Institution: The University of Manchester

Unit of Assessment: UoA09 Physics

Title of case study: The impact of the production and characterisation of graphene.

1. Summary of the impact

The isolation and characterisation of graphene by Geim and Novoselov demonstrated its potential to underpin disruptive technological change across an incredibly broad range of industries. This resulted in rapid global uptake of new technologies in the REF period, with at least $200m recent commercial investment in graphene production. Blue-chip companies have also made significant investments leading to the generation of 7740 industrial patents. The first set of graphene-based products has reached the market with revenues already exceeding $10m per month. This commercial activity has been matched by global shifts in public research and innovation funding of at least $2.4bn, as governments have moved to facilitate graphene research and commercialisation.

2. Underpinning research

Research on properties of thin materials was initiated in the UoA in 2001, and resulted in the discovery of a new class of materials – free-standing two-dimensional crystals, including single layers of graphite, boron nitride, several dichalcogenides and complex oxides – by key researchers, Andre Geim (in post 1999 onwards) and Konstantin Novoselov (in post 2001 onwards). Unexpectedly, these atomically thin sheets (essentially gigantic 2D molecules unprotected from the immediate environment) are stable under ambient conditions, exhibit high crystal quality and are continuous on a macroscopic scale. The isolation and characterisation of monolayers of graphite, an allotrope of carbon known as graphene, have opened pathways for a range of applications. Amongst the many research findings are the demonstrations of:

- The feasibility of working with atomically thin films, including metal dichalcogenides, boron nitride and complex oxides and freestanding graphene films [1,2], opening up countless possibilities for many new applications and devices.
- The electric field effect in graphene films [1], showing that transistor operation based on graphene is possible.
- The relativistic behaviour of charge carriers in graphene [3] and of a new kind of Quantum Hall Effect [4], observations of fundamental importance for science.
- The feasibility of graphene as electrodes in liquid crystal devices [5], demonstrating further the practicality of the use of graphene in electronics.
- The observation of fast spin currents in graphene [6], showing that potential for spintronics replacement of electronics for data processing and transfer.

3. References to the research

The award of the Nobel prize in 2010 to Geim and Novoselov is a clear indicator of the quality of the research. Indicative publications from prestigious science journals include the following:

Key References

[1] "*Electric field effect in atomically thin carbon films*" Novoselov K.S., *et al. Science* 306, 666, (2004) doi: 10.1126/science.1102896. (11245 citations on Web of Science 20th Sept 13)

[2] "*Two dimensional atomic crystals*" Novoselov K.S., *et al. Proceedings of the National Academy of Sciences* 102, 10451 (2005) doi: 10.1073/pnas.0502848102. (2082 citations)

[3] "*Two-dimensional gas of massless Dirac fermions in graphene*" Novoselov K.S., *et al.*, *Nature* 438, 197 (2005) doi: 10.1038/nature04233. (5858 citations).

Other References

[4] "Unconventional quantum Hall effect and Berry's phase of 2π in bilayer graphene" Novoselov K.S., et al. Nature Physics 2, 177 (2006) doi: 10.1038/nphys245. (869 citations)

[5] "Graphene-based liquid crystal device" P. Blake, et al. Nano Letters 8, 1704 (2008) doi: 10.1021/nl080649i. (478 citations)

[6] "Giant Nonlocality Near the Dirac Point in Graphene", D. A. Abanin, et al. Science 332, 328 (2011) doi: 10.1126/science.1199595. (43 citations)

4. Details of the impact

The production of graphene and subsequent characterisation of extraordinary thermal, electron transport, mechanical and gas-barrier properties, together with high specific surface area, led to the realisation it could be used in potentially disruptive technologies. The opportunities span an incredibly broad range of applications, including printed electronics, new transistors, super capacitors, transparent conductors, biomedical sensors, automotive batteries, and composites and coatings with enhanced mechanical and electrical performance. Companies have moved rapidly to exploit this potential, with significant investment in both new and existing businesses, new jobs and the first graphene-based products reaching the market. Alongside these economic impacts, there have been significant public policy impacts, with substantial shifts globally in science and innovation budgets.

ECONOMIC IMPACTS

It has been estimated [A] that by 2010, 210 companies globally had made significant corporate investments in bringing graphene and graphene-based products to market – 88 between 2008-10 in the US, Japan, Korea, Germany, UK and China. This activity covers three broad sectors: graphene production, graphene-based technologies, and graphene-based products.

Graphene Production: Demand for graphene has grown rapidly, prompting investment in scaling up and reducing the cost of production. Total graphene output in 2009 was 12 tons, rising to 155-205 tons in 2013 [B (ii)], with a market value of around $10 million. Over 55 companies have entered the sector, with at least 24 formed since 2008. It was estimated in 2011 that there was already $40M invested in small graphene producers [B (iii)]. During the past two years there has been significant investment in scaling up production. As examples: XG Sciences (revenues of $4 million in 2012) have invested $10.5 million to scale-up production from 3 tons to 80 tons pa with staff numbers increasing from 8 to 30 between 2010-12 [C]; Ningbo Morsh Technology have invested $30 million in a 300 ton pa production line in Zheijian Province, China [D]; and Garmor Inc have invested in a 100-ton pa facility in Orlando, with plans to employ 80-100 employees over 5 years [E]. Although financial data is not available for all 55 companies active in the field, these three alone account for recent investments of around $50m, leading to a conservative estimate of at least $200m invested in scaling-up production capacity.

