Advancement, Testing and Validation of an Innovative SmallSat Solar Panel Fabrication Process

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ABSTRACT

For universities, solar panels can be some of the highest expenditures of CubeSat development. In response, groups often opt to purchase solar panels from commercial providers to avoid in-house production complications; unfortunately, this option greatly restricts subsystem customizability and design flexibility. For those groups that choose to build, test and integrate solar panels internally, the process can turn into a monumental effort due to the lack of readily-available validated procedures outside of industry. In addition to being labor and cost intensive, traditional methods of solar panel fabrication contain intrinsic inefficiencies that compromise the subsystem's overall reliability and reproducibility. Using techniques developed by University of Colorado Boulder and previously validated by University of Michigan, that paradigm is being shifted. The procedure uses a double-sided adhesive tape along with surface mounted tabs as a simplified method for mounting; it can be adapted to purely use silver epoxy if additional tabs cannot be procured. The solar panel fabrication techniques and testing results from the MinXSS and QB50-Challenger satellite will be presented, demonstrating substantial improvements to subsystem reliability, performance, and manufacturability. These results will be affirmed by the highly promising on-orbit results from MinXSS. Two procedures will be outlined, both of which can be readily adapted for a variety of solar cells and panel configurations. Overall, these procedures empower cost and time-constrained groups to fabricate solar panels to their unique system specifications, providing the option of high-performance panel production in a single day.

INTRODUCTION

Solar panels are pivotal to operating CubeSats in space as they are the only source of power for long duration missions. In the university setting, solar panels can be costly compared to the overall budget and thusly have often been out of reach for manufacturing in-house. The University of Colorado Boulder now has flown three CubeSats, CSSWE, MinXSS-1 and QB50-Challenger, that have worked on orbit with in-house built solar panels. Methods that will be described in detail are those for the MinXSS and QB50-Challenger CubeSats.

MinXSS and QB50-Challenger each implemented unique methods of solar panel fabrication. For MinXSS, it was decided to purchase AzurSpace TJ 3G30C solar cells with tabs and coverglass already integrated on the cells, whereas QB50-Challenger used donated Emcore BTJM cells with no coverglass or tabs on the cells. The three traditionally most labor intensive and costly steps in the solar panel fabrication process have been as follows: attaching tabs/coverglass to the cells, handling long strings of cells, and adhering the cells to the solar substrate. The methods described below address these steps, while also maximizing the amount of decoupled cell.

MINXSS CUBESAT

Fabrication Process

The MinXSS team's selection of AzurSpace TJ 3G30C Coverglass Interconnect Cells (CIC) solar cells was motivated by their high power needs to support the utilization of the Blue Canyon XACT attitude control unit on-board. Because these cells come with coverglass and interconnects pre-integrated, a mounting solution was determined that allowed for the cells to be decoupled and electrically connected via both their interconnects (negative terminals) and their rear faces (positive terminals). A method [Mason] was devised that would allow adhesion of the cells to the Printed Circuit Board (PCB) with double-sided Kapton tape, a previously verified method [Sandberg], with rear-facing holes for silver epoxy that could connect the cells back faces. Figure 1 shows the Kapton tape, which was 1-inch-wide and cut to fit the PCB pad form.

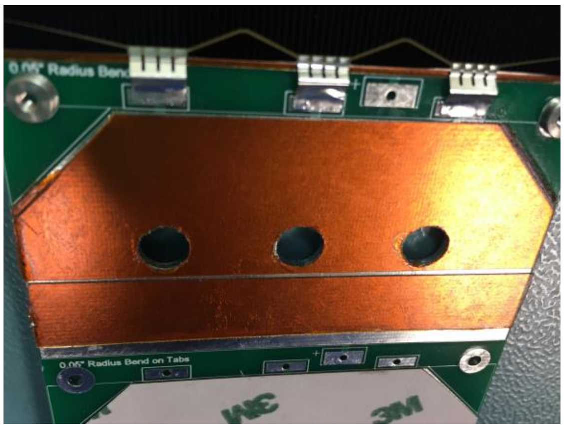

Figure 1: MinXSS Kapton tape adhesion Method

After the cells were mounted to the PCB, they were placed in a vacuum bag to ensure proper uniform adhesion of the Kapton (which is coated with a Pressure Sensitive Adhesive). Figure 2 shows the silver epoxy after being applied to the back of the PCB, which took 3 hours to cure.

