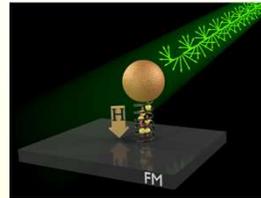
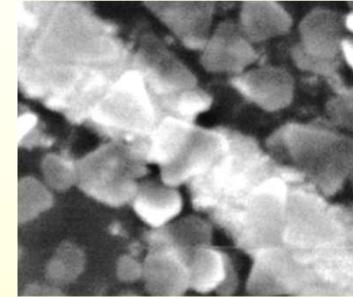


Chiral Spintronics - High density memory utilizing chiral-chiral interaction



Yossi Paltiel

Applied Physics Department
The Hebrew University
Jerusalem, Israel



Q N E
L a b



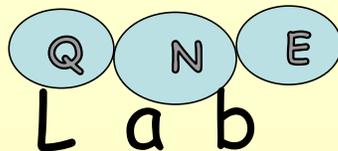
Our Current Group: Prof. Yossi Paltiel, Dr. Shira Yochelis,
Dr. Ohad Golan, Yael Kapon, Avi Schneider, Naama Goren, Meital Ozery,
Chana Fridman, Ofek Vardi, Naama Mordus Sa, Nir Yuran, Omer
Shoseyov, Ofek Marely, Gur Aminadav, Daniel Voignac, Sheli Muzafe,
Noga Havshosh, Daniel Goldberg, Lilach Brann, Roi Ben Zion.

Prevuious members

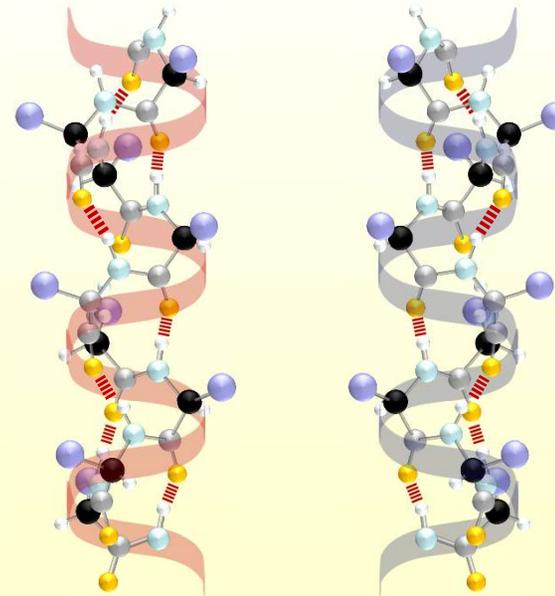
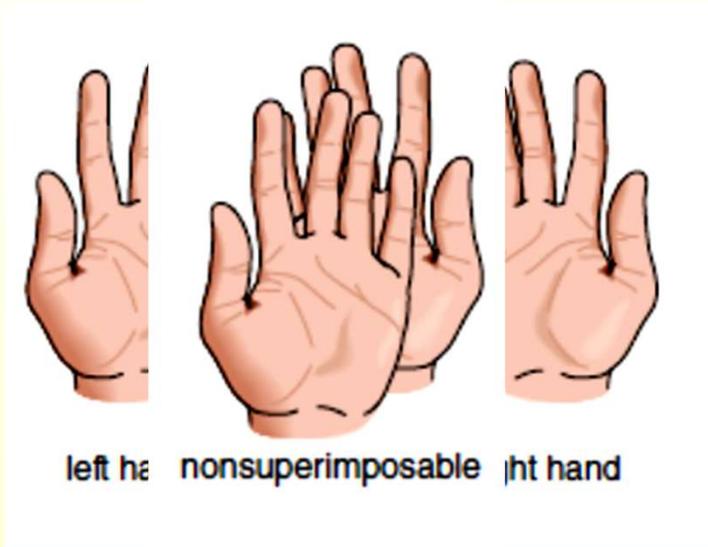
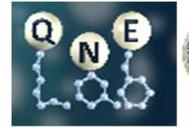
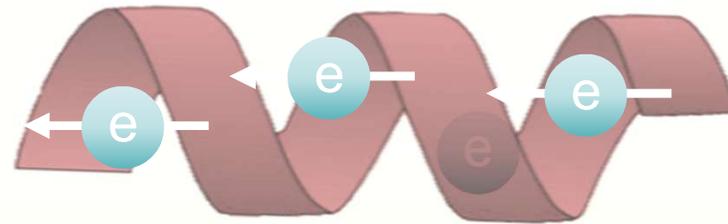
Dr. Oren Ben Dor, Dr. Eran Katzir, Dr. Guy Koplovitch, Dr. Ohad Westrich,
Dr. Amir Ziv, Dr. Nir Sukenik, Dr. Yuval Koldney, Dr. Hen Alpern, Dr.
Tzuriel Metzger, Dr. Hammam Al Bustami, Eytan Avigad, Yuval Shifris,
Shoshan Vortman, Lilach Salton, Amitai Meir.

Collaborators;

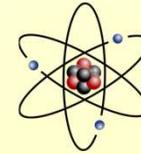
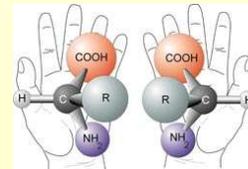
Ron Naaman, Dave Waldeck, Yves Geerts, Narcis Avarvari, Jonas
Fransson, Vladimiro Mujica, Christoph Tegenkamp, Thomas
Baczewski, Stuart Parkin, Mathis Kläui, Angela Wittmann, Furkan
Ozturk, Dimitar Sasselov,, Jason Robinson.
Nir Keren, Oded Millo, Oded Shoseyov, Shlomo Magdassi, Meital
Rechtes



Chirality

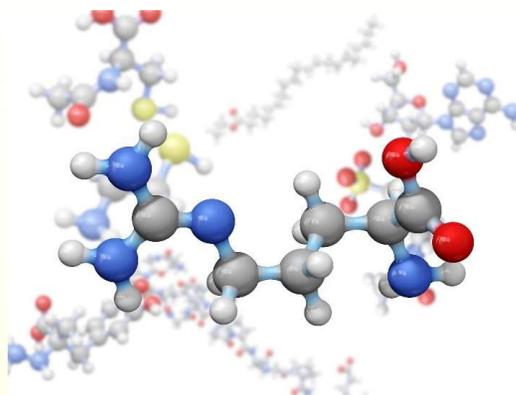


Chirality at any length scale

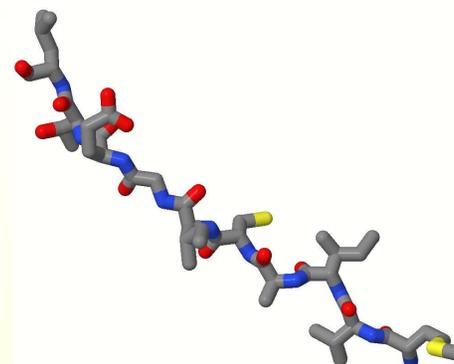


Q N E
L a b

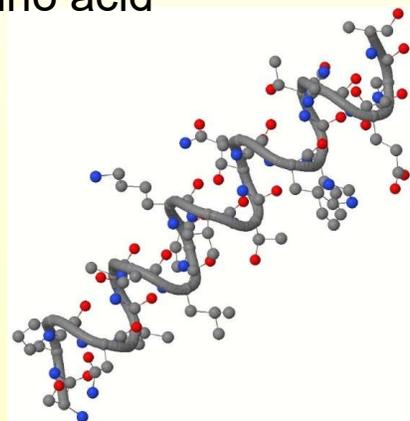
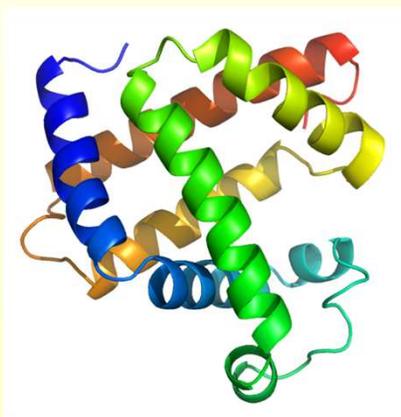
Chirality matters – Life is homochiral



L-amino acid

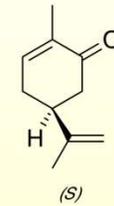
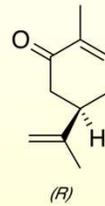


peptides





spearmint



caraway



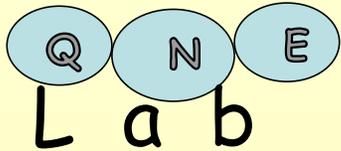
Chirality matters

Breaking the mirror symmetry

- How did our single-handed world develop from a primordial chemical soup that was both left- and right-handed?
- Why was this asymmetry breaking preserved?

In any chemical synthesis, without intervention, an almost equal or racemic mixture of left- and right-handed molecules will form. So where did our homochiral world come from?

We think the answer relate to spin



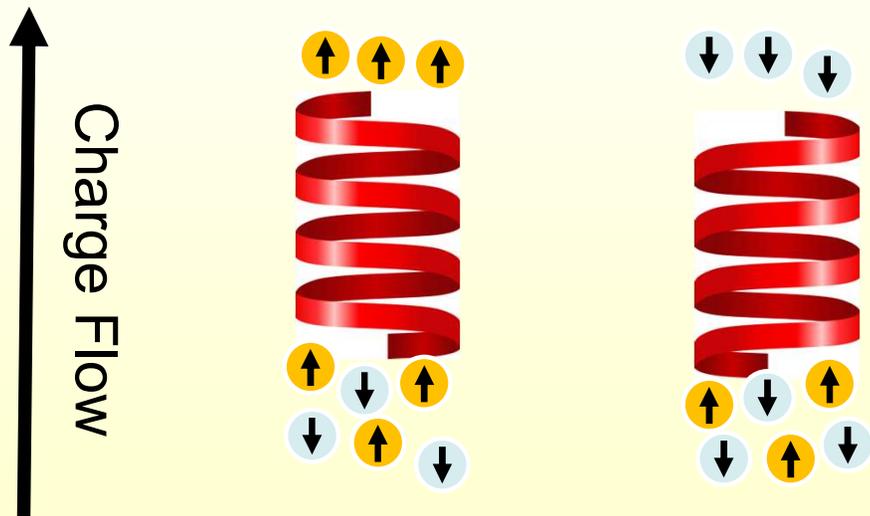
The CISS Effect

Chiral molecules as spin filters.

$$\bar{B}_{eff} = \frac{\bar{E} \times \bar{P}}{mc^2}$$

$$H_{SO} = \mu_B \left(\frac{\bar{E} \times \bar{P}}{mc^2} \right) \cdot \bar{\sigma}$$

CISS – Chiral I nduced Spin S electivity



1. **Multiple particle picture!**
 - I. Electrons
 - II. Phonons
2. **Polarization in critical**
3. **Thermal vibrations usually enhance CISS**

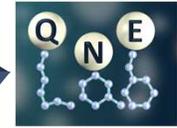
The rotating football

- Throwing the football right to reach the catcher



- Persevering angular momentum

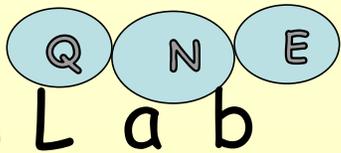
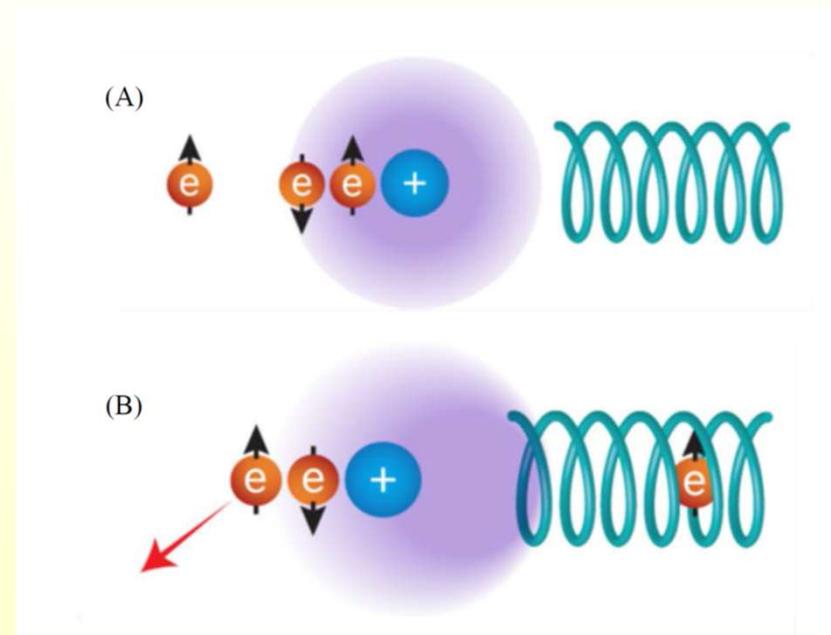




Why it is so hard to understand CISS

- Multiparticle effects (phonons and electrons)
- Polarization (electric and spin) and CD (optical activity).
- Nonlocal effect – Electron wavefunction nonlocal preserving J.
- Chiral phonons at elevated temperatures (special dissipation).
- Strong effective SOC coming from dynamical spin polarization.
- Breaking time reversal symmetry.

The MIPAC effect.

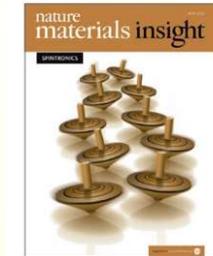


Spin electronics (Spintronics)

- **Energy and heat-** For spintronics, less scattering and higher frequency operation

However,

Spintronics usually require devices that are complicated to realize, and spin injection efficiency is low.



Spintronics

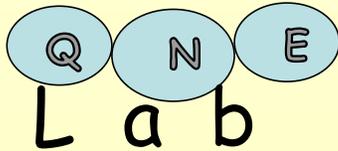
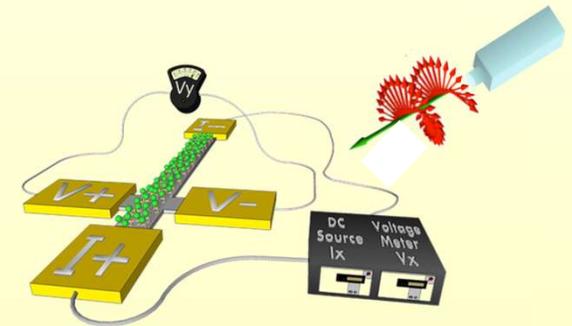
Spintronics is the area of condensed-matter physics that studies the properties of the electron spin with a view to improve the efficiency of electronic devices and to enrich them with new functionalities.

Such a broad definition implies that the range of subjects that fall under the umbrella of spintronics is inevitably very wide. In one extreme, researchers explore the control of single localized spins, realized on single atomic sites in crystals — such as nitrogen-vacancy centres in diamond — or in semiconductor quantum dots. These are regarded as spin qubits, ideal for quantum

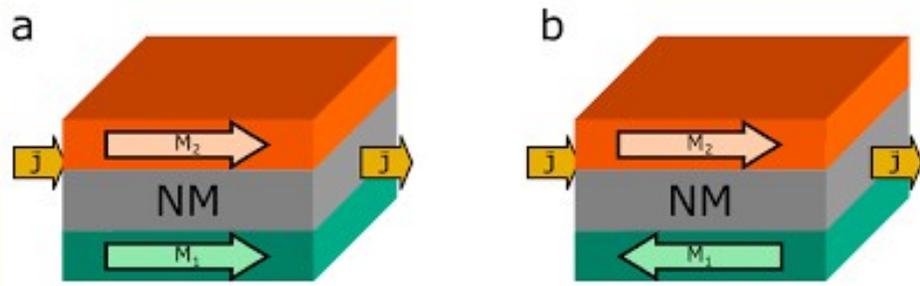
Chiral spintronics may solve both problems

- Easily reproducible
- Inexpensive
- Very high efficiency

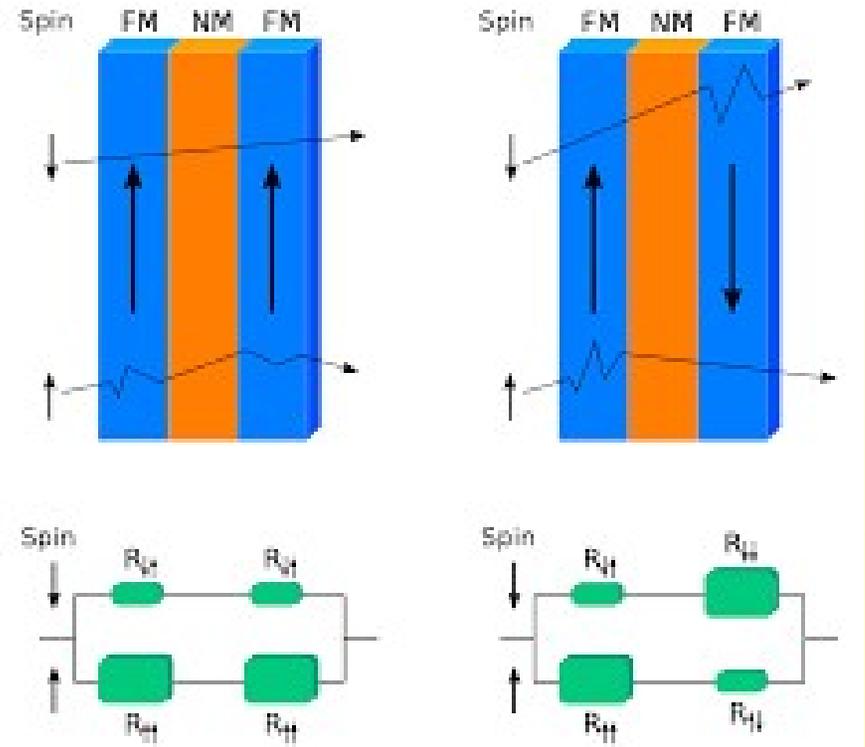
See- Hun Yang, Ron Naaman, Yossi Paltiel and Stuart S. P. Parkin, *Chiral spintronics* Nature Review Physics 3, 328–343 (2021).



