Space-qualified, abuttable packaging for LBNL p-channel CCDs, Part II

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ABSTRACT

Fully depleted, back-illuminated, p-channel CCDs developed at Lawrence Berkeley National Laboratory exhibit high quantum efficiency in the near-infrared (700-1050nm), low fringing effects, low lateral charge diffusion (and hence small, well-controlled point spread function), and high radiation tolerance. Building on previous efforts, we have developed techniques and hardware that have produced space-qualified 4-side abuttable, high-precision detector packages for 10.5µm pixel, 3.5k x 3.5k p-channel LBNL CCDs. These packages are built around a silicon carbide mounting pedestal, providing excellent rigidity, thermal stability, and heat transfer. Precision fixturing produces packages with detector surface flatness better than 10µm P-V. These packages with active areas of 36.8mm square may be packed on a detector pitch as small as 44mm. LBNL-developed Front End Electronics (FEE) packages can mount directly to the detector packages within the same footprint and detector pitch. This combination, along with identically interfaced NIR detector/FEE packages offers excellent opportunities for high density, high pixel count focal planes for space-based, ground-based, and airborne astronomy.

Keywords: JDEM, SNAP, SiC, Silicon Carbide, Radiation Tolerant

1. INTRODUCTION

Charge-coupled devices (CCDs) developed at Lawrence Berkeley National Laboratory (LBNL) have several characteristics giving them advantages over other designs for astronomy, particularly space-based applications[1,2]. Back-illumination through their relatively large, fully-depleted thickness (100-300µm) enables higher quantum efficiency (QE) at near-infrared (NIR) wavelengths (up to one micron), with reduced fringing. Operation with high bias voltage reduces lateral charge diffusion, and contributes to a small, well controlled point spread function (PSF), which is essential for several types of science, for example precision morphology used in weak lensing observations[3,4]. Employing p-channel architecture makes these devices intrinsically more radiation tolerant than conventional n-channel technologies[5].

Large-format versions of the LBNL CCDs (including 2k x 4k x 15µm, 2k x 2k x 15µm, and the presently-described 3.5k x 3.5k x 10.5µm devices) have been packaged using various configurations and materials by teams at institutions including University of California at Santa Cruz (Lick Observatory), LBNL, Fermi National Accelerator Laboratory (Fermilab), and Yale University[6,7,8]. This paper reports on developments built upon those efforts, including recent efforts described in part I of this paper[9]. The device described here and designed at LBNL is a 3.5k x 3.5k x 10.5µm-pixel CCD, four of which are shown prior to dicing on the wafer in Figure 1. This device is manufactured on 150mm wafers by DALSA Semiconductor, with thinning, backside processing, and metallization at the LBNL Microsystems Laboratory[10]. It has an active area that is 36.8mm square, and overall size of 39.5mm x 38.9mm. Electrical interconnection is through wirebond pads along two edges. For this application, the device is thinned to 200µm.

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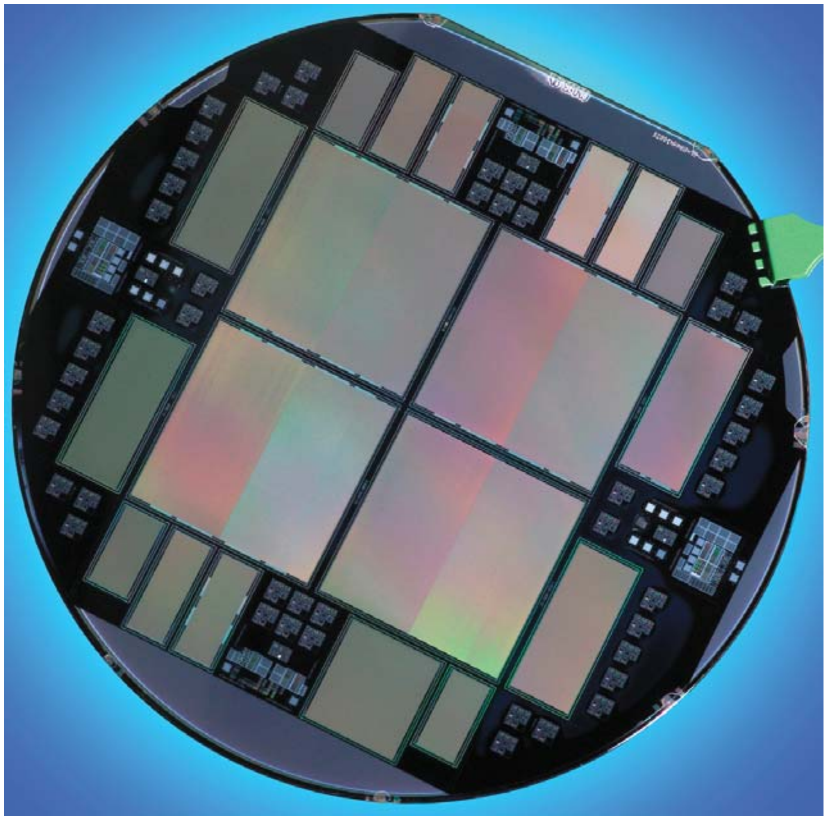

Figure 1: LBNL CCD 150mm wafer, with four 3.5k x 3.5k CCDs in the center.

