ETMOS

JTC-2019

1 April 2020 – 31 March 2023

Epitaxial **T**ransition **M**etal dichalcogenides **O**nto wide bandgap hexagonal **S**emiconductors for advanced electronics

F. Giannazzo, F. Roccaforte, A. La Magna

CNR-IMM, Catania, Italy

filippo.giannazzo@imm.cnr.it

A. Michon, M. Al Khalfioui, Y. Cordier

CNRS-CRHEA, Valbonne, France

S. Chromik, M. Španková

SAS-IEE, Bratislava, Slovakia

B. Pécz, A. Koos

MFA-EK, Budapest, Hungary

S. Agnello, M. Cannas

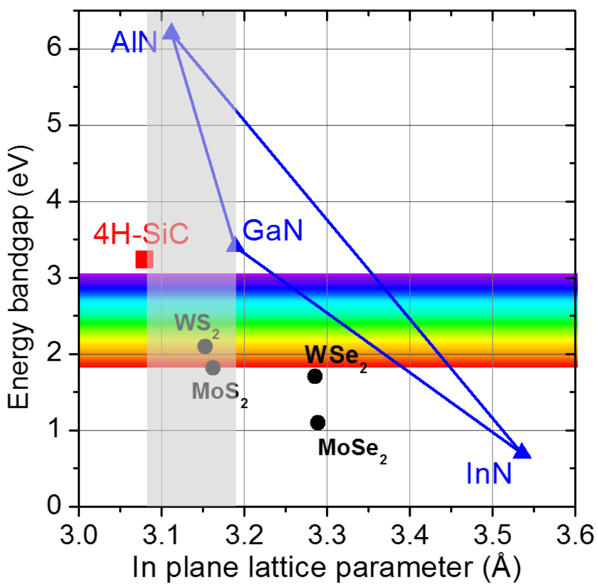
University of Palermo, Italy

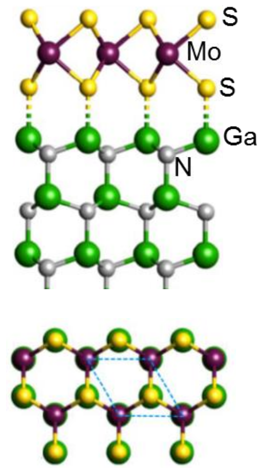
FLAG-ERA Workshop 2021

March 16, 2021

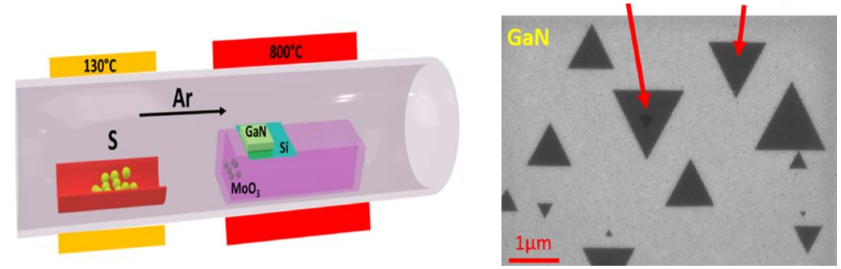
Motivations

- Hexagonal wide band-gap (WBG) semiconductors (4H-SiC,GaN, AlN, $Al_xGa_{1-x}N$) are nearly ideal substrates for highly oriented epitaxial growth of TMDs



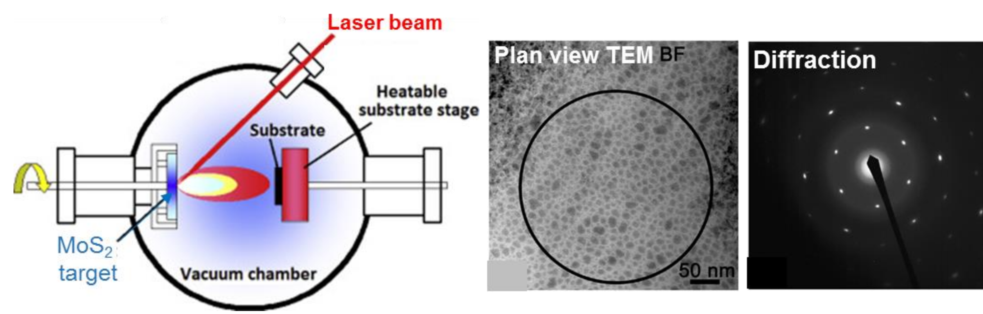


CVD of MoS_2 on GaN



D. Ruzmetov, et al., ACS Nano 10, 3580−3588 (2016).

Pulsed Laser Deposition few layer MoS_2 on GaN



S. Chromik, et al., Appl. Surf. Sci. **395**, 232–236 (2017).

- Development of advanced electronic/optoelectronic devices based on the 2D/3D semiconductor heterojunctions between TMDs and WBG.

FLAG-ERA JTC-2019

ETMOS: Epitaxial Transition Metal dichalcogenides Onto wide bandgap hexagonal Semiconductors for advanced electronics

Objectives:

(i) **Epitaxial growth of TMDs** (MoS_2, WSe_2) on WBG hexagonal semiconductors (SiC, GaN, AlN and AlGaN) by physical deposition techniques: **molecular beam epitaxy (MBE) and pulsed laser deposition (PLD).**

