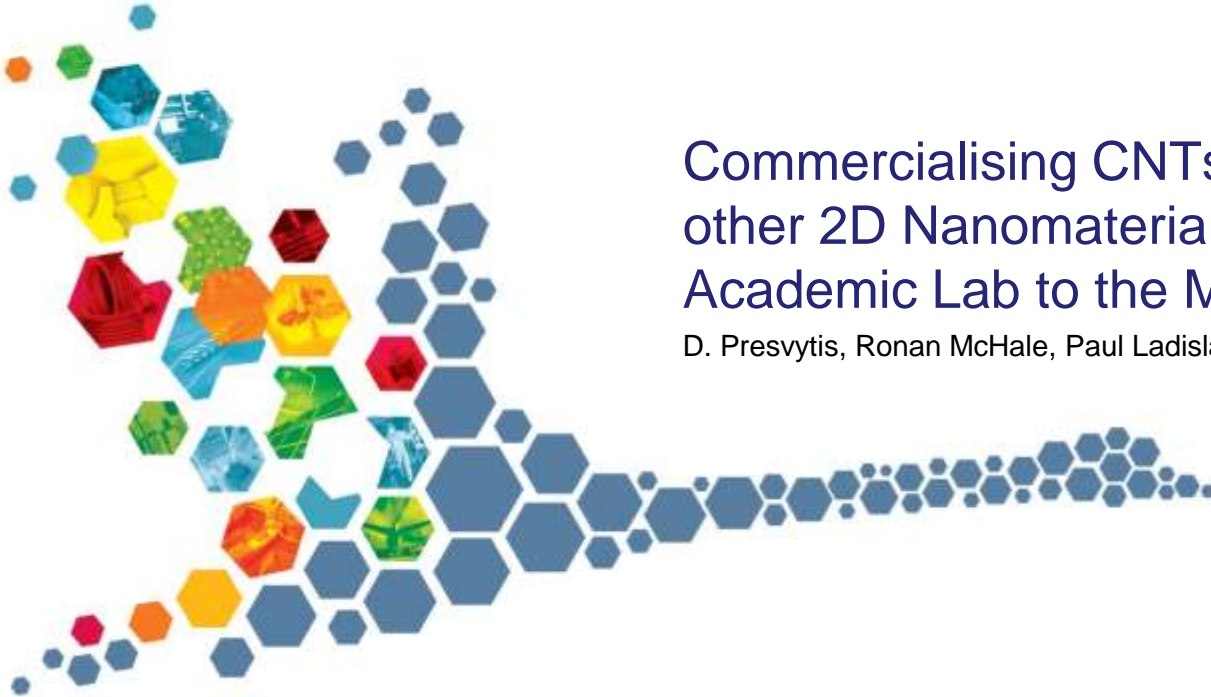


# Commercialising CNTs, Graphene and other 2D Nanomaterials: From the Academic Lab to the Marketplace

D. Presvytis, Ronan McHale, Paul Ladislaus, Andy Goodwin



*Leaders in Performance and  
Speciality Chemicals*

Graphene 2016  
19-22 April 2016, Genova, Italy

# Presentation Outline

- Introduction to Thomas Swan
- Carbon Nanotubes
- The Direct Liquid Exfoliation Process
- Graphene and Boron nitride
- Applications for 2D materials
- Concluding remarks

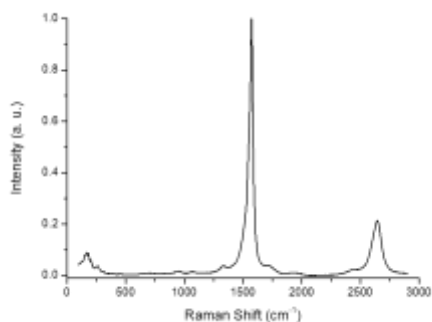
# Thomas Swan & Co. Ltd.

