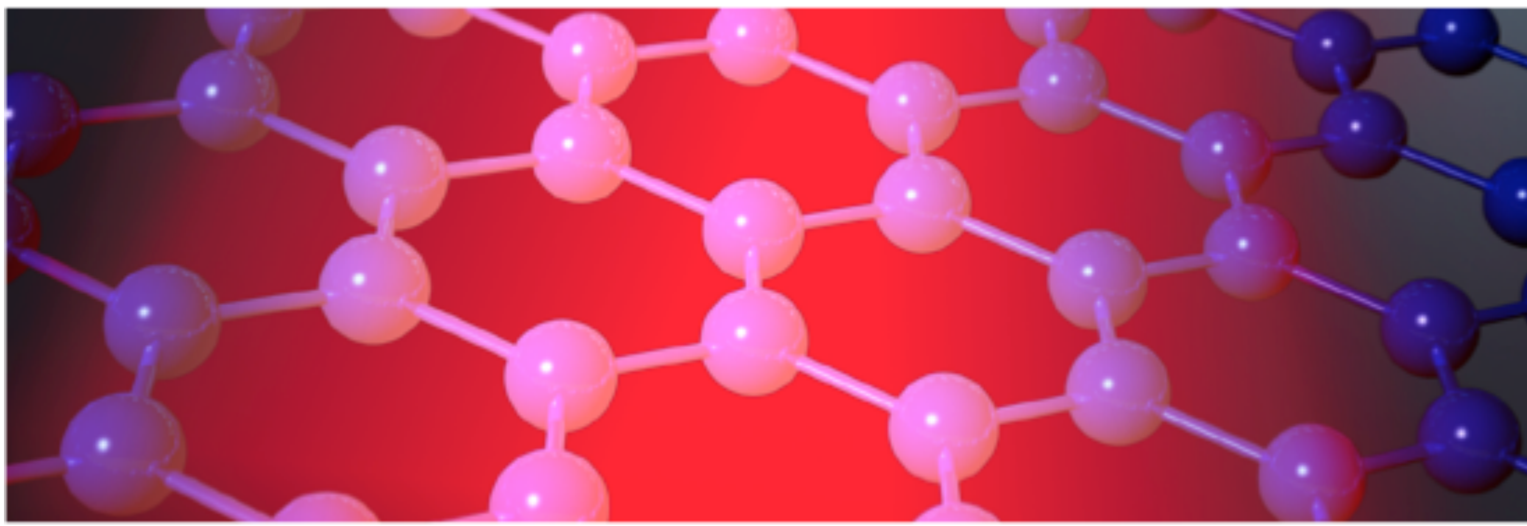
Graphene: Wafer scale production

Amaia Zurutuza
Scientific Director



Graphenea

Content

Graphenea

Important milestones

Geim & Novoselov publiish Science paper

SIGMA-ALDRICH

REPSOL

Sigma-Aldrich selects Graphenea as supplier

Repsol Energy Ventures joins Graphenea €1 m

US branch opened

2.5M $ investment for scale up secured

First funding round closed $1,8 m

First Graphene produced in Graphenea

Moving to a larger laboratory

€1 m sales milestone

2004	2008	2009	2010	2011	2012	2013	2014	2015	2016

Jesus de la Fuente writes first Business Case

Graphenea founded

First commercial order

NOKIA Connecting People

PHILIPS

Graphene Flasghip approved €1B 10 years project

GRAPHENE FLAGSHIP

Global Top 100 Ones to Watch

2014 Global Cleantech 100 One to Watch

Capacity Expansion

20x times

Graphenea

We are expanding our global presence

Graphenea sites

Research @ CIC nanogune (San Sebastian, Spain)

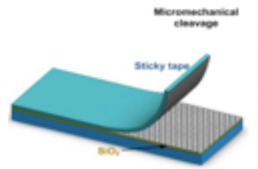
CVD & GO Production Lab @ Miramon Technology Park
(San Sebastian, Spain)

Graphenea

Graphene synthesis

Graphene Powder

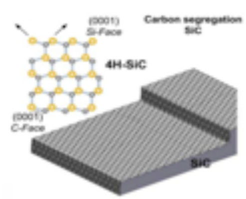
Micro-mechanical exfoliation



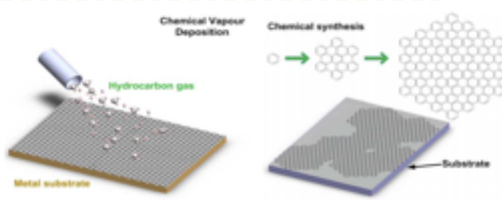
Liquid phase exfoliation (chemical)

Graphene Films

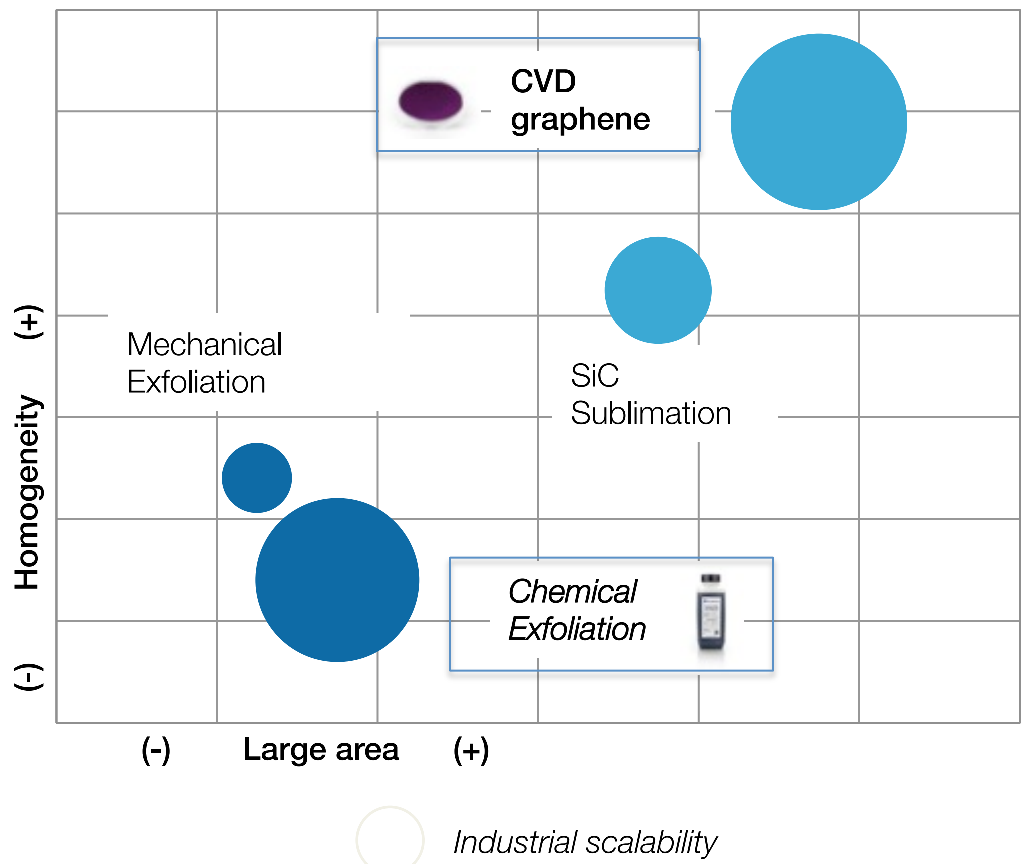
SiC Sublimation



CVD



Graphene synthesis technologies comparison



Graphenea

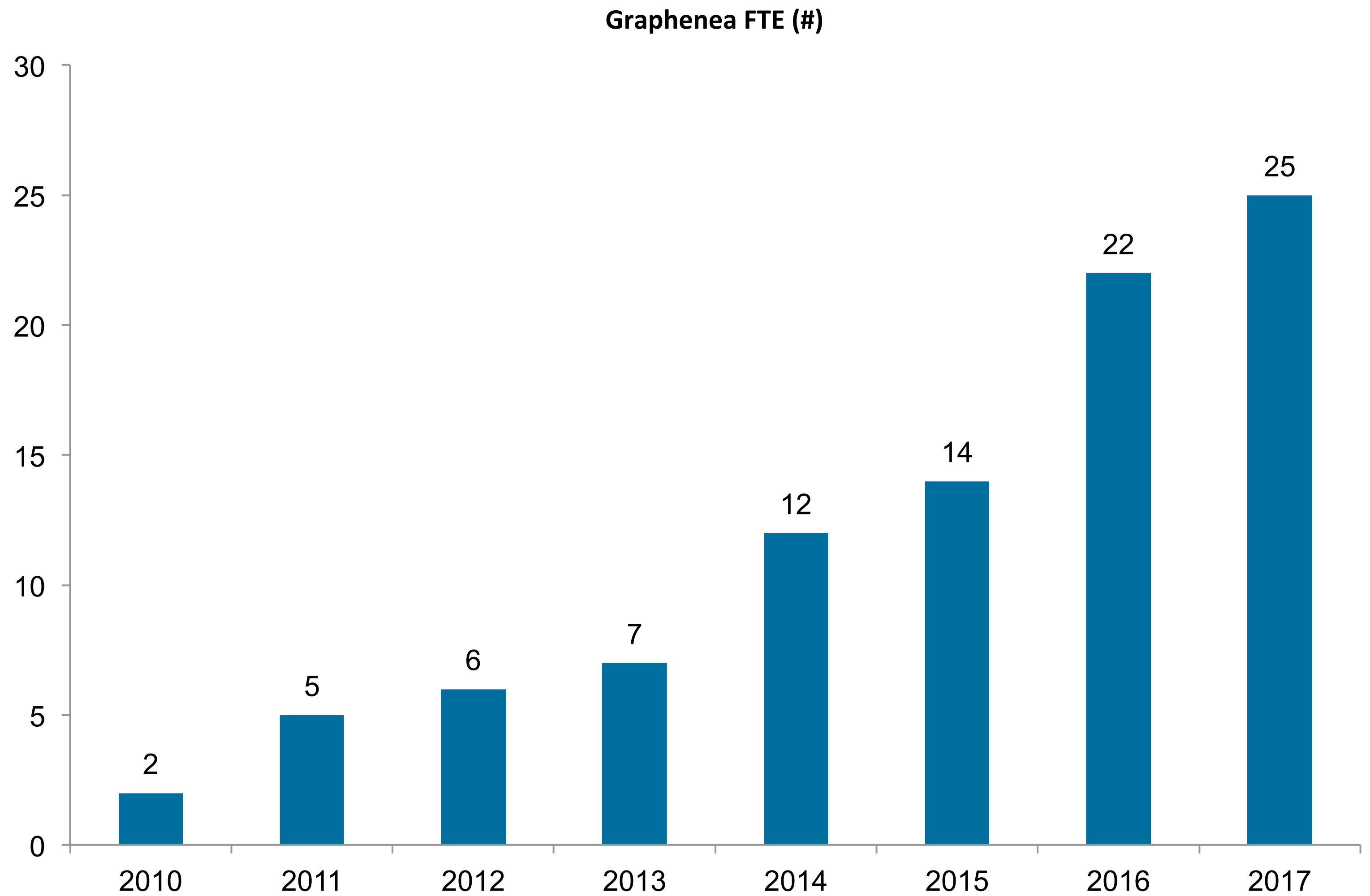
New facilities

- New 8” CVD system
- Cleanroom class ISO7
- GO pilot plant 1Tone/year

Clean room CVD graphene

GO Pilot plant

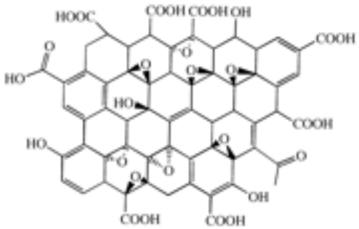
Large team



Source: Graphenea

Graphenea GO Product Range

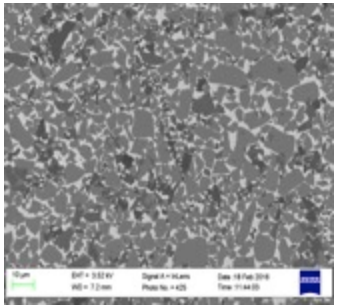
Graphene oxide



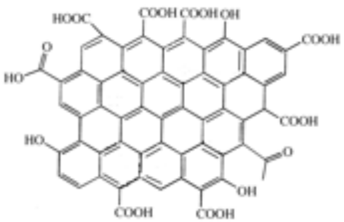
Form	Dispersion of graphene oxide sheets
Particle size	D90 29.05 - 32.9 µm
	D50 14.30 - 16.6 µm
	D10 5.90 - 6.63 µm
pH	2,2-2,5

