Space-qualified, Abuttable Packaging for LBNL p-Channel CCDs, Part I

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ABSTRACT

We have developed a design for packaging Charged Coupled Devices (CCDs) for use as optical imaging devices for space applications, although the design is also useful for any large ground-based mosaic. We have constructed and assembled prototype packages using this design. Testing of these prototypes has demonstrated that these packaged CCDs are flight worthy. The design, construction, and testing of these prototypes are described in this article.

Keywords: CCD detectors, space, packaging

1. INTRODUCTION

Silicon Charged Coupled Devices (CCDs) have proved to be powerful optical imaging devices in a variety of space missions. The packaging and the mounting of these devices to the focal plane in a space telescope has to meet very demanding specifications to survive vibrational loads and thermal excursions. The work presented here is further motivated by several mission specific issues, which we outline in general here. First, we want to easily assemble focal planes with a mosaic array of detectors. This requires four-side abuttable packaging. Second, the telescope optics places stringent flatness tolerances on the focal surface. We require that each detector package be flat relative to its mounting surface and that the overall package thickness be well controlled so that detectors can be placed on the focal plane without shimming. Third, the focal plane is cooled to approximately 140K by edge contact at a few locations. We require the focal plane and detector materials be good thermal conductors with little temperature gradient across them. Fourth, the coefficient of thermal expansion of all materials should be well matched. We require that materials have CTEs compatible with the silicon of the CCD to avoid stress artifacts in images. Lastly, we require that mounting footprint of the CCD package match that of the one being developed independently for near infrared detectors so that the detectors can be intermixed in the mosaic as desired.

We have developed a method of packaging CCDs that meets the stringent requirements described above. This work was done as part of the R&D program for the JDEM space mission to study the nature of the recently discovered, mysterious component of our universe called Dark Energy. The CCDs we were working with are fully depleted back illuminated devices developed at the Lawrence Berkeley National Laboratory (LBNL) for this purpose[1]. The device format is 3508 × 3512, 10.5 µm pixels. They are 200 µm thick and are fully depleted to provide good quantum efficiency up to 950 nm with good spatial resolution. The physical size of the finished devices is $38.8 \times 39.4\ \text{mm}^2$ with 37 contact pads on each of two opposite sides, as shown in Figure 1.

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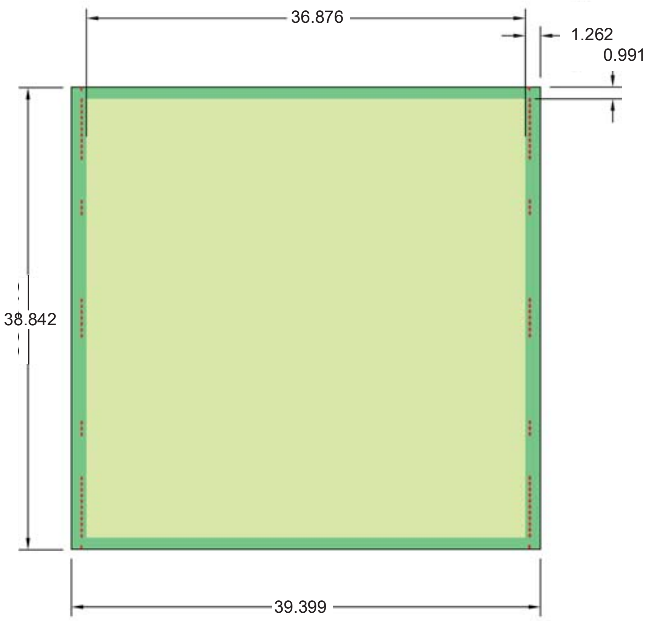

Figure 1 The CCD developed for JDEM by LBL. The contact pads are along the left and right edges in this image, 37 along each edge. Dimensions shown are in mm.