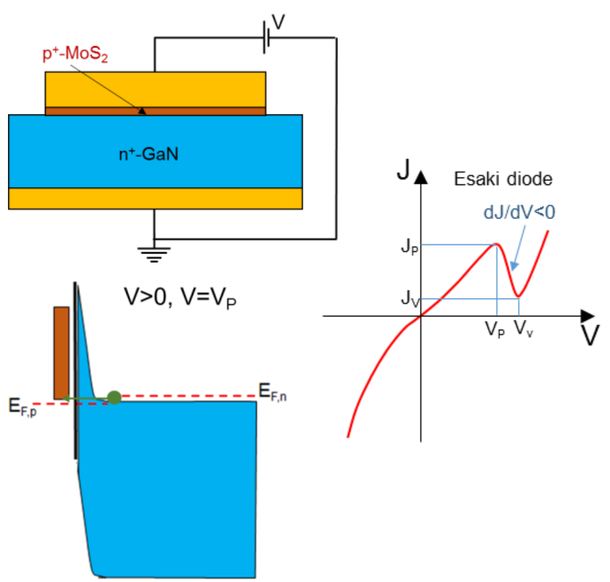
(ii) Multi-scale **characterization** (structural, chemical, optical and electrical) of the grown TMDs; **benchmarking** against materials grown with the same or complementary depositions methods (CVD); **simulations** of the growth process and electronic properties.

(iii) **Processing** and **device prototypes** based on TMDs/WBG heterojunctions.

Low dissipation digital electronics

Tunnelling diode

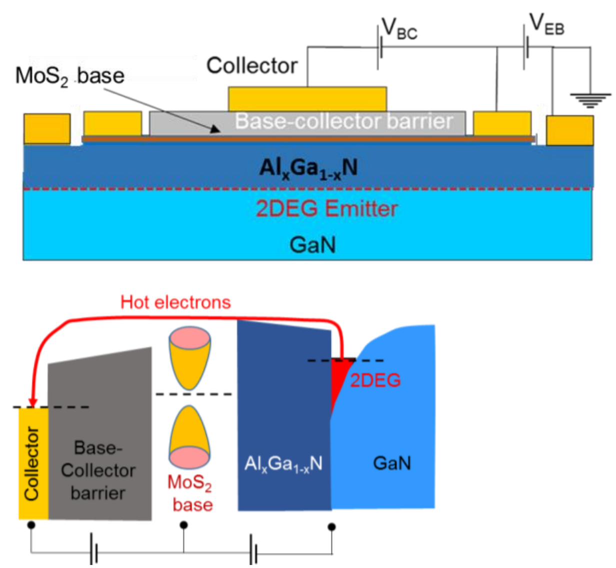
p^+-MoS_2/n^+-GaN or p^+-MoS_2/n^+-SiC



Ultra-high frequency (THz) electronics

Hot electron transistor

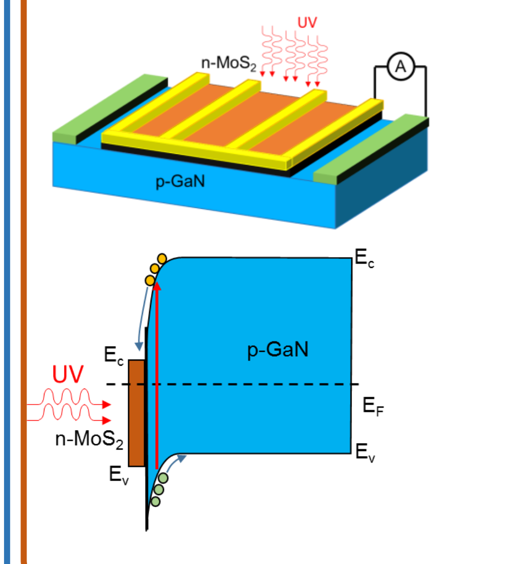
AlGaN/GaN emitter and 1L-MoS_2 base



Sensors

UV photodetectors

n-MoS_2/p-GaN or n-MoS_2/p-SiC



ETMOS

IMM

- Nanoscale and device level electrical characterizations.
- Simulations of deposition processes and of electronic transport.
- TMDs/WBG heterojunction devices

ETMOS Consortium

5 partners with complementary competences in materials growth, characterization and devices

- Optical characterizations (Raman, PL) of TMD layers.
- Post growth thermal treatments of TMDs for ex-situ doping
- Electro-optical characterization of TMD/WBG UV photodetectors

CNRS CRHEA

- MBE/MOCVD growth of GaN, AlN and AlGaN templates.
- MBE deposition of TMDs (MoS_2, WSe_2).
- Preliminary characterization of substrates and epitaxial layers.

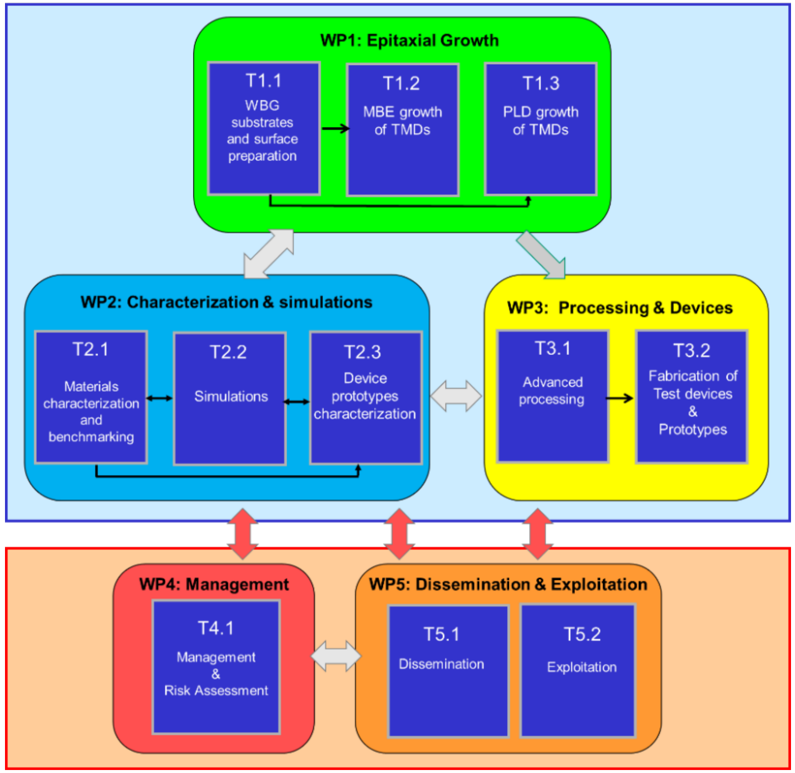
MFA

- TEM, STM/STS characterization of TMD/WBG heterostructures.
- CVD growth of MoS_2 on sapphire and WBG substrates.