Carbon	49-56%
Hydrogen	0-1%
Nitrogen	0-1%
Sulfur	2-4%
Oxygen	41-50%

SEM image



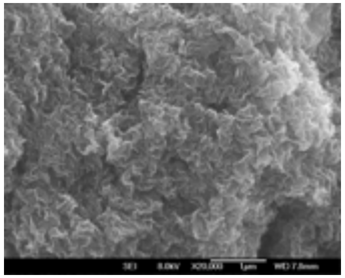
Reduced graphene oxide



Form	Powder
Electrical conductivity	≈ 667 S/m
BET surface area	422.69-499.85 m^2/g
Particle size (z-sizer in NMP at 0,1 mg/mL):	260-295nm
Density	1,91 g/cm^3

Carbon	77-87%
Hydrogen	0-1%
Nitrogen	0-1%
Sulfur	0%
Oxygen	13-22%

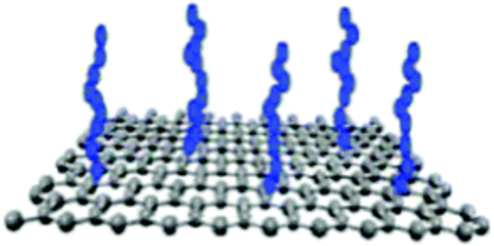
SEM image



Functionalized graphene oxide

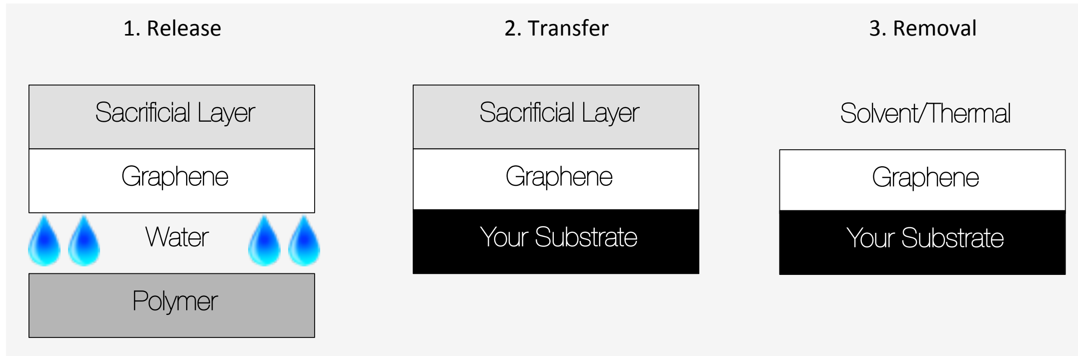
Customised functionalization:

- Compatibilisation with matrix



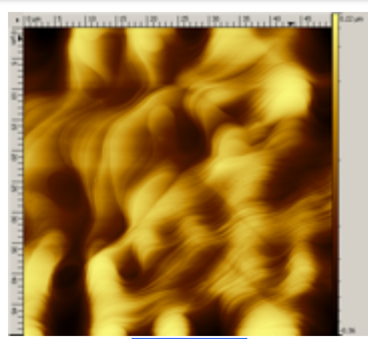
Graphenea CVD Product Range

Easy transfer graphene

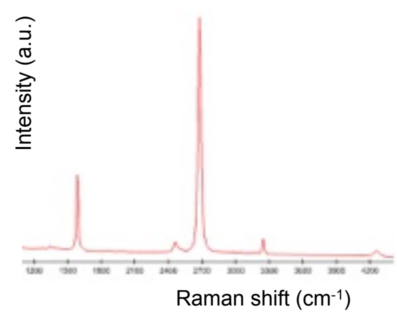


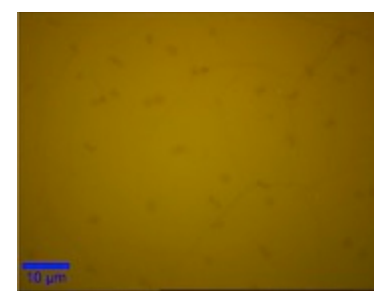
Graphene on different substrates

Graphene on Cu



G/Cu





G/SiO_2/Si

Graphenea

Graphenea CVD production capacity roadmap

2010-2012

PHASE 0
1 cm x 1 cm/2 hour

1,000 cm2/year

310 $/cm2

2013-2014

PHASE 1
4” wafer/ 2 hour

85,000 cm2/year
1,000 x 4” wafers/year)

5 $/cm2

2015-2016

PHASE 2
8” wafer/ 30 min

2,250,000 cm2/year
7,000 x 8” wafers/year

< 0.80 $/cm2

2017-…

PHASE 3
12” wafer/30 min
Roll-to-Roll 300 mm wide

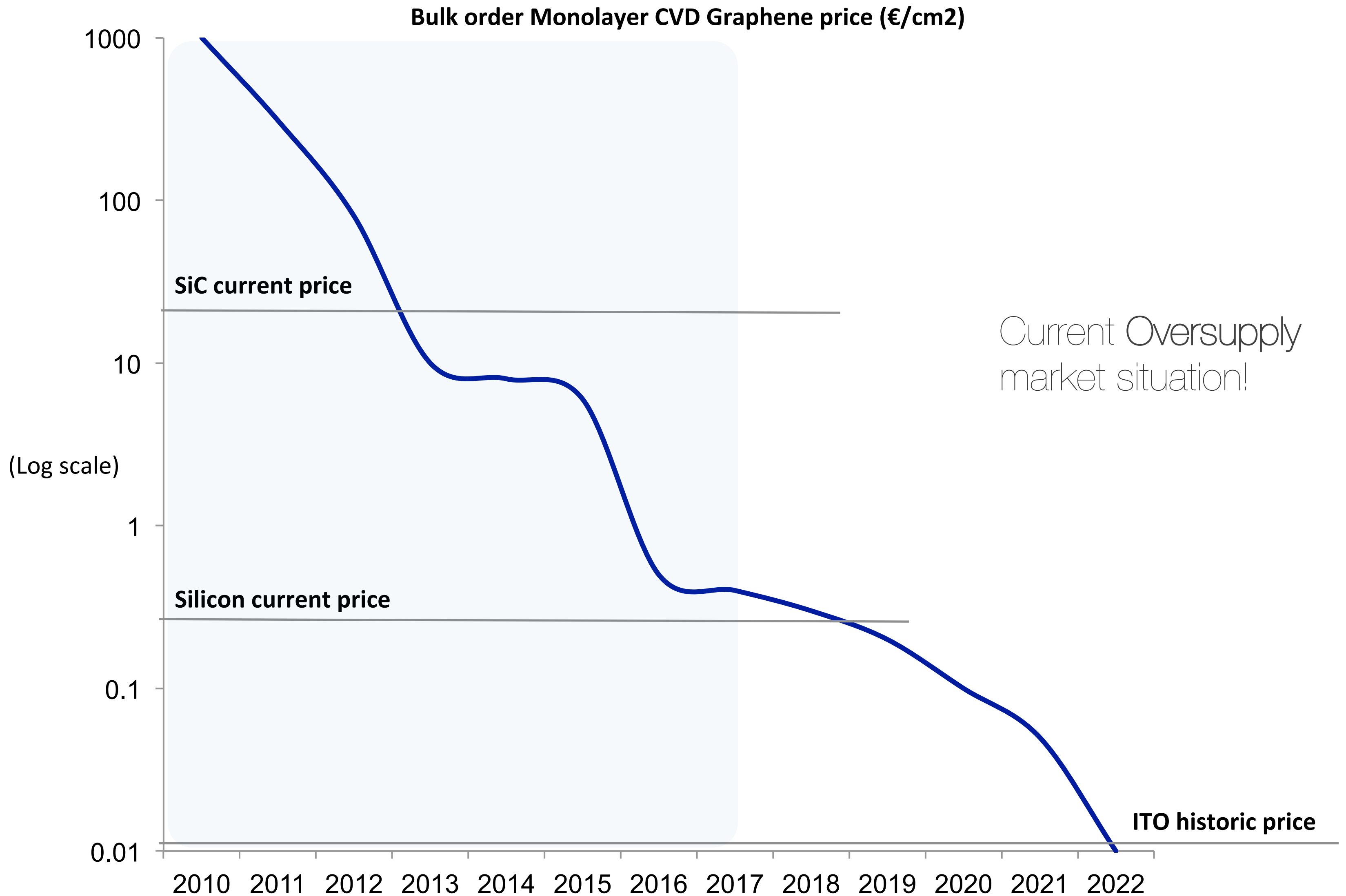
+15,500,000 cm2/year

< 0.25 $/cm2

CMOS compatible

RESEARCH → DEVELOPMENT → COMMERCIAL

Graphene is intrinsically cheap due to low marginal cost!



Source: Graphenea estimations

Graphene films

CVD Graphene

GROWTH

TRANSFER

INTEGRATION

Production scale

- 3 cold walled CVD reactors
- Production of 100mm, 150mmm and 200mm graphene wafers

100mm CVD reactor

150mm CVD reactor & 200mm reactor

Research scale

Commercial scale

GROWTH

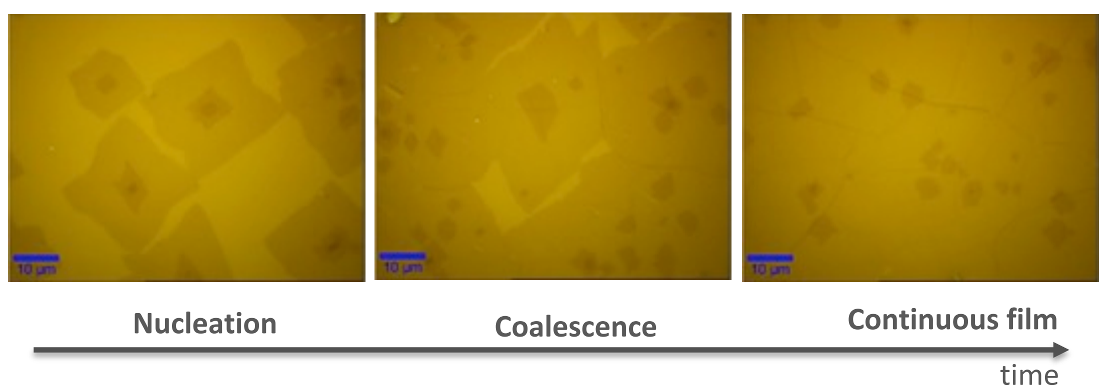
Graphenea

Monolayer Graphene Chemical Vapour Deposition (CVD)

Catalyst: Cu foil

❖ **Advantages:**

- Homogeneous growth
- >95% Monolayer
- Few defects
- Good properties
- Optimized transfer process

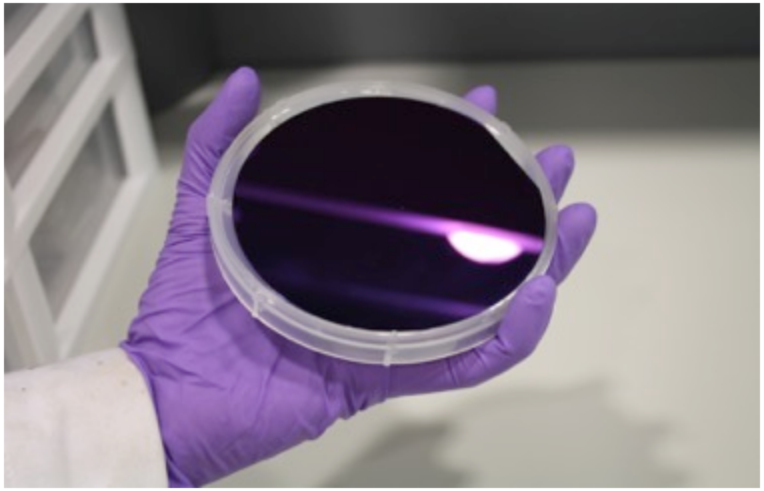


TRANSFER

Graphenea

CVD Graphene Transfer

Graphene on catalyst → Graphene onto the desire substrate



- The quality of the transfer and the substrate supporting graphene together with the quality of the interface between graphene and the substrate have large impacts on the properties of graphene and device performance

