Institution: University of Warwick

Unit of Assessment: B15 General Engineering

Title of case study: Electronic noses for food, health and other applications (Case Study B15.7)

1. Summary of the impact:

The first commercial electronic nose (aka e-nose) instruments were designed, developed and built by researchers in Warwick's School of Engineering in the 1990s, and commercialized by [text removed for publication]

Warwick's patents in chemical sensing also led in 2008 to the creation of a spin-out company, Cambridge CMOS Sensors Ltd (CCS), which provides low-cost low-power gas-sensing technology and is already established in the gas-sensing market.

The smart sensors and instrumentation developed as a result of the pioneering research in artificial olfaction and chemical sensing have had economic impacts across a wide range of sectors, in particular in food quality, healthcare and consumer electronics. The two companies employ around 100 people and the thousands of e-nose instruments sold help quality assurance of foods, beverages and are now being deployed in hospitals for bacterial detection.

2. Underpinning research:

The measurement of smell is critical to industries worth billions of pounds, such as food processing, drinks, air quality, security (drugs) and cosmetics. Furthermore, malodour can be an indicator of bacterial infection and diseases so important for healthcare. Human (organoleptic) panels are routinely used to measure smell but are costly, slow and subjective hence the desire for an e-nose that can detect smell. To classify odours, the human olfactory system uses hundreds of different olfactory receptors and a specialized neural architecture. The functionality of such a complex system can be mimicked by an artificial system that uses electronic sensor arrays and pattern recognition algorithms. Building on the concept of an artificial nose - first proposed by the biochemists Dr George Dodd (Warwick until 1990) and Dr Krishna Persaud (Warwick until 1983) – Professor Julian Gardner (founder in 1987 of the Sensors Research Laboratory in Warwick's School of Engineering) and then PhD student Tim Pearce (graduated 1994) designed, developed and built the first commercial e-nose instruments in 1993 [1].

Warwick's first electronic nose comprised an array of non-selective resistive metal oxide (MOX) gas sensors coupled to signal pre-processing algorithms, with its output fed into a pattern recognition system based upon neuralinspired algorithms [2,3]. [text removed for publication]

[text removed for publication]

Early Warwick work included the use of metal oxide gas sensors and novel pre-processing and artificial neural networking algorithms [3] to solve complex multi-variate problems. The replacement of an organoleptic panel was very attractive to save cost and quantify different types of odours. In 1998, Gardner started work funded by an EPRSC grant [7] on silicon-based gas sensors. The project developed and proved the concept of low-power, silicon-on-insulator technology for metal oxide semiconductor field effect transistor (MOSFET) micro-hotplate heaters in gas detection that led to the first of several patents filed worldwide by Warwick [5]. This is the first proposed use of a transistor embedded in a thin silicon membrane to make a micro heater, i.e. an ultra low-power and low cost heater that can be integrated with standard complementary metal oxide semiconductor (CMOS) circuitry.

Gardner and Florin Udrea (former Warwick masters student (1999-2002) who moved to Cambridge in 2003) started a research collaboration funded by the EPSRC in 2008 [8]. Warwick specifically led the UK's silicon-based gas-sensor developments, as exemplified by a patented tungsten-based micro-hotplate designed using high-temperature CMOS) electronics [6] in 2006, which led to a 'smart-drive'-integrated on-chip control of a micro heater and hence silicon based gas sensor in

2008 [4].

Gardner and Udrea realised that silicon-based gas sensors had significant market potential in consumer electronics because cheap, low-power sensor devices (<$5) with high output-signal stability could now be made. The silicon-based gas sensors were thus designed to have low power consumption and accurate temperature control, and also a one-order-of-magnitude higher sensitivity to hydrogen, ammonia, ozone, carbon dioxide and nitrogen dioxide gases and to volatile hydrocarbons such as benzene than the metal–oxide gas sensors. These sensors overcame previous technical challenges that prevented existing MOX gas sensors from being used in portable, battery-powered instruments to measure hazardous toxic gases and in low-power automotive units for polluting combustion gases. The scope of the invention was covered by patents filed by Warwick.

Gardner (currently head of Warwick's Microsensors & Bioelectronics Laboratory, formerly known as the Sensors Research Laboratory) continues to push forward the research and development of electronic noses, in particular the optimization of instrumentation for a range of commercial applications, such as breath analysis for low-cost healthcare monitoring.

Key researchers were: Pearce (1993–1994), Hines (1993–1994) and Gardner (1993–2013).

3. References to the research:

Publications:

1. Pearce, T. C. and Gardner, J. W. "Machine olfaction: intelligent sensing of odours", *Proc. of IEEE conference on Systems, Man and Cybernetics* (Le Touquet, France, 17–20 October 1993) **5**, 165–170 Vol. 5, pp.165-170. (1993). DOI: 10.1109/ICSMC.1993.390843.

2. Hines, E. L. and Gardner, J. W. "An artificial neural emulator for an odour sensor array", *Sensors and Actuators B* **19**, 661–664 (1994). DOI: 10.1016/0925-4005(93)01117-M.