- Independently owned manufacturer of speciality chemicals
- Medium sized enterprise (SME)
  - **165 employees**
  - **£25M (31M €) turnover 2013/14**
  - **UK manufacturing base**
  - **Consett, North East England**
- Export performance
  - **UK/EU/Outside EU**
- Commitment to highest standards

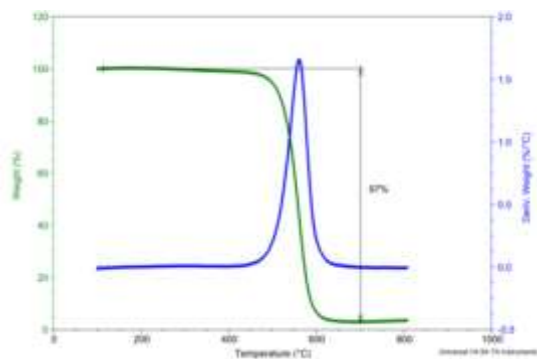


# Elicarb<sup>®</sup> SW products

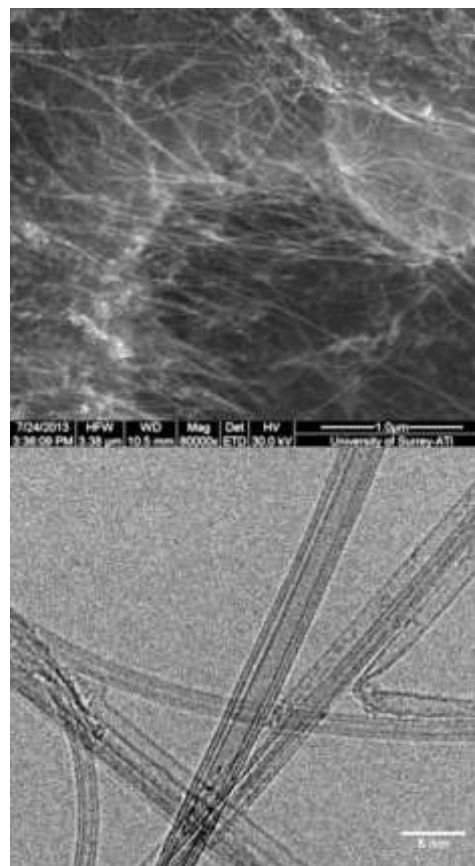
- **Elicarb<sup>®</sup> SW** and **Elicarb<sup>®</sup> SW Low Residue** are market leading SWNT products for advanced electronics.



Raman shows high graphitic carbon content



TGA shows high carbon content



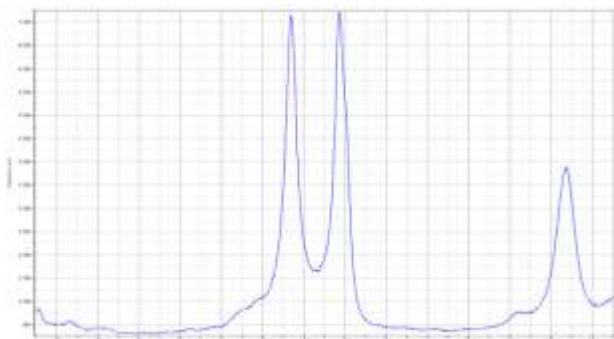
SEM shows high SW carbon nanotube content.

TEM shows high SWNT & DWNT content.

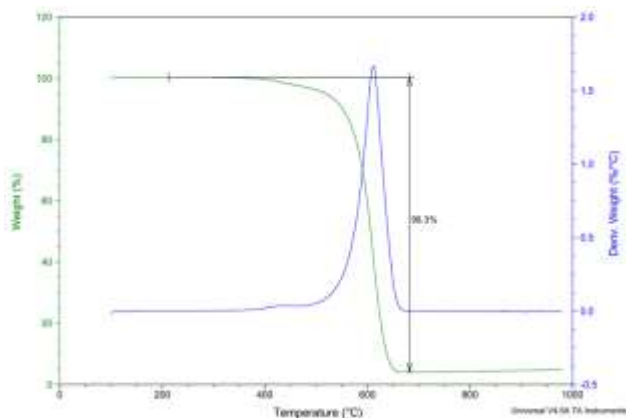
Typical Diameter  
= 2nm

# Elicarb<sup>®</sup> MW products

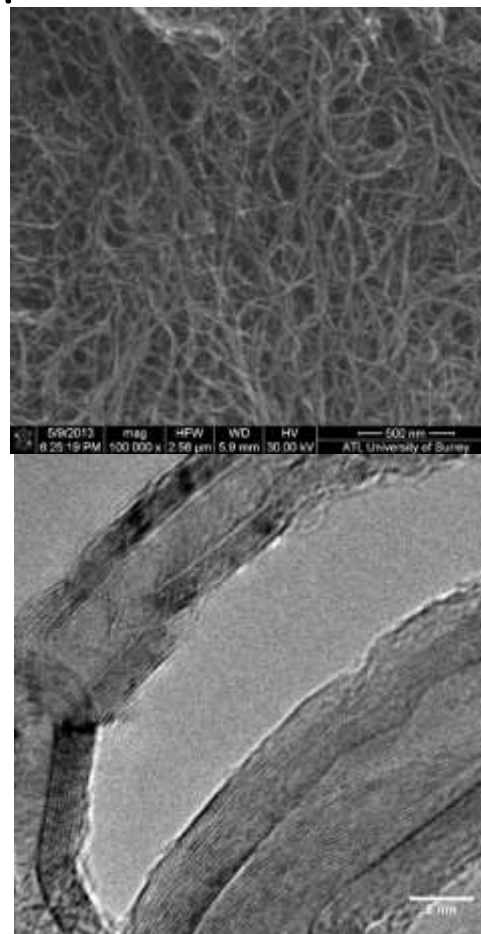
- **Elicarb<sup>®</sup> MW** is a specialist MWNT product which Thomas Swan provides in development & prototyping quantities.



