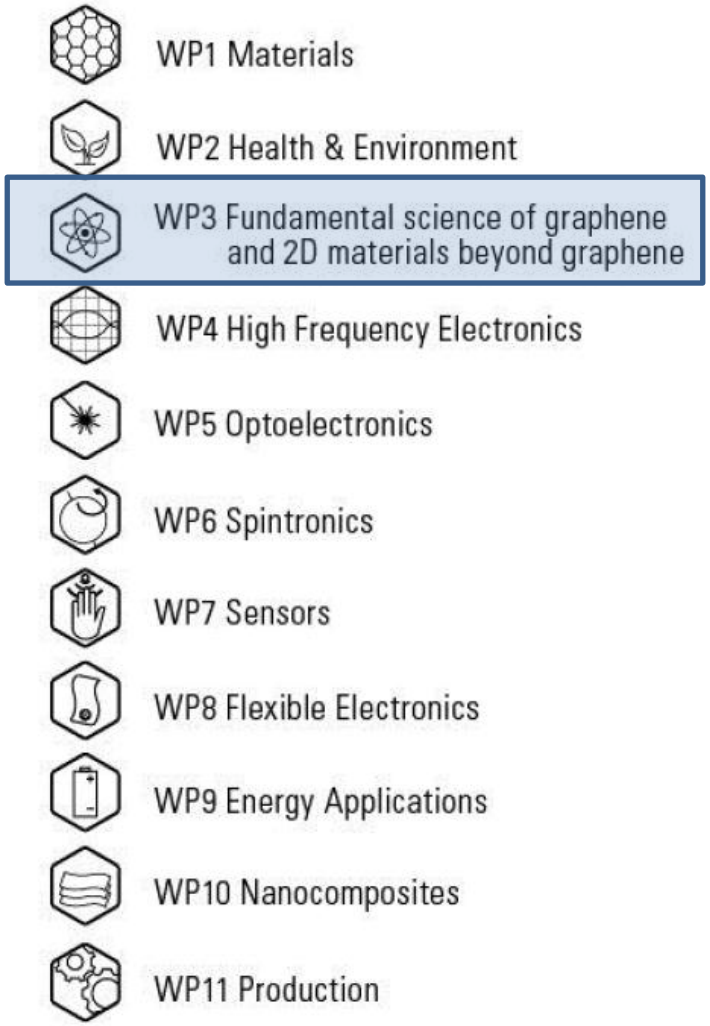
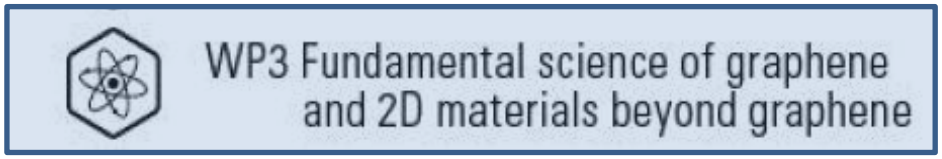
Flagship: Graphene-Based Revolutions in ICT And Beyond

RTD work packages :



Initial stage



WP	WP leader	WP deputy
Fundamental graphene science	V. Falko, U Lancaster (UK)	A. Morpurgo, U. Geneva (SUI)

14 (16) Participants : Sweden [1], Spain [1], U.K. [4], France [2-(3)], Germany [4], Switzerland [2]

Participant number [10]	Participant short name [11]	Person-months per participant
1	CUT	50.00
4	CSIC	40.00
6	UNIMAN	110.00
10	RWTH	30.00
18	CNRS **(2 groups, 3 labs)**	155.00
29	MPG	30.00
58	UNIGE	54.00
59	TUD	48.00
60	ETH Zurich	48.00
61	NPL	45.00
62	OXINT	9.00
63	ULANC	80.00
64	UHAM	30.00
76	UniHB	30.00
	Total	759.00

Initial stage: WP3 Participants

CHALMERS TEKNISKA HOEGSKOLA AB, CUT, Sweden

THE UNIVERSITY OF MANCHESTER, UNIMAN, United Kingdom

RHEINISCH-WESTFAELISCHE TECHNISCHE HOCHSCHULE AACHEN, RWTH, Germany

AGENCIA ESTATAL CONSEJO SUPERIOR DE INVESTIGACIONES CIENTIFICAS, CSIC, Spain

CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE, CNRS, France

2 teams : GRE-CNRS (LNCMI & NEEL) and TQM-IMPMC

UNIVERSITE DE GENEVE, UNIGE, Switzerland

TECHNISCHE UNIVERSITEIT DELFT, TUD, Netherlands

EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZURICH, ETH Zurich, Switzerland