2. REQUIREMENTS

Requirements for this CCD packaging effort are based on requirements established for the former proposed SuperNova/Acceleration Probe (SNAP) space telescope[11], and for the proposed NASA/Department of Energy Joint Dark Energy Mission (JDEM) space telescope[12]. These stringent requirements for space applications make this packaging technology suitable for other space missions as well as for ground-based applications. Some of the key requirements include: Detector surface flatness better than 10µm P-V, 4-side abuttable packaging on a 44mm pitch focal plane, accommodating an optical mask and/or filter mount, blind-mating with a front-end electronics (FEE) module that fits within the detector footprint, rejecting heat through conduction into the focal plane via the mounts, maintaining less than a 1K gradient across the CCD itself, mounting scheme compatible with near infrared (NIR) detectors on the same focal plane[13], and survival of launch and service environments per NASA specifications[14]. Notable environmental requirements include surviving mechanical vibration to 14.1g RMS qualification levels and thermal cycling from 110K to 323K. Electrical requirements are not addressed in this paper beyond the requirement that CCD electronic and imaging functions must be shown to survive the environments previously described.

3. DETECTOR PACKAGE DESIGN

Figure 2 illustrates the mechanical stack up of the CCD package. The CCD is bonded to a 0.75mm thick silicon substrate, to which a portion of the flex circuit is bonded. The contacts on the CCD are wirebonded to the nearby wirebond pads on the flex circuit. The silicon carbide (SiC) pedestal is bonded to both the silicon substrate and part of the flex circuit. The connector is retained using the hardware shown, which allows the connector to float relative to the package. The package is mounted to a focal plane using three M3 screws through three precision molybdenum spacers, not shown in Figure 2, which compensate for slight errors in tilt and piston in the package. With the precision spacers, at room temperature, the detector surface is located 15.000mm above the surface to which the package is mounted.

The substrate provides mechanical backing for the CCD, in addition to acting as a heat spreader to maintain temperature uniformity across the CCD. Its edges nearest the wirebond pads are beveled to improve access by a wirebonder head. In other packaging iterations, an aluminum nitride (AlN) substrate with circuit traces printed on it has been employed. In the current design we avoid metallization of the substrate by using a separate flex circuit to carry the signals from the outer edge of the package toward the center. Therefore only one wirebonding step is required (between the CCD and the flex circuit) rather than the two required with the metallized AlN substrate (from CCD to substrate, then from substrate to flex circuit). In addition, the substrate now does not need to be an electrical insulator. We employ a silicon substrate for this design, with a coefficient of thermal expansion (CTE) essentially identical with the silicon detector's at all temperatures. Another factor in selecting silicon as a substrate material was that we have observed visible glowing of our AlN substrates after exposure to ultraviolet light. This is a process and vendor dependent phenomenon, traced to the presence of yttrium oxide in certain AlN substrates.

CoorsTek's "UltrasSiC" is a single phase, direct-sintered alpha Silicon Carbide with mechanical and thermal properties making it very well-suited to be the detector package pedestal material. It has fairly low mass density, high strength, high modulus of elasticity, high thermal conductivity, and a CTE which is a good match to that of silicon. In addition, it may be ground to extremely tight tolerances, being used as an optical substrate material for mirrors in some applications. In fact, these same properties make it our material of choice for the focal plane cold plate itself. However, it is a ceramic, and as such it is brittle and requires special considerations for fastening and joining. We employ bonded metallic inserts for threaded connections. Alternatives to SiC for the pedestal include Molybdenum and Invar, neither of which has the combination of advantageous attributes SiC does for this application.

The floating electrical connector minimizes the influence of the front end electronics (FEE) on the detector package. Reliable Hypertronics-brand pins and sockets in custom-machined PEEK connector bodies make for very reliable, blind-mateable electrical connections to the FEE, test equipment, or shorting plugs.