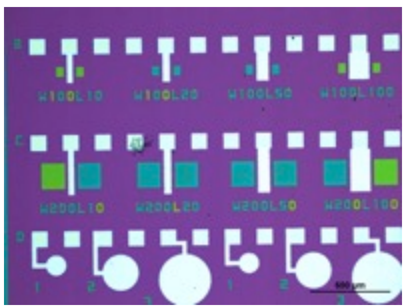
TRANSFER

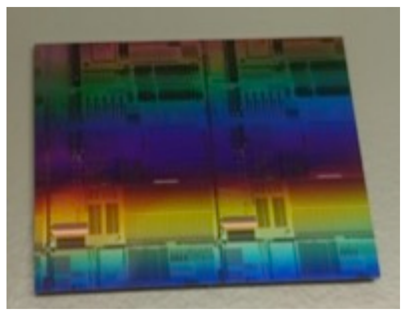
Graphenea

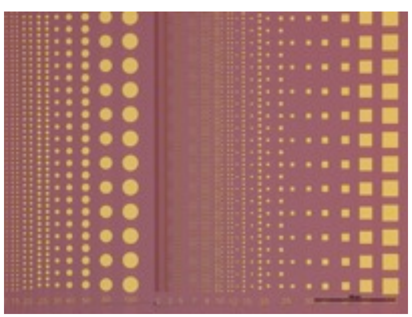
CVD Graphene Transfer

Importance of the substrate

The type of substrate will define the transfer process







- Structured substrates
- Perforated substrates: holes, cavities
- Water soluble substrates
- Number
- Size: $1x1mm^2$ up to 4”
- Shape: rectangular, circular..
- Type of Material: CaF_2, Si_3N_4, Al_2O_3..
- Roughness
- Hydrophobicity

TRANSFER

CVD Graphene Transfer

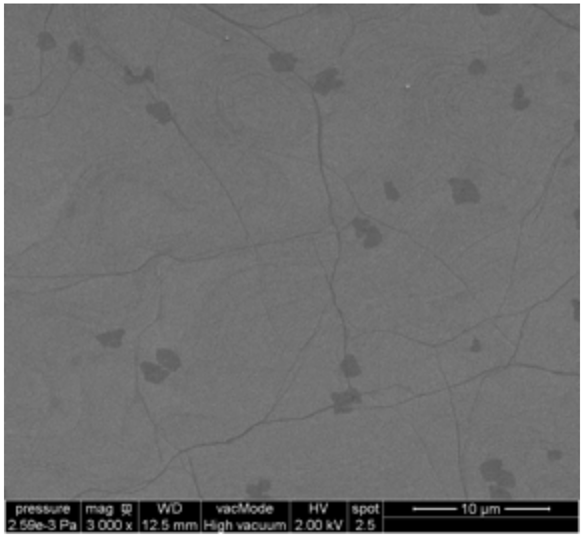
There is no standard process for all the substrates and applications

- Wet Transfer
- Dry Transfer
- Semi-dry Transfer

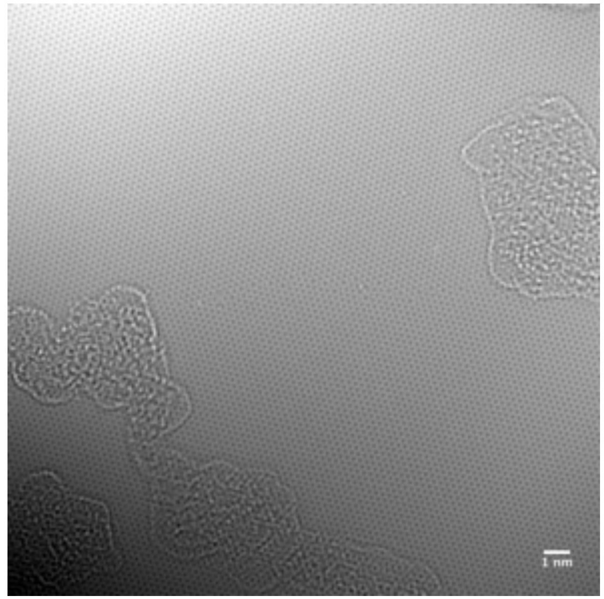
ANALYSIS

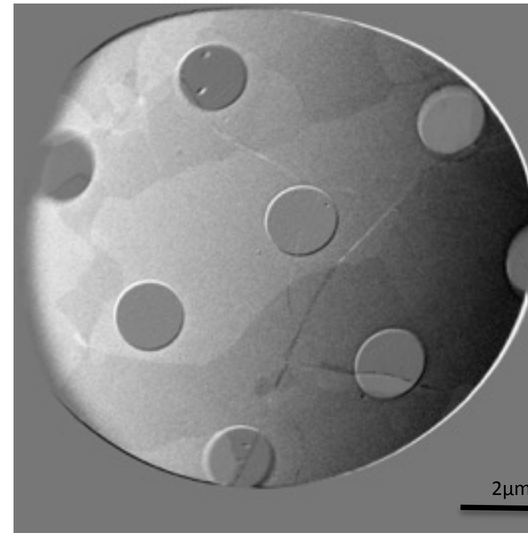
CVD Graphene characterisation

Scanning Electron Microscopy (SEM)

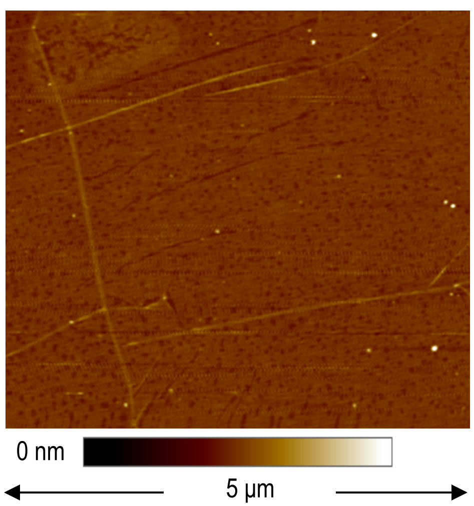


Transmission Electron Microscopy (TEM)

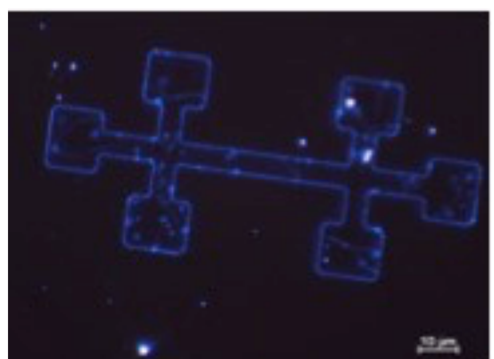


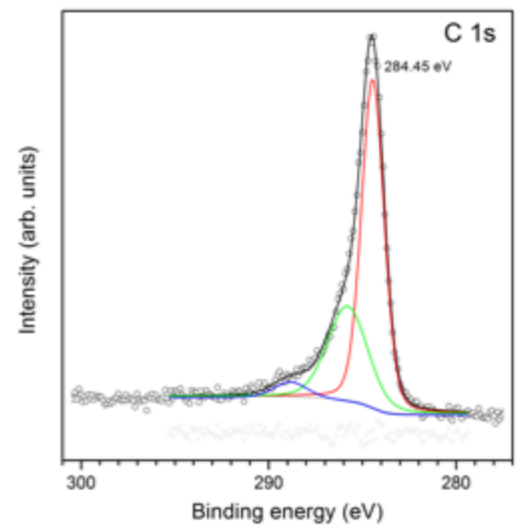


Atomic Force Microscopy



Electronic characterisation



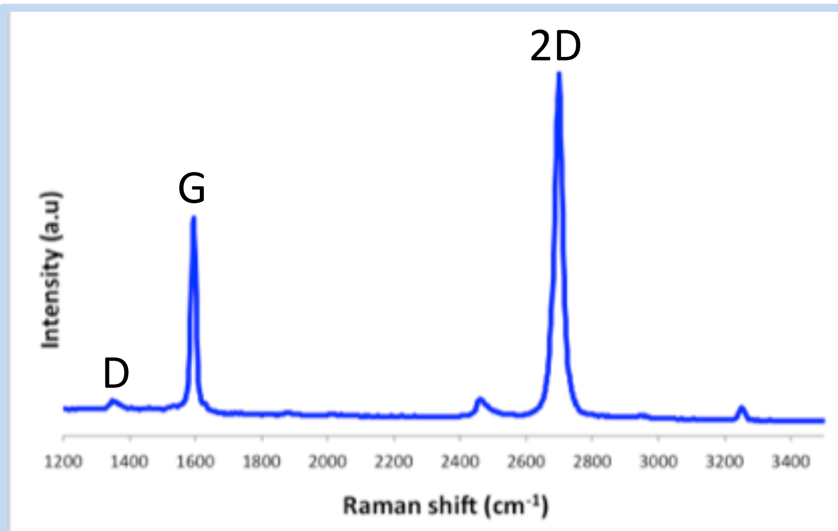


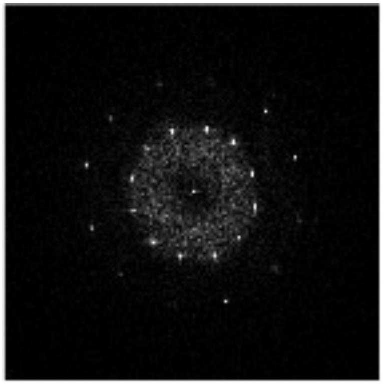
X-Ray Photoelectron Spectroscopy (XPS)

