EuS/Al bilayers for future superconducting spintronics

Elia Strambini
NEST, Istituto Nanoscienze-CNR & Scuola Normale Superiore, Pisa, Italy

SPICE workshop
Exotic New States in Superconducting Devices:
The Age of the Interface
Mainz, Germany
27 Sept 2017

Marie Skłodowska-Curie Actions

Collaboration

- Giorgio De Simoni, F. Giazotto

NEST Istituto Nanoscienze-CNR and Scuola Normale Superiore, I-56127 Pisa, Italy

- F. S. Bergeret, Vitaly N. Golovach

CFM-MPC, CSIC-UPV/EHU, San Sebastian, Spain

- Jagadeesh Moodera

MIT, Cambridge, Massachusetts 02139, USA.

Marie Skłodowska-Curie Actions

Outline

- Motivations
  - Why we study EuS/Al bilayers
- Experimental results
  - Single EuS/Al bilayer
    - Tunneling spectroscopy of EuS/Al
    - Interplay between the EuS domains and Al superconductivity
  - Double EuS/Al bilayer
    - The absolute Spin valve
    - Towards the superconducting magnetic RAM
- Conclusions and perspectives

Motivations

- Magnetism & Superconductivity
  (The age of the interface) --> EuS/Al

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  (The age of the interface) --> EuS/Al

EuS:

- High Curie temperature
- Strong exchange field
- High quality interfaces with Al

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LETTER

doi:10.1038/nature17635

A high-temperature ferromagnetic topological insulating phase by proximity coupling

Ferhat Katmis[1,2,3]*, Valeria Lauter[4]*, Flavio S. Nogueira[5,6], Badih A. Assaf[7,8], Michelle E. Jamer[7], Peng Wei[1,2,3], Biswarup Satpati[9], John W. Freeland[10], Ilya Eremin[5], Don Heiman[7], Pablo Jarillo-Herrero[1] & Jagadeesh S. Moodera[1,2,3]

nature materials

LETTERS

PUBLISHED ONLINE: 28 MARCH 2016 | DOI: 10.1038/NMAT4603

Strong interfacial exchange field in the graphene/EuS heterostructure

Peng Wei[1,2]*, Sunwoo Lee[3,4], Florian Lemaitre[3,5†], Lucas Pinel[3,5†], Davide Cutaia[3,6], Wujoon Cha[7], Ferhat Katmis[1,2], Yu Zhu[3], Donald Heiman[8], James Hone[7], Jagadeesh S. Moodera[1,2] and Ching-Tzu Chen[3]*

Motivations

- Magnetism & Superconductivity
  (The age of the interface) --> EuS/Al

  EuS:
  - High Curie temperature
  - Strong exchange field
  - High quality interfaces with Al

- Applications
  - Hybrid systems (integration of magnetic fields to engineer exotic state)
  - Spin-resolved tunneling spectroscopy
  - Huge thermoelectric effect and heat valves
  - Superconducting logical switching elements
  - Spin polarized-current, spintronics

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Motivations

- Magnetism & Superconductivity

PRL 112, 057001 (2014) PHYSICAL REVIEW LETTERS week ending 7 FEBRUARY 2014

Predicted Very Large Thermoelectric Effect in Ferromagnet-Superconductor Junctions in the Presence of a Spin-Splitting Magnetic Field

A. Ozaeta,[1] P. Virtanen,[2] F. S. Bergeret,[1,3,4] and T. T. Heikkilä[2,5]

- Strong exchange field
- |

PRL 116, 097001 (2016) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2016

Observation of Thermoelectric Currents in High-Field Superconductor-Ferromagnet Tunnel Junctions

S. Kolenda, M. J. Wolf,* and D. Beckmann†

- Appl

- Hybrid systems (integration of magnetic fields to engineer exotic state)
- Spin-resolved tunneling spectroscopy
- Huge thermoelectric effect and heat valves
- Superconducting logical switching elements
- Spin polarized-current, spintronics

Motivations

- Magnetism & Superconductivity

APPLIED PHYSICS LETTERS **102**, 132603 (2013)

CrossMark

Phase-tunable colossal magnetothermal resistance in ferromagnetic Josephson valves

F. Giazotto[1,a)] and F. S. Bergeret[2,3,4,b)]

  - Strong exchange field
  - High quality interfaces with Al

nature physics | REVIEW ARTICLES

PUBLISHED ONLINE: 2 APRIL 2015 | DOI: 10.1038/NPHYS3242

Superconducting spintronics

Jacob Linder[1*] and Jason W. A. Robinson[2*]

- Applications
  - Hybrid systems (integration of magnetic fields to engineer exotic state)
  - Spin-resolved tunneling spectroscopy
  - Huge thermoelectric effect and heat valves
  - Superconducting logical switching elements
  - Spin polarized-current, spintronics

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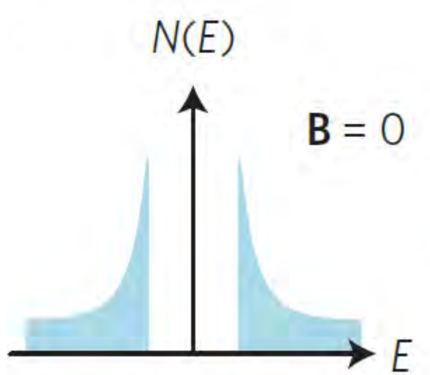
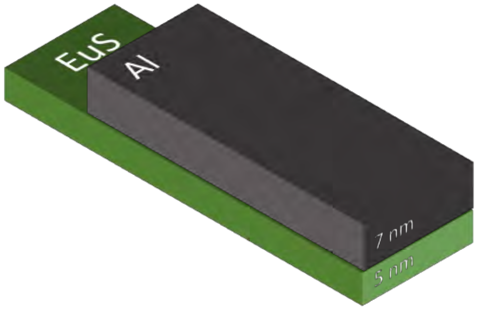
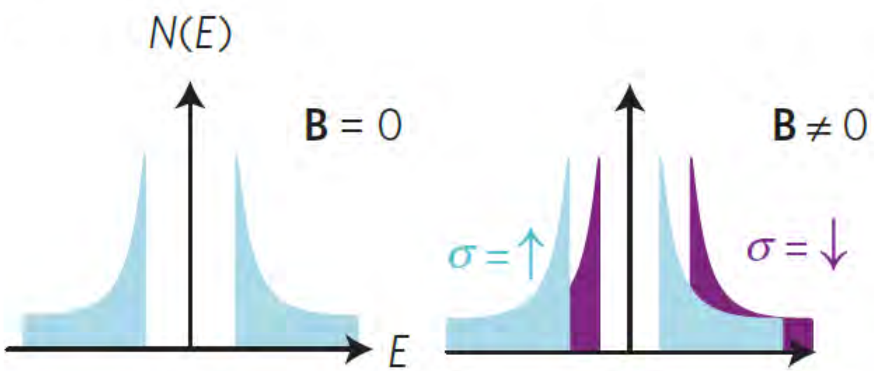
Measuring the induced magnetism



J. Linder and J. W. A. Robinson, "Superconducting spintronics," *Nat Phys*, **11**, 307–315, (2015)

Measuring the induced magnetism





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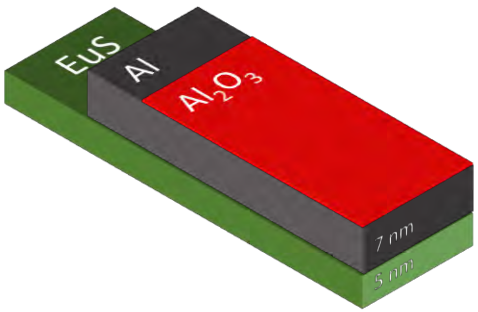
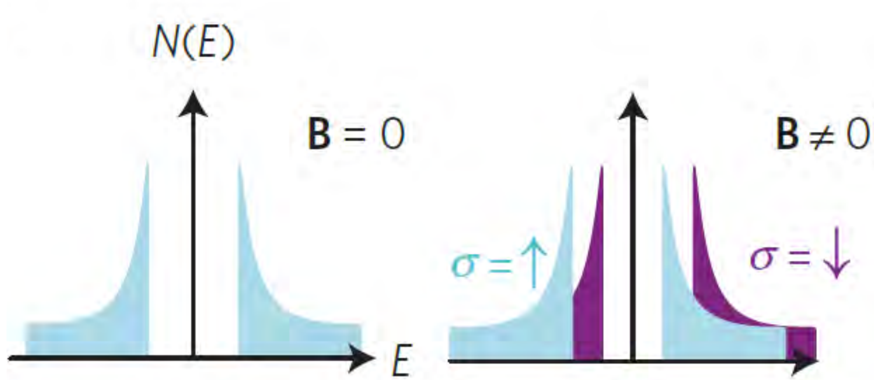
Measuring the induced magnetism





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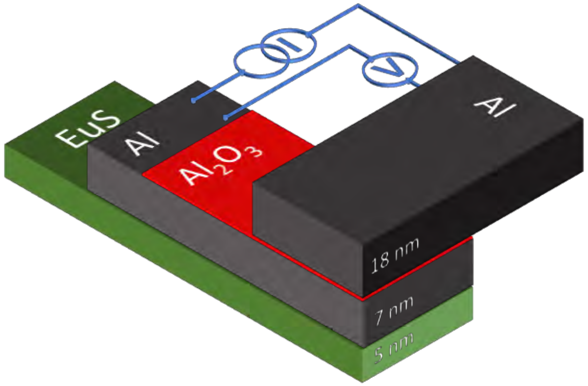
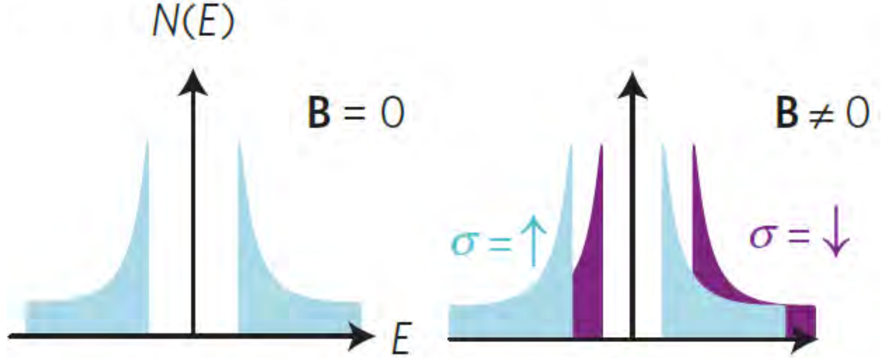
Tunneling Spectroscopy





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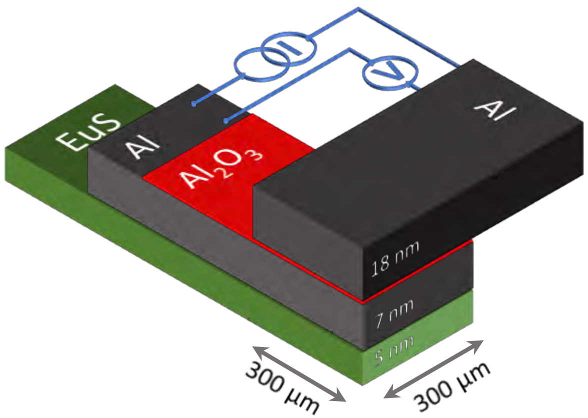
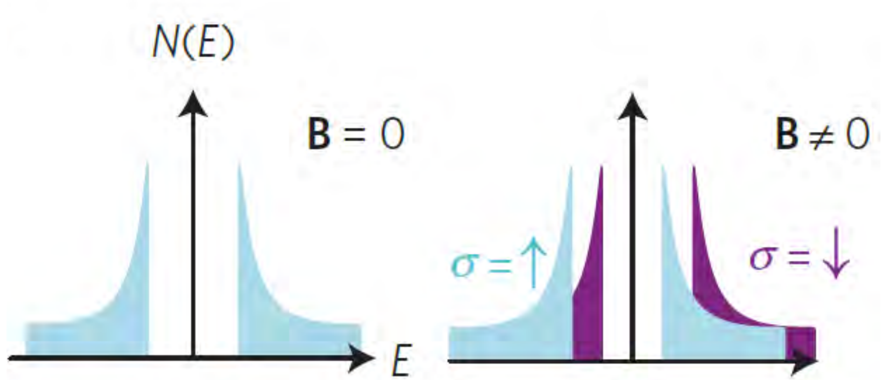


$$\frac{dI}{dV}(V) = \frac{1}{eR_T}\frac{d}{dV}\int_{-\infty}^{\infty} dE\ \ DoS_{Al}(E+eV)DoS_{EuS/Al}(E)\,(f(E)-f(E+eV))$$



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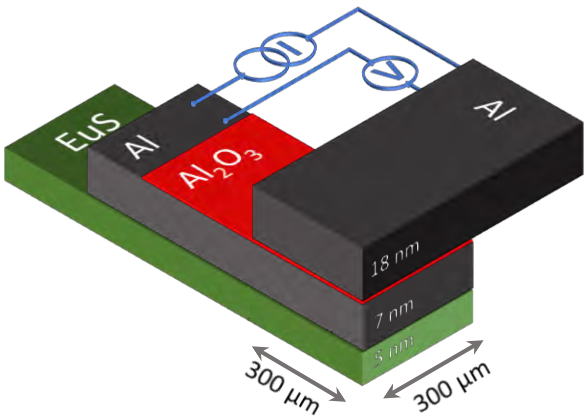
Tunneling Spectroscopy



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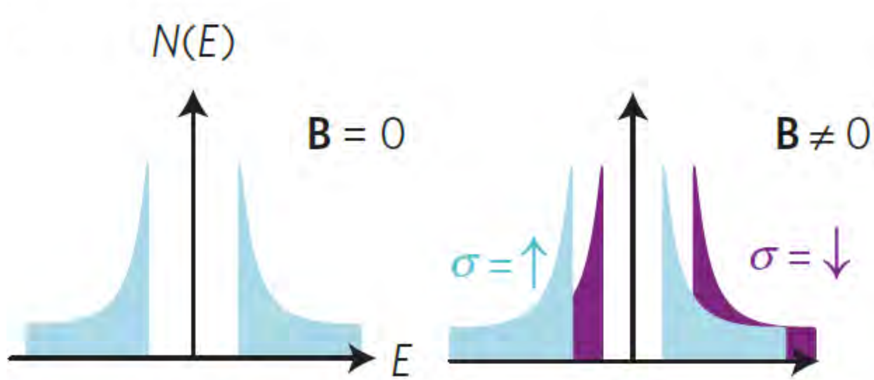

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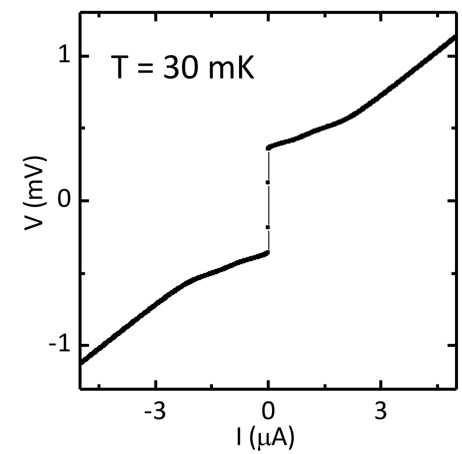
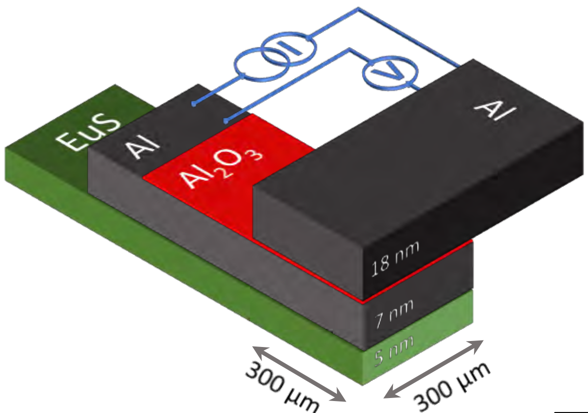


