OPERA COST Action
Training School 2025

Applications and Characterization of Epitaxial Materials

COST Action CA20116

OPERA

European Network for Innovative and Advanced Epitaxy

Presentation of OPERA COST action

Dr. Noelle Gogneau - Chair
Dr. Yamina André – Scientific Grant Holder

COST Action CA20116

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European Network for Innovative and Advanced Epitaxy

Development of high-efficient and ultra-compact piezo-transducers based on III-N NWs for supplying µ-sensors and medical implants

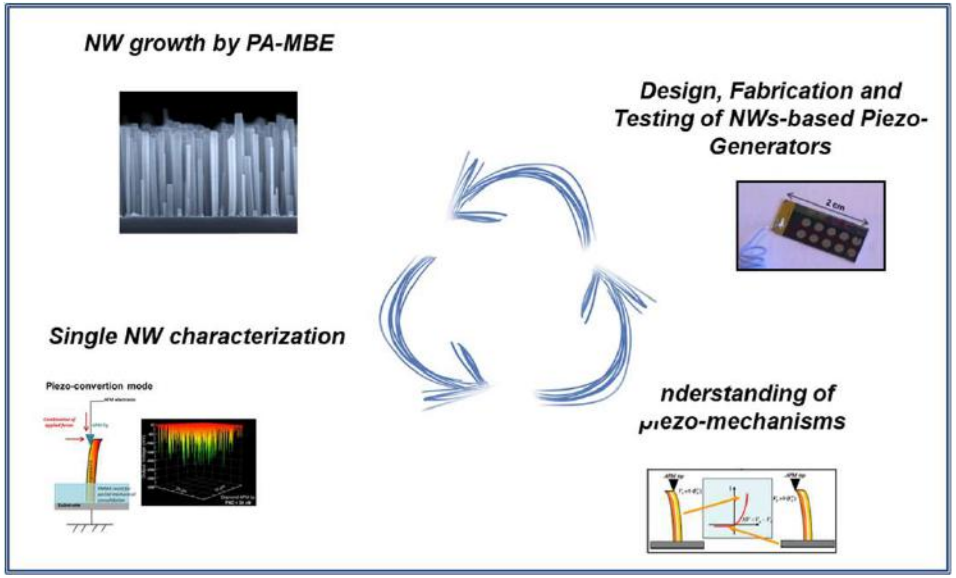
Dr. Noëlle Gogneau

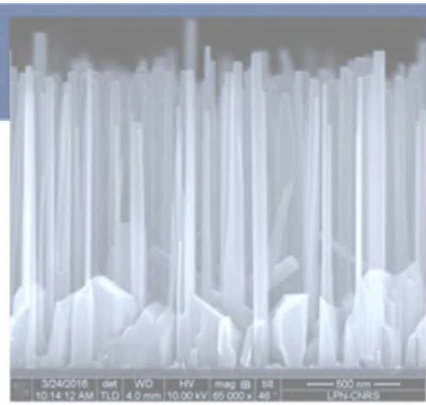
C2N Centre de Nanosciences & de Nanotechnologies

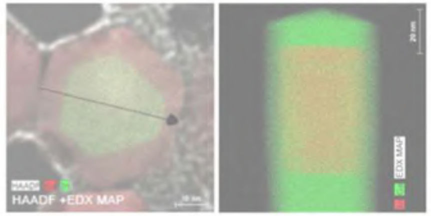
cnrs

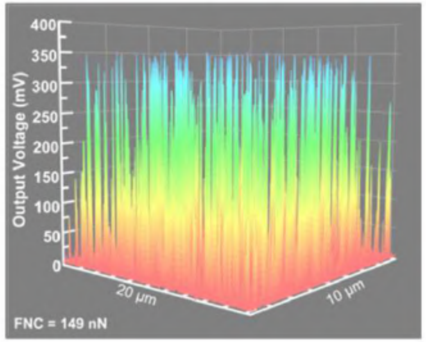
université PARIS-SACLAY

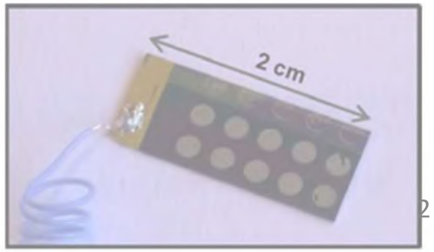
Université Paris Cité











C2N

université PARIS-SACLAY

410
PERSONNES

120
CHERCHEURS ET ENSEIGNANTS-CHERCHEURS

80
INGÉNIEURS, TECHNICIENS ET ADMNISTRATIFS

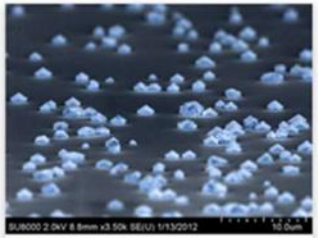
18 000 m²
DONT 2 900 M² DE SALLES BLANCHES

Innovation is essential for the R&D of tomorrow!

4 DEPARTMENTS

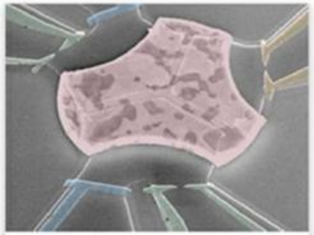
Photonics Dept.

From fundamental research to the development of new photonic devices



Materials Dept.

Epitaxy of materials and study of the properties of new structures with advanced functionalities



Electronic Dept.

Understanding of phenomena and realization of devices at the nanometric scale

Microsystem & Microfuidic Dept.

Study and understanding of innovative micro / nano devices

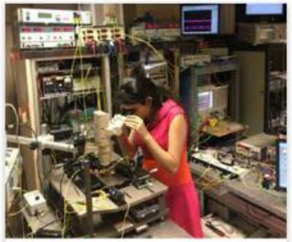
6 PLATFORMES

PIMENT
PLATEFORME D'INNOVATION EN MICRO ET NANO-TECHNOLOGIES

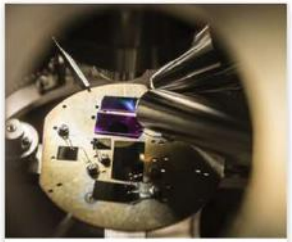
POEM
PLATEFORME D'ELABORATION DE MATÉRIAUX

PANAM
PLATEFORME D'ANALYSE DES MATÉRIAUX

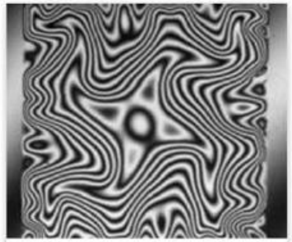
Technology platform



Expérimentation RF et optique



Instrumentation



Plateforme multi-physique

Clermont-Ferrand

A central position in Europe... and in France !