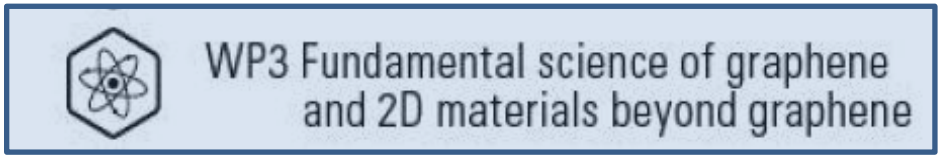
NPL MANAGEMENT LIMITED, NPL, United Kingdom

OXFORD INSTRUMENTS NANOTECHNOLOGY TOOLS LIMITED, OXINT, United Kingdom

LANCASTER UNIVERSITY, ULANC, United Kingdom

UNIVERSITAET HAMBURG, UHAM, Germany

UNIVERSITAET BREMEN, UniHB, Germany



Initial stage

Objectives
To establish the fundamental limits for functional graphene nanostructures in electronics beyond CMOS. This will be achieved via microscopic characterisation of single- and poly-crystalline graphene (G) and graphene-based nanostructures, studies of kinetic processes, investigation of the influence of defects, disorder, and influence of substrate/environment on graphene electronic properties, and multiscale modelling of graphene-based structures. To explore the use of exfoliated TMDC in electronics: to characterise microscopically the electronic properties of these 2D crystals, and to investigate transport and vertical tunneling properties of these materials and atomic layers of h-BN, in view of their later use in hybrid superstructures with graphene.

WP3 Fundamental science of graphene and 2D materials beyond graphene

Initial stage: more exploratory studies

Description of work and role of partners

The work will be organized in the following tasks, addressed by partners listed in brackets.

T3.1. [CNRS, RWTH, ULANC, UHAM, CSIC] Optical and STM spectroscopic studies of graphene and TMDCs, including characterization of edges and defects, in single crystalline and polycrystalline graphene and TMDCs on different substrates.

T3.2. [UNIMAN, UNIGE, CNRS, MPG, TUD, ETH, CUT, CSIC, ULANC] Electronic and heat transport studies of graphene-based devices (including suspended layers, nanoribbons, quantum dots, and their circuits), investigation of their dynamical properties, and their interaction with substrates and environment (such as BN layers), and two-layer structures.

T3.3. [CSIC, UHAM, CNRS, ULANC] Theoretical mesoscale modelling of graphene-based structures, functionalised graphene, defects in graphene, and the influence of the environment. This will include density functional theory and quantum Monte Carlo modelling of materials and defects, and microscopic scattering theory and quantum transport modelling of nanostructures.

T3.4. [TUD, ETH, CUT] Advancement of nanofabrication technology for graphene-based devices, including development of vertically aligned multi-layered structures and devices, cleaning methods, hybrid graphene-TMDC devices, and durability and stability of graphene-based structures.

T3.5. [NPL, CUT, OXINT, ULANC] Implementation of graphene in metrology, for the development of fundamental resistance and current standards. Exploration of the operational bounds of graphene-based standards of electrical resistance based on the half-integer quantum Hall effect and of electrical current based on the single-electron pumps, identification of the underlying physical mechanisms limiting their performance, optimisation of the fabrication, cryogenic and measurement technologies.

T3.6. [UNIMAN, UNIGE, ULANC, CSIC, CNRS] Experimental characterisation and theoretical modelling of lateral transport characteristics of two-dimensional atomic crystals of TMDCs and vertical (tunneling) transport properties of graphene-TMDC multilayers.

