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Assembly and Integration Process of the First High Density Detector Array for the Atacama Cosmology Telescope

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ABSTRACT

The Advanced ACTPol (AdvACT) upgrade on the Atacama Cosmology Telescope (ACT) consists of multichroic Transition Edge Sensor (TES) detector arrays to measure the Cosmic Microwave Background (CMB) polarization anisotropies in multiple frequency bands. The first AdvACT detector array, sensitive to both 150 and 230 GHz, is fabricated on a 150 mm diameter wafer and read out with a completely different scheme compared to ACTPol. Approximately 2000 TES bolometers are packed into the wafer leading to both a much denser detector density and readout circuitry. The demonstration of the assembly and integration of the AdvACT arrays is important for the next generation CMB experiments, which will continue to increase the pixel number and density. We present the detailed assembly process of the first AdvACT detector array.

Keywords: Cosmic Microwave Background, Array packaging, Advanced ACTPol

1. INTRODUCTION

Advances in modern Cosmic Microwave Background (CMB) experiments typically demand an increase in the number of detectors to integrate down the noise faster. Recent findings in the field also highlight the importance of observation at multiple frequencies to better disambiguate the galactic foreground emission from the CMB. Multichroic Transition Edge Sensor (TES) polarimeter arrays with high density pixels are the core of the Advanced ACTPol (AdvACT) upgrade on the Atacama Cosmology Telescope (ACT), increasing the number of detectors for sensitive measurements of the CMB polarization anisotropies at multiple frequencies. AdvACT will deploy a total of four multichroic arrays for observation at five different frequency bands between 28 and 230 GHz.

We present the assembly process of the AdvACT high frequency (HF) array, sensitive to both 150 and 230 GHz. This AlMn-based TES multichroic array is fabricated on a 150 mm diameter wafer at NIST. It contains approximately 2000 TES bolometers with twice the detector density compared to the ACTPol arrays, which are individually composed of multiple 75 mm wafers (full and half), adding up to a comparable total size of the focal plane. Using a single 150 mm wafer allows for a higher pixel density for the HF array, which is read out with a scheme also more compact than before. The full readout circuitry (Figure 1) consists of the flexible superconducting wiring (flex) [1], superconducting quantum interface device (SQUID) multiplexing (mux) chips, bias interface chips, wiring chips, series array SQUID modules, wire bonds, and printed circuit boards (PCBs). Demonstrating the assembly of this high pixel density array with the compact readout design is an important step towards stringent requirements of the next generation CMB experiments, which are aimed at 10^5-10^6 detector arrays[2].

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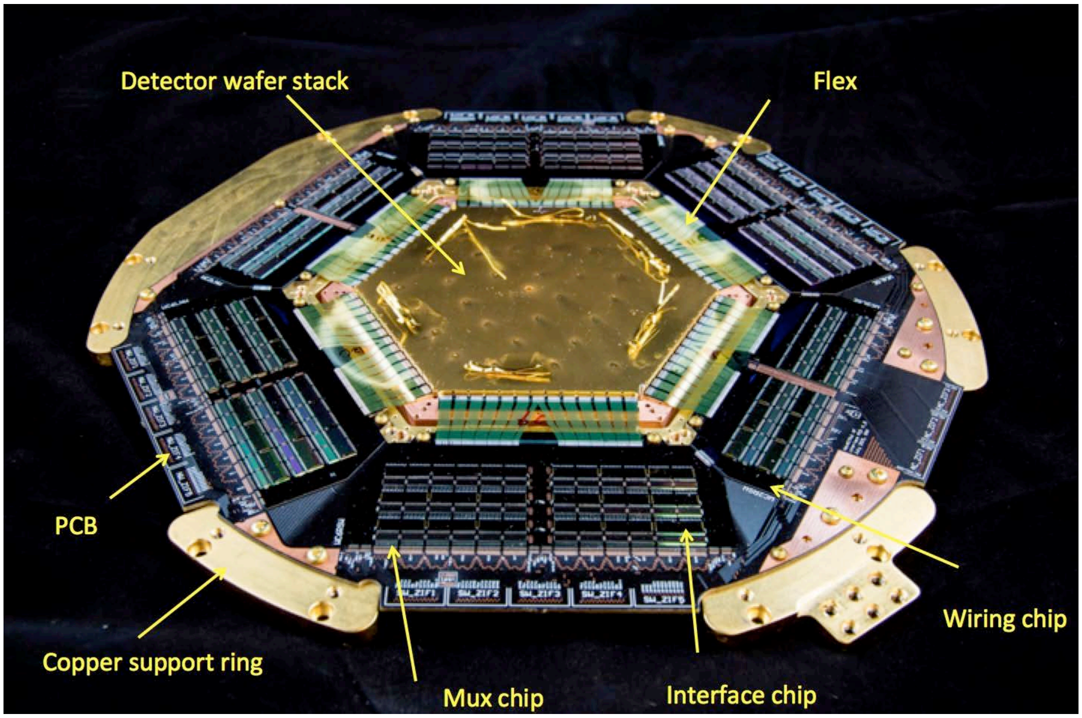

