HYTEC INCORPORATED

Bend Tests of Silicon Ladders to Determine Ultimate Strength

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Abstract

Samples of the silicon detectors were subjected to bending to determine the ultimate strength. The testing was done on HYTEC, Inc.'s Dillon load frame with a 25 pound Omega load cell. The silicon detector samples were salvaged from previous tray and ladder tests. Four tests of tray silicon detectors and seven tests of baby silicon detectors were performed. The mean stress at which failure occurred for the 11 tests was 30.3 ksi, with a standard deviation of 6 ksi.

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Revision Log

Rev.	Date	Author(s)	Summary of Revisions/Comments
-	8/03/2000	M. Steinzig	Initial release.

Table of Contents

1. Test Setup and Procedure

The tests described here were performed to get a quick estimate of the failure stress for the silicon detectors to be mounted on the GLAST tracker trays. Three point bend testing was planned for these tests. A Dillon load frame was used to perform the tests, with an Omega 25 pound load cell, as shown in Figure 1.

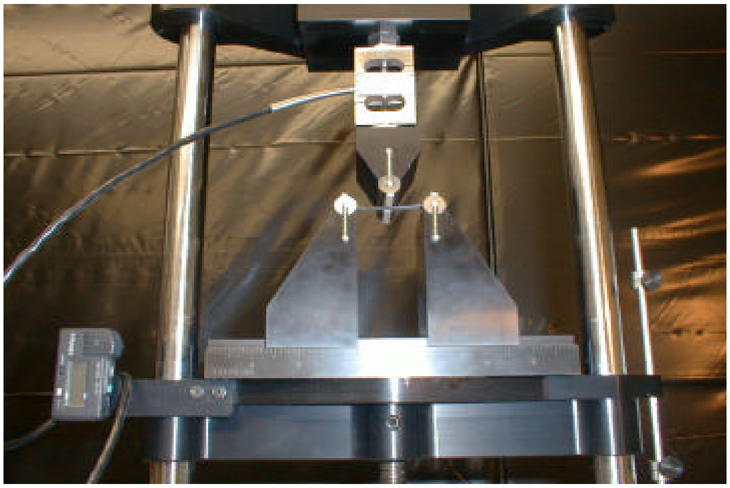

Figure 1: Dillon Load frame during testing of a baby silicon detector sample

Previously, thermal cycling tests had been performed on a prototype tracker tray, and on ladder "baby" detectors with different face sheet and converter materials. The silicon for the bend tests was salvaged from these tray and ladder tests. Each salvaged piece was examined under a 67x optical microscope, and any visible edge fractures were marked on the piece. Several of the pieces were in perfect or near-perfect condition, although the edge condition did not seem to have any effect on where the fractures occurred during testing. Before testing, each piece was measured with a micrometer for width and thickness. The length between the two base supports is set with the load cell fixtures. Ambient temperature was recorded before each sample was tested. The load frame was set to travel at its lowest speed (~1.5 mm/min), and a digital output recorder (Omega) was used to read the force from the load cell in Newtons. The output recorder stored in memory the force applied at failure.

The samples were tested in two groups; one comprising the silicon from the baby silicon detector thermal tests, and the other comprising samples from the prototype tracker tray. The baby samples are designated by the letter "s" following the test number, and the tray samples are designated by a letter "t". In many cases, after a sample failed there were large pieces remaining suitable for additional tests. In these cases, successive tests are designated by lower case letters a, b, c, etc. All samples were manufactured by Hamamatsu from wafers cut in the (1,1,1) plane, using diamond saws. The history of the samples follows.

TRAY SAMPLES

- The individual detectors were 64 mm on a side.
- Original tray built for the random vibration tests performed at Goddard in 1999.
- Following vibration testing, the tray was tested at HYTEC, Inc., under operational, (40 to -10°C) and survival (60 to -55°C) thermal conditions.
- Test samples were peeled up from the center of the T shape pattern of the tray. Bonding had been with 3 epoxy spot bonds per detector.
- Samples were individually numbered and tested with the strip side up in the load frame, i.e, the strip side in compression.
- The length of the sample is the distance between the two bottom supports of the load frame (see Figure 1). This length is parallel to the "beam" direction, used as a reference in the discussion here. All samples were tested with the conducting strips parallel to the beam direction.

