J Low Temp Phys (2016) 184:473–479
DOI 10.1007/s10909-015-1454-z

High-Density Superconducting Cables for Advanced ACTPol

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Received: 30 September 2015 / Accepted: 21 December 2015 / Published online: 11 January 2016

Abstract Advanced ACTPol (AdvACT) is an upcoming Atacama Cosmology Telescope (ACT) receiver upgrade, scheduled to deploy in 2016, that will allow measurement of the cosmic microwave background polarization and temperature to the highest precision yet with ACT. The AdvACT increase in sensitivity is partly provided by an increase in the number of transition-edge sensors (TESes) per array by up to a factor of two over the current ACTPol receiver detector arrays. The high-density AdvACT TES arrays require 70 μm pitch superconducting flexible cables (flex) to connect the detector wafer to the first-stage readout electronics. Here, we present the flex fabrication process and test results. For the flex wiring layer, we use a 400-nm-thick sputtered aluminum film. In the center of the cable, the wiring is supported by a polyimide substrate, which smoothly transitions to a bare (uncoated with polyimide) silicon substrate at the ends of the cable for a robust wedge wire-bonding interface. Tests on the first batch of flex made for the first AdvACT array show that the flex will meet the requirements for AdvACT, with a superconducting critical current above 1 mA at 500 mK, resilience to mechanical and cryogenic stress, and a room temperature yield of 97 %.

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Keywords Atacama Cosmology Telescope · ACTPol · Detector · Flex · Superconductor · Wire bonding

1 Introduction

ACT is a telescope in the Atacama Desert, Chile, designed for measurement of the CMB with arcminute angular scale resolution. Currently, we are observing with the ACTPol polarization-sensitive receiver [1]. In 2016, we will begin replacing the three ACTPol detector arrays with the higher sensitivity Advanced ACTPol (AdvACT) detector arrays. By measuring the CMB temperature and polarization anisotropies down to small angular scales and cross correlating our findings with shorter wavelength surveys, AdvACT will probe the primordial helium abundance, number of neutrino species and the sum of the neutrino masses, dark energy and structure formation, and the running of the spectral index of inflation (see, e.g., [1]) (Fig. 1).

Especially if multichroic pixels are used, as in AdvACT, CMB experiments can receive large scientific returns by increasing the number of detectors in the usable focal plane area [2,3]. With an advanced 32 column × 64 row superconducting quantum interference device (SQUID) time-domain multiplexing (TDM) readout scheme,

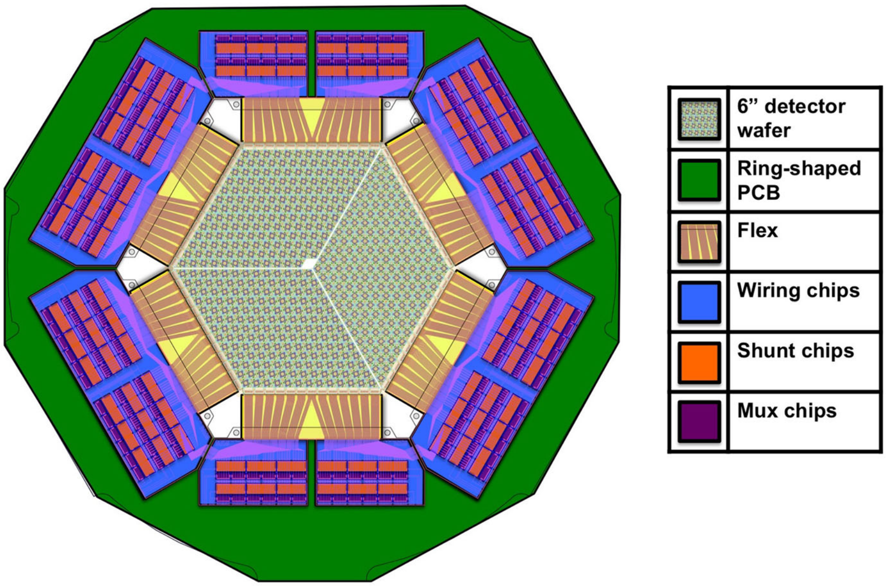


Fig. 1 A diagram of the AdvACT HF array assembly. More details about the AdvACT HF array architecture can be found in Henderson et al. [4]. The detectors are monolithically fabricated on one 150 mm wafer shown in the center of the figure above. A ring-shaped PCB holding the first-stage readout components surrounds the detector wafer. Large wiring chips are mounted to the PCB to provide high-density superconducting wiring for the individual TES bias circuits. The first-stage readout components reside on multiplexing (mux) and shunt chips that are mounted on top of the wiring chips. The flex connects the detector wafer to the wiring chip. Aluminum wire bonds electrically connect all components (Color figure online)

each of the multichroic AdvACT arrays will accommodate up to 2048 transition-edge sensors (TESes) [4–6].

