CIC nanoGUNE
nanoscience cooperative research center

Spintronics with Organic Materials

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San Sebastián, Spain

OUTLINE

- Spintronics: some current challenges
- Carbon-based Spintronics
- C_{60}-based Spin Devices. Recent experiments
- Conclusions and open questions

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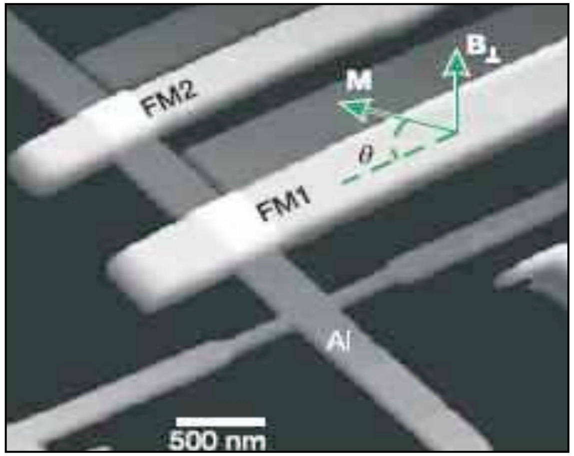
SPINTRONICS: SOME CURRENT CHALLENGES

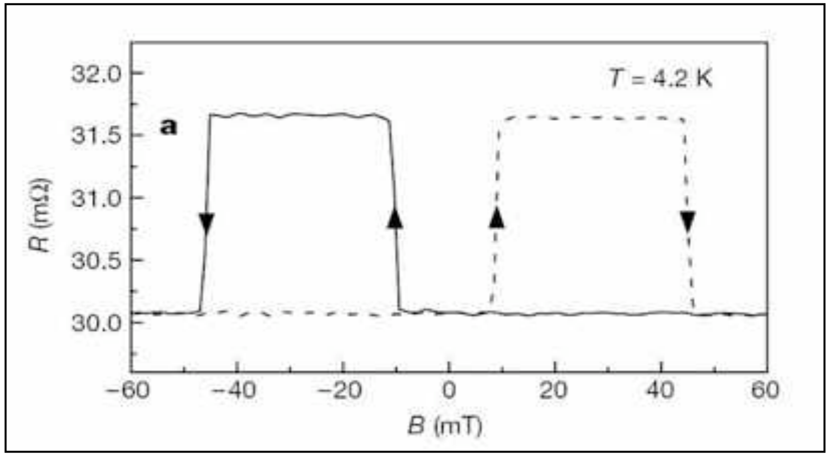
- Micrometer transport of spin information. Spin transport in metals

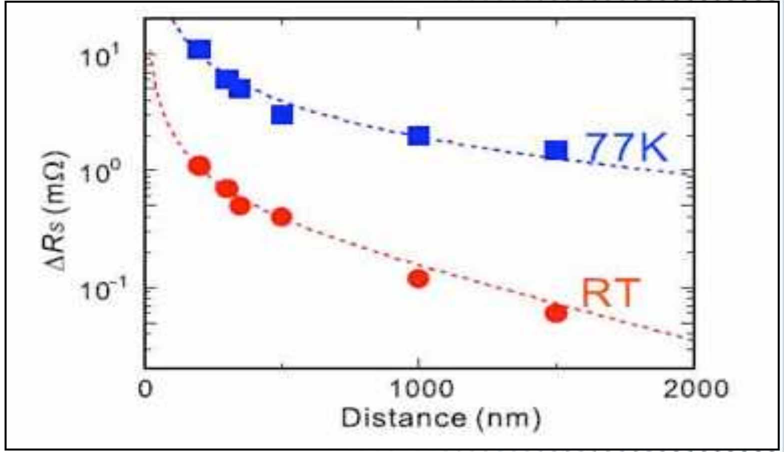
Good current understanding of spin transport in non-ferromagnetic metals

Very novel and sophisticated physics (such as spin Hall effect, spin thermoelectricity, etc.)

Difficulties for efficient spin manipulation but probably good prospect for spin currents and related phenomena







Au: M. Johnson and R.H. Silsbee, Phys Rev. Lett. 55, 1790 (1985)
Cu: F.J. Jedema *et al.*, Nature 410, 345 (2001); 416, 713 (2002)
Al: S.O. Valenzuela *et al.*, Nature 442, 176 (2006)
Ag: T. Kimura *et al.*, Phys. Rev. Lett. 99, 196604 (2007)

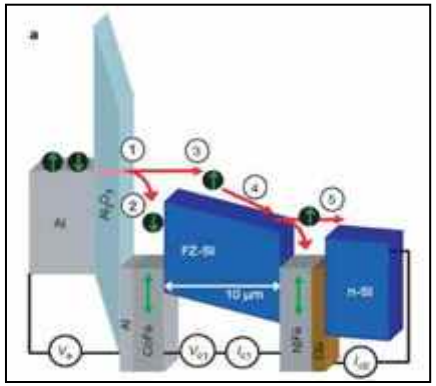
SPINTRONICS: SOME CURRENT CHALLENGES

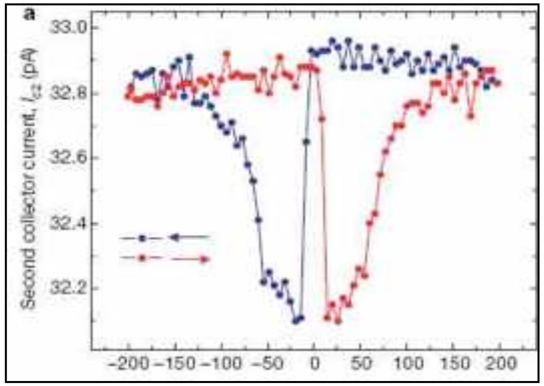
- Micrometer transport of spin transport. Spin transport in semiconductors

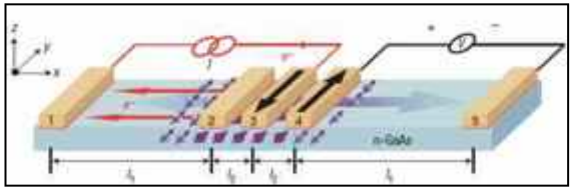
Difficulties in the integration of semiconductors and ferromagnetic metals

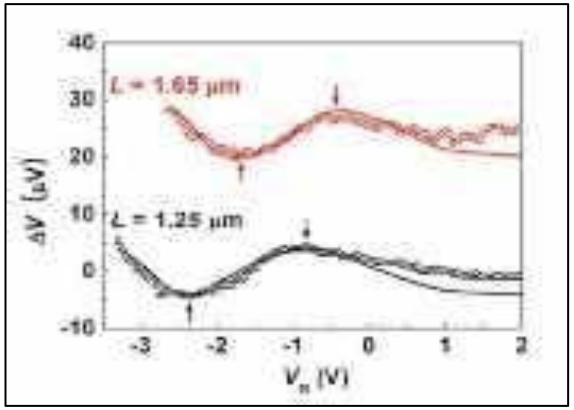
Materials with non-optimum properties (interfacial states, spin relaxation time, scattering by defects, etc.)

