1. Publishable summary

SIDAM

The aim of the project is to discover how to derive quantitative, predictive information from X-ray Diffraction Imaging (XDRI), and thus to enable a new metrology of wafer inspection.

In detail the **objectives** are:

- To model the stresses around microcracks and slip bands in silicon wafers
- To model the XRDI images observed on wafers with a variety of microcrack and slip patterns
- To model the relationship between the above stress patterns and Rapid Thermal Annealing (RTA) failures
- To verify the above models by controlled nanoindenation, XRDI and RTA experiments
- To obtain a procedure for predicting likely catastrophic wafer failure during processing.

This will be usable in several ways by semiconductor manufacturing companies:

- to avert catastrophic failure by preventative metrology,
- to diagnose catastrophic failure in a problem-solving mode,
- to qualify all tools and wafer-handling procedures against the introduction of "killer" microcracks.

Silicon wafer are always, to some extent, damaged during handling and shipping. This can arise either through contact with the cassettes used for transport or the grips of the handling tools. All wafers that we have examined show microcracks at the wafer edges. During thermal processing, some microcracks grow, resulting either in generation of slip bands and loss of device performance or catastrophic total wafer breakage. In the latter case alone, the estimated cost in lost production time taken to stop the line, recover the broken wafer, clean and restart the affected tool is estimated[1] to be $2.5M per annum for every 300mm silicon fab line in the world.

X-ray Diffraction Imaging, also known as X-ray Diffraction Topography, is a metrology that reveals the strain associated with internal defects, such as buried microcracks and slip bands. However, wafers that produce perfectly satisfactory devices show defects and it is not known which ones are dangerous to the manufacturing process. The objective of the project is to develop a rapid imaging metrology based on the BedeScan™ x-ray tool[2] that will identify wafers that are in danger of failing by catastrophic fracture. The aim of the project is to quantify this technique to enable process-critical defects to be identified.

This is being achieved by a strategy of introduction of controlled damage through use of nanoindentation and quantification of local strain by x-ray and micro-Raman measurements. Detailed modelling of the impact of microcracks due to the associated strain fields is being done by finite element calculations.

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[1] Source: International SEMATECH Industry Economic Model v8.1ss
[2] D.K. Bowen, M. Wormington & P Feichtinger, *A novel digital X-ray topography system*, J. Phys. D **36** A102 (2003) Patent granted in 2004

Progress to date

The Consortium has continued to work extremely well together and close scientific links have been made between all partners, with extensive co-authorship of papers and presentations. Mechanisms for sample preparation and distribution have worked extremely smoothly to date; early establishment of sample numbering and handling protocols removed potential confusions. All partners have willingly and promptly fulfilled their obligations to requests in an exemplary way. There has been an outstanding spirit of cooperation between the partners and the scientific progress has been very good. Although we have failed as yet to find thermo-mechanical conditions which result in catastrophic wafer fracture, we have developed a good understanding of the origin and mechanisms of thermal slip arising from wafer damage. We have also qualified the images from the BedeScan™ tool against high resolution images recorded at synchrotron radiation facilities and we have successfully measured and modelled the strain distribution and crack propagation around controlled indents.

Recent Scientific Highlights from the 2nd Reporting Period

The Dublin City University group have overcome significant challenges in instrumental stability to extend the capability of micro-Raman spectroscopy to undertake high-resolution mapping. Data collection time is typically 30 hours. Tensile stress, exactly below the indenter central apex, is seen prior to annealing. The symmetry breaking in the compressively strained regions of the map shown in Fig. 1.1 arises from the presence of material breakout. There is excellent agreement between the experimental results and those from finite element modelling.

