Institution: University of Warwick

Unit of Assessment: B12 – Engineering

Title of case study: Gas sensor technology: achieving global sales and developing innovative solutions for indoor air quality

Period when the underpinning research was undertaken: 2001 – 2016

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:
Julian Gardner	Professor	1987- Present
James Covington	Professor	2001 - Present
Prasanta Guha	Research Fellow	2008 - 2010

Period when the claimed impact occurred: August 2013 to December 2020

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

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

Low power gas sensors have a broad and profitable range of applications, including environmental monitoring and usage in smart homes and personal healthcare devices. Based on research from the Universities of Warwick and Cambridge, the spin-out Cambridge CMOS Sensors (CCS) was founded in 2008, with Warwick-patented IP built into the flagship CCS801 and CCS811 air quality sensor ranges. By 2016 CSS had attracted over GBP8,000,000 investment, and was subsequently sold to form ams Sensors UK Ltd in a deal in excess of EUR31,000,000. Based on strong performance of ams Sensors UK, in 2019 the CCS technology was used by ams to create a joint venture named ScioSense, valued at approximately USD120,000,000. The original Warwick IP remains of strategic importance to the new multinational, allowing them to better penetrate the consumer smart home market worldwide through continuing strong sales of CCS801 and CCS811.

2. Underpinning research (indicative maximum 500 words)

Professors Julian Gardner and James Covington of the Sensors and Devices group in the Warwick School of Engineering, in collaboration with Professors Florin Udrea (a former Warwick student) and Bill Milne of the University of Cambridge, undertook research on gas sensors, published in 2001, which proposed a new generation of sensors embedded in SOI (silicon on insulator) micro-hotplates, offering ultra-low power consumption (under 100 mW), high sensitivity, low noise, low unit cost, reproducibility and reliability through the use of on-chip integration **[3.1]**.

Between 2005 and 2011 the Warwick-Cambridge partnership built on earlier work with their research into nano-structured micro-power smart gas sensors, with Alphasense (UK) as an industrial collaborator **[G1]**. The Warwick team developed the underlying circuitry of the SOI CMOS (Complementary Metal-Oxide Semiconductor – an on-board, battery powered semiconductor chip inside computers that stores information) device, using nested meandering resistors. The Cambridge team were responsible for aspects of the SOI component design, including the tungsten micro hot-plate and a deep-reactive ion etch process.

A core advantage of the sensor was the possibility of fabricating both the CMOS circuitry with the micro-heater in a single step, greatly reducing the complexity of the manufacturing process due to the circuitry's integration into the device. Warwick additionally played a vital role in testing the measurement capabilities of the prototypes, developing a test-rig for gas sensing which could simulate different levels of humidity, heat the sensor and maintain appropriate pressures of different gases. This proprietary technology was incorporated into two patents filed at Warwick in

2005 and granted in 2009 and 2010 respectively, which protected the key innovative single step fabrication of a SOI or CMOS gas sensing device with its electronic circuitry **[3.2-3.3]**.

The devices were designed to detect ethanol, H_2, NH_3, O_3, CO, NO_x, and benzene-related hydrocarbons (collectively known as VOC, or volatile organic compounds), with lower power consumption, more accurate temperature control and order of magnitude improved sensitivity to gases when compared with silicon micro-electro-mechanical system (MEMS) devices **[3.4-3.6]**.

The research outcomes include innovative use of materials and proprietary designs such as CMOS-compatible tungsten for the thermal wire, gold for electrodes, and ultra-high temperature SOI diodes for temperature sensing **[3.1, 3.4-3.5]**. The physical properties of the tungsten metal layer provide a high melting point and resistance against electro migration but also CMOS compatibility (the main technology in the microelectronics industry). This is a clear advantage over competitors using platinum heaters.

The resulting platform incorporates temperature, gas, humidity, pressure and flow sensors. The research also covered fabrication, involving two major steps: (i) a microelectronics process, which ensures compatibility with integrated circuit processing and on-chip drive and read-out circuits, and (ii) membrane formation using deep reactive ion etching. Both steps have been integrated in a single commercial foundry. **[3.1, 3.4]**

From 2011 to 2016, during which time CCS was acquired by ams (Austria), Gardner and Udrea continued research, together with CCS / ams and others, into smart SOI sensing systems operating at high temperature (SOI-HITS), in a collaborative project in the EU FP7 programme **[G2]**. This research focused on a micro-inkjet printing technique for the deposition of carbon nanoparticles and fullerene adlayers onto SOI infrared light sources to enhance their infrared emission. The work showed a significant increase in the infrared emission efficiency of the coated emitters, and a 90% improvement in IR emission power density. Built-in electronic interfaces enabled the sensors to work in harsh, high-temperature (225°C) environments, compared to 125°C for conventional sensors **[3.7]**.

