Institution: University of Glasgow (UofG)		
Unit of Assessment: UoA12 Engineering		
Title of case study: Photonics research delivers improved commercial gas sensors used in the food packaging, aerospace, personal safety systems industries.		
Period when the underpinning research was undertaken: 2011–2018		
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:**
Prof Marc Sorel	Professor	1998–present
Prof Iain Thayne	Professor	1995–2020
Prof David Cumming	Professor	1999–present
Dr Matthew Steer	Research Assistant; KTP Associate; Research Associate	2008–2012; 2012–2015; 2015–2020
Period when the claimed impact occurred: 2014–present		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

UofG photonics research developed antimonide-based gas sensors in collaboration with Gas Sensing Solutions Ltd., generating economic and healthcare impacts. The resulting new products have been strategically important to Gas Sensing Solutions, enabling the company to place their wearable and portable gas sensing products in food packaging, aerospace, personal safety systems markets. This has resulted in sales of >250,000 gas sensors in >46 countries, to customers including NASA. Gas Sensing Solutions sensors are central to healthcare products including N-Tidal, a new lung function-monitoring device generating **[text removed for publication]** revenue for Scottish product design SME Wideblue Ltd., through the production of >1,000 devices for NHS hospitals amidst the COVID-19 pandemic. The Gas Sensing Solutions/UofG partnership underpins the GBP6 million MIRAGE industrial collaboration project, which has established Scotland at the forefront of the global sensors and imaging market.

2. Underpinning research

Non-dispersive infrared (NDIR) sensors are commonly used to measure carbon dioxide (CO_2) gas. NDIR gas sensors comprise an infrared (IR) light source, a sample of CO_2 gas and a detector. As the IR light passes through the gas sample, the CO_2 gas molecules absorb a specific band of IR light, while allowing other wavelengths of light to pass through. At the detector end, an IR detector reads the remaining amount of light that was not absorbed by the CO_2 molecules.

Light-emitting diodes (LEDs), made with semiconductors, are commonly used as the light source in NDIR sensors. Antimonide based LEDs have emerged as a disruptive source technology for gas sensing as they are low power, low cost, fast, compact and robust.

Molecular-beam epitaxy (MBE) is a method for thin-film deposition of single crystals used widely in the manufacture of semiconductor devices. Researchers at UofG have over 30 years of experience in MBE growth and characterisation, with UofG researchers driving research programmes specifically developing LEDs. The UofG MBE capability led Gas Sensing Solutions to initiate a collaboration with UofG in 2010 and to fund research projects focused on the development of antimonide semiconductor LEDs.

The first period of Gas Sensing Solutions-funded collaboration with UofG (2011–2013) identified novel growth processes and, within months, quality antimonide semiconductors were produced

for use in the manufacture of prototype LED sensors that opened new markets for Gas Sensing Solutions. Subsequent research focused on improving the quality and sensitivity of the antimonide semiconductors and the NDIR devices in which they were used [3.1, 3.2]. An accompanying Gas Sensing Solutions-sponsored Industrial CASE studentship (2011–2015) to investigate the behaviour of the prototype devices, advanced UofG understanding of the electrical and optical properties of antimonide LEDs through characterisation of the material and fabrication of prototype devices [3.3, 3.4]. This delivered a 3-fold enhancement in the emitted light, making the NDIR sensors more efficient.

The integration of the new LEDs into prototype gas sensors was undertaken in a KTP (2012–2015) with Dr Matt Steer, UofG, to industrialise UofG-based academic-style processes and transfer the technology to Gas Sensing Solutions. This assured an in-house supply of antimonide materials and thus Gas Sensing Solutions' supply chain for device manufacture. The project facilitated the production of new, larger area, antimonide semiconductor materials, which reduced production costs. UofG research incorporated the new antimonide semiconductor materials to improve the LED efficiency and reduce power consumption, thus making possible battery life of the order of decades.

The MIRAGE project (https://censis.org.uk/censis_projects/mirage/, 2015–2019) was a GBP6 million collaborative research and development project, supported by Scottish Enterprise and CENSIS. This project led to the development of novel epitaxial structures which produced multispectral mid-infrared LEDs facilitating the simultaneous sensing of multiple gases using the same source [3.5, 3.6].