400 000 inhabitants (37 000 students)

UNESCO heritage (2018)

OPERA

COST ACTION CA20116 https://cost-opera.eu

OPERA Grant Holder

Franziska Fischer
Administrative Grant Holder

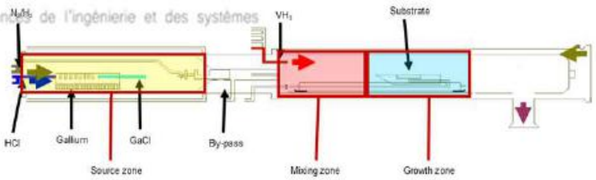
Yamina André
Scientific Grant Holder

A dynamic economy

Some big company names :
Michelin,
Limagrain,
Volvic
IBM...

Sectors with international reach:
Logistics and transports,
Mechanics,
Biotechnology,
Food industries...

Institut Pascal – Clermont Auvergne University (UCA) – Clermont Auvergne INP



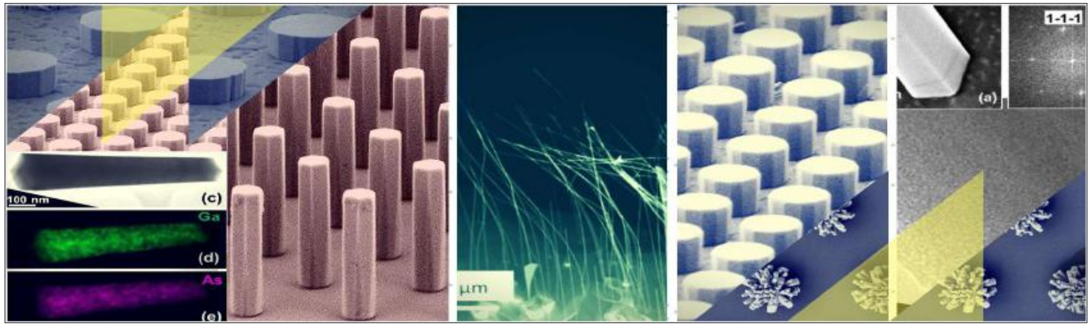
III Elements : III-Cl_x (GaCl, InCl, $InCl_3$)
V : VH_3 (NH_3, AsH_3)
Low material consumption
(average total flow 3L/min)

III-V

$$IIICl_g + VH_{3g} + H_{2g} \rightleftharpoons III\text{-}V + HCl_g + 2H_{2g}$$

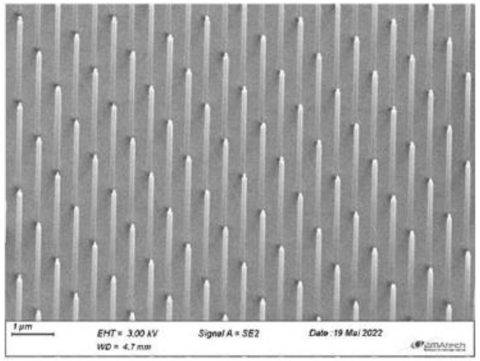
Good selectivity in SAG

Possibility to tune the growth rate from (1 µm/h to 130 µm/h)



Epitaxy of III-V nanostructures and nanowires

by Hydride Vapor Phase Epitaxy (HVPE)



Pattern characteristics:
Pitch = 1 µm
Hole diameters = 80 nm

Photodetection
Energy Conversion

Outline

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Epitaxy – a little history !

OPERA COST Action

Opening Calls

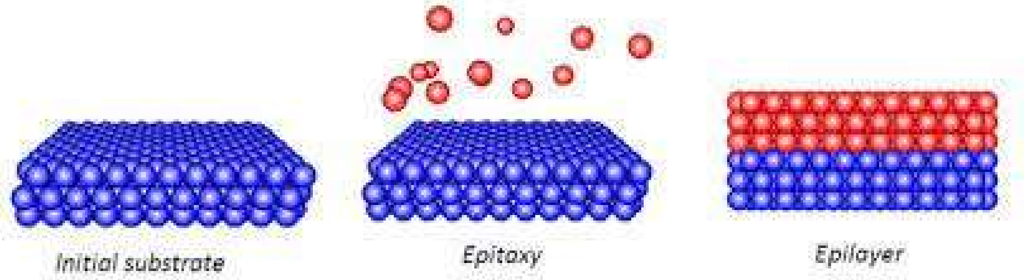
Epitaxy

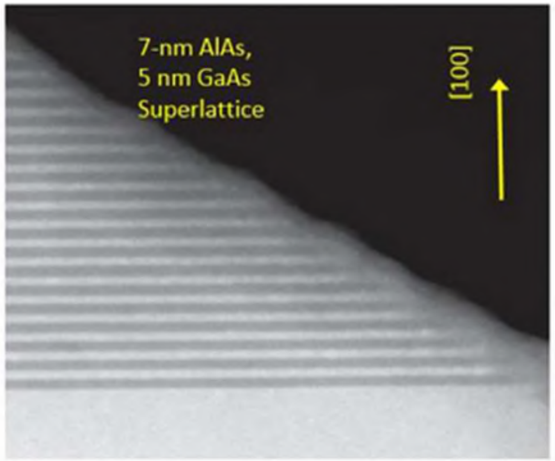
The word ***epitaxy*** derives from the **Greek prefix**

epi meaning "upon" or "over"

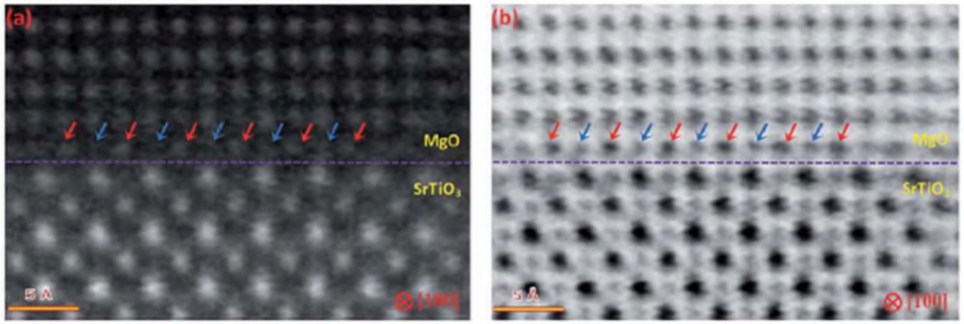
taxis meaning "arrangement" or "order"