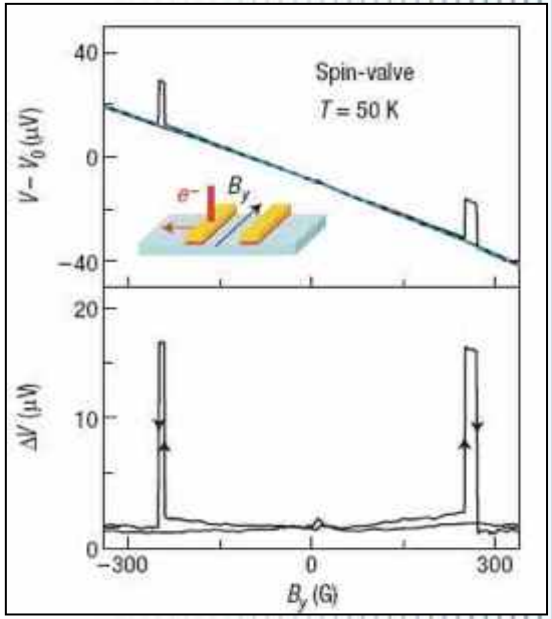
Good prospects for long distance transport and efficient spin manipulation











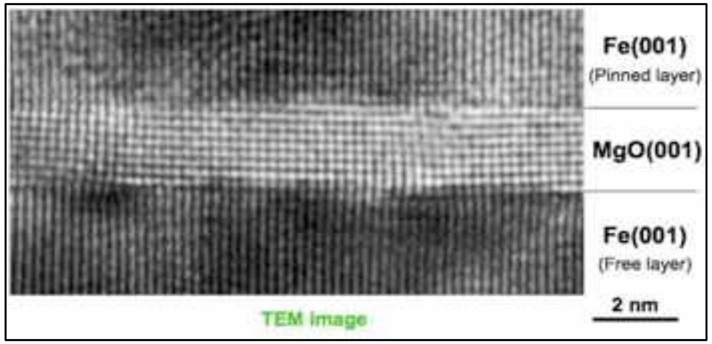
Si: I. Appelbaum *et al.*, Nature 447, 295 (2007)
Si: S.P. Dash *et al.*, Nature 462, 491 (2009)
GaAs: X. Lou *et al.*, Nature Phys. 3, 197 (2007)
InAs: H.C. Koo *et al.*, Science 325, 1515 (2009)

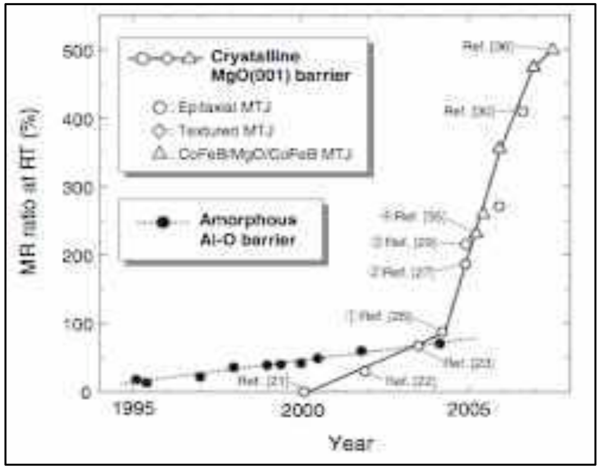
SPINTRONICS: SOME CURRENT CHALLENGES

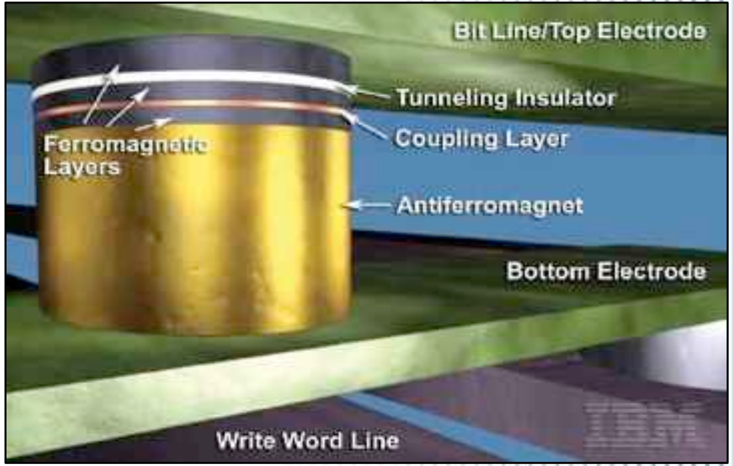
- Nanometer transport of spin information. Spin tunneling in metal/oxide layers

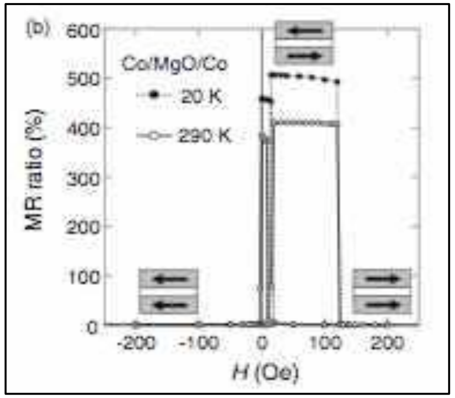
Extreme scientific and technological success

From MgO preferential tunneling to current hard-disk read heads









S.S.P. Parkin *et al.*, Nature Mater. 3, 382, (2004); S. Yuasa *et al.*, J. Phys. Soc. Japan 77, 1031001 (2008)

SPINTRONICS: SOME CURRENT CHALLENGES

- Long-distance spin transport. Injection and transport regime

Difficulties in the integration of semiconductors and ferromagnetic metals

Materials with non-optimum properties (interfacial states, spin relaxation time, scattering by defects, etc.)

Difficulties for efficient spin manipulation

- Small-distance spin transport. Tunnel regime

Need of epitaxial systems with complex interfacial chemistry

Possible Solutions

New materials with new properties. Carbon-based materials?

