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Research Article

Path to meter class single crystal silicon (SCSi) space optics

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Abstract

With the global financial crisis affecting funding for space systems development, customers are calling for lower cost systems. Yet, at the same time, these lower cost systems must have increased thermal response to operational environments and load survivability. We submit that single crystal silicon (SCSi) meets both of these requirements. This paper will highlight some key SCSi material properties, discuss the opportunities that led to the development of McCarter processing methods, and present the latest steps in the manufacturing path of McCarter Mirrors using SCSi, GFB (glass frit bonding) and MSF (McCarter super finish), including the concept drawing of a one meter SCSi lightweight mirror, which together sets up the last step toward a lower cost, high performing one meter SCSi space optic.

Keywords: optics; silicon; space.

1. Main idea

A common misconception is that base substrate materials do not matter because coatings compensate for the inferior materials. Even on the surface, this is not true because collection of light is less efficient with a scattering finish. There are telescope materials that do not survive coatings because of internal stresses. There are some materials used that have to be misfigured at room temperature in the hope that the cryo-figure will meet specifications. There are materials that require costly and schedule-consuming heating/cooling cycles to help reduce dimensional instability even at room temperature. There some are materials whose properties change and/or dimensions when exposed to space radiation. There are materials that are hazardous to handle and exposed workers are subject to disease. Even ground-based large telescopes can require full-time focus management to survive small temperature fluctuations or vibratory loads. There are materials used in space where acquisition and/or spacecraft slew can create a ‘Lost in Space’ condition. There are large space telescopes that are functioning at a limited mission goal and survival life. Therefore, it should be clear that substrate material quality and behavior is of paramount importance. We have found a material that does not succumb to these shortcomings – single crystal silicon (SCSi).

SCSi can meet the challenges of lower cost and higher performance which can be grouped into two main areas – the material properties of SCSi and the processing methods used. The US patent 6,443,817 ‘Method of Finishing a Silicon Part’ allows for manufacturing induced stress and/or subsurface damage to be removed from silicon (Figure 1). Glass frit bonding (GFB), the process of applying shattered glass powder to prepared silicon surfaces and then fusing together using heat and pressure, is employed. Although glass frit was first discovered by the Ethiopians for bonding stones/gems to metal rings and jewelry, most 21st century uses are to protect glaze pottery or assemble computer bread boards. The X-ray synchrotron industry began using glass frit bonded silicon in 1983. McCarter began R&D for silicon optics in 1993. This R&D process development effort along with the material itself has been third party tested by universities and laboratories for reliability, performance, and survivability. Other testing has included mirror specimens for long-term stability testing, fabrication of GFB lightweight mirrors for cryo-use, and vibration test structures, all of which tested as dimensionally stable.

2. Technical details

A recent Springerlink paper by Exp Astron (2009), titled ‘Future technologies for optical and infrared telescopes and instruments’ by Colin Cunningham, on page 187, states why it is so difficult and expensive to explore deep space: ‘the intensity of the photons carrying information about most astrophysical phenomena is very low and the photons are highly contaminated by sources of background radiation’.

Therefore, to collect more photon signal the logical solution is to increase the primary mirror size for the past space missions. These large telescope mirrors use materials such as glasses (Hubble), silicon carbide (Herschel), and/or beryllium (James Webb Space Telescope) and the resulting geometry of large mirrors comprises differing cross-section masses. When temperature change occurs it takes longer for thicker sections to change when compared to thinner sections. Even large ground telescopes encounter this temporary loss of focus but most have thermal management systems for compensation. The important property that determines the speed of equilibrium is thermal diffusivity, which is a combination of thermal conductivity, density, and specific heat and then combining it with the steady state and transient thermal coefficients of SCSi we have the material of choice.

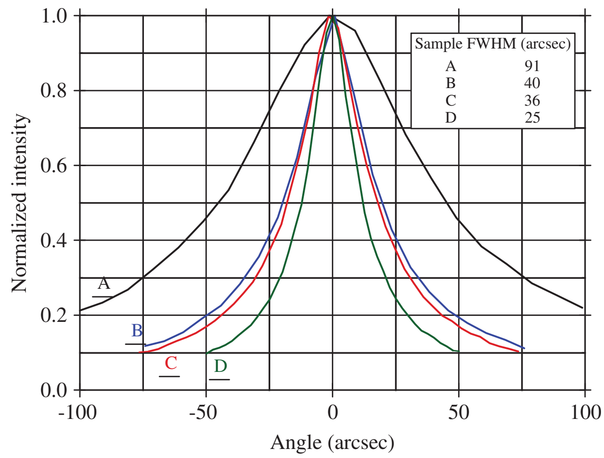

Figure 1 MSF rocking curve analysis.