Refers to the growth of a material with a highly ordered atomic arrangement (thin films, nanostructures, 2D materials, inorganic or organic materials) on top of another one (crystalline, amorphous material)

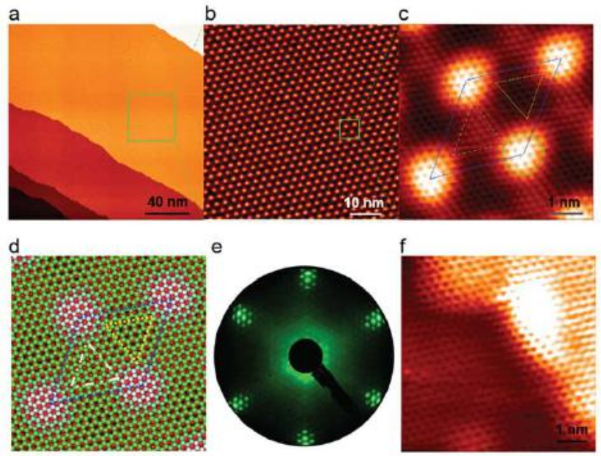




MBE of AlAs/GaAs superlattice [1]



(a) HAADF and (b) ABF STEM image of the MgO/STO heterointerface [2]



Epitaxially-grown wafer-size graphene on a Ru(0001) surface [3]

Epitaxy – A little history

[4] CHM Computer History Museum

“In 1951 Gordon Teal and Howard Christensen at Bell Labs developed a process, now called epitaxial deposition, to grow a thin layer of material on a substrate that continues the underlying crystalline structure. Sheftal', Kokorish, and Krasilov described similar work on germanium and silicon in the U.S.S.R. in 1957.”

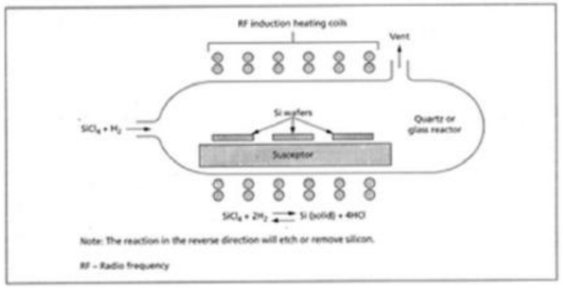
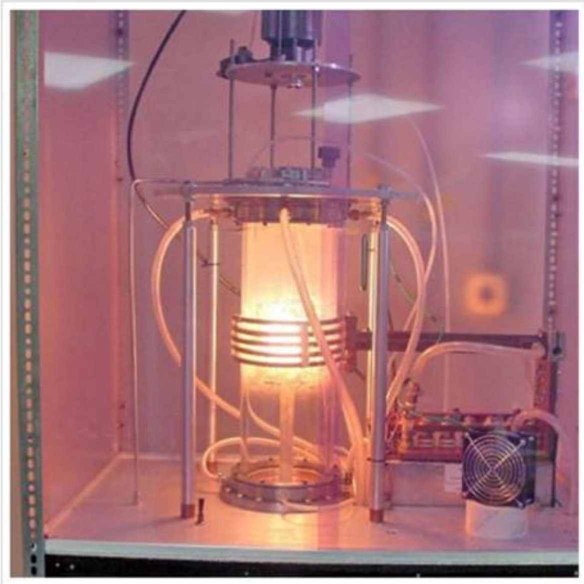
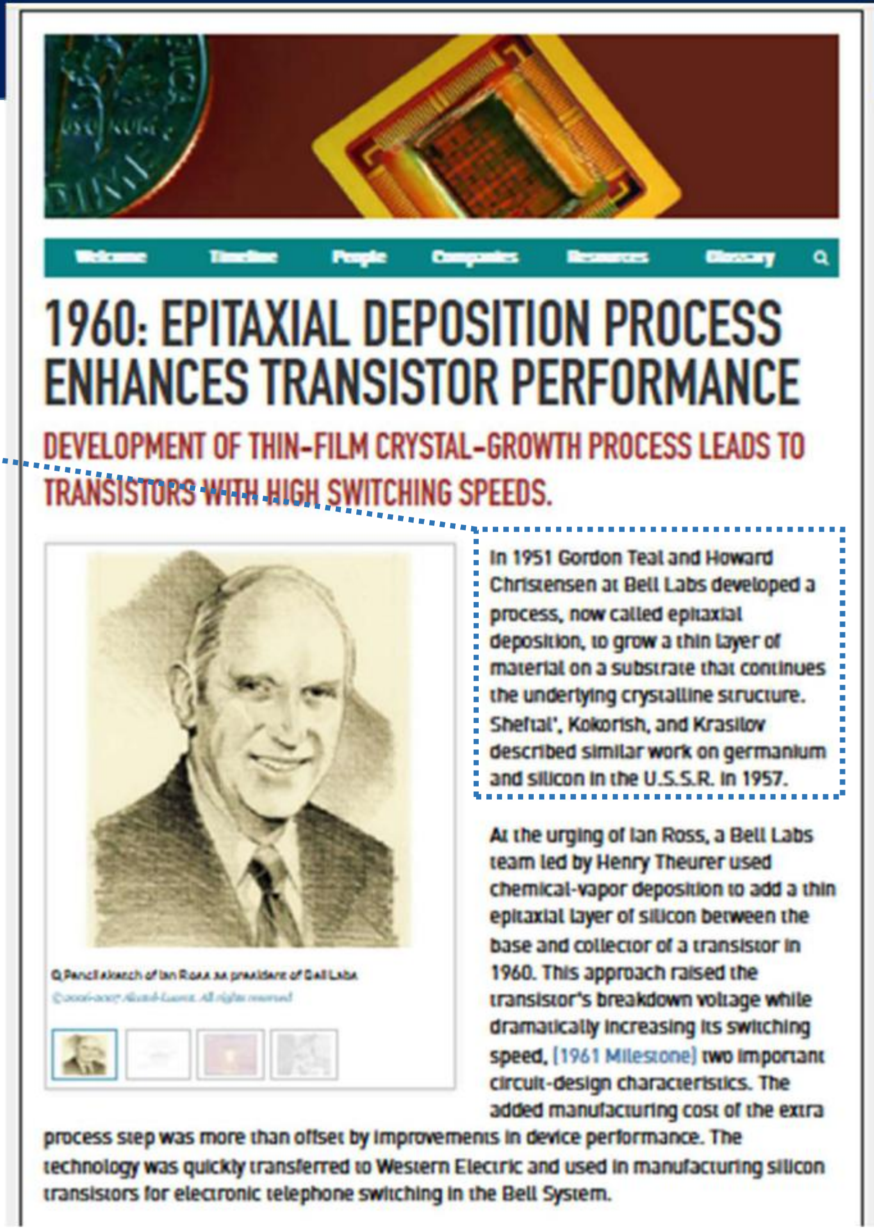