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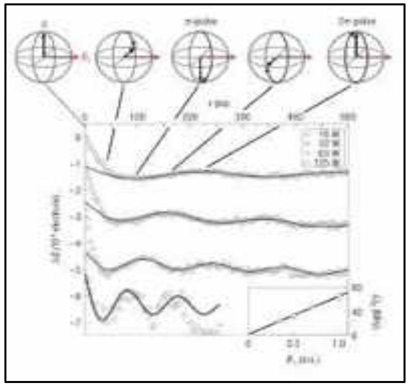
CARBON-BASED SPINTRONICS: STATE OF THE ART

✓ Spin relaxation times larger than microseconds ($\tau_{SF} > \mu s$)

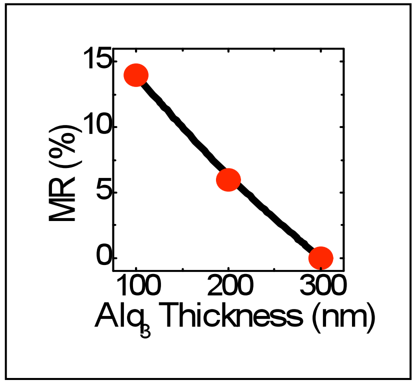


D.R. McCamey *et al.*,Nature Mater. 7, 723 (2008)

CARBON-BASED SPINTRONICS: STATE OF THE ART

✓ Spin relaxation times larger than microseconds ($\tau_{SF} > \mu$ s)

✓ Spin relaxation lengths larger than 100 nm (l_{SF} >100nm)



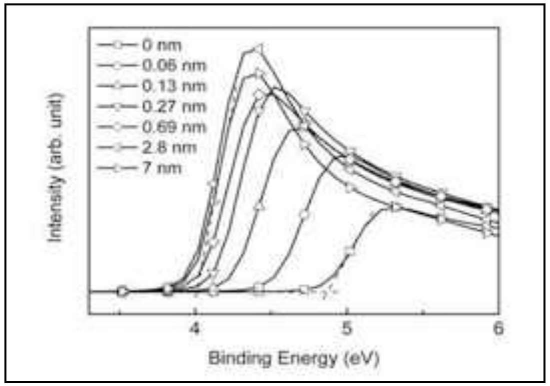
V. Dediu, L.E. Hueso *et al.*, Phys. Rev. B 78, 115203 (2008)

CARBON-BASED SPINTRONICS: STATE OF THE ART

✓ Spin relaxation times larger than microseconds ($\tau_{SF} > \mu$ s)

✓ Spin relaxation lengths larger than 100 nm (l_{SF} >100nm)

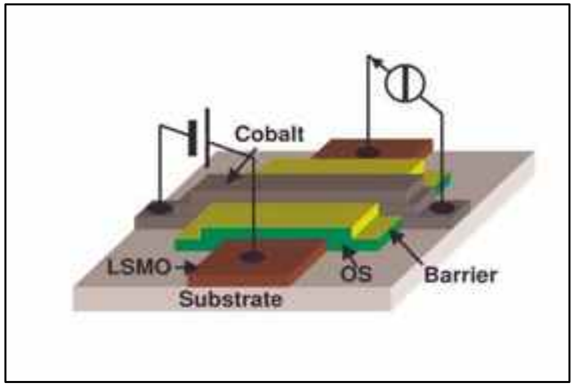
✓ Interface energy balance is fundamental for spin injection in organics



Y.Q. Zhan, L.E. Hueso *et al.*, Phys. Rev B 76, 045406 (2007)

CARBON-BASED SPINTRONICS: STATE OF THE ART

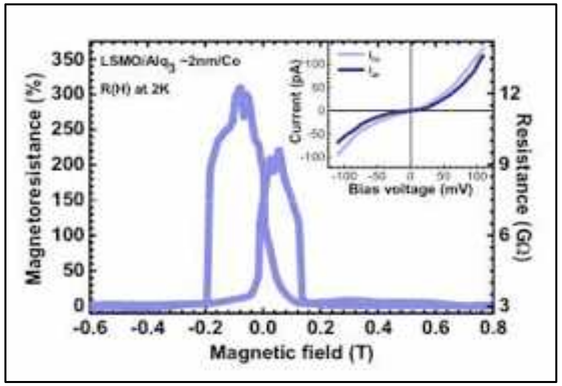
- ✓ Spin relaxation times larger than microseconds ($\tau_{SF} > \mu$ s)
- ✓ Spin relaxation lengths larger than 100 nm (l_{SF} >100nm)
- ✓ Interface energy balance is fundamental for spin injection in organics
- ✓ Vertical organic spintronic devices are most popular in the literature



L.E. Hueso *et al.*, Adv. Mater. 19, 2639 (2007)

CARBON-BASED SPINTRONICS: STATE OF THE ART

- ✓ Spin relaxation times larger than microseconds ($\tau_{SF} > \mu s$)
- ✓ Spin relaxation lengths larger than 100 nm ($l_{SF} >100nm$)
- ✓ Interface energy balance is fundamental for spin injection in organics
- ✓ Vertical organic spintronic devices are most popular in the literature
- ✓ Spin tunneling enhancement by surface-orbital hybridization



C. Barraud, P. Seneor, A. Fert,…, L.E. Hueso *et al.*, Nature Physics 6, 615 (2010)

CARBON-BASED SPINTRONICS: GENERAL OBJECTIVE

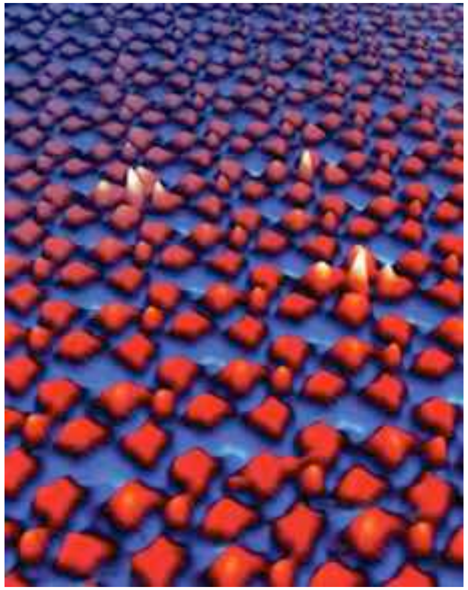
✓ Obtain a deterministic control of the spin current across an organic material

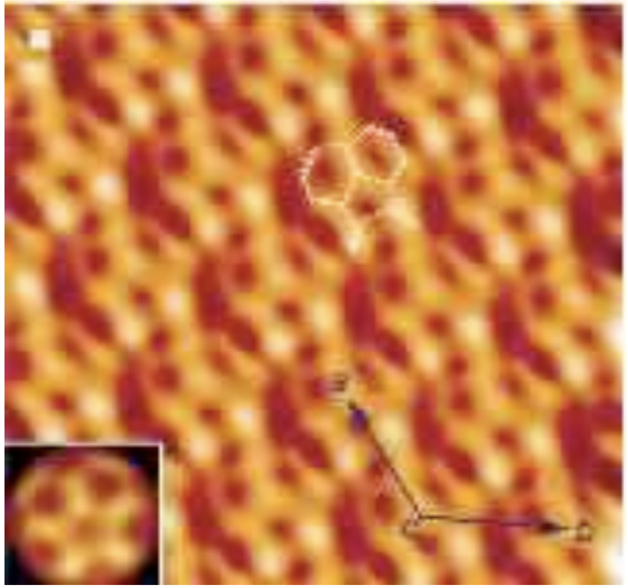
✓ Organic preferential spin tunnelling devices

