Institution: Durham University		
Unit of Assessment: UoA 9:Physics		
Title of case study: A fully automated X-ray tool for in-line defect metrology during semiconductor manufacture (Bruker JV)		
Period when the underpinning research was undertaken: Between January 2008 and June 2013		
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:**
Prof. Brian Tanner	Professor of Physics Emeritus Professor of Physics	1973 to 2016 2016 to present
Period when the claimed impact occurred: Between August 2013 and December 2020		
Is this case study continued from a case study submitted in 2014? Y		

1. Summary of the impact

Semiconductor wafers are subject to damage from misaligned handling tools, leading to cracks. Most of these are benign, but a few propagate to cause silicon wafer breakage during high temperature processing, leading to losses in production time costing millions of dollars per year. Research in Durham showed that X-ray Diffraction Imaging can be used to identify which cracks will fail catastrophically. As a consequence of this research, Jordan Valley UK Ltd, now a division of Bruker, designed and is selling multi-million pounds-worth of X-ray imaging tools to the semiconductor industry, turning what was a specialist laboratory technique into an in-line industrial metrology capability. The Durham-based division of Bruker identifies its new, fully automated, product as being critical to its continued profitability, safeguarding 30 jobs in the North East of England. The economic benefit to Bruker semiconductor manufacturing customers is estimated to be in the region of GBP10millions to GBP100millions per annum.

2. Underpinning research

X-ray Diffraction Imaging (XRDI), also known as X-ray Topography, has been used to study extended defects in single crystal materials since the 1950s. XRDI has been used extensively in the semiconductor industry to provide valuable physical insights for feedback into the manufacturing process control, including assessing the perfection of crystal wafers (Fig. 1) and to understand the defects generated during device processing, the latter via measurements of the strain associated with these defects. However, due to long data collection times, such studies were performed off-line and on selected sample wafers only [R1].

Current industrial silicon device fabrication facilities (fabs), are totally automated production facilities that are hugely, and increasingly, expensive to build and operate, with a typical cost of USD4billion at the current manufacturing node. In order to gain a return on this investment, semiconductor manufacturing volumes must be extremely high. Catastrophic wafer breakage during high temperature processing is thus an increasingly expensive and unacceptable industry process hazard, resulting in the need to halt a production line to clear away wafer fragments, leading to a high cost in lost device yield. However, the origin of this wafer fracture was unclear, as most silicon wafers show some damage due to handling in the manufacturing process, yet only a few such defects nucleate catastrophic failure.

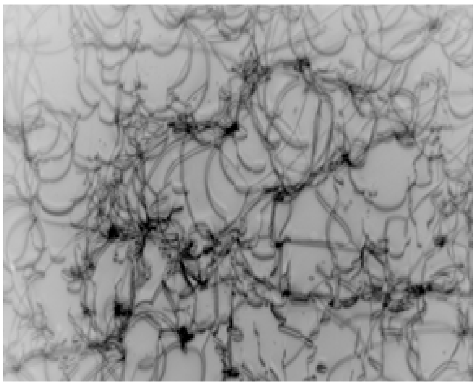

Fig.1. X-ray diffraction image of dislocations in a SiC wafer for high temperature electronics. Field width 3mm.

In January 2008, an international research consortium led by Durham University, coordinated by Professor Brian Tanner in Physics, began research work to understand which wafers were at risk of failure and to develop a method for predicting this failure, using XRDI to analyse handling damage on wafers. Unlike optical imaging, XRDI measures the residual strain on the material as a diffraction image, and is sensitive to the changes in the lattice plane spacing, for example, around dislocations, as shown in Fig.1. In simple terms, XRDI is the X-ray equivalent of transmission electron microscopy of crystalline materials. The international consortium included academic (Durham, Freiburg, Dublin City and Navarra Universities) and industrial partners, and was funded between 2008 and 2011 under a EUR2.65million European Commission Framework 7 ICT project, '*Investigation of Silicon wafer damage in manufacturing processes*' *(SIDAM)*. *SIDAM* was strongly supported by major semiconductor companies; its advisory board included representatives from Intel, MEMC, Siltronic and AMD (Global Foundries). The EU Framework 7-funded SME industrial partner was Jordan Valley Semiconductors (UK) Ltd. This was a 30 year-old spin-out from Durham University Physics Department (Bede Scientific) that, just prior to the project starting, had been acquired by Jordan Valley Semiconductors, headquartered in Israel.

