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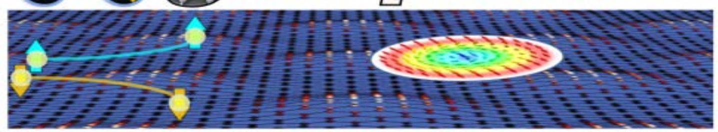
SOgraphene



Tailoring Spin-Orbit effects in graphene for Spin-Orbitronic applications

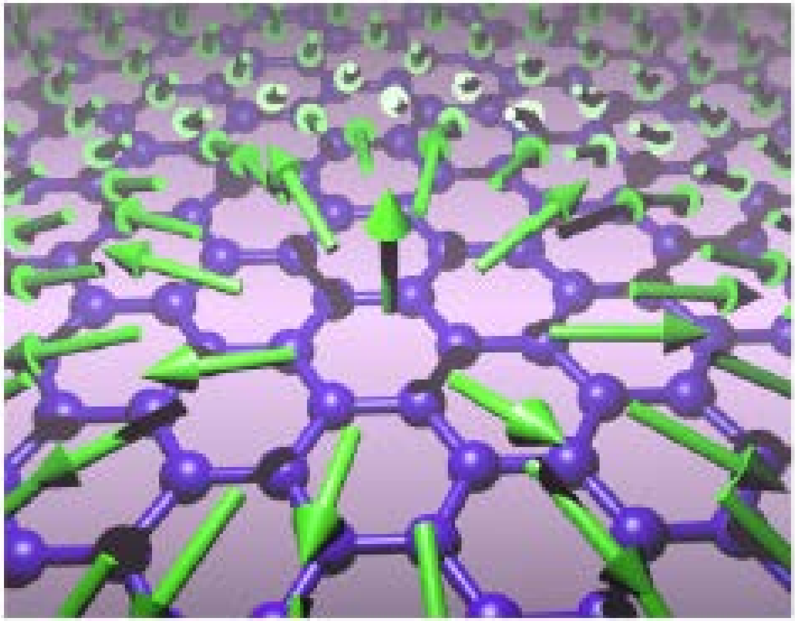
Rodolfo Miranda

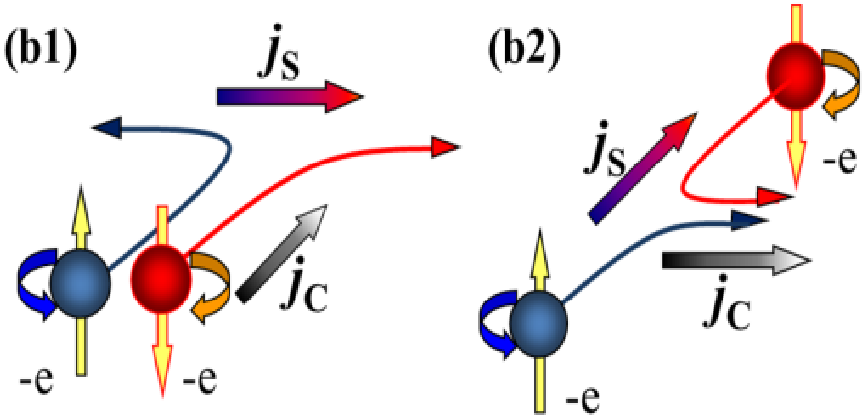
UMPHY CNRS-THALES

IMDEA nanoscience	CNRS	SOLEIL SYNCHROTRON	IPM *srl*
MINECO	ANR	ANR	MIUR

Creating a giant Spin-Orbit Coupling in graphene

- Hosting magnetic skyrmions
- Spin Hall Effect: Production or detection of pure spin currents





SHE

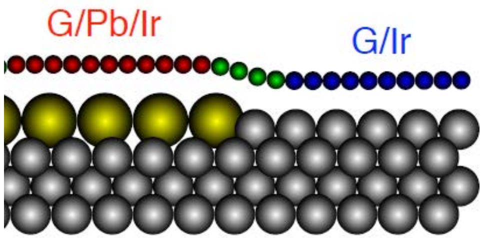
iSHE

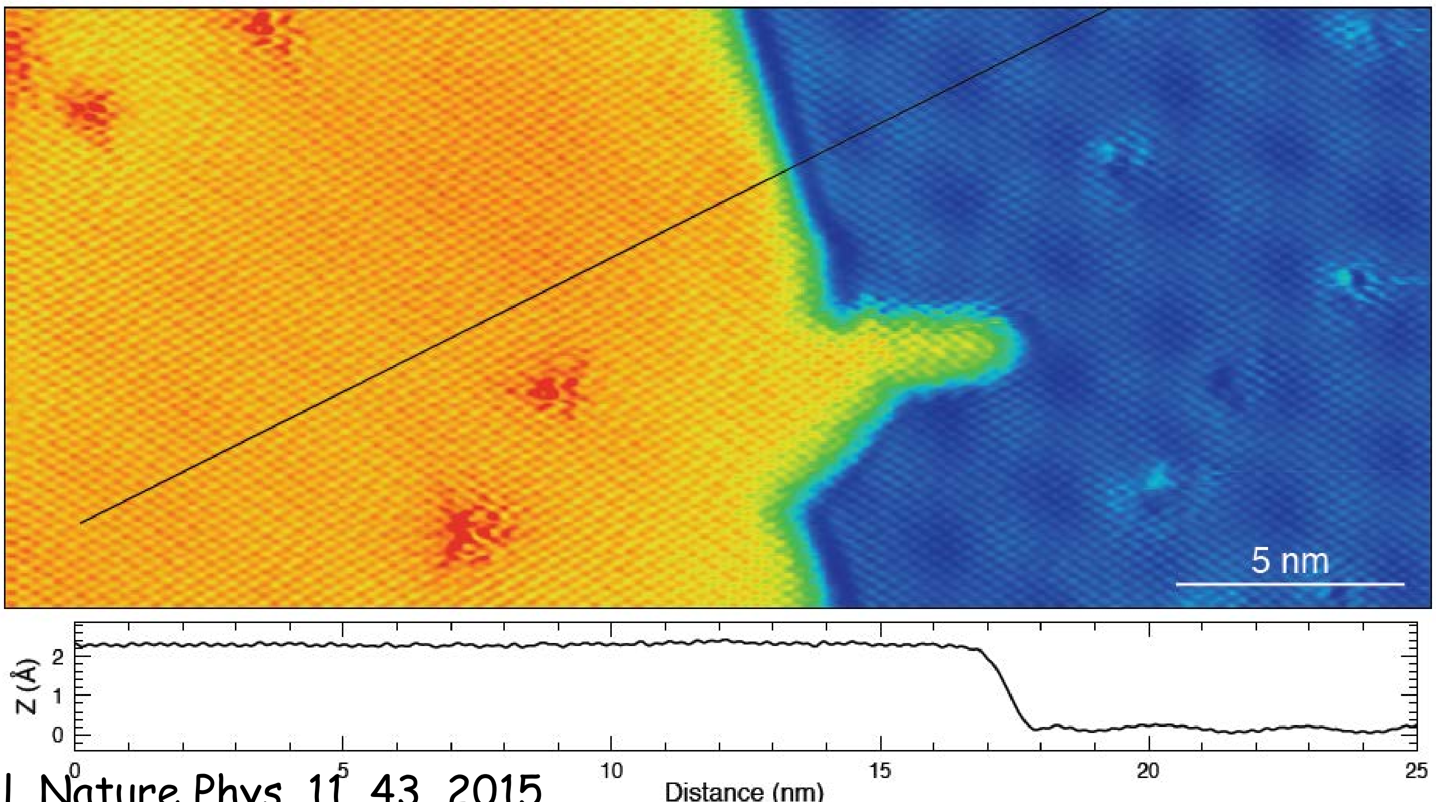
SpinOrbitronics in graphene

Pb-intercalated Graphene/Ir(111)

Inducing a giant Spin-Orbit Coupling in graphene

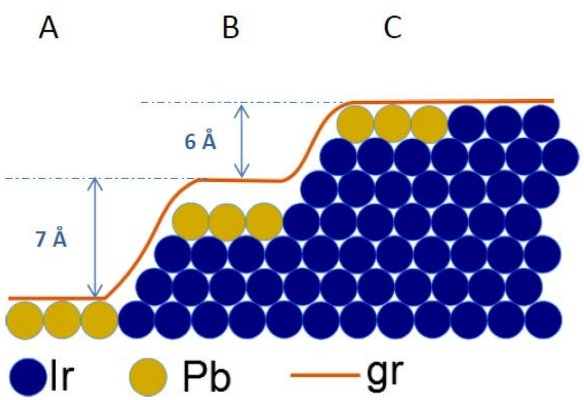
- By intercalation of suitable elements (Pb)
- By proximity with semiconducting WSe2
- By proximity with Topological Insulators

