Institution:
University of Cambridge

Unit of Assessment:
UoA9

Title of case study:
Hitachi

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

Research in the Microelectronics Group of the Cavendish Laboratory in the area of single-electron nanoelectronics, quantum computing and spintronics has been exploited by Hitachi, one of world's leading microelectronics companies. Research breakthroughs made in the Cavendish have defined Hitachi's R&D directions in quantum computing and spintronics, led to several Hitachi product developments and influenced senior Hitachi strategic decision makers regarding the future of computing.

2. Underpinning research (indicative maximum 500 words)

In the late 1980's and early 1990's the Microelectronics Group of the Cavendish Laboratory under the leadership of Prof. H. Ahmed (retired 2003) developed a world-leading competence in the fabrication and measurement of very small semiconductor and metal nanostructures (Ref.1) and their use in single-electron devices. Under Prof. Ahmed's leadership single-electron transistor (SET) and memory devices were realized, including the phase-state, low-electron number drive memory (PLEDM) in 1999.

This competence in fabrication and measurement of nanoscale single electron devices then became the basis of pioneering research projects in the field of quantum information processing (QIP) and spintronics. The Cavendish group, by then under the leadership of Dr. D. Hasko (Assistant Director of Research at the Cavendish from 1996, Senior Research Associate from 2006, joined the Department of Engineering 2009) and funded by a Basic Technology grant from EPSRC, reported in 2004 the realisation of a solid state quantum bit based on a single-electron double quantum dot in silicon for QIP (Ref. 2). This double dot architecture represents a powerful solid-state implementation of a quantum bit, which can be integrated in conventional silicon technology.

In 2004, with the appointment of Prof. H. Sirringhaus as Hitachi Professor of Electron Device Physics the research focus was expanded and a new research direction on spintronics was established. Dr. A. Irvine, a senior assistant in research in the Microelectronics Group since 2002, developed the critical fabrication of advanced spintronic device architectures. Dr. Irvine's fabrication led in 2006 to the realisation of a new concept for a highly sensitive magnetoresistance device, the Coulomb blockade anisotropic magnetoresistance (CBAMR) (Ref. 3), in 2009 to the first demonstration of the spin-injection Hall effect (Ref. 4, patent application JP2010122211) and in 2010 to the first realisation of a spin-Hall effect transistor (Ref. 5). The CBAMR is based on a single-electron transistor with a ferromagnetic semiconductor, in which small changes of the magnetic field strength or direction induce variations in the electrochemical potential of the SET island and associated changes in the device resistance. The spin-Hall effect transistor can be considered as the first realisation of a spin transistor (as originally postulated theoretically by Datta and Das) and uses an external gate field to modulate the spin precession of an injected spin current in a semiconducting channel. The discovery of the CBAMR and the spin-injection Hall effect, which were first fabricated by Irvine, have been recognized by awards of two, highly prestigious Hitachi R&D group technology prizes (Kenkai) in 2006 and 2009, respectively.

A third breakthrough was achieved by Dr. A Ferguson, an Hitachi sponsored Senior Research Fellow in the Cavendish since 2007. Dr. Ferguson has extensive experience in the physics of electron dynamics in single-atom and single-spin solid-state quantum systems. In 2012 Dr. Ferguson's realized a novel, very sensitive magnetoresistance device structure. In this architecture the gate electrode of a transistor is fabricated from a magnetic material with a strong magnetic anisotropy, which can transduce changes in the applied magnetic field into changes in the effective gate voltage (Ref. 6, European Patent application, EP12172627).

3. References to the research (indicative maximum of six references)

1. Fabrication of 5-7nm wide etched lines in silicon using 100 keV electron beam lithography and polymethylmethacrylate resist,
   Chen, W.; Ahmed, H.
   Appl. Phys. Lett. 62, 1499 (1993).

2. * Charge-qubit operation of an isolated double quantum dot
   Gorman, J; Hasko, DG; Williams, DA
   Physical Review Letters 95, 090502 (2005), DOI: 10.1103/PhysRevLett.95.090502

3. Coulomb blockade anisotropic magnetoresistance effect in a (Ga,Mn)As single-electron transistor
   Wunderlich, J.; Jungwirth, T.; Kaestner, B.; Irvine AC;
   Physical Review Letters 97, 077201 (2006), DOI: 10.1103/PhysRevLett.97.077201

4. * Spin-injection Hall effect in a planar photovoltaic cell
   Wunderlich, J.; Irvine, A. C.; Sinova, Jairo; et al.,
   Nature Physics 5, 675 (2009), DOI: 10.1038/nphys1359

5. * Spin Hall Effect Transistor
   Wunderlich, J.; Park, BG; Irvine, AC.; et al.
   Science 330, 1801 (2010), DOI: 10.1126/science.1195816

6. Spin gating electrical current
   Ciccarelli, C.; Zârbo, L.P.; Irvine, A.C.; Campion, R.P.; Gallagher, B.L.; Wunderlich, J.; Jungwirth, T.; Ferguson, A.J.
   Applied Physics Letters, 101, 122411 (2012), DOI: 10.1063/1.4752013

* References which best represent the quality of the underpinning research

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

In 1989 Hitachi was attracted to a collaboration with the Cavendish's Microelectronics Group because of its world-leading expertise in fabrication and measurement of semiconductor nanostructures. Hitachi established a corporate research laboratory in Cambridge, the Hitachi Cambridge Laboratory (HCL), which has since provided UK employment to 10-15 Hitachi researchers at any point in time. Between 2008-2012 HCL has generated 17 patents, 8 of which are joint with Cavendish researchers.