TMR and GMR memories



- In a device soft and hard magnetic material is used in proximity
- To reverse local magnetization we need good and efficient spin current injector
- Two different magnets (limit memory size)
- FM material have large magnetic crosstalk



Chiral spintronics

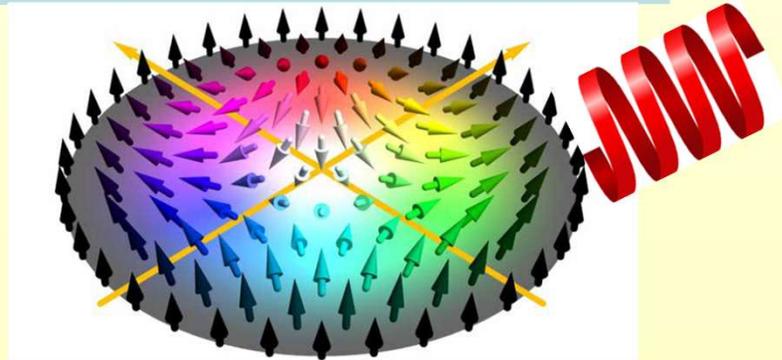
See- Hun Yang, Ron Naaman, Yossi Paltiel and Stuart S. P. Parkin,
Chiral spintronics Nature Review Physics 3, 328–343 (2021).

The chiral molecules supply an efficient and simple spin filter

- Easily reproducible
 - Inexpensive
 - Very high efficiency
- The CISS effect**

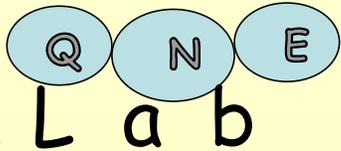
The spin in chiral molecules is coupled to the molecular frame

Can the CISS be utilized
to control and manipulate
magnetic impurities?

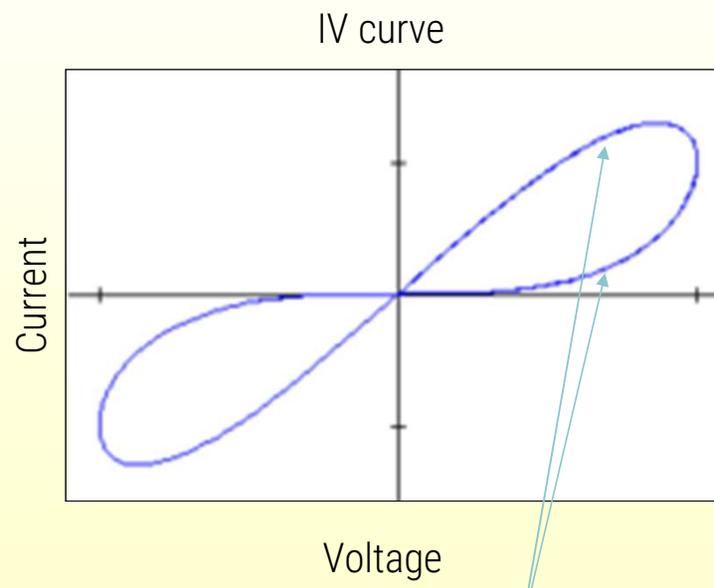
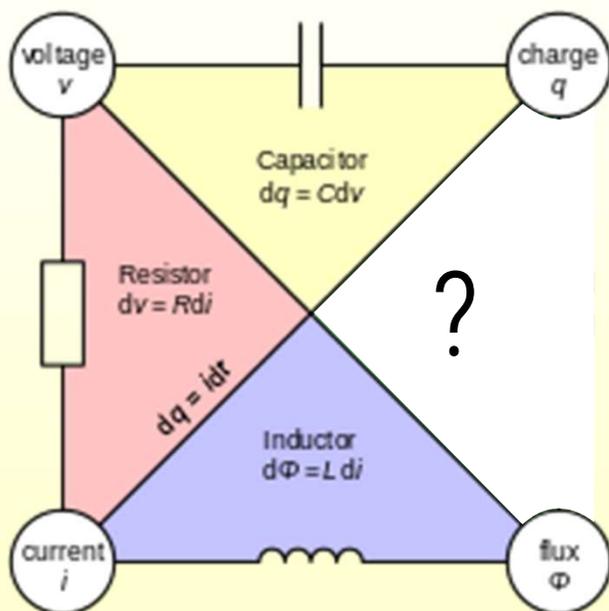
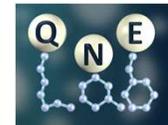
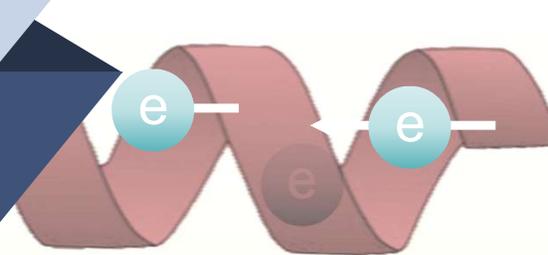


What are the gaps?

- The need to find a simple way to read and write a memory bit.
- To be compatible with IT technology we need to replace the organic molecules with oxides.
- **The need to enhance the memory density**
- The need for efficient interconnect (quantum and classical bits)



Memristor – The missing element



Different resistance states

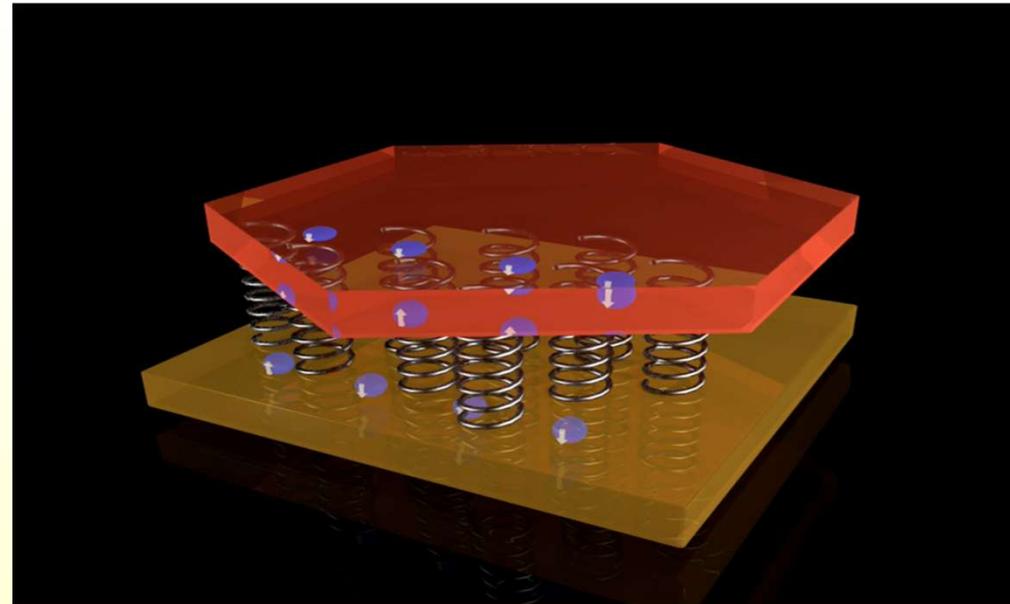
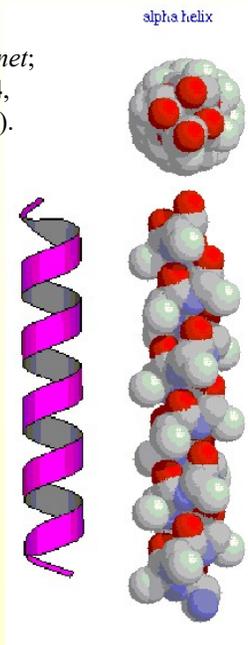
Chua, L. O. (1971), "Memristor—The Missing Circuit Element", *IEEE Transactions on Circuit Theory*, CT-18 (5): 507–519



L a b

Read and write with two terminal device

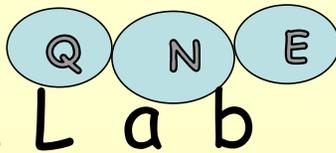
O. Ben Dor, S. Yochelis, S. P. Mathew, R. Naaman, and Y. Paltiel *A chiral-based magnetic memory device without a permanent magnet*; *Nature Communications* **4**, 2256 DOI: 10.1038 (2013).



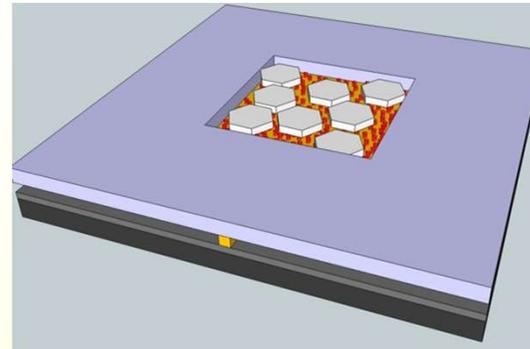
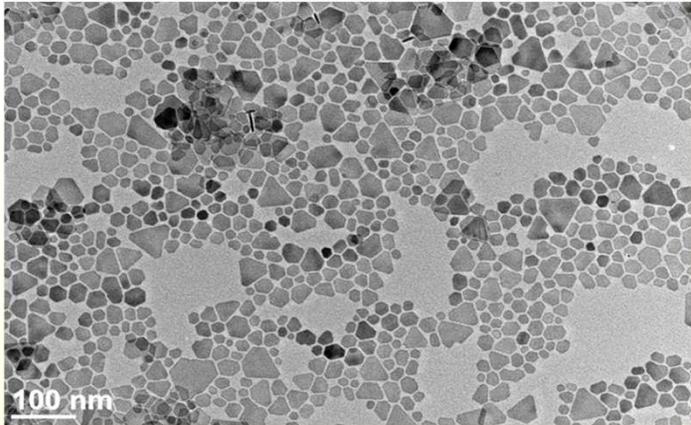
Ba-hexaferrite

L or D PAL (polyalanine), thiolated α -helix -
CAA^{AA}AK^{AA}AA^{AA}AK^{AA}AA^{AA}AK^{AA}AA^{AA}AK^{AA}AA^{AA}AK^{AA}AA^{AA}AK-SH
C, A, and K represent cysteine, alanine, and lysine

G. Koplovitz, D. Primc, O. Ben Dor, S. Yochelis, D. Rotem, D. Porath, and Y. Paltiel; *Magnetic nano platelets based sn memory device operating at ambient temperatures* *Advanced Materials* **29** 1606748 (2017). (**Back cover**). DOI: 10.1002/adma.201606748

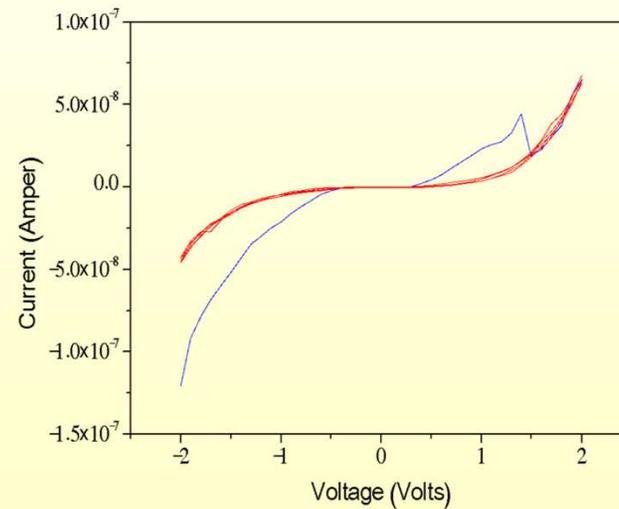
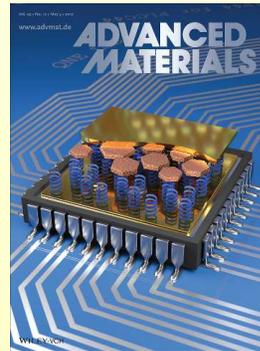


Vertical Memory Device

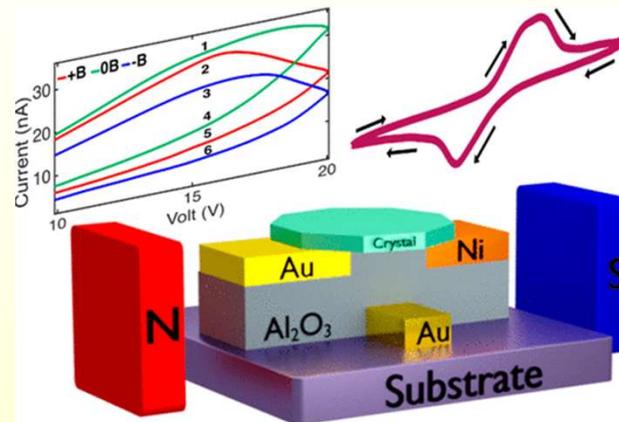
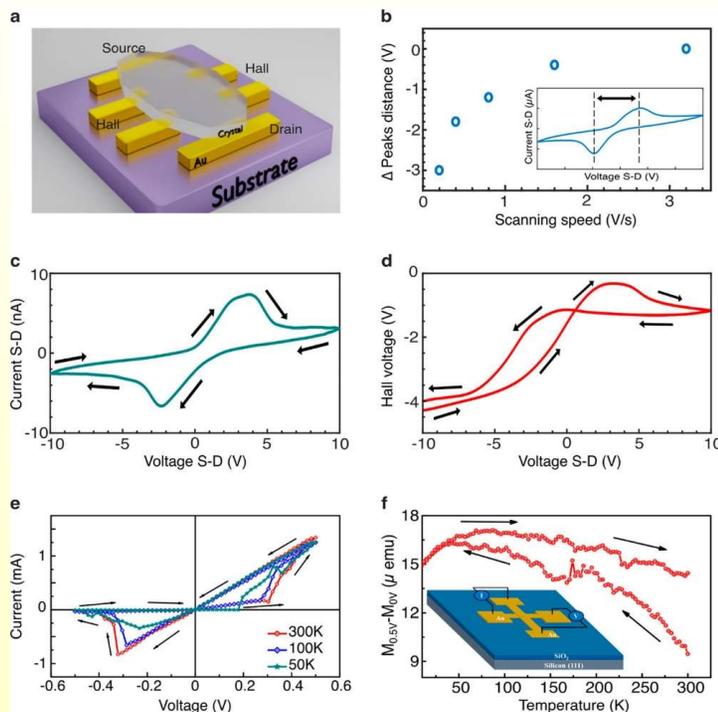
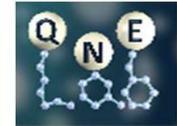
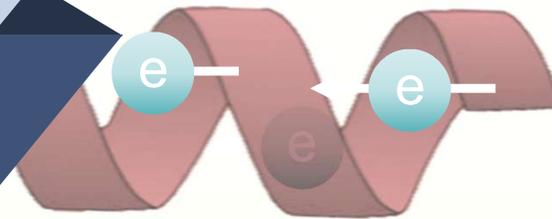


- Bottom electrode
- Adsorb AHPA-L or AHPA-D and multiple FMNPs
- Al_2O_3 tunnel barrier
- Top electrode

AHPA chiral molecules-
 [H]-CAAAAKAAAAKAAAAKAAAAKAAAAK
 AAAAKAAAAK-[OH]

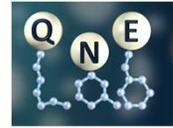
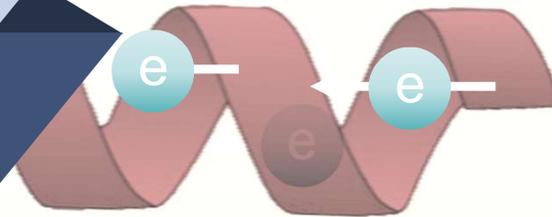


Metal Organic Spin Transistor



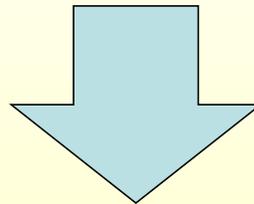
The MOC we used consists of chiral Cu-phenylalanine crystals (*Nano Lett.* 2021, 21, 20, 8657–8663).

Two major problems



- Unit size should be reduced to the nano scale

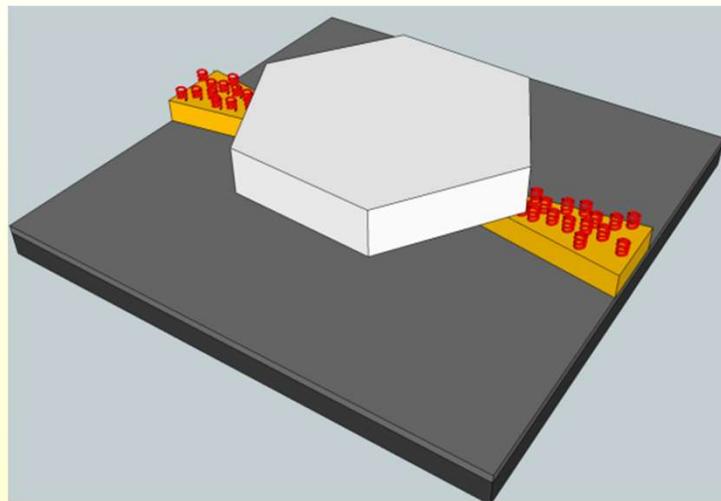
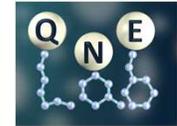
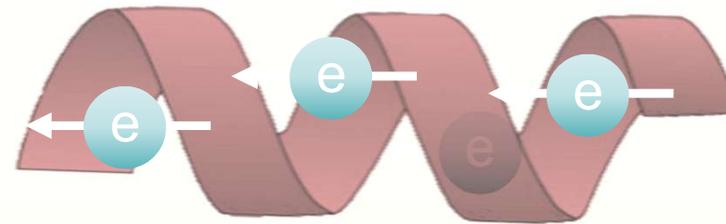
- No erasing mechanism



Nano scale device with hysteresis behavior



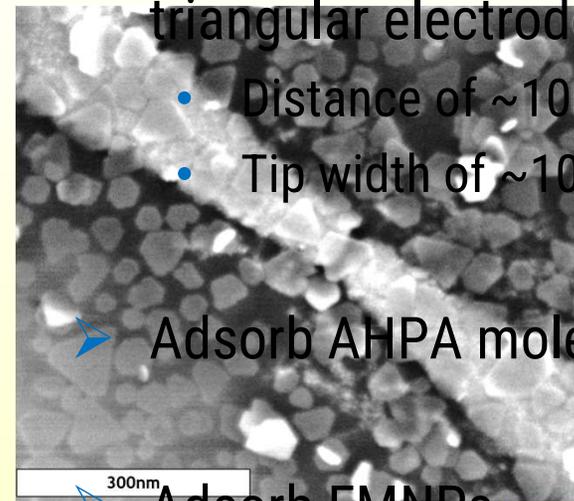
Single FMNP device



Single nanoparticle magnetic spin memristor
H. Al Bustami, *et al.* Small 1801249 (2018).