3. References to the research (indicative maximum of six references) **Warwick = Bold**

All research papers were published in peer-reviewed journals

[3.1] Udrea, F., **Gardner, J. W.**, Setiadi, D., **Covington, J. A.**, Dogaru, T., Lu, C. C. and Milne, W. I. (2001) *Design and simulations of SOI CMOS micro-hotplate gas sensors*. Sensors and Actuators B: Chemical, 78 (1). pp. 180-190. doi: 10.1016/S0925-4005(01)00810-3

[3.2] Gardner, J. W., **Covington, J. A.** and Udrea, F.: 'Gas-sensing semiconductor devices'. US Patent US7495300B2, February 2009 (priority date January 2005)

[3.3] Gardner, J. W., Udrea, F, **Iwaki, T.** and **Covington, J. A.**: 'Gas-sensing semiconductor devices'. US Patent US7849727B2, December 2010 (priority date September 2005).

[3.4] Ali, S. Z., Udrea, F., Milne, W. I. and **Gardner, J. W.** (2008) *Tungsten-Based SOI Microhotplates for Smart Gas Sensors*. Journal of Microelectromechanical Systems, 17 (6). pp. 1408-1417. doi: 10.1109/JMEMS.2008.2007228

[3.5] Santra, S., **Guha, P. K.**, Ali, S. Z., Hiralal, P., Unalan, H. E., **Covington, J. A.**, Amaratunga, G. A. J., Milne, W. I., **Gardner, J. W.** and Udrea, F. (2010) *ZnO nanowires grown on SOI CMOS substrate for ethanol sensing*. Sensors and Actuators B: Chemical, 146 (2). pp. 559-565. doi: 10.1016/j.snb.2010.01.009

[3.6] Ali, S. Z., Santra, S., Haneef, I., Schwandt, C., Kumar, R. V., Milne, W. I., Udrea, F., **Guha, P. K.**, **Covington, J. A.**, **Gardner, J. W.** and Garofalo, V. (2009) *Nanowire hydrogen gas sensor employing CMOS micro-hotplate* SENSORS, 2009 IEEE, pp 114-117. doi: 10.1109/ICSENS.2009.5398224

[3.7] De Luca, A., Udrea, F., Li G., Zeng, Y., André, N., Pollissard-Quatremère, G., Francis, L. A., Flandre, D., Racz, Z., **Gardner, J.W.**, Ali, S. Z., Buiu, O., Serban, B.C., Cobianu, C. and Wotherspoon, T. (2016) *Sensors and Sensor Systems for Harsh Environment Applications.* In Semiconductor Devices in Harsh Conditions, Ch5, pp87-107, CRC Press, Delaware. doi:10.1201/9781315368948

Awards:

[A1] Gardner received the Instrumentation and Measurement Society's 2017 IEEE Technical Award "*for outstanding contribution to the field of chemical sensing over a period of 25 years… Gardner is a pioneer in the measurement of gases and odours using electronic based instrumentation."* Gardner was made a Fellow of IEEE in 2019 for contributions to electronic noses and gas sensors*. https://ieee-ims.org/awards/technical-award*

[A2] Professor Julian Gardner FREng and Professor Florin Udrea FREng were jointly awarded the 2018 Royal Society Mullard Award "*for their work as renowned academics and serial entrepreneurs who together founded and led the most successful Cambridge University spin-off in the physical sciences, active in environmental and air quality sensors*". This award is given to academics whose work is making a contribution to national prosperity in the UK. https://tinyurl.com/4j6nd7ak

Grants:

[G1] Gardner, J., Covington, J. A. *Nano-structured micro-power smart gas sensors.* **Sponsor:** EPSRC [EP/F002971/1] **Duration:** Feb 2008 – Jan 2011 **Award**: GBP242,828

[G2] Gardner, J. *Smart Silicon on Insulator Sensing Systems Operating at High Temperature* (SOI-HITS). **Sponsor:** European Commission [288481] **Duration:** Sep 2011 – Dec 2014 **Award:** EUR3,025,382

[G3] Gardner, J. *Real-Time H2 Purification and Monitoring for Efficient and Durable Fuel Cell Vehicles.* **Sponsor:** ESPRC [EP/L018330/1] **Duration:** Mar 14 - Sep 18 **Award:** GBP1,005,820