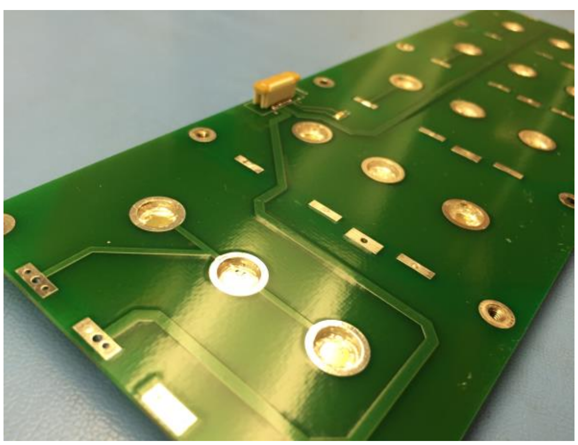

Figure 2: MinXSS PCBs with silver epoxy added

Once the cells were attached, the electrical connections on the top side of the cells could be made by soldering the tabs to pads on the PCBs. Figure 3 shows the completed panels.

Figure 3: MinXSS Final Solar Panels

Testing Results

The MinXSS solar cells were each individually classified by AzurSpace using a reversed bias I-V curve method to verify that each produced the correct voltage and current under a load before shipment.

Once the solar panels were assembled, each panel was tested outside under a representative load on a cloudless day to confirm that the panels were producing the expected amount of power. Open circuit voltage and short circuit current are shown in Table 1, These values were as expected based on the solar cell datasheets.

Table 1: MinXSS Sunlight Solar Panel Testing

Test	Voltage (V)	Current (A)
String 1 Full Sun, Full Batteries	18.7	.345
String 2 Full Sun, Full Batteries	12.94	.262
String 3 Full Sun	18.91	.345

Figure 4: MinXSS solar panel testing

TVAC and Vibration Testing Results

Thermal vacuum (TVAC) testing was performed to determine panel performance in a space-representative thermal and vacuum environment. Seven cold and hot cycles were run from -20 to +30° C to fulfill NASA and Nanoracks requirements, with initial Hot and Cold Survival Cycles implemented from +60 to -30C. The panels were fully tested after the TVAC test and showed no sign of degradation. Power generation closely matched that of pre-TVAC testing.

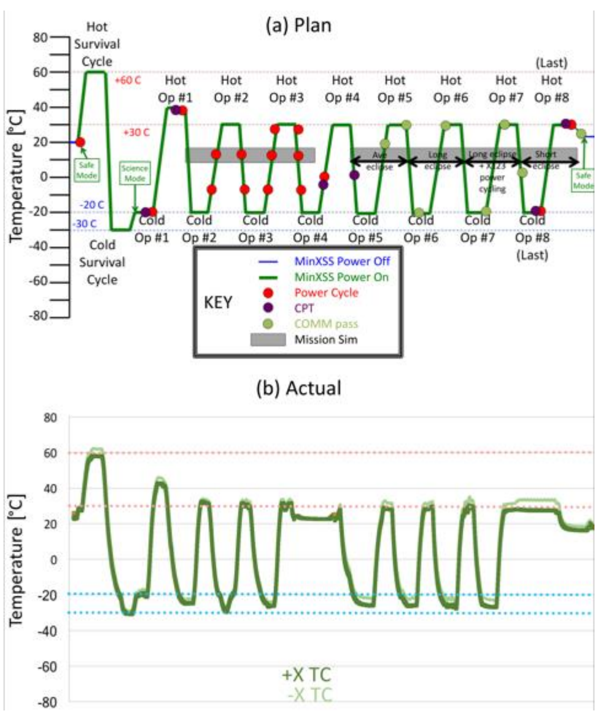

Figure 5: MinXSS TVAC Cycles

Vibration testing of MinXSS was done at Ball Aerospace in Boulder, CO to the requirements which are noted in Table 2.

Table 2: MinXSS Vibration Testing Loads

		Slope	Accel
Freq(Hz)	**ASD(G^2/Hz)**	**dB/OCT**	**Grms**
20	0.0288	*	*
40	0.0288	0.00	0.76
70	0.072	4.93	1.43
700	0.072	0.00	6.89
2000	0.0187	-3.86	9.65

On-Orbit Results

All three panels for the MinXSS CubeSat performed as expected throughout the whole mission providing ample power to the satellite and producing expected results.