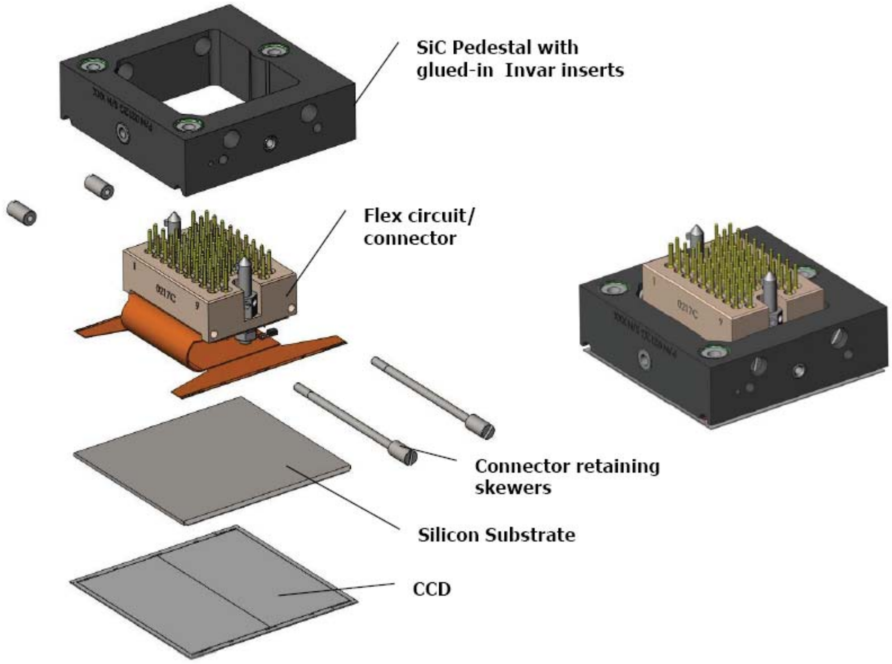

Figure 2: Mechanical Stack up of CCD Package

4. DETECTOR PACKAGING PROCESS

4.1 Bonding of flex circuit to substrate

The flex circuit is bonded to the substrate in a two-part process. First, a pre-cut piece of 3M™ VHB™ F9460PC pressure sensitive adhesive (PSA) is applied to the flex circuit then the flex circuit/PSA are applied to the substrate using a guide (not shown). The flex circuit, pre-cut PSA, and substrate are shown in Figure 3. This is a straightforward bonding step that provides a uniform, well-controlled bond thickness using simple fixturing.

Figure 3: Flex circuit, PSA, and substrate separately (left) and assembled (right)

In the first assemblies that used this technique, the PSA was sized to exactly match the footprint of the flex circuit on the substrate. It was found that reliable wirebonds could not be made to the pads on the flex circuit due to the relatively spongy nature of the PSA. Later versions employ a PSA that is cut smaller so it does not extend under the wirebond pads on the flex circuit. When the flex circuit is first bonded to the substrate, there is a gap between the flex circuit and the substrate along the edges where the wirebond pads are. Epo-Tek® 301-2 epoxy, which has low mixed viscosity and good cured stiffness, is underflowed into this gap and allowed to cure, providing greater mechanical resistance to the wirebonder and ensuring reliable wirebonds. Figure 4 shows the application of epoxy to this gap. After bonding the flex circuit to the substrate, the connector is soldered to the flex circuit and a shorting plug installed on the connector to help protect against electro-static discharge (ESD) events.

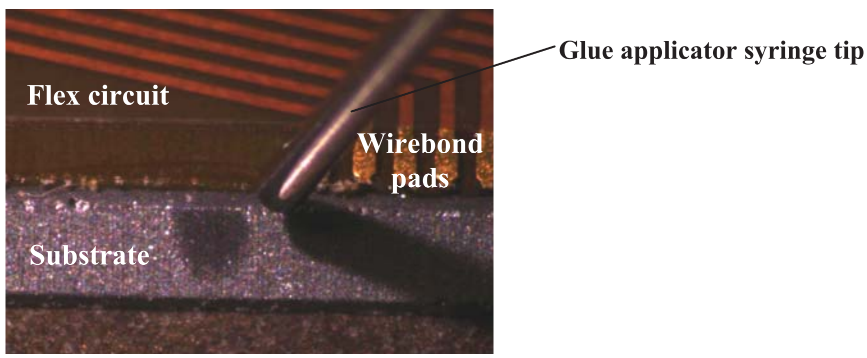

Figure 4: Underflowing Epo-Tek® 301-2 behind wirebond pads

4.2 Bonding of flex/substrate assembly to CCD

To minimize thermal distortions, to maintain flatness, and to minimize variations in CCD performance that might depend on glue thickness, a very uniform layer of epoxy is required between the CCD and the substrate. No glue voids of any kind are acceptable as these are 'seen' as features in CCD images. Film adhesives have been found unacceptable for this application due to the difficulty in preventing voids. Reliable and effective bonds are made by chucking the CCD and the substrate a controlled distance apart, then underflowing Epo-Tek® 301-2 epoxy between them. Figure 5 shows the vacuum chuck for the CCD. Three static-dissipative delrin pins locate the CCD precisely on its chuck, vacuum is applied via the vacuum channels, then the alignment pins are removed to provide clearance for the mating chuck. The CCD is located precisely relative to the precision bushings on the chuck and its surface is held flat to a few microns against the lapped surface of the temperature-controlled chuck. The CCD remains on this chuck through the entire packaging process to minimize risk of damage and to maintain surface flatness.

Figure 7 shows the vacuum chuck for the substrate, which employs removable locating pins and is temperature-controlled like the CCD chuck. The opening through the center of the chuck is necessary to give the flex and connector a place to go out of the way during bonding. The precision pins that mate with the precision bushings on the CCD chuck are visible to the right and left of the substrate. The three precision micrometer heads that adjust the position of the substrate relative to the CCD are at the ends of each 'spider' leg.