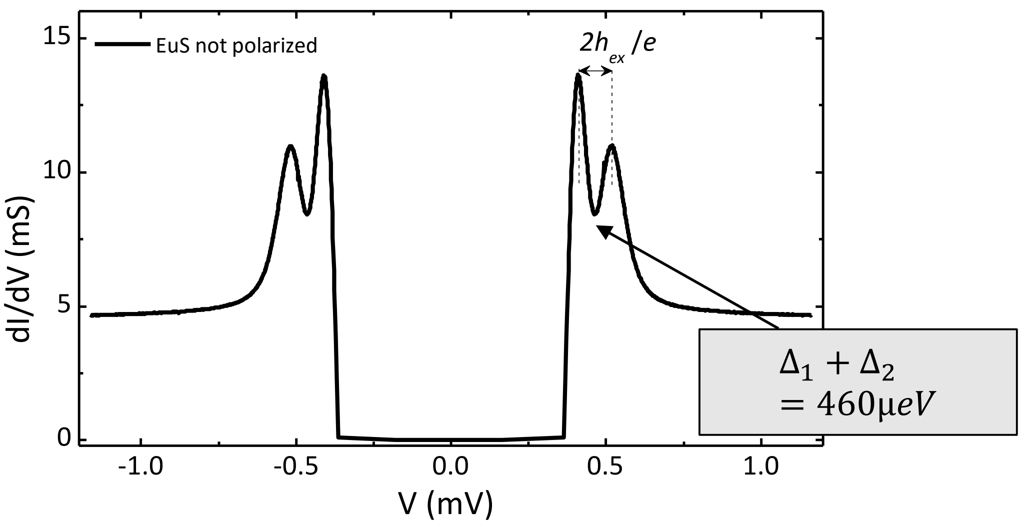
Unpolarized state

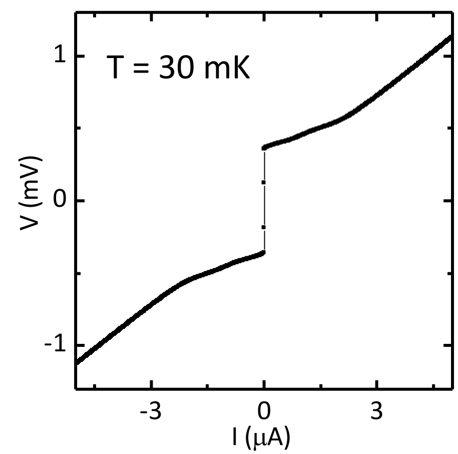


$$\frac{dI}{dV}(V) = \frac{1}{eR_T}\frac{d}{dV}\int_{-\infty}^{\infty} dE\ \ DoS_{Al}(E+eV)DoS_{EuS/Al}(E)\,(f(E)-f(E+eV))$$

$$eV_{peaks} \cong \pm(\Delta_1+\Delta_2) \pm h_{ex}$$

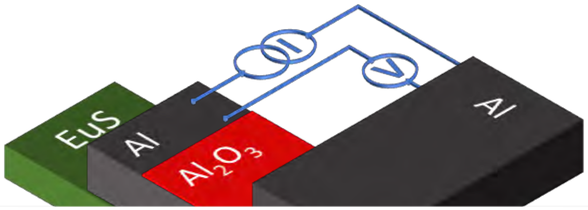
$$2\mu_B B_{ex} = 110\ \mu eV\ \ \rightarrow B_{ex} \sim 1\ T$$





E. Strambini, *et al.,* Phys. Rev. Mat. ***00****, 004400 (2017)*

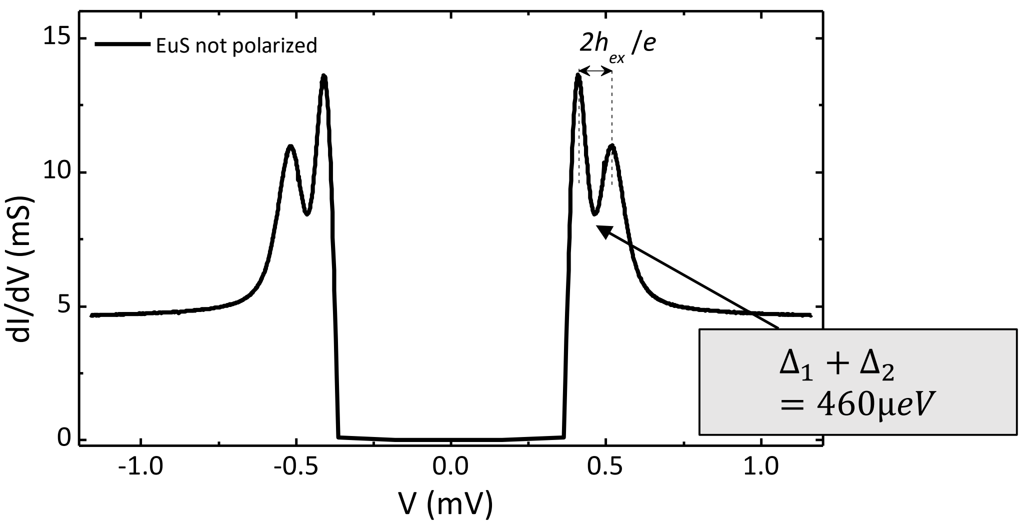
Unpolarized state

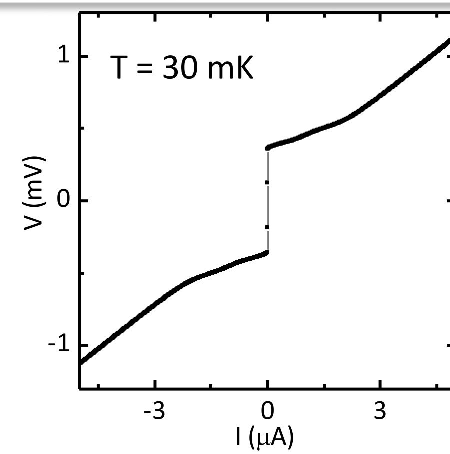


$$\frac{dI}{dV}(V) = \frac{1}{eR_T}\frac{d}{dV}\int^{\infty} dE\ \ DoS_{Al}(E+eV)DoS_{EuS/Al}(E)\ (f(E) - f(E+eV))$$

- Peaks are resolved also in the unmagnetized state
- Inner peaks are higher than outer ones

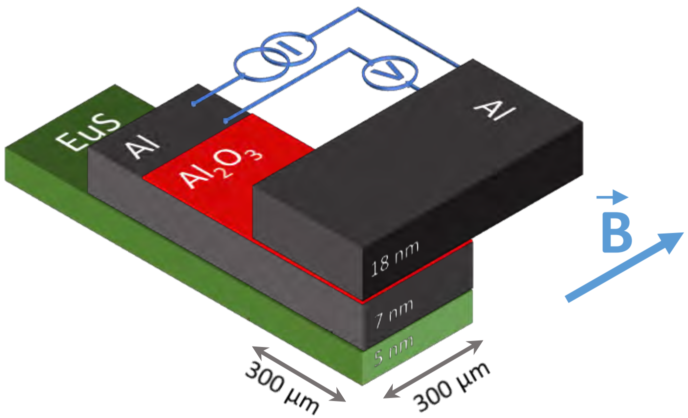
$2\mu_B B_{ex} = 110\ \mu eV\ \ \rightarrow B_{ex} \sim 1\ T$

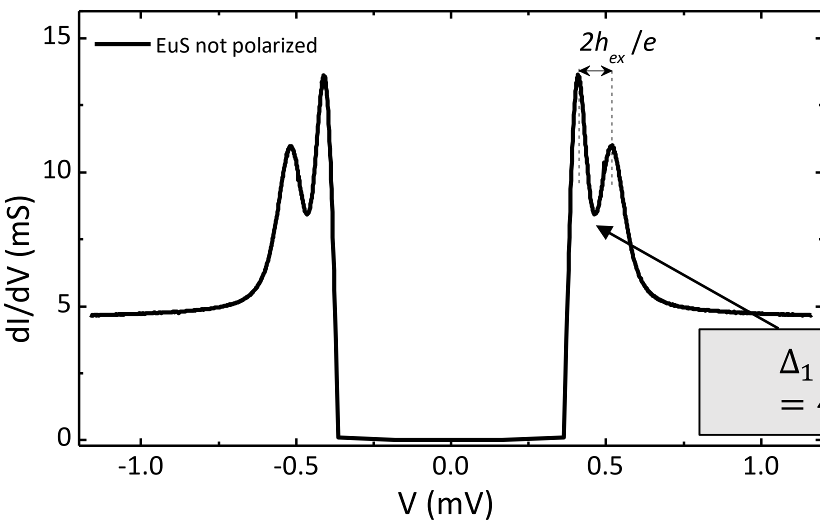




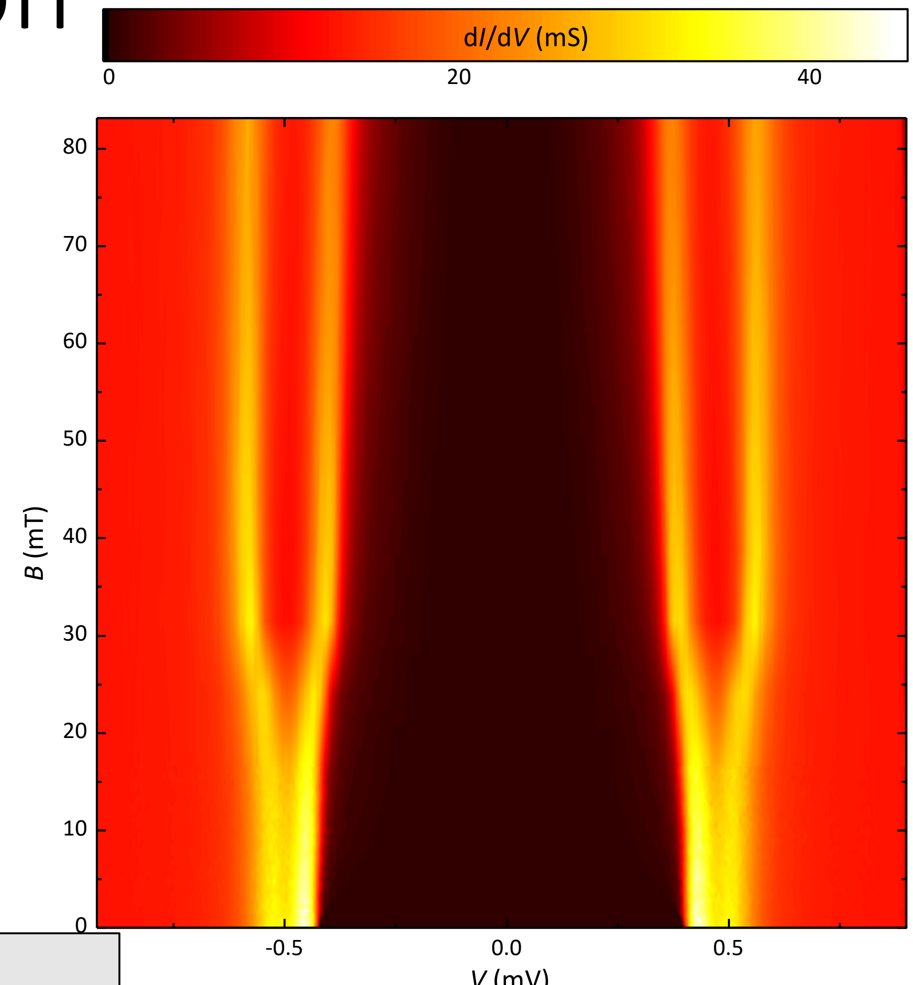
E. Strambini, *et al.*, Phys. Rev. Mat. ***00**, 004400 (2017)*

First Magnetization





$\Delta_1 + \Delta_2$
$= 460\mu eV$



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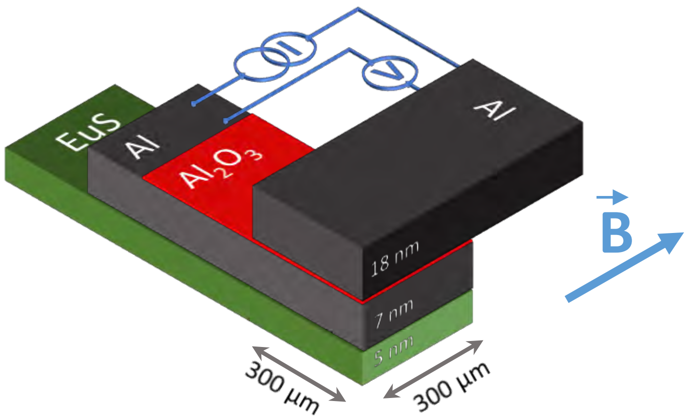
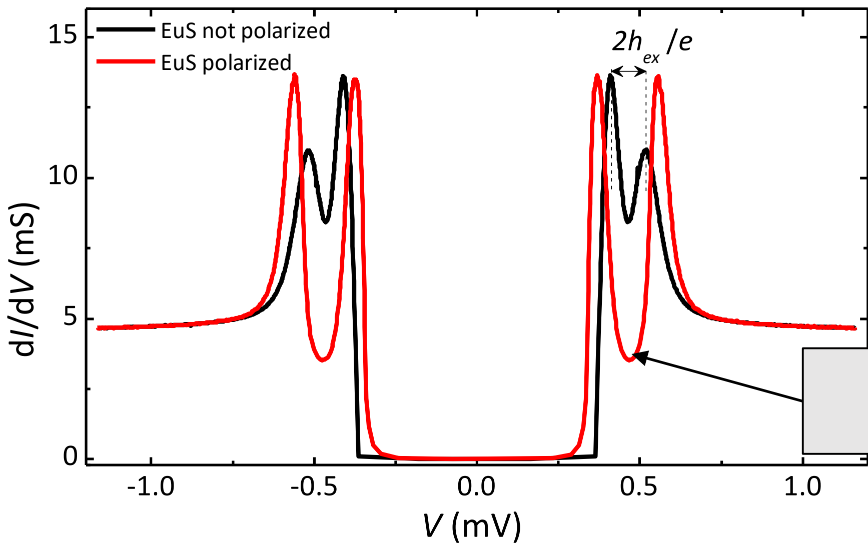


