Institution: University of Sussex

Unit of Assessment: UoA 9 Physics

Title of case study: Electric Potential Sensor Technology – From Fundamental Physics to Product

1. Summary of the impact

A ground-breaking range of innovative sensor products – the EPIC Sensors – has been developed and marketed world-wide by Plessey Semiconductors Ltd. The EPIC Sensors allow contact-free measurements of electric phenomena, initially aimed at the health, sports and automotive markets. They operate on the non-invasive, low-cost, generic, award-winning Electric Potential Sensor (EPS) technology invented and developed at Sussex as a spin-off from fundamental low-temperature physics research. Income to the University from licence fees, costs and royalties started during 2012. Sustained industry engagement with key strategic partners in the medical, forensic, security, materials testing and geophysics sectors, including government organisations, industry and academia, is leading to a wider awareness and adoption of this novel technology.

2. Underpinning research

Electric Potential (EP) Sensor Technology was originally conceived as part of a fundamental low-temperature quantum circuit physics research project funded by EPSRC (GR/J35146/01, 1993–96, £232k; GR/K15565/01, 1994–97, £110k). The focus of this activity was to study, both theoretically and experimentally, the behaviour of SQUID systems as simple macroscopic quantum objects, akin to single atoms [see Section 3, R1]. Probing the energy-level structure and investing the conjugate flux and charge behaviour in a non-invasive, adiabatic manner involved the use of extremely sophisticated low-noise experimental techniques. Specialised shielded rooms and ultra-low noise temperature electronics were specifically developed for this project [R2]. As part of this programme of instrumentation development, a cryogenic electrometer was developed with extremely high input impedance and commensurately low input capacitance to enable the charge on the quantum system to be measured accurately. From the start it was apparent that this was a device with generic sensing capability quite unlike anything that had existed before. Initial funding for the sensor, as an independent research activity, was provided by two EPSRC awards (GR/H57516/01, 1993–94, £80k; GR/K38021/01, 1995–97, £81k). During this period the programme of fundamental physics research continued in parallel with the development of the sensor. This separate funding stream enabled research on the fundamentals of measurement at extreme impedances to be undertaken and for the measurement capability to be demonstrated in a range of different scenarios. The results of this work were to show that the sensor could operate using very small displacement currents (~10^{-15} A), through weak (<10^{-15} F) capacitive coupling over a broad range of frequencies from quasi-DC upwards [R3]. Additionally, the results revealed that this sensor could be used as the basis for a novel imaging microscope system [R4] which was not restricted to working within the tunnelling distance of the surface of the sample. Initial work on larger-scale electrode structures also yielded interesting results when applied to electro-physiological measurements. Conventionally these would use low impedance wet-gel electrodes. By adapting the EP sensor to operate through a larger (>10^{-12} F) coupling capacitance, it was possible to demonstrate low-noise electrocardiogram signal acquisition without the need for gel or resistive contact with the skin, so simplifying the procedure considerably [R5]. It is intrinsically stable, electrically and mechanically robust, and chemically and biochemically inert.

This work was followed by an RCUK Basic Technology award (GR/R87550/01, 2002–06, £1.1m) where the sensors were configured to measure either electric field, spatial potential or static charge, either through weak capacitive coupling or in free space. During this period, extensive research led to significant publications – including [R6], which won the IOP Measurement Science and Technology 'Best Paper Award' (2002) – and to the first of a suite of seven patents filed. A number of these are now granted worldwide (EP1451595, US7885700, JP4391823, TWI308066,

EP2002273, AU2007228660, US8264247, US8054061, CN101490564, EP2047284, US12/278214, JP2008552874), with the rest in process. In addition, there were 25 other journal publications relating to EP sensors in this period. Continued funding from the EPSRC (Translation grant EP/E042864/1, 2007–11, £893k) and industry (£1m) has since enabled a broad range of projects to be undertaken spanning a wide range of possible future application areas which clearly demonstrate the disruptive potential of the technology. These include electrophysiological sensing [R5,R6], movement detection and tracking, human machine interfacing, NMR instrumentation, materials characterisation [R3,R4], surface-charge imaging for forensic fingerprinting, and stress monitoring for geophysical applications and structural-health monitoring. At this stage it became clear that applications could span all length scales, ranging from μm to metres, with corresponding levels of spatial resolution, and sensors could also be integrated into one- or two-dimensional imaging arrays.

