UTS:ENGINEERING AND INFORMATION TECHNOLOGY

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UNIVERSITY OF TECHNOLOGY, SYDNEY

GRAPHENE: HYPE OR HOPE?

(AND HOW THE DoD HAS TAKEN UP THE CHALLENGE……)

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OUTLINE

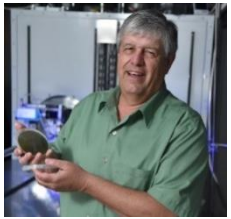
- Acknowledgements
- What’s the big deal about graphene?
- What’s the problem about graphene?
- Our contribution, collaboration with the US DoD
- Hype or hope?

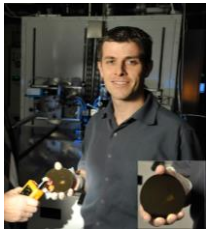
ACKNOWLEDGMENTS





ACKNOWLEDGMENTS





Australian Government
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NCRIS
National Research Infrastructure for Australia
An Australian Government Initiative

ANFF

AFOSR
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Science & Technology

Major collaborators:

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- Nunzio Motta, Queensland University of Technology, Australia
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- Paul Pigram, Rob Jones, La Trobe University, Australia
- Anton Tadich, Australian Synchrotron, Australia
- Michael Fuhrer, Jack Hellerstedt, Mark Edmonds, Monash University, Australia
- Barbara Nichols, ARL, Adelphi MD, USA
- Fouad Karouta, Australian National University, Australia

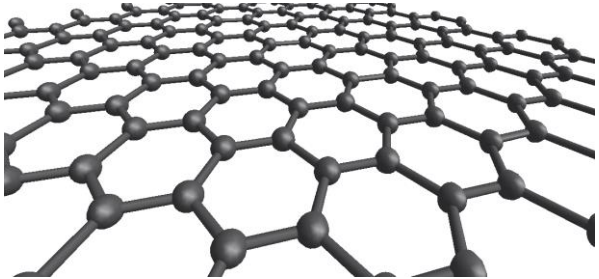
GRAPHENE 2010

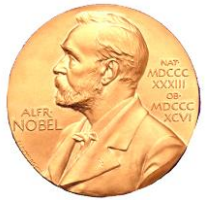
Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov,[1] A. K. Geim,[1]* S. V. Morozov,[2] D. Jiang,[1] Y. Zhang,[1] S. V. Dubonos,[2] I. V. Grigorieva,[1] A. A. Firsov[2]

We describe monocrystalline graphitic films, which are a few atoms thick but are nonetheless stable under ambient conditions, metallic, and of remarkably high quality. The films are found to be a two-dimensional semimetal with a tiny overlap between valence and conductance bands, and they exhibit a strong ambipolar electric field effect such that electrons and holes in concentrations up to 10^{13} per square centimeter and with room-temperature mobilities of ~10,000 square centimeters per volt-second can be induced by applying gate voltage.

22 OCTOBER 2004 VOL 306 SCIENCE www.sciencemag.org

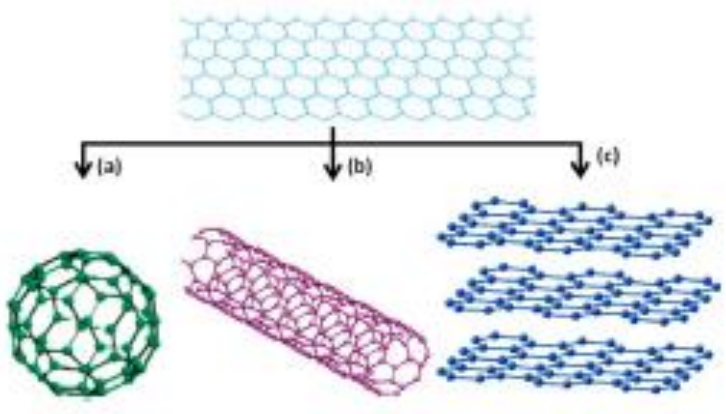


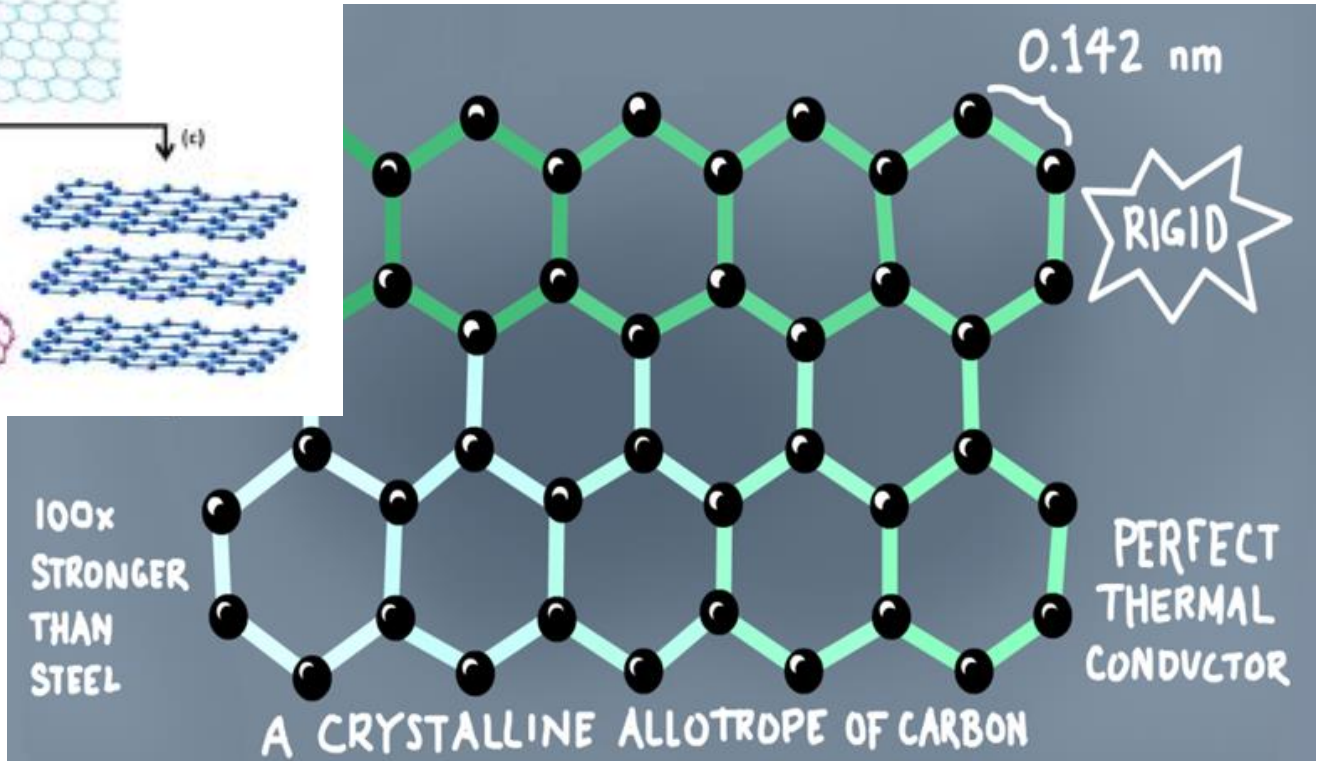


Nobelprize.org
The Official Web Site of the Nobel Prize

The Nobel Prize in Physics 2010 was awarded jointly to Andre Geim and Konstantin Novoselov *"for groundbreaking experiments regarding the two-dimensional material graphene"*

WHAT'S THE BIG DEAL ABOUT GRAPHENE?





WHAT'S THE BIG DEAL ABOUT GRAPHENE?

Electronic properties

- Semi-metal or zero-gap semiconductor
- Linear dispersion relation
- Massless dirac fermions, v ~ c/300
- Intrinsic carrier mobility (suspended graphene in vacuum)

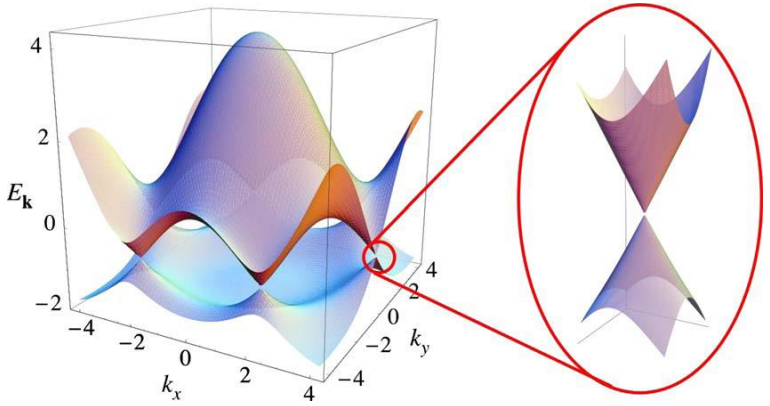
  $\mu = 200.000\ cm^2\ V^{-1}s^{-1}$

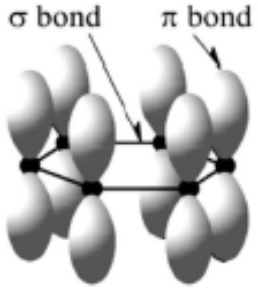
- Carrier mobility of graphene on SiO_2 at room-temperature

  $\mu = 10.000\text{-}20.000\ \ cm^2\ V^{-1}s^{-1}$ (speed ~ I_{on} ~ μ)

- Maximum current density

  $J > 10^8\ A/cm^2$

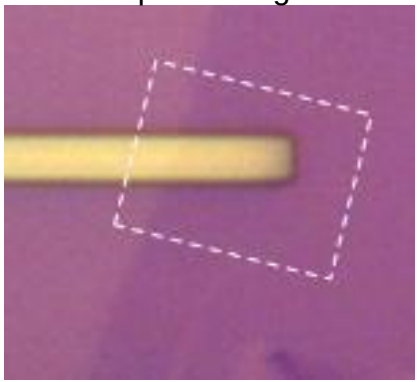




WHAT'S THE BIG DEAL ABOUT GRAPHENE?