Zerodur and ULE have also been used for space optics even though the thermal diffusivity (TD) of Zerodur is only 0.9 and ULE is only 0.4. SCSi ranks number one in TD at 1130 in cryo-environments (100 K). Of all optical materials, SCSi has the highest TD at room temperature and at cryo-temperatures the TD of SCSi is an order of magnitude greater than most glasses and 38% greater than Beryllium, as shown in Table 1. The table, 'Material properties of selected optical materials', was compiled by Roger Paquin from the open literature.

A coauthor on several McCarter technical papers, Paquin, retired as lead material scientist at PerkinElmer and is the principal at Advanced Materials Consultants. Roger has over 50 years experience and is author of many SPIE publications, teacher of SPIE material, and is a SPIE Fellow.

According to Roger, at room temperature SCSi is competitive across all properties and excels in thermal diffusivity; however, no one material stands out above the others. For the properties at cryo-temperatures (100 K), Paquin focused on thermal properties alone as the mechanical properties change very little with temperature. Overall, the table shows that SCSi is preeminent in thermal properties. SCSi thermal diffusivity shows that SCSi can rapidly handle temperature changes without distortion. Then taking the thermal diffusivity the ability of SCSi to handle sudden temperature changes is shown. Because of this, SCSi does not require expensive and time-consuming cryo-figuring, special cladding, or thermal and/or vibratory stress relieving to function properly during temperature changes. It is TD that sets SCSi apart from all other candidate materials (Table 1).

In addition to the attractive thermal properties of SCSi, it is a pure material, non-toxic, and poses no danger to workers or the environment. Therefore, there is no costly hazardous waste disposal or extensive handling regulations associated with its manufacture and use. Pure zero-defect (ZD) SCSi is defect-free and readily available from many suppliers at reasonable cost. It is grown as single crystal round bars using the well-established Czochralski method. Available from global suppliers it will be the same from supplier to supplier from lot-to-lot.

The purity and absence of defects in SCSi raw material means no residual stress from the start. However, once machining begins, processing stresses are induced into the material. Proper manufacturing methods, which utilize standard machine tools, minimize induced stresses during rough machining and then remove any remaining stresses by our patented superfinishing method (MSF). Any residual surface

Table 1 Properties at room temperature and 100 K.

Property	Symbol	Units	SCSi	Beryllium	Silicon carbide	Zerodur	ULE	6061-T6 Al
Room temperature (RT)								
Density	ρ	g/cm^3	2.33	1.85	3.15	2.53	2.21	2.7
Modulus	E	GPa	159	303	410	90	68	68
Yield strength	S_{ty}	MPa	n/a	298	n/a	n/a	n/a	240
Modulus of rupture	MOR	MPa	339	n/a	480	294	50	n/a
Specific stiffness	E/ρ	10^6 m^2/s^2	68.2	164	130	35.7	30.3	25.2
Mass-deflection factor	$(\rho^3/E)^{1/2}$	arb.	28.2	14.5	27.6	42.4	40.1	53.8
Thermal expansion coefficient	α	10^{-6}/K	2.62	11.4	2.25	0.03	0	22.5
Specific heat	C_p	J/g·K	713	1925	700	800	766	896
Thermal conductivity	k	W/m·K	156	216	175	1.5	1.3	167
Thermal diffusivity	$D=(k/\rho \cdot C_p)$	10^{-6} m^2/s	93.9	60.7	79.4	0.7	0.8	69
Steady state therm. dist. coeff.	α/k	10^{-8} m/W	1.68	5.28	1.2	6.85	0.2	1.35
Transient therm. dist. coeff.	α/D	10^{-2} s/m^2·K	2.79	18.8	2.6	13.9	0.4	3.26
100 K								
Thermal expansion coeff.	α	10^{-6}/K	-0.34	1.32	0.14	-0.19	-0.9	12.2
Total strain from RT	$\Delta L/l$	ppm	-240	-860	-220	20	81	-2540
Specific heat	C_p	J/g·K	259	177	240	350	61	481
Thermal conductivity	k	W/m·K	913	268	160	0.8	0.6	213
Thermal diffusivity	$D=(k/\rho \cdot C_p)$	10^{-6}m^2/s	1130	818	209	0.9	0.4	164
Steady state therm. dist. coeff.	α/k	10^{-8}m/W	0.37	4.9	0.88	237	1500	5.7
Transient therm. dist. coeff.	α/D	10^{-2} s/m^2·K	0.3	1.61	0.67	211	2250	74

Compiled by Paquin, 2010.

damage and related stresses are easily removed with etching [1, 2]. At this point, the mirror is considered a substrate and is ready for optical finishing.

