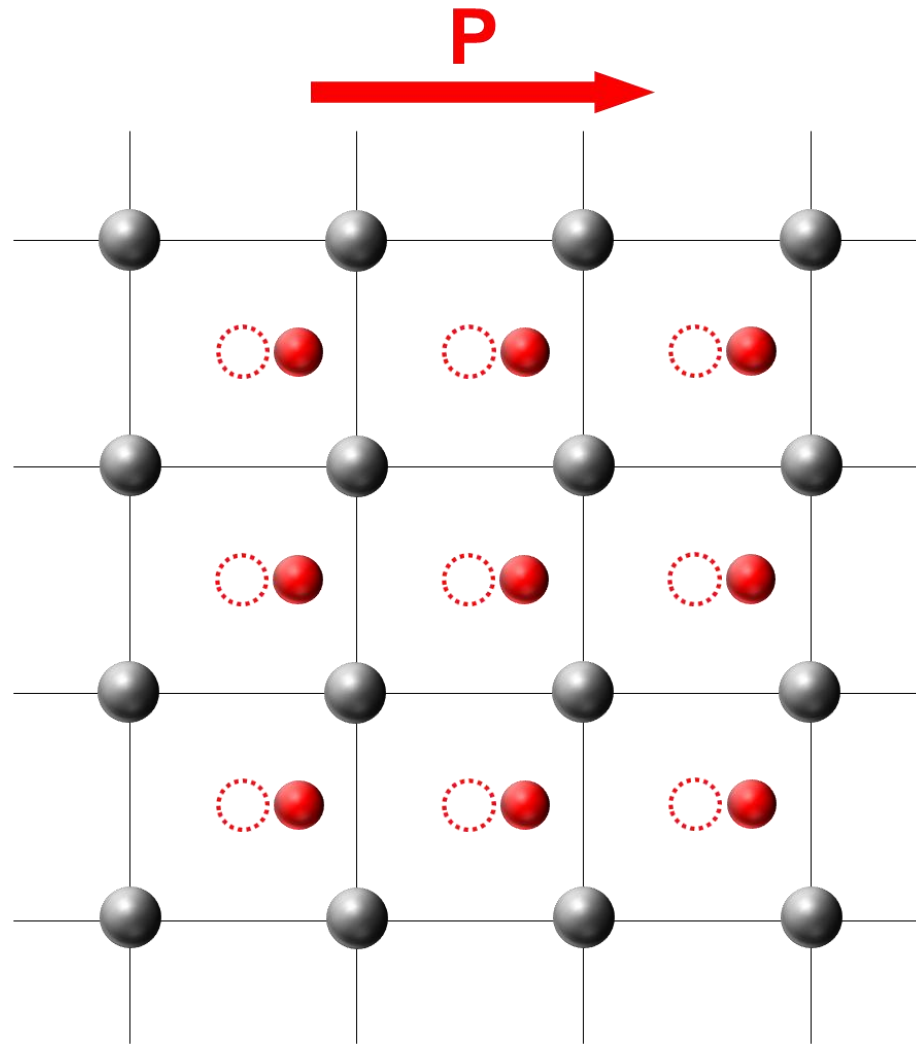
- ☺ *high output amplitude*
- ☺ *abundant selections of materials*

1

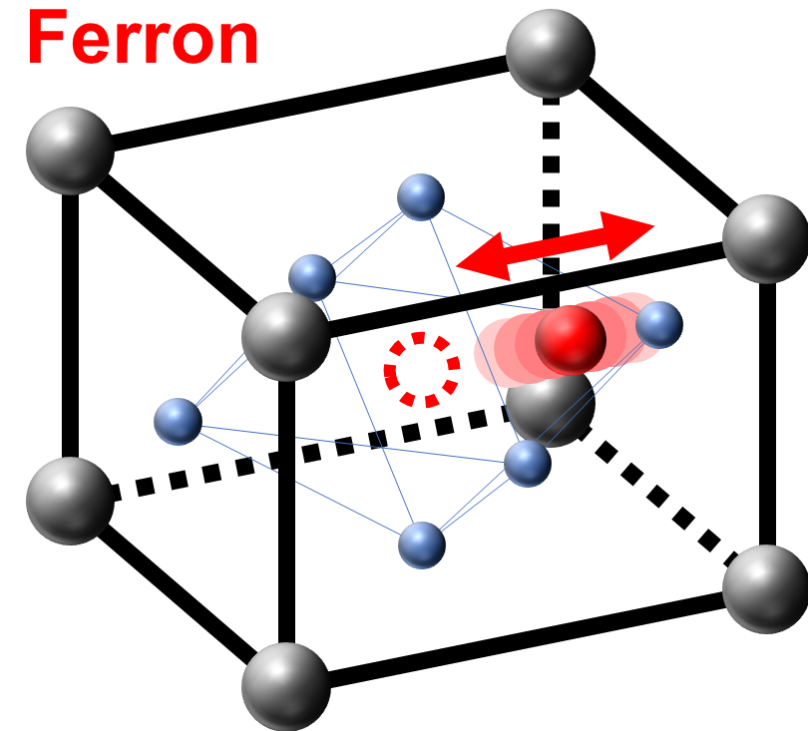
Magnon-mediated MESO

2

Ferron Transport for Potential MESO Applications



Ferroelectrics



Ferron

- Collective excitations of the ferroelectric order
- Carry energy as well as (constant) electric dipoles

Ferrons enable

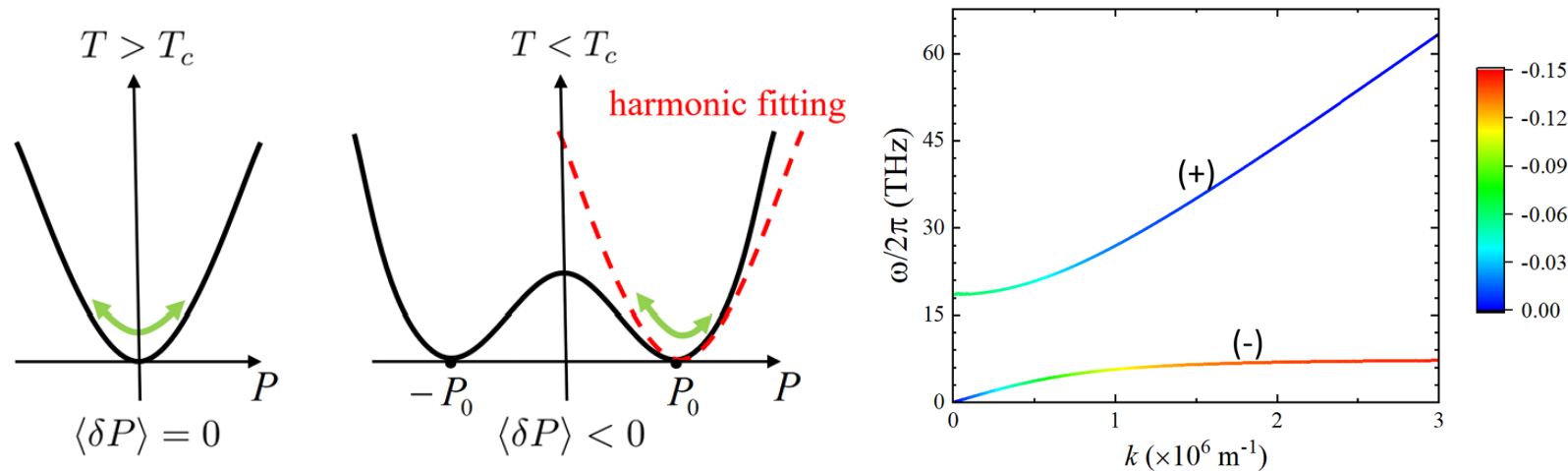
- *electric polarization transport*
- *electric-field-tunable heat transport*
- *nonlocal drag-induced thermoelectricity*