3. Gardner, J. W., Pearce, T. C., Friel, S., Bartlett, P. N. and Blair, N "A multisensor system for beer flavour monitoring using an array of conducting polymers and predictive classifiers", *Sensors and Actuators B* **18**,(1-3) 240-243 (1994). DOI: 10.1016/0925-4005(94)87089-6.

4. Ali, S. Z., Udrea, F., Milne, W. I. and Gardner J. W. "Tungsten-based SOI microhotplates for smart gas sensors", *J. Microelectromechanical Systems* **17**(6), 1408-1417 (2008). DOI: 10.1109/JMEMS.2008.2007228.

Patents: (two of the thirteen assigned by Warwick to CCS)

5. Udrea, F. and Gardner J. W,, UK Patent GB 2321336A, "Smart MOSFET gas sensor", July 1998. International Publication Number WO 98/32009, "Gas-sensing semiconductor devices", July 1998.

6. Gardner, J. W., Covington, J. A. and Udrea, F., UK Patent Application 0505192.5, "CMOS-compatible tungsten micro heaters", April 2006.

The Warwick patents relate to the invention of new CMOS micro-hotplates for mass application in gas sensing. Specifically, the use of both MOSFET and tungsten based heating elements which are compatible for a standard CMOS technology. This permits high temperature gas sensing sensors to be operated at much lower power, made at lower cost and integrated with interface circuitry.

Grants/awards:

7. PI: Gardner, J. W., "Smart MOSFET Gas Sensors Using SOI Technology", EPSRC GR/L92426/01, 01December 1998-31 August 2002, £99,179.

8. PI: Gardner, J. W., "Nano-structured Micro-power Smart Gas Sensors", EPSRC EP/F002971/1, 01-Feb-February 2008-31 January 2011, £242,828.

4. Details of the impact:

The research described in section two has had considerable economic and commercial impact. A

few examples of the impact that are not affected by confidential commercial considerations are described below.

A new business sector

In 1993, Gardner designed, developed and built the first commercial electronic nose for [text removed for publication]

[text removed for publication]

These instruments have meant improved quality assurance of food and beverage; polymers, plastics, and food packaging; pharmaceutical; tobacco; chemicals/petrochemicals; as well as in personal care; health; and environment industries.

Warwick and Alpha MOS developed customised electronic noses that could overcome challenges in the identification of complex odours in the absence of a standard reference or product [11]. The sensors have been used mainly in the food and drinks industry to identify taints and malodours (in coffees, teas, fish, meat, beers, colas and cheeses). Hundreds of companies are using Alpha MOS electronic noses today across the world to design new products, test them and also monitor manufacturing processes. The instruments have enable companies to save millions of pounds through reduced using of human panels and reduce product recalls due to malodours or taints.

Establishment of CCS

Cambridge CMOS Sensors (CCS) — a spin-off company founded in 2008 by Gardner with Udrea and Milne from Cambridge [12] [text removed for publication]

[text removed for publication]

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Another demonstration of investment is that CCS is a collaborative partner [text removed for publication] in the €10m EU project Smart Silicon-on-Insulator Sensing Systems Operating at High Temperature SOI-HITS, where the goal is to develop sensors designed to work in harsh (i.e. high-temperature, high humidity) environments. These devices could then be used in domestic boilers for combustion control (reduced carbon consumption) as well as inside engine exhausts.

Awards:
In October 2011, CCS was shortlisted and given a "Highly Commended" award for the category Start Up of the Year at the British Engineering Excellence Awards in recognition of its achievements [15].

In March 2013, CCS was elected CleanTech Company of the Year at the Business Weekly Award 2012 event, in recognition of its contribution to a range of sensor application areas [16].

Gardner was elected Fellow of The Royal Academy of Engineering in recognition of his achievements in gas sensors [17] and has served as Vice-President and then President of the International Society for Olfaction and Chemical Sensing (ISOCS) [18]. He is still a director of the society and a member of its Executive Committee.

5. Sources to corroborate the impact:

9. Alpha MOS website http://www.alpha-mos.com/analytical-instruments/heracles-electronic-nose.php

10. Letter from the Chief Executive Officer and Founder, Alpha MOS

11. Gardner, J. W. "Electronic nose technology today", *Proc. 1st Int. Symp. Olfaction & Electronic Noses, Toulouse, France, 26-27 September 1994,* organized by Alpha MOS.

12. CCS website http://www.ccmoss.com/home.html

13. Letter from the CTO of Cambridge CMOS Sensors corroborating impact in Section 4

14. Article in The Engineer 27 July 2009 focussing on CCS commercialisation in varying ways such as licenses for applications included in smoke alarms, laboratory analysis, medicine, automobiles, and industrial safety http://www.theengineer.co.uk/news/common-sensor/312407.article

15. British Engineering Excellence Awards (BEEA) 2011 programme p11 http://www.beeas.co.uk/winners/beeas-2011-winners.pdf

16. Article in Business Weekly, 19 March 2013.http://www.businessweekly.co.uk/hi-tech/15193-arm-takes-business-of-the-year-glory

17. List of academic Fellows of the Royal Academy of Engineering. http://www.raeng.org.uk/about/fellowship/default.htm

18. The International Society for Olfaction and Chemical Sensing (ISOCS) website. http://www.olfactionsociety.org/node/19