instituto imdea nanociencia

https://nanociencia.imdea.org/sograph mem/

EXCELENCIA SEVERO OCHOA 2017-2021

www.nanoscience.imdea.org

GRAPHENE FLAGSHIP

FLAG-ERA

Area: 4. Spin torque and layered-materials-based memory building blocks

Synergy and Complementary to Spintronics WP2 Core program

3. Scalable growth & device integration of UltraLow Power Spin-Orbit Memories based on GRMs JTC2021

Spin Orbit functionalized GRAPHene for resistive-magnetic MEMories *SOgraphMEM*

Paolo Perna, Coordinator

1st January 2020 – 31st December 2022

(+9 months extension)

Kick-off FLAG-ERA 16th March 2021

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

ANR-19-GRF1-0001

DFG MI 1247/18-1

FNRS R.8012.19

instituto imdea nanociencia · cnrs · SOLEIL SYNCHROTRON · ALBA · namlab nanoelectronic materials laboratory · JÜLICH Forschungszentrum · UCLouvain

General overview

Structural perfection

→ *Epitaxial Gr/Co/HM grown on insulating oxides*
→ *FCC structure of Co, pseudomorphic with HM*
→ ***Enabling Transport & Modelling***

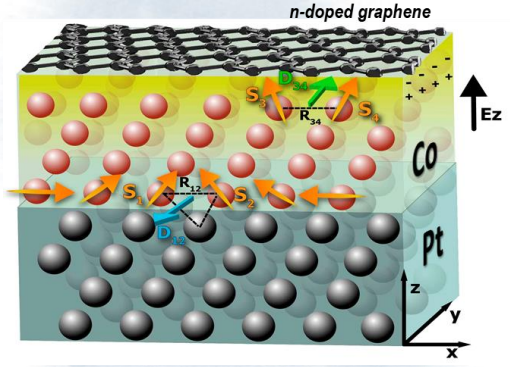
Tuneable SOC-induced interactions

→ *Large PMA, extended up to 20MLs Co*
→ *Rashba-DMI @ Gr/Co OPPOSITE to SOC-DMI @ Co/Pt*

→ ***Enable Electric Field control of:***
- *Orbital magnetic moments*
- *Interfacial magnetic anisotropy*
- *Interfacial Rashba-DMI*

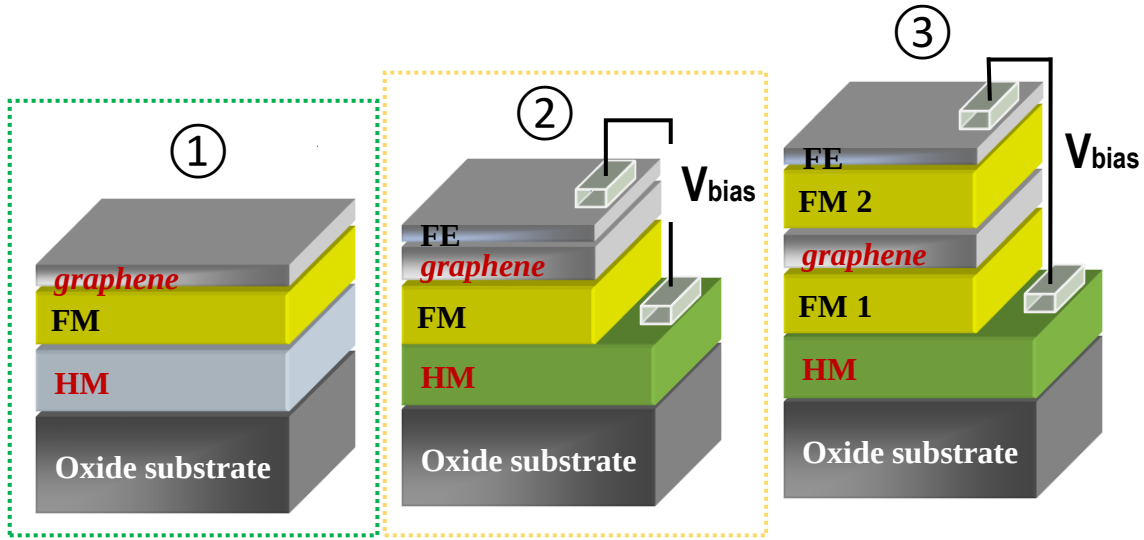
Device fabrication

→ *Chiral Spin texture stable at RT and protected by Gr*
→ *Spin-to-charge conversion*
→ *SOT, magnetic and electric switching*



Continuation of SOgraphene JTC-2015

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



Objectives

O1
- ***Fabrication of Gr/FM/HM ①, FE/Gr/FM/HM ② & SAF ③***
- ***Electric polarization effects***

O2
- ***Effects of electric field on PMA***
- ***Effects of electric field on DMI***

O3
- ***Interfacial exchange interactions***
- ***SHE, SOT-STT***

O4
- ***Magnetic/ferroelectric switching for low consumptive, fast, stable & programmable spin-orbitronics technology***

A *multidisciplinary* Consortium

5 experimental (2 large scale facilities)
2 theoretical

7 partners, 4 EU countries

Consortium Agreement (v 23/02/2021)
Data Management Plan (v1.6, submitted)

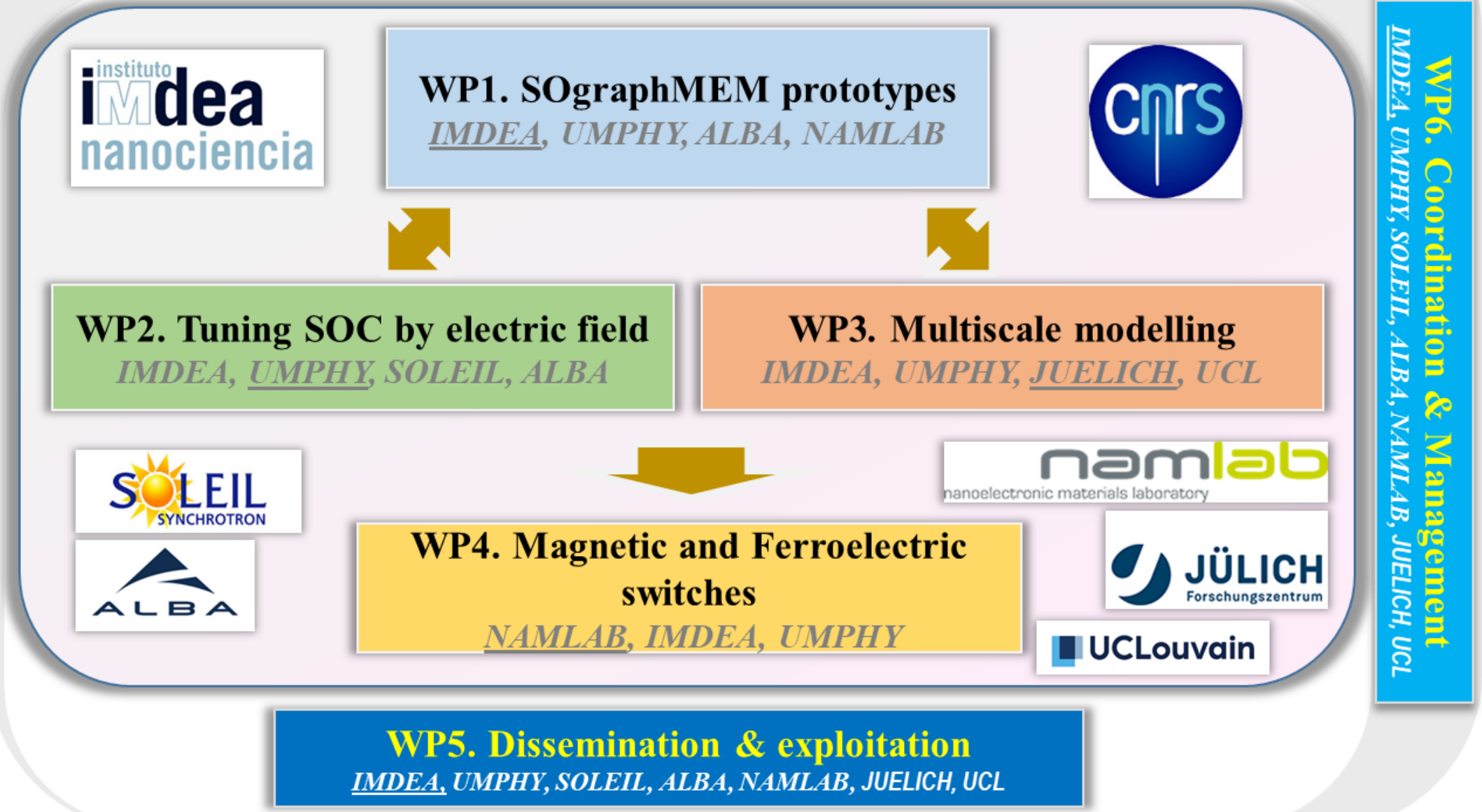
https://nanociencia.imdea.org/sographmem/