Another critical processing method for SCSi large and/or complex substrates is GFB [3]. Bonding of SCSi provides a way to overcome the size limitations of SCSi raw material and also allows for complexity and cost savings by simplifying manufacturing. GFB also saves considerable amount of time and consequently schedule. Testing of bond strength has shown the GFB to be at least as strong as SCSi itself and the bond is virtually stress-free. SCSi has low reactivity and no low melting or brittle eutectics are formed. High viscosity and low flow allow good control of the extent and thickness of the bond line.

An important study on the selection of bonding candidates is noted in an open literature report LS Note 249 'Silicon bonding techniques for X-ray optics', which summarizes the R&D work carried out by the Experimental Facilities Division Optics Group (XFD-OP) through July 1995. P.B. Fernandez with the Experimental Facilities Division discovered that glass frit bonding has almost zero strain when glass frit bonding silicon to silicon (p. 8). This report has X-ray results of several types of bonding and bonding agents. GFB methods have improved since this paper was published.

3. Proven results

A very important space test for silicon as well as other space candidates materials was presented at the 44th AIAA Aerospace Sciences Meeting and Exhibit 9–12 January, 2006, Reno, Nevada Article AIAA 2006-472: 'In August 2001 during the STS-105 mission to the International Space Station (ISS), astronauts Daniel Berry and Patrick Forrester deployed two suitcases of (hundreds of) materials samples to be passively exposed to the space environment.' Samples were exposed to 'atomic oxygen-AO, ultraviolet radiation-UV, particulate radiation, thermal cycling and the induced environment of an active space station. […] The planned exposure for MISSE-1 and -2 was nominally one year. After the Columbia accident, (the samples) were not retrieved until STS-114, after nearly four years of exposure' (p. 1). […] 'The samples were exposed to a thermal environment of mostly -40C to +40C. MISSE-1 and -2 went through approximately 22,800 thermal cycles. […] as well as extended UV, AO exposure and multiple (119) impacts from space debris' (p. 3).

SCSi mirror samples were carried to this International Space Station for space environment evaluation (Figure 2). The MISSE-1 and -2 samples included not only coated and uncoated SCSi samples but also SCSi samples that were processed using McCarter's patented superfinish (MSF[1]) and proprietary glass frit bonding (GFB). These SCSi samples survived the almost 4 years of direct space exposure of 22,000 thermal cycles, atomic oxygen, and radiation and returned to earth unchanged.

The SCSi MISSE samples not only returned unchanged but also according to Dr. Jon Arenburg in a communication with the author, 'showed no signs of fatigue […] and showed no degradation […] over the course of almost four years and tremendous amount of cycling. […] In all, silicon and frit-bonded silicon is space qualified and more robust than previously predicted', (Figure 3). In addition, concurrent ground base testing was conducted on SCSi samples and they also remained unchanged.

Figure 2 SCSi MISSE samples on ISS.

In 1996, there was a requirement for the prototype demonstration of a meter class SCSi annular optic in which SCSi bricks were to be used as the building blocks (Figure 4). The MSF method for SCSi was proved integral to successful bonding because the MSF eliminates the subsurface damage and the accompanying strain as shown in Figure 2, MSF rocking curve analysis. The annular optic for this customer was not lightweight (Figure 3) and many applications require optics that are lightweighted.

Typically, a lightweight meter class SCSi optic calls for a backsheet to increase stiffness and frequency. In 1999, the processing methods for adding backsheets to optics was developed which led to the delivery of a 6″ GFB lightweighted SCSi mirror to the Goddard Space Flight Center, currently in use as an incoming inspection standard for cryo-stable optics [4]. This lightweight silicon mirror has remained unchanged for over a decade, which demonstrates that SCSi manufactured using proper processing methods produce an optic with

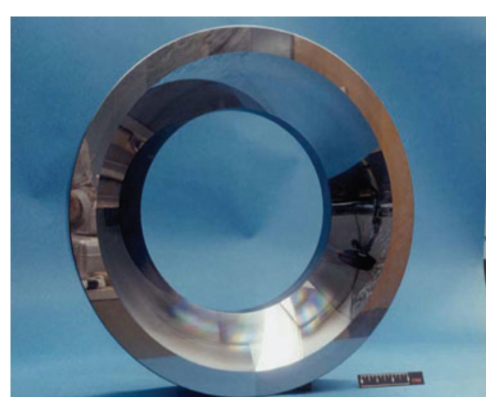

Figure 3 SCSi SPDT finished meter size robust annular optic.