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

To exploit patented innovations from both Warwick and Cambridge, Cambridge CMOS Sensors (CCS) was founded by Julian Gardner (Warwick) along with Florin Udrea and Bill Milne (Cambridge) in August 2008 with seed investment from the University of Cambridge and Cambridge Angels. A shareholding was released for Warwick through transfer of its IP (patents **[3.2-3.3]**, among others) into the new spin-out. From its inception in 2008, CCS grew to be one of the most successful physical sciences spin-offs in Cambridge University's history **[A2]**, producing a range of novel gas sensing solutions:

Impact on technology and innovation: from big industry to small and smart wearables

Gas sensor technology, patented by Warwick and developed from 2008 by CCS into the original CCS801 and CCS811 sensor ranges, is still in use to this day in the form of metal oxide (MOX) sensors to monitor indoor air quality **[5.1-5.2]**. The technological advancements made in these sensors offered a radical improvement in performance over the competition, opening up multiple markets which were previously unserviceable **[5.3]**. Key features of this technology include **[5.4]**:

- Ultra-low power consumption: the CCS811 requires 46 mW; the main competitor from Applied Sensors needs 100 mW.
- Very small form factor: it requires a module 1/10 in size compared to others.
- Cost advantage: it has a 50% to 90% cost advantage over the competition, enabling lowest unit cost.
- Multi-sensor integration: full CMOS compatibility – this enables integration of additional sensor modalities like relative humidity, temperature and pressure, and other 'on-chip' functions like amplifiers, and close loop control of temperature.
- Ease of volume manufacture: this is due to the use of standardised automated high-volume semiconductor manufacturing processes, which also delivers high yields.

Initially, the markets for these sensors were industrial, medical and automotive, where the applications (fibre optics, air cleaners and purifiers) were in specialist equipment normally used by trained operators. Later, the tech was deployed in smart buildings and homes (heating, ventilation and air conditioning, or HVAC, systems, cooker hoods). Recently, a new range of MOX sensors

have been developed which promise smaller sizes, lower prices, and embedded 'intelligence' for ease of use and integration, in a wide range of consumer-oriented products (handheld and portable devices such as smartphones and wearables), with no special experience or knowledge needed by the end user.

Upon acquisition of CCS by ams in 2016 to create ams Sensors UK Ltd (see Impact on commerce), the company used this sector-leading technology to attract new clients and break into advantageous marketplaces. Since August that year HiCling, the leading Chinese wearable device manufacturer, has used the CCS gas sensors to enable their Cling VOC smart fitness wristband to measure indoor air quality and alcohol in breath. When integrated in the Cling VOC wristband, the CCS801 gas sensor can detect low levels of volatile organic compounds (VOCs) typically found indoors – cigarette smoke or solvents, for example. These measurements provide an indication of air quality on the display. The wristband also provides alcohol breath analysis, as the sensor can detect ethanol on human breath. The small footprint and low profile of the CCS8xx family of gas sensors mean that they fit the slim and sleek design of the Cling VOC. Their ultra-low power consumption and fast response times are also critical for wearable devices **[5.5]**.

Richard Chen, CEO of HiCling, stated that "*ams group company CCS has developed the world's smallest and lowest-power MOX gas sensors on the market… Most people spend most of their time indoors, so it is important that they are able to monitor air quality easily and to take appropriate action – something that wearers of the Cling VOC wristband can now do*" **[5.5]**

Impact on commerce: from small seed-funded spinout to leading global manufacturer

By 2014, under the strong leadership of Gardner as Chief Technology Officer (CTO) and Udrea as Chief Executive Officer (CEO), CCS had become an industry leader in advanced sensor solutions, providing sensor technology across multiple global markets with high-volume supply chains **[5.3]**. Over the next 2 years CCS increased its staff to 33, moved to larger offices within Cambridge, and – after establishing a customer base in the Greater China region – opened an office in Taiwan in 2015 **[5.3, 5.6]**. Between June 2013 and December 2015 with excitement building around the spin-out's technological offering, CCS attracted GBP8,000,000 from investors, with the IP from original Warwick patents **[3.2-3.3]** being integral to this investment **[5.1, 5.7]**.

Later that year, ams – an Austrian-based multinational specialising in sensor technology and sensor solutions – acquired CCS to form ams Sensors UK Ltd. While the total multimillion euro sales price remains undisclosed, as part of the deal ams committed to pay profit-dependent purchase price share of up to EUR31,000,000 (06-2016), based on sales of CCS technology up to 2020 as an earn-out provision **[5.8]**. On the significant value added to ams from the acquisition, Alexander Everke, CEO of ams, stated: "*The addition of [CCS] … completes ams' portfolio of products and technologies for the environmental sensor market. This highly strategic acquisition is therefore another key step in making ams the world's leading provider of sensor solutions for consumer, automotive, industrial, and medical applications*" **[5.6]**. The former Senior Director of Engineering at ams Sensors UK Ltd stated that the CCS801 and CCS811 ranges – inseparable from the original Warwick IP – were "*at the heart of the ams acquisition of CCS"* **[5.1]**.