By working closely with advisory board members, the consortium research established that misaligned handling tools generated cracks at the edge of Si wafers. The key problem was then to determine which cracks would propagate during high temperature processing, causing catastrophic fracture, and which were benign. The research team reproduced this cracking in a controlled manner using nano-indentation close to the wafer edge. These 'control' wafers were studied at high resolution using XRDI at the Diamond Light Source. The key research breakthrough [R2] came in 2011, when Prof. Tanner of Durham University showed that the crack propagation condition could be simply quantified, as the opening stress was related directly to the length of the crack, while the width of the crack tip on the XRDI gives a measure of the back stress [R2]. The research discovered that cracks with a small length to image width ratio are benign (A, which appears broad in Fig 2), while those with a large length to image width ratio (B, which appears sharp in Fig 2) are highly likely to lead to fracture. Critically, this diagnostic condition can be used to predict whether a crack will or will not subsequently propagate under specific thermal processing conditions. The team confirmed the validity of the analysis and defined the basic mechanism of crack propagation and imaging via *in situ* experiments conducted at the ANKA synchrotron radiation source [R3, R4] and *ex situ* by experiments at the Diamond Light Source [R5]. These experiments [R6] continued beyond the end of the SIDAM project. Furthermore, the research team developed a software tool, based on this model and using the data from the non-destructive XRDI images, capable of predicting the probability of wafer fracture under specified furnace conditions [R2].

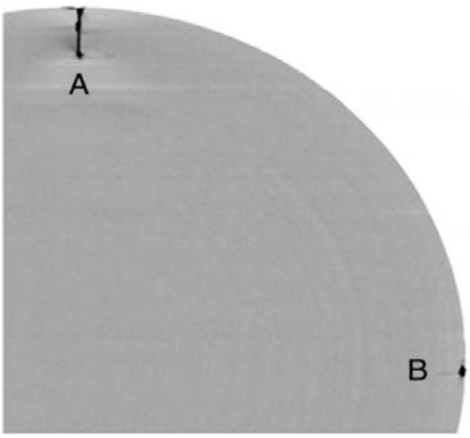

Fig. 2. XRDI image of benign (A) and critical (B) cracks in a 200mm Si

3. References to the research

[R1] *X-ray Metrology in Semiconductor Manufacturing*, D. K. Bowen and B. K. Tanner. CRC Taylor and Francis, Boca Raton, 2006. pp 279 +xi, DOI: 10.1201/9781315222035
[R2] *Prediction of the propagation probability of individual cracks in brittle single crystal materials*, B. K. Tanner, M. C. Fossati, J. Garagorri, M. R. Elizalde, D. Allen, P. J. McNally, D. Jacques, J. Wittge and A. N. Danilewsky , Appl. Phys. Lett. **101** (2012) 041903. DOI: 10.1063/1.4738994
[R3] *Crack propagation and fracture in silicon wafers under thermal stress*, A. N. Danilewsky, J. Wittge, K. Kiefl, D. Allen, P. J. McNally, J. Garagorri, M. R. Elizalde, T. Baumbach and B.K. Tanner, J. Appl. Cryst **46** (2013) 849-855**.** DOI: 10.1107/S0021889813003695
[R4] *X-ray Diffraction Imaging for Predictive Metrology of Crack Propagation in 450-mm Diameter Silicon Wafers*, B. K. Tanner, J. Wittge, P. Vagovič, T. Baumbach, D. Allen, P. J. McNally, R. Bytheway, D. Jacques, M. C. Fossati, D. K. Bowen, J. Garagorri, M. R. Elizalde and A. N. Danilewsky, Powder Diffraction **28** (2013) 95-99. DOI: 10.1017/S0885715613000122
[R5] *The Geometry of Catastrophic Fracture during High Temperature Processing of Silicon,* B. K. Tanner, J. Garagorri, E. Gorostegui-Colinas, M. R. Elizalde, R. Bytheway, P. J. McNally and A. N. Danilewsky, International Journal of Fracture **195** (2015) 79-85. DOI: 10.1007/s10704-015-0050-1
[R6] *X-ray Asterism and the Structure of Cracks from Indentations in Silicon,* B. K. Tanner, J. Garagorri, E. Gorostegui-Colinas, M. R. Elizalde, D. Allen, P. J. McNally, J. Wittge, C. Ehlers, A. N. Danilewsky, J. Appl. Cryst. **49** (2016) 250-259. DOI: 10.1107/S1600576715024620