Prof. G. E. W. Bauer

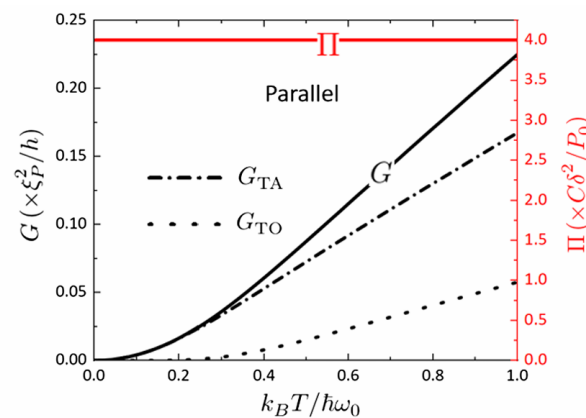
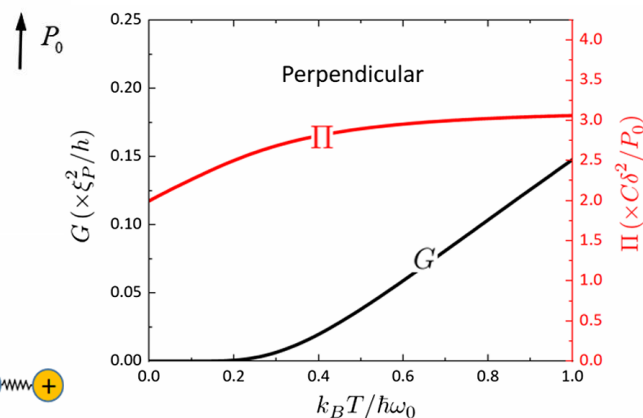
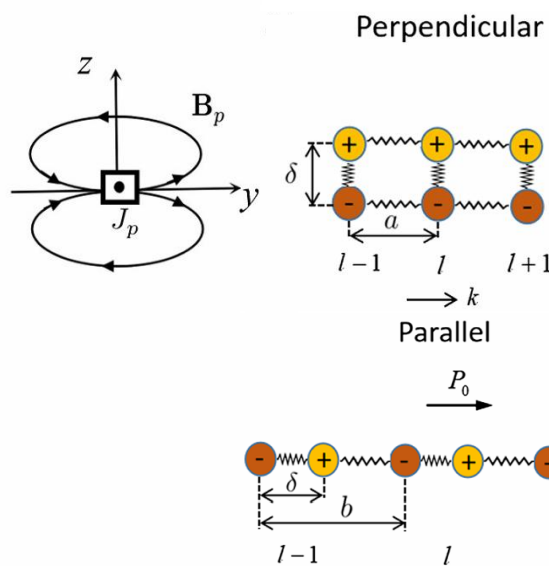
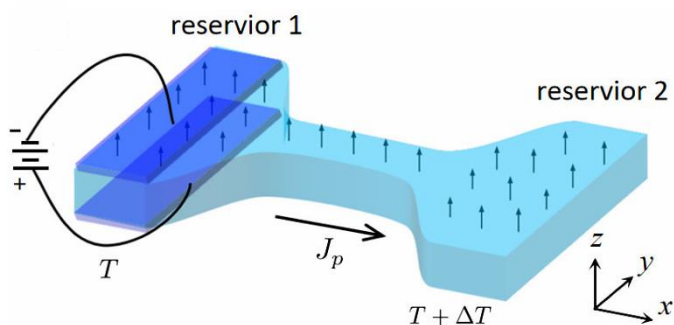
Tohoku University

Ferrons: excitations of the ferroelectric order



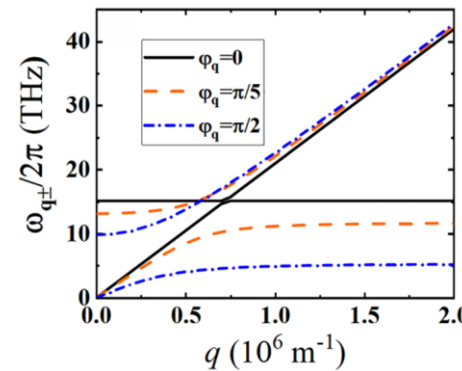
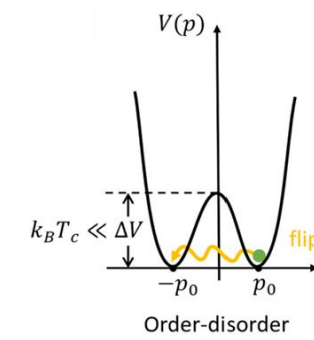
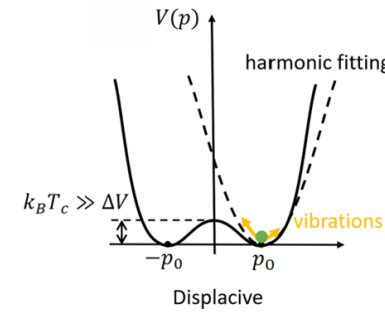
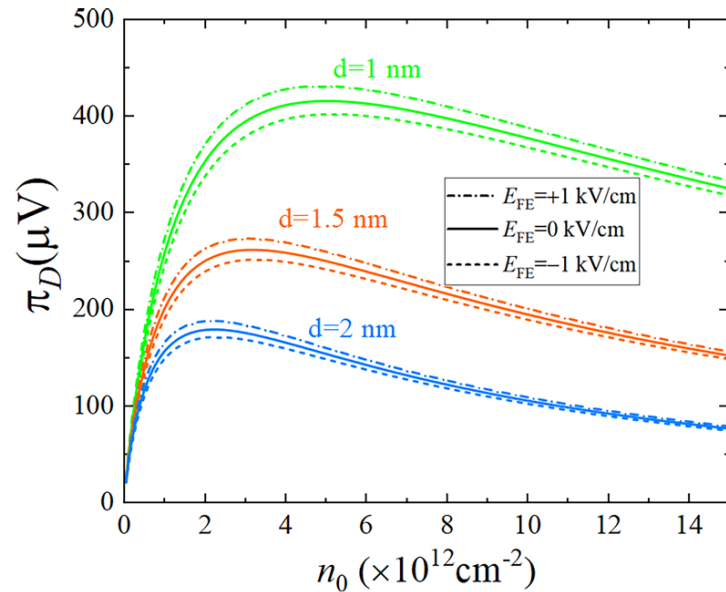
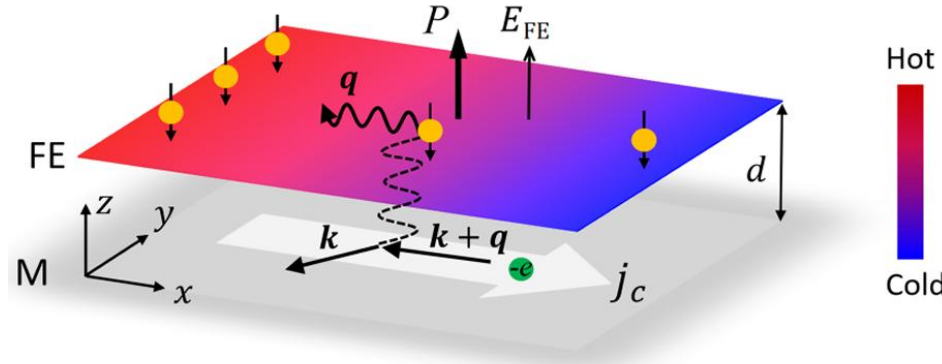
P. Tang, R. Iguchi, K. Uchida, G. E. W. Bauer. *Phys. Rev. B* **106**, L081105 (2022).

Electric polarization transport

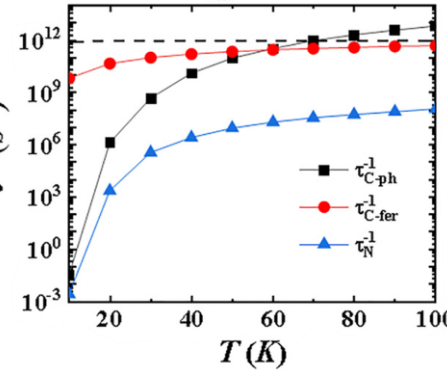
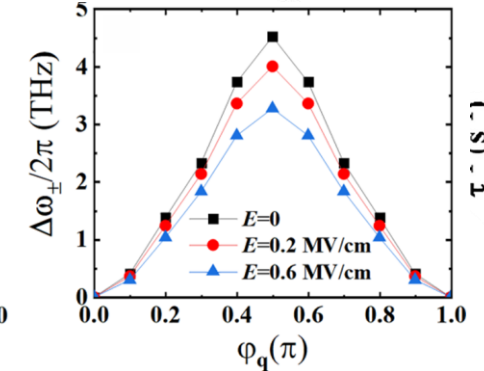
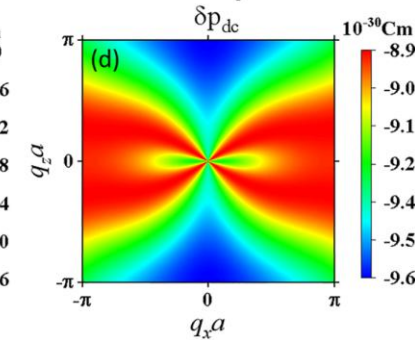
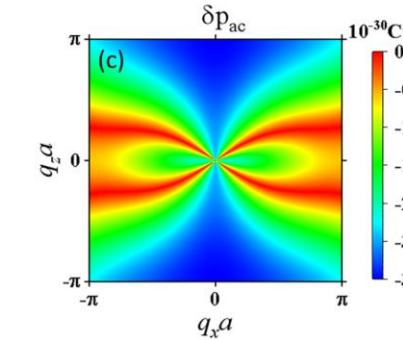
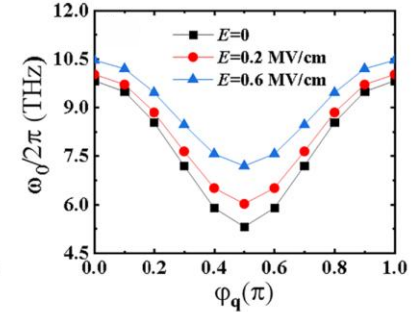
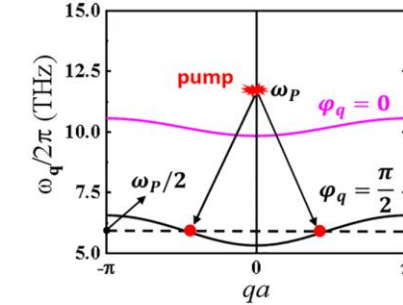