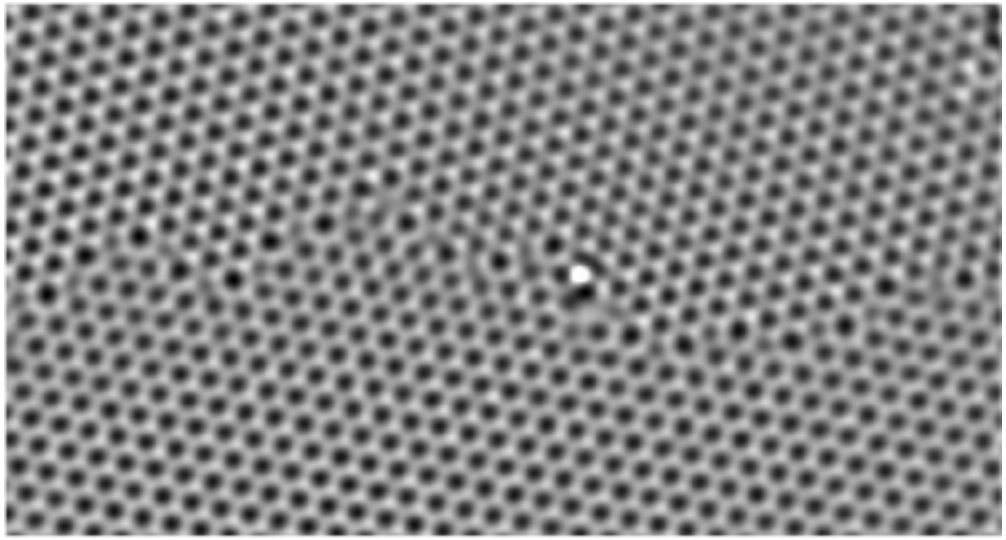
ANALYSIS

Graphenea

CVD Graphene characterisation







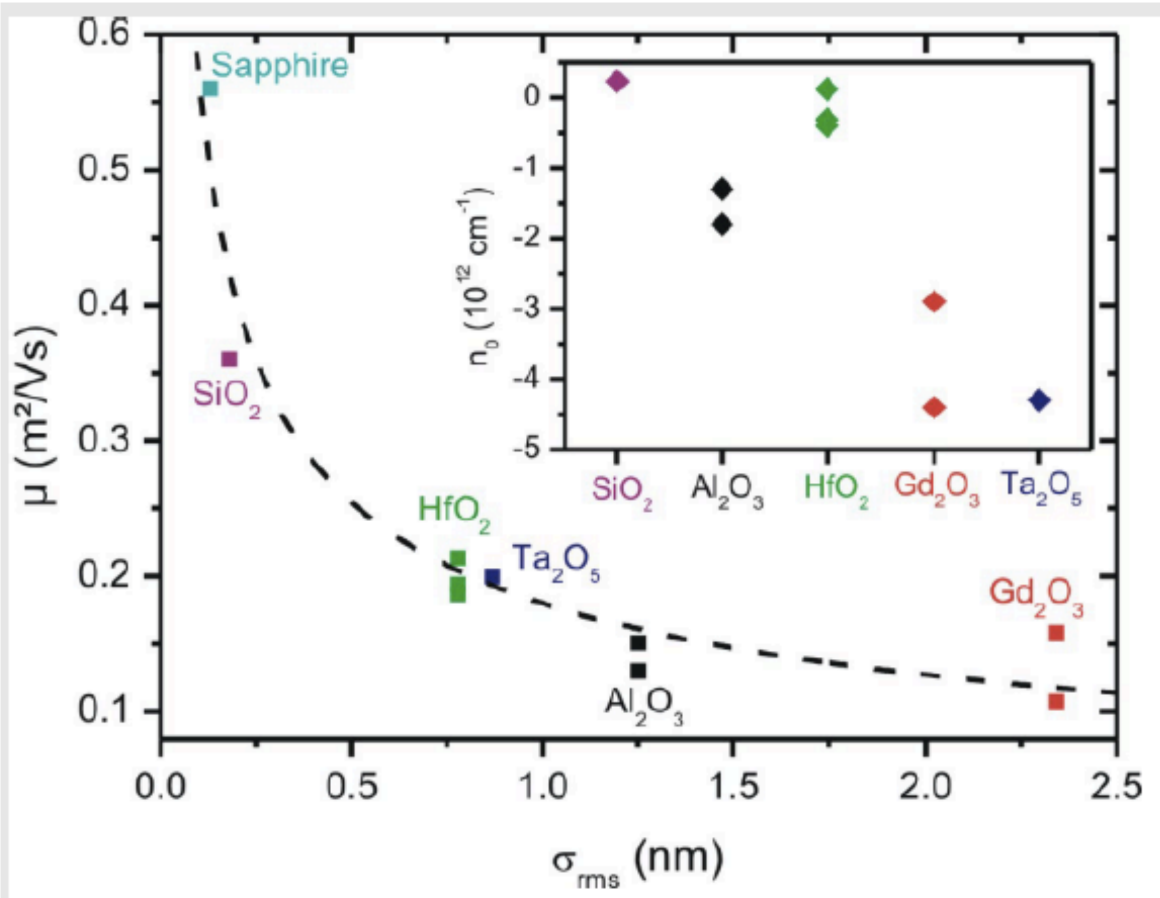
- ✓ Monolayer continuous films
- ✓ Polycrystalline: grain sizes up to 20μm

INTEGRATION

Graphenea

Substrate effect on Graphene

Electronic characterisation



Substrate influence on mobility

AMO

INTEGRATION

Encapsulation

Ambient air, organic solvents, chemicals, lithography resist

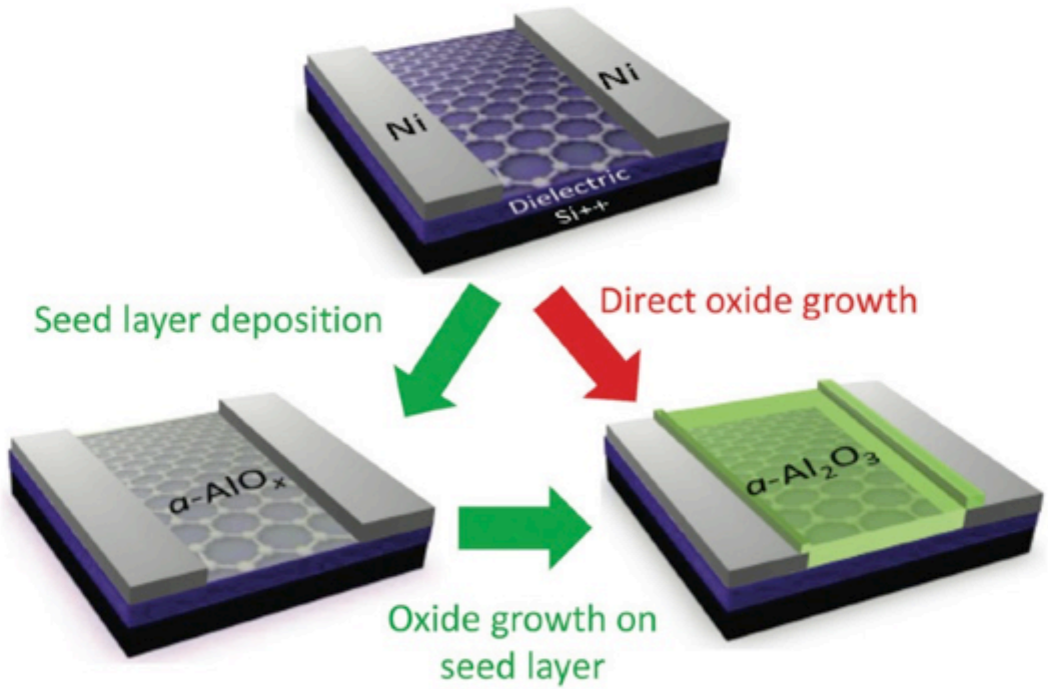
- ✓ Lead to graphene doping and hysteretic behaviour in DC characteristics of FETs

Encapsulation of graphene with Al_2O_3

*A.A. Asade et.al. Nanoscale **7**, 3558 (2015)*

INTEGRATION

Encapsulation



- ✓ Direct deposition of Al_2O_3 by ALD
- ✓ Al seed layer growth by e-beam evaporation + Al_2O_3 by ALD

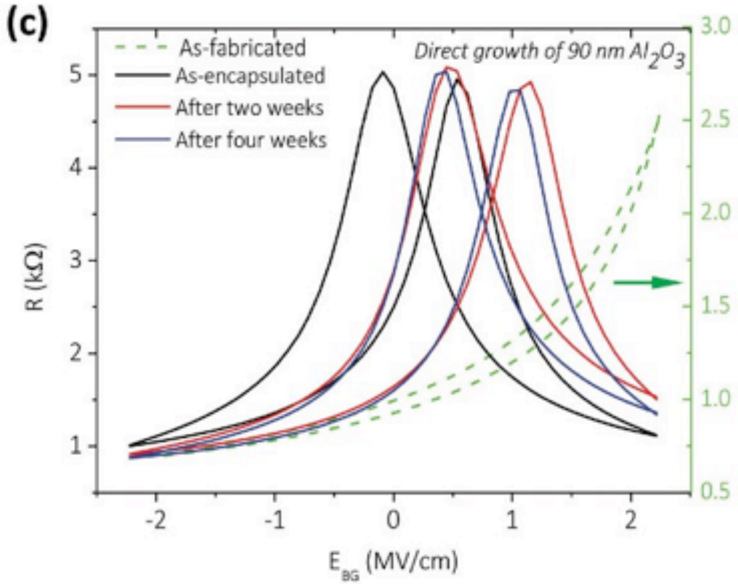
A.A. Asade et.al. Nanoscale ***7****, 3558 (2015)*

INTEGRATION

Encapsulation

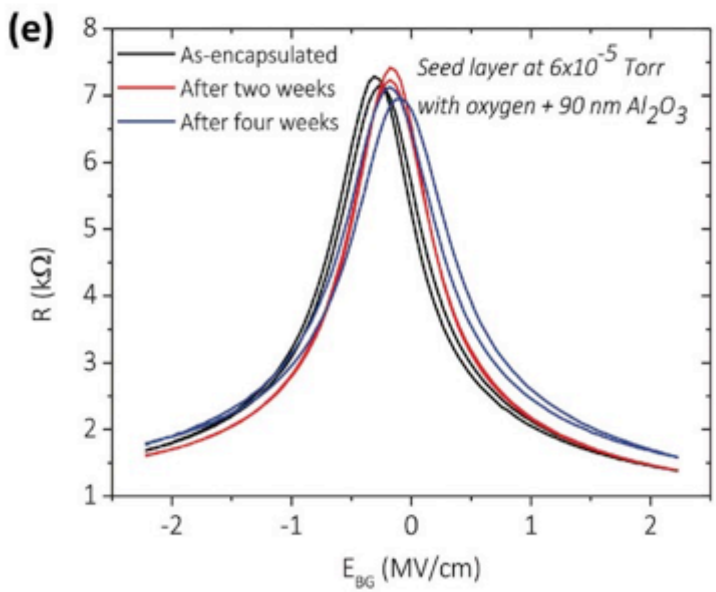
Graphenea

AMO



Direct growth of Al_2O_3 by ALD

- ✓ Hysteresis
- ✓ Not stable over time



Al seed layer + Al_2O_3 by ALD

- ✓ No hysteresis
- ✓ Stable over time

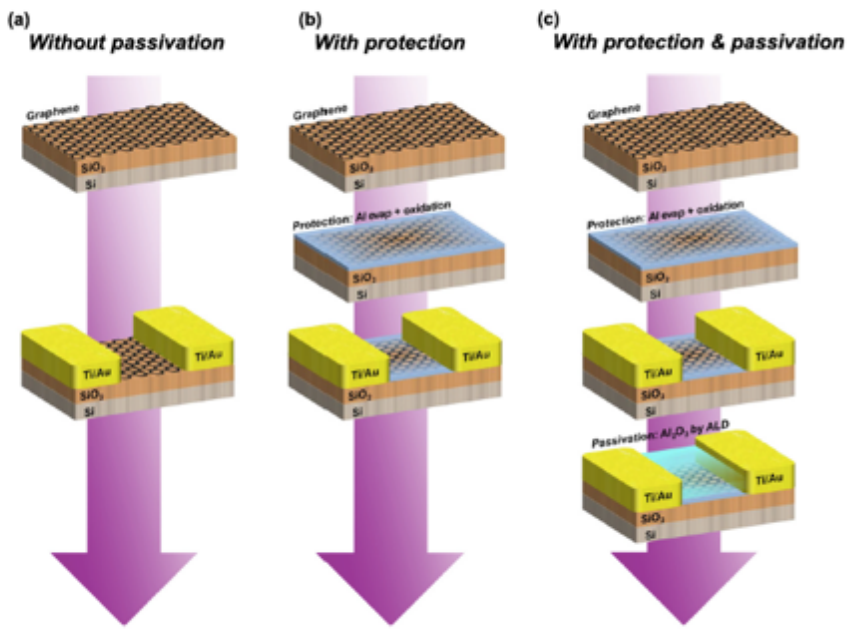
*A.A. Asade et.al. Nanoscale **7**, 3558 (2015)*

INTEGRATION

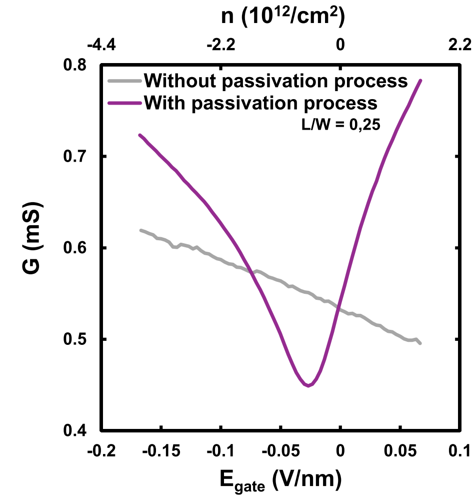
Working on strategies to improve mobility