Diagram of a simple epitaxial reactor



A research-scale epitaxial reactor in operation
Credit: University of South Carolina



Welcome | Timeline | People | Companies | Resources | Glossary

1960: EPITAXIAL DEPOSITION PROCESS ENHANCES TRANSISTOR PERFORMANCE

DEVELOPMENT OF THIN-FILM CRYSTAL-GROWTH PROCESS LEADS TO TRANSISTORS WITH HIGH SWITCHING SPEEDS.

Pencil sketch of Ian Ross as president of Bell Labs

In 1951 Gordon Teal and Howard Christensen at Bell Labs developed a process, now called epitaxial deposition, to grow a thin layer of material on a substrate that continues the underlying crystalline structure. Sheftal', Kokorish, and Krasilov described similar work on germanium and silicon in the U.S.S.R. in 1957.

At the urging of Ian Ross, a Bell Labs team led by Henry Theurer used chemical-vapor deposition to add a thin epitaxial layer of silicon between the base and collector of a transistor in 1960. This approach raised the transistor's breakdown voltage while dramatically increasing its switching speed, [1961 Milestone] two important circuit-design characteristics. The added manufacturing cost of the extra process step was more than offset by improvements in device performance. The technology was quickly transferred to Western Electric and used in manufacturing silicon transistors for electronic telephone switching in the Bell System.

Epitaxy – A little history

The beginning of the 21st century is also marked by Nobel Prizes highlighting the strong impact of epitaxy in research and innovation

Between 2009 and 2014, the Nobel Prize foundation has honored numerous scientists for their **works using epitaxy and has enabled and encouraged applications that are now commonly used**

2000, H. Kroemer & Z. I. Alferov
"for developing semiconductor heterostructures used in high-speed- and opto-electronics"

2007, A. Fert and P. Grünberg
"for the discovery of Giant Magnetoresistance."

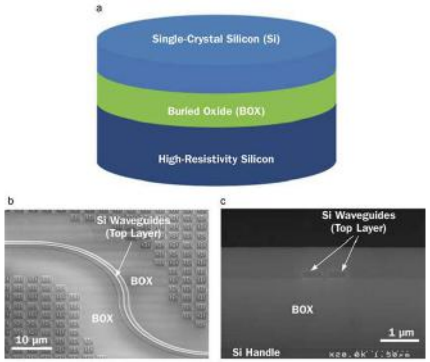
2009, W.S. Boyle & G. E. Smith
"for the invention of an imaging semiconductor circuit – the CCD sensor"

2014, I. Akasaki, H. Amano & S. Nakamura *"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"*

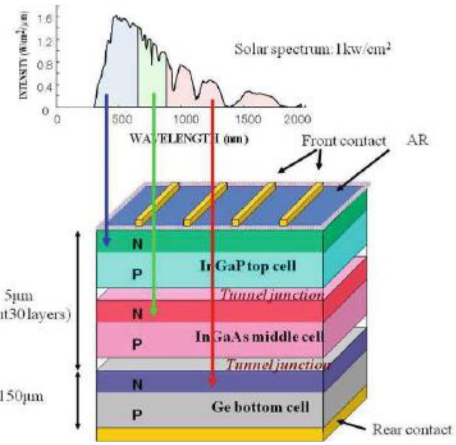
Epitaxy – Towards applications

“Conventional” semiconductors, the first grown, represent the most prominent used materials in applications of epitaxy

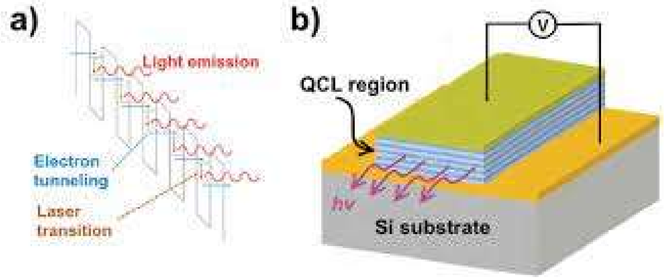
High potential in terms of innovation



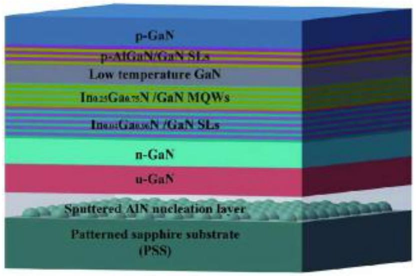
SOI Technology Lights Up the Next Wave of Photonics Solutions [10]



High-Efficiency GaAs-Based Solar Cells [9]



Quantum Cascade Laser [5-7]



Green light-emitting diode (LED) epitaxial structure [8]

Although epitaxial 2D-layers based on silicon and III-V semiconductors have largely demonstrated their potential in terms of innovation, continuous efforts in the development of **epitaxy have realized new breakthroughs opening the way towards more efficient, low cost and/or more eco-friendly devices.**

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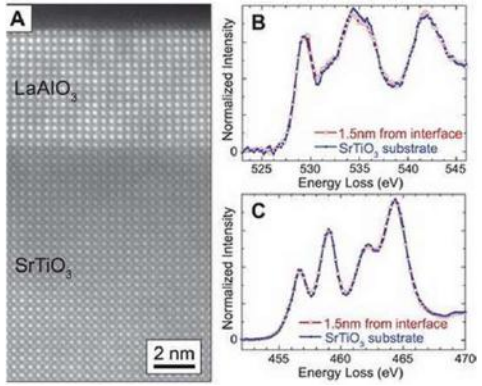
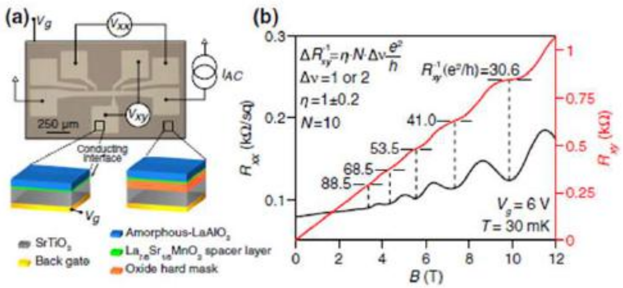
The past two decades have also seen an impressive boom and development of a wide range of novel epitaxial materials, combinations and forms of materials