$2\mu_B B_{ex} = 190\ \mu eV \ \rightarrow B_{ex} \sim 1.6\ T$



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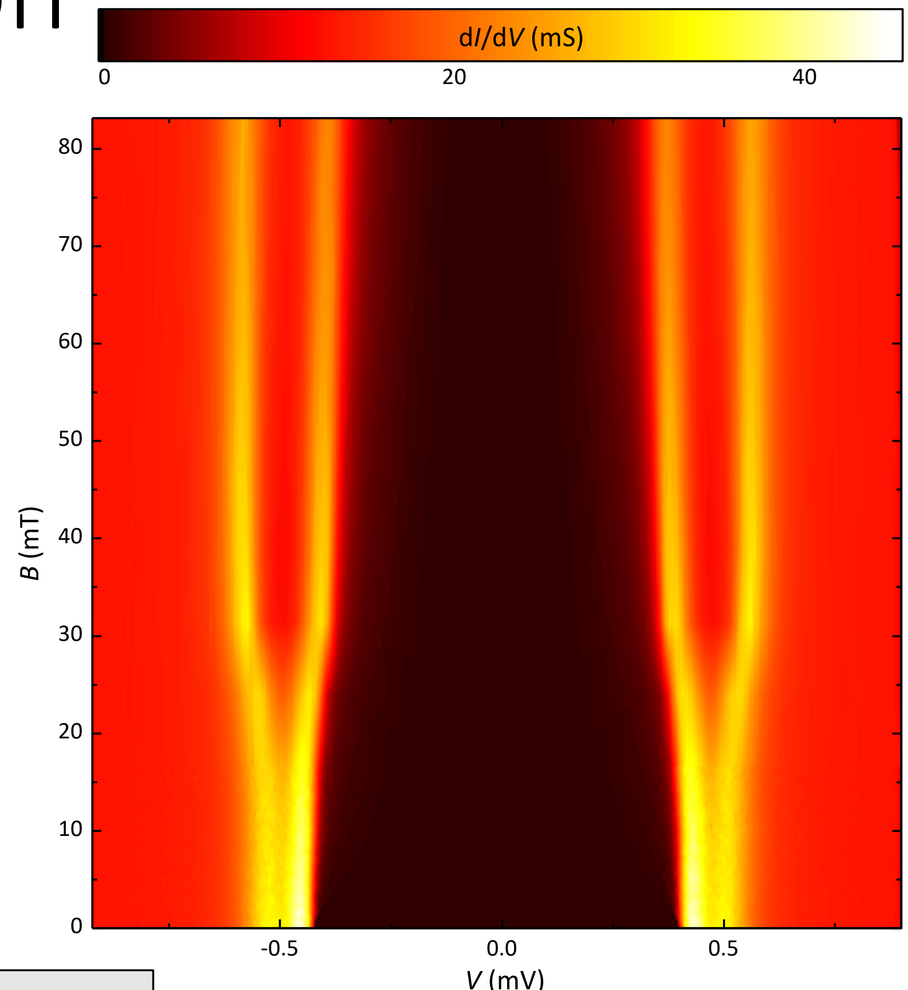

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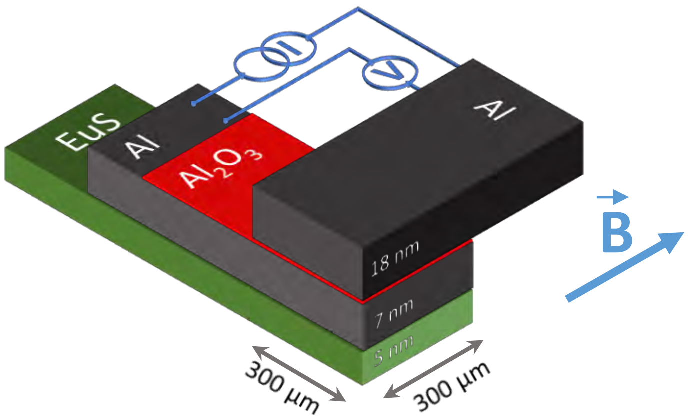

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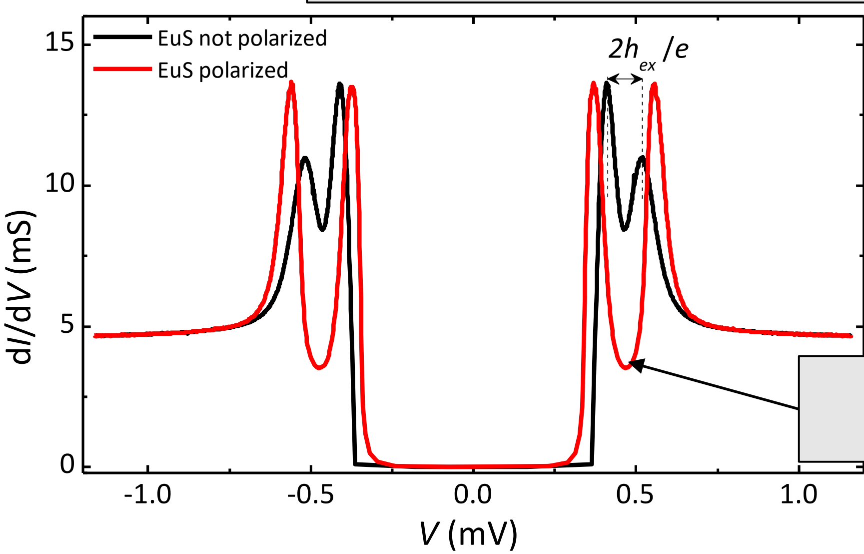

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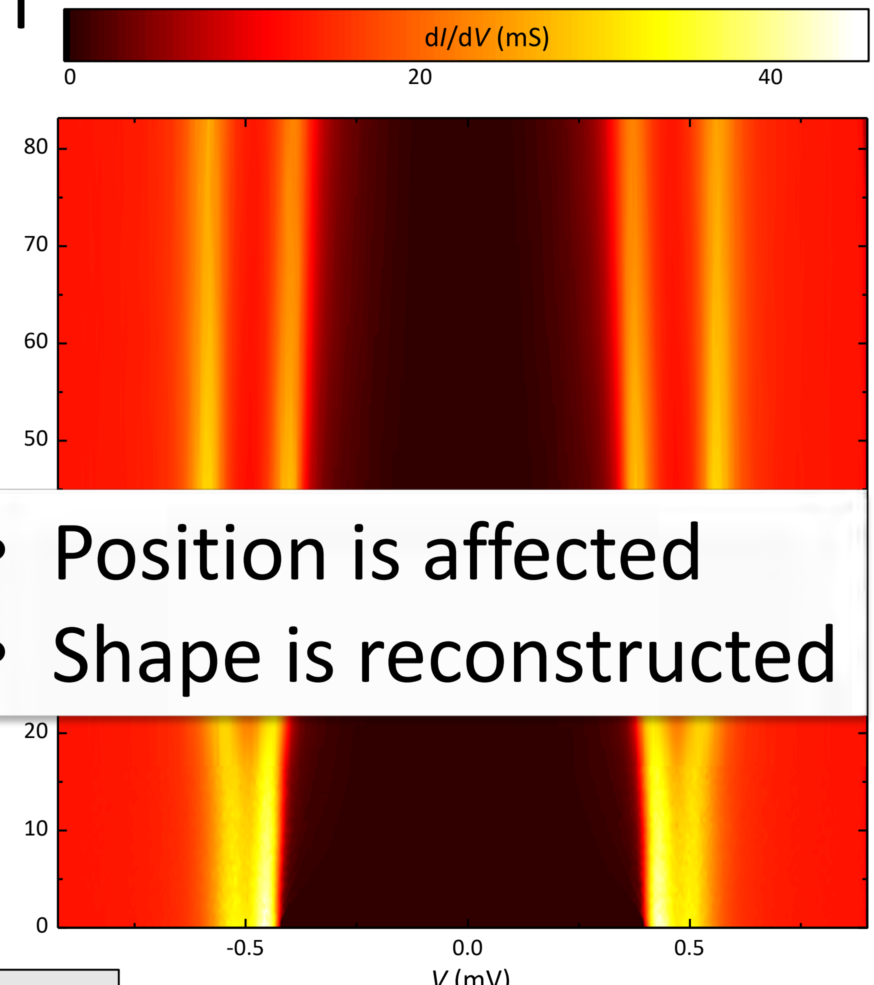
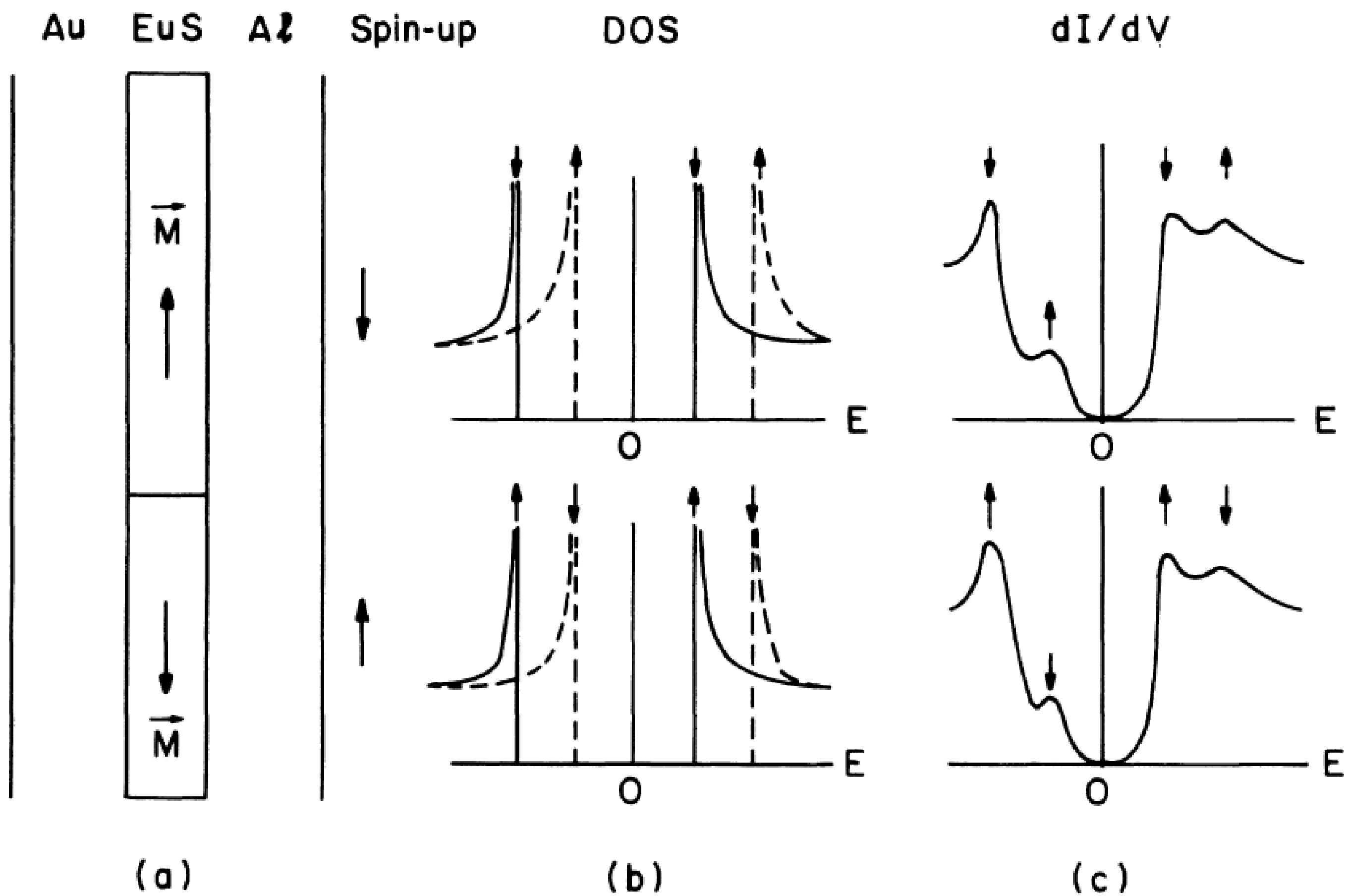


- Position is affected
- Shape is reconstructed

E. Strambini, *et al.*, Phys. Rev. Mat. ***00***, *004400 (2017)*

Theoretical Model (Role of Domains)



X. Hao, J. S. Moodera, and R. Meservey, “Spin-filter effect of ferromagnetic europium sulfide tunnel barriers,” Phys. Rev. B, **42**, 8235 (1990)

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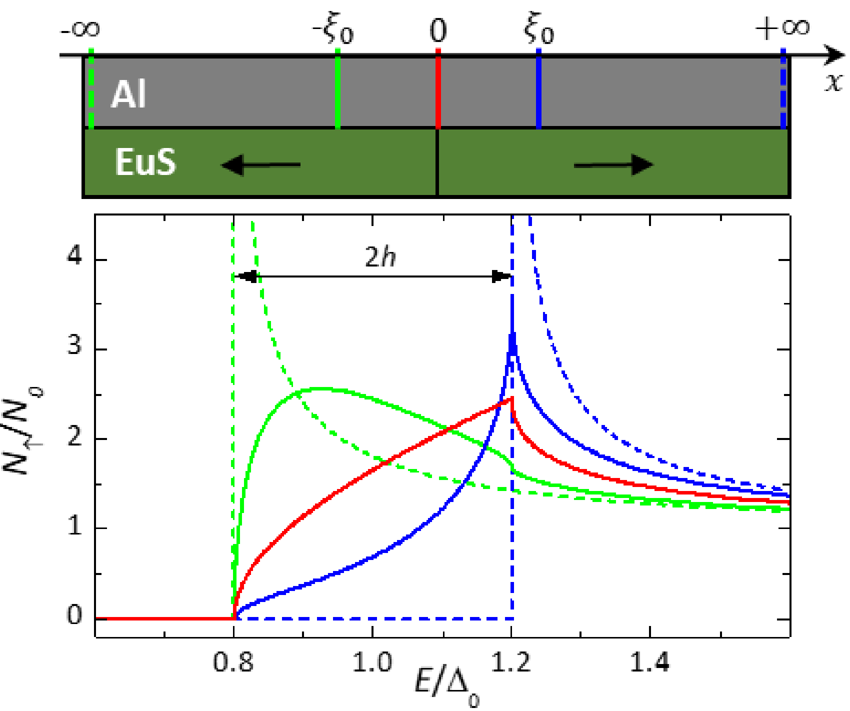

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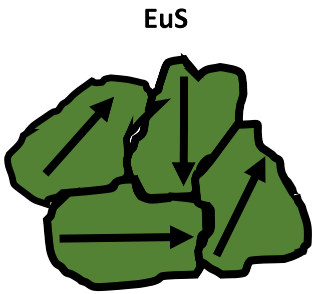
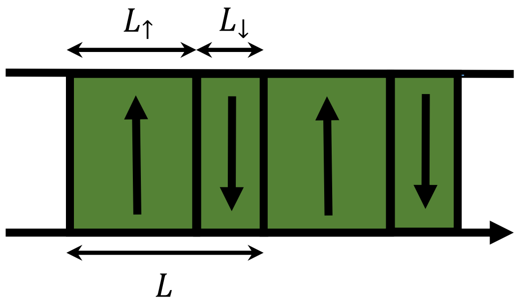
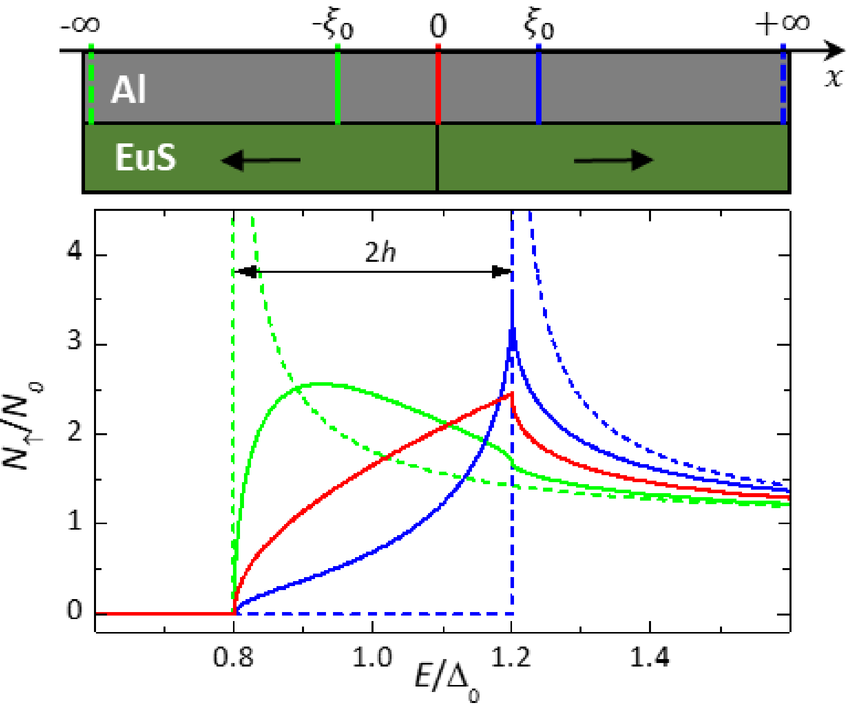