This research was funded between January 2008 and June 2011 by EUR2million from the European Commission Framework 7 ICT programme (FP7-ICT) for the project 'Investigation of Silicon wafer damage in manufacturing processes' (SIDAM), (https://cordis.europa.eu/project/rcn/85246/factsheet/en).

Evidence of the quality of the research is that the assessors of the SIDAM project final report stated that "*the project has fully achieved its objectives and technical goals ….and has even exceeded expectations*" [E10]. The work is cited as an exemplar Scientific Highlight in the 2012/2013 Diamond Light Source Annual Review, (highlighted on page 67 in introduction to Materials and more details from Tanner et al; on pages 72-73 [E9]). The underpinning research was all published in the most relevant peer reviewed international journals. The combined citations for the underpinning research papers exceeds 50 to date.

4. Details of the impact

As a result of the outcomes of the SIDAM research programme, Jordan Valley Semiconductors UK invested in the design, development and manufacture of clean room-compatible XRDI tools for off-line inspection of Si wafers. They developed both transmission (QC-TT) and reflection (QC-RT) geometry systems, which were launched in 2012. Since 2013 these tools have addressed an important and growing applications need for defect identification, and subsequent elimination with resulting improvements in production device yield, in the compound semiconductor industry [E1]. There has been particular interest from producers of [redacted] substrates. Between August 2013 and April 2019, [redacted] of these tools were sold worth [redacted] [E1].

However, the initial research challenge came from the industrial need of high-volume silicon manufacturers and the overall research project objective was to establish the XRDI technique potentially as an in-line, not an off-line, metrology. Off-line sampling results in the loss of the sampled wafer, a cost which is saved with in-line inspection, and in which preferably scanning of every wafer, can be achieved. However, this requires extremely high tool throughput and, as all fabs are entirely automated, robotic handling of 300mm silicon wafers is essential.

Fig.3. Bruker JVSensus tool for automated, high-throughput, X-ray Diffraction Imaging of silicon wafers [E2]

With the development of the simple criterion for assessing fracture probability that emerged from the SIDAM research, automatic defect recognition, analysis and interpretation in XRDI can be performed in an automated environment. With the confidence of the scientific understanding from the SIDAM project, Jordan Valley Semiconductors UK made the strategic decision to develop a fully automated tool for in-line inspection, the *JVSensus*, shown in Fig. 3 [E2]. Such tools cost in excess of [redacted]. In late July 2013, Jordan Valley installed the first *JVSensus* automated robotic handling XRDI tool in a South-East Asian semiconductor foundry, and in August 2013 began a three-year joint development programme with that company [E1].

Together this consortium established a correlation between wafer breakage and specific defects, and dramatically reduced wafer breakage rates by process adjustment. As a result, the company purchased a further [redacted] *JVSensus* tools in 2016. In November 2015, a North American manufacturer purchased a tool and also found correlations between their wafer breakage and another, but similarly specific, type of defect. A further *JVSensus* tool was shipped in January 2018, the total value of the [redacted] tools being [redacted] [E1].

In November 2015, because of its strength in X-ray semiconductor metrology, Jordan Valley Semiconductors was acquired by the Bruker Corporation [E3]. Bruker, which had a USD1.7billion turnover in 2017 and with 6,000 employees worldwide, is one of the world's largest scientific instrument manufacturers. Jordan Valley remains intact as its Semiconductor Division. Operations in Durham in the design and manufacturing facility have not been affected, where there are 30 employees working in highly skilled jobs, and since 2013, the Durham division revenue has risen.