P. Tang, R. Iguchi, K. Uchida, G. E. W. Bauer. *Phys. Rev. Lett.* **128**, 047601 (2022).

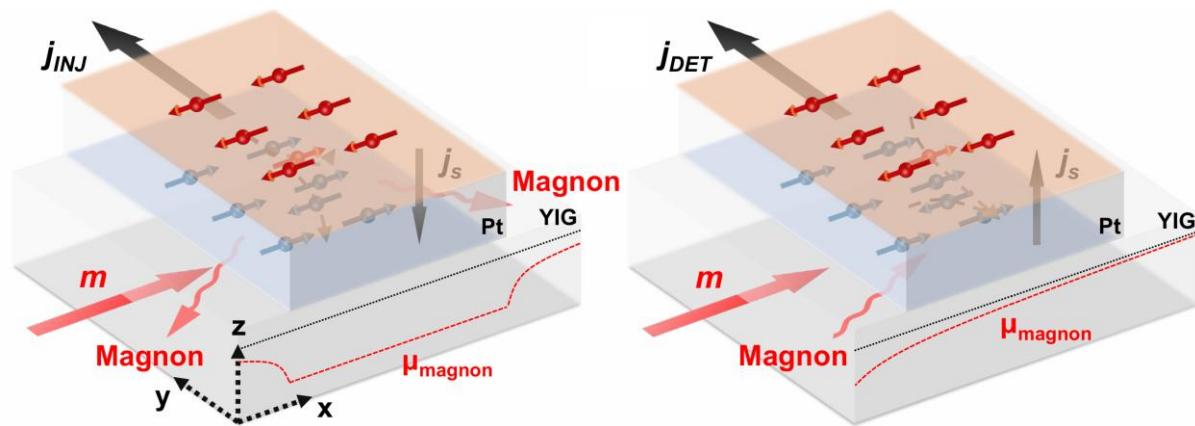
Non-local Ferron-drag Peltier effect



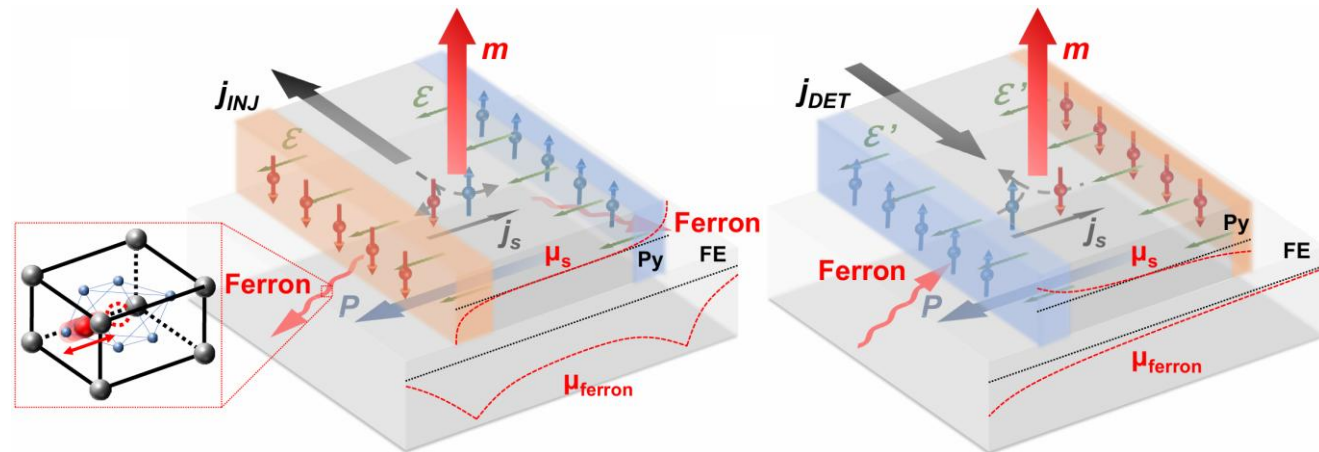
Ferron excitations in order-disorder ferroelectrics