As a leading manufacturer of supercomputers Hitachi has a strategic interest in quantum computing for applications including communication security or weather/climate modelling. The silicon qubit structure realised originally by Hasko (Ref. 2) is currently the main development direction pursued by Hitachi for solid-state quantum computers and has led Hitachi to invest considerable development resources in its R&D laboratories in Japan and Europe. The attraction of the approach is that it can be implemented using silicon-based mass manufacturing techniques. Hitachi's teams in Cambridge and Japan are focussed on improving the reproducibility of these silicon double quantum dot devices and on realising computing systems based on integrating multiple quantum bits. At present the Hitachi team in HCL developing silicon-based quantum computing comprises 10 engineers and scientists. The team is interacting closely with Hitachi's main R&D Laboratory in Tokyo, where a state-of-the-art silicon fabrication line is used to supply HCL with full-scale wafers of quantum computing structures based on the University's original double dot design. In this way the original university research has contributed directly to securing 23 Hitachi jobs in the UK since 2008.

Up to 2012 Hitachi owned Hitachi Global Storage Technologies (HGST), a world-leading, hard-disk manufacturer and Hitachi's main interest in spintronics was focussed on novel approaches to enable higher hard-disk storage capacity. The novel spintronics architectures realized by Irvine and Ferguson (Ref. 3 & 7), became candidates for the next-generation of hard-disk read-heads and were actively being developed by HGST. In 2012 Hitachi sold HGST to Western Digital for $4.6

billion. Western Digital is actively developing magnetic random access memory (MRAM) technology based on the spin Hall effect (Wunderlich et al, Phys. Rev. Lett. 94, 047204 (2005) and Ref. 4 & 5). The merit of spin-Hall effect induced switching is that no spin-polarized charge current is flowing across a tunnelling barrier minimizing heat and fatigue of the barrier. In the industry it is widely expected that the next generation of MRAM devices will use this technology.

The focus of the spintronics R&D in Hitachi shifted. Hitachi is a world leading manufacturer of high-end microprocessors and retains a strong interest in spintronics for ultralow power electronics. In particular, the spin-injection Hall effect device and the spin-Hall transistor first fabricated by Irvine (Ref. 4 and 5) have provided Hitachi with powerful architectures for realising spin-based logic circuits with very low power dissipation. Hitachi currently employs 10 researchers in the UK who develop these architectures and who interface with a larger spintronics development team in Hitachi's Central R&D laboratory in Tokyo of about 15 scientists and engineers. This company-internal, spintronics development effort in the UK and Japan is supported mainly by Hitachi funds.

Hiroaki Odawara, General Manager of European R&D for Hitachi, comments on the impact of the University research on Hitachi's past and present product portfolio: "The work performed on single electron devices within the Microelectronics Group in the 1990s had a direct impact on a large-scale memory device subsequently developed by Hitachi for a leading computer manufacturer and which forms part of the International Technology Roadmap for Semiconductors. This went into large-scale preproduction but unfortunately not into production as the client developed severe financial difficulties. However, it provided the technology / manufacturing basis for Hitachi's current exploitation of the University's double quantum dot architecture for the development of a quantum computer. Since 2008 the University spintronics research had a significant impact in HGST. Several of the architectures realized first by University researchers were being developed by HGST for hard-disk drive (HDD) read-head sensors prior to the sale of HGST to Western Digital in 2012. Currently, single-electron and spintronic devices, whose provenance is directly traceable to work in the Microelectronics Group of the Cavendish are being investigated as candidate sensors in healthcare applications which is an increasingly important business area for Hitachi."

At a higher, possibly slightly less tangible, but not less important level Hitachi's continued investment in fundamental physics research is generally aimed at identifying new and fundamental approaches to future information processing. This is of strategic importance for Hitachi. As a systems company Hitachi needs to understand important trends in computing to provision its customers with computing solutions that will satisfy future needs and requirements. The continued collaboration with the Cavendish has allowed the company to understand how fundamental breakthroughs in fundamental physics could impact computing in the long, > 10 year timescale and has already influenced the strategic directions Hitachi is taking in its own, internal development of quantum supercomputers and ultralow power electronics, as explained above. In 2008 Hitachi staged a 2-day technology exhibition, "Hitachi inspire life", at the QEII Conference Centre opposite the Houses of Parliament. It was visited not only by Hitachi customers but also key decision makers in government. One of the technology stands was dedicated to the technology developed in the collaboration between the Cavendish and HCL.

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

- General Manager of European R&D for Hitachi – statement on file
- Chief Research Scientist and Laboratory Manager, Hitachi Cambridge Laboratory
- "Hitachi inspire life" exhibition: http://www.hitachi.co.uk/about/press/pressrelease.jsp?id=667
- Press release on CBAMR discovery: http://hitachi-eu.net/about/PRDetail.jsp?prid=254 (also held on file)
- Press release on spin transistor: http://www.hitachi.eu/about/press/pressrelease.jsp?id=665