SLOVENSKÁ AKADÉMIA VIED · ACADEMIA SCIENTIARUM SLOVACA

- PLD deposition of MoS_2
- Preliminary characterization of MoS_2 grown by PLD

WPs structure



Gantt

	Task	Partners	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
			First Year												Second Year												Third Year											
WP 1 Epitaxial growth	T1.1	**CNRS**, SAS												D1.1																								
	T1.2	**CNRS**, SAS																								D1.2	M1											
	T1.3	**SAS**, CNRS																								D1.3												
WP2 Characterizations & simulations	T2.1	**HAS**, CNR, CNRS, SAS, U-Pa														D2.1				D2.3								D2.4			D2.6	M3						
	T2.2	**CNR**, CNRS, SAS,HAS, U-Pa																D2.2										D2.5										
	T2.3	**CNR**, U-Pa																																				D2.7
WP3 Processing & Devices	T3.1	**CNR**, CNRS, HAS, U-Pa																				D3.1								M2								
	T3.2	**CNR**, CNRS, HAS																						D3.2										D3.3				
WP4 Management	T4.1	**CNR**, CNRS, SAS, HAS, U-Pa					D4.1							D4.2												D4.3												D4.4
WP5 Dissemination & Exploitation	T5.1	**U-Pa**, CNR, CNRS, SAS, HAS			D5.1									D5.2																								
	T5.2	**CNRS**, CNR, SAS, HAS, U-Pa																												D5.3								

Status of activities at M12

1 Apr. 2020 — 31 Mar. 2021

	Task		Partners	1	2	3	4	5	6	7	8	9	10	11	12
				First Year											
WP 1 Epitaxial growth	**T1.1**	WBG substrates and surface preparation	**CNRS**, SAS												**D1.1**
	T1.2	MBE growth of TMDs	**CNRS**, SAS												
	T1.3	PLD growth of TMDs	**SAS**, CNRS												
WP2 Characterizations & simulations	**T2.1**	Materials characterization and benchmarking	**HAS,** CNR, CNRS, SAS, U-Pa												
	T2.2	Simulations	**CNR**, CNRS, SAS,HAS, U-Pa												
	T2.3	Device prototypes characterization	**CNR**, U-Pa												
WP3 Processing & Devices	**T3.1**	Advanced processing	**CNR**, CNRS, HAS, U-Pa												
	T3.2	Fabrication of test devices and prototypes	**CNR**, CNRS, HAS												
WP4 Management	**T4.1**	Management & Risk Assessment	**CNR**, CNRS, SAS, HAS, U-Pa					**D4.1**							**D4.2**
WP5 Dissemination & Exploitation	**T5.1**	Dissemination	**U-Pa**, CNR, CNRS, SAS, HAS			**D5.1**									**D5.2**
	T5.2	Exploitation	**CNRS**, CNR, SAS, HAS, U-Pa												

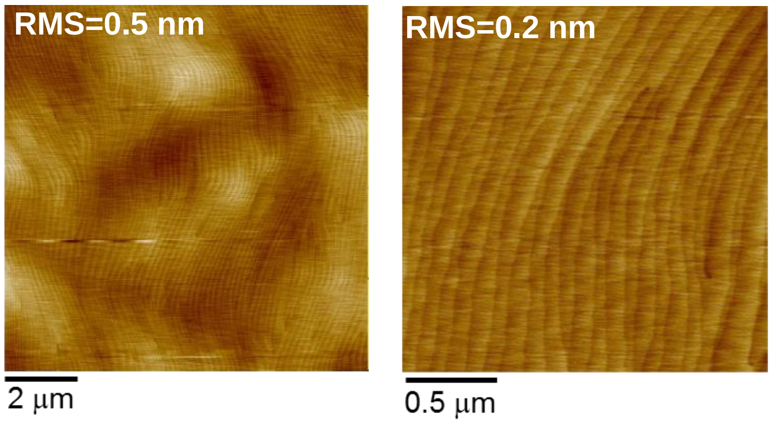
Deliv n.	**Title**	**Delivery month**	**Partner in charge**	**Status**
D5.1	Project website	M3 (31 July 2020)	**CNR**, all	**Done**
D4.1	Data Management Plan	M5 (30 Sept 2020)	**CNR,** all	**Done**
D5.2	Plan for Dissemination	M12 (31 March 2021)	**U-Pa,** all	**In prep**
D1.1	Report on the growth and surface preparation of hexagonal WBG substrates	M12 (31 March 2021)	**CNRS**	**In prep**
D4.2	1st Progress Report	M12 (1 April 2021)	**CNR,** all	**In prep**

Preparation of WBG substrates for TMD deposition

- III-N templates (GaN, AlN and AlGaN) grown by MOCVD or MBE
- Preliminary characterization by AFM, XRD, XPS

