Institution: University of Sussex

Unit of Assessment: 9 – Physics

Title of case study: Commercial exploitation of nanoparticle-based inks for defence, authentication and retail use

Period when the underpinning research was undertaken: 2016 – 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:
Alan Dalton	Professor	2016 – present
Matthew Large	Research Fellow	2016 – present
Sean Ogilvie	Research Fellow	2017 – present

Period when the claimed impact occurred: 2017 – 2020

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

1. Summary of the impact

In 2017, Advanced Material Development (AMD) was established to exploit IP developed by the Materials Physics Group at Sussex. Consequently, AMD has established itself as a leader in cutting-edge technologies applicable to a range of markets including defence, authentication and sustainable retail. The company has generated a significant patent portfolio (3 patents filed based on Sussex research, and exclusivity to 2 other university patent applications); has extensive Non-disclosure Agreements (NDAs, 58), Letters of Intent (LoIs, 2) and Material Transfer Agreements (MTAs, 4) in place with global leaders; has lucrative government defence contracts in both the UK and the US; is a materials provider to several leading companies and government bodies; and is partnering with industry leaders (including Honeywell and Marks and Spencer) to monetize proprietary IP through the development of bespoke technologies. To date, the company has raised GBP2,300,000 [text removed for publication] and is conservatively valued at GBP30,000,000.

2. Underpinning research

Since 2016, Dalton and his team have been developing highly conducting inks based on graphene and other 2D materials. This nanoparticle ink technology was originally conceived as part of a fundamental materials physics research project funded by the European Union's Horizon 2020 programme [G1]. The focus of this activity was to study graphene and other layered material dispersions [R1] and their incorporation in various larger scale arrays, such as Pickering emulsions [R2]. Pickering emulsions stabilised with nanomaterials provide routes to a range of functional macroscopic assemblies. The viscosity of these inks can be easily modified and can therefore be deposited on a range of substrates using commercial printing techniques such as ink-jet and screen. This has led to further application realisations in several commercially relevant areas which are now being exploited by AMD.

For example, using a process developed by the Sussex labs [R1, R2], the nHance product is a patented scalable platform technology [R4] of 2D nanomaterial dispersions for a range of applications. It can contain a range of materials including graphite nano platelets (GNPs), boron-nitride and other transition metal dichalcogenides (WS_2 and MoS_2) with dispersions being used within onward formulations for commercial application development. Importantly, the advanced formulations provide a very wide range of ink and coating products which can achieve conductivities of more than $500kSm^{-1}$. To their developers' knowledge, this has substantially higher conductivity than any other carbon-based printing inks.

Through direct funding from AMD [G2], the Sussex team (Dalton, Large and Ogilvie) has undertaken new research to develop a methodology to scale the production of these inks. The technical details of these advances are outlined in two filed patents [R3, R4]. In this work, the use of liquid jet homogenisation to prepare dispersions of nanoplatelets in large quantities is

identified as possible. Key to their exploitation by AMD, the inks can be used in coatings that are, to its developers' knowledge, the most conductive all-carbon based systems ever produced. As a result, they are ideal candidates for next generation of printable electronics such as electromagnetic shields and electromechanical sensors. In particular, the latter technology has received a great deal of interest from various media bodies including the BBC Radio 4 Inside Science (interview at University of Sussex labs and on BBC website); *The Times*; the *Financial Times*; *The Irish Times*; and many others.

Most recently, the Sussex and AMD teams have demonstrated a radio-frequency antenna application, which is competitive with the state-of-the-art in terms of readability, flexibility and cost. Another key outcome of this work was the development of a route to recycling of such printed short-lifetime electronic devices to lower the environmental impact [R5]. Currently, billions of radio-frequency identification (RFID) tags are produced annually, which are mostly single-use and treated as disposable. Funded by the ESRC [G3], a new programme brings together researchers from the social sciences (University of Sussex Business School) with those in Materials Physics (Sussex), who will work closely with AMD and Walmart – the world's largest company by revenue – to examine how AMD's innovative, environmentally-friendly RFID tags contribute to creating a zero-waste business and its implications for the organisation of work in the retail sector.

3. References to the research

[R1] Ogilvie, S. P., Large, M. J., O'Mara, M. A., Lynch, P. J., Lee, C. L., King, A. A. K., Backes, C., and Dalton, A. B. 'Size selection of liquid-exfoliated 2D nanosheets.' 2D Materials 2019, 6 031002. https://doi.org/10.1088/2053-1583/ab0dc3

[R2] Large, M. J., Ogilvie, S. P., Meloni, M., Graf, A. A., Fratta, G., Salvage, J., King, A. A. K., and Dalton, A. B. 'Functional liquid structures by emulsification of graphene and other two-dimensional nanomaterials.' Nanoscale 2018, 10 (4), 1582-1586. https://doi.org/10.1039/C7NR05568D

[R3] Dalton, A. B., Large, M. J. and Ogilvie, S. P., 'Pickering Emulsions', Worldwide Patent Application WO2019135094A1, University of Sussex, 2019.