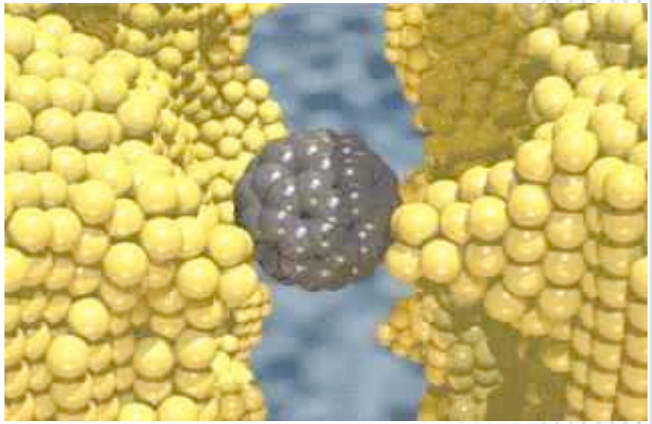
✓ Disentangle the role of interfacial states and organic-metal bonding in spin transfer

✓ Spin – Photon - Charge Devices

✓ Roadmap to single molecular spintronics







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P. Gambardella, CIN2 (Spain)

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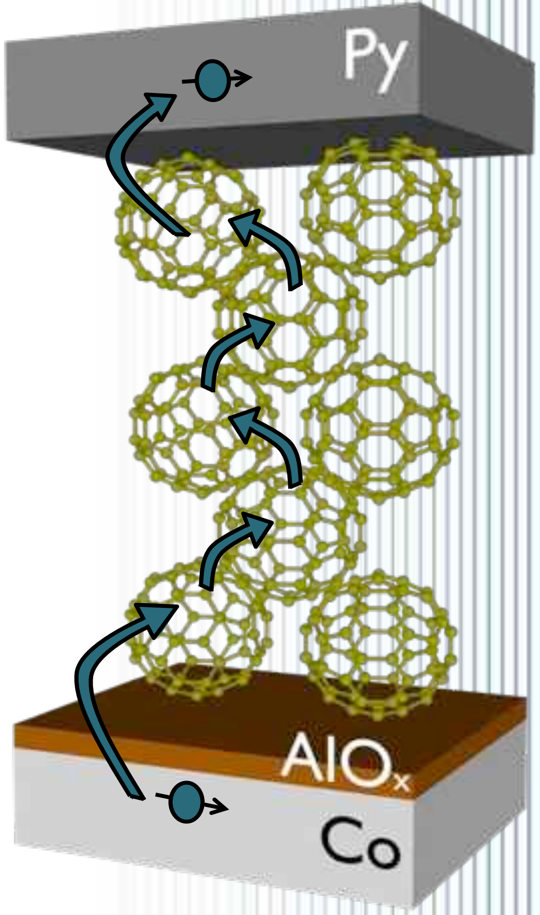
C_{60}-BASED SPIN DEVICES. OUR INITIAL (SPECIFIC) APPROACH

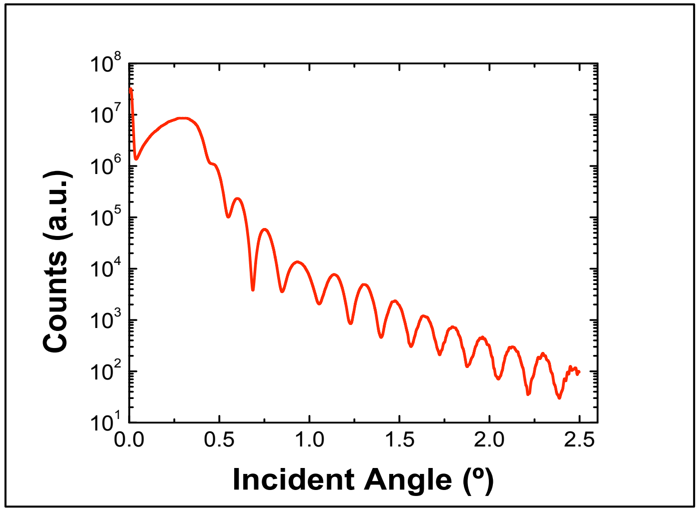
- Study of vertical hybrid spin valves
- Ferromagnetic Metallic electrodes: Cobalt and Permalloy
  - ✓ Growth in UHV conditions
  - ✓ Standard electrodes in fully inorganic devices
- Organic material: C_{60} fullerene
  - ✓ Growth by sublimation in UHV conditions
  - ✓ Robust molecule
  - ✓ Carbon-only (reduced hyperfine interaction)
  - ✓ Possible future comparison with C_{60}-based Spin-OFET



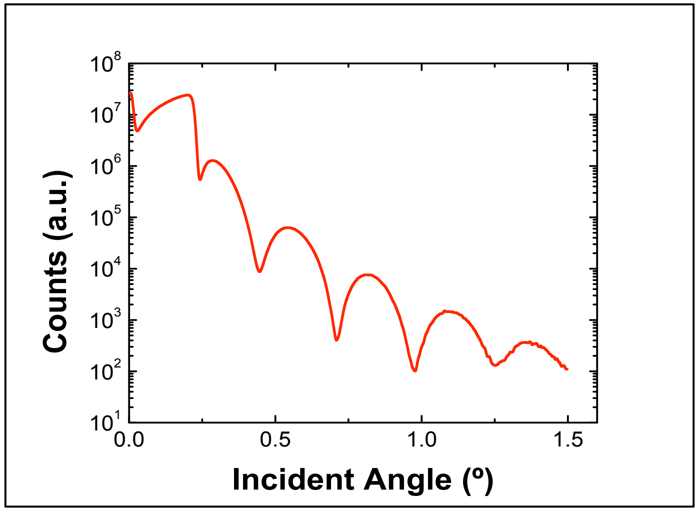
C_{60}-BASED SPIN DEVICES. STRUCTURAL CHARACTERIZATION

X-Ray characterization

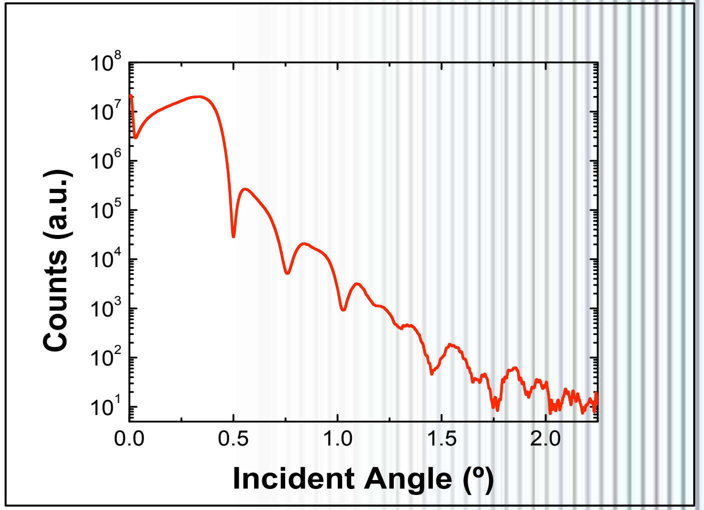
- Metal and Organic films show excellent long-range structural quality
- Very low roughness values (below 1 nm)