Raman shows typical MW graphitic carbon content



TGA shows high carbon content



SEM shows high MW carbon nanotube content.

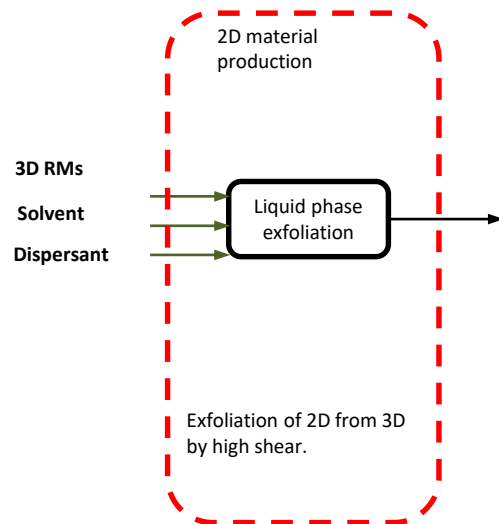
TEM shows multi-wall structure.

Typical Diameter  
=  $11 \pm 2$  nm

# The Direct Liquid Exfoliation Process

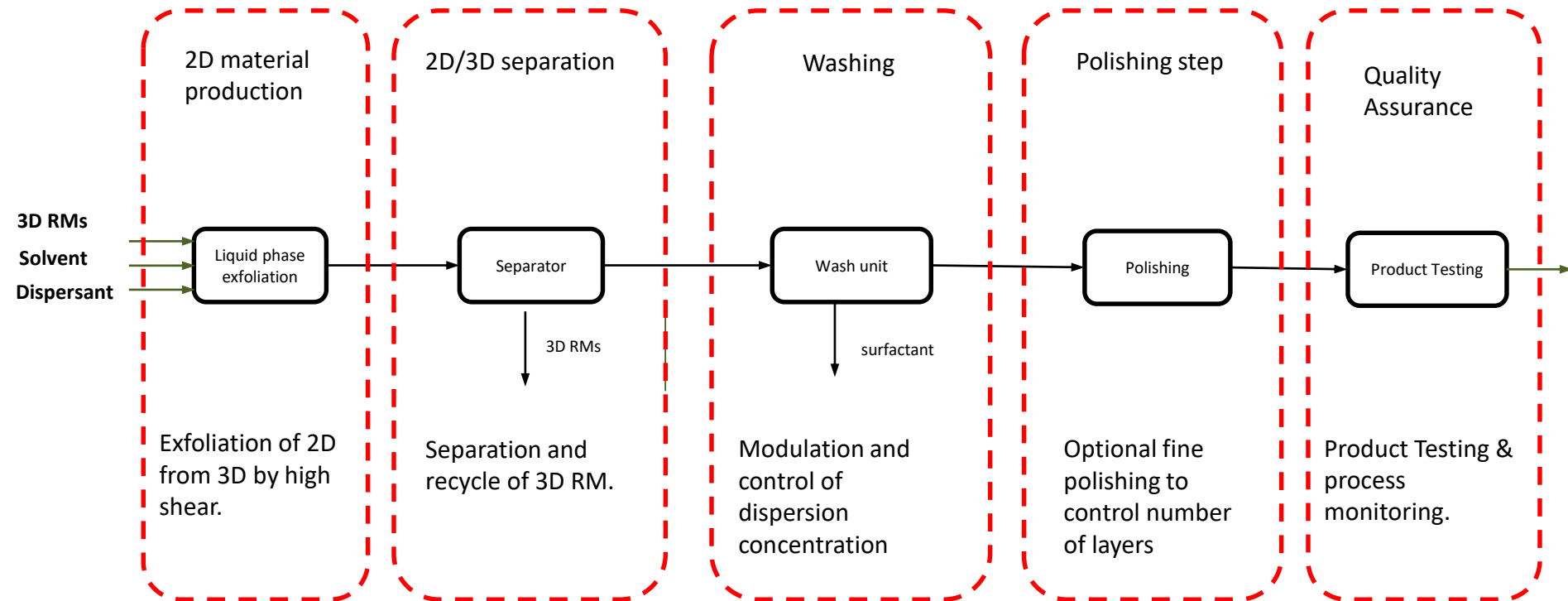
We selected a scalable high shear exfoliation route:

- Ambient conditions.
- No ultra-sonication.
- No aggressive chemistry.
- Range of solvents – including water.
- Range of mineral raw materials.
- Scalable mineral processing.
- Products are stabilised 2D dispersions and powders.



10 kg of “Materials Grade” graphene!

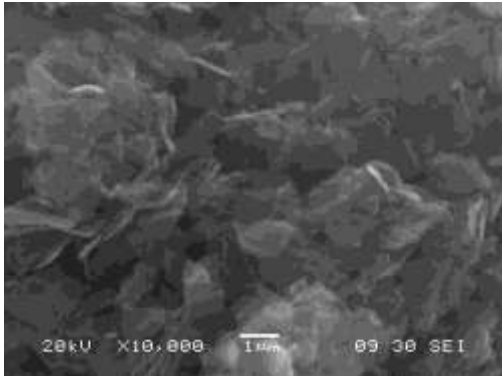
# The Direct Liquid Exfoliation Process



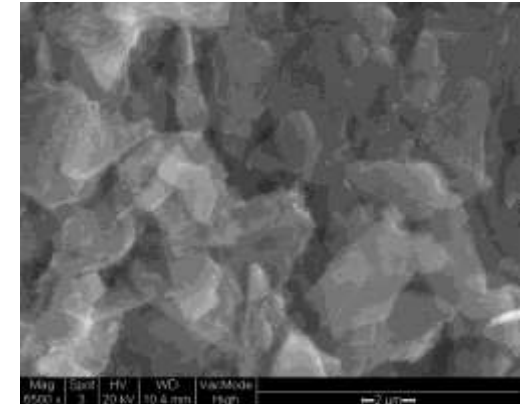
Multi-step tunable process from Few Layer to Multi-layer 2D materials

We are currently upgrading our capability to the order of 15 metric tonnes per year

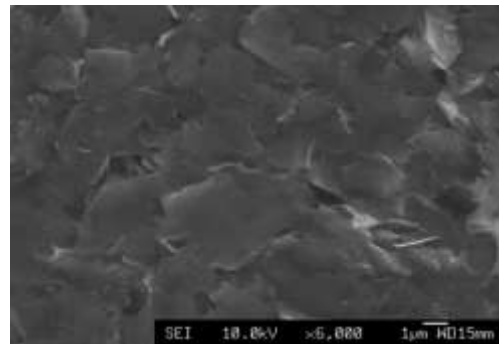
# Thomas Swan Graphene products



**Elicarb® Premium Grade**  
Typically 1-5  $\mu\text{m}$   
D/G 0.2-0.3  
Sheet resistance 5-10  $\Omega/\square$



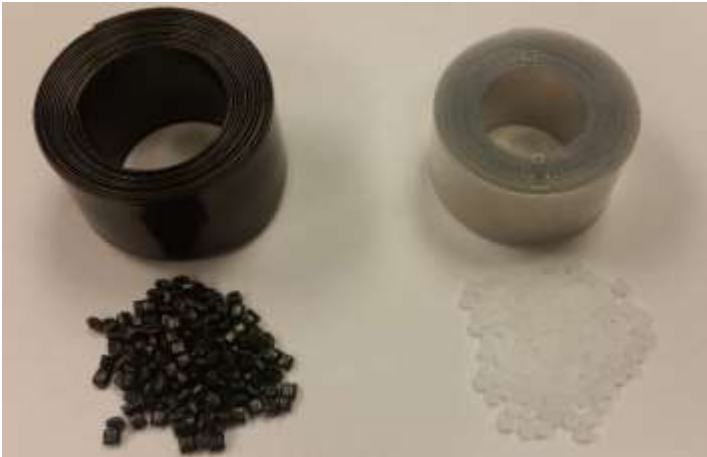
**Elicarb® Materials Grade**  
Typically 1-5  $\mu\text{m}$   
D/G 0.07-0.1  
Sheet resistance <22  $\Omega/\square$



