R&D OF THE MANUFACTURING OF A MICRO-MACHINED COLLIMATOR FOR A COMPACT X-RAY SPECTROMETER FOR PLANETARY MISSIONS *[UPDATE]*

Author: Geoff McBride[1]
Co-author: Dario C Castiglione[2]
[1] Space Science and Technology Department, The Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, OX11 0QX, UK
[2] The University of Reading, School of Chemistry, PO Box 224, Whiteknights, Reading, RG6 6AD, UK
E-mail: g.mcbride@rl.ac.uk, d.c.castiglione@reading.ac.uk

Abstract

As part of the SMART-1 Mission, The Rutherford Appleton Laboratory (RAL) Space Science and Technology Department (SSTD) has developed ***DCIXS***, the Demonstration Compact Imaging X-ray Spectrometer, which uses Swept Charge Device (SCD) detectors and a low profile micro-machined X-ray collimator. SMART-1 is the first of the Small Missions for Advanced Research and Technology in the ESA Horizons 2000 Science Plan.

The spectrometer will provide high quality spectroscopic mapping of the lunar surface. Research and development and subsequent manufacturing of the X-ray collimators conducted at The Rutherford Appleton Laboratory were completed spring 2002. The collimator realisation was achieved using UV lithographic methods and precision micro-machining. The collimator structure has a thickness measured in millimetres but a pattern with characteristic sizes measured in tens of microns. SU-8, a UV sensitive epoxy resin based, negative photo resist was utilised. This resist was exposed through a chrome/quartz mask to UV light filtered to 365nm. The mask incorporates a positive image of the desired collimators through which the collimated UV exposes the resist and forms a negative image. Once developed, a 400 micron high SU-8 mould is formed on the highly conductive silicon wafer substrate. Copper may then be electroformed on to the silicon substrate through the SU-8 mould, up to the required 400 microns. A CNC mill is used to remove the irregularity of the upper surface of the copper. Substrate and SU-8 mould are subsequently removed and the final structure electroplated with gold. The collimators are then stacked in holders to the required heights to give the 8 and 12 degree fields of view.

DCIXS will provide the first comprehensive analysis of the lunar surface in X-rays, providing measurements of Fe, Mg, Al and Si under normal solar conditions and several others during solar flare events. The combination of ***DCIXS*** data with information obtained from other instruments on SMART-1 and from previous missions, will allow a more detailed look at some of the fundamental questions that remain regarding the origin and evolution of the Moon and will help to map lunar resources more effectively.

Introduction

The ***DCIXS*** (Demonstrator Compact Imaging X-ray Spectrometer) is one of the instruments on ESA's SMART-1 mission to the Moon due for launch 2003. ***DCIXS*** will conduct a global survey of the lunar surface from secondary X-ray florescence. The spectrometer consists of an array of twenty-four Swept Charge Devices each with a low profile collimator stack.

DCIXS Objective

For the first of the ESAs SMART (Small Missions for Advanced Research and Technology) missions the Space Science and Technology Department (SSTD) at the Rutherford Appleton Laboratory (RAL) has developed ***DCIXS***, the Demonstrator Compact Imaging X-ray Spectrometer**,** which uses Swept Charged Detectors and a low profile micro-machined collimator[1]. Solar electric propulsion will be used to transfer the SMART-1 spacecraft from Ariane 5 to an elliptic lunar orbit. ***DCIXS*** will be used to make observations of secondary X-ray emission from the lunar surface.

X-ray remote sensing of the Moon

Access to lunar sites and samples is highly restricted. Therefore remote-sensing data is crucial in achieving a global coverage as much of our understanding of lunar geochemistry comes from analysis of the returned Apollo samples which represented a restricted subset of the variety of lunar terranes.

The importance of remote-sensing was shown by Apollo missions 15 and 16 which carried remote X-ray detection instrumentation. Maps of the Mg/Si and

Al/Si ratios for *ca.* 9% of the Moon around equatorial regions were produced and showed the heterogeneity of the lunar surface across different terranes, revealing differences in elemental abundance across those regions.