Partners and participants involved in the realisation of the project

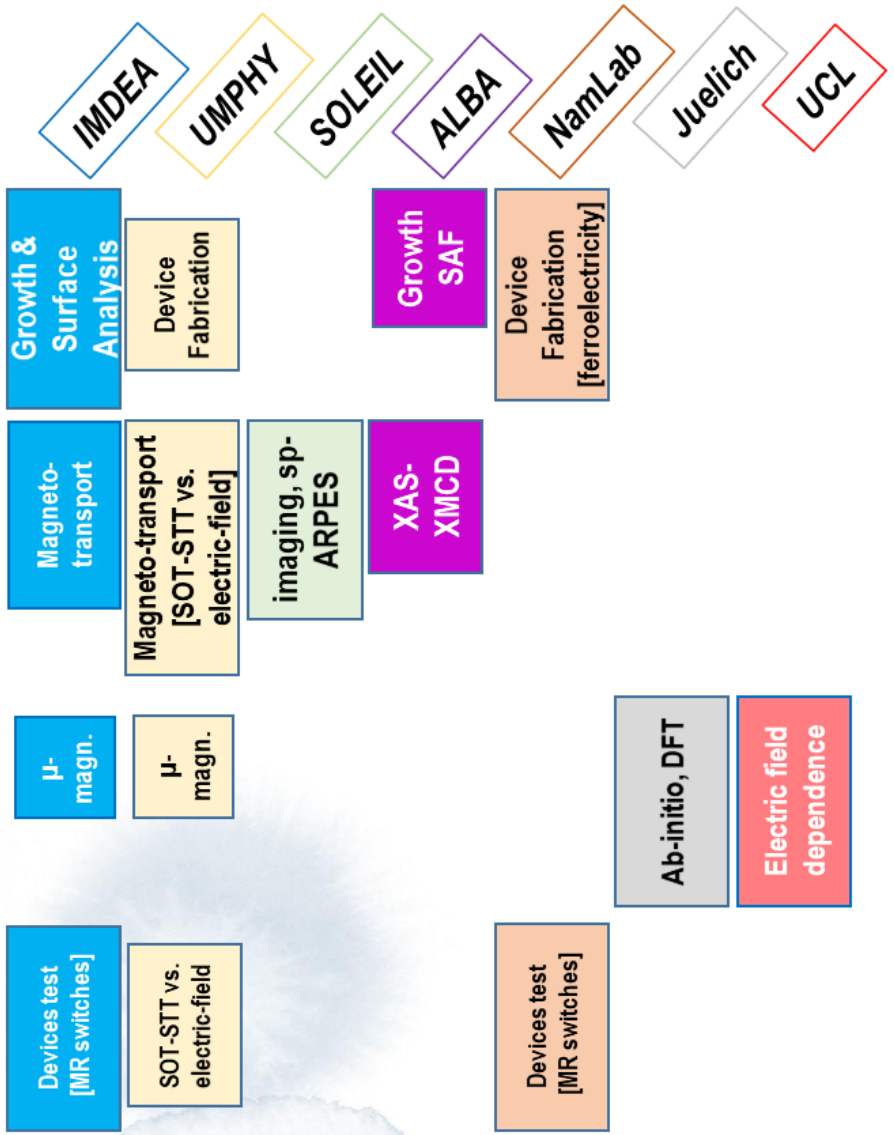
Partner Number	Country	Institution/ Department	Name of the Principal Investigator (PI)	Name of the co-Investigators	
1 *Coord.*	Spain	IMDEA Nanociencia **IMDEA**	Dr. Paolo Perna (coord.)	Prof. Rodolfo Miranda (surface science); Dr. Julio Camarero (growth); Prof. Francisco Guinea (theory)	Core *SOgraph* JTC2015
2	France	CNRS-UMPhy **UMPHY**	Dr. Vincent Cros (magneto-transport)	Prof. Pierre Seneor (spintronics with gr)	
3	France	Soleil Synchrotron **SOLEIL**	Dr. Nicolas Jaouen (scattering)	Dr. Maurizio Sacchi (holography); Dr. François Bertan (Spin ARPES); Dr. Patrick Lefevre (ARPES)	
4	Spain	ALBA Synchrotron **ALBA**	Dr. Manuel Valvidares (magnetic dichroism)	Dr. Pierluigi Gargiani (XMCD under E-field)	
5	Germany	TU Dresden **NaMLab**	Dr. Stefan Slesazeck (memory)	Prof. Dr.-Ing. Thomas Mikolajick; Dr. Uwe Schroeder (FE-HfO_2 material)	
6	Germany	PGI & IAS **JUELICH**	Prof. Dr. Stefan Blügel (SOC modelling)	Prof. Dr. Yuriy Mokrousov	
7	Belgium	UC Louvain **UCL**	Prof. Jean-Christophe Charlier (FE modelling)		Core PI

Synergy and Complementary to Spintronics WP2 Core program

Overview WPs



Overview WPs and *techniques*



SOgraph

Scheme of WPs

WP1. SOgraphMEM prototypes *(IMDEA, UMPHY, ALBA, NAMLAB)*

- *Gr/FM/HM ①, FE/Gr/FM/HM ② & SAF ③.*
- *Electronic and chemical surface properties and magnetic properties*
- *Polarization-Voltage characteristics, PFM-MFM.*

WP2. Tuning SOC by electric field *(IMDEA, UMPHY, SOLEIL, ALBA)*

- *SOT-STT and v-Kerr Magnetometry vs. electric field*
- *XRMR, XR holography and ptychography, MFM, NVM*
- *SP-ARPES*
- *XAS-XMCD*

WP3. Multiscale modelling *(IMDEA, UMPHY, JUELICH, UCL)*

- *SOC-induced parameters (ab-initio, DFT)*
- *FE and SAF (first-principle)*
- *Micromagnetic simulation.*

WP4. Magnetic and ferroelectric switches *(NAMLAB, IMDEA, UMPHY)*

- *Prototype fabrication (lithography)*
- *Magnetic & Ferroelectric switches*
- *Logic operations*

WP5. Dissemination & exploitation (IMDEA, all)

WP6. Coordination & Management (IMDEA, all)

