Spintronics and Superconducting Spintronics based on Chiral Molecules

25.9.2017
Special thanks to
the organizers Spice
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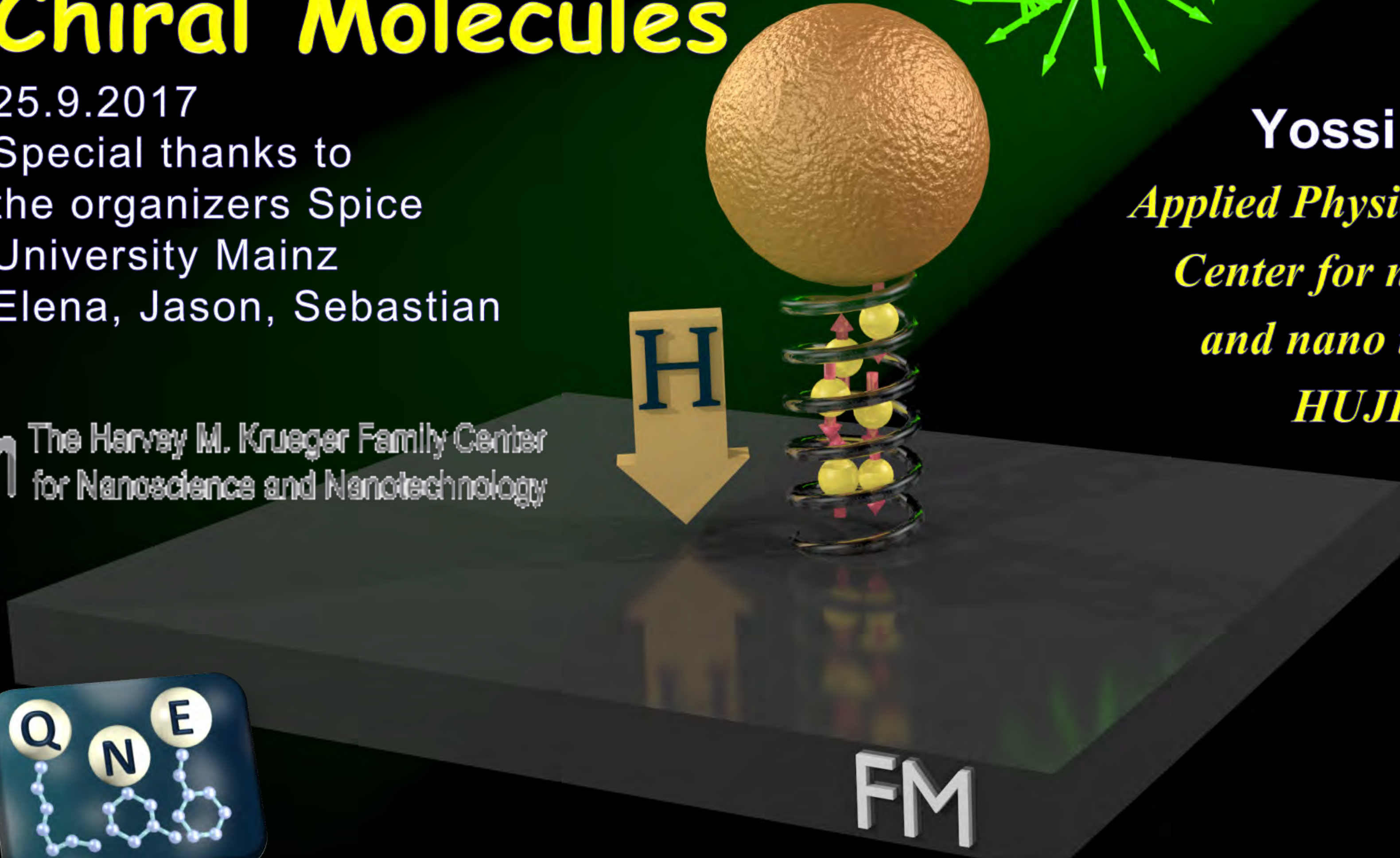


The Harvey M. Krueger Family Center
for Nanoscience and Nanotechnology

QNE Lab

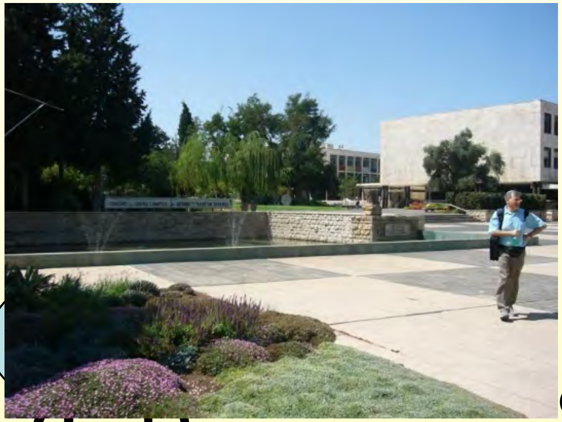
The Hebrew University of Jerusalem האוניברסיטה העברית בירושלים
Est. 1925

Jerusalem and The Hebrew University

Inauguration ceremony 1925

The Hebrew University of Jerusalem is Israel's oldest (1925) university. The First Board of Governors included Albert Einstein, Sigmund Freud, Martin Buber, and Chaim Weizmann.

In the Academic Ranking of World Universities index, Hebrew University is the top university in Israel and among the world's 100 top universities. (ranked 57)

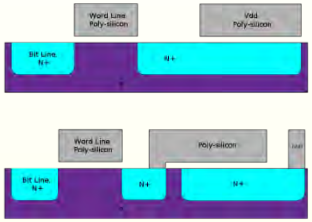


Memory devices

Fast but need constant power

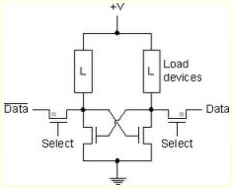
DRAM - Dynamic random-access memory

refreshed periodically



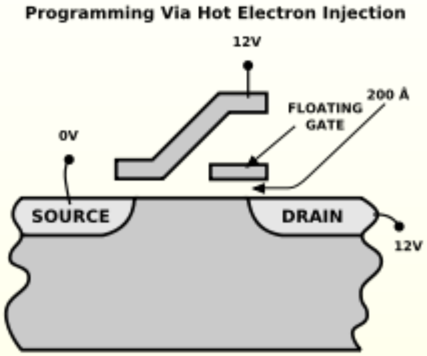
SRAM- Static random-access memory

Does not need to be periodically refreshed



Slow last for 10 years

Flesh memory



From Computer Desktop Encyclopedia
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All existing memory technologies challenged when critical size is smaller than 45 nm

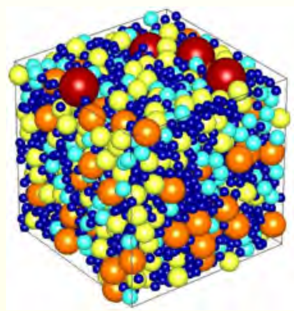
We are looking for:

No need for power, long lived, fast, standard technology

Simple Universal Magnetic Memory

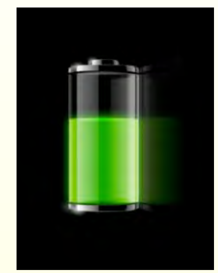
Fast

Dense



Non-Volatile

Power efficient



The industry needs are met without compromising in <u>cost,</u> compatibility to <u>standard Si process</u> & complexity of <u>design</u>

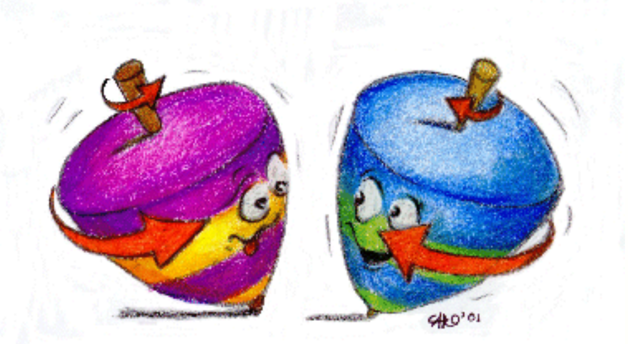
Spin Electronics

Electrons have charge and spin 1/2

- Conventional electronic devices ignore the spin property and rely strictly on the transport of the electrical charge of electrons

- Adding the spin degree of freedom provides new effects, new capabilities and new functionalities

Why Spintronics?

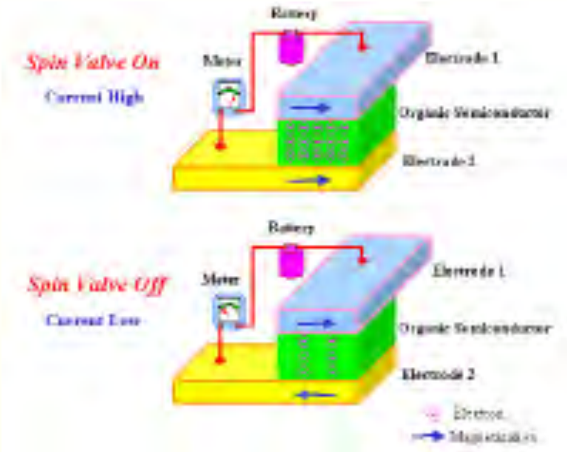


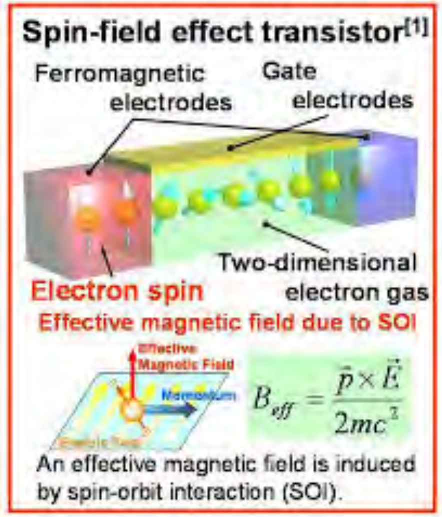
The electron as "Spinning top"

- **Energy and heat-** For Spintronics, less energy

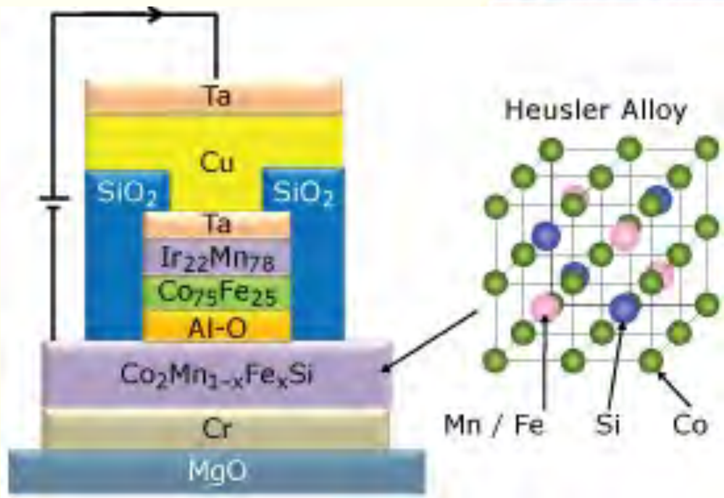
- **Quantum effects** -It may be a way for introducing the spin properties to our tool arsenal.

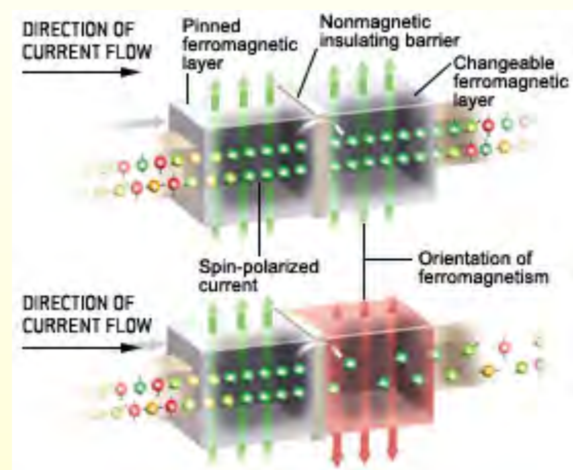
Spintronics Devices





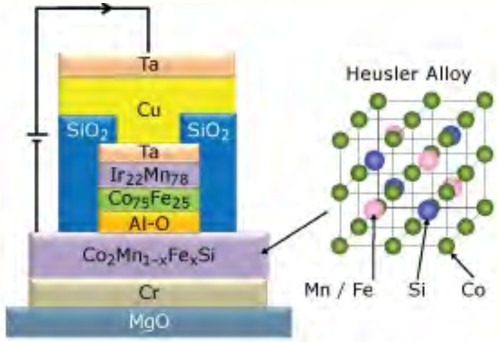
The 2007 Nobel Prize in Physics was awarded to :
Albert Fert and Peter Grünberg
for the discovery of GMR