diffusive magnons

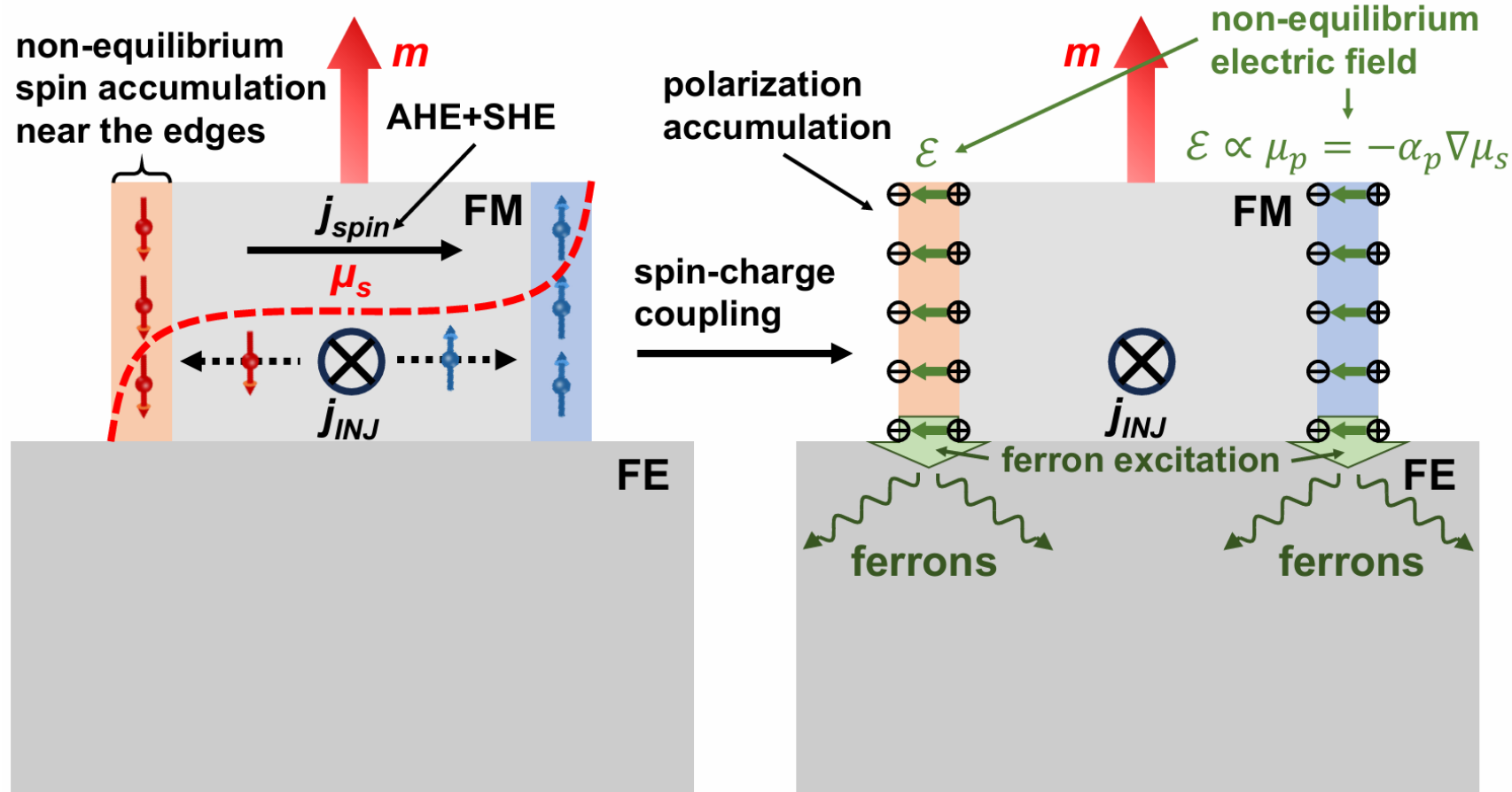


diffusive ferrons



- magnons (spin) as media of information transmission

- spin is used to excite ferrons
- ferrons as media of information transmission



Input current j_{INJ}

↓ AHE+SHE

Non-equilibrium spin accumulation μ_s near the edges

↓ Spin-charge coupling in ferromagnetic metals

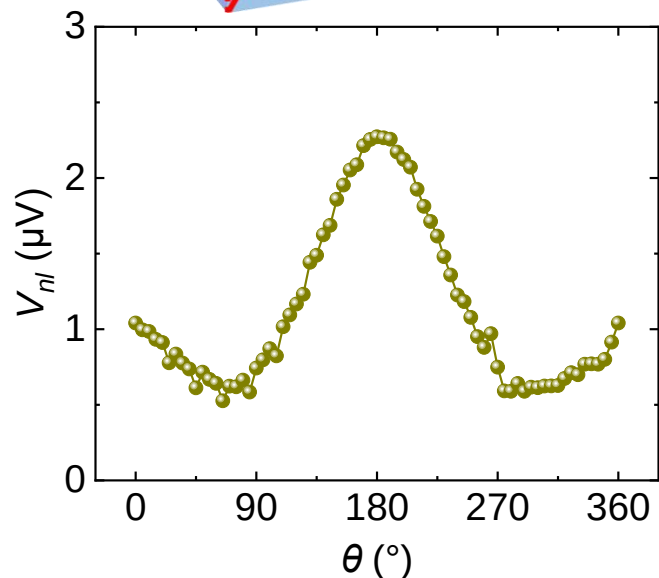
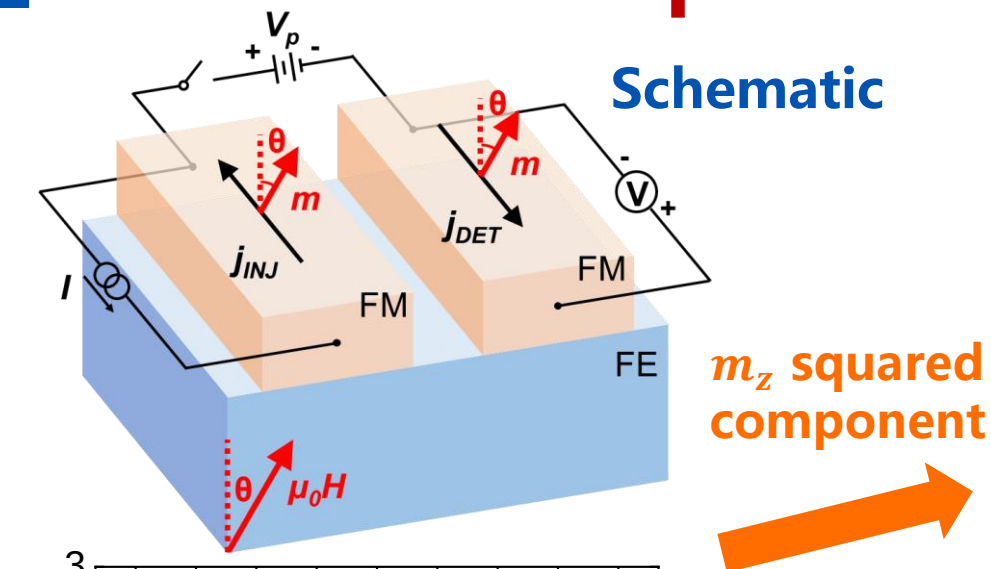
Polarization accumulation μ_p

↓

Ferron excitation by non-equilibrium electric fields ϵ

Ferron: Transport in Ferroelectrics

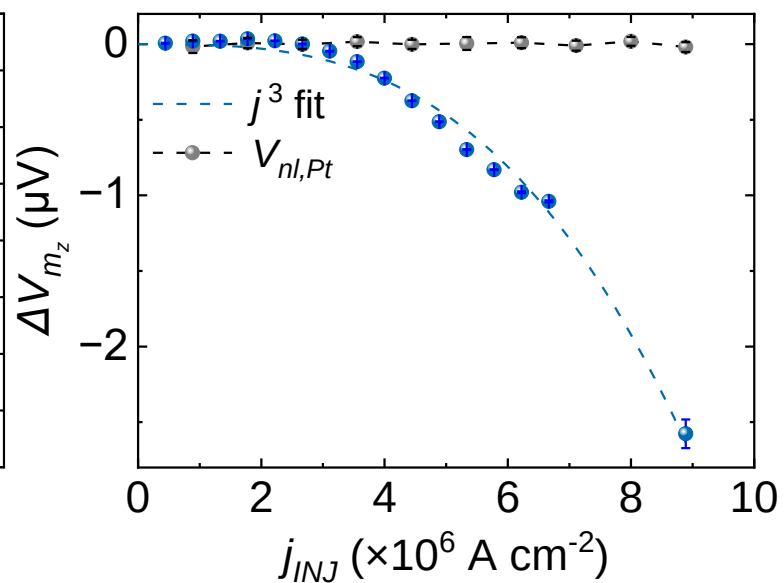
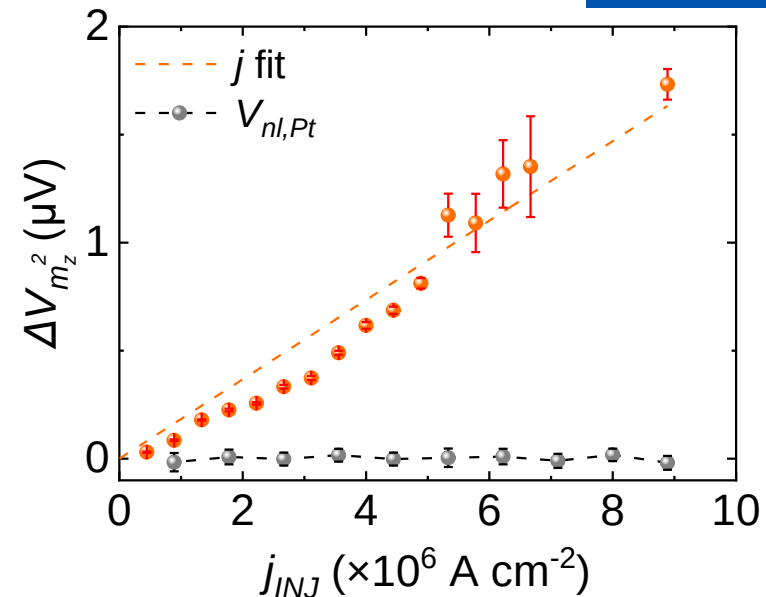
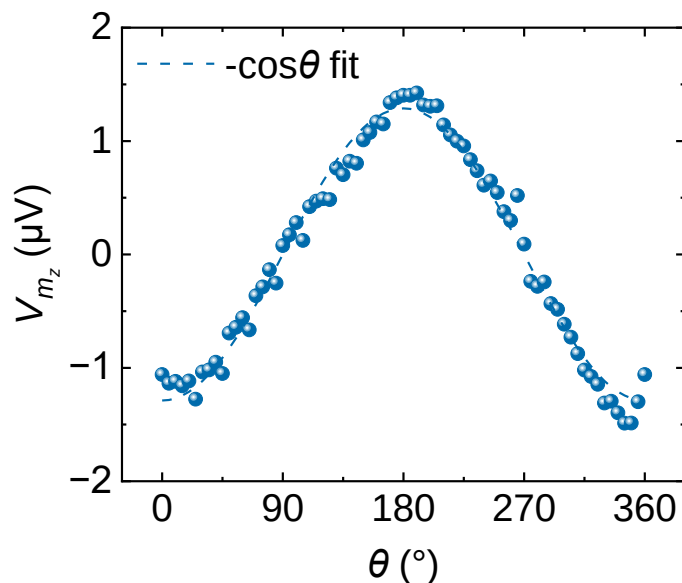
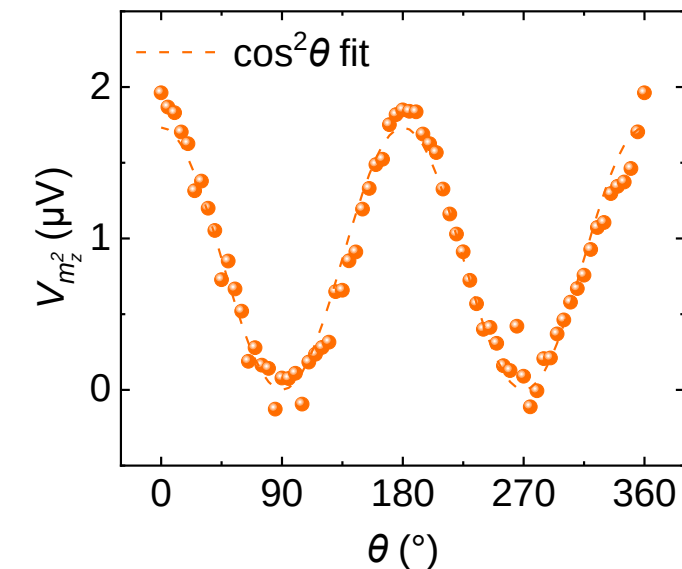
24



