



# Graphene Measurement and Standards

Andrew Pollard

National Physical Laboratory (NPL)

[www.npl.co.uk/graphene](http://www.npl.co.uk/graphene)

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# Outline

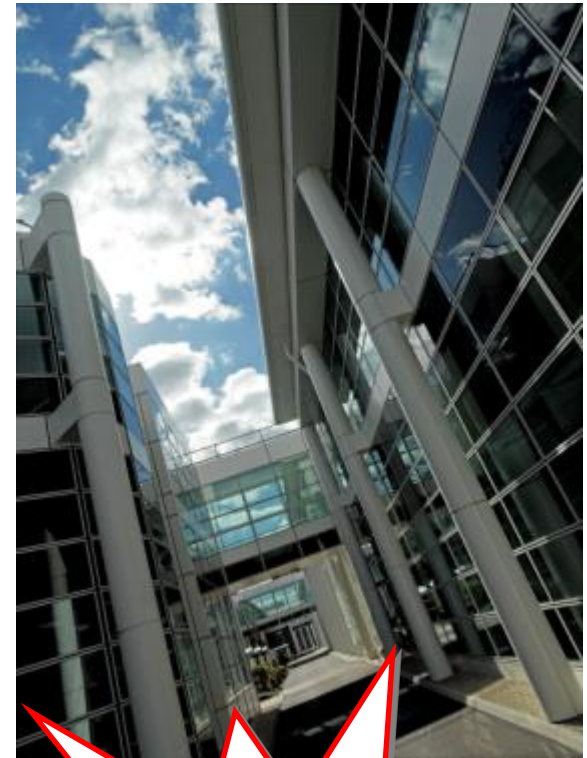
- NPL
- Graphene
- Graphene for Metrology
- Metrology for Graphene and other 2-D materials
- Measurement Techniques
- ISO and IEC Standards
- NIST



# About NPL ...

The UK's national standards laboratory

- Founded in **1900**
- World leading **National Measurement Institute**
- 450+ specialists in **Measurement Science**
- State-of-the-art laboratory facilities
- The heart of the UK's **National Measurement System** to support business and society
- Experts in **Knowledge Transfer**
- **GSA Lifetime Member**
- **Documentation available!**



**35 746 m<sup>2</sup>**  
**388 Laboratories**  
**Purpose built**

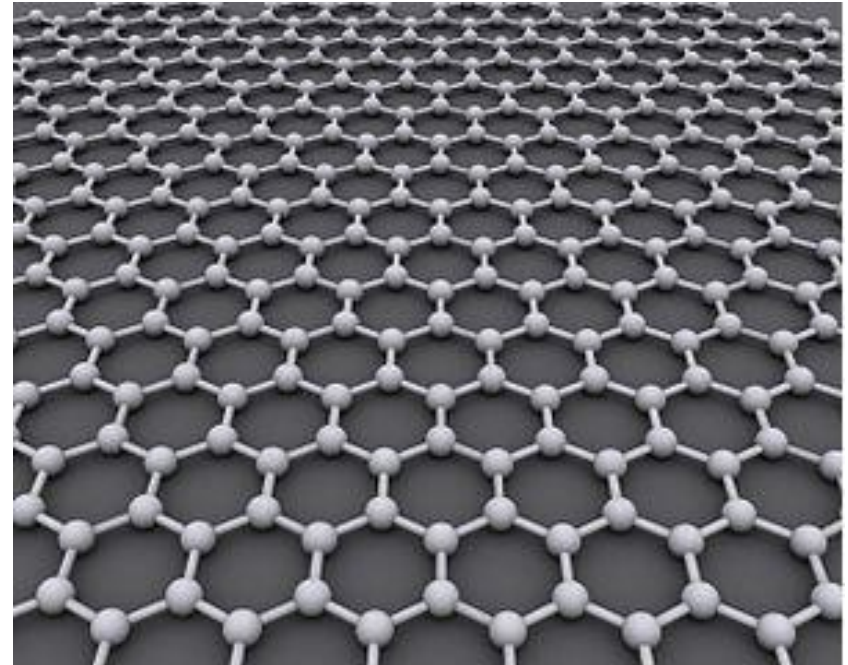
# Graphene

## Some properties:

- 2-D material
- High electron mobility
- Almost transparent
- High thermal conductivity
- Strongest material ever tested
- Bends and stretches