Table 3: MinXSS Solar Panel On-Orbit Results

Test	Voltage (V)	Current (A)
String 1 Full Sun, Full Batteries	19.8	.257
String 2 Full Sun, Full Batteries	9.70	.52
String 3 Full Sun	19.85	.223

QB50-CHALLENGER CUBESAT

Fabrication Process

For QB50-Challenger, because the cells did not come with tabs/coverglass pre-integrated, there was flexibility with regards to how the cells could be integrated on to the panel. The QB50 team focused on developing a method that required no long strings of cells or complex epoxy processes.

The interconnect tabs on each cell were attached using a reflow solder gun with a 2% silver solder paste. Figure 6 and Figure 7 show the implemented tabbing method. Tabs were placed on the top and bottom of each cell to allow them to be individually attached to the PCB rather than strung directly together.

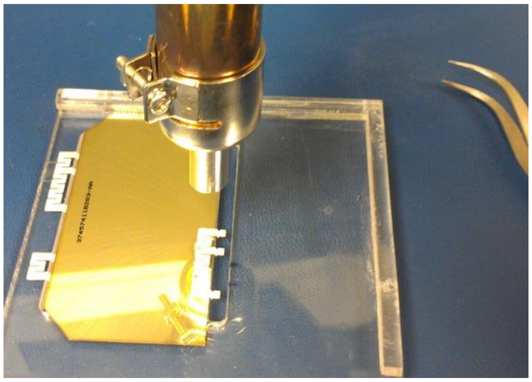

Figure 6: Challenger Back Tab Solder Method

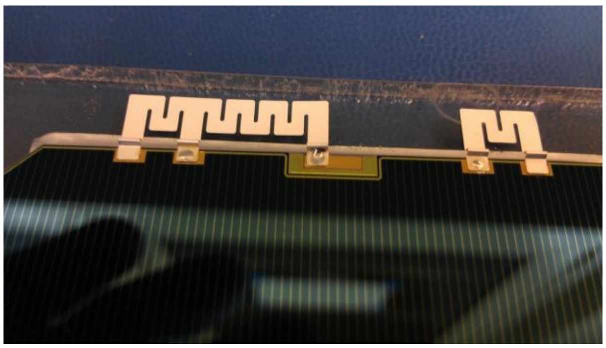

Figure 7: Challenger Front Tabs Soldered

The donated solar cells then needed coverglass integration to minimize cell degradation due to solar radiation on-orbit. Using Dow-Corning 93-500 encapsulate, which is the industry standard used by companies such as AzurSpace, the coverglass was adhered to the cells by placing a drop of the mixed encapsulate on the cell face and then placing the coverglass on top, gently pushing the encapsulate to the edges. Once the encapsulate cured, the edges were trimmed with an exact-o knife.

Now that the cells were fabricated, they could be attached to the PCBs. Double-sided Kapton tape was selected, specifically, High-Temperature Kapton® Electrical Tape with adhesive on both sides, 2 inches wide and 0.005 inches thick. This tape was selected because it had a temperature range of -40° to 149° C and used an acrylic based adhesive, thus demonstrating lower off-gassing. The Kapton tape was placed on the PCB and then cut to fit, making sure to leave cutouts for the tabs located on the bottom. There were some bubbles and voids in the tape from the factory process, but after extensive vacuum chamber testing, these did not show to be an issue.

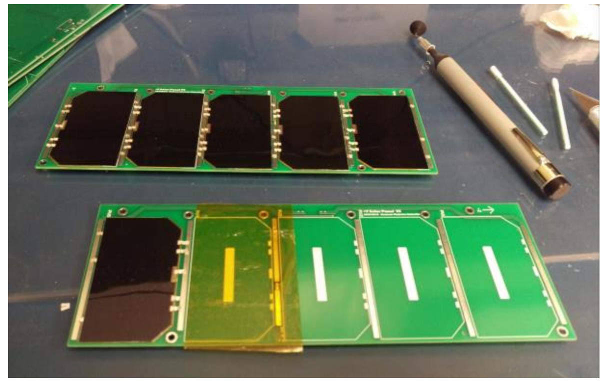

Figure 8: Challenger Kapton tape adhesion method

The final step once all the cells were attached was to solder the tabs to the PCB to make an electrical connection to each cell. This method allowed each cell to be soldered and attached individually instead of requiring alignment and handling of an entire string at once. The total manufacturing time for three 2U solar panels was a week, including the time for curing the Dow Corning 93-500. Figure 9 shows the completed panels.

