Institution:	**University of Warwick**
Unit of Assessment:	**B9 Physics**
Title of case study:	**The impact of the floating low-energy ion gun (FLIG) on the consumer electronics industry**

1. Summary of the impact

This case study describes the invention, development and subsequent commercial application of the floating low-energy ion gun (FLIG), a key enabling technology for high-resolution depth profiling, in particular of semiconductor devices. Following its invention at the University of Warwick, the FLIG was commercialised and now plays an important role in the semiconductor industry as a key analytical instrument. Intel and its competitors have used the FLIG in developing specific technologies, such as the Pentium™, Xeon™ and Core™ i7 processors. Its impact extends beyond the electronics industry to consumers worldwide since the FLIG has played a key role in the development of multicore processors for personal computers, intense low-energy lighting for automotive and civil engineering, mobile telecommunications technology, and many other areas of advanced electronic, and other material, technologies. This invention has also led directly to an ISO standard for depth resolution.

2. Underpinning research

The FLIG was invented by Dowsett, (then a Principal Research Fellow and now a Professor in the Dept. of Physics at the University of Warwick), assisted by Noel Smith (his PhD student in Warwick between 1992 &1996) whose thesis describes a significant fraction of the early work [1].
The underlying science behind the FLIG concept has two major drivers:

(i) In the late 1980s, the depth resolution provided by secondary ion mass spectrometry (SIMS) in profiling devices was falling short of that demanded by the International Technology Roadmap for Semiconductors. SIMS instruments were using a high energy (several keV) primary ion beam, both to laterally focus the bombarding ions and to achieve a measureable yield of secondary ions ejected from the device under test; however, this high energy limited vertical resolution. In defiance of the literature of the time, and based on extrapolation of his own laboratory results at energies down to below 1 keV, Dowsett was convinced that lowering the SIMS beam energy still further, to a few hundred eV would improve the depth resolution of SIMS.

(ii) In order to do this in a way that could be developed into a routine analytical technique, it was necessary to greatly improve ion transport in focussed ion beam columns, from the source outwards and to reduce chromatic and spherical aberrations within the ion column to maximize the usefulness of the transported current. At that time a few pA on target into a spot size of 50 µm was typical for a beam energy of 1 keV.

No real progress on reducing beam energy was made until, in 1995, Dowsett demonstrated dramatic improvements of the ion optics in a sub-keV ion column [2] which he created with initial support from the Royal Society's Paul Instrument Fund [8]. The success of the prototype depended on the superb electronics and mechanical engineering support in the Warwick Dept. of Physics, reflected by co-authorship of several technical staff on the early papers. Subsequently, precise details of the instrumentation could no longer be published as they became and remain commercially confidential.

A central part of the FLIG concept is that most of the ion column is 'floating' at a high negative potential, so that ions are transported and conditioned at high velocities, but then slowed down to impact energies of 100's or even 10's of eV just before striking the sample. This was the key to improving the space-charge transport, generating useful impacting fluxes up to 50,000 times higher than would otherwise have been possible, and improving vertical resolution because the impact velocity at the sample is so much less. Consequently, higher-resolution data can now be obtained in minutes or hours, rather than in impractical time periods of months or years.

The research output comprises: (i) conference papers, related patents [9] and PhD theses deriving directly from the original research; (ii) key papers that establish Dowsett's contribution to the applications research, for example, developing the concept of the SIMS response function [3, 4] that led to an ISO standard for depth resolution (Section 4); (iii) numerous contributions [e.g. 5,6], to the subsequent development of ultra-low-energy (ule) SIMS as a quantitative technique that is now being used extensively in the semiconductor industry; and (iv) papers and advances in materials processing and device technology made by other owners of the instrumentation.

Maximum initial impact of this research was notably achieved by presenting the early results at the *SIMS X* conference in Münster (October 1995) where both instrument manufacturers and users were present [2]. Within a few minutes of the presentation describing the device, the three principal SIMS manufacturers of the time all tried to close deals to use the technology. Atomika were the successful bidders, and made an exclusive OEM deal with Ionoptika Ltd., a UK SME based near Southampton to whom the University of Warwick had licensed the FLIG. The Atomika (now Cameca) 4500, 4550 and 4600 instruments were the outcome of that initial intellectual property (IP) licensing agreement.