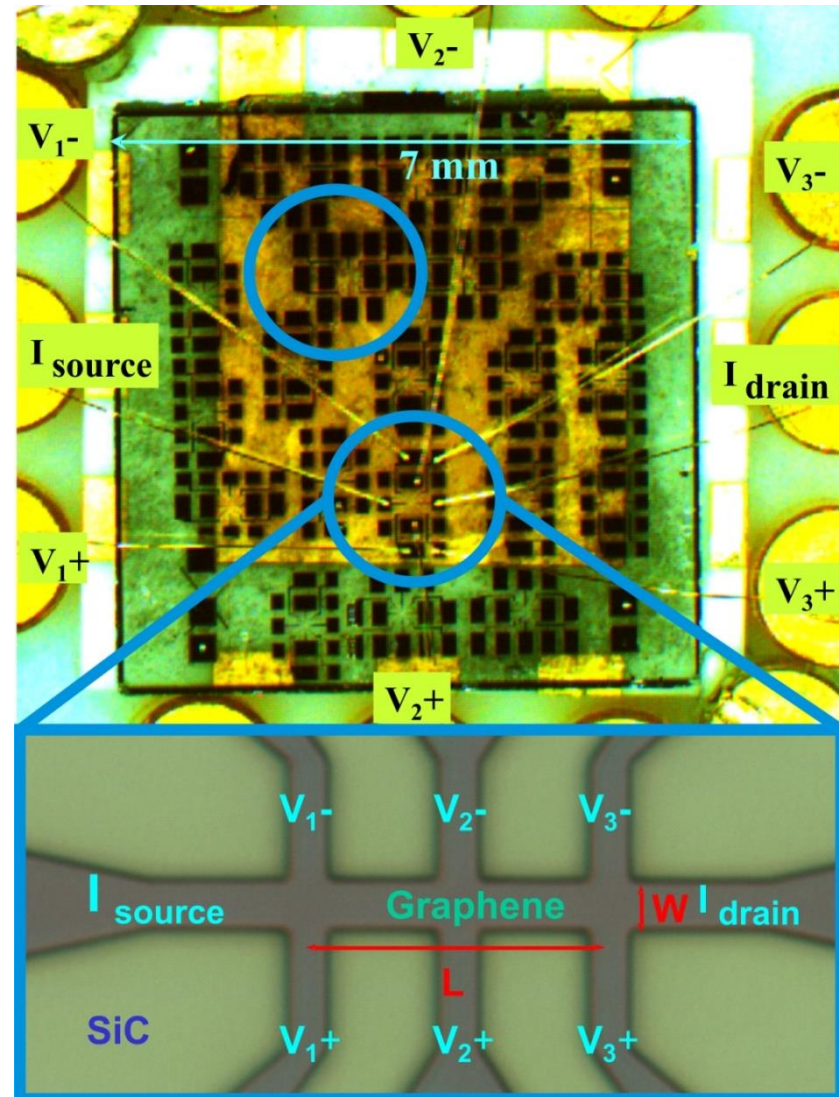
## Possible commercial uses:

- Nanocomposites
- Transparent conductor
- High-frequency graphene electronics
- Sensors
- Energy Storage
- Flexible electronics