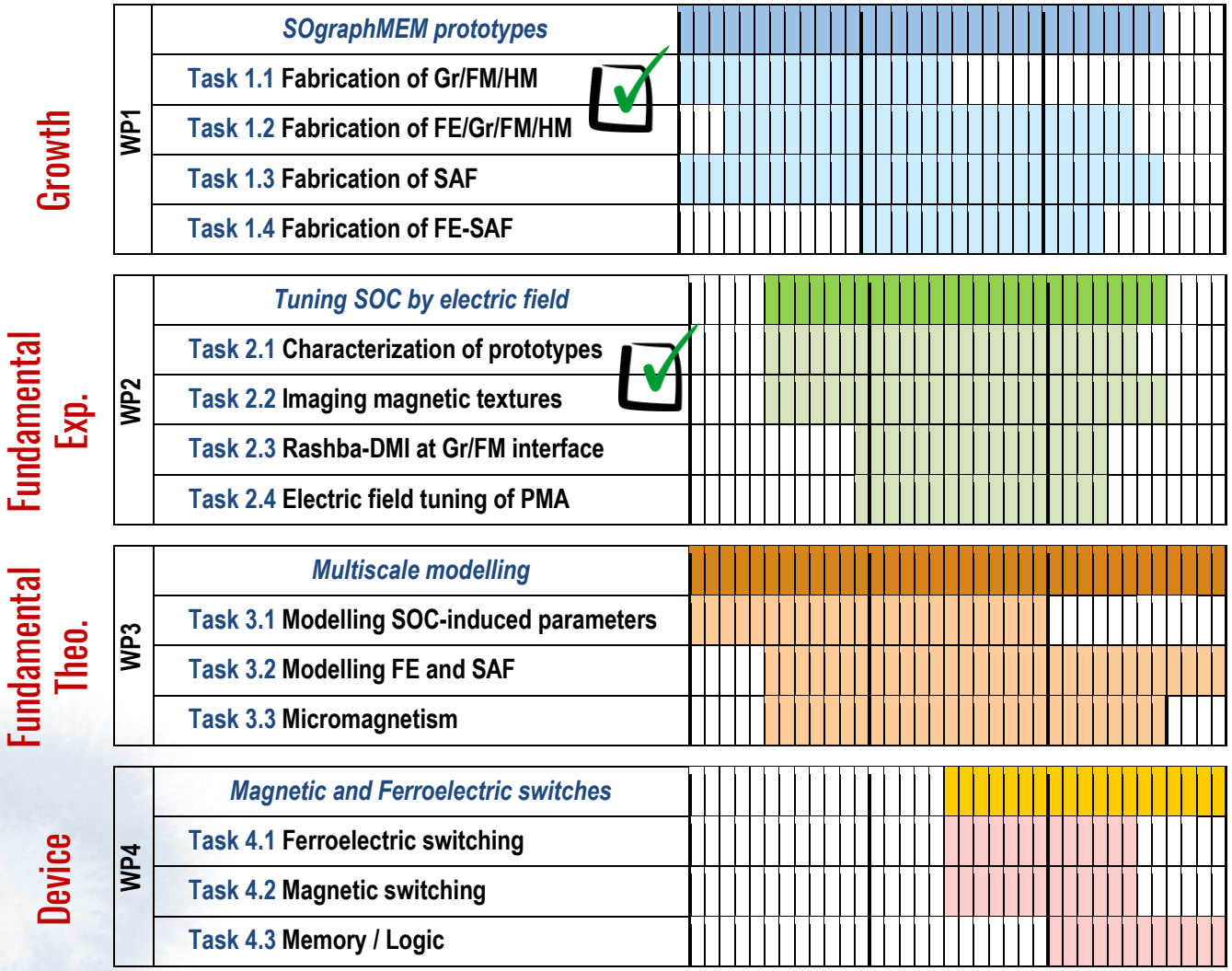
SOgraph

Timeline

SOgraphMEM kick-off, Dec. 2020

FLAGERA kick-off, Mar. 2021

+ 9 months extension



IMDEA: Gr/FM/HM
NamLab: FE
ALBA: SAF

IMDEA, UMPHY: magnetic/current charact.
SOLEIL, ALBA, UMPHY : imaging
SOLEIL, IMDEA: Rashba
ALBA, IMDEA: PMA tuning by electric field

JUELICH: DFT SOC-parameters
UCL: modelling FE
UMPHY, IMDEA: micromagnetism

IMDEA, UMPHY: Magnetic switching
NamLab, all: FE switching, Memory/Logic Operation

new:
Spin-filtering
Spin conversion

Monthly meetings

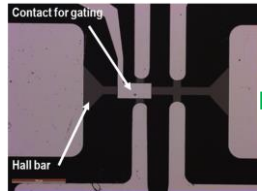
Report on April 2021

Deliverable	Month of delivery	Title of deliverable	*Resp. Partner*
D1.1	12	Report on growth methodology	IMDEA
D1.2	24	Report on FE/Gr/FM/HM fabrication	
D1.3	24	Report on FE-SAF fabrication	
D1.4	24	Report on *Lithography*	NamLab

Deliverable	Month of delivery	Title of deliverable	
D2.1	24	Report on the SOT-STT (vs. electric field) in Gr based systems	CNRS
D2.2	32	Report on imaging of chiral magnetic textures	
D2.3	30	Report on the nature of DMI at Gr/FM (Rashba or intrinsic SOC)	
D2.4	30	Report on modification of orbital magnetic moment by electric field	

Deliverable	Month of delivery	Title of deliverable	
D3.1	24	Report on modelling SOC	JUELICH
D3.2	36	Report on SAF and FE capped magnetic heterostructures	
D3.3	32	Report on Micromagnetic simulations	IMDEA

Deliverable	Month of delivery	Title of deliverable
D4.1	32	Report on ferroelectric switching
D4.2	32	Report on magnetic switching
D4.3	36	Report on memory/logic operations



new:
Spin-filtering
Spin conversion

Deliverable	Month of delivery	Title of deliverable
D5.1	2	Creation of a SO*graphMEM* webpage and public project presentation
D5.2	6	Elaboration of printed materials to promote the project.
D5.3	36	Report on the socio-economic impact of the results.

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Deliverable	Month of delivery	Title of deliverable	
D6.1	18	Risks identification revision	IMDEA
D6.2	12-24-36	Periodical report on the obtained results	
D6.3	36	Final report	

