Institution:
University of Cambridge

Unit of Assessment:
UoA15

Title of case study:
Nanoinstruments

1. Summary of the impact (indicative maximum 100 words)

Innovative deposition equipment manufactured by AIXTRON Nanoinstruments, a company created to exploit research outputs of the University of Cambridge Department of Engineering, is used around the world to grow carbon nanotubes and graphene. These materials are subject to intensive efforts to refine and commercially exploit their unique properties. AIXTRON Nanoinstruments is based in the UK and has produced almost 100 products, the majority of which were after 2008 and sold to customers internationally. Products range in price from GBP80k to GBP1.5M. [Text removed for publication]

2. Underpinning research (indicative maximum 500 words)

The Principal Investigators for the research in the University of Cambridge Department of Engineering (DoEng) that led to the company formation are:

- Bill Milne – appointed as Lecturer in 1976 and promoted to Professor in 1996
- Gehan Amaratunga – appointed Professor in 1998
- Ken Teo – appointed as Junior College Research Fellow in 2002, Royal Academy of Engineering Research Fellow in 2004 and then Lecturer in 2006, before moving to AIXTRON Nanoinstruments at the end of 2007 (Teo had previously been a PhD student in Milne's group)
- Nalin Rupesinghe – appointed as a postdoctoral researcher in 2002 before moving to AIXTRON Nanoinstruments at the end of 2007.

Milne, Amaratunga, Teo and Rupesinghe worked closely together throughout their time in the DoEng researching the growth of carbon nanomaterials including diamond-like carbon and carbon nanotubes (CNTs). These materials generated a great deal of interest, because of their novel structure and properties. Many applications were proposed. The field was extremely competitive. Milne *et al* realised that controlled production and optimisation of the material was essential for all of the possible applications. This was the area in which they chose to focus.

They identified Plasma-Enhanced Chemical Vapour Deposition (PECVD) as the technology most likely to yield the best control of CNT growth for research and manufacturing. They won a series of grants to fund the research that ran from 2002 to 2008 from the EPSRC and EC. Further funding came from DTI (now Technology Strategy Board) grants and other sources.

In this work, Milne *et al* examined the fundamental physical processes of growth through experiments using heavily-customised instruments that they made in house. They built a unique understanding of the effect of PECVD instrument configurations and settings on CNT growth [ref 1-3].

They also conducted research on the integration of carbon nanomaterials into various nanoelectronic devices such as transistors, interconnects, electron guns, displays, supercapacitors, batteries and microfluidic systems. The challenge of creating complex working devices drove them to refine their understanding of growth processes and optimise the experimental PECVD rigs. Their novel use of plasma enhancement enabled vertical alignment of CNTs, lower growth temperatures, improved uniformity of growth over large areas and reproducibility. This understanding and precise control of processes enabled the application of CNTs as:

- electron sources in microwave devices [ref 4] with significant advantages over metallic tip alternatives such as robustness, low turn on voltage, high emission current, high brightness and low energy spread
- the channel in transistors [ref 5] creating arguably the best molecular transistor available today, with a diameter of 1nm, a 0.54eV bandgap and both p/n-type channels
- superhydrophobic coatings for microfluidic systems [ref 6].

3. References to the research (indicative maximum of six references)

1. *M. Chhowalla, K.B.K. Teo, C. Ducati, N.L. Rupesinghe, G.A.J. Amaratunga, A.C. Ferrari, D. Roy, J. Robertson and W.I. Milne, "Growth process conditions of vertically aligned carbon nanotubes using plasma enhanced chemical vapor deposition", Journal of Applied Physics,