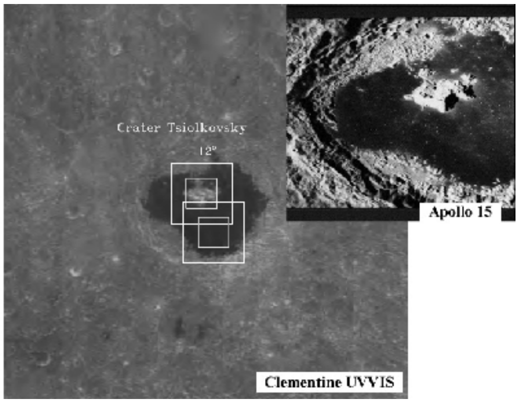

Figure 1 - Crater Tsiolkovsky, showing the resolution available with *DCIXS*.

DCIXS in operation

During normal solar conditions, ***DCIXS*** will be able to detect elemental Fe, Mg, Al and Si on the lunar surface. During solar flare events, it will be possible to detect other elements such as Ca, Ti, V, Cr, Mn, Co, K, P and Na, although a global survey of these elements is beyond the scope of the baseline mission[2]. To date the absence of global maps of the elemental abundance of Mg, Al and Si represents a significant impediment to our understanding of the Moon. The global mapping of these elements and in particular Mg#, the 'magnesium number' (MgO/[MgO+FeO]), is the prime goal of the ***DCIXS*** experiment. The precise mix of science to be achieved will be dependant upon various factors, including altitude and the occurrence of solar flares during the mission.

Instrument description

DCIXS has a mass of 3.5kg can be contained in a volume of 110 x 150 x 180mm and has a power consumption of less than 8W. The energy range of interest is from 0.5 to 10keV, and an energy resolution sensitivity of ~150eV to 200eV FWHM.

The Swept Charge Device (SCD) X-ray detectors are based on proven CCD (Charge Coupled Device) technology but have the advantage of offering equivalent X-ray detection and spectroscopic measurement capabilities, whilst also operating at near room temperature. Unlike conventional imaging CCDs which have two transfer directions, the SCD has only one readout direction which both simplifies the clocking of charge, and also enhances the effect of dark current suppression during dynamic clocking.

Figure 2 - Early CAD design of the *DCIX* instrument

Compared to the multiple transfers in a conventional CCD, the comparatively low number of readout clocks, needed to relay the entire array, lead to high frame rate, and hence a reduced requirement for cooling to overcome dark current. In addition, the dynamic suppression of surface-generated dark current, which occurs during clocking with high substrate voltage, reduces dark current still further. Thus the need for the large passive cooling radiator that was previously required to cool large X-ray focal plane CCDs is avoided. In-flight calibration of the detector field of view and energy resolution, using observations of well-known astronomical X-ray sources, will take place over a period of a year in the cruise phase. Subsequent measurements made of the low flux levels from the lunar surface against the background of the solar wind electrons will then demonstrate the design possibilities of the micro-collimation techniques. The aim is to produce high quality lunar science.

Collimators

A key feature in the progress of the ***DCIXS*** instrument has been the development of low profile collimators, which define the instrument field of view θ.

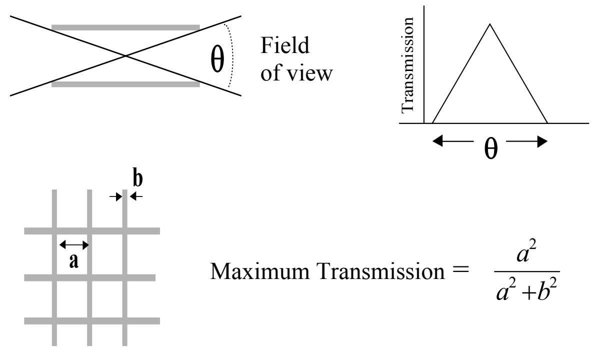

Figure 3 - Collimator Basics.

The innovation in ***DCIXS*** has been to micro-fabricate the collimator using the techniques of micro engineering to produce a very low profile device, which is robust and ideally matched to the detector array placed immediately behind. By making use of MEMS engineering, the cross section is an entirely free design. Additionally, the material walls can be optimised for a particular application. Thus in the ***DCIXS*** instrument, the collimator is constructed from an 'appropriate' electro-depositable material e.g. copper or gold, ideally of sufficiently high z (atomic number) to avoid fluorescence radiation through the interaction of high energy cosmic rays with low z wall materials. In high radiation environments this would effectively blind the detector; but more critically in the presence a low intensity cosmic ray flux, such interactions would produce a contaminating signature indistinguishable from the primary fluorescence of the object under study. For this reason, low z materials such as Si and O, for example, found in the glass microchannel plate designs for similar optics, are to be avoided[3].