Co (23nm)



C_{60} (20nm)

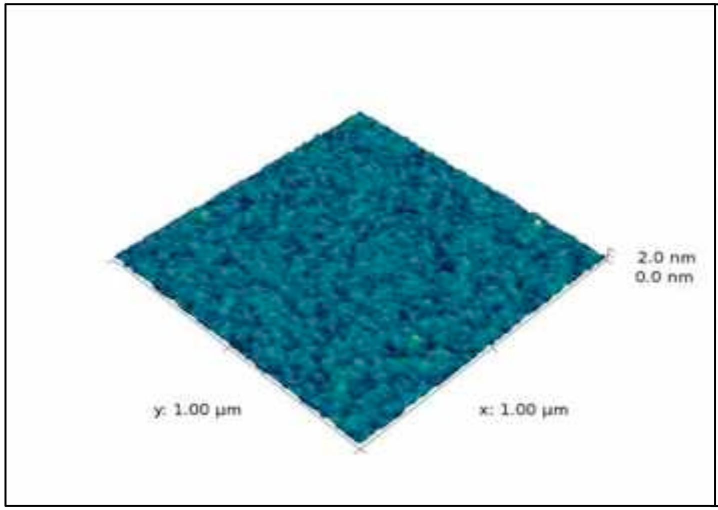


C_{60}/Py (15nm)

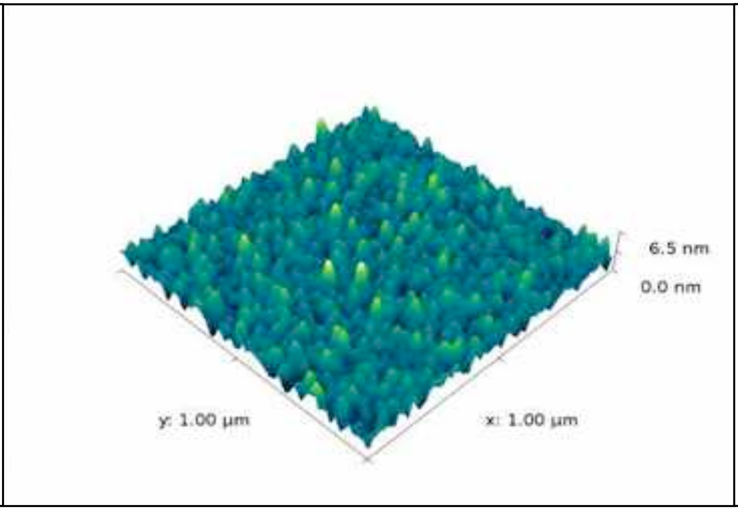
C_{60}-BASED SPIN DEVICES. STRUCTURAL CHARACTERIZATION

AFM Characterization

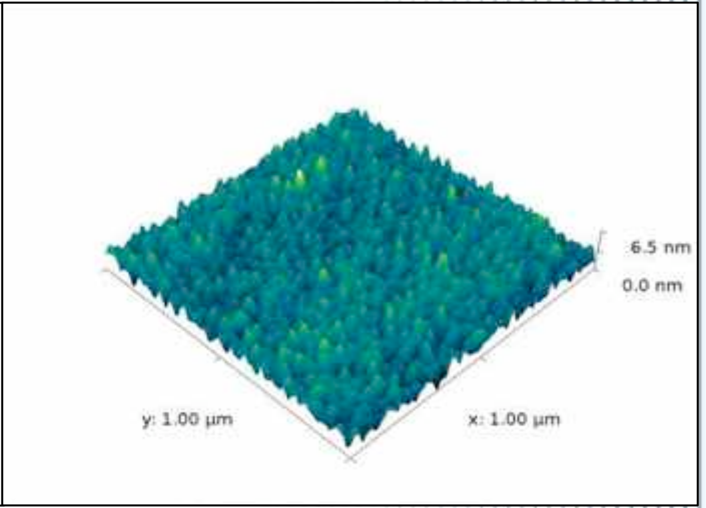
- Small rms and peak-to-peak roughness
- Permalloy top metallic layer follows organic topography



Co (23nm)
Rms = 0.17 nm



Co/C_{60} (15nm)
Rms = 0.77 nm

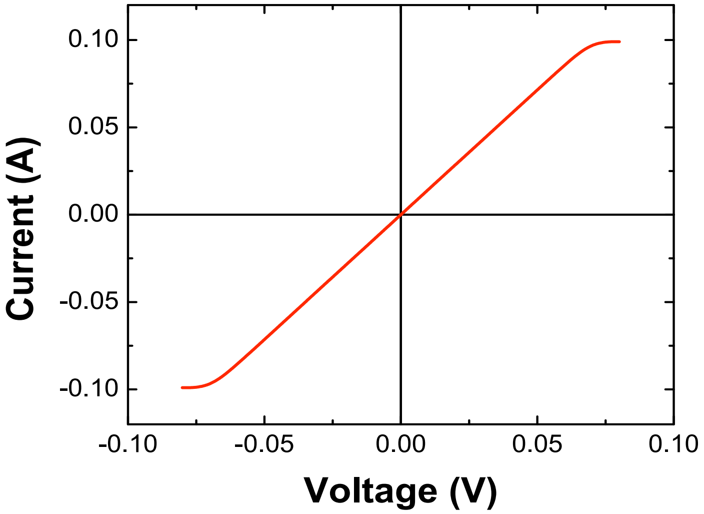


Co/C_{60}/Py (15nm)
Rms = 0.76 nm

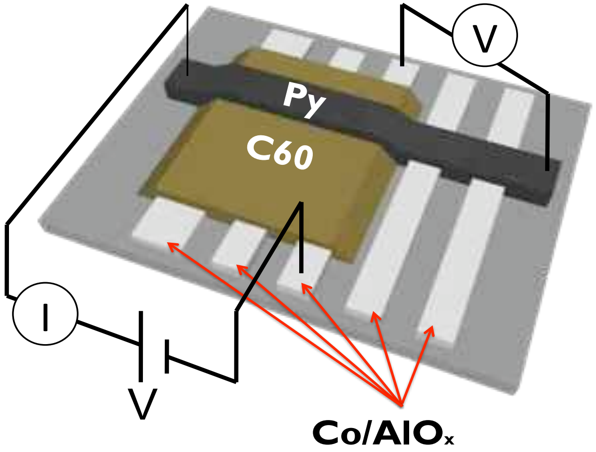
C_{60}-BASED SPIN DEVICES. ELECTRICAL CHARACTERIZATION

Current-Voltage Characteristics (Room Temperature measurements)