Figure 1. Components of the HF detector array.

The HF array implements a new type of mux chip, mux-15b [3], as part of the time-division multiplexed readout. The Multi-Channel Electronics (MCE) is utilized at a higher efficiency to read out approximately twice the number of detectors compared to ACTPol, by doubling the number of row to 64 on 32 columns with 24 detector bias lines [4]. These mux chips are three times smaller than those used in ACTPol (mux-11c). Bias interface chips include shunt resistors to allow voltage biasing of the TESes and several options for additional series inductance. Both mux and interface chips, fabricated on silicon substrates, are glued to the silicon wiring chips. The wiring chips, glued to the PCB, compactly guide the wirings from the PCB through the shunt and interface chips to the flex, which connects to the detectors on the wafer stack. The hexagonal detector wafer stack consists of four layers of silicon wafers including the detector wafer, mechanical back short cap wafer, back short cavity wafer, and the waveguide interface plate (WIP) wafer [5]. Each of the six flexes has two silicon stiffeners on either side, one of which glues to the PCB and the other to the WIP. Reliable gluing of various parts is crucial as it not only provides the cryo-mechanical stability as an interface between parts with different coefficients of thermal expansion (CTEs), but also the rigid platform for robust wire bonding. Given the increased density of the detectors and hence various readout circuitry, many bond pads are only 120 μm wide with 140 μm pitch, 50-60 μm smaller than in ACTPol. This may present a great challenge as poor bonds can open up possibly leading to a loss of 2% to 4% of the TESes with just a single open bond, or short with neighboring bonds possibly leading to shorting of detector bias lines. All chips and the flexes are glued to high accuracy in position to maintain the misalignment between groups of bond pads as small as possible, making wire bonding manageable. During all wire bonding, the wafer stack sits on a temporary copper base, which at the end gets replaced with a spline-profiled feedhorn stack [6].

In Section 2, we describe various methods and jigs developed to achieve the demanded accuracy for gluing of all parts. We also present the details of the wire bonding and the mounting of the feedhorn stack. We conclude in Section 3 with future plans.

2. ASSEMBLY PROCESS

The assembly process proceeds in six stages, which are described in more detail below. The first (Section 2.1) is the gluing of the mux and interface chips to the wiring chips. All mux and shunt chips are screened cryogenically prior to any assembly [3]. In the second stage (Section 2.2), the assembled wiring chips are glued to the PCB, which is mounted to the copper support ring. The third stage is the wire bonding of the mux, interface and wiring chips. We describe all the wire bonding in Section 2.4. The 150 mm detector wafer stack is mounted to a temporary base plate and aligned to the PCB in the fourth stage, which also includes gluing the flex to the PCB and to the detector wafer (see Section 2.3). The fifth stage is the wire bonding of the flex, and the final stage (Section 2.5) is the mounting of the feedhorn array to the detector wafer and copper support ring.

2.1 MUX and interface chips gluing

The AdvACT assembly process begins with gluing the mux and the interface chips to wiring chips using the Stycast 1266, instead of the rubber cement as in ACTPol. In ACTPol, the mux chips (mux-11c) are directly glued to the PCB with rubber cement. However, since the size of mux-15b (3 mm by 6 mm) is only one third of the size of mux-11c, the rubber cement is not strong enough to hold the new type of mux chips during bonding, and the bonding test turns out to have poor wire bond strength. The adhesive hence is changed to Stycast.