Large TES arrays need to be packed to high density due to cryogenic space constraints, so we need high-density superconducting wiring to read them out. Although SQUID multiplexing reduces the number of wires at higher temperature stages, two superconducting wires must connect each TES to the first readout component (the SQ1 input coil in TDM or the resonator in frequency-domain multiplexing (FDM)) [7].

To allow for differential thermal contraction between the AdvACT detector arrays and the readout, we make electrical connections between them using superconducting flexible cables (flex), as shown in Fig. 3. We connect the flex to electrical contacts placed around the perimeter of the detector array (see, e.g., [8,9]) for a simple wire bonding assembly. For larger and/or higher density TES arrays, the density of the detector array electrical contacts in this configuration is quite high, and flexible circuitry (flex) with the necessary superconducting wiring density to match is not readily available commercially. In recent years, researchers in the field have started developing fabrication processes capable of creating custom superconducting flexible circuitry with smaller feature sizes [10–12].

In this paper, we present our fabrication process for the high-density, superconducting AdvACT flex and test results on the first flex fabricated for the first AdvACT array, the High Frequency (HF) array [4]. The flex is similar in concept to that successfully used in the "semihex" wafer assemblies of the third ACTPol array, with improvements made to the fabrication process [9,12]. The AdvACT HF array flex has a trace density of about 14 traces per mm (70 µm trace pitch). However, the fabrication process presented here can produce superconducting flex with tighter trace density. The smallest pitch attainable depends on the superconducting critical current needed for the traces, the minimum bond pad pitch allowable by the wire bonding process, and the number of bond pad rows.

Another challenge of fielding large TES arrays is the large-scale detector-readout assembly required. The AdvACT HF array will require over 20,000 aluminum wire bonds and die bonding (gluing) of 300 chips and flex. Wedge wire bonding to bond pads on soft substrates is challenging [13]. The flex presented here features a robust wedge wire bonding interface to bond pads that sit on a hard silicon (uncoated with polyimide) substrate. For context, note that by increasing the bondability of flex in the ACTPol arrays through improved mechanical mounting of the commercial flex from Tech-Etch[1] used and replacing some of the Tech-Etch flex with flex similar to that presented here, we were able to increase the TES electrical yield by 8 % [9,12].

2 Advanced ACTPol Flex Design

Images of the AdvACT HF array flex are shown in Fig. 2. Each piece of flex is 61 mm wide and 20 mm long, including the 5 mm long silicon stiffeners on each side, and carries 676 traces. In the center of the cable, the aluminum traces are 50 µm wide, placed at a 70 µm pitch. At the ends of the cable, we use two rows of bond pads so

1 Tech-Etch, Inc., 45 Aldrin Road, Plymouth, MA 02360 USA

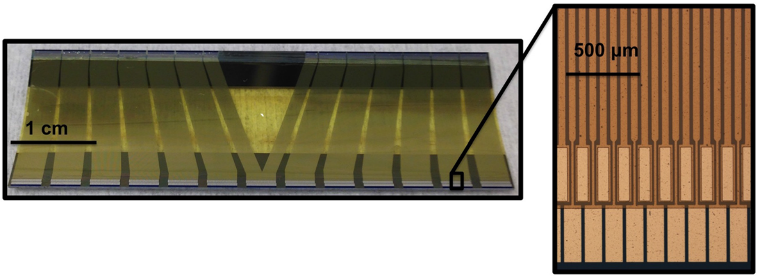
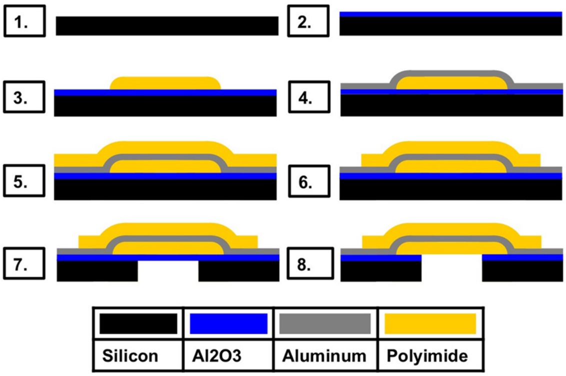


Fig. 2 Images of the HF flex. *Left* Photograph of a piece of HF flex. *Right* Microscope image showing detail of HF flex traces and bond pads (Color figure online)