2. REQUIREMENTS FOR THE PACKAGED CCDS

Each CCD is intended to be part of a larger, closely packed mosaic of detectors on a flat focal plane. For backside operation the CCDs are mounted with the pad side facing down. To reduce the dark current to a tolerable level the plan is to operate the CCDs at a temperature of -120°C. These considerations led to the following requirements:

a. Packaged devices must be four-side buttable to fit into a mosaic with minimal gaps.
b. Packaged devices must be stable over a temperature range from room temperature down to -150°C.
c. The surface of the CCDs exposed to light must be flat within 10 µm at the cold operating temperature of -120°C (i.e. all points of the upper surface are within a total range of 10 µm).
d. The entire package must have a uniform thickness to within 10 µm.
e. The thermal resistance of the package, from CCD to the focal plane, must be less than 1°C/watt. This is needed to be able to conduct the heat absorbed by the CCD away and keep the temperature of the CCDs constant to less than 1°C.
f. The substrates on which the CCD is mounted must be opaque to photons up to a wavelength of 1000 nm so that electric traces and mounting holes will not be observed in reflection by the CCD.
g. Robust space flight proven connector to make the connections to the CCD read out and control electronics.
h. Resistance to shock and vibrations inherent in the launching process of the spacecraft.

We note that most of these requirements apply for any mosaic focal plane detector, whether used on a mountain top or in space.

3. THE DESIGN OF THE CCD PACKAGE

3.1 Description of the Design

In the design, shown in an exploded view in Figure 2, the CCD is glued face down to a 0.75 mm thick aluminum nitride (AℓN) substrate. The AℓN substrate is in turn glued to a stiff silicon carbide (SiC) pedestal which in turn is then bolted to the SiC focal plane. The SiC pedestal is 40.5×42.2 mm^2, and the total package, from the top of the CCD to the surface of the focal plane is 17.6 mm thick. The edges of the CCD with the contact pad extend slightly beyond the AℓN substrate so that the pads are exposed. The electrical connections are made by Aℓ wire bonds from the pads on the bottom of the CCD to the pads and traces on the bottom of the AℓN substrate. There is a hole in the center of the SiC pedestal where the 58-pin custom Hypertronics[2] connector is located, as shown in Figure 2. Some of the 74 CCD pads are interconnected within the CCD or by traces on the AℓN substrate so that only 58 connections are needed at the connector. Traces on the bottom of the AℓN substrate carry the signals to the hole in the pedestal, where wire bonds connect them to traces on a flexible Kapton® circuit which in turn connect to the pins on the Hypertronics connector. An enlarged view of the traces on the bottom of the AℓN substrate (the side away from the CCD) is shown in Figure 3. These connections are shown in Figure 4 with the SiC pedestal removed for clarity. Note that Figure 4 is "upside down" from Figure 2. The final assembly is shown in Figure 5. Note the grooves in the SiC pedestal on the two edges where it extends over the wire bonds to protect the wire bonds from accidental damage during subsequent handling.

