Institution: University of Surrey

Unit of Assessment: 12 Engineering

Title of case study: Carbon based Nanotechnology: From Science to Industry

Period when the underpinning research was undertaken: 2000-2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Ravi Silva	Professor, Director of ATI	1995 – present
Vlad Stolojan	Senior Lecturer	2001 – present
Christopher Smith	Research Fellow	2017 – present

Period when the claimed impact occurred: 2014- 2020

Is this case study continued from a case study submitted in 2014? N

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

- Continued contribution to Surrey Nanosystems (a NEC@ATI spin-out), with input to new R&D (2014-) creating Vantablack™, tripling the liquidation value since 2014 (£24M in 2018, ~£30M in 2020). Vantablack™ became a global brand at the Hyundai Pavilion (2018 Winter Olympics) and in 2019 at the Frankfurt Motor Show with the BMW VBX6.
- Nanotechnology coating innovation led to Airbus committing €10M to take patented solutions to higher TRLs in their Copernicus Extension, Earth Explorer and Science Cosmic Vision programmes, now on trials with the European Space Agency (ESA).
- Nanotechnology innovation at the NEC@ATI resulted in 12 patents filed, 2 spin-outs (SilverRay in 2018, Radical Fibres in 2020) with a combined value ~£2M, and the creation of 10 high-skill jobs.

2. Underpinning research (indicative maximum 500 words)

New and continued research at the NanoElectronics Centre at the Advanced Technology Institute (NEC@ATI), headed by Professor Silva, has expanded on developing **applications, manufacturing solutions and capabilities for carbon nanotechnologies**, for areas ranging from space and flight technologies to energy conversion and recovery, and healthcare sensing and monitoring applications.

Manufacturing nanomaterials compatible with electronics and the creation of a nanomaterial global brand:
Surrey NanoSystems (SNS) was founded as a NEC@ATI spin-out in 2006 and provides an established commercial outlet for nanomaterials developed through innovative research at the University of Surrey. The spin-out commercialised a manufacturing process **[R1]** for novel carbon nanotube (CNT) electronics and low permittivity dielectrics, a solution that permitted nanostructures typically grown at high temperatures (>700°C) for high specification devices, whilst keeping substrates below 400°C (a semiconductor industry requirement). In 2014, the low-temperature CNT growth capacity led to a project partnership with the National Physical Laboratory (NPL) and ABSL Space Products to develop super-black coatings to enhance the performance of sensitive electro-optical imaging systems in a satellite application **(see E1, E2)**. This resulted in the creation of Vantablack™ – Vertically Aligned NanoTube Array Black - an array of carbon nanotubes with remarkable properties for trapping light, briefly holding a Guinness World

Record for the blackest man-made material, at 99.96% absorbance. It is now considered the default industry standard for highest quality black material.

Coating and nanomaterial innovation for space exploration and aerospace:
The traditional manufacturing of satellite devices has used precision engineering of metals and ceramics (a resource intensive and costly procedure). More recently satellites have been manufactured from carbon-fibre-reinforced-polymers (CFRP), which have higher tolerance to mechanical failure, a decrease in weight and cost. However, there are issues with the release of trapped moisture from the CFRP when in flight/vacuum or on launch; this release affects the dimensional stability of the coatings, rendering them defective.

NEC@ATI collaborated with Airbus, over the last 10 years **(see E3)**, to develop a novel carbon fibre coating process to prevent moisture absorption and release from materials that can distort dimensions, which removes the need for weeks of outbaking of CFRPs prior to flight, and many £100,000's in costs. The coating is an effective moisture barrier, and effective for protecting satellites in flight, in vacuum, or on launch. This allows the industry to move away from the precision engineering metals and high-performance ceramics. The developed technology allows deposition of thin multi-layer coatings onto complex surfaces, evenly and reproducibly **[R2]**.

The original CNT manufacturing process **[R1]** was used with Bombardier to improve aerospace composite manufacturing by using CNTs grown on fibres to strengthen the mechanical bond between the resin and the fibre, significantly increasing the fracture toughness and removing the need for sizing **[R3]**.

NEC@ATI research has shown that embedding nanofibre veils and carbon nanomaterials in aerospace composites can significantly improve their mechanical properties and have innovated solutions for scaling up the production of polymer nanofibres **[R4]**.

Leading research into efficient energy conversion **[R5]**, NEC@ATI researchers developed a printing-based manufacturing technique for very efficient, flexible, organic X-ray detectors, resulting in a significant advance in X-ray detection technology, with 2-3 order of magnitude higher sensitivities and low voltage operation.