CRHEA

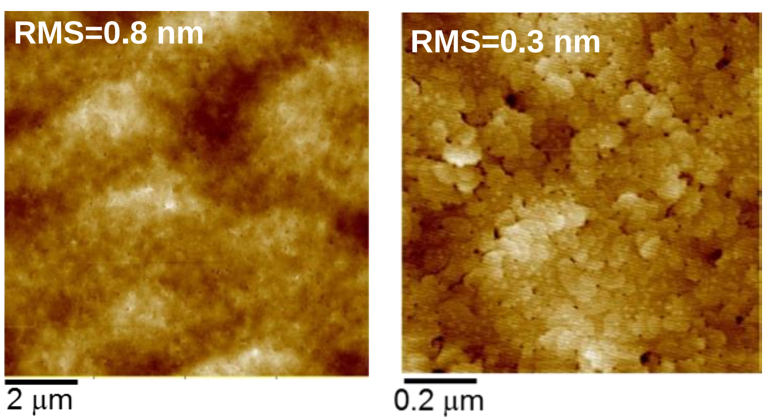
3.5 µm GaN/Sapphire



Dislocation density
~ 3x10^8 cm^{-2}

FWHM on XRD rocking curves:
GaN (002) = 396 ’’
GaN (302) = 360 ’’

100 nm AlN/Si (111)

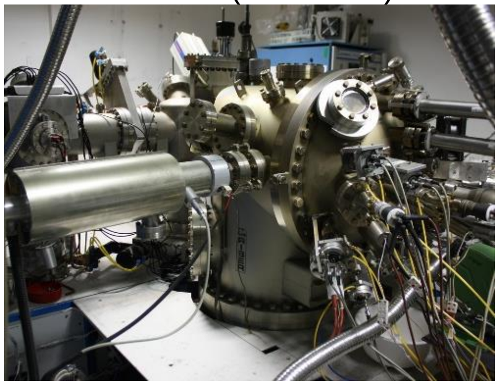


Dislocation density
~ 5x10^{10} cm^{-2}

FWHM on XRD rocking curves:
AlN (002) = 2880 ’’
AlN (103) = 3350 ’’

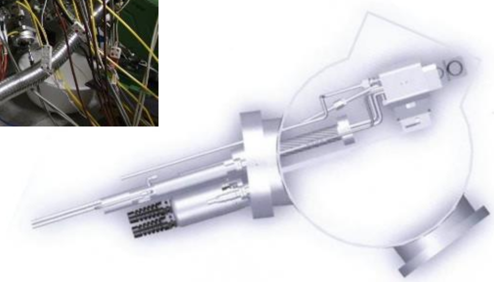
Molecular Beam Epitaxy of TMDs

MBE reactor (Riber 32P)



- MBE growth of MoS_2 and WSe_2 in progress
- Preliminary characterization by AFM, XRD, XPS

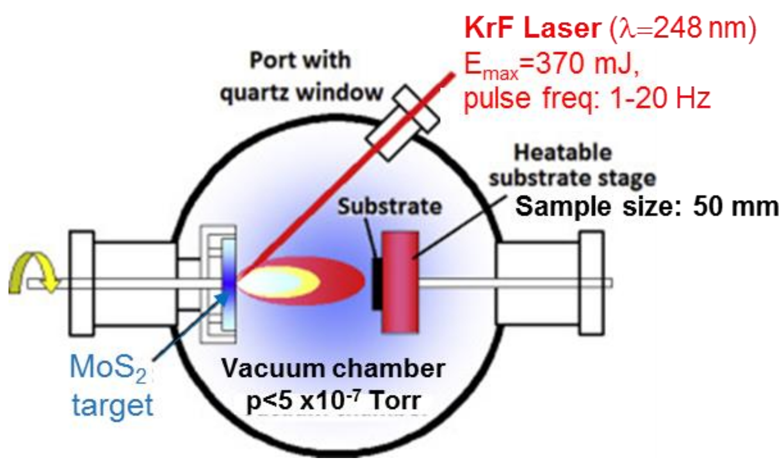
IN PROGRESS



- Order and installation e-beam evaporators for Mo and W.
- Design and order for the H_2S gas line

