Institution:
Durham University

Unit of Assessment:
UoA 9: Physics

Title of case study:
Durham Magneto Optics – a spin-out company from thin film magnetism research

Period when the underpinning research was undertaken:
October 2000 to September 2005

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:
Russell Cowburn	Lecturer/Reader	2000 to 2005
James Buchanan	Research Assistant	2004 to 2005
Del Atkinson	Research Associate (now Professor)	2001 to present
Daniel Allwood	Research Associate	2001 to 2005
Brian Tanner	Professor (now Emeritus) -PI on RDA/ERDF grant	1973 to present

Period when the claimed impact occurred: Between 1 August 2013 and 31 December 2020

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

1. Summary of the impact

Research in Durham on nano-magnetism led to the development of a precision instrument to characterise magnetic field domains using a tightly focused laser beam to raster scan across the surface. Durham Magneto Optics Ltd was spun out to make these commercially available for nanotechnology R&D, but the breakthrough came with the realisation that this technique can also be employed to fabricate nano-magnetic devices by directly writing them onto a photoresist, giving flexible and rapid lithography for electronics device development. The company has grown substantially since 2014, with revenue of [redacted] in 2019 and over 100 machines installed across 24 countries.

2. Underpinning research

Durham University Physics Department has a longstanding record of internationally recognised research in magnetic materials. Russell Cowburn joined this group as a Lecturer in October 2000, with research interests in building nanoscale magnetic switches. However, there are many technical problems in making and studying the magnetic functionality of these spintronic devices as a feasible alternative to the logic of silicon chips. Key research challenges are the small scale and high sensitivity needed to locally probe magnetisation in magnetic nanostructures. One way to study the local magnetization structure and reversal processes in thin film magnetic structures is via the magneto-optic Kerr effect (MOKE), which senses the change in polarisation of light reflected from a magnetised surface. Cowburn's group needed to make more sensitive MOKE measurements than were possible with off-the-shelf apparatus. With Dan Allwood and Del Atkinson, Cowburn designed, built, tested and developed a very sensitive, high spatial resolution, MOKE system to probe the magnetisation reversal behaviour. This included developing techniques to maximise the signal-to-noise at each stage and to tightly focus the laser spot to enable local probing of magnetisation within single nanowires. They successfully developed the performance required [R1] and were able to image by raster scanning the laser across a sample, differencing from a reference beam to null-out the laser fluctuations. Crucially, they were able to sensitively resolve changes in magnetic structures in real time. The instrument resulted in several high impact publications, including ones in Science and Nature Materials [R2-5]. Cowburn was elected to Fellowship of the Royal Society in 2010.

Nano-devices used in the research programme were normally fabricated at Durham using electron beam (EBL) and focussed ion beam (FIB) lithography, which are slow processes because of their extremely high resolution. Cowburn realised that the lithographic process could be speeded up

dramatically if EBL was used only for small components, with a faster, lower resolution method used for larger components, such as electrical contacts. In October 2003, a 2-year, GBP215,000, grant for the development of novel patterned nanostructures was awarded to Professor Brian Tanner in the Durham Physics Department by the Regional Development Agency (ONE-NE) from its Single Pot fund and the European Regional Development Fund. One half of this was to exploit the Durham expertise in laser-based technology that was applied in nanomagnetism research, to develop a rapid, inexpensive lithographic method using direct laser writing onto photoresist.

Fig. 1. 2005 prototype of the MicroWriter

Because the litho-mask pattern is held in software, a direct laser writing system is extremely versatile. Circuit design can be changed at very low cost, making it very suitable for R&D. While optical direct writing devices were on the market, they were very slow. The Durham instrument used a new short wavelength diode laser (405nm) with high speed gating and a novel integrated combination of fast (laser) and slow (wafer) motion. When combined, this fast digital synchronisation, between the sample motion and laser switching, reduced pattern writing time by approximately an order of magnitude compared to existing commercial systems. The concept was successfully demonstrated and a prototype built by the summer of 2005 (Fig. 1). As Cowburn had moved to a Professorship at Imperial College in January 2005, Tanner oversaw the final part of the programme to September 2005 [R6].

No publications resulted from the project as the intention was to exploit the device commercially. At the end of grant assessment, Jerel Whittingham, the Commercial Director of CENAMPS (Centre of Excellence for Nanotechnology, Micro and Photonic Systems), the subsidiary company of One NorthEast that was monitoring the project, concluded that such commercial prospects looked good [R6, E11]. It was evident, however, that major software and hardware development was required to turn the demonstration into a product. The prototype was therefore transferred to Imperial College, where Cowburn was overseeing the operation of the Durham University spin-out company Durham Magneto Optics (DMO), then based in Gerrards Cross. Subsequent commercial development of the MOKE and direct write systems has taken place within DMO.

