

GRMs JTC2021



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# GRAPHENE FLAGSHIP



Area: 4. Spin torque and layered-materialsbased memory building blocks Synergy and Complementary to Spintronics WP2 Core program 3. Scalable growth & device integration of UltraLow Power Spin-Orbit Memories based on

dea

# Spin Orbit functionalized GRAPHene for resistive-magnetic MEMories SOgraphMEM

UCLouvain

Paolo Perna, Coordinator 1st January 2020 – 31st December 2022 (+9 months extension)

*Kick-off FLAG-ERA 16th March 2021* 2nd workshop FLAG-ERA 21st March 2022

AEI PCI2019-111867-2 + PCI2019-111908-2

ANR-19-GRF1-0001 DFG MI 1247/18-1 FNRS R.8012.19





## **General overview**

**Objectives** 



*Realize voltage-controlled resistive and magnetic switching RT devices by exploiting Gr, FM, HM and FE* 

#### Structural perfection

- → Epitaxial Gr/FM/HM and Gr-SAF /Co/HM grown on insulating oxides
- $\rightarrow$  FCC structure of Co, pseudomorphic with HM

#### **Tunable SOC-induced interactions**

- $\rightarrow$  Large PMA, extended up to 20MLs Co
- $\rightarrow$  DMI @ Gr/Co OPPOSITE to DMI @ Co/Pt
- $\rightarrow$  Chiral Spin texture stable at RT and protected by Gr

#### Enabling Electric Field control of:

- Orbital magnetic moments (MAE)
- Interfacial DMI

#### Device fabrication

- $\rightarrow$  magnetic and electric switching
- $\rightarrow$  Spin-charge conversion and spin-filtering





#### F. Ajejas, PP et al. Nano Lett. 2018, 18, 5364





# A multidisciplinary Consortium





## **Consortium Agreement (v 23/02/2021) Data Management Plan (v1.7 submitted)**

#### https://nanociencia.imdea.org/sographmem/

Partner Number	Country	Institution/ Department	Name of the Principal Investigator (PI)	Name of the co- Investigators	
1 Coord.	Spain	IMDEA Nanociencia IMDEA	<u>Dr. Paolo Perna</u> (coord.)	Prof. Rodolfo Miranda (surface science) Dr. Julio Camarero (growth) Prof. Francisco Guinea (theory)	015
2	France	CNRS-UMPhy UMPHY	<u>Dr. Vincent Cros</u> (magneto-transport)	Prof. Pierre Seneor (spintronics with gr)	Core <i>Tore</i>
3	France	<u>Soleil</u> <u>Synchrotron</u> <b>SOLEIL</b>	<u>Dr. Nicolas Jaouen</u> (scattering)	Dr. Maurizio Sacchi (holography) Dr. François Bertan (Spin ARPES) Dr. Patrick Lefevre (ARPES)	SOgr
4	Spain	ALBA Synchrotron ALBA	Dr. Manuel Valvidares (magnetic dichroism)	Dr. Pierluigi Gargiani (XMCD under E-field)	
5	Germany	<u>TU Dresden</u> NaMLab	<u>Dr. Stefan Slesazeck</u> (memory)	Prof. DrIng. Thomas Mikolajick Dr. Uwe Schroeder (FE-HfO <sub>2</sub> material)	
6	Germany	PGI & IAS JUELICH	Prof. Dr. Stefan Blügel (SOC modelling)	Prof. Dr. Yuriy Mokrousov	_
7	Belgium	UC Louvain UCL	<u>Prof. Jean-Christophe</u> <u>Charlier</u> (FE modelling)		Core P

Synergy and Complementary to Spintronics WP2 Core













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2

Pt(111)

Ir(111)

### WP1: Fabrication of Gr/FM/HM





• Epitaxial growth of Gr/FM/HM on insulating oxides

- Epitaxial growth FE capped Gr/FM/HM on insulating oxides
- Epitaxial growth of RE based Gr-SAF
- Analysis in-situ of the structural, electronic and chemical surface properties
- Analysis ex-situ of the structural and magneto-transport properties
- Analysis ex-situ of electric-polarization properties

Ajejas et al., Nano Lett. 18, 5364 (2018) Ajejas et al., ACS Appl. Mater. Interfaces 12, 4088 (2020) Blanco-Rey et al., ACS Appl. Nano Mater. 4, 4398 (2021) Anadon et al., APL Mater. 9, 061113 (2021) Lancaster et al., submitted (2022) arxiv