DONE

Pulsed Laser Deposition of MoS_2



Substrates

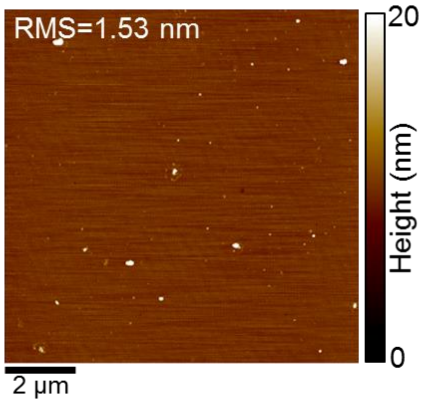
(i) Sapphire

(ii) GaN / Sapphire

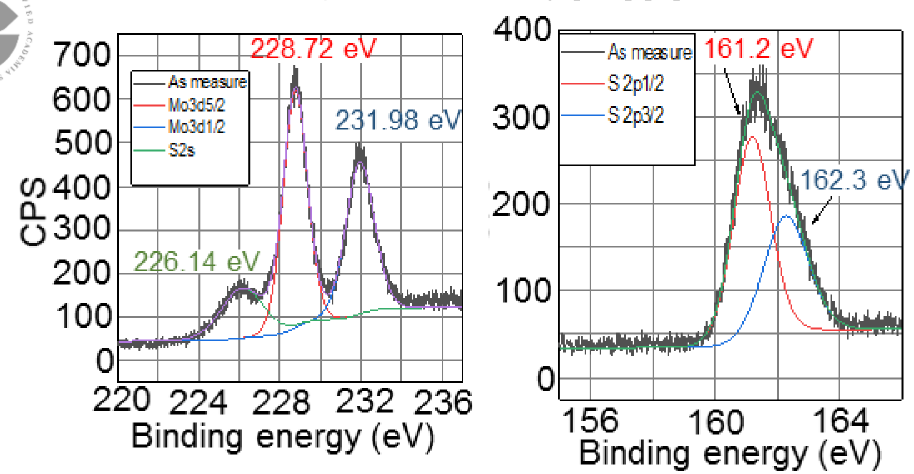
Development of PLD process on sapphire

AFM

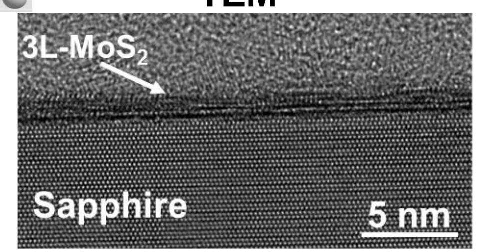
Very flat surface



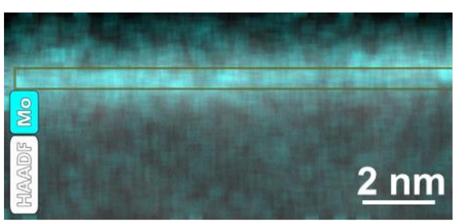
XPS Stoichiometry [Mo]:[S]=1:2



TEM

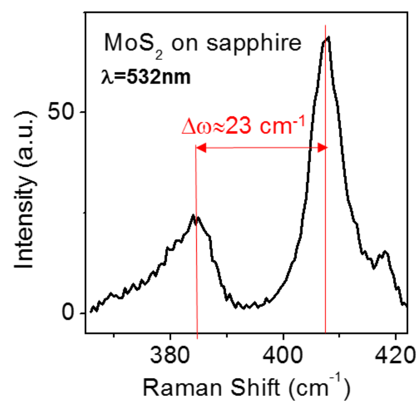


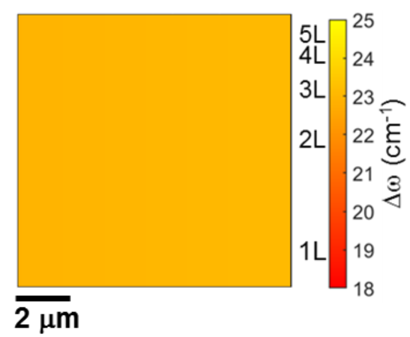
STEM-HAADF

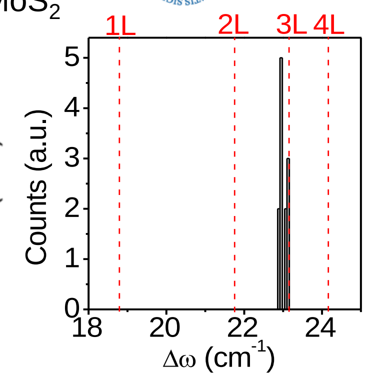


Micro-Raman mapping

Very uniform coverage with 3L MoS_2







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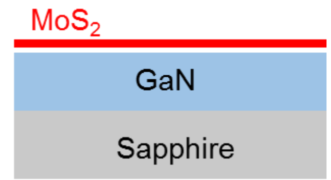
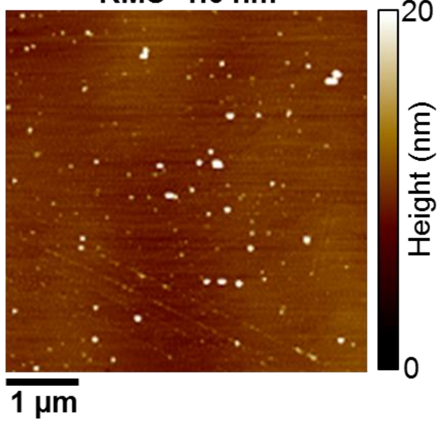
PLD of MoS_2 on GaN-on-sapphire