Introduction to collimator manufacture

The collimators for ***DCIXS*** are made using standard UV lithographic techniques in a novel way, the foundation of this research being in the manufacture of millimetre wave components[4]. Epon resin SU-8 manufacture by Shell Chemicals (hereafter SU-8), is an epoxy based negative photoresist and is used to lithographically pattern electroplating moulds onto the Boron-doped (i.e. conductive) silicon wafer substrates[3]. Once metallisation is complete, both the mould and wafer are removed to leave high profile collimators.

Beginnings and prototype

Collimator development began before all parameters had been defined. A test mask was made which consisted of $\sim 1cm^2$ prototype collimators which had a 30µm wall thickness and $150µm^2$ apertures, see Figure 4.

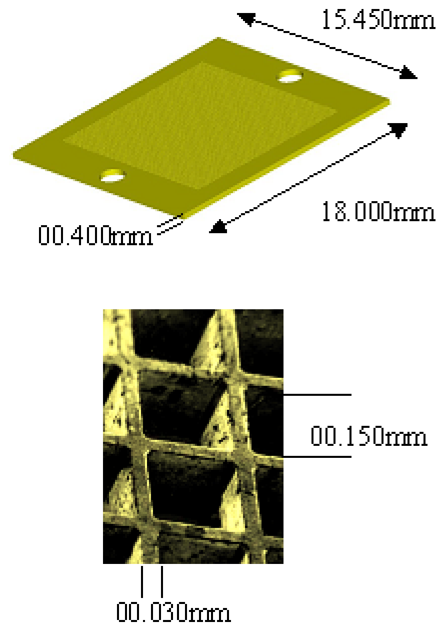

Figure 4 - Collimator Prototype.

With all parameters defined, the flight model mask design was finalised in line with the mechanical design of the instrument. Drawings were then converted to the mask-manufacturing format at the Central Microstructure Facility (CMF). The specifications of the mask were well within the capabilities of the Facility (1.8µm minimum line width) and the mask layout was customised to exploit the UV beam footprint to give maximum yield. SU-8 negative photoresist, if cured in sufficient volume over a large area, would bend the substrate and hence distort the structures so the mask was designed to minimise the amount of curing SU-8 on the silicon wafer.

The collimator specifications were set: Collimator hole size is $168µm^2$ with 30µm walls. The collimated area was set at hole to wall ratio of 80:20. Two fields of view are required for the ***DCIXS*** instrument of 8 and 12 degrees giving collimator heights of 2.4 and 1.8mm respectively.

Manufacture in detail

The substrates were custom designed, 3" silicon wafers with an increased conductivity (by doping with boron [Resistivity: < 0.0025ohm.cm]) to assist electroplating of the collimator structure. Wafer thickness was 1mm to counterbalance stress caused by cured SU-8, electroplating and CNC machining. Wafer preparation for the lithography consisted of immersion in a hydrofluoric acid solution (to remove the oxide layer on the surface of the silicon wafers) and a high temperature drying process. The resist must be applied in good time to prevent reoxidation of the silicon surface.

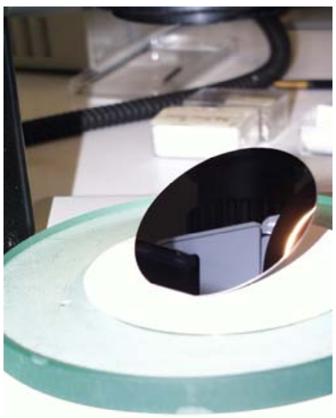

Figure 5 - 3" Boron doped Silicon wafer, 1mm thickness.