To ensure that the mux and interface chips are placed in the correct position with the right amount of glue, a tape mask is used, as follows. Silicon templates with the same physical dimensions as the wiring chips and with patterns outlining the positions of the mux and interface chips are aligned and secured on a metal base with a low-tack transparent tape on top of it (Figure 2). After cutting out rectangular holes from the low-tack tape according to the outline on the silicon template, the tape is partially lifted so that the wiring chip can be inserted instead of the silicon template, retaining the same alignment to the metal base. The Stycast is then deposited evenly through the rectangular holes in the tape onto the wiring chip. After the removal of the low-tack tape mask, the Stycast is pre-cured for 5min so that it becomes semiliquid and the chips are able to stay without moving. The mux and interface chips are placed on the wiring chip using a die bonder and aligned with the corresponding wiring chip bond pads under a microscope. The whole piece is left overnight for Stycast curing.

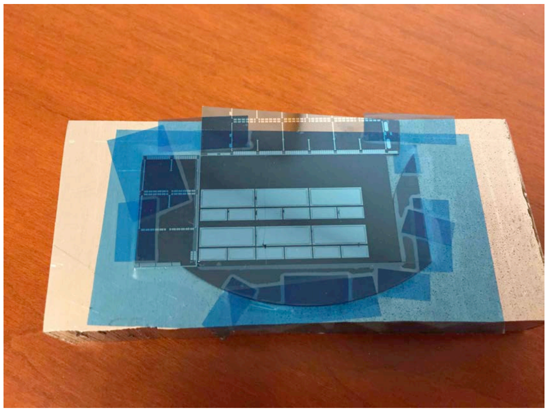

Figure 2. A silicon rectangular template that has outlines for mux and interface chips is taped down to a metal base with blue low-tack tape. The surrounding four silicon pieces are also taped down, so that later when replacing the template with a real wiring chip, the wiring chip will sit on the metal base in exactly the same position as the template.

2.2 Wiring chips gluing

The wiring chips for AdvACT are also substantially bigger than those from the ACTPol. Four large and four small (30 mm by 49 mm) wiring chips (40 mm by 105 mm) are glued with rubber cement onto the PCB. Cryo-mechanical stability was tested with parts of similar shape and size, given the CTE differences between Si and the PCB over a large physical length. The wiring chips were positioned to accuracy of 50 μm using alignment jigs. Such position accuracy was required for preventing misalignment of the bond pads between wiring chips and flex. L-shaped 500 μm thick Silicon pieces are first positioned to on the PCB with dowel pins. Then 200 μm thick low-tack tape is cut into 1mm width, and placed on the PCB, near where the edges of the wiring chips would eventually sit. The position and the thickness of the rubber cement are controlled with these tapes. Rubber cement is filled entirely within the boundary formed by the tapes, then the excess rubber cement is scraped off with a flat plastic board while pressing its edge against the tapes, leaving rubber cement of 200 μm thickness on the PCB. After the tapes are removed, the wiring chips are placed down immediately. Then precise alignment is achieved by pushing the wiring chips laterally into the corner of the L-brackets. Lastly, the wiring chips are pressed down with rectangular Teflon blocks precisely machined and positioned on a copper block, which is again aligned to the dowel pins aligning the L-brackets. The Teflon blocks are positioned to avoid mux and interface chips, and at least 50 μm away from any bond pads on the wiring chips.

2.3 Flex gluing

The wafer base (Figure 3) provides physical support for the detector wafer stack during wire bonding before the feedhorn array is mounted. It is a hexagonal disk that has screw holes and alignment pin holes to allow precision alignment of the detector wafer to the wiring chips on the PCB. Slots are cut on the top surface along six edges which can be connected to vacuum, preventing the wafer from moving vertically during wire bonding. The wafer base also has functions in flex gluing and bonding process, described below.