Vol 90, pp 5308-5317, DOI: 10.1063/1.1410322 (2001) (cited 679 times)
2. *K.B.K. Teo, S–B. Lee, M. Chhowalla, V. Semet, V.T. Binh, O. Groening, M. Castignolles, A. Loiseau, G. Pirio, P. Legagneux, D. Pribat, D.G. Hasko, H. Ahmed, G.A.J. Amaratunga and W.I. Milne, "Plasma enhanced chemical vapour deposition carbon nanotubes/nanofibers – how uniform do they grow?" Nanotechnology 14, pp 204-211, DOI: 10.1088/0957-4484/14/2/321 (2003) (cited 160 times)
3. *K.B.K. Teo, M. Chhowalla, G.A.J. Amaratunga, W.I. Milne, D.G. Hasko, G. Pirio, P. Legagneux, F. Wyczisk and D. Pribat,"Uniform patterned growth of carbon nanotubes without surface carbon "A.P.L., Vol 79, Issue 10, pp 1534-1536 DOI: 10.1063/1.1400085 Published: Sep 3 2001 (cited 243 times)
4. K.B.K. Teo, E. Minoux, L. Hudanski, F. Peauger, J-P. Schnell, L. Gangloff, P. Legagneux, D. Dieumegard, G.A.J. Amaratunga and W.I. Milne "Microwave Devices: Carbon Nanotubes as Cold Cathodes", Nature, Vol 437, p 968, DOI: 10.1038/437968a (2005).(cited 187 times)
5. M.H. Yang, K.B.K. Teo, W.I. Milne and D.G. Hasko, "Carbon nanotube Schottky diode and directionally dependent field-effect transistor using asymmetrical contacts" A.P.L., Vol 87, Issue 25, Article 253116, DOI: 10.1063/1.2149991 Published: Dec 19 2005 (cited 88 times)
6. K.K.S. Lau, J. Bico, K.B.K. Teo, M. Chhowalla, G.A.J. Amaratunga, W. I. Milne, G. H. McKinley and K. K. Gleason, "Superhydrophobic carbon nanotube forests", Nano Letters Vol 3, pp 1701-1705 (2003), DOI: 10.1021/nl034704t (cited 795 times)

*Research outputs that best represent the quality of the research.

4. Details of the impact (indicative maximum 750 words)

Nanoinstruments Limited was founded by Teo (Managing Director), Rupesinghe (Technical Director), Amaratunga (VP Engineering) and Milne (VP Research) in October 2005. The capitalisation of the company was provided by the founders. The product, based on the research conducted by the founders at DoEng and developed by Nanoinstruments, was equipment for growth of nanomaterials that incorporated both conventional thermal CVD and the team's novel PECVD modes. The equipment can reliably produce virtually all variations and morphologies of CNTs. In addition, the equipment and the associated understanding of the control of growth processes mean that it is very well suited to the production of graphene.

The company grew organically by manufacturing one system at a time and reinvesting the profits. Demand for nanomaterials accelerated and the company became widely known. AIXTRON AG acquired the company in October 2007. AIXTRON Nanoinstruments' products are still based on the original DoEng research.

The demand for equipment to grow CNTs has been strong, as industry starts to integrate them with consumer devices, trying to seize their share of a market that commentators predict *"…will increase to over $2.8bn by 2023"* [7]. Graphene is a newer material, but, again, industry is investing in equipment for production to pursue a market in which it is predicted that *"100 million dollars' worth of graphene will be sold in 2018"* [8]. Nanoinstruments has designed its products to serve this high-growth market.

AIXTRON Nanoinstruments' products range from R&D to industrial scale, covering 2-inch wafer size (selling price GBP80k) to production-scale 12-inch wafer size (selling price GBP1.5M). The proprietary name for the range of products was originally Black Magic and is now abbreviated to BM. Almost 100 of Nanoinstruments' products have been produced, the majority of which were after 2008 and sold to customers internationally. [9]

[Text removed for publication]

Customers who have bought the equipment between 2008 and 2013 include: companies such as Thales, Porifera and Graphenea (please note that many companies will not allow their purchases of Nanoinstruments products to be revealed because the purchases can reveal their strategic intentions to competitors); research institutes such as Lawrence Berkeley National Labs (USA), Georgia Tech Research Institute (USA), Masdar Institute of Science and Technology (United Arab Emirates), National Centre for Microelectronic (Spain), National Institute of Advanced Industrial Science and Technology (Japan), Institute of Metal Research at the Chinese Academy of Sciences (China), Daegu Gyeongbuk Institute of Science and Technology (South Korea), Italian Institute of Technology (Italy), Nanotechnology Center (public private partnership between IBM Research and ETH Zurich based in Switzerland); and universities such as University of Texas (USA), Nanyang