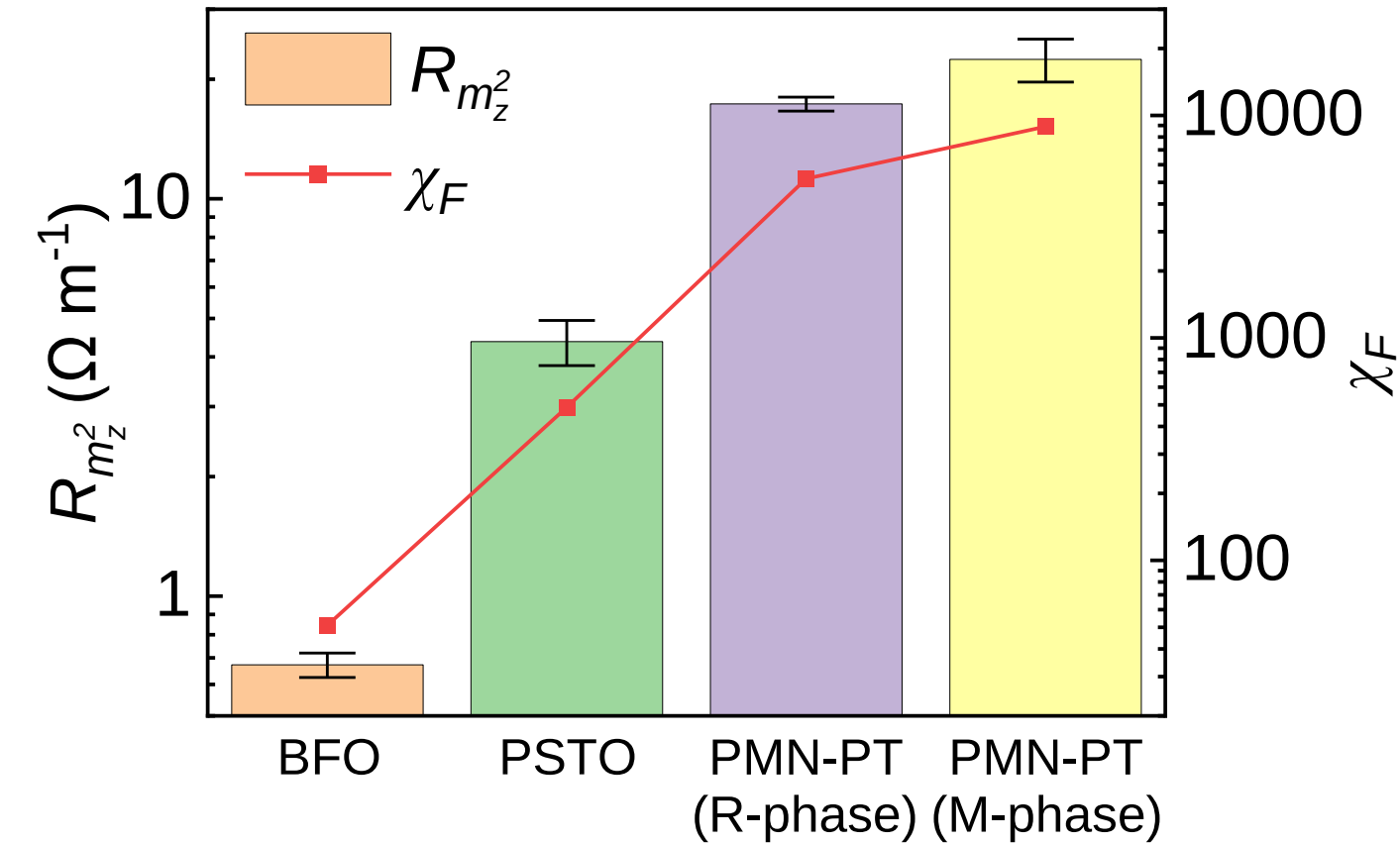
$$V_{nl}^{odd} \approx Am_z^2 j_{INJ} + Bm_z P_x j_{INJ}^3$$

Ferron transport data in PMN-PT/Py

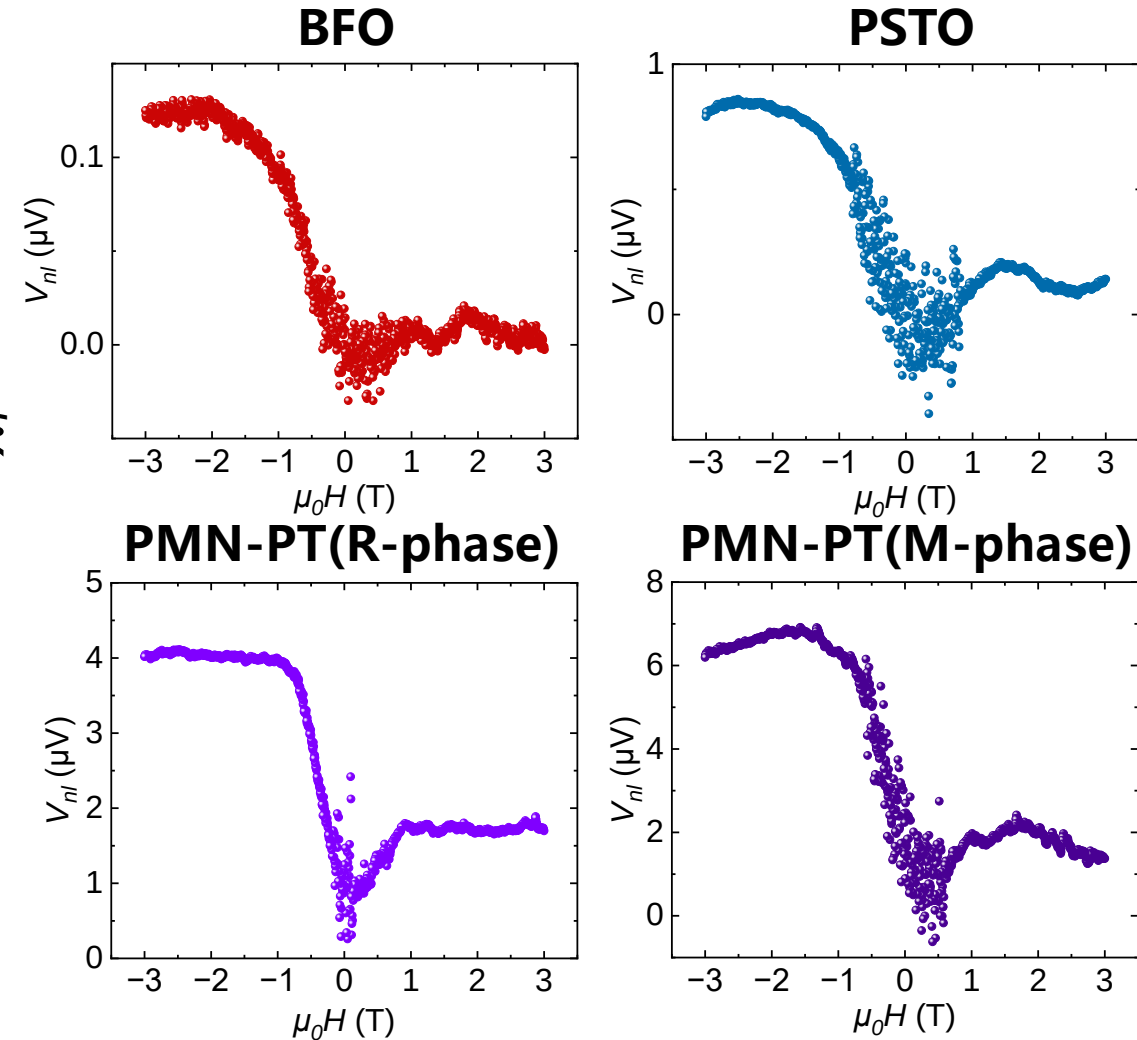
m_z linear component



j_{INJ} dependence



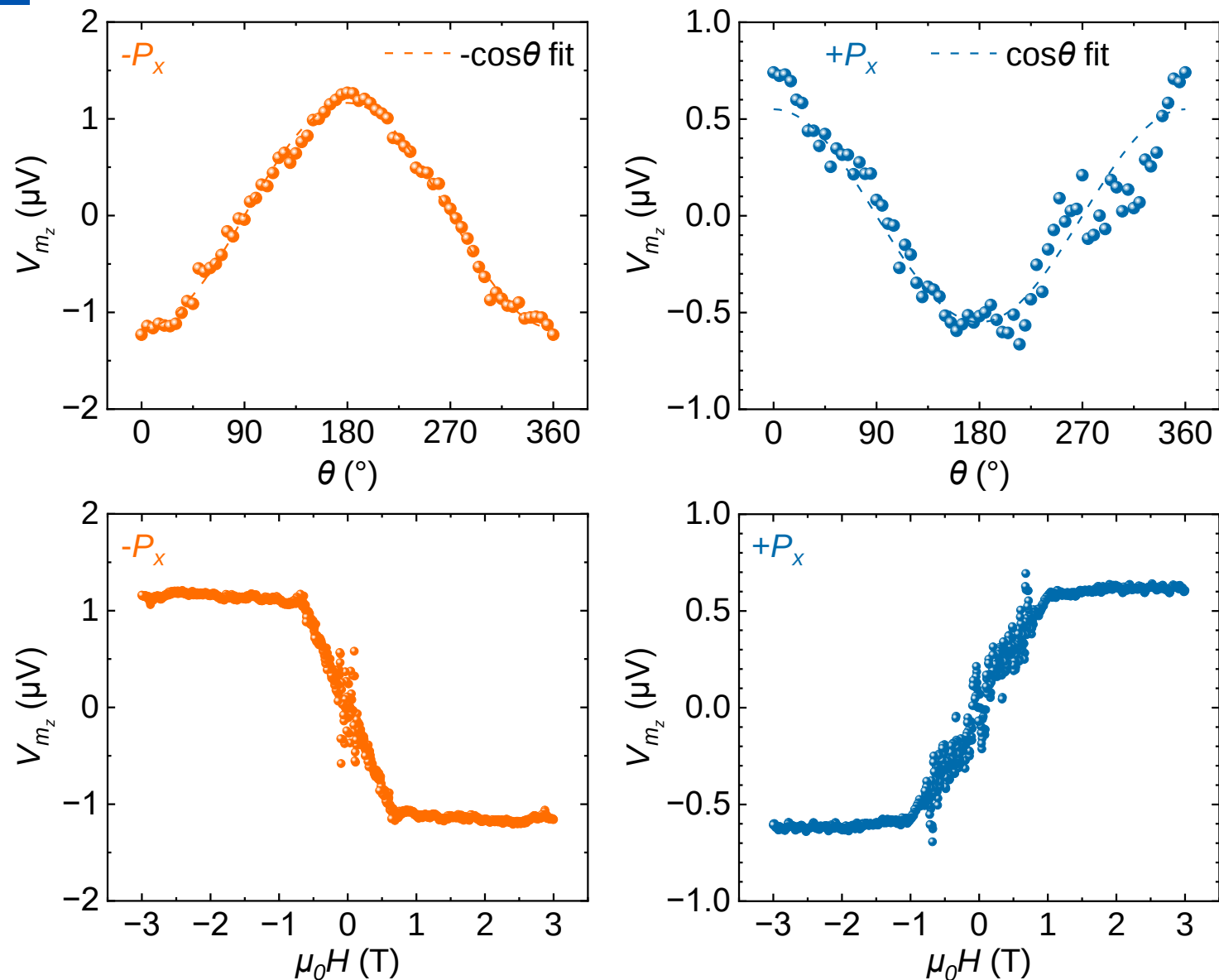
$$R_{m_z} = C \frac{\lambda \theta'_{\text{SHE}}}{w^2 t \sigma} \tanh \frac{w}{2\lambda} \frac{\alpha_P}{1 - \alpha_P^2} e^{-d/\lambda_f} \chi_F^0 m_z^2$$