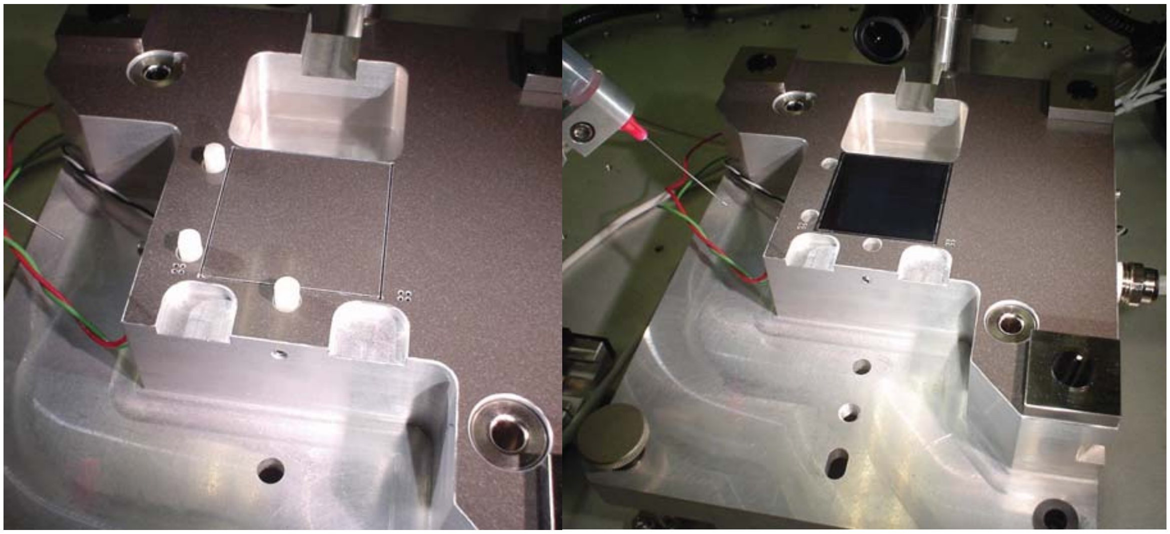

Figure 6: CCD vacuum chuck with locating pins and vacuum channel visible (left) and with CCD in place (right)

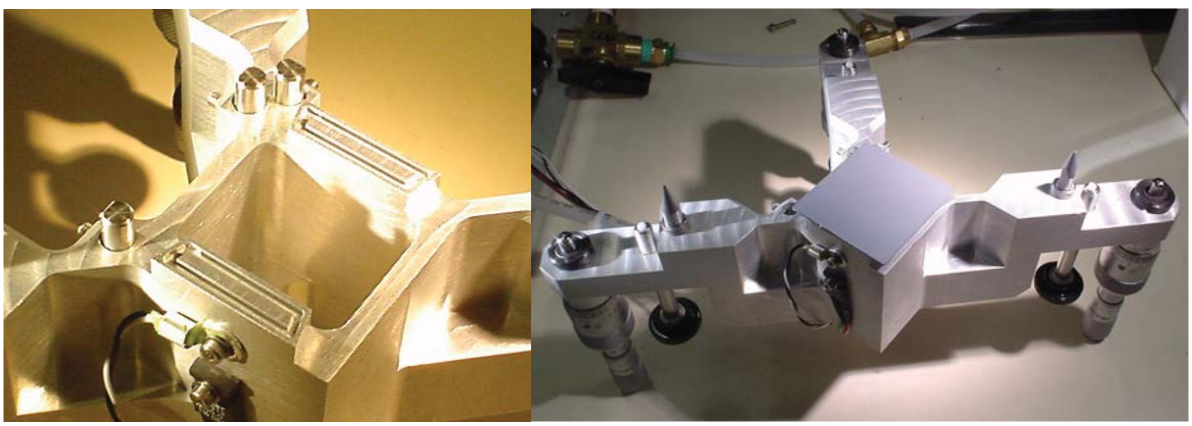

Figure 7: Substrate chuck shown upside-down. Locating pins, vacuum pads, and clearance for connector shown on left. Substrate on chuck shown on right.

Figure 8 shows the substrate chuck mated with the CCD chuck. Digital video cameras with calibrated telecentric lenses are used to visually measure the gap between the CCD and the substrate in three different locations. The three micrometer heads through which the substrate chuck rests on the CCD chuck are adjusted to make the gap between the substrate and chuck 70±3um. A pneumatically-actuated epoxy-applying syringe tip is positioned between wirebond pads, just above the surface of the CCD, directly adjacent to the substrate, and glue is metered into the gap, where it wicks by capillary action to fill the entire volume between the substrate and CCD (see Figure 9). The underflow process is monitored using video cameras watching all four edges of the substrate, and is halted when a small fillet exists around the entire perimeter, a process that typically takes about 50 minutes. The bond is allowed to cure undisturbed for 36 hours at 32°C before any other operations are performed.