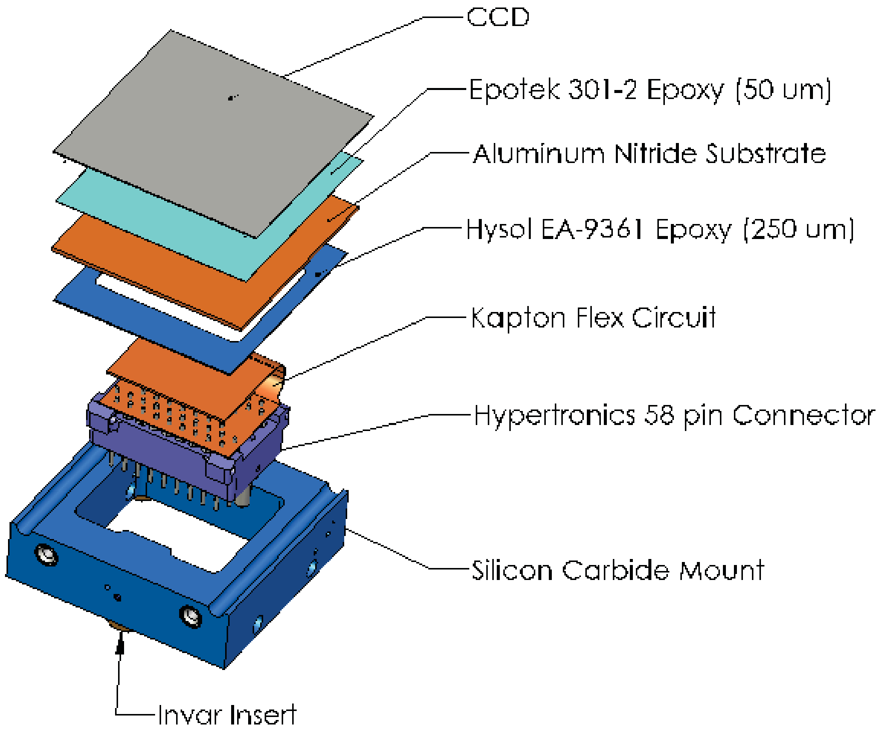

Figure 2. Exploded view of the CCD package.

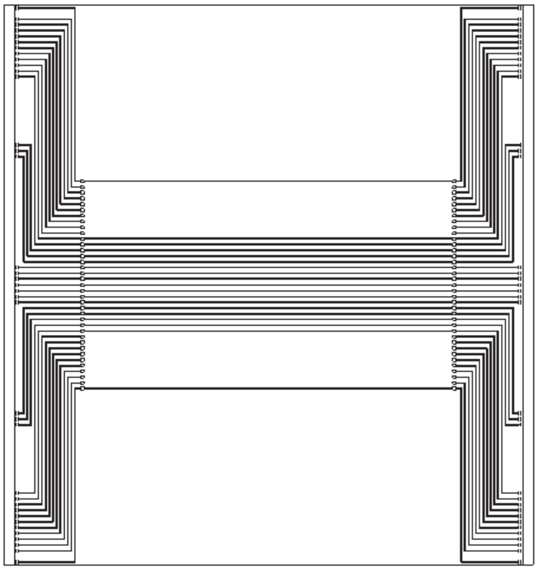

Figure 3. Drawing showing the traces on the aluminum nitride substrate.

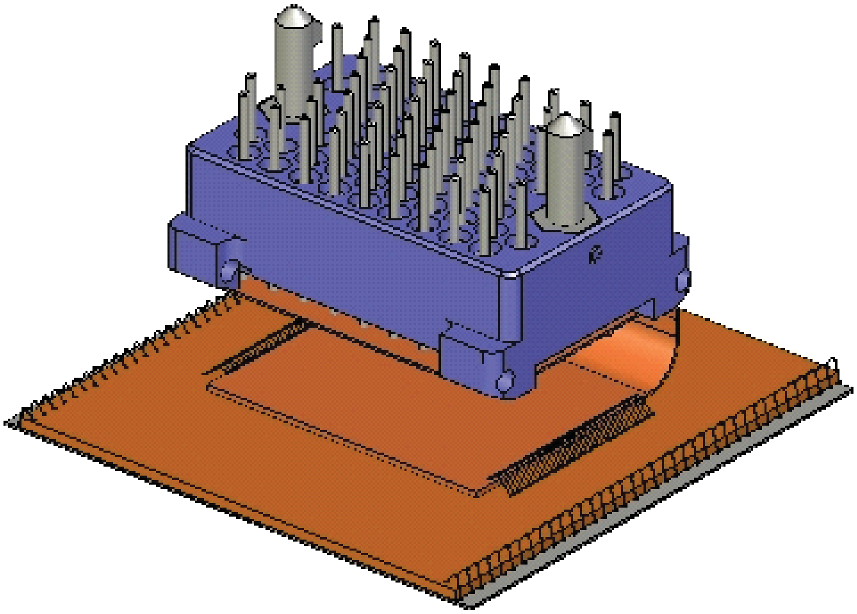

Figure 4. View of the package without the pedestal showing the location of the wire bonds.