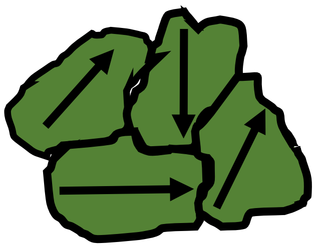


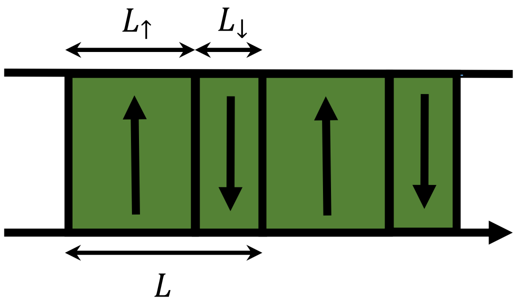
$L_\uparrow = L_\downarrow$ (Non Polarized)

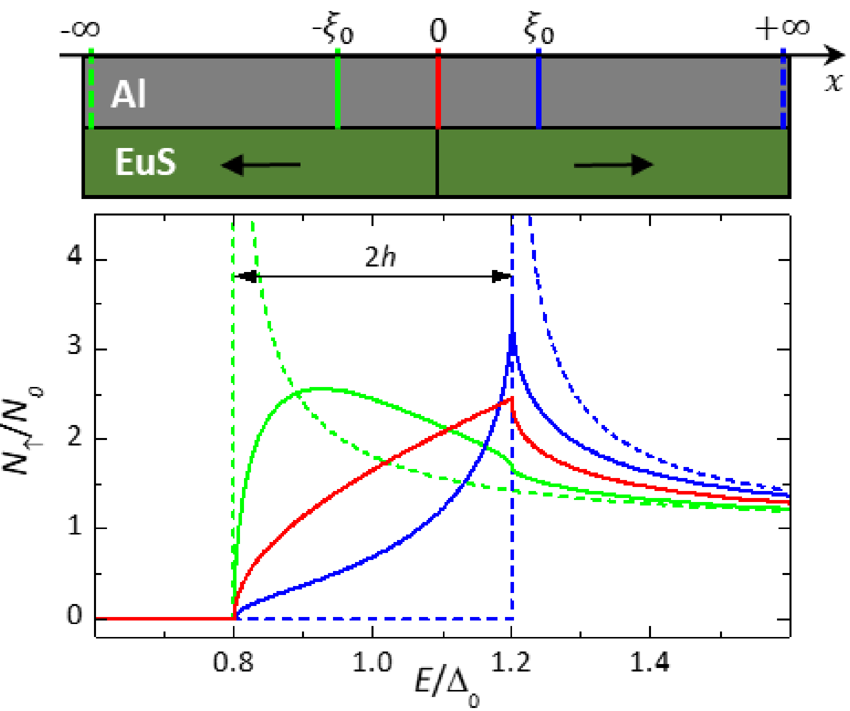


Theoretical Model (Role of Domains)

EuS







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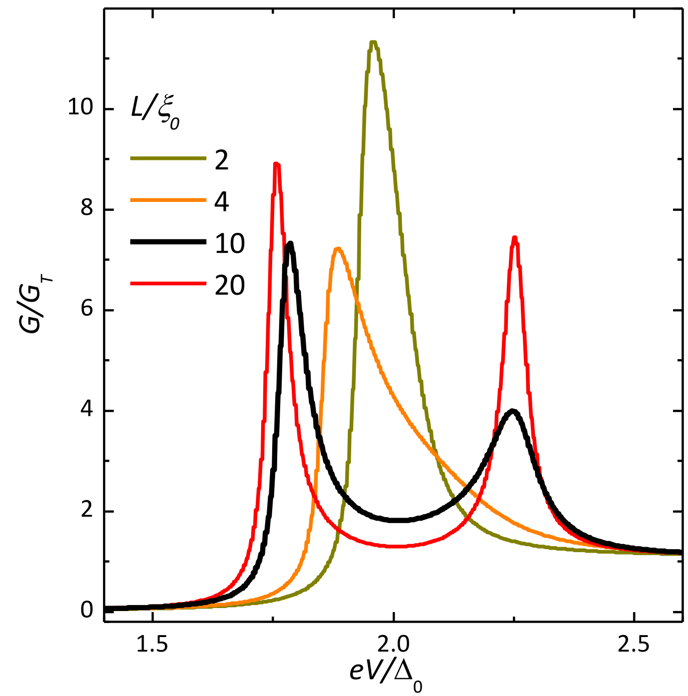

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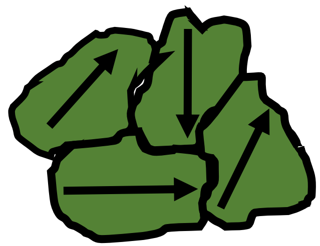
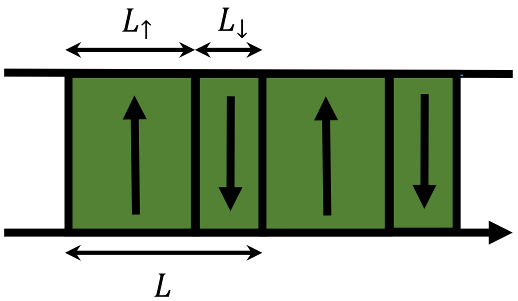
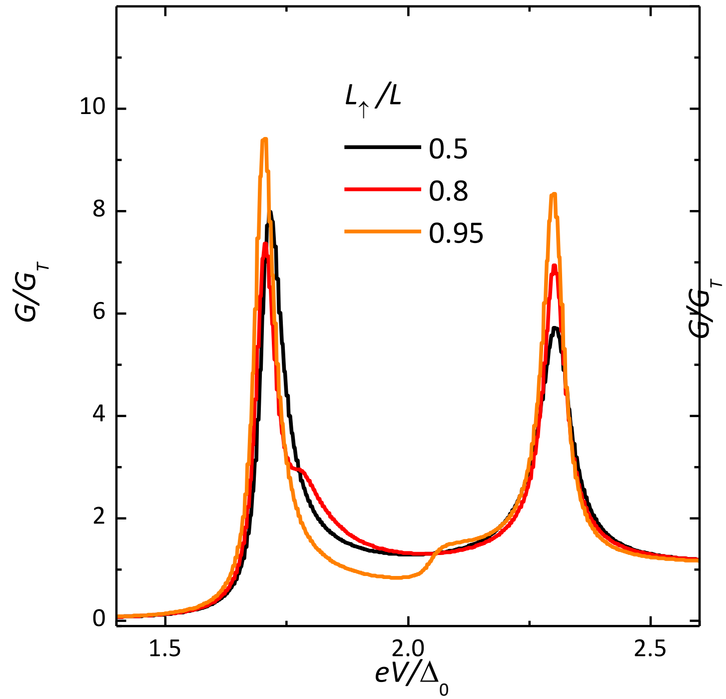




$L_\uparrow \neq L_\downarrow$ (Polarized)



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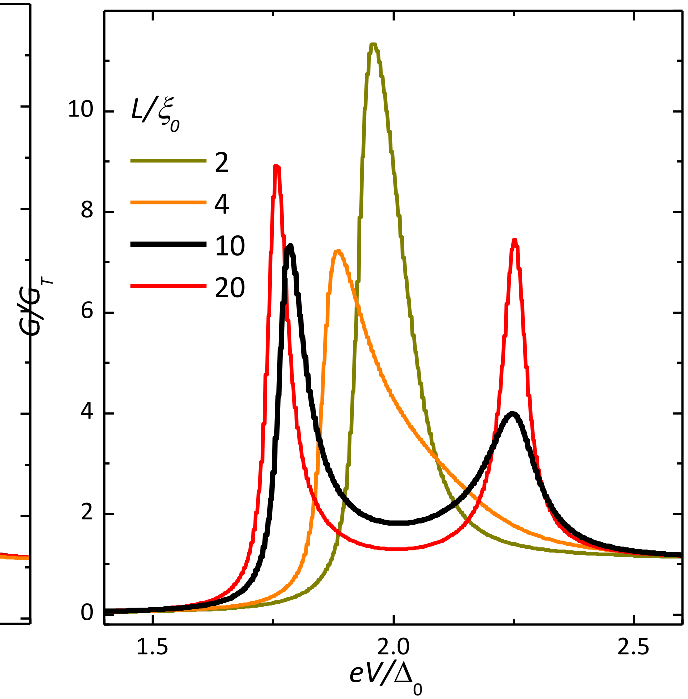

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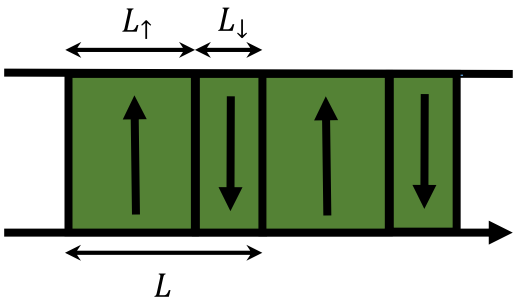
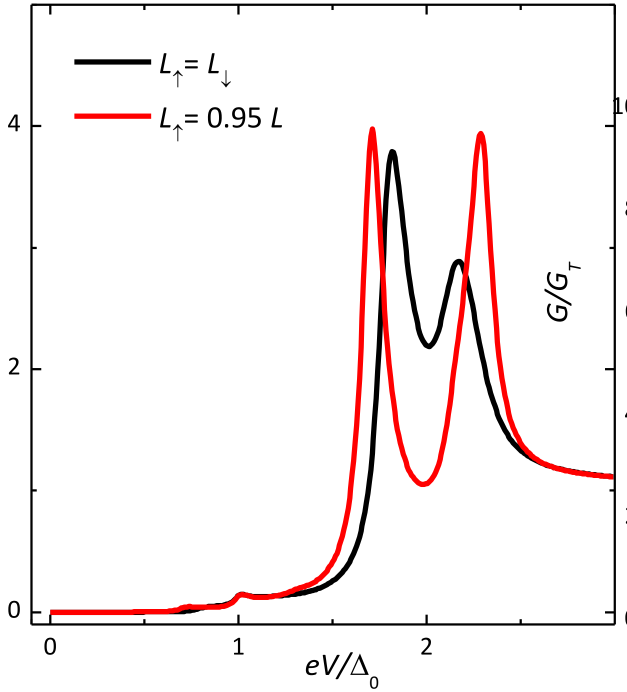


Different distributions



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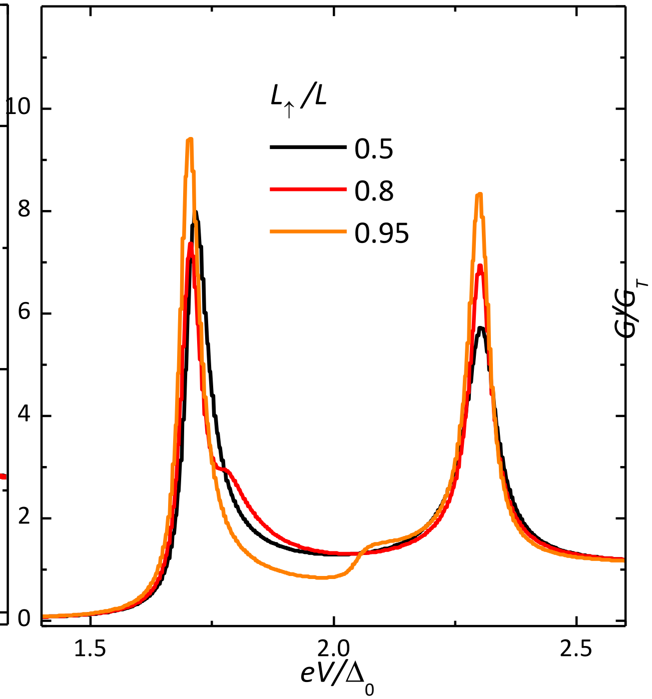

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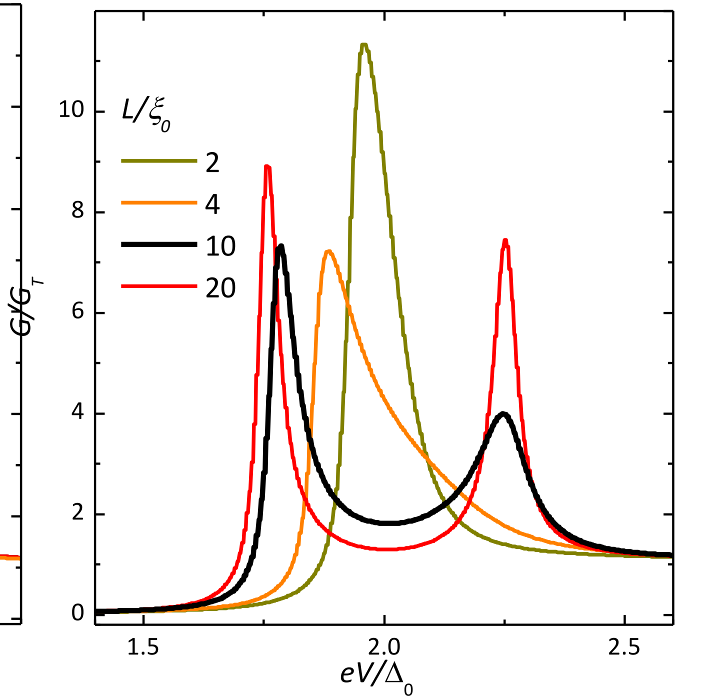

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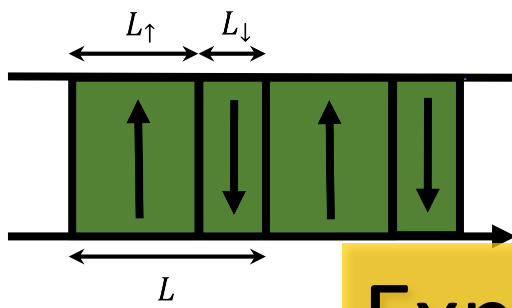
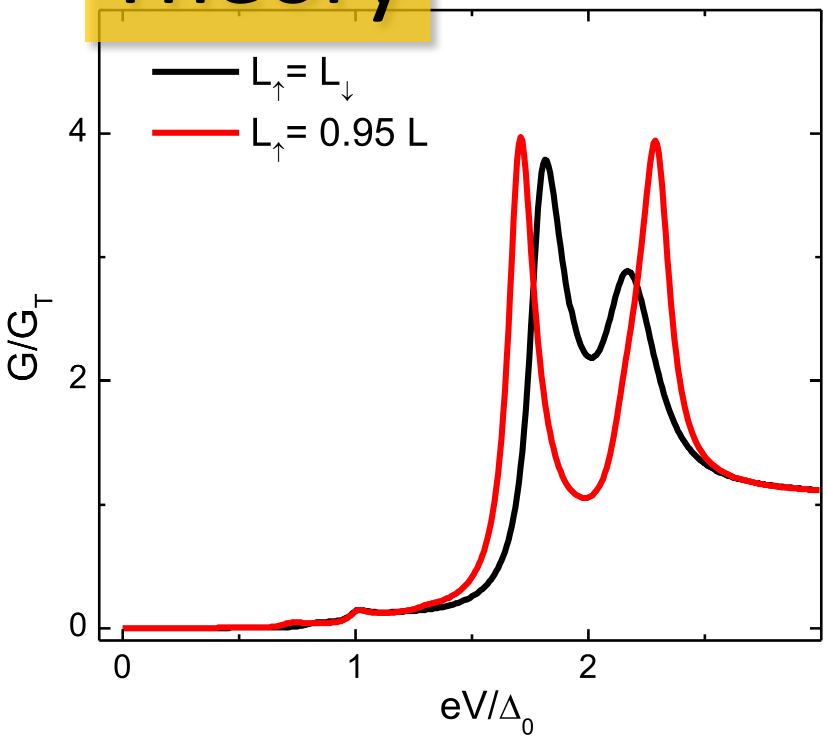
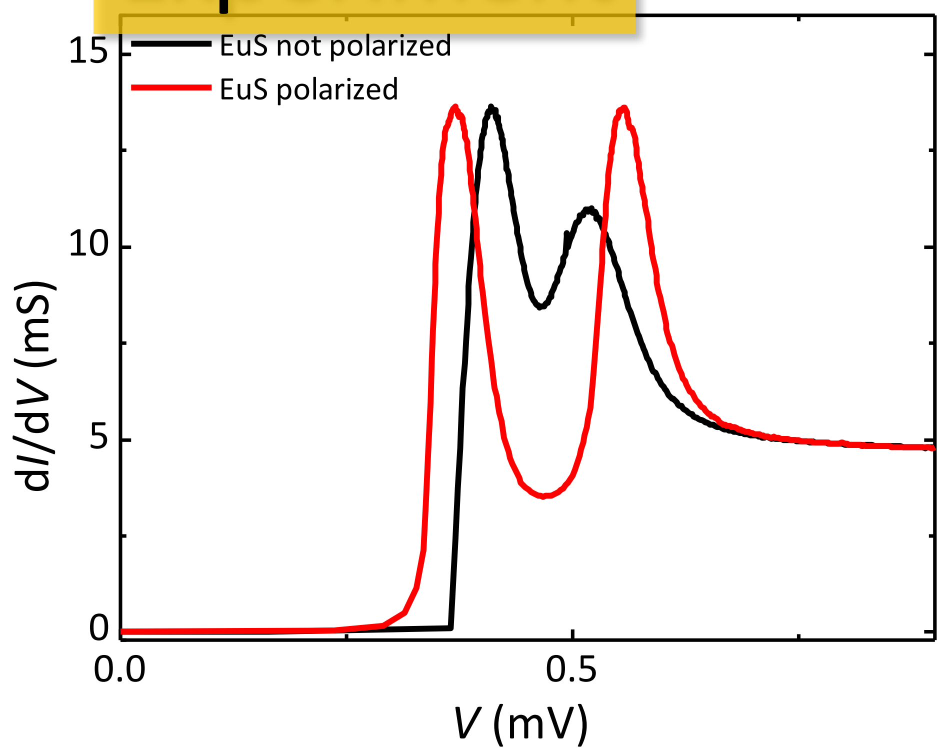