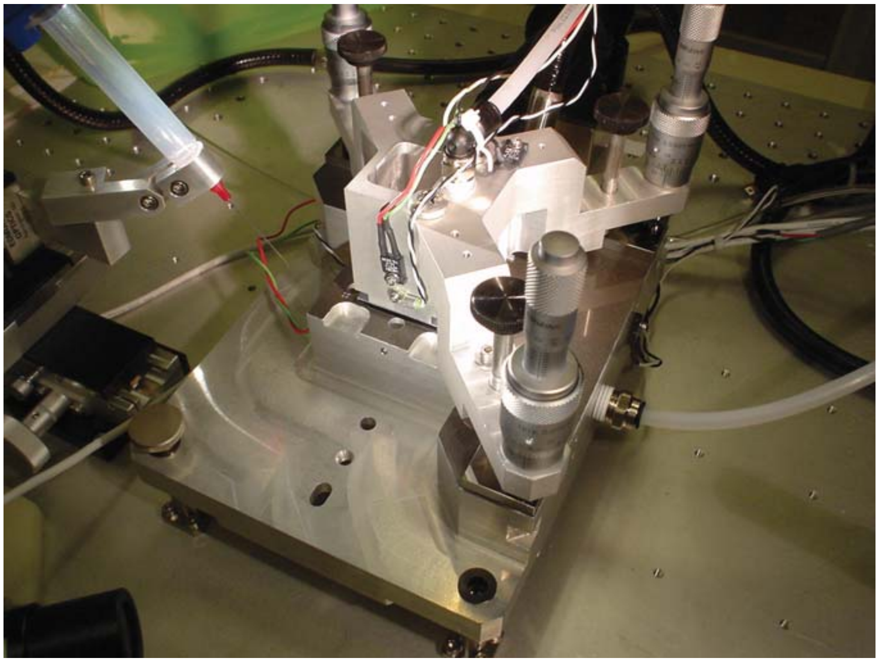

Figure 8: Substrate chuck mated with CCD chuck, glue application syringe visible to left

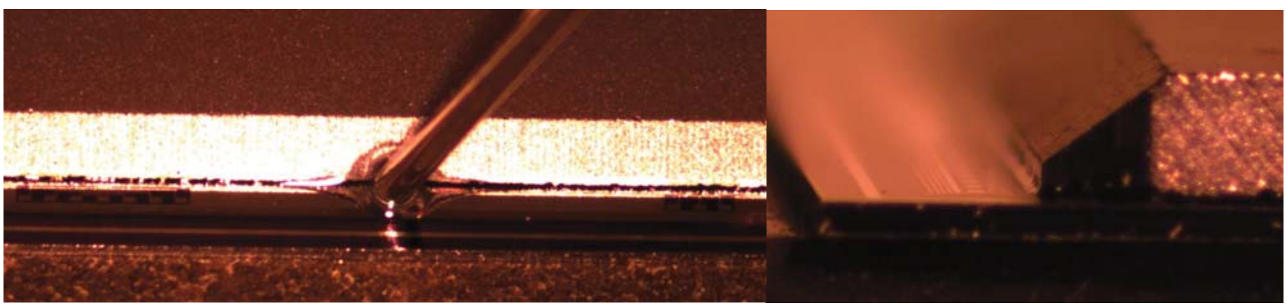

Figure 9: Left: Close-up of epoxy being administered by syringe tip into gap between substrate (top) and CCD (bottom). Note wirebond pads on CCD to either side of syringe tip. Gap is 70um, syringe tip diameter is 0.52mm. Right: Close-up of corner of glued substrate/CCD assembly, showing epoxy fillet.

4.2.1 Fermilab study on the effect of Epo-Tek® shrinkage

Epo-Tek® 301-2 epoxy has been observed to experience shrinkage during curing, by noting that the fillet size diminishes as the cure progresses. A study was undertaken at Fermilab to determine what effect that shrinkage might have on the gluing process. Specifically, the forces generated by resisting the epoxy shrinkage were measured during underflow and cure.

Two AlN substrates, with approximately half the area of the 3.5k x 3.5k CCD described in this paper, were chucked so there was a 100um gap between them, where the upper chuck was supported by a load cell, as shown in Figure 10. Epoxy was manually administered several drops at a time using a pointed tool. The force on the load cell was measured and the steady-state weight it supported was subtracted. The results over time are shown in Figure 11.

The epoxy is applied during the first 38 minutes. The bi-modal nature of the tension trend reflects lower tensions immediately after epoxy is applied, which rise as the epoxy is taken up into the gap. In all cases where the tensions are lower, epoxy has just been applied. This trend continues until around minute 38, when the entire gap is filled with epoxy, at which time the tension drops dramatically. Over the cure period of the following 24 hours, the tension increases as the epoxy cures and tries to shrink in its constrained volume.

The force generated by the epoxy was found to have insignificant effects on the packaging process. The only compensation for epoxy shrinkage in the packaging process is that epoxy is underflowed until there is a slightly larger fillet than the desired final size.