**Elicarb® Electrical Grade**  
Typically 1-3  $\mu\text{m}$   
D/G 0.1-0.2  
Sheet resistance 5-10  $\Omega/\square$



## 2D Materials Applications - Graphene



Graphene containing masterbatch (2% in LDPE)

Extruded in tape form

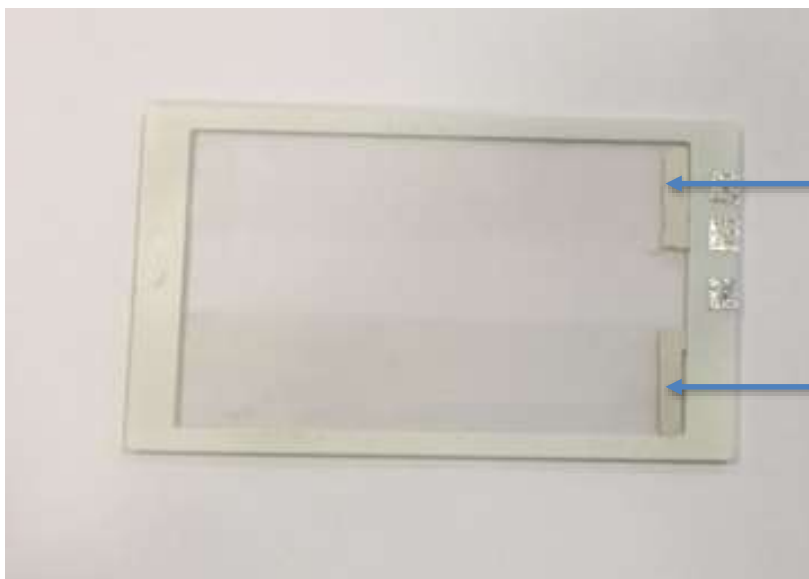
Very easily incorporated into polymer – free flowing powder

**Increased** Young's modulus  
by 16.5%

**Increased** thermal conductivity  
by more than 80%

**Increased** surface resistivity

# 2D Materials Applications - Graphene



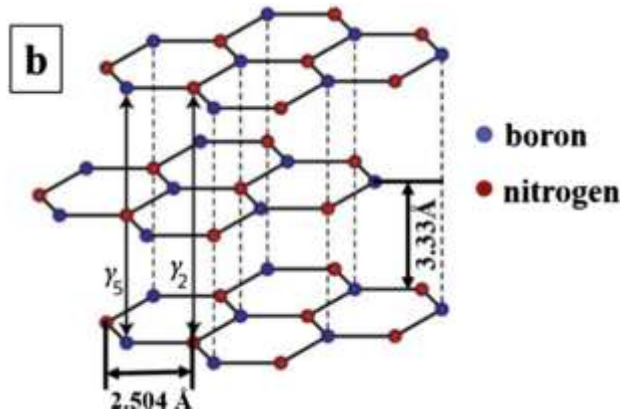
Silver Nanowire electrode

Silver Nanowire/Graphene composite electrode

Graphene composite electrode has lower sheet resistance than Ag nanowire

Courtesy of Prof. Alan Dalton,  
A.B.Dalton@sussex.ac.uk

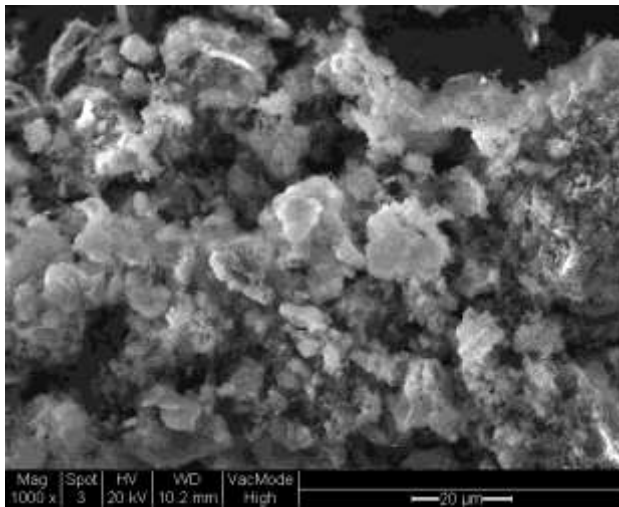
# What is Boron Nitride?