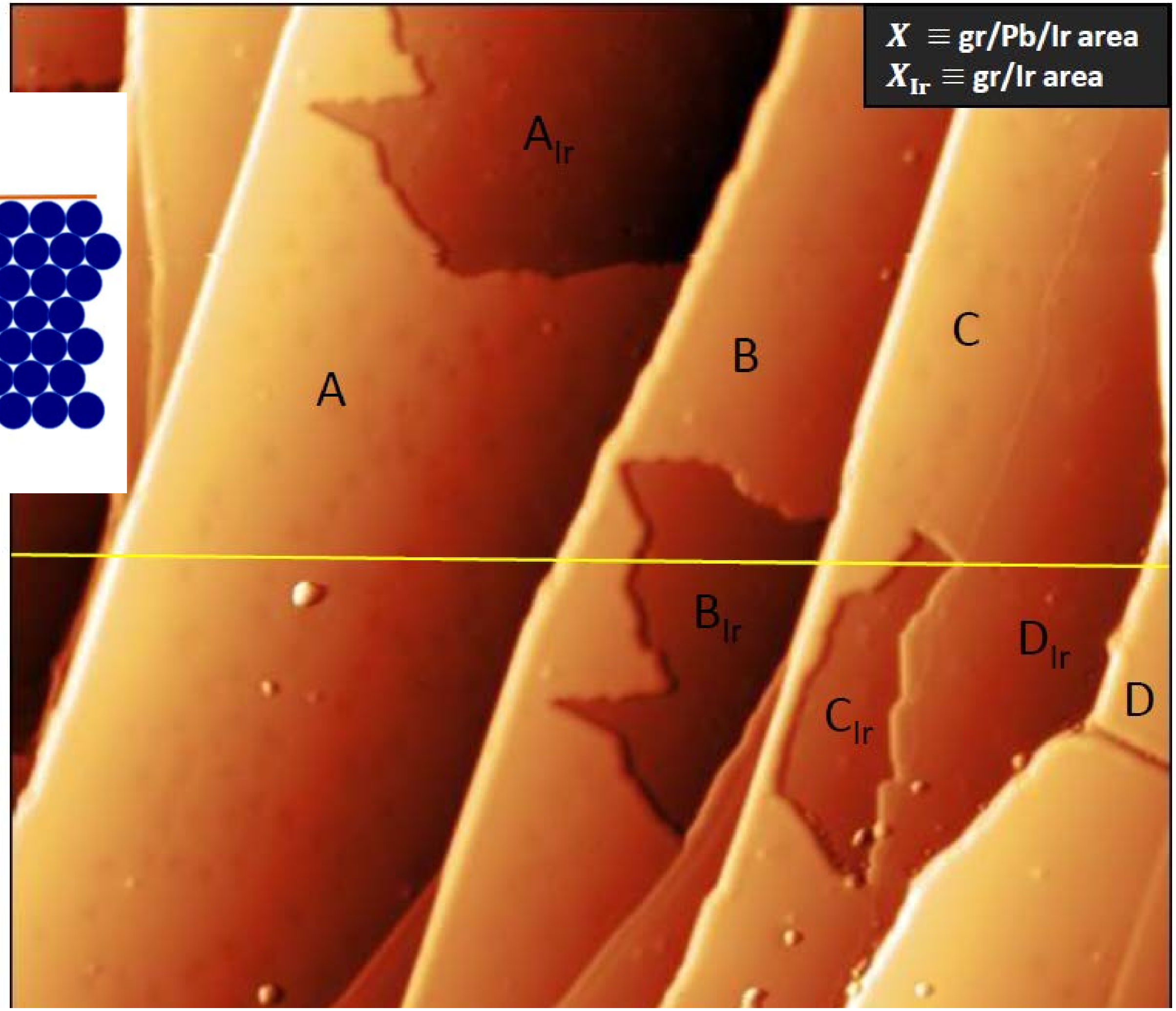




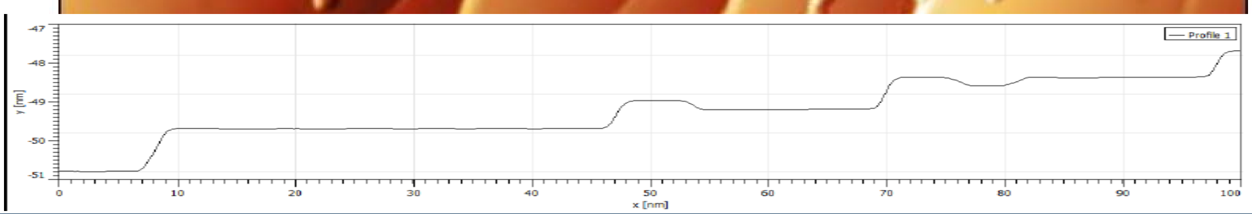
F. Calleja et al, Nature Phys. 11, 43, 2015

Pb-intercalated Graphene/Ir(111)