WP3 Fundamental science of graphene and 2D materials beyond graphene

CNRS LNCMI & NEEL

Initial stage: more exploratory studies

CNRS TQM-IMPMC

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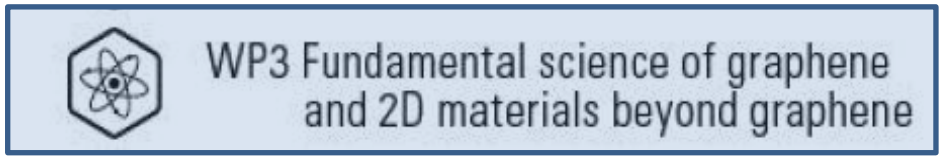
responsibility

contribution

contribution

contribution

contribution



Long term objectives: >>> towards devices (design, prototypes) and exploring new 2D materials

- **To exploit graphene for both classical and quantum information processing in the post-CMOS era.**
  For classical information processing, we shall develop vertical transistors and atomic scale MESFETs where graphene is used as active component, as interconnect, or transparent gate. We shall also produce the technology evaluation for WP4. For quantum information processing, we shall exploit the long-lived spin coherence of electron in graphene (using the data obtained in WP6) to develop monolayer and bilayer quantum dot qubits, readouts, and their scalable circuits.

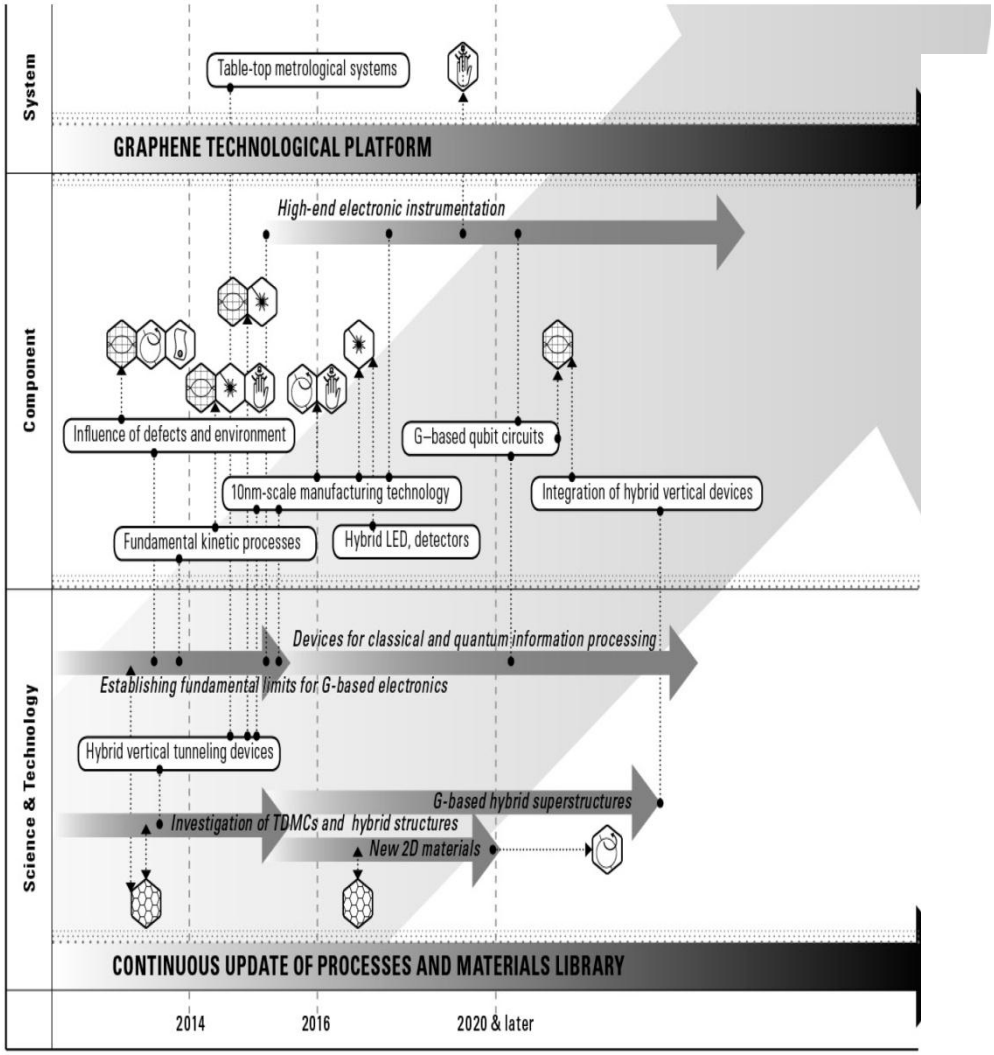
  high frequency electronics
  spintronics
- **To build graphene-based metrological applications and high-end electronic instrumentation.**
  For metrology and standardisation, we aim to develop transferable table-top quantum resistance standard based on the quantum Hall effect, and stable quantised current sources. High-end instrumentation will include highly sensitive bolometers, ultra-sensitive Hall probes, new types of scanning probes, on which we shall collaborate with WP7.