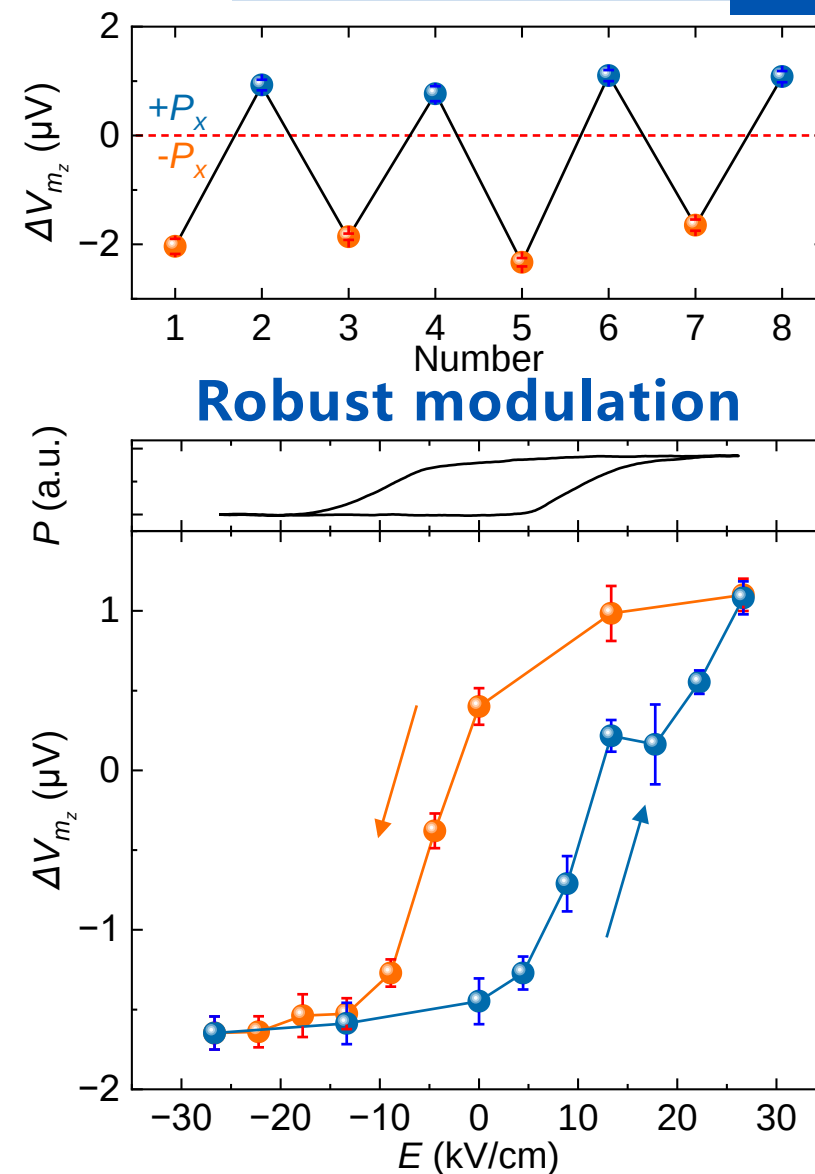
Ferron transport is observed in several ferroelectrics.
Ferroelectric susceptibility matters.

Ferron: Electric Field Modulation

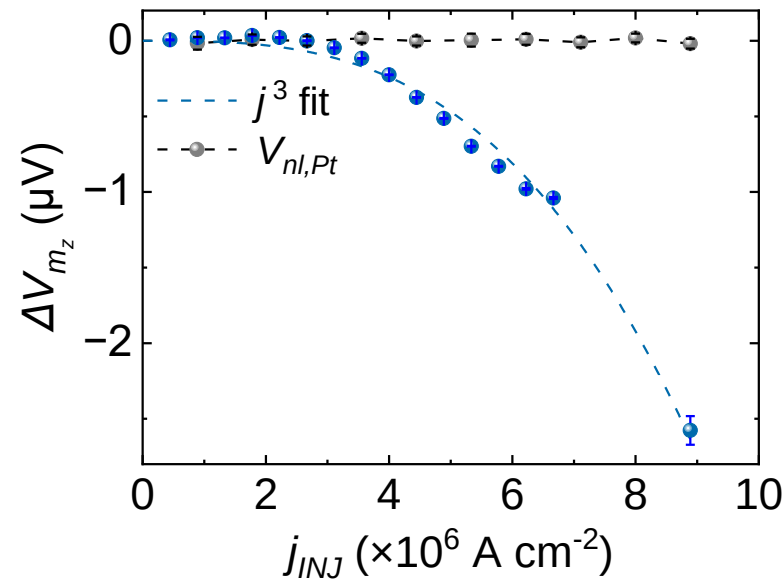
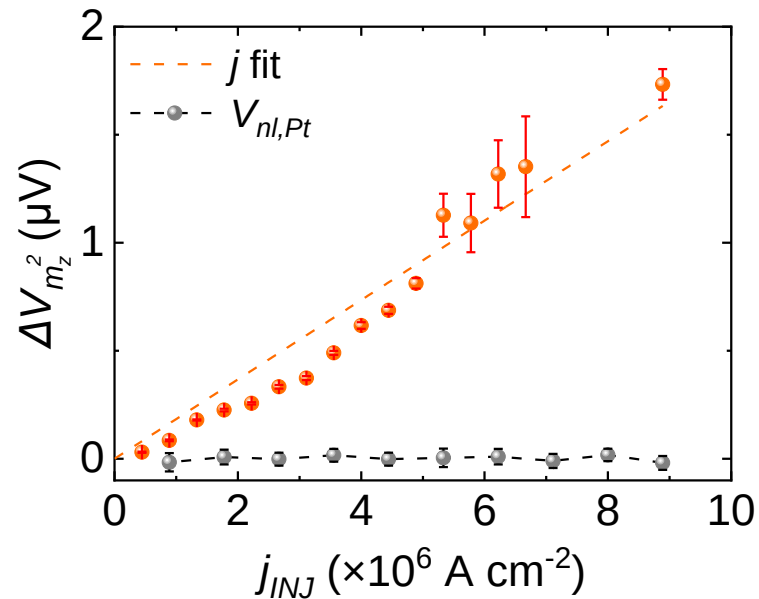
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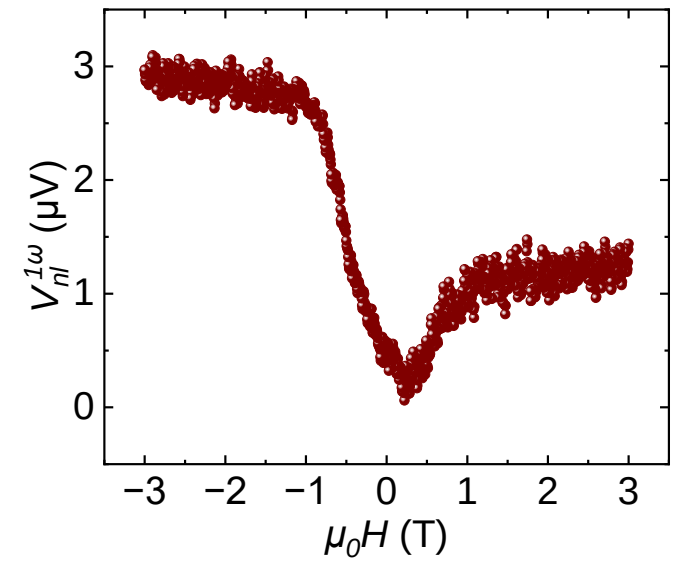
Reversed V_{m_z} - θ curve under opposite polarizations