M. Varela, M. Cabrero, A. Guedeja-Marron, UCM



3.0

(2.0 nuits)

,1.0 XAS (arb. 0.0

-1.0

L<sub>3</sub>

Co

760 780 800 820

40

20

-20

-40

-4

XMCD (%)

#### WP1: Fabrication of Gr-SAF

L<sub>3</sub>

Co

Co

Fu

0.5

760 780 800 820

M<sub>5</sub>

M<sub>4</sub>

Eu

1160

1120

FM coupling

Gr-mediated

Super-exchange

x-rays //  $\mu_0 H$ 

NI

TEY

Photon energy (eV)

— хмср (µ<sup>-</sup>-µ<sup>+</sup>)

µ0H=0T, T=3.5K





Eu(1 ML)/Gr/Co(5 ML)/Ir(111)

1120

Photon energy (eV)

— XMCD (μ<sup>-</sup> - μ<sup>+</sup>)

µ0H=6T, T=3.5K

M<sub>5</sub>

M₄

Eu

1160

Gr/Eu(1 ML)/Co(5 ML)/Ir(111)



L. De Melo Costa, PhD thesis UAM 2021, IMDEA+ALBA

0

μ<sub>0</sub>Η (Τ)

-0.5



#### WP1: Fabrication of FE on Graphene





accumulation of charges at the bottom interface



3

W W W



### Spin textures in Gr/FM



## Hybrid DWs and chirality by XRMS



Appearance of the SOP is a signature of a change of the chirality in the z-direction

E. Burgos-Parra, et al, submitted PRB (2022)



C. Leveillé et al, Phys. Rev. B 104, L060402 (2021)



B

C







### WP2: E-field tuning of PMA



SQGM



Exp. No. 2019023333 @ ALBA-BOREAS Exp. No. 2020094733 @ ALBA-BOREAS Exp. No. 2021024903 @ ALBA-CIRCE In-house planned in 2022 @ ALBA-BOREAS

# Small changes of Co-holes, $\mathbf{m}_{\mathrm{L}}$ and $\mathbf{m}_{\mathrm{S}}$ Agreement with modelling















\*100 (µ<sub>B</sub>) , MAE (meV)

5



L1

0.8

#### **Nature of PMA:**

Strong (interfacial) orbital moment anisotropy 00



B  $\geq$ MM

## Nature of interfacial DMI at the Gr/Co



#### Anatomy of the DMI at (1) Co/Pt interface (b,d) (2) gr/Co interface (a,b)

No physical reason to distinguish different DMI mechanisms at (1) and (2)

Blanco-Rey et al., submitted to PRB, arXiv:2111.08556

## **Electric field manipulation of SOC parameters**



0.02

-0.02

-0.04

0.0

0.2

0.4

E-field (eV/Å)

0.6



Non equilibrium Green's function formalism Charlier, et al. in preparation (2022)





Modelled anisotropic response:









#### Ferroelectric and magnetic switches



- Inert metal (Pt) blocks the scavenging òf óxygen at bottom interface
- Ti/Pt top electrode can be used to remove any internal bias field

S. Lancaster et al., IEEE ISAF 2022, accepted



Pr + = 9.4



### WP 4: Spin filtering

Graphene Flagship WP2 Spintronics UMPhy CNRS-Thales, Univ. Cath. Louvain, Univ. of Cambridge



## 2D-MTJs with hybridized graphene Very high MR >80% in single layer graphene nano-MTJs



#### The role of graphene in MTJ

#### Identification of key factors for efficient spin filtering:

- Selection of well-defined spin polarized channels
- hybridization effects
- Spin purification by bulk band structure of the graphene layers

Paper submitted by UCLouvain & UMPHY



### Towards large scale 2D heterostructures band engineering









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AEI PCI2019-111867-2 + PCI2019-111908-2

>4 in preparation

6 submitted

13 experiments at synchrotrons

16 publications [2020-2021]

2 PhD theses defended in 2021



Picquemal-Banci et al. Nat. Comm. 11, 5670 (2020) Ajejas et al. ACS Appl Mat & Inter. 12, 4088 (2020) Olleros et al. ACS Appl Mat & Inter. 12, 25419 (2020) Naganuma, et al. APL (2020) Galbiati et al . ACS Applied Electronic Materials 2, 3508 (2020)