Theory



Experiment



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Absolute Spin valve

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Absolute Spin-Valve Effect with Superconducting Proximity Structures

Daniel Huertas-Hernando,[1] Yu. V. Nazarov,[1] and W. Belzig[2]

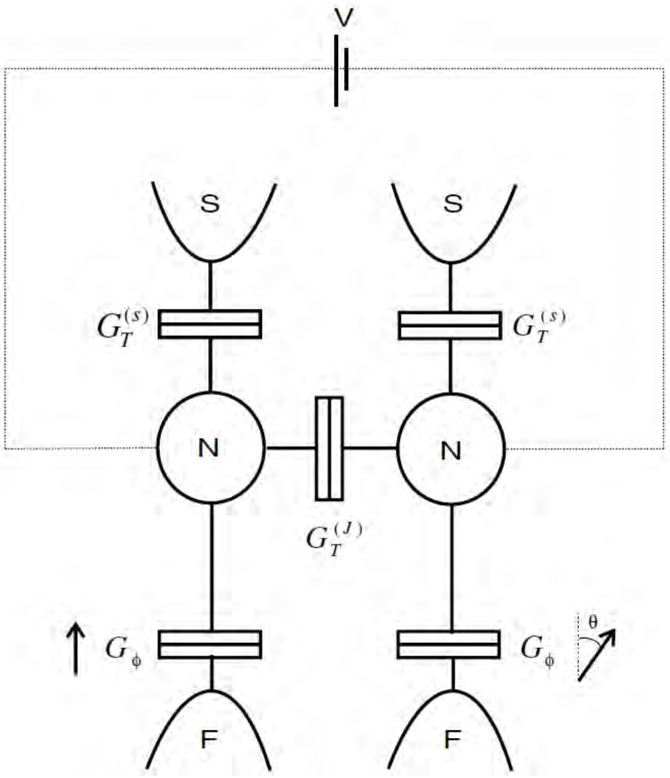
[1]*Department of Applied Physics and Delft Institute of Microelectronics and Submicrontechnology, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands*

[2]*Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland*

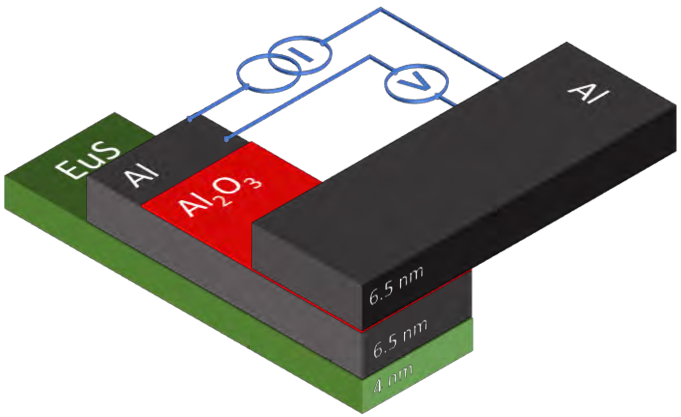
(Received 16 July 2001; published 11 January 2002)

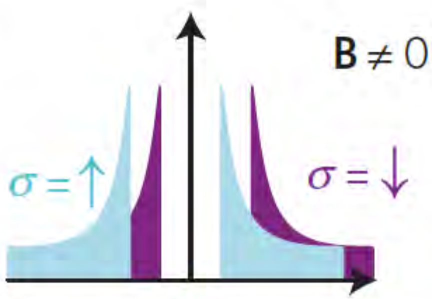
We investigate spin-dependent transport in hybrid superconductor–normal-metal–ferromagnet structures under conditions of the proximity effect. We demonstrate the feasibility of the absolute spin-valve effect for a certain interval of voltages in a system consisting of two coupled trilayer structures. Our results are also valid for noncollinear magnetic configurations of the ferromagnets.

DOI: 10.1103/PhysRevLett.88.047003 PACS numbers: 74.50.+r, 72.10.–d, 74.80.Dm



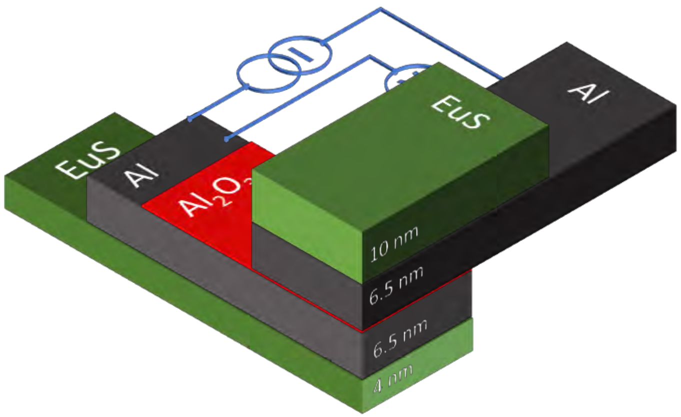
Absolute Spin valve

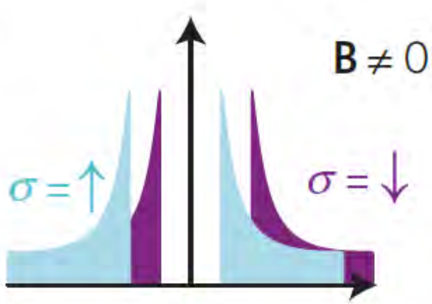




J. Linder and J. W. A. Robinson, "Superconducting spintronics," *Nat Phys*, **11**, 307–315, (2015)

Absolute Spin valve





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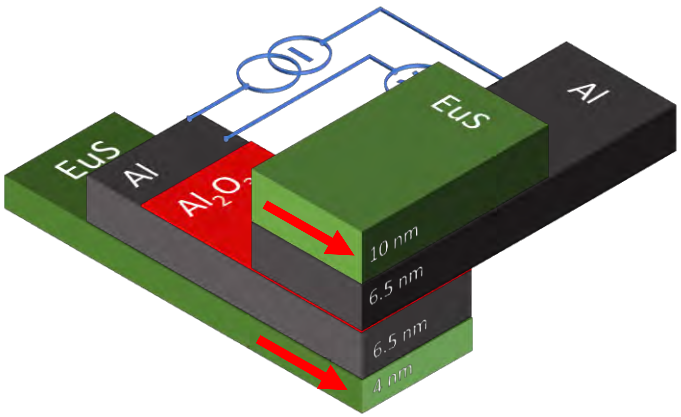
Absolute Spin valve



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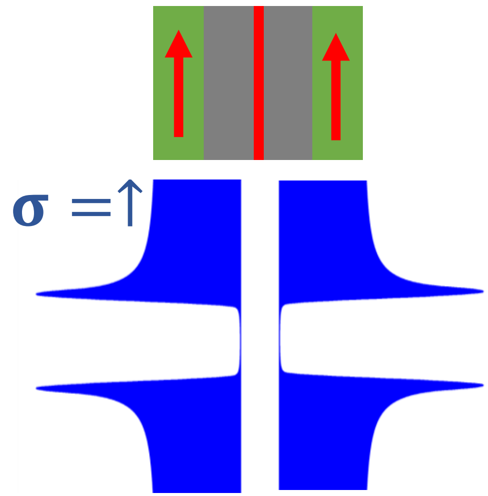
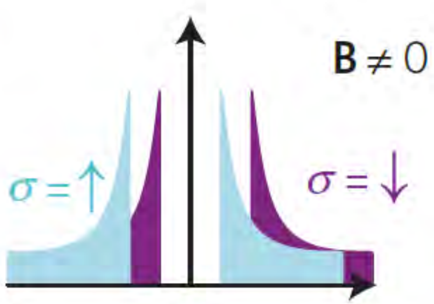
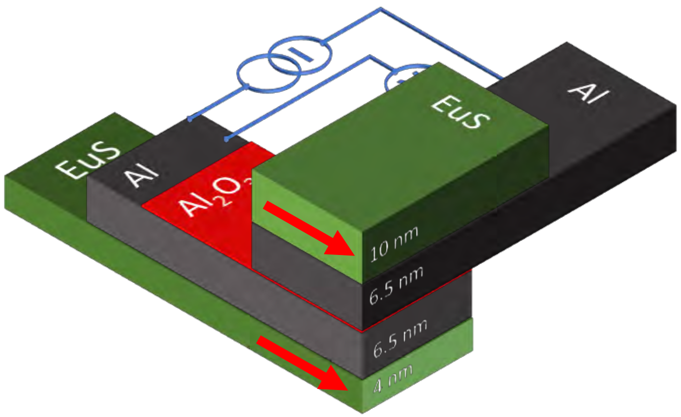
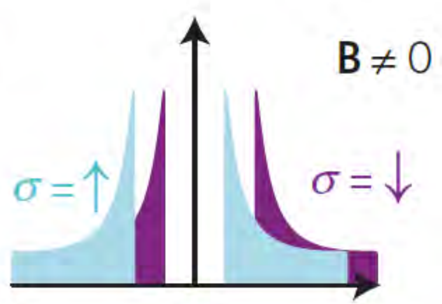


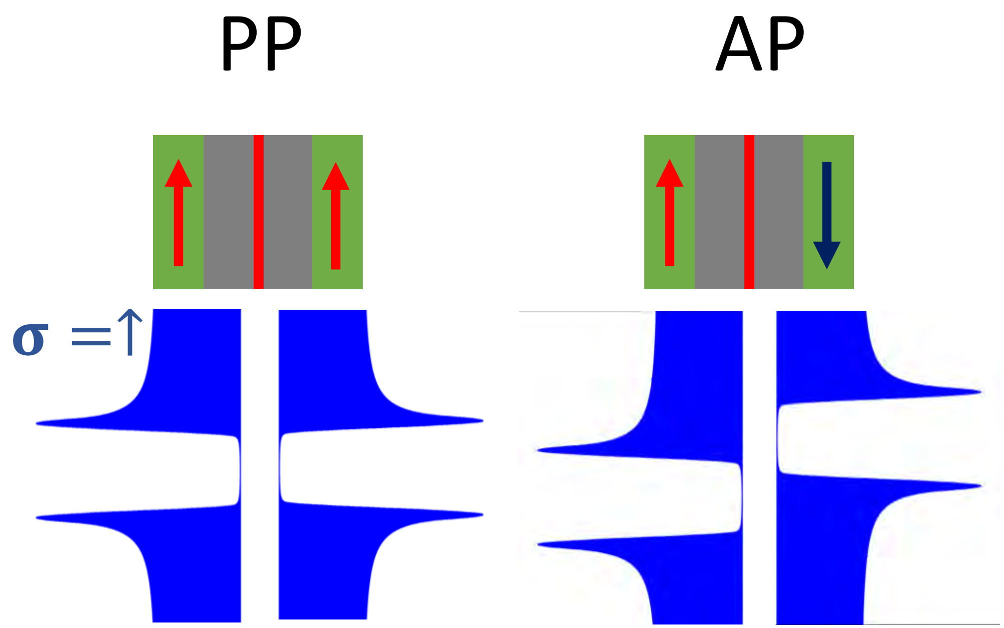


J. Linder and J. W. A. Robinson, “Superconducting spintronics,”
Nat Phys, **11**, 307–315, (2015)

Absolute Spin valve







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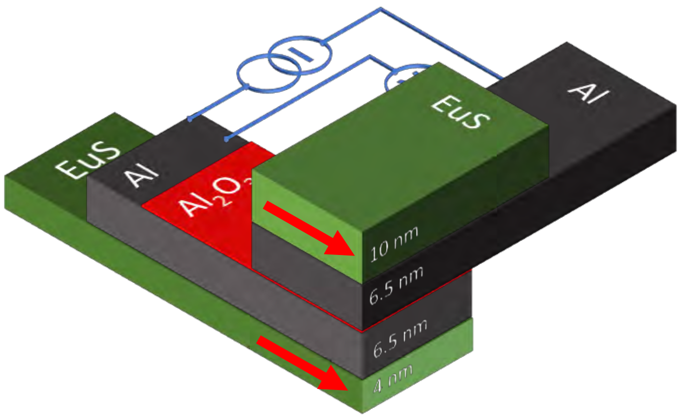
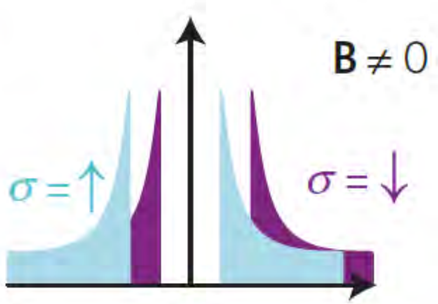
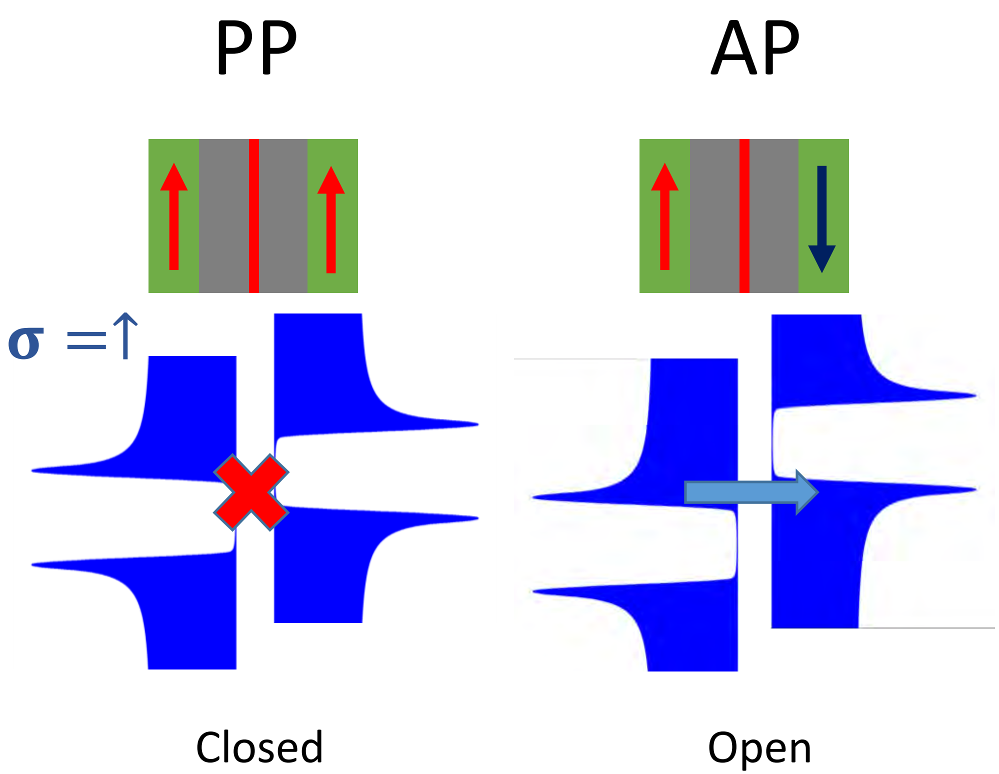
Absolute Spin valve