[R4] Dalton, A. B., Large, M. J. and Ogilvie, S. P., 'Liquid-Exfoliated Nanomaterials', Worldwide Patent Application WO2020074698A1, Advanced Material Development, 2019.

[R5] Large, M. J., Ogilvie, S. P., Graf, A. A., Lynch, P. J., O'Mara, M. A., Waters, T., Jurewicz, I., Salvage, J. P., and Dalton, A. B. 'Large-Scale Surfactant Exfoliation of Graphene and Conductivity-Optimized Graphite Enabling Wireless Connectivity.' Advanced Materials Technologies 2020, 5 (26) 2000284. https://doi.org/10.1002/admt.202000284

R1 – R5 were all led and planned by A. B. Dalton.

Key research funding includes:

[G1] European Union. Horizon 2020 – Marie Skłodowska-Curie Innovative Training Networks (ITN-ETN) (642742): 'Graphene-based nanomaterials for touchscreen technologies: Comprehension, Commerce and Communication' (2015-2019). Lead: Centre National de La Recherche Scientifique (CNRS); Total EUR3,358,044, of which EUR546,575 to Sussex.

[G2] Advanced Material Development Ltd. (2018-2021) GBP1,665,851.

[G3] ESRC (ES/V002414/1). 'Bringing Environmental Radio Frequency Identification (RFID) Tags to Market' (2020-2021). GBP138,879 to Sussex. Co-I: Dalton.

4. Details of the impact

4.1 Underpinning the creation of a spin-out company and subsequent jobs

Advanced Material Development (AMD) was founded in 2017 to exploit the intellectual property (IP) on graphene exfoliation and ink processes developed by the Materials Physics Group at Sussex. Through a generalised Research Framework Agreement (RFA) [S1], AMD has exclusive access to both background and foreground IP generated by the Sussex lab [R3, R4]. Their

sustained use of Sussex research is further consolidated through Prof Dalton's role as the company's Chief Scientific Advisor. The relationship allows AMD both to direct – and to benefit directly from – the work of the lab, thus enhancing their capacity to further develop these technologies, in response to the demands of emerging markets. The company has subsequently filed further patents for new technologies it has developed with the lab, based on the original Sussex IP [R4]. AMD directly employs 9 people (all 1.0 FTE) and funds 6 postdoctoral research jobs (headcount: 6, FTEs: 6, 17 FTE-years in total) plus 3 PhD positions (all 1.0 FTE) at UK universities [S2].

4.2 Enabling AMD to establish market leadership through its unique offering

In a letter [S2], AMD's CEO John Lee "highlights some of the important advances [AMD] have made over the past three years through exploitation of IP developed by [Dalton] and [his] team":

> "AMD's work is based on an essential 'platform technology' of liquid processing of 2D (nano) materials developed by you [Dalton] and your team at Sussex. Over the last 3 years, we have exploited this technology enabling application development in several key areas such as Advanced Sensors, Electronics & Devices, Composites, Photonics, Functional Coatings and nMark (anti-counterfeiting)."

AMD has raised a total of GBP2,300,000 with the last funding round of GBP1,500,000, in May 2019, on a pre-money valuation of GBP15,000,000. Since this last fundraising, AMD has made significant progress in the development of its core IP and in identifying key end markets to develop and monetize this technology. [Text removed for publication]

As a result of the "truly unique relationship with your group at Sussex", Lee confirms that:

> "AMD are now leaders in the field of cutting-edge nanomaterials… with applications that can provide solutions to a range of end markets including defence, authentication / anti-counterfeiting, sustainable retail and wind power."

He adds that "exploiting the Sussex technology for optical shielding applications has emerged as a lucrative market for AMD" and that the advancing success of a series of development contracts with UK and US defence agencies (details below) has "enabled the business to establish significant relationships, understand defence and security challenges, and provide innovations that have been funded both sides of the Atlantic."

These have enabled AMD to benefit from "collaboration discussions… with leading defence companies." Lee continues: "Our partners, both government and commercial, see these materials as potentially disruptive."

On the basis of AMD's capacity – enabled by Sussex research – to offer specialist nanotechnologies and materials for such a range of industrial applications, the company has been able to attract and establish partnerships with several international companies, [text removed for publication]. As of December 2019, NDAs have been signed with a total of 58 organizations, Letters of Intent with two companies (Marks and Spencer, Honeywell), and Material Transfer Agreements with four companies [text removed for publication] to allow close partnership on the development of new products which further draw on Sussex IP (see below) [S2].

