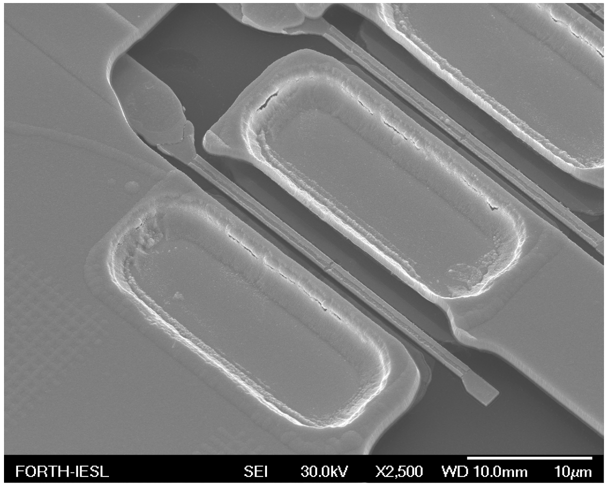
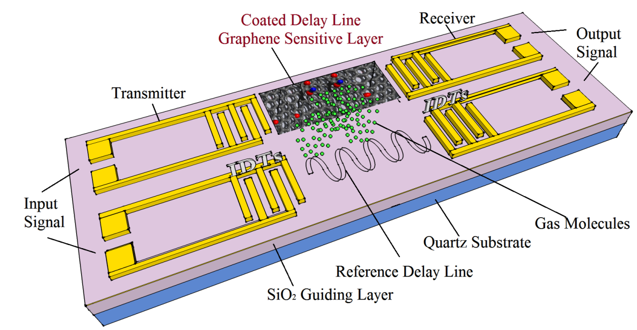
Two dimensional materials

A new pathway for electronics and sensing





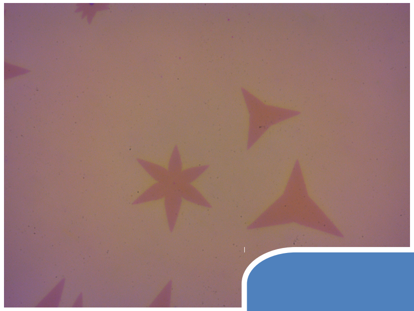
George Deligeorgis, PhD ***deligeo@physics.uoc.gr***

Researcher

FORTH
Institute of Electronic Structure and Laser

11^{η} επιστημονική διημερίδα ΙΤΕ, Ηράκλειο 2017

Roadmap instead of an outline



Science of two dimensional materials

High quality material growth

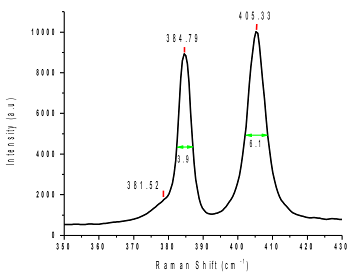
Low cost material for high impact applications

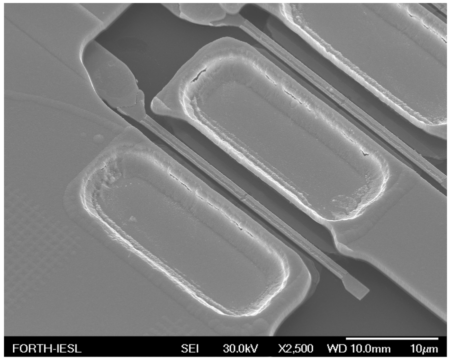
New physics
- **Relativistic particles**
- **Topological insulators**

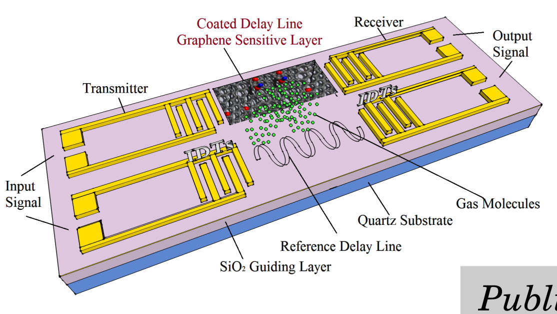
High frequency & flexible optics & electronics

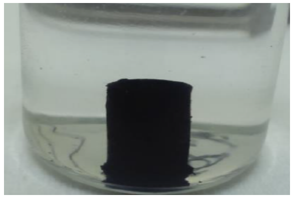
Chemical sensing

Tissue engineering









Open issues

Good points

Publications from other groups

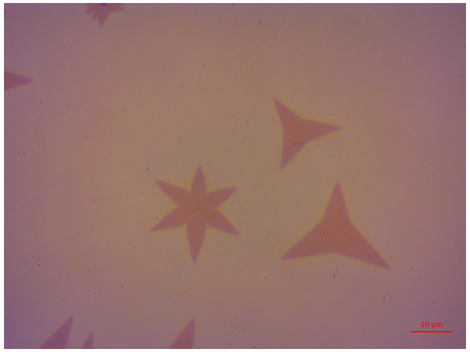
Publications from our group

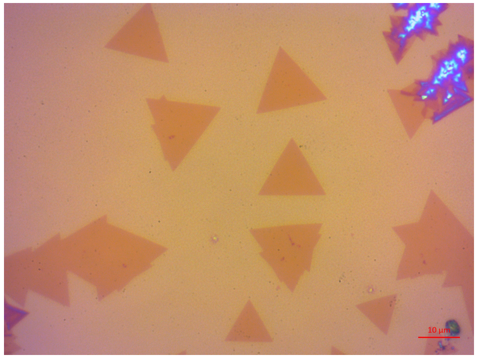
2D material growth

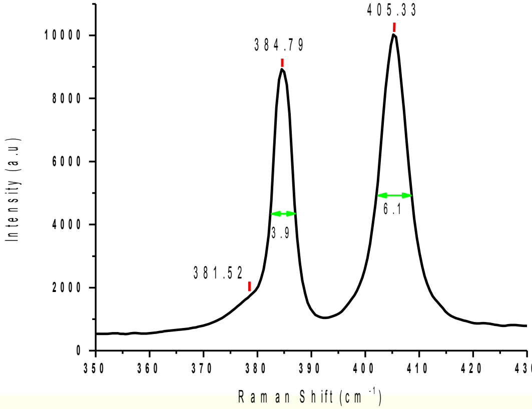
2D material based electronics

2D materials for sensing

Exploring novel ideas

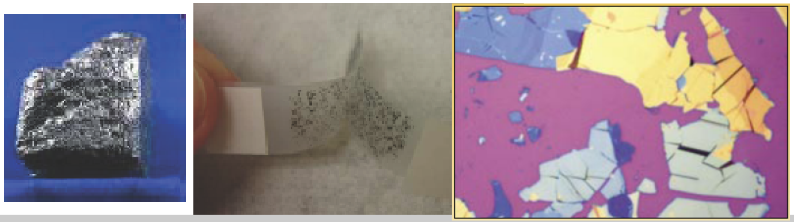






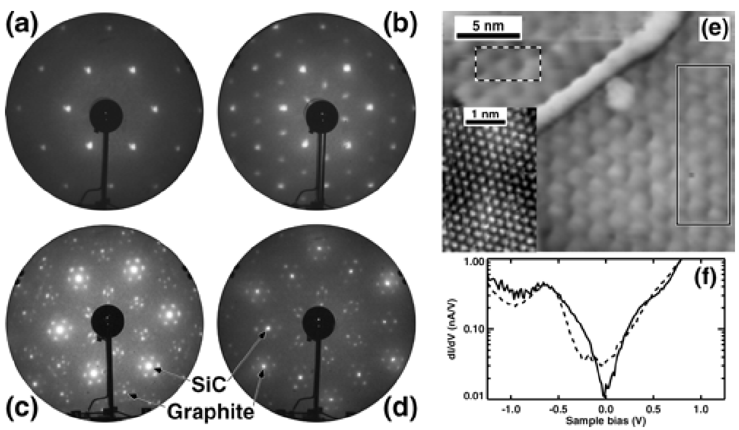
2D material availability and flavours

"exfoliation" (scotch tape)



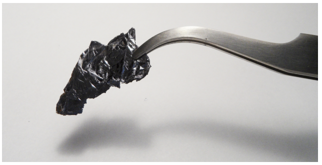
Y.Cheng, and I. Jovanovic, Perdue Univ.
http://www.physics.purdue.edu/quantum/Talks/ari_2009b.pd
A.K. Geim, P. Kim, Sci. Am., April 2008, 90

- *Liquid phase ex-foliation*
    - *Small size ex-foliated flakes in solutions*
    - *All 2D materials*
- *CVD grown large area*
    - *Graphene and recently other 2D materials*

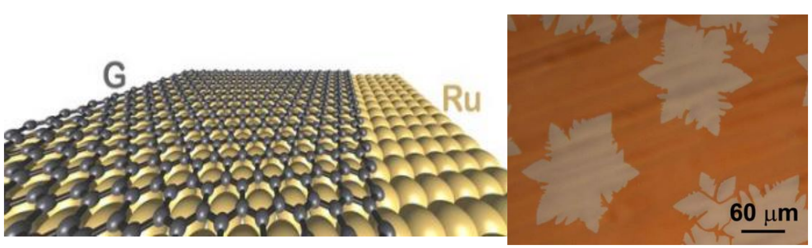


J. Phys. Chem. B, 2004, 108 (52), pp 19912–19916

MoS$_2$

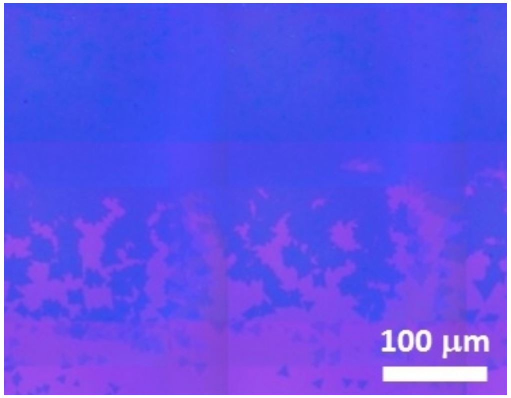


s- CNT

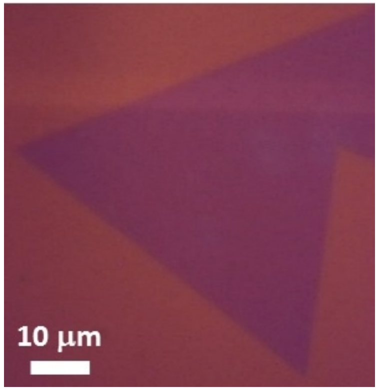


P.W. Sutter et. al., Nature Materials 7, 406 - 411 (2008)