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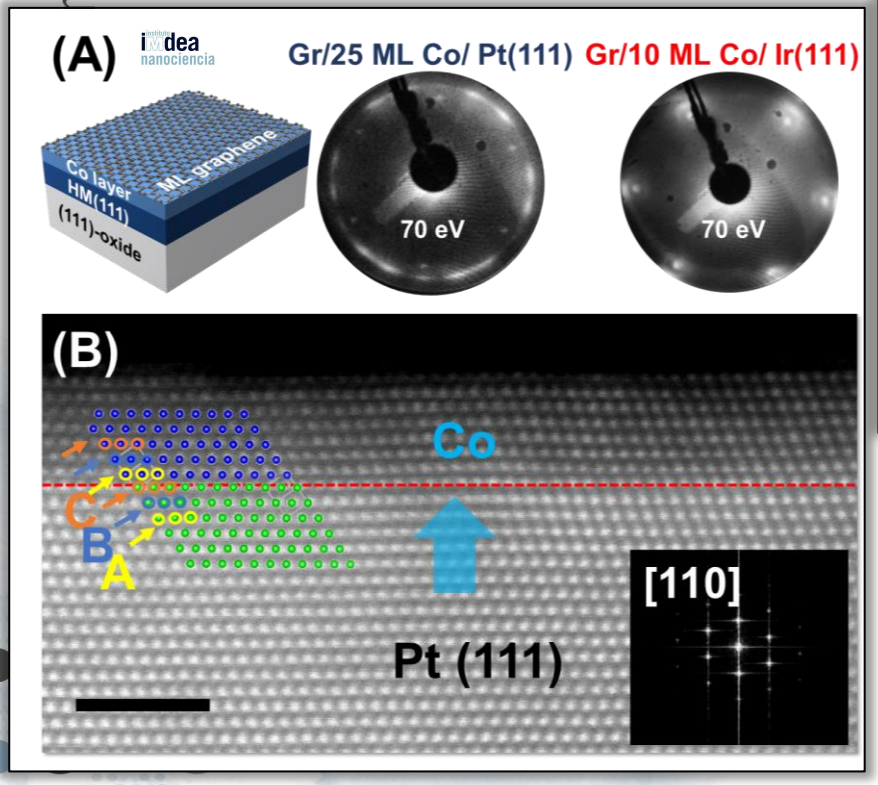
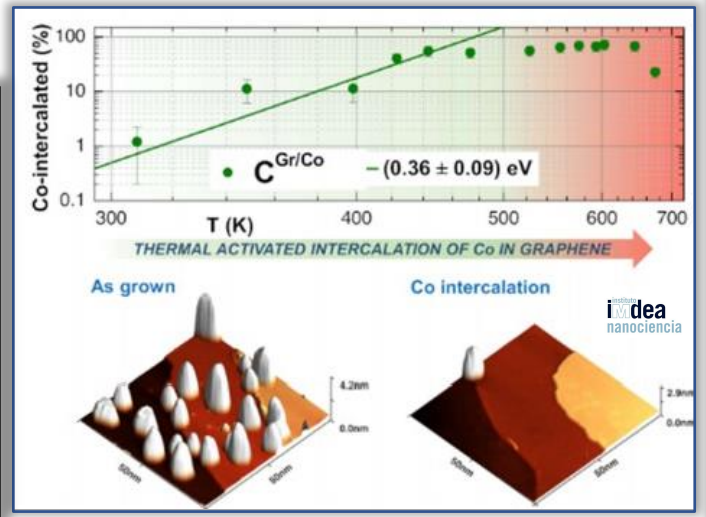
WP1: Fabrication of prototypes

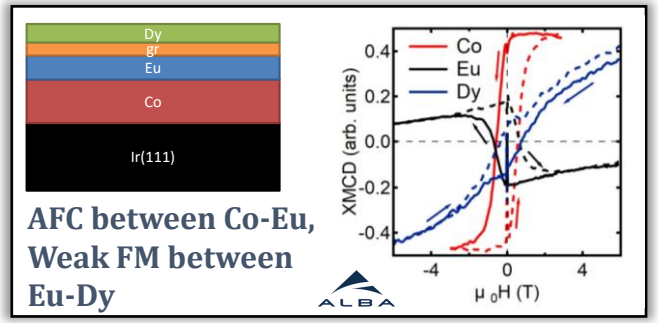
F. Ajejas, et al. ACS Appl. Mater. Interfaces 2020, 12, 4088
M. Blanco-Rey, et al. ACS Applied Nano Mater. 2021
S. Lancaster, et al. 2021 in progress (HZO)
L. De Melo Costa, PhD thesis 2021 in progress (4f-Gr)

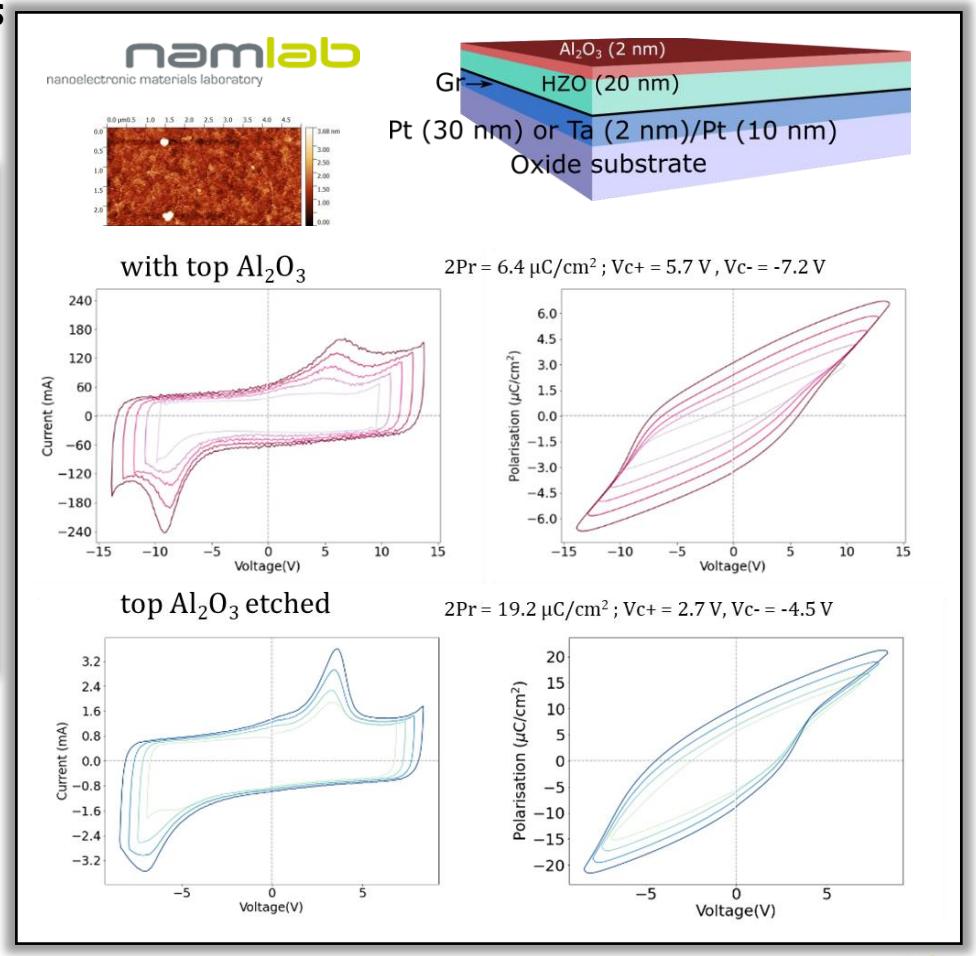
- **@ IMDEA: Growth of Epitaxial, Gr/Co/HM structures onto Al2O3(0001) and STO(111) by UHV CVD + MBE**
- **@ NamLab: Growth of FE ZrHfOx, by ALD, optimization of layer stack, interlayer, ..**
- **@ ALBA: Growth of SAF**
- **Analysis in-situ of the structural, electronic and chemical surface properties**
- **Analysis ex-situ of the structural and magneto-transport properties**
- **Analysis ex-situ of electric-polarization properties**



