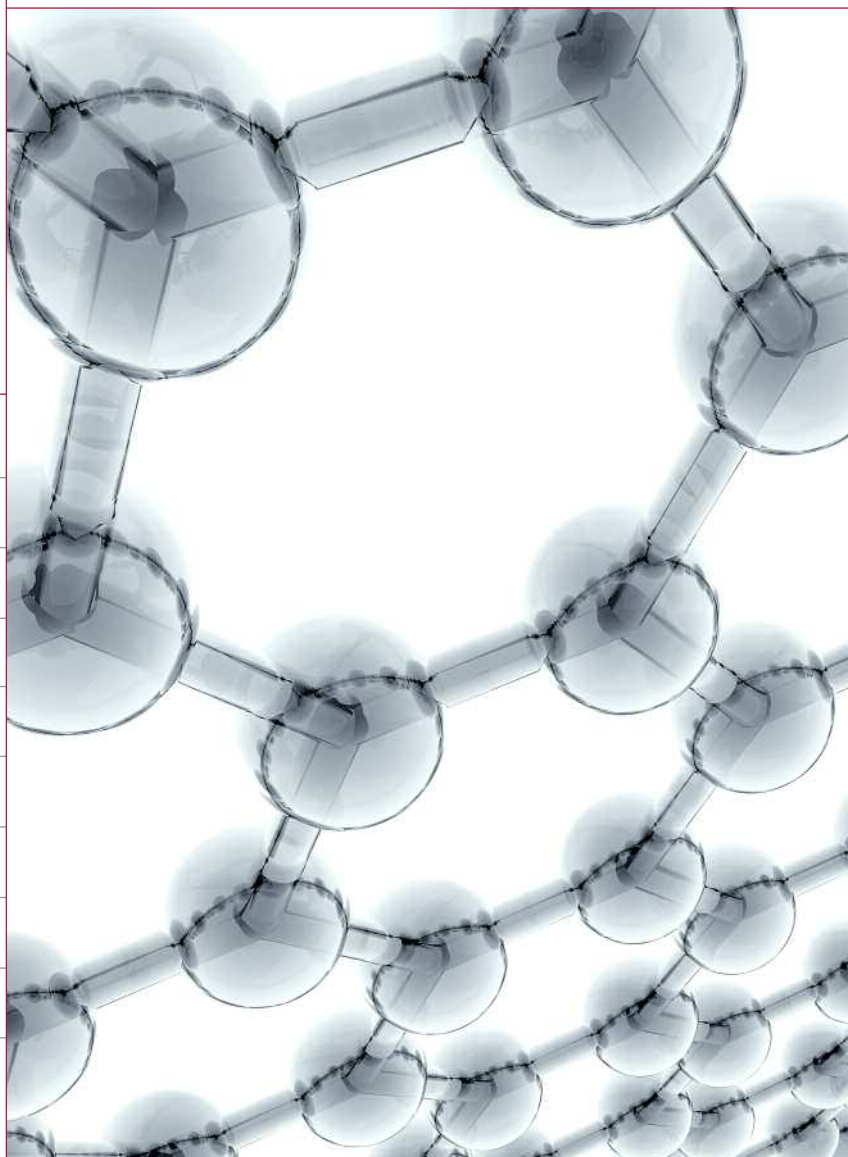


Graphene has attracted considerable funding from government for universities and academic-industry collaborations. The start up sector has been particularly active.



Having had no home-grown opportunity to play the graphene market, by the first half of 2014 investors had the choice of four companies to invest in. Was the stock market too forward looking, or is a dynamic graphene industry in the UK really going to materialise? This report provides an overview of some developments in the industry.

### Manchester hub

The Nobel Prize awarded to Andre Geim and Kostya Novoselev of Manchester University, in 2010, helped to stimulate significant funding by the UK government. Manchester has attracted the largest portion of funds. The government has established The National Graphene Institute within the University, followed more recently by the establishment of the even more ambitious, 'Graphene Engineering Innovation Centre', half of the funding for which was provided by the Masdar Institute in Abu Dhabi. With around 200 graphene researchers already working in and around the University, Manchester stands on a level with the leading centres in the USA and the Far East.