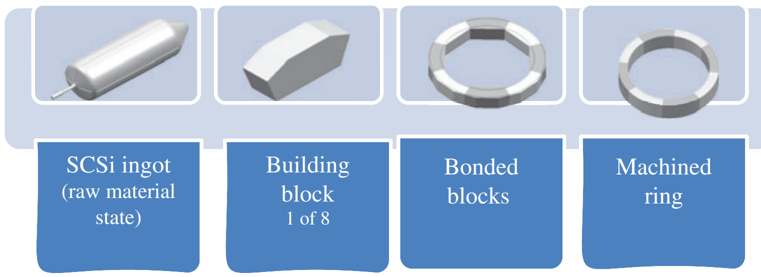

Figure 4 SCSi meter size annular optic processing.

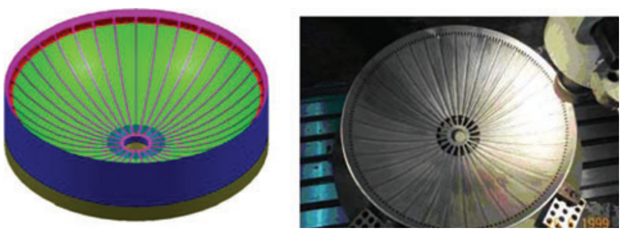

Figure 5 EUV, assay concept and finished part.

temporal stability and encourages the use of SCSi in missions requiring long-term stability.

Several years later, an opportunity arose for the demonstration of planform bonding (PB), a method that bonds SCSi planks together to form a single plane. The resulting plank can then be machined as would a monolithic piece. A customer needed a prototype all-SCSi 22″ cooled extreme ultraviolet, EUV, assembly consisting of 24 separate pieces that, when assembled, would be helium leak tight in a vacuum. Silicon producers have a current size limit of SCSi ZD Boules is 18″ diameter. The successful fabrication and testing of this EUV assembly proved the producibility and reliability of both the material and the PB method (Figure 5).

In the mid-2000s, a hybrid SCSi telescope was manufactured. The complexity of the 4-mirror telescope required innovative machining and bonding techniques. This telescope incorporated a new demonstration – an attachment method for SCSi (Figure 6). The attachment method used for the telescope involves the use of metal inserts GFB directly into the SCSi optic enabling the elimination of extensive holding devices. The GFB inserts are threaded 39 NIFE with CTE close to SCSi over a wide temperature range. The 2.5″ secondary mirror had three metal inserts in the back, which were used to directly attach to the metal spyder. The primary and tertiary mirrors were fabricated using a radial honeycomb substructure GFB to a radial meniscus. Subsequent to the successful fabrication of the hybrid SCSi telescope, a dozen SCSi mirrors with metal inserts for attachment ranging in size from 3″ to 8″ for the customer's test bed facility was delivered.

These latest SCSi mirrors with metal inserts will undergo rigorous testing, expected in 2012, to prove whether they will survive launch. The test mirrors include fast steering mirrors (FSMs), turning flats, and secondary mirrors (Figure 7). If these mirrors are successful during the testing then this technology will move to a TRL 6 and the probability of flight would move much closer. TRL 6 is defined as a 'System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space)' [5]. Obviously, success is significant to the development of a meter class primary. In addition, this SCSi technology provides the customer with space systems that are modular, producible, and high performing. Modularity means that parts can be changed easily which facilitates rapid repair and reuse. Producibility means that parts are delivered quickly and cost efficiently. High performing means that the technology can be fielded and relied upon. Therefore, with SCSi ZD we have super stable systems but, most importantly, in the current economy we have products that can be mass produced cost-efficiently.

4. Future prospects

The SCSi manufacturing plan is mature and third party testing has proved that SCSi is worthy of investment. It now seems logical to build a ground-based version of a space

Figure 6 SCSi lightweight primary telescope mirror using GFB and McCarter attachment metal inserts.

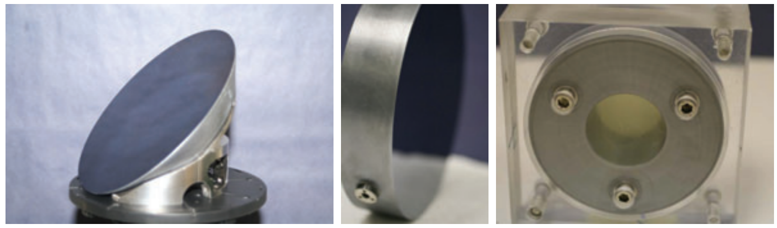

Figure 7 All SCSi mirrors, fast steering mirror, turning flat, and secondary mirror.