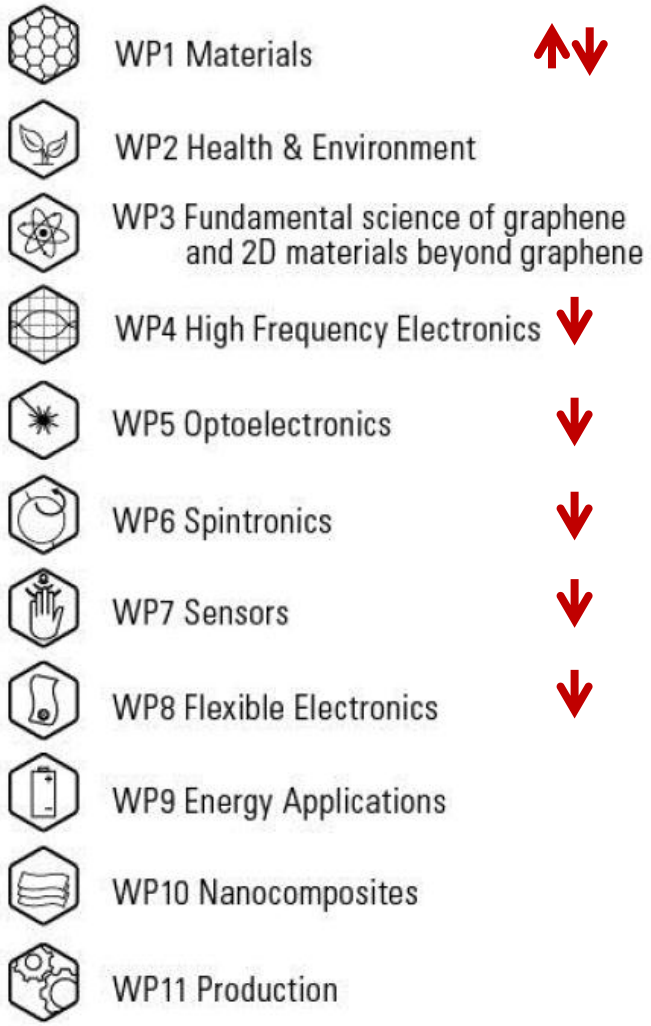
  sensors
- **To produce new inorganic 2D crystals, systematically investigate their physical properties, and evaluate the potential for optoelectronic applications**
  Using the experience developed in the first stage, objective II, we shall explore a broad range of LMs beyond graphene, BN, and TMDCs initially studied in objective I. The issues that we shall address will include material stability, compatibility with nanofabrication processes, and the entire range of structural, optical and electrical characterisation. The results of these studies will be passed to WP1 and WP5.

  materials
  optoelectronics
- **To study electronic, optical, and thermo-mechanical properties of hybrid structure combining graphene with various gap-full 2D crystals.**
  We shall study the microscopic charge transfer and transport in multilayer hybrid structures, optical processes and hot carrier dynamics, electron spin memory and relaxation. Understanding these processes will enable the development of devices such as transistors and switches, light emitting diodes (LEDs), photovoltaic cells and photo-detectors. Promising new prototype hybrids will be passed to WP5, for a further development of optoelectronics applications.

  optoelectronics

Figure 1-14 *The fundamental science part of the Flagship time line, showing the connections between WP3 and the other work packages.*





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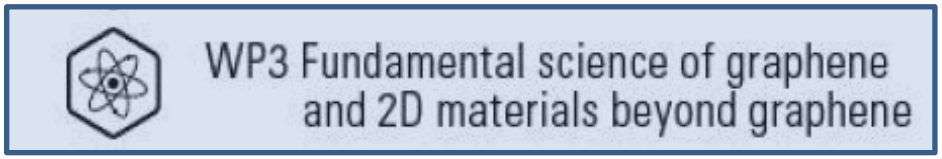