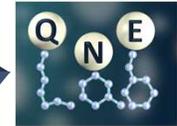
➤ Fabricating metal triangular electrodes

- Distance of ~10nm
- Tip width of ~10nm

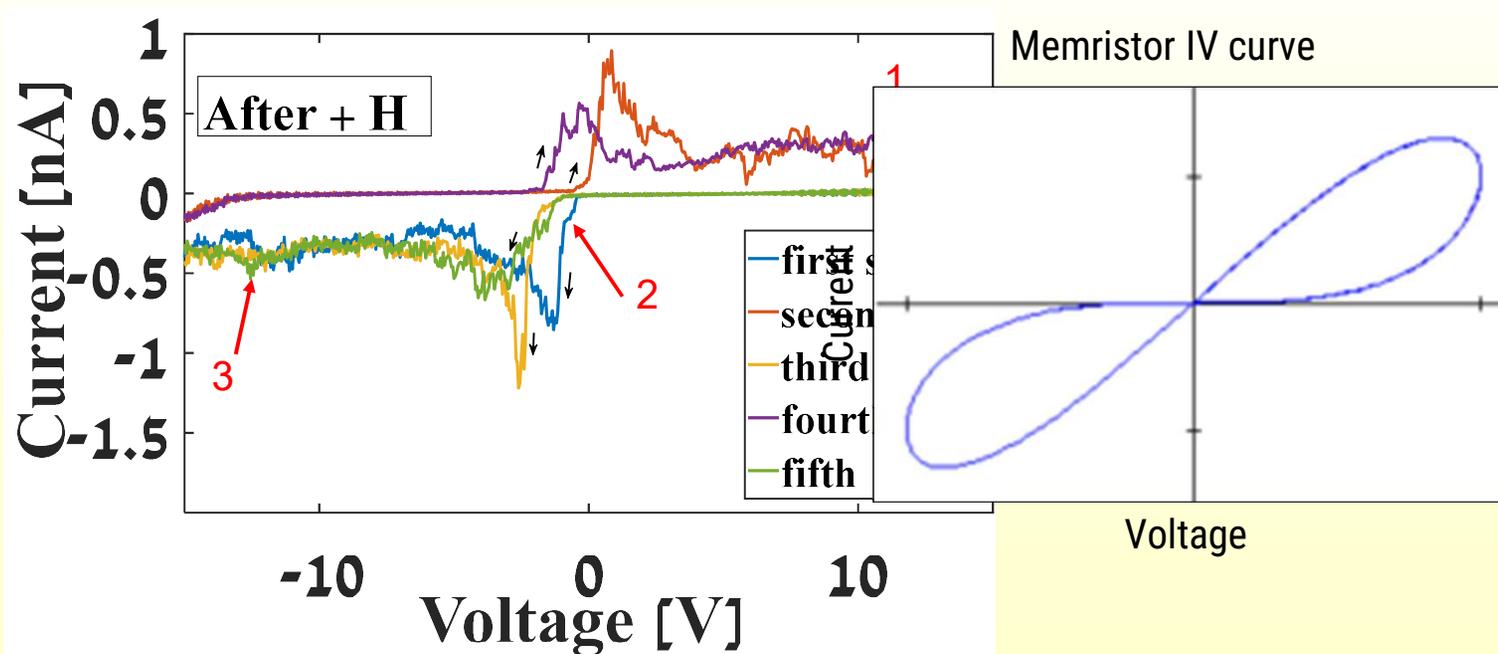


➤ Adsorb AHPA molecules

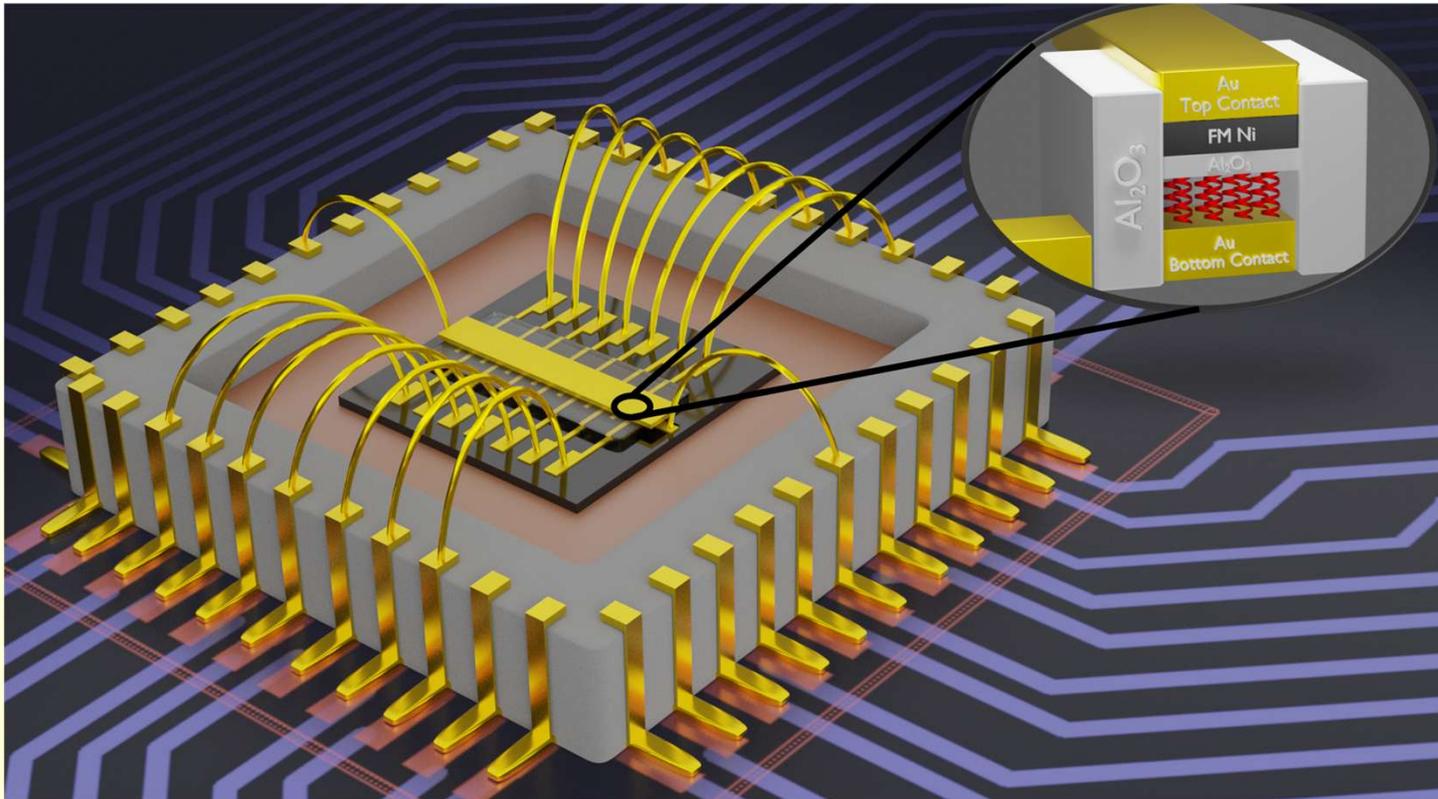
➤ Adsorb FNMNs



Single FMNP device Results - 2 states logic device

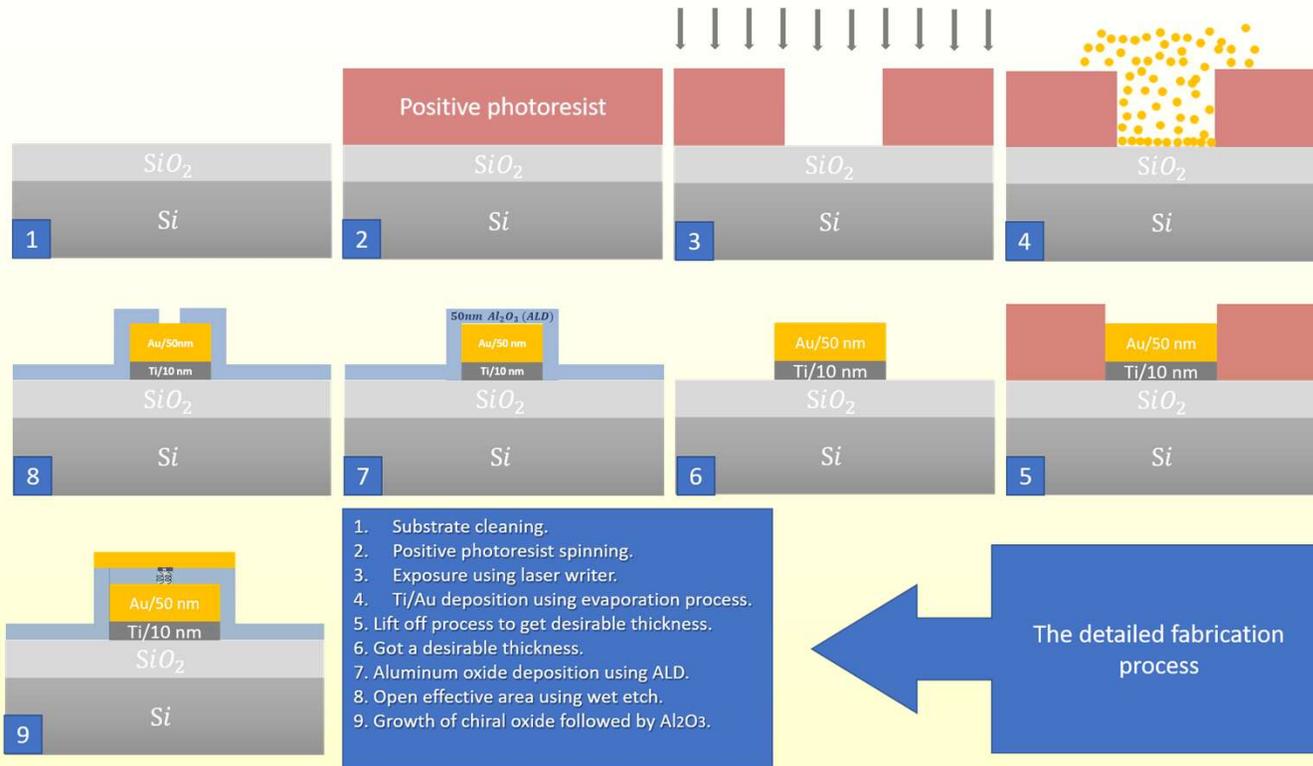


ALD grown Al_2O_3 chiral oxides

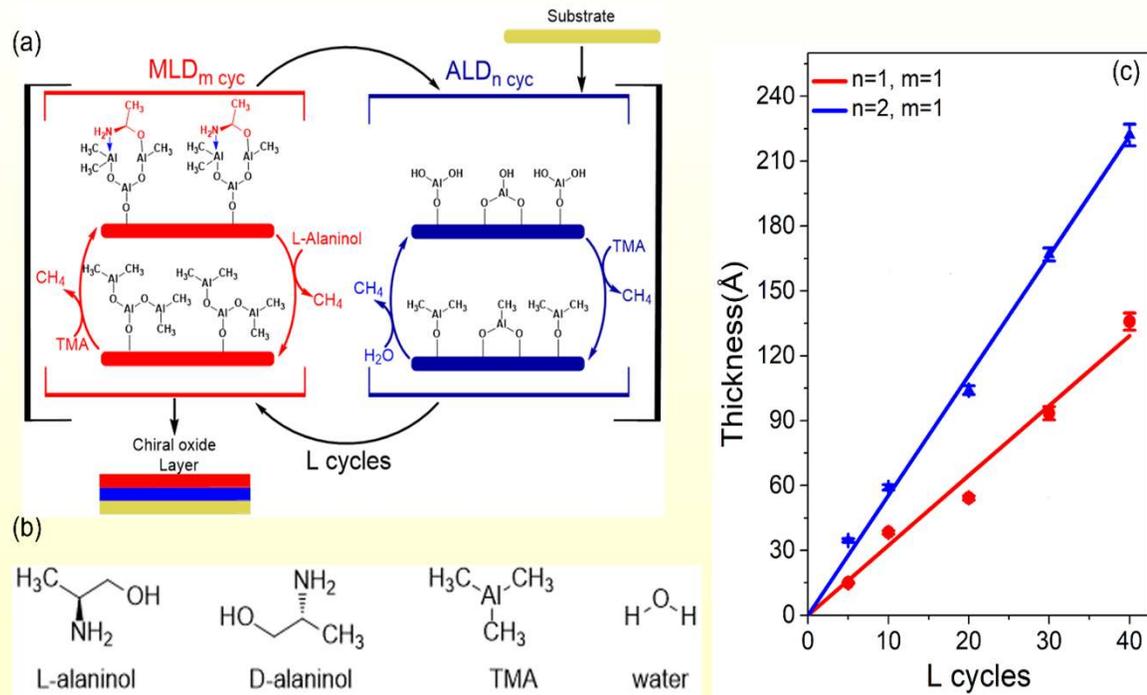


H. Al-Bustami, S. Khaldi, O. Shoseyov, S. Yochelis, K. Killi, I. Berg, E. Gross, Y. Paltiel,* and R. Yerushalmi*, Atomic and Molecular Layer Deposition of Chiral Thin Films Showing up to 99% Spin Selective Transport Nano Letters 22, 12, 5022 (2022).

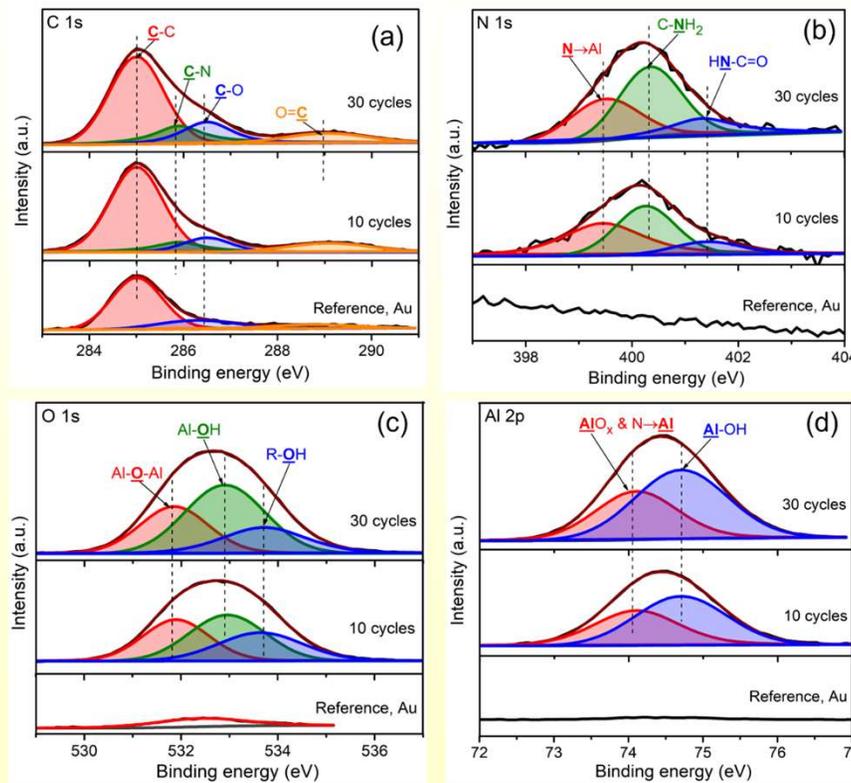
ALD grown Al_2O_3 chiral oxides



A/MLD deposition of hybrid organic-inorganic chiral thin films



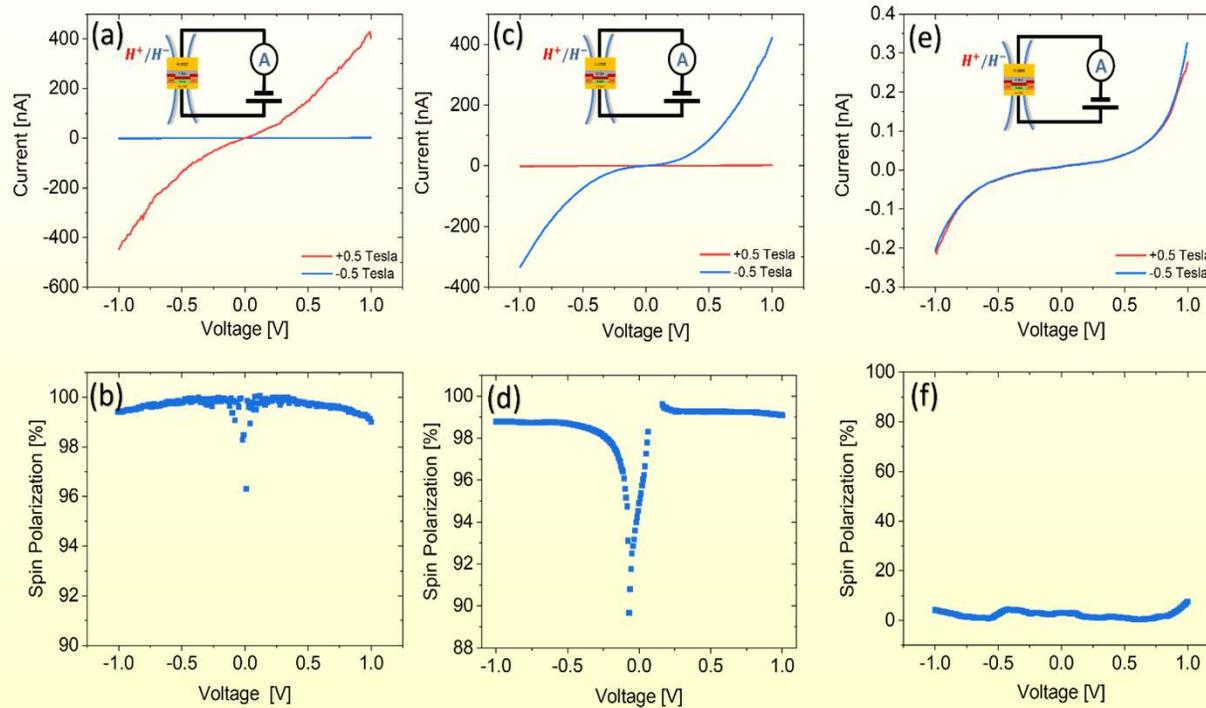
High resolution XPS spectra for the thin film deposited on gold



(L-alaninol, TMA, H₂O, TMA, n=1, m=1, L=30). (a)

Deconvoluted C 1s spectra, (b) N 1s spectra, (c) O 1s spectra, (d) Al 2p spectra. Chemical species are indicated.

