Opto-Mechanical Structures Using Single Crystal Silicon

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ABSTRACT

Single Crystal Silicon (SCS) is proving to be an excellent material for the fabrication of lightweight optical components. As part of the feasibility studies performed prior to space flight applications, is important to measure the mechanical properties on complex structures manufactured form individual sections of single crystal silicon. Here we report the vibration test results performed on Feb 2002 with the objective to measure the structural damping characteristics of future typical silicon structures and verify their structural stability after exposure to random vibration. Also as an integral building block of future multi- component SCS structures, the behavior of the McCarter Machine proprietary frit-bonded metal insert technology was examined.

The tests were designed to better understand single crystal not only as a mirror substrate but also as a structural material. If successful and leveraging from the already proven McCarter Machining manufacturing techniques, new lightweight and stable opto-mechanical assemblies can therefore be manufactured entirely out of single crystal silicon. As requirements for larger and more sophisticated structures ideally manufactured using single crystal silicon and while individual pieces are still limited by the practical size of available SCS boules, the behavior of frit-bonded structures using SCS needs to be better understood.

MATERIALS CONSIDERATION /DISCUSSION

It is important to recognize that an experimental measurement of frequency transmissibility or in this case damping represents the characteristics of a system and may not correspond directly to the intrinsic parameters of a particular material. Consideration of the formal connections of the various structural components often dominates the dynamic response characteristics of a system[3]. The variety of mechanisms that can contribute to the as measured material damping and the interference between those mechanisms inevitably leads to a very complex response which is very difficult to unravel and therefore lends itself to be preferably measured under the expected environmental conditions. In this case, this reasoning suggested that a measurement of damping or transmissibility while exposing the sample test article to random and sine excitations is the most direct and least controversial way to extrapolate the behavior of SCS structures assembled using fit-bond or bolted connections utilizing the available fit-bonded insert technology.

SCS is an ideal material for the manufacture of optical components. It’s inherit stability resulting from its microscopic structure homogeneity yields a near perfect substrate, free of residual stress that could manifest itself in undesirable distortion. The material high thermal conductivity nearly as high as that of aluminum and it’s machine and polish ability combined with the relatively low thermal expansion coefficient makes its ratio of conductivity to thermal expansion rival those of ULE and Zerodur.

TEST ARTICLE DESCRIPTION

The simple structure selected for this study consists of a one piece cantilever beam with a concentrated mass on it's free end and the fixed end frit-bonded to an also single crystal silicon base. A cantilever beam configuration was chosen because it was easy to analyze and ultimately generate correlated test models from which to extrapolate results on to more complex configurations/geometries.

Both the base and the free end of the cantilevered mass had integral optically flat surfaces to be used as references. The normal to these flat reference surfaces were measured/characterized before and after the test. For comparison purposes an identical structure was manufactured using aluminum and simultaneously tested as seen on figure #1