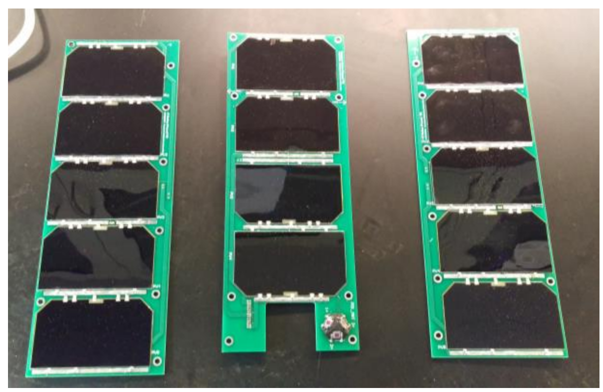

Figure 9: Challenger completed solar panels

Testing Results

QB50-Challenger solar cells were each individually classified using a reversed bias I-V curve method and tested to make sure each one produced the correct voltage and current under a load before being selected for final assembly.

Once the solar panels were assembled, each panel was tested outside under a representative load on a cloudless day to check that the panels were producing the correct amount of power. Closed circuit and open circuit voltage data from these tests are shown in Table 4. These values were as expected based on the solar cell datasheets. This method was then further tested in [Sandberg] to characterize the procedures.

Table 4: QB50-Challenger Sunlight Solar Panel Testing

Test	Voltage (V)	Current (A)
String 1 Full Sun, Full Batteries	16.77	.19
String 2 Full Sun, Full Batteries	16.83	.19
String 1 Full Sun, Low Batteries	9.66	.44
String 2 Full Sun, Low Batteries	9.60	.44

Figure 10: Challenger solar panel testing

TVAC and Vibration Testing Results

TVAC testing was performed to the QB50 requirements of four cold and hot cycles from -20 to 40° C. The panels were fully tested after the TVAC test and showed no sign of degradation.

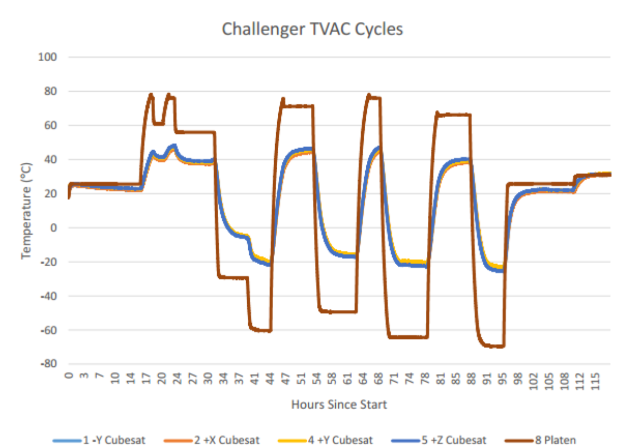

Figure 11: Challenger TVAC Cycles

Vibration testing of QB50-Challenger was done at Lockheed Martin in Littleton, CO to the QB50 requirements, which are noted in Figure 12.

	Qualification	
Random vibration test	Required	
Reference Frame	{BRF}	
Direction	X, Y, Z	
RMS acceleration	8.03 g	
Duration	120 s	
Profile	**Frequency,** *[Hz]*	**Amplitude,** *[g^2/Hz]*
	20	0.009
	130	0.046
	800	0.046
	2000	0.015

Figure 12: QB50 Vibration loads

On-Orbit Results

Results for QB50-Challenger on-orbit show no degradation of the cells and both strings are performing nominally.

Table 5: QB50-Challenger Sunlight Solar Panel On-Orbit Results

Test	Voltage (V)	Current (A)
String 1 Full Sun, Full Batteries	17.92	.18
String 2 Full Sun, Full Batteries	17.92	.18
String 1 Full Sun, Low Batteries	8.43	.43
String 2 Full Sun, Low Batteries	8.43	.43

FUTURE CUBESATS

Fabrication Plan for MAXWELL and CU-E3

MAXWELL and CU-E3 are both 6U CubeSats that will carry high data rate communication payloads and are currently being designed and built at the University of Colorado Boulder. These panels will take the lessons learned from MinXSS and QB50-Challenger and apply them to better fabricate solar panels in house.