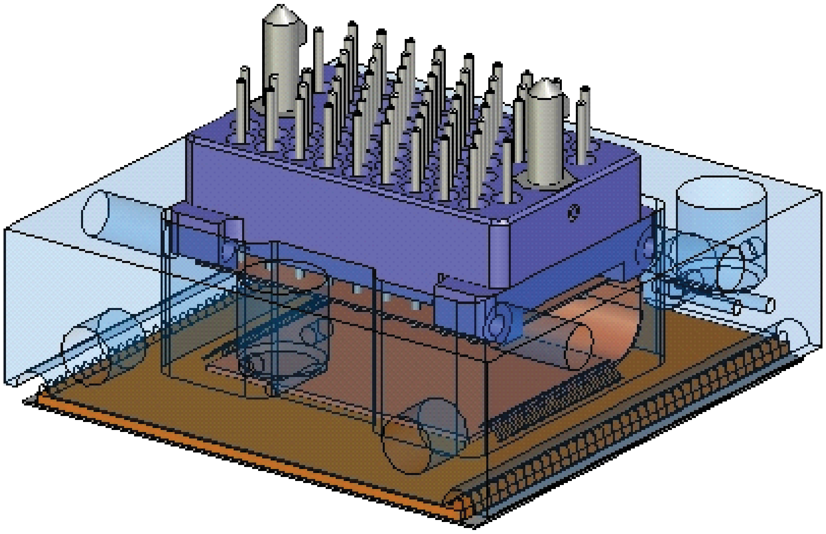

Figure 5. View of the assembled package with the sensitive surface of the CCD on the bottom.

3.2 Choice of Materials

An important consideration in the design process was the choice of materials to use in the package. Not only had the design to insure mechanical stability during the large temperature change from room temperature to the operating temperature, but the very tight flatness tolerance had to be maintained. Materials with very similar coefficients of thermal expansion (CTE) over this range of temperatures have been chosen to prevent buckling of the CCD as the package was cooled down or heated up. Figure 6 shows the integrated expansion for a variety of materials. AℓN is a very good match to silicon so it is an obvious choice for the substrate material. Molybdenum is not a good choice for the pedestal, but either SiC or Invar 36 is acceptable.[3] SiC was chosen since the material of choice for the focal plane is SiC. For an application with an Invar 36 focal plane, Invar 36 would be the preferred material for the pedestal. We have built prototypes pedestals with both SiC and Invar 36 and both were satisfactory.

Another important consideration was the bonding materials and their thickness used in the glue joints. After an extensive R&D program, we chose a 50 μm thick layer of EPO TEK 301-2 for the CCD to AℓN joint[4] and a nominal 250 μm thick layer of Hysol® EA - 9361 for the joint[5] between the AℓN substrate and the pedestal. The Hysol layer is compressed during the curing process to adjust the entire package to the target height established by precision ground spacers.

3.3 Finite Element Analysis

Detailed calculations were carried out to check the thermal stability and flatness distortions during the required thermal cycling. These calculations indicated that the choice of materials is indeed appropriate to ensure mechanical robustness and to satisfy the required flatness and thickness tolerances over the relevant temperature range. They also showed that the mechanical stresses in the materials and the glue layers are at an acceptable level with a good margin of safety.