Two Major Problems

- Material problem

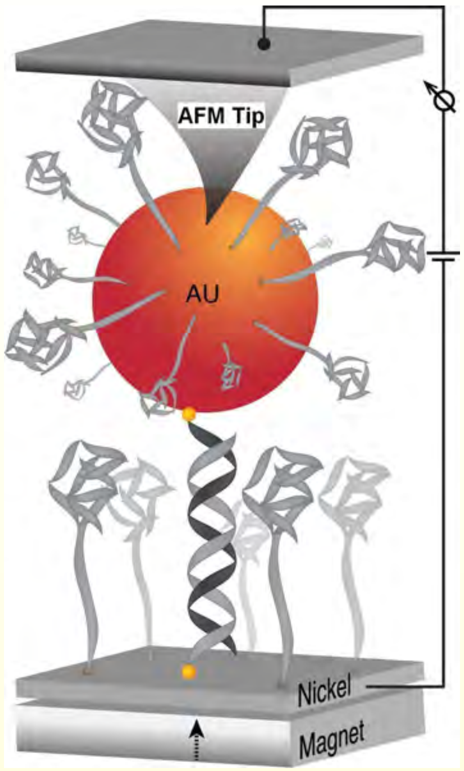


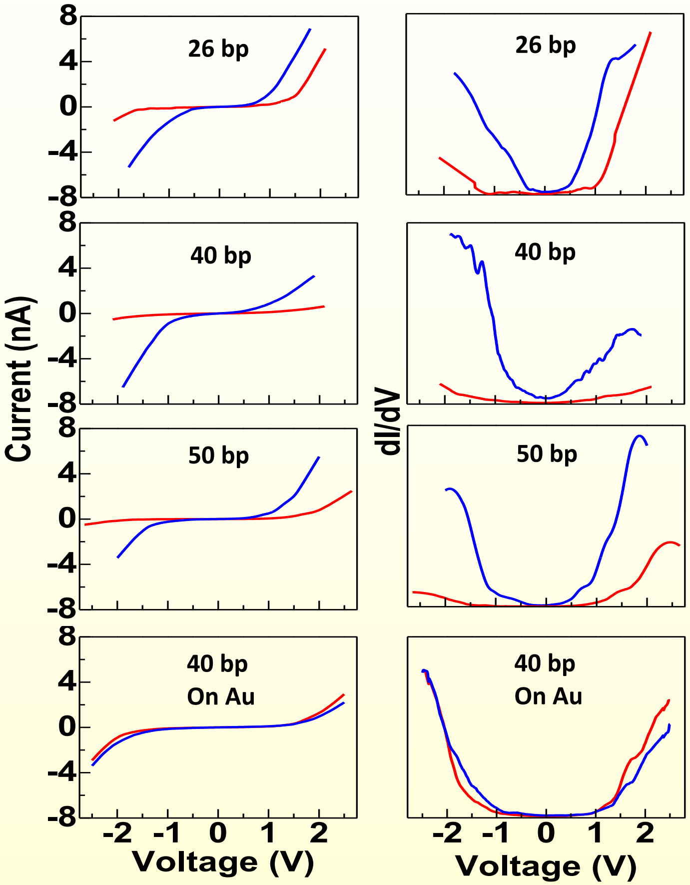
- Spin separation requires high current

Q N E Lab

The CISS Effect

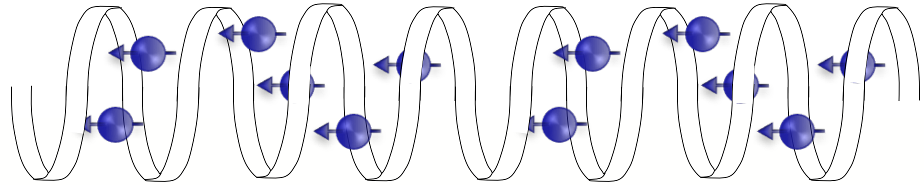
· Chiral Induced Spin Selectivity - CISS





Zuoti Xie, Tal Markus, Sidney Cohen, Zeev Vager, Rafael Gutierrez, Ron Naaman
Nano Letters, **11**, 4652–4655 (2011).

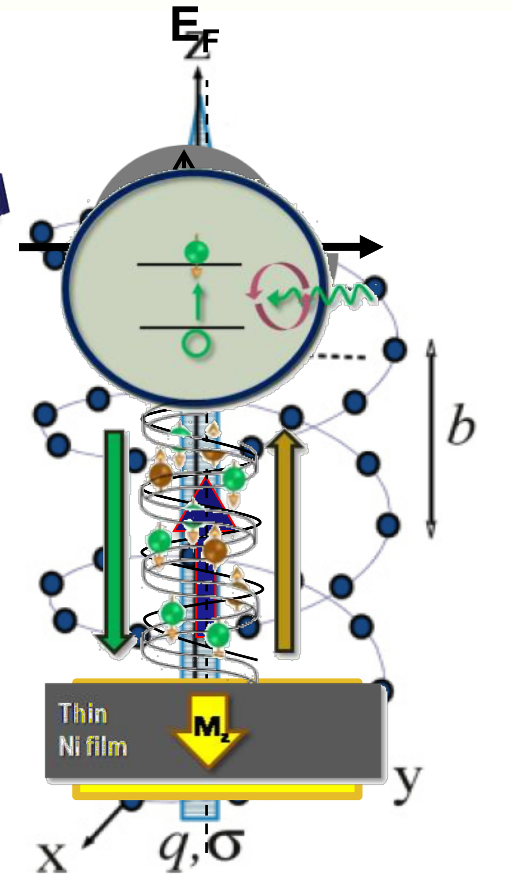
Theory



- Chirality Induced Spin-selectivity (CISS) effect

Major Transport mechanism is Spin-Orbit Coupling (SOC)

$$\vec{B} = \frac{\vec{v}}{c^2} \times \vec{E}$$

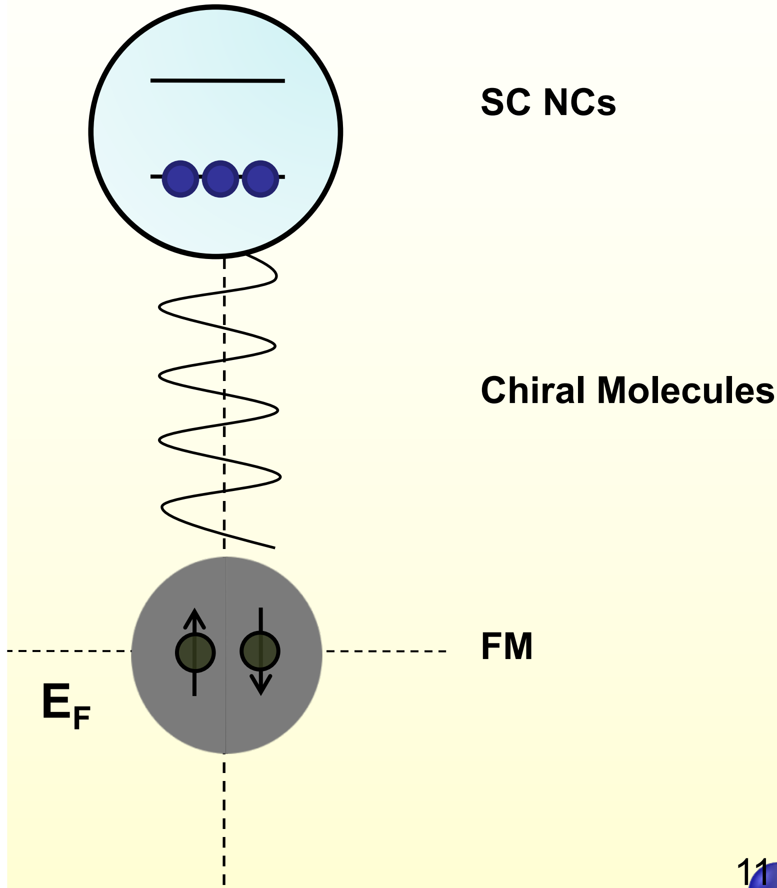


Rashba like term due to chiral orbit

E. Gutierrez, E. D´ıaz, R. Naaman, and G. Cuniberti1, PHYSICAL REVIEW B 85, 081404 (2012)

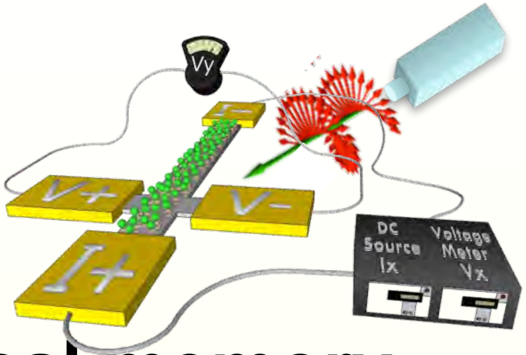
Transport Vs Optics

- Chirality Induced Spin-selectivity (CISS) effect



CISS Devices solves material problem RT simple devices

Nano letters **14** 6042 (2014).
ACS Photonics, , **2** (10), pp 1476–1481 (2015).

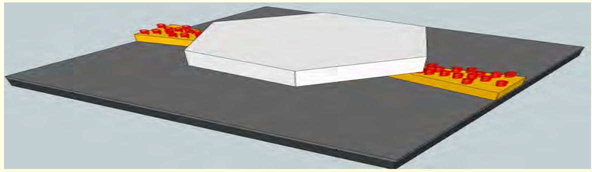


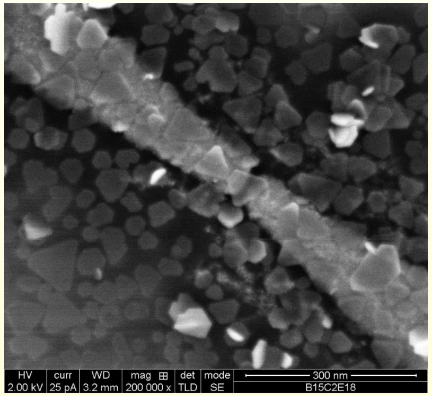
Optical – photon driven:

- Local magnetization/local optical memory.
- Nano metric charge separation.

Electrical – electrons driven:

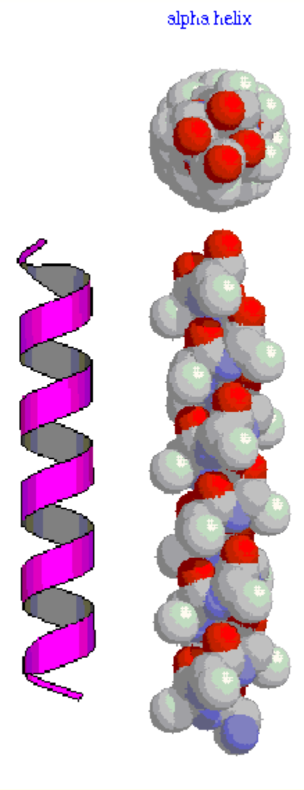
- Spin injector
- Nano memristor.

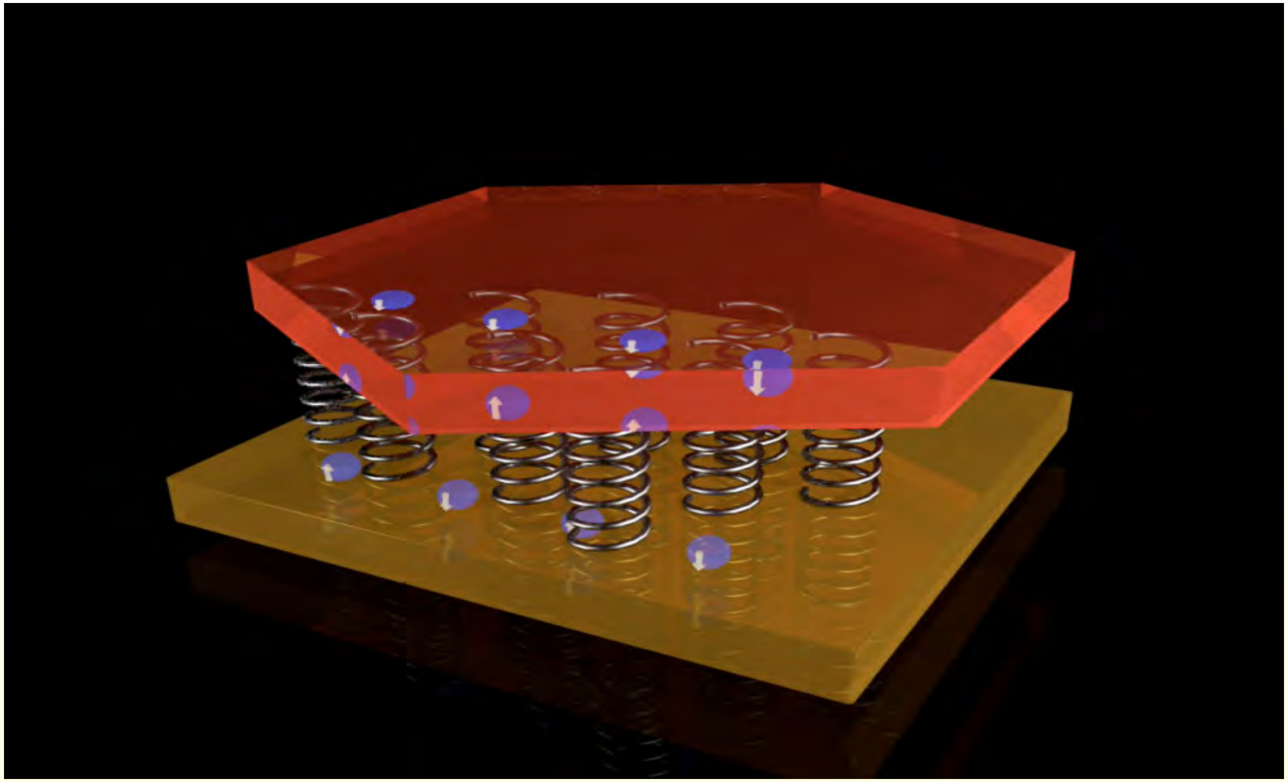




Nature Communications **4**, 2256 (2013).
Applied Physics Letters, **105** 242408 (2015).

Electrical CISS Memory

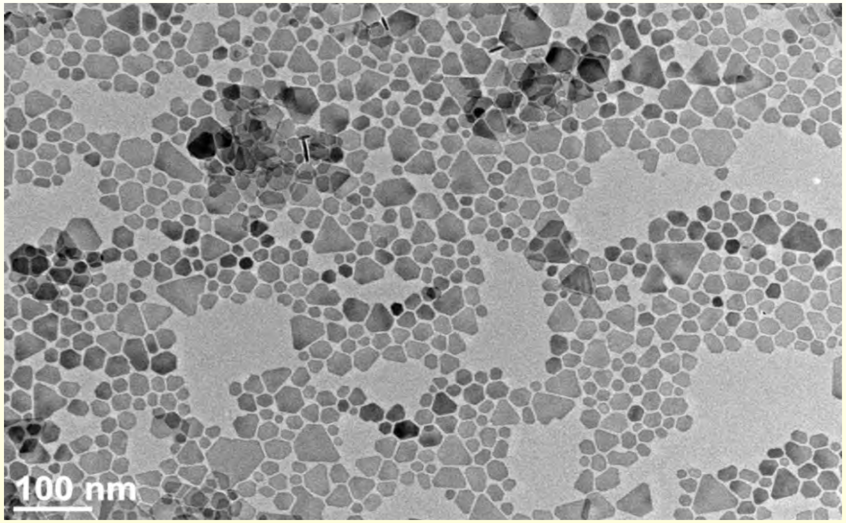




L or D PAL (polyalanine), thiolated α-helix -
CAAAAKAAAAKAAAAKAAAAKAAAAKAAAAKAAAAK-SH
C, A, and K represent cysteine, alanine, and lysine

Room Temperatures CISS Memristors

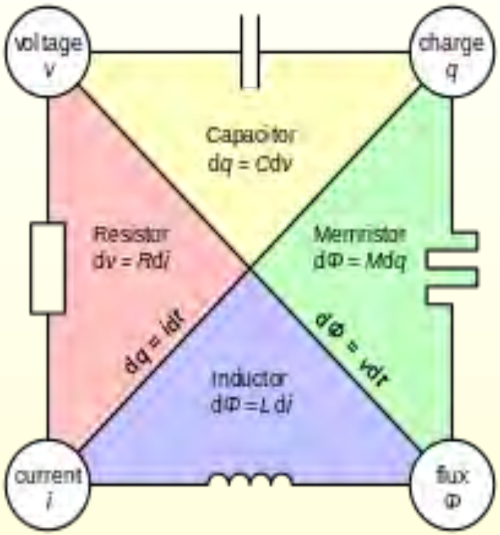
Embedded memory using the CISS effect and magnetic nano particles

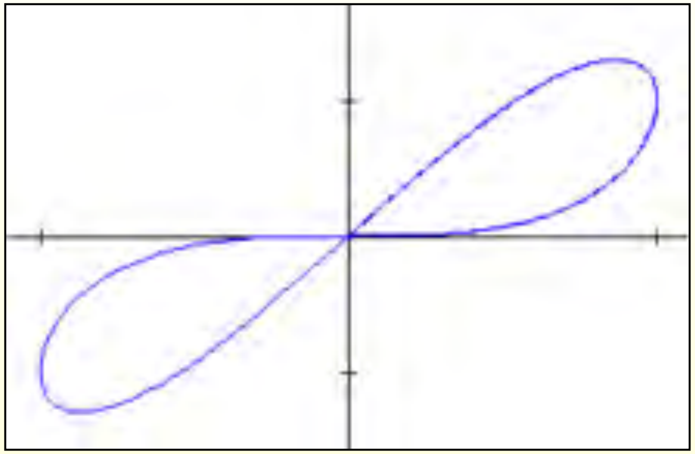


FerroMagnetic Nano Platelets (FMNPs)

Two designs for embedded memory devices based on the CISS effect and magnetic nano palettes.