Between 2016 and 2019 ams Sensors UK achieved a respectable turnover of approximately GBP5,500,000 **[5.9]**, with sales of CCS801 and CCS811 being fundamental to this success **[5.1]**. Based on a unit price of GBP2.95 (incl. VAT) for bulk purchases of CCS801 **[5.10]**, this represents approximately 1,850,000 unit sales over the four-year period. Later in 2019, Wise Road Capital – a global private equity firm specialising in emerging high-tech industries – created a joint venture with ams called ScioSense (Netherlands), valued at approximately USD120,000,000 (03-2019) **[5.11]**. A key element of Wise Road Capital wanting to set up the venture was the perceived value of the CCS801 and CCS811 ranges **[5.1]**. Overall, ScioSense brought together the IP, employees and sensor products of ams Sensors UK and other parts of the ams group **[5.2]**.

In 2020, ScioSense has surpassed the successes of CCS and ams Sensors UK, employing over 100 staff, with offices in four countries (China, Germany, Italy and the Netherlands) and a network

of distributors in Europe, Asia and the US. A world leader in environmental and flow sensing technology, the company provides across the automotive, industrial, consumer goods and environmental markets to OEMs, Tier 1s, Tier 2s and more **[5.2]**.

CCS801 and CCS811 continue to add value to the company, with both sensor ranges supporting jobs and being sold in "*considerable volumes*" up to the end of 2020. Further, they are strategically important to ScioSense's product portfolio, allowing it to penetrate the consumer home automation and building automation (smart home and office) markets more successfully than they could do otherwise **[5.2]**. R&D based on the original IP **[3.2-3.3]** remains active in ScioSense and important to the company's future, with their CTO confirming, "*Further sensor ranges are currently under development based in part on these original patents, which are expected sell in multimillion quantities in the coming years starting in 2021*" **[5.2]**.

Overall, the journey from Cambridge CMOS Sensors through to ams Sensors UK and then onto ScioSense marks a story of award-winning and lucrative entrepreneurship with its roots in academic collaboration. Continuing development and sales based on university IP, in the words of the former Senior Director of Engineering of ams Sensors UK, is an indication of its "*enduring value"* **[5.1]**.

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

[5.1] Statement from former Senior Director of Engineering, ams Sensors UK Ltd, 2017 – 2019 (current VP of Engineering, Flusso Ltd)
[5.2] Statement from Chief Technology Officer, ScioSense
[5.3] *Cambridge CMOS Sensors Opens Taiwan Office* (Business Wire, 29.09.15 https://tinyurl.com/yysld9ma)
[5.4] ScioSense CCS801 and CCS811 product pages (CCS801: https://tinyurl.com/y5r4p6ey; CCS811: https://tinyurl.com/3mea9uwr)
[5.5] *Innovative gas sensors from ams enable new Cling VOC fitness wristband to measure indoor air quality and alcohol in breath* (ams, 16.08.16, https://tinyurl.com/y3eh6ubn)
[5.6] *Cambridge CMOS Sensors acquired by ams to become world leader in gas and infrared sensing* (Cambridge Enterprise, 16.06.16, https://tinyurl.com/y3ks9srl)
[5.7] Cambridge CMOS Sensors 2014 and 2015 abbreviated accounts, covering GBP8,000,000 investment (share premium) between June 2013 and December 2015 (2014: https://tinyurl.com/ep43sd73; 2015: https://tinyurl.com/2pkja4we)
[5.8] ams annual report 2017 https://tinyurl.com/v3zte8d7 (exerts provided as PDF evidence)
[5.9] ams Sensors UK accounts in 2017 and 2019, covering turnover 2016-2019 (2017: https://tinyurl.com/5b7952s8, 2019: https://tinyurl.com/3khese2m)
[5.10] CCS801 GBP2.46 unit price for 5000 units (GBP2.95 with VAT) from Digi-Key Electronics, an approved supplier of ScioSense https://tinyurl.com/2bcn7wjk
[5.11] *ams and Wise Road Capital advance further development for environmental flow and pressure sensors through creation of a joint venture* (ams, 18.03.19, https://tinyurl.com/7kbew3nd)