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



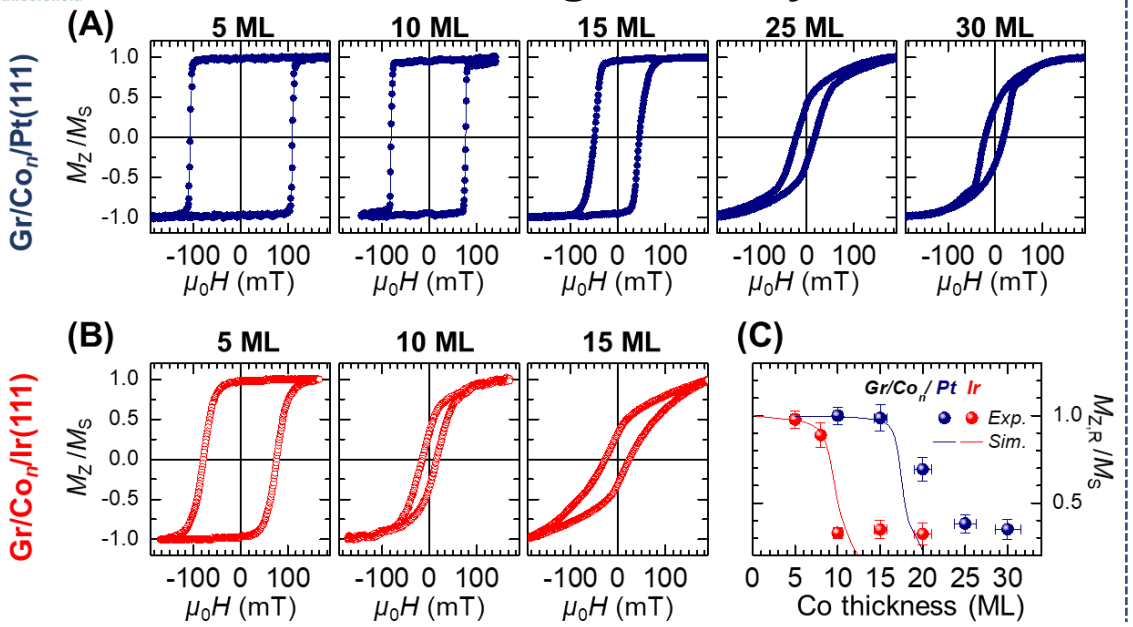




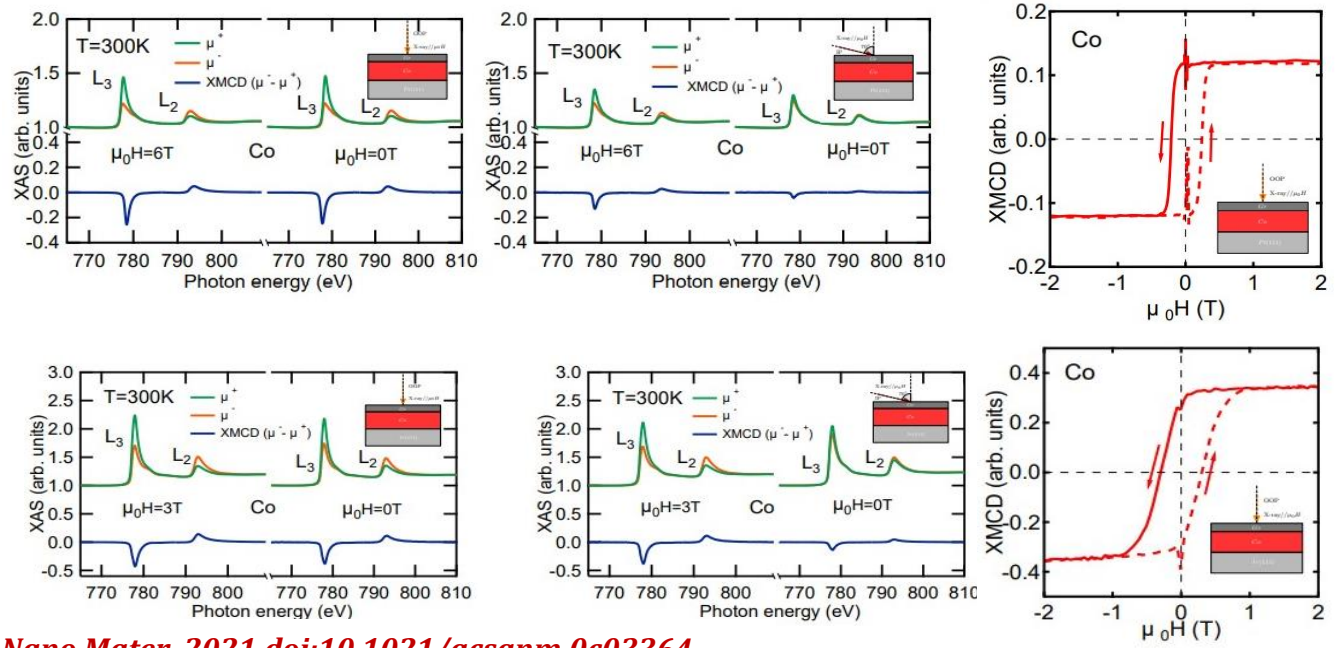
WP2: magneto-transport characterization

WP2
- Tuning SOC by electric field
- Task 2.1 Characterization of prototypes
- Task 2.2 Imaging magnetic textures

Kerr magnetometry



XAS-XMCD experiments

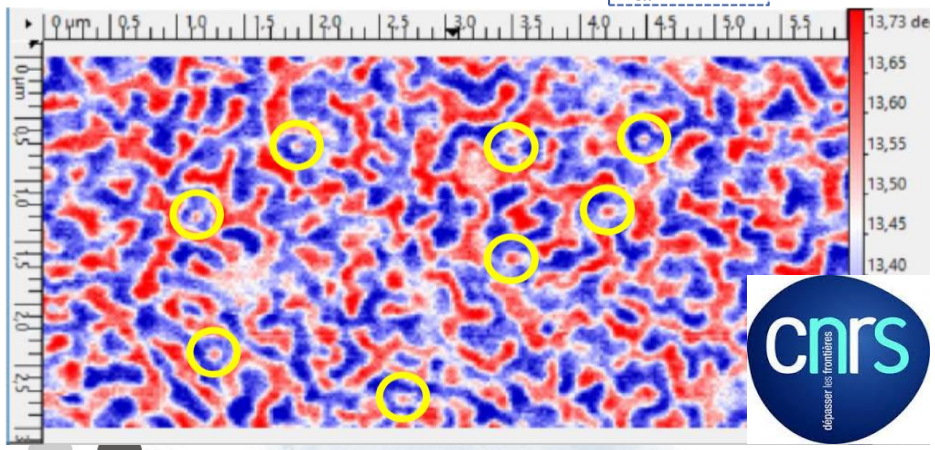


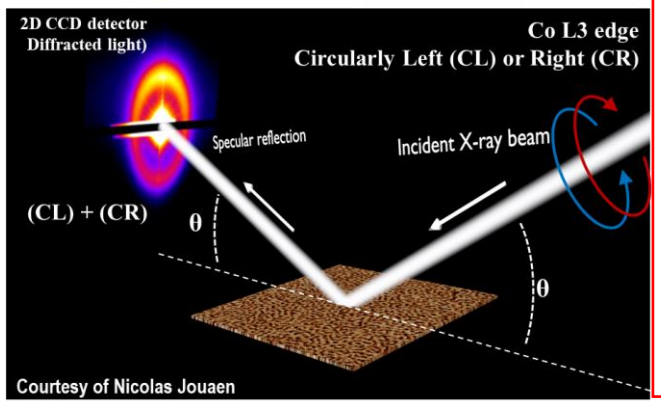
M. Blanco-Rey, et al. ACS Applied Nano Mater. 2021 doi:10.1021/acsanm.0c03364