- Four layers vertical printable device (easy to fabricate).
- Lateral 40nm device based on two layers.

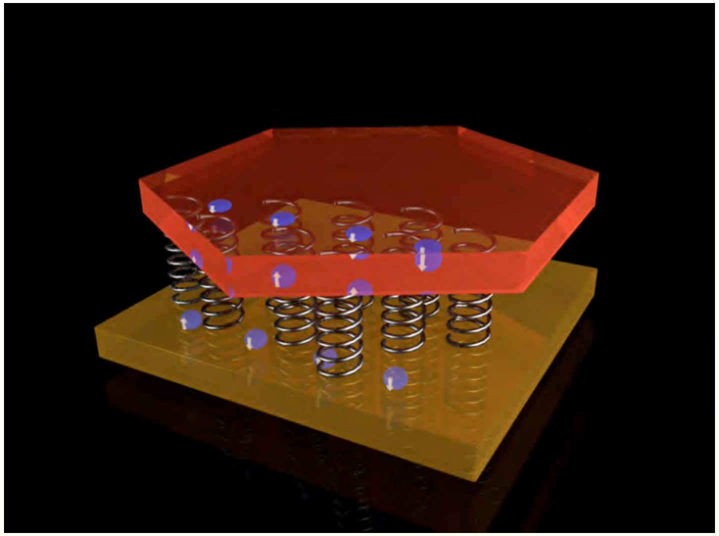


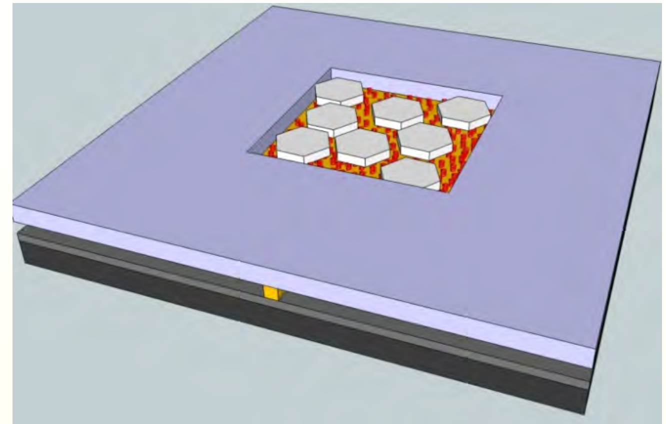


Different resistance states

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

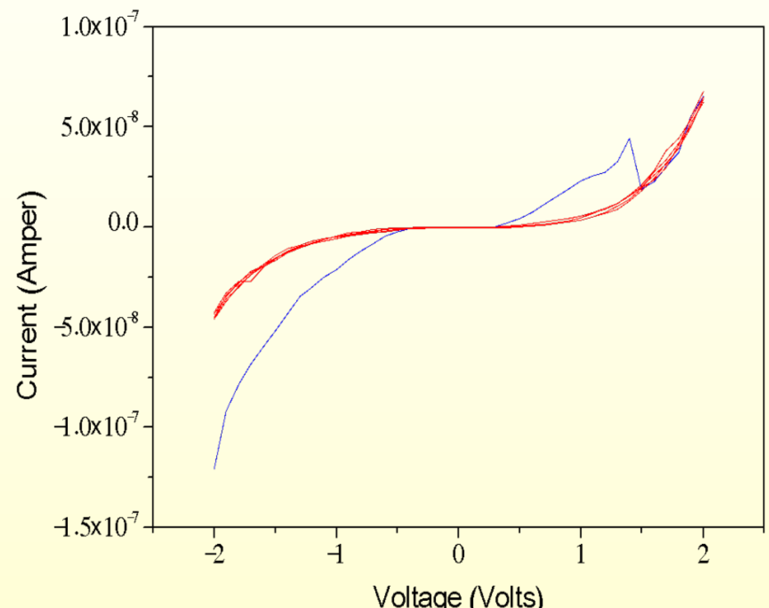
Vertical Memristor Device





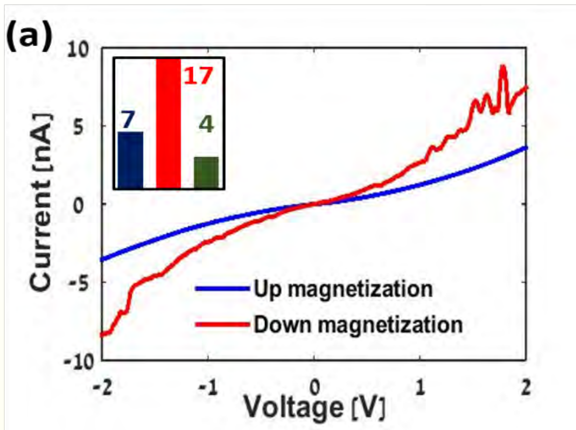
- Bottom electrode
- Adsorb AHPA-L or AHPA-D and multiple FMNPs
- Al_2O_3 tunnel barrier
- Top electrode

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

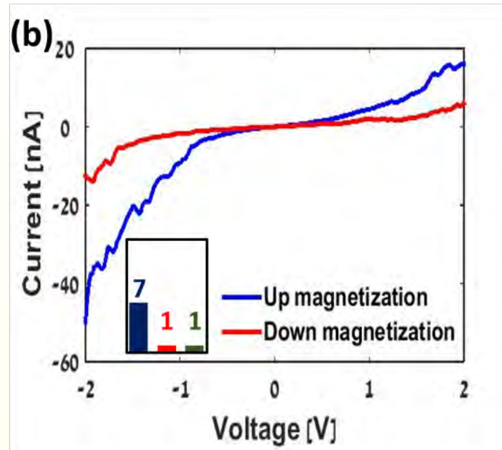


Vertical Memristor Device

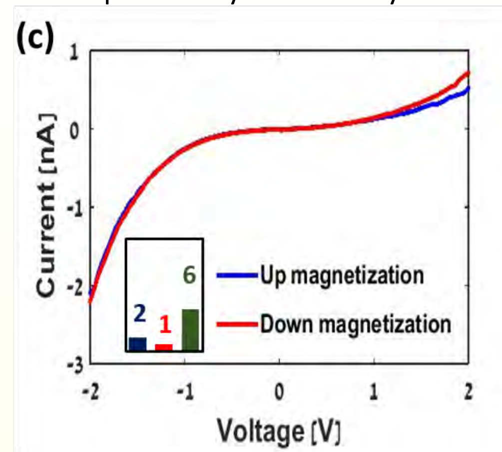
AHPA-L (α-Helix Poly-Alanine –L)

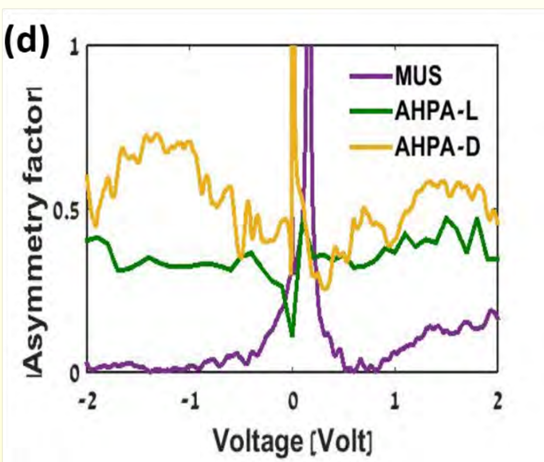


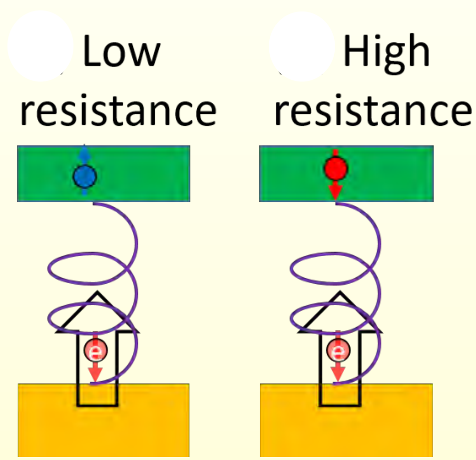
AHPA-D (α-Helix Poly-Alanine – D)

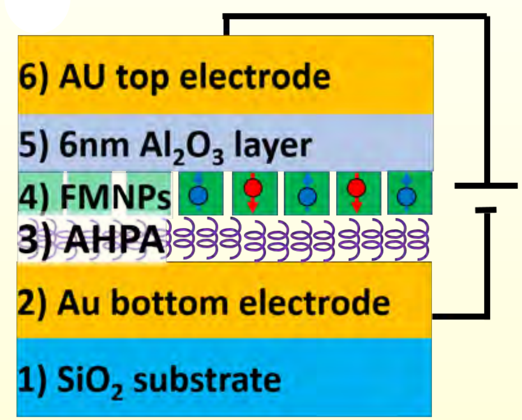


MUS- non-chiral 11-mercaptoundecyl-trimethoxysilane









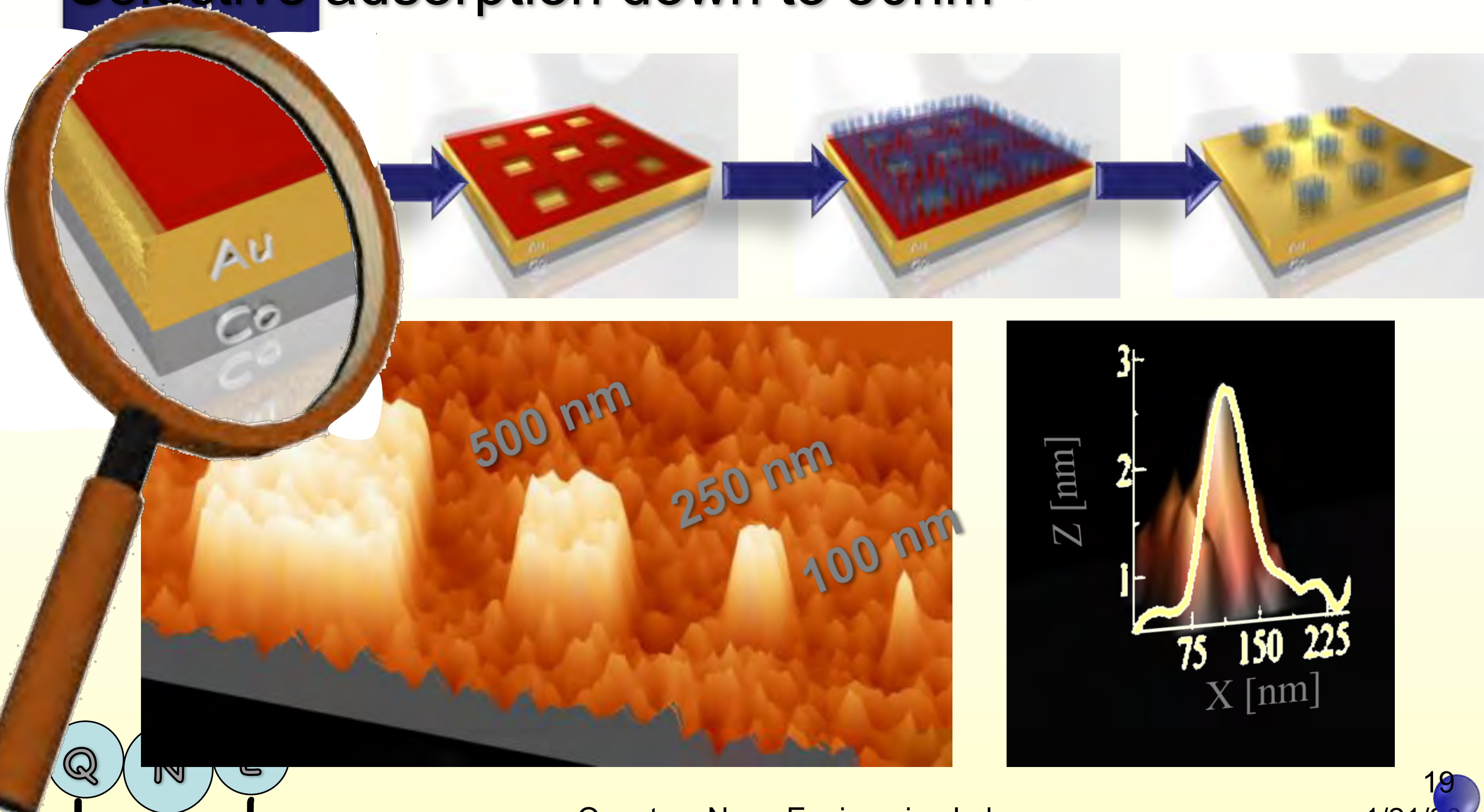
Advance materials 2017

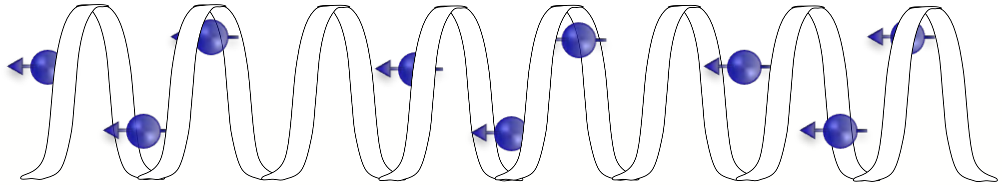
What can we say about the coherence in CISS?