Statistical analysis of 500 GFETs on 4” wafer

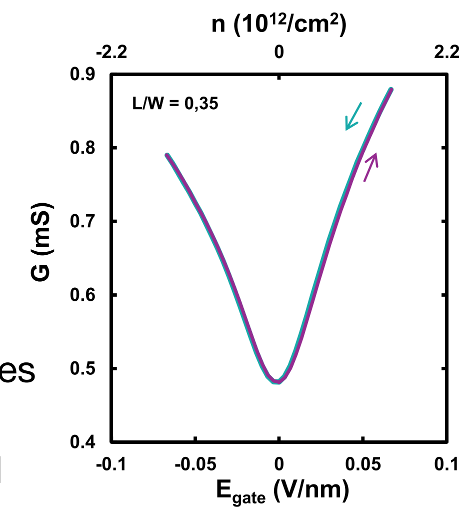
Fabrication Process



n=1-1.5x10^{13}cm^{-2} n=2.5-3x10^{12}cm^{-2} n=0-5x10^{11}cm^{-2}



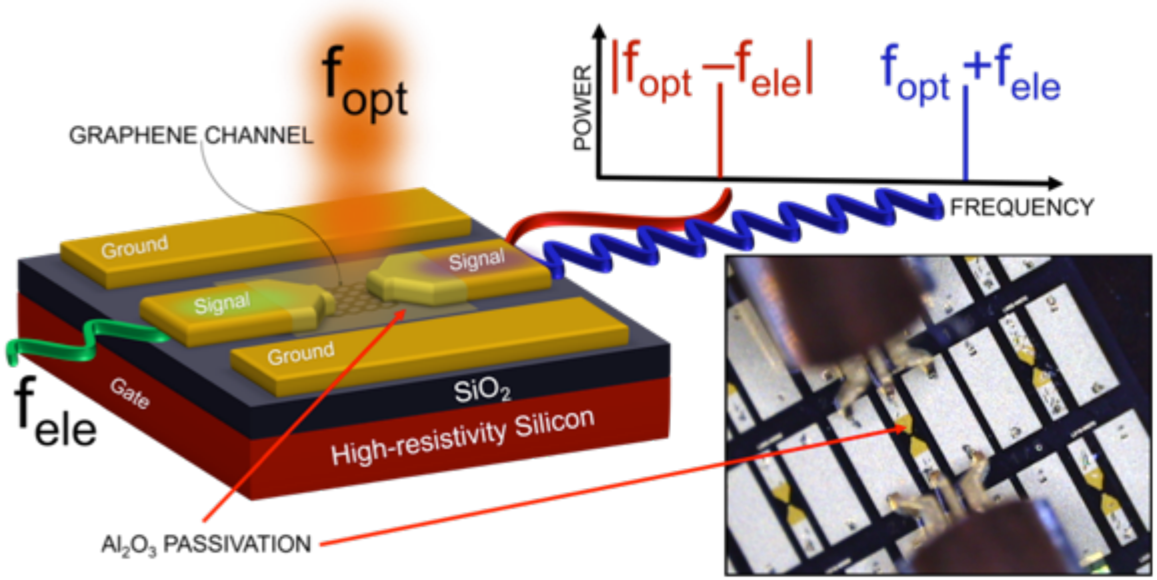
- The two-step fabrication process leads to lower doping levels
- Field effect mobility up to 6900cm^2/Vs on protected/passivated devices
- 75% of passivated transistors exhibited a conductance minimum and low hysteresis



S. Mzali et.al. Appl. Phys. Lett. ***109****, 253110 (2016)*

INTEGRATION

Graphene optoelectronic mixer



- ✓ 30 GHz optoelectronic mixing
- ✓ Frequency down conversion to 100MHz

A. Montanaro et.al. Nano Lett. 16, 2988 (2016)

Graphenea

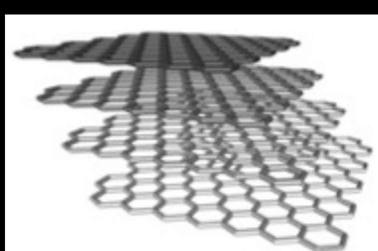
APPLICATIONS

Graphene Integration

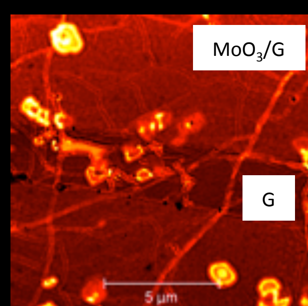
The application will define the graphene requirements

- Properties: Mobility, sheet resistance, transparency…
- Contamination limits: polymer residues, metal content
- Integration: Suspended, back-end, front-end..

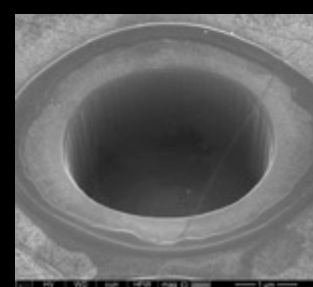
Multilayer samples
Stacking



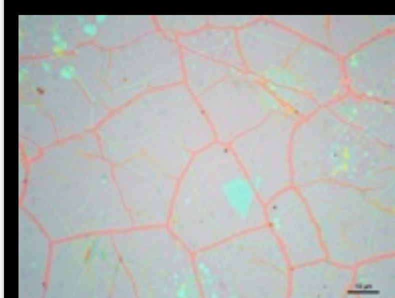
Doped Graphene



Suspended graphene

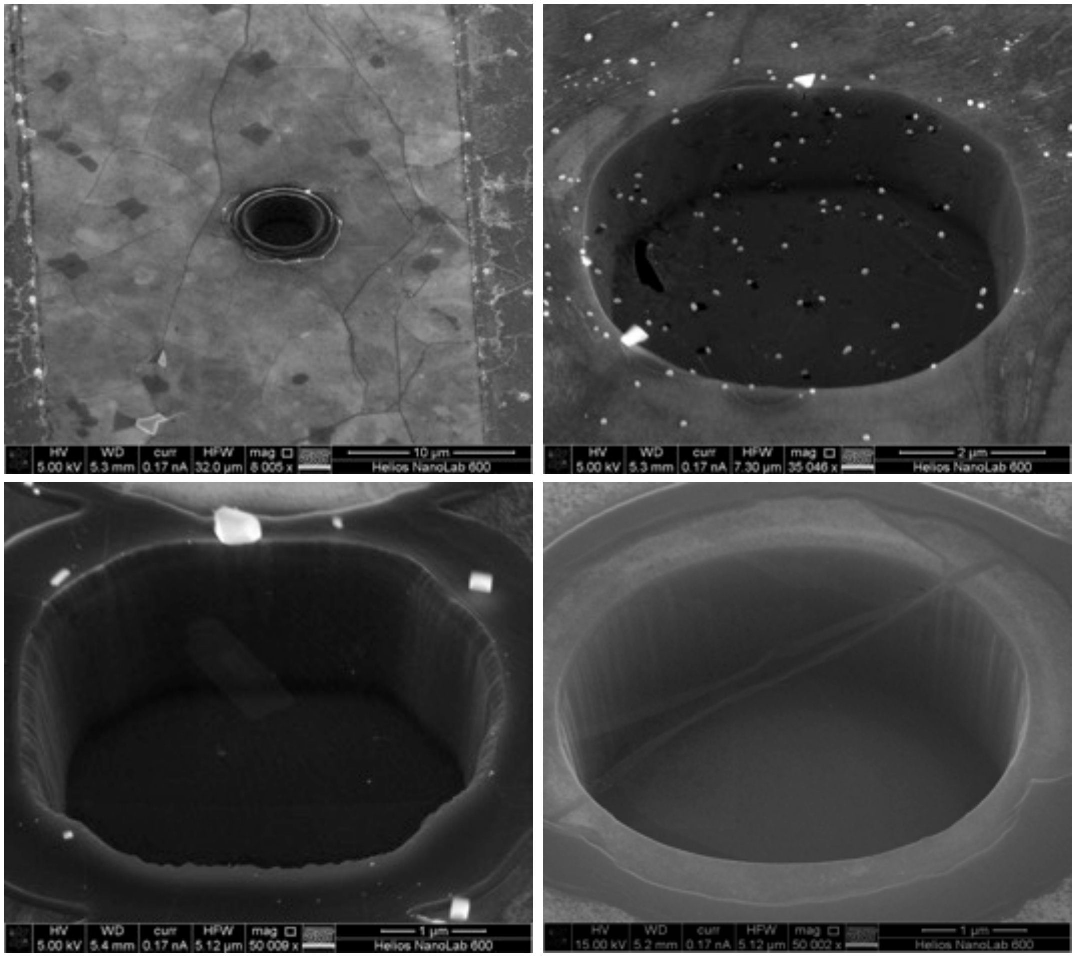


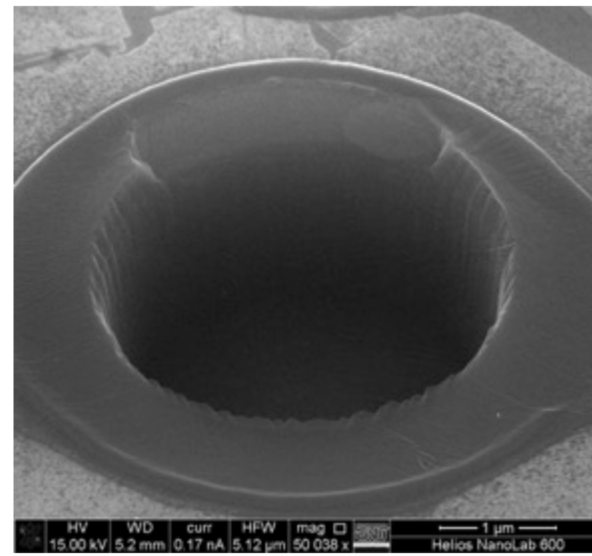
Encapsulation



Graphene in NEMS/MEMS

Suspended graphene in pressure sensors





Courtesy of University of Siegen

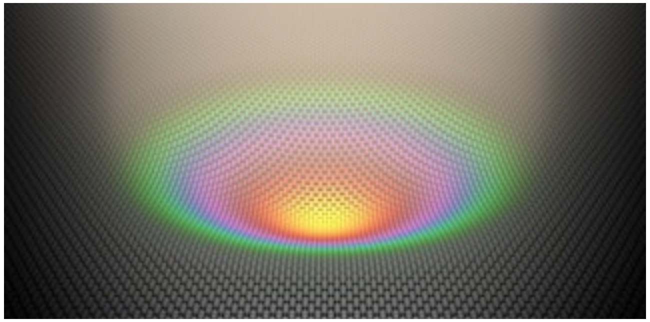
EU Project: NanoGram Consortium

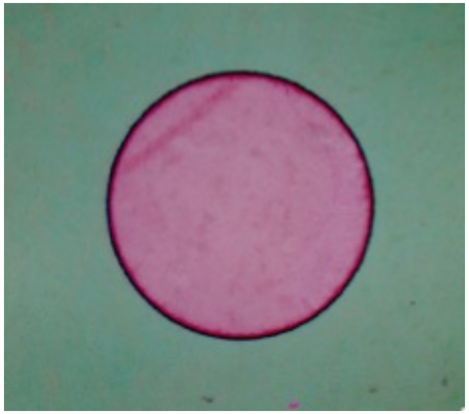
- Development of homogeneous and high quality CVD graphene