MoS$_2$



WS$_2$



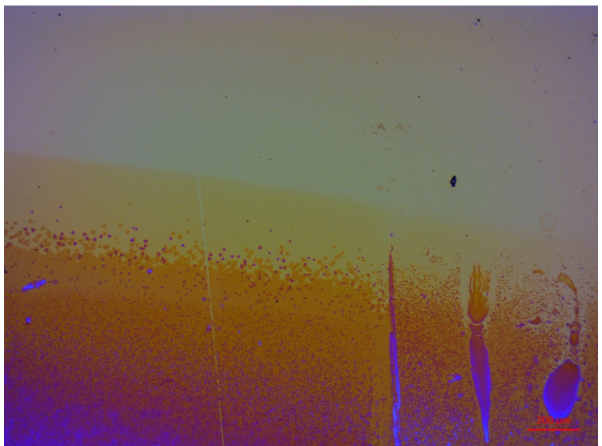
www.2dsemiconductors.com

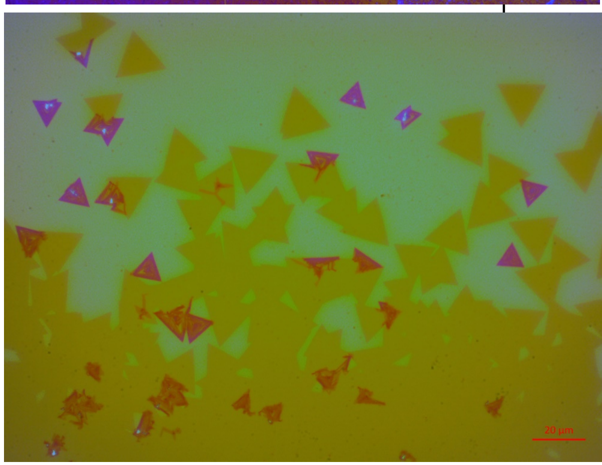
Material growth in FORTH – IESL

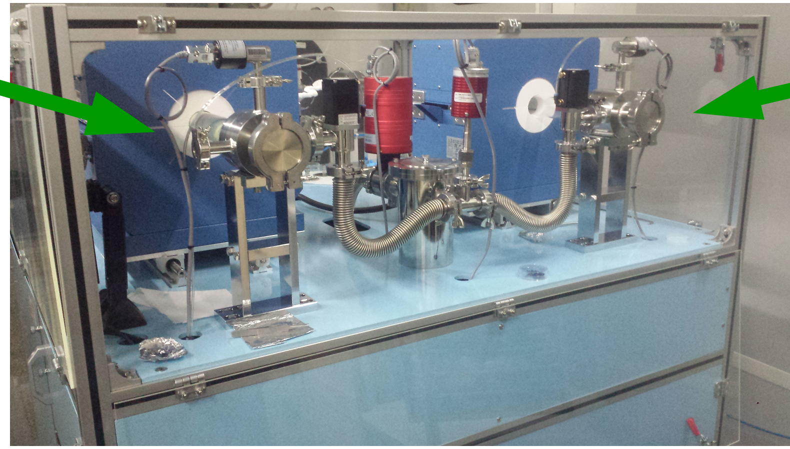
Commissioned Jan 2017

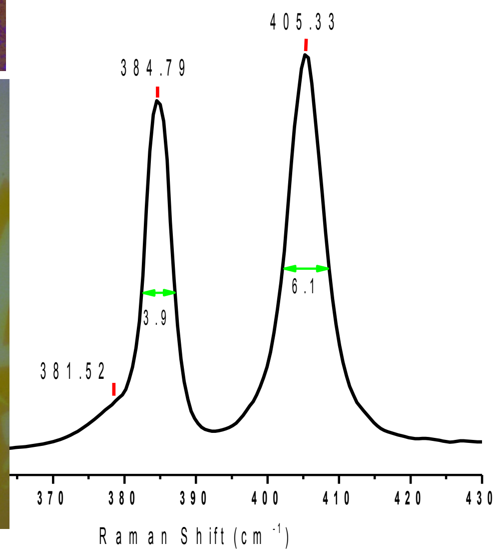
MoS_2 & WS_2

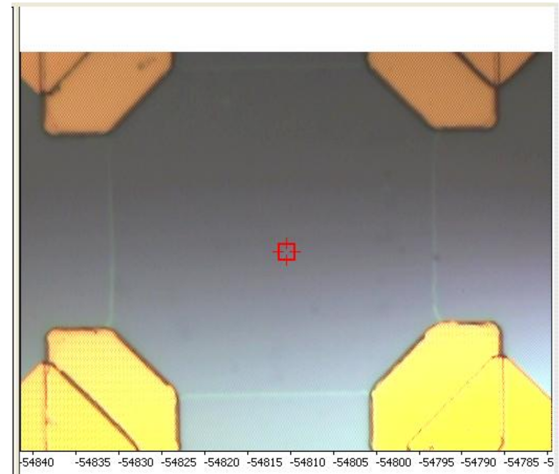
Graphene

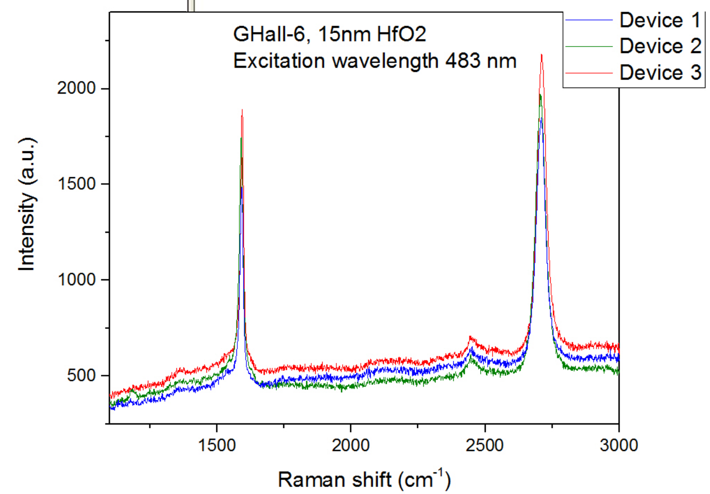












State of the art material (verified by Raman)

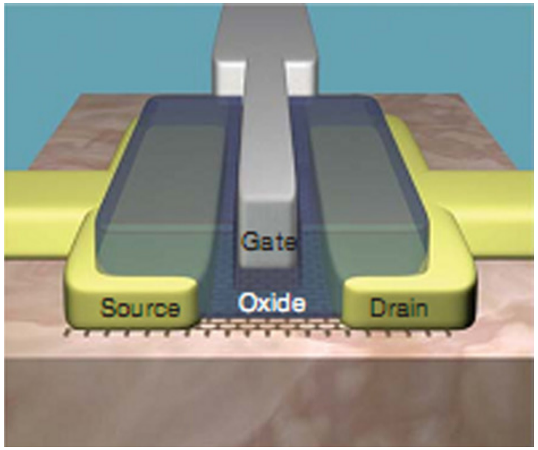
Advanced growth and devices (see next slides)