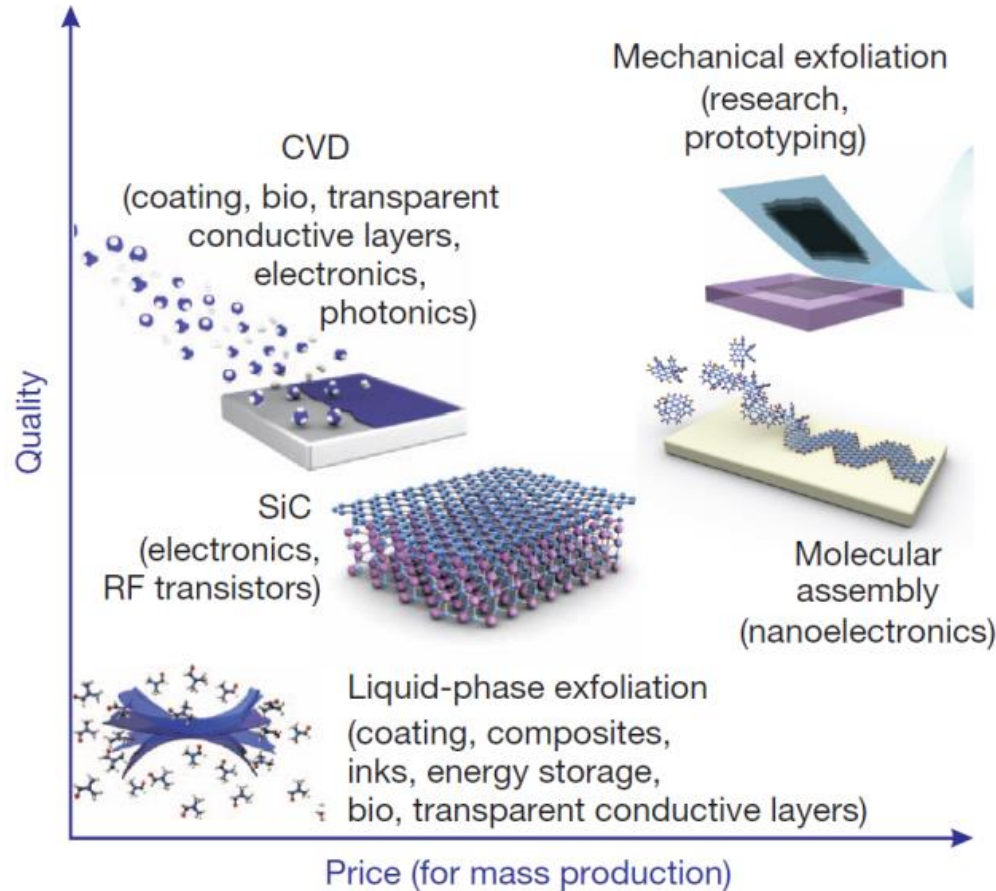
# Graphene for Metrology

- NPL have demonstrated a graphene-based quantum Hall resistance standard for electrical metrology
  - Superior to those based on silicon field-effect transistors and group III-V semiconductors presently used
    - Much longer development history

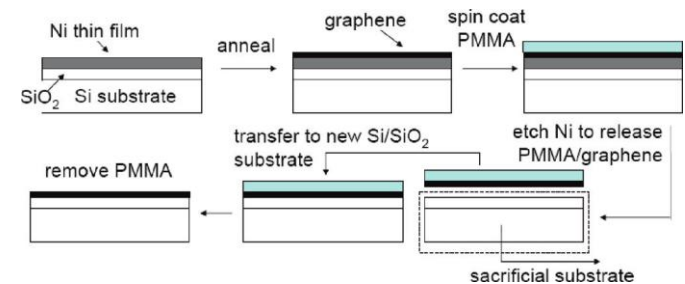


Images courtesy of Prof. Alexander Tzalenchuk  
(A. Tzalenchuk, et al. *Nature Nanotech*, **5**, 186 (2010))

# Graphene Growth



- Scotch Tape
- SiC
- CVD
  - Transferrable
- Nanoribbons
- Liquid phase exfoliation