Artist impression of National Graphene Institute, Manchester.

### Companies mentioned in this report:

Advanced Graphene Materials plc:  
Spinout, IPO

Cambridge Graphene Ltd:  
Spinout

Cambridge Nanosystems Ltd:  
Spinout

Haydale Graphene Industries plc:  
SME, IPO

Perpetuus Carbon Ltd:  
Start up

Cientifica plc:  
Start up, IPO

Thomas Swan Ltd:  
SME

2-DTech Ltd:  
Spinout (acquired)

Versarien plc:  
Start up, IPO

Zapgocharger Ltd  
(formerly London Graphene):  
Start up

# Graphene industry overview

## An overview of the emerging graphene industry in the UK

### Cambridge hub

The other major university hub is Cambridge. Here the government has provided funding for a 'Graphene Research Centre' which we featured in Issue 12 of 'inside:technology'. This is taking a more applied approach than Manchester, based on the successful collaborative model pioneered by the Centre for Applied Photonics and Electronics (CAPE) at the University.

### Northeast hub

A third centre of excellence is being established in the north-east of England which is already home to a strong chemicals industry. Here the government has provided funding to establish a 'Graphene Applications Centre' at the Centre for Process Innovation (CPI), located next to the former ICI petrochemical plant at Wilton.

### Former Soviet contribution

There are, as well, several other important academic centres undertaking leading research in graphene; these include: Lancaster, Exeter, Bath, Imperial College, Oxford and Durham. These are part of what the government calls the, 'UK Global Science Hub for Graphene Research'. A fact to note is that many key members of these research groups are former Soviet scientists who emigrated to the UK, including the Nobel Prize winners, Andre Geim and Kostya Novoselev.

### Graphene Clusters

The four primary centres in the UK:

#### Manchester

- The National Graphene Institute, which has an emphasis on fundamental research, based on the work of the University's Condensed Matter Research Group.
- The Graphene Engineering Innovation Centre which will help translate research into industry.
- Graphene Industries Ltd., an early spinout from the University set up to supply high quality graphene to the research community.
- 2-DTech, spinout from the University, acquired by a UK materials company, Versarien plc. The R&D remains in Manchester.
- Bluestone Global Tech Inc., a US graphene producer which has established its European manufacturing base in Manchester.

#### Cambridge

- The Cambridge Graphene Centre, which is designed around industry collaboration.
- Nokia Cambridge Laboratories, which has its materials research activity located in Cambridge.
- Aixtron Cambridge [see Issue 10 of 'inside:technology'] which designs and manufactures graphene production reactors on its site in Cambridge.
- Cambridge Graphene Ltd., which is a spinout from the Centre of Applied Photonics and Electronics at the University.
- Cambridge Nanosystems, which is a spinout from the Materials Science Department of the University.

#### The Northeast

- The Centre for Process Innovation at Wilton which is establishing a Graphene Applications Centre to work alongside other application and process development activities on the site.
- Durham University, which spin out Applied Graphene Materials plc, now listed on the London Stock Exchange AIM section. Applied Graphene Materials is based at Wilton and is expanding its manufacturing on the site.
- Thomas Swan Chemicals Ltd., a privately-owned speciality chemicals company, which is a major supplier of carbon nanotubes and is now building a reputation as a manufacturer of high quality graphene.