What happens in equilibrium?

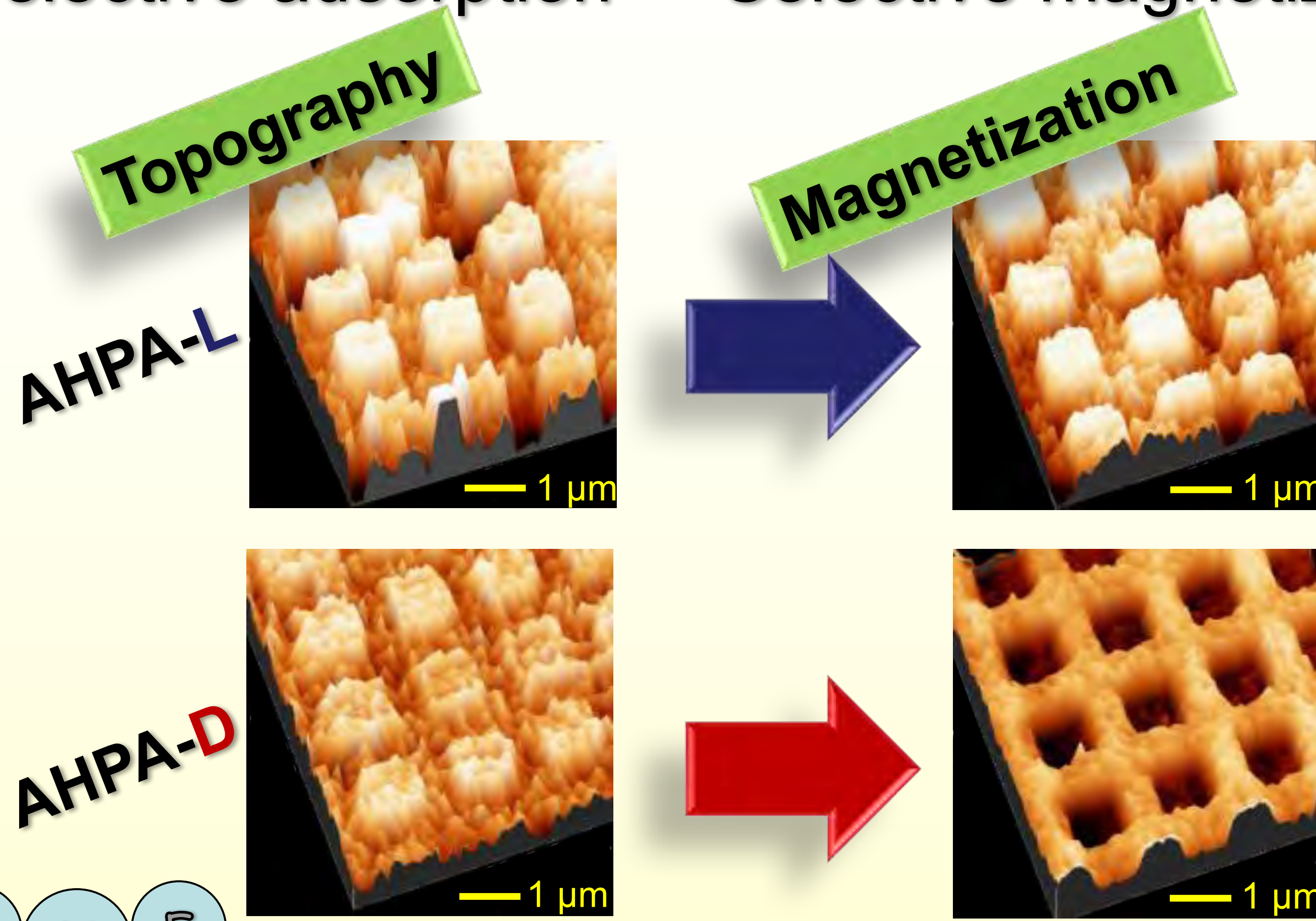
Magnetization with no current

- Selective adsorption down to 50nm



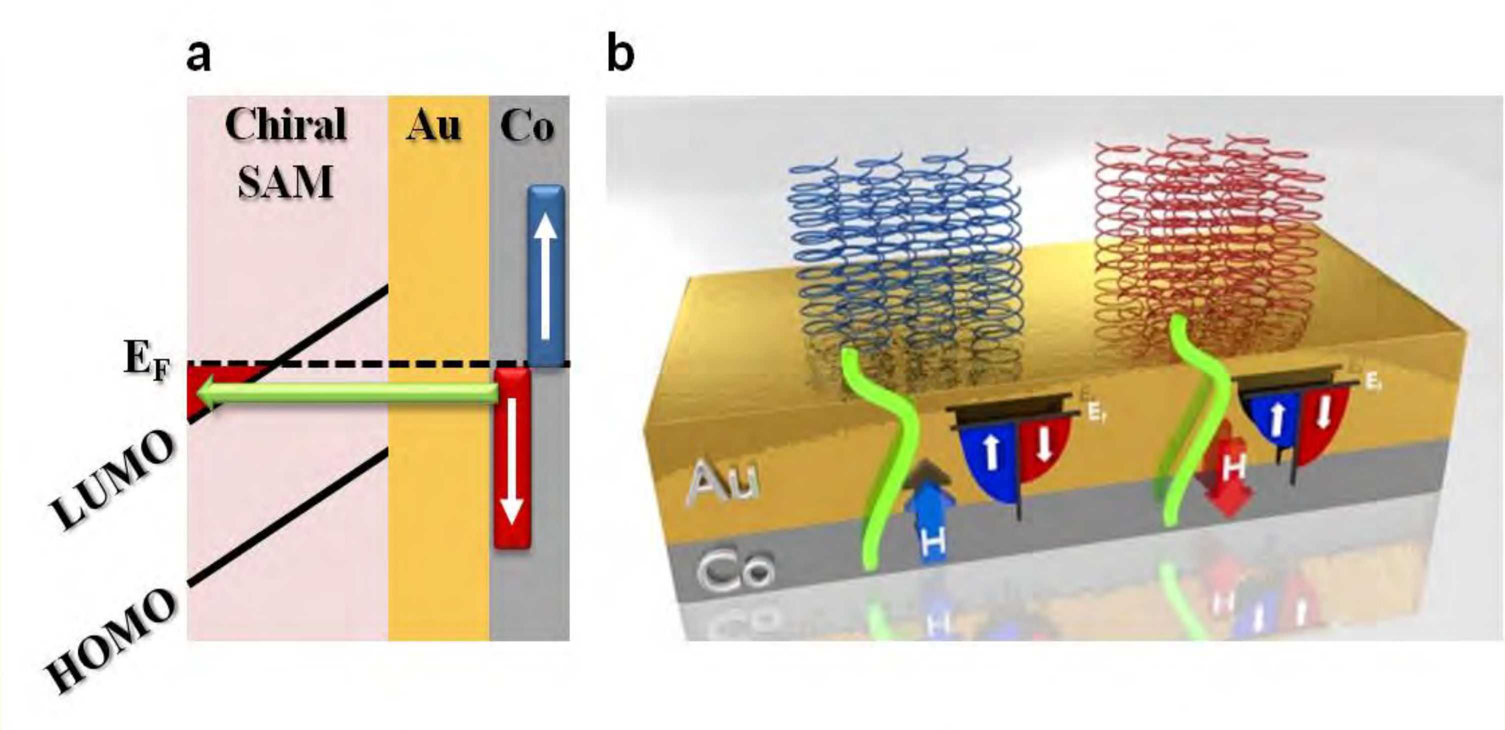


Selective adsorption -> Selective magnetization



Ben Dor *et al*. Nature Communications **8** 14567 (2017).

Semi- Classical Vs Quantum



Fraction of a charge?? Coherent???

Magnetization with no current!!!!

Magnetization with no current?

- The current density required for the spin-transfer torque (STT) is of the order of 10^6 A/cm^2
- STT – current density equals10^{25} electrons/ s cm^2
- Adsorption of molecules 10^{13} molecules/cm^2

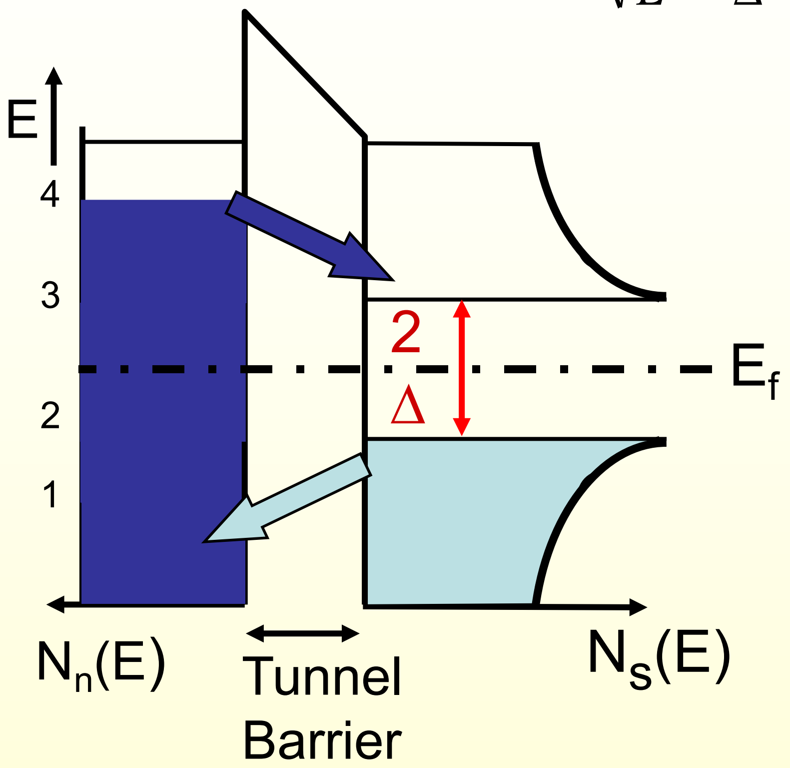
Here if 1 electron is transfer per molecule
10^{13} molecules/cm^2

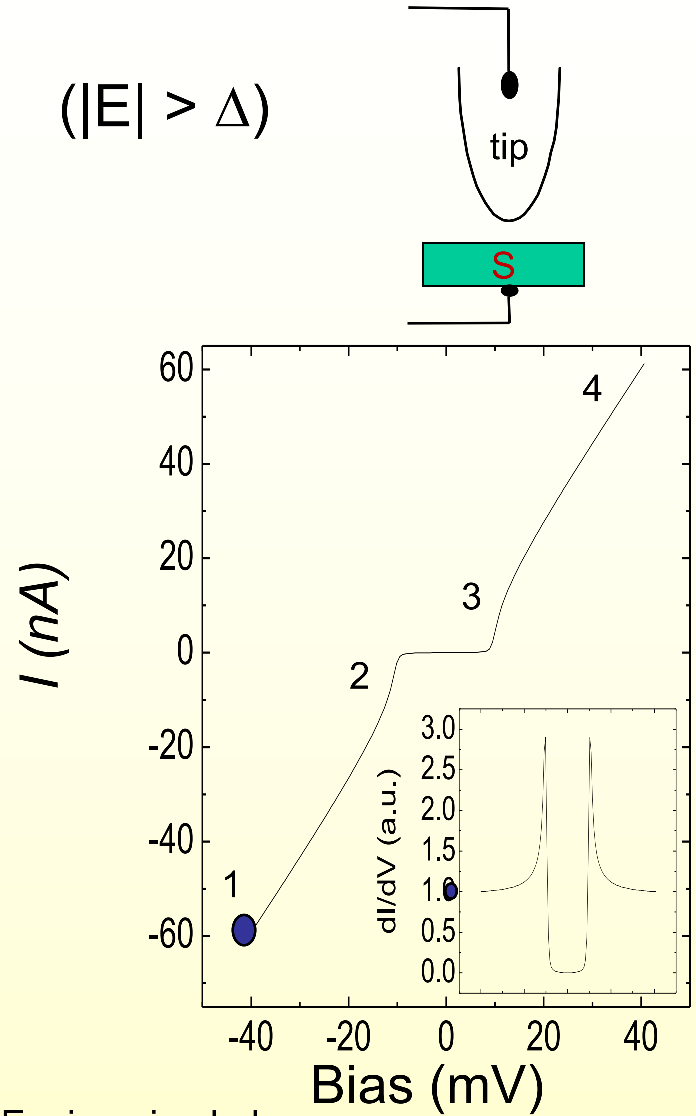
Do we have a spin induced long range coherent order?
Or the CISS is creating a local magnetic impurity?

superconducting proximity effect?