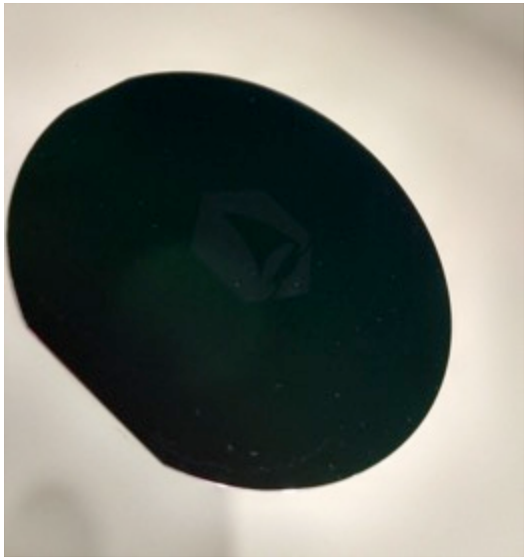
APPLICATIONS

Graphene Interferometric Modulator Display (GIMOD)

Graphene for mechanical pixels







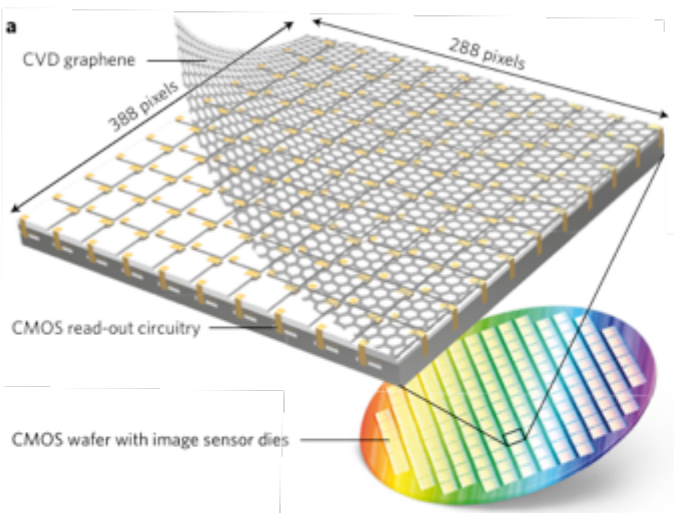
- Bilayer CVD Graphene suspended onto 50microns cavities that compose the Flagship logo

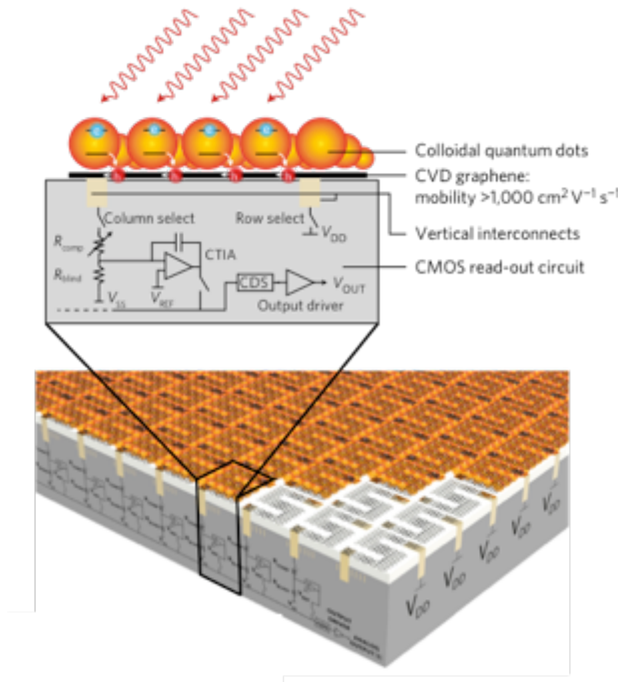
APPLICATIONS

Broadband image sensor array

Graphene-quantum dot photodetector array

- Monolithic integration of CMOS ROIC with graphene
- Graphene operates as a high mobility phototransistor
- QDs sensitising layer (PbS)
- Sensitive to UV, visible and IR light (300-2,000nm)





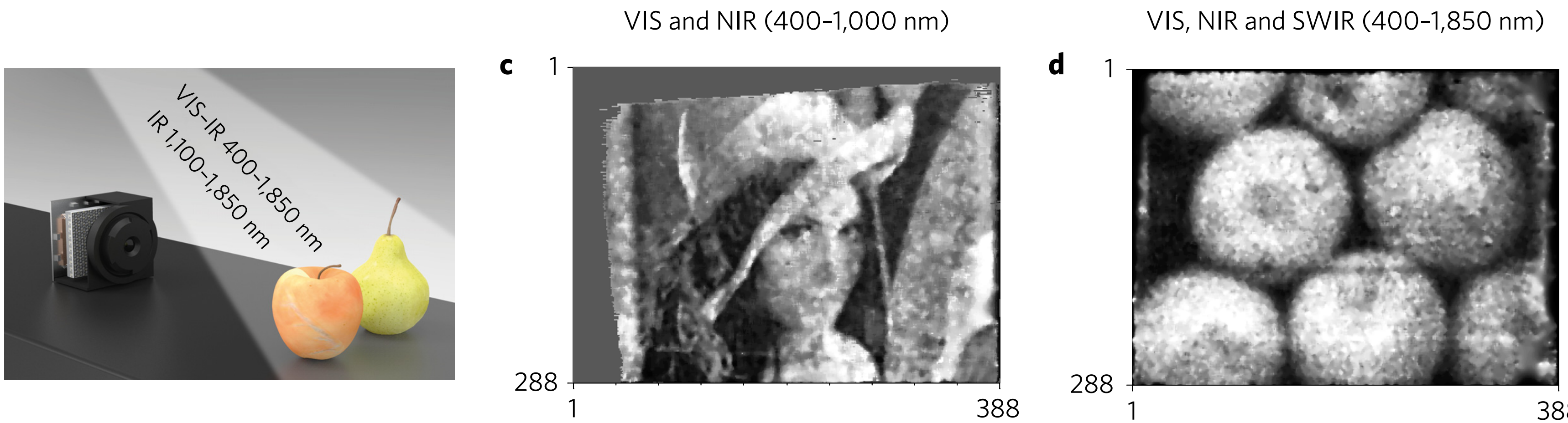
S. Goossens et.al. Nat. Photon. ***11****, 366 (2017)*

APPLICATIONS

Broadband image sensor array

Operates as digital camera

- Graphene-QD image sensor captures reflection images from objects illuminated by a light source (office illumination)



- 99.8% of pixels functional
- >95% pixels sensitive to irradiance corresponding to partial-moon and twilight conditions

S. Goossens et.al. Nat. Photon. ***11****, 366 (2017)*

APPLICATIONS

Ultra-sensitive and low-cost Graphene Quantum-Dot Photodetector

Non-invasive health monitoring applications

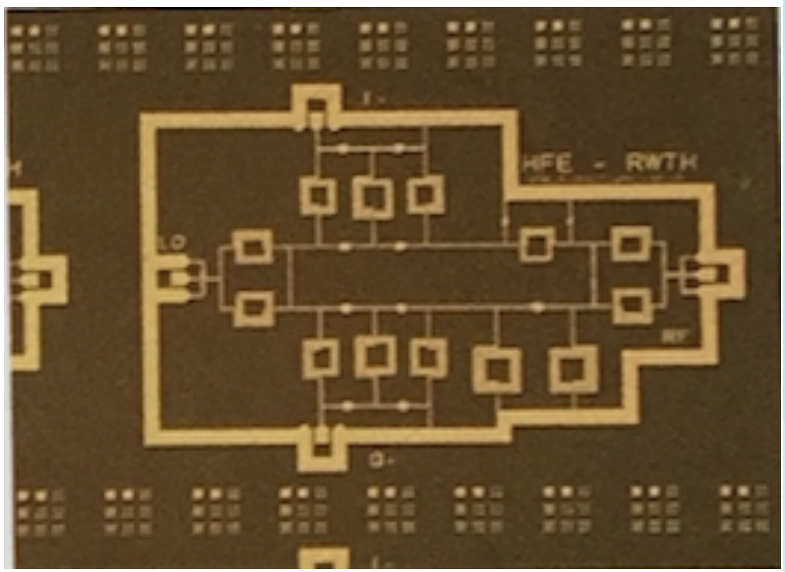
- ✓ Flexible and transparent
- ✓ Blood volume
- ✓ Heart rate
- ✓ Ultra-sensitive with a gain of 10^8 carriers per absorbed photon
- ✓ Sensitive to both visible and infrared light
- ✓ No cooling required