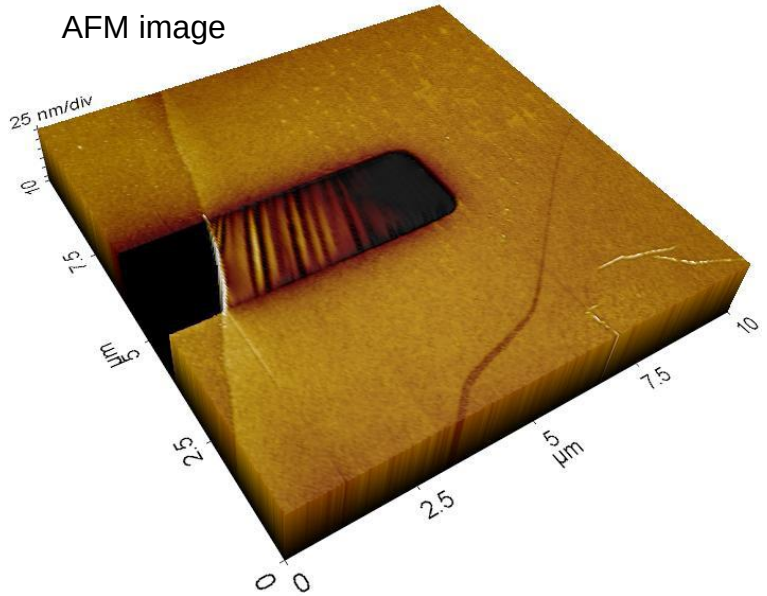
Being only a single atom thick, and possessing an intrinsically perfect lattice, graphene is very strong and can withstand elastic deformations up to 20%.

Optical image



Single layer graphene deposited over sharp trench

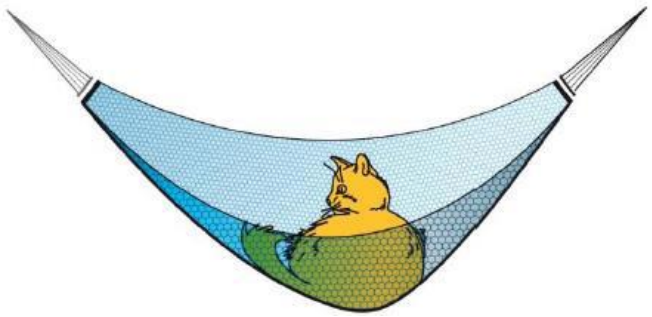
AFM image



- 40 N/m breaking strength (**100x steel)**
- Young's modulus ~1 TPa
- density: 0.77 mg/m^2

Lee et al., Science 321, 385 (2008)

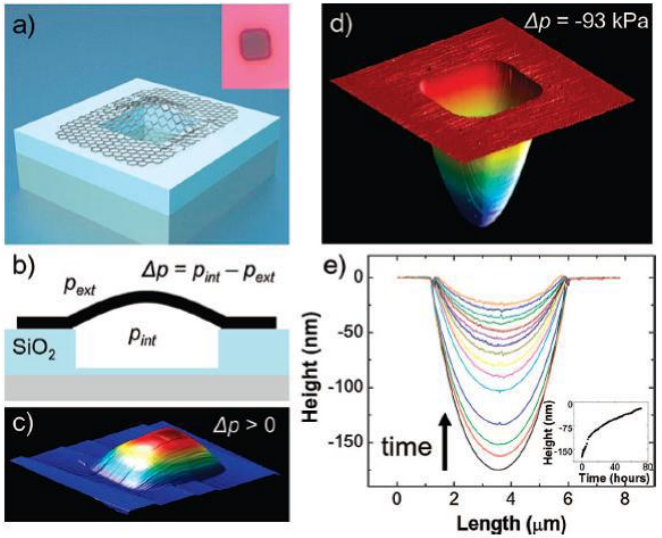
WHAT'S THE BIG DEAL ABOUT GRAPHENE?



A hypothetical 1 m^2 hammock would weigh only 0.77 mg (less than a cat's whisker) but:

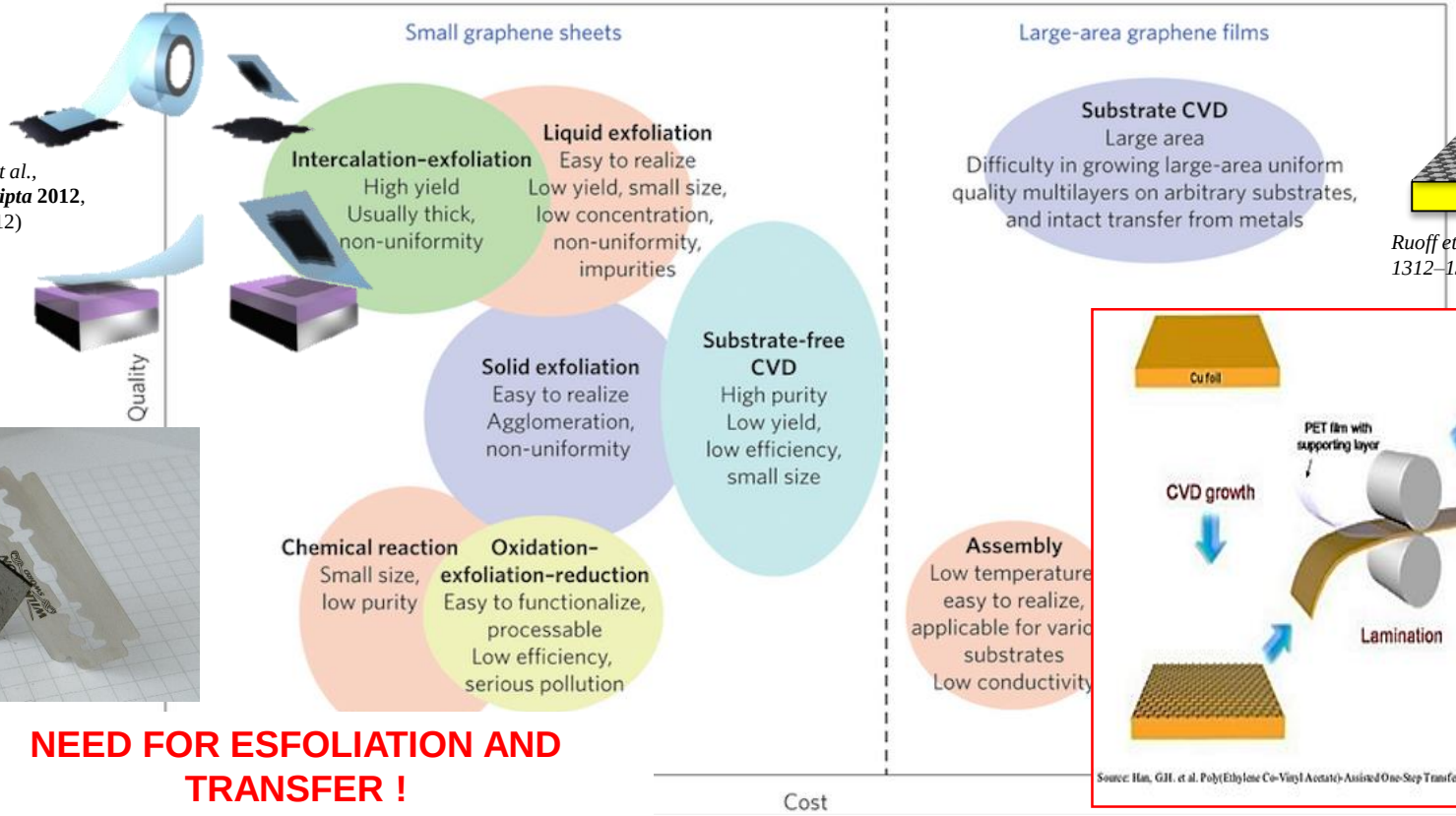
- It would bear the weight of a cat without breaking (up to ~4 kg)
- **It would be invisible!**

A graphene membrane is impermeable to most gases (including Helium

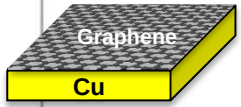


Bunch et al., Nano Lett. 8, 2458 (2008)

SO WHAT'S THE PROBLEM WITH GRAPHENE?



Novoselov et al., ***Physica Scripta* 2012**, 014006 (2012)

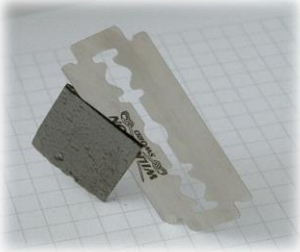


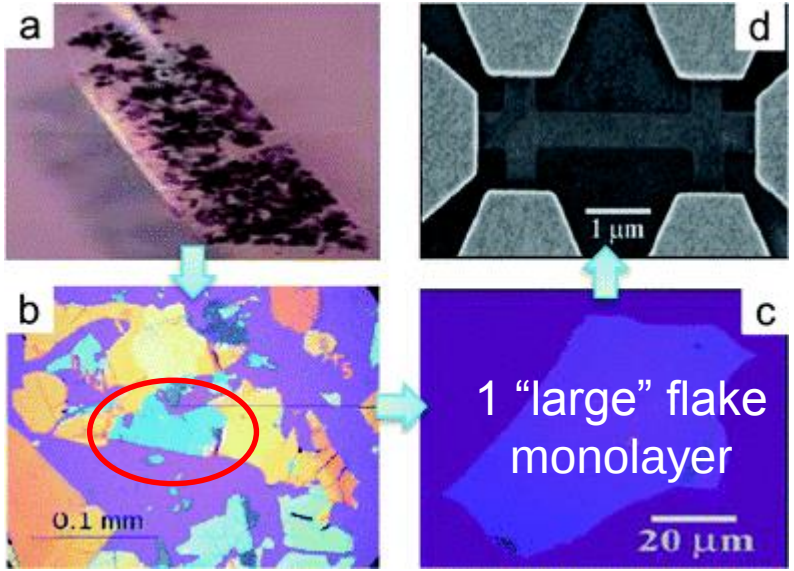
Ruoff et al. ***Science 324***, *1312–1314 (2009)*

NEED FOR ESFOLIATION AND TRANSFER !