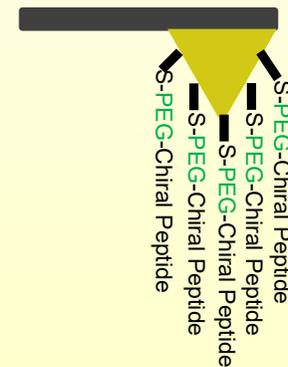
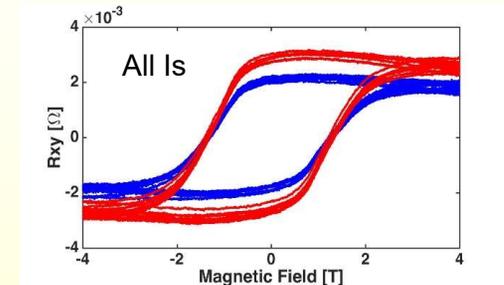
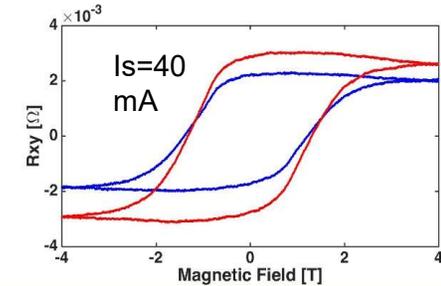
Chiral Thin Films Showing up to 99% Spin Selective Transport



Enhancing memory density

Using the MIPAC effect

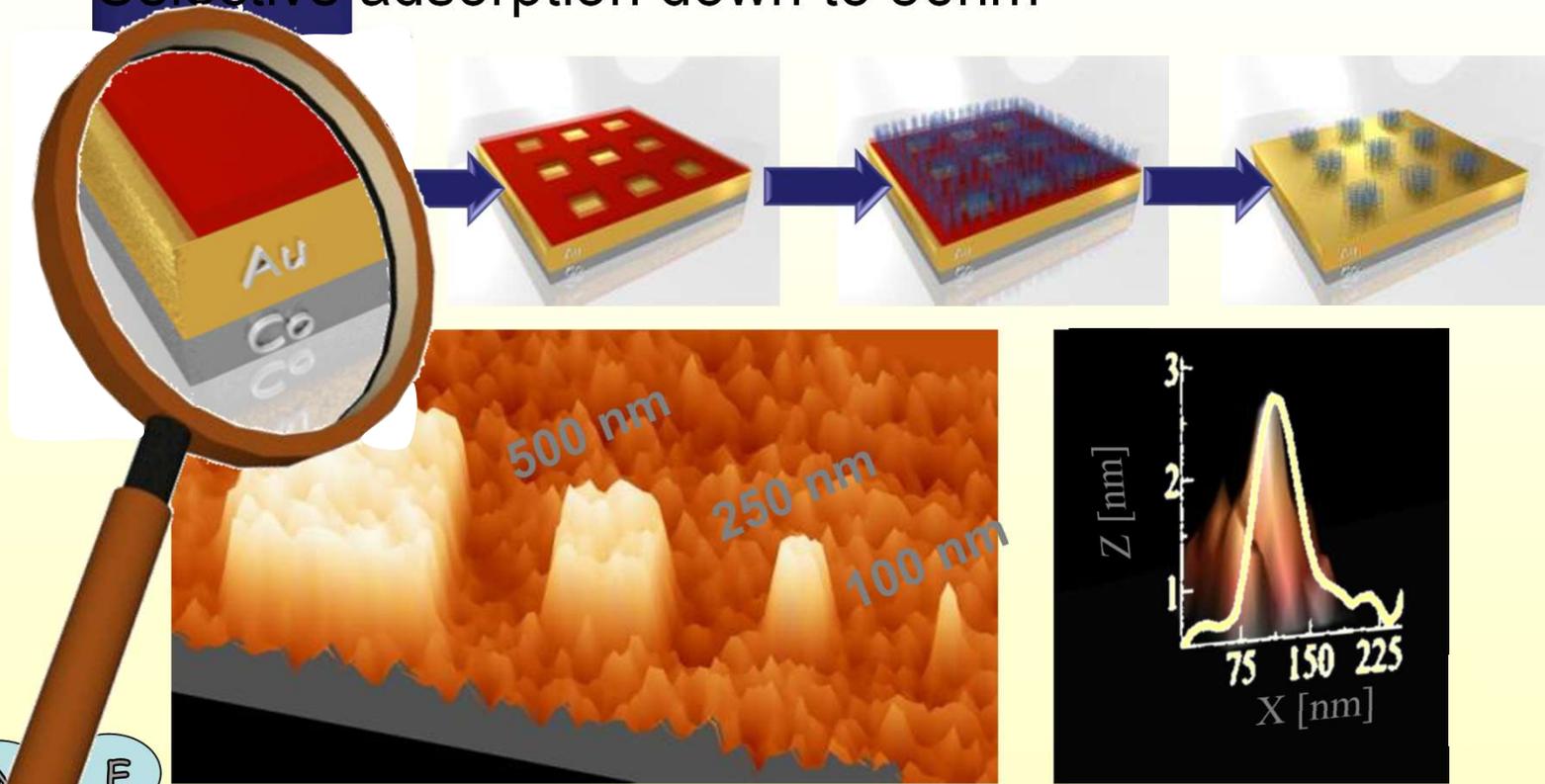
- Paramagnets
- Ferromagnetic skyrmions
- Anti-ferromagnets
- Superconducting and magnetics
- Multi-gated devices



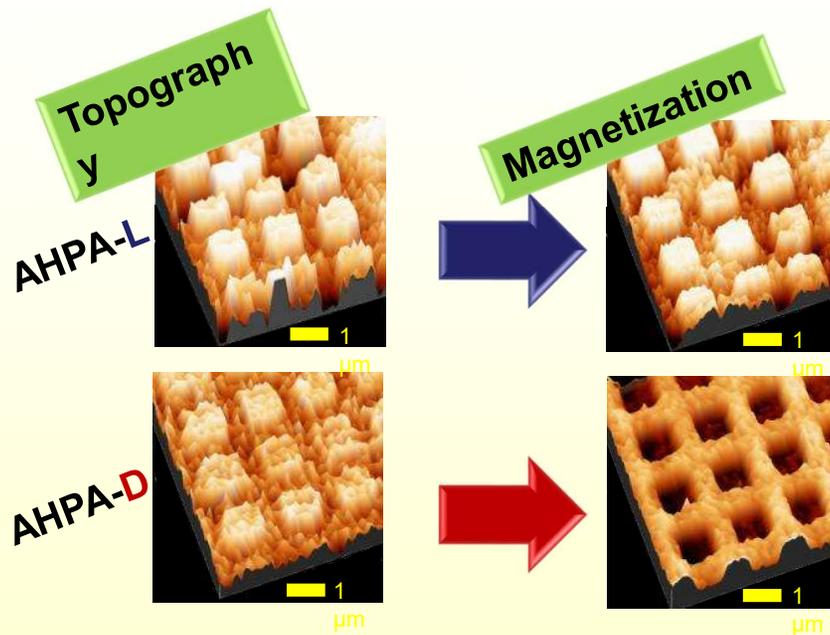
Chiral molecules on magnet

Samples Stuart S. P. Parkin (IBM) and Lech Tomasz Baczewski (Warsaw)

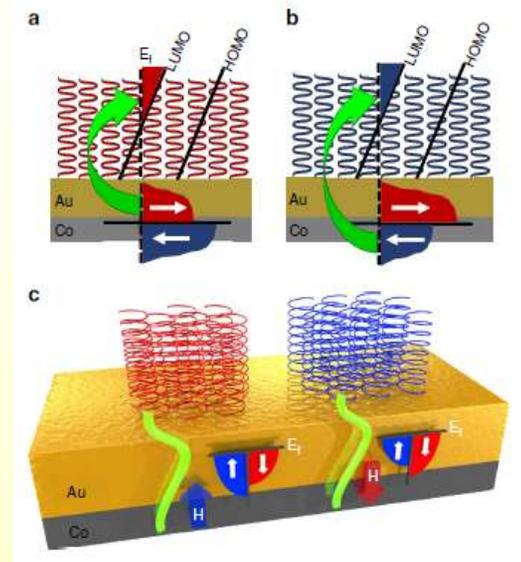
Selective adsorption down to 50nm •



Selective adsorption -> Selective magnetization (MIPAC)



Selective adsorption of α helix polyaniline results in selective magnetization of a ferromagnet



H

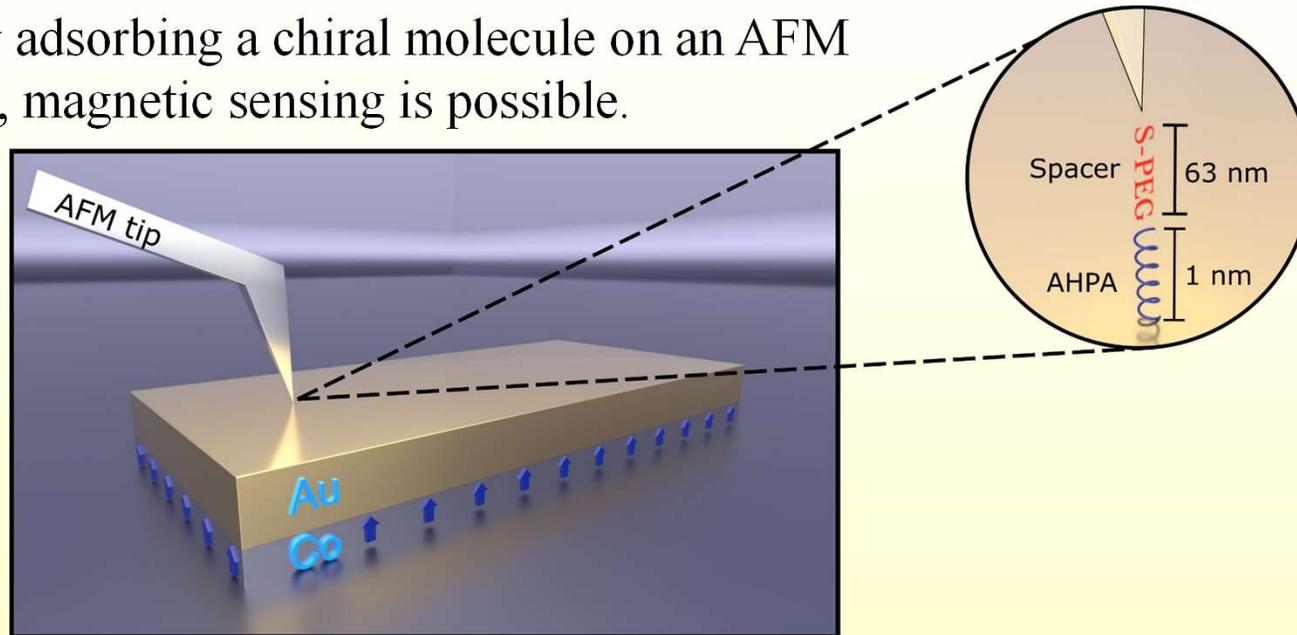
O. Ben Dor, *et al.* **Nature Communication.** 2017, **8** 14567 (2017).

Quantum Nano Engineering Lab

2/16/2026

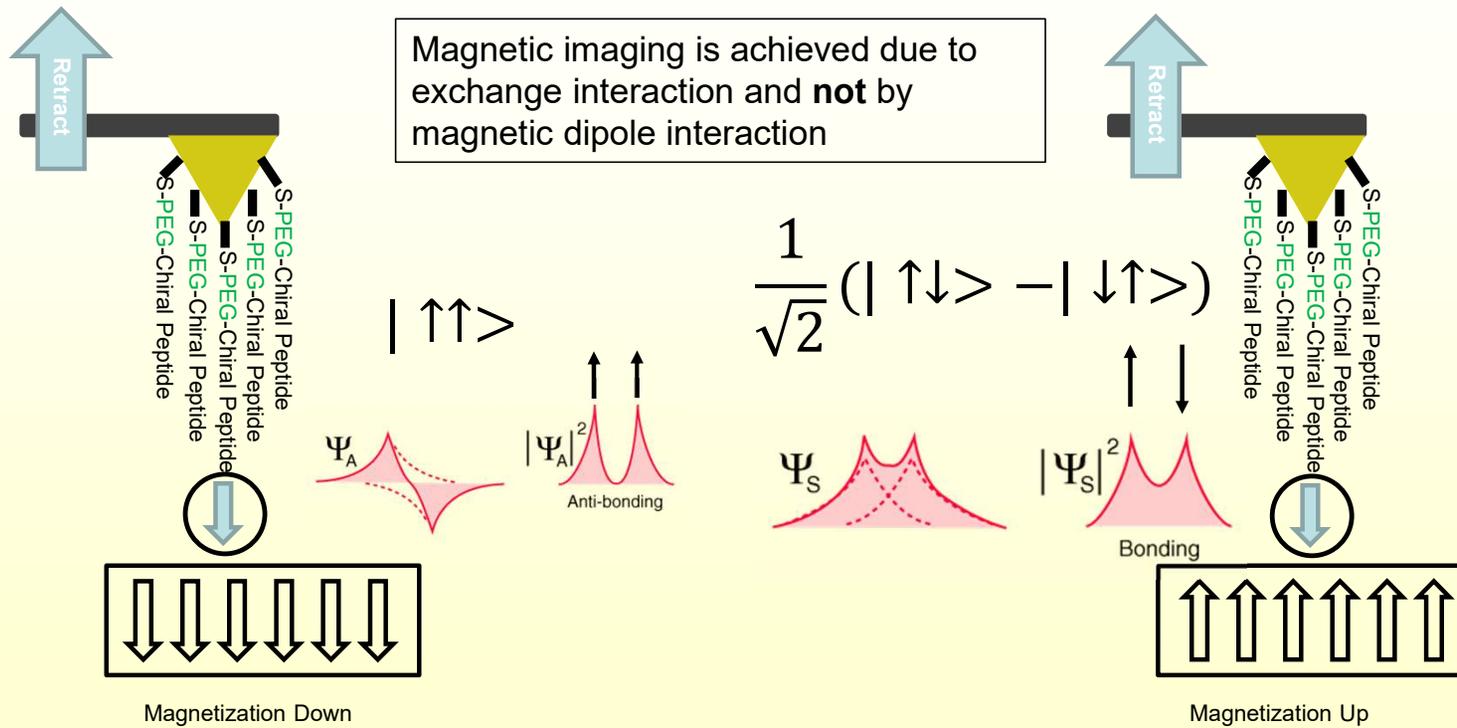
AFM-Based Spin-Exchange Microscopy Using Chiral Molecules

By adsorbing a chiral molecule on an AFM tip, magnetic sensing is possible.



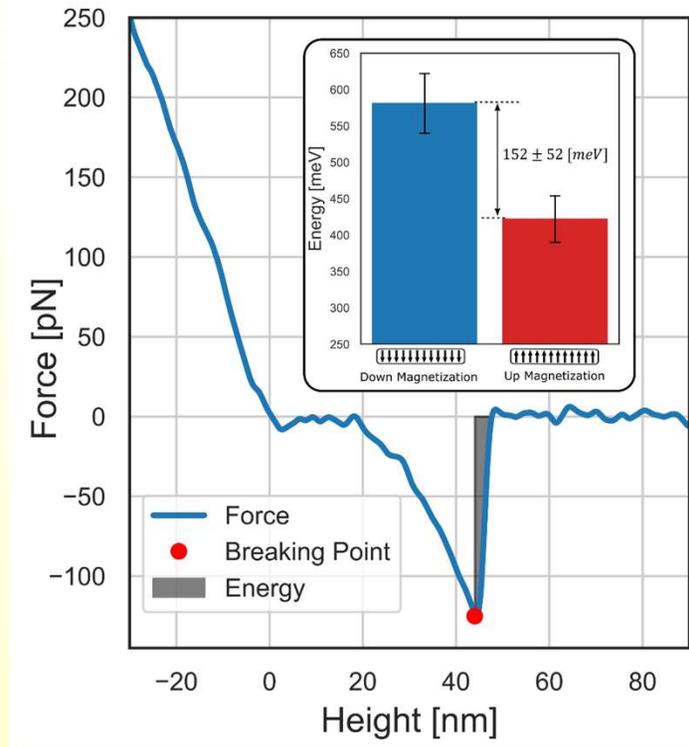
Amir Ziv, Abhijit Saha, Hen Alpern, Nir Sukenik, Lech Tomasz Baczewski, Shira Yochelis, Meital Reches,* and Yossi Paltiel*; *AFM-Based Spin Exchange Microscopy Using Chiral Molecules*, Advanced Materials (2019).

Chiral spin AFM



Atomic resolution of magnetic mapping!!!!