Functional oxides include a wide diversity of material systems ranging from simple binary materials to complex oxide heterostructures

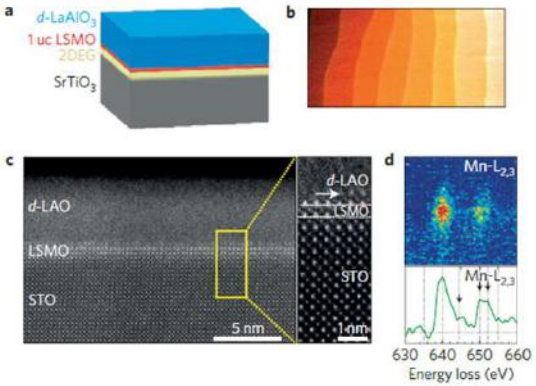
Their large variety of properties offers a step change across a multitude of applications spanning from electronic devices to energy applications [11-12]



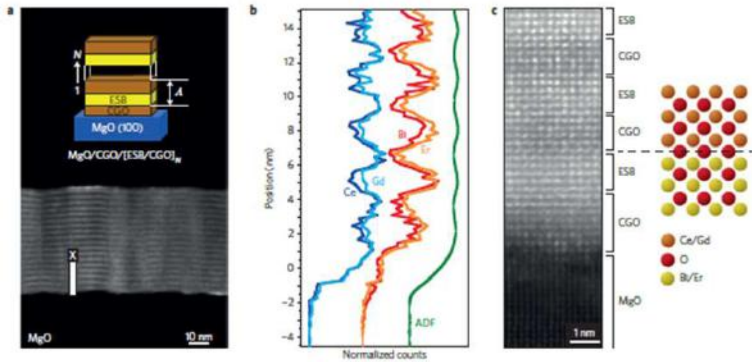
Superconductivity [16]



Observation of the quantum Hall effect [15]



2D electron gas [13] with high mobilities [14]



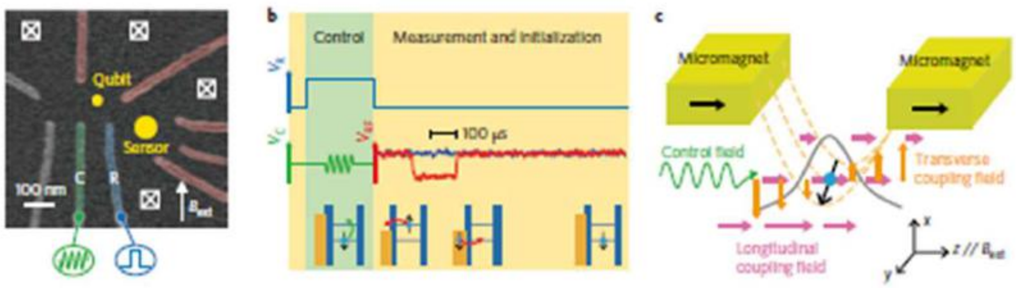
Energy [17]

Epitaxy – Towards applications

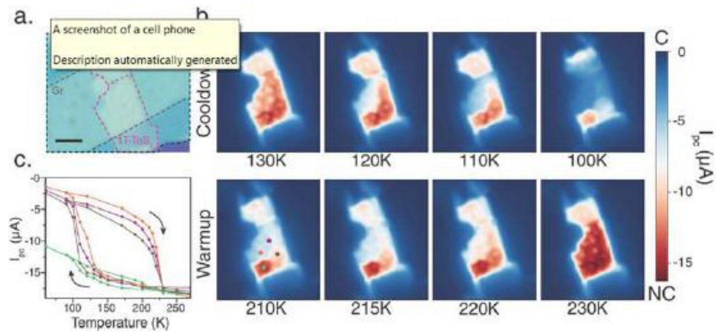
The past two decades have also seen an impressive boom and development of a wide range of novel epitaxial materials, combinations and forms of materials

2D-materials have unambiguously demonstrated their high potential for the observation of novel quantum phenomena such as in electronics and photonics [28]

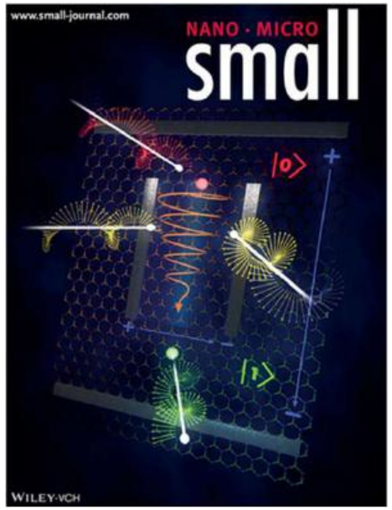
Recent works on graphene- and beyond-graphene-materials have established their large capacity for applications in various domains



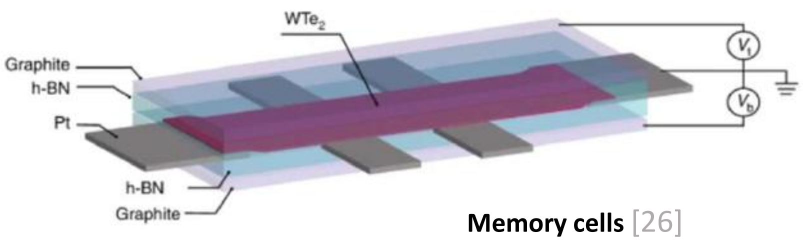
Transistors [18-19]



Photodetectors [20-21]



Valleytronics [27]



Memory cells [26]

Batteries [22]
Transparent electrodes [23]
Energy storage [24-25]

What do all these applications have in common?

Epitaxy

Epitaxial materials are the basis for device innovation

Motivations

- Epitaxial growth is useful for applications that place stringent demands on a deposited layer:
  * High purity
  * Low defect density
  * Abrupt interfaces
  * Controlled material thickness and carrier concentration
  * Controlled doping profiles
  * Possibility to grow p-n junction & other multilayer structures
  * High repeatability and uniformity
  * Safe, efficient operation

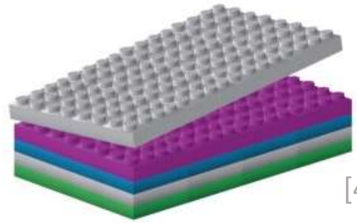
Better structural, optical, electrical… properties

- Can create clean, fresh surface for device fabrication

Epitaxy Fundamentals – few words !