CNR IMM

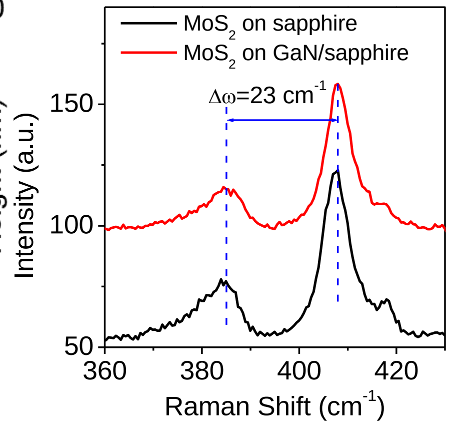
AFM

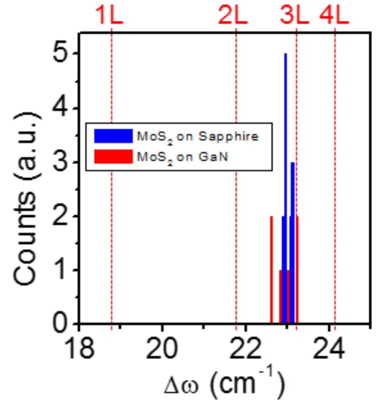
RMS=1.6 nm

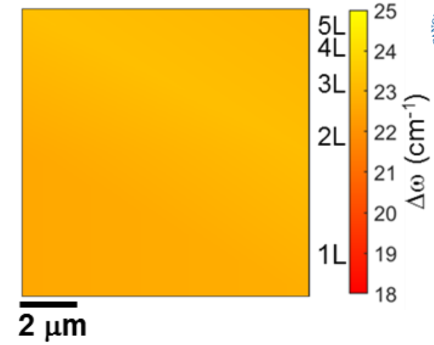


Raman mapping

Very uniform 3L-MoS_2



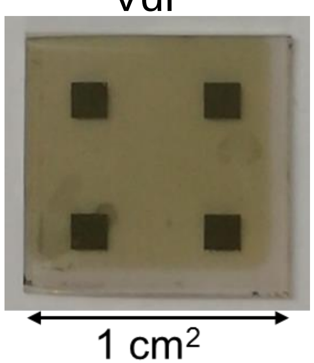




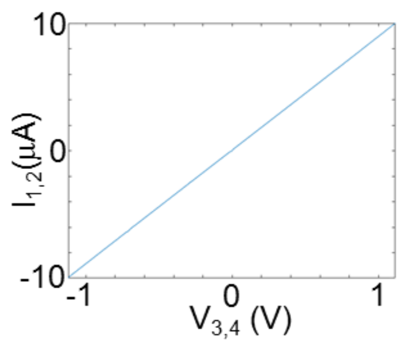
Electrical characterization

CNR IMM

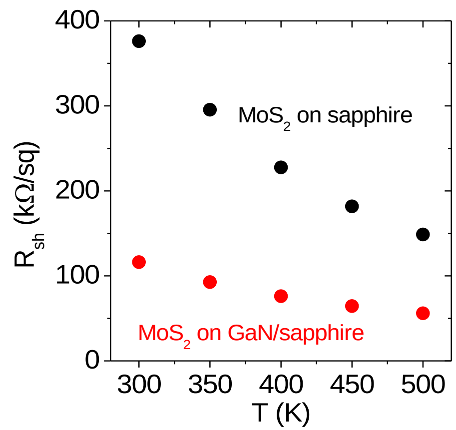
VdP



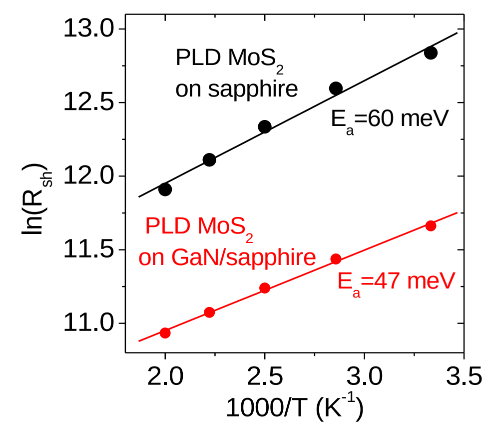
Ni (20 nm)/Au(80 nm) Ohmic contacts onto MoS_2



Temperature dependent sheet resistance measurements



$R_{sh} \sim \exp(E_a/k_BT)$



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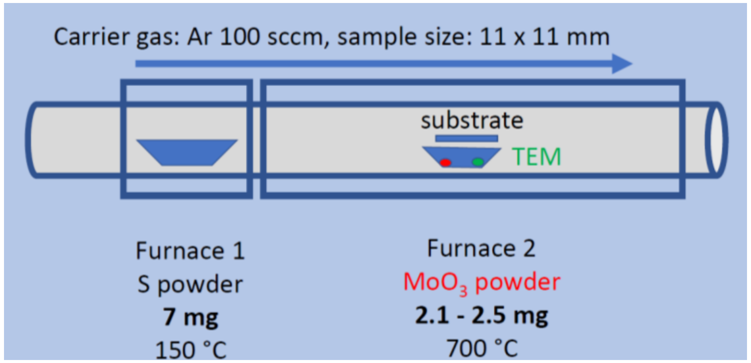
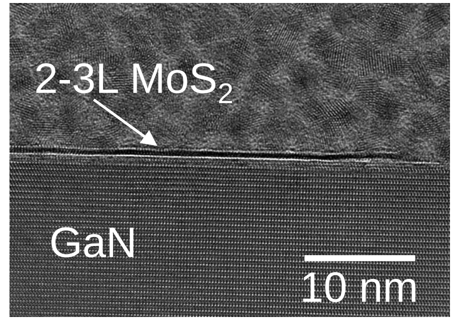
Benchmarking with other large area synthesis methods