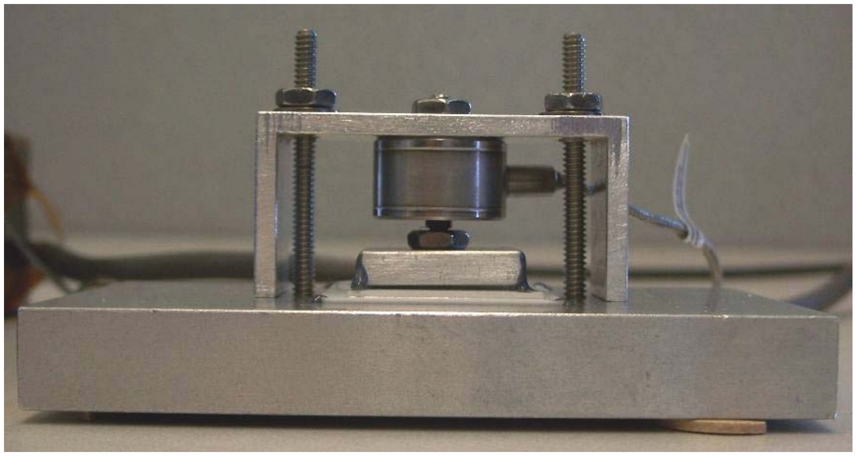

Figure 10: Epoxy load measurement apparatus with load cell supporting upper chuck.

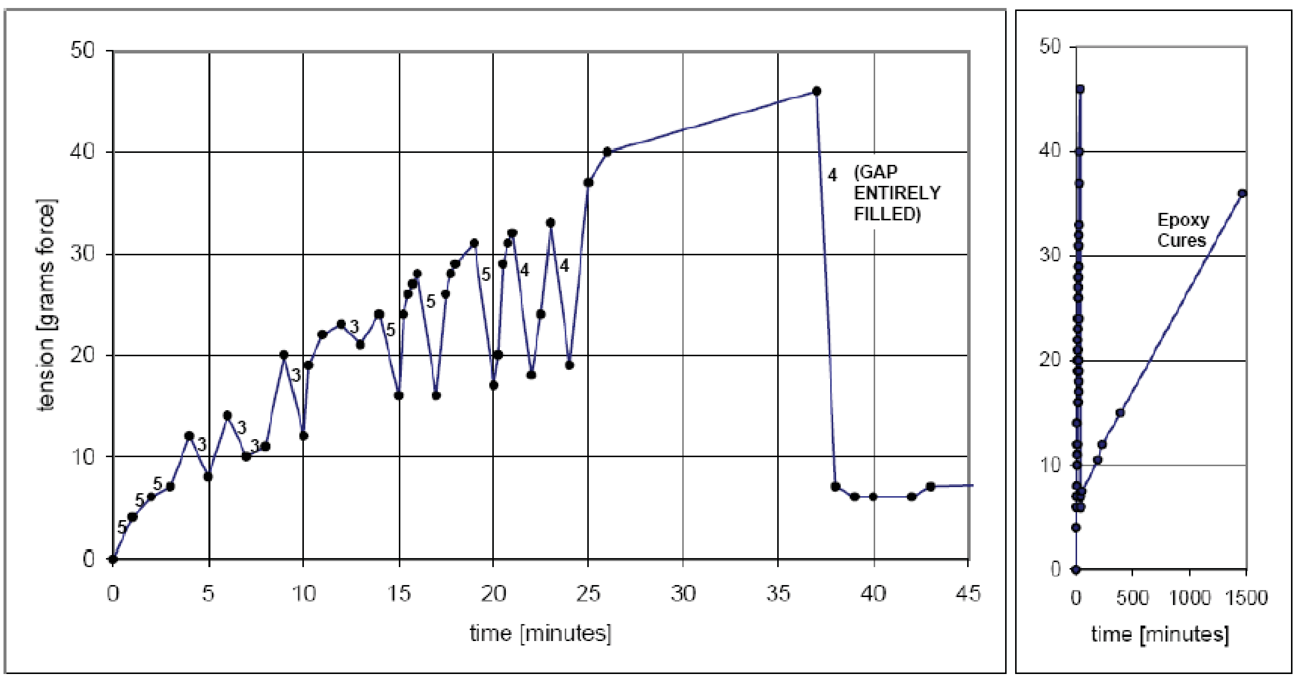

Figure 11: Tension between substrates during Epo-Tek® 301-2 epoxy underflow and cure. Both charts are same data with different time scales. Numbers above trend line indicate number of drops of epoxy administered during that time interval.

4.3 Wirebonding

After the Epo-Tek® epoxy cures, the substrate chuck vacuum is vented, and the substrate chuck is removed, leaving the CCD/substrate/connector assembly on the CCD chuck. The vacuum to this chuck is maintained using flexible tubing between the vacuum source and the chuck, and the assembly is moved to a nearby wirebonder. Wirebonds electrically connect the CCD to the flex circuit, and thereby to the detector connector.

4.4 Bonding pedestal to CCD/substrate/flex assembly

The SiC pedestal is bonded to the CCD/substrate/flex assembly using Hysol® EA 9361 epoxy. In contrast with the low-viscosity Epo-Tek® 301-2 epoxy used to bond the CCD to the substrate, Hysol® EA 9361 has high mixed viscosity and tends not to flow unless forced to. It is well-suited to this bonding step because the size of the nominal gap varies from 0.250mm between the substrate and the pedestal to 0.100mm where the flex circuit is present on the substrate. The Hysol® EA 9361 is applied to the substrate using a photo-etched, 0.38mm thick, stainless steel epoxy mask, in the pattern shown in the left side of Figure 12. Precision fixturing locates the pedestal over the CCD/substrate/flex assembly so that the overall height of the package is well-controlled at 13.000mm. The epoxy pattern just fills the resulting gaps between the pedestal and substrate and between the pedestal and flex circuit, without creating voids.