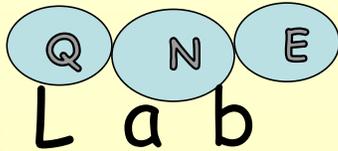
Interaction Energy



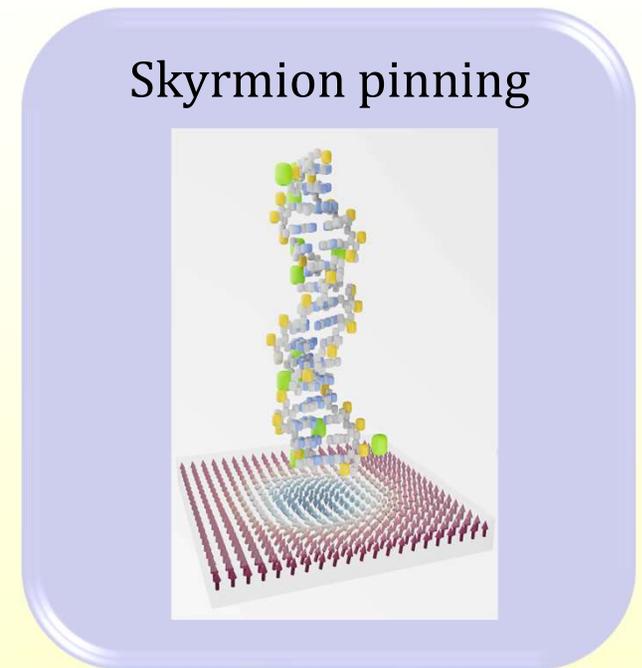
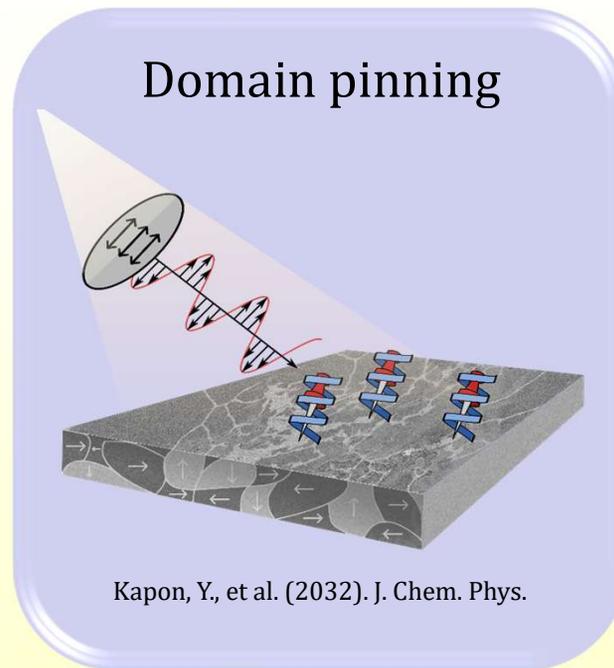
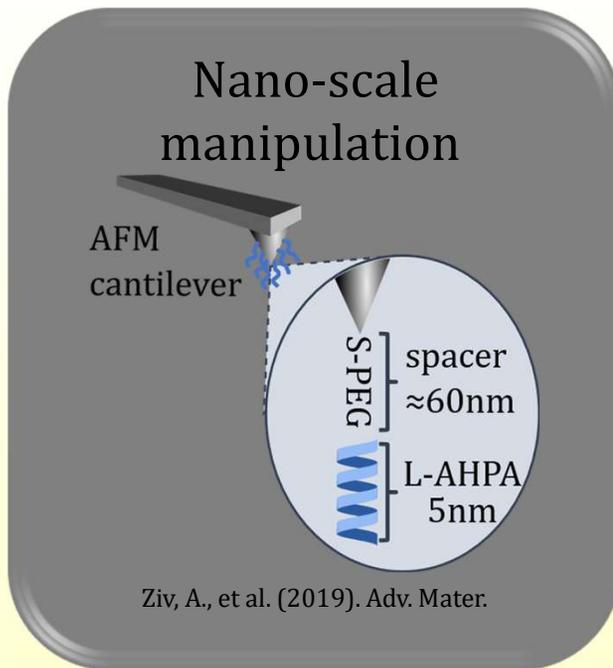
Calculating the energy difference between the down and up magnetization yielded a difference of 152 ± 52 [meV] which corresponds to first principle calculations.

Ziv, A. Saha, A. et al. AFM-Based

Amir Ziv, Abhijit Saha, Hen Alpern, Nir Sukenik, Lech Tomasz Baczewski, Shira Yochelis, Meital Rechtes,* and Yossi Paltiel*; *AFM-Based Spin Exchange Microscopy Using Chiral Molecules*, *Advanced Materials* (2019).



Chiral-Chiral magnetic devices



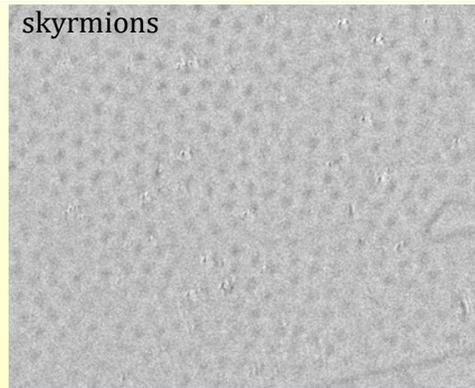
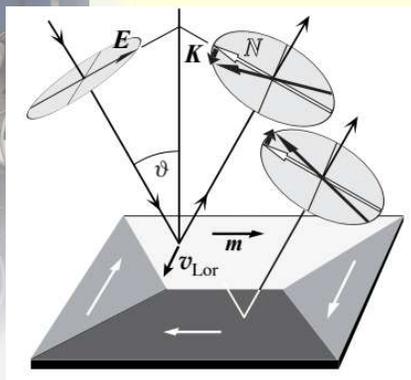
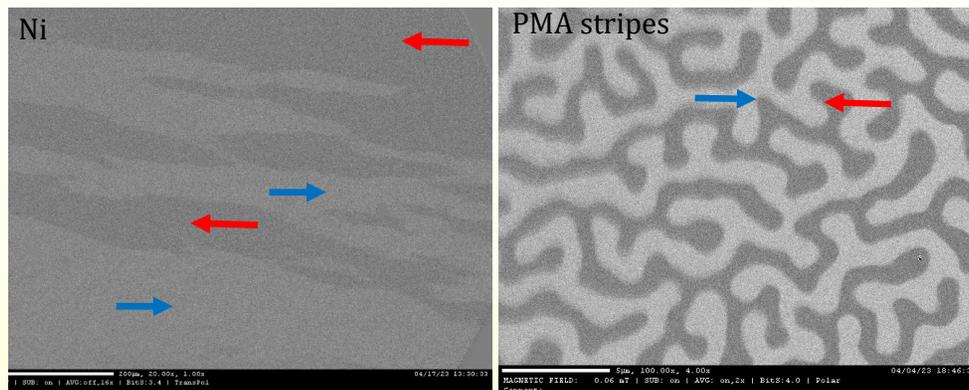
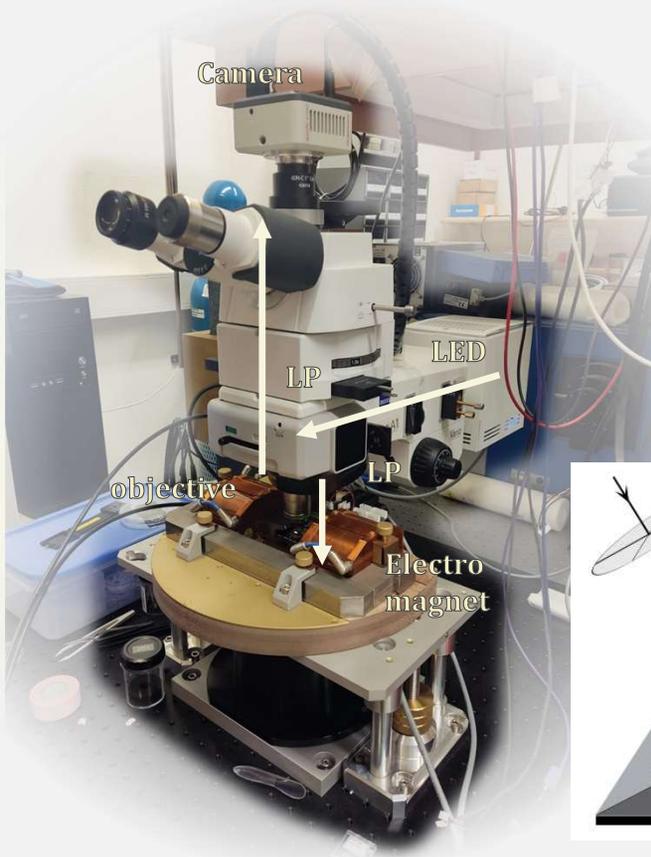
Origin of homochirality

Temperature dependence

Q N E
L a b

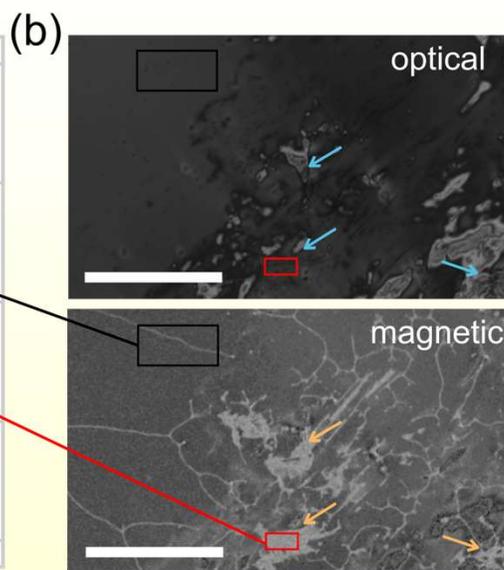
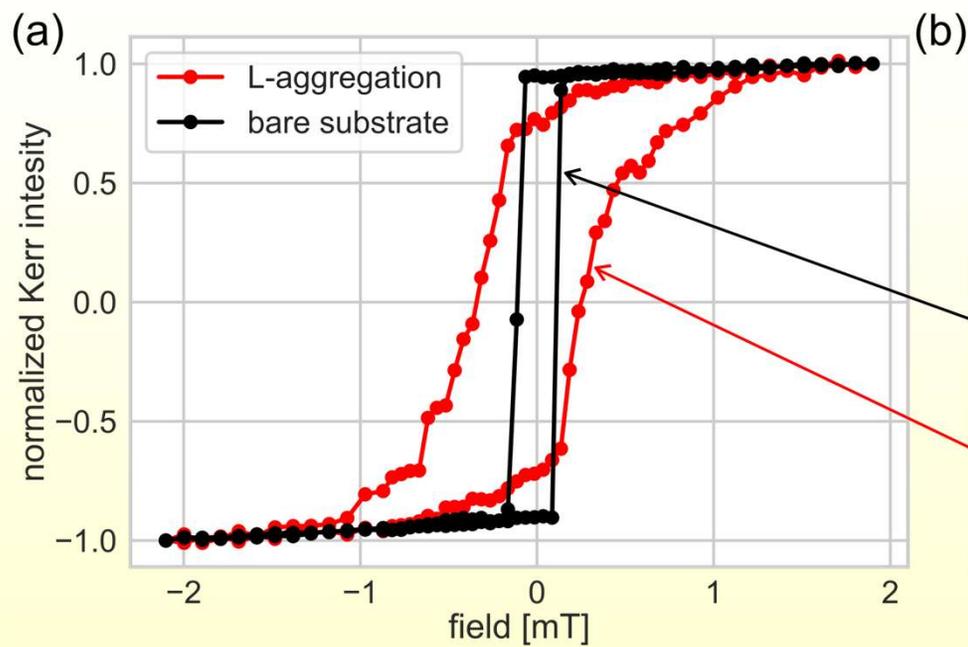
Magneto-Optical Kerr Effect setup

Rudi Schaefer IEEE MAGNETICS



Quantum Nano Engineering Lab

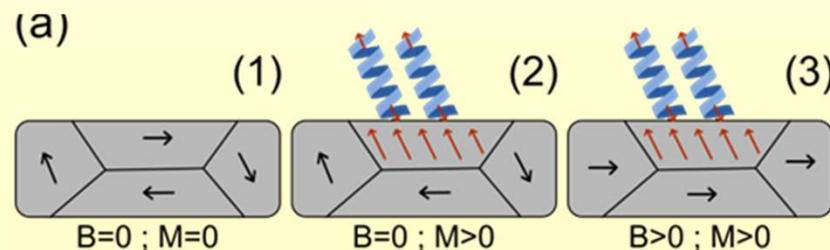
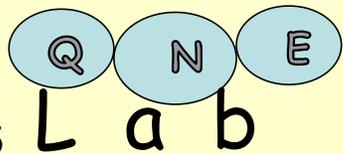
2/16/2026



Increase of 1 mT of the coercive field
Aggregates pin domains

Au (5)
Ta (2)
MgO (2)
CoFeB (0.9)
Ta (5)

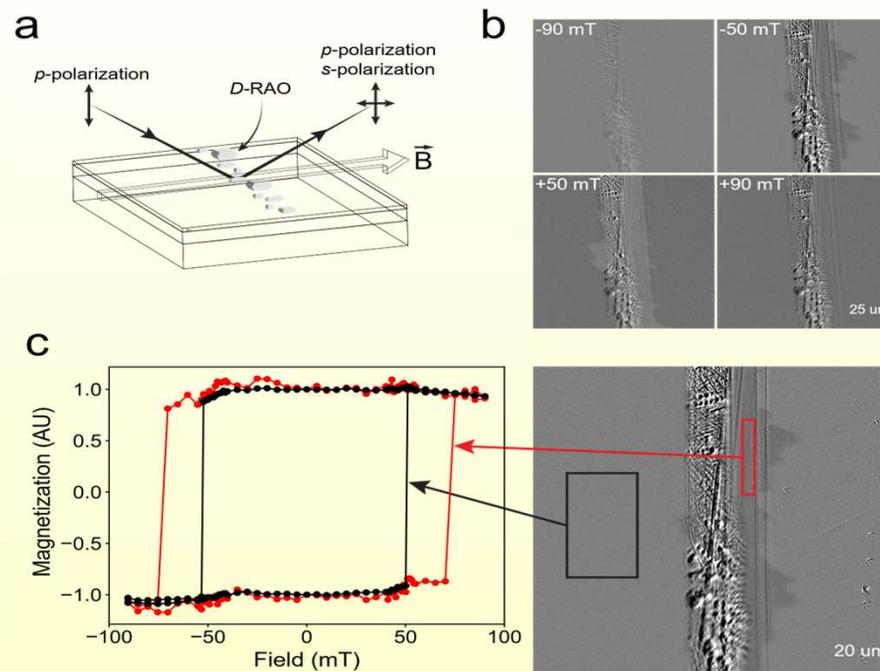
Kapon, Y., et al. (2032). J. Chem. Phys. 159, 064701



Breaking the symmetry

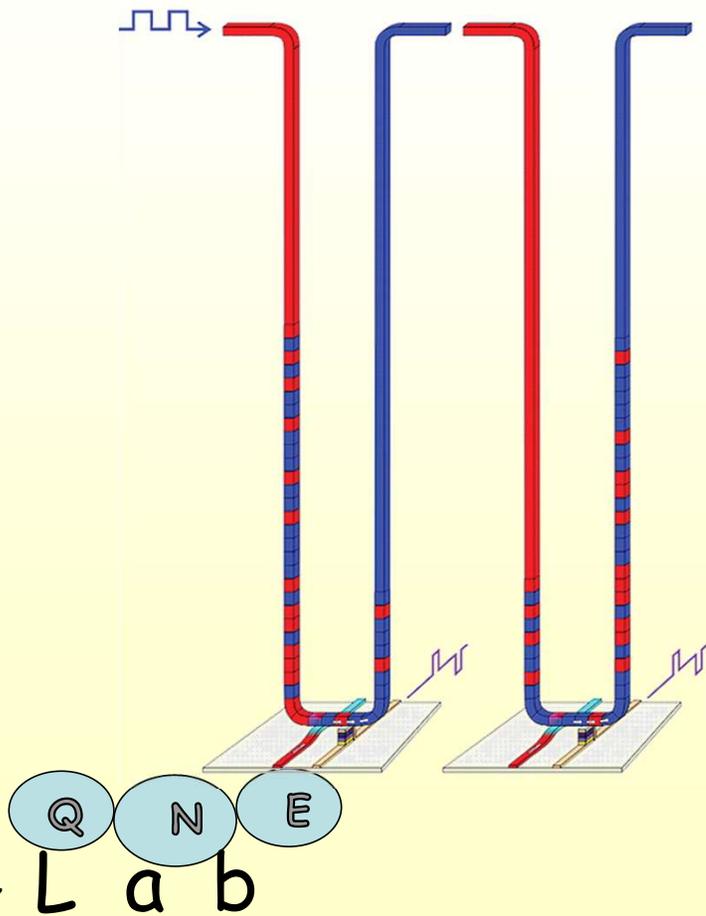
Chirality Induced Magnetization of Magnetite by an RNA Precursor

S Furkan Ozturk, Deb Kumar Bhowmick, Yael Kapon, Yutao Sang, Anil Kumar, Yossi Paltiel, Ron Naaman, Dimitar D Sasselov, Chirality-induced avalanche magnetization of magnetite by an RNA precursor, *Nature Communications* **14** 6351(2023). <https://doi.org/10.1038/s41467-023-42130-8>



K. B. Ghosh, O. Ben Dor, F. Tassinari, E. Capua, S. Yochelis, A. Capua, S.-H. Yang, S. S. P. Parkin, S. Sarkar, L. Kronik, L. T. Baczewski, R. Naaman, and Y. Paltiel; *Enantio-Specific Interaction of Chiral Molecules with Magnetic Substrates* *Science* **360** 1331 10.1126/science.aar4265 (2018).