MFM at ZF after in-plane demagnetization

Gr / Co (3nm) / Pt(111) on Al_2O_3(0001)

d_{sk} < 100 nm

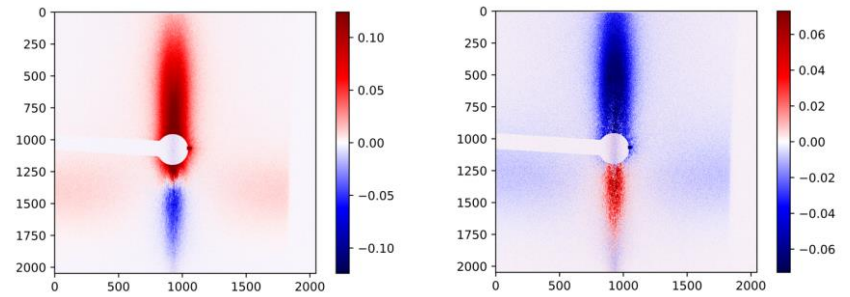




Bloch Skyrmions in Gr / Co (3 nm) / Pt

H= 0 mT

H= 20 mT



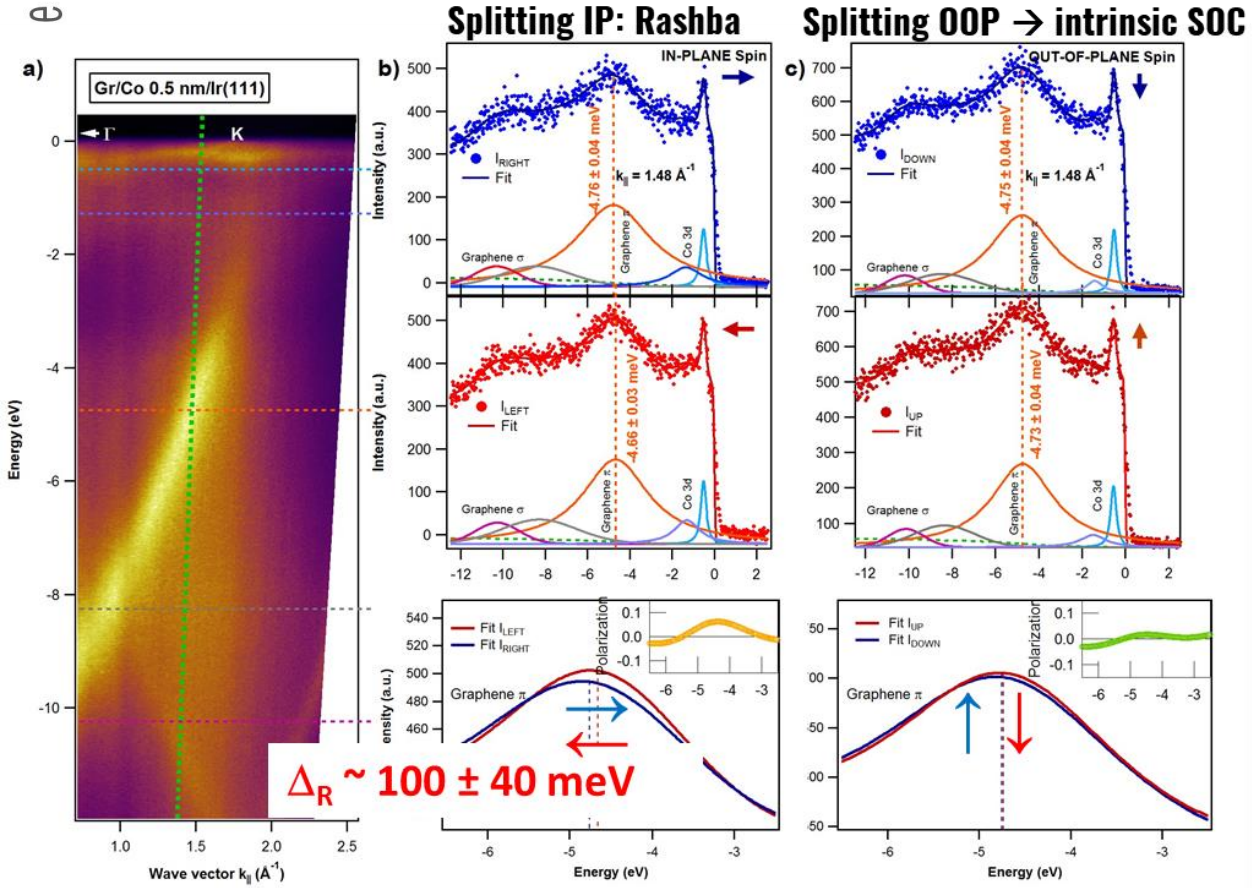
A. Gudin, et al. 2021 in progress (scattering)

WP2: magneto-transport characterization

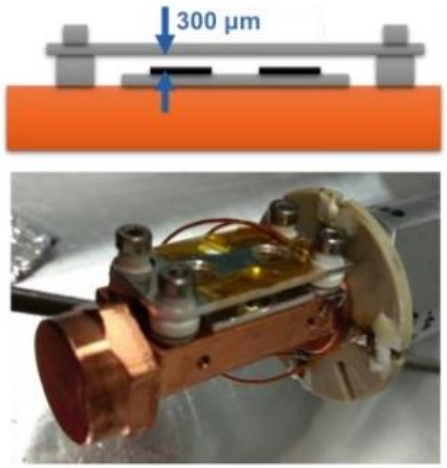
WP2	
	Tuning SOC by electric field
	Task 2.1 Characterization of prototypes
	Task 2.2 Imaging magnetic textures
	Task 2.3 Rashba-DMI at Gr/FM interface
	Task 2.4 Electric field tuning of PMA

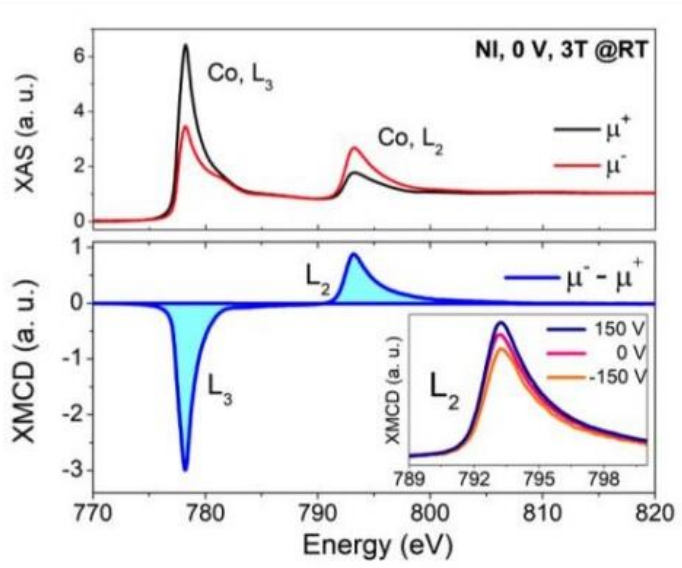
Cancelled SP-ARPES in BESSY II
Collaboration with ELETTRA
Proposal SOLEIL
Exp. ALBA on June 2021
Exp. ESRF on June 2021

Exp. 20181593 @ CASSIOPHEE + new Exp. 2021



Exp. No. 2019023333 @ BOREAS + new exp. 2021





A. Gudin, JM Diaz, M. Valbuena, et al. 2021 in progress (sp-ARPES)
A. Gudin, I. Arnay, et al. 2021 in progress (electric field XMCD)

WP3: Modelling SOC

WP3	
	Multiscale modelling
	Task 3.1 Modelling SOC-induced parameters
	Task 3.2 Modelling FE and SAF
	Task 3.3 Micromagnetism