2D material growth

2D material based electronics

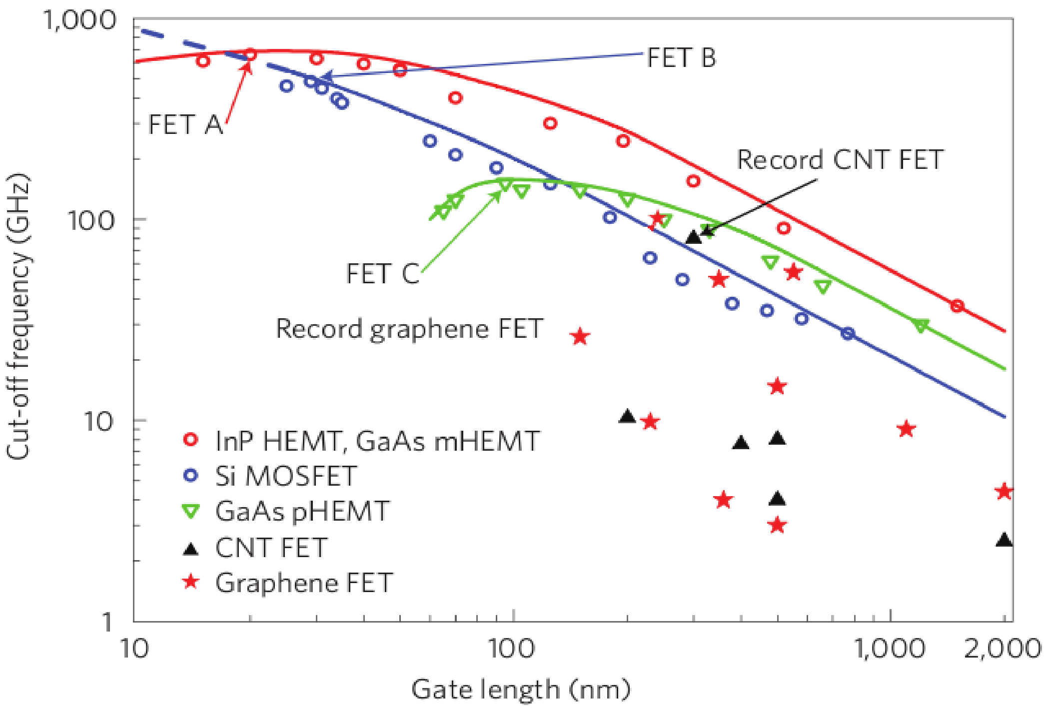
2D materials for sensing

Exploring novel ideas



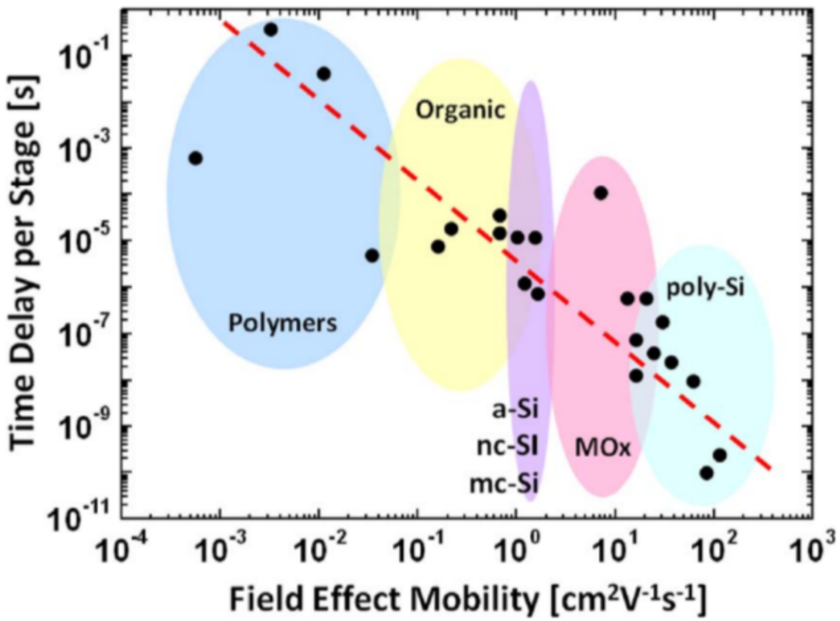
Current transistor technology

Our society is based on availability of ever faster communications



F.Schwierz Nature Nanotechnology 5 p487 (2010)

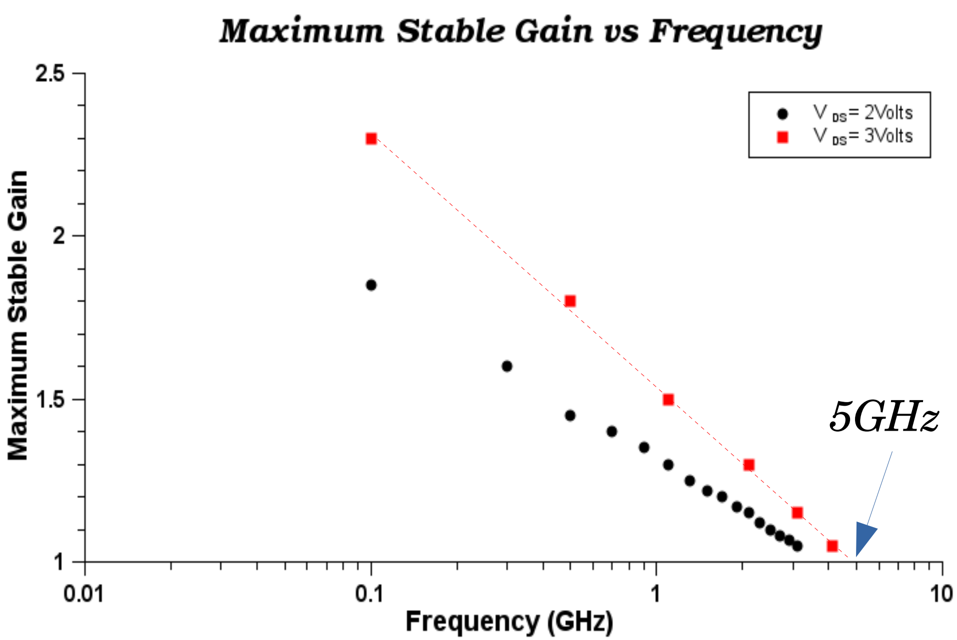
Available transistor technologies

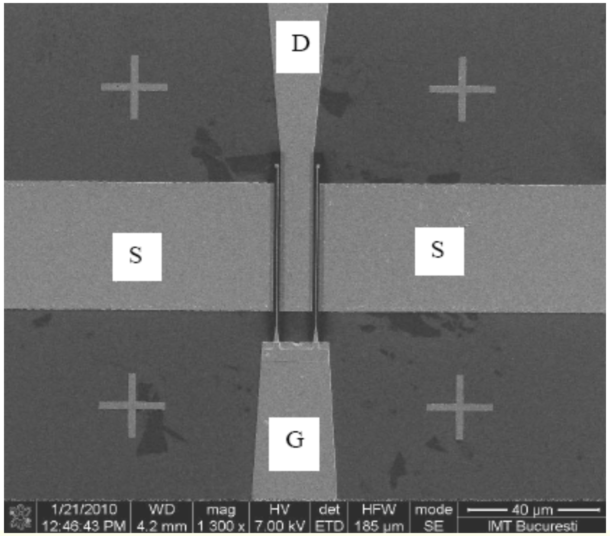


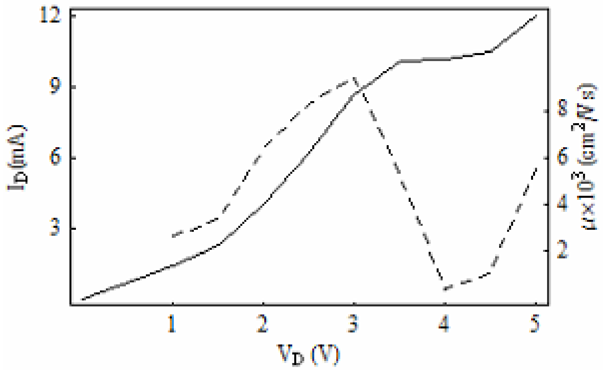
Flexible transistor technologies overview

A.Nathan et al Proceedings of IEEE 10.1109/JPROC.2012.2190168 (2012)

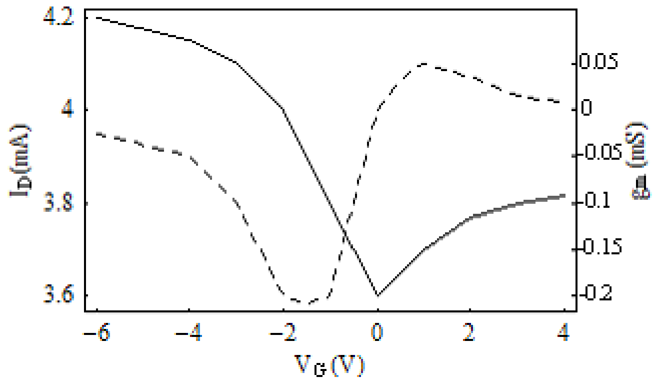
1st FORTH graphene FET







(a)



(b)

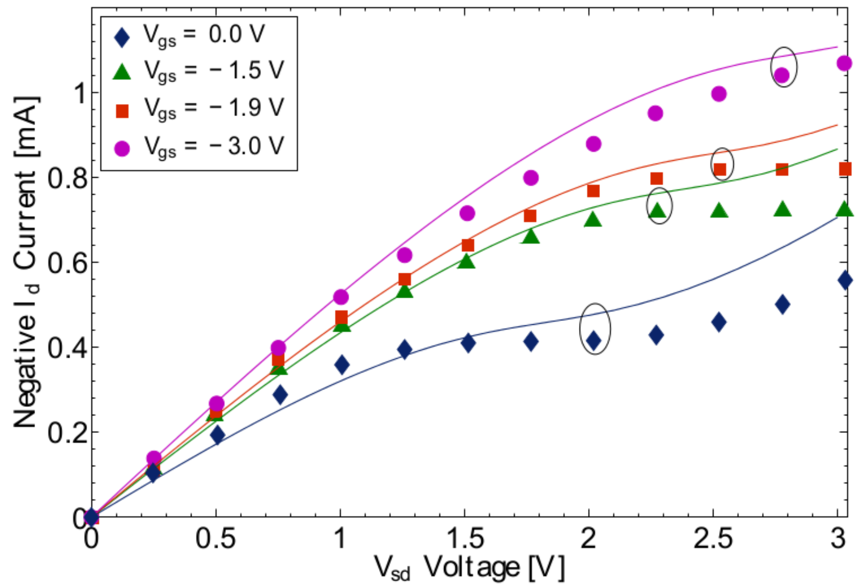
- Polycarbonate low-k gate dielectric
- I_{SD} ~10mA, G_m ~ μSiemens

Deligeorgis et al Appl. Phys. Lett. 96 103105 (2010)