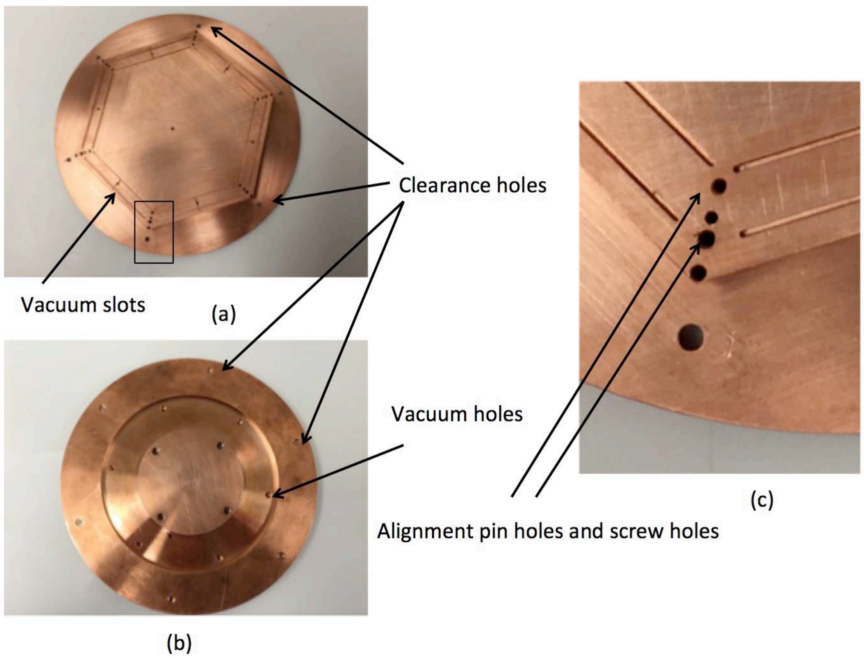

Figure 3. (a) and (b) show the top and the bottom surface of the wafer base. (c) shows the portion around the corner the hexagonal disk. Six clearance holes on the circular disk part are used for attach the wafer base to the copper support ring. Six vacuum slots are cut on the top surface and six vacuum screw holes connect the vacuum slots and vacuum tubes. In (c), around each corner of hexagonal disk, there are two alignment pin holes, one for fixing the detector wafer, the other for aligning the Delrin flex gluing jig. There’s also a 4-40 screw hole that is used for attaching the copper clamps after the flex is glued (this part will be described with more details in section 2.4).

Flex gluing. In AdvACT, six flex act as bridges connecting the detector wafer and the circuits on the PCB through wire bonding. Each flex is a stack of layers of 20.6 mm by 2 mm polyamide containing etched superconducting aluminum traces with a 5 mm wide Si stiffener on both sides [1]. One stiffener is mounted on the WIP. The WIP is the bottom and largest wafer in the detector stack[4]. Mounting the flex to the WIP brings the flex traces into the plane of the detector wafer's bond pads. The second flex stiffener is mounted on the PCB in front of a wiring chip (see Figure 1). The flex gluing process is challenging because the distance between the edge of the detector wafer and the edge of the wiring chips is about 0.23 mm shorter than the flex to allow for differential movement between the PCB and the detector wafer during assembly with the feedhorn array. This length mismatch means that the polyamide part of the flex is curved, causing tension that makes it challenging to keep the stiffener in position while the adhesive is curing. The bond pads on the flex and detector wafer are 100 to 120 μm wide and separated by 20 to 40 μm, so a misalignment of such densely packed bond pads might cause shorts during wire bonding. Therefore the targeted maximum misalignment is half the width of a bond pad: 50 μm.

To meet the aforementioned requirements, a set of two jigs was designed (Figure 4). One is made of Delrin, and includes a pair of 1.5mm-diameter alignment pin holes and a vacuum feature to hold the flex's stiffener securely. The other jig is made of aluminum with a pair of alignment pin holes and vacuum features. The aluminum jig also has a scale indicator for alignment, made from a silicon bar with a 50 µm dicing marker. The vacuum tube connected to the aluminum jig has two valves to control how tightly the flex is held to allow small positional corrections. The wafer base, the Delrin jig, and the aluminum jig all share the same alignment pin hole features.

After mounting the wafer base to the copper support ring and fixing its position with alignment pins on the corner, the gluing process begins with putting the flex on the aluminum jig next to the silicon indicator. The the Delrin jig then transfers the flex to the wafer base by turning on the Delrin jig's vacuum and turning off aluminum jig's vacuum. Through a microscope the misalignment between bond pads on detector wafer and flex can be estimated by the width of bond pads. The flex is then transferred back to the Delrin jig and moved along the longer edge of the silicon indicator according to its grids for the estimated distance. This step can be repeated until the alignment between flex and detector wafer is less than half a bond pad. Rubber cement is then deposited on the wafer by a syringe connected to an electronic dispenser. After putting the stiffener on the glue, a copper clamp is then mounted on the glued stiffener and fixed down to the wafer base by two screws. Two cylindrical spacers are then put on the gap between the wafer base and the copper support ring underneath the flex polyimide to help the flex form a curved shape so that its other edge sits right next to the edge of the wiring chip. Similarly to the wafer side, rubber cement is deposited on the PCB with a syringe and a dispenser, and another clamp that mounts to the copper support ring holds the stiffener down until the rubber cement is cured.