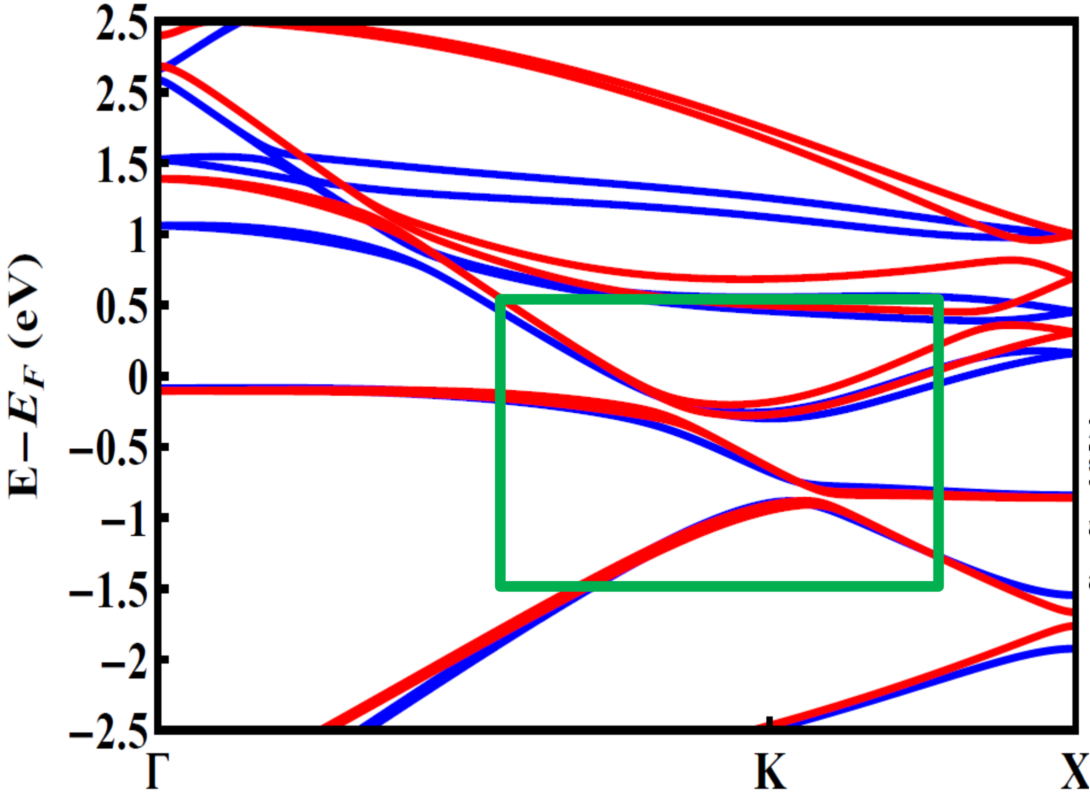


100 nm x100 nm



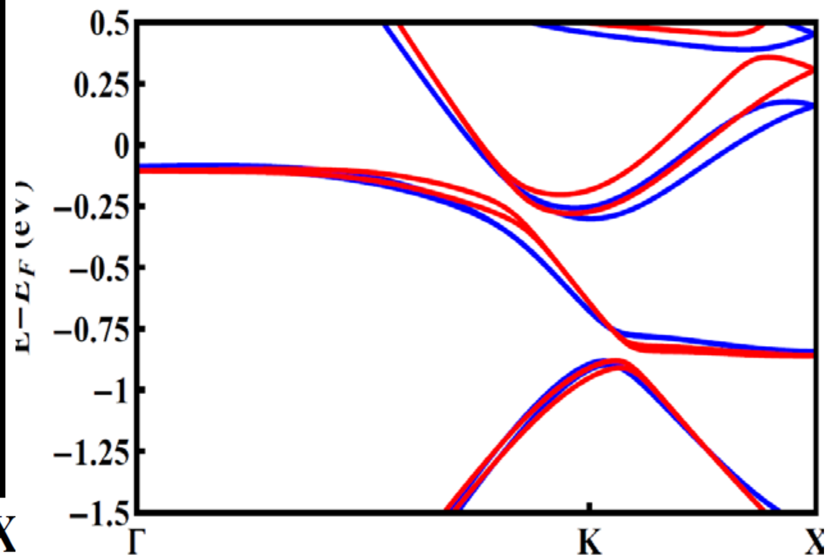
Spin-split Graphene bands by a Giant Spin Orbit interaction induced by Pb atoms

Δ_{SO} > 50 meV



DFT band structure

Tight Binding band structure

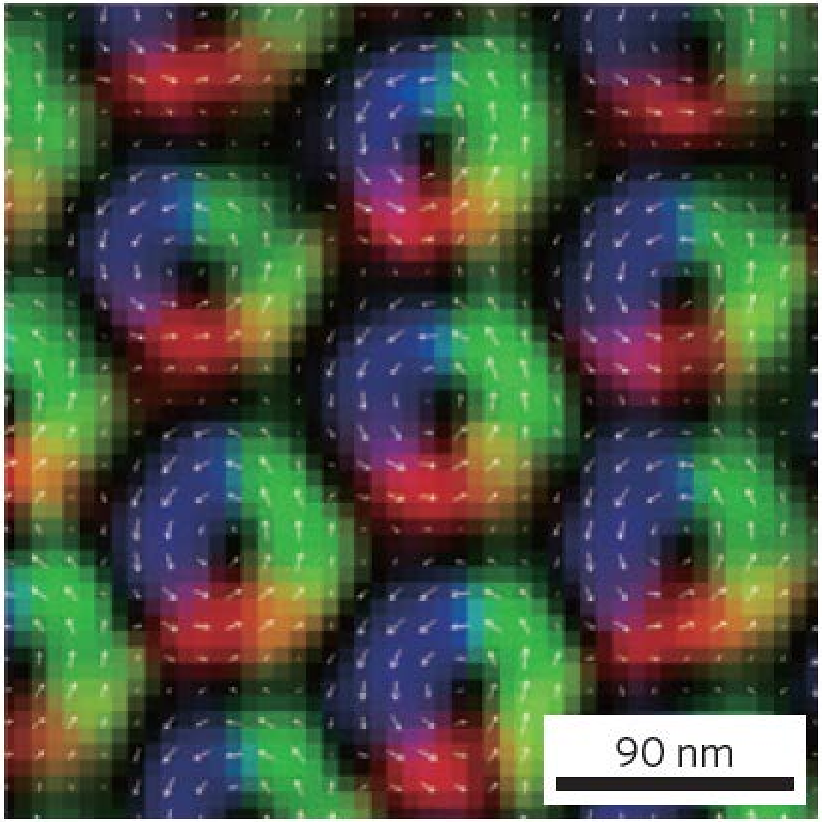


F. Calleja et al, Nature Phys. 11, 43, 2015

Magnetic skyrmions

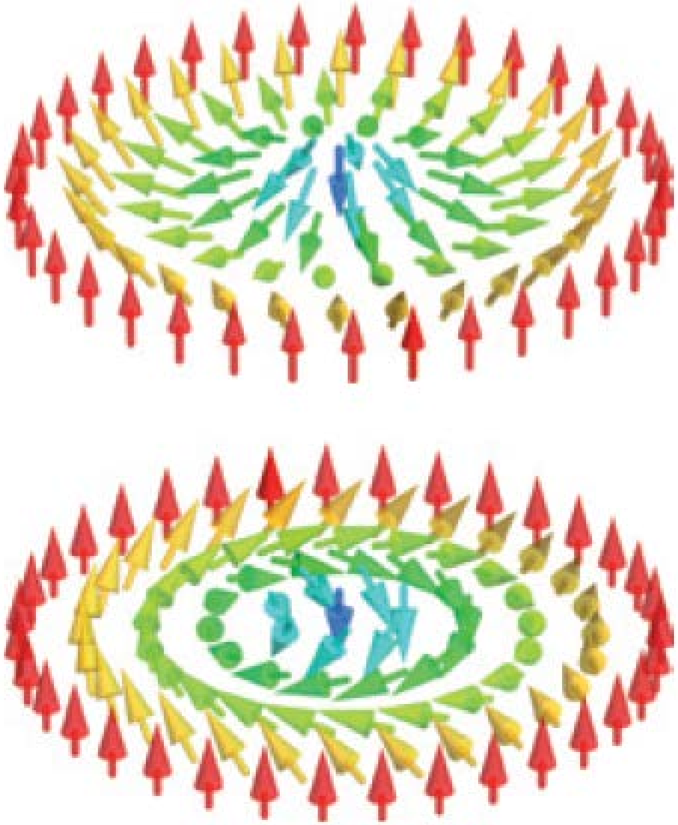
Topologically protected spin configurations