# Graphene industry overview

An overview of the emerging graphene industry in the UK

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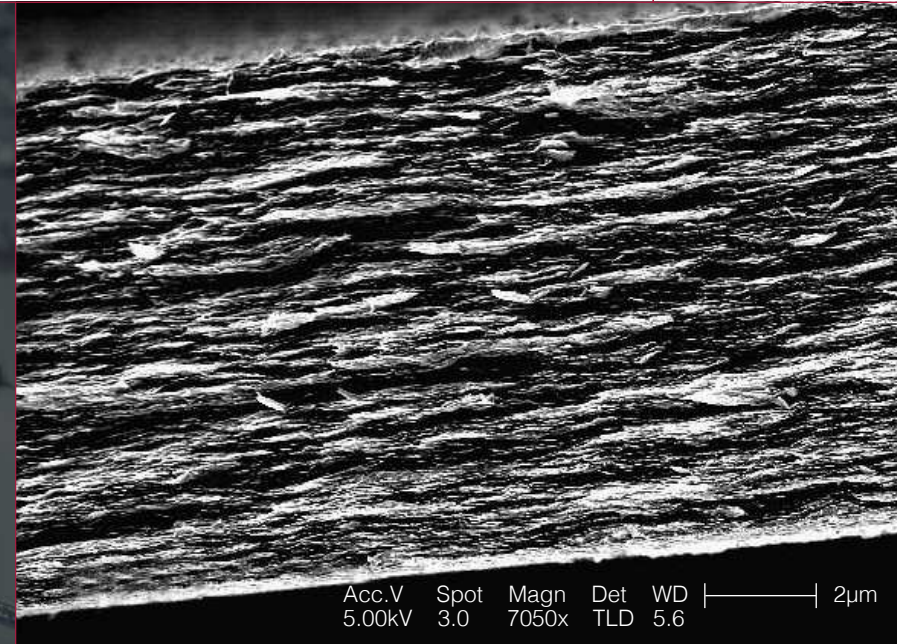
## Graphene Clusters (continued)

### South Wales/West

- University of Swansea's Centre for Printing and Coating, which is supporting local SME Haydale Graphene to formulate, test and evaluate graphene inks and coatings.
- Haydale Graphene Industries plc who have an enabling technology to enhance dispersion into target materials and end applications.
- Perpetuus Carbon Ltd, who have designed a process technology to supply graphene powders.
- Gwent Electronic Materials Ltd, which initially helped Haydale to formulate graphene based inks.
- Versarien plc, based on the Welsh Borders, which acquired Manchester-based 2-DTech and plans to establish the largest graphene production site in the UK.

## Graphene material

The term 'graphene' originally described a single 2-D sheet of carbon atoms. It has gradually been widened to encompass both sheet and flake carbon materials produced by a variety of production methods. Graphene nanoplatelets (GNPs) are an example of flake carbon materials. These materials can be produced by a 'top-down' or 'bottom-up' method. Few layer graphene (FLG) comprises several atomic layers of carbon, and so-called many-layer graphene, or graphene nanoplatelets (GNPs) typically comprise up to 100 layers. Thereafter the material can be described as Graphite.



## Graphene production methods

The Top-Down Exfoliation route is currently the most widely adopted method for the production of larger volumes. Its disadvantage is that it is restricted to batch production and requires many steps to reduce the graphite; it is also prone to leave residual graphite agglomerations, so quality can be an issue.

The Bottom-Up CVD process is relatively expensive because of the need to recover or remove the metal substrate from the final film. It is well suited to the production of films, and it is expected that it can be manufactured using roll-to-roll techniques, which will make it suitable for industrial-scale volume production. Innovations here, include a bottom-up, substrate-free synthesis process developed by Applied Graphene Materials.

Top right; microscopic image of graphene laminate flakes courtesy of 2-DTech Ltd.

# Graphene industry overview

An overview of the emerging graphene industry in the UK

## Applied Graphene Materials:

Est: 2010

Status: AIM listed (2013)

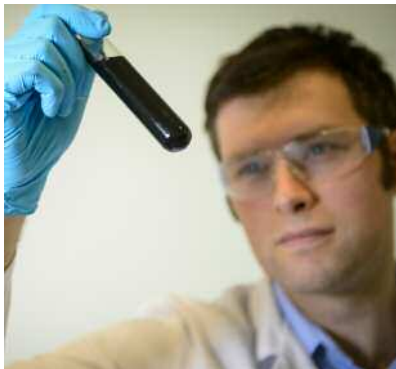
CEO: Jon Mabbitt

Employees: 29

Technology: Bottom-up synthesis of graphene nanoplatelets

Unique point: Graphite-free few-layer graphene readily dispersible in a variety of host matrices

Product: Graphene NanoPlatelets (GNPs) and GNP dispersions



## AGM's method

Applied Graphene Materials' bottom-up process uses an alcohol solution as a source of carbon atoms. The atoms are nebulised in a hot reaction zone, then while in the gas phase, the graphene nanoplatelets self-assemble with no substrate required. AGM states that the advantages of this process are: the feedstock is readily available; the product is free of graphite and transition metal impurities; and it is readily dispersible. The process is also continuous so it lends itself to manufacturing large volumes especially for dispersion in composites, coating and lubricants, and for energy storage applications.