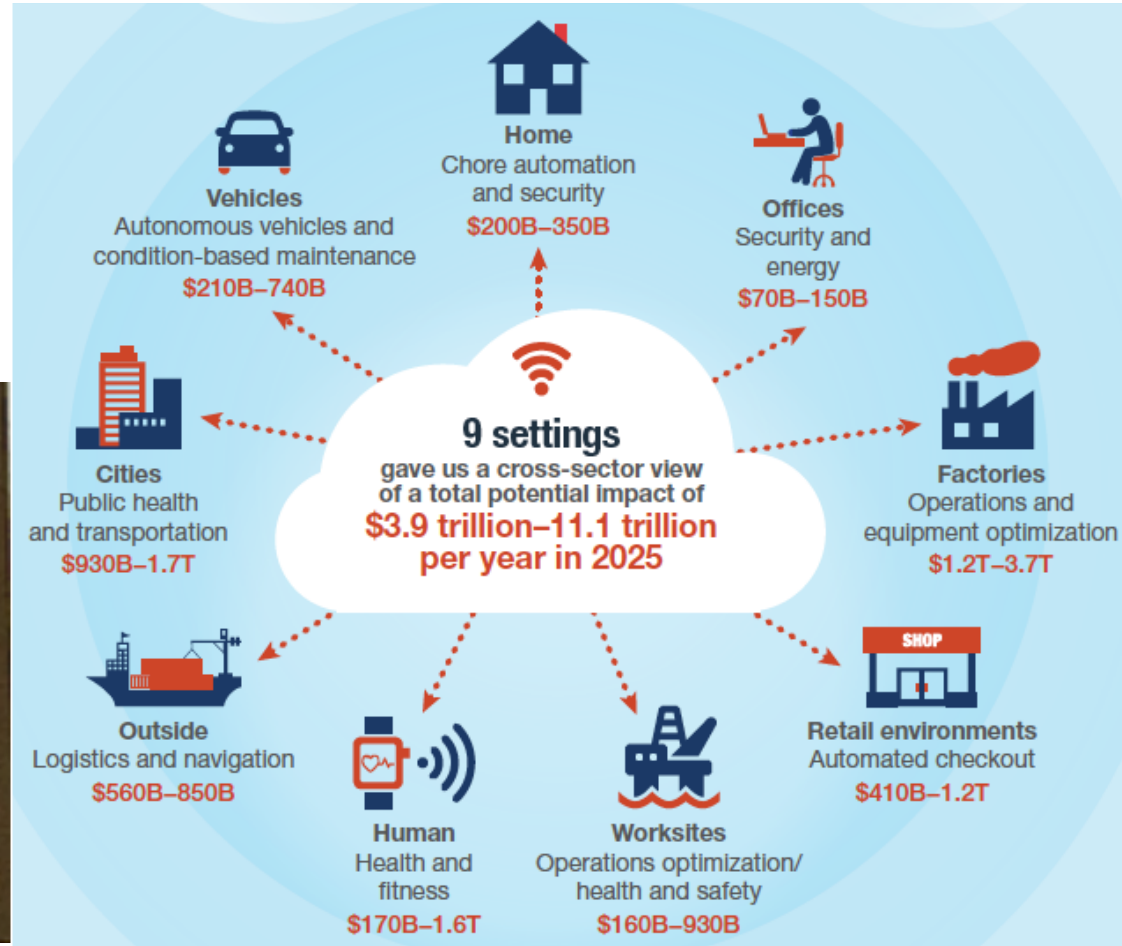
APPLICATIONS

Graphene flexible WiFi receiver

AMO

- 2.4 GHz receiver circuits on plastic
- Ideal for IoT and flexible electronics





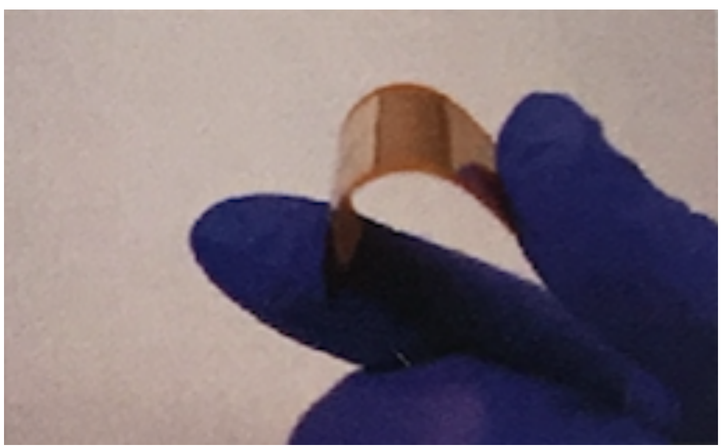
Source: McKinsey

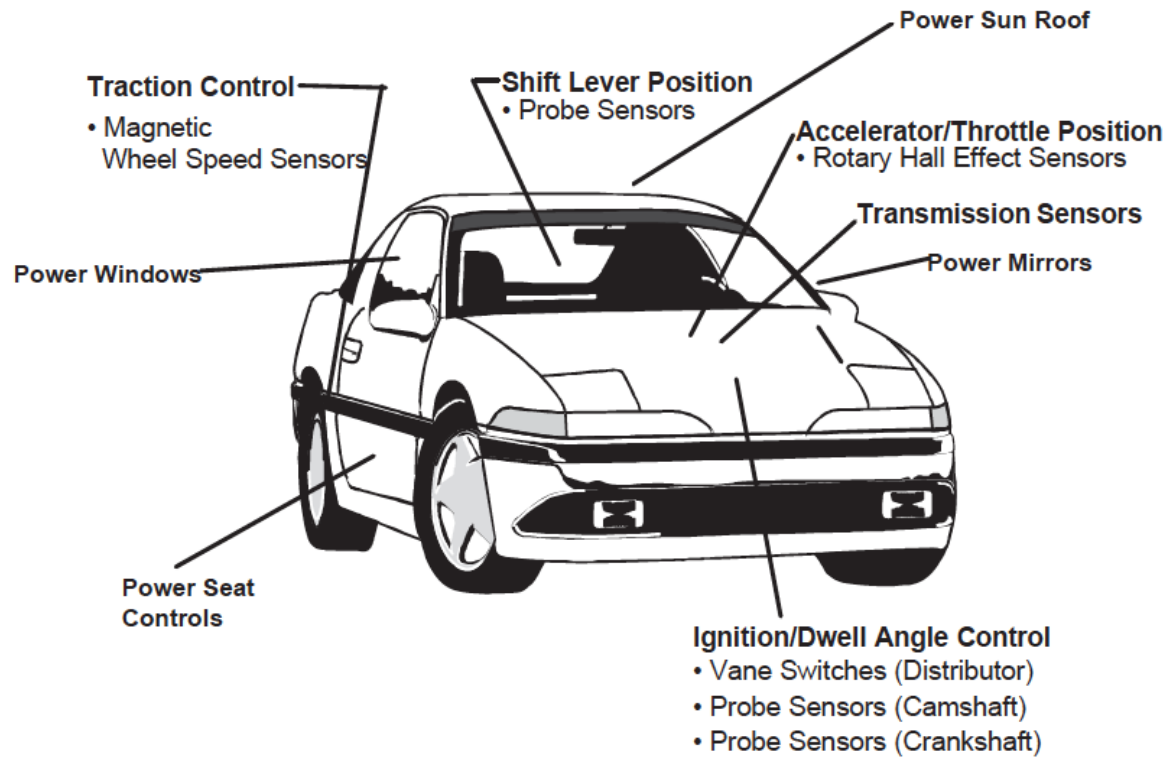
GRAPHENE FLAGSHIP

APPLICATIONS

Graphene flexible Hall sensor

- High sensitivity, linearity and flexibility
- The key factor determining sensitivity of Hall effect sensors is high electron mobility





Source: Honeywell

Challenges

It is necessary to develop a customised material depending on the application and provide an easy integration method in order to promote graphene into commercial applications

Graphene Customisation

Scale-up

Integration

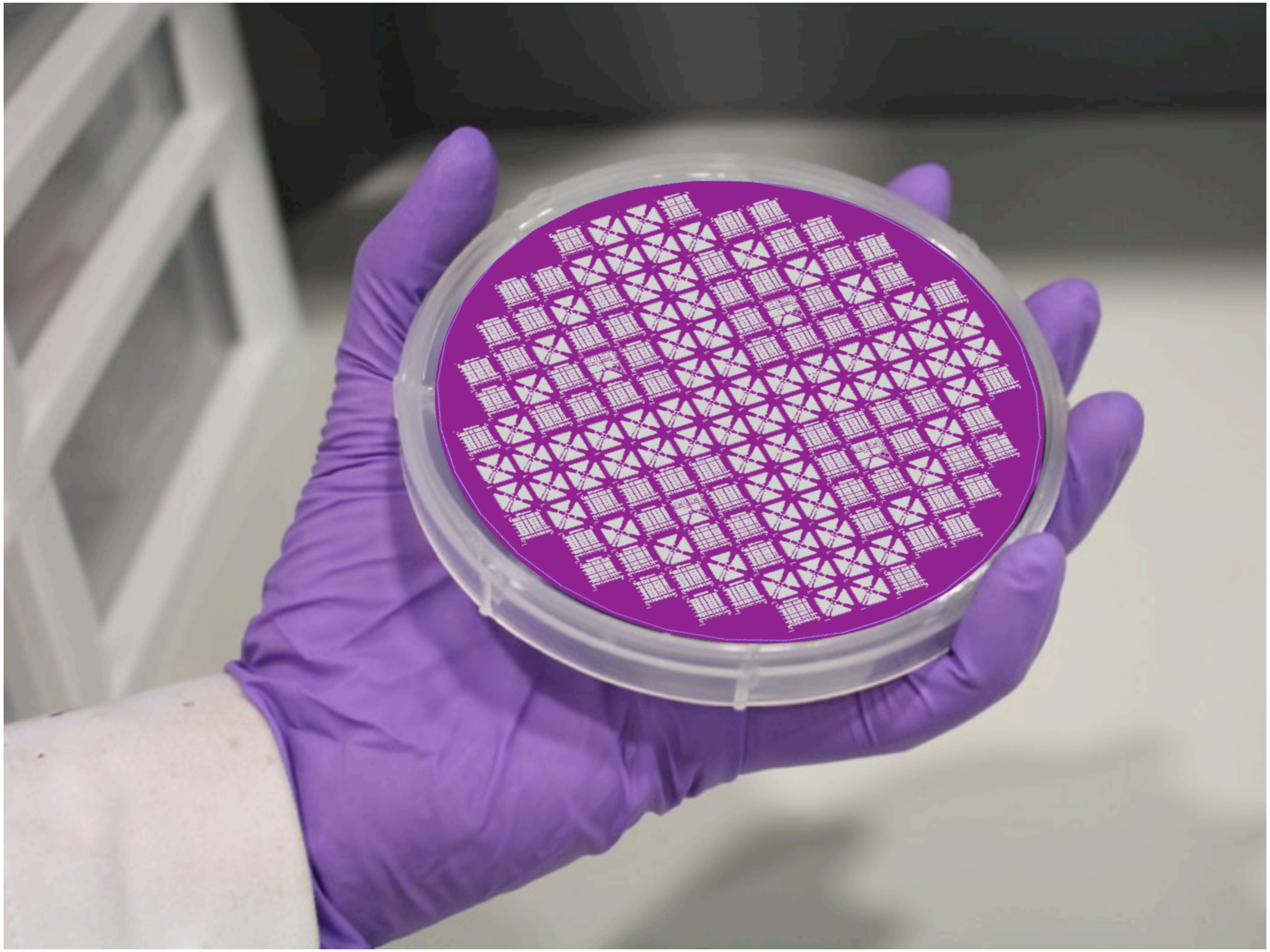
Integration Opportunities - GFET platform

Strategy to aid graphene integration into commercial products

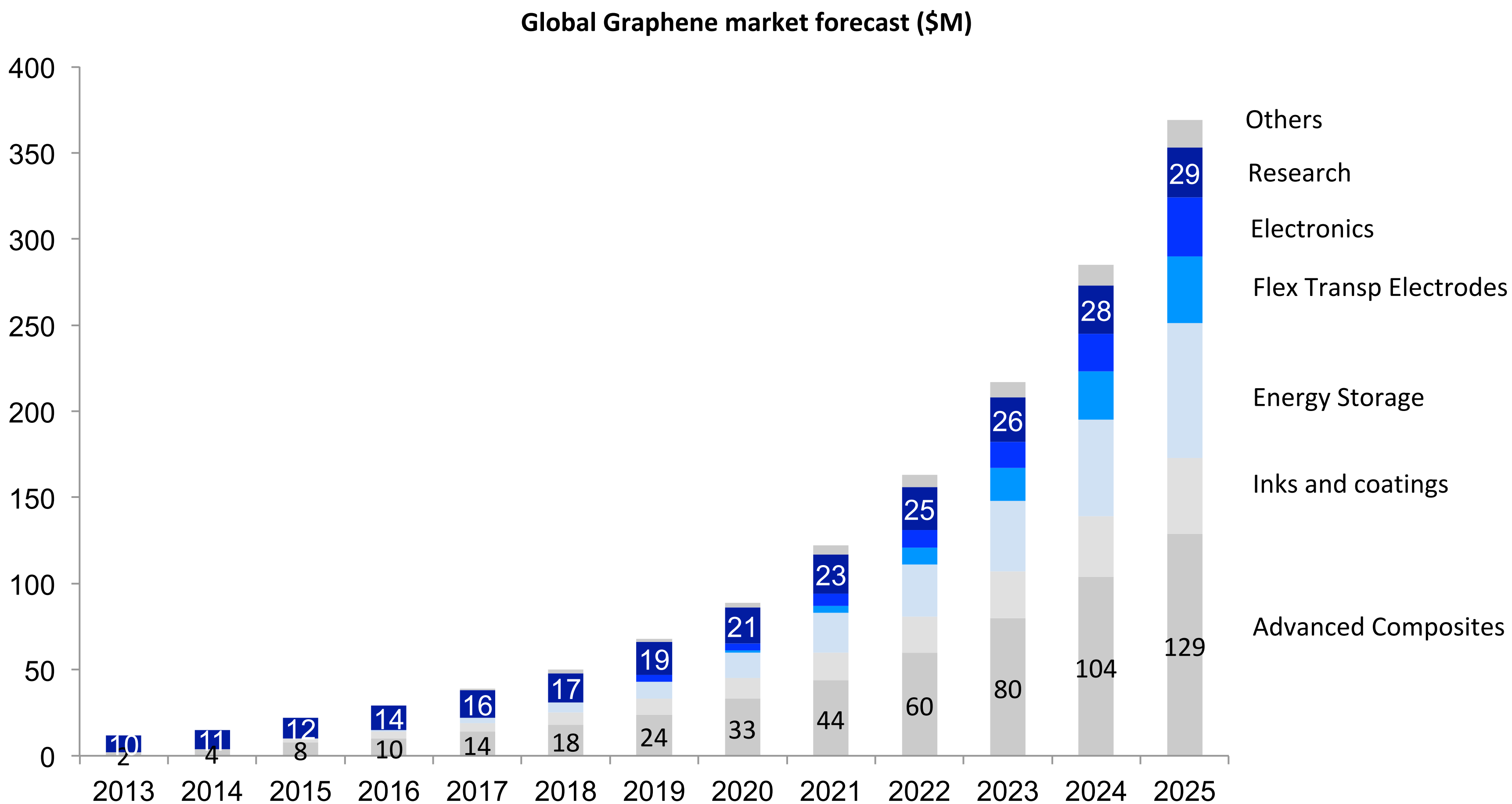
- Semiconductor industry not interested in few thousand wafers market – fill gap in value chain
- Commercialise GFET wafers
- Targeted markets: biosensors, sensors (photosensors), etc.