During that time proprietary work continued to develop an in-line tool and by October 2017 the goal of a throughput analysis of [redacted] wafers per hour was achieved [E5]. These X-ray diffraction images are of the full area of 300mm silicon wafers. At this inspection rate (less than [redacted] per wafer) a full cassette of wafers can be inspected during the furnace temperature ramp times between steps in production processes. The first high volume tool capable of in-line monitoring was shipped in November 2017. [redacted] Bruker XRDI tools were sold between April 2019 and October 2020 [E5]. XRDI revenue rose to [redacted] for the 2019 financial year, while sales from April to September 2020 stand at [redacted] and are anticipated to reach [redacted] by the end of the 2020 financial year [E5]. UK Site Manager, *Bruker Semiconductor Division* said in 2019: "*The scientific understanding that came from the SIDAM project allowed us to make the investment in the JVSensus tool with confidence. The contribution of XRDI to the Durham facility's revenue since August 2013 has been* [redacted] *and without this, the site would not have remained viable*" [E4]. He added in October 2020: "*For the UK organisation, XRDI products now account for* [redacted] *of sales revenue over the last 5 years and is growing. We benefit from the learnings from the SIDAM project every week when interacting with customers, understanding their problems and selling products which give them real value. … It's easy to forget where we were 10 years ago when we see the performance of the tools now. It's been a terrific effort from a brilliant team, built on the solid foundations created by SIDAM*" [E5]

An assessment of the impact on the silicon industry can be construed from the fact that volume semiconductor manufacturing companies, who are extremely sensitive to production costs, are now investing in the unique [redacted] Bruker XRDI tools, in order to reduce the number of catastrophic wafer failures occurring. Such companies only introduce new inspection tools when other strategies fail to contain critical manufacturing problems. It is important to recognise that the costs associated with wafer breakage are extraordinarily difficult to obtain from the silicon industry. Companies such as Samsung, TSMC and Huawei are now at the 7nm node [E6] where individual wafers are valued in excess of USD10,000. Some breakage events can result in 300 pieces being lost and this is an USD3million loss of sales solely from the broken wafers. However, it is the halting of the production process that has the greatest impact. A typical fab throughput is 1,000 wafers per day. Thus, as it takes a day to clean a broken wafer from a processing chamber, if the production line is halted as a result, the revenue loss associated with a single wafer break can be estimated to be of the order of USD10million per event [E1, E7]. The actual overall costs of halting a fab line are difficult to ascertain as such information is strictly guarded, but it is known to be enormous. In January 2015, the South Korean media outlet Digital Daily reported that "production at Samsung Electronics' 3D NAND Flash facility in Xi'an, China, recently came to a temporary halt [for an undisclosed reason]. Over 30,000 wafers were scrapped as the result of the interruption, and loss was estimated at USD60 million" [E8]. One of the Bruker customers had an unsustainable breakage rate of [redacted] per 1,000 wafers prior to purchase of the *JVSensus* tool [E7]. This gives some indication of the economic impact that has resulted from the reduction in wafer breakage at the fabs of Bruker's customers.

5. Sources to corroborate the impact

[E1] Email from DJ of Bruker Semiconductor Division, Belmont Industrial Estate, Durham.
[E2] Bruker webpage on JVSensus.
[E3] Article from www.analytica-world.com: 'Bruker completes acquisition of Jordan Valley Semiconductors Ltd'. (4 November 2015).
[E4] Email (dated 23 September 2020) from Site Manager, Bruker Semiconductor Division, Belmont Industrial Estate, Durham.
[E5] Email (dated 1 October 2020) from Site Manager, Bruker Semiconductor Division, Belmont Industrial Estate, Durham.
[E6] Article from www.semiwiki.com: '14nm 16nm 10nm and 7nm – What we know now' (4 July 2017).
[E7] Case study draft commented on by DJ of Bruker Semiconductor Division, Belmont Industrial Estate, Durham.
[E8] Article from technews.co: 'Production at Samsung's memory fab in Xi'an halts temporarily with little impact' (29 January 2015; accessed and screenshot taken 19 March 2019).
[E9] 2012/2013 Diamond Light Source Annual Review, (highlighted on page 67 in introduction to Materials and more details from Tanner et al; on pages 72-73 (page 38 of the pdf)).
[E10] SIDAM technical review report (quote from the ticked box on page 3).