Wafer Preparation and Resist Deposition

Two methods of resist deposition were developed. SU-8 was purchased in crystal form and was then ground to a fine powder. The SU-8 powder was then mixed with an appropriate amount of solvent (by weight) and a photoinitiator to give a suitable solution for the relevant deposition method. The first method developed was a spreading technique. For spreading, the SU-8 mixture was given a lower solvent content (25% wt) to make the solution quite viscous. After preparation, the wafer is held in a vacuum chuck on the spreader and the spreader blade is set to the require height using a micrometer adjuster. A line of the viscous SU-8 solution is poured at one edge of the wafer and the blade is drawn across, see Figure 6. The process was successful but slow and often messy.

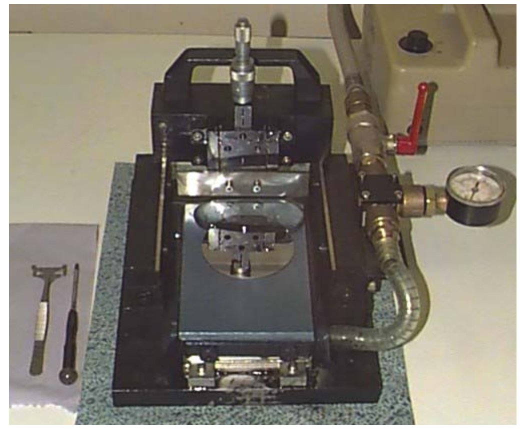

Figure 6 - Spreader with Silicon wafer and SU-8.

As an alternative, a pipetting technique was developed. In this case the solvent content is increased (50% wt) so the resist becomes more liquid. A known amount is pipetted onto the wafer to give the required resist height. This method allowed bulk preparation of eighteen wafers per batch.

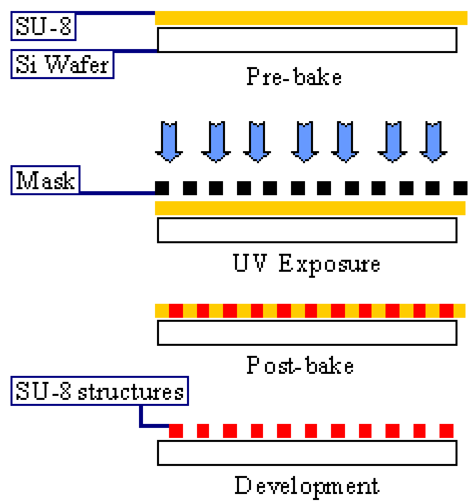

Figure 7 - UV Lithography.

In both cases the solvent level must be reduced by *ca.* 95% through pre-baking using a digitally controlled hotplate. For pipetting, the pre-bake timings were approximately 20 hours due to the higher solvent content.

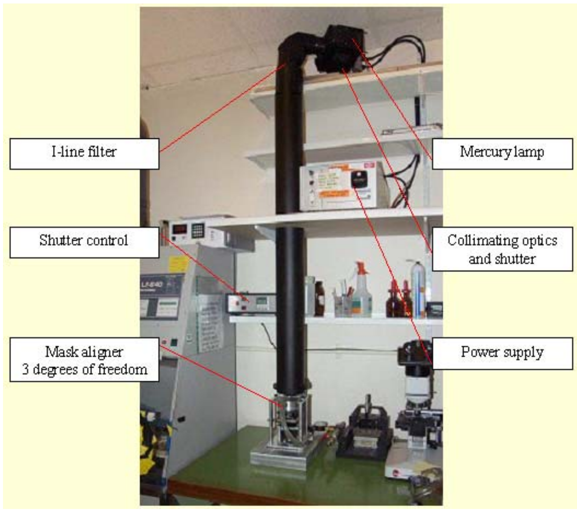

Figure 8 - Collimated UV light and mask aligner set-up.

Exposure and Development

Once cooled the wafer is placed in the mask aligner and the mask lowered into light contact. Collimated UV light from a mercury lamp with an I-line filter exposes the resist for a calibrated length of time through the mask. The lamp and mask aligner set-up was designed and built by the Millimetre Wave Technology Group (MMT)[5] at the Rutherford Appleton Laboratory. After the exposure the wafer is left to rest for a short period and then subsequently returned to the digital hotplate for a post-bake process which initiates cross-linking of the exposed resin, thereby producing a hardened collimator mould. Unexposed resist is removed using a solvent developer and a reactive ion etch process removes any residual debris. High aspect ratio resist structures were achieved (500µm high) by this process to provide a negative mould ready to form the collimators.