Initial stage, CNRS/France involvement

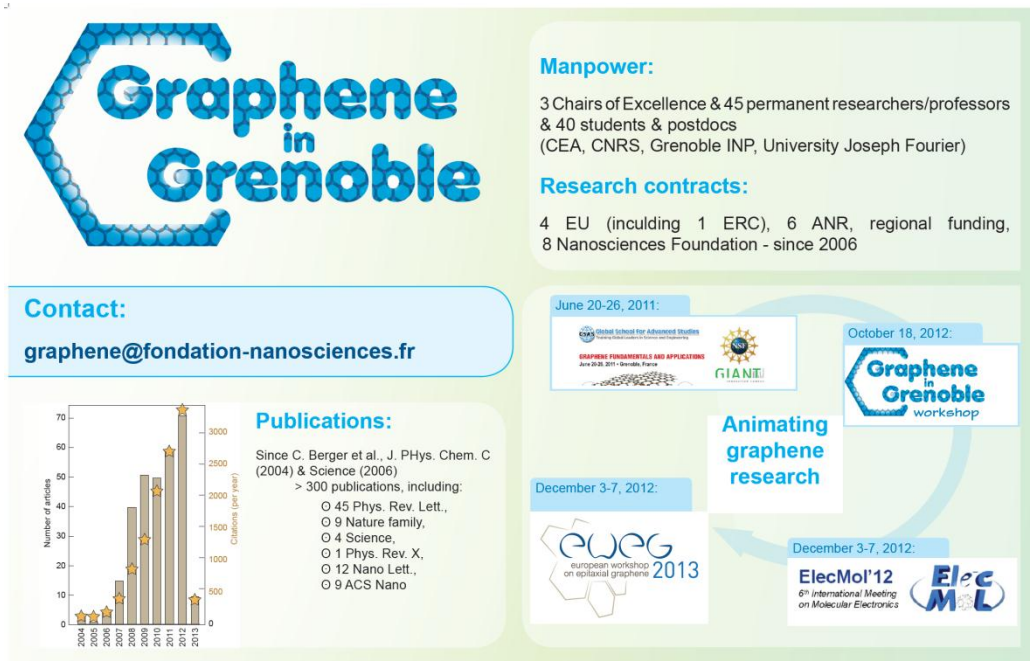
Organization full name	Centre National de la Recherche Scientifique, CNRS
Department / Group	LEM/NEEL/LNCMI/ICT/CIRIMAT-ECOLAB/LPA-ENS/TQM-IMPMC/CNRS-THALES
Principal Investigator(s)	A. Loiseau, C. Berger, M. Potemski, A. Bianco, E. Flahaut, L. Gautier, B. Plaçais, F. Mauri, A. Fert

2 teams from CNRS (3 labs, 4 research groups) acting in WP3 :

CNRS – Grenoble (*experiments*)
Marek Potemski, Milan Orlita, Clement Faugeras , ***Laboratoire National des Champs Magnétiques Intenses***
V. Bouchiat, Laetitia Marty, ***Institut Néel***
Jean-Yves Veuillen, Pierre Mallet, ***Institut Néel***

CNRS – TQM-IMPMC (*theory*)
Francesco Mauri *et al*, *Théorie Quantique des Matériaux, Institut de minéralogie et de physique des milieux condensés*

Digression : beyond WP3, flagship,



Flagship, WP3, initial stage :

CNRS – Grenoble (*experiments*)
Marek Potemski, Milan Orlita, Clement Faugeras *, **Laboratoire National des Champs Magnétiques Intenses***
Vincent Bouchiat, Laetitia Marty, ***Institut Néel***
Jean-Yves Veuillen, Pierre Mallet, ***Institut Néel***

CNRS-GRE group: LNCMI-G, Semiconductors and Nanophysics team

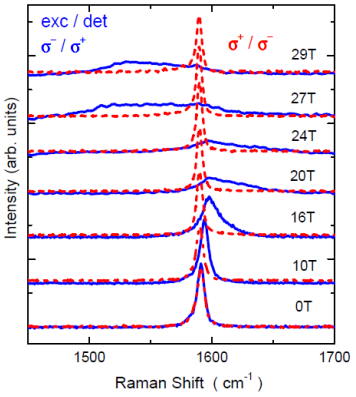
Researchers involved: **M. Orlita** (CR2), **C. Faugeras** (CR1), **M. Potemski** (DR1), + 24 months postdoc