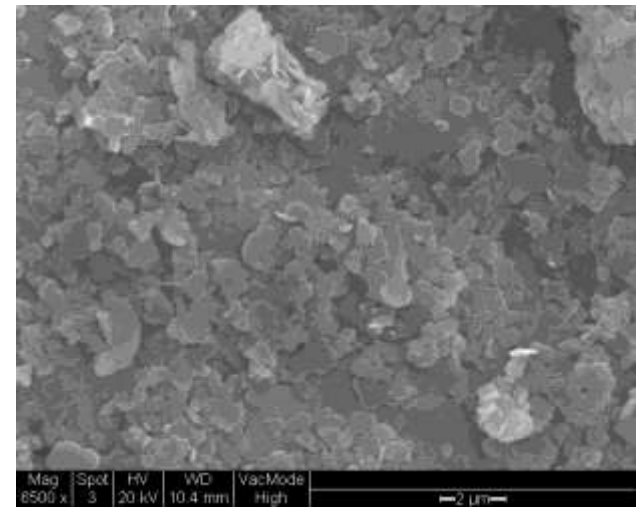
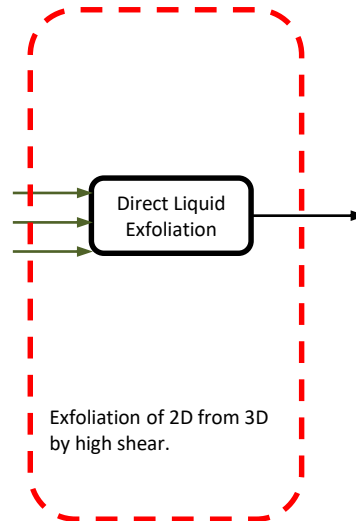
Reprinted from Progress in Materials Science, 73, Gupta et al, Recent development in 2D materials beyond graphene, 44-126, Copyright 2015, with permission from Elsevier

- Synthetic material (not mineral)
- White powder
- Honeycomb structure of alternating B and N atoms
- Dielectric material – B-N bond is ionic
- Ceramic material
- Good oxidation and corrosion resistance
- Very high thermal conductivity