3. References to the research

[R1] D.A. Allwood, G. Xiong, M.D. Cooke and R.P. Cowburn, 'Magneto-optical Kerr effect analysis of magnetic nanostructures', *J. Phys. D: Appl. Phys*. **36** (2003) 2175. DOI: 10.1088/0022-3727/36/18/001
[R2] D.A. Allwood, G. Xiong, M.D. Cooke, C.C. Faulkner, D. Atkinson, N. Vernier and R.P. Cowburn, 'Submicrometer Ferromagnetic NOT gate and Shift Register', *Science* **296** (2002) 2003. DOI: 10.1126/science.1070595
[R3] D. Atkinson, D.A. Allwood, G. Xiong, M.D. Cooke, C.C. Faulkner and R.P. Cowburn, 'Magnetic Domain-wall Dynamics in a Submicrometer Ferromagnetic Structure', *Nature Mater*. **2** (2003) 85. DOI: 10.1038/nmat803
[R4] N. Vernier, D.A. Allwood, D. Atkinson, M.D. Cooke and R.P. Cowburn, 'Domain wall propagation in magnetic nanowires by spin-polarized current injection', *Europhys. Lett.* **65** (2004) 526. DOI: 10.1209/epl/i2003-10112-5
[R5] D.A. Allwood G. Xiong, C.C. Faulkner, D. Atkinson, D. Petit, and R.P. Cowburn, 'Magnetic Domain-Wall Logic', *Science* **309** (2005) 1688. DOI: 10.1126/science.1108813
[R6] J.D.R. Buchanan, R.P. Cowburn and B.K. Tanner "Top-down Patterning of Nanostructures using High Speed Direct Write Optical Lithography" July 2005 presentation.

The research was published in the most appropriate peer-reviewed international journals, together the key underpinning papers have been cited over 3,900 times.

R6 is evidenced in: J Whittingham, “Initial Review of Commercialisation Prospects”, CENAMPS August 2005 (Review of “Novel patterned nanostructures”, ERDF and One NorthEast Grant to Durham University, October 2003 to September 2005). [The review and a confirmatory email from Mr Whittingham are in E11.]

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

Durham Magneto Optics Ltd (DMO), in which Durham University holds 15% of the equity, was spun out from Durham University by Russell Cowburn in 2002 to commercialise the nano-scale MOKE system developed through research at Durham [E1, E11]. The initial business model had very low overheads, the company hiring space in the Durham Physics Department for a limited period to assemble each machine as orders came in. This early successful organic growth has been key to the sustainability of DMO and subsequent development of its products.

Sales of the NanoMOKE® instrument were initially to research departments of companies in the magnetic recording industry. NanoMOKE is currently used to monitor the magnetic properties of the complex multilayer films used to manufacture giant magnetoresistance (GMR) read heads in computer hard disc drives (HDDs). This industry, which is highly consolidated amongst a small number of companies, shipped nearly 90million HDDs in Q4 (October, November, December) 2018, according to Forbes [E2]. MOKE magnetometry is also used to monitor the local switching of similar magnetic layers used in Magnetic Random Access Memory (MRAM) devices. This is presently a niche market, but analysts Objective Analysis and Coughlin Associates predict revenues from MRAM will grow linearly, from USD26million in 2018, to almost USD4billion in 2029 [E3].

Fig.2. DMO NanoMOKE3®

The upgrade to the NanoMOKE3® system (Fig. 2) gives access to higher magnetic fields, now up to 1T, and since August 2013, continues to provide a steady stream of revenue with a long term average of 3 sales per annum. These have been worldwide, including installations in North and South America, Europe, China, Japan and India [E4] (it should be noted that, as in the electronics industry, magnetic recording companies do not permit release of installation information or even acknowledgement that they use specific metrologies, let alone particular products). The significance of this small, but important market, is demonstrable. Where DMO has introduced and sold a manually loading NanoMOKE3® mapping system for 200mm wafers, it faces major competition in such applications from the fully automated, robotic handling, 300mm wafer system of Microsense, a KLA company [E5], which evidences the impact of the original Durham research.

Revenue from NanoMOKE® and NanoMOKE3® was invested in the development of the MicroWriter from laboratory demonstrator to product, without recourse to debt or equity finance. In 2010, the company was able to introduce an initial product, the MicroWriter ML based on the prototype system originally developed within the Durham Nanomagnetism group [R6]. It was a direct-write photolithography machine for rapid prototyping of patterned thin film devices. The improved MicroWriter ML2, first installed in September 2013, added greyscale lithography and better microscopy and alignment features to the original machine. The system has since been further upgraded; the ML3 Pro tool uses a 386nm laser to achieve a 0.5mm resolution.