Lorentz microscopy



$Fe_{1-x}Co_xSi$ in 150 mT

Yu et al, Nature 2010



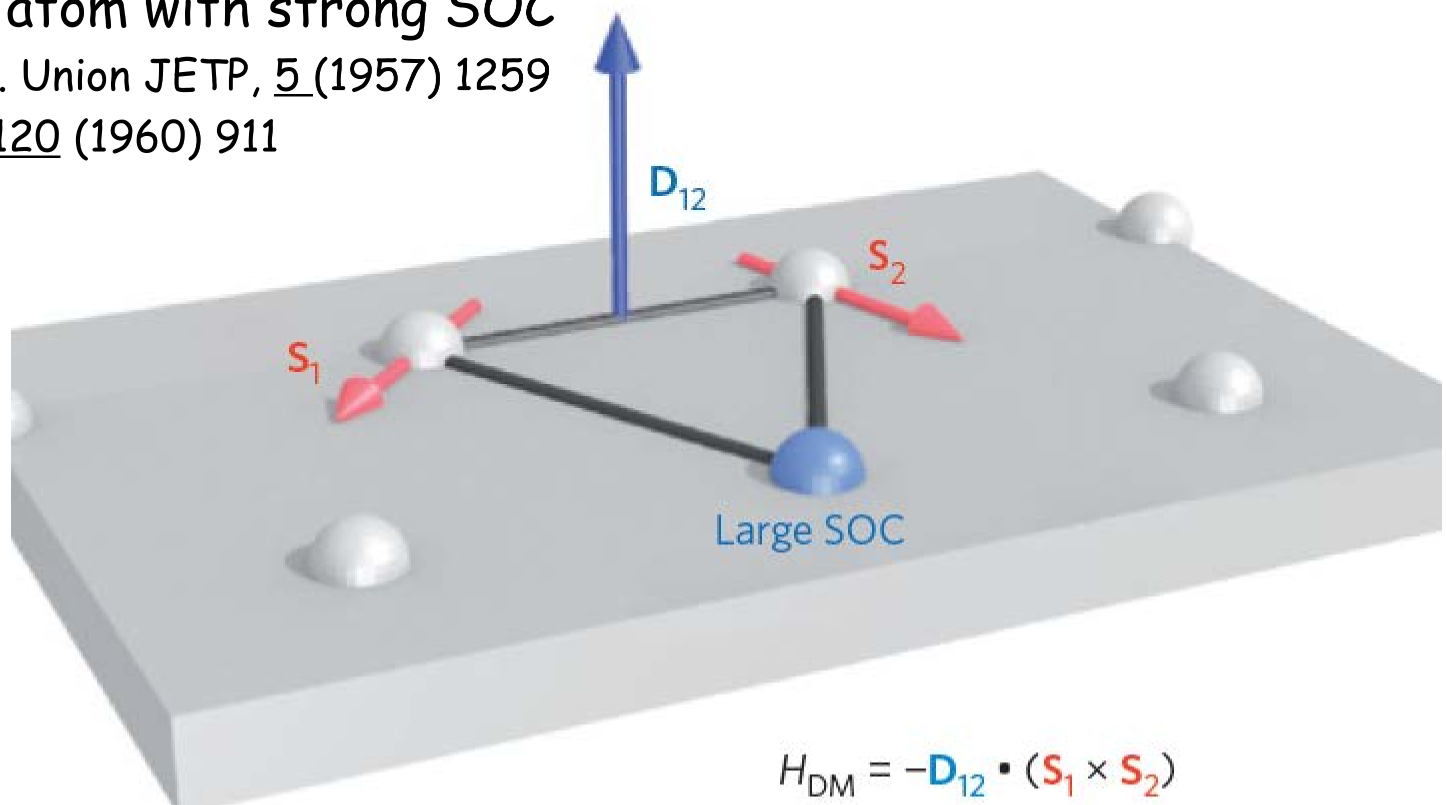
Magnetic skyrmions

- Originate from chiral interactions (DMI) induced by SOC and breaking of the inversion symmetry in lattices or at interfaces

- DMI generated by indirect exchange between two spins and an atom with strong SOC

Dzyaloshinskii, Sov. Union JETP, 5 (1957) 1259

Moriya, Phys. Rev. 120 (1960) 911

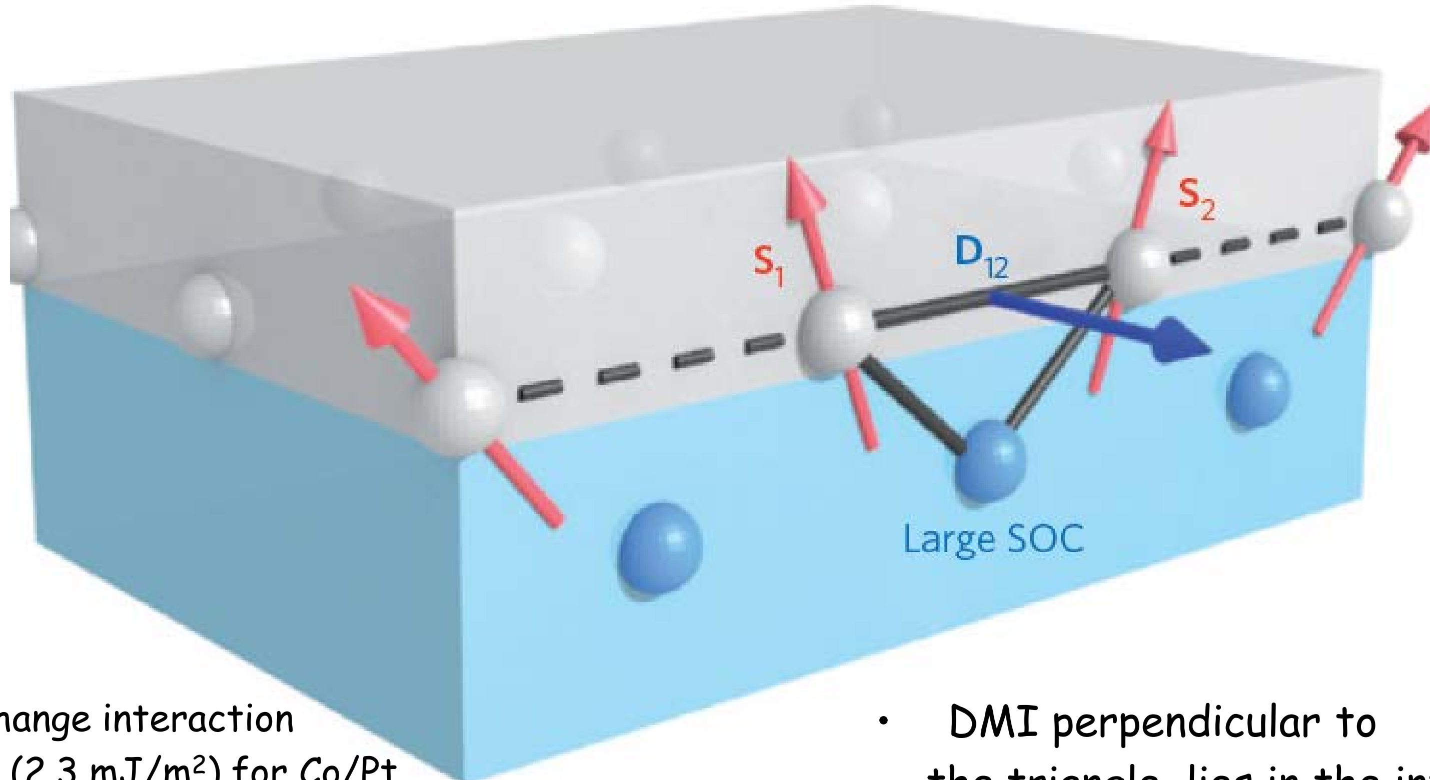


$H_{DM} = -\mathbf{D}_{12} \cdot (\mathbf{S}_1 \times \mathbf{S}_2)$

A. Fert and P.M. Levy, PRL, 44, (1980)1538

SOC-induced DMI chiral interaction at interfaces

- Ultrathin Ferromagnetic metal (e.g. Co) with out of plane anosotropy/ Material with large SOC (eg. Pb, Pt)

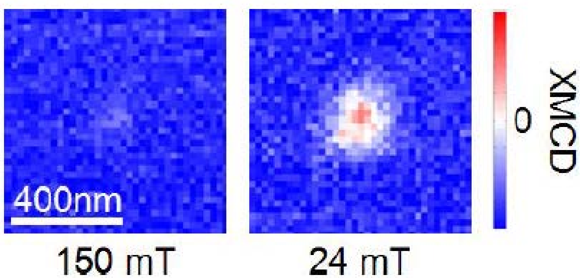


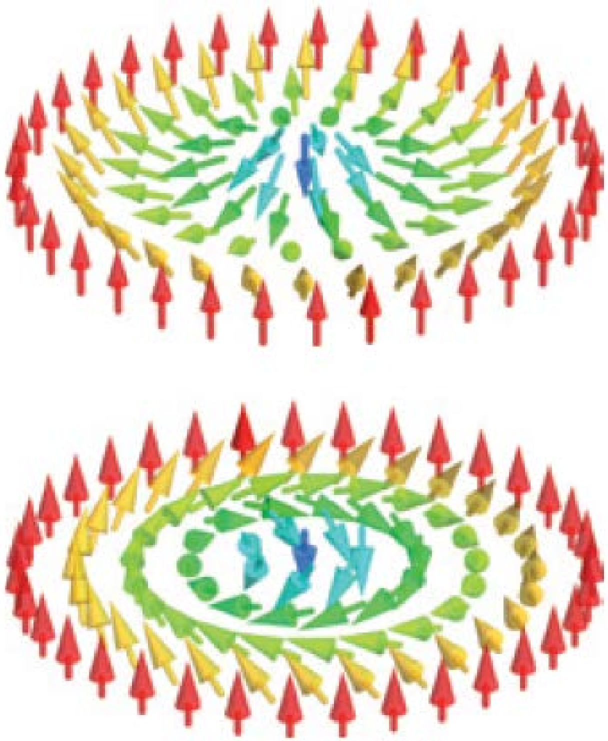
20% of the Exchange interaction
D≈ 1.8 meV/pair (2.3 mJ/m^2) for Co/Pt

- DMI perpendicular to the triangle, lies in the interface

DMI chiral interaction

- In a 2D ferromagnet with uniaxial (perpendicular) anisotropy (K), a non-negligible DMI results in a skyrmion structure