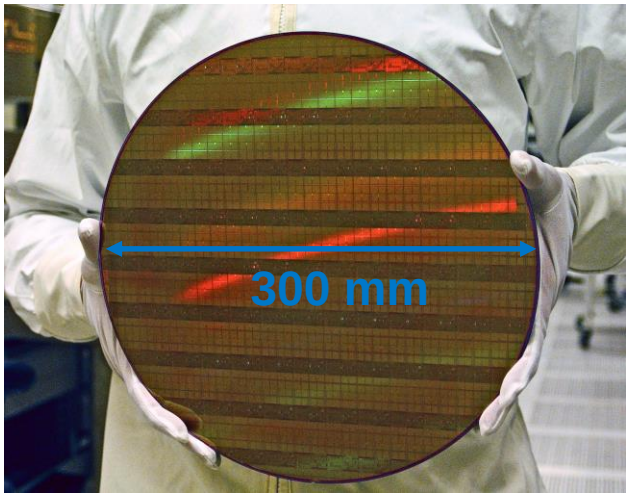
Source: The global growth of graphene. Nature Nanotechnology 9, 726-730 (2014)

SCALING TO WAFER –LEVEL?



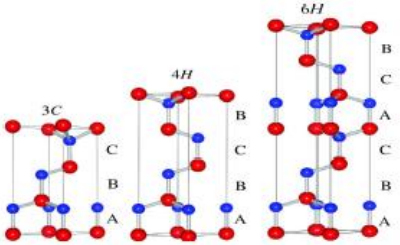


Not feasible
(**x10^{8}** area factor)

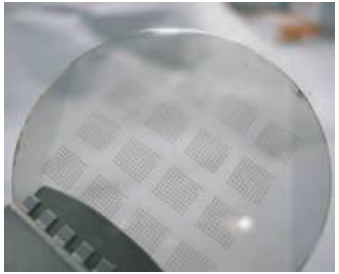


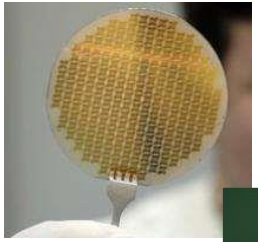
Manufacturability, reproducibility, yield, standards, predictability, reliability: more important than absolute quality!

GRAPHENE FROM SIC WAFERS

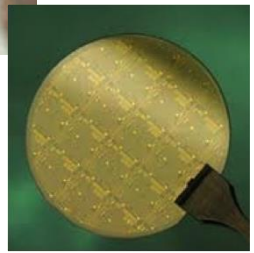


IBM TJ Watson



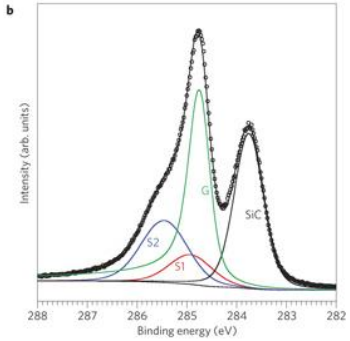


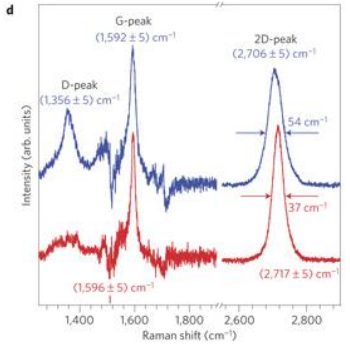
PennState

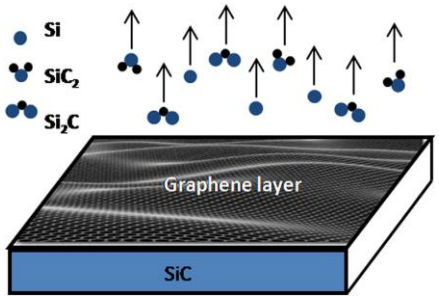


NRL

Emtsev, 2009





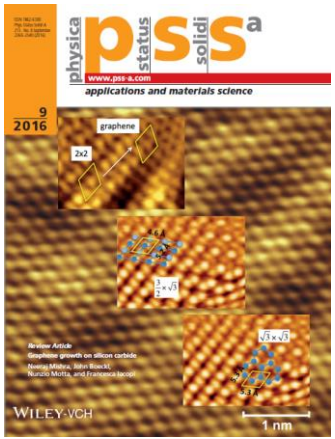


12

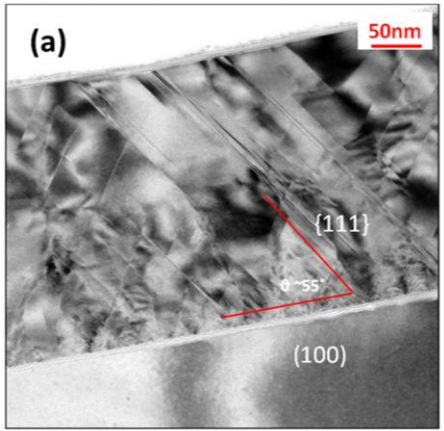
Templated, solid –source growth

…BUT LITTLE PROGRESS ON SIC/SI

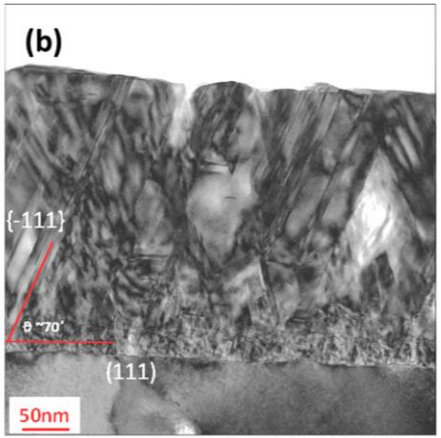
Sublimation from SiC/Si not quite the same….

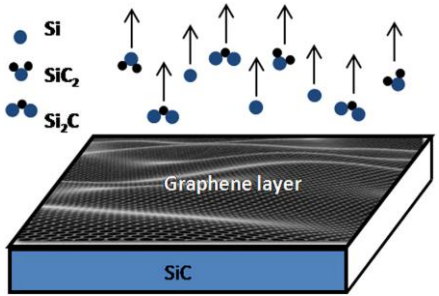


SiC(100)



SiC(111)





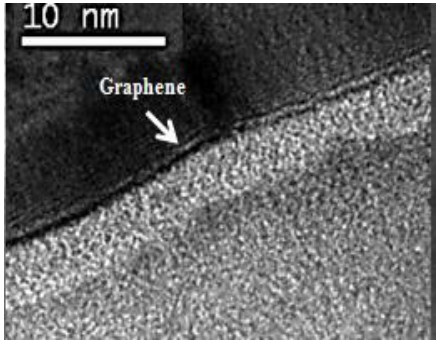
F.Iacopi et al, APL 2013

NI-CU ASSISTED GRAPHENE

I_D/I_G 0.22 ± 0.05

I_{2D}/I_G 1.2-1.5

Over 1 cm^2



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Catalytic alloy used to grow high quality graphene on SiC on Si wafers

By Meg Marquardt

Materials Research Society/MRS Bulletin | Published: 13 February 2015

When it comes to creating wafer graphene technology on widely

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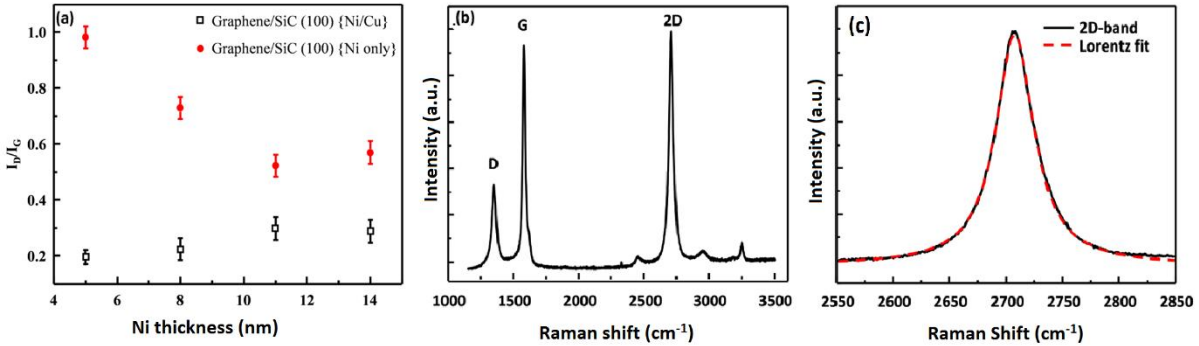
New Silicon Carbide Field Emitter May Improve



FWHM 40 cm^{-1}

Monolayer on SiC(100)