CVD from S and MoO_3 powders

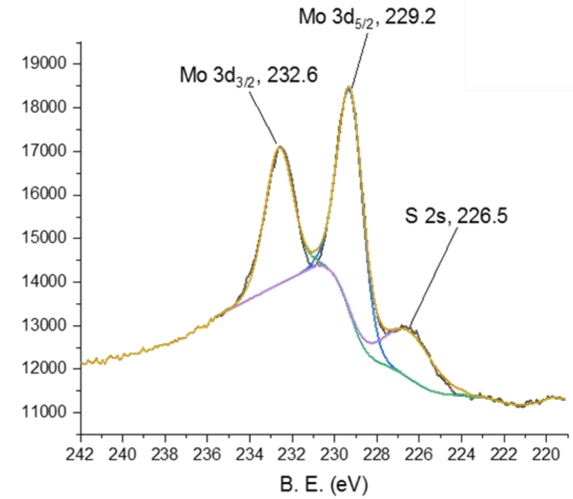


HRTEM



XPS

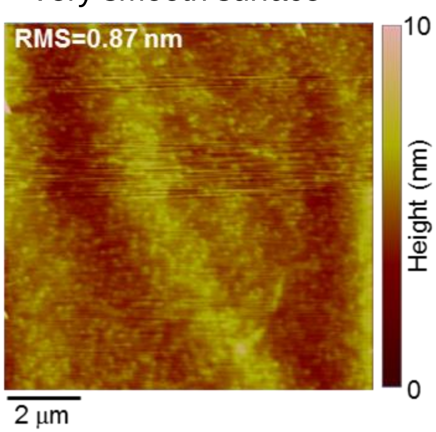
Stoichiometry [Mo]:[S]=1:1.9



IMM

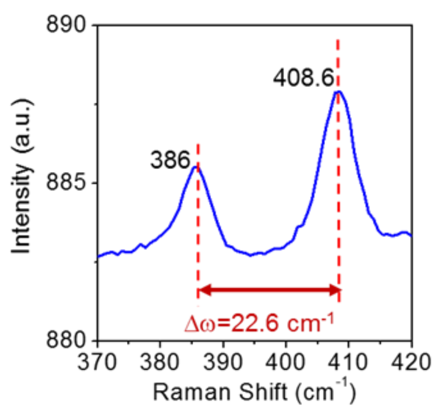
AFM

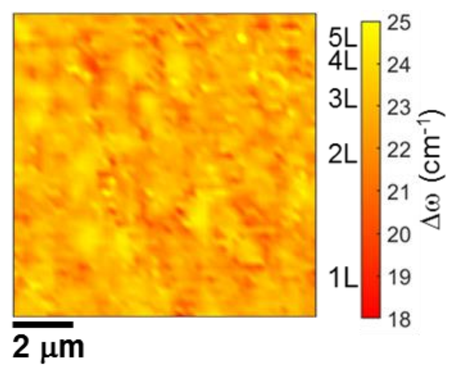
Very smooth surface

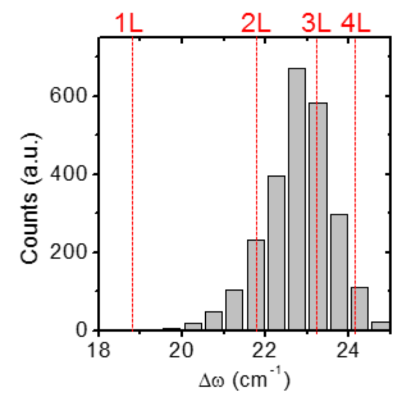


Raman mapping

MoS_2 thickness from 2L to 4L







ETMOS

Management

Project meetings:

- 1st online ETMOS meeting with all partners: 16 June, 2020
- 2nd online ETMOS meeting with all partners: 15 December, 2020
- Monthly updates about progress in joint experiments between involved partners

Association of ETMOS to the Graphene Flagship

GRAPHENE FLAGSHIP

Memorandum of Understanding (MoU)

for association of a Partnering Project to the Graphene Flagship

Following the submitted application and the approval by the Graphene Flagship Management Panel, the project:

Epitaxial Transition Metal dichalcogenides Onto wide bandgap hexagonal Semiconductors for advanced electronics

(ETMOS)

becomes associated to the Graphene Flagship initiative as a Partnering Project (PP).

The following organisations shall be granted the status of **Associated Member:**

Slovak Academy of Sciences, Slovenia (new PI)[2]
Università degli Studi di Palermo, Italy

On behalf of the Graphene Flagship Core 3 Project:

WP1 Leader
Vladimir Falko
Name and signature:

Professor Vladimir Falko, Director of National Graphene Institute

Digitally signed by Professor Vladimir Falko, Director of National Graphene Institute
DN: cn=Professor Vladimir Falko, Director of National Graphene Institute, o=The University of Manchester, ou, email=vladimir.falko@manchester.ac.uk, c=GB
Date: 2020.02.20 14:13:59 Z

On behalf of the Partnering Project:

PP coordinator
Filippo Giannazzo
Name and signature:

Consortium Agreement: signed by all partners on 17 October 2020;
sent to FLAG-ERA Secretariat on 23 October 2020

Dissemination

ETMOS website *(available since July 2020)*

- Information on ETMOS consortium and scientific activities
- Dissemination of project results (publications)
- Videos of presentations
- Organized events (symposia, seminars)
- Links to FLAG-ERA and Graphene Flagship events

Dissemination

- **SPECIAL ISSUE** of Nanomaterials on "Nanoscale Electrical Characterization of Low Dimensional Materials for Electronics", Eds. Giannazzo, Celano
- **BOOK CHAPTER**: F. Giannazzo, E. Schilirò, R. Lo Nigro, P. Prystawko, Y. Cordier, Integration of 2D materials with nitrides for novel electronic and optoelectronic applications, Ch. 11 of *Nitride Semiconductor Technology: Power Electronics and Optoelectronic Devices* ed F Roccaforte and M Leszczynski (Weinheim: Wiley-VCH Verlag). pp 397–438

Publications:

1. E Schilirò, R Lo Nigro, SE Panasci, FM Gelardi, S. Agnello, Rositsa Yakimova, F Roccaforte, F Giannazzo, *Aluminum oxide nucleation in the early stages of atomic layer deposition on epitaxial graphene*, Carbon **169**, 172-181 (2020).
2. F Giannazzo, R Dagher, E Schilirò, SE Panasci, G Greco, G Nicotra, F Roccaforte, S Agnello, J Brault, Y Cordier, A Michon, *Nanoscale structural and electrical properties of graphene grown on AlGaN by catalyst-free chemical vapor deposition*, Nanotechnology **32**, 015705 (2020)
3. F. Giannazzo, E. Schilirò, G. Greco, F. Roccaforte, *Conductive Atomic Force Microscopy of Semiconducting Transition Metal Dichalcogenides and Heterostructures*, Nanomaterials **10**, 803 (2020)

Conference Talks (invited):

1. F. Giannazzo, et al., *Nanoscale probing the electronic transport in transition metal dichalcogenides by conductive atomic force microscopy*. NanoInnovation 2020, Roma, 16 September 2020 (online).
2. F. Giannazzo, et al., *2D materials heterojunctions with Nitride semiconductors: from synthesis to applications*, ICTF-JVC 2020 online conference, Budapest, 24 November 2020 (online).
3. F. Giannazzo, et al., *Conductive Atomic Force Microscopy of 2D Materials and Heterostructures for Nanoelectronics*, Nanoscientific Symposium China, 10 December 2020 (online).
4. S. Agnello, et al., *Graphene and transition metal dichalcogenides: from structural properties to doping,* SIF conference, 18 September 2020 (online).
5. Š. Chromik et al., *The properties of MOS_2 two-dimensional system prepared by PLD and ex-situ methods on different substrates,* 11th International Conference on Solid State Surfaces and Interfaces, Smolenice, Slovakia, 23-26 November 2020.