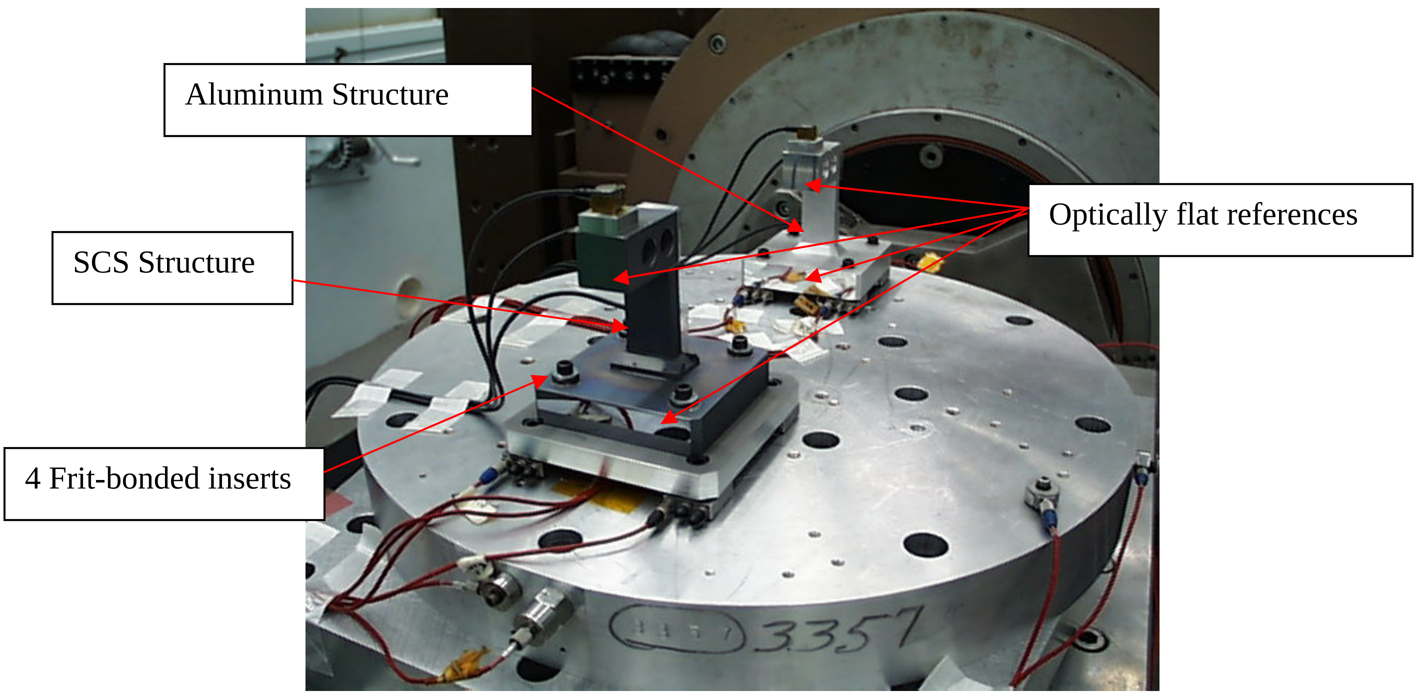


Figure #1

TESTS OBJECTIVE

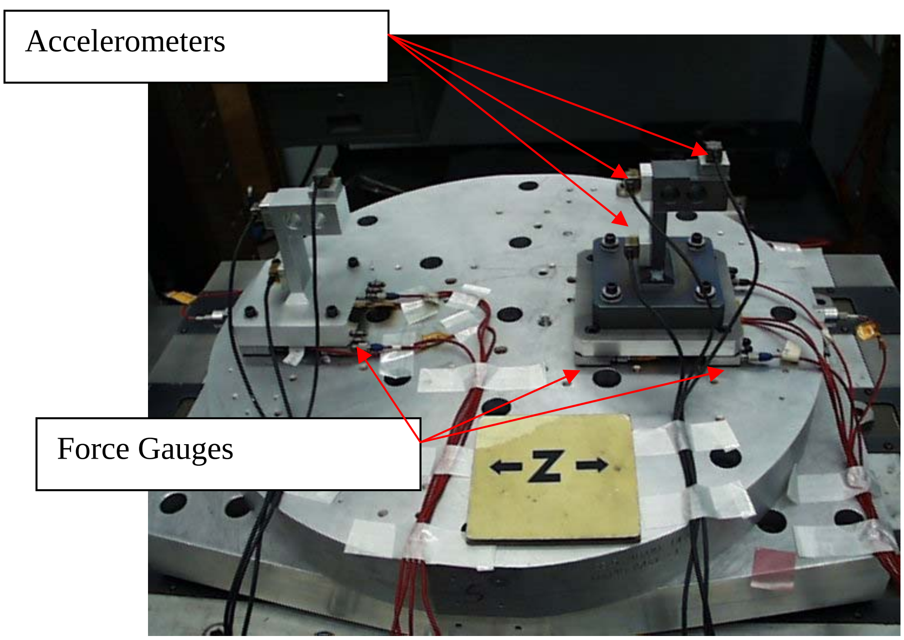
The objectives of these series of test were to measure the structural characteristics of silicon and to study the assembly structural stability by subjecting the test article to random excitation. Of particular interest was the frit bond at the bottom of the cantilever beam and the McCarter proprietary insert technology.
An aluminum test item with similar dimensions was also tested for comparison.

