Spintronics and Superconducting Spintronics based on Chiral Molecules

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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

**Flash memory**

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 cost, compatibility to standard Si process & complexity of design.
Why Spintronics?

• **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
The CISS Effect

Chiral Induced Spin Selectivity - CISS

Zuot Xie, Tal Markus, Sidney Cohen, Zeev Vager, Rafael Gutierrez, Ron Naaman

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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

Gutierrez, E. D´iaz, R. Naaman, and G. Cuniberti1, PHYSICAL REVIEW B 85, 081404 (2012)
Transport Vs Optics

Chirality Induced Spin-selectivity (CISS) effect

SC NCs

Chiral Molecules

FM

E_F

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CISS Devices solves material problem
RT simple devices

Nano letters 14 6042 (2014).

Optical – photon driven:
• Local magnetization/local optical memory.
• Nano metric charge separation.

Electrical – electrons driven:
• Spin injector
• Nano memristor.

Electrical CISS Memory

L or D PAL (polyalanine), thiolated α-helix -
CAAAAAAKAAAAKAAAAAKAAAAKAAAAA-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.

Vertical Memristor Device

- Bottom electrode
- Adsorb AHPA-L or AHPA-D and multiple FMNPs
- $\text{Al}_2\text{O}_3$ tunnel barrier
- Top electrode

AHPA chiral molecules-
$\text{[H]}$-AAAAAKAAAAAKAAAAKAAAAKAAAAKAAAAKAAAAKAAAAKAAAAKAAAAKAAAAKAAAAKAAAAKAAAAKAAAAKAAAAK-
$\text{[OH]}$
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  
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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

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 equals $10^{25}$ 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

\[ \frac{dI}{dV} \propto D_s(r,E) \propto \frac{|E|}{\sqrt{E^2 - \Delta^2}} \quad (|E| > \Delta) \]

E

N_n(E) \quad \text{Tunnel Barrier} \quad N_s(E)

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

\text{Bias (mV)}

\text{I (nA)}

\text{dI/dV (a.u.)}

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Measuring Scheme

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

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, (~3 nm 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)

Temperature Dependence

\[ T = 4K \]
\[ T = 6.5K \]
\[ T = 6.5K \]
\[ T = 7.5K \]
Control samples

all surface treatments including solvent deposition, but no molecules

\[ T_C = 7.5 \text{ K} \ ; \ \Delta \approx 1.1 \text{ meV} \]

non-chiral di-silane molecules

\[ T_C = 8 \text{ K} \ ; \ \Delta \approx 1.2 \text{ meV} \]
Superconducting Spintronics

Interaction between superconducting and spin-polarized orders

**Superconducting spintronics**
Jacob Linder & Jason W. A. Robinson

Hikino, S. & Yunoki, S.
Long-range spin current driven by superconducting phase difference in a Josephson junction with double layer ferromagnets,

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. $V$

![Graph showing the relationship between $dI/dV$ and voltage for different temperatures.](image-url)
3 probe configuration

![Diagram of a 3 probe configuration](image)

Graph showing the comparison between 2 probe and 3 probe configurations.

Voltage [mV]

Norm $dI/dV$

-5 0 5
Anisotropy factor, C, is introduced, and in the equation above $D_0$ is replace by $\Delta_0 = \Delta_0 (1 + C * \cos(4\theta))$. 

Theoretical fits

Low Z
Two gap model

High Z
P wave model
Results- analysis

Similar results were measured experimentally on P-wave superconductor Sr$_2$RuO$_4$

Chiral P ZBC

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 hysteresis 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.
Our Group: Prof. Yossi Paltiel, Dr. Shira Yochelis, Eyal Cohen, Eran Katzir, Avner Neubauer, Guy Koplovitz, Oren Ben Dor, Ido Eisnberg, Ohad Westrich, Hen Alpern; Amir Ziv, Nir Sukenik, Aviya Perlman Illouz, Yuval Koldny, Daniel Kagnovitch, Lior Bezen

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