Graphene-based Technologies: Several large multinational companies are known to be active in developing graphene-based technologies, including IBM, Samsung, BASF, Nokia, Sandisk, and Fujitsu [B, F, G]. Although details of the financial investments involved are not available, the scale of activity from these companies can be judged by the volume of associated graphene-related patents. Between 2008-12 7740 patents were published, roughly half by the corporate sector [G]. Continuing investment is exemplified by the 33% growth in the patent family portfolios of the top corporates in the field since 2010.

Graphene-based Products: Graphene-based products have begun to reach the market, for example: HEAD graphene composite tennis racquets, Vorbeck conductive inks, Powerbooster touchscreens, Ovation Polymers ExTimaTM graphene/polymer masterbatch compounds, Bluestone Grat-PowerTM SiGP graphene-enhanced anode materials, and Cabot LITX G700 graphene-based battery additive. Although it can be difficult to obtain commercially sensitive financial information on the investments needed to bring products to market or the resulting sales, we provide three illustrative examples:

- HEAD has an established reputation in hi-tech sports equipment. In 2012, they brought to market a range of graphene-reinforced-composite racquets, exploiting the high specific bonding area characteristics of graphene to achieve a significant advance in strength-to-weight ratio [H]. This allowed the weight of the mid-section of the racquet to be reduced, leading to significant improvements in handling. By late June 2013, the company reported they were on course to sell 200k graphene racquets in 2013 [H]. Retailing for around $150, this equates to a sales value of $30m, at least half of which is likely to have been in the REF period. It is also noted that sales of graphene-based racquets are displacing other racquets that the company markets [H].

- Shanghai-based Powerbooster, working with graphene producers, Bluestone Global Tech, are manufacturing graphene-based touch screens. In a June 2013 online interview with the Wall Street Journal, they reported monthly sales of 2m screens, which translate to revenues of roughly $10m per month [I].
- Vorbeck Materials introduced Vor-ink™, graphene-based conductive ink for printed electronics in 2009. With MeadWestvaco, a global packaging company, they developed a printed anti-theft packaging system that is now used by major US retailers including Home Depot and CVS [J], generating annual revenues for Vorbeck of $1m-$2.4m [K]. To meet customer demand for Vor-ink™, Vorbeck invested in real-estate and equipment in 2012 to increase their production capacity to over 40 tons pa, with further investment in a new production facility opening in late 2013 [L].

POLICY IMPACTS

The isolation and characterisation of graphene also led to significant shifts in science funding policy, with major public investments in graphene research and commercialisation around the globe. A 2011 survey of European funding for graphene-related R&D found significant funding in 26 countries, with major priority progammes in 7 [M]. In total, European national funding in the period 2008-11 was €177m, compared to €2.5m before 2008, with the European Commission providing €87m over the same period. In Jan 2013, the Commission announced a further €1000m investment over ten years in a graphene Future and Emerging Technologies Flagship Initiative. In the USA, the National Science Foundation awarded around $200m in the period 2008-12 [N]. In Asia, South Korea is reported to be spending more than $350m on graphene commercialisation initiatives [B(ii),O]; the National University of Singapore invested $31M in a Graphene Research Center in 2010, attracting $47M support from the National Research Foundation a year later [P]; and China invested $81m in government funds between 2002-2012, on a rapidly rising trajectory [Q]. Cumulatively, these initiatives represent a seismic shift in public funding for science, with at least $2.4bn committed to date.

5. Sources to corroborate the impact

(>10 sources are needed to cover the reach of the impact.)

[A] Philip Shapira, et al. J. Nanopart. Res. 14, 811 (2012). Estimates of corporate entries in graphene.

[B] Reports of graphene market analyses: (i) The World Market for Graphene, Future Markets Inc., Report No. 59, Sept 12. (ii) Graphene: The Global Market, Future Markets Inc., Aug 13. (iii) Graphene: Analysis of Technology, Markets and Players, IDTechEx Report Oct 12. *Graphene production estimates, lists of companies & news of production scale-ups.*

[C] Article in Plastics News June 13. *Information about XG Sciences investments, production scaleup and job creation.*

[D] Press Release May 13 by Ningbo Morsh. *Information about Ningbo Morsh investment and production scale up.*

[E] Press Releases July 13 by Garmor Inc. *Information about production scale up and job creation.*

[F] Graphene-Info web resource on graphene material technology. *Further lists of companiesinvolved in graphene technologies.*

[G] Graphene: The Worldwide Patent Landscape in 2013, The Intellectual Property Office, March 2013. *Analysis of patent activity and further lists of companies.*

[H] Presentation by Ralf Schwenger, Director R&D Raquetsports, Head Sport, at the Graphene Commercialisation And Applications Summit 2013. *Information on graphene racquet development, expected sales figures and displacement of non-graphene racquet sales.*

[I] Wall Street Journal interview 2013. *Powerboost sales figures*

[J] Gigaom article Feb 2013. *Information on the use of graphene-based inks in anti-theft* *packaging.*

[K] Company information from www.manta.com. *Vorbeck annual revenues.*

[L] Vorbeck Press Release 2012. *Information on Vorbeck new production facility.*

[M] EC Report on Status of graphene research activities and planned investments, Oct 2011 *Information on EU and European national government initiatives*

[N] Jan Youtie, Seminar Talk, Manchester, Mar 2013. *Information on US-NSF investments.*

[O] IoP Physics World, Special Report, Republic of Korea Sept 2013 *Information on Korean government investments.*

[P] NUS Press release. *Information on Singaporean Government investment*

[Q] Kexin Chen, Mater. Res. Soc. Symp. Proc. 1505, 185, (2013). *Information on Chinese Government investments.*