Step	Process Description
1.	4” Si wafer, 525 μm thick
2.	110 nm Al_2O_3, ALD
3.	Polyimide base layer, 15 μm
4.	400 nm aluminum wiring layer
5.	Polyimide top layer, 15 μm
6.	Etch top polyimide layer with O_2 plasma, chrome etch mask
7.	DRIE silicon backside etch
8.	Remove Al_2O_3 layer with Al wet etchant

Fig. 3 Diagram showing cross-sectional view of the flex at each fabrication process step, not drawn to scale (Color figure online)

that the bond pad pitch is 140 μm. This bond pad pitch is easily accommodated using 25 μm thick aluminum wire and a 90 μm wide tool tip. The traces narrow to 20 μm when passing between bond pads in the inner row to reach the outer row of bond pads.

A diagram of the AdvACT flex from a cross-sectional view is shown in Fig 3. In the center of the cable, 400-nm-thick sputtered aluminum traces sit on a flexible 15-μm-thick polyimide substrate. At the ends of the cable, the traces transition from the polyimide substrate to a polyimide-coated silicon substrate to an aluminum oxide (Al_2O_3)-coated silicon substrate. The hard silicon substrate at the ends of the cable allows for a robust wire-bonding interface, as discussed above. The traces are covered on top everywhere but the bond pads by a protective 15-μm-thick polyimide layer.

3 Flex Fabrication Process

The flex fabrication process is similar to that presented in Pappas [12], with improvements to make the process more time-efficient and to produce more consistent results. In particular, we use a deep reactive ion etch (DRIE) process to remove the silicon in the center of the cable instead of the gold release process, and we decrease the fabrication time to produce the polyimide films.

We fabricate the polyimide films with HD Microsystems™ PI-2611 polyimide precursor solution [14]. [2] The solution is spun onto the wafer, soft baked on a hot plate, then cured in a furnace under a nitrogen atmosphere to form a polyimide film. We produce the cables' top and base 15-μm-thick polyimide layers using a very slow spin speed recipe: 250 rpm for 15 s, 500 rpm for 15 s, 750 rpm for 60 s, with a ramp rate of 100 rpm/s between steps. Next, the wafer is transferred to a 90 °C hot plate and soft baked for about 10 min, until the film is dry, then transferred to a 90 °C nitrogen-atmosphere furnace. The furnace temperature is ramped at 1 °C/min to 350°C, where it is held for 60 min, then the furnace is turned off and allowed to cool slowly to room temperature. Before spinning the top and bottom polyimide films, we apply the HD Microsystems™ VM-651 adhesion promoter according to the manufacturer's instructions to improve the adhesion between the polyimide film and the substrate.

The flex fabrication process steps are outlined in Fig. 3. We start with a 100 mm diameter, 525 μm thick silicon wafer (Step 1) and grow 100 nm Al_2O_3 by atomic layer deposition (ALD) (Step 2). This acts as an etch stop to protect the polyimide during the backside etch of the silicon. To pattern the base layer of polyimide (Step 3) so that the last 2 mm of the cable, where the bond pads will be placed, are left uncoated, we place a shadow mask on the wafer during spinning of the polyimide precursor solution [12]. This process is outlined in Fig. 4. It produces a patterned polyimide layer with shallow-sloped sidewalls that the aluminum wiring layer can fully coat. The shadow mask stays on the wafer by electrostatic forces alone and no adhesive is used, so there is no residue left on the uncoated regions. It is also a quick process, taking almost as little time as fabricating an unpatterned polyimide layer.

The wiring layer is formed by sputtering a 400 nm aluminum film and wet etching it into traces (Step 4). As discussed in Pappas [12], we treat the polyimide surface with a light oxygen plasma etch before depositing any metal on top to improve the adhesion between the metal and polyimide layers [12]. After fabricating the aluminum traces, we spin and cure the top polyimide layer according to the recipe described earlier (Step 5). To pattern the top polyimide layer to reveal the bond pads, we perform an oxygen plasma etch with a 50-nm-thick sputtered chrome etch mask (Step 6). First, we etch the bulk of the polyimide with an oxygen plasma excited by a parallel plate bias, then we clean the residue with an isotropic inductively coupled plasma (ICP) oxygen etch. After the etch, we remove the chrome etch mask in Cyantek CR-7 chrome wet etchant, which does not significantly attack the exposed aluminum bond pads.

