Institution: University of the West of Scotland		
Unit of Assessment: 9: Physics		
Title of case study: Global economic and performance impact through world-leading innovations in optical thin film manufacturing		
Period when the underpinning research was undertaken: 2014 - 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:**
Des Gibson	Professor	2014 - 2020
Stuart Reid	Professor	2012 - 2017
Dr Shigeng Song	Reader	2012 - 2020
Dr David Hutson	Lecturer	2007 - 2020
Dr Ross Birney	Research Assistant / Lecturer	2014 - 2020
Period when the claimed impact occurred: 2013 - 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

The impact addresses a worldwide requirement for enhanced throughput manufacturing processes for high performance precision optical coatings, aligned with high-growth GBP10,800,000,000 global market need for high-volume/ low-cost optically coated components. Enhanced throughput is based on novel patented plasma assisted optical coating processes – two specific processes utilising microwave or direct current based plasma technology. Plasma technology has been deployed into production usage, providing low temperature/ high throughput processes compatible with temperature-sensitive substrates and enhanced performance optical thin films. The technology has been deployed into three UK optical coating companies, Laboratory for Laser Energetics – University of Rochester (USA) and China.

2. Underpinning research

Context: From 2004, underpinning research was carried out in the physics department's Thin Film Centre, 2014 reconstituted as the Institute of Thin Films, Sensors & Imaging (ITFSI). UWS ITFSI have pioneered a number of breakthrough plasma technologies applied to physical vapour deposition (PVD) processes – primarily electron beam evaporation and sputtering. The use of novel direct current and microwave-generated plasmas and associated ion beams have been shown to address significant challenges relating to existing PVD manufacturing processes. UWS work has opened a broader range of deposition conditions (*e.g.* ion energies, plasma density and reactivity) whilst enabling low-temperature processes through more efficient ionisation cross-section and targeted energy delivery at the atomic level. The research included experimental demonstrations of new plasma based deposition processes, complemented by full theoretical analysis.

Key findings: Underlying research into new vacuum vapour deposition techniques utilising plasmas is motivated by depositing optical coatings with high laser induced damage threshold and multilayer dielectric mirror coatings deployed within laser interferometric systems for gravitational wave detection. The most notable UWS developed plasma technologies deployed in optical thin film PVD processes are described as follows:

2.1 UWS ITFSI 2015 & 18 publications **[3.1, 3.2]**, a novel plasma source for assisted deposition of optical coatings. Use of a separate high-pressure cathode region demonstrated a method for enabling hollow cathode operation at low deposition pressures and sustained operation without inductive heating. Pressure within the hollow cathode area was optimised at ≈2.0E−3 mbar, while maintaining the deposition chamber pressures at the lower values of≈2.0E−4mbar, required for efficient plasma ion assisted electron beam deposition. This research, which has been conducted from 2014 to the present, is founded upon two company-sponsored PhD studentships

2.2 Microwave plasma ion beam sputtering (MPIBS), based on novel electron cyclotron resonance (ECR) plasma generation, has been first pioneered and demonstrated by UWS and University of Stirling This has enabled ion beam deposition with a factor ~10 greater range of available ion energies (extraction potentials up to 20kV) and the fabrication of extreme performance optical coatings. This technology was first demonstrated by UWS, and shown to produce the most stable amorphous structure of pure Ta_2O_5 reported at room temperature **[3.1]** and the world's lowest optical absorption amorphous silicon **[3.3, 3.4]** for use in multilayer optical thin film mirrors deployed in laser interferometric gravitational wave detection.

2.3 Microwave plasma assisted sputtering (MPAS), utilising novel surface wave plasma (SWP) generation - microwave power is transferred via a waveguide and is launched to the plasma generation region through a dielectric window, which is configured at one face of the waveguide coupler. SWP is most commonly used in materials processing for etching and Chemical Vapour Deposition, however developed at UWS for MPAS scalable deposition and fabrication of high-throughput, high-performance coatings over large area **[3.5]**. This technology has already been demonstrated for small-scale deposition and patented by UWS for use in next generation durable optical and engineering coatings **[3.6].**

Underpinning research 2014 to present has establishing the underlying physics to enable production deployment of methods 2.1, 2.2 and 2.3 and scalability in optical thin film production processes.

3. References to the research

3.1 Child, D., **Gibson, D.,** Placido, F. and Waddell, E., (2015) Enhanced hollow cathode plasma source for assisted low pressure electron beam deposition processes. *Surface and Coatings Technology*, 267: 105-110. https://doi.org/10.1016/j.surfcoat.2014.12.030

3.2 Hui, B., Fu, X., **Gibson, D.,** Child, D., **Song, S.,** Fleming, L., Rutins, G., Chu, H., Clark, C. and **Reid, S.,** (2018) Automated Control of Plasma Ion-Assisted Electron Beam-Deposited TiO_2 Optical Thin Films. *Coatings*, 8(8): 272. https://doi.org/10.3390/coatings8080272