TESTS DESCRIPTION

1. VIBRATION

The first series of tests were performed on a Ling B-335 lateral vibration slip table in Building 7 at NASA Goddard Space Flight Center. The test articles were first subjected to low level random excitation to estimate the natural frequencies and damping. Next, the test articles were subjected to several different levels of sine sweeps to asses linearity. Finally, high-level random excitation was used to investigate the structural stability.

The in-axis input forces were measured with force gages, and the response accelerations were measured using several accelerometers mounted on the test article. A photograph of the test setup and instrumentation can be seen in Figure #1 and #2.



Figure#2

VIBRATION TEST SPECIFICATION

Test Specifications (As-Run):

Random: 50-3000 Hz 1.21 grms 60 secs [ZRan03]

Freq. [Hz]	Accel. [g2/Hz]	Slope Type [-]	Alarm [dB]		Abort [dB]	
50	0.0005	Slope	-3	3	-6	6
3000	0.0005	Slope	-3	3	-6	6

Sine Sweep: 50-3000 Hz 0.1 gpk 2 Oct./Min [ZSwp04]

Freq. [Hz]	Accel. [g]	Veloc. [inSA/s]	Displ. [inDA]		Slope Type	Alarm [dB]		Abort [dB]	
50	0.1	1.23e-01	7.83e-04	Auto Acc.	0 dB/Oct	-3	3	-6	6
3000	0.1	2.05e-03	2.17e-07	Auto Acc.	0 dB/Oct	-3	3	-6	6

Sine Sweep: 50-3000 Hz 0.25 gpk 2 Oct./Min [ZSwp05]

Freq. [Hz]	Accel. [g]	Veloc. [inSA/s]	Displ. [inDA]		Slope Type	Alarm [dB]		Abort [dB]	
50	0.25	1.23e-01	7.83e-04	Auto Acc.	0 dB/Oct	-3	3	-6	6
3000	0.25	2.05e-03	2.17e-07	Auto Acc.	0 dB/Oct	-3	3	-6	6

Sine Sweep: 50-3000 Hz 0.5 gpk 2 Oct./Min [ZSwp06]

Freq. [Hz]	Accel. [g]	Veloc. [inSA/s]	Displ. [inDA]		Slope Type	Alarm [dB]		Abort [dB]	
50	0.5	1.23e-01	7.83e-04	Auto Acc.	0 dB/Oct	-3	3	-6	6
3000	0.5	2.05e-03	2.17e-07	Auto Acc.	0 dB/Oct	-3	3	-6	6

Random: 50-3000 Hz 7.68 grms 60 secs [ZRan07]

Freq. [Hz]	Accel. [g2/Hz]	Slope Type [-]	Alarm [dB]		Abort [dB]	
50	0.02	Slope	-3	3	-6	6
3000	0.02	Slope	-3	3	-6	6

As shown on the table above, the test articles were subjected to low level random vibration (1.2grms), followed by three sine sweep tests at 3 different levels (.1 gpk, .25 gpk and .5 gpk) ending with exposure to random excitation at 7.68 grms for a full minute.

2. MODAL SURVEY

It is known that the natural frequencies and damping values can be better measured by performing a modal survey. To correlate and verify the vibration test data a modal survey was also conducted in the Modal Survey Test Facility at NASA Goddard Space Flight Center. For this test the test items were not removed from the vibration adapter plate after the vibration test so that similar boundary conditions could be achieved for both test.

A calibrated modal impact hammer was used to excite the silicon test article at two separate locations. This was to determine which location would best excite the first mode of the test article. The two locations were both at the end of the cantilevered mass. One impact location was on the mounting block of the accelerometer, while the other was directly on the test item. The mounting block proved to be a better impact location because it allowed the impact to occur closer to the end of the cantilevered mass. For the aluminum structure, only the impact location on the accelerometer mounting block was used.