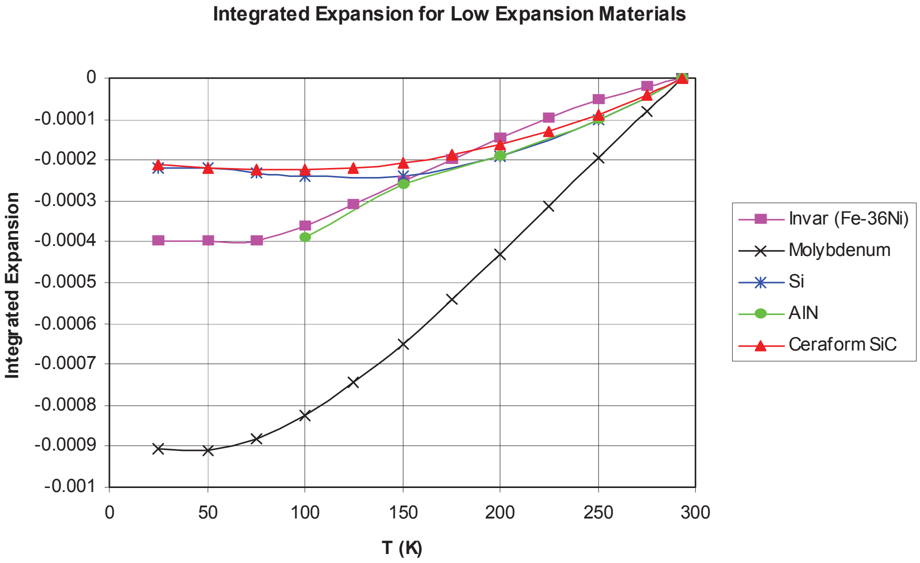

Figure 6. Integrated fractional thermal expansion for various materials. The intended operation temperature is -120°C.

4. ASSEMBLY PROCEDURES AND TOOLING

After the completion of the design, component parts sufficient for the prototype packages were purchased from commercial sources. Pedestals made both of SiC and Invar 36 were obtained. A set of these parts, with a shorting connector to be used during assembly, the Hypertronics connector with the Kapton flex circuit, the invar pedestal, the AℓN substrate and an actual CCD, are shown in Figure 7.

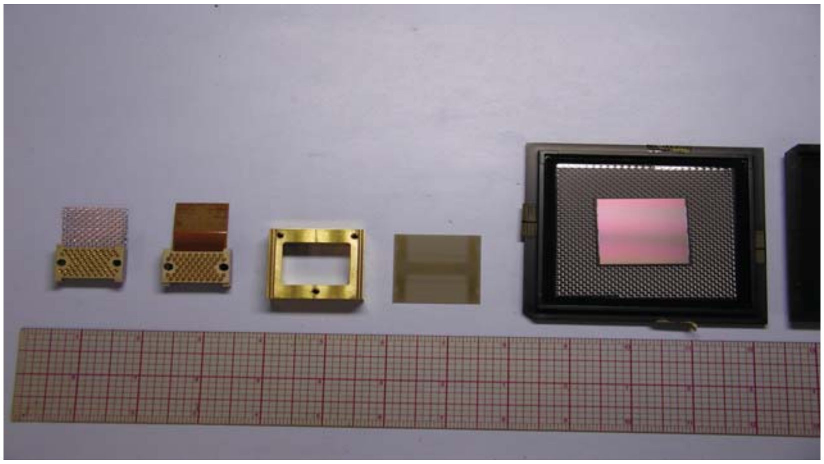

Figure 7. Components of the package before assembly. The object on the left of the row is a shorting plug used to protect the CCD during wire bonding.

A set of custom tooling, with vacuum chucks and guide pins to hold the pieces, was built in the Yale machine shop to facilitate the assembly of the packages and to insure the exacting tolerances. The assembly proceeded in several steps, with exhaustive quality control and electrical continuity checks between the steps as appropriate:

a. Solder the Kapton flex circuit to the back of the Hypertronics 58 pin connector.

b. Bond the CCD to the AℓN substrate with the EPO-TEK 302-2 adhesive using vacuum chucks and alignment pins of the assembly tooling.

c. Glue the free end of the Kapton flex circuit, with the Hypertronics connector on the other end, to the back of the AℓN substrate.

d. Place the shorting plug on the Hypertronics connector to protect against ESD damage to the CCD during wire bonding. Wire bond the CCD pads to the AℓN substrate pads, and then wire bond from the AℓN traces to the traces on the Kapton flexible circuit.

e. Glue the SiC or Invar 36 pedestal to the AℓN substrate using a nominal 250 µm layer of Hysol EA - 9361 adhesive. In this step precision ground stainless steel plates of the assembly tooling are used with precision ground spacers to compress the Hysol glue layer to achieve the strict thickness tolerance of the entire package.

f. Secure the Hypertronics connector inside the pedestal using pins machined for that purpose.