Racetrack memory



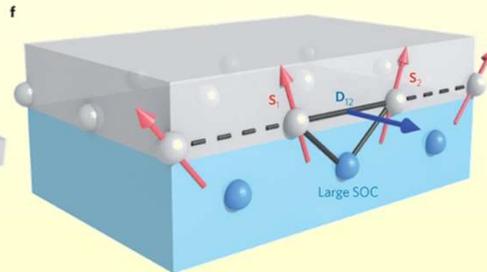
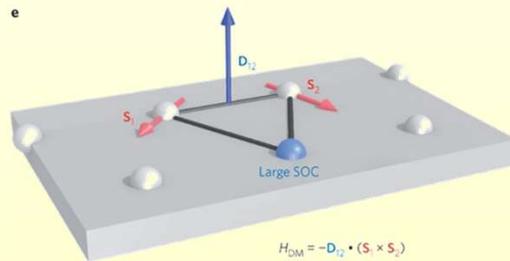
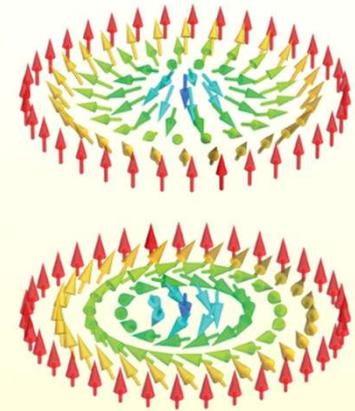
With skyrmions, racetrack memory can be cheaper in energy

See-Hun Yang, Ron Naaman, Yossi Paltiel & Stuart S. P. Parkin. **Chiral Spintronics**. *Nature Reviews Physics* 3, 328–343 (2021)

Chiral spin textures

($\uparrow\uparrow$) Exchange interaction $\propto S_i \cdot S_j$

($\leftarrow\uparrow$) Dzyaloshinskii Moriya interaction $\propto S_i \times S_j$ - **chiral**

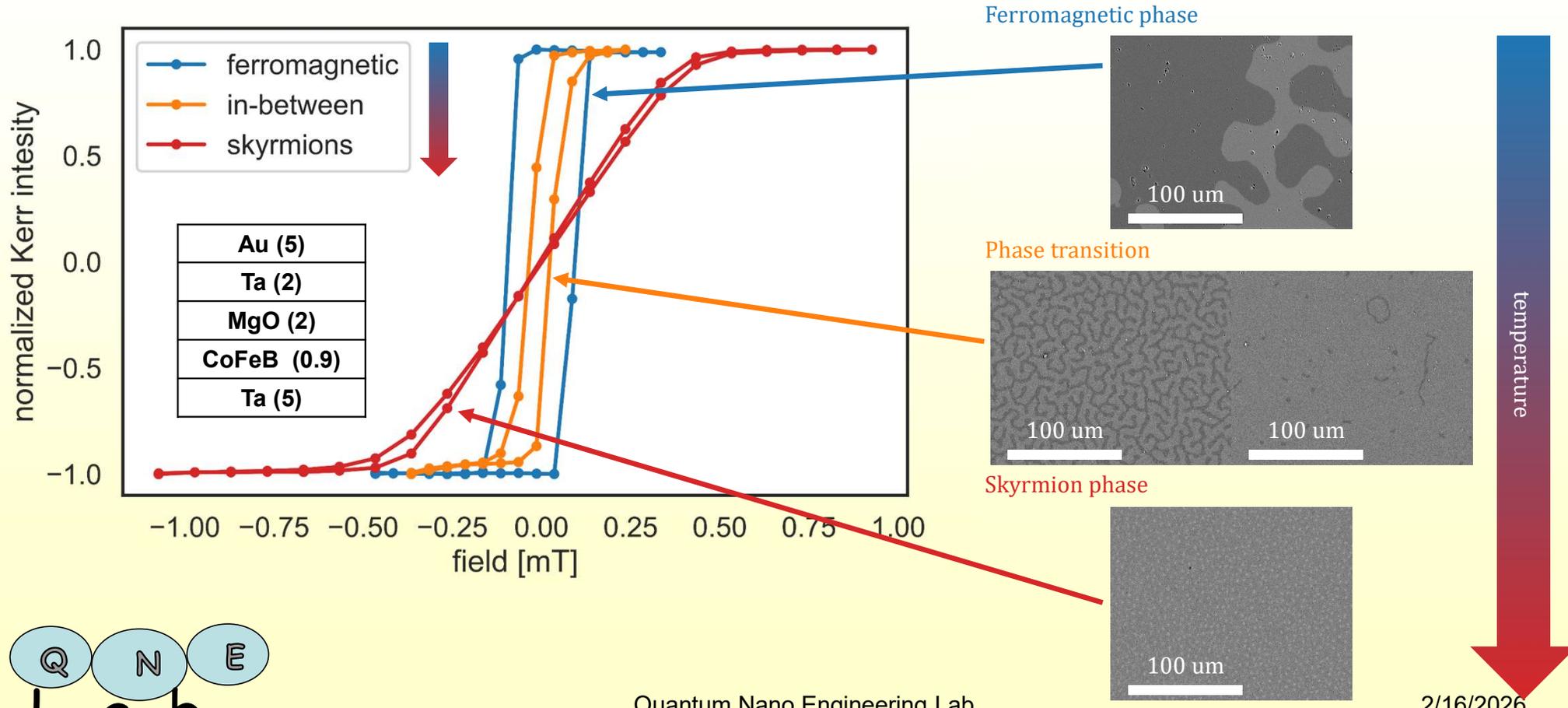


Fert, A., et al. *Nature Nanotech* (2013)

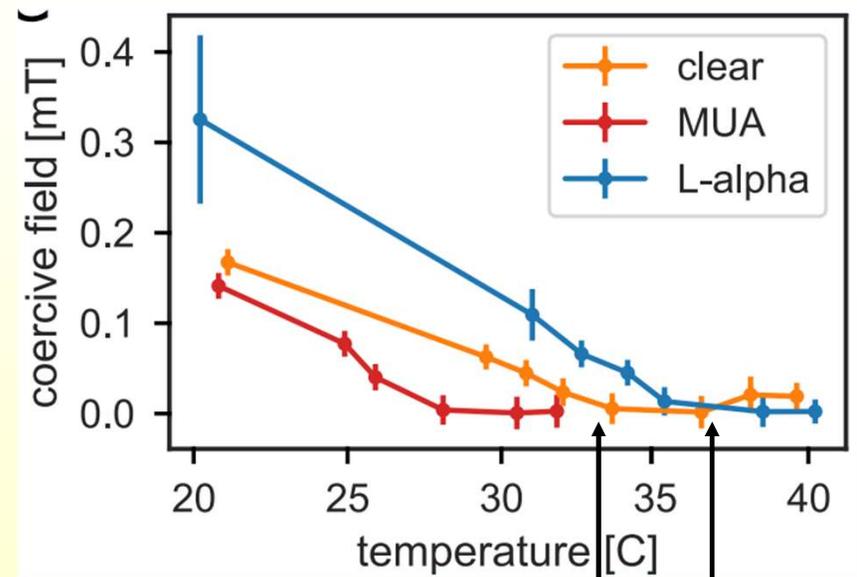
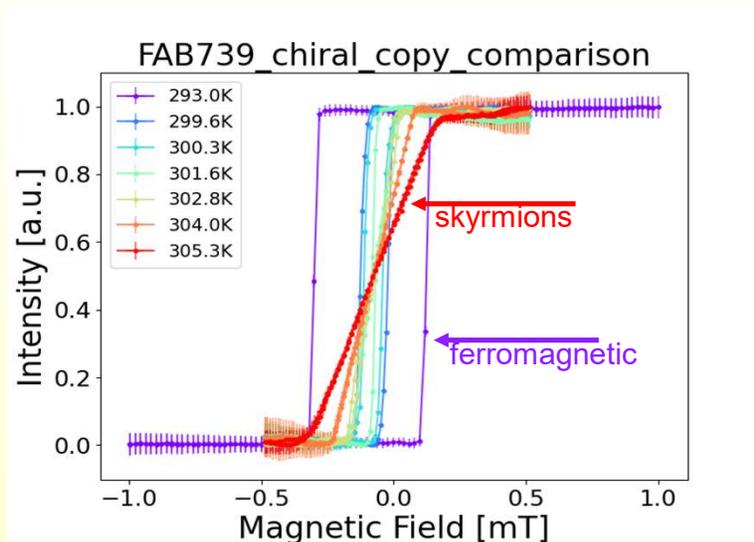


Mathias Klaui

The skyrmion phase in PMA films

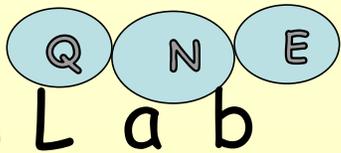


Changes in the phase transition



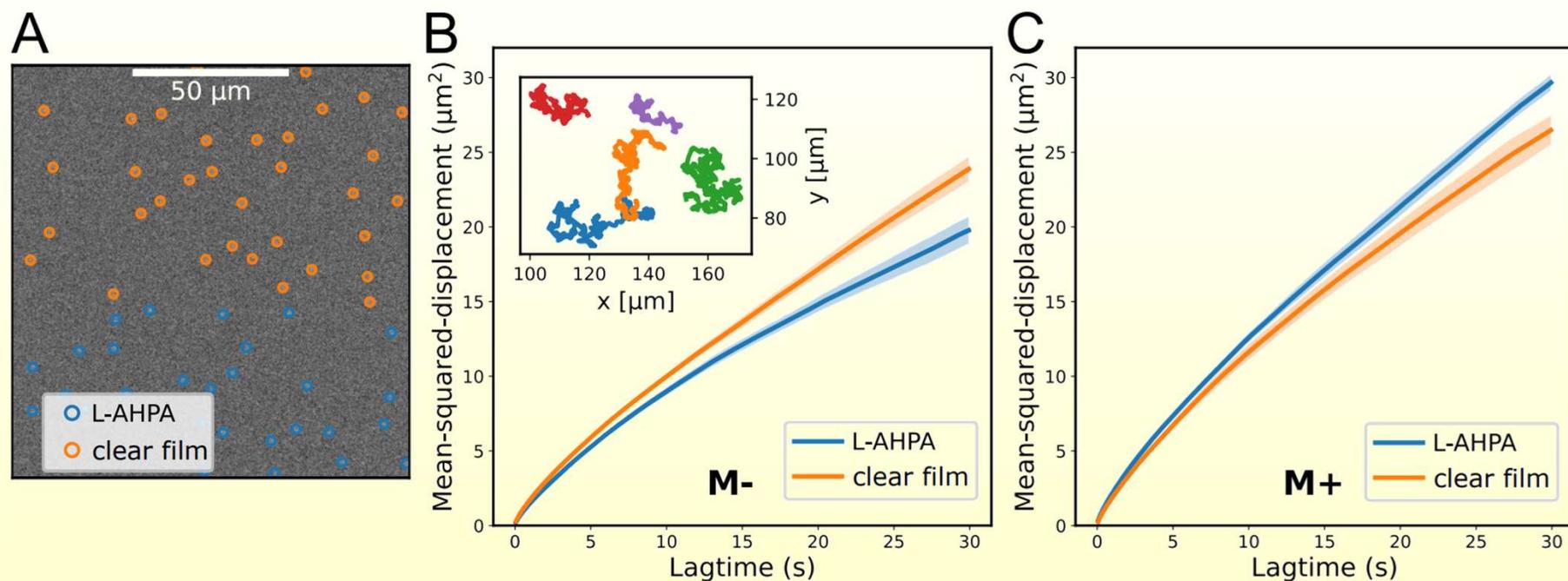
Fabian and Theo results

5C change in the spin reorientation temperature

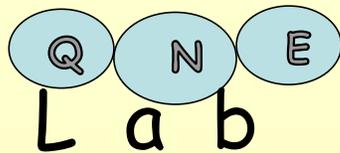


Thermal Diffusion Enhancement/Reduction

Fabian and Theo results



Yael Kapon, Fabian Kammerbauer, Theo Balland, Shira Yochelis, Mathias Kläui, and Yossi Paltiel, *Effects of Chiral Polypeptides on Skyrmion Stability and Dynamics*, *Nano Letters*, **25**, 1, 306–312 (2025). <https://doi.org/10.1021/acs.nanolett.4c05035>



Gating Effects

Could maybe act as FM transient memory

Adsorbed area

0V

High temp

10s later

40 um

Top view

M

6V

10s later

40 um

Room temp

40 um

0V

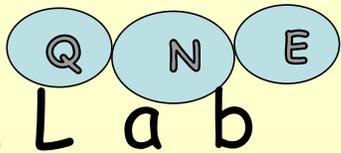
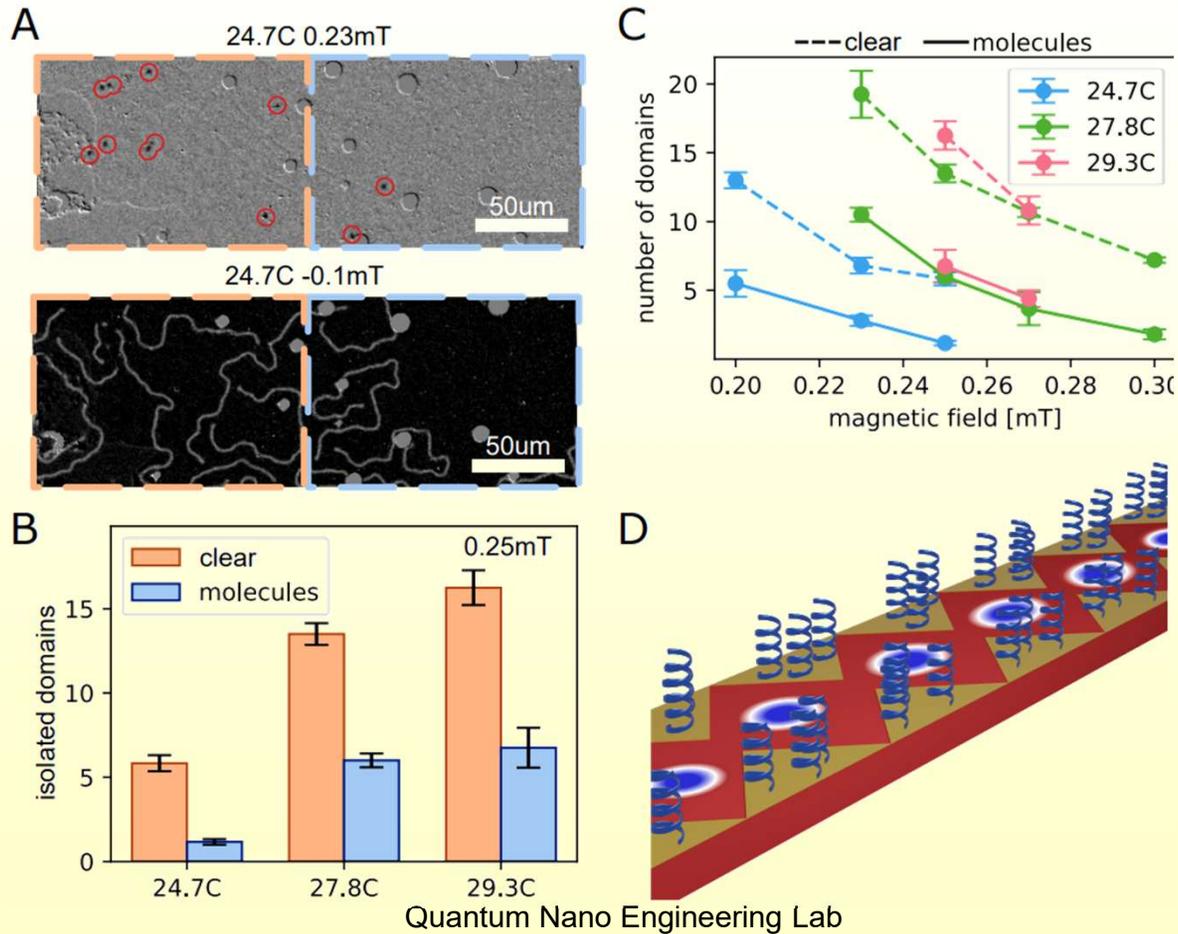
6V

Quantum

2/16/2026



Chiral Molecules Change Skyrmion Density

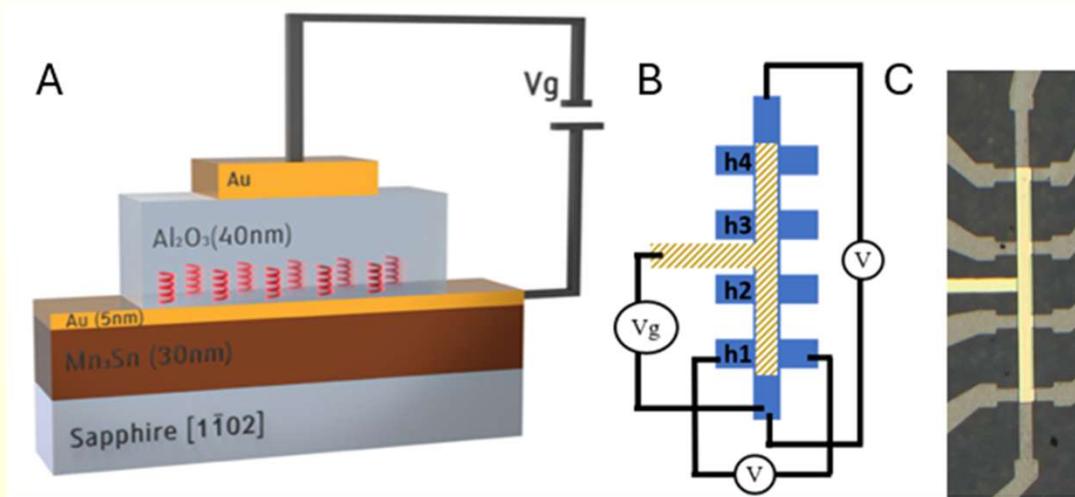


Anti-ferromagnetic and chirality

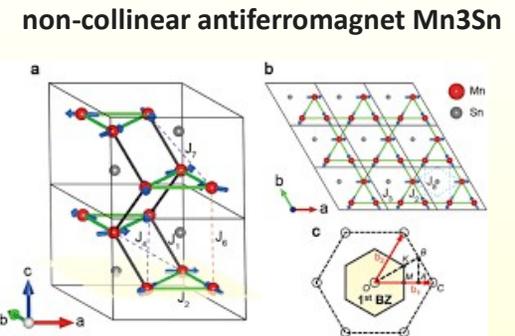
**Antiferromagnetic Local Volatile Memory Utilizing
Non-Collinear Mn₃Sn Thin Films and Chiral Gating**