The right side of Figure 12 shows the fixturing set-up while the pedestal epoxy cures. The assembly toward the top of the photo restrains the detector connector within the hole in pedestal.

A complete, packaged CCD is shown in Figure 13 and Figure 14.

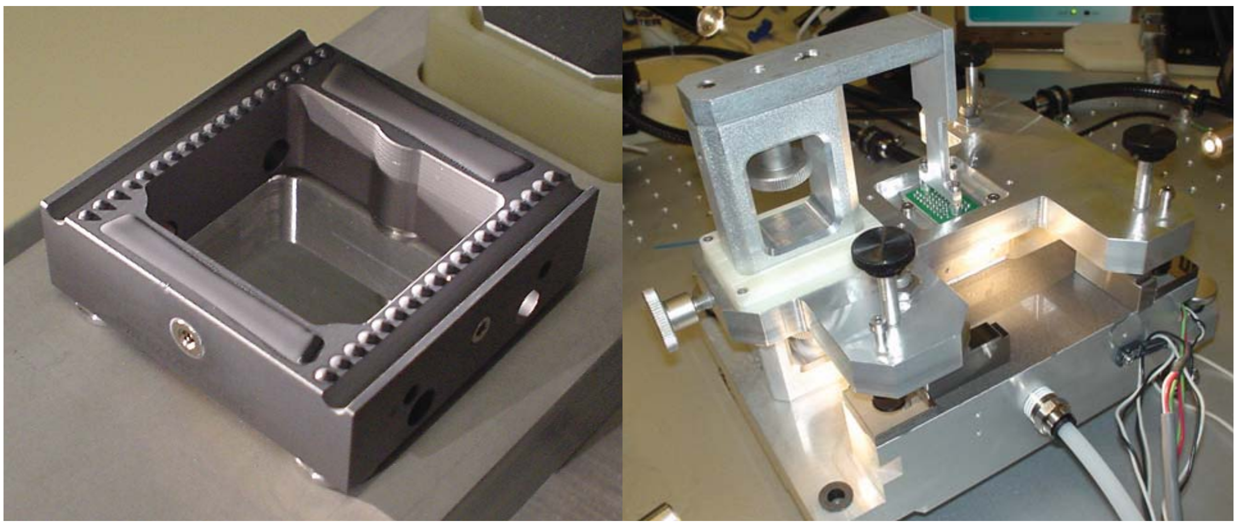

Figure 12: Left: SiC pedestal with Hysol® EA 9361 epoxy applied (38 circular bumps and two 'bowtie' regions), ready to be turned over and bonded to the substrate. Note two 'troughs' outside glued area that provide clearance for wirebonds. Right: Fixturing for bonding of pedestal to substrate.

Figure 13: Complete packaged CCD on precision spacers. Threaded insert on the left is one of three available for mounting a detector guard or filter frame. The insert to the right is for handling.

Figure 14: End view of complete packaged CCD. Two threaded inserts seen here are two of the three available for a detector guard or filter frame. Precision spacer visible at bottom in middle. The wirebonds can be seen in the two troughs.

5. TESTING/PERFORMANCE

After each detector is packaged, it is functionally tested under vacuum at 140K and the flatness of its front surface is measured using a vision metrology machine. Of the ten most recently packaged CCDs, seven have been functionally tested. Six of those seven were found to be functional after packaging, and six of the seven were submitted for surface metrology. The flatness values of the detectors that have been measured range from 4.6um P-V to 8.0um P-V, with a mean value of 5.5um P-V, readily meeting the flatness requirement. An example of the surface metrology results is shown in Figure 15, for the detector pictured in Figure 13 and Figure 14. Figure 15 shows results corrected for a few microns of tilt and piston, which are corrected relative to the focal plane using custom-ground shims.