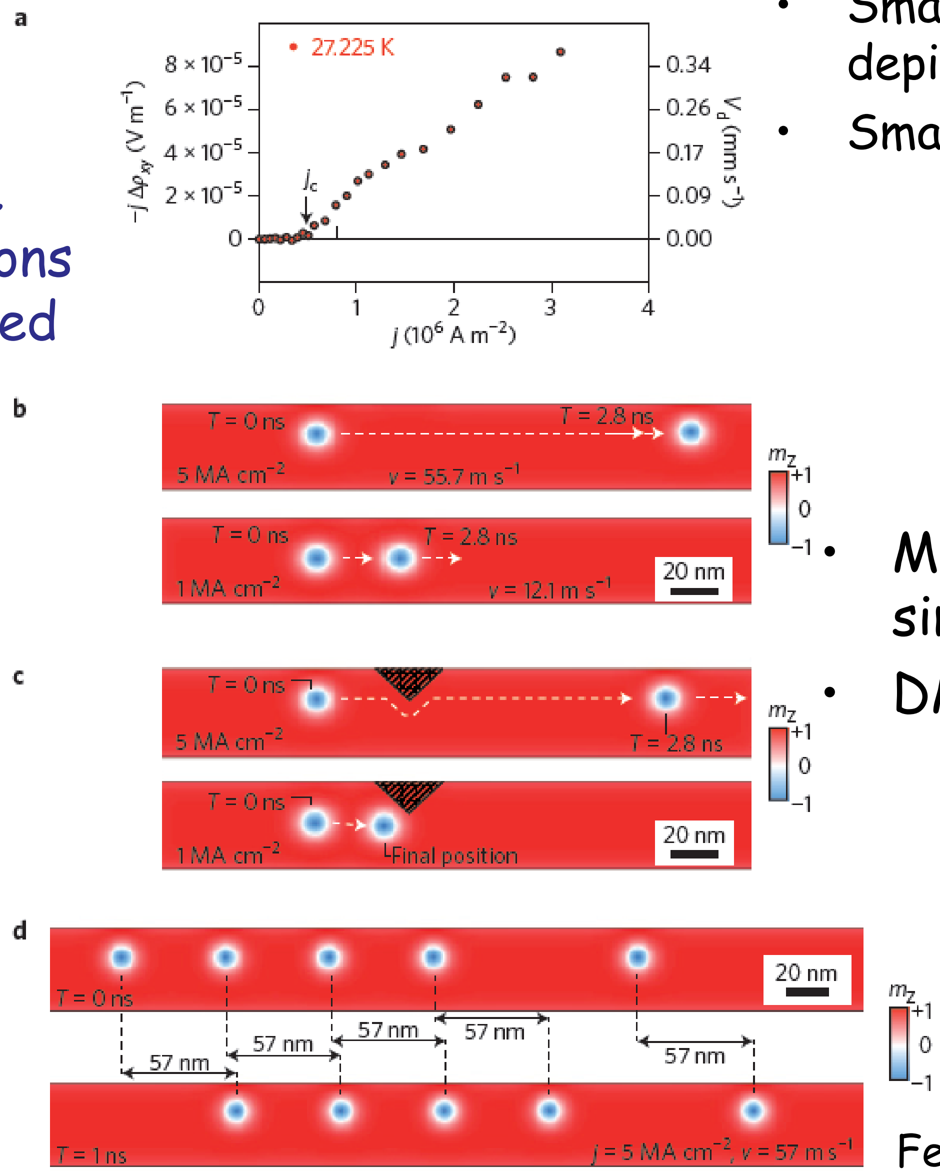
- $D_{crit} \approx (KJ)^{\frac{1}{2}}$
- Small K

- Larger D/J ratio (at interfaces), Smaller skyrmion size

Skyrmions on the move

Skyrmions are particle-like spin configurations that can be moved by Spin Torque

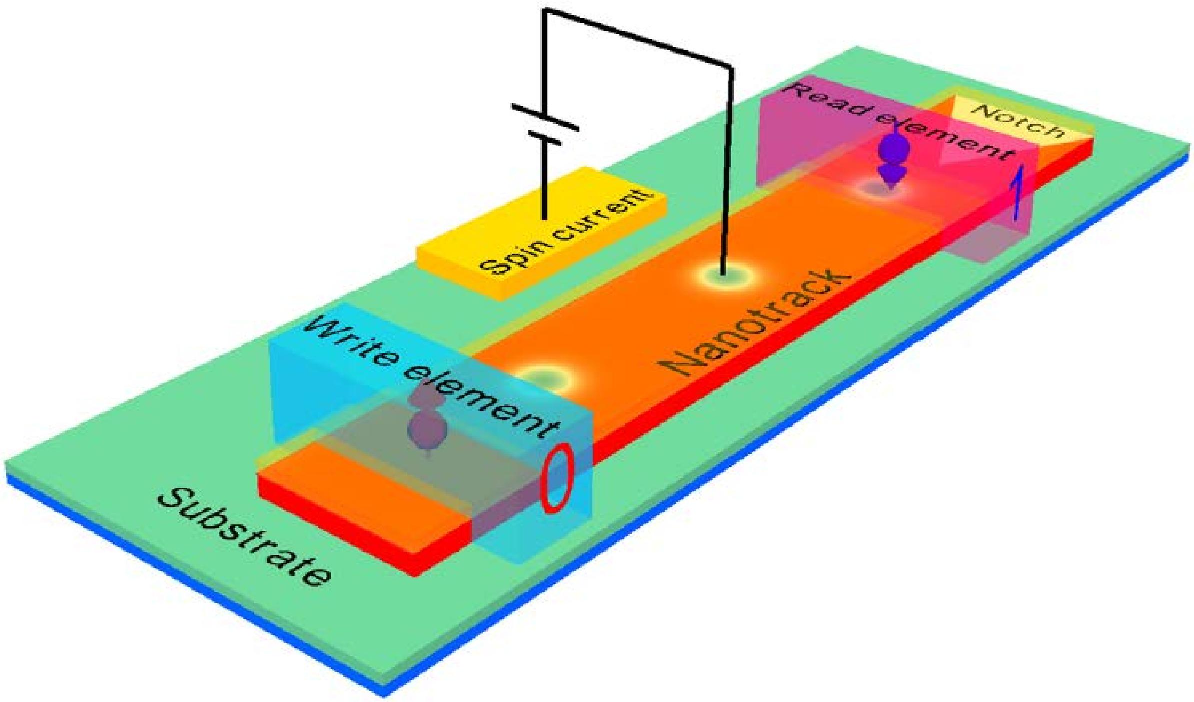
- Small (10^6 A/m^2) depinning current density
- Small (10^{-4} m/s) velocity



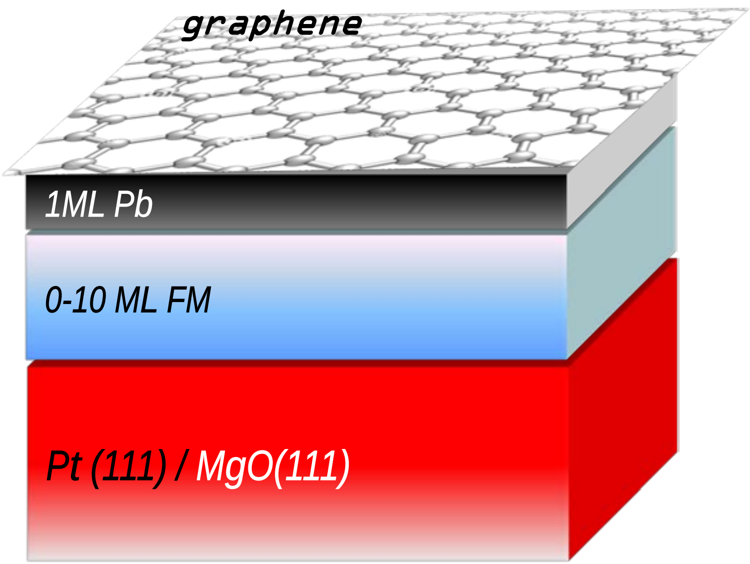
- Micromagnetic simulations
- DMI 1.4 meV/atom