Graphene-oriented research **: >40 papers, (>15 in +PRL), cited >1400**

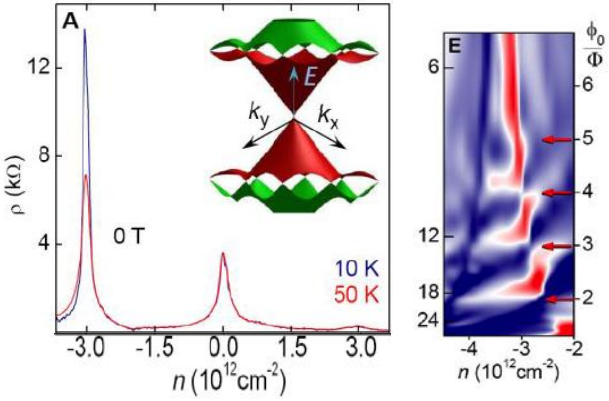
Other, running graphene related projects: : **ERC ARG** (Potemski)

Experimental expertise :
optical magneto-spectroscopy (microwaves, far-infrared –FTIR, micro-magneto-Raman scattering)
electric transport
applications of magnetic fields (35 T) and low temperatures

Current research on graphene:
electron-phonon interaction QHE in graphene superlattices



Circular dichroism
of magneto-phonon resonance
in doped graphene



Cloning of Dirac fermions in
graphene superlattices

Role in the project: optical magneto-spectroscopy of graphene and TMDCs (different substrates, edges, stacking, defects)

CNRS-GRE group, Néel Institute Hybrid syst. team.

Researchers involved: **L. Marty** (CR1), **V. Bouchiat** (DR2) + 24 months postdoc

Graphene-related research **: 29 publications on graphene/nanotubes/fullerene since 2006**
(1 Nature, 5 in Nature family journals,1PRX, 3 PRL), among which **10 papers on Graphene**.

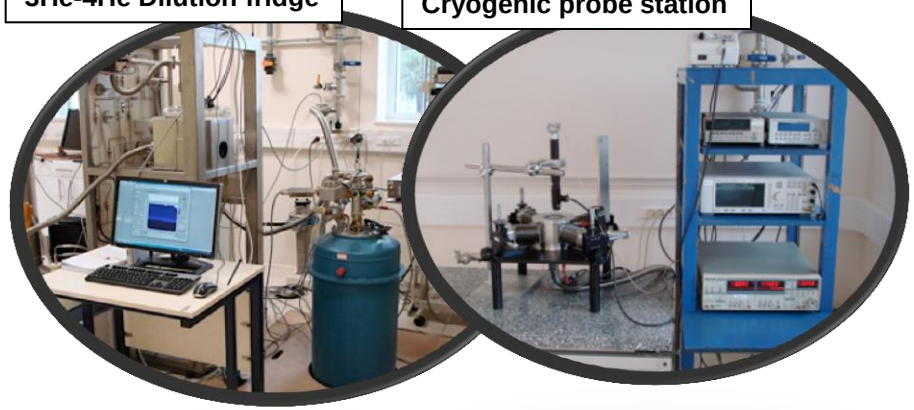
Other, running graphene related projects: **ANR Blanc Supergraph** (LPS, INAC Grenoble) **TRICO** (ILM Lyon)

Techniques: 2 Dilution fridges T<0.035 K
Dual axis magnets 6 + 1.5K probe station

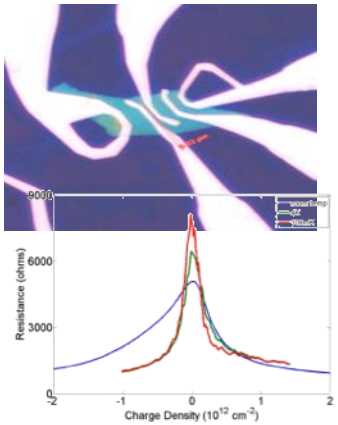
Current areas of research: proximity superconductivity in graphene, transport properties in hybrid graphene devices, coupling to nanomechanics

3He-4He Dilution fridge

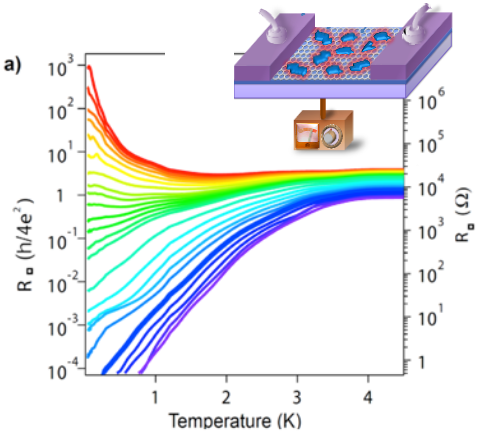
Cryogenic probe station



+ facilities for CVD growth of Gr on Cu
and fast characterization (Raman, AFM etc…).