Graphene FET DC modelling

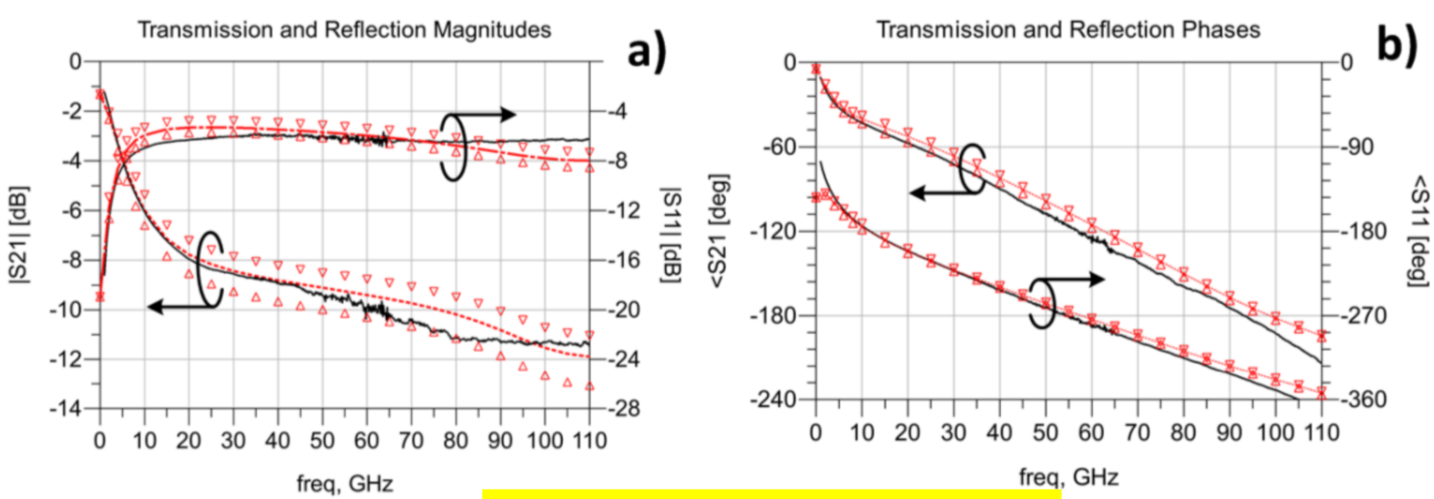
*Developed a model **correctly predicting ballistic** transport properties by extending the “top of the barrier” diffusion transport.*

*Model valid and **much simpler** than existing NEGF based computations.*



G.Vinzenzi et al S.S.El., vol. 76, pp. 8–12, Oct. 2012

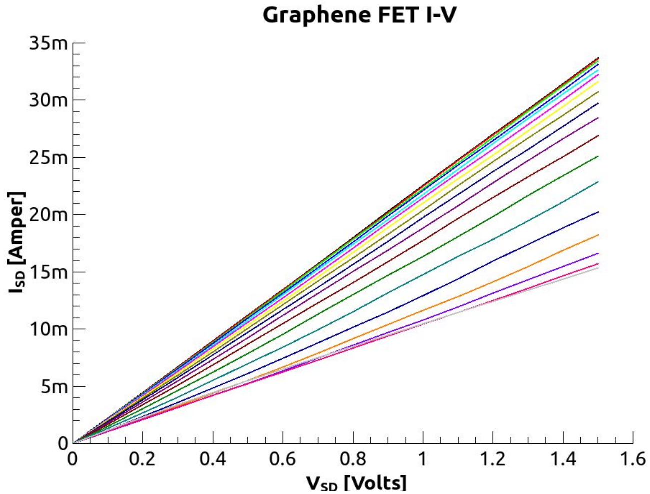
RF graphene lumped element model

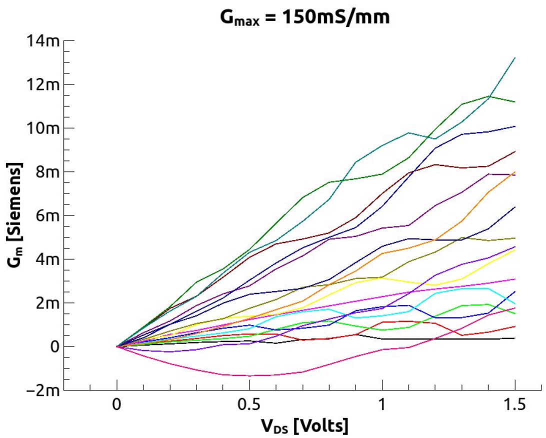


G.Vinzenzi et al IEEE-IMS. 2014

Graphene FET current control

Wide gate (1µm)

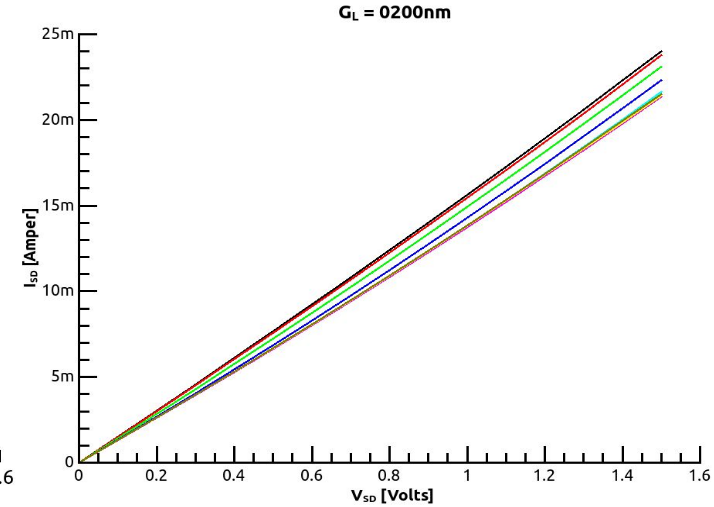


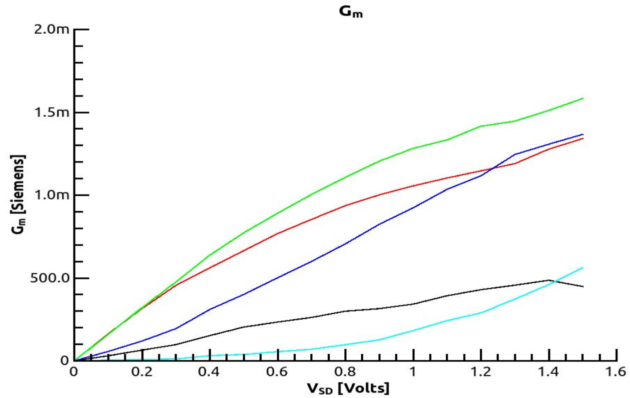


Large gates

Slow operation

Narrow gate (0.2µm)

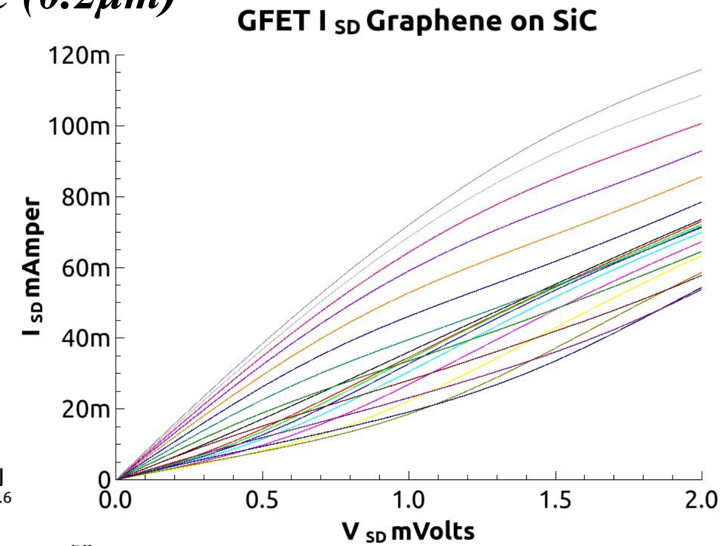


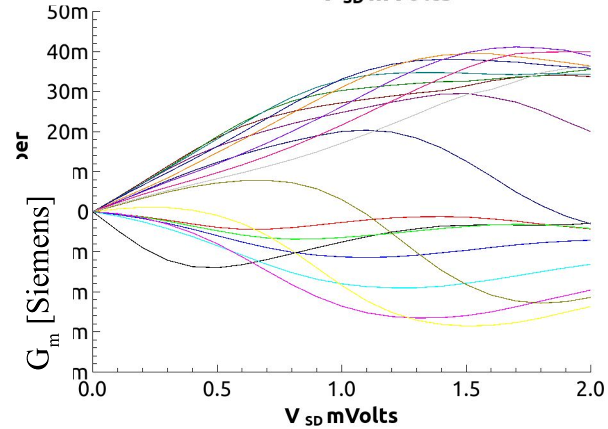


Narrow gates (downscaling)

Carrier mass ~ 0

Klein tunneling reduces current control





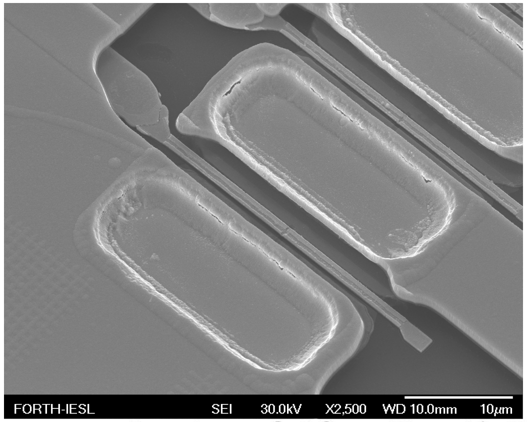
Klein tunneling suppression technology (Patent pending)