Fert et al, Nature Nano 2013

Skyrmion-based Racetrack Memory



Graphene Skyrmionic systems



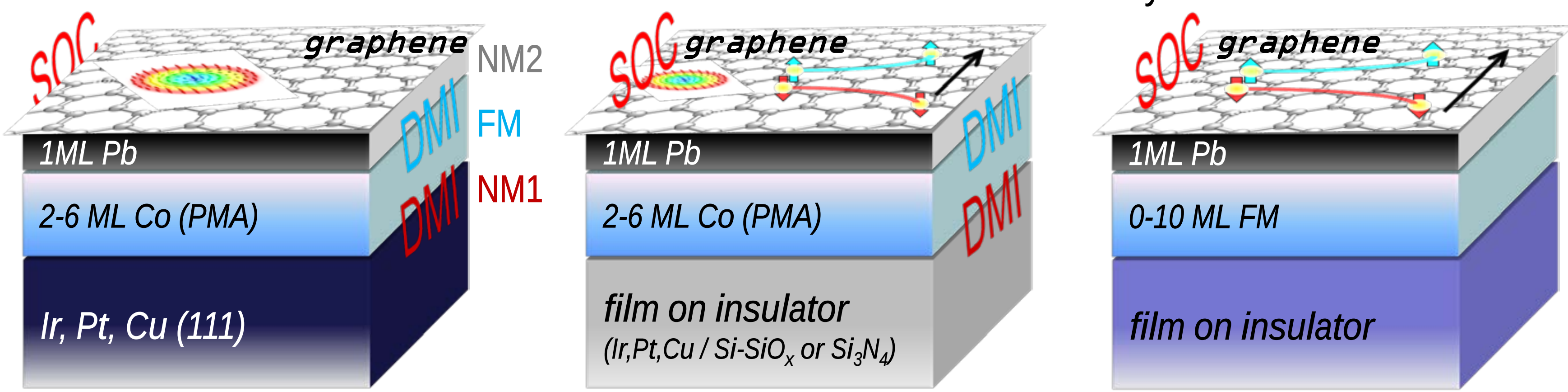
Control of **Spin-Orbit Coupling in graphene** as a source of large chiral exchange interaction (Dzyaloshinskii-Moriya Interaction, DMI),

leading to stabilization and manipulation of **magnetic skyrmions**

and/or as efficient source of large pure spin current by **Spin Hall Effect** (SHE).

The SOgraph systems

(a) *model system* (b) *scalable system* (c) *spin/charge conversion system*

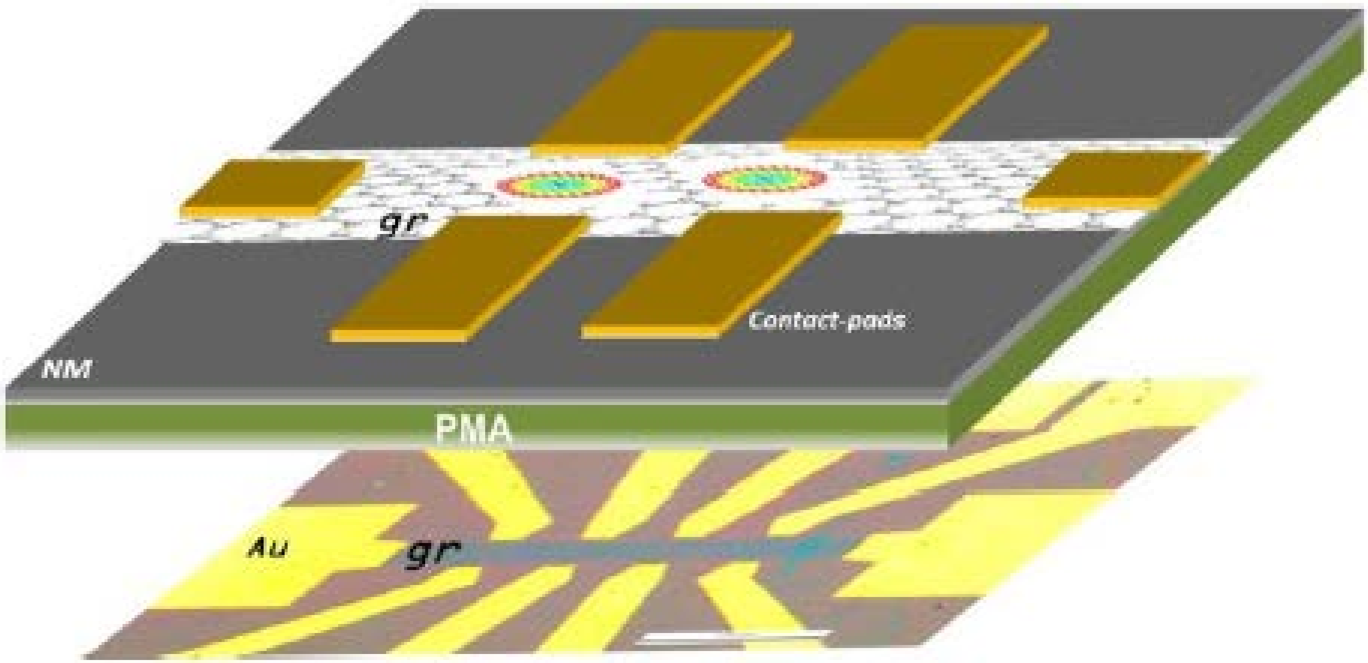


- Production of the SOgraph building blocks (MBE, CVD, sputtering)
- Characterization (magnetic, transport, dynamics, etc)
  - *In-situ*: LEED, XPS, STM
  - *Ex-situ*: v-MOKE, VSM, XAS, XMCD, MR-OKE, SHE, ISHE, STT
- Imaging of skyrmions on graphene (sp-STM, MFM, XMCD, holography)
- Modelling
- SOgraph prototype

SOgraph systems: Prototype Device

Prototype device for local and non local measurements

Pure spin and Spin-Charge conversion device



Consortium partners and specific role

SOgraphene

FLAG-ERA

Coordinator

imdea nanoscience

Preparation of SOgraphene samples on model and scalable systems, In-situ Characterization (XPS/UPS) and Imaging of skyrmions (sp-STM in UHV), Theoretical Modelling, Ex-situ magnetic (MOKE) and MagnetoResistence characterization, Nanofabrication and evaluation of the spin-orbitronic device

cnrs

Preparation of SOgraphene samples for spin-charge conversion systems
Magnetic Characterization (AGFM, SQUID, FMR), Imaging of skyrmions (MFM),
Magnetotransport, Spin pumping, Micromagnetic simulations of chiral interactions

SOLEIL SYNCHROTRON

Synchrotron experiments (Resonant X-ray Scattering, X-Ray Holography, ARPES) to determine magnetic properties with element selectivity and spatial resolution
Imaging of skyrmions by X-ray ScanningTransmission Magnetic Circular Dichroism

IPM *srl*

Theoretical studies and simulations (Micromagnetic, modelling of skyrmions and their dynamics)
Definition of the optimized design for the spin-orbitronic prototype device

Partners and participants

Partner Number	Country	Institution/ Department		Name of the Principal Investigator (PI)	Name of the co-Investigators	Others participants
1 *Coord.*	Spain	IMDEA Nanociencia	IMDEA exp	Prof. Rodolfo Miranda	Dr. Julio Camarero (growth, holography) Dr. A.L. Vázquez de Parga (sp-STM)	Dr. Paolo Perna (magnetotransport) Dr. Daniel Granados (nanofabrication) Dr. Ruben Guerrero (nanofabrication)
			IMDEA Theory	Prof. Francisco Guinea (Modelling)		
2	France	CNRS UMPhy UMPHY		Dr. Vincent Cros (magneto-transport)	Prof. Pierre Seneor (spintronics with gr)	Dr. Nicolas Reyen (magnetotransport) Dr. Bruno Dlubak Prof. Albert Fert
3	France	SOLEIL		Dr. Nicolas Jaouen (X-ray scattering) SEXTANTS and CASSIOPEE beamlines	Dr. Maurizio Sacchi (holography) Dr. Amina Taleb (ARPES)	Dr. Horia Popescu (holography) Dr. Roland Gaudemer (tech. SEXTANT) Dr. François Bertan (ARPES) Dr. Patrick Lefevre
4	Italy	IPM *srl* IPM		Dr. Konstantin Zvezdin (theory & simulations)	Dr. Flavio Abreu Araujo (simulation) Prof. Anatoly Zvezdin, (theory)	Dr. Pietro Perlo Dr. Petr Skirdkov Mr. Stefano Deola

SOgraphene

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Work Packages

EUROPEAN UNION STRUCTURAL FUNDS

WP1

SO*graphene* systems:

- gr/NM$_2$/FM/NM$_1$ *on single crystals*
- *gr/NM$_2$/FM/NM$_1$ on thin film/buffer*
- *gr/NM$_2$/FM(t) on film/insulator*