After mounting the wafer base with the detector wafer stack to the copper support ring and fixing its position with alignment pins on the corners, the gluing process begins with putting the flex on the aluminum jig next to the silicon indicator. The Delrin jig is then used to lift the flex off the aluminum jig to transfer the flex to the wafer base. The flex's position relative to the alignment pins is maintained during the transfer by first turning on the Delrin jig's vacuum and then turning off the aluminum jig's vacuum. The first placement is a trial run. A microscope is used for estimating the first-try misalignment between bond pads on the detector wafer and on the flex (using the width of the bondpads as a scale). The flex is then transferred back to the Delrin jig and moved along the longer edge of the silicon indicator according to its grid markings for the estimated distance. This step can be repeated until the alignment between flex and detector wafer is less than half a bond pad. Rubber cement is then deposited on the wafer by a syringe connected to an electronic dispenser. After putting the stiffener on top of the glue, a copper clamp is mounted on the top of the stiffener and fixed down to the wafer base by two screws. Two cylindrical spacers are placed in the gap between the wafer base and the copper support ring, underneath the flex polyamide, to help the flex form the curved shape required to account for the extra length mentioned above. The wafer side of the flex is glued next with a similar process. Rubber cement is deposited on the PCB with a syringe and a dispenser, and another clamp that mounts to the copper support ring holds the stiffener down until the rubber cement is cured.

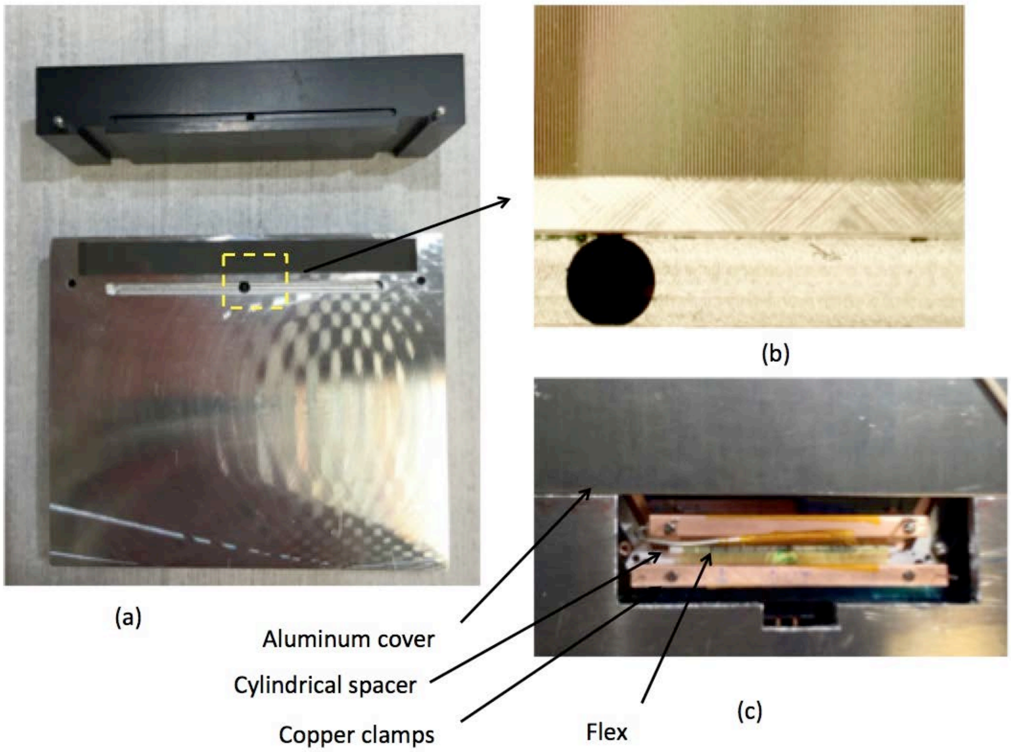

Figure 4. Image (a) shows the Delrin jig (up) and the aluminum jig (bottom). And image (b) shows a portion of aluminum jig around the silicon indicator. When gluing the flex, an aluminum cover is used to protect wiring chips and wire bonds, shown in image (c).