- From Al_2O_3 leaky junctions to highly resistive C_{60} evaporated junctions
- From ohmic to tunnelling transport changing organic thickness



Py
Al_2O_3 (0.9nm)
Co



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Current-Voltage Characteristics (Room Temperature measurements)

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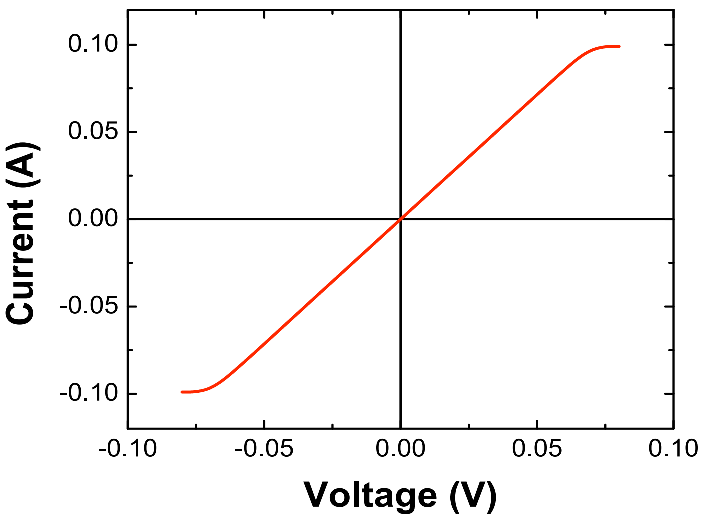
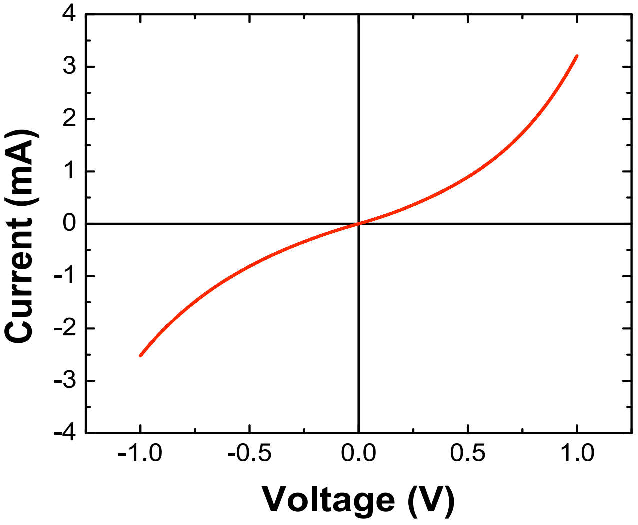
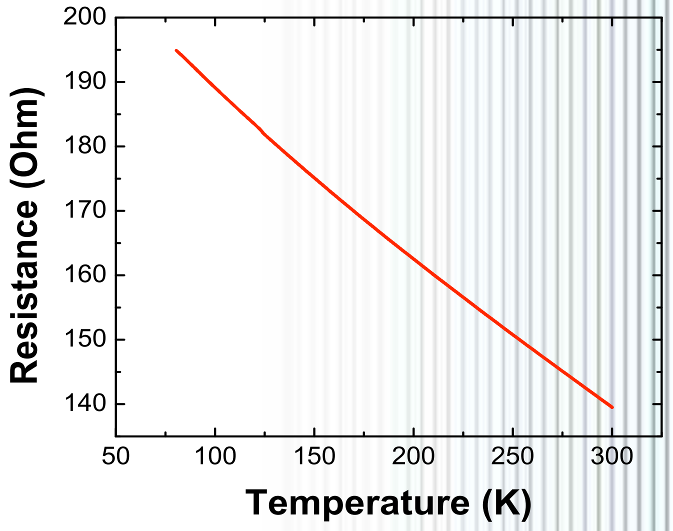






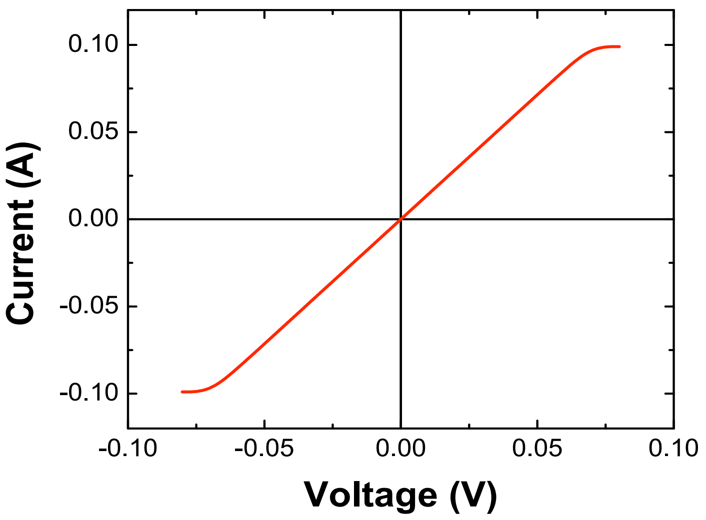
Py
Al_2O_3 (0.9nm)
Co

Py
C_{60} (8nm)
Al_2O_3 (0.9nm)
Co

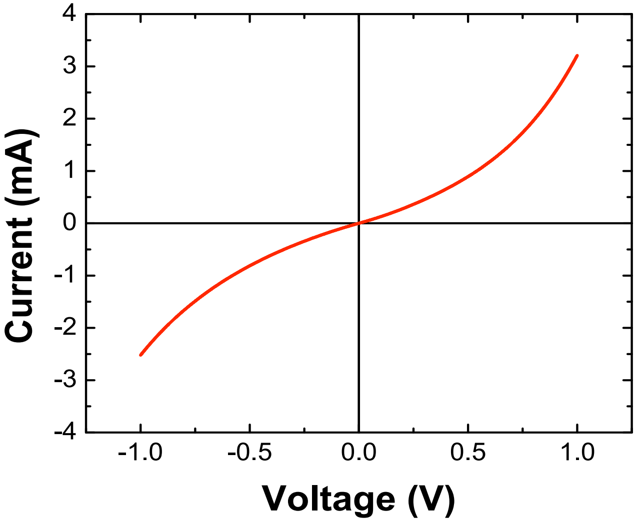
C_{60}-BASED SPIN DEVICES. ELECTRICAL CHARACTERIZATION

Current-Voltage Characteristics (Room Temperature measurements)