IMDEA, UMPHY, SOLEIL

WP2

UMPHY, IMDEA, IPM, SOLEIL

in-situ

Structure	***Electronic***	***Magnetic***
LEED	*XPS, UPS*	*MOKE*
STM	*XAS, ARPES*	*sp-STM*

averaged properties

Electronic	***Magnetic***	***Transport***
XAS	*VSM & SQUID*	*M(R)OKE*
ARPES	*v-MOKE*	*SHE, ISHE*
	XMCD	*STT effects*

Modelling

Electronic
Micromagnetic

clean-room instrumentation for

lithography
+
contacting

WP3

SOLEIL, IMDEA, UMPHY

spatially-resolved properties

Element-resolved

- *sp-STM, AFM, MFM*
- *x-ray magnetic scattering*
- *x-ray magnetic holography*

WP4

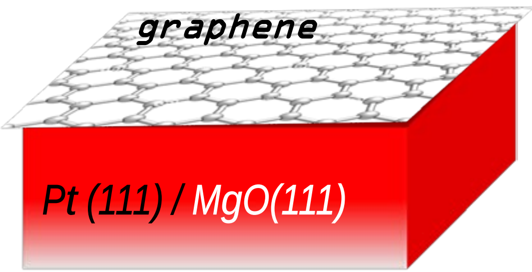
IPM, IMDEA, UMPHY

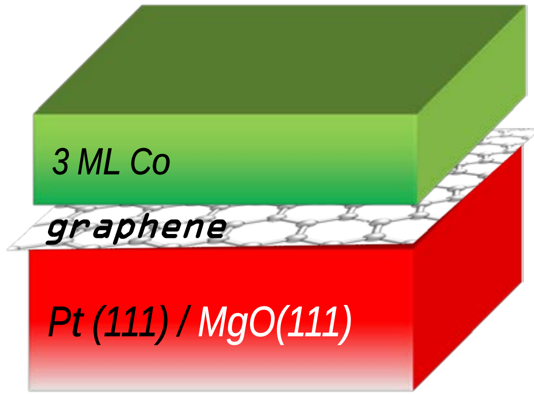
SO*graphene* prototype: proof of concept of **graphene based spin-orbitronic** devices

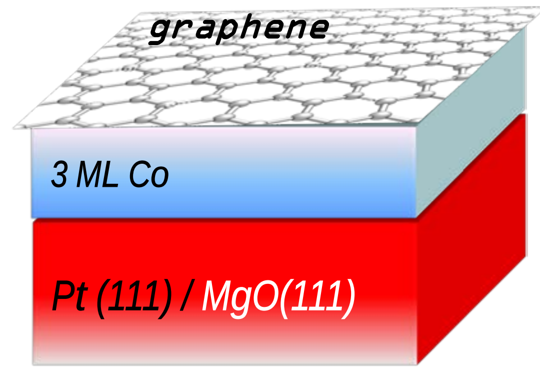
Graphene Skyrmionic systems

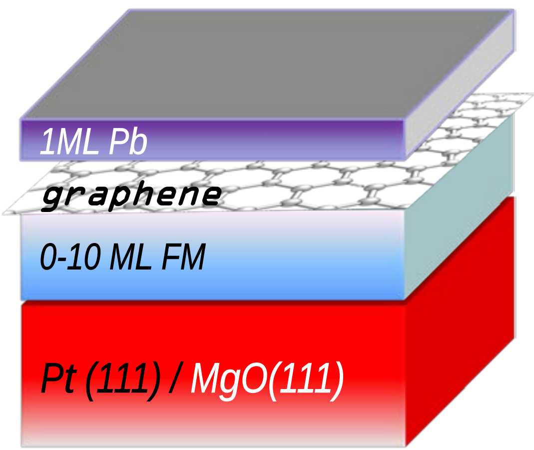
Model systems: On single crystal metallic substrates

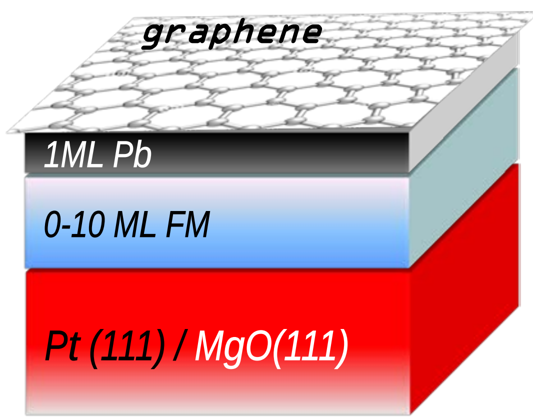
Scalable systems:











Spin-charge conversion systems

Membrane systems

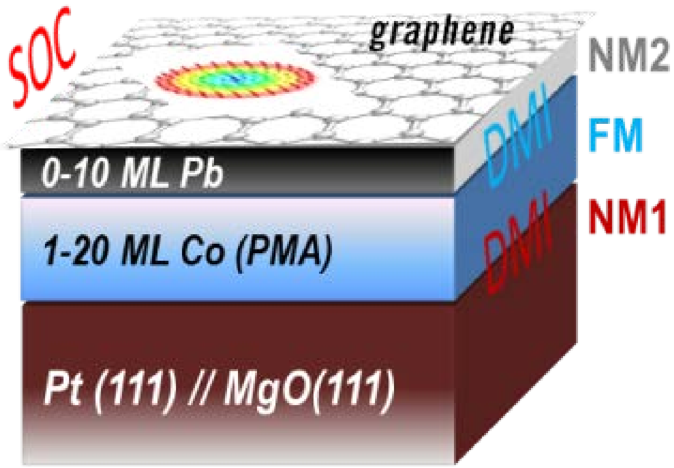
Interactions with Flagship core projects

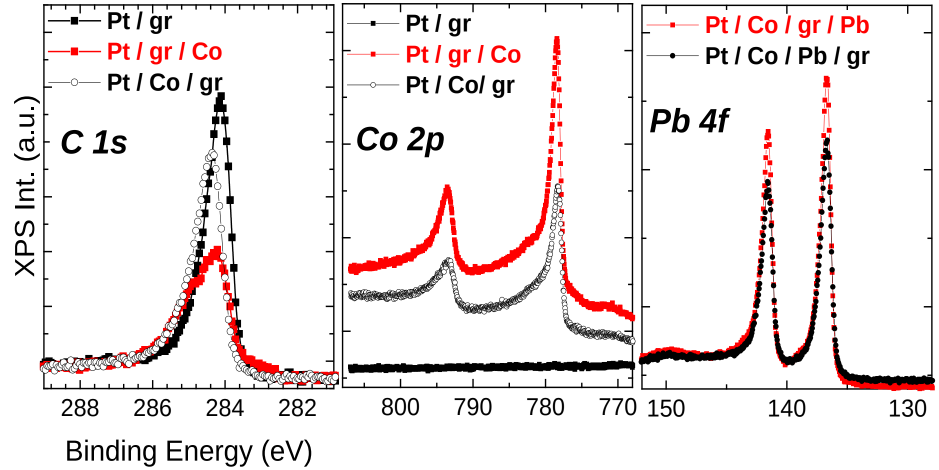
SpinOrbitronics in graphene

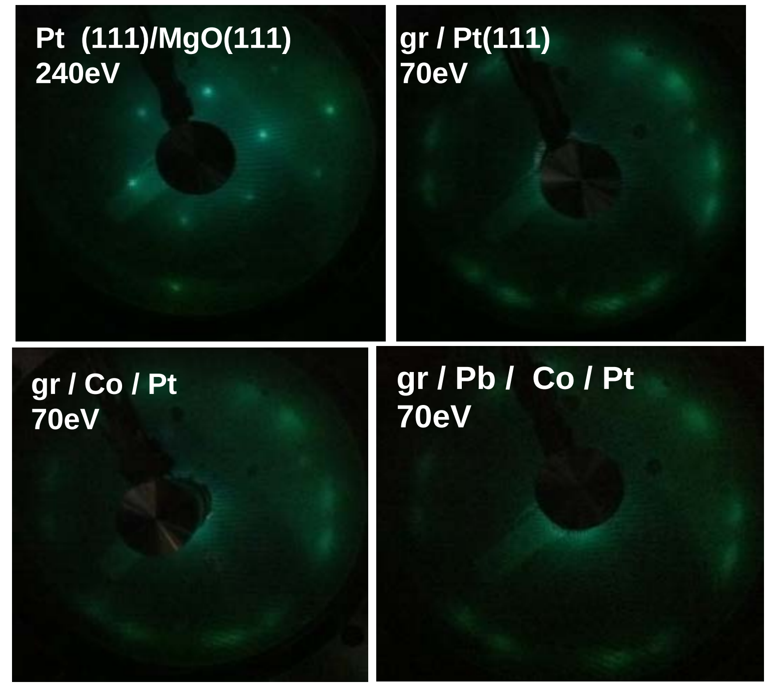
WP1: Materials
WP3: Fundamental Science
WP6: Spintronics

- **WP1**: task 1.6: synthesis of graphene on metals, task 1.7: UHV growth on arbitrary substrates, and task 1.10: characterization.
- **WP3**: task 3.1: STM spectroscopic studies, task 3.3: theoretical mesoscale modeling of graphene based structures, task 3.4: nanofabrication technology for gr-based devices.
- **WP6**: task 6.1: Optimizing materials and devices for graphene spintronics; task 6.2: magnetism in graphene and its interaction with spin transport, task 6.5: towards practical graphene spintronic devices.