Electroplating

The wafer with the SU-8 mould is now first electroplated with 10µm of Nickel. This acts as an adhesion/keying layer for the subsequent copper electroplating. Attempts were made to directly electroplate with copper but unfortunately the adhesion of the copper to the wafer was insufficient to be used as the only electroplating process.

Figure 9 - Electroplating bath and motorised arm assembly.

To encourage plating down in between the resist structures, the wafer swings on a motor driven arm in the electroplating fluid. To achieve the required height uniformly across the wafer, it is over-plated with copper.

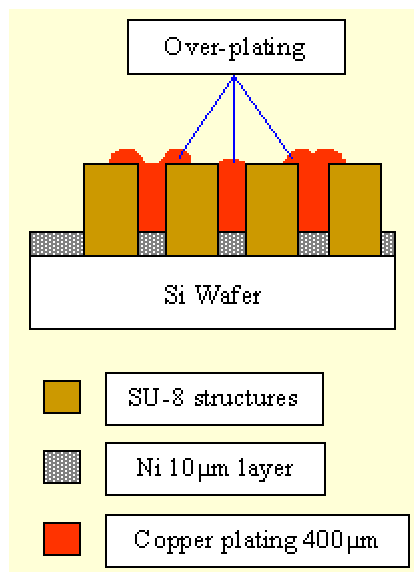

Figure 10 - Schematic showing over-plating.

Machining

To achieve a sooth surface for stacking and filter application, the copper must be machined down to the required height but the wafers become slightly bent by the electroplating process. This problem is overcome by the use of a novel vacuum/clamp assembly. The machine used for this process is a 3-axis Computer Numerical Control (CNC) machine using the latest programming software, precision collet chucks and solid carbide cutters to ensure the accuracy and quality of the finished component. The wafers are located by the CNC machine and a roughing cut is taken to reduce the height close to the required dimension. Finally, a high level finishing cut is taken in order to obtain the surface finish required.

Figure 11 - Machining of collimators.

To remove the collimators from the wafer it is immersed in liquid nitrogen and the collimators are released from the silicon wafer by thermal shock.

SU-8 Removal

The removal of the SU-8 was somewhat problematic. Initially, high temperature baking in an inert atmosphere appeared to work as the SU-8 turned to ashes but detailed inspection of the collimators showed distortion in the collimator structure. Subsequent attempts were made using commercially available chemical etchants but this was also damaging to the metal structure. The problem was finally solved by imposing a long heating process close to the glass transition temperature of the SU-8, which caused shrinkage and distortion of the SU-8 enough for it to be removed in an ultra sonic bath.

Collimator Preparation

The last process in the manufacture is to electroplate all surfaces of the collimator with gold. The final flight products were then cleaned for stacking/assembly.

The end product is a collimator element 400µm high ±10µm. To achieve the heights of 1.8 and 2.4mm required, the elements are stacked in a holder. As the detector is sensitive to visible light, a light blocking filter is required, but more importantly, the filter must also reduce to insignificant levels the isotropic flux of low energy solar electrons.

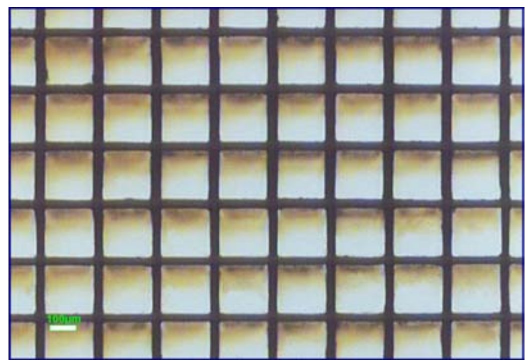

Figure 12 - 1.8mm collimator stack.

A total thickness of 4000Å of aluminium filter reduces the electron flux to essentially zero whilst allowing the transmission of 1-10keV fluorescence X-rays. For maximum electron suppression and immunity to pinholes, the filter is realised as two separate foils. Freestanding filters of this thickness would be far too fragile to survive launch, thus a suitable mesh support is required. The collimators themselves make ideal filter support structures[3].