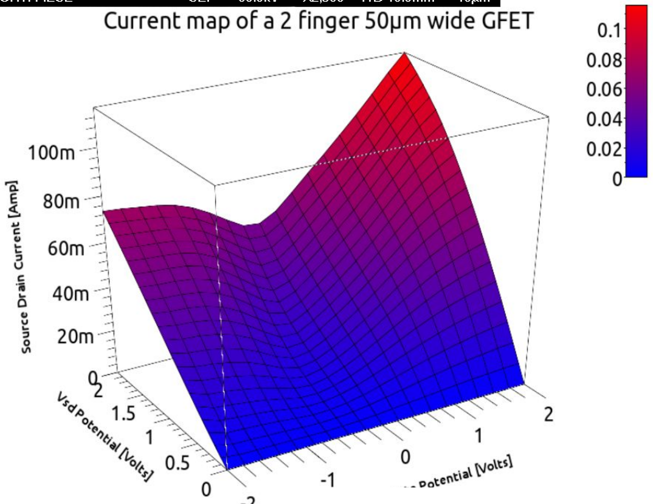
Largest EU reported gain

g_m ~ 250mS/mm

F_{max} = 4GHz

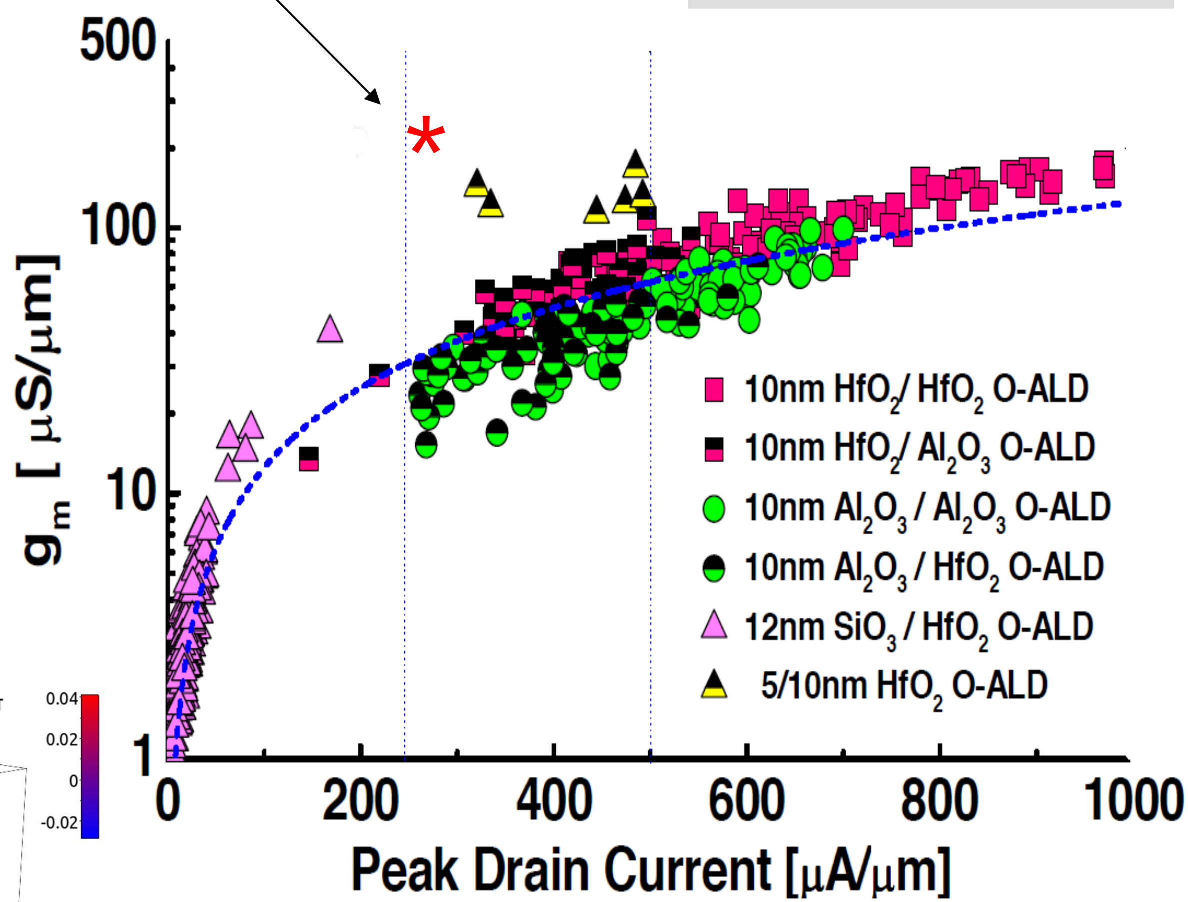
Comparison to State of the art

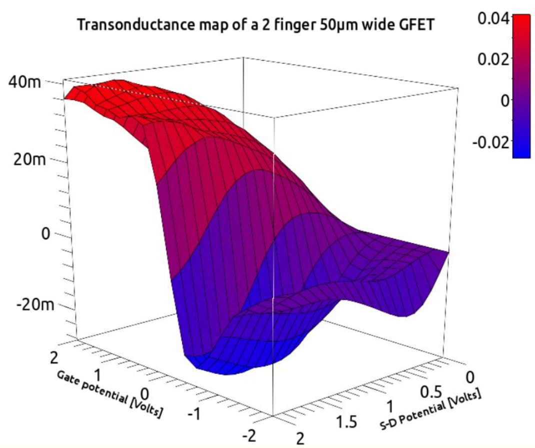




We are currently here

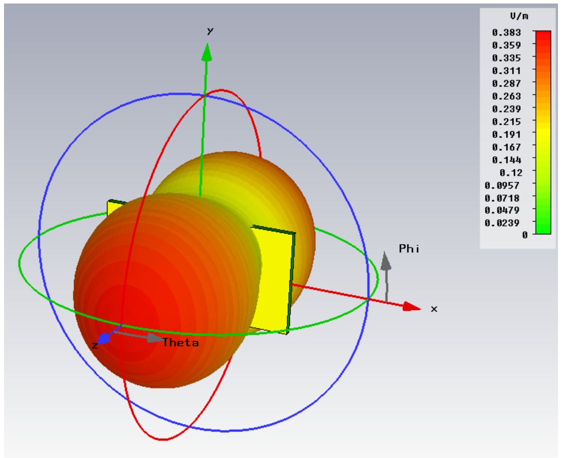
H. Madan et al. ECS (2013)