Progress so far: Growth & Surface Analysis





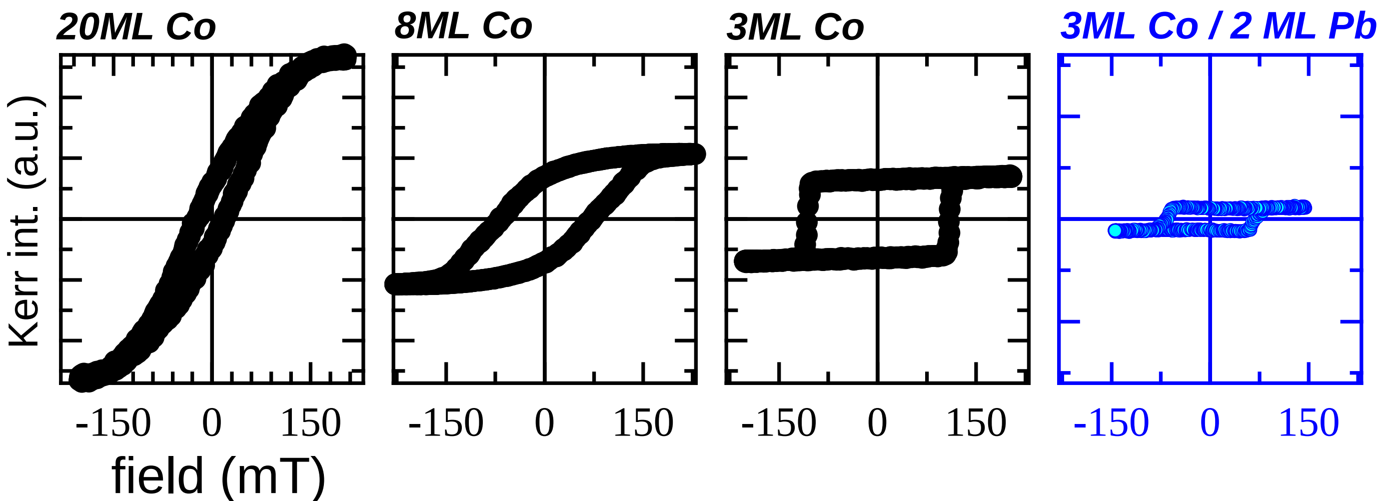


Growth:

1- Sputtering 100nm Pt @ 500°C
2- CVD graphene (ethylene) @ 800°C
3- MBE evaporation Co, Pb @ RT
4- Intercalation by thermal annealing @ 100 - 400°C

Progress so far: Magnetic characterization

Polar MOKE @ RT



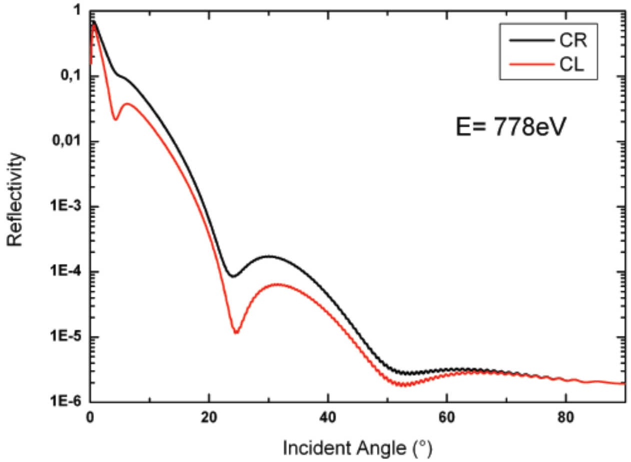
VSM: M_{sat} = 162.55 emu/gr (20 ML=6nm Co)

→ Successful intercalation process (Co, Pb)
→ Up to 20MLs of Co with Perpendicular Magnetic Anisotropy
→ Different Magnetization Reversal Mechanisms depending on the thickness
→ Effective graphene capping (samples inert in air)

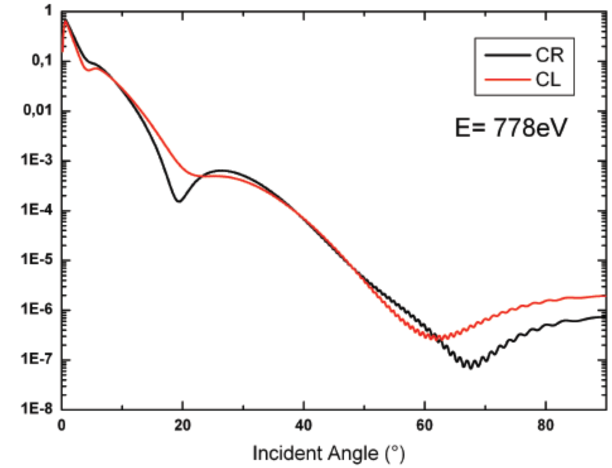
Progress so far: X-Ray Resonant Magnetic Scattering

=> Position of the Gr layer: simulations

Gr/Co(2.1nm)/Pt(100nm)/MgO

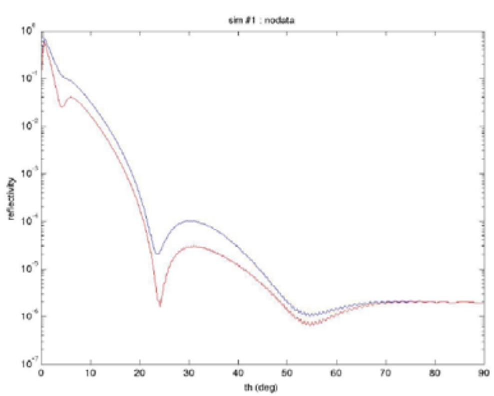


Co(1nm)/Gr/Co(1.1nm)/Pt(100nm)/MgO

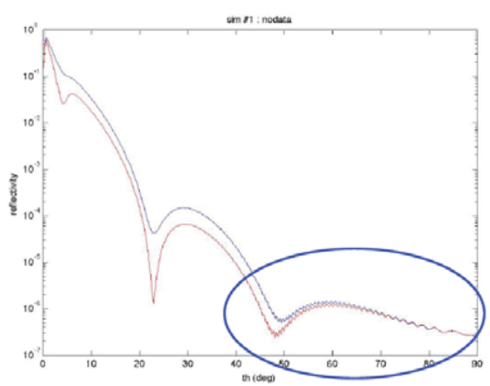


Simulations @ 778eV

Pb(1ML)/gr(1ML)/Co(20ML)/Pt(100nm)/Mg0



gr(1ML)/Pb(1ML)/Co(20ML)/Pt(100nm)/Mg0



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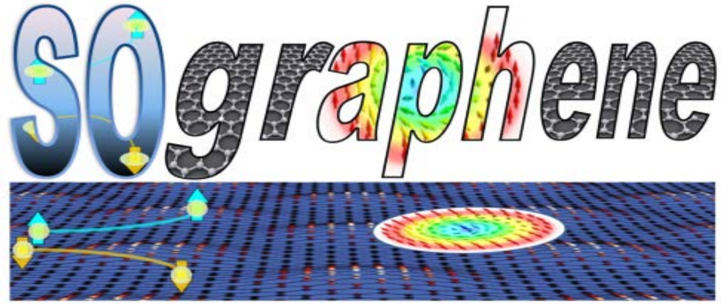

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