Institution: University of Bristol

Unit of Assessment: 9 - Physics

Title of case study: Infinitesima – pioneering atomic force microscopy applications for industry

1. Summary of the impact

Research from the Nanophysics Group at the University of Bristol has resulted in the setting up of Infinitesima Ltd to commercialise active Q control, which improves the imaging of soft samples using atomic force microscopy (AFM). For several years, Infinitesima sold over 50 Active Q Control units and today most commercially available AFMs include the technology. The company has also commercialized high-speed AFM, a technology pioneered at Bristol, and has, since 2008, attracted more than £7 million investment from angel investors and venture capital firms in order to develop this technique for the semiconductor market, resulting in the creation of 12 new jobs.

2. Underpinning research

In 2000, active Q control for low-force tapping-mode AFM imaging in liquid environments was invented in the Nanophysics Group [1] by group members Tamayo (Marie Curie Fellow), Humphris (Royal Society 1851 Fellow), and Miles (Professor of Physics). From the equations describing the dynamics of an oscillating cantilever, it can be seen that higher the Q, the quality factor, the lower the force on the sample. The idea of actively damping an oscillation (decreasing Q) using negative feedback on its velocity was turned around by using positive feedback to increase Q and sharpen the resonant peak. It was applied not only for improving image quality of soft delicate samples, but also the measurement of the complex mechanical properties of single molecules such as the unfolding process of protein molecules, and increasing the sensitivity of cantilever sensors for the detection of molecules in medical samples. This active Q technique was developed in the research group, patented [2] by the University and the patent subsequently transferred to Infinitesima.

In 2003, the development of high-speed scanning probe microscopy began with the invention of the high-speed scanning near-field optical microscope which decreased the imaging time from ten of minutes to 1/100 of a second. Using the same high-speed scan stage and high-speed data capture hardware and software, the possibility of high-speed AFM was explored. It was achieved through an unexpected observation that above a certain tip speed threshold (about 1mm/s), the tip-sample friction suddenly decreased and to a first degree damage to the sample decreased significantly instead of increasing with higher speed as might be expected. Simulations and measurements now show that this is a result of a super lubricity effect in which the tip lifts off the surface by about 1 nm at these high speeds. This led to the development in the Nanophysics Group of high-speed AFM by Miles (Professor of Physics), Humphris (Royal Society 1851 Fellow) and Hobbs (EPSRC Advanced Fellow) and its patenting [3]. This patent has also been assigned to Infinitesima.

3. References to the research

[1] Tamayo J, Humphris ADL, Miles MJ, “Piconewton regime dynamic force microscopy in liquid”, *Appl Phys Lett* **77**, 582-584 (2000), doi:10.1063/1.127051 (99 citations)

[2] Tamayo J, Humphris ADL, Miles MJ, “Resonant probe driving arrangement and a scanning probe microscope including such an arrangement”, e.g. US patent: 6,906,450 granted June 14, 2005.

[3] *Humphris ADL, Miles MJ, Hobbs JK, “A mechanical microscope: High-speed atomic force microscopy”, *Applied Physics Letters* **86** (2005) 034106, doi:10.1063/1.1855407 (128 citations)

[4] Humphris ADL, Miles MJ, Hobbs JK, "Resonant scanning probe microscope", e.g., US patent: 7,473,887 granted January 6, 2009.

[5] *Picco LM, Bozec L, Ulcinas A, Engledew DJ, Antognozzi M, Horton MA, Miles MJ, "Breaking the speed limit with an atomic force microscope", *Nanotechnology* **18** (2007) Art. No. 044030, doi:10.1088/0957-4484/18/4/044030 [78 citations]

[6] Vicary JA, Miles, MJ, "Real-time nanofabrication with high-speed atomic force microscopy", *Nanotechnology* **20** (2009) Art. No. 095302, doi:10.1088/0957-4484/20/9/095302