Technological University (Singapore), Osaka University (Japan), Zhejiang University (China), University of Oulu (Finland), Pusan National University (South Korea). [9]

Examples of customer statements are given below:

- **Graphene production** - *"Graphenea bought a Nanoinstruments BM system in 2010. We chose it because we believed it was the most suitable system to synthesise graphene at the time. Since 2010 we have been using the BM system to develop graphene synthesis processes and at the same time manufacture graphene samples to sell to customers worldwide including Canon, Philips and Nokia. We still believe it is the best system that is available to produce graphene. The BM system has helped us to lead the CVD Graphene production sector and obtain a greater than 30% market share in 2013."* Scientific Director, Graphenea SA. [10]
- **Manufacture of electron sources** - *"After a 10-year collaboration with Cambridge University on carbon nanotube based electron sources, Thales purchased a Nanoinstruments Aixtron Black Magic (BM) system in 2011. The BM system was chosen for the unique rapid heating and plasma technologies. Moreover, the system is highly versatile and offers a user-friendly system interface that allows precise control and monitoring of the growth parameters. Since 2011, Thales has performed around one thousand growth recipes and has developed "state of the art electron" sources. This quick development could not have been made without the BM system."* Manager responsible for electron source studies at Thales R&T (TRT) and Head of the Nanocarb Lab (joint lab between CNRS, Ecole Polytechnique and TRT). [11]
- **Applications in electronic, communication, nano-electromechanical and robotic systems** - *"The unique devices we are developing require the controlled deposition of individual, vertical aligned carbon nanotubes at precise locations. This is where AIXTRON's plasma-based BM system really stands out against other options we considered. Indeed, the BM system enables us to reliably achieve carbon nanotube growth with unparalleled control over growth parameters and nanotube alignment in a reproducible manner…The BM system enables us to grow a single vertical carbon nanotube with controlled dimensions at pre-defined locations through a process that is compatible with existing silicon technology. The vertical orientation of single nanotubes is a key feature, as it allows us to decrease the device cell area significantly over conventional device approaches. We are applying the use of vertical nanotubes to not only electronic and communication devices, but also to novel applications such as nano-electromechanical and robotic systems."* Professor from the Department of Information and Communication Engineering at Daegu Gyeongbuk Institute of Science and Technology (DGIST), South Korea. [12]
- **Rapid turnover and large-area processing for patentable graphene technology** - *"Due to the turnover time and process control the system has played an instrumental role in our progress towards gentle, large-area graphene transfer as well as large-area characterisation, which has allowed us to submit several patents and high impact articles. The research has been of key importance for our successful funding track record, involving two large national application-oriented graphene projects with strong industry involvement, a national centre of excellence, a European project in 2013, NMP-Gladiator, as well as the Graphene Flagship."* Associate Professor at the Technical University of Denmark [13].

5. Sources to corroborate the impact (indicative maximum of 10 references)

7. "Carbon Nanotubes (CNT) for Electronics & Electrics 2013-2023: Forecasts, Applications, Technologies", Cathleen Thiele and Raghu Das, Description of a market report produced by IDTechEx, updated 2013, http://www.idtechex.com/research/reports/carbon-nanotubes-cnt-for-electronics-and-electrics-2013-2023-forecasts-applications-technologies-000342.asp
8. "Graphene Markets, Technologies, Opportunities 2013-2018", Dr Khasha Ghaffarzadeh and Cathleen Thiele, Description of a market report produced by IDTechEx, 2013 http://www.idtechex.com/research/reports/graphene-opportunities-2013-2018-technology-markets-players-000333.asp
9. Statement by Director of Nanoinstruments at AIXTRON SE
10. Statement by Scientific Director, Graphenea SA
11. Statement by Manager responsible of electron source studies at Thales R&T (TRT) and Head of the Nanocarb Lab (joint lab between CNRS, Ecole Polytechnique and TRT)
12. "Korea's DGIST to produce individual nanotube arrays with AIXTRON system", AIXTRON press release, 9 August 2012, http://www.aixtron.com/nc/en/press/press-releases/detail/news/koreas-dgist-to-produce-individual-nanotube-arrays-with-aixtron-

system/
13. Statement by Associate Professor of the Technical University of Denmark