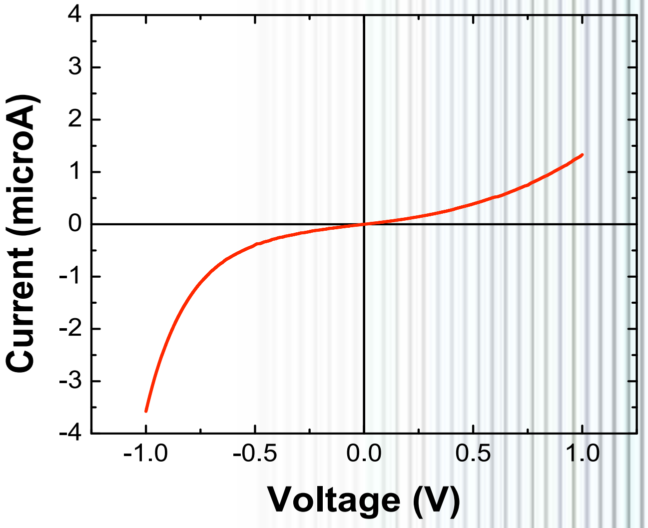
- From Al_2O_3 leaky junctions to highly resistive C_{60} evaporated junctions
- From ohmic to tunnelling transport changing organic thickness



Py
Al_2O_3 (0.9nm)
Co



Py
C_{60} (8nm)
Al_2O_3 (0.9nm)
Co

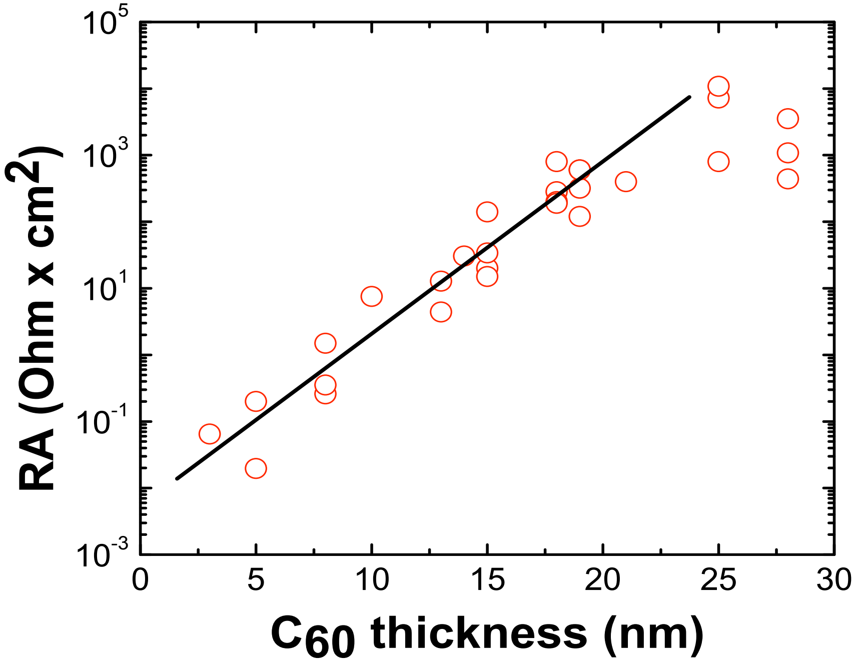


Py
C_{60} (25nm)
Al_2O_3 (0.9nm)
Co

C_{60}-BASED SPIN DEVICES. ELECTRICAL CHARACTERIZATION

Current-Voltage Characteristics (Room Temperature measurements)

- From Al_2O_3 leaky junctions to highly resistive C_{60} evaporated junctions
- From ohmic to <u>tunnelling</u> transport changing organic thickness



Tunnel probability:

$$D \propto e^{-\frac{\sqrt{m\phi}}{h}d}$$

C_{60}-BASED SPIN DEVICES. ELECTRICAL CHARACTERIZATION

Current-Voltage Characteristics (Room Temperature measurements)

- From Al_2O_3 leaky junctions to highly resistive C_{60} evaporated junctions
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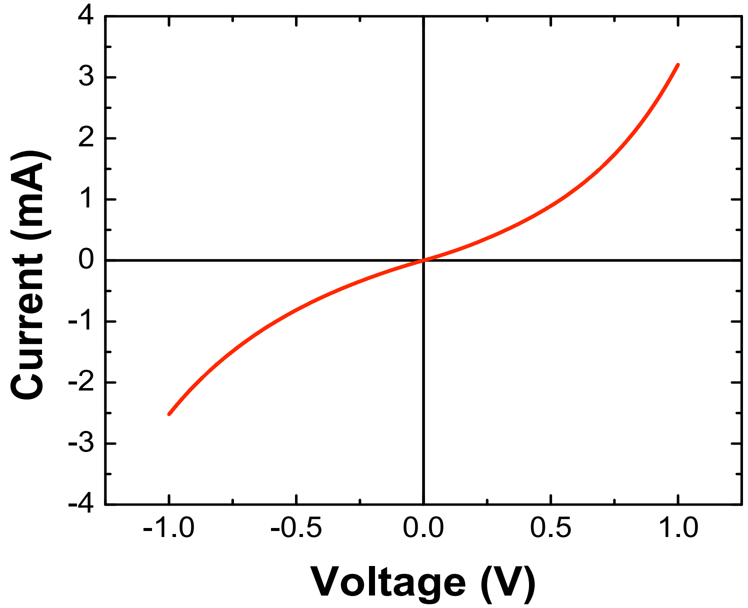

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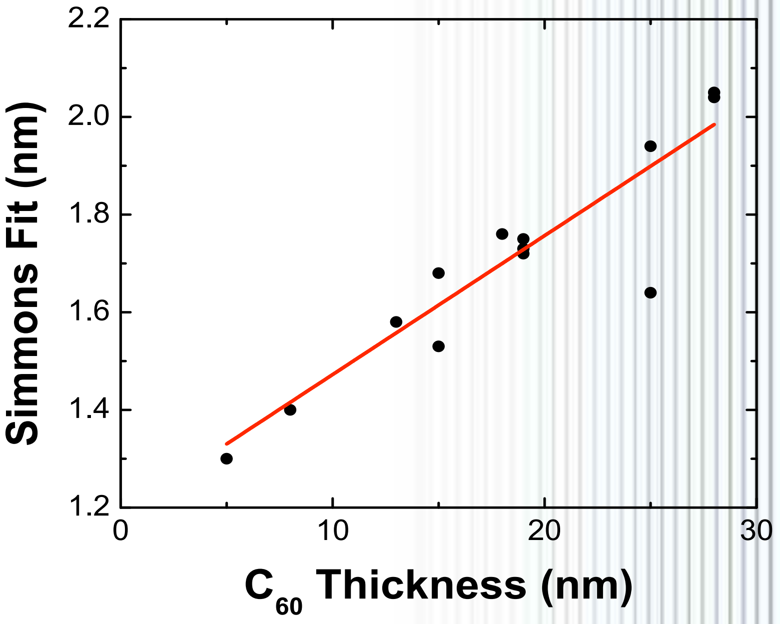

C_{60}-BASED SPIN DEVICES. ELECTRICAL CHARACTERIZATION

Current-Voltage Characteristics (Room Temperature measurements)