I-V & dI/dV-V Tunneling Spectroscopy

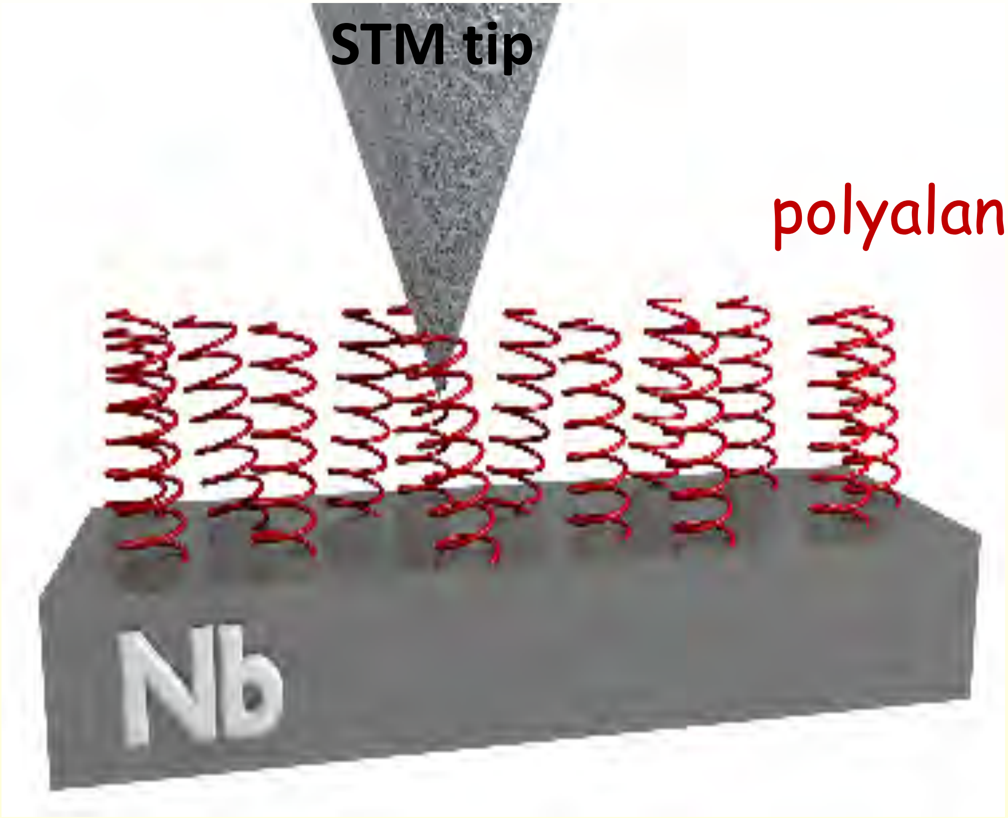
$$dI/dV \propto D_s(r,E) \propto \frac{|E|}{\sqrt{E^2-\Delta^2}} \qquad (|E| > \Delta)$$





Measuring Scheme

So what will happen if we adsorb chiral molecules on superconductors surface?

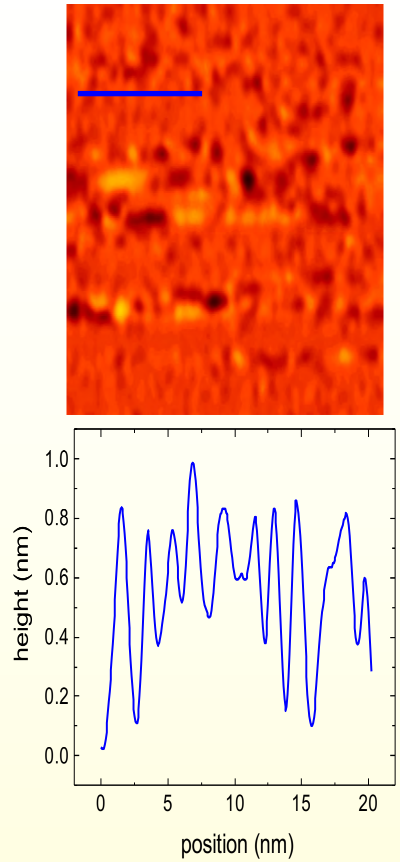


polyalanine alpha-helix

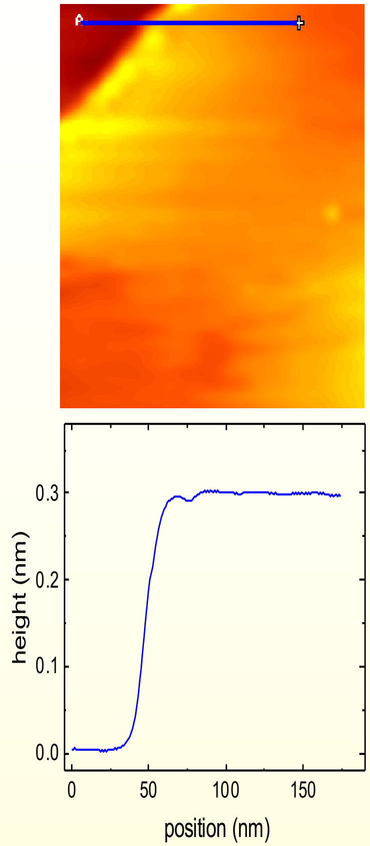
In collaboration with Oded Millo

sample characterization

molecule-covered area

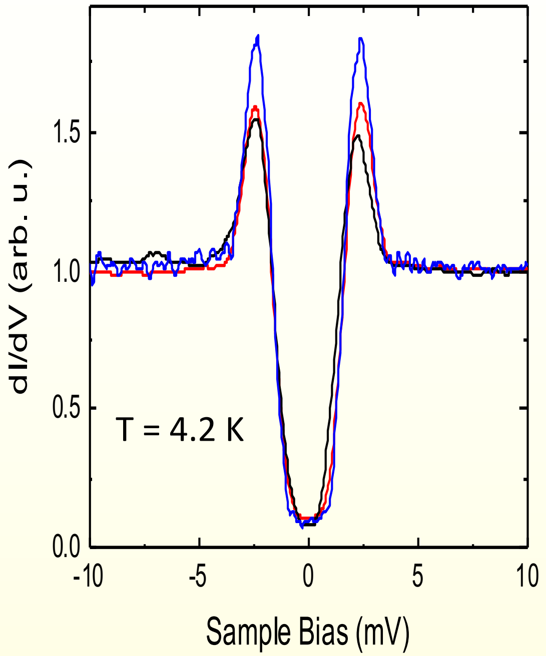


molecule-free area



on pristine film

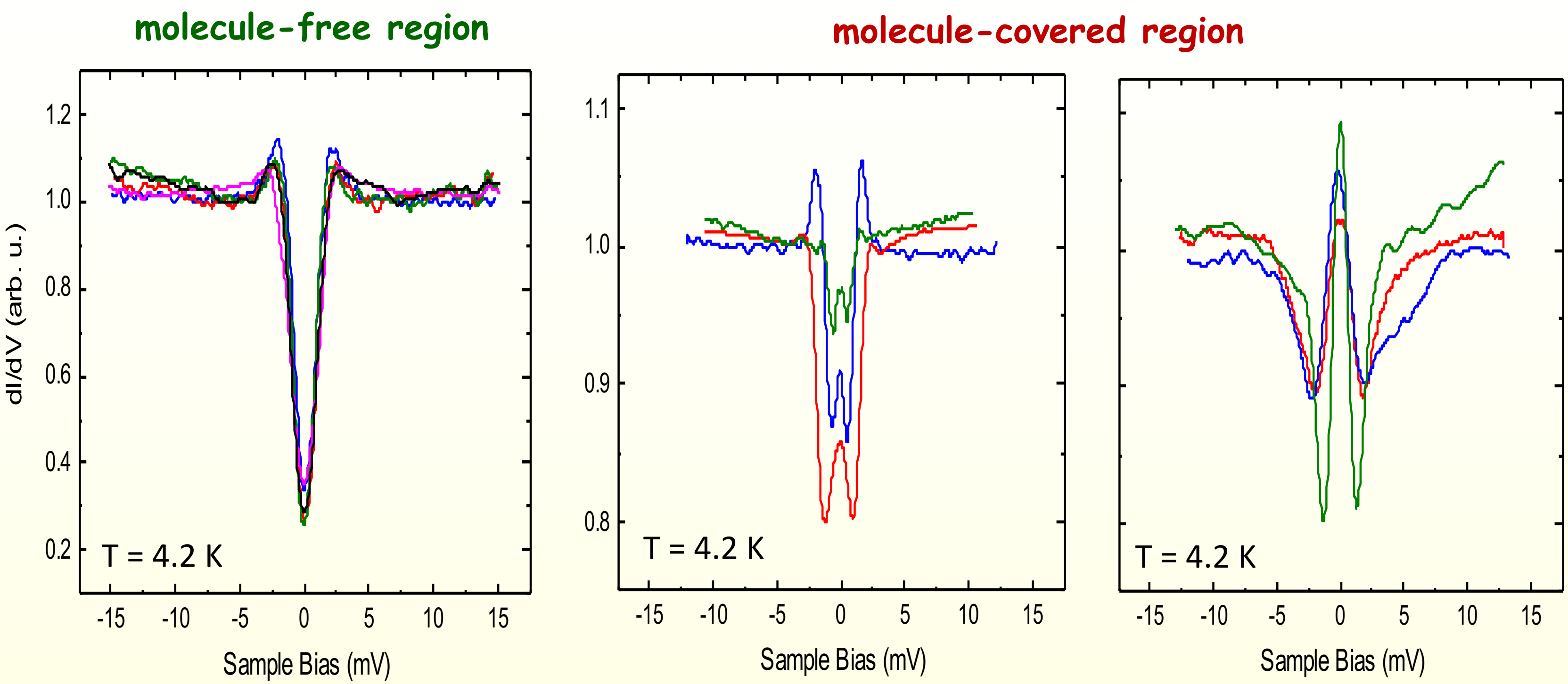
gaps of $\Delta \approx 1.55$ meV.



60 nm thick Nb films on Si. T_C between 7.5 to 8.5 K.

Polyalanine alpha-helix molecules, (~ 3nm long, ~1 nm wide).

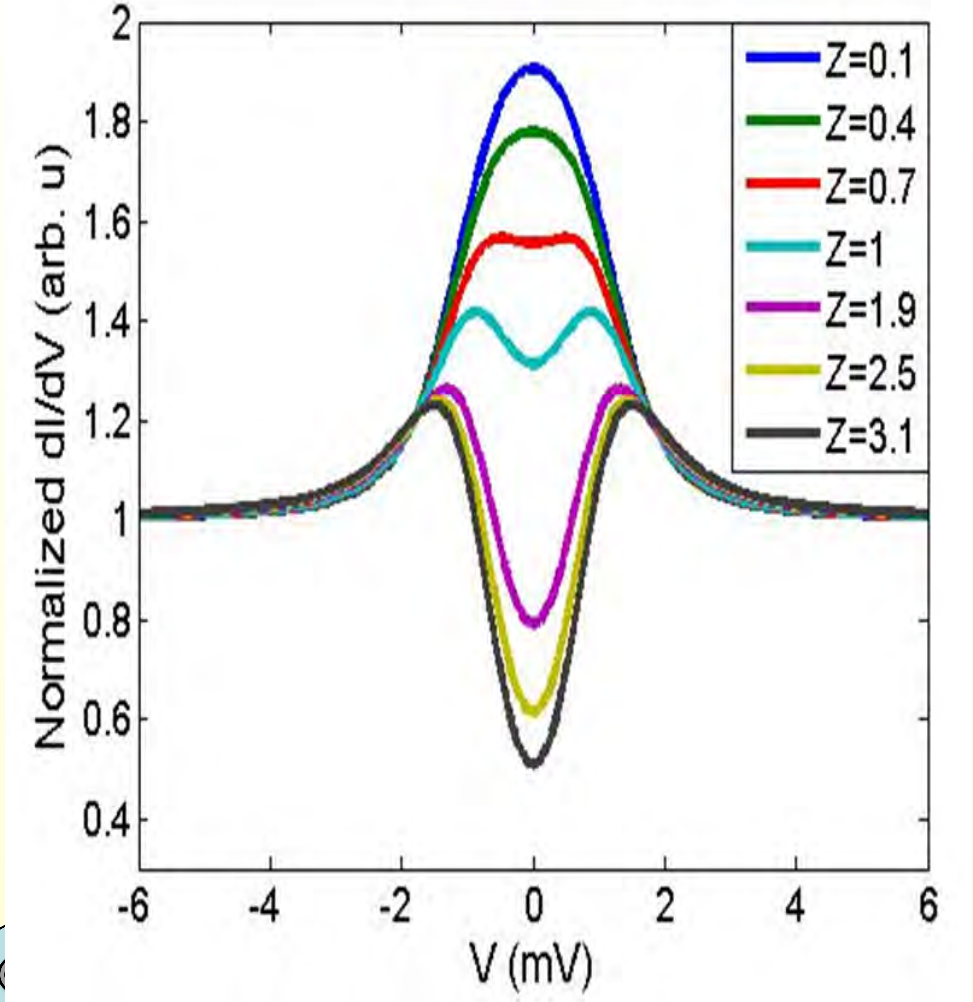
Three types of spectra

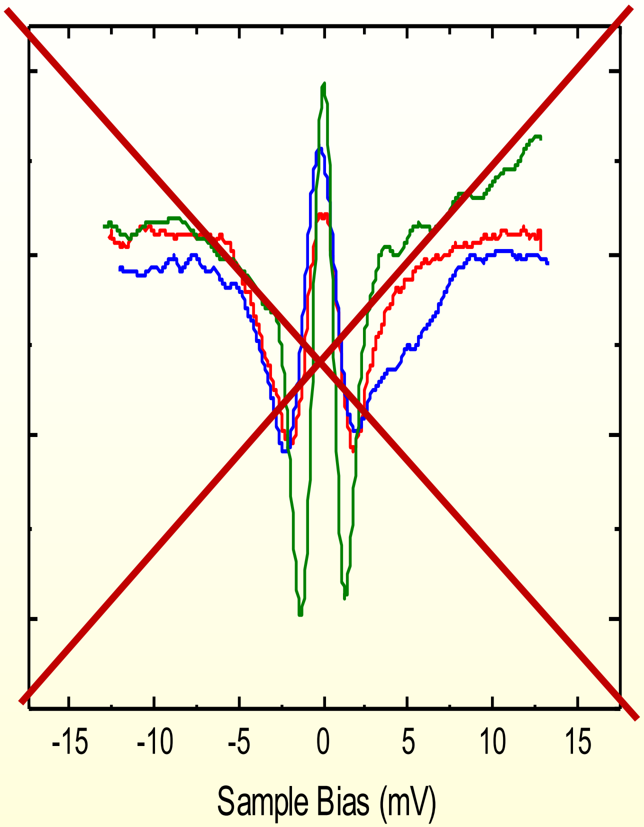


- **molecule-free regions**: smeared BCS-like spectra.
- **molecule covered regions**: zero-bias conductance peaks inside gaps.

Could s-wave symmetry explain these results?