BABY SAMPLES

- The baby samples were 107 mm by 8mm.
- These samples were taken from the edges left over after detector squares were cut from the wafers.
- The samples had been mounted to various ladder layups, and tested at HYTEC, Inc., under operational, (40 to -10°C) and partial survival (60 to -23°C) thermal conditions.
- Test samples of the baby silicon detectors were peeled up from the kapton sheets to which they had been spot bonded with epoxy.
- Samples were individually numbered and tested with the strip side up in the load frame, i.e, the strip side in compression.
- All samples were tested with the conducting strips parallel to the beam direction.

2. Results

Table 1 gives the data recorded during the tests, and the calculated values of failure stress. Failure stress was calculated using the pure bending formula,

$$s_{Max} = \frac{MC}{I} = 1.5P\frac{l}{wt^2} \qquad (1)$$

where M is the maximum moment, C is the maximum distance from the neutral axis to the outermost surface (1/2 *t*), I is the moment of inertia, P is the applied load, l the length of the sample parallel to the beam direction, w the width, and t the thickness. The mean of the failure stress is 30.3 ksi (ksi = 1000 $^{lb}/_{in^2}$), with a standard deviation (based on n-1) of 6 ksi. The graph in Figure 2 shows the calculated failure stress values as a function of the calculating parameter length over width times thickness squared.

Sample #	T ambient (°F)	Width (in)	Thickness (in)	Length (in)	Load at failure (lbf)	Failure stress (ksi)
1t	-	2.52	0.0152	2.0	5.79	29.8
2t	73	2.52	0.0154	2.0	6.11	30.7
3t-a	74	1.626	0.0152	1.0	6.30	25.2
3t-b	74	0.997	0.0152	1.2	3.71	29.0
1s-a	-	0.321	0.0167	2.0	0.62	20.8
1s-b	-	0.321	0.0167	2.0	1.15	38.5
1s-c	74	0.321	0.0167	2.0	0.76	25.5
2s	73	0.321	0.0167	1.2	2.07	41.6
3s-a	73	0.321	0.0167	3.8	0.49	31.2
3s-b	73	0.321	0.0167	1.0	1.91	32.0
3s-c	73	0.321	0.0167	1.2	1.33	26.7

Table 1: Data from bend tests and calculated failure stress

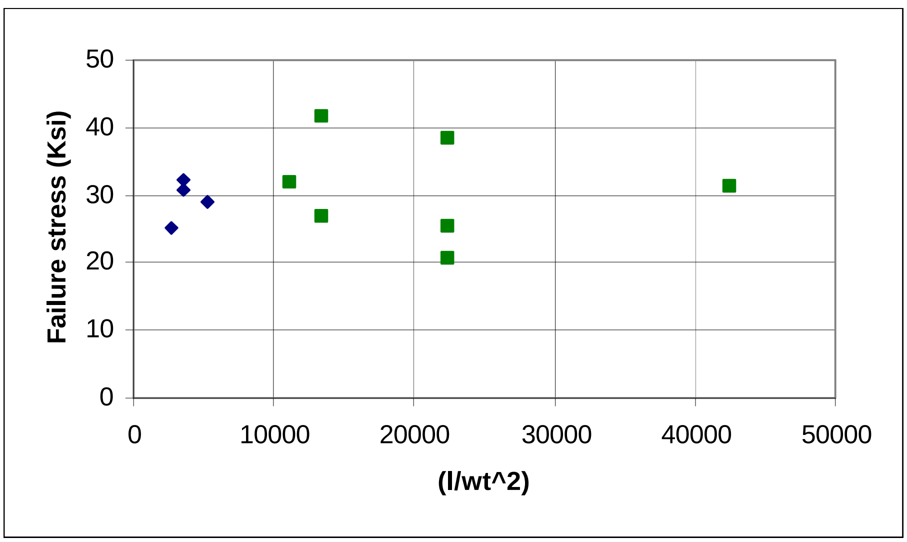

Figure 2: Bend test failure stress results, for strip samples (diamonds) and square tray samples (squares)