Graphene nanoplatelets in powder form. Images courtesy of AGM Ltd.

Top; research scientist, Andrew Strudwick, working in 2-D Tech's R&D facility.



## 2-DTech

Est: 2012

Status: 85% Versarien plc; 15% Manchester University

CEO: Dr Nigel Salter

Employees: 5

Technology: CVD and Mechanical Exfoliation (milling)

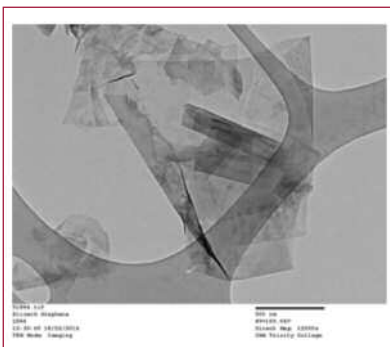
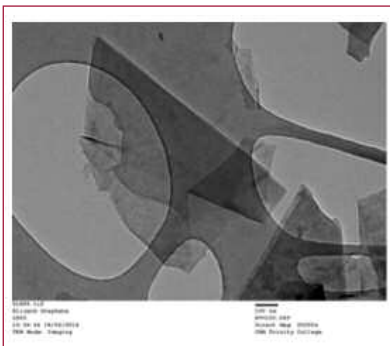
Unique point: High grade analytical capabilities enabled by academic links with Manchester University

Product: High quality CVD Graphene, Graphene Oxide and Graphene Nanoplatelets

## 2-DTech's method

Manchester spinout, 2-DTech, currently produces graphene using a bottom-up CVD process and is in the process of developing a top-down 'milling' process in collaboration with the Universities of Manchester and Ulster. Adding the Top-down approach will give it the flexibility to offer customers either: higher quality graphene using the bottom-up process, or a price-performance trade-off using the top-down milling process. The company's close links to Manchester University gives it access to high-grade analytical tools and expertise which is going to become particularly important as quality standards rise, says its CEO, Nigel Salter.





TEM analysis of Elicarb® Graphene Powder from Thomas Swan showing high quality graphene platelets typical of the liquid exfoliation process.



Elicarb™ graphene nanoplatelets.  
Image copyright Thomas Swan & Co.

### Thomas Swan & Co

Est: 1926

Status: Privately owned

Commercial Director: Dr Andrew Goodwin

Employees: 165

Technology: High shear liquid exfoliation at scale

Unique point: Ability to achieve high volumes of low defect, few layer graphene nanoplatelets

Product: Elicarb® Graphene and Elicarb® Graphene Dispersions

### Thomas Swan's activity

Thomas Swan is a leading manufacturer of carbon nanotubes based in the northeast of England. Working with Trinity College Dublin it has developed an industrially scalable route to manufacture non-oxidised graphene nanoplatelets. Its Elicarb® Graphene Powder and Elicarb® Graphene Dispersion are already available for sample delivery. The company says its liquid exfoliation process produces a material with high conductivity based on reduced-layer graphene nanoplatelets.

### Graphene functionalisation

Haydale Graphene and Perpetuus Carbon, which both have their roots in Swansea, South Wales, have developed ways of adding certain chemicals to the graphene to change the morphology for a particular function. The desired properties of the material can then be enhanced for specific applications.

### Graphene functionalisation

The functionalisation of graphene can be performed by covalent and non-covalent modification techniques (strong or weak forces which either bind atoms together or allow them to be prised open). Surface modification aims to prevent agglomeration and to facilitate the formation of stable dispersions.