AFM small cross talk but hard to measure



<https://www.nature.com/articles/s41535-018-0137-9#citeas>

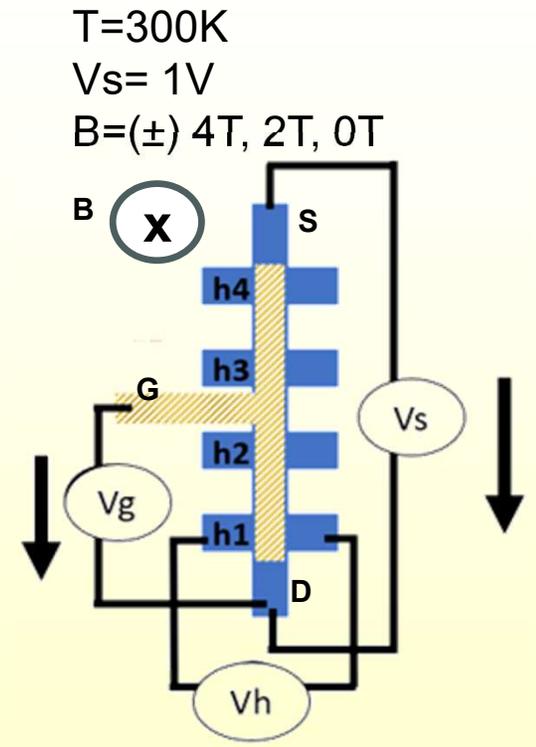
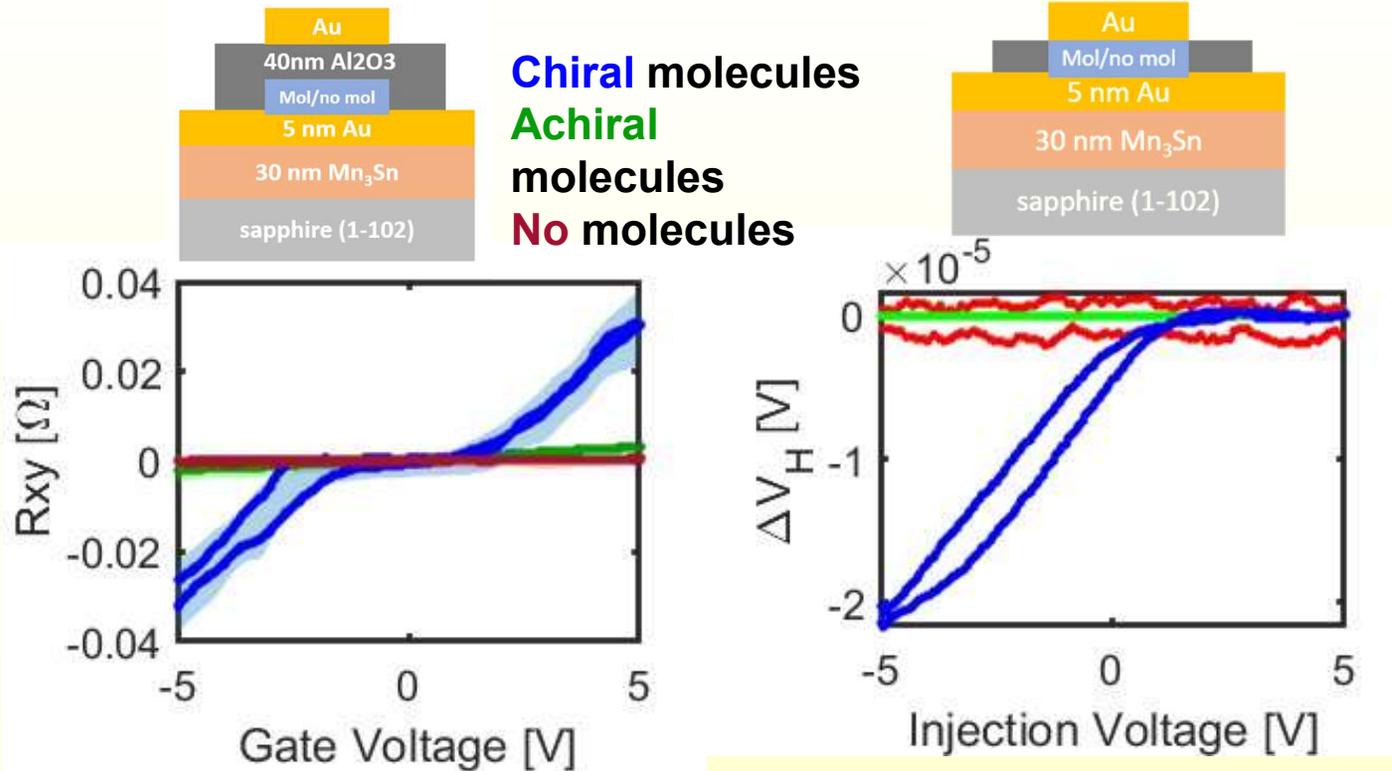


Pal, B.; Hazra, B. K.; Göbel, B.; Jeon, J.-C.; Pandeya, A. K.; Chakraborty, A.; Busch, O.; Srivastava, A. K.; Deniz, H.; Taylor, J. M.; Meyerheim, H.; Mertig, I.; Yang, S.-H.; Parkin, S. S. P.

Setting of the Magnetic Structure of Chiral Kagome Antiferromagnets by a Seeded Spin-Orbit Torque. *Science Advances* **2022**, *8* (24), eabo5930. <https://doi.org/10.1126/sciadv.abo5930>.

Results: Gate Voltage Dependency

Chiral gate enhancement



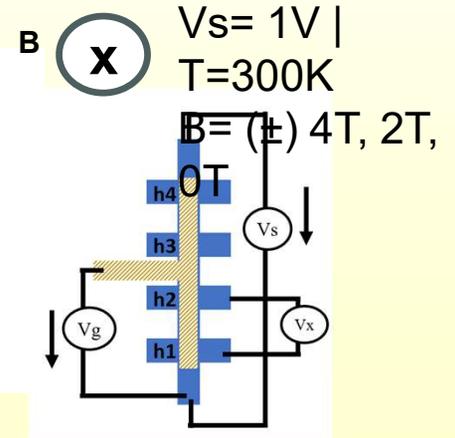
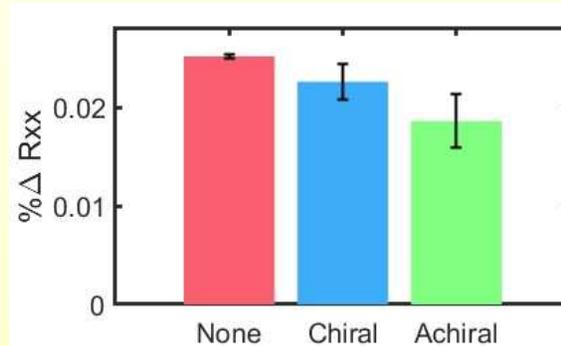
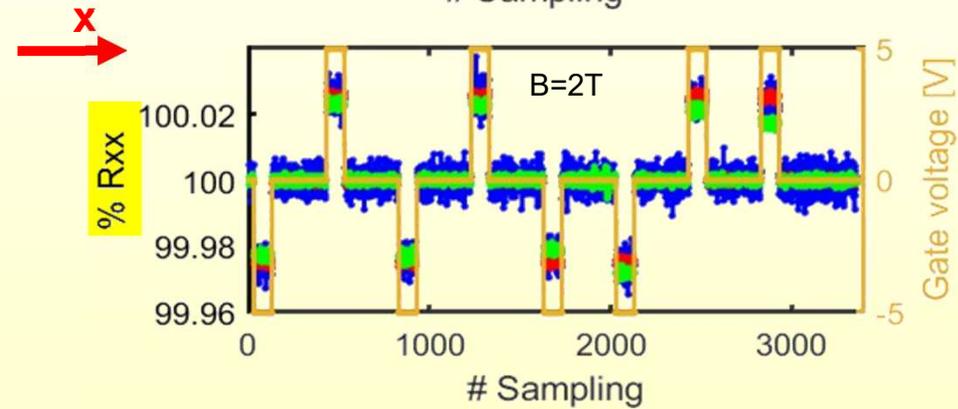
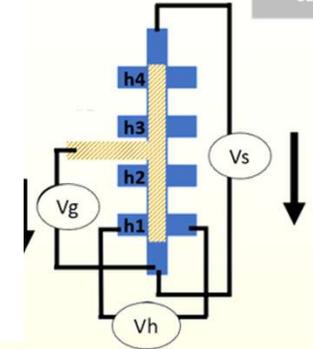
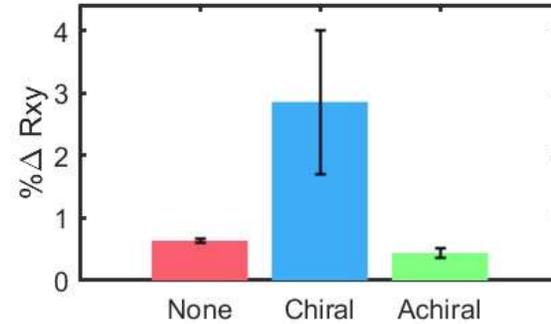
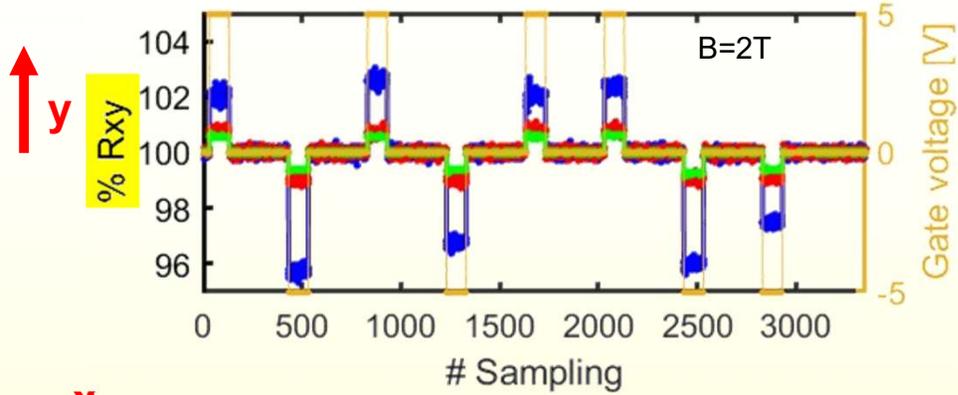
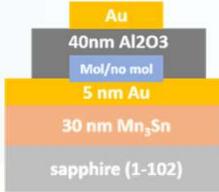
Naama Goren, Binoy Krishna Hazra, Tian-Yi Zhang, Shira Yochelis, Qing-Feng Sun, Stuart S.P. Parkin and Yossi Paltiel, *Antiferromagnetic Local Volatile Memory Utilizing Non-Collinear Mn_3Sn Thin Films and Chiral Gating*, *Communications Materials* (2025).

Quantum Nano Engineering Lab

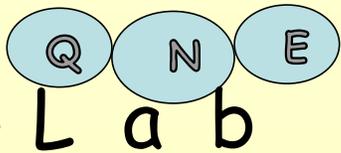
2/16/2025



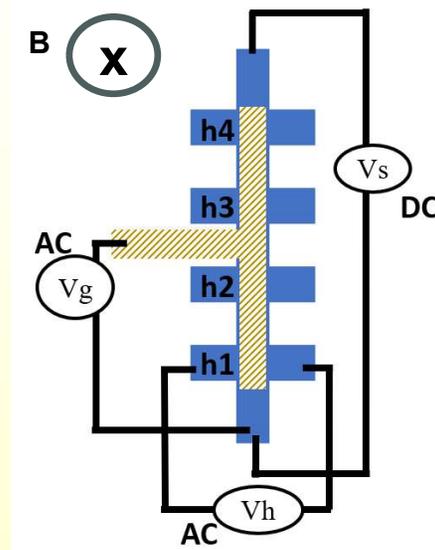
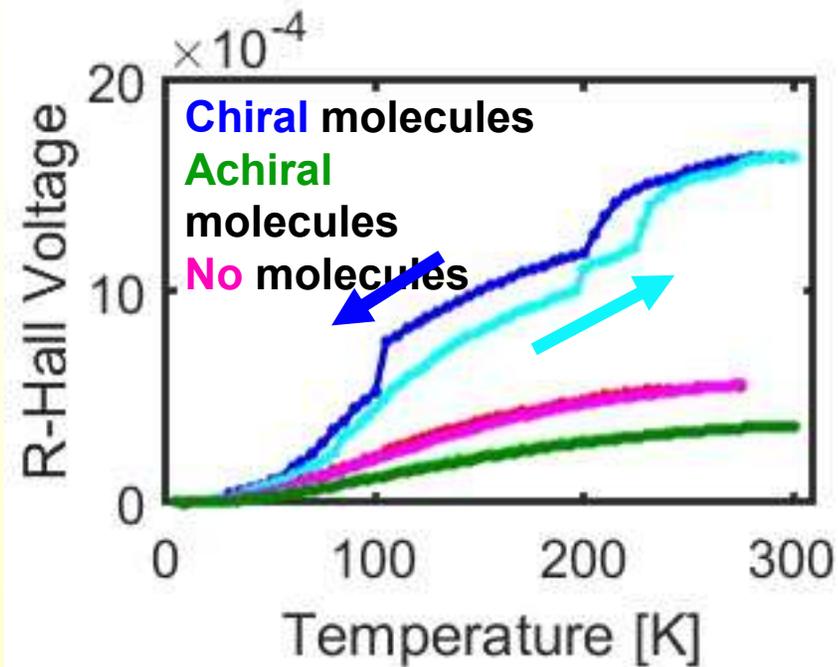
Results: Gate Voltage Dependency – time mode



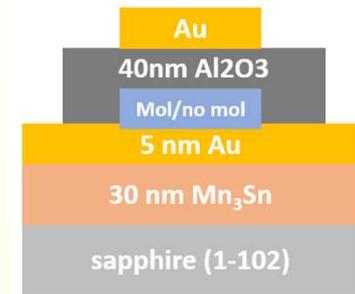
Chirality boost magnetic response to gate



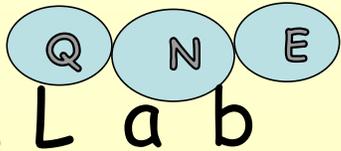
Results: Temperature Dependency - AC



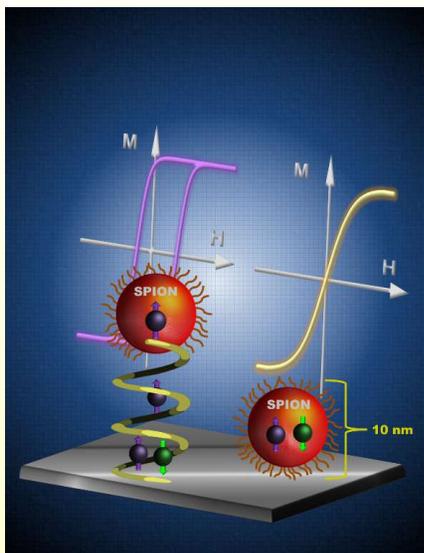
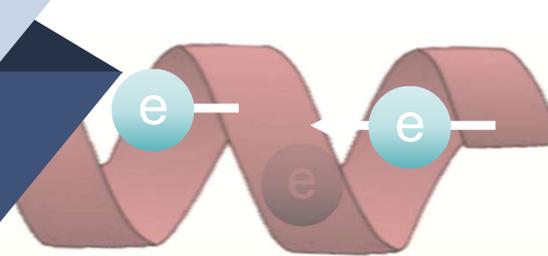
$T=300\text{K}$
 $V_s= +1\text{V}$
 $B= +4\text{T}$
 $V_g= 0.1\text{Vpp (AC)}$
 7809 Hz
 $+1\text{V (DC)}$



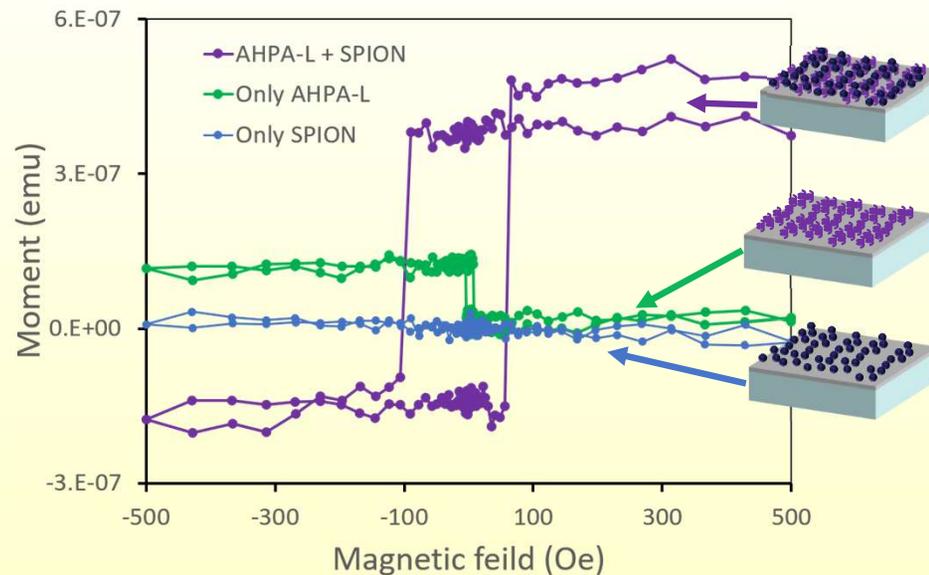
Chiral gating coupled to magnetic phase transition



Going to 10nm size



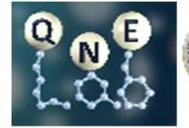
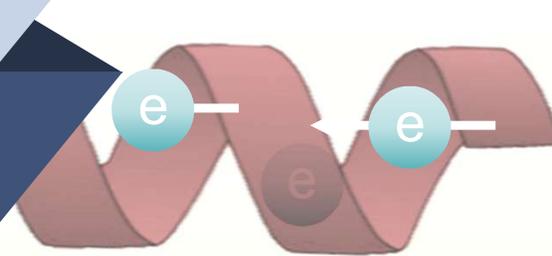
G. Koplovitz, *et al.*, Small 1804557 (2019).