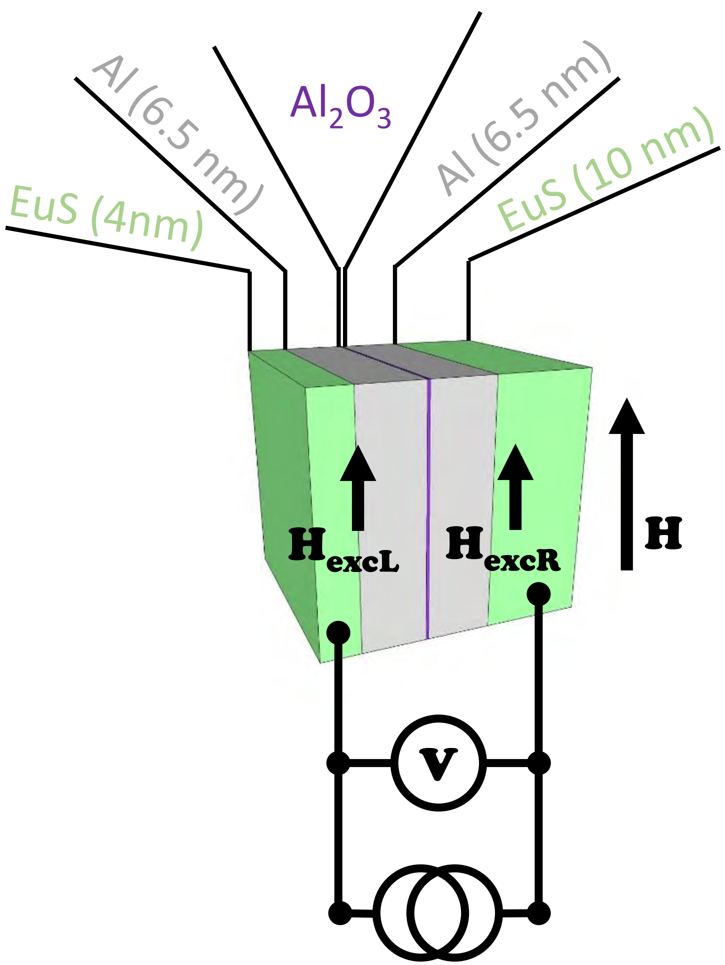


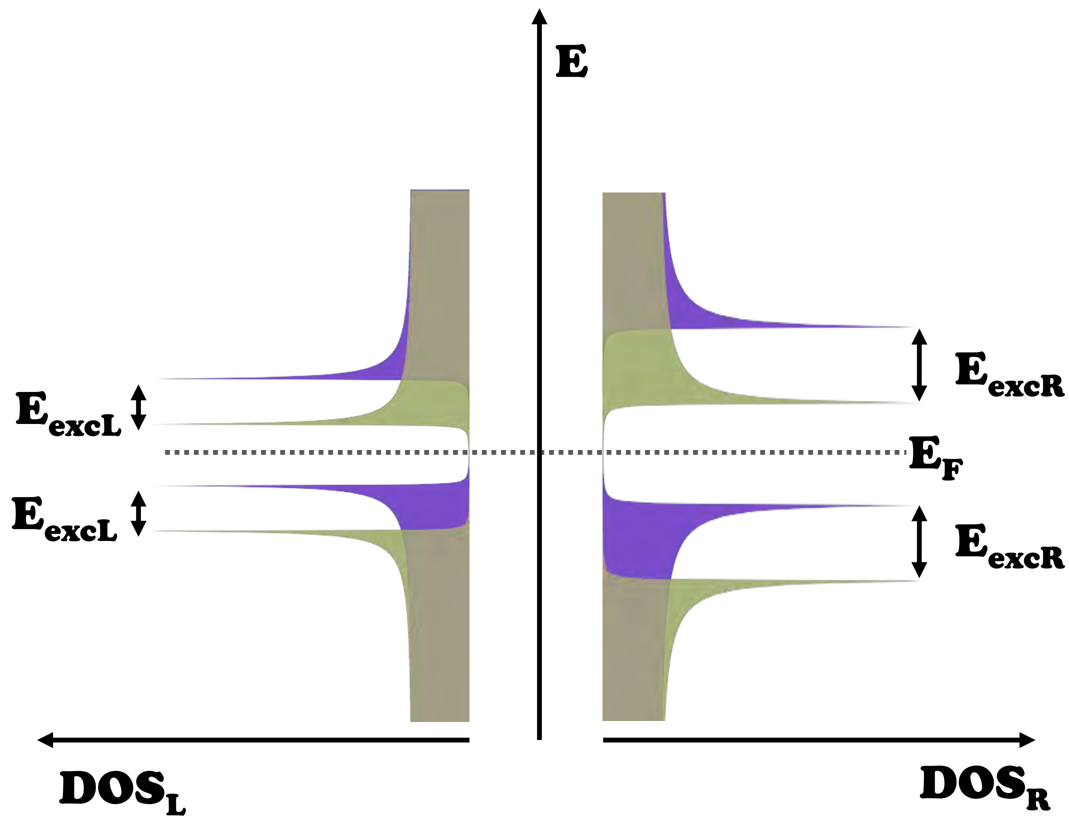
$$2\Delta > eV_{bias} > 2\Delta - 2\, h_{ex}$$



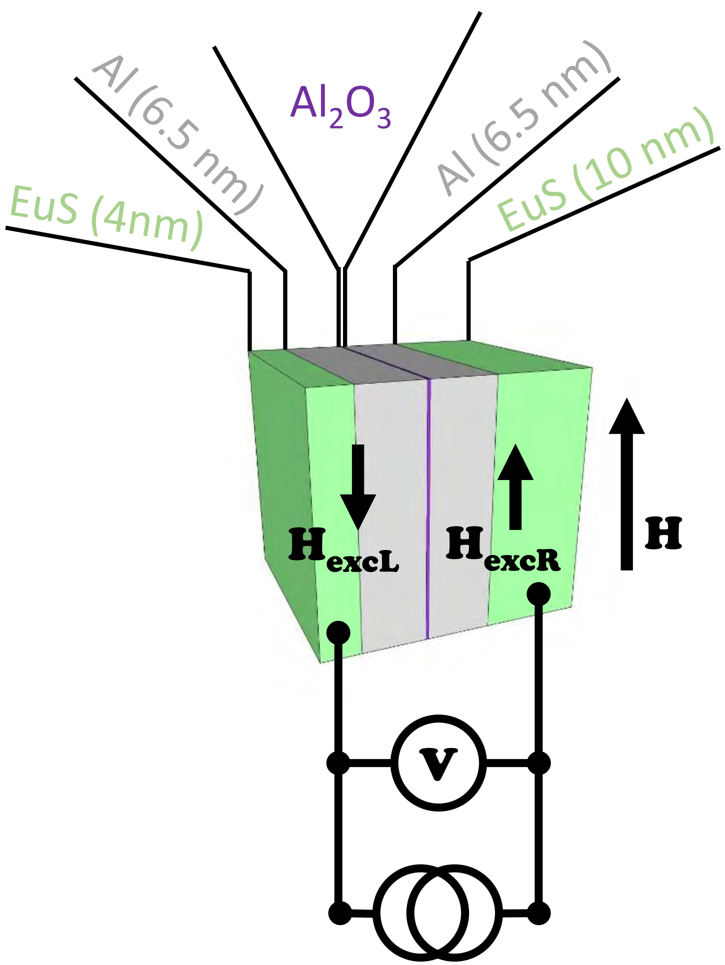
J. Linder and J. W. A. Robinson, "Superconducting spintronics," *Nat Phys*, **11**, 307–315, (2015)