### Functionalisation and Dispersion

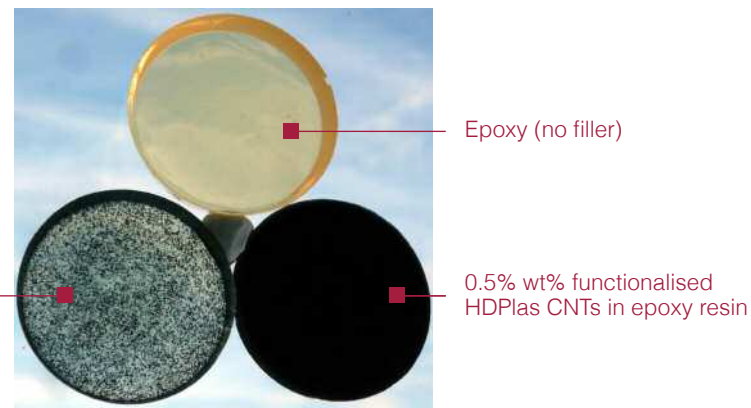


Image courtesy of Haydale Graphene Industries Ltd.

0.5% wt% **NON** functionalised HDPlas CNTs in epoxy resin

Epoxy (no filler)

0.5% wt% functionalised HDPlas CNTs in epoxy resin

# Graphene industry overview

An overview of the emerging graphene industry in the UK



## Haydale Graphene Industries

Est: 2003

Status: AIM listed (2014)

CEO: Ray Gibbs

Employees: 14

Technology: Proprietary plasma process, HDPlas™

Unique point: Supply and functionalisation of a suitable graphene source material, coupled with the appropriate functionalisation for the application required. Functionalised materials independently verified by the National Physical Laboratory in February 2014.

Product: Functionalised graphene



## Haydale's method

Haydale Graphene's technology originated from an idea to use a plasma process to bond recycled rubber crumb and virgin nitrile covalently to make a cost effective floor tile. The company considered that the same process could be applied to carbon nanotubes, and Haydale later applied it to other nano particles such as graphene. A patent is currently under examination and likely to be granted in 2015, but the company points out that much of the IP protection resides in the 'dark arts' of how the process itself is controlled.

## Product development

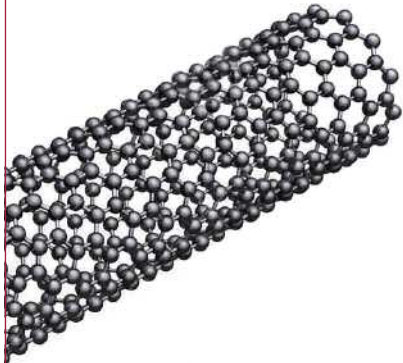
The aim of most of the companies reviewed here is to move up the value chain, from material components to products designed for specific applications. Given as well their limited resources they are more willing to consider collaborative methods of working; for example, specialised materials companies may at times outsource to companies like Haydale when they want to offer their customers a wider range of options for product functionalisation. A key to this "toll processing" is repeatability and flexible production capability.

## Production plans

Company	Amount
Applied Graphene Materials	Completed construction of a 1t/yr reactor in 2014 and has plans to expand capacity by over 10 t/yr by the end of 2015.
Cambridge Nanosystems	Plans to start volume production in 2015 on a site near Cambridge.
2-DTech	Plans to install its first production reactor by the end of 2014 with capacity for 1t/yr.
Thomas Swan	Launched production in October 2014 at an initial scale of 350kg/year.
Haydale Graphene	Second generation reactor commissioned in mid-2014. Two more on order for delivery in December 2014 taking capacity to over 3t/yr.
Perpetuus Carbon	Currently, the only UK company claiming to make graphene in large volumes (10 t/yr as of mid-2014).

# Graphene industry overview

## An overview of the emerging graphene industry in the UK



### Emerging companies

Cambridge Nanosystems is a spinout from Cambridge University which was established to manufacture single walled carbon nanotubes. The research was undertaken originally in Poland. The lead academic, Dr Krzysztof Koziol, decided to establish the company in Cambridge 'because of the unique start-up community'. The plan is to exploit a recently developed bottom-up method of manufacturing high-grade graphene using natural gas as the carbon precursor without the need of a catalyst.