2.4 Bonding

For the AdvACT detector arrays, more than 23,000 wire bonds are required to complete the circuits, including bonds from MUX chips to wiring chips, interface chips to MUX chips, interface chips to wiring chips, wiring chips to the PCB, detectors to flex, and flex to wiring chips.

One critical failure mode involves shorts between detector bias lines. Adjacent TES signal and return lines on the flex may originate from different multiplexed bias lines. Therefore, all flexes are probed for open and short lines before they are mounted on the array. In case some shorts are not found by probing, an automated digital circuit (Figure 7) continuously measures connecting resistances across a subset of pins on the PCB. This continuity checker can check the cross-pin connections between a maximum of 8 pins, which are hard-wired to be 4 out of the 6 detector bias lines per quadrant. Not every connection between the 6 bias lines is probed simultaneously, but a DPDT switch enables continuous short monitoring for those sets of bias lines that share a flex. If shorts between any two pins not representing a single bias line signal-return pair are detected, wire bonds are pulled until the short returns to open.

During bonding, the array is maneuvered by the motorized table of the bonding machine. The bonding jigs that create this mechanical connection (shown in Figure 6) were designed and machined to ensure that the array remains stable and flat during the rapid movements of the bonding table. The jig is comprised of several parts, including a cap that can attach to the wafer base, a cylindrical body to the upper part of which the cap is bolted, and a lower flange sitting upon a base block. The cylinder itself has an inner clearance hole that slides over a long dowel press-fit into this base block. The base block, which is screwed to the bonding table, features twelve screw holes arranged in a circle allowing 4-screw clamping of the flange to the block in increments of 30 degrees. This arrangement provides great stability even at the perimeter of the wiring chip while allowing for identical bonding programs (1 for each type of interconnect) to be run on each quadrant. For the present array, about 40% of the bonding was performed in an automatic mode laying down 1-2 bonds per second.

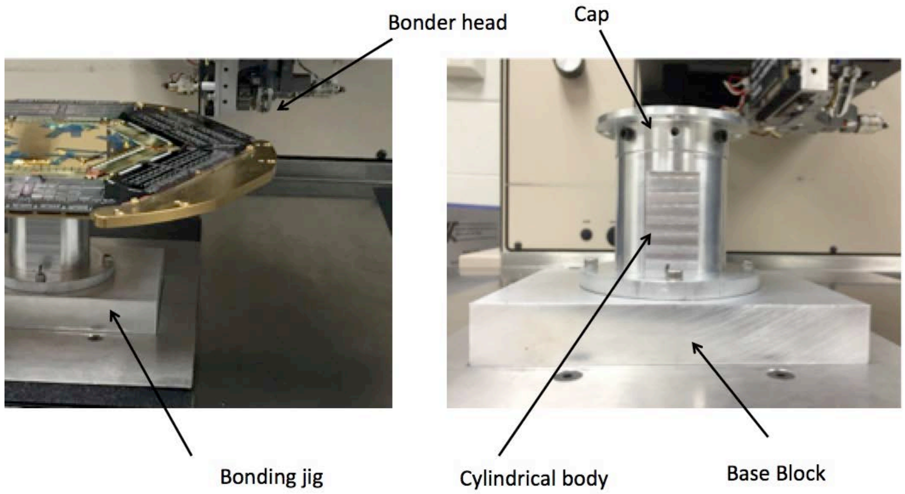

Figure 5. The bonding jig consists of a cap, a cylindrical body and a base block. The detector array is first mounted on the top surface of the cap and secured with 4 screws from beneath. Since placing two bond feet for each bond should be in the order that the wire bond's direction is outward from the detector wafer, the jig should be able to do 360-degree rotation to have the access of the whole area.

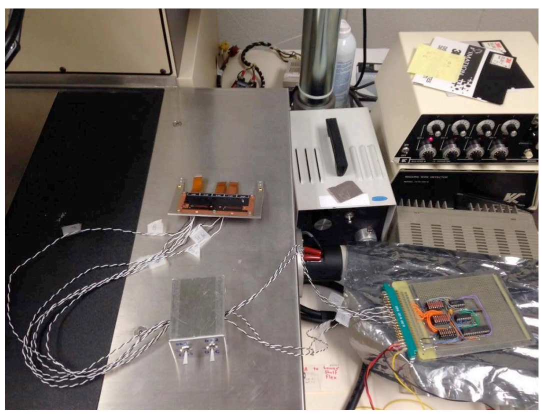

Figure 6. Continuity checker (photo courtesy of Kevin Crowley). The circuit is connected to the PCB through flexible circuitry and ZIF connecters. The circuit is able to update the cross check-pin resistance every few seconds.