Which epitaxial technique for the semiconductors ?

[43]



[44]

When selecting an epitaxial growth technology for a particular material system and/or device application, the choice needs to take into account:

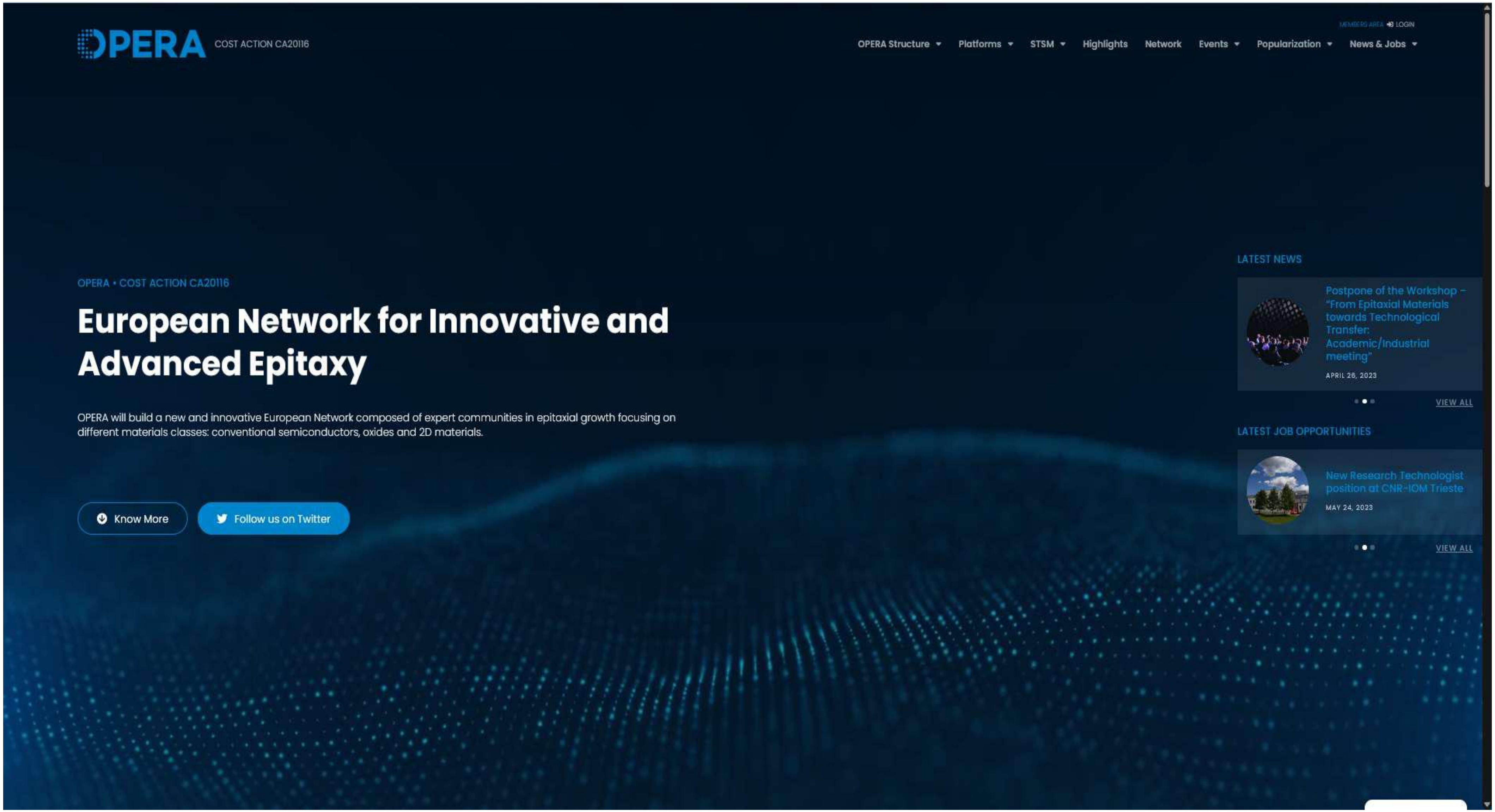
- ✓ The basic principles of thermodynamics,
- ✓ Kinetics,
- ✓ Surface energies
- …

As well as practical issues of:

- ✓ Reproducibility,
- ✓ Scalability,
- ✓ Process control,
- ✓ Instrumentation,
- ✓ Safety and capital equipment costs.

Several epitaxial techniques have been used for the growth of epilayers of III-V, II-VI compound semiconductors, Oxyde and 2D-materials.

- Liquid Phase Epitaxy (LPE),
- Molecular Beam Epitaxy (MBE) and the hybrid systems
- Vapor Phase Epitaxy (VPE) and the related techniques
- Pulsed laser deposition (PLD)
- Atomic Layer Depostion (ALD)
- …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European Network for Innovative and Advanced Epitaxy
OPERA will build a new and innovative European Network composed of expert communities in epitaxial growth focusing on different materials classes: conventional semiconductors, oxides and 2D materials.
Know More
Follow us on Twitter
LATEST NEWS
Postpone of the Workshop – "From Epitaxial Materials towards Technological Transfer: Academic/Industrial meeting"
APRIL 26, 2023
VIEW ALL
LATEST JOB OPPORTUNITIES
New Research Technologist position at CNR-IOM Trieste
MAY 24, 2023
VIEW ALL

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OPERA - Context & Needs

EUROPEAN COOPERATION IN SCIENCE AND TECHNOLOGY

Today, material innovation is more vital than ever and needs to be more efficient, design-driven and environmentally friendly

Different "epitaxial" communities

- Materials oriented: *Silicon, III-V semiconductors, wide-band-gap materials, oxides, 2D-materials, 3D-metamaterials…*
- Deposition techniques: *MOVPE & MBE; LPE, CVD, ALD/ALE & MLD/ MLE, PLD*
- Focused communities: *NWs or QDs, epitaxial process (Van der Waals epitaxy), targeted applications (photovoltaic cells, gas sensors, white LEDs or flexible electronics…*