To remove the silicon in the center of the cable, where we want it to be flexible, we perform a Bosch process DRIE silicon etch using a thick photoresist mask (Step 7). Then, we remove the Al_2O_3 etch stop layer in Cyantek Al-11 aluminum wet etchant, heated to about 50 °C, to reduce stress in the flex and prevent curling (Step 8). Unlike strong acids that could be used to remove the Al_2O_3, such as hydrofluoric (HF) acid,

[2] HD Microsystems™ 250 Cheesequake Road Parlin, NJ 08859-1241 USA

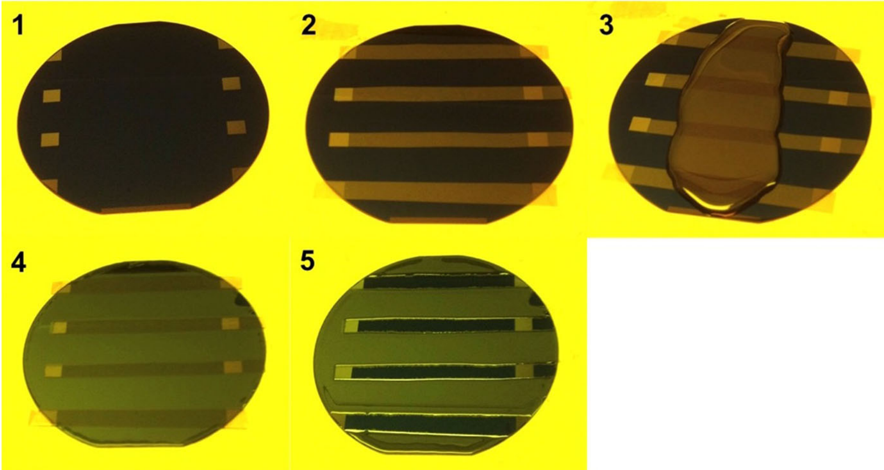


Fig. 4 Adhesiveless shadow mask process for patterning PI-2611 precursor solution. Three pieces of AdvACT HF flex, shown in Fig. 2, will be fabricated on the wafer shown above, with the flex traces oriented vertically. The flex bond pads will sit on the strips of the wafer left uncoated with polyimide. Step 1: The Al_2O_3 layer is patterned to mark where the Kapton® shadow mask should be placed. Step 2: Strips of 1 mil thick Kapton® are placed on markers. Step 3: The wafer and Kapton® are covered with PI-2611 solution. Step 4: The wafer is spun with the usual recipe, described in Sec. 3. Step 5: The Kapton® strips are removed and the PI-2611 solution relaxes at the boundary to create a shallow-sloped sidewall (Color figure online)

the aluminum etchant will not attack the polyimide layer [14]. Finally, we dice the flex, then remove it from the carrier wafer by soaking in acetone.

4 Flex Performance

We have run several tests on the flex to ensure its performance will meet the requirements of AdvACT. The flex design is very similar to that used to assemble the ACTPol PA3 semihex wafers, which has been used successfully both in lab tests and in the ACTPol receiver this season [9,12]. In particular, the thickness and width of the aluminum traces in the AdvACT flex are identical to the ACTPol flex, so we expect this flex to carry the same superconducting critical current (I_c). ACTPol and AdvACT both require flex with an I_c of about 1 mA at the operating temperature of 80 mK.

We measured the I_c of 36 AdvACT flex traces at 500 mK in steps of 1 mA, 3.16 mA, and 10 mA. Three groups of 12 traces were wire bonded in series, and a 4-lead resistance measurement of each group was performed. The I_c at 500 mK exceeded 1 mA for all 36 traces and at least 24 traces held above 10 mA of superconducting current. Because I_c increases with decreasing temperature [15], this indicates that I_c at our operating temperature of 80 mK will well exceed the AdvACT requirement of about 1 mA.

We have also tested the robustness of the flex to cryogenic cycling and mechanical stress. The flex was first subjected to a cryogenic cycling stress test, during which it was cryogenically cycled between room and liquid nitrogen temperature 10 times.

Next, we performed a mechanical stress test. The flex was bent 180 degrees at a 1.3 mm radius of curvature 10 times in one direction and 10 times in the other. To detect any damage to the flex traces due to the stress tests, the flex was examined under the microscope and 260 traces were probed for continuity before and after the tests. The flex successfully withstood both stress tests—all 260 traces were still continuous afterwards and no cracks in the traces were observed under the microscope.

The average room temperature yield of the first three pieces of flex produced for the AdvACT HF array is 97 %. This shows that the aluminum wiring layer fully coats the polyimide step, that we have successfully avoided dust contamination in the base polyimide layer (this is discussed more in Pappas [12]), and that the fabrication process and handling of the flex are at most