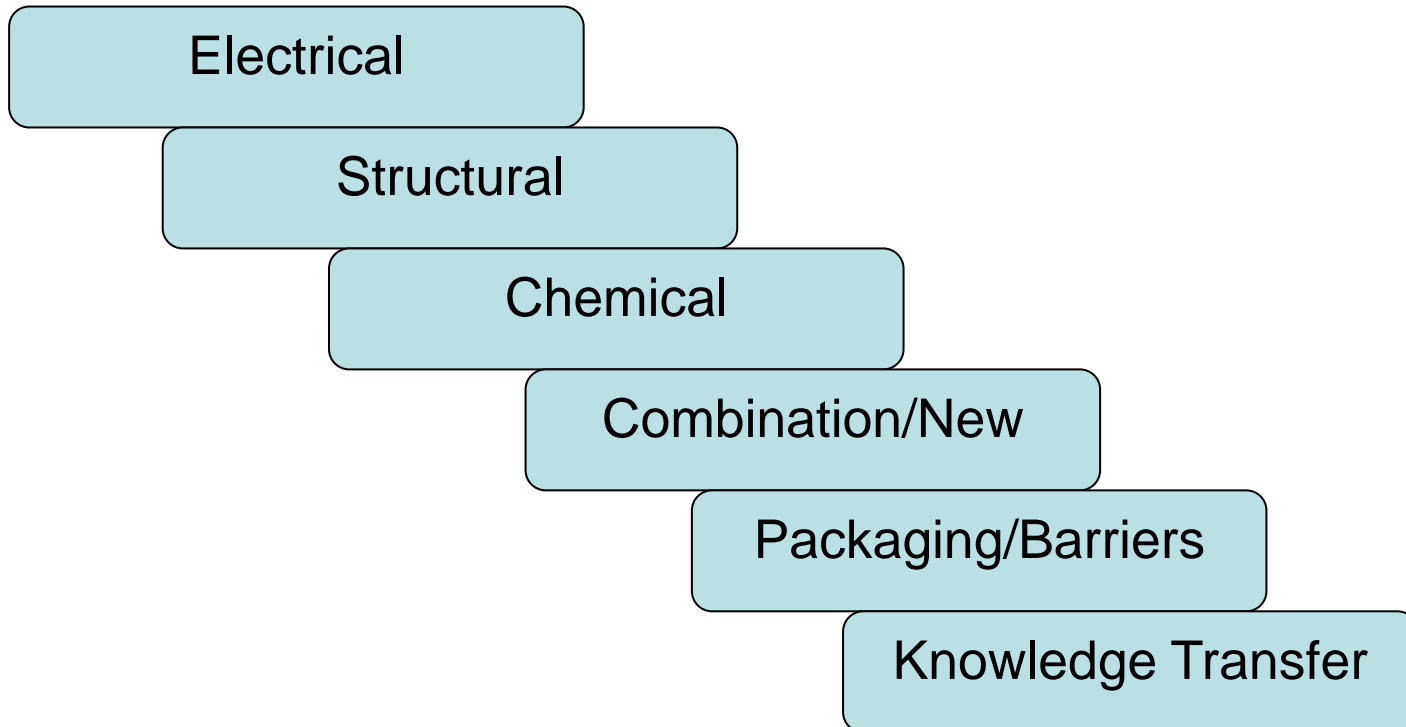


Novoselov *et al.* Nature, **490** 192 (2012)

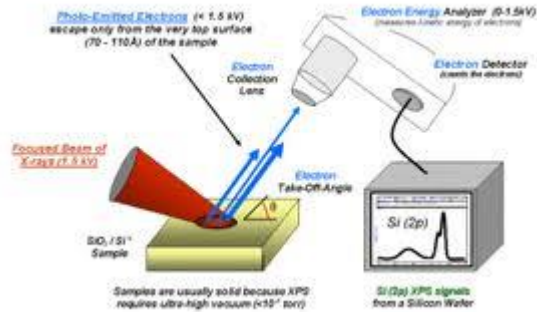
Pollard *et al.* J. Phys. Chem. C, **113** 16567 (2009)

# Metrology for Graphene

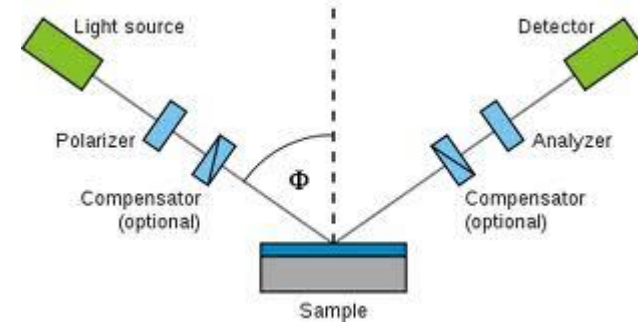
- Develop and understand the application of analytical techniques
  - Graphene, similar 2-D materials and associated devices
  - Benefit from experience in other nanomaterials
  - Characterisation of the material properties
    - Defects, Contamination
- Combination of techniques