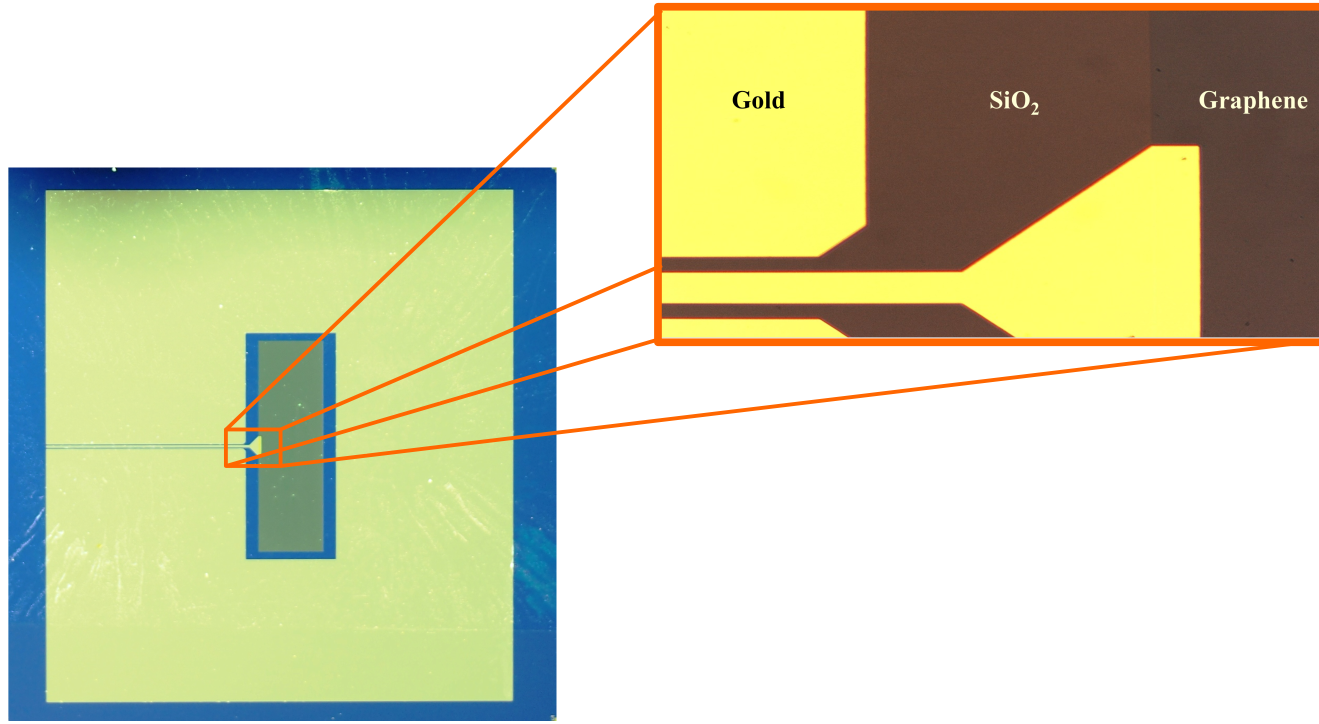


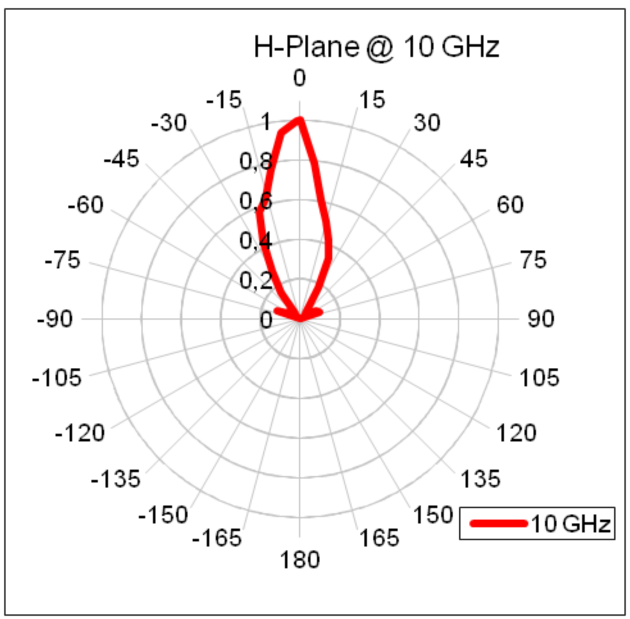


VS. Prudkovskiy et al Carbon Vol.109 p.221 Nov. 2016

Graphene antenna







- *Graphene patch antenna*
- *Verified transmission at design frequency*

High losses due to graphene layer resistance

M. Dragoman et al Appl. Phys. Lett. 106, 153101 (2015)

Roadmap: 3D integration of 2D devices

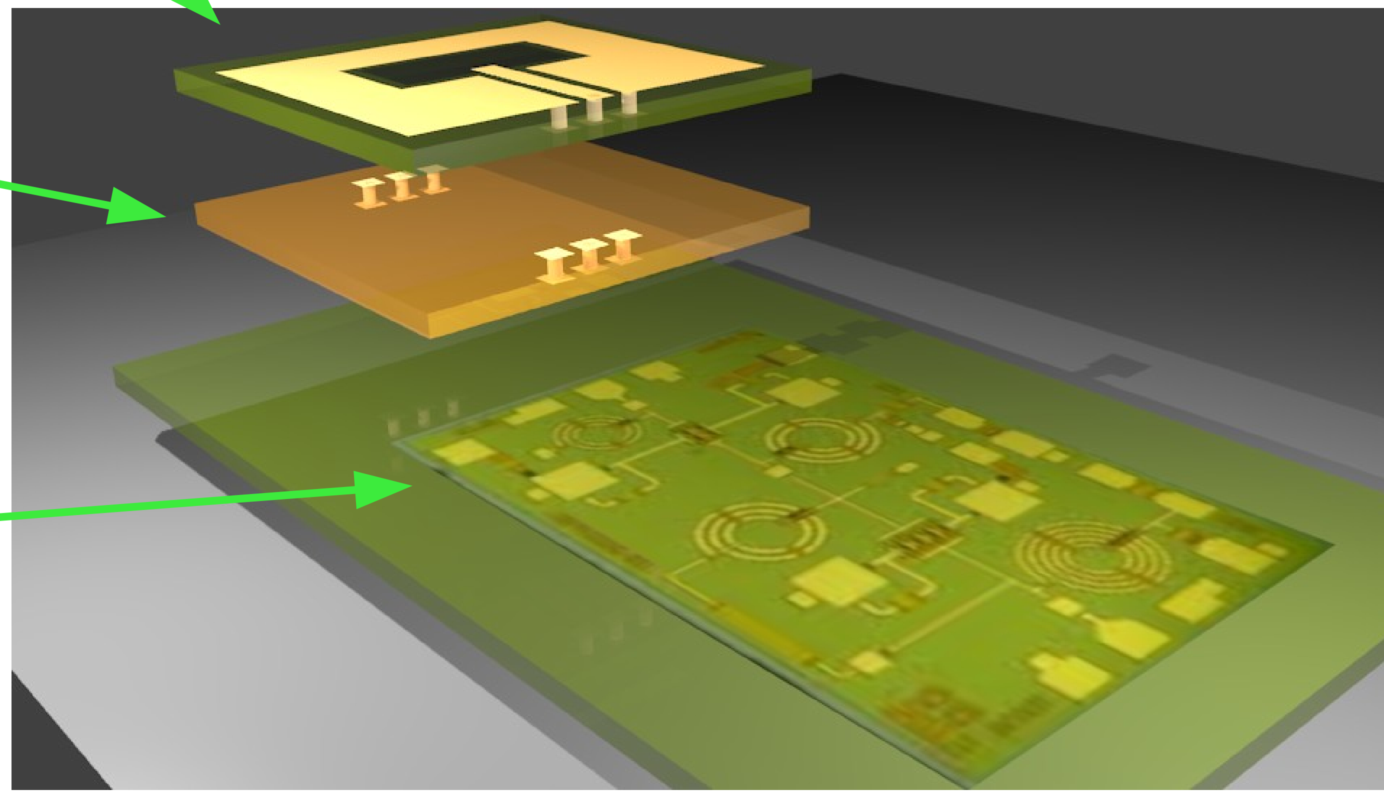
Graphene Antenna

M.Dragoman et al Appl. Phys. Lett 106 (15), 153101 (2015)

CNT interconnects

T.Wang et al Nanotechnology 20 (48), 485203 (2009)

Graphene or other 2D materials low noise receiver (LNA)



G. Deligeorgis et al Appl. Phys. Lett. 96 103105 (2010)
G.Deligeorgis et al Appl. Phys. Lett. 101(1),013502 (2012)
G.Vinzenzi et al S.S.El., vol. 76, pp. 8–12, (2012)
M.Dragoman et al J. Appl. Phys. 112 (8), 084302 (2012)
F.Coccetti et al IEEE MTT-S IMS (MTT) (2013)
G.Vinzenzi et al IEEE IMS (2014)
VS. Prudkovskiy et al Carbon Vol.109 p.221 Nov. 2016