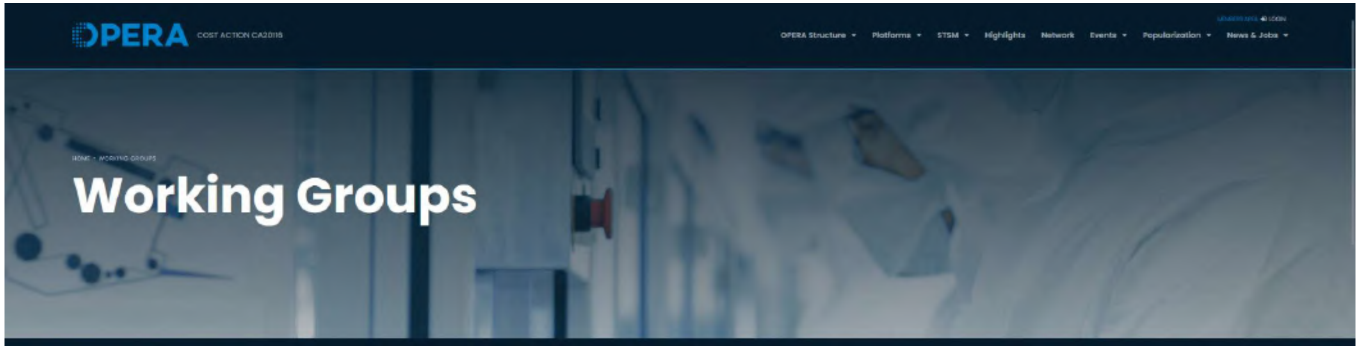
Organization of international conferences, workshops centered on materials, epitaxial techniques
a good illustration of these community partitions !

Integrate and concern only a small part of working groups

We need

A broader structure of the epitaxy community in the thematic sense, with the aim of addressing common problems and pushing innovations beyond the boundaries !

Only by joint efforts from researchers from different communities, startup & industry with a sharing and open mindset



WG1

Fundamental research – New Materials

In material science, the ambition is to address new challenges, pushing the frontiers of knowledge. To address Sustainable Development Goals: the fundamental key in the epitaxy field must be addressed for mastering "actual" materials and developing new materials.

Objectives: To master the material growth under various forms (2D film, 3D structures, nanostructures); and to develop and control the growth of new materials, it is essential to understand the fundamental mechanisms driving their synthesis by closely combining experimental and theoretical approaches.

- **WG1.1** Fundamental aspects of epitaxy
- **WG1.2** Theory of epitaxy
- **WG1.3** Substrates and pre-growth: Towards hybridization
- **WG1.4** In-situ growth and characterization

WG2

Applications-oriented material developments

Optimization of materials for innovative devices: Novel device performances rely on material properties. In this regard, materials must be developed considering device requirements.

Objectives: To make the bridge between fundamental researches (WG1) and industrial applications (WG3).

- **WG2.1** Characterization and control of novel functional materials;
- **WG2.2** Engineering epitaxial strategies for functional properties of devices;
- **WG2.3** Theoretical simulation of fundamental properties and functional devices;
- **WG2.4** New/optimized tools for growth and characterization.

WG3

Industry-oriented materials development and technological transfers

To develop technological transfer-ready devices, the fundamental challenges of tasks 1 & 2 must be addressed by taking into account market-proof device specifications.

Objectives: To convert scientific excellence into innovative solutions and establish disruptive technologies.

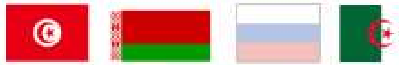
- **WG3.1** Assessment of materials requirements, development of advanced materials and technological transfers for: Photonics, Electronics, Energy, communication/information, Health and Environment;
- **WG3.2** Epitaxial tools and techniques: Because of the assessment of materials requirements, development of advanced materials/nanostructures and technological transfers is also based on the development of new techniques, new material sources and adequate and new substrates.

OPERA COST ACTION CA20116

Gender distribution **ITC grantees** **Young researchers**

COST members: 34
ITC countries: 18

4 Near-neighbouring countries



3 International partner countries

Today: More than 800 persons subscribing the mailing list

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

OPERA Action – Workshops/Conferences

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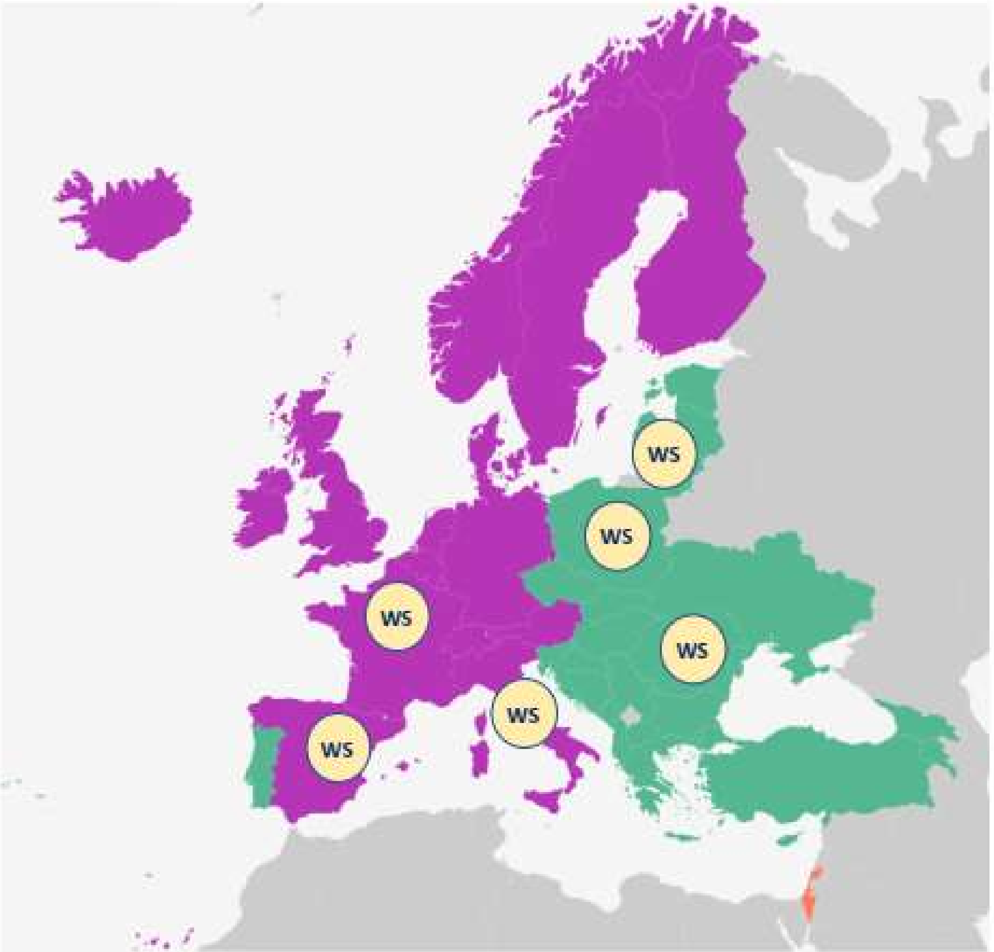