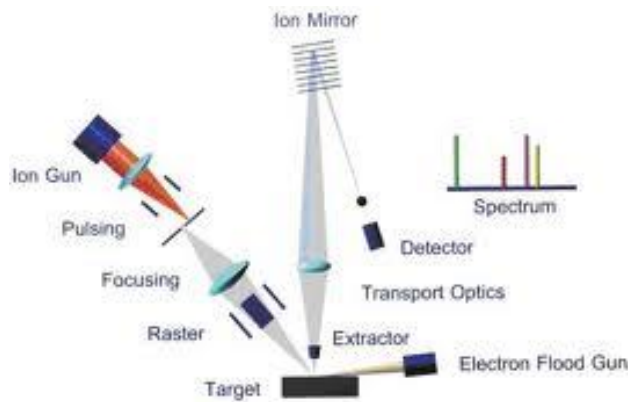
# Measurement Capabilities



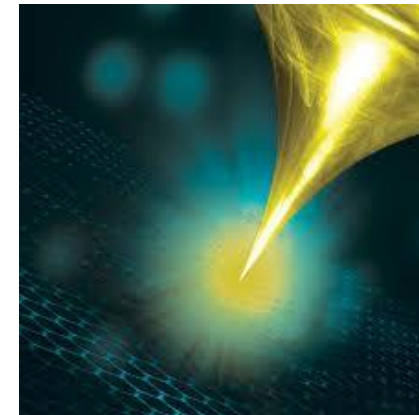
X-ray Photoelectron Spectroscopy (XPS)



Ellipsometry



Secondary Ion Mass Spectroscopy (SIMS)



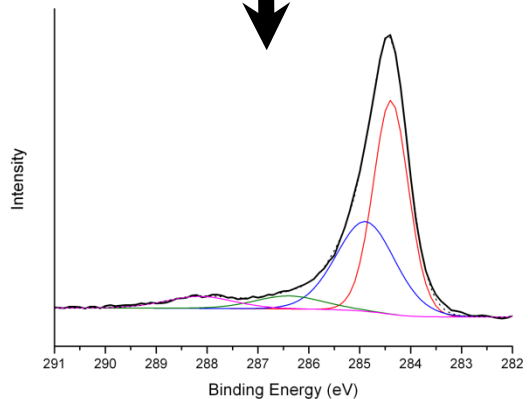
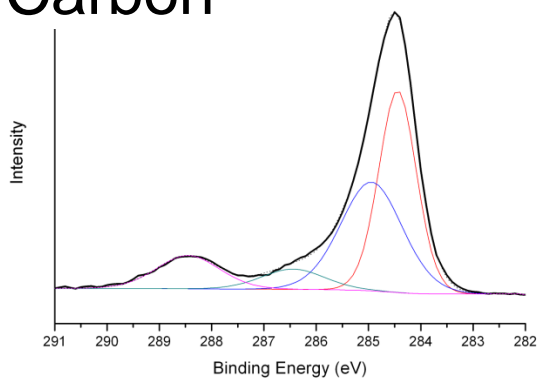
Raman Spectroscopy  
(micro and tip-enhanced)



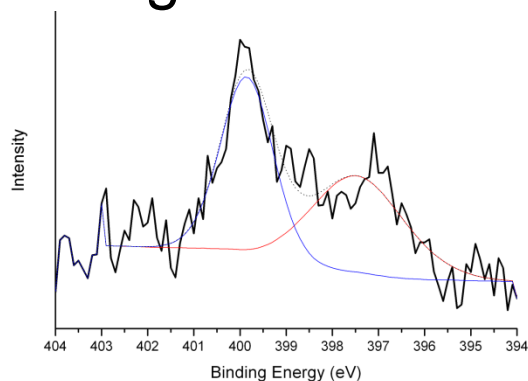
# Measurement Metrology Example

- X-ray Photoelectron Spectroscopy (XPS) of nitrogen-doped graphene on copper

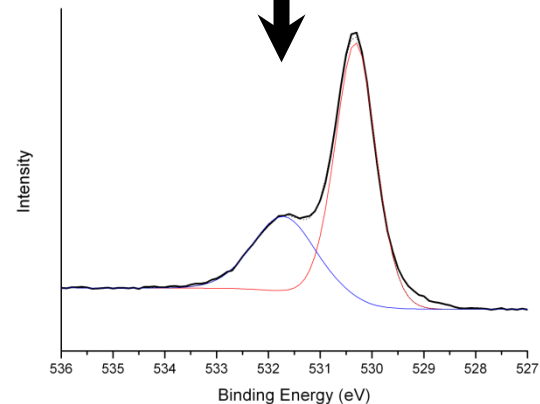
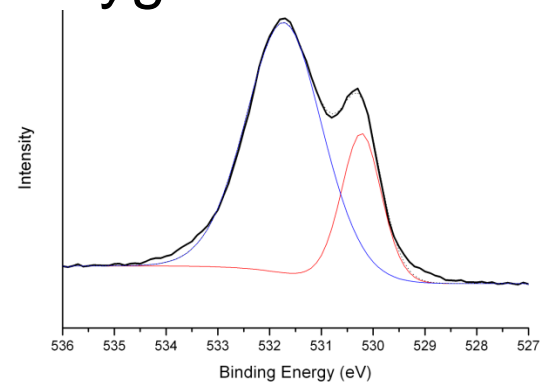
## Carbon