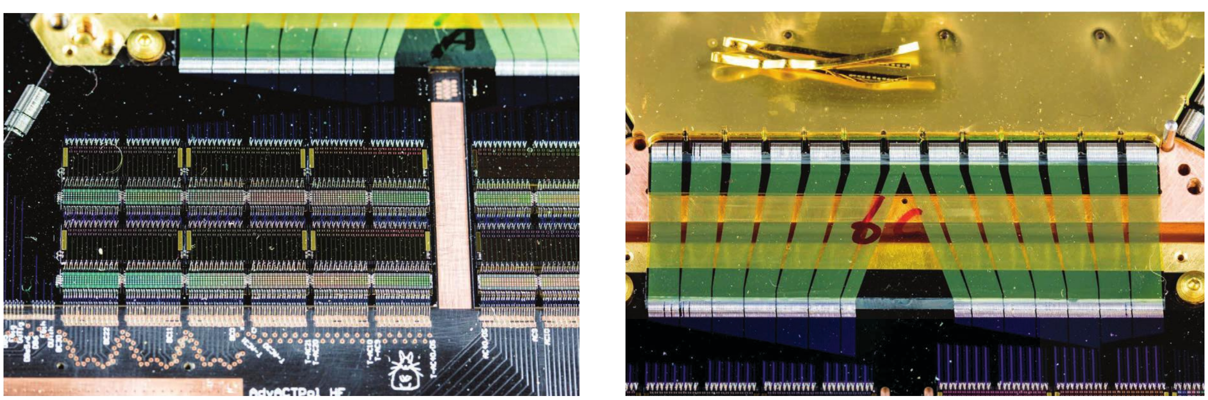

Figure 7. Wire bonds on the wiring chips (left) and on the flex (right).

2.5 Detector wafer transferring and feedhorn mounting

The detector wafer has been sitting on the copper wafer base, which also serves as a part of the bonding jigs. After bonding, the feedhorn stack needs to be mounted to the copper support ring and aligned to the detector wafer through dowel pins. The feedhorn stack[3] is a set of etched silicon wafers that are glued together, forming spline-profiled pathway to each pixel. Since silicon feedhorn stack and the copper support ring have different thermal contractions under cryogenic environment, the feedhorn stack won't directly mounted to the copper support ring, but instead through BeCu L-brackets and array support posts that are made from gold-plated OFHC copper. The L-brackets serve as a soft bridge between the feedhorn stack and the copper support ring, and array support posts s act as mechanical interface connecting L-brackets and the copper support ring.

Since the array support posts' vertical surfaces constrain the space and position for L-brackets, the feedhorn and L-brackets won't be able to be inserted between the array support posts if there is a misalignment of L-brackets orientation with respect to the feedhorn stack. To align the direction of L-brackets, a Delrin base (Figure 8) with a cutout that is the same size as the feedhorn stack is used. The Delrin base also has the same features as the array support posts' screw holes and the copper support ring. By putting the feedhorn stack into the jig, the direction of the L-brackets can then be adjusted to the correct position according to the array support posts.

The wafer transferring process begins with mounting the copper support ring to an aluminum ring base that is supported by three long cylinders (Figure 9). The vacuum chuck is then slowly lowered until it slightly touches the top surface of the detector wafer. After turning on the vacuum, the vacuum chuck holds the detector wafer. The wafer base no longer supports the detector wafer and can thus be dismounted from the copper support ring. The feedhorn stack with aligned L-brackets is then put on the elevating plate. As the feedhorn stack is slowly lifted, the XY stage allows it to adjust position and rotate. At the same time, two cylindrical cameras pointing straight down at two corners of the detector wafer assist in the alignment between the detector wafer and the feedhorn array. After the feedhorn stack is lifted up and secured to array support posts with screws and L-brackets, the vacuum can be turned off and the entire upper mechanic part containing the vacuum chuck can be dismounted.