4.3 Facilitating AMD's clients' advancement towards nanomaterial use

Through AMD's contracts with government and commercial organisations, Sussex research is underpinning these organisations' strategic investments, planning and decision-making around their future use of specific technological solutions:

4.3.a Advancing military organisations' and their suppliers' capability to develop improved protective materials

In November 2020, through a competitive process, AMD were successful in moving to contract with the [text removed for publication] US Department of Defense, to develop an advanced eye protection system based on the materials developed by the Sussex team. The value of this award is [text removed for publication] with work commencing in April 2021 [S3]. Using their nLight technology, AMD is developing a set of innovative thin film coatings composed of the

Sussex-lab-developed nHance materials, to be used to mitigate the worst effects of direct laser radiation exposure. These narrow bandpass filters allow the frequency of interest to be blocked whilst letting others through, such that the ability to observe is not obscured. A range of films will be delivered for both integration as a new component in eyewear technologies and as 'tear off' films for rapid deployment on existing eyewear. These applications will reduce the risk of flash blindness and permanent retina damage from targeted lasers, reducing injury and protecting the lives of police officers, first responders, pilots and other military and emergency service personnel. This work marks AMD's strategic move to establish a leading position for the global directed energy weapons protection market, which is estimated to grow to USD75,000,000,000 by 2028 – an annual growth rate of 23% [S2].

In the UK, AMD has been accepted as an approved supplier to the new Weapons Sector Research Framework programme (2020 – 2025), a GBP300,000,000 group funding award from the Ministry of Defence that is led by QinetiQ. An initial 6-month contract for [text removed for publication] has been awarded to use nHance coatings for effective electromagnetic shielding in military-significant windows of the spectrum [S2, S4]. Additionally, based on Sussex research [R4], AMD has successfully completed a programme funded by the UK Defence and Security Accelerator (DASA) to develop infra-red obfuscation technology that could be used on soldiers' clothing, or on land, sea and air systems [S2, S5].

The company has also been developing radar mitigation materials, in an ongoing partnership with the US Army funded through their Foreign Comparative Testing programme. [Text removed for publication]

Based on the IP developed by the Sussex team, AMD have also been developing sensors for structural-health monitoring. In November 2019, they signed a Letter of Intent to work with Honeywell to develop materials-based solutions for non-destructive testing of moulded materials such as helmets or body armour that may have been subjected to high impact damage [S2, S7].

4.3.b Facilitating the retail and consumer sector in implementing a green recyclable track-and-trace technology within their supply chain

The apparel industry currently deploys approximately 11,000,000,000 radio-frequency identification (RFID) tags annually and most of these end up in landfill sites or incinerators. The RFID for retail market is estimated to grow by 24% per annum by 2025 [S2]. AMD's solution is to replace incumbent metal and plastic RFID tags (ubiquitous in the supply chain) with a graphene-based material printed on recyclable paper. As retail leaders drive towards 100% sustainability, the supply chain must respond to the challenge. In 2019, AMD signed a Letter of Intent with high street retail giant Marks and Spencer to use the metal-free graphene conductive ink technology invented by the Sussex team [R5], in the development of a "green and sustainable" RFID solution for the apparel and packaging industry [S2, S8].

4.3.c Advancing the automotive sector's ability to fully integrate Internet of Things (IoT) functionality inside the vehicle

The opportunity for incorporating RFID in tyres and sensor components in powertrains is significant. The tyre industry alone was valued at USD112,000,000,000 in 2019 and is projected to reach USD154,000,000,000 by 2027 [S2]. Given this environment, leading tyre manufacturers look for innovation to drive market share and protect profit margins. Using recent technology developments at the Sussex labs, the nHance inks have been reformulated to be stretchable and compatible with rubber products, opening up market opportunities. AMD's collaboration with industrial partners in this area over the last two years has led to an understanding of the potential for AMD's elastomeric conductive inks, and they are now receiving ongoing funding from a leading player [text removed for publication].

During 2018-2019, [text removed for publication] one of the world's leading suppliers of technical rubber products – contracted AMD to produce a protype stretchable RFID antenna based on AMD's nHance inks [text removed for publication]. The antennas were [text removed for publication] in terms of read distance and mechanical/thermal stability, with promising outcomes. [Text removed for publication] This customer has now ratified that electronically (in terms of read range etc.) they are fit for purpose. [Text removed for publication]

4.4 Extending AMD's capacity to co-develop technologies for additional markets

More recently, AMD – enabled by Sussex research, and the above-mentioned successes – has expanded to develop and exploit the IP generated in partnerships with three additional universities located in the UK and the US. All of these partnerships involve use of the nHance product. Commenting on the expanded collaboration John Lee said:

> "Driven by the success the company have had through its collaboration with Sussex, we have expanded our network to support a range of materials science research at several leading universities including the University of Surrey, the University of Utah and the University of Texas." [S2].

In 2018, based on the collaboration with the University of Texas, an AMD subsidiary Com3D was founded and has raised a further USD1,500,000 of private investment focusing on 3-D printing of pharmaceuticals [S9].

5. Sources to corroborate the impact

[S1] Research Framework Agreement between the University of Sussex and AMD

[S2] Testimonial letter from John Lee, CEO of Advanced Material Development

[S3] [Text removed for publication]

[S4] Article showcasing AMD's joining of the WSRF programme and initial contract award

[S5] Email confirmation of the DASA award, 2019.

[S6] Testimonial letter from [text removed for publication]

[S7] Article announcing Letter of Intent to collaborate between AMD and Honeywell International

[S8] Article outlining collaborative agreement with Marks and Spencer for a green RFID solution

[S9] Article describing funding of Com3D