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

[R1] Boskovic, B.O., **Stolojan, V.**, Khan, R., Haq, S., **Silva, S.R.P**. (2002). Large-area synthesis of carbon nanofibers at room temperature. *Nature Materials*, 1, 165-168. DOI: 10.1038/nmat755

US Patent: 8,715,790 (2014) and WO2003011755A1 – Production of carbon nanotubes

[R2] Anguita, J.V., **Smith, C.T.G**., Stutte, T., Funke, M., Delkowski, M., **Silva, S.R.P**. (2020). Dimensionally and environmentally ultra-stable polymer composites reinforced with carbon fibres. *Nature Materials*, 19, 317-322. DOI: 10.1038/s41563-019-0565-3

Patent: A carbon fibre reinforced plastic WO2014140535A1

[R3] Pozegic, T.R., Hamerton, I., Anguita, J.V., Tang, W., Ballocchi, P., Jenkins, P., **Silva, S.R.P.** (2014). Low temperature growth of carbon nanotubes on carbon fibre to create a highly networked fuzzy fibre reinforced composite with superior electrical conductivity, *Carbon*, 74, 319-328. DOI: 10.1016/j.carbon.2014.03.038

Pozegic, T., Anguita, J.V., Hamerton, I., **Silva, S.R.P**. (2016) Multi-Functional Carbon Fibre Composites using Carbon Nanotubes as an Alternative to Polymer Sizing. *Scientific Reports*, 6, 37334. DOI: 10.1038/srep37334

Patent: WO2016092293A1 – Fibre-reinforced components including nanostructures

[R4] Pozegic, T.R., King, S.G., Fotouhi, M., **Stolojan, V**., **Silva, S.R.P**., Hamerton, I. (2019). Delivering interlaminar reinforcement in composites through electronspun nanofibres, *Advanced Manufacturing: Polymer & Composites Science*, 4(5), 155-171, DOI: 10.1080/20550340.2019.1665226

[R5] Thirimanne, H.M., Jayawardena, K.D.G.I., Parnell, A.J., Bandara, R.M.I., Karalasingam, A., Pani, S., Huerdler, J.E., Lidzey, D.G., Tedde, S.F., Nisbet, A., Mills, C.A., **Silva, S.R.P**. (2018) High sensitivity organic inorganic hybrid X-ray detectors with direct transduction and broadband response. *Nature Communications*, 9, 2926. DOI: 10.1038/s41467-018-05301-6

Patent: Wo2018078372A1 – Direct conversion radiation detector

Key research grants:

S.R.P. Silva, EPSRC Portfolio Partnership Award in Integrated Electronics, £6,686,246.00, April 2003 – March 2009.

S.R.P. Silva, J. D. Carey, V. Stolojan, T. Coreless, EPSRC National Graphene Growth Facility award with contributions from industry (Tata, Tetreon, NPL, Thomas Swan, Intel, BAE Systems) and the University of Surrey, £1.2M total; EPSRC £400k, July 2014 – May 2024.

S.R.P. Silva, Extension to EADS Atrium Moisture Barrier Coating Technologies, £232k, December 2014 – June 2022.

V. Stolojan, R. Gwilliam S.R.P. Silva, EPSRC award for Manufacturing Lightweight Carbon Nanotube Electrical Cables: Increasing the Conductivity, £398k, March 2016 – June 2019.

S.R.P. Silva, Airbus Extension to Outgassing and Moisture Barrier Coating Technologies, £150k, January 2017.

S.R.P. Silva, Wei Zhang, EU H2020 CORNET “Multiscale modelling and characterization to optimize the manufacturing processes of Organic Electronics materials and devices (CORNET)”, £278k, January 2018 – March 2021.

S.R.P. Silva, Airbus Outgassing, Barrier and Moisture Coating Technologies, £240k, September 2018 – December 2020.

S.R.P. Silva, Airbus Moisture Barrier Layer coating Technologies, £150k, November 2019 – December 2020.

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

Continued economic and societal impact through original spin-out Surrey NanoSystems and the creation of a global brand product, Vantablack™:
The creation of the Vantablack™ product and its subsequent establishment as a global brand involved significant innovation, input, metrology and testing **[R1]** from the NEC@ATI group (see **E1, E2**). As a result of this successful project, the company has changed its business model and is now focused solely on the production and application of Vantablack™. The **company value has tripled in 2020, compared with 2014 [E1** and **Companies House]**. Vantablack™ has since progressed to market in a number of sectors, including space/aerospace, automobiles, cameras, standards, and telescopes.

As a technological material, Vantablack™ was tested as a coating material for optical probes aboard the Kent Ridge 1 satellite (launched December 2015 for the purpose of disaster monitoring and relief in Asia) and is now space-qualified over 8 critical areas for use as blackbody calibration units, complex baffles and spectrometers, with instruments coated in Vantablack™ being part of the latest Northrop-Grumann’s CRS12 Cygnus launch to the International Space Station

(November 2019) **[E4]**. This has led to a significant revenue increase to Surrey Nanosystem, triggering a doubling of the highly skilled workforce and a move to new, larger (doubling footprint) premises in 2019.