# Thomas Swan Materials Grade h-BN



Starting Material

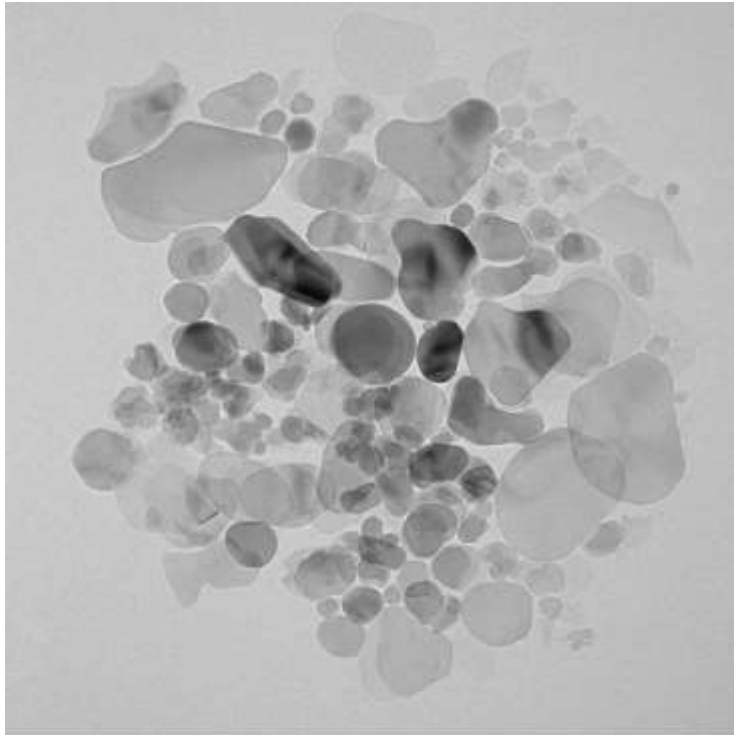


Thomas Swan  
“Materials Grade”  
Boron Nitride



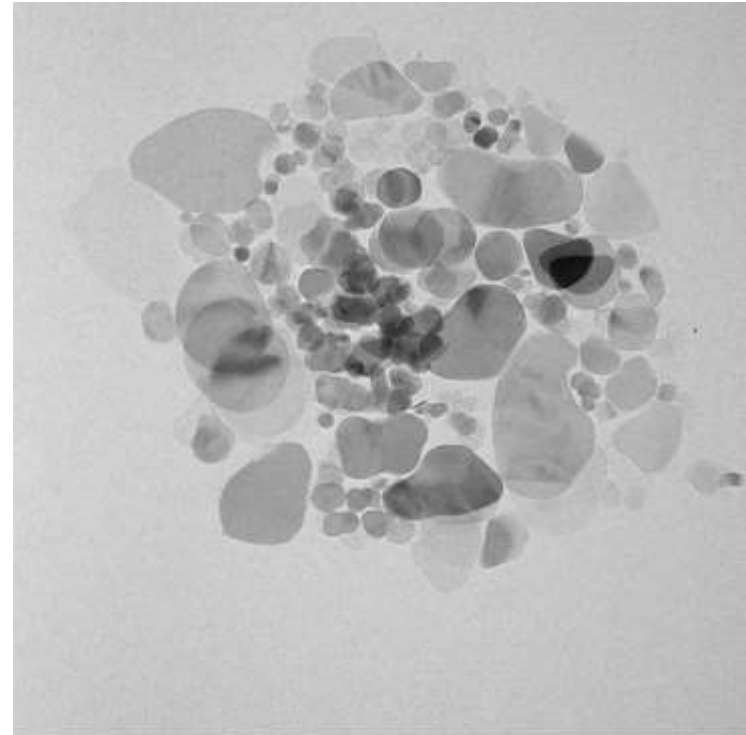
# Thomas Swan Premium Grade BN

## Transmission Electron Microscopy



5\_34kx.tif  
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16:07:24 18/11/15

500 nm  
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EM Research Services

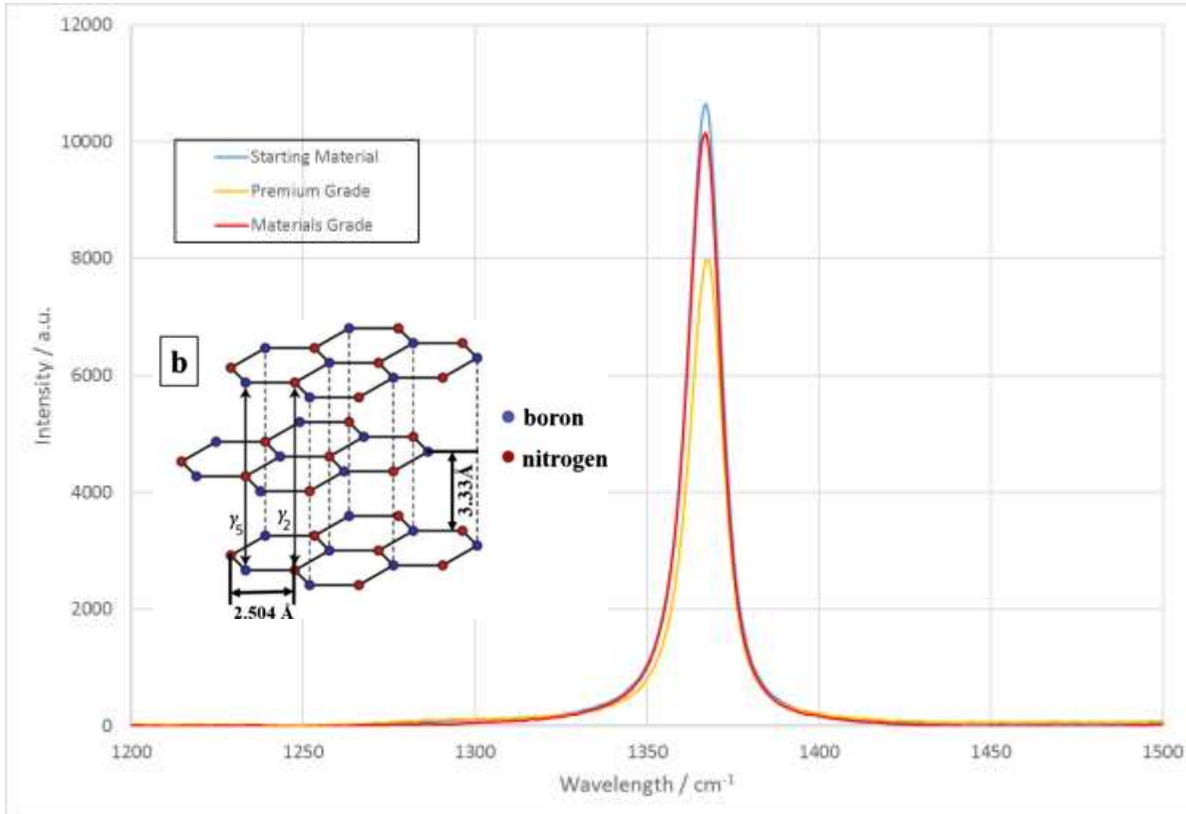


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500 nm  
HV=100.0kV  
Direct Mag: 34000x  
EM Research Services