MAXWELL will utilize the QB50-Challenger and MinXSS fabrication process almost exactly. Each cell will be mounted individually with Kapton tape and silver epoxy will be applied to the back of the cell to provide electrical conductivity. Figure 13 shows an electrical diagram of the planned mounting for the cells. MAXWELL will use Spectrolab ITJ cells with tabs and coverglass to comprise two 6U panels.

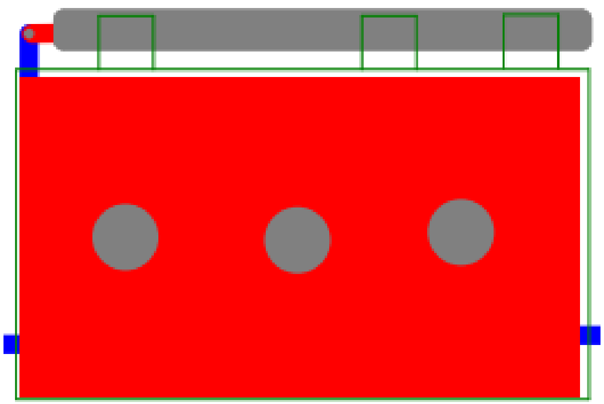

Figure 13: MAXWELL Solar Cell Layout

CU-E3 will use a slight modification to the QB50-Challenger and MinXSS fabrication processes to accommodate deep spaceflight and the need for more power. They will use AzurSpace TJ 3G30C solar cells with tabs and coverglass which will be coupled together in pairs to allow for maximum cells to be placed on each panel. Kapton tape will then be used to adhere the cells to the PCB. Silver epoxy will be applied to the back of one of the cells to provide electrical conductivity for the pair of cells. Figure 14 shows an electrical diagram of the planned mounting for the cells.

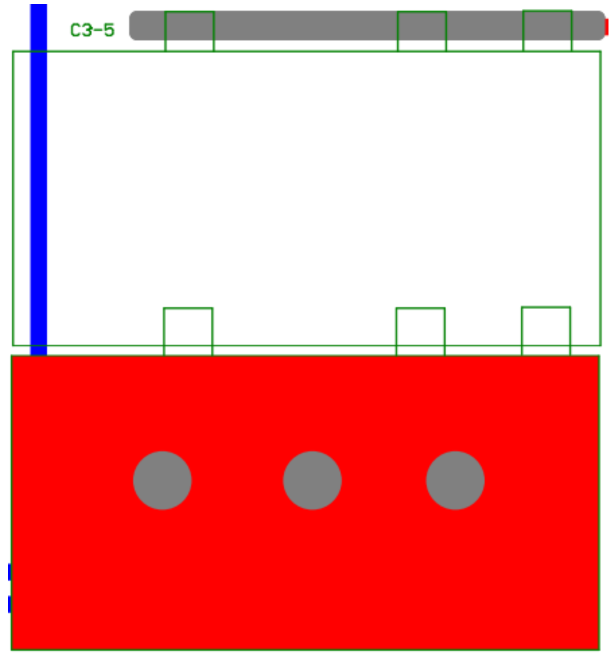

Figure 14: CU-E3 Solar Cell Layout

CONCLUSIONS

The methods presented in this paper will allow other universities to produce panels of their own without the added cost of purchasing off the shelf. Because of the versatility of this method developed at the University of Colorado Boulder, both of these methods can be easily adapted for a wide variety of missions such as MAXWELL and CU-E3. Should universities want a more detailed method with step-by-step instructions, they should contact the author.

Acknowledgments

The author would like to acknowledge Ariel Sandburg for her contributions to fully testing out this method in which results are presented in her paper in the references. The author would also like to acknowledge James Paul Mason for his work to develop and test the MinXSS solar panel procedures.

References

1. Mason, James Paul, and Bena Mero. "MinXSS Solar Cell Mounting FAI." Laboratory for Atmospheric and Space Physics, 2015. Web. 20 May. 2017.
2. Sandberg, Ariel. "Streamlining CubeSat Solar Panel Fabrication Processes", 2016. Web. 10 Jun. 2017.