BTK model for various barrier strength Z values



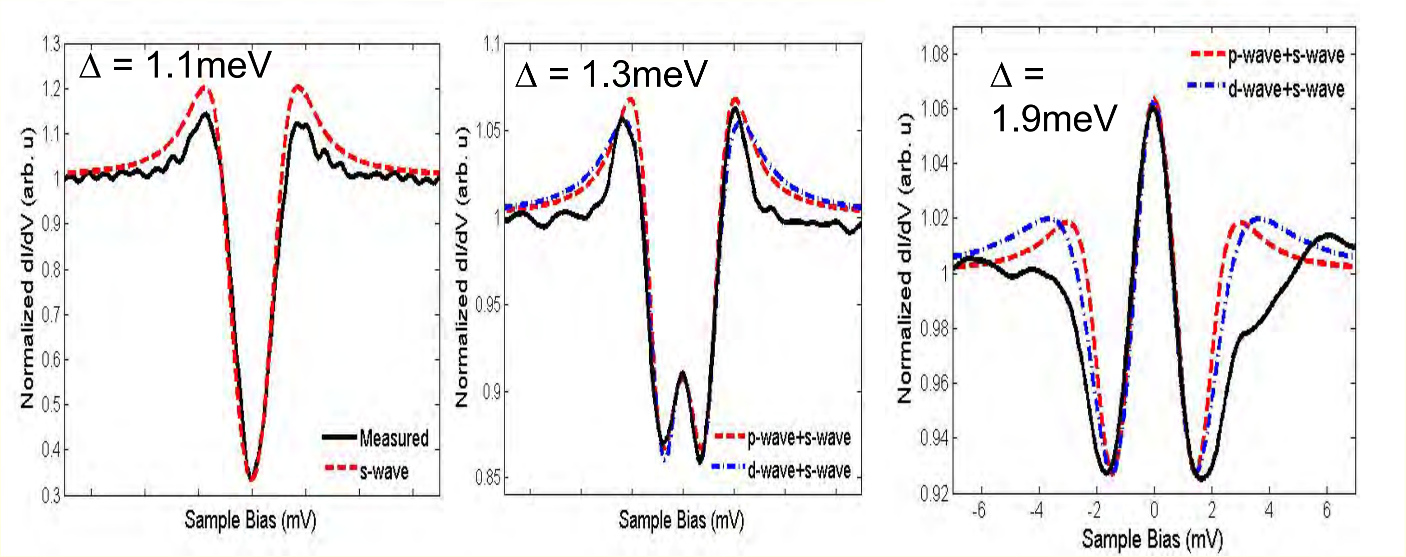


Fits to the three types of spectra

Combination of s-wave, d-wave and chiral p-wave pairing potentials. T = 4.2 K

chiral p-wave : $\Delta_{\uparrow\uparrow} = \Delta_0 \sin\theta(\cos\phi + i\sin\phi)$ (triplet)

d-wave ($d_{x^2-y^2}$) : $\Delta = \Delta_0 \cos(2\theta)$ (singlet or odd-frequency triplet)



s-wave only

p-wave + s-wave (61% p-wave)

d-wave + s-wave (50% p-wave)

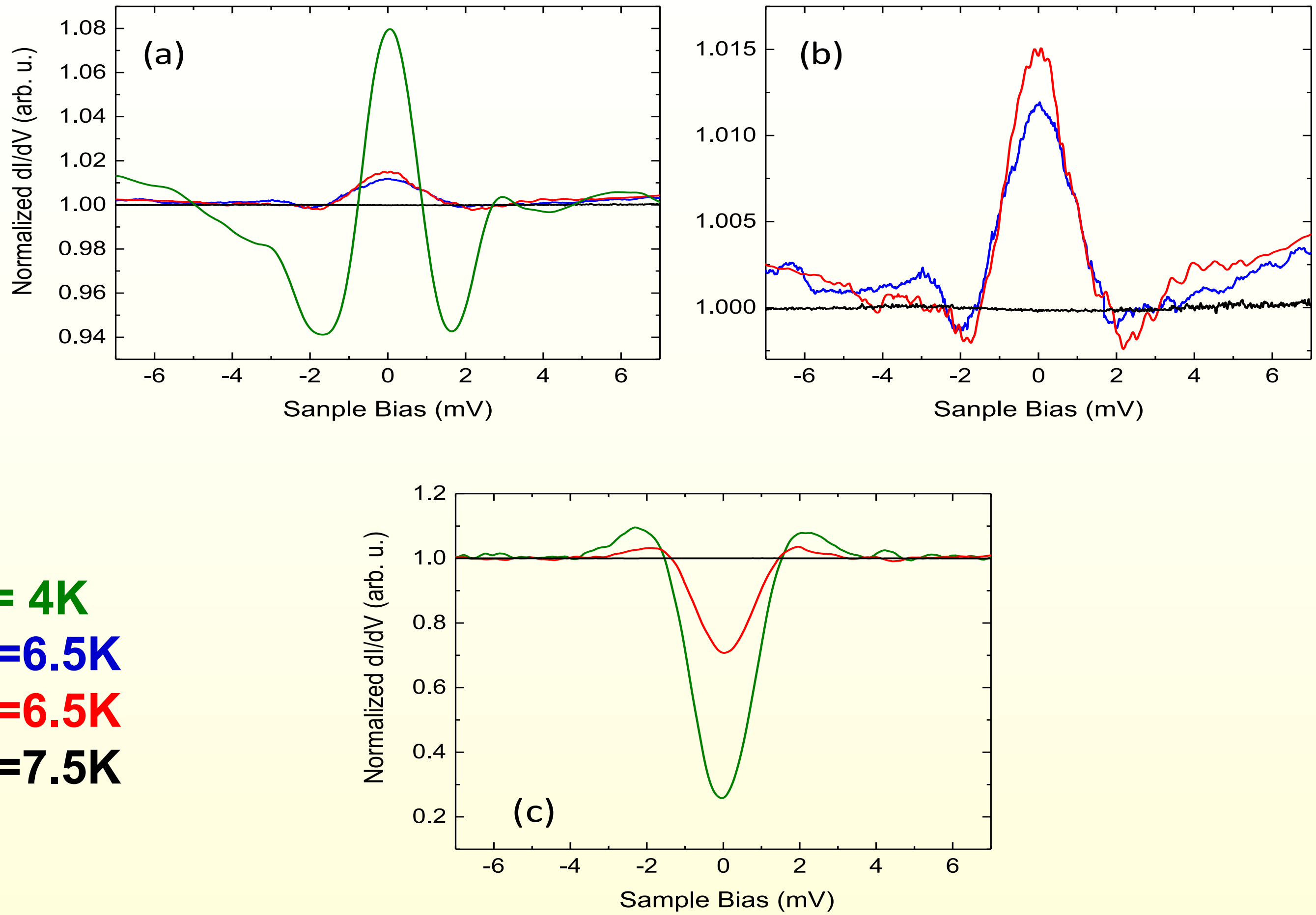
p-wave + s-wave (73% p-wave)

d-wave + s-wave (65% p-wave)

New J. Phys. 18 113048 (2016).

QNE Lab

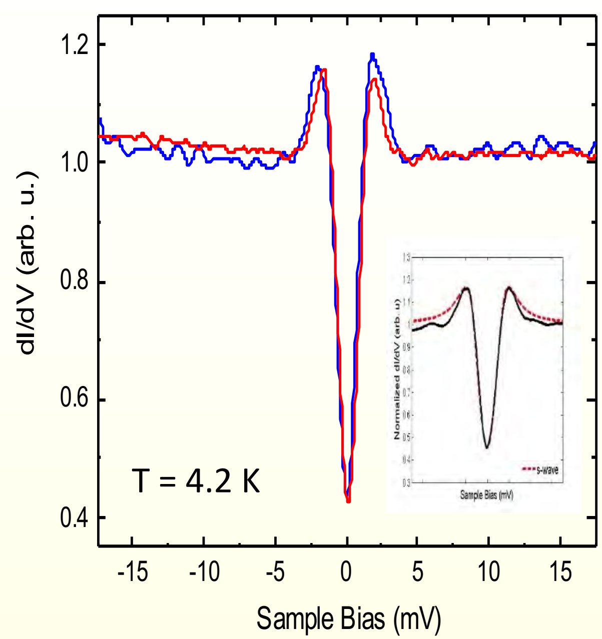
Temperature Dependence



T= 4K
T=6.5K
T=6.5K
T=7.5K

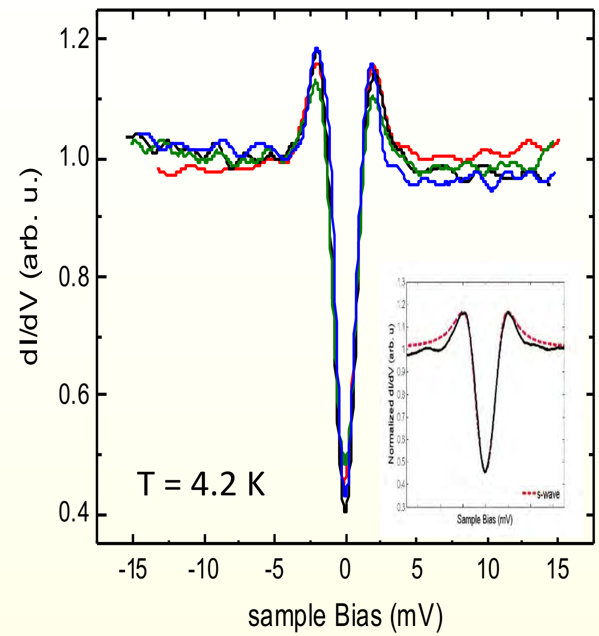
QNE Lab

Control samples



all surface treatments including solvent deposition, but no molecules

T_C = 7.5 K ; Δ ≈ 1.1 meV



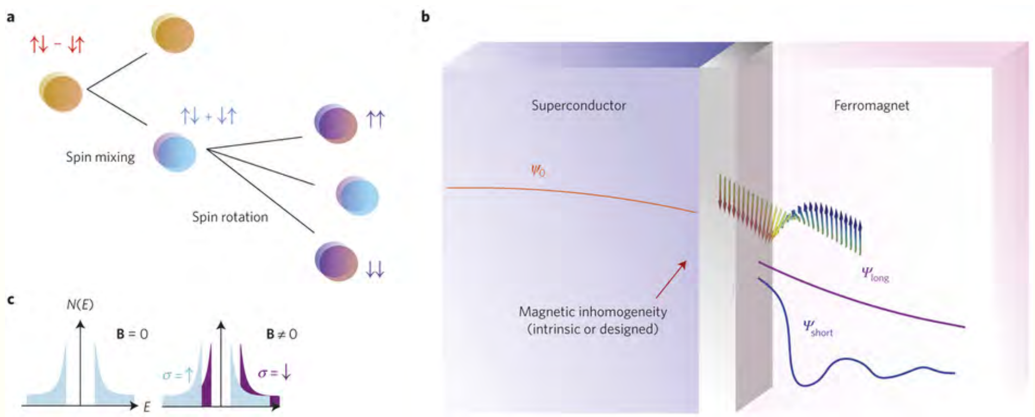
non-chiral di-silane molecules

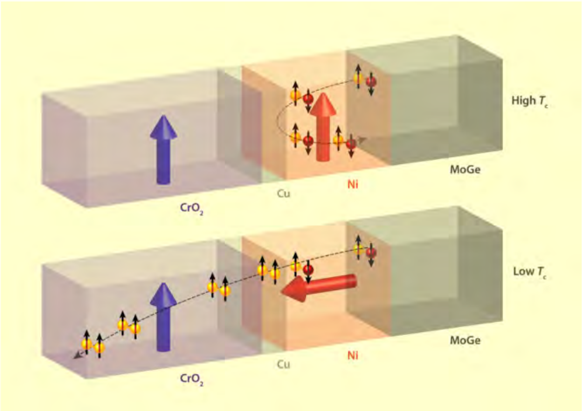
T_C = 8 K ; Δ ≈ 1.2 meV

Superconducting Spintronics

Interaction between superconducting and spin-polarized orders

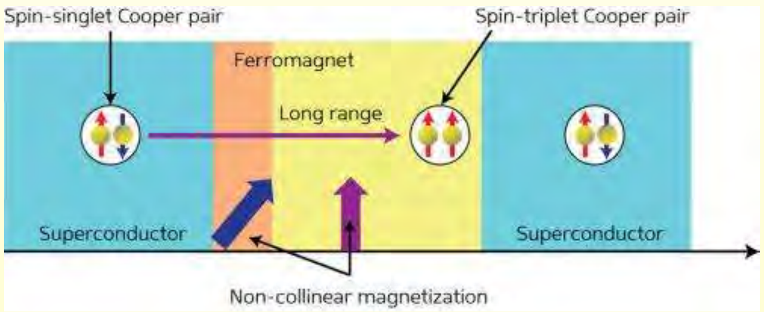
Superconducting spintronics
Jacob Linder & Jason W. A. Robinson
Nature Physics **11**, 307 (2015).



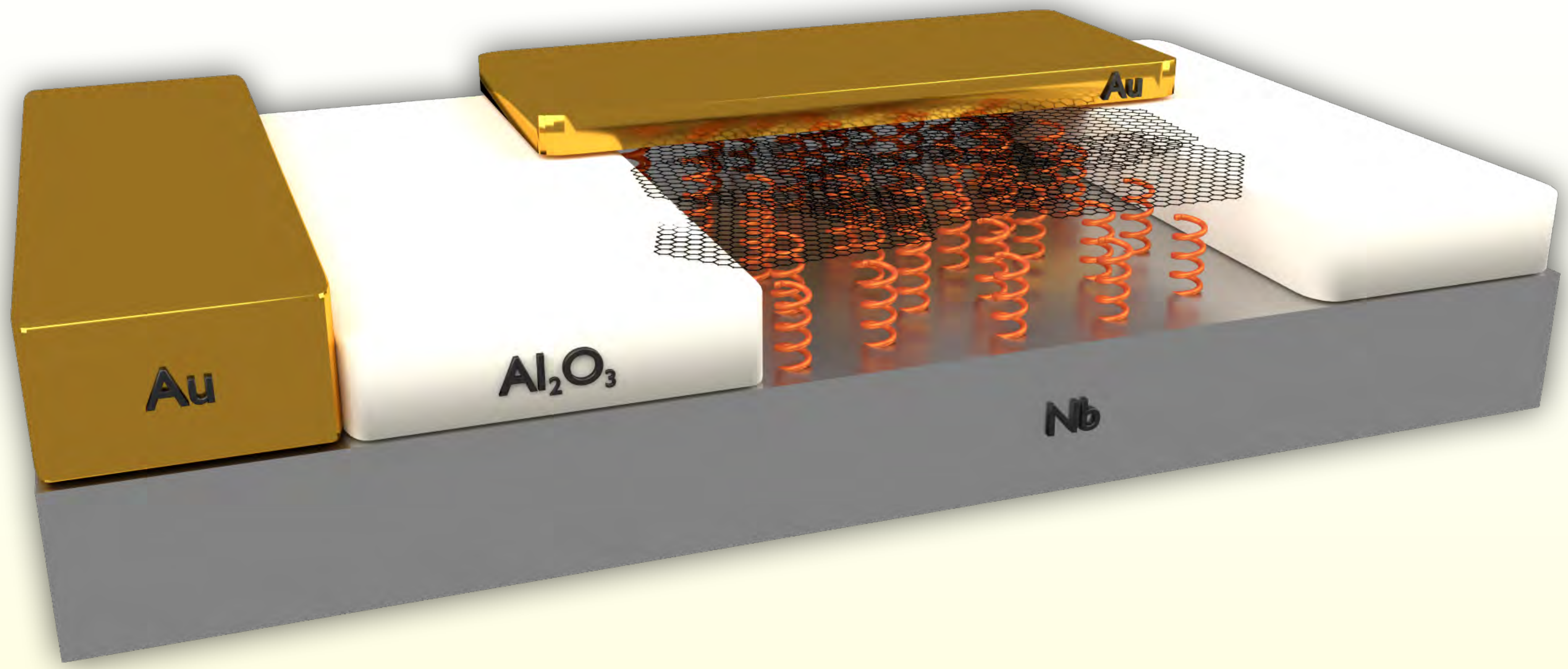


A. Singh, S. Voltan, K. Lahabi, and J. Aarts, "Colossal Proximity Effect in a Superconducting Triplet Spin Valve Based on the Half-Metallic Ferromagnet CrO2," Phys. Rev. X **5**, 021019 (2015) .