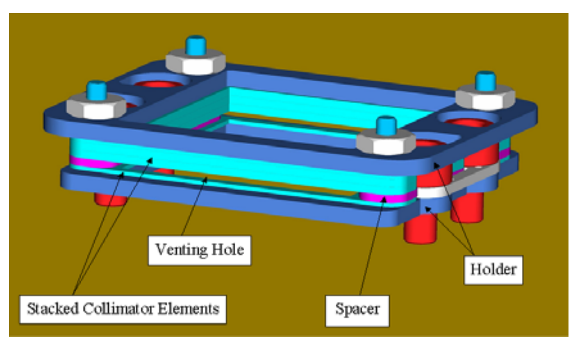

Figure 13 - CAD representation of collimator stack with holder.

Conclusions

The ultimate goal of this project, to produce “flight-quality” structures within a firm deadline whilst conforming to strict quality assurance inspections, has been achieved, thus proving that fast-track R&D of high quality, high throughput MEMS structures is possible. The complete manufacture of a low profile, micromachined, X-ray collimator has been described in detail and its application and importance to the ***DCIXS*** instrument and SMART-1 mission described. Some innovative ideas with respect to techniques in UV lithography, electroplating of microstructures, precision micromachining of theses structures and the removal of Epon resin SU-8 have been exemplified. ***DCIXS*** is set for launch in August 2003.

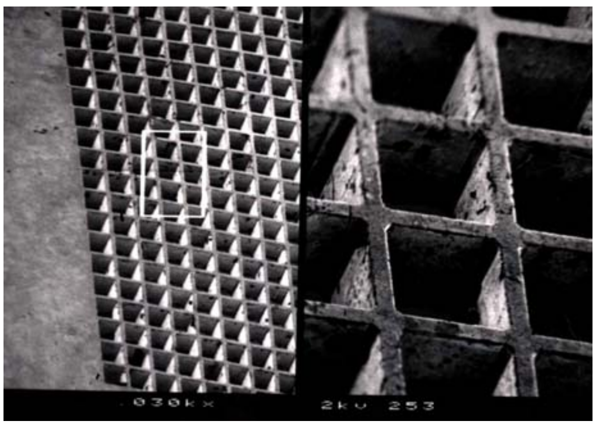

Figure 14 - Electron microscope photograph showing the finished prototype. Walls are ~30mm thick.

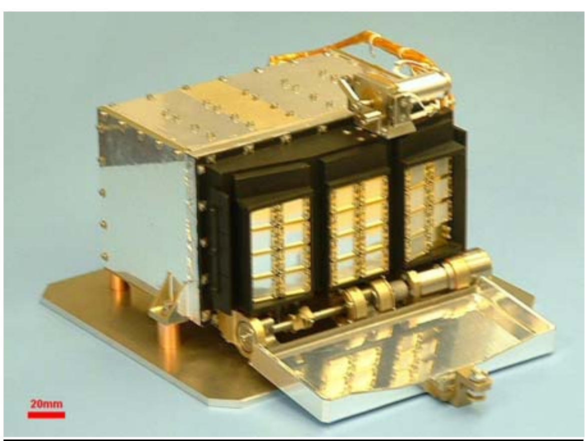

Figure 15 - *DCIXS* flight instrument prepared for environmental testing.

References

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Acknowledgements

The *DCIXS* Team:

- M. Grande, R. Browning, S. Dunkin, B. Kellett, C. H. Perry, N. Waltham, B. Kent, B. Swinyard, A. Perry, J. Fereday, D. Parker, C. Howe, G. McBride, D. Castiglione*, J. Spencer, P. Hiscock, M. Mann, D. Jenkins, Rutherford Appleton Laboratory (*and The University of Reading)
- J. Huovelin, University of Helsinki Observatory
- D. Hughes, H. Alleyne, Sheffield University
- S. Maurice, C. L. Duston, OMP, Toulouse
- R. Lundin, S. Barabash, IRF, Kiruna
- M. Grady, S. Russell, Natural History Museum
- C. D. Murray, A. Christou, QMW, London,
- I. Casanova, UPC,
- B. Foing, D. Heather, ESTEC
- M. Kato, ISAS,
- P. Clark, NASA GSFC
- N. Thomas MPAE, Lindau,
- J. Guest, University College London,
- D. Baker, LASP, Colorado University