Dowsett has continued to develop the technology. The commercial version of the FLIG, which can now deliver around 500 nA of usable beam current at 500 eV, has re-engineered optics and its own custom high brightness duoplasmatron with a low energy spread (both designed by Dowsett, in 1995 and 2004, respectively, the latter being descended from an earlier design by Drummond & Long.) The success of the commercial FLIG depended on the development of this very high brightness, cold cathode duoplasmatron, which delivers both oxygen and other gas species such as inert gases and nitrogen (that normally require a hot cathode source). Further elements of the innovative design include a matched column that transports the beam at high energy to the vicinity of the sample, and a multi-element, low aberration retarding lens to reduce the impact energy by a factor of 10 to 30. Dowsett also designed the secondary ion optical and detector systems of the Atomika 4550 and the 4600, and continues to provide support and expertise to Ionoptika and users of the technology as a consultant. Warwick has recently signed a further licence agreement with Ionoptika, covering new FLIG-related ion source technology developed by Dowsett and his son David, who completed his PhD at the University of Warwick in 2007 [7].

3. References to the research (Principal Warwick authors in bold, Warwick technical staff in red)

Publications:

1. **N.S. Smith**, *Ultra low energy SIMS depth profiling*, PhD thesis, University of Warwick (1996)
2. **M.G. Dowsett, N.S. Smith,** R. Bridgeland, D. Richards, A.C. Lovejoy & P. Pedrick, An ultralow energy ion column for sputter profiling. In *Secondary Ion Mass Spectrometry (SIMS X)*, eds. A. Benninghoven, B. Hagenhoff & H.W. Werner, (Wiley 1996) p.367 ISBN: 0471958972; **N.S. Smith, M.G. Dowsett,** B. McGregor & P.J. Phillips, Rapid low energy depth profiling using SIMS, *ibid.* p.363; **G.A. Cooke, N.S. Smith, M.G. Dowsett,** H.R.G. Burke & P.J. Phillips, Ultra low energy SIMS depth profiling and the dilute limit, *ibid.* p.371.
3. **M.G. Dowsett, G. Rowlands, P.N. Allen and R.D. Barlow,** An analytic form for the SIMS response function measured from ultra-thin impurity layers, *Surf. Interface Anal.* **21**, 310-315 (1994) DOI: 10.1002/sia.740210508 (Cited 65 times)
4. **D.P. Chu and M.G. Dowsett,** Dopant spatial distributions: Sample-independent response function and maximum-entropy reconstruction, *Phys. Rev. B* 56, 15167-15170 (1997). DOI: 10.1103/PhysRevB.56.15167
5. **M.G. Dowsett,** Depth profiling using ultra-low-energy secondary ion mass spectrometry, *Appl. Surf. Sci.*, **203**, 5 (2003) DOI: 10.1016/S0169-4332(02)00630-X (Cited 47 times)
6. **R.J.H. Morris and M.G. Dowsett,** Ion yields and erosion rates for $Si_{1-x}Ge_x$ ($0 \le x \le 1$) ultralow energy O_2^+ secondary ion mass spectrometry in the energy range of 0.25-1 keV, *J. Appl. Phys.* **105**, 114316 (2009) DOI: 10.1063/1.3139279
7. **D.M.F. Dowsett**, *High brightness ion sources for surface analysis*, PhD thesis, University of Warwick (2007). Led to Patent application GB0815077.3 *Ion Sources For Secondary Ion Mass Spectroscopy (SIMS)* (2008).

Grants/awards:

8. Royal Society's Paul Instrument Fund, PI **M.G. Dowsett**, *The development of a sub-keV ion column*, 1990-1993, £38,225

Patents:

9. J.L. Maul, **M.G. Dowsett**, *Sample Analysis Method* EP 0878827 (1998) & US 6078045 (2000); **M.G. Dowsett**, J.L. Maul, *Secondary ion mass spectrometer with aperture mask*, US 6080986 (2000)

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4. Details of the impact

All modern semiconductor devices depend on highly reproducible, nanometre-scale multilayer engineering for dielectrics, semiconductor doping and heterostructures. The FLIG system has enabled semiconductor companies to develop new generations of devices with ever increasing miniaturisation and hence has been an essential technology in the development of all modern electronics. The nanoanalysis capability that the FLIG provides has contributed to the creation of many of today's small computers, mobile phones, communications & entertainment technologies.