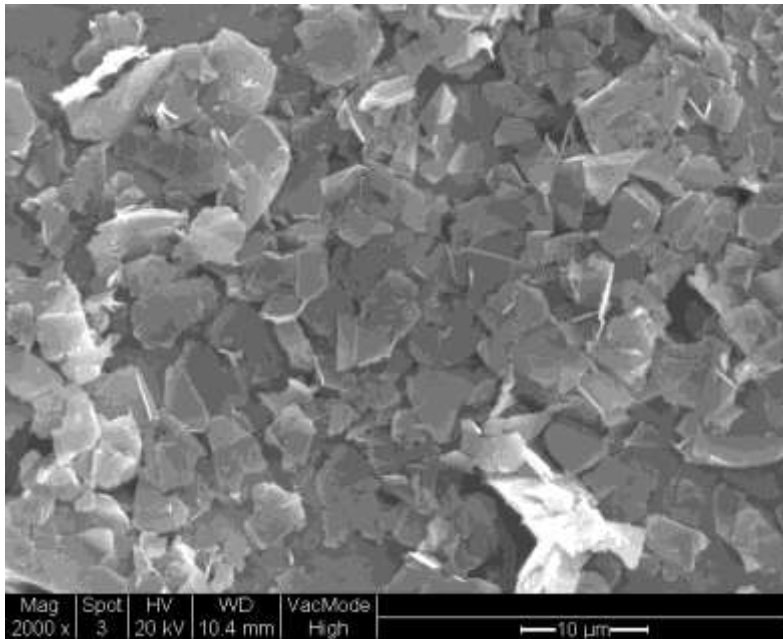
# Thomas Swan Premium Grade BN

## Raman Spectroscopy



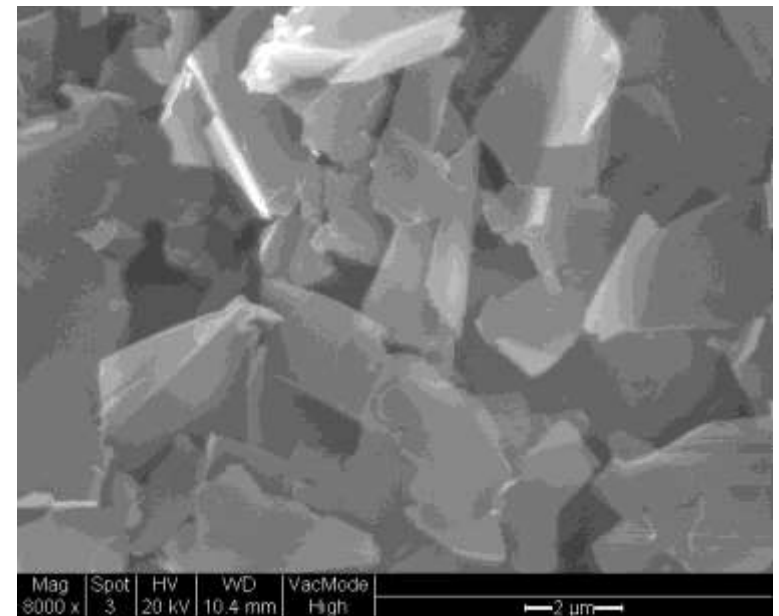
- Peak position in agreement with literature
- Reduction of intensity in agreement with literature
- Peak analogous to G peak in graphene ( $E_{2g}$  phonons), attributed to B-N vibrational mode within h-BN layers (breathing mode)
- For monolayer BN the peak intensity is expected to be 50 times lower than the initial intensity

# Latest development of 2D-BN



Increased lateral size BN platelets 😊

Thomas Swan continues to invest in new product options...



## What's Next from Thomas Swan?

- Continuing collaborative application development with key customers and partners – we want to work with you to support your 2D material needs
- Continuing to scale-up multi-kg supply capabilities for 2D materials
- Application development with UK and EU government grants in electronics and separations
- Product extensions including alternate grades of 2D boron nitride.
- New non-carbon 2D materials – next up is MoS<sub>2</sub>
- Plastic masterbatch products with graphene and 2D boron nitride



# Advanced Materials Division

*Reliability and Quality in carbon nanomaterials*

**Innovate UK**  
Technology Strategy Board



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For further information, visit us at stand no. H16

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**Thomas Swan**  
Chemical manufacturing since 1926