

# **FRIT BONDING**

## **A Way to Larger and More Complex Silicon Components**

Frank M. Anthony, Douglas R. McCarter, Matthew Tangedahl, Mallory Wright  
McCarter Technology, Inc. 1312 Underwood Rd. Deer Park, TX 77536

### **ABSTRACT**

The value of glass frit bonding to assemble silicon parts was demonstrated by the successful evaluation of cryostability of a small multi-piece silicon mirror. This bonding technique has been extended to the assembly of a 44kg block of silicon, 113 x 400 x 400mm. Such an assembly was considered to be a cost competitive alternative to the purchase of a custom sized silicon boule. Various types of evaluation provided the foundation upon which this accomplishment is based. Included were cryocycling of frit bonded plates, comparison of the strength of bonded silicon bend bars with that of silicon bend bars, and the fabrication and cryotest of a small concave frit bonded silicon mirror. Of the 16 bonded bars in two groups only 2 had failures in the bondline, 11 failed in the silicon, and origins could not be determined for 3 bars. The two groups of bonded silicon bars had average strengths that were 84% and 91% of the average strength of the plain silicon bars. In view of the relatively small number of bars in each group this is not surprising. The cryostability of the concave bonded silicon mirror was demonstrated by a figure error of less than 0.06 wave rms at 633nm, cold to warm, compared to a specification of 0.1 wave rms, and 0.014 wave rms, warm to cold to warm, over an 80% clear aperture. These results are reviewed before interesting features of the large block are discussed. Finally, projections are made regarding possible future applications for this bonding process.

**Keywords:** Frit Bonding, Glass Bonding, Silicon

### **1. INTRODUCTION**

One of the interesting opportunities offered by glass bonding of silicon is the ability to produce components that are larger than conventional boules. During the past year McCarter Technology, Inc. took a major step in this direction. There was a need for a silicon component of 400mm diameter, 113mm thick. The customer agreed to fund the assembly of silicon planks as the starting material for the component. The planks were cut from 150mm boules and were frit bonded to form a relatively thick square plate, from which the major portion of the desired component was machined.

The potentially high risk associated with bonding this large plate was reduced by a sequence of developmental steps that began several years ago. Although the focus was on complexity and light weighting and not specifically on large silicon components, they provided an appropriate technology base. A review of the sequential developments allows an appreciation for the modest level of risk involved. Nevertheless it was gratifying to be successful on the first attempt to produce the large plate.

### **2. BACKGROUND**

The original goal of the frit bonding activity was to produce light weighted silicon structures, such as mirrors, for space applications. Hence some of the developmental effort is not directly related to producing large sizes. Nevertheless it is summarized for completeness and to show that confidence can be built through familiarity with materials even when the applications may be different. Aspects of importance included:

- 2.1 Polishability of bonded silicon surfaces
- 2.2 Compatibility of the bond with silicon at cryogenic temperature
- 2.3 Effect of cryogenic exposure on bond strength
- 2.4 Fabrication demonstration
- 2.5 Performance evaluation

## 2.1 Polishability

Because the glass bond is softer than the silicon, it is logical to expect preferential removal from the bond. This is the case but by working with a polishing shop, the effect is quite small, as shown in Figure 1.

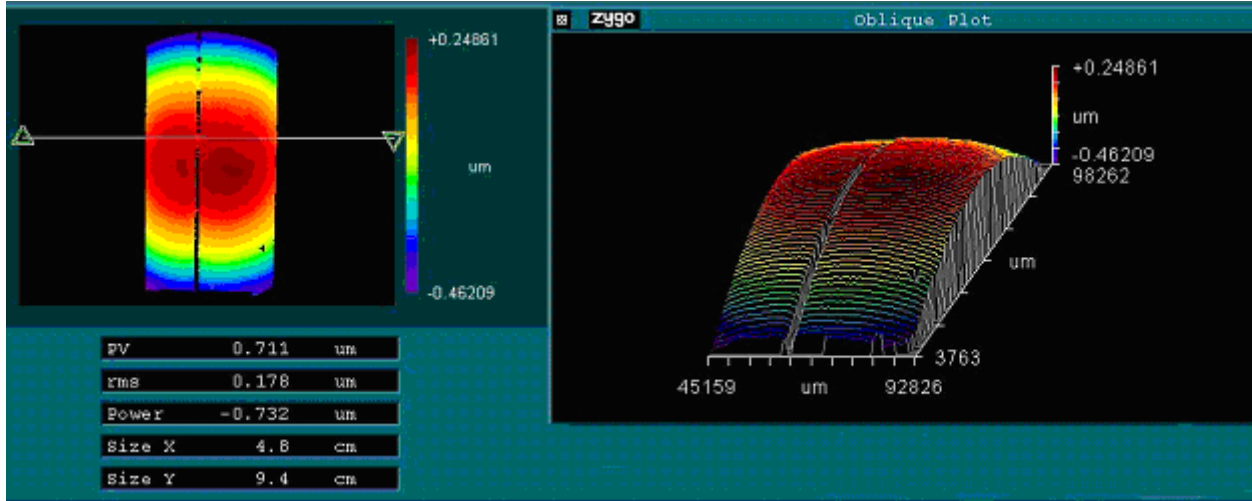


Figure 1: Caustic Damaged the Frit Bond Joint

Using lessons learned from Figure 1, McCarter manufactured a 210mm x210mm x24mm square shaped frit bonded assembly, using three equal sized silicon planks. Then, it was polished after waxing into a silicon waster. Fig 2



Figure 2: Flat Silicon Mirror Composed of Three Planks

The mirror surface had less bond line degradation and none of the bond lines was noticeably visible. Fig 3

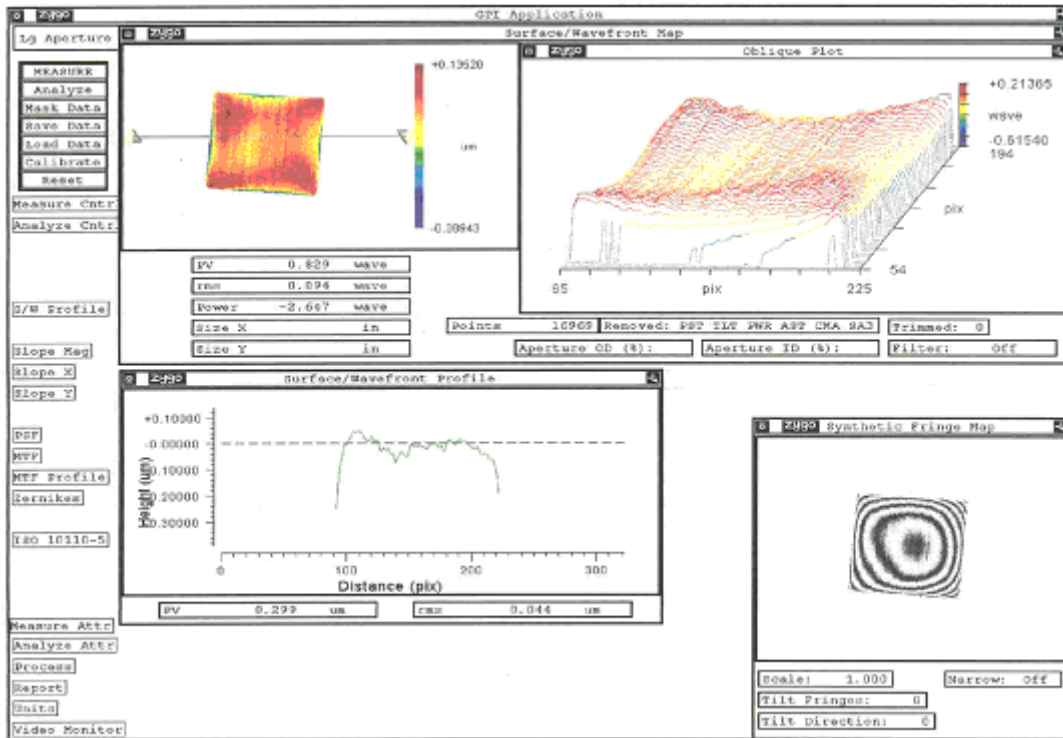


Figure 3: Zygo of Bond Line on Planked Mirror

## 2.2 Cryogenic Compatibility

This characteristic was demonstrated by cyclic immersion of glass bonded silicon plates in liquid nitrogen. Fig 4 After three cycles, there was no evidence of degradation. See reference 1 for details. To validate the absence of damage the plates were machined into bend bars so strength could be compared with glass-bonded bars that had not been cryocycled and with bars that had not been bonded.



Figure 4: Submerged Frit Bonded Silicon Planks

## 2.3 Bend Strength

Table 1 provides comparisons of 4-point bend strengths of three types of bars – silicon, bonded silicon and cryocycled bonded silicon. All bars were made according to MIL-STD 1942(MR) with the added enhancement of the McCarter Superfinish, U S Patent 6,443,817, references 2 and 3, but at different times. Because of the limited number of strength values, it is difficult to draw conclusions. Results suggest that the bonded silicon bars are slightly weaker than solid silicon bars and that cryocycling may enhance strength. On the other hand, the variations may be within the variability of the statistical strength distribution. Figure 5 shows representative fractures of bend bars. Of the 16-bonded silicon

bars, 11 had fracture origins in the silicon, see bars at left and center. Of the two that had origins in the bond line one propagated along the bond line and the other is shown at the right of Figure 5.

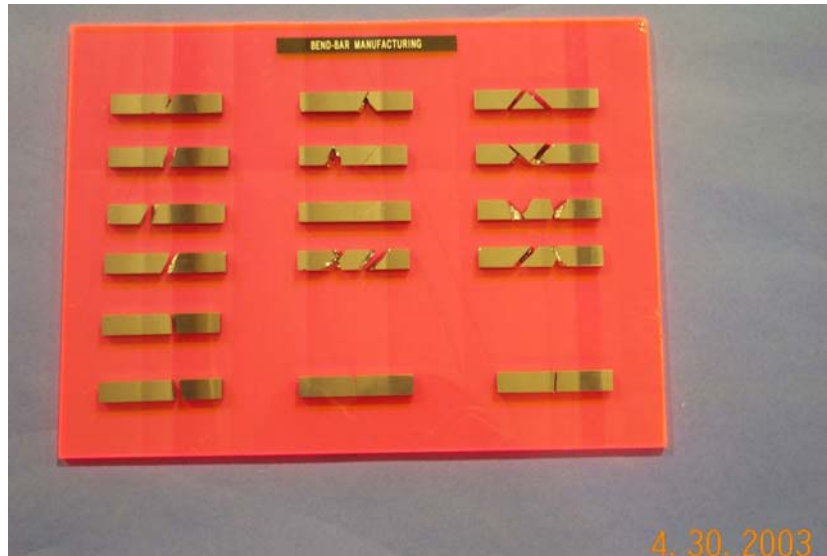


Figure 5: Silicon Frit Bonded Bend Bars

| Type of Bar    | Number | Average Strength (psi) | Standard Deviation (psi) | S.D. Avg. |
|----------------|--------|------------------------|--------------------------|-----------|
| Silicon        | 5      | 14711                  | 2891                     | .1965     |
| Bonded Silicon | 10     | 13350                  | 3086                     | .2312     |
| Cryocycled     | 7      | 12480                  | 2423                     | .1942     |
| Bonded Silicon | 8      | 16092                  | 3136                     | .1949     |

Table 1 – 4-Point Bend Strength Test Performed at Alfred University 7/19/00

#### 2.4 Fabrication Demonstration

The positive nature of the early results led to a decision to fabricate a complex assembly. A light weighted silicon mirror was selected and fabricated. Fig 6 It consisted of two flat faces and a core of concentric rings and radial webs. Close tolerance machining allowed assembly without custom fitting.



Figure 6: McCarter Prototype Frit Bonded Mirror

#### 2.5 Performance Evaluation

A second light weighted silicon mirror was designed for better optical performance and successfully fabricated. Fig 7 The mirror face had a 600mm spherical radius and the core was integrally machined in a modified square cell pattern.

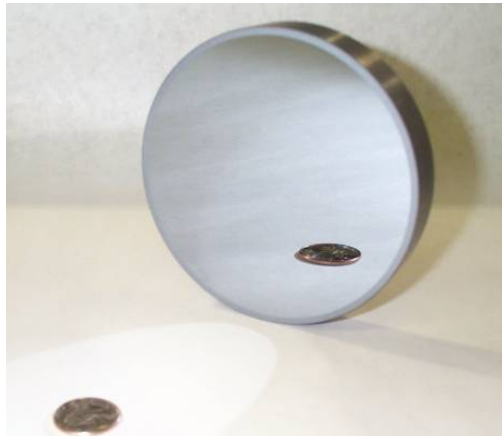


Figure 7: 600 mm Frit Bonded Silicon Mirror

### Figure Waves@633nm

| Specification     | 0.1   | ---- |
|-------------------|-------|------|
| Overall           | 0.074 | 0.37 |
| Low Frequency(1)  | 0.063 | 0.34 |
| High Frequency(2) | 0.040 | 0.20 |
| Overall, 10cm CA  | 0.067 | 0.33 |

1. Fitted to first 36 Zernike Terms
2. With first 36 Term Zernike fit subtracted

### Surface Roughness in nm

|               | RMS  | P/V   |
|---------------|------|-------|
| Specification | 1.0  | ----  |
| Loc 1         | 0.54 | 5.68  |
| Loc 2         | 0.46 | 13.43 |
| Loc 3         | 0.54 | 6.17  |
| Loc 4         | 0.56 | 8.72  |
| Avg.          | 0.52 | 8.5   |

Table 2: Optical Quality of Test Mirror (Courtesy of GSFC)

Surface quality over the full aperture was better than requirements for 80% aperture. Figure measured 0.074 wave rms versus a spec of 0.1 and roughness was 0.52nm rms versus 1.0. The low frequency error was 0.063-wave rms, the high frequency error was 0.04 wave rms, and the combined error was 0.067 wave rms.

The surface deformation, warm to cold, was <0.06 wave, 38nm. The surface deformation, post-cold warm to pre-cold warm, was only 0.014 wave, 9nm. See Reference 16 for details.

### McCarter 12.5 cm SILICON SPHERICAL MIRROR

| 100% (full) aperture    |       |       | piston/ tilt removed |
|-------------------------|-------|-------|----------------------|
| subtraction             | PV    | RMS   | PWR                  |
| cold - (pre cold) warm  | 0.436 | 0.071 | -0.047               |
| cold - (post cold) warm | 0.598 | 0.071 | -0.053               |

| 80% (clear) aperture    |       |              | piston/ tilt removed |
|-------------------------|-------|--------------|----------------------|
| subtraction             | PV    | RMS          | PWR                  |
| cold - (pre cold) warm  | 0.345 | <b>0.057</b> | 0.068                |
| cold - (post cold) warm | 0.325 | <b>0.053</b> | 0.066                |
| post cold - pre cold    | 0.094 | 0.014        | 0.001                |

Table 3: Surface Quality – (Courtesy of GSFC)

### 3. INTERESTING FEATURES OF LARGE-BLOCK ASSEMBLY

McCarter's previous success with machining and frit bonding silicon encouraged a Customer to order a 17" diameter large block assembly. This assembly required cooling passages, metallic inserts for mounting and parabolic surface of mirror quality. There are two primary features of interest which were discovered during machining operations which followed the frit bond process. The first being the durability of frit joints which stayed intact without chipping or cracking while aggressive machining took place. Sawing allowed producing of two parts per assembly, eliminating waste and saving material cost. Trepanning allowed utilization of unneeded areas to save for additional parts. Fig 8, 9 and 10



Figure 8: Silicon Frit Bonded Sub-assembly before Sawing



Figure 9: Silicon Frit Bonded Sub-assembly after Sawing

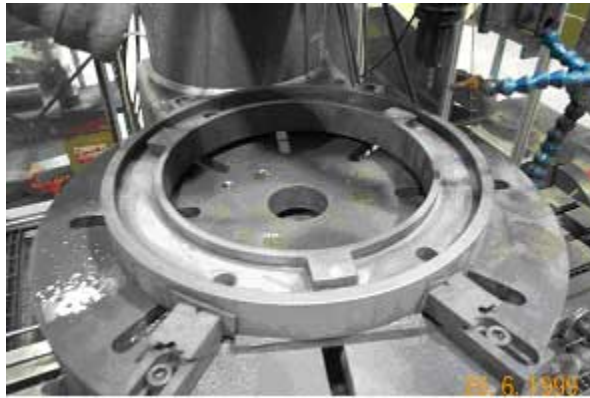


Figure 10: Trepanned Sub-assembly

Coredrilling 180 places produced .049mm diameter x 157mm long cores that stayed intact without failure. These cores then can be used as samples and verification of integral strength of bond lines. Fig 11

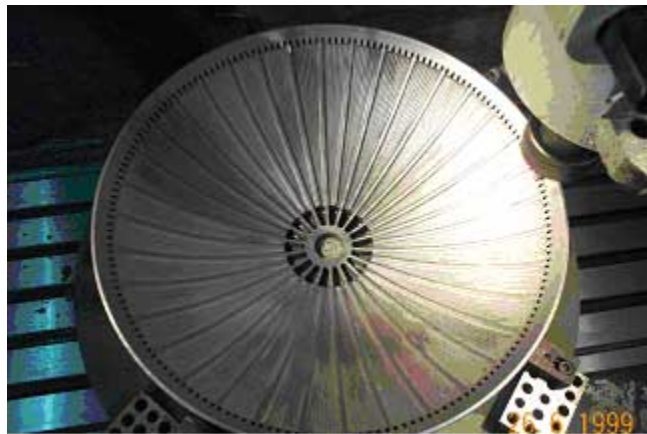


Figure 11: Coredrilled Sub-assembly

The balance of machining operations such as planing, facing, turning, beveling, slotting, and boring also showed no negative responses when crossing bond lines. Fig 12



Figure 12: Slotted Sub-assembly

The second notable feature was the even consistency and continuity of bond lines throughout the entire stack of silicon planks. Post frit bond inspection revealed no bond line voids or uneven squeeze out variance from plank to plank. Fig 13



Figure 13: Frit bonded Joint

The large complex frit bonded assembly was pressure-tested by submerging the frit-bonded assembly in DIH2O after pressuring to 20 psi using Helium Gas. There were no escaping bubbles or pressure loss over the 30-minute period. Fig 14



Figure 14: Submerged Final Assembly

#### 4. PROJECTIONS FOR FUTURE FRIT BONDING APPLICATIONS

The successful manufacture of the complex silicon component using frit bonded single crystal silicon makes possible the production of the following:

- Lightweight Mirrors
- Optical Benches
- Spacecraft Instrumentation
- Cooled Mirrors
- Corner Cubes
- Substructures
- Metal Threaded Inserts
- Mechanical Apparatus
- Housings and Shields

## REFERENCES

1. McClelland, R.S. and Content, D.A., "Design, Manufacture and Test of a Cryo-stable Offner Relay Using Aluminum Foam Core Optics," Proceedings of SPIE, Vol. 4451, 2001
2. Reed, T. et al, "Final Results of the Subscale Beryllium Mirror Demonstrator (SBMD) Program," Proceedings of SPIE, Vol 4451, 2001.
3. Hadaway, J.B. et al, "Cryogenic Optical Testing Results for the Subscale Beryllium Mirror Demonstrator (SBMD)," "Proceeding of SPIE, Vol 4451, 2001.
4. Personal Communication with Thomas W. Tonnensen, InSync, Inc. Albuquerque, NM 87107
5. Personal Communication with Dr. A. M. Khounsary, Argonne National Laboratory, Argonne IL 60439
6. Faufel, J.H., Engineering Design, Wiley and Sons 1964
7. Loytty, E.Y., "Lightweight Mirror Structures" from NASA SP-233, 1970
8. Barnes, W.P., "Hexagonal vs Triangular core Lightweight Mirror Structures," Applied Optics, Vol 11, No 12, December 1972
9. Valente, M. and Vukobratovich, D., "A Comparison of the Merits of Open-Back, Symmetric Sandwich, and Contoured Back Mirrors as Light weighted Optics," Proceedings of SPIE, Vol 1167, 1989
10. "Material Defects in Silicon Carbide Manufactured by CVD," Unpublished memo, Naval Weapons Center, 1989
11. Holt, T., "The Low Flow Mirror and Its Operational Envelope," RDA Logicon, Albuquerque, NM 87119, Briefing Charts, 1986.
12. Personal Communication with S. Daignault., Itek Corporation, Lexington, MA 02173
13. Anthony, F.M. et al, "McCarter Superfinish for Silicon," Proceedings of SPIE, Vol 3782, 1999
14. Anthony, F.M. et al, "McCarter Superfinish Grinding for Silicon and Update," Proceedings SPIE, Vol 4145, 2000
15. U S PATENT 6,443,817 Method of Finishing a Silicon Part
16. Anthony, F.M. et al, "A Lightweight Frit Bonded Spherical Silicon Mirror Demonstrates Cryostability" Cospar 40393, Oct 10,2002
17. Lowery, William H. and Anthony, Frank M., "Cutting Costs with Planform Bonding", Photonics Spectra, April 1992.