NanoRF

European Commission

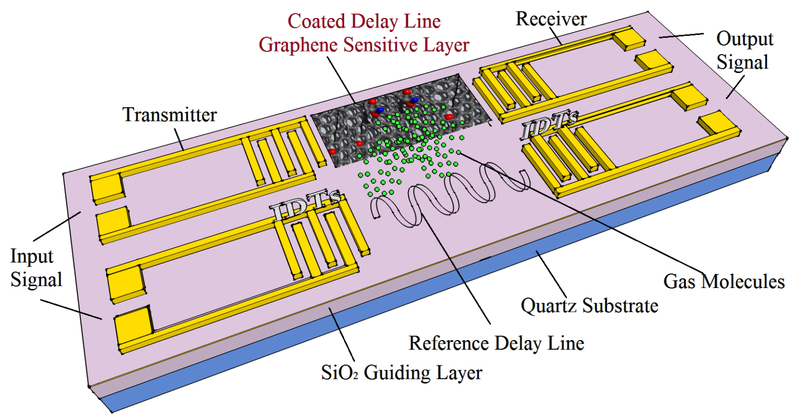
SEVENTH FRAMEWORK PROGRAMME

2D material growth

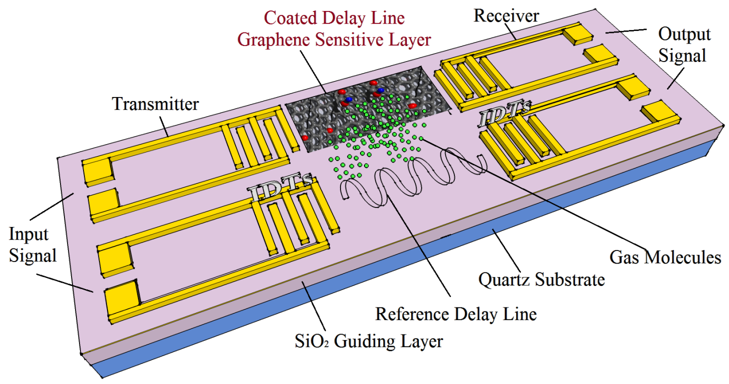
2D material based electronics

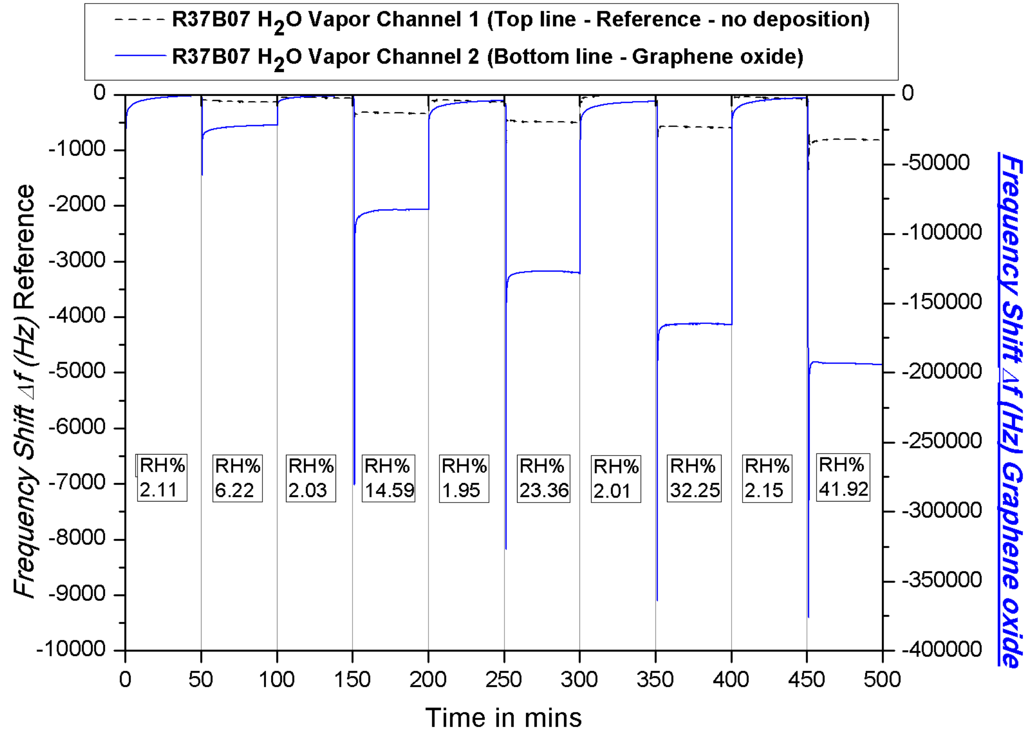
2D materials for sensing

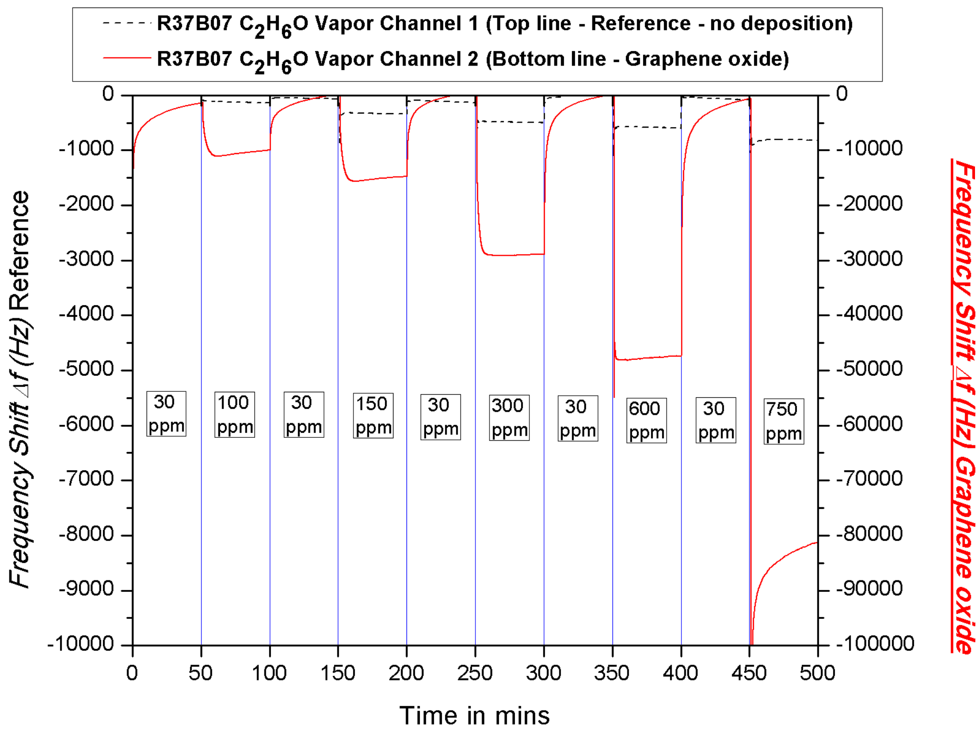
Exploring novel ideas



Inkjet printed graphene oxide for sensing







Graphene RF LOVE sensor for

→ Relative humidity

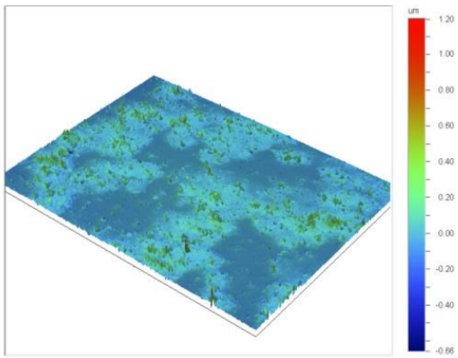
→ Ethanol concentration

Excellent linearity

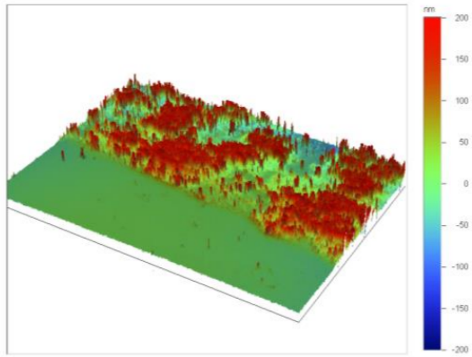
Nikolaou et al. SPIE Microtechnologies 951716 (2015)

Inkjet printed sensing

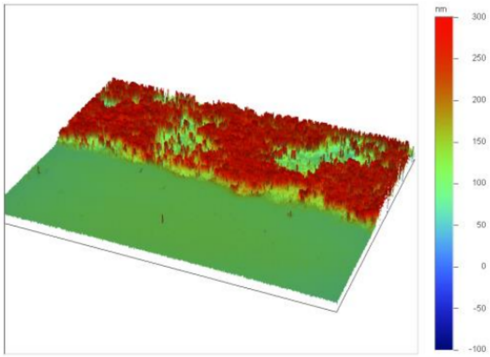
1 inkjet layer



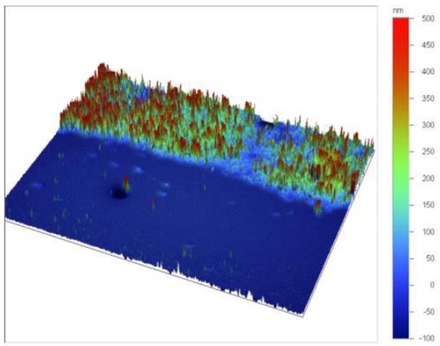
2 inkjet layers

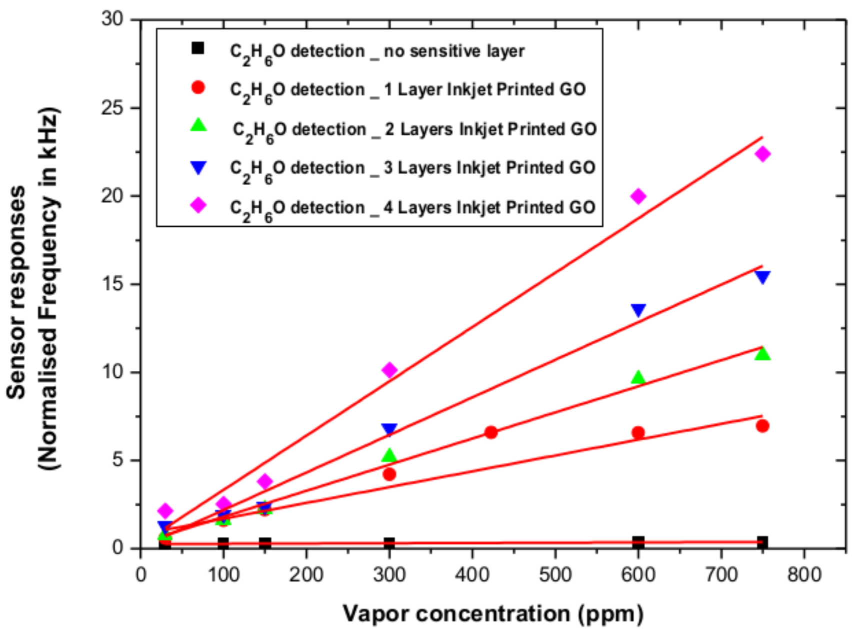


3 inkjet layers

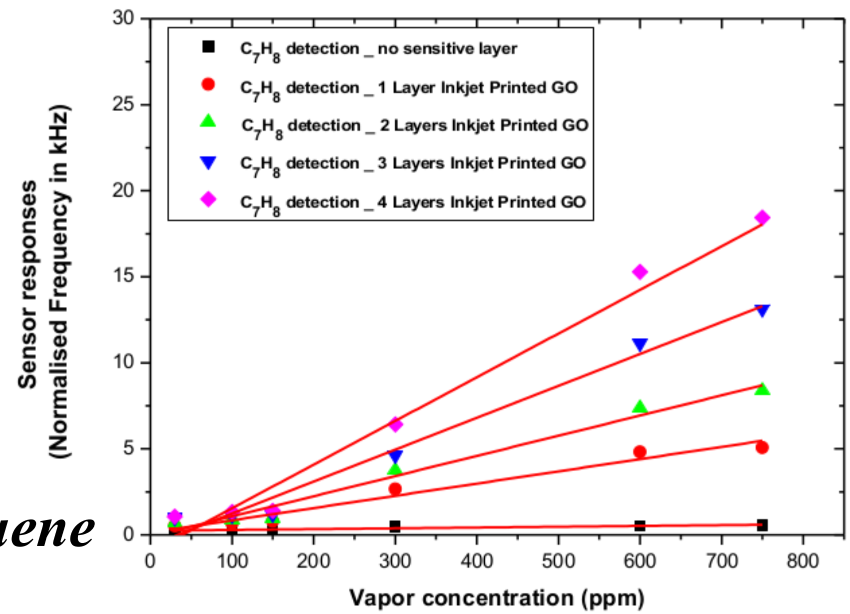


4 inkjet layers





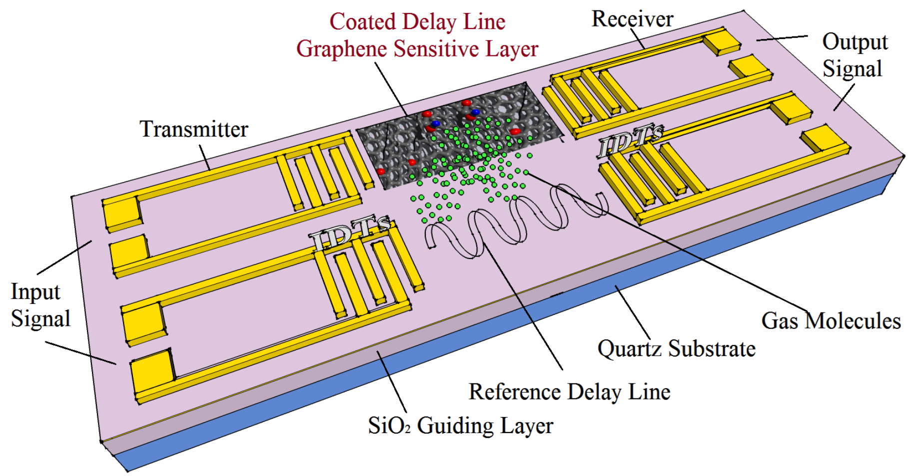
Ethanol



Toluene

Nikolaou et al IEEE Sensors V.16(21) p 7620 (2016)