## Nitrogen



## Oxygen



# ISO Standards



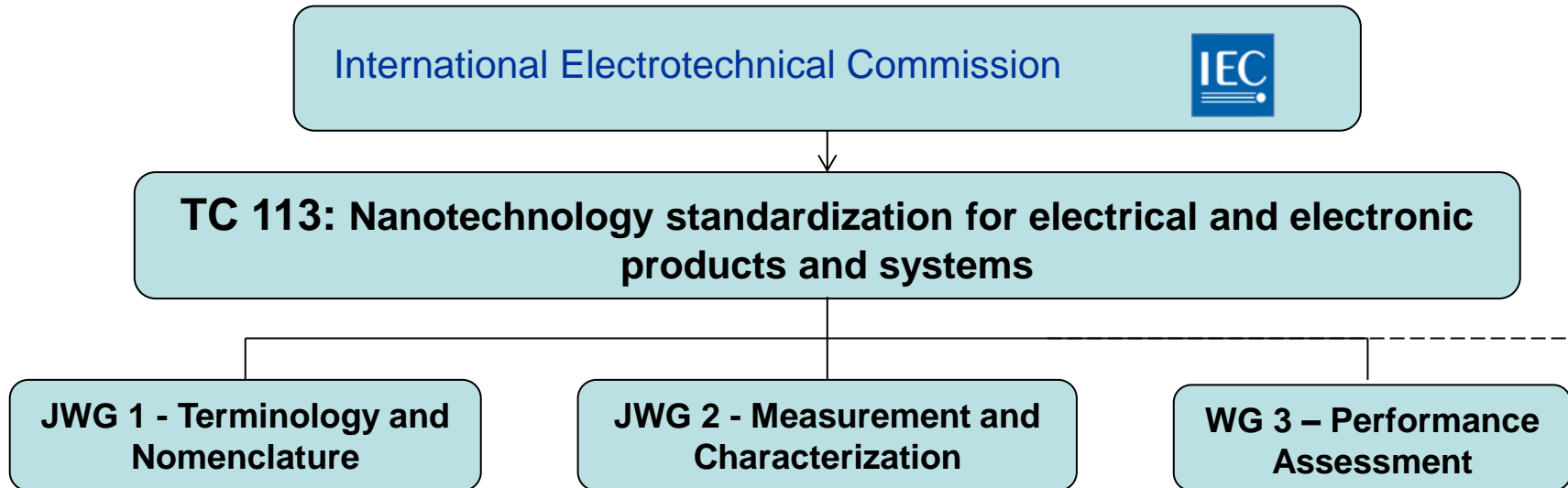
## ISO/TC 229 Nanotechnologies

JWG 1 - Terminology and Nomenclature

JWG 2 - Measurement and Characterization

- Already highly experienced in difficulties of nanomaterials
- JWG 1: ISO TS 8004 series 'Graphene and other two dimensional materials' terminology standard
  - Nonmenclature – NPL, 2013
- JWG2: Graphene Technical Report
  - How to perform measurements – NIST, KRISS

# IEC Standards



- **PT 62565-3-1** - Graphene Material Specification (IEEE)
- **PT 113-72** - Graphene Material Specification: Nano-ink
- Nanomanufacturing - Key control characteristics - Electrical characterization of graphene
- Nanomanufacturing - Key control characteristics - The method to evaluate the number of layers of graphene
- Nanomanufacturing - Key control characteristics - The method to evaluate the defect level in the graphene layer

# The NIST Approach to Graphene



Resistance and Optical  
Transparency



Physical Standards

ISO TC229  
IEC TC113  
IEEE



Documentary Standards



Measurement Science

# Graphene Research at NIST

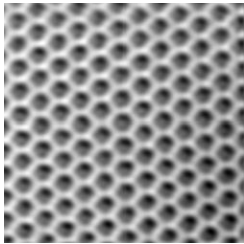
And other carbon structures, i.e nanotubes, graphene oxide



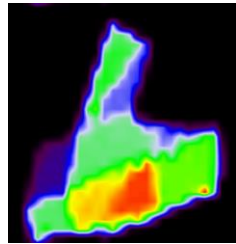
The goal is to develop a measurement suite to enable the use of graphene in a broad range of innovative devices.