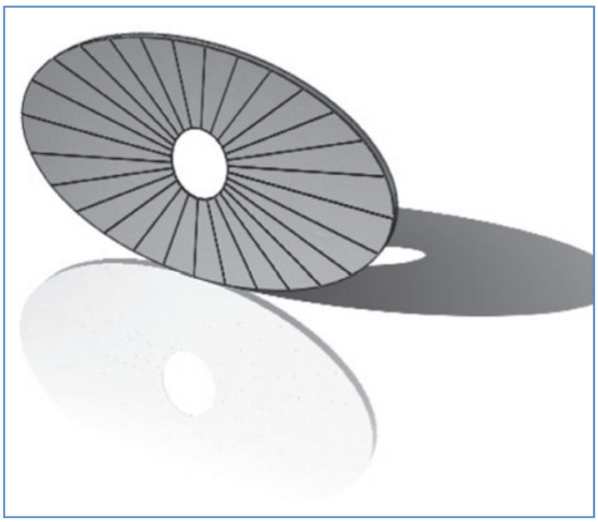

Figure 8 Meter class SCSi space optic.

meter class mirror built without using active cooling, heating, and/or adjusting pizo-actuators to compensate for the problems common with heritage materials. This laboratory demonstrator while actually performing ground-based missions will be used to verify, quantify, and direct design changes for making a Space SCSi Telescope.

Discussions on the best approach for SCSi meter class space optics primary mirror have led to the concept model as shown in Figure 8, which can be fabricated with or without the center hole. Commercially available SCSi comes in 12″ to 18″ diameter sizes and will be machined into bricks and then bonded with GFB techniques as discussed previously. This concept incorporates all of the previous steps plus one new method, pie-shaped GFB planks with bevels at the contact points surrounding a circular center. Adding a backsheet by frit bonding will also increase the stiffness and raise the frequency [6–8].

Currently, the lightweight SCSi design is anticipated to have aerial density that will be close to 20 kg m^2 and have an aerial density of 10:1. The mounting will be based on a three-tier design of three-point kinetic mounts. Flexures will be built into the 39 NIFE mounting inserts vs. the SCSi material itself. Overall, the system will be simple yet robust and not require expensive and heavy complicated subsystems to make the SCSi optics usable. SCSi optics and optomechanical structures are stand-alone products. The money and scheduled saved by using SCSi can be invested in additional SCSi mirrors and structures creating the first SCSi Space Telescope.

References

[1] F. Anthony, A. Khounsary, D. McCarter, F. Krasnicki, M. Tangedahl, Proc. SPIE 4145, 37 (2000).

[2] F. Anthony, D. R. McCarter, J. L. Bertelsen, M. Tangedahl, Proc. SPIE 3782, 51 (1999).

[3] F. Anthony, D. McCarter, M. Tangedahl, M. Wright, Proc. SPIE 5179, 194 (2003).

[4] F. Anthony, D. R. McCarter, M. Tangedahl, D. A. Content, Proc. SPIE 4822, 23 (2002).

[5] C. Cunningham, in 'Future Technologies for Optical and Infrared Telescopes and Instruments' (Springer Science and Business Media B.V., 2009) p. 187. http://www.springerlink.com/content/d127611x043x5ht3/.

[6] P. B. Fernandez, in 'Silicon Bonding Techniques for X-ray Optics' (Argonne National Laboratory, 31 August 1995) p. 8.

[7] M. M. Finckenor, in 'The Materials on International Space Station Experiment (MISSE): First Results From MSFC Investigations' (American Institute of Aeronautics and Astronautics, 44th AIAA Aerospace Sciences Meeting and Exhibit 9–12 January 2006, Reno) Nevada Article AIAA 2006-47.

[8] L. Philip, 'Definition of Technology Readiness Levels' (NASA, 2005). http://esto.nasa.gov/files/TRL_definitions.pdf.

Doug McCarter, Vice-President and co-Founder of McCarter Machine, serves as technical integrator and customer liaison. He has worked in and with the petrochemical industry for over 30 years providing troubleshooting expertise on reciprocating equipment as well as supplying custom-machined parts. Since 1999, Doug has co-authored and authored seven technical papers concerning SCSi processing and its application.