3.3 Birney, R., Steinlechner, J., Tornasi, Z., MacFoy, S., Vine, D., Bell, A., **Gibson, D.,** Hough, J., Rowan, S., Sortais, P., Sproules, S., Tait, S., Martin, I. and **Reid, S.,** (2018) Amorphous Silicon with Extremely Low Absorption: Beating Thermal Noise in Gravitational Astronomy. *Physical Review Letters*, 121(19): 191101. https://doi.org/10.1103/PhysRevLett.121.191101

3.4 Birney, R., Gibson, D., Reid, S., et.al, (2018) Effect of elevated substrate temperature deposition on the mechanical losses in tantala thin film coatings. *Classical and Quantum Gravity*, 35(7): 075001. https://doi.org/10.1088/1361-6382/aaad7c

3.5 Li, C., **Song, S., Gibson, D.,** Child, D., Chu, H. and Waddell, E., (2016) Modeling and validation of uniform large-area optical coating deposition on a rotating drum using microwave plasma reactive sputtering. *Applied Optics*, 56(4): C65-C70. https://doi.org/10.1364/AO.56.000C65

3.6 Gibson, D., Song, S., Fleming, L., Ahmadzadeh, S., Chu, H., Sproules, S., Swindell, R., Zhang, X., Navabpour, P., Clark, C. and Bailey, M., (2020) Durable infrared optical coatings based on pulsed DC-sputtering of hydrogenated amorphous carbon (a-C:H). *Applied Optics*, 59(9): 2731-2738. https://doi.org/10.1364/AO.378266

<u>**Grants**</u>

3.A Gibson, D., Reid, S., *Investigations in Gravitational Radiation*, Science & Technology Facilities Council, October 2013 to September 2017, GBP319,410

3.B Gibson, D., Reid, S., *Investigations in Gravitational Radiation*, Science & Technology Facilities Council, October 2016 to September 2017, GBP581,344

3.C Gibson, D., Shigeng, S,. *High Density Plasma Assisted Electron Beam Deposition of Precision Optical Coatings offering enhanced throughput and retrofitability to existing & new deposition*

systems, UK-China Industry Academia Partnership Programme, Royal Academy of Engineering, April 2017 to March 2019, GBP47,468.

3.D Gibson. D., Shigeng, S., *Novel microwave plasma sputter process enhanced durability coatings NMPLAS*, Innovate UK, January 2018 to December 2020, GBP161,408.

3.E Gibson. D., Shigeng, S., Vichare, P., *Novel microwave plasma sputter (NMPLAS) deposition process providing high throughput optical coating*, Innovate UK Shanghai-UK industrial challenge programme, January 2018 to December 2020, GBP145,732.

3.F Gibson. D., Shigeng. S., Vichare. P., **Birney. R.,** Knowledge Transfer, *Microwave plasma assisted sputter deposition of optical coatings*, Innovate UK: KTP with Teer Coatings Ltd, November 2020 to July 2023, GBP169,886.

Patents

3.G Gibson, D., Hutson, D., Song, S., & The University of the West of Scotland, 2020, "*An absorber, a detector comprising the absorber and a method of fabricating the absorber*", application number P123804.GB.01.

3.H Gibson, D., Song, S., & The University of the West of Scotland, 2017, "*Apparatus and methods for depositing durable optical coatings*", application number GB1706581.4.

3.I Gibson, D., Hutson, D., Song, S., & The University of the West of Scotland, 2017 "*Apparatus and Methods for Depositing Variable Interference Filters*", application number GB1702478.7.

4. Details of the impact

Process from research to impact: Fundamental research into new plasma sources for assisted electron beam (section 2.1) and microwave plasma sputter deposition (sections 2.2 & 2.3) was conducted by ITFSI researchers, publishing regularly in some of the most influential journals and protecting intellectual property via three patents **[3.G-3.I]**. The ITFSI researchers led the initial and follow-on work, all conducted at UWS, funded by a series of Knowledge Transfer awards (approximately. GBP353,000) alongside research council grants (approximately GBP1,800,000). Research work and knowledge transfer was strengthened through two industry-funded PhD projects - Thin Film Solutions Ltd (TFSL) **[5.1** (EPSRC CASE PhD Studentship – 2012 to 2015), **[3.1]** and Helia Photonics Ltd (HPL) **[5.2, 3.2]** sponsored PhD studentship (2015 to 2018) **[3.2],** progressing theoretical and performance investigation of the hollow cathode plasma source for low pressure plasma ion assisted electron beam deposition **[3.C].**

The Coating Division Manager at Orion Photonics Ltd (OPL), who have deployed two UWS ITFSI plasma sources, commented **[5.3]:** *"The knowledge exchange programme has retrofitted UWS ITFSI patented plasma technology into Orion Photonics Ltd electron beam deposition production, providing transformative low temperature processes with higher throughput, enhanced laser induced damage thresholds and capability to deposit optical coatings onto temperature sensitive substrates*."