4. Details of the impact

Infinitesima (www.infinitesima.com) is a spin-out company from the Nanophysics Group of the School of Physics. It has commercialized two patented innovations from the research of this group. The company was founded in 2001 based on the invention of the active Q resonance control technique for atomic force microscopy (AFM). This technique allows the effective quality-factor value to be controlled at will through an electronic feedback system. This is important particularly for using the AFM to image delicate samples in liquid environments where increasing the effective Q value of the AFM cantilever results in a considerable decrease in the force that needs to be applied for tapping-mode imaging in liquid. The result is the capability to image, for example, extremely delicate biomolecule samples. From 2001 to around 2005, the company sold about 50 Activ-Q units ($15k each) to customers around the world for operation with most brands of commercial AFM instruments. Since that time, the technique has been incorporated into most leading commercial AFM systems including instruments from the market leader, Bruker, as well as the other major companies in the field such as JPK, Asylum Research, and Agilent. The AFM market is estimated to be worth about $350 million per annum* and the active Q control technique has been incorporated into 1000s of AFMs. *Future Markets, Inc 2011

From around 2005, the focus of Infinitesima moved to high-speed AFM following its invention in the Nanophysics Group. Although conventional AFM is a very versatile microscopy capable of generating 3D images up to atomic resolution in environments from ultra-high vacuum to liquid environments, resulting in applications from inorganic materials to living functional biological systems, each image typically requires several minutes to collect. The invention of the high-speed AFM by the group opened up the possibility of video rate imaging and beyond. This is important for following processes occurring on short timescales such as crystallization, melting, enzyme degradation, self-assembly processes, etc., which would otherwise be over before the first image had been collected. High-speed AFM provides new information about, for example, the nucleation sites and the sequence of events occurring in such processes.

Infinitesima developed commercial versions of this new type of AFM and sold about eight instruments ($100k each) internationally to research laboratories in both academia and industry [A]. At this point, the company took the decision to concentrate on developing the high-speed AFM essentially exclusively for the silicon fab applications for the review of nanoscale defects occurring at various stage of silicon chip fabrication on the production line. This required a high-specification version of the high-speed AFM to meet the extreme requirements of such environments. To achieve this focus and development, further investment, totaling £7 million was acquired from ARCIntercapital [B], Sussex Place Ventures [C] and others.

Its high-speed AFM (trade name: Rapid Probe Microscopy) has been developed for silicon wafer defect review and eUV mask review. Infinitesima is partnering with multi-billion dollar companies which supply silicon device manufacturing companies such as Intel with the manufacturing and quality control equipment [A].

Infinitesima's Rapid Probe Microscope is intended to replace scanning electron microscopes (SEM) for the Intel's P1274 node (10 nm feature size) scheduled for 2015. At this size scale, SEMs cause unacceptable contamination and charging. Infinitesima is collaborating to incorporate its RPM technology in a joint project with a major instrument supplier to silicon fabs.

Nanotechnology is a flourishing field for innovation and research with excellent opportunities for impact [F]. Infinitesima is a first generation company providing the 'picks & shovels' for this nanotechnology boom, and is receiving validation for its approach in the media [G,H,I]

Today (and since 2008) Infinitesima has typically employed 12 on its staff.

5. Sources to corroborate the impact

Company and Investors:

[A] Jeff Lyons, CEO of Infinitesima Ltd.
Commercial sensitivity makes it difficult to state explicitly the current success of Infinitesima in the silicon wafer fabrication defect review etc. business. Jeff Lyons could confirm the latest information about the company.

[B] Andrew Dixon was the founder of ArcIntercapital (2001) and has been a consistent investor in Infinitesima. He can provide confirmation of the successes and impact of Infinitesima one step away from the company itself.

[C] Richard Gourlay is the managing director of Sussex Place Ventures, a principal investment firm investing in Infinitesima. He can provide the long view of Infinitesima's success and impact.

Customers include:

[D] Prof Clive Roberts is Director of The Nottingham Nanotechnology and Nanoscience Centre, University of Nottingham. He purchased two high-speed AFMs from Infinitesima Ltd.

[E] Prof Joachim Loos is in transition between Glasgow University and Eindhoven Technical University. He purchased an early version of Infinitesima's high-speed AFM and could corroborate the user experience.

The press:

[F] RCUK's "Excellence in Impact: Nanotechnology under the microscope" http://www.rcuk.ac.uk/research/xrcprogrammes/prevprogs/nano/Impact/Pages/themicroscope.aspx

[G] "Not as boring as you thought: Watching paint dry may lead to some exciting new technologies" http://www.economist.com/node/3535767

[H] "Downsizing: Companies both large and small hope to make big money from tiny particles" http://www.economist.com/node/3494694

[I] "Infinitesima Announces the High Resolution Imaging Module™ With High-Speed Nano-Scale Imaging Capability" http://www.angelnews.co.uk/article.jsf?articleId=5132