## Novel Measurements

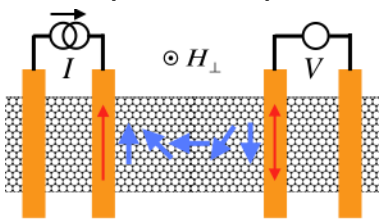
STM: Topography and spectroscopy



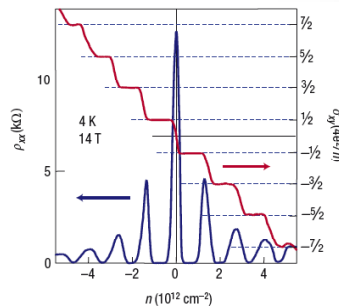
Raman: Map of defects & coupling



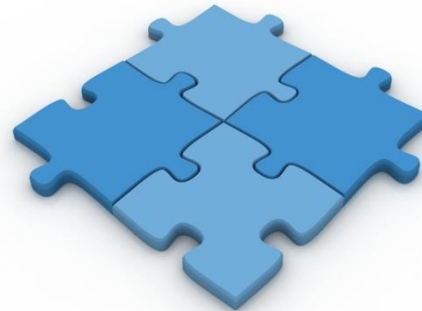
Spin Transport



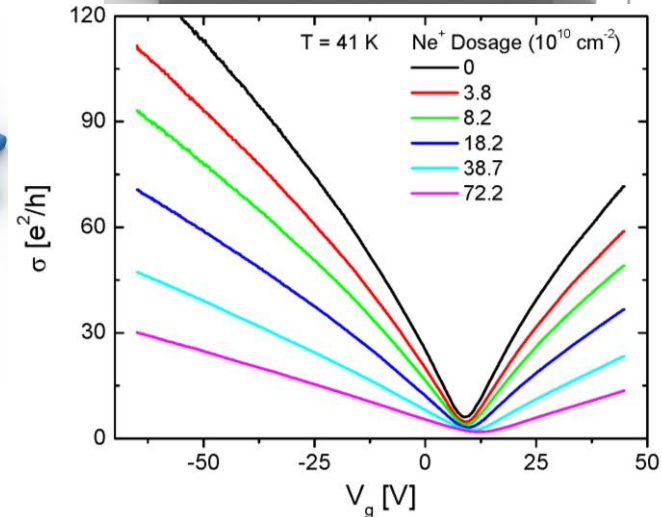
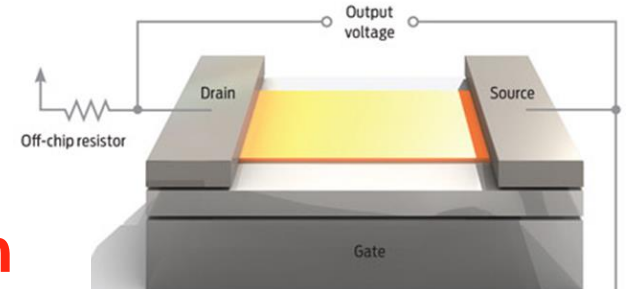
Quantum Hall states



**will be correlated with**



## Device Performance



# Summary

- NPL strategic graphene-metrology initiative
  - Support research, innovation and commercialisation
- Graphene electrical metrology standard
- NPL world-class capability for electrical, structural and chemical characterisation measurement
- International standardisation of graphene as an enabler for industry
- NPL open to collaboration and input

**Dr Andrew Pollard**  
**National Physical Laboratory**  
[andrew.pollard@npl.co.uk](mailto:andrew.pollard@npl.co.uk)  
[www.npl.co.uk/nanoanalysis](http://www.npl.co.uk/nanoanalysis)