WAFER-LEVEL GRAPHENE ON SILICON

Epitaxial SiC on Silicon

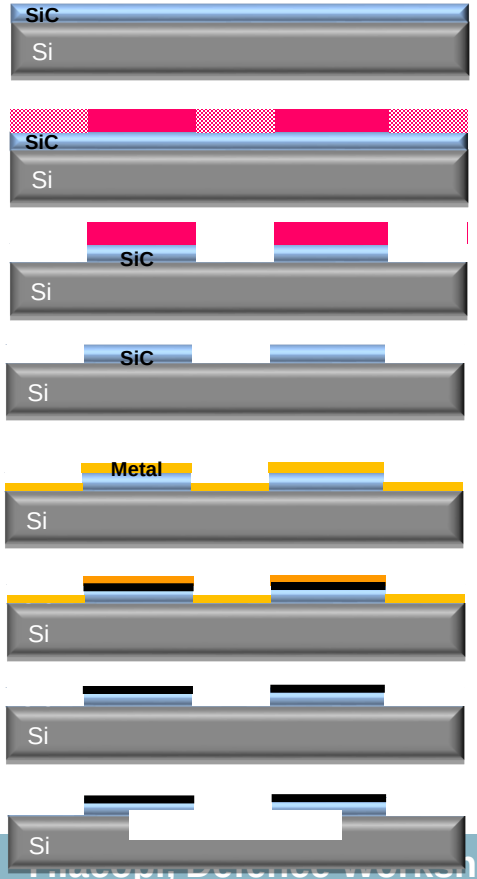
Patterning of the SiC

Deposition of metal alloy (Ni-Cu)

Catalytic self-aligned graphitization at 1000-1100 C

Wet removal of the metal layer

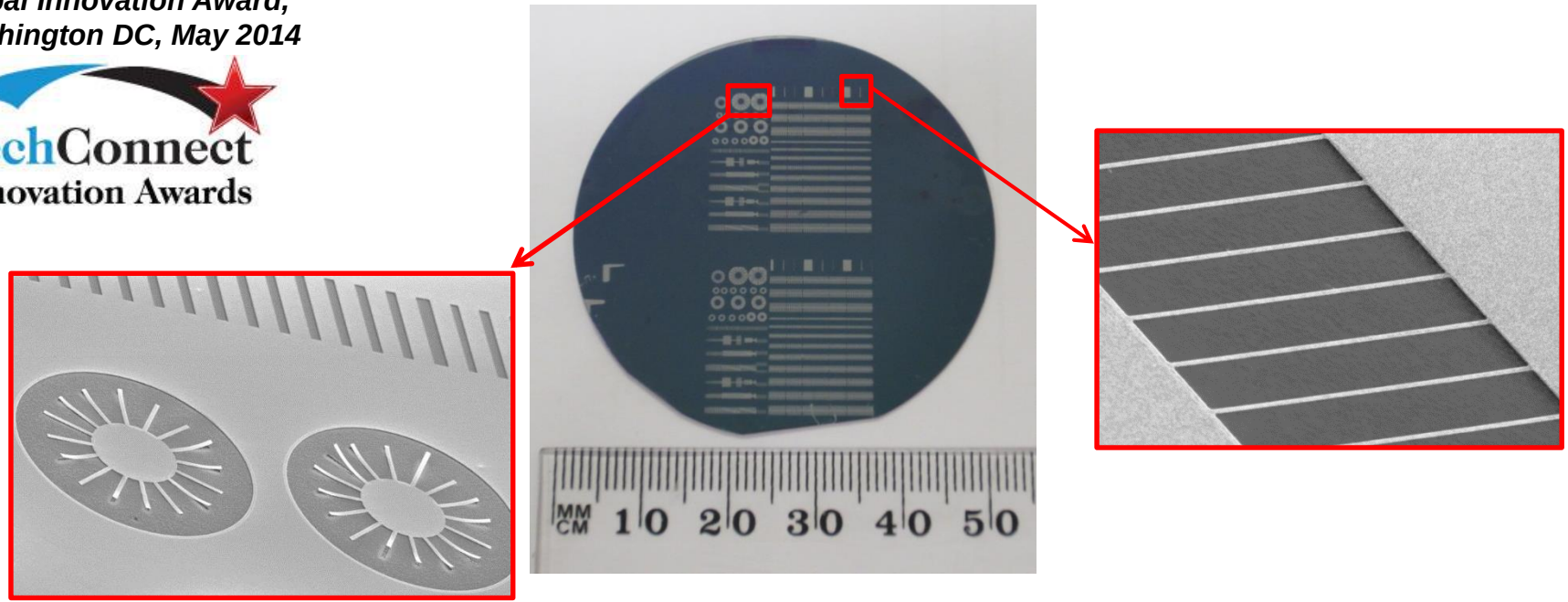
Release of the micro-structures



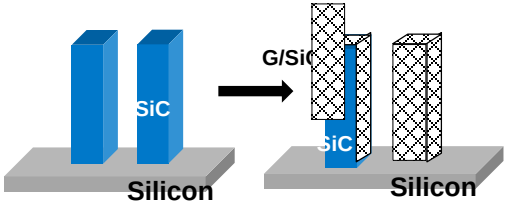
WAFER-LEVEL GRAPHENE ON SILICON

Global Innovation Award, Washington DC, May 2014

TechConnect Innovation Awards

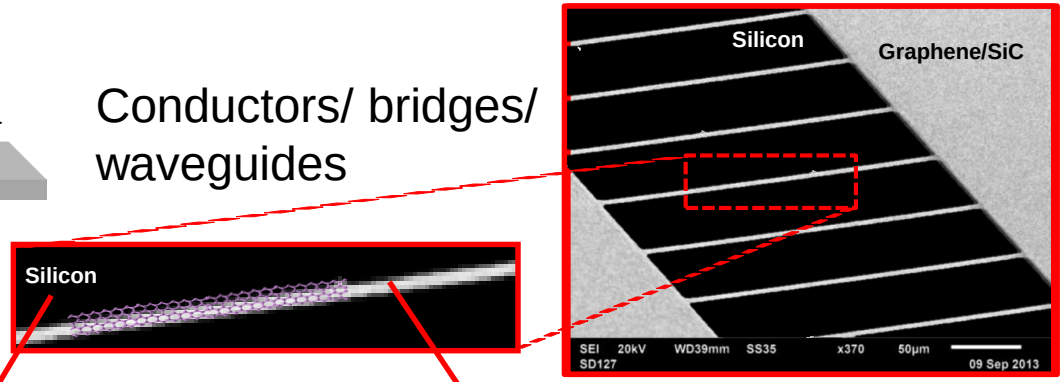


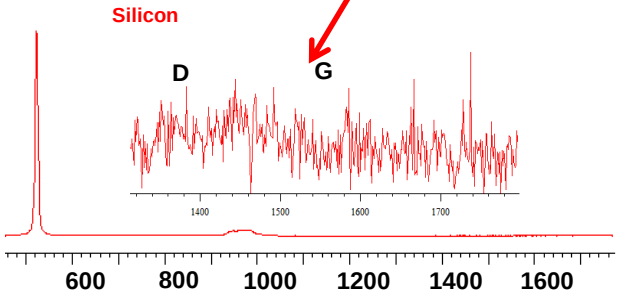
SELECTIVE GRAPHITIZATION @WAFER LEVEL

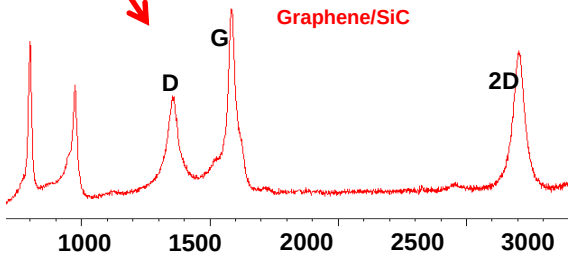


Pillars/Antennas

Conductors/ bridges/ waveguides





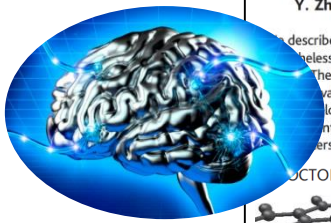


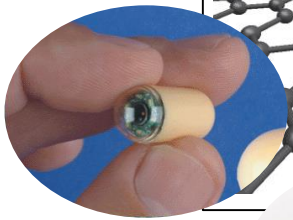
ENABLING THE ULTIMATE MINIATURIZATION WITH *GRAPHENE ON SILICON*

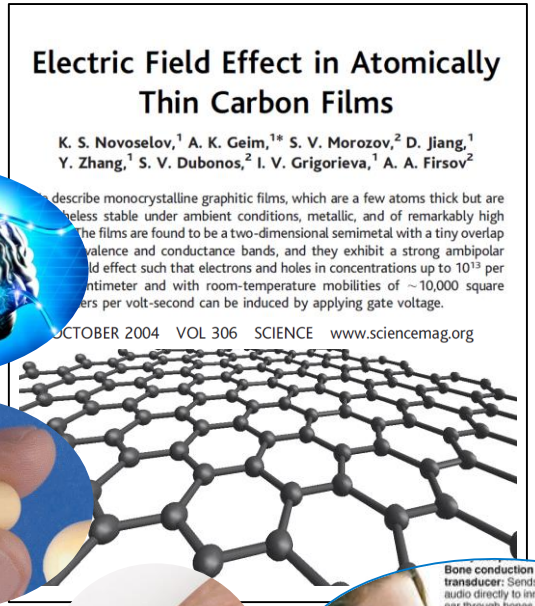
Graphene on silicon could augment quite a few functionalities!

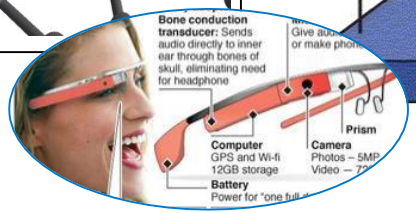
- Interconnects
- Energy storage
- Photonics
- (bio)Sensing
- Thermal management

➔ Is it a Holy Grail?