Electron transport in high mobility Gr/h-BN, Nanomechanics in suspended Gr



Superconducting/insulator quantum phase transition in Tin-decorated graphene

Role in the project : transport measurement of hybrid systems including stacked graphene heterostructures

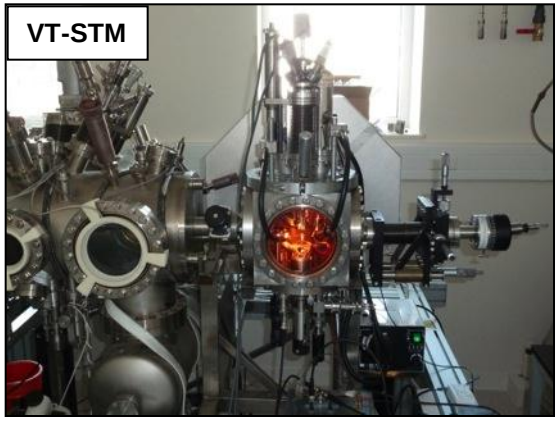
CNRS-GRE group, Néel Institute UHV STM team.

Researchers involved: **P. Mallet** (CR1), **J-Y Veuillen** (DR2) + 24 months postdoc

Graphene-related research **: 23 publications on graphene since 2007** (3 PRL, 3 PRB RC), average citation/paper: 33.3,

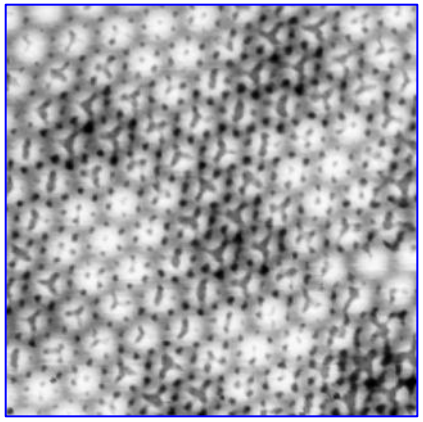
Other running, graphene related projects: : **non**

Techniques: STM/STS in UHV.
1 VT-STM and 1 LT-STM.

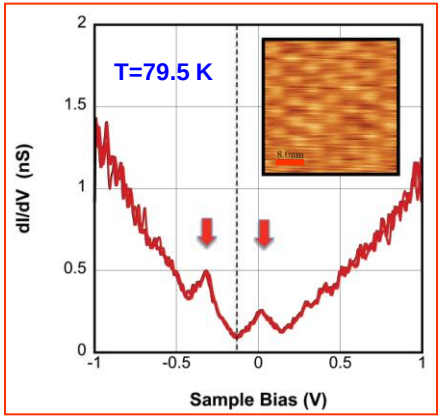


+ facilities for in-situ growth of Gr on SiC and fast characterization (LEED, Auger).

Current areas of research: interaction of graphene with its environment (substrate and twisted layers stacks), electron scattering in graphene.



Stacking dependent interaction of Gr on SiC(2x2) substrate.
Composite -0.2/+1.5 V image, 6x6 nm², SiC-C face.



vHs inthe DOS of twisted bilayers.
STS (LT-STM) on a SiC-C face grown sample. Inset: image of the corresponding Moiré pattern**.**

Role in the project: STM/STS analysis of supported graphene layers and of TMDC samples (including defects and edges, influence of the substrate and of the layers stacking)

French partners outside flagship
running collaborations on graphene supported by common publications/work in progress

In house :

LNCMI-G&T: A.L. Barra, B. Piot, W. Escoffier, D.K. Maude, P. Plochocka, B. Raquet

NEEL: O. Arcizet, N. Bendiab, J. Coraux, O. Fruchart, L. Levy, L. Magaud, C. Naud, D. Mayou

External (France)

LPMMC-Grenoble (theory):	D. Basko
LPS-Orsay (theory):	M. Goerbig, J-N. Fuchs
CEMES-Toulouse (devices):	E. Dujardin
LPTM-Cergy (theory):	G. Trambly de Laissardière
INAC-Grenoble (TEM) **:**	G. Renaud
LTM-Grenoble (plasma, XPS):	G. Cunge
LNE (QHE, metrology)	W. Poirier, F. Schopfer
IPCMS-Strasbourg	S. Berciaud