Research and process development at this level requires analytical tools with sufficient sensitivity and spatial resolution to measure prototype and production wafer compositions accurately, and uleSIMS is a key method in this area. Dowsett's prototype FLIG–based SIMS instrument (EVA 3000) was the first SIMS instrument in the world capable of routine SIMS analysis at energies down to 200 eV. Subsequently, the IP for the FLIG was licensed to Ionoptika Ltd (UK) and the Atomika Instruments GmbH 4500 SIMS depth profiler was specifically developed as a vehicle for the FLIG. This was the world's first commercial instrument with ultra-low energy SIMS capability.

Since its initial development in late 1993, its commercialization for OEM application by Ionoptika Ltd. [10] and the first sale to Intel of a FLIG-based instrument in 1996 by Atomika Instruments GmbH [11], the FLIG has been in constant use in the R&D laboratories of the world's major semiconductor and technology companies, such as AMD, Fibics, IMEC (Belgium), Intel, MA-tek, Motorola, Nichia, Osram, Toshiba, TSMC4, and around 20 more worldwide, as well as in universities such as Imperial College, NUS (Singapore) & Warwick [12].

The FLIG was the founding product for Ionoptika Ltd. Their CEO says:

> "I would point out the benefit to my company, a small British enterprise, only recently started up at the time that we took on the FLIG licence from the University of Warwick. The FLIG quickly became the mainstay of our business and remained so for the next 6 years. In that time it earned us close to £4M in revenue… However, the biggest impact is yet more significant. This unique ion beam system has held its place as the state of the art in shallow depth profiling from the day of its first application in the Department of Physics at Warwick right up until the present. Nothing else matches its depth resolution (measured in Angstroms) and etch rates. The FLIG gave the semiconductor companies the ability to develop new generations of devices with ever increasing miniaturisation. So, the FLIG was an essential technology in the development of all modern electronics…" [10].

Through mounting FLIG systems onto instruments by Atomika, and more recently Cameca ISA, further sales worth tens of millions of pounds have been generated and it remains an integral part of the Atomika (Cameca) range of SIMS instrumentation [13]. Ionoptika continues to supply the FLIG amongst other instrumentation that includes state-of-the-art time-of-flight-SIMS. Substantial royalties have also been paid to the University of Warwick, the inventor, and the Paul Instrument Fund (who recovered their initial investment).

The impact of FLIG-based tools has been continuous since 1996 and continues to grow alongside the expansion of microelectronic technology into every area of modern life. They are in routine use today as process control tools for the most demanding silicon industry, such as Intel, where they have contributed to the development of Pentium™, Xeon™ and Core™ i7 (2008-date) processors:

> "The development of the floating low energy ion gun (FLIG) by Professor Mark Dowsett and his colleagues at the University of Warwick in the early 1990's was one of the most significant developments in analytical instrumentation in the last 20 years. The refinement of the design and the subsequent implementation on commercial SIMS instrumentation enabled reliable, fast and accurate SIMS depth profiling of thin layers and ultra-shallow junctions. This capability was critically important to the semiconductor industry that was in an era of continuous junction scaling. Intel was an early adopter of the FLIG technology in the mid 90's and the FLIG remains a key capability in our laboratory today." [14]

FLIG-based tools are routinely employed in research on established electronic materials and new semiconductors, such as diamond, carbides and nitrides [15]. The high resolution depth profiling enabled by FLIG-based tools is invaluable in developing a wide range of generic semiconductor devices and other technologies, such as dynamic random access memory (DRAMs) central to all computer data storage, quantum wells e.g. for GaN light emitting diodes (LEDs), silicon germanium alloys, and high and low-k dielectrics. Furthermore, the FLIG has had;

> "… wider impact in organic electronics, pharmaceuticals, medical devices and the characterisa-

> tion of nanoparticles … Dowsett and colleagues pioneered the development of floating low energy ion gun technology (FLIG) to achieve the high depth resolution necessary for inorganic semiconductors. This continues to be state-of-the-art for the semiconductor sector." [16]

To date, there are over 1,000 Google hits on FLIG associated items. Dowsett's name for the ion gun and its acronym FLIG, although trademarked by Ionoptika (US Trademark No. 75047263), have become generically synonymous with this type of technology. There are at least 100 peer reviewed papers, from a wide range of international academic and commercial bodies, that acknowledge use of the FLIG or Atomika / Cameca 4500, 4550 and 4600 instruments and hundreds of presentations at semiconductor workshops [e.g. 17], which are the principal means of dissemination in the industry. Use of the FLIG has spread well beyond its original technological drivers of silicon, silicon germanium [17] and gallium arsenide, into nanotechnology, diamond electronics, and cultural heritage [18].