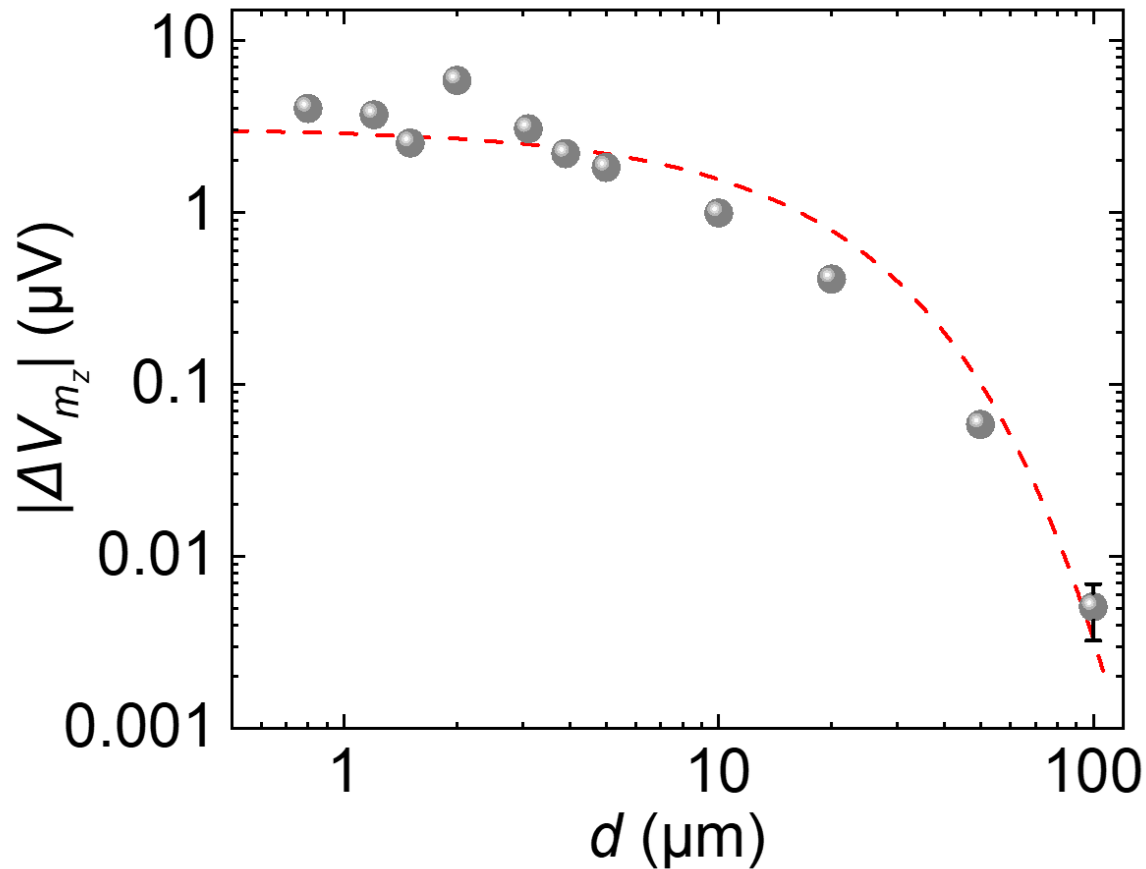
ΔV_{m_z} - E hysteresis loop



No signal in PMN-PT/Pt



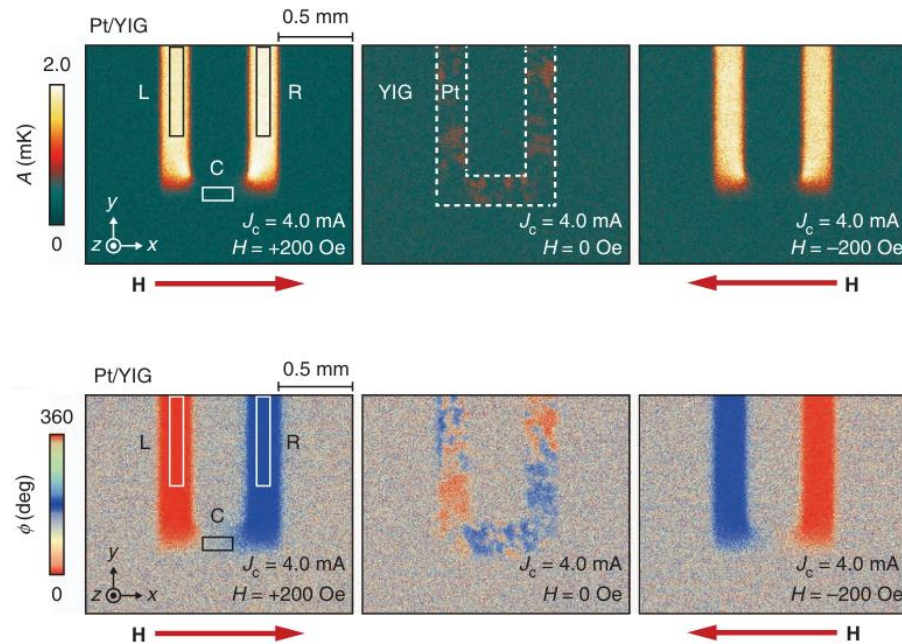
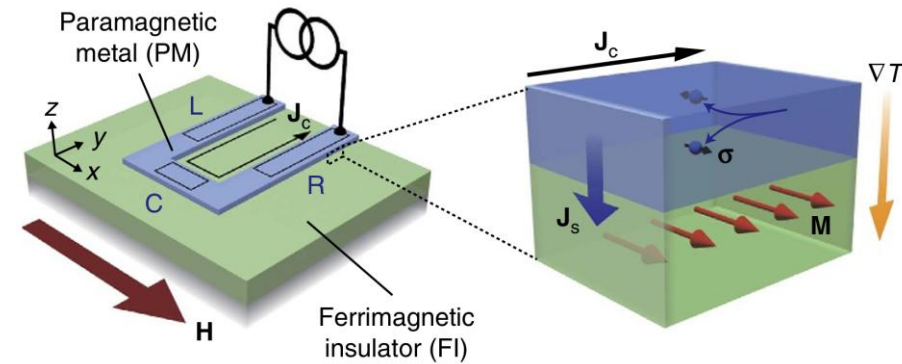
Lock-in based repeated experimental result



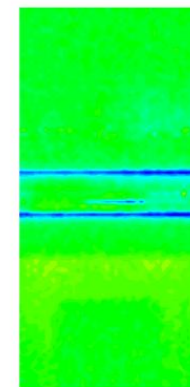
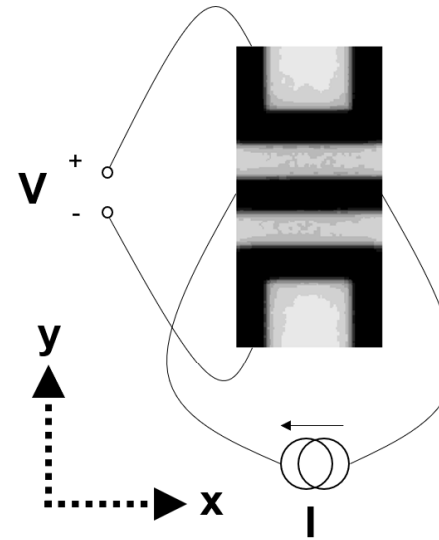
Ferron diffusion length in PMN-PT
 $\lambda \approx 14.8 \pm 1.2 \mu\text{m}$

Magnon diffusion length in BFO
 $\lambda < 0.3 \mu\text{m}$

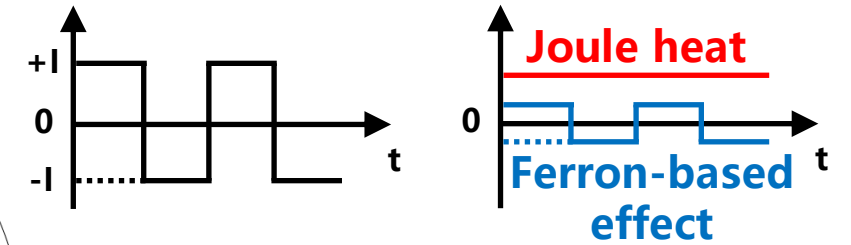
Long-range diffusive ferron transport



Spin Peltier effect [1]