3. Discussion of Results

The silicon average failure strength is 30.3 ksi with a standard deviation (σ) of 6 ksi. One might expect 99.7% of all test results to fall within ±18 ksi, ±3σ, assuming a normal distribution (crude assumption). This is a large error band, probably due to the effect of micro-defects in the silicon wafers. That is, these defects make some samples much weaker than others. It is possible that the samples tested had more defects than would be expected for a new sample, since these were salvaged from previous tests. In this case, it might be that the average ultimate strength would increase if repeat tests were performed using all new samples.

All the data for the two types of samples (baby and tray detectors) has been analyzed together. Figure 2 shows no significant difference in the test results from the two types of samples. Figure 2 also indicates that there is not a significant effect of the geometry parameters length, width, or thickness, although the thickness was close to the same in all the samples.

It is interesting to note that the breakage plane for almost all the baby samples was 60°, as shown in Figures 3 and 4 below. This is also true for the tray samples, as shown on the right side of the break in Figure 5. In some cases, the break is an alternating array of 60° angle breaks, as shown on the left side of the break in Figure 5. Figure 6 shows a reconstructed tray panel after two bend tests. The first bend test fractured the sample in the familiar 60° pattern, but also broke the sample along one of the strip conductor lines, which may also be a primary failure plane for this crystal structure. The large remaining piece was subjected to a second bend test. These fractures are visible as the thin lines in Figure 6, emanating from the bottom edge of the sample.

In all the baby sample tests, the failures seem to have occurred very close to the center of the span between the two supports (point of applied load). This was true even in the cases where obvious edge defects were noted with the microscope prior to testing. In no case of the baby samples did the failure seem to emanate from one of these edge defects. It is more difficult to ascertain where failure began in the tray sample tests because the breakage planes might run across the entire sample in a 60° direction. However, theory shows that the highest point of stress is concentrated at the center of the span, along the free edges. Therefore, it can be concluded that all samples failed at the point of highest stress and not at distant edge defects, but should be verified.

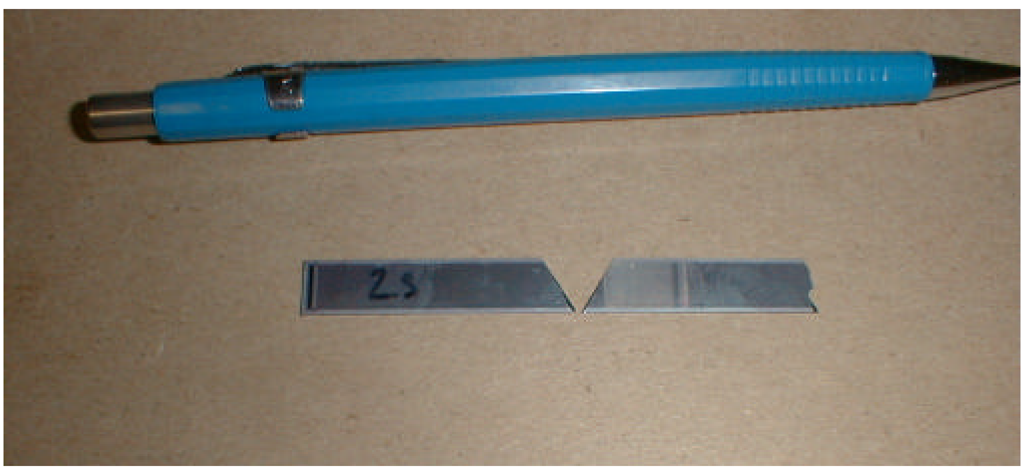

Figure 3: Baby sample 2s after failure in a bend test. Note the smooth breakage plane at 60° from the long edge.