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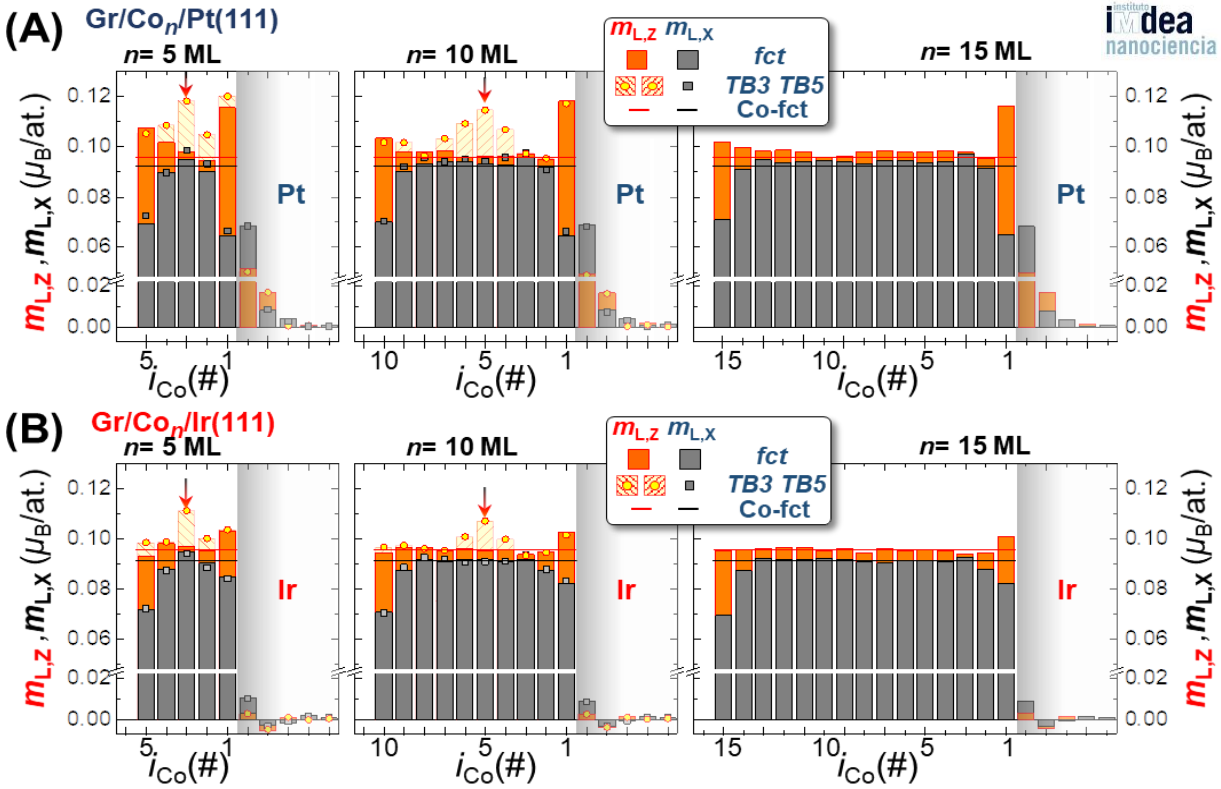
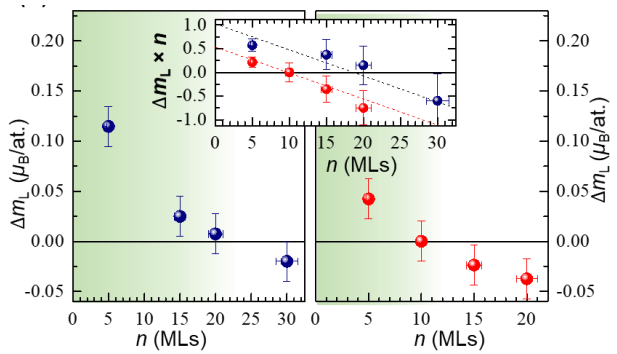
JUELICH: DFT SOC-parameters
UCL: modelling FE
UMPHY, IMDEA: micromagnetism

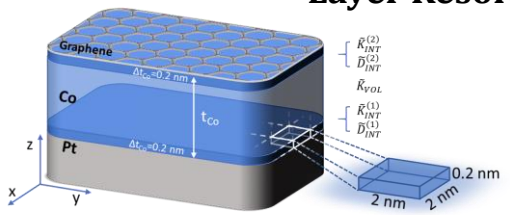




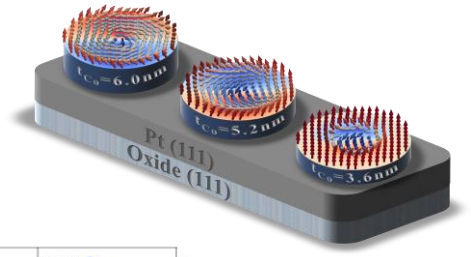
M. Blanco-Rey, et al. ACS Applied Nano Mater. 2021 doi:10.1021/acsanm.0c03364

Collaboration ICMM-CSIC, UPV/EHU, UCM, ALBA, IMDEA

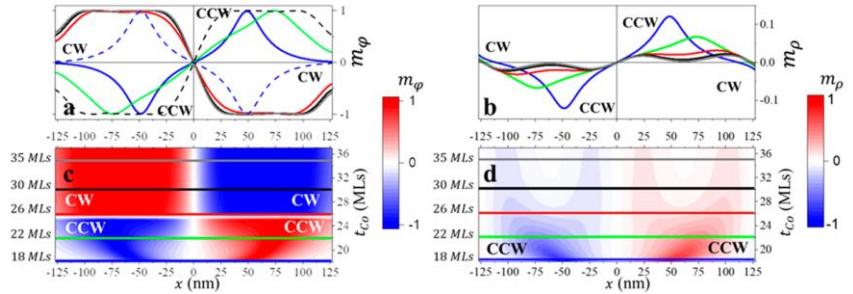
Layer Resolved Micromagnetic Model



P. Olleros, et al. ACS Appl. Mater. Interfaces 2020, 12, 25419



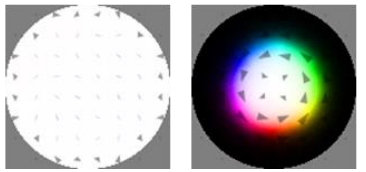
Intrinsic Mixed Bloch–Neel Character and Chirality of Skyrmions in an Asymmetric Epitaxial Trilayer



JÜLICH Forschungszentrum
UCLouvain
spirit github.com/spirit-code
fleur

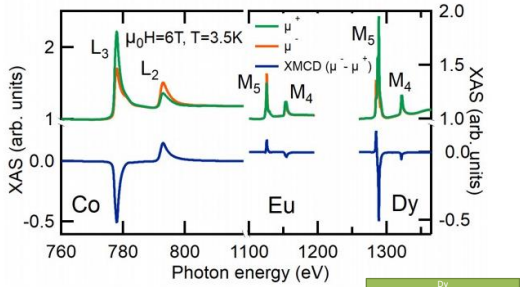
SOC & skyrmion vs. E AFM & FM Coupling

Nucleation in 256nm dots with voltage pulse
Initial saturated state After voltage

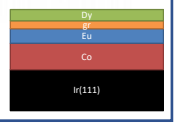


P. Olleros, et al. 2021 in preparation

L. De Melo Costa, PhD thesis 2021 in progress (4f-Gr)



ALBA



WP 4: Device

- ☑ *Lithography design*
- ☑ *Ferroelectric and magnetic switches*
- ☑ *Spin-filtering, Spin Charge Conversion*