Hikino, S. & Yunoki, S.
Long-range spin current driven by superconducting phase difference in a Josephson junction with double layer ferromagnets,
Physical Review Letters **110**, 237003 (2013).

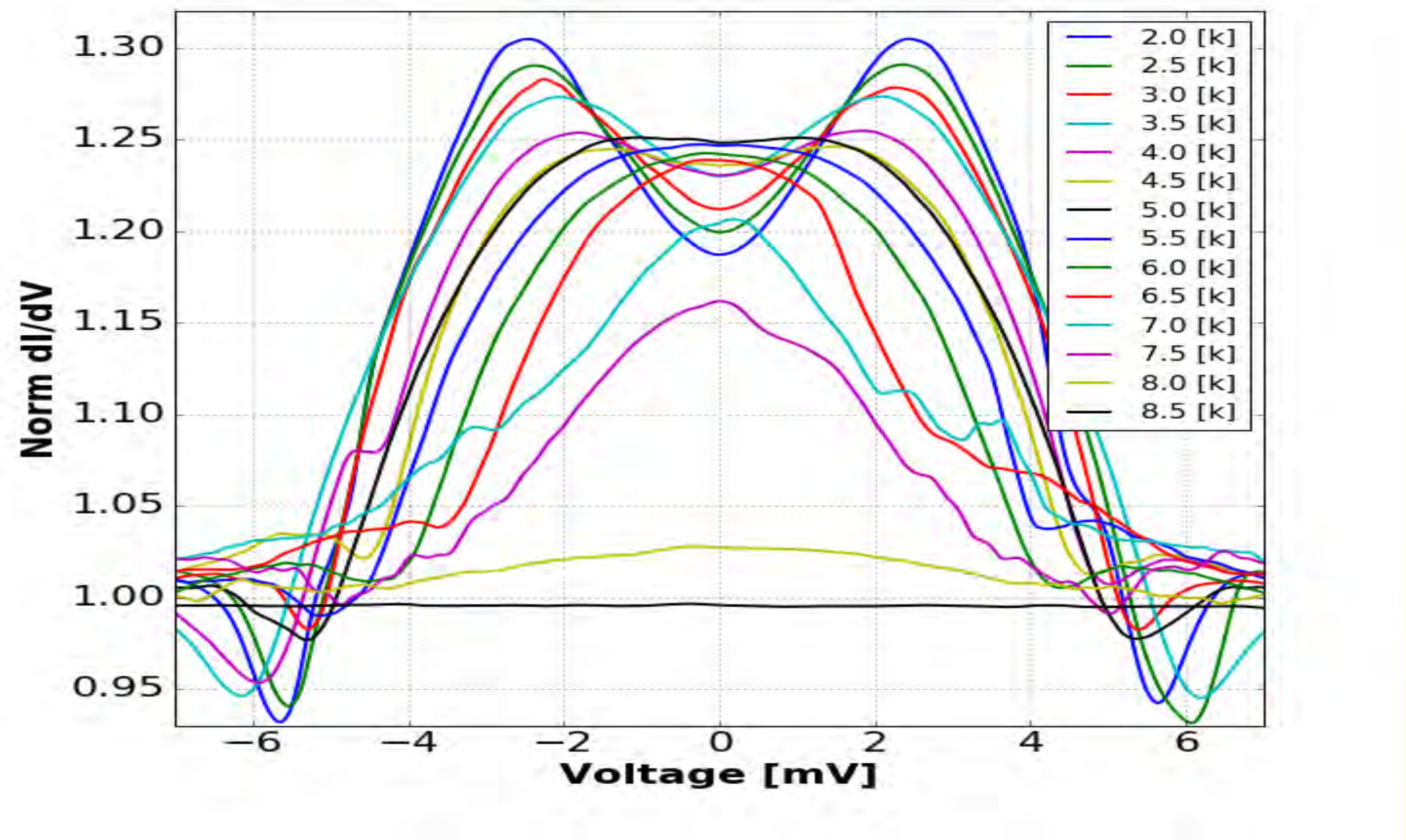


Device Sketch

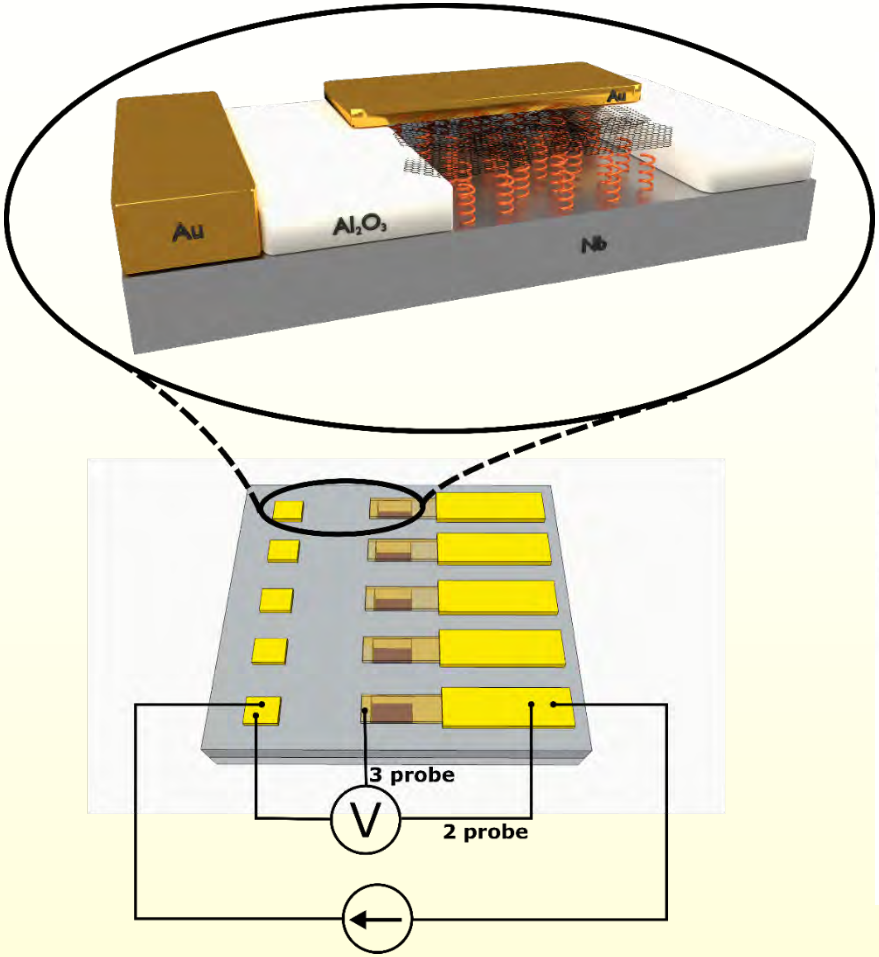


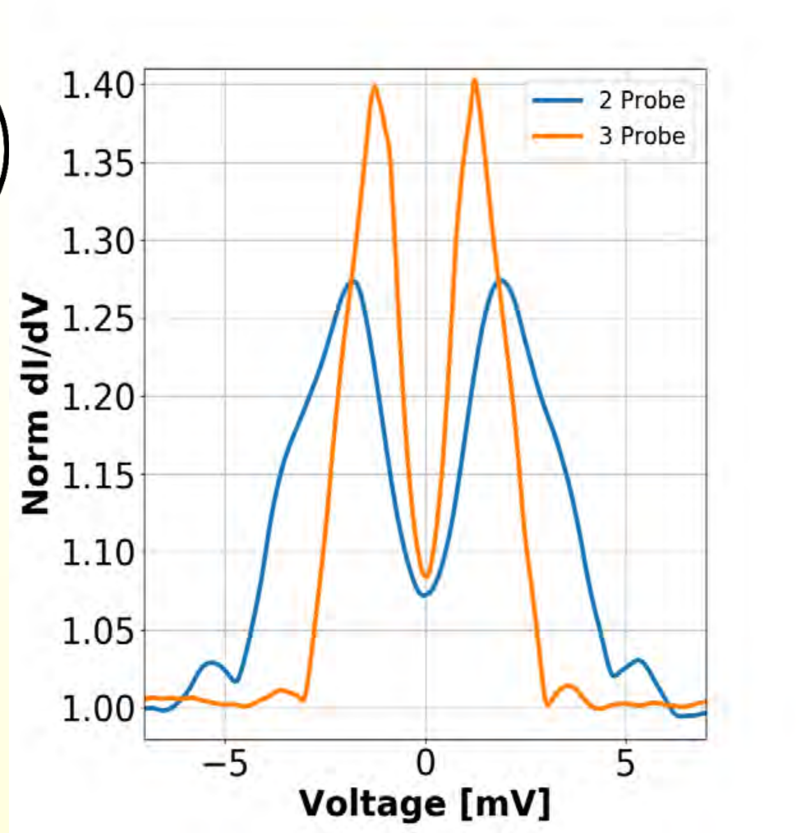
the junction measured consists of a Nb substrate, chiral polyalanine molecules, conductive graphene flakes and a top gold electrode. The measurement is done between the gold electrodes