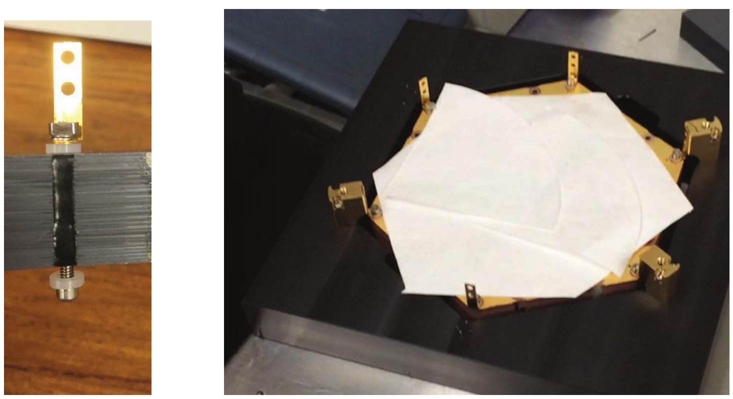

Figure 8. Screws stack silicon wafer together (left, photo courtesy to Shuay-Pwu Ho). To protect the silicon wafers, two Teflon washers are used for each screw, separating the wafer stack and metal part. The Delrin jig helps to align the L-brackets orientations (right). It is designed so that the top surface of the feedhorn stack is at the same level as the top surface of the jig.

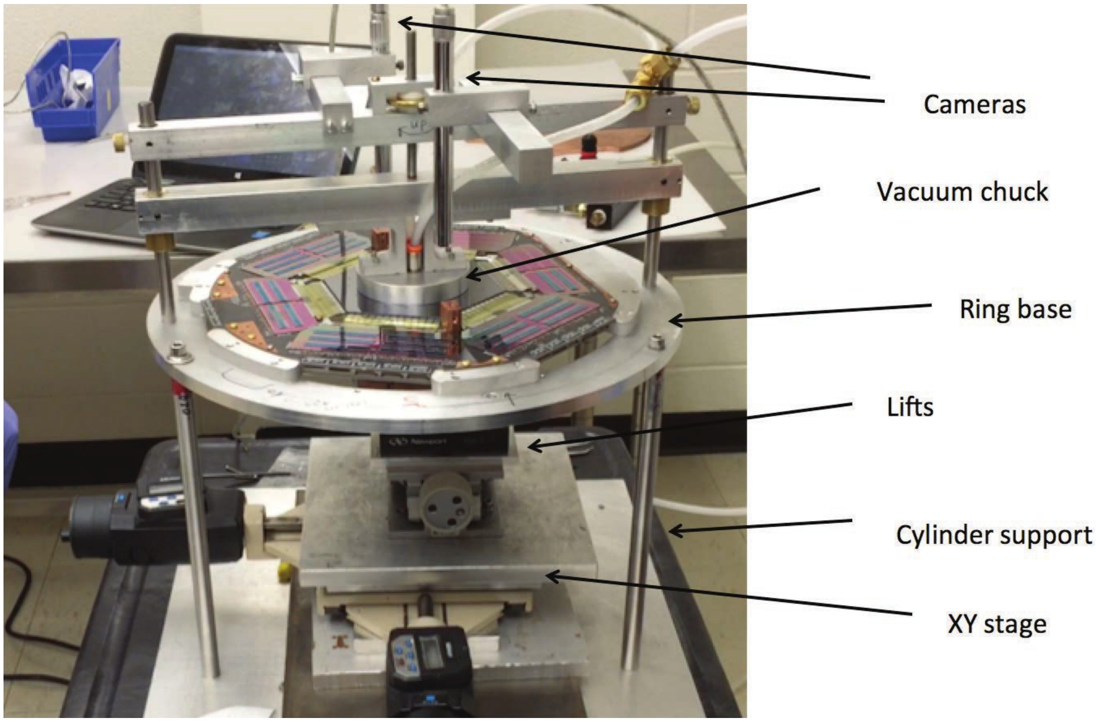

Figure 9. The mechanical setup for feedhorn transferring.

3. FUTURE WORK

The integration work for the first detector array for AdvACT is effective and has a TES yield higher than 95%. The AdvACT group plans to deploy the first array in June 2016 and assemble another three detector arrays in the following years with similar methods.

4. ACKNOWLEDGEMENTS

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