Finally, the SIMS response function developed, in 1994, by Dowsett to relate the data obtained from a SIMS instrument to the underlying material profile has given rise to a current ISO standard (ISO 20341:2003) [19]. The function itself is thus also a significant outcome of the original FLIG development. It is becoming known in the field as the 'Dowsett Function' [20] and has become important both for the semiconductor depth profiling community and outside of the original research field in the new science arising from depth profiling of organic materials [21].

> "… the Dowsett function could be used to characterise the sputtering process in these very different materials ... This now allows modern organic electronic devices to be imaged in 3D with exquisite chemical detail." [16]

5. Sources to corroborate the impact

10. Supporting letter from CEO Ionoptika Ltd.
11. Supporting statement from Sales Director Atomika GmbH/Cameca GmbH
12. www.ionoptika.com ; www.cameca.com/instruments-for-research/sims4550.aspx
13. List of further companies and institutions with FLIG-based instruments available on request.
14. Supporting letter from Senior Engineer, Intel Corporation.
15. E.g. Fibics Inc. (operating from the Canadian Government's Materials Technology Laboratory) uses an Atomika 4500 to offer SIMS services www.fibics.com/SC_SIMSOverview.html
16. Supporting letter from National Physical Laboratory (NPL) Fellow.
17. Publication from IMEC at recent workshop:
    R. Pureti and W. Vandervorst, Quantification of Ge in $Si_{1-x}Ge_x$ by using low-energy Cs^+ and O_2^+ ion beams, *Surf. Interface Anal.* **45**, 402-405 (2013) DOI: 10.1002/sia.5049
18. Publications with reach into nanotechnology: Li Yang *et al.* Depth Profiling and Melting of Nanoparticles in Secondary Ion Mass Spectrometry, *J. Phys. Chem*. **117**, 16042-16052 (2013) DOI: 10.1021/jp4048538; R.J.H. Morris *et al.*, The use of low-energy SIMS (LE-SIMS) for nanoscale fuel cell material development, *Surf. Interface Anal.* **43**, 635-638 (2010) DOI: 10.1002/sia.3526; diamond electronics: R. Edgington *et al.* Growth and electrical characterisation of d-doped boron layers on (111) diamond surfaces, *J. Appl. Phys.* **111**, 033710 (2012) DOI: 10.1063/1.3682760; cultural heritage: M.G. Dowsett, *et al.*, The use of ultra-low-energy dynamic SIMS in the study of the tarnishing of silver, *Nucl. Instrum. Meth. Phys. Res.* **B239** 51-64 (2005). DOI: 10.1016/j.nimb.2005.06.179; G. Spoto & G. Grasso, Spatially resolved mass spectrometry in the study of art and archaeological objects, *TrAC – Trends in Analytical Chemistry* **30**, 856-863 (2011) DOI: 10.1016/j.trac.2011.01.016
19. ISO 20341:2003 (reviewed and confirmed in 2009) can be downloaded from the Standards Centre at http://tinyurl.com/ptsde9e, or at www.iso.org/obp/ui/#iso:std:iso:20341:ed-1:v1:en
20. Demonstrates the 'Dowsett Function' as referred to by [20]: P. Sjovall, *et al.*, Sample cooling or rotation improves C60 organic depth profiles of multilayered reference samples: Results from a VAMAS interlaboratory study, *J. Phys Chem. B* **114** 769-774 (2010)
21. Examples in: Proceedings of the Seventeenth International Conference on Secondary Ion Mass Spectrometry, SIMS XVII, *Surf. Interface Anal.* **43**, 1-676 (2011); *Cluster Secondary Ion Mass Spectrometry: Principles and Applications* Ed. C.M. Mahoney (Wiley 2013) ISBN:1118589246