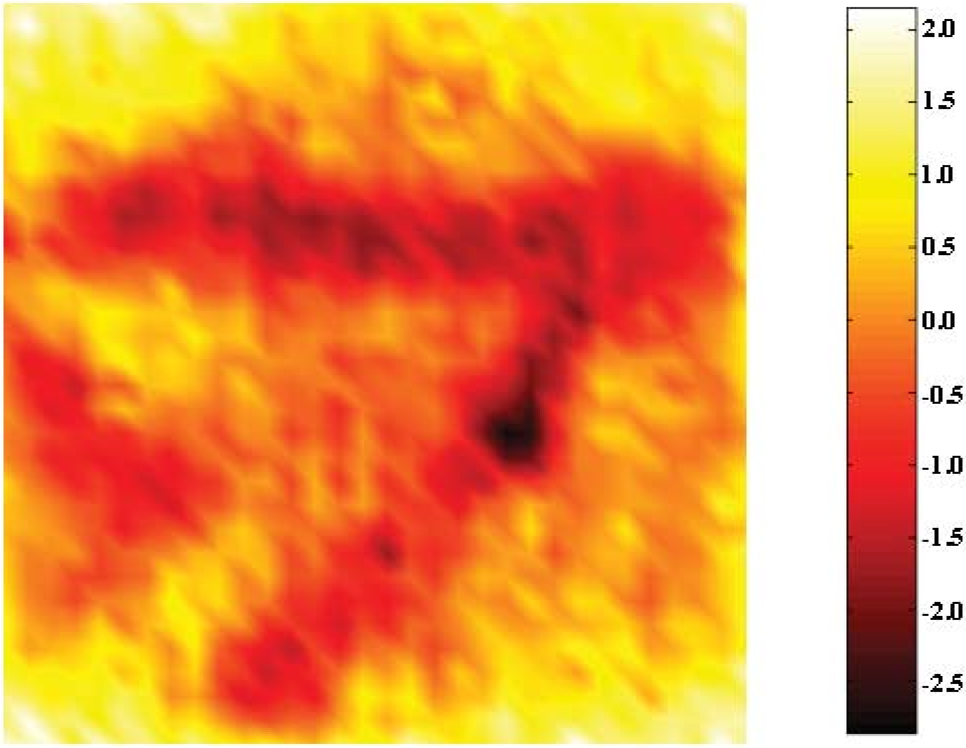

Figure 15: Best-fit surface flatness of CCD#13. The 2-3 µm deep, chevron shaped feature also appears on other packaged devices, therefore is assumed to be caused by a feature on the vacuum chuck. Units are µm. Flatness is 4.9µm P-V.

Vibration testing to NASA qualification levels (14.1Grms, 20-2000Hz, three axes[14]) was done on a packaged detector mounted to a 3 x 3 demonstration focal plane section, which is shown in Figure 16. The detector was functionally tested before and after the vibration testing, and no change in function was found. A coordinate measuring machine was used to measure the position of the detector before and after vibration and no motion was detected within the accuracy of the measuring equipment (approximately 2µm).

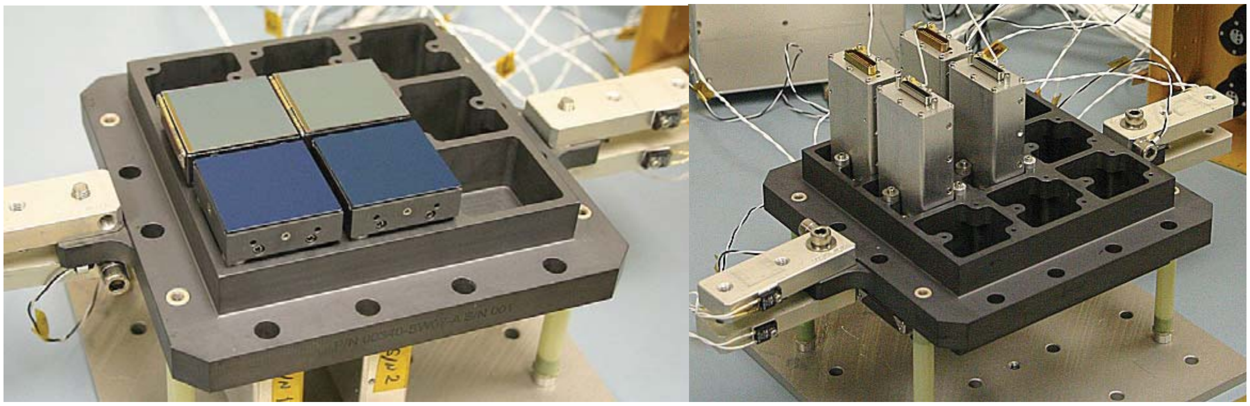

Figure 16: Left: Two CCDs (near) and two NIR detectors (behind CCDs), mounted to 3x3 demonstration focal plane. Configuration shown is for functional and cross-talk testing in thermal vacuum. The same demonstration focal plane serves as a vibration fixture. Right: Other side of demonstration focal plane showing front end electronics modules behind each detector.

The 3 x 3 demonstration focal plane section was also used to perform thermal cycling and cold functional testing. The two detectors shown in Figure 16 were cycled to qualification temperatures between 110K and 323K for eight cycles, and there was no measurable change in function before and after cycling. Electronic performance verification and cross-talk testing, with NIR detectors present is currently on-going.

6. CONCLUSION

We have developed a detector package and a packaging process for the LBNL 3.5k x 3.5k, 10.5µm CCD that reliably meets our mechanical and electrical requirements. These packaged CCDs have flatness better than 10µm P-V, are 4-side abuttable on a 44mm detector pitch, have high radiation tolerance, high NIR QE, low diffusion, and are space-qualified. We are currently packaging additional devices, with the goal of producing science grade devices for astronomical applications. Future efforts will include measuring flatness at the operating temperature of 140K, and system testing on a 4 x 8 mixed mosaic with CCDs and NIR detectors. In addition, the packaging technology can be used to package other formats of LBNL CCDs, including 4k x 2k x 15µm and 4k x 4k x 15µm CCDs.

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