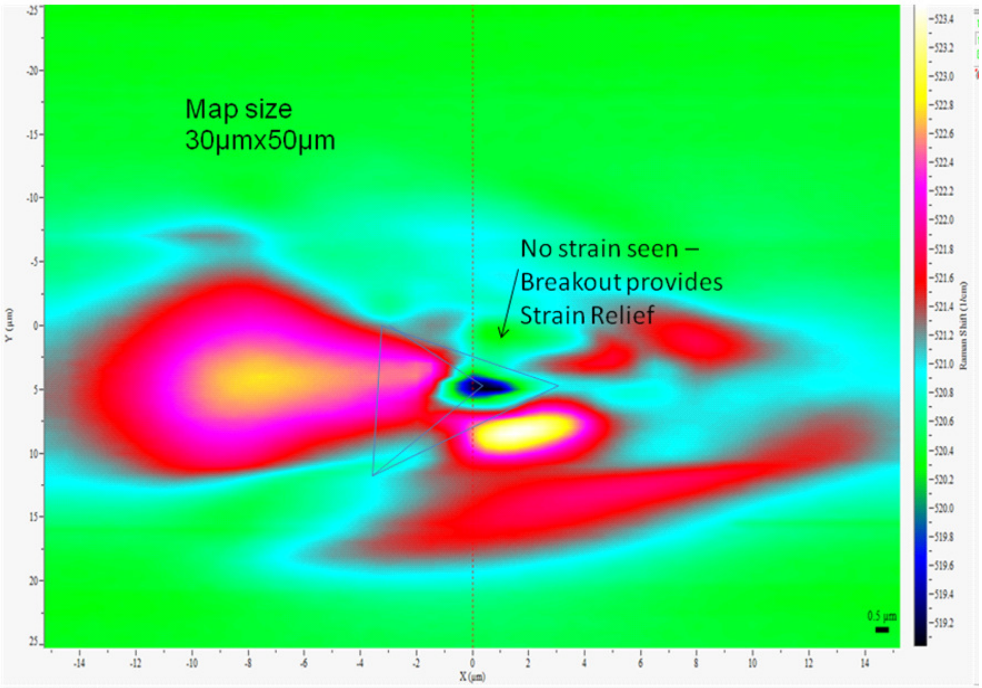

***Fig. 1.1** 2D micro-Raman spectroscopic map of the (tensile – blue) and compressive (red) stress below and around a 600mN loaded indent.*

The stress-relieving effect of breakout has been shown to account for the variation in the extent of the X-ray diffraction images from indents from identical loads (Fig 2.2). Cracks are observed to originate at the apices of the indenter tips and run almost in line with the projection of the inclined edges of the indenter tip. They do not follow low index crystallographic directions. The extent of the contrast in the diffraction image represents a good measure of the residual stored elastic energy.

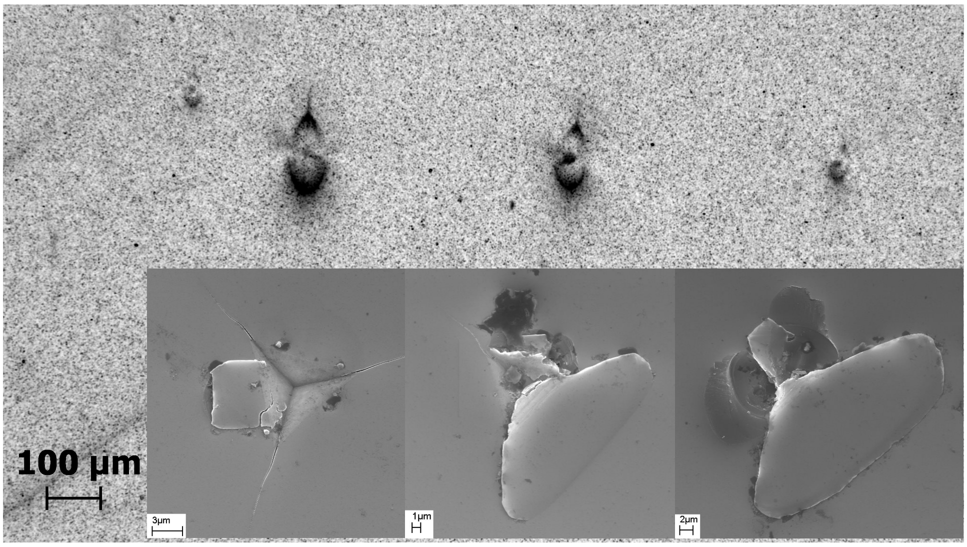

Fig 1.2 *X-ray diffraction images of the strain field around nominally identical indents. The smaller images correspond to indentations that have released the stored energy by fracture and breakout of material. Indenter load 600mN*

At smaller indenter loads, breakout does not occur. Here the symmetry, cross-sectional profile and magnitude of the stress are modelled extremely well with finite element code. The simulations also predict accurately the shape of the experimental load-displacement indentation curves measured during the indentation. Finite element modelling has been extended to include crack formation. Excellent agreement has been found between the simulated crack shape and position and that observed experimentally by sequentially imaging the surface with the scanning electron microscope as material is removed by focused ion beam milling and reconstructing the crack shape from the images (Fig 1.3).