Figure 4: Baby sample 1s-c after bend test

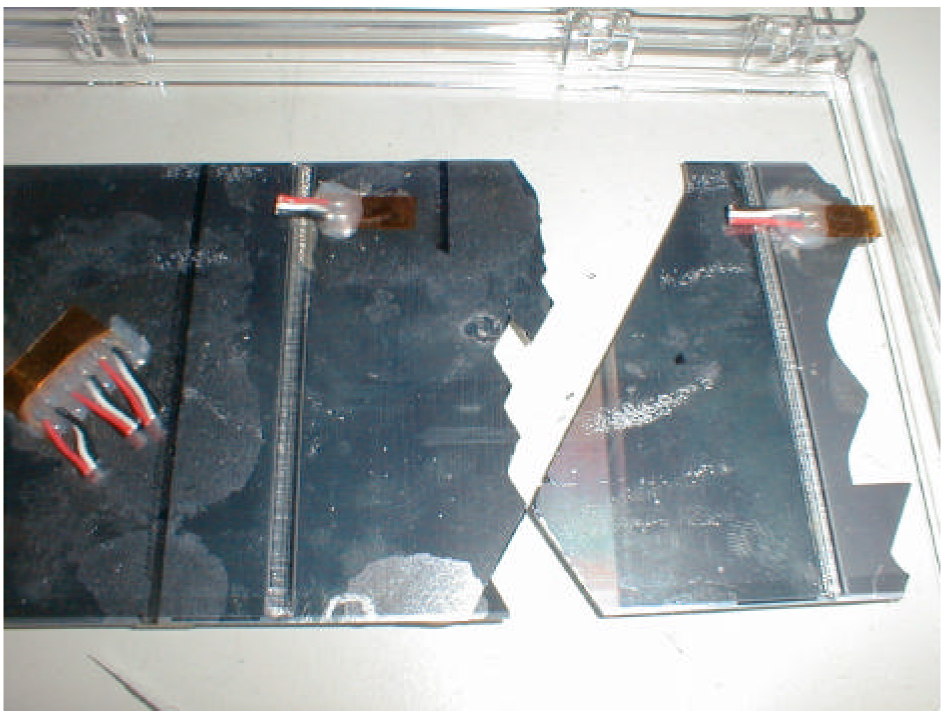

Figure 5: Tray sample 2t after bend test. The breakage at the far right is a result of the original thermal testing on this sample. The breakage in the center is a result of the bend test.