Vantablack™ as a cultural artifact and raising public awareness of carbon nanotubes technologies:
Vantablack™ has been introduced as a new pigment of colour in the palette of artists and was licenced for sole artistic use by Sir Anish Kapoor **[E5]** – creator of the London 2021's Orbit sculpture – prompting media debate on the 'licensing of colour'. Vantablack™ has been used to striking effect in the Hyundai pavilion at the 2018 Winter Olympics, with 60K visitors in 5 weeks, to launch the new BMW VBX6 (The Beast) at the 2019 Frankfurt Motor Show and manufacture high-end bespoke timepieces (e.g. MCT S110EVO), as well as launch several consumer products, including the Call of Duty's Black Ops 4 tested by England's footballer, Dele Alli, raising public awareness and discussion on the use of carbon nanotubes and emerging technologies.

Innovation and bespoke manufacturing solutions for aerospace applications, developing moisture barrier layers for Airbus:
Ongoing collaborations between NEC@ATI and Airbus Defence and Space have leveraged the NEC@ATI group's experience in nano-manufacturing technologies **[R2, R3]** to solve issues of coating complex, 3D-shapes and devices for space applications and the need to develop appropriate moisture barriers within the Earth, Observation, Navigation and Science (ENS) perimeter. This research has resulted in the development of unique processes, novel multilayers compatible with space structures and novel vacuum chambers for coating large pieces of equipment, to be used by Airbus for future space missions **[E1].**

The novel coating method and materials developed by NEC@ATI **solved a previously intractable problem** for the space industry (that needed components to be wrapped in a third-party material that reduced lifetime), as well as reducing the cost associated with the bench-to-space system **(ca. £100k/component)**. The promising results have led to Airbus Defence and Space, and European Space Agency **adopting the business case for this technology** at division level and investing over €10M to be implemented in the radar instruments/payload (TRL 7, currently) and optical instruments/payload (TRL 6), to cover IP, facility industrialisation, testing and certification. It is expected that this will become the standard for ESA space missions.

Innovation culture within the NEC@ATI group has led to 12 patent applications and 2 spin-out companies exploring some of these innovations and associated know-how:
SilverRay Ltd: started in 2018 to commercialise NEC@ATI's IP **[R4], providing 4 highly skilled industrial jobs and has secured private and government funding [E6]** to take flexible, organic detectors to large scale manufacturing, leveraging their ease of production and conformability with complex surfaces.

***Radical Fibres Ltd*:** since starting in January 2020, has secured >£300k **[E7]** in funding to commercialise NEC@ATI's IP **[R5]** towards applications such as energy harvesting textiles, leveraging the know-how developed in the past 6 years on piezoelectric, triboelectric and solar energy harvesting. The company has already created **4 highly skilled industrial jobs and is forecast to have a revenue of £400k in the first year,** growing to £1M in 2021**.** Radical Fibres had one of the highest scoring applications to the Business-led innovation in response to global disruption (*de-minimis*) to manufacture anti-viral nanofibre-based face masks **[E7]**.

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

[E1] Testimonial Letter from Ben Jensen CTO Surrey NanoSystems Ltd (PDF); additional information available from https://www.surreynanosystems.com/

[E2] Testimonial Letter from Professor Fernando Castro, Head of Science-Materials, National Physical Laboratory. (PDF)

[E3] Testimonial Letter from Christian Wilhelmi, Head of Mechanical Subsystems and R&T FHN; Günther Kling, Head of Mechanical & Thermal Architecture, Optical Instruments; Christopher Hess, Head of Radar & Microwave Payloads Earth Observation, Navigation and Science – Space Systems, Airbus Defence and Space GmbH. (PDF)

[E4] Space applications of Vantablack™, and Space qualification evidence available https://www.surreynanosystems.com/news-media

[E5] Telegraph article on Sir Anish Kapoor; "Anish Kapoor interview: 'How can a bit of paint on a canvas be worth £50 million?'" by Chris Harvey, Telegraph Newspaper, 23rd May (2020). https://www.telegraph.co.uk/art/artists/anish-kapoor-interview-can-bit-paint-canvas-worth-50million/

[E6] Innovate UK grant number 24290, 24302, 25712,36723, NIHR 200313, NIHR 141 Connect 2 Business 23812.

[E7] Innovate UK grant numbers 51113, 57034, 42944, https://www.ukri.org/our-work/tackling-the-impact-of-covid-19/recovery-and-rebuilding/innovate-uks-business-led-innovation-in-response-to-global-disruption/