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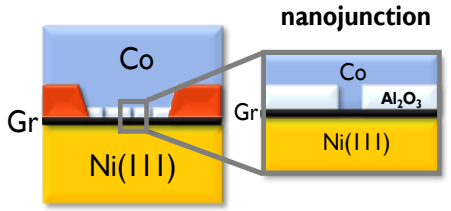
2D-MTJs with hybridized graphene

Very high MR >80% in single layer graphene nano-MTJs

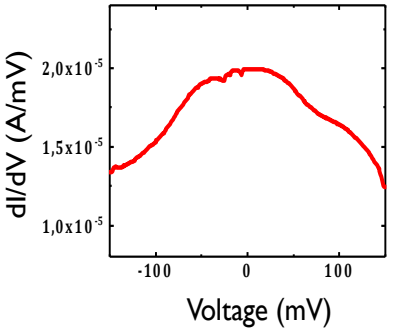
Graphene Flagship WP2 Spintronics

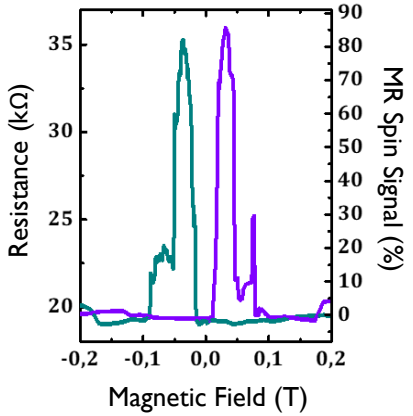
UMPhy CNRS-Thales, Univ. Cath. Louvain, Univ. of Cambridge

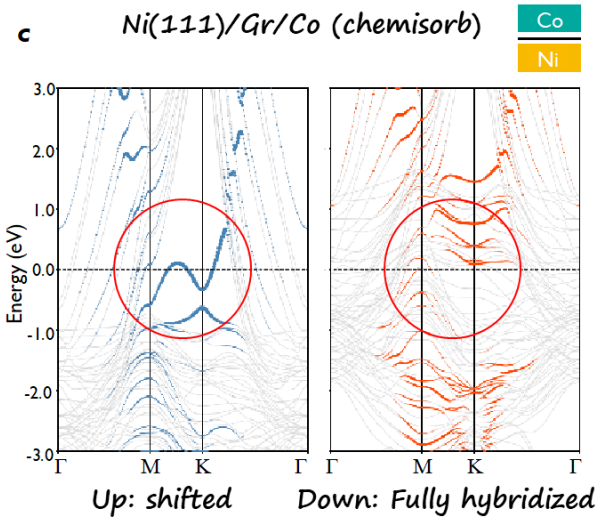
M. Piquemal-Banci et al. Nat Com (2020)



Ni(111)/Gr/Co



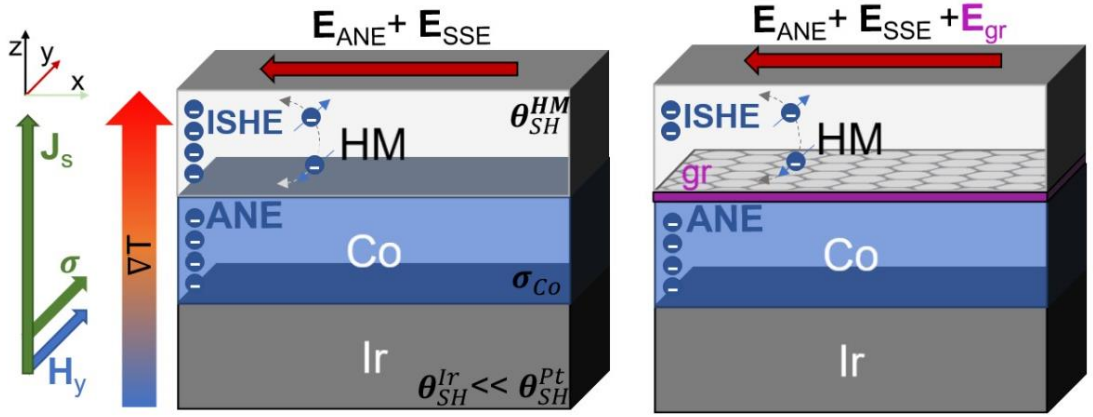


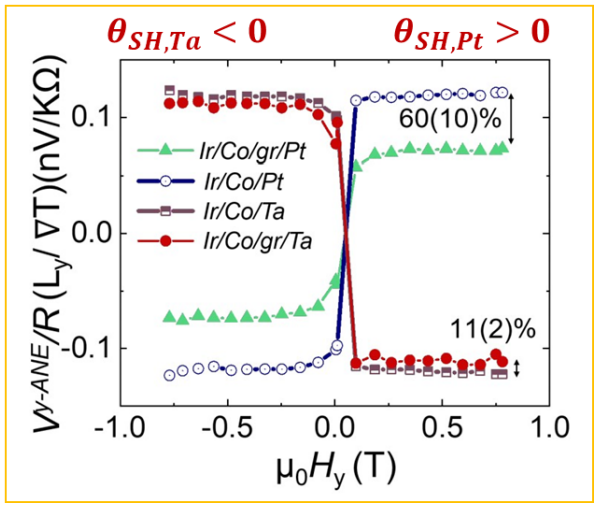


Spin filtering

High TMR explained by interfacial hybridization (i.e. spinterface)

Engineering Spin-Conversion in Graphene / FM epitaxial stacks





IREE

Spin memory loss

A. Anadon et al. APL Mater. (2021) submitted

Responsible Research Innovation (RRI) at *SOgraphMEM*

RRI dimension	Activities to carry out at SOgraphMEM	Metrics/Target
Public engagement	- **Science events-Initiatives**: • *Madrid Science Week* • *Madrid Science and Innovation Fair* • *International Day of Women and Girls in Science* • *Events and conferences organized by FLAGERA* • *Graphene2020 - conference online (October 19-23), https://www.grapheneconfvirtual.com* - **Stakeholders relevant to the Project:** Policy makers, Companies (*Samsung, ANTAIOS, Tower Semiconductor Ltd, NVIDIA*).	- Number of attendees per event - Number of meetings with companies and policy makers: 1 with Samsung Oct. 2020 **M. Picquemal-Banci et al. Nat. Comm. 2020, 11, 5670** **F. Ajejas et al. ACS Appl Mat & Inter. 2020, 12, 4088** **P. Olleros et al. ACS Appl Mat & Inter. 2020.,12, 25419** **A. Anadon et al. ACS Appl Nano Mater. 2021, 4, 487** **M. Blanco-Rey et al. ACS Appl Nano Mater. 2021, *doi:10.1021/acsanm.0c03364***
Open Access/Open Science	- **Data repositories**: IMDEA Nano´s Open Access Repository linked to the OpenAire portal & other public repository (arXiv.org), UCLouvain Open Access Repository DIAL.pr, repository at SOLEIL and ALBA. - **Data Management Plan** (research & 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.	- Total Number of publications, reviews, open access - Number of datasets stored /published - Number of plans created / published **Consortium Agreement (v 23/02/2021)** **Data Management Plan (v1.6, submitted)**
Science education	- Master programme at univerties: Nanotechnology and Condensed Matter at UAM, **Specialized Master in Nanotechnoloy at UCLouvain,** (etc., UAM, UPS, TU, ..) - "**Nanociencia to-go"** is an initiative of IMDEA Nanociencia to bring Nanoscience & Nanotechnoology to an older generation of students.	- Number of students registered per training course/programme - Number of sessions developed
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 **Gender Plan** 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).	The consortium strongly encourages the equal participation of all gender for the new recruitment staff, and promotes gender balance at decision-making level.