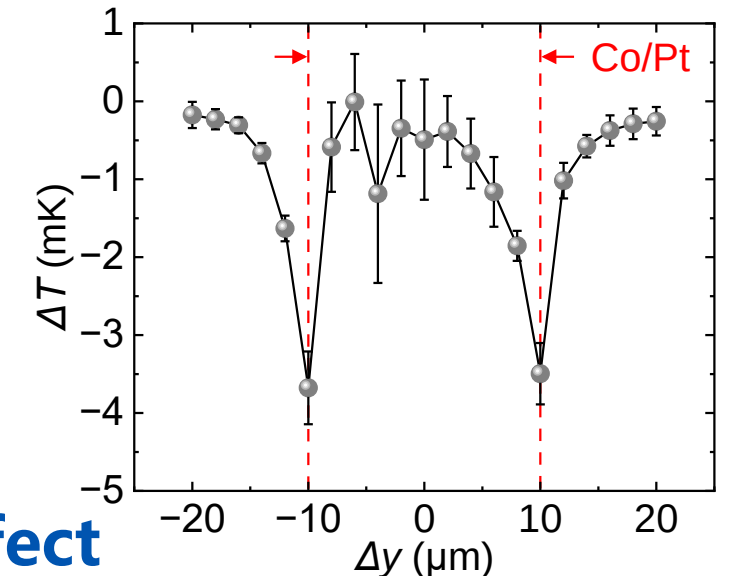
**Ferron Peltier effect
in our work**

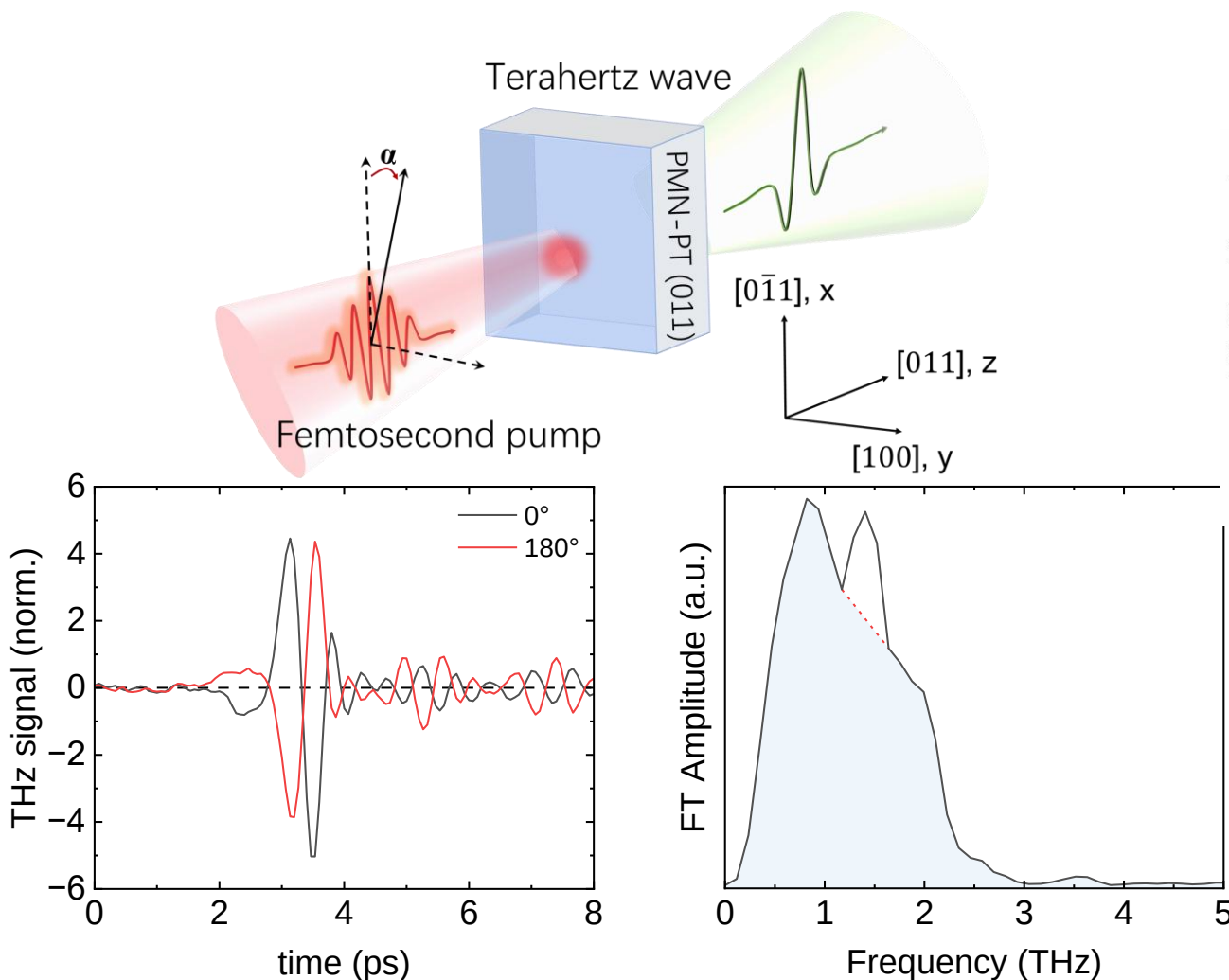


Input

Output

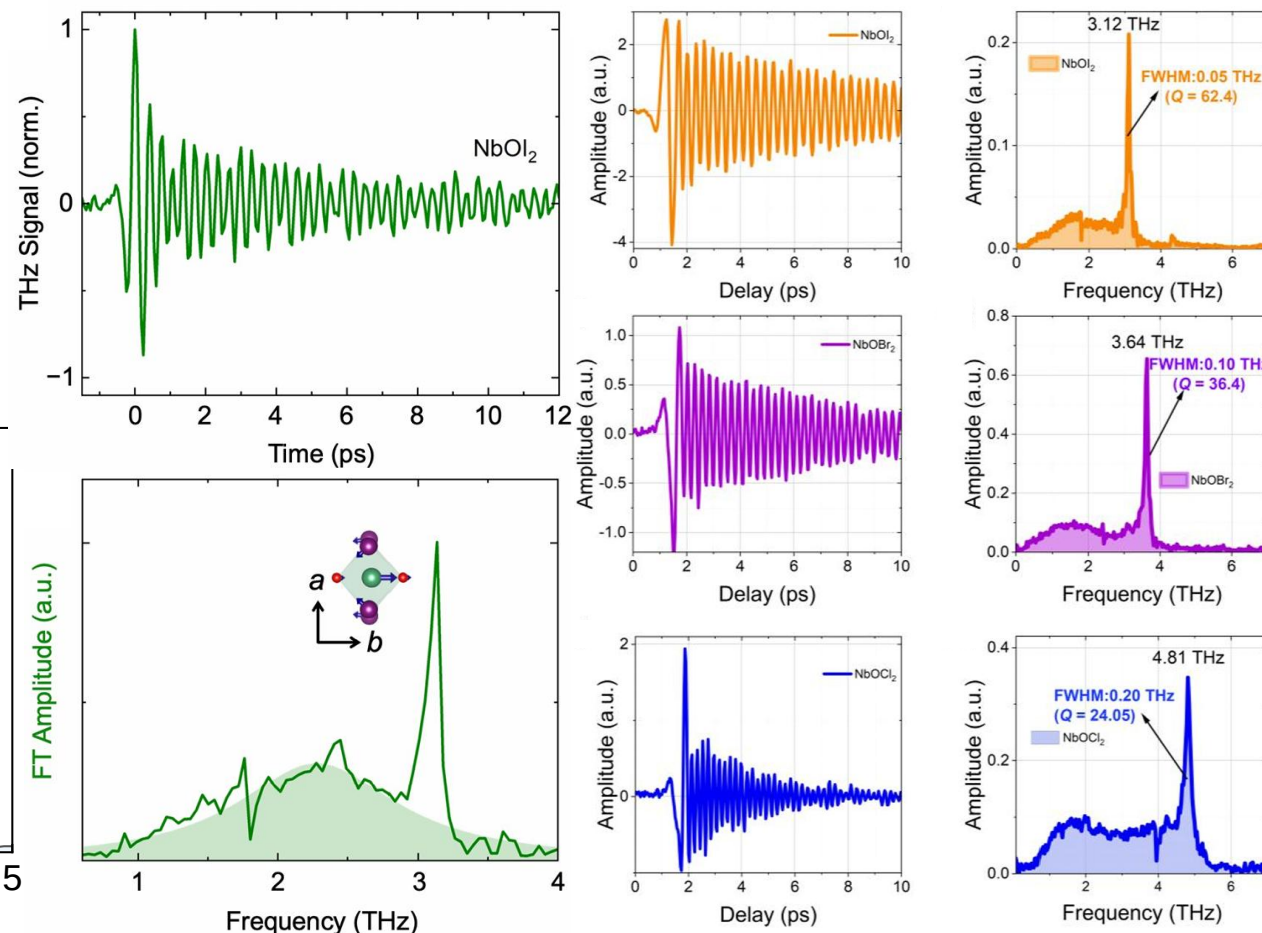
Lock-in infrared imaging





THz emission from ferrons in PMN-PT in our work

K. Shen, P. Tang, X. Chen*, G. E. W. Bauer, M. Liu. *et al.*
[arXiv:2505.24419](#) (2025).



THz emission from ferrons in NbOI₂, NbOBr₂ and NbOCl₂ [1,2]

[1] J. Choe, X. Y. Zhu. *et al.* [arXiv preprint arXiv:2505.22559](#) (2025).
 [2] B. Zhang, R. Singh. *et al.* [arXiv preprint arXiv:2509.06057](#) (2025).

Magnon-mediated MESO Device

Key results:

- Electric field controlled chiral magnon transport is realized in multiferroic BFO, and the spin torque that the magnons in BFO carry is used to efficiently switch the magnetization of adjacent magnets.
- An all-oxide, energy-scalable magnon-mediated MESO logic is demonstrated composed of spin-orbit injection, detection and magnetoelectric control.

Ferron Transport in Ferroelectrics

Key results:

- Ferromagnetic metal/ferroelectric insulator bilayer enables efficient ferron injection and detection, achieving non-local signal transmission up to tens of micrometer distances in several ferroelectric materials.
- The transmission efficiency can be modulated by external magnetic fields and switched by gate electric fields that control the ferroelectric polarization.

Publications

- [1] X. Huang, X. Chen*, R. Ramesh*, *et al.* *Nat. Mater.* **23**, 898–904 (2024).
[2] K. Shen, P. Tang, X. Chen*, G. E. W. Bauer, M. Liu, *et al.* **arXiv:2505.24419** (2025).

Acknowledgements

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