Blanco-Rey et al. ACS Appl. Nano Mater. 4, 4398 (2021) Anadon et al. ACS Appl Nano Mater. 4, 487 (2021) Anadon et al. APL Mater. 9, 061113 (2021) Leveillé et al, Phys. Rev. B 104, L060402 (2021) Zatko et al. ACS nano 15, 7279 (2021) Och et al . Nanoscale 13, 2157 (2021) Mouafo et al. Adv. Func. Mat. 31, 2008255 (2021) Bedoya-Pinto, et al. Science 374, 6567 (2021) Huang, et al. Nature nanotechnology, 16, 981 (2021) Spree, et al. Adv. Funct. Mater. 2021, 31, 2105516 (2021) Giulia, et al. AIP Advances 11, 075302 (2021)

Lancaster, et al., submitted, available on arXiv (2022) Lancaster et al., IEEE ISAF, accepted (2022) Burgos-Parra, et al, submitted PRB (2022) Blanco-Rey, et al., submitted to PRB, arXiv:2111.08556 (2022) Olleros, et al. submitted (2022) Valbuena, et al. submitted (2022)

> Gudin et al. in preparation (2022) Olleros et al. In preparation (2022) De Melo Costa et al. in preparation (2022) Charlier et al. in preparation (2022)

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ANR-19-GRF1-0001

**DFG MI 1247/18-1** 

FNRS R.8012.19





## **Responsible Research Innovation (RRI) at** *SOgraphMEM*



RRI dimension	Activities to carry out at SOgraphMEM	Metrics/Target
Public engagement	<ul> <li>Science events-Initiatives:         <ul> <li>Madrid Science Week</li> <li>Madrid Science and Innovation Fair</li> <li>International Day of Women and Girls in Science</li> <li>Events and conferences organized by FLAGERA</li> <li>Graphene2020 - conference online (October 19-23), https://www.grapheneconfvirtual.com</li> </ul> </li> <li>Stakeholders relevant to the Project: Policy makers, Companies (Samsung, ANTAIOS, Tower Semiconductor Ltd, NVIDIA).</li> </ul>	<ul> <li>Number of attendees per event</li> <li>Number of meetings with companies and policy makers: 1 with Samsung Oct. 2020</li> <li>16 publications [2020-2021] 6 submitted</li> <li>&gt;4 in preparation</li> <li>13 experiments at synchrotrons</li> <li>2 PhD theses defended in 2021</li> </ul>
Open Access/Open Science	<ul> <li>Data repositories: IMDEA Nano's Open Access Repository linked to the OpenAire portal &amp; other public repository (arXiv.org), UCLouvain Open Access Repository DIAL.pr, repository at SOLEIL and ALBA.</li> <li>Data Management Plan (research &amp; laboratory data, scientific texts, dissemination material and exploitation documents), DMPonline.be is a platform that hosts several DMP's template and is available for every researcher of the UCLouvain.</li> </ul>	<ul> <li>Total Number of publications, reviews, open access</li> <li>Number of datasets stored /published</li> <li>Number of plans created / published</li> <li>Consortium Agreement (v 23/02/2021)</li> <li>Data Management Plan (v1.6, submitted)</li> <li>Data Management Plan (v1.7, submitted Dec 21)</li> </ul>
Science education	<ul> <li>Master programme at univerties: Nanotechnology and Condensed Matter at UAM, Specialized Master in Nanotechnoloy at UCLouvain, (etc., UAM, UPS, TU,)</li> <li>"Nanociencia to-go" is an initiative of IMDEA Nanociencia to bring Nanoscience &amp; Nanotechnoology to an older generation of students.</li> </ul>	<ul> <li>Number of students registered per training course/programme</li> <li>Number of sessions developed</li> </ul>
Gender equality	The consortium supports its commitment regarding the Factsheet of 9/12/2013 published by the EU Commission about Gender Equality in Horizon 2020. IMDEA Nanociencia established a <b>Gender Plan</b> including conciliatory measures and formalised a Working Group on Gender Equality in 2018. These past years, the UCLouvain gradually tied the issue of men and women equality in its institutional development by taking very concrete measures (Louvain 2020 project for gender policy). Gender equality is a continuous guiding principle in all fields of action of Forschungszentrum Jülich. It will continue to place a strong emphasis on the recruitment of excellent female scientists, in particular at the professor level. The establishment of structures and key instruments, such as flexible childcare services, specific programs and networks	The consortium strongly encourages the equal participation of all gender for the new recruitment staff, and promotes gender balance at decision-making level. https://nanociencia.imdea.org/sographmem/