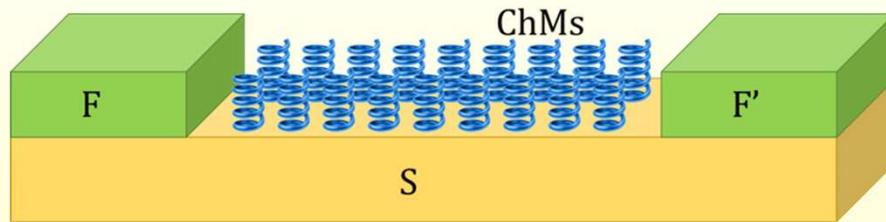
Reiss, Sheli Muzafe, et al. "Chiral Magnetic Memory Device at the 10 Nm Scale Using Self-Assembly Nano Floret Electrodes." *ADVANCED ELECTRONIC MATERIALS* (2025).

Preserving spin phase

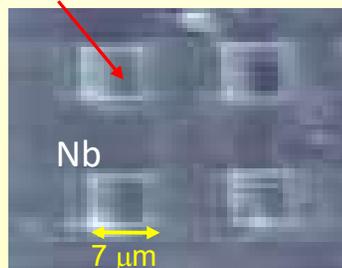
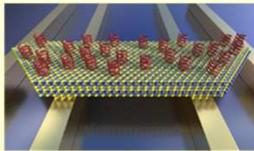
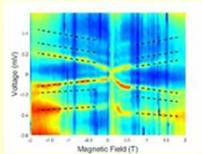
Spin Interconnects



➤ Superconducting chiral triplet state



[Nano Letters](#) **19** 8, 5167-5175 (2019).

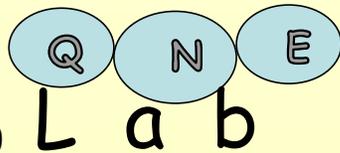


[Advanced Materials Interfaces](#), 2201899 (2023).

➤ Chiral Gold

Long-Range Spin Transport in Chiral Gold

[Adv. Mater.](#) **2025**, *37*, 2506523



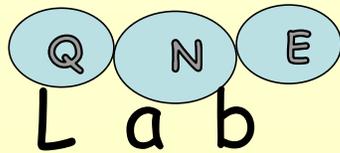
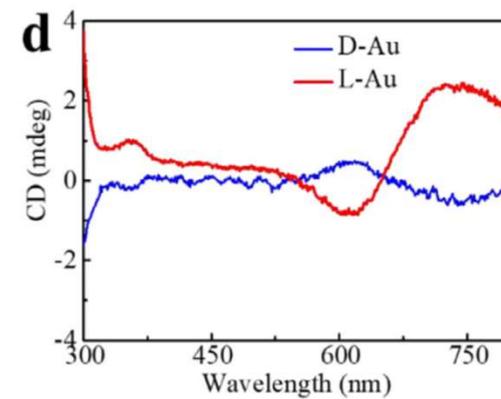
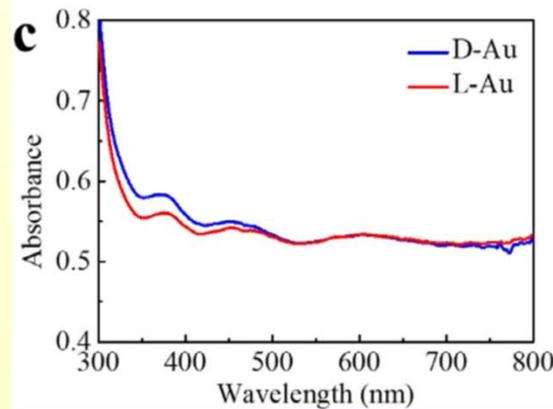
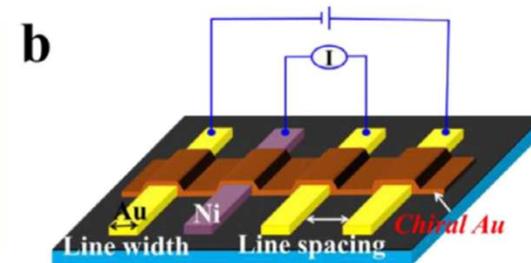
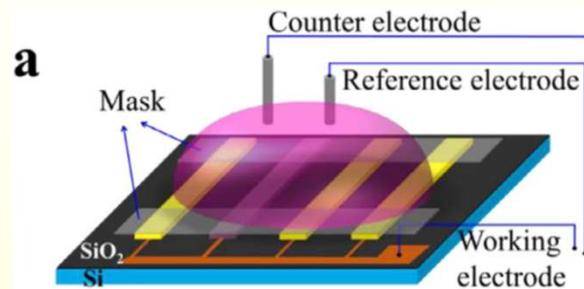
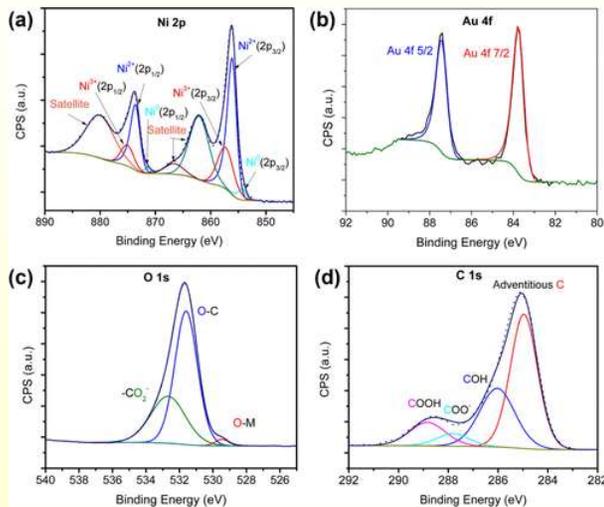
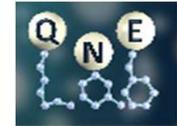
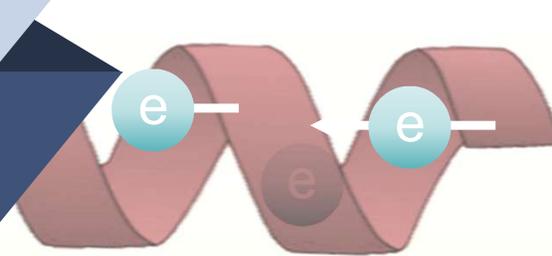
Quantum Nano Engineering Lab

2/16/2

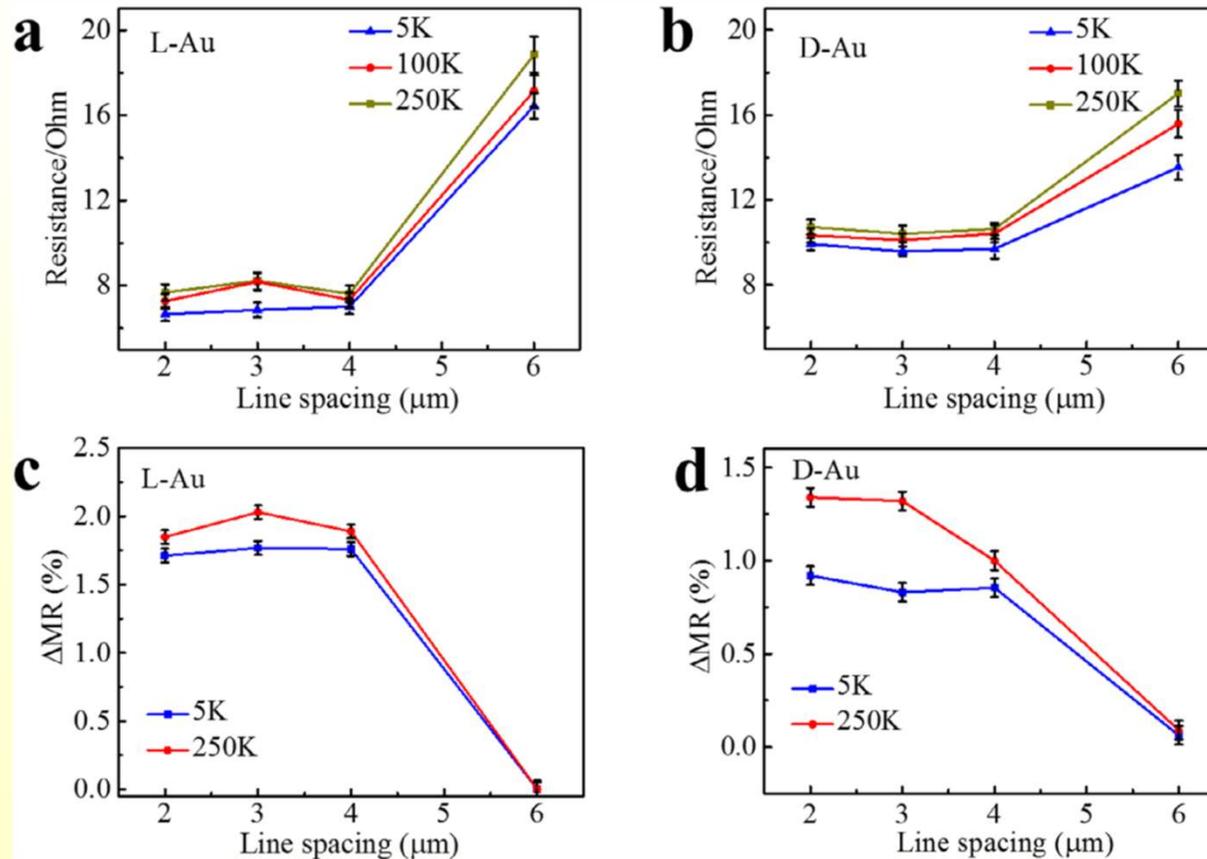
50

The system

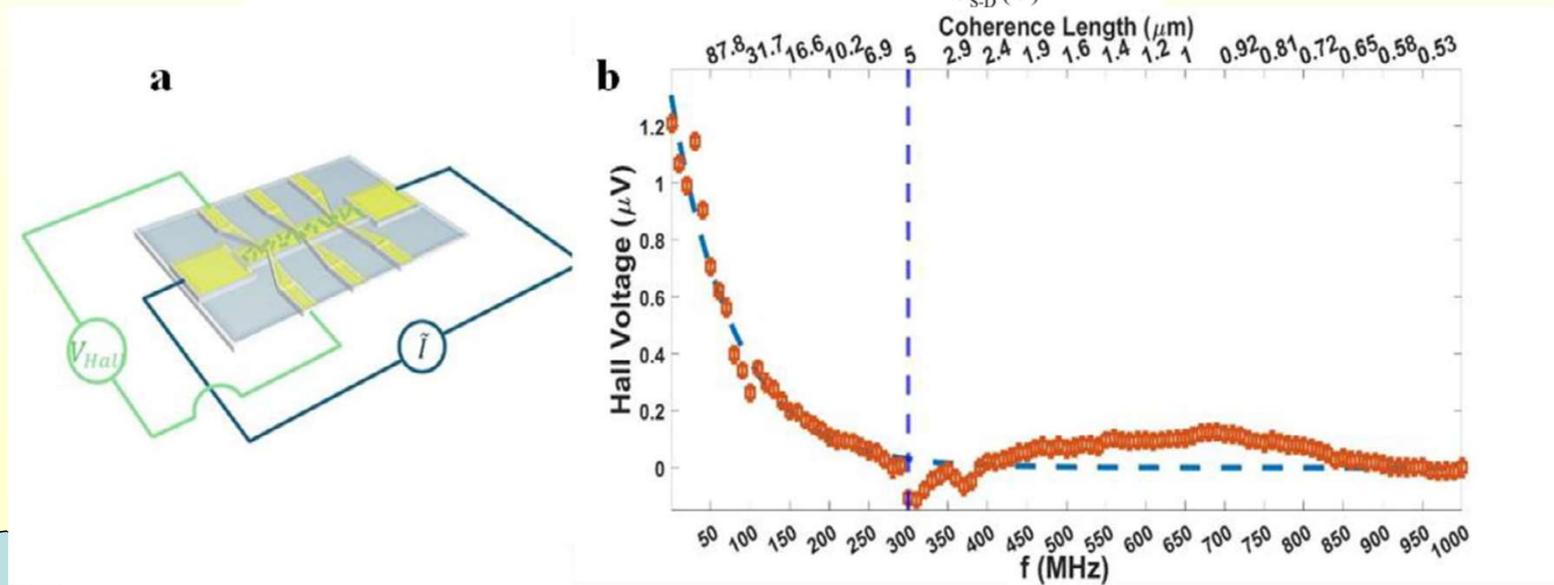
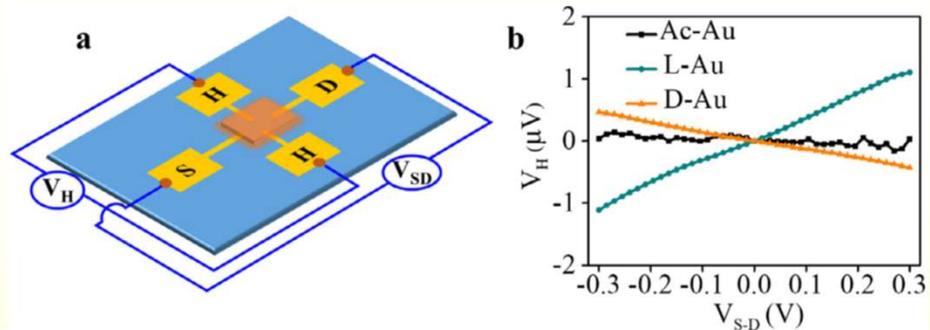
Chiral Gold



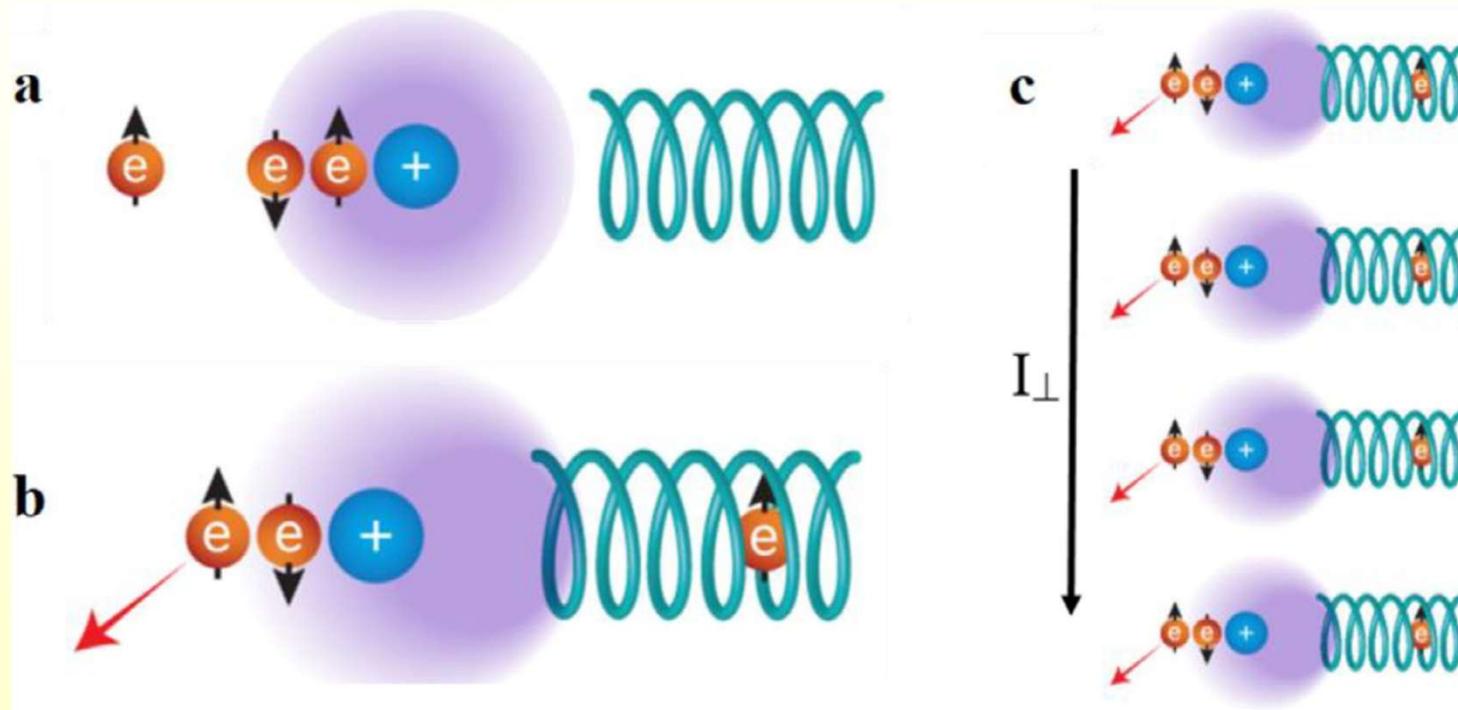
Distance dependence of the transport and magnetoresistance



High frequency Hall measurements



A scheme of the topological anomalous Hall effect (TAHE)



Applications

- Spintronics
- Green Energy
- Pure drugs

H2 electrolyzers



Full cells

Pure drugs



Summary

- **We show a simple way to solve material and current problems in spintronics**
 - CISS based devices work as electrical memory at ambient in a device of 40x40 nm.
 - We can scale devices down to 10nm in size.
 - We can enhance density using skyrmions and antiferromagnetic material
 - Chiral interconnect can achieve long range spin coherence transport