A photograph of the assembly tooling used in steps b) and c) is shown in Figure 8, and a photograph of a flight-ready package is shown in Figure 9.

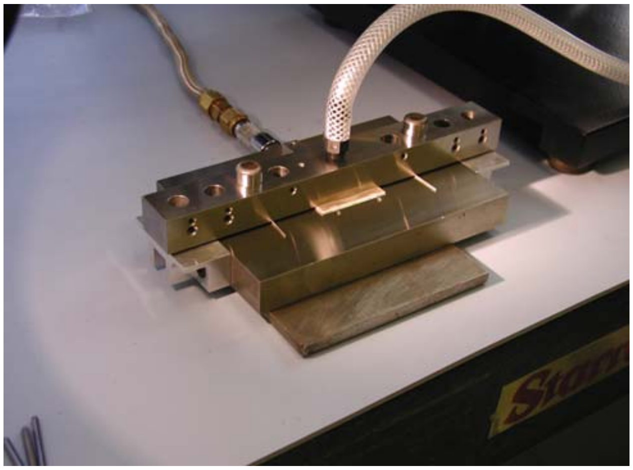

Figure 8. Photographs of some pieces of the assembly tooling.

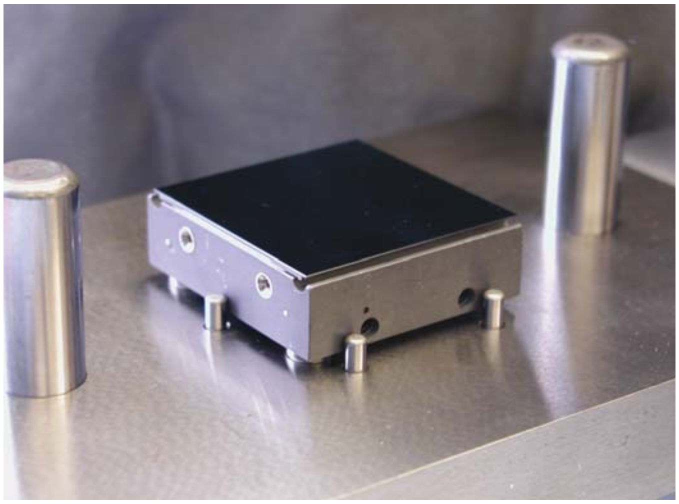

Figure 9. Photograph of a completed package.

5. TESTING OF THE PROTOTYPE PACKAGES

The fully assembled prototypes were subjected to a rigorous testing program carried out at all three of the collaborating institutions.

5.1 Readout and Image Quality

The packaged CCDs were illuminated by uniform, monochromatic flat field illumination with wavelength adjustable from 470 nm to 940 nm, as well as the conventional Air Force test pattern, shown in Figure 10. An 1800 second dark exposure with typical cosmic ray and lab natural background radiation traces is shown in Figure 11. (The hot pixel visible near the left hand edge of this CCD was identified before this device was packaged.) As these images indicate the packaged CCD is reading out correctly, checking the correctness of the wire bonded connections, the traces, the connector, etc.

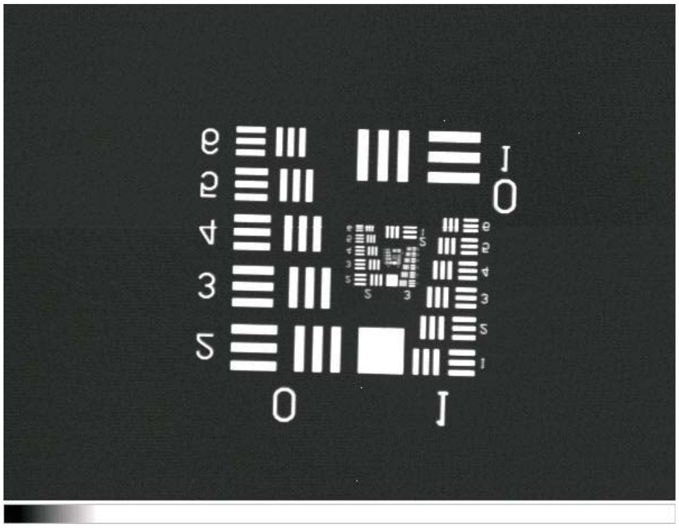

Figure 10. Read out of the completed package exposed toan Air Force test pattern.