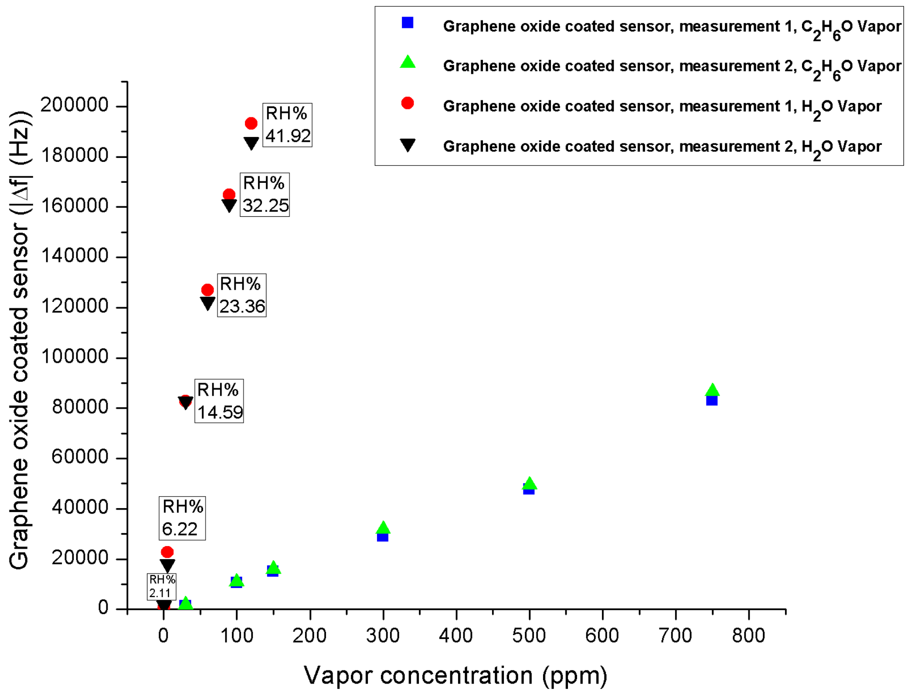
Sensitivity and repeatability

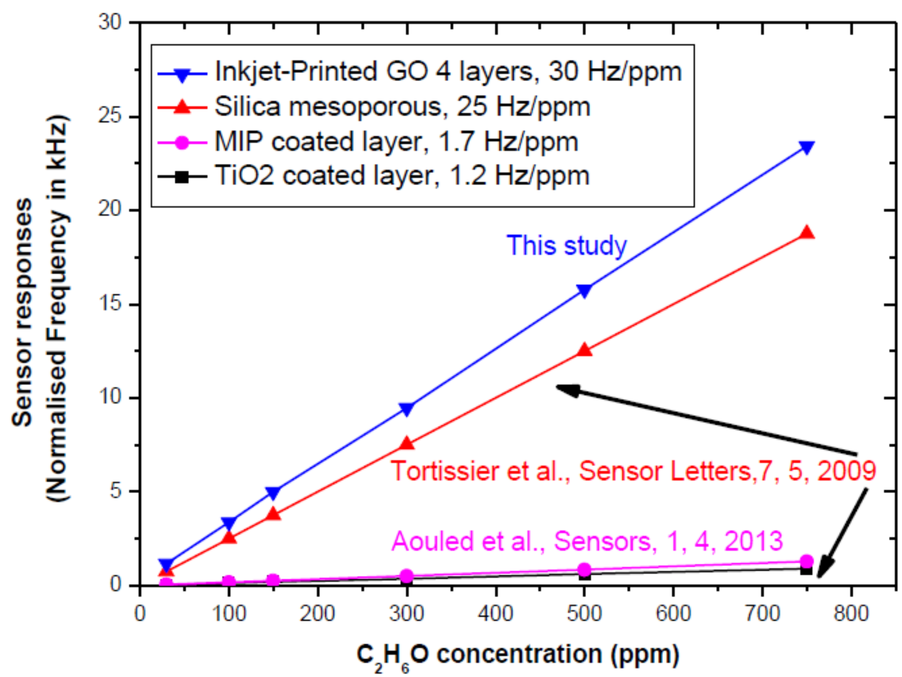


→ *Better than 10ppm Ethanol*

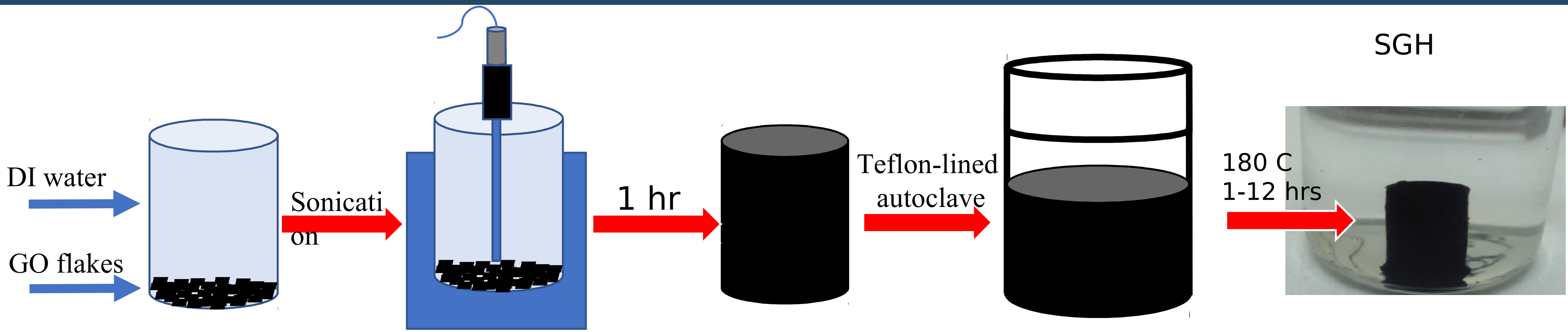
→ *Better than 2% Humidity*

Excellent linearity

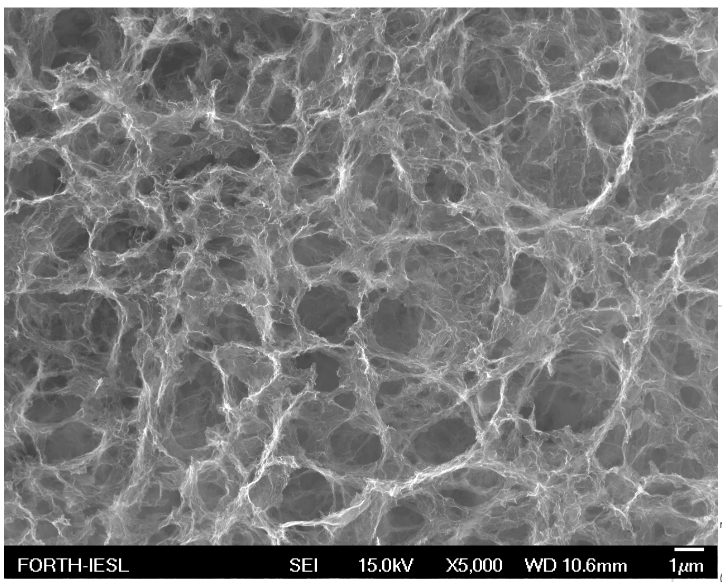




Self assembled graphene hydro-gels

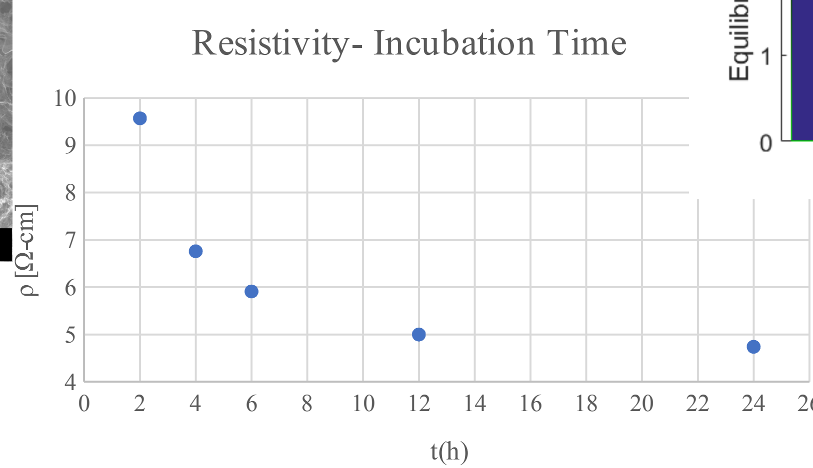


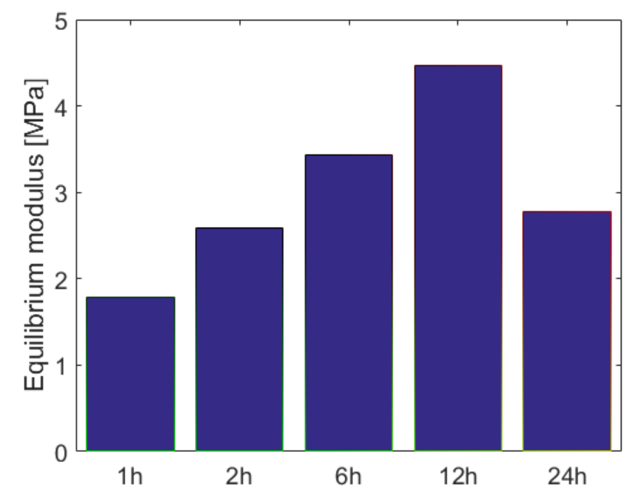
Schematic of self-assembled graphene oxide hydrogels (SHGs) fabrication.



- → *Highly porous*
- → *Chemically stable*
- → *Filtration applications*

- → *Conductive*
- → *Electromagnetic radiation absorbers*





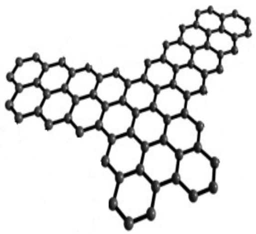
- → *Bio - compatible*
- → *Potential tissue engineering material*

B. Gabritchidze et al. In preparation

Conclusions - Acknowledgements

QCN — CRETE CENTER FOR QUANTUM COMPLEXITY AND NANOTECHNOLOGY

- *Collaborators:*
  - *F. Iacovella (Postdoctoral Fellow)*
  - *G. Kaklamani (Junior Researcher. Tissue engineering)*
  - *N. Chatzarakis (M.Sc student, 2D growth)*
  - *K. Triantopoulos (ex M.Sc. student now in NEEL France)*
  - *V. Prudkovskiy (ex Postdoctoral Fellow, now in CEA France)*
  - *B. Gabritchidze (ex M.Sc. now Ph.D at Cornell & UoC)*
  - *A. Ziaei (THALES Research & Technology, France)*
  - *D. Gournis (Univ. of Ioannina, Graphene oxide material)*
  - *D. Tzeranis (NTUA & IMBB, Mechanical testing)*
  - *G. Konstantinidis (IESL, Clean room support)*



NanoRF

European Commission

SEVENTH FRAMEWORK PROGRAMME

2D materials for

- ***Electronics (High frequency, flexible)***
- ***Sensing***
- ***Bio applications***