3. References to the research

3.1. Peralagu, U. , Povey, I. M., Carolan, P., Lin, J., Contreras-Guerrero, R., Droopad, R., Hurley, P. K.and Thayne, I. G. (2014) Electrical and physical characterization of the Al_2O_3/ *p*-GaSb interface for 1%, 5%, 10%, and 22% $(NH_4)_2S$ surface treatments. *Applied Physics Letters*, 105(16), 162907. (doi:10.1063/1.4899123)

3.2. Meriggi, L., Steer, M. J., Ding, Y., Thayne, I. G., MacGregor, C., Ironside, C. N. and Sorel, M. (2015) Enhanced emission from mid-infrared AlInSb light-emitting diodes with p-type contact grid geometry. Journal of Applied Physics, 117(6), 063101. (doi:10.1063/1.4905081)

3.3. Xie, C., Pusino, V., Khalid, A.-u.-H., Steer, M., Sorel, M., Thayne, I. and Cumming, D. (2015) Monolithic integration of an active InSb-based mid-infrared photo-pixel with a GaAs MESFET. IEEE Transactions on Electron Devices, 62(12), pp. 4069-4075. (doi:10.1109/TED.2015.2492823)

3.4. Ding, Y., Meriggi, L., Steer, M., Fan, W., Bulashevich, K., Thayne, I., Macgregor, C., Ironside, C. and Sorel, M. (2016) Design, simulations, and optimizations of mid-infrared multiple quantum well LEDs. Procedia Engineering, 140, pp. 36-42. (doi:10.1016/j.proeng.2015.10.153)

3.5. Pusino, V., Xie, C., Khalid, A., Steer, M. J., Sorel, M., Thayne, I. G. and Cumming, D. R.S. (2016) InSb photodiodes for monolithic active focal plane arrays on GaAs substrates. IEEE Transactions on Electron Devices, 63(8), pp. 3135-3142. (doi:10.1109/TED.2016.2578982)

3.6. Aziz, M., Xie, C., Pusino, V., Khalid, A., Steer, M., Thayne, I. G. and Cumming, D. R.S. (2017) Multispectral mid-infrared light emitting diodes on a GaAs substrate. Applied Physics Letters, 111(10), 102102. (doi:10.1063/1.4986396)

4. Details of the impact

Gas Sensing Solutions was founded in 2005, focussing on the development of antimonide-based solid state LED detectors for carbon dioxide (CO_2) sensing. Antimonide wafers were originally obtained using molecular beam epitaxy (MBE) under licence from a UK government funded Qinetiq facility. Following the withdrawal of government funding for Qinetiq, UofG first acquired the MBE facility before selling it to Gas Sensing Solutions (2010). A relationship developed from this and UofG continued to support Gas Sensing Solutions by carrying out specialist research through funded projects, leading to the development and production of NDIR sensor products that underpin Gas Sensing Solutions' commercial success.

The UofG research has led to:

(a) commercial and economic impacts for Gas Sensing Solutions and its customers.
(b) health and safety impacts from their use in a precision lung function-monitoring device and in astronaut safety experiments carried out by NASA.

Commercial and economic impacts

The global gas sensing market was valued at USD2.19 billion in 2019 by Grand View Research and is anticipated to grow at 8.3% per annum between 2020 and 2027 [5.1]. The UofG/ Gas Sensing Solutions partnership has produced the next generation of mid-IR sensors that enabled Gas Sensing Solutions to enter new sensing markets, including healthcare, aerospace and the personal safety market for wearable and portable gas sensors [5.2, 5.3]. As a direct result of the collaboration with UofG, since 2010 Gas Sensing Solutions have sold >250,000 non-dispersive infrared (NDIR) sensors worldwide, exporting to >46 countries [5.2].

Gas Sensing Solutions won the prestigious Innovation Award from the Institute of Physics for development and commercialisation of their range of LED-based CO_2 sensors (2014) [5.4]. Acknowledging the technology developed at UofG and its innovative and commercial significance to Gas Sensing Solutions, a KTP was established to strengthen the relationship between UofG and Gas Sensing Solutions in 2012, which was shortlisted for the 'Best of the Best' KTP Award (2015) [5.5].