Responsible Research Innovation (RRI) in the ETMOS project

Science Education

- Direct involvement of PhD students in the project's activity
- Organization of dedicated initiatives for **secondary schools and university students** in collaboration with teachers: laboratory visits, experimental demonstrations and training,...

Public engagement

- Participation to public events (e.g.,**"European Researchers' Night**") with specific activities aimed at illustrating the societal and environmental benefits of new technologies based on advanced materials (2D materials, WBG semiconductors)
- Use of broad audience channels (interviews in newspapers/magazines, dedicated web pages in social networks Facebook, LinkedIn) to disseminate relevant project's achievements.

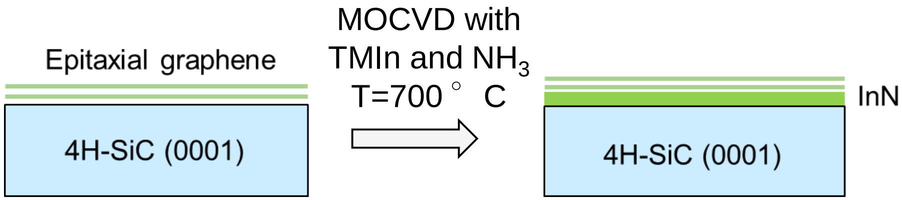
Engagement of stakeholders

- The CNR-IMM and CNRS-CRHEA partners of ETMOS are involved in National and EU projects on WBG semiconductors (SiC, GaN) with leading **microelectronic industries**, such as **STMicroelectronics** (Italy and France) and small medium enterprises, such as **TopGaN** (Poland).
- Representatives of these industries are involved as **ETMOS Advisory Board Members,** providing guidelines for the compatibility of processes developed in the project with industrial requirements.
- Organization of dedicated seminars/meetings for potential industrial end-users, with the assistance of the advisory board members.

Interaction with other FlagERA projects

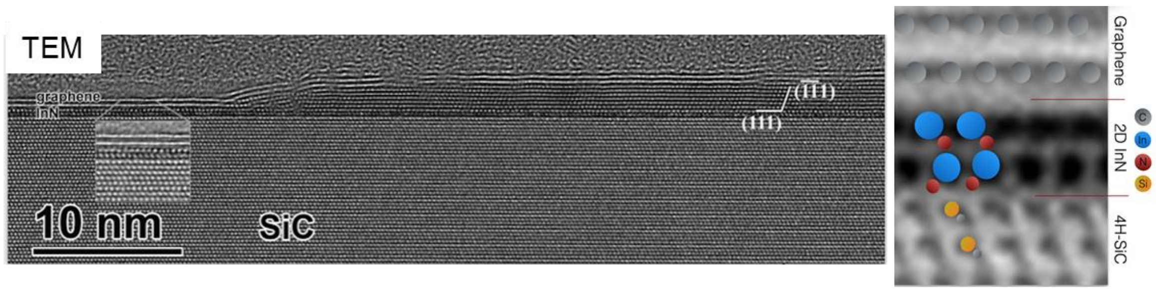
FLAG-ERA JTC 2015 GRIFONE *(coord. A. Kakanakova-Georgieva, Univ. Linkoping, Sweden)*

Nitride semiconductors (InN, AlN, GaN) at the 2D limit

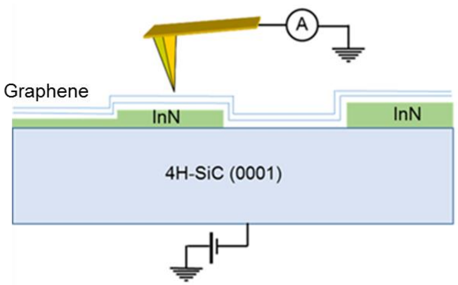


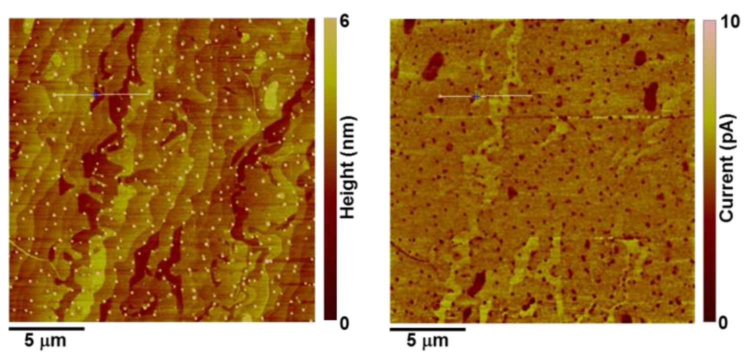
Intercalation of ultra-thin InN at epitaxial graphene/SiC interface in a MOCVD process

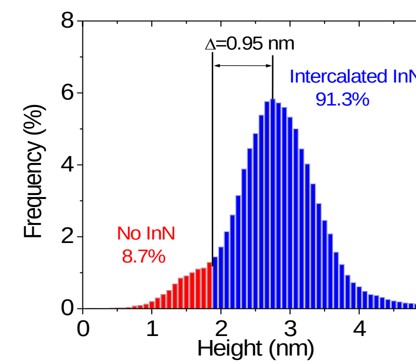
Atomic resolution structure of 2D-InN



Uniformity of intercalated 2D-InN







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Summary

- Scientific activities of ETMOS project are almost on schedule after the first year:
  - *Activities on WBG substrates preparation and characterization completed*
  - *Running activities on MBE and PLD growth on TMDs and their characterization*
- Dissemination of project results through papers' publications and participation to online conferences
- Successful interaction with another FlagERA project: GRIFONE
- RRI in ETMOS: dissemination to general public; interaction with industrial stakeholders

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