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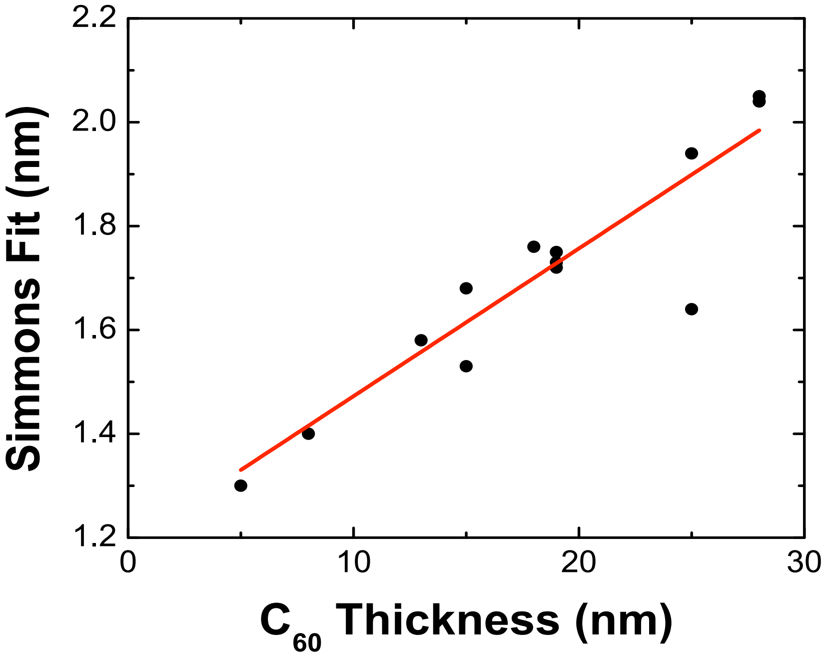


$$D \propto e^{-\frac{\sqrt{m\phi}}{h} d}$$

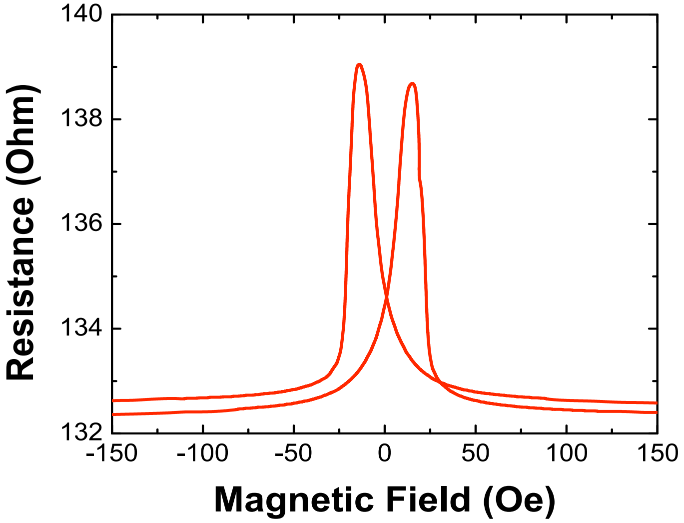
$$D \propto t_i \times \prod_n t_n$$

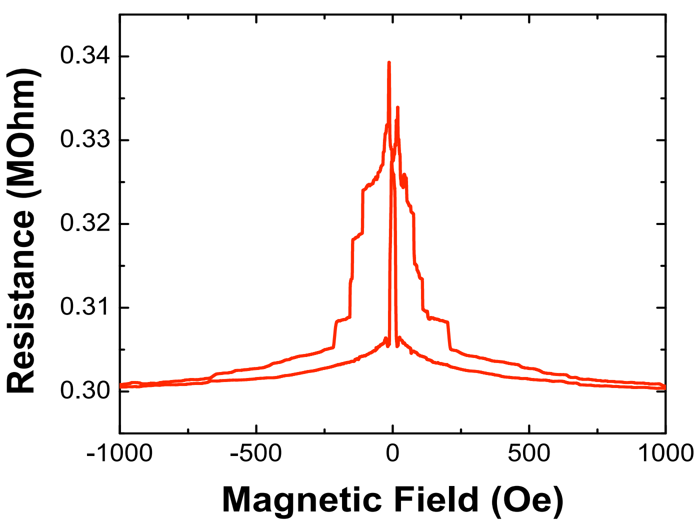
$$D \propto e^{-a_i} \times \prod_n e^{-a_n} = e^{-(a_i + n a_n)}$$

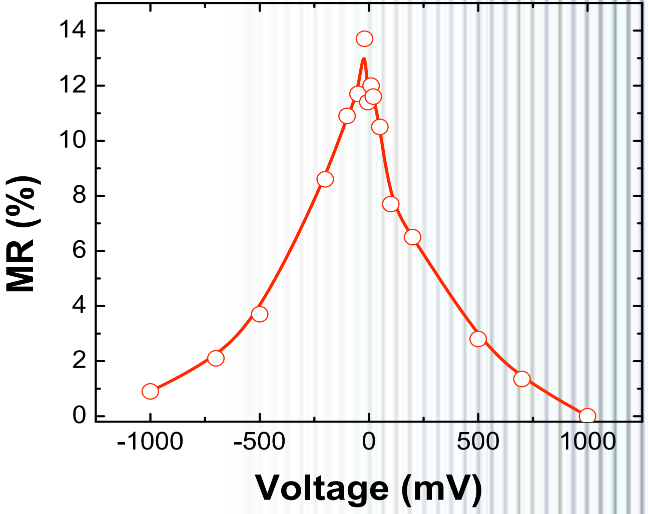
C_{60}-BASED SPIN DEVICES. MAGNETORESISTANCE

Magnetoresistance measurements. Spin transport at different C_{60} thicknesses

- Examples showing magnetoresistance data at room temperature







Py
C_{60} (5nm)
Al_2O_3 (0.9nm)
Co

Py
C_{60} (28nm)
Al_2O_3 (0.9nm)
Co

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CONCLUSIONS AND OPEN QUESTIONS

- ✓ Carbon-based materials offer new opportunities for spintronics
- ✓ Experimental demonstration of spin transport in C_{60} molecules
- ✓ Coherent spin transport up to room temperature
- ✓ Coherent spin transport up to (at least) 30 nm
- ✓ Many basic issues still open (decoherence mechanisms, spin manipulation,…)
- ✓ Challenging, exciting and interdisciplinary topic

COLLABORATORS

- V. A. Dediu, I. Bergenti, A. Riminucci
- A. Fert, P. Seneor, R. Mattana
- M. Gobbi, F. Golmar, R. Llopis, F. Casanova

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FUNDING

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

Transporte de Espín a Larga Distancia en Semiconductores Orgánicos

European Research Council
erc

SpinTrOS: Spin Transport in Organic Semiconductors

PEOPLE

Q-NET: Quantum Nanoelectronics Training Network

ITANOSCIMON: Injection, transport and manipulation of spin currents

COOPERATION

HINTS: Next Generation Hybrid Interfaces for Spintronic Applications