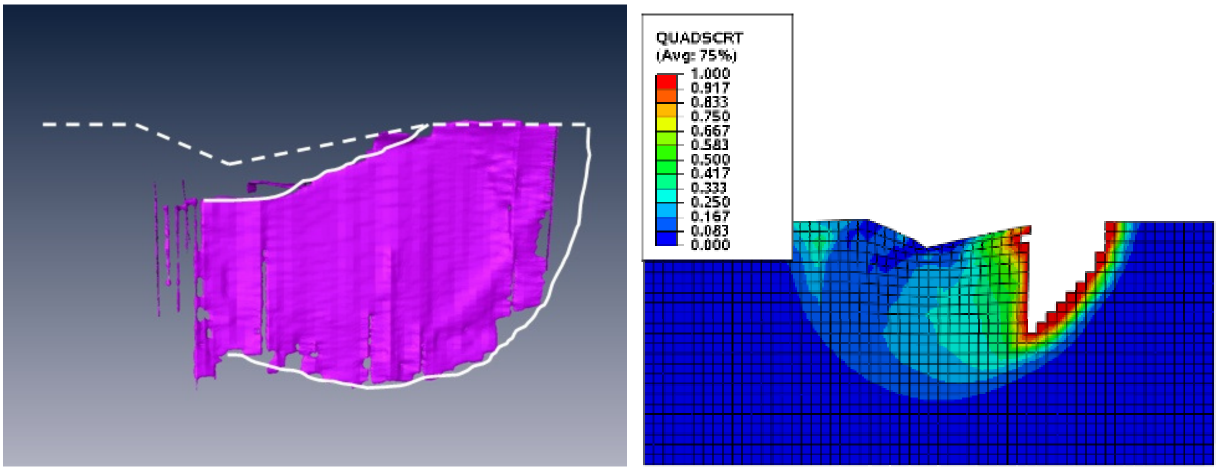

Fig. 1.3 *Cross section of experimental and simulated crack structures below an indent*

The nucleation of dislocations during rapid thermal annealing has been studied by *in-situ* X-ray diffraction imaging (topography). At controlled indents above about 600mN, concentric loops extending over pairs of inclined {111} planes were formed, the velocities of the inclined and parallel segments being almost equal. Following loss of the screw segment from the wafer, the velocity of the inclined segments almost doubled, due to removal of the line tension of the screw segments (Fig 1.4). The loops acted as obstacles to slip band propagation. As illustrated in Fig 1.4, there was considerable variation in slip band development, depending on the amount of breakout on indentation. After identical heat treatment, nominally identical indents might not initiate sources, might produce easily resolvable sources or result in slip bands of high dislocation density. The slip band length varied linearly with plateau annealing time, as expected for a constant dislocation

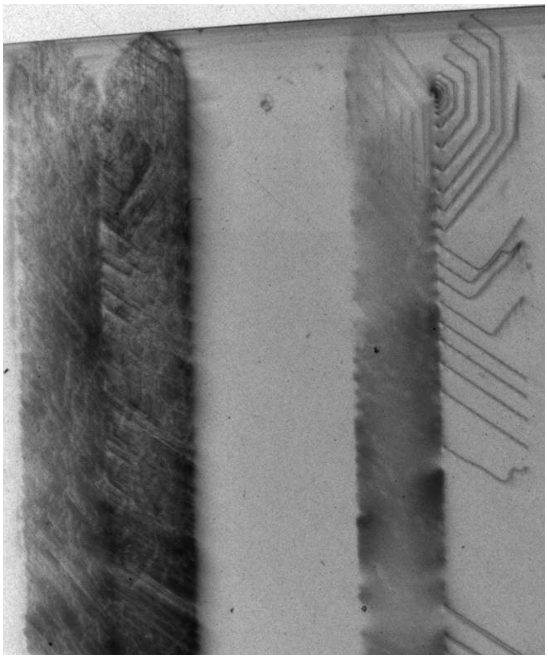

Fig. 1.4. X-ray diffraction images of dislocation sources on inclined {111} slip planes originating at indents at the start of the bevel after plateau annealing at

velocity. The slip band length as a function of temperature varied exponentially, dominated by the dislocation mobility. Much thermal slip was observed to originate at the wafer edge, either at the very extremity of the wafer or at the beginning of the bevel. The density of slip bands varied with position around the wafer and the greatest density corresponded to the region where shear resolved stresses at the wafer edge, predicted by finite element modelling, were maximum.

The project remains on course to deliver a quantitative metrology to determine the statistical probability of wafer breakage during semiconductor processing. The typical loss of wafers through breakage is of the order of €2m per annum for a single fabrication line and as a result of the SIDAM project will be significantly reduced.

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Recent Publications

J. Wittge, A. N. Danilewsky, D. Allen, P. McNally, Z. Li, T. Baumbach, E. Gorostegui–Colinas, J. Garagorri, M. R. Elizalde, D. Jacques, M. C. Fossati, D. K. Bowen and B. K. Tanner, *J Appl. Cryst.* (in press) "Dislocation sources and slip band nucleation from indents on silicon wafers"

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J.Garagorri, E.Gorostegui-Colinas, M.R. Elizalde, D. Allen & P. McNally, *Anales de Mecánica de la Fractura* **27**, (2010), 559-564 "Nanoindentation Induced Silicon Fracture and 3D Modelling"

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