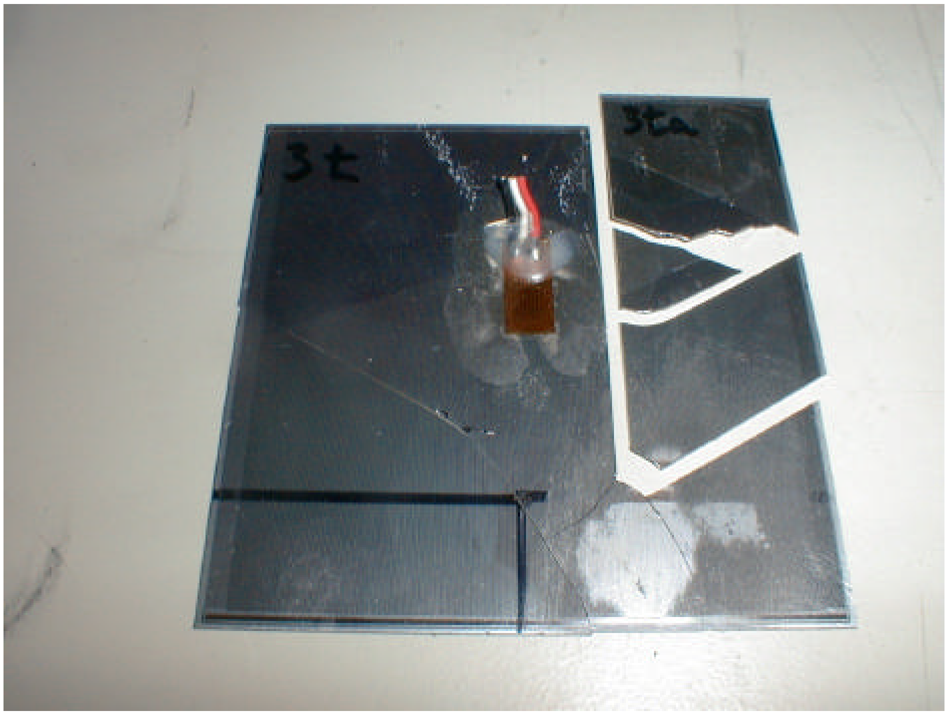

Figure 6: Tray sample 3t after two tests. First breaks are clearly shown by separation, second break is evident as thin lines from bottom to left side.

4. Conclusions and Recommendations

The goal of these tests was to begin addressing the issue of determining an acceptable design value for the strength of silicon. Design strength of ductile materials is often reported assuming the data follows a normal distribution, and thus the standard deviation can be used. However, in the case of brittle materials, the distribution is not expected to be normal, and thus reporting a design strength would require significant testing to develop a distribution. The average measured failure stress of 30.3 ksi is significantly less than predicted by theory, which is to be expected for a brittle material. General theory predicts failure strength in the range of

$$s_{th} \approx \frac{E}{5} to \frac{E}{10}. \qquad (2)$$

For brittle materials, such strengths have been measured only for thin fibers of fused silica, or whiskers of crystalline oxides. Most commercially available brittle materials have strengths more on the order of E/100 to E/1000, or 276 to 27.6 Ksi. This is attributed to the existence of flaws in the material, as suggested by Griffith[1]. This theory has the consequence that the strength is statistical in nature, and depends on the distribution of flaws in the material. An additional consequence is that the observed strength of a sample in a bend test is higher than the observed strength of a tensile test[2]. This is thought to be due to the volume of material under stress: in the bend test the stress is highest at the surface and decreases to zero at the neutral axis. In a pulltype tensile test, the entire cross section of the sample is subject to stress, and the apparent result is more likely to encounter a micro-defect that will lead to failure. So, in order to convert the measured value of failure stress to a design value, a significant amount of data should be taken to develop a frequency distribution of observed strengths.

It should be noted that none of the fractures in the tests described here seemed to emanate from the edge chips that were noted under the microscope. As discussed above, much of the literature indicates that flaws will have a significant effect on the failure strength of the material. We suspect that the chipped edges in the samples did not contribute to failure because they do not penetrate into the surface in the same way that cracks do.

In addition to the effect of flaws, there are other issues that should be considered before a design value of strength can be determined.

- temperature dependence
- time dependence (fatigue) and loading rate
- moisture dependence
- sample size; larger samples will be weaker[3]
- sample orientation in relation to crystal plane orientation
- orientation of conductor strips in relation to bend direction
- surface condition

It is common in brittle materials that all of these effects can reduce the safe value of design strength from the theoretical value, as discussed by Kingery. It is therefore not prudent to use a design value based simply on theoretical results, or on the results of a single type of testing, such as the bend tests reported here.

Further testing should be performed to better estimate the ultimate strength of silicon and determine an acceptable design value. Higher design values would ultimately reduce the problems associated with the SuperGLAST CTE mismatch, thereby reducing development time and cost. Lower design values would increase current problems. However, current design values account for such micro-defects and are considered conservative. A thorough testing plan would likely reveal a higher design value and should be included in the tracker development.

5. References

[1] Philos. Trans. R. Soc., A221, 163 (1920)

[2] W.D. Kingery, Intro. To Ceramics, Wiley and Sons, 2nd ed. 1976. P. 787.

[3] J.C. Fisher and J.H. Hollomon, Trans. AIME, 171, 546 (1947)