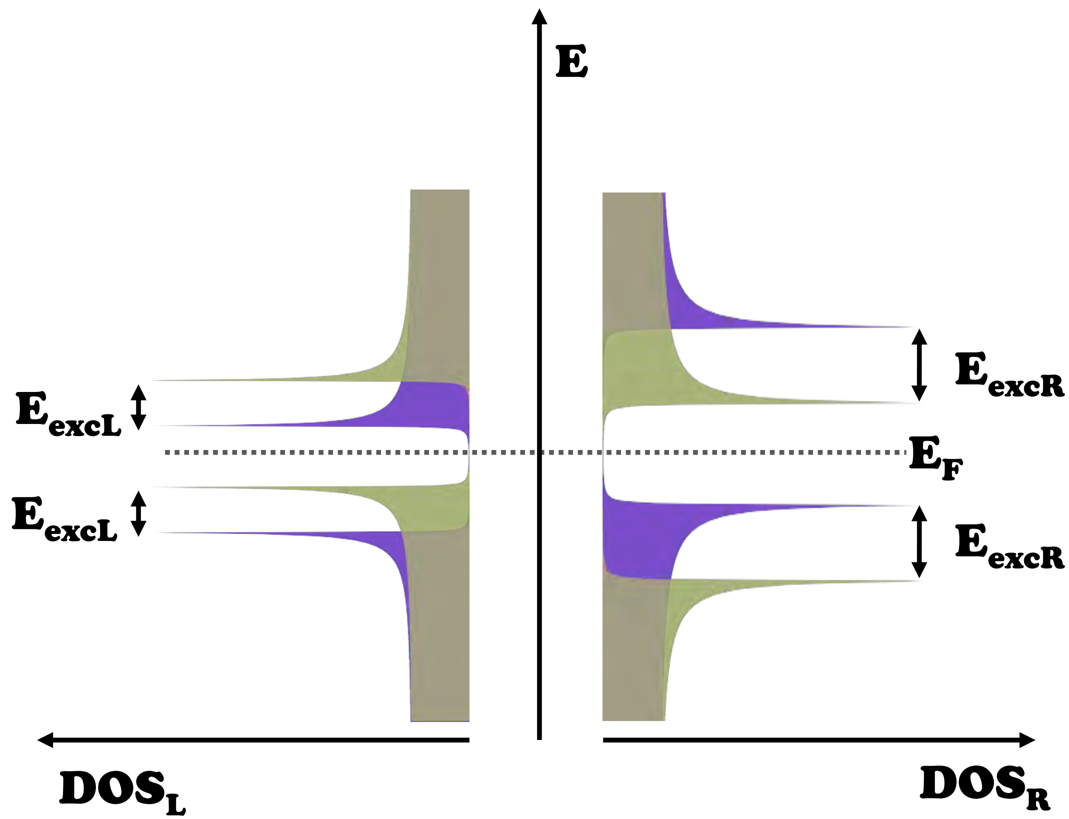
Absolute spin valve



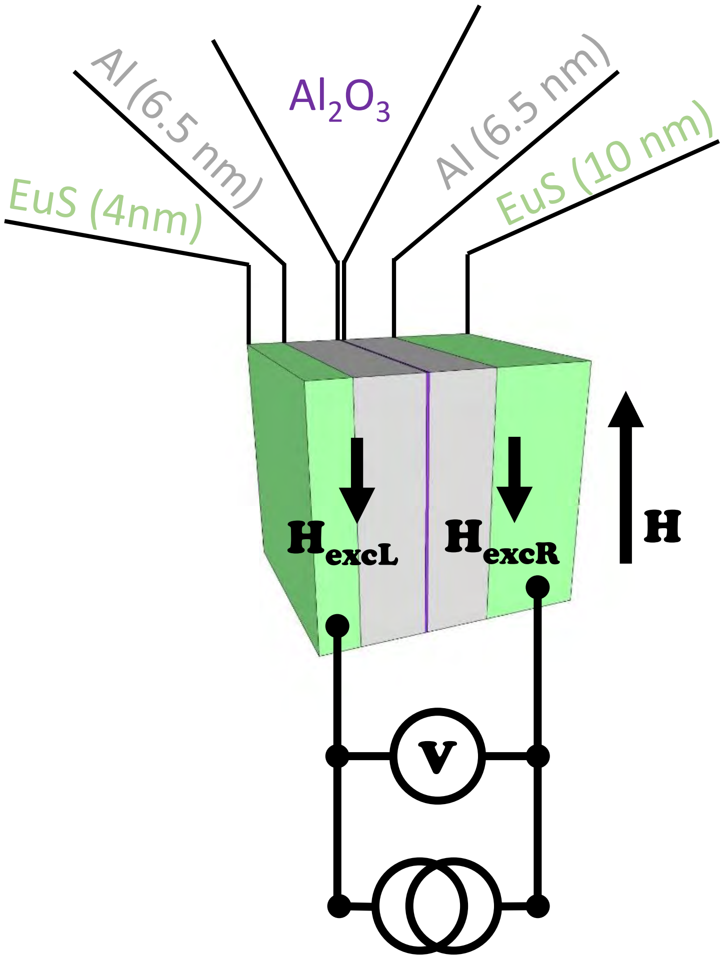


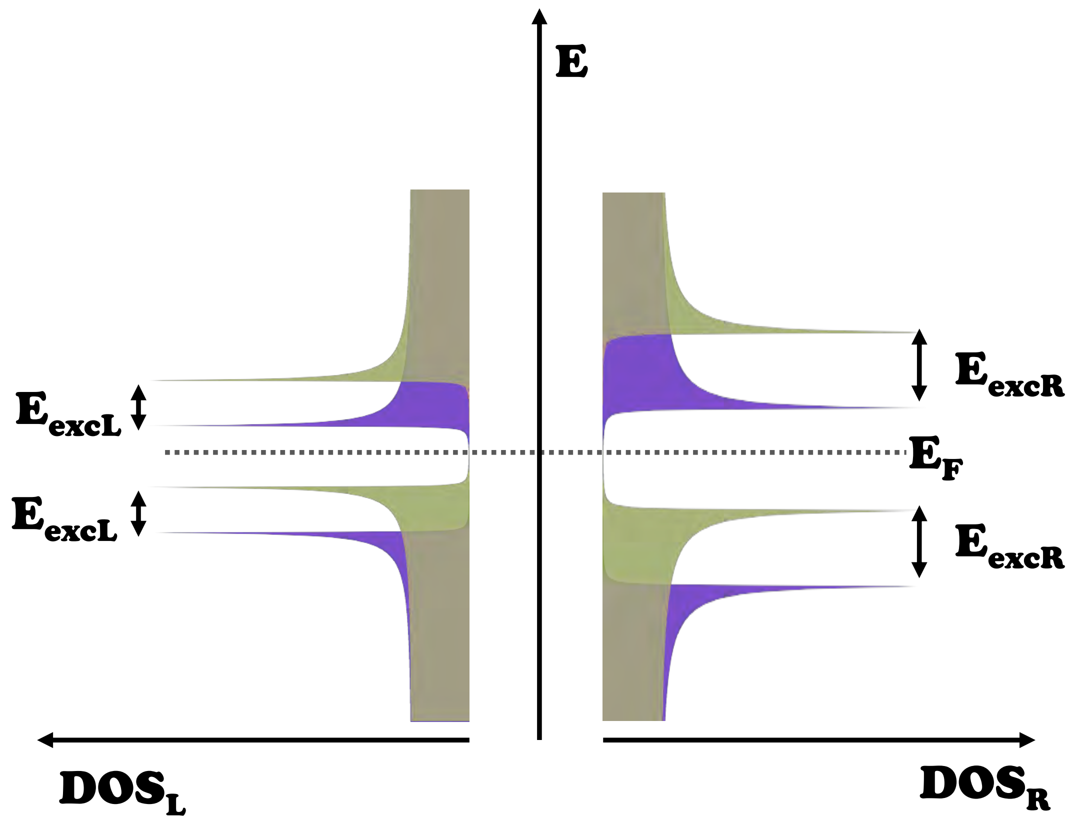
Absolute spin valve





Absolute spin valve



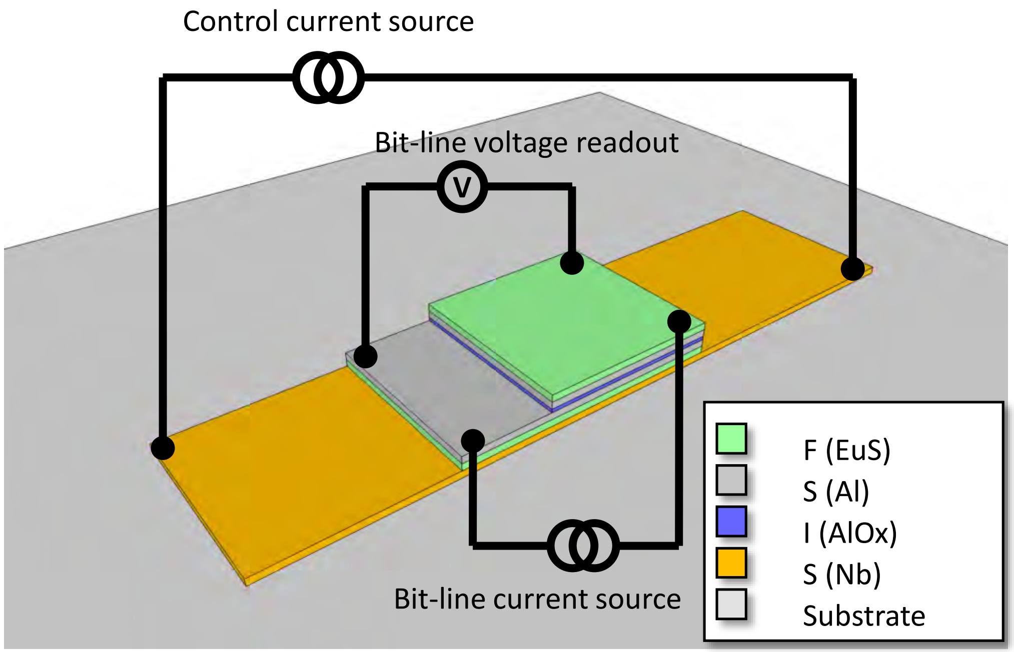


Conclusions and perspectives

- Role of magnetic domains
  - Tunneling spectroscopy experiment
  - Theoretical model

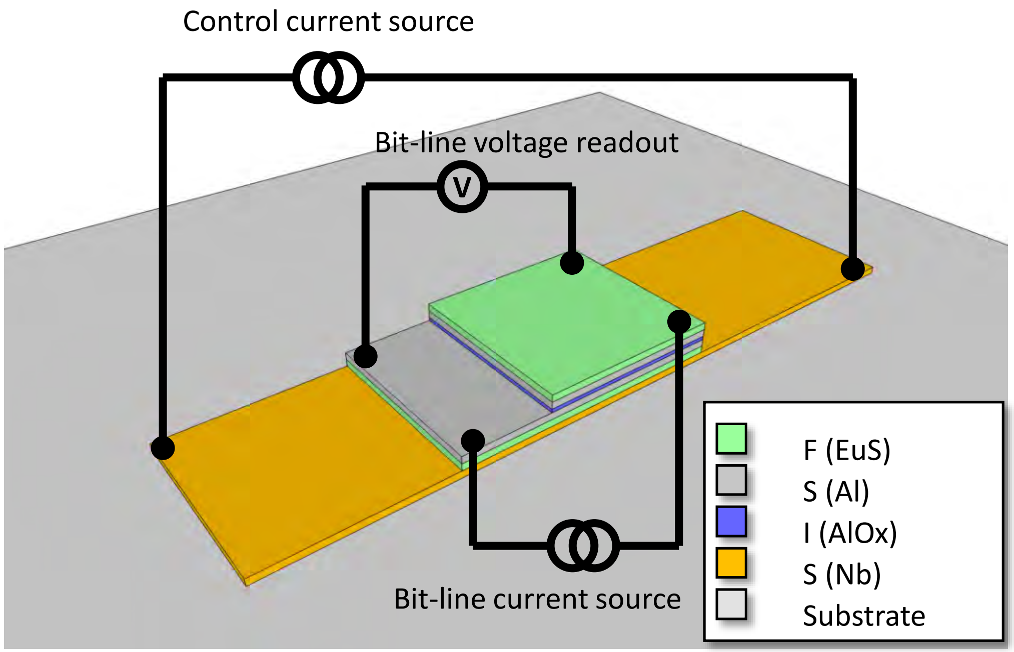
- The superconducting ASV
  - Demonstration and performance
  - Large scale superconducting RAM?

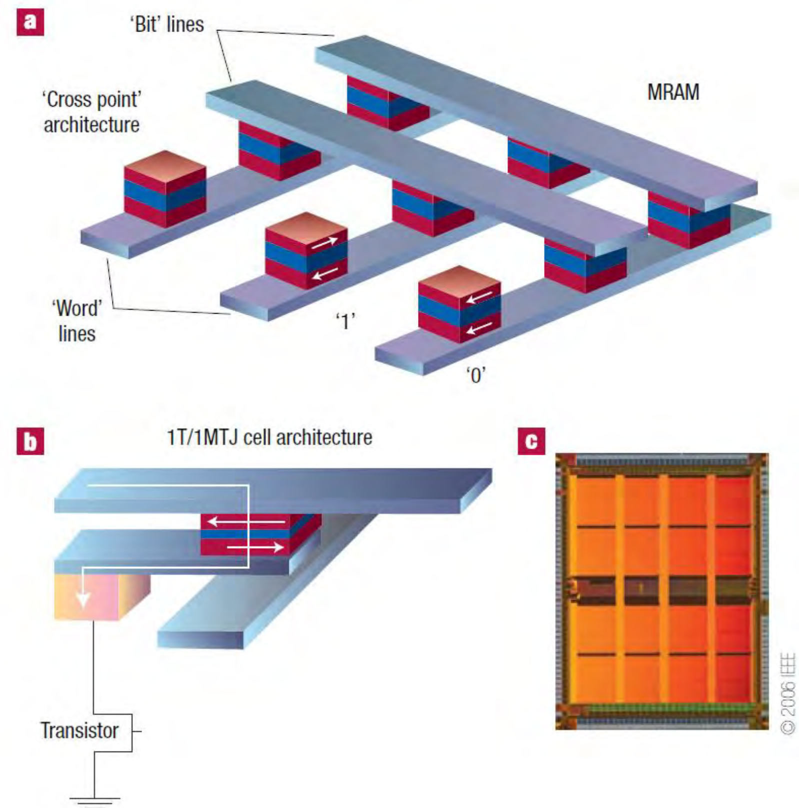
Conclusions and perspectives



Patent filed@UIBM, "Elemento logico a superconduttori", filing number 102017000095994, prior. date 24 August 2017

Conclusions and perspectives





C. Chappert, A. Fert, and F. N. Van Dau,
"The emergence of spin electronics in data storage,"
Nat Mater, **6**, 813, (2007).

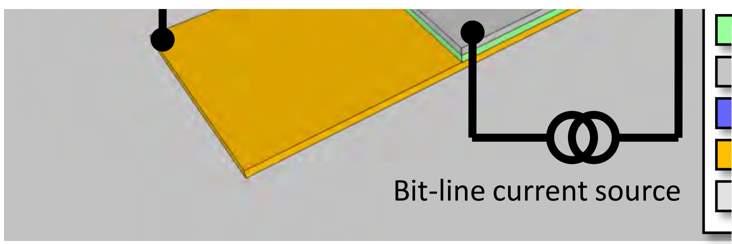
Patent filed@UIBM, "Elemento logico a superconduttori", filing number 102017000095994, prior. date 24 August 2017

Conclusions and perspectives

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 23, NO. 3, JUNE 2013 1701610

Energy-Efficient Superconducting Computing—Power Budgets and Requirements

D. Scott Holmes, *Senior Member, IEEE*, Andrew L. Ripple, and Marc A. Manheimer



Superconducting memories seem most promising for register and cache memory on the processor chip where speed is extremely important. Significant improvements in physical density and energy efficiency will be required even for these applications.

CMOS memories designed and fabricated to operate at 4 K can be integrated with SFQ circuits. Hybrid Josephson-CMOS memories up to 64 Kibit have been developed and tested [40], [41]. While these are larger and denser than purely superconducting memories built to date, the power and energy dissipation is too large to serve in an exascale superconducting computer.

The search for more suitable memories has begun and some concepts are promising, however none have been demonstrated.

Patent filed@UIBM, "Elemento logico a superconduttori", filing number 102017000095994, prior. date 24 August 2017

Thank you

- Acknowledgements:
  - V. N. Golovach,
  - F. S. Bergeret,
  - J. S. Moodera,
  - G. De Simoni,
  - F. Giazotto

E. Strambini, V. N. Golovach, G. De Simoni, J. S. Moodera, F. S. Bergeret, and F. Giazotto,
"Revealing the magnetic proximity effect in EuS/Al bilayers through superconducting tunneling spectroscopy,"
Phys. Rev. Mat. ***00**, 004400 (2017)*

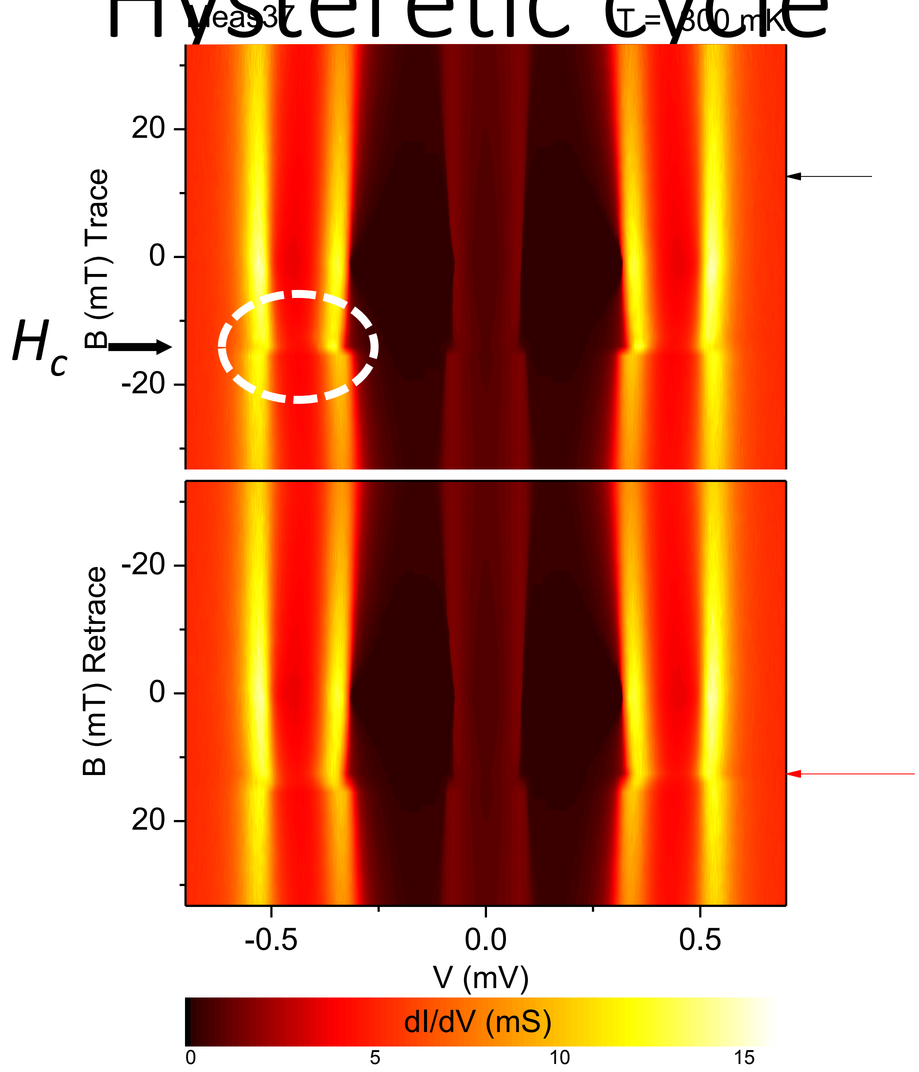
G. De Simoni, E. Strambini, J. S. Moodera, F. S. Bergeret, and F. Giazotto,
«Superconducting absolute spin valve", in preparation

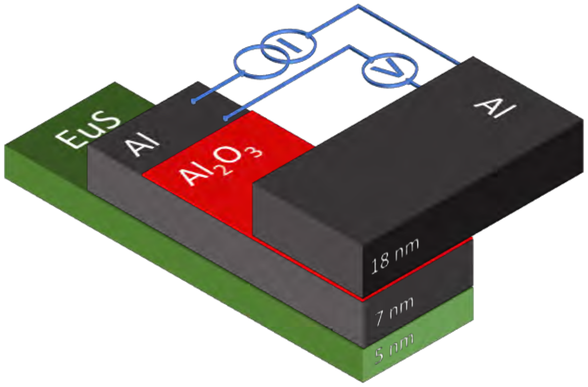
Patent UIBM, "Elemento logico a superconduttori", filing number 102017000095994, prior. date 24 August 2017

Marie Skłodowska-Curie Actions

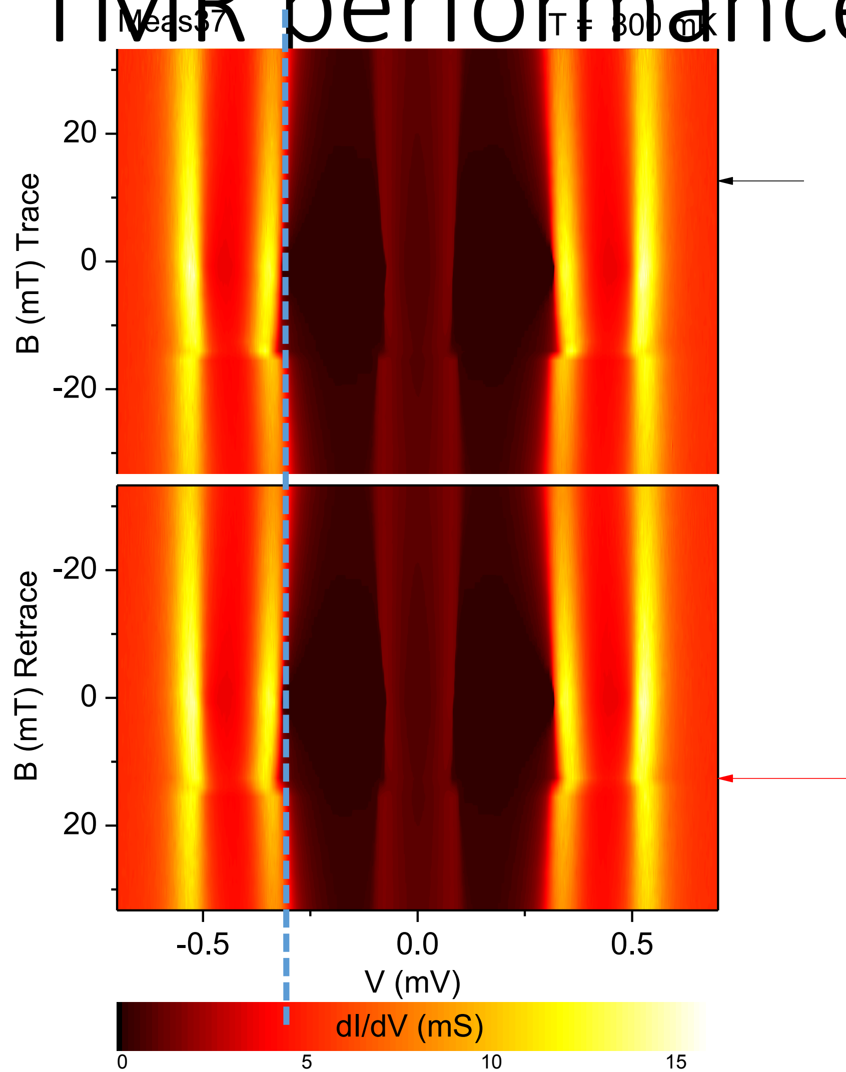
Acknowledgement:
Marie Curie Individual Fellowship No. 660532-SuperMag
ERC consolidator grant No. 615187-COMANCHE