Fig. 3. MicroWriter ML Baby

In 2013, DMO launched a smaller version of the same tool, the MicroWriter ML Baby. Still based on the Durham research concept [E1], it exploits improved engineering design, with 1mm resolution, to lower cost and use less cleanroom space than the larger model (Fig 3). The first MicroWriter ML Baby was installed in IFW Dresden, one of Germany's non-university research institutes, in November 2013. Take-off for DMO was 2017, when 18 systems were shipped, and a further 24 installations were delivered in 2018 (Fig 4).

The company sees new markets are opening for the MicroWriters, e.g. for fabrication of microfluidic devices in the life sciences. This application, still in its infancy, enables custom microfluidics channels to be inexpensively configured and fabricated for study of cell growth and division [E6].

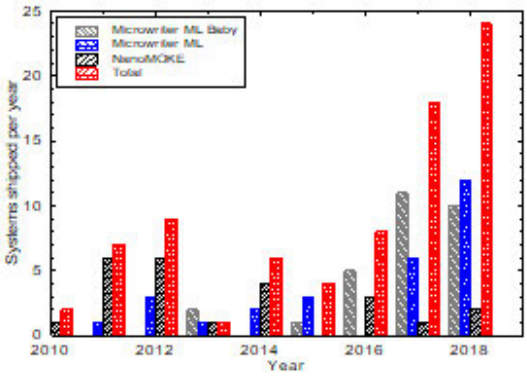

Fig. 4. DMO sales year on year figure

Fig. 5. Global installs of Nano Moke(red) and Microwriter blue

Revenue has increased from an average of approximately [redacted] prior to 2011 to [redacted] in 2019 [E7]. The company's cash reserve has risen from [redacted] in July 2013 to [redacted] in July 2019 [E8]. Its workforce in 2014 was 1.5 full time equivalent (FTE) employees. Following Dr Peter Seem becoming Chief Technology Officer in summer 2013 and DMO's moving to dedicated facilities in Cambridgeshire in 2015, the workforce is growing and is currently 10 people. As it is estimated [E9] that one manufacturing job generates between 1.5 and 2 jobs in the supply chain and associated activity, about 30 people share the direct local economic impact of the DMO manufacturing operation.

In the past three years, DMO Ltd has transformed from a somewhat opportunistic micro-business to a fully-fledged scientific instruments company, providing high-level employment. Its magneto-optics technology continues to be in steady demand but it is in a novel enabling technology, namely the direct writing of patterned microstructures, that it has seen greatest growth since late 2013. This technology, originally developed by the group while at Durham, has taken a decade to mature but is now being adopted worldwide. DMO has installed over 100 machines for over 50 customers across 24 countries and continues to partner with Quantum Design [E10] for sales and marketing, to provide global reach.

5. Sources to corroborate the impact

[E1] Durham Magneto Optics website http://www.durhammagnetooptics.com/
[E2] Hard disc drive sales for 2018. Each unit contains GMR read heads. https://www.forbes.com/sites/tomcoughlin/2019/02/04/2018-hard-disk-drive-results/#62a3a8f445a7

[E3] Analysts' predictions of growth of MRAM market from MRAM-info website (https://www.mram-info.com/analysts-expect-mram-revenues-grow-170x-2029-reach-4-billion).
[E4] Webpage with map showing Durham Magneto Optics reach (https://www.durhammagnetooptics.com/?page_id=786).
[E5] MicroSense webpage showing a competitors MOKE mapping product (http://www.microsense.net/products-magnetic-metrology-mrampolarkerr.htm).
[E6] Example publication from the Crick Institute using the DMO MicroWriter for microfluidics: 'Cellular geometry scaling ensures robust division site positioning', Y. Gu & S. Oliferenko, *Nature Comm*. 10 (2019) 268. DOI: 0.1038/s41467-018-08218-2.
[E7] DMO Annual accounts from 2010-2019, filed with evidence.
[E8] PDFs highlighting the cash reserves in 2013 and 2019 in evidence. Information also available within the DMO entry on Companies House website (https://beta.companieshouse.gov.uk/company/04492798).
[E9] Keith D. Nosbusch and John A. Bernaden (both from Rockwell Automation), 'The Multiplier Effect: There Are More Manufacturing Related Jobs Than You Think.' (2015) *Manufacturing Executive Leadership Journal.*
[E10] Quantum Design websites detailing DMO products – the NanoMOKE3, the MicroWriter 3 Pro and the MicroWriter 3 Baby (https://qd-europe.com/de/en/product/materials-science/magnetometers/kerr-magnetometer, https://qd-europe.com/de/en/products/materials-science/photo-lithography-systems)
[E11] Letter (24 April 2019), report (August 2005) and further research presentation (2006) relating to R6. The letter provides confirmation from Jerel Whittingham, the Commercial Director of CENAMPS, that was monitoring the project, that commercial prospects looked good, in relation to presentation of the Durham Research in R6.