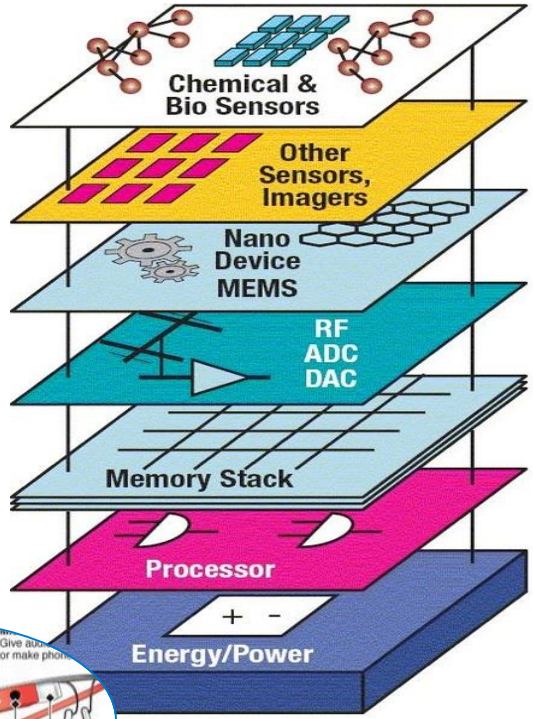


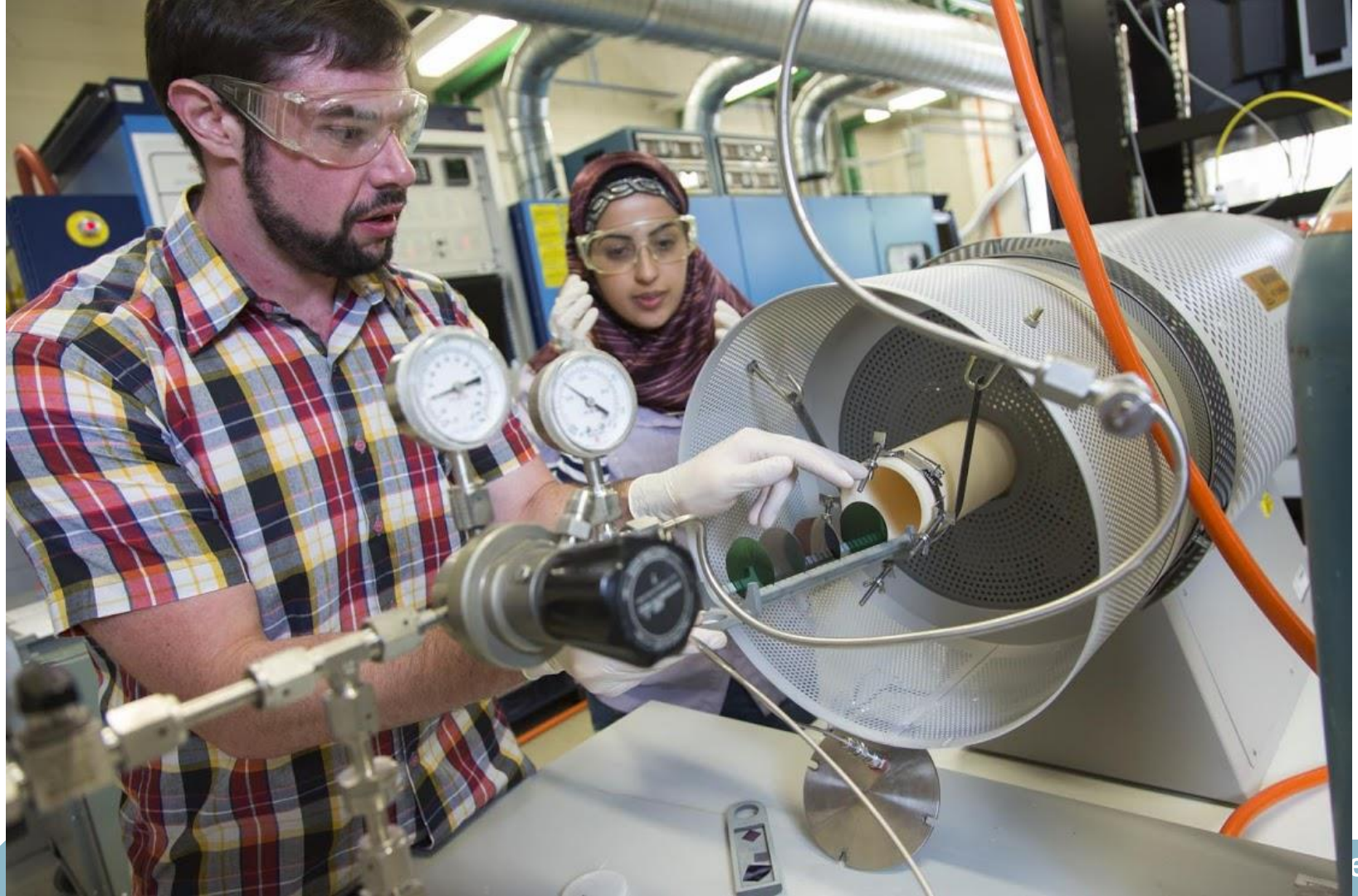






Monolithic 3D Inc

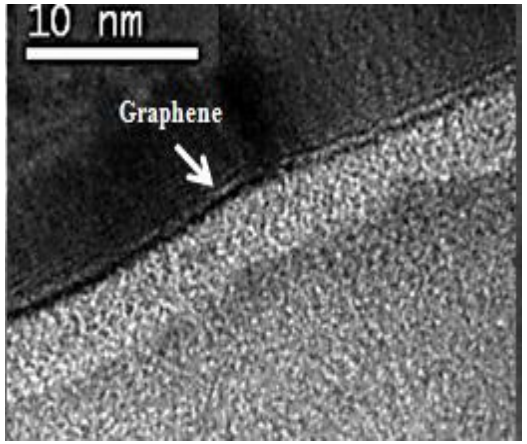




HOW DO YOU “SEE” GRAPHENE?

Dr.John J Boeckl, AFRL
Microscopy of nanocarbons

Dr.Neeraj Mishra (just graduated)
Worked in close collaboration w Boeckl



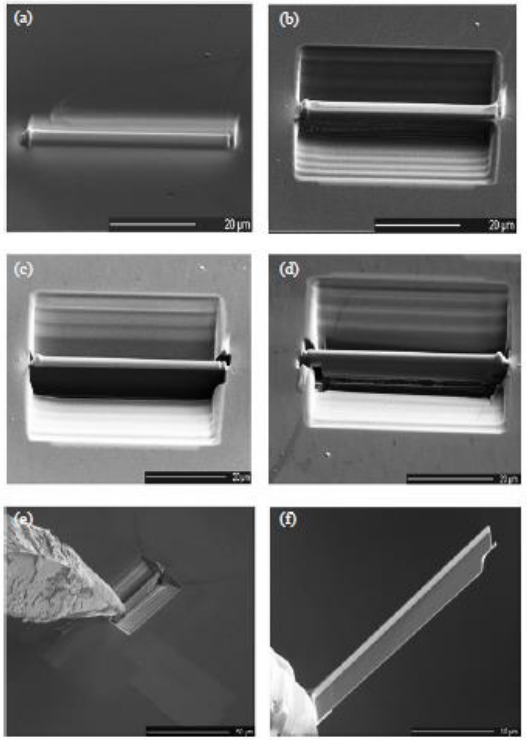
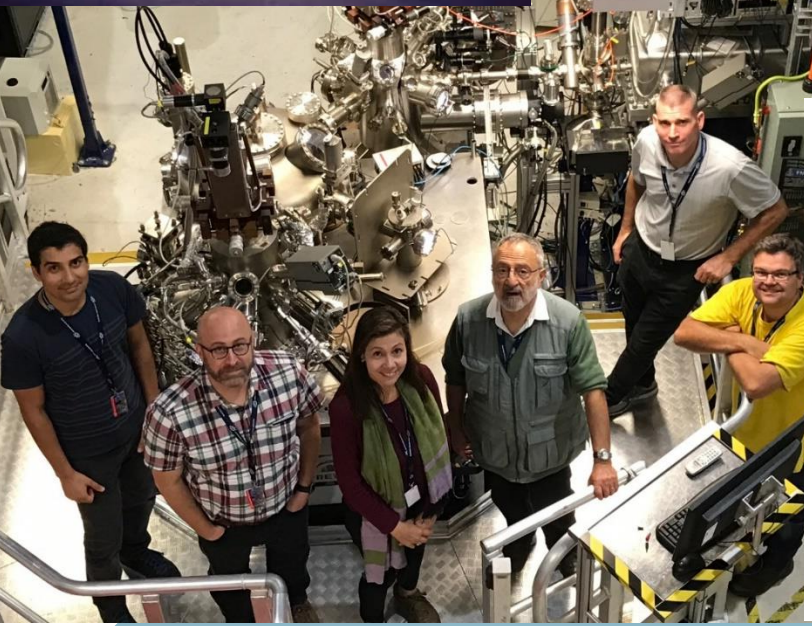
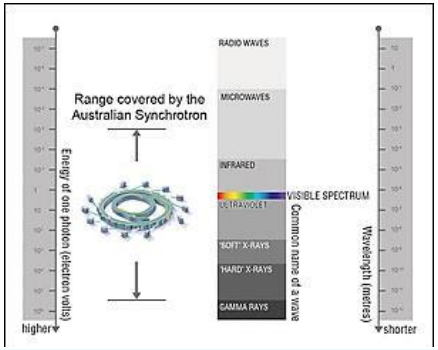
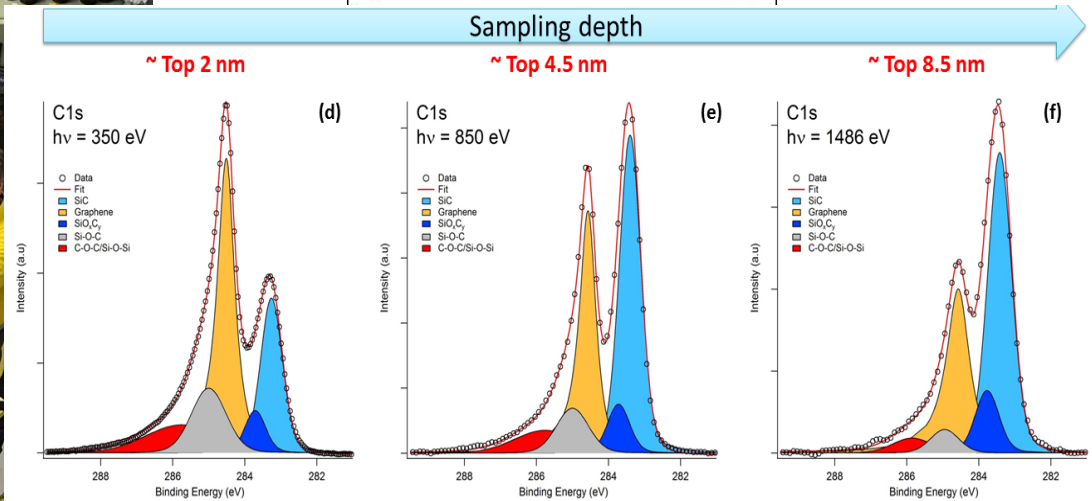