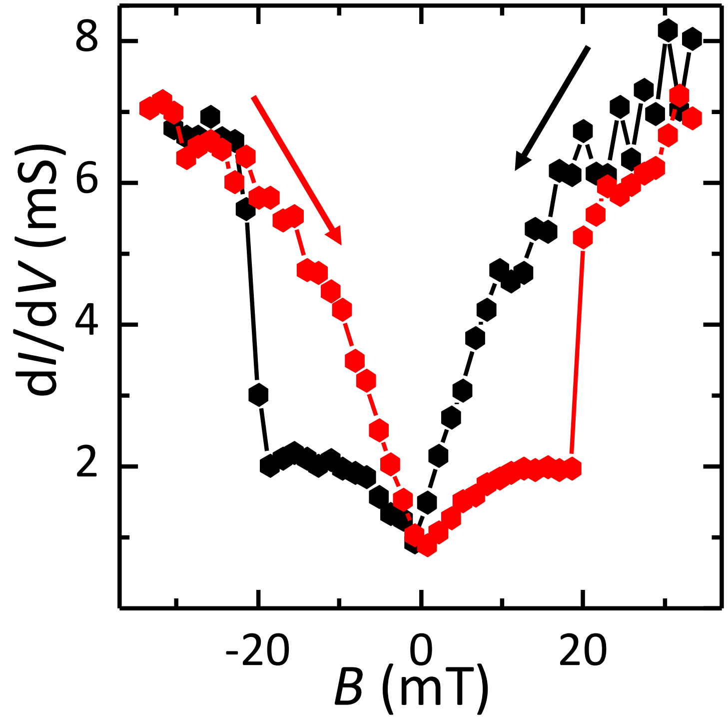
Hysteretic cycle





TMR performance

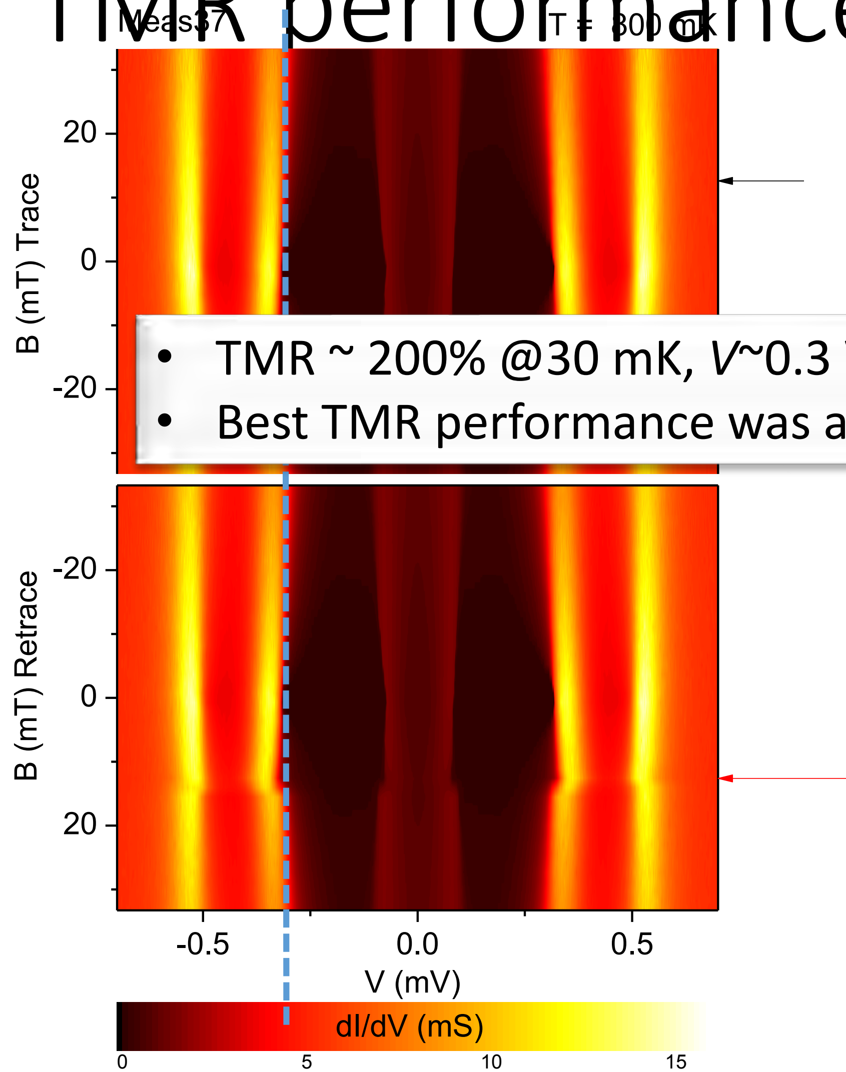




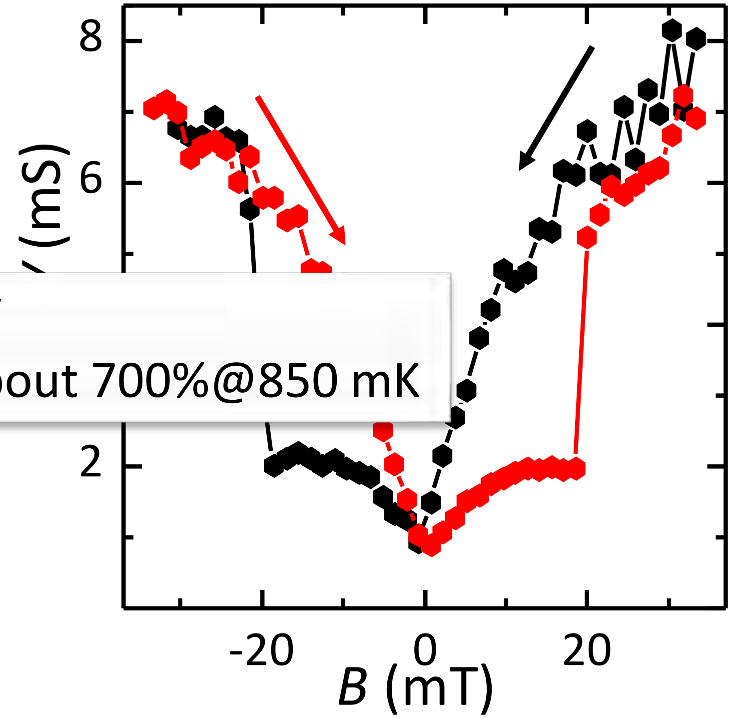
$$\text{TMR} = \frac{\frac{dI}{dV}(Trace)}{\frac{dI}{dV}(Retrace)} - 1$$

E. Strambini, G.D.S., *et al.,* arXiv:1705.04795, in press on Phys. Rev. Mat.

TMR performance



- TMR ~ 200% @30 mK, *V*~0.3 V
- Best TMR performance was about 700%@850 mK

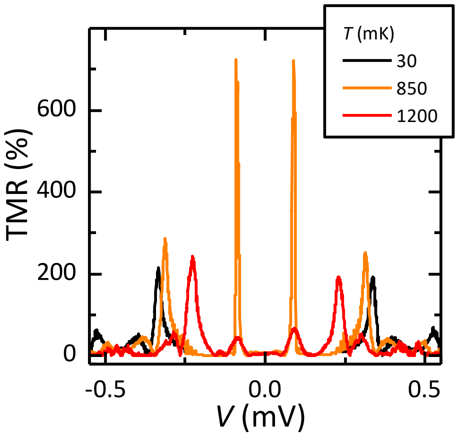


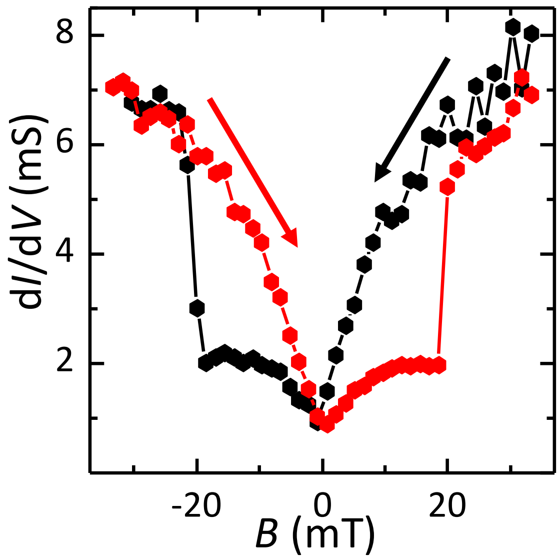
$$\text{TMR} = \frac{\frac{dI}{dV}(Trace)}{\frac{dI}{dV}(Retrace)} - 1$$

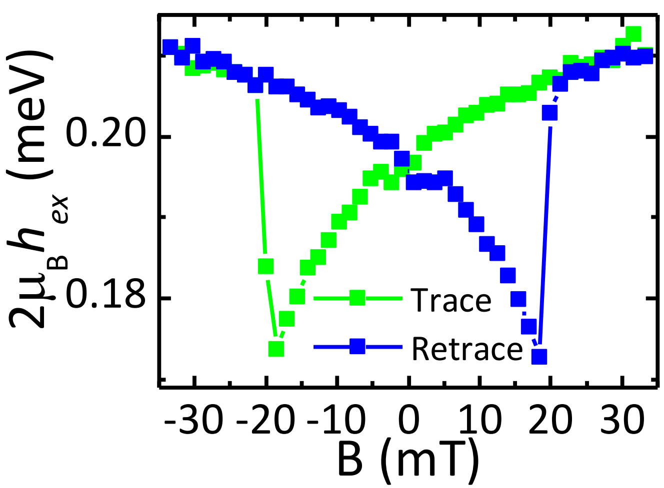
E. Strambini, G.D.S., *et al.*, arXiv:1705.04795, in press on Phys. Rev. Mat.

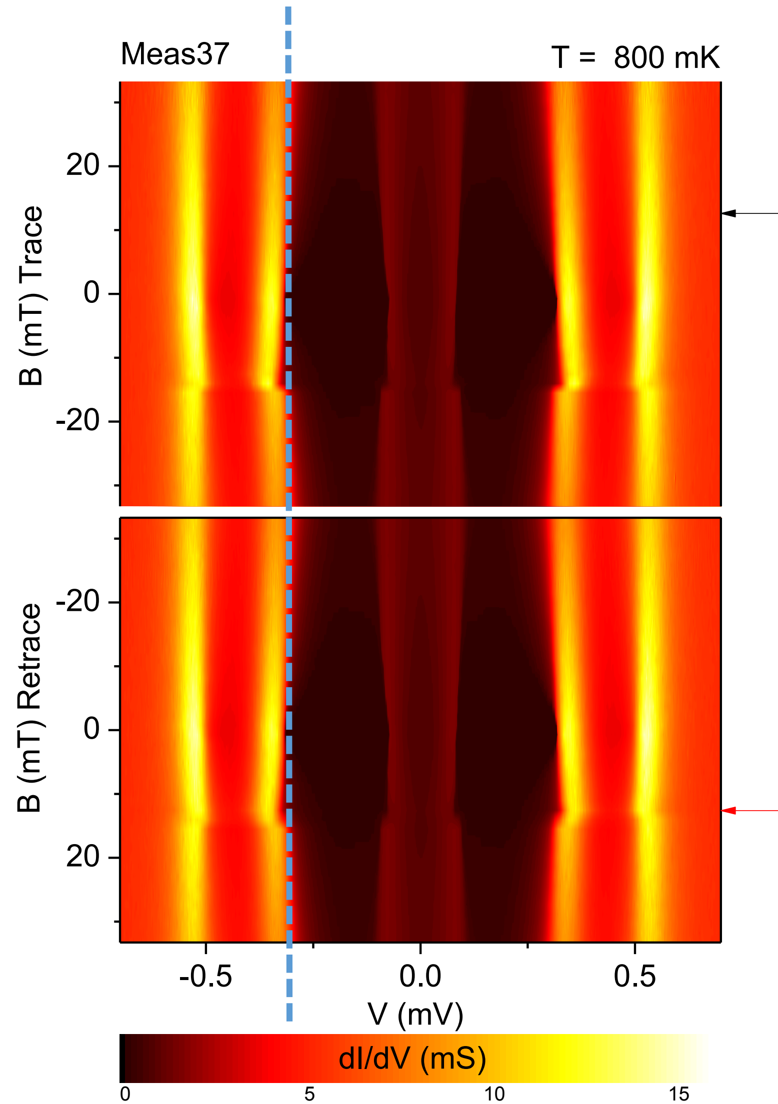
Giant TMR

$$\text{TMR} = \frac{\frac{dI}{dV}(Trace)}{\frac{dI}{dV}(Retrace)} - 1$$

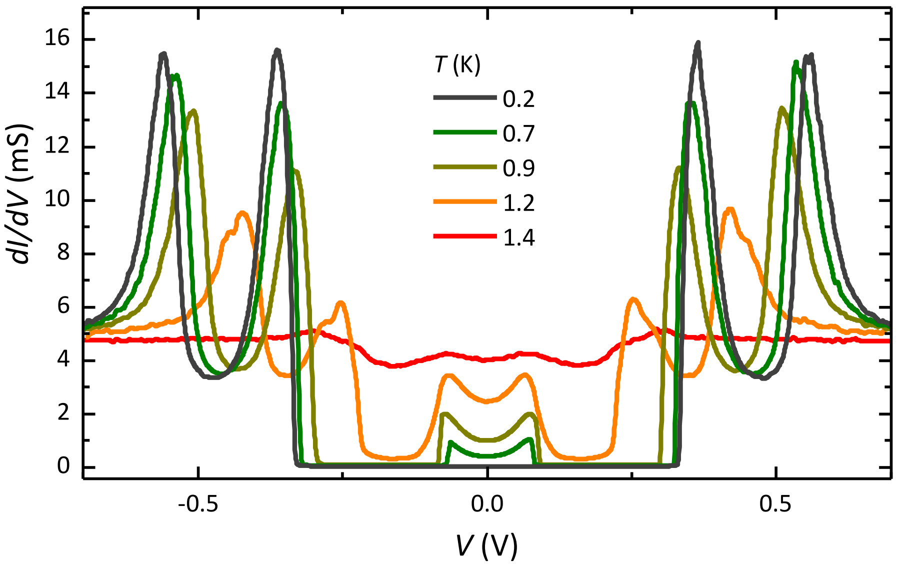








Temperature Evolution



$$eV_{peaks} \cong (\Delta_1 - \Delta_2) \pm h_{ex}$$