3. OPTICAL CHARACTERIZATION

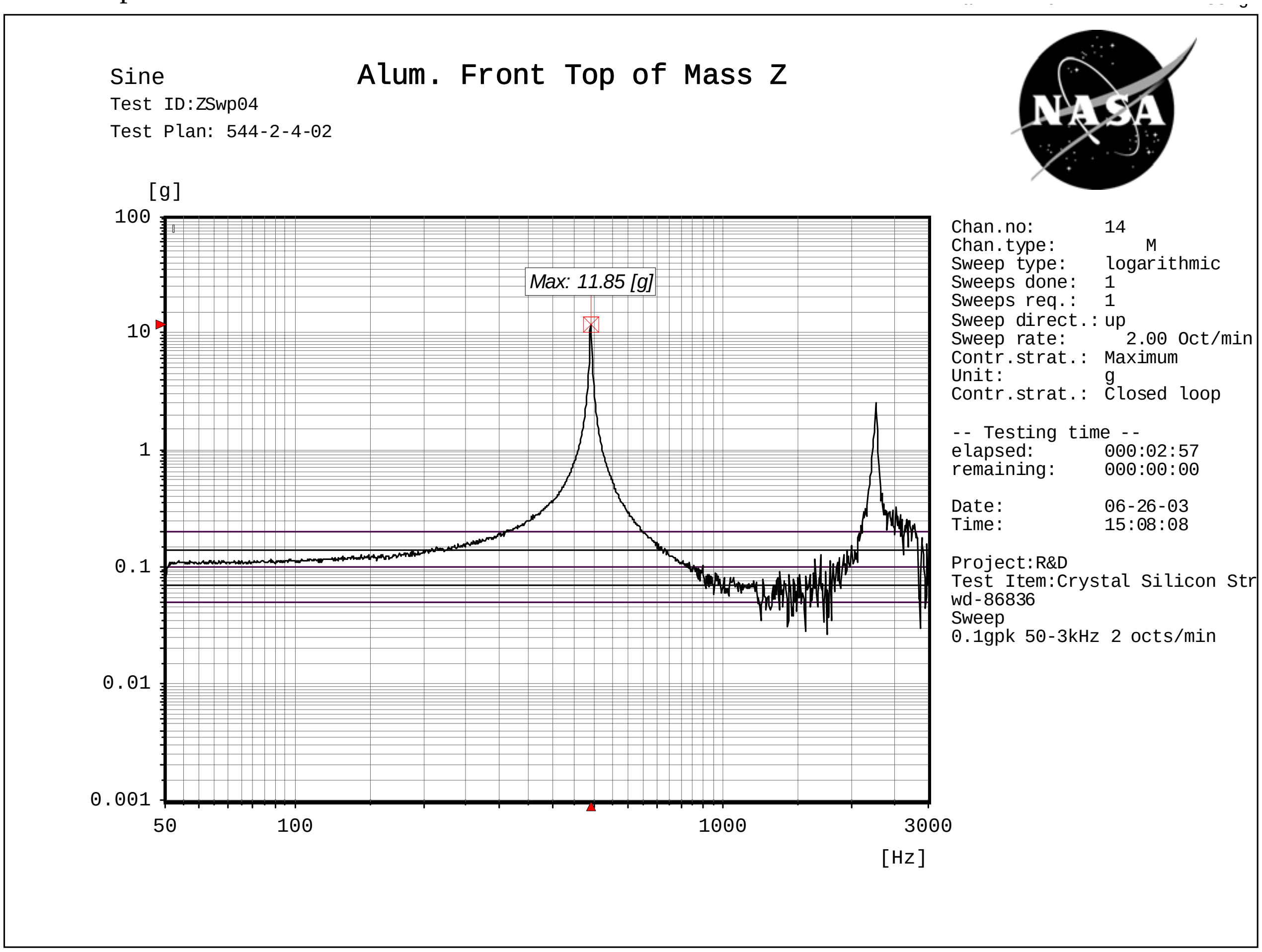
Before and after the vibration and modal survey tests and in order to measure the dimensional stability of the silicon structure and its suitability for precision optical applications, the two optical reference surfaces were measured relative to each other. The measurements were performed using a theodolite.