3. References to the research

R1 Prance, H., Prance, R.J., Clark, T.D., Spiller, T.P. and Clippingdale, A.J. (1993) 'Probing the nonlinear electric susceptibility of ultra-small capacitance weak links', *Physics Letters A*, 181(3): 259–266.

R2 Whiteman, R., Schollmann, V., Everitt, M., Clark, T.D., Prance, R.J., Prance, H., Diggins, J., Buckling, G. and Ralph, J.F. (1998) 'Adiabatic modulation of a SQUID ring by an electromagnetic field', *Journal of Physics: Condensed Matter*, 10(44): 9951–9968.

R3 Clippingdale, A.J., Prance, R.J., Clark, T.D. and Brouers, F. (1994) 'Non-invasive dielectric measurements with the Scanning Potential Microscope', *Journal of Physics D: Applied Physics*, 27(11): 2426–2430.

R4 Prance, R.J., Clark, T.D., Prance, H. and Clippingdale, A. (1998) 'Non-contact VLSI imaging using a scanning electric potential microscope', *Measurement Science and Technology*, 9(8): 1229–1235.

R5 Clippingdale, A.J., Prance, R.J., Clark, T.D. and Watkins, C. (1994) 'Ultrahigh impedance capacitively coupled heart imaging array', *Revue of Scientific Instruments*, 65: 269–270.

R6 Harland, C.J., Clark, T.D. and Prance, R.J. (2002) 'Electric potential probes: new directions in the remote sensing of the human body', *Measurement Science and Technology*, 13(2): 163–169.

Outputs R2, R3, R6 best indicate the quality of the underpinning research.
Outputs can be supplied by the University on request.

4. Details of the impact

Following directly from the outputs of the fundamental research programme above, a generic version of the EP sensor system was showcased at a 'Position Sensitive Detectors in Physics' meeting organised by the Research Instrumentation Special Interest Group (RSIG), held in London in May 2010. The event was intended to facilitate interaction between the high-energy physics, security and medical sectors. As a direct result of this, a dialogue with Plessey Semiconductors began which culminated in an exclusive manufacturing licence, signed in December 2010. By September 2011, the first integrated-circuit version of the sensor had been successfully implemented by Plessey and was ready for designing into products. A second sales licence was agreed with Plessey in June 2012. The technology is now being marketed as the Electric Potential Integrated Circuit (EPIC) sensor [see Section 5, C1].

The main impact of this sensor technology to date has been on Plessey Semiconductors [C1]. Following a restructuring of the company, two new technologies were acquired from UK universities, with the specific aim of transforming the company from a foundry manufacturer of semiconductor components to a product-oriented company focused around two major product lines. EP sensor technology from Sussex is one of these two and has had a significant impact on both the shape and the direction of the company. Plessey has made a major investment and commitment to EP sensors. The current levels of investment within Plessey stand at £x, with x employees dedicated full-time to the technology, in applications support, sales and marketing, and development through funded collaborative programmes. Revenue to the University of Sussex from the licences is a mixture of licence fees (£x for 11/12), patent costs and royalty payments, which started in 2013. Royalties are based on sales of £x for 2012 and projected sales of £x for 2013 and £x for 2014.

In addition to this overt commercialisation of the technology, work has been carried out in conjunction with the Research and Enterprise Division and the Innovation Centre (SInC) at Sussex, with funding from the Enterprise Panel (University of Sussex) and the South East Health Technologies Alliance (SEHTA) to develop awareness of the technology in the wider community. EP sensors have been judged to be disruptive in a number of market sectors, by both a multi-national company [C10] and independent consultants [C11]. There was therefore a perceived need to engage with and educate the market and potential users about the capabilities of this new disruptive technology. Necessarily, due to the generic nature of the sensors, this involved a diverse range of institutions and companies across a broad spectrum of market sectors. The model used for this engagement process was to issue evaluation licences to organisations for a 12-month period with a small fee to cover costs and the requirement of a confidential written report at the termination of the licence. The funding enabled a batch of pre-production prototypes to be manufactured by a local SME (Interface2 Ltd, Newhaven) [C2], for distribution under these evaluation licences to interested commercial organisations (from multi-nationals to SMEs, both within the UK and outside) and to potential partners (including universities, government laboratories and organisations). To date the University has placed 20 evaluation licences and has direct involvement with collaborative projects across all market sectors, including healthcare, sports, security [C4], safety, aerospace [C3], automotive and geophysics [C6].