6 workshops/Conferences

COST Action CA20116

European Network for Innovative and Advanced Epitaxy

OPERA Action – Training Schools

4 Training Schools

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

OPERA Action – STSM (Y1-Y3)

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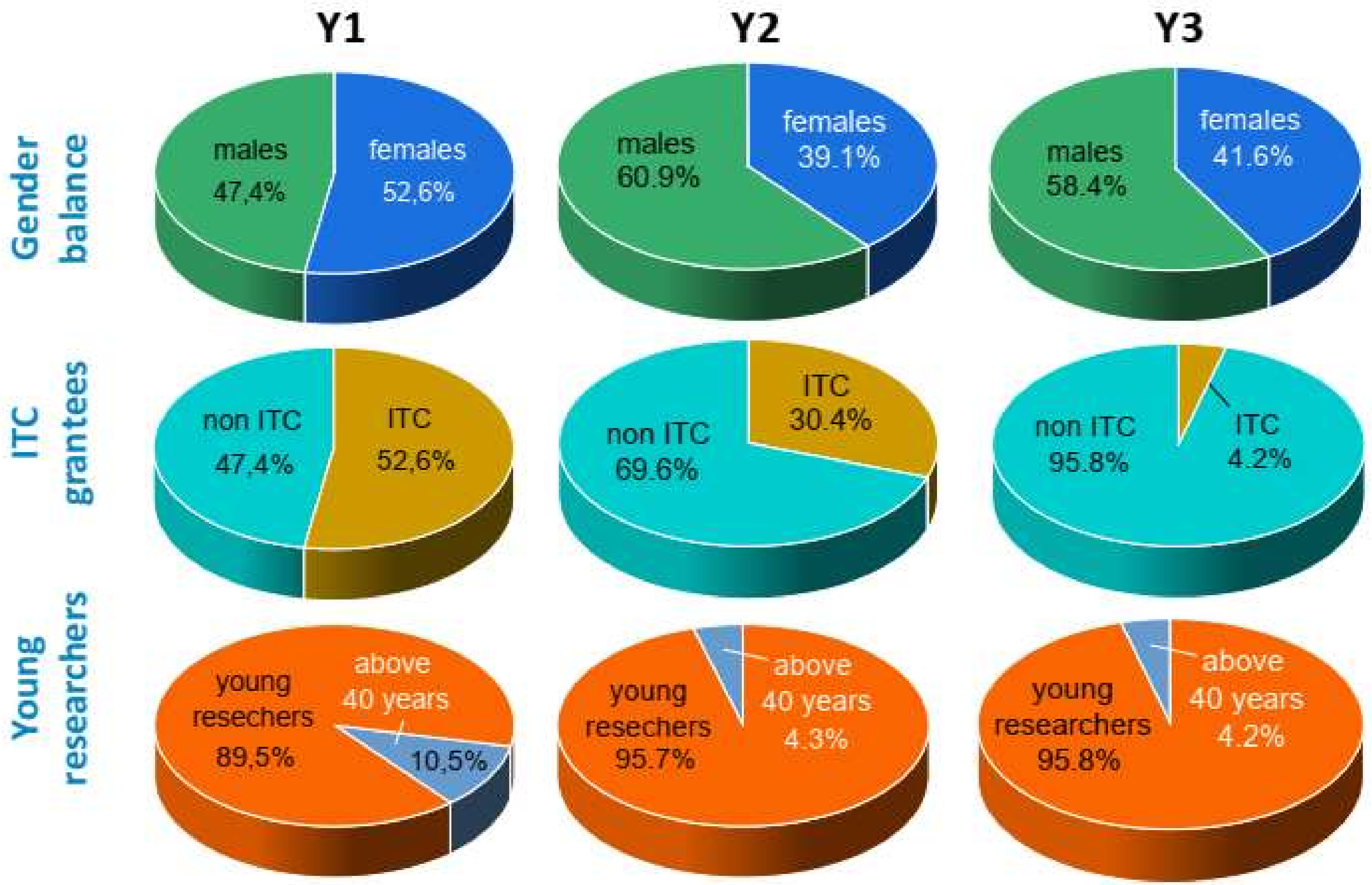

Home Countries: 19 + 1 NNC

Host Countries: 19 + 1IPC

Average duration: 25,7 days

Total Budget (Y1 – Y3) 129 k€

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Survey on the OPERA COST Action impact for

- Women, Young Researchers and ITC members
- Development of new collaboration
- Publications

COST Actions are a career accelerator for young researchers. 88% indicate that participation has led to advancement

COST Actions are gender inclusive: During Horizon 2020, 42% of participants were women

COST
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

OPERA Action – Stakeholders

COST Action CA20116
OPERA
European Network for Innovative and Advanced Epitaxy

36 Stakeholders

SUMMA SEMICONDUCTOR
comptek solutions
ORSAY PHYSICS TESCAN ORSAY HOLDING
THALES
nanovation
3D-OXIDES MULTI-FUNCTIONAL THIN FILMS
AIXTRON
SEMILAB
LAYTEC Knowledge is key
EPINOVATECH
IQE
Photin MOCVD Services
CrayoNano
OSRAM Opto Semiconductors
EpiCentre LAAS CNRS - RIBER
SurfaceNet
KLA Keep Looking Ahead
PalmSens Compact Electrochemical Interfaces
ROYAL SOCIETY OF CHEMISTRY
SpectroInlets Enabling real-time analysis
ST life.augmented
EDEN INSTRUMENTS
DEMCON
attocube WITTENSTEIN Group
NEXTRON MICRO PROBE SYSTEM
ATLANT 3D NANOSYSTEMS
HORIBA Scientific
Hexagem
University of Surrey Ion Beam Centre
IPVF
Łukasiewicz Institute of Microelectronics and Photonics
easygan
IMINA TECHNOLOGIES

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