Two additional self-funded PhD studentships and STFC funding **[3.A]** established novel microwave sputtering research [(section 2.2 – MPIBS**) [3.3, 3.4, 3.A, 3.B]** (section 2.3 – MPAS) [**3.5, 3.6, 3.D, 3.E; 3.G, 3.H, 3.I].**

The chief technical officer Teer Coatings Ltd (TCL), commented **[5.4, 3.F]:*"****The MPAS equipment, funded from an InnovateUK project (UWS and TCL project partners), is production capable. This unique capability opens up access to new global markets for TCL, specifically sale of MPAS equipment into existing TCL markets and opening up new markets in optical coating deposition equipment*."

All cited PhD studentships were completed within the REF period.

Description of impact: During the period 2014-2020, the plasma based thin film manufacturing technologies in question have had impact in a wide range of sectors. For example, the Advanced Process & Coatings Director at Qioptiq, Europe's largest optical coating manufacturing facility, writes: "*This resulting novel optical thin film technology is relevant to a range of Qioptiq product areas*, providing enhanced performance and competitiveness", **[5.5]**. In recognition of exemplary knowledge exchange, HPL **[5.2]** won the Centre for Engineering Education & Development Knowledge Exchange Award 2020 **[5.8]**. The specific knowledge exchange related to transfer of UWS ITFSI plasma assisted deposition technology to HPL; now in full production at HPL **[5.2]**, Orion Photonics **[5.3]** and Jason Vacuum Company Shanghai (JAVAC) **[5.6].** This represents a total economic value of approximately GBP11,000,000, with a further breakdown provided in the following section and corroborating sources. The impact, therefore, is evidenced in societal as well as economic benefits. High level physics jobs have been created, as also detailed below and in corroborating sources.

Reach and significance: Through a Royal Academy of Engineering UK-China Industry Academia Partnership Programme **[3.C],** WS hollow cathode plasma source technology has been transferred to Shanghai Jason Vacuum Co. Ltd (JAVAC) - plasma source deployed by UWS into a production electron beam deposition system at JAVAC facility **[5.6].** Tongji University (Shanghai) was the Chinese university partner **[5.7].** Technology is now being actively marketed by JAVAC for deployment in production electron beam deposition systems with sale of approximately 30 to 50 systems per year, value GBP2,200,000 per annum **[5.6].**

The director of the optical coating research group, Tongji University Shanghai **[5.7],** commented: *"The project brought together the expertise of both academic partners UWS ITFSI and Tongji University optical coating research group. We aim to further our collaboration in gravitational wave detection. The process for obtaining high performance optical coatings to meet the requirements of the next generation of gravitational wave detectors."*

UWS hollow cathode plasma technology has also been retrofitted into previous configuration UWS plasma sources at the Laboratory for Laser Energetics (LLE), University of Rochester USA **[5.1].** LLE have deployed four plasma sources, upgraded with the new hollow cathode configuration, for assisted electron beam deposition of optical thin films utilised in the laser optics utilised in the USA laser inertial confinement fusion development at the LLE and Lawrence Liverrmore facilities **[5.1].**

UWS ITFSI plasma source technology applied to thin film manufacturing and additional income and personnel is summarised as follows: sales accrued over the REF period 2014 to present from UK companies TFSL **[5.1]**, HPL **[5.2]** and OPL **[5.3]** is approximately GBP5,000,000, with an additional six physics graduate based personnel.

The MPAS technology has been proven in UK companies HPL **[5.2]**, TCL **[5.4]** and Qioptiq **[5.5]** via an Innovate UK project **[3.D, 3.6, 3.G, 3.H, 3.I]**. This programme has now completed and is followed by a Knowledge Transfer Partnership **[3.F],** Forecast sales from combined MPAS equipment and coating service sales is approximately GBP980,000 per annum and two additional personnel from TCL **[5.4].** Chinese company JAVAC MPAS equipment sales USD 7,000,000 per annum **[5.6]**. The CEO and founder of JAVAC commented **[5.6]:**

"As circa 90% of the world market for such optical coatings are satisfied from China based production, this new UK developed sputter technology provides JAVAC with innovative optical coating deposition technologies to satisfy the Chinese requirement for high throughput vacuum deposition systems".

Commercial exploitation of the MPAS technology is being progressed through UWS ITFSI spinout company Albasense Ltd, with a license based business model.

5. Sources to corroborate the impact

5.1. Thin Film Solutions Ltd – plasma source for assisted optical coating deposition deployed globally

5.2. Helia Photonics Ltd – plasma source deployed and in full production usage

5.3. Orion Photonics Ltd - plasma source deployed and in full production usage

5.4. Teer Coatings Ltd – MPAS deployed and follow-on KTP to implement

5.5. Qioptiq Ltd – MPAS processes relevant to Qioptiq business

5.6. Jason Vacuum Company Shanghai – plasma source assist technology and MPAS machine deployed introducing new high throughput optical coating deposition capability

5.7. Tong Ji University Shanghai – Plasma assisted technology characterisation and application to gravitational wave detection

5.8: Ceed Knowledge Exchange Award (Ceed knowledge exchange award re transfer of plasma assisted electron beam deposition technology from UWS to Helia Photonics Ltd - https://www.linkedin.com/posts/johnnymone_the-ceed-centre-for-engineering-education-activity-6636560045154816001-WgYN