Graphenea

GFET platform

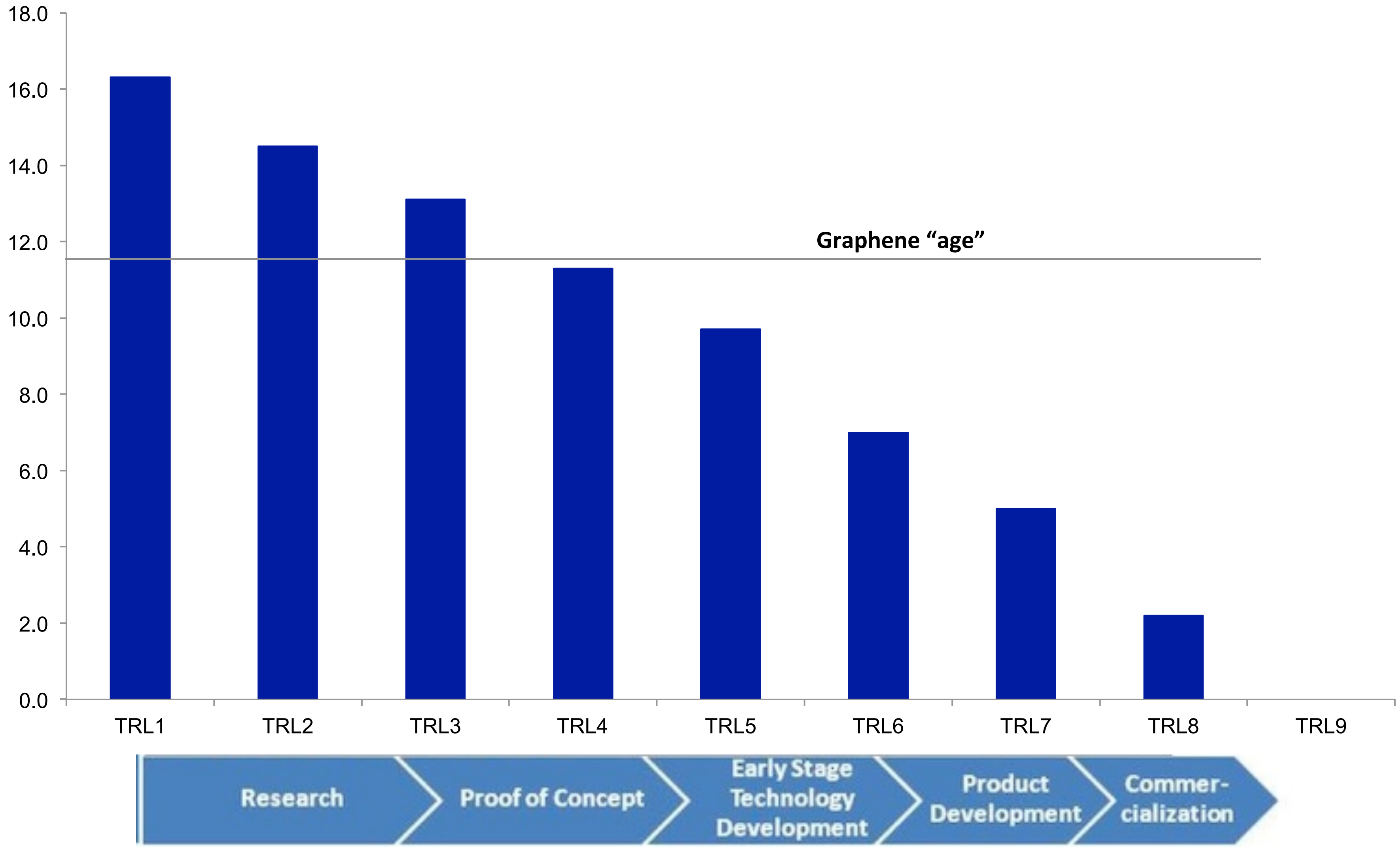


Graphene market is very small and driven by Research-related demand



Source: Graphenea estimations

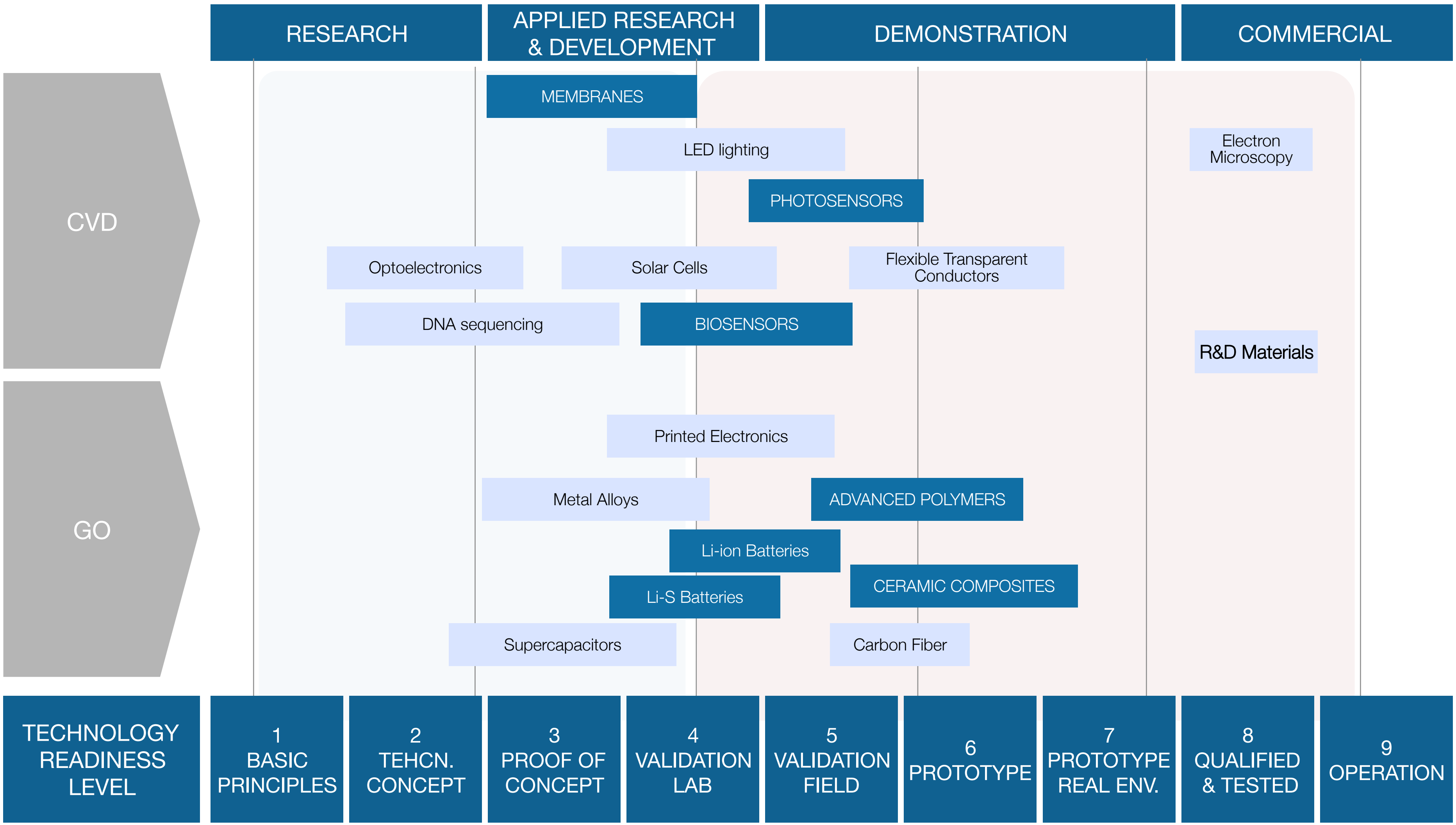
Time to market – Aerospace industry



Source: ESA

Graphenea

Each application requires a specific type and grade of graphene



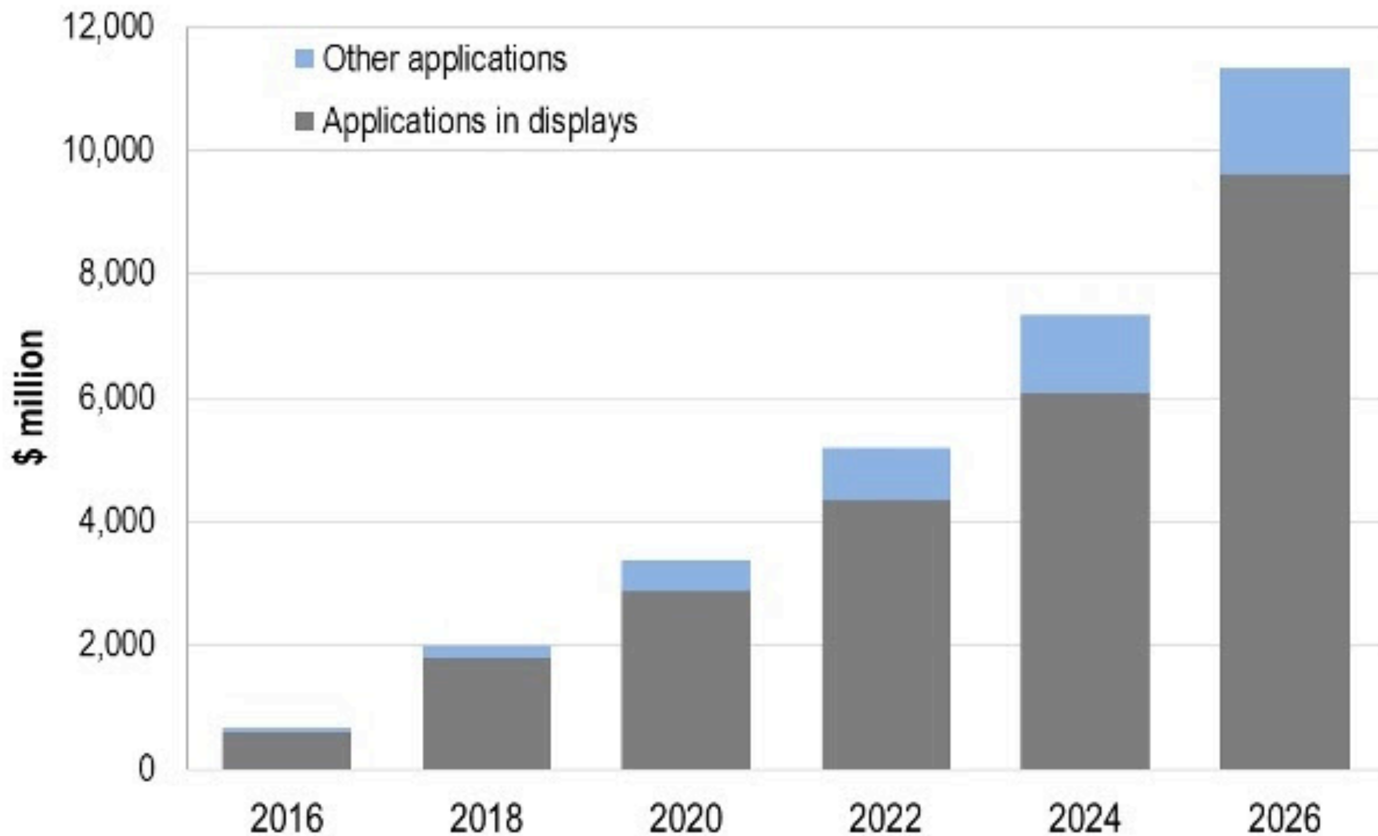
Illustrative TRL application map

Advanced materials that needed > 20 yrs

- ✓ Transistor
- ✓ Carbon fibre
- ✓ Fluorescent lamp
- ✓ Liquid crystals
- ✓ Kevlar
- ✓ PVC
- ✓ PE

Bell Labs 1947

Quantum dots - How things can change dramatically



IDTechEx Research

Conclusions

- ✓ Customised graphene material is required for each specific application
- ✓ Many technological challenges still remain
- ✓ Many diverse multifunctional prototypes have been successfully fabricated
- ✓ We hope graphene will be a success story – similar to QDs