Junction dI/dV Vs. V



3 probe configuration

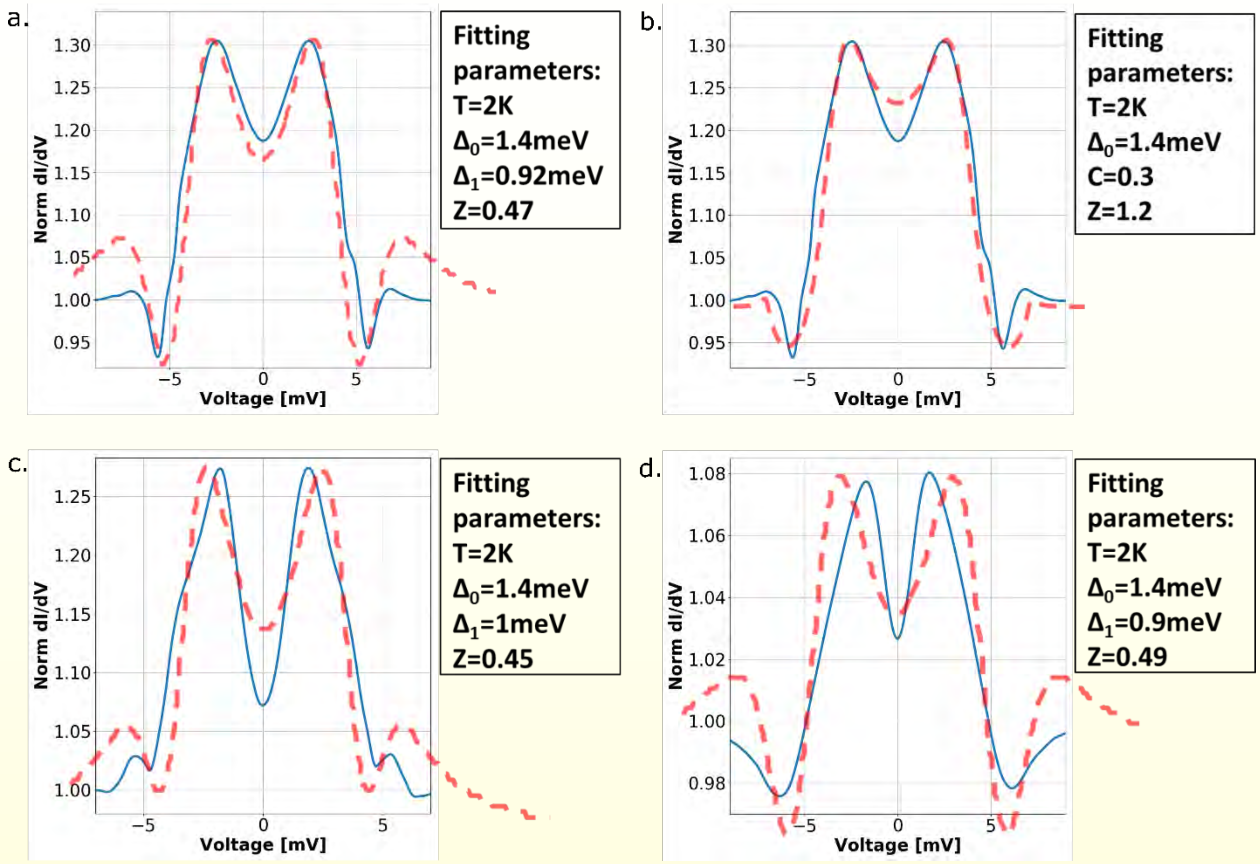




 QNE Lab

Theoretical fits

Low Z
Two gap
model

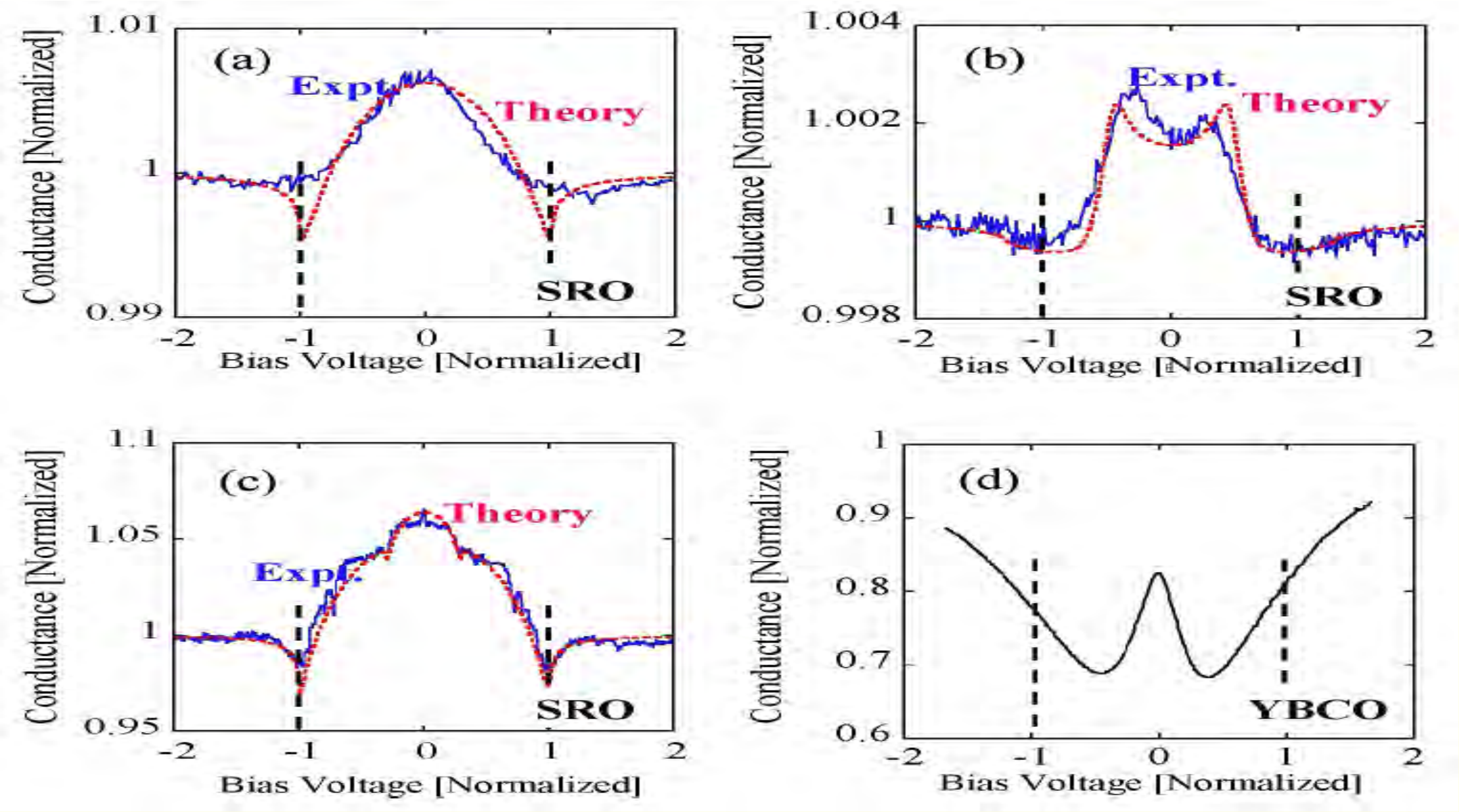


High Z
P wave
model

Anisotropy factor, C, is introduced, and in the equation above D_0 is replace by $\Delta_0 = \Delta_0(1 + C * \cos(4\theta))$.

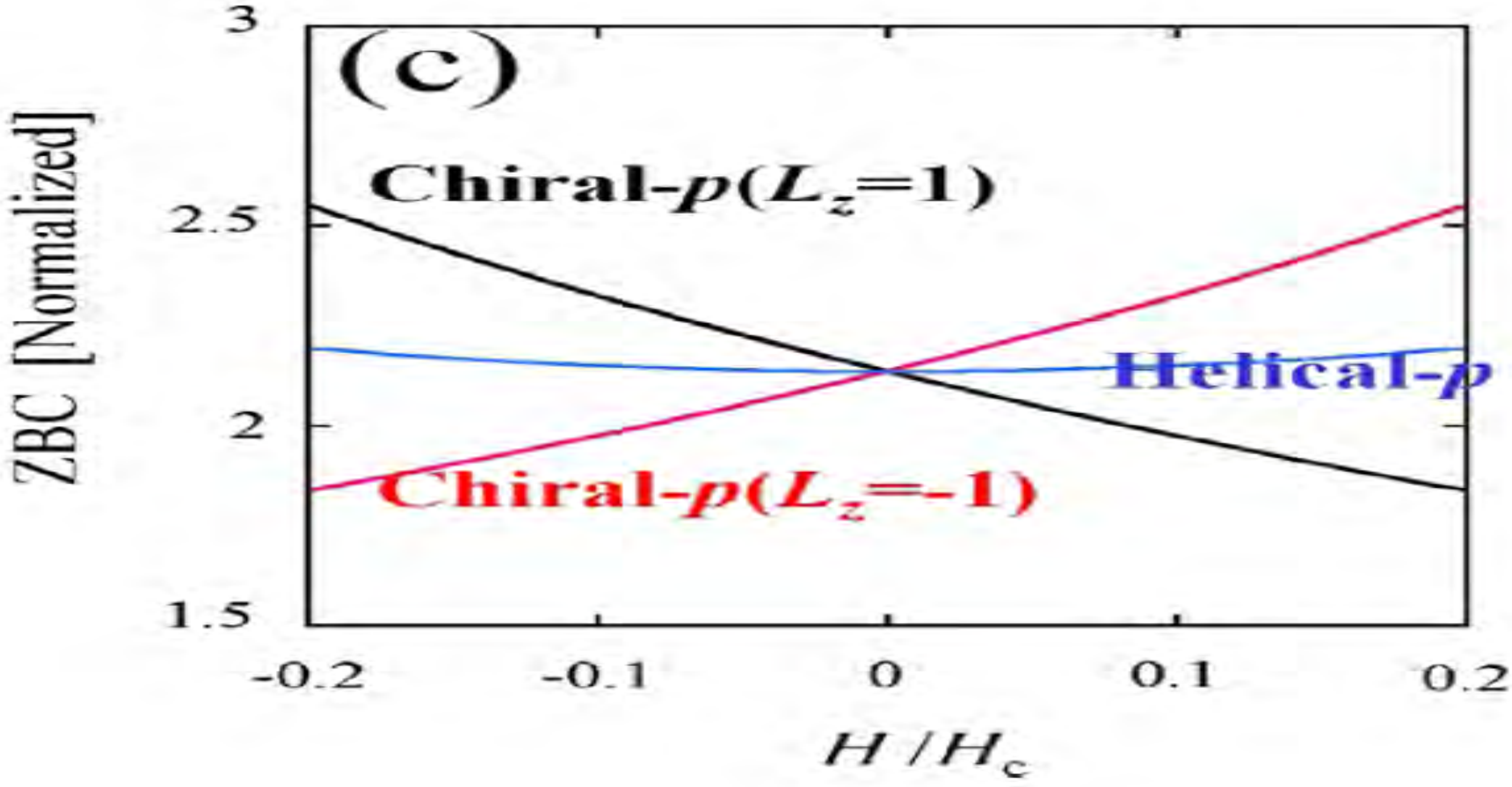
Results- analysis

Similar results where measured experimentally on P-wave superconductor Sr_2RuO_4



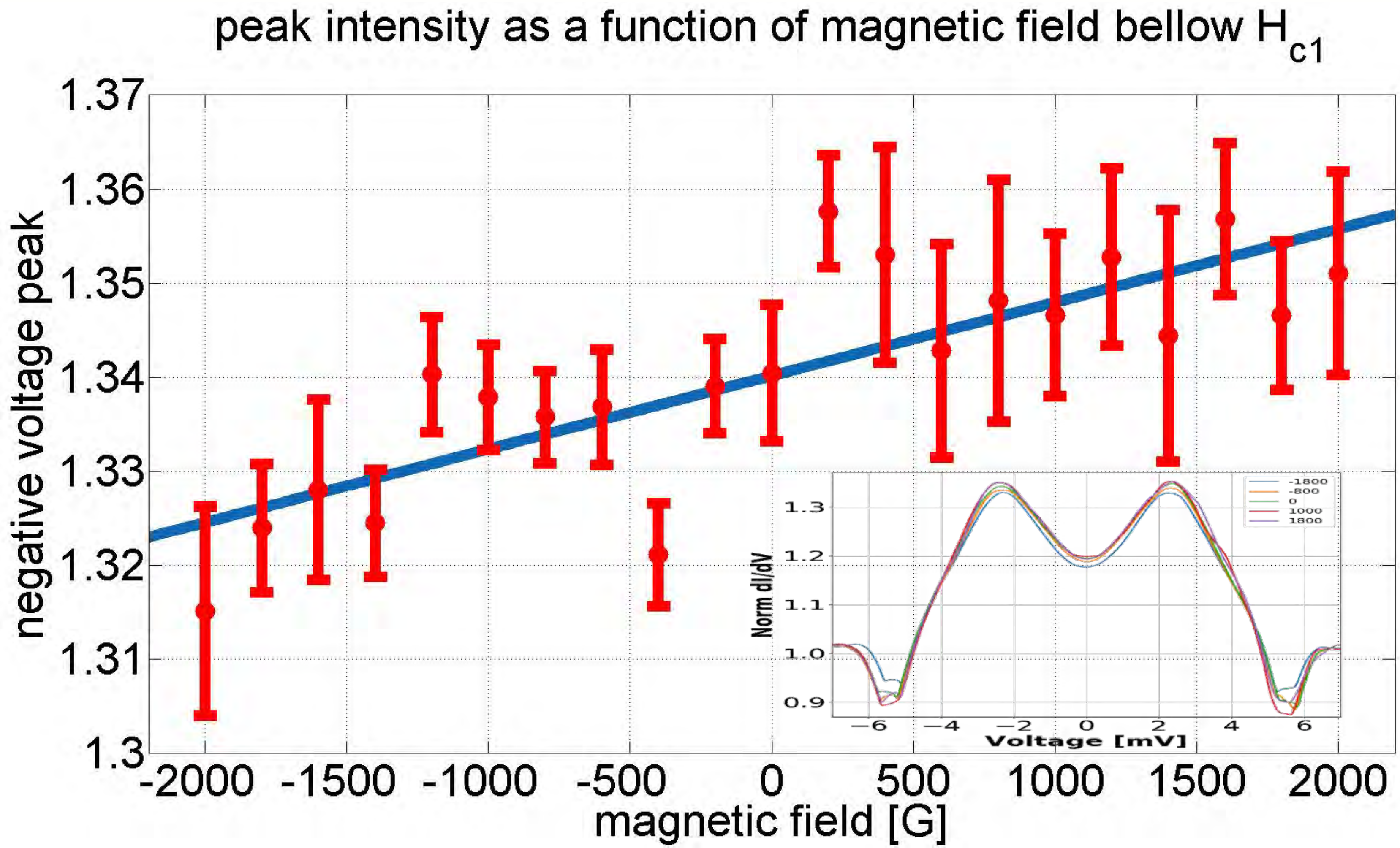
S. Kashiwaya *et al.*, "Edge States of Sr_2RuO_4 Detected by In-Plane Tunneling Spectroscopy," *Phys. Rev. Lett.*, vol. 107, no. 7, p. 077003, Aug. 2011.

Chiral P ZBC

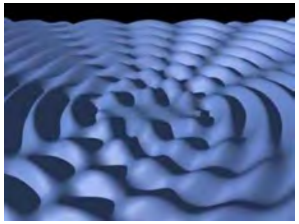


S. Kashiwaya, H. Kashiwaya, K. Saitoh, Y. Mawatari, and Y. Tanaka, “Tunneling spectroscopy of topological superconductors,” *Phys. E Low-Dimens. Syst. Nanostructures*, vol. 55, pp. 25–29, Jan. 2014.

Magnetic measurements at 1.7K may hint to induced long range order



Collective effects

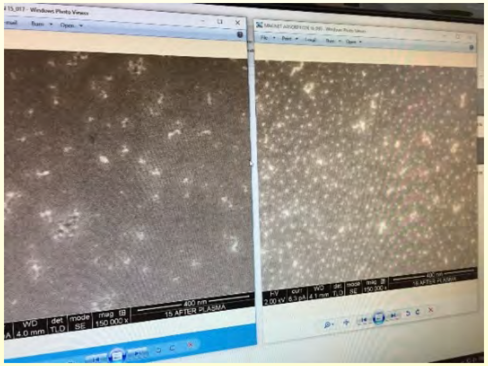


- We see a strong surface spin interface effect using chiral molecules in equilibrium.

- We may see collective long range coherent ordering
- Or local magnetization and Zeeman splitting in the molecules

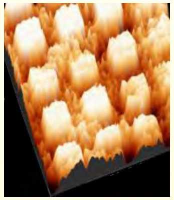
- Simple superconducting spintronics devices can be realized.

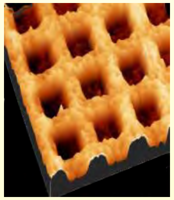
Can we see the opposite effect? Magnetization of the surface influence the adsorption rate by CISS?



Summery We show a simple way to solve material and current problems

- CISS based devices work as optical/electrical memory at ambient in a device of 40x40 nm.
- It works as a reading head at ambient with dimensions of 10x10 nm.
- The hystheresis is “meristor like” which can be used as embedded memory in integrated circuits.
- Induced local magnetization switching by local adsorption of chiral molecules on ferromagnets
- No need for current or external magnetic field – down to single domain size only 0.5nm deep.





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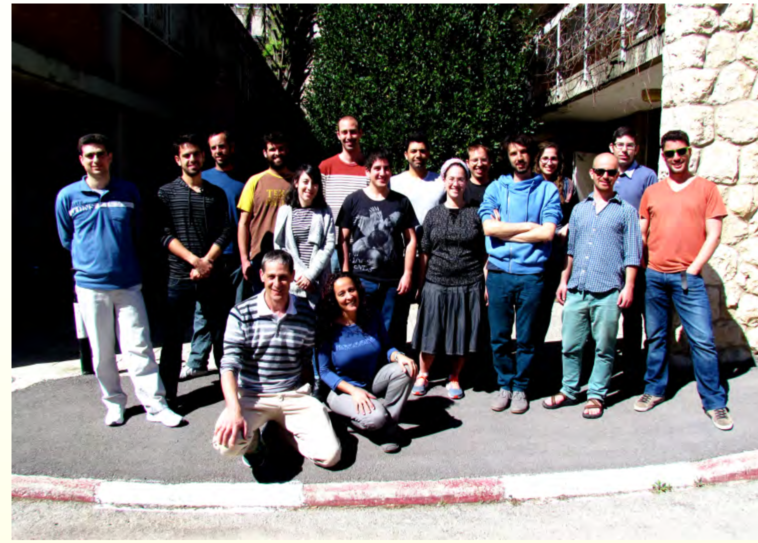

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