Figure 3.8 FIB images of the TEM sample preparation steps. a) A ~2 μm thick Pt deposited on the surface. b) Gross cut on both sides of the Pt layer. c) Thinning and smoothening the foil to ultimate ~1 μm. d) U-cut on the foil. e) Microprobe needle brings in contact and attached to the foil. f) Released foil on the microprobe needle.

SOFT X-RAYS, AUSTRALIAN SYNCHROTRON



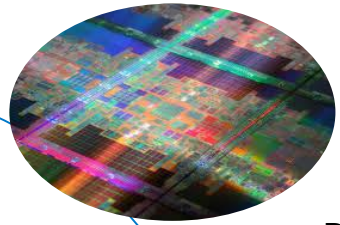


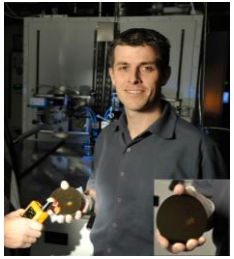


APPLICATIONS

Prof Guoxiu Wang, UTS

Energy Storage





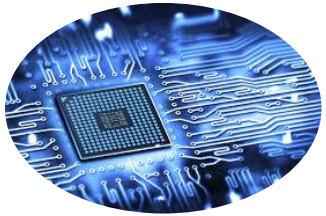
Dr.Joshua Caldwell, NRL

Dr.Dennis Delic, DSTG

Low-loss Nanophotonics

A/Prof Igor Aharonovich, UTS

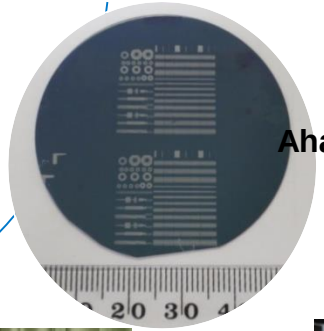
Electrical and thermal nanocoating



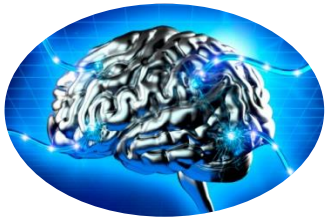
Self- aligned, synthesis and patterning @ wafer -level

Best monolayer graphene on silicon to-date

Strong adhesion to the substrate



Biocompatible nanodevices



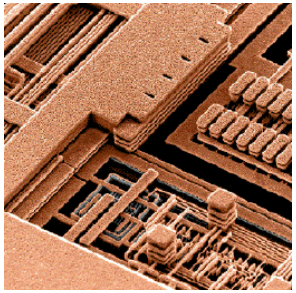
Low-power and HF electronics

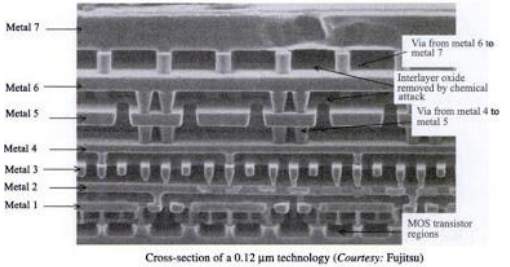
Prof.Jay Guo, UTS

Dr.Kurt Gaskill, NRL

F.Iacopi, De kshop feit

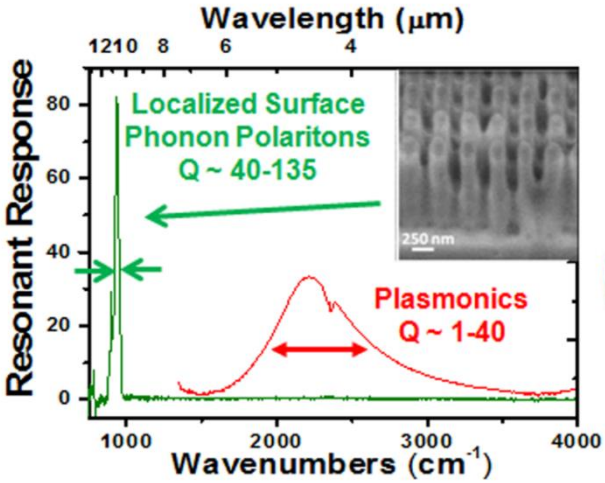
NANOPHOTONICS

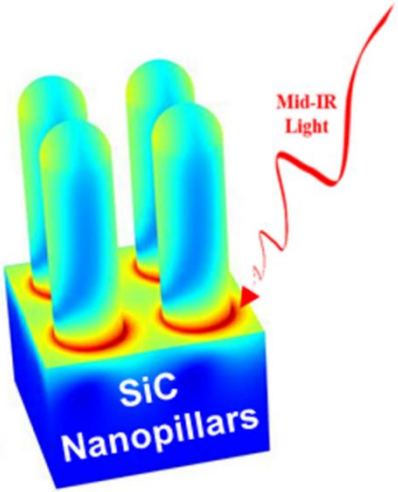


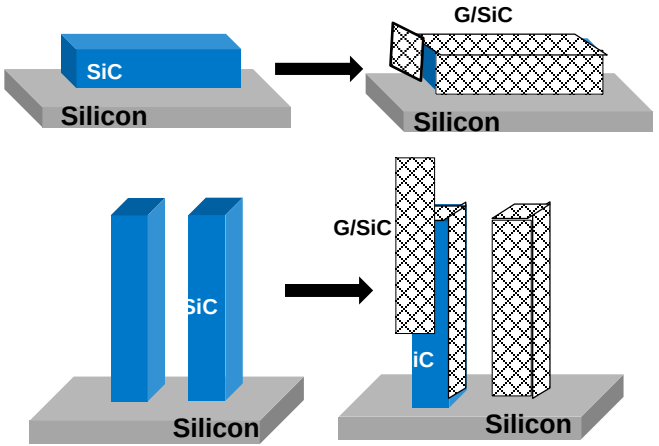


Cross-section of a 0.12 µm technology (*Courtesy:* Fujitsu)

Low-loss photonics for on-silicon
(and free space) communications:







Plasmon-polariton coupling
In graphene/SiC antennas & waveguides on silicon!

NANOPHOTONICS

DEPARTMENT OF THE AIR FORCE
WASHINGTON, DC

2 3 AUG 2016

OFFICE OF THE UNDER SECRETARY

MEMORANDUM FOR SEE DISTRIBUTION

FROM: SAF/IAP
1080 Air Force Pentagon
Washington, DC 20330-1080

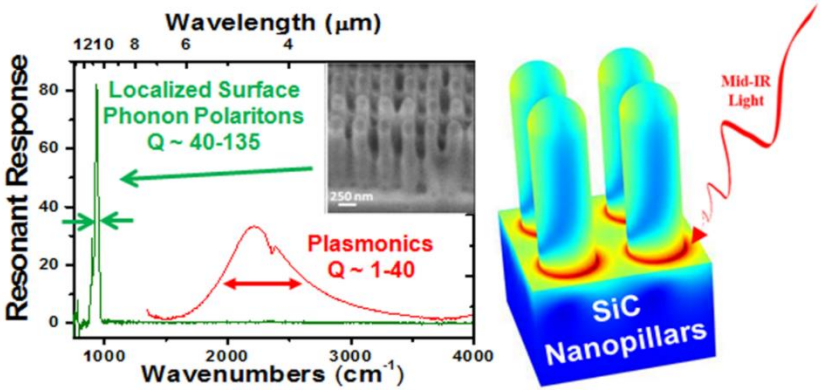
SUBJECT: Headquarters Air Force (HAF) Review Panel Results – FY18 International Cooperative Research & Development (ICR&D) Program Funding

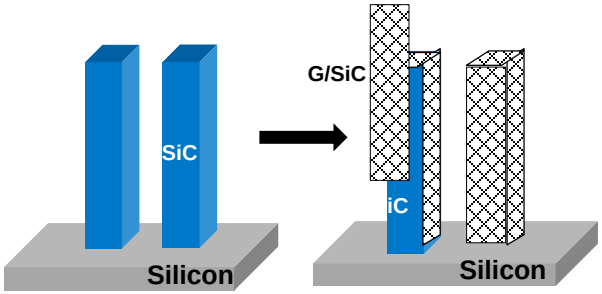
ICR&D Awarded Project:

Graphene on 3C-SiC on Si for low-loss nanophotonics

to J.J.Boeckl (AFRL/RX) for Australian collaboration, FY18-19

(only Australian collaboration of 11 total awarded Korea, Japan, UK, Germany, Canada, Israel) – ***DSTG counterparts: Robert Peile, Dennis Delic***

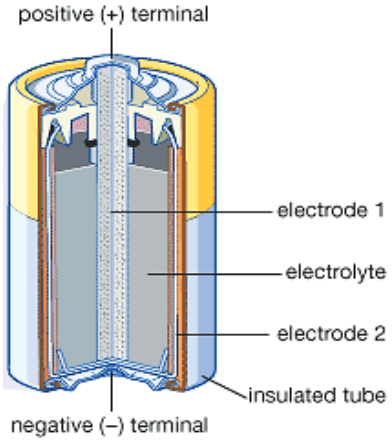


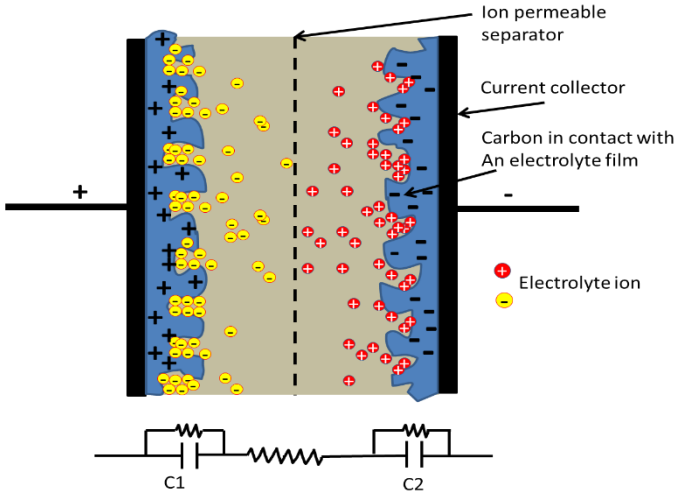


ENERGY STORAGE

BATTERIES

- High energy density
- Highly reactive and hazardous
- Limited cyclability & lifetime
- Low power density





SUPERCAPACITORS

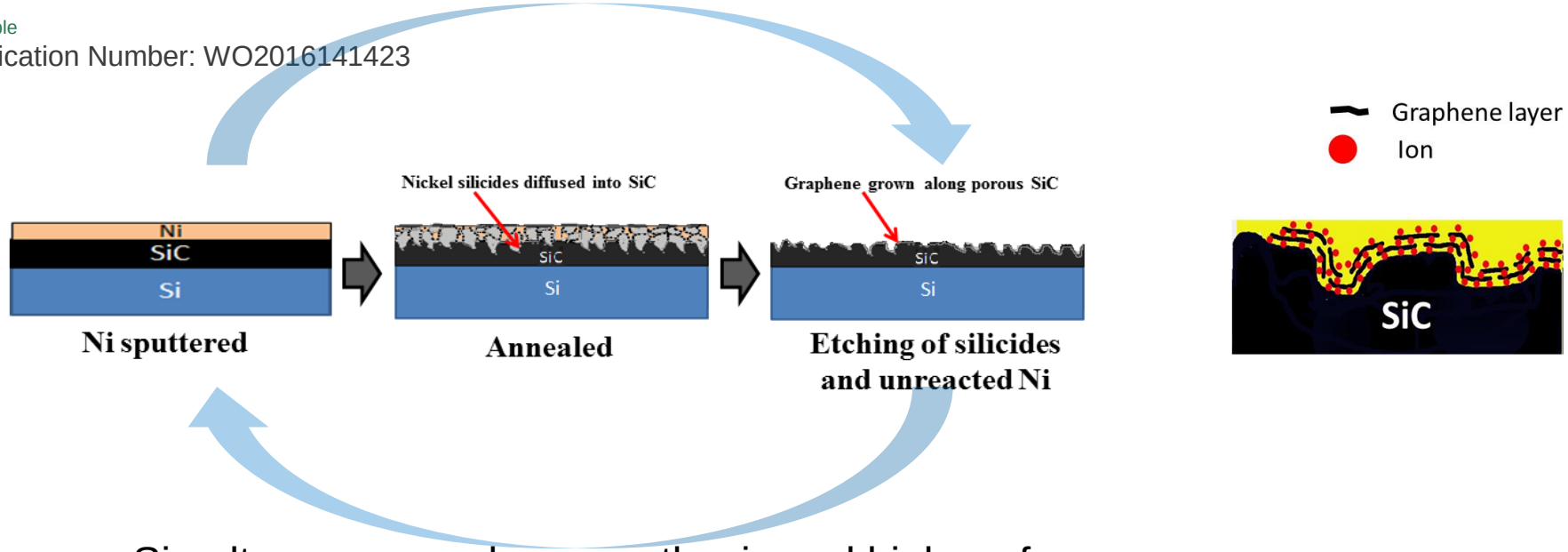
Porous electrode, electrolyte, current collector

- High power density
- Environmentally friendly and lightweight
- High cyclability, long lifetime
- Lower energy density than batteries

ON-SILICON SUPERCAPACITORS CONCEPT

A Method, A Structure, And A Supercapacitor

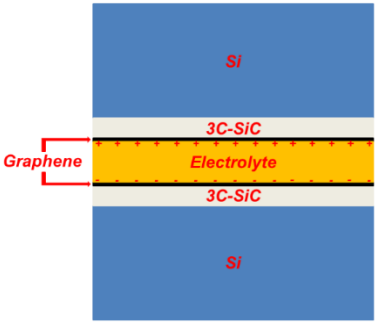
Available
Publication Number: WO2016141423

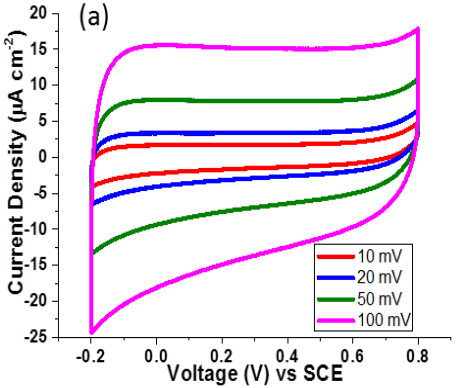


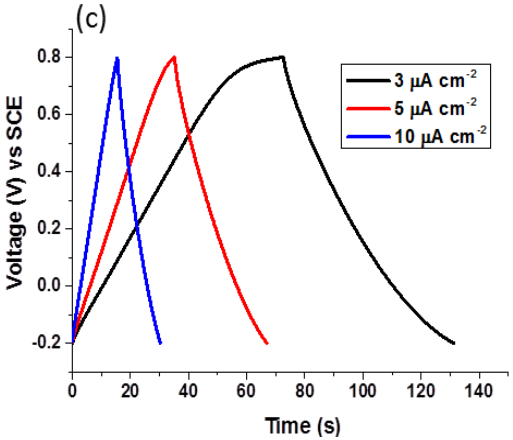
- Simultaneous graphene synthesis and high surface area
- On-wafer, benefits from self-alignment as in previous slides

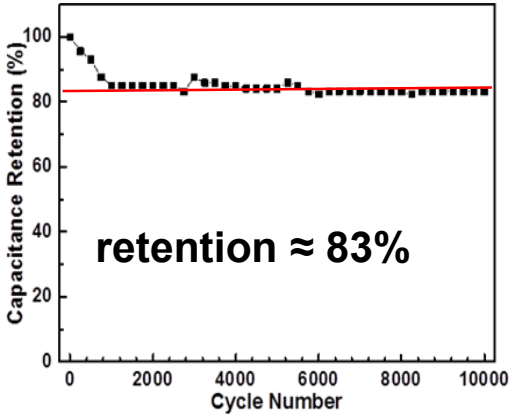
ENHANCED PERFORMANCE

Sandwiched, double-layer capacitor (long ionic path)

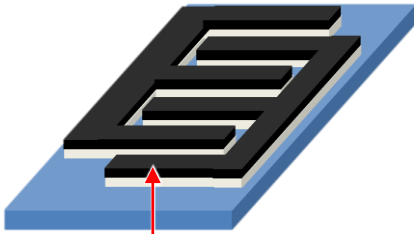




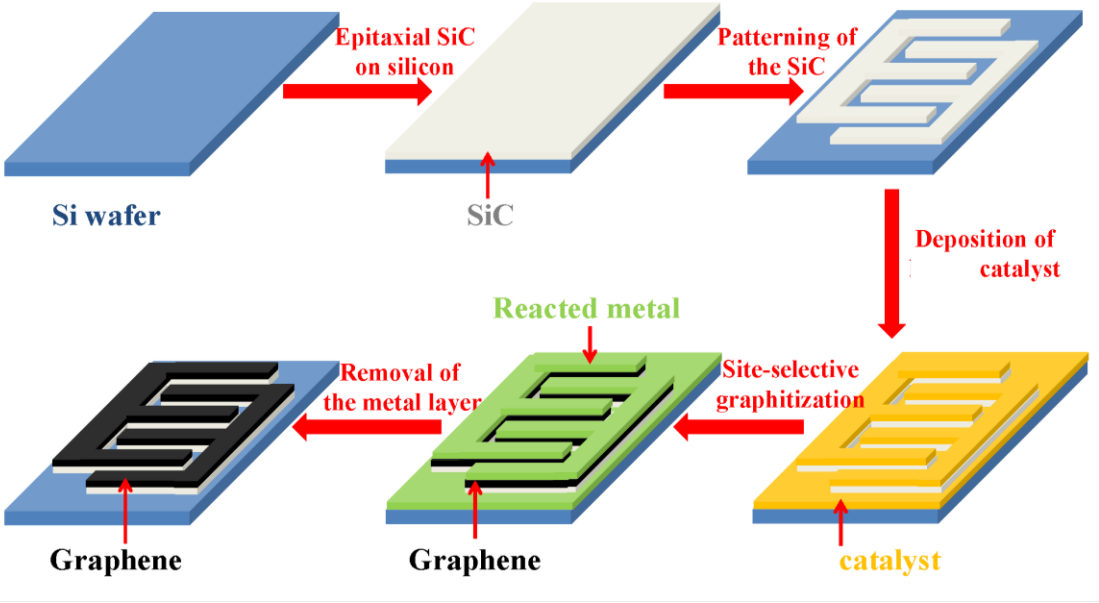




WHAT NEXT? INTEGRATED ENERGY STORAGE



Planar, interdigitated structure: short ionic path (mm ➔ μm)



WHAT NEXT?