### Downstream companies

Zapgocharger Ltd, who are now based in Oxford, started life in 2013 as London Graphene. Using a novel chemical vapour deposition process licensed from the Materials Science Department at the University of Oxford it is planning to launch a graphene supercapacitor for charging any type of mobile device.

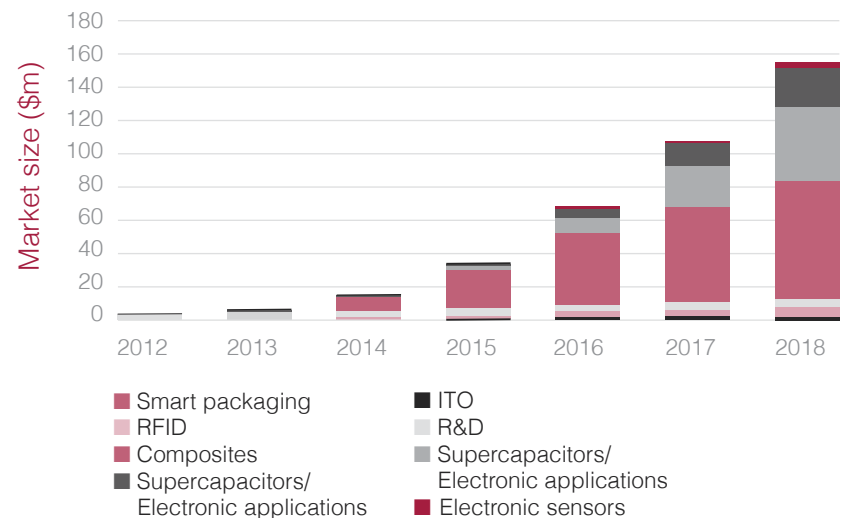
Cientifica plc, based in London, listed on the AIM market earlier in 2014 with a goal to invest in downstream opportunities in graphene. It may be one of the casualties of the mini-graphene boom after the shares were suspended from trading at the end of October 2014.

### Commercial applications

Composite materials is a market where the UK remains strong and is likely to be an early adopter of graphene. Noteworthy therefore is that Haydale recently announced the acquisition of a composites specialist, EPL Composite Solutions, based in Loughborough. Haydale say that having trialled their material both sets of management agree that Haydale's proprietary technology opens up a range of opportunities in the composites world not previously available to EPL.



### Forecast growth of graphene markets



# Graphene industry overview

## An overview of the emerging graphene industry in the UK

The UK government's Technology Strategy Board together with the Engineering and Physical Sciences Research Council (EPSRC) launched a competition in June 2014 called, 'Realising the Graphene Revolution' which will provide up to £2.5m in grants for feasibility studies to accelerate commercial applications.

### Possible applications for graphene:

- structural composites
- conductive fillers, such as for aerospace applications
- sensors
- conductive inks
- conductive layers as, for example, in solar cells, smart windows, antistatic layers, electromagnetic shielding
- barrier coatings for food packaging
- non-copper connects in electronic circuits
- corrosion protection
- transparent electrodes
- rollable e-paper, foldable organic light-emitting diode (OLED) displays, flexible electronics
- electronic devices and touch screens
- electronic high frequency transistors
- thermal heat dissipation in polymers
- electrodes for batteries and super capacitors
- optical photon detectors and ultra-fast lasers
- drug delivery, wound dressings, scaffold for tissue replacement.

Source: Technology Strategy Board, 'Realising the Graphene Revolution'.

### Innovation Nation

The government believes the future of the UK as a manufacturing nation lies increasingly in the combination of new insights from academia (especially in materials), advanced manufacturing processes and novel applications. A good example is the Cambridge University spinout, Plastic Logic Ltd, which has worked with the University to incorporate graphene for the first time in a transistor-based flexible device. It is this combination of university IP and novel application which the government is hoping will retain the UK's position as a leading centre for graphene development. ■