Figure 11. An 1800 second dark exposure of the completed package showing cosmic ray and lab natural background radiation tracks.

An early concern in the design was that at wavelengths beyond 800 nm the silicon CCD and the AℓN substrate would become somewhat translucent. In that case some fraction of the light entering the CCD could penetrate the CCD and the AℓN and be reflected back into the CCD by the metal traces on the back of the AℓN substrate. A careful examination of the flat field images does not show any measurable sign of reflections from the traces or from the glue layer between the CCD and the AℓN substrate even at the longest wavelength of 940 nm.

5.2 Flatness and Thickness Tolerances

Flatness and thickness measurements were carried out at the collaborating institutions, both at room temperature and at the operating temperature of -120°C. All of the measurements of all of the prototypes satisfied the required tolerance of 10 μm.

Measurements of three prototypes at room temperature at Yale were carried out. The flatness was within 3 μm, 6 μm, and 7 μm peak to valley on the three prototypes respectively. Measurements of the thickness uniformity at Yale showed the thickness variations to be less then 6 μm. More detailed measurements of the flatness at room temperatures carried out at LBNL showed the variation of the surface from a best fit flat plane to be from -5 μm to +2 μm, well within the 10 μm tolerance required. Flatness measurements of a prototype at -120°C were carried out at FNAL, showing the surface to be flat to better then the 10 μm tolerance.

5.3 Thermal Cycling

Several of the prototypes were repeatedly immersed in liquid nitrogen and allowed to warm to room temperature between immersions. This is a more rigorous test than the anticipated thermal cycle that these packages are expected to experience in that the liquid nitrogen temperature is well below the actual operating temperature, and the cool down in immersion is more rapid than expected in space flight. Nevertheless, after multiple immersions no ill effects were observed, and flatness measurements gave the same result as were obtained before immersions.

5.4 Pedestal Mount Flight Qualification

SiC pedestals with identical mounting features to the flight CCD packages were used to qualify the CCD pedestal mounting design. Four SiC pedestals were mounted to a SiC focal plane for thermal cycle and vibration qualification tests. The assembly was cycled in a thermal vacuum chamber between the qualification survival temperatures of 100K and 323K. Precision metrology using a coordinate measurement machine (CMM) before and after the eight-cycle test demonstrated that the pedestals did not shift within the CMM measurement accuracy of ~2 µm. Visual inspection of the joints showed no cracks, fretting, or other damage. A three axis random vibration test of the assembly was performed to the GEVS[6] qualification levels (14.1 G rms, 2 minutes per axis). Low level sine sweeps were performed before and after each random vibration to monitor any changes. No changes were detected in the low level sine sweep tests. CMM measurements before and after the vibration test sequence showed no measurable shift in positions, and visual inspection of the joints indicated no cracks, fretting, or other damage.

5.5 Preparation for Mass Production

Many new ambitious space missions as well as ground based facilities require sizeable CCD mosaics consisting of a large number of CCD packages. Therefore, after several successful prototypes were assembled at Yale, a program was initiated at LBNL to facilitate mass production of these CCD packages. A number of modifications to the tooling and the assembly procedures were initiated to make the assembly process more routine, reliable, and able to use automatic wire bonders available at the LBNL silicon facility. These modifications have been tested and prototypes have been assembled that could be read out successfully. The procedures are thus ready for the production of a large number of packages as described in the companion paper "Space-qualified, Abuttable Packaging for LBNL p-Channel CCDs, Part II"[7]

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6. CONCLUSIONS

In conclusion, this R&D program has produced a flight-ready design and assembly procedure for packaged CCDs. Prototypes have been produced and the devices meet space flight requirements. Furthermore, the design is applicable to any focal plane requiring a mosaic of CCDs.

7. ACKNOWLEDGEMENTS:

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