- high area capacitance with 3D approach
- fast wireless charging
- high current/voltage operation
- **integrated** supercapacitor/battery solution

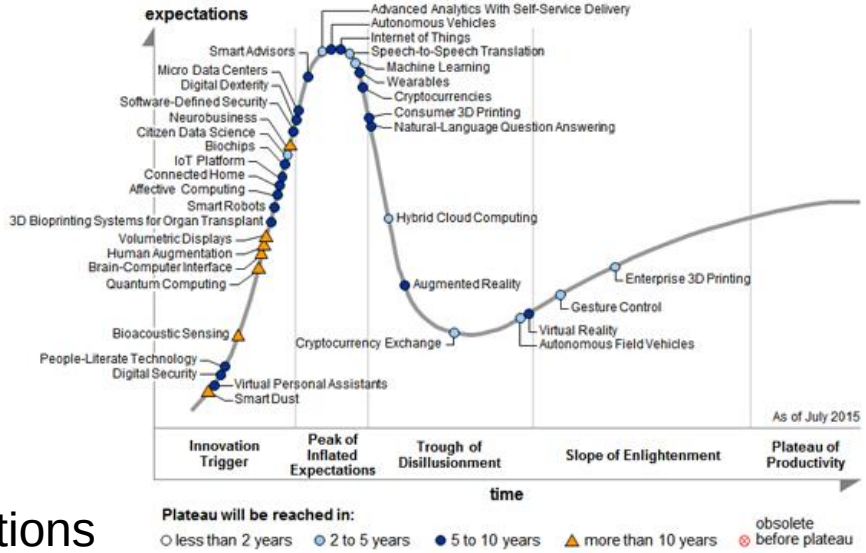
Areas of application:

- Consumer portable electronics, internet of things (sensors, etc),
- Autonomous remote sensing (energy harvester+ energy storage)
- Medical applications (powering endoscopic devices)
- Aerospace harsh-environment applications

HYPE OR HOPE?

Graphene and 2D materials:

new paradigm



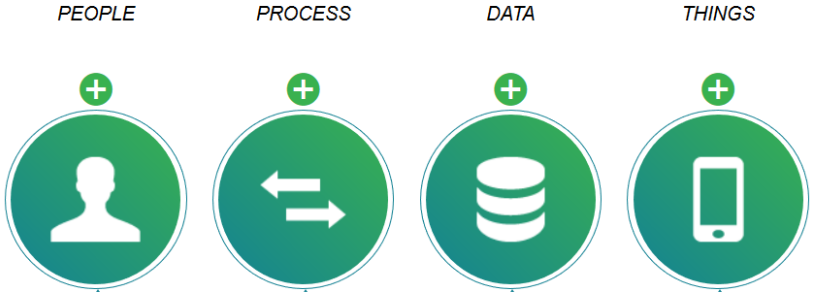
- "Hype" syndrome led to unrealistic expectations
- Typically >10 years needed to embed novel material in a product
- Graphene may take longer: 2D nature requires new concepts
- ***Manufacturability*** and reliability -where our contribution plays key role!

  ➔ low –power consumption devices and integrated energy storage

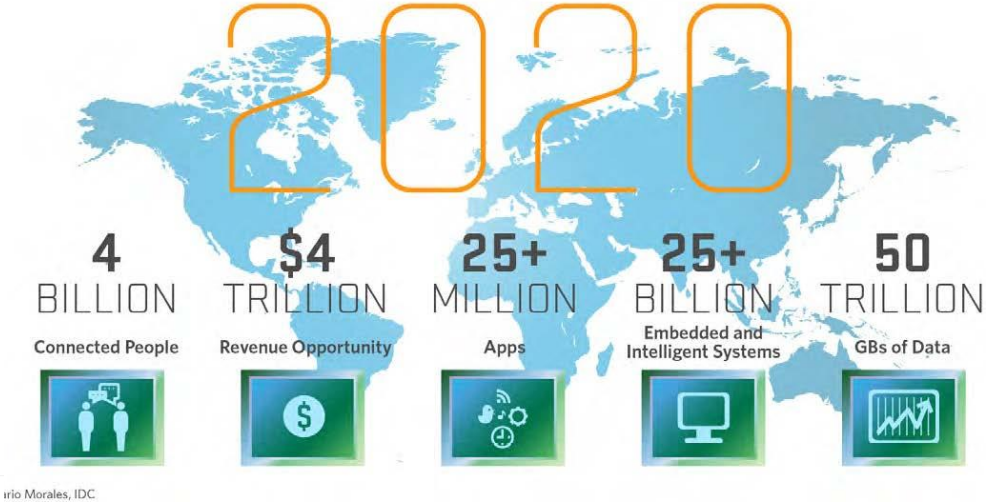
Major innovation @ X-point of Academia, Industry and Defense

INTERNET OF THINGS

The Internet of Everything is the networked connection of people, process, data, and things.



Over the next decade, IoE can help governments create value by saving money, improving effectiveness and productivity, generating new revenue and enhancing citizen benefits.



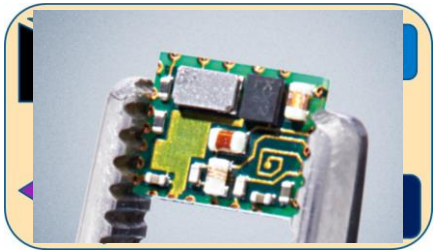
ırio Morales, IDC

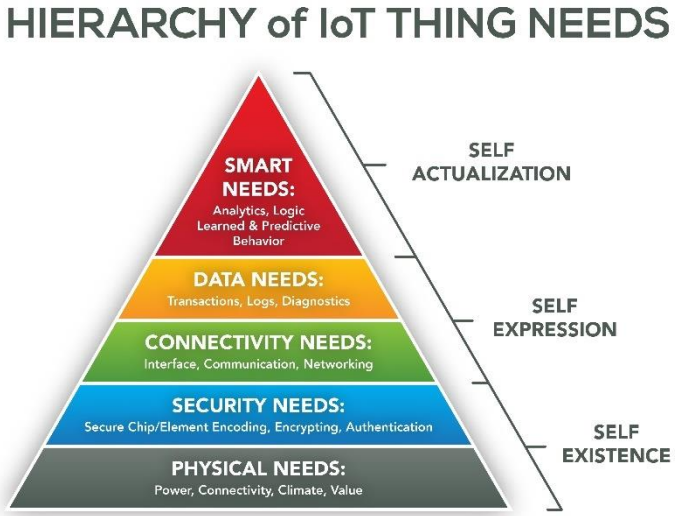
Source: Cisco

INTERNET OF THINGS

Imperatives:

- low power **consumption**
- efficient energy **storage**
- Often **embedded logic**



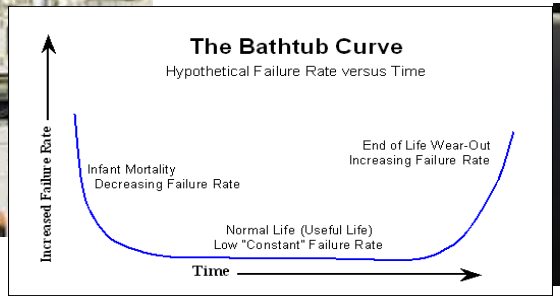


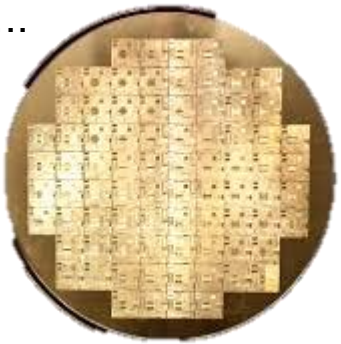
IMPACT BEYOND THE LAB:
AN AUSTRALIAN SEMICONDUCTOR R&D?

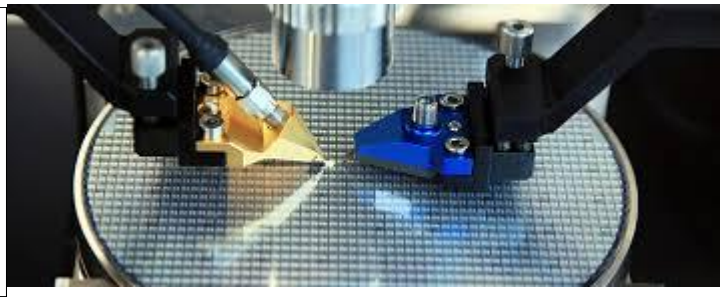
Independent, Sydney -centric serving semiconductor industry, academia, CSIRO, and Defence…..

imec

➔ Down Under?







2D MATERIALS ELSEVIER 2016