In partnership with a number of commercial organisations, proof-of-concept designs were developed spanning electrophysiological measurement, with Plessey funding 3 postdoctoral positions at Sussex; Rescon Ltd, two DARPA contracts – £150k; a multi-partner EU grant with Philips Healthcare and Plessey (2012–16, >£20m); surface-charge density imaging, including forensic fingerprinting, in collaboration with the Home Office/CAST [C4]; movement sensing, MOD funded, 2009–10, £98k; aerospace instrumentation, TSB-funded project 'Novel Electric Field Sensors for Advanced Aero-Engine Monitoring' with Meggitt Sensing Systems [C3] and Plessey Semiconductors [C1], 2012–14, total £1.1m, £524k industry; and geophysical and structural health monitoring with British Geological Survey, Keyworth [C5].

The additional impact directly resulting from this engagement activity is:

- Interface2, a local SME, is now the main sub-contractor for a much larger organisation, Plessey, with responsibility for building the EPIC chip into a variety of products [C1] for them.
- The evaluation licensees are in direct contact with Plessey either as customers or as potential customers for Plessey products.
- Market sectors identified by evaluation licences form the major market sectors for Plessey (Automotive, Sports, Healthcare).
- The pre-production prototype design was adopted directly by Plessey as their first commercial demonstration unit and manufactured by Interface2.
- One postgraduate student was funded by and seconded to Plessey as a postdoc. x Plessey employees work directly on EPIC-related projects and products.

EP sensor technology has received external recognition for both the research contribution and the commercialisation activity, including awards at international trade fairs and product reviews:

- EPSRC, Basic Technology Review Panel Report [C6] (2010)
- RCUK, 'Big Ideas for the Future' [C6] (2011)

- IET Innovation Award 2011, 'Measurement in Action' [C7]
- Gold award at 'Best of Sensors Expo 2011' [C8]
- EDN 'Hot 100 products' list [C9] (2011): 'The most innovative and significant products and technologies as selected by the editors', 250,000 website viewings per month
- Finalist for *Times Higher* Innovation Award 2011
- Shortlisted for Army Research Office award 2012
- (2008) *Nature Research Highlights* 454(21): 920 (Impact Factor 36.101, estimated readership of 424,000) doi:10.1038/454920b.
- *New Scientist*, 2812: 22, 14 May 2011, estimated readership of 905,726, http://www.newscientist.com/article/mg21028126.800-static-charge-provides-clue-to-age-of-fingerprints.html
- *Homeland Security Newswire*, 23 May 2011, 30,000 specialist subscribers http://www.homelandsecuritynewswire.com/sensors-detect-crime-solving-clues-our-fingertips
- *The Economist*, 13 October 2012, Weekly circulation 1.5 million, http://www.economist.com/node/21564614

In summary, the original basic research has spawned multi-million-pound investment in developing it into concrete engineering applications, supported by strategic university elements, giving rise to sustained impact on industrial sensor solutions that are now starting to generate substantial world-wide revenue for a UK company. It is clear that this is an activity with the potential to grow both in magnitude and in the diversity of its applications.

5. Sources to corroborate the impact

C1 Technology Director, Plessey Semiconductors: http://www.plesseysemiconductors.com/products/epic/

C2 Sales Manager, Interface2 Ltd.

C3 Research and Technology Manager, Meggitt Sensing Systems.

C4 Research Scientist, Home Office CAST.

C5 Head of Science Land Use, British Geological Survey.

C6 Featured in: 'Evaluation of the Basic Technology Programme, Findings and Recommendations of the Review Panel', EPSRC Theme Day, 19 May 2010, Manchester www.epsrc.ac.uk/SiteCollectionDocuments/Publications/reports/BTReport.pdf and the RCUK 'Big Ideas' report, 2011 http://www.rcuk.ac.uk/documents/publications/BigIdeasfortheFuturereport.pdf

C7 Winner of the IET 'Measurement in Action' Innovation award 2011 http://conferences.theiet.org/innovation/categories/measurement/index.cfm

C8 Winner of the Gold Award at the 'Best of Sensors Expo', Sensors Expo, Chicago, 2011 http://memslibrary.com/events/34-conferences/28-the-2011-best-of-sensors-expo-award-winners-announced.html

C9 Selected for the EDN 'Hot 100 Products' list, 2011 http://www.edn.com/electronics-news/4368490/Plessey-samples-electric-potential-sensor-item-2

C10 Kodak European Research Ltd, Cambridge (No longer trading in UK)

C11 Scientific Generics Ltd, Cambridge (Confidential report by consultant for University of Sussex)