UofG / Gas Sensing Solutions' solid-state CO_2 sensors are used extensively by the horticulture and food packaging industries. Typical applications include grain storage, plant growth, incubators, and mushroom and dairy farms. Modified Atmosphere Packaging (MAP) for food uses CO_2 to prolong the shelf-life of food produce [5.2]. Food quality control requires accurate and rapid monitoring of CO_2 levels on the packing line. Conventional CO_2 sensors take several minutes to stabilise and produce readings whereas the Gas Sensing Solutions portable CO_2 analyser, based on UofG research, takes seconds. an essential characteristic for high-speed packing lines. Gas Sensing Solutions supplies these analysers to companies worldwide, including Storage Control Systems (UK and USA), TecSense (Germany) and Iijima (Japan) [5.2]. Gas Sensing Solutions' customers now have faster quality control checks. Although unable to disclose financial savings, Gas Sensing Solutions are aware that these faster checks have generated economic impacts for their customers [5.2].

The Gas Sensing Solutions / UofG partnership formed the foundation of the GBP6 million MIRAGE industrial collaboration project, backed by Scottish Enterprise and CENSIS, which enabled Gas Sensing Solutions to meet commercial strategy objectives centred around collaboration [5.2, 5.3]. MIRAGE was launched in 2016 and brought together four Scottish companies to establish Scotland at the forefront of the global sensors and imaging market. Between 2016 and 2026, the

project is expected to bring GBP56 million to the Scottish economy. As co-founders of the MIRAGE project, Gas Sensing Solutions accessed UofG technical expertise which enabled them to begin the development of a new sensor for methane [5.2]. Gas Sensing Solutions is now developing a uniquely low-power, portable methane sensor for safety assurance in the home [5.2].

Health and safety impacts

Gas Sensing Solutions' gas sensors are critical to a new device developed in a consortium with Wideblue Ltd. and Cambridge Respiratory Innovations Ltd (CRiL) [5.2, 5.6, 5.8]. The device, called N-Tidal™, is a CE-marked, hand-held device for monitoring and managing lung diseases [5.8]. Gas Sensing Solutions' antimonide LED is at the heart of the new sensor [5.2, 5.6, 5.7]. N-Tidal was launched in 2017 for clinical trial data collection and its advanced prototypes have been used over 40,000 times in six clinical studies [5.6]. The annual economic burden of asthma and COPD on the NHS in the UK is estimated as GBP3 billion and GBP1.9 billion respectively, and N-Tidal is reducing this burden by providing early warnings to the >6 million people in the UK with lung diseases.

In response to the COVID-19 pandemic, CRiL accelerated the development of N-Tidal and its approval for clinical use for the early detection of lung function deterioration and patient responses to therapeutic interventions [5.9]. Additional economic impacts have been generated for product designers, Wideblue Ltd, **[text removed for publication]**

NASA recently carried out research at the International Space Station to determine the effects of CO_2 on astronauts [5.9, 5.10]. CO_2 analysers from Gas Sensing Solutions, developed using UofG technology, were selected because of the tiny amount of power used by their proprietary, mid-range, infrared LEDs and the resulting long operational life of their batteries [5.10]. This research identified that crew members develop CO_2-related symptoms at lower CO_2 levels than would be expected terrestrially. NASA reported that this research will facilitate design of *"appropriate wearable technology for future space missions"* [5.9].

5. Sources to corroborate the impact

[PDFs available, unless otherwise indicated]

5.1. Gas Sensing Market Size, Share and Trends Analysis Report by Grand View Research.
5.2. Testimonial: CEO of Gas Sensing Solutions.
5.3. Testimonial: former CEO of Gas Sensing Solutions.
5.4. IOP Innovation Award Article.
5.5. Gas Sensing Solutions press release: KTP 2015 Award Nomination.
5.6. CRiL overview February 2019 video. https://www.youtube.com/watch?v=vHZoUdVZm3w
5.7. Commercial information from Wideblue Ltd.
5.8. Medical Technology Article: 'Catch your breath: A Device that Spots Critical COVID-19 Cases'.
5.9. Gas Sensing Solutions press release: NASA Research Update.
5.10. Press Release: 'GSS CO_2 Sensors Used on International Space Station'.