TEST RESULTS

1. VIBRATION RESULTS

The two test articles were successfully tested on the B335 lateral vibration table at NASA Goddard Space Flight Center on. Details of the test setup and procedure can be found in the test report document “Single Crystal Silicon Structure Vibration Test Report,” document number ATAC-23-15-86836.

From the vibration data, it can be seen that the structure responded linearly with increased excitation levels. There was virtually no shift in the frequency of the first mode as the sine sweep magnitude was increased from 0.1 to 0.5 G. There was also no change in the damping or magnitude of the test article response.



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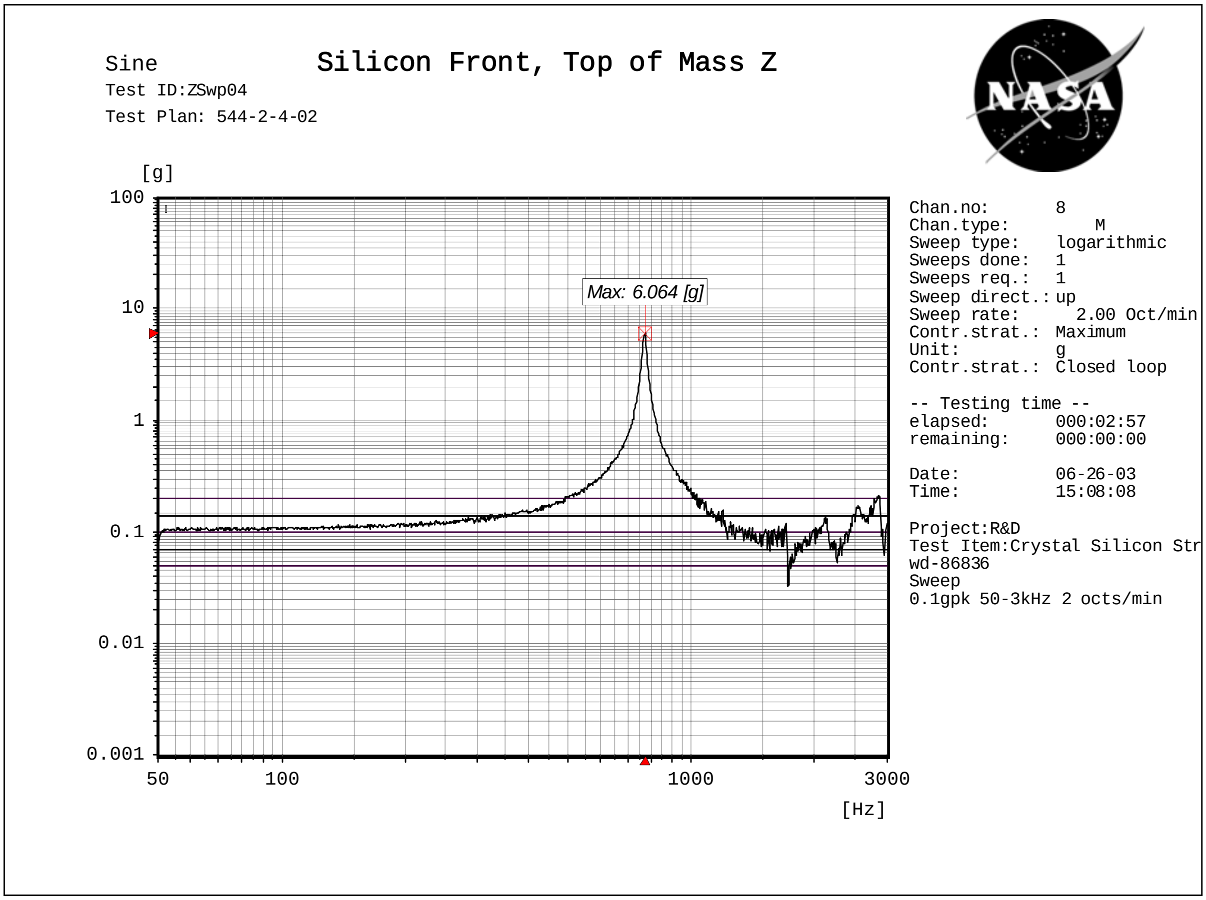

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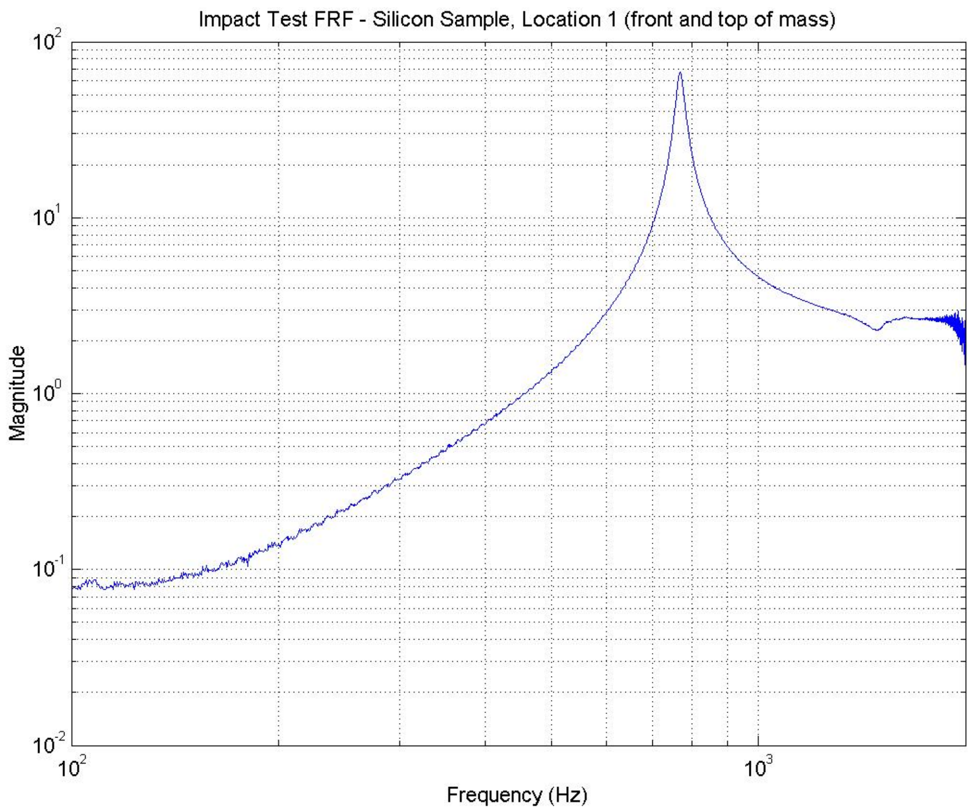
2. MODAL SURVEY RESULTS

From the modal survey, it was determined that the first mode of the silicon structure occurs at 768 Hz with a damping value of 1.40%. For the aluminum structure the first mode occurs ate 490 Hz with a damping value of 0.50%.



3. OPTICAL CHARACTERISATION RESULTS

In order to test the structural stability of the silicon structure, a relative measurement was made between the two optical surfaces of the test article both before and after being subjected to a high level random vibration environment. The results show a change of only 0.1 arcsecond in both the horizontal and vertical directions from the pre and post test measurements. This shows excellent structural stability for the level of random vibration for which the test item was subjected (it should be noted that 0.1 arcsecond is in the noise floor of the measurement).

The aluminum structure exhibited a variation of 7.5 arcseconds in the horizontal direction and a variation of 4.0 arcseconds in the vertical direction.

REFERENCES

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2. Anthony, F.M. et al, “A Lightweight Frit Bonded Spherical Silicon Mirror Demonstrates Cryostability” Cospar 40393, Oct 10,2002

3. Berry B.S “Damping Mechanisms in Thin Layer Materials”

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