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
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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.
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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EuS:
• High Curie temperature
• Strong exchange field
• High quality interfaces with Al
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• 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
Motivations

• Magnetism & Superconductivity

Applications

• Hybrid systems (integration of magnetic fields to engineer exotic state)
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Motivations

- Magnetism & Superconductivity
  - Phase-tunable colossal magnetothermal resistance in ferromagnetic Josephson valves
    - Strong exchange field
    - High quality interfaces with Al

- Applications
  - Hybrid systems (integration of magnetic fields to engineer exotic state)
  - Spin-resolved tunneling spectroscopy
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Measuring the induced magnetism

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Tunneling Spectroscopy

Tunneling Spectroscopy

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

Tunneling Spectroscopy

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

Unpolarized state

\[ \frac{dI}{dV}(V) = \frac{1}{eR_T} \frac{d}{dV} \int_{-\infty}^{\infty} dE \; DoS_{Al}(E + eV)DoS_{EuS/Al}(E) \left(f(E) - f(E + eV)\right) \]

\[ eV_{\text{peaks}} \approx \pm(\Delta_1 + \Delta_2) \pm h_{ex} \]

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

\[ \Delta_1 + \Delta_2 = 460 \mu eV \]

Unpolarized state

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

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

\[ 2\mu_B B_{\text{ex}} = 110 \mu eV \rightarrow B_{\text{ex}} \sim 1 T \]

\[ \Delta_1 + \Delta_2 = 460\mu eV \]

First Magnetization

\[ \Delta_1 + \Delta_2 = 460 \mu eV \]

**First Magnetization**

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

First Magnetization

- Position is affected
- Shape is reconstructed

\[ 2\mu_B B_{\text{ex}} = 190 \, \mu eV \rightarrow B_{\text{ex}} \approx 1.6 \, T \]

\[ \Delta_1 + \Delta_2 = 460 \, \mu eV \]

Theoretical Model (Role of Domains)

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\[ L_\uparrow = L_\downarrow \text{ (Non Polarized)} \]
Theoretical Model (Role of Domains)

\[ L_{\uparrow} = L_{\downarrow} \text{ (Non Polarized)} \]
Theoretical Model (Role of Domains)

\[ L_{\uparrow} \neq L_{\downarrow} \text{ (Polarized)} \]

\[ L_{\uparrow} = L_{\downarrow} \text{ (Non Polarized)} \]
Theoretical Model (Role of Domains)

Different distributions

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

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

\[ L_{\uparrow} = L_{\downarrow} \]

\[ L_{\uparrow} \neq L_{\downarrow} \]
Theoretical Model (Role of Domains)

\[ L_\uparrow \quad L_\downarrow \]

\[ L \quad \frac{dI}{dV} \quad G/G \quad eV/\Delta_0 \]

Theory

- \( L_\uparrow = L_\downarrow \)
- \( L_\uparrow = 0.95 \ L \)

Experiment

- EuS not polarized
- EuS polarized

Theory vs. Experiment

Graphs showing comparison between theoretical and experimental results.
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• Conclusions
Absolute Spin Valve

Absolute Spin-Valve Effect with Superconducting Proximity Structures

Daniel Huertas-Hernando,¹ Yu. V. Nazarov,¹ and W. Belzig²

¹Department of Applied Physics and Delft Institute of Microelectronics and Submicronotechnology,
Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands
²Department 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 non-collinear magnetic configurations of the ferromagnets.

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PACS numbers: 74.50.+r, 72.10.−d, 74.80.Dn
Absolute Spin valve

Absolute Spin valve

Absolute Spin valve

Absolute Spin valve

Absolute Spin valve

\[ 2\Delta > eV_{bias} > 2\Delta - 2h_{ex} \]

Absolute spin valve

$\text{Al}_2\text{O}_3$

$\text{Al} (6.5 \text{ nm})$

$\text{Al} (6.5 \text{ nm})$

$\text{EuS} (10 \text{ nm})$

$\text{EuS} (4 \text{ nm})$

$H_{\text{excL}}$

$H_{\text{excR}}$

$E_{\text{excL}}$

$E_{\text{excR}}$

$\text{DOS}_L$

$\text{DOS}_R$

$E_{\text{excL}}$

$E_{\text{excR}}$

$E_F$

$V$

$E$

$H$
Absolute spin valve

\[
\begin{align*}
H_{\text{excL}} & \leftrightarrow H_{\text{excR}} \\
E_{\text{excL}} & \uparrow \downarrow \\
E_{\text{excR}} & \uparrow \downarrow \\
E_{\text{excL}} & \\
E_{\text{excR}} & \uparrow \downarrow \\
E_F & \\
E_{\text{excL}} & \\
E_{\text{excR}} & \uparrow \downarrow \\
DOS_L & \\
DOS_R & \uparrow \downarrow \\
\end{align*}
\]
Absolute spin valve

Al₂O₃

DOSₗ

DOSᵣ

H

HₓₑₓcL

HₓₑₓcR

EₓₑₓcL

EₓₑₓcR

Eₚ

Eₚᵣ

EuS (4nm)

Al (6.5 nm)

Al (6.5 nm)

EuS (10 nm)
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

Control current source

Bit-line voltage readout

Bit-line current source

F (EuS)
S (Al)
I (AlOx)
S (Nb)
Substrate

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,”

Patent filed@UIBM, “Elemento logico a superconduttori”, filing number 102017000095994, prior. date 24 August 2017
Conclusions and perspectives

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 Kbit 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
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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
Hysteretic cycle

Hc

B (mT) Trace

B (mT) Retrace

V (mV)

dl/dV (mS)
TMR performance

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

TMR performance

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


\[ \text{TMR} = \frac{\frac{dI}{dV}(\text{Trace})}{\frac{dI}{dV}(\text{Retrace})} - 1 \]
Giant TMR

\[ \text{TMR} = \frac{\frac{dl}{dV}(\text{Trace})}{\frac{dl}{dV}(\text{Retrace})} - 1 \]

\[ T = 800 \text{ mK} \]

\[ dI/dV (\text{mS}) \]

\[ B (\text{mT}) \]

\[ \mu_B h_{\text{ex}} (\text{meV}) \]

\[ T (\text{mK}) \]

- 30
- 20
- 10
0
10
20
30

-0.5
0.0
0.5

-0.5
0.0
0.5

-20
0
20

-20
0
20

-0.5
0.0
0.5

0
200
400
600

20
0
-20

0
5
10
15

0
15

0.18
0.20

Trace
Retrace

Meas37
Temperature Evolution

\[ eV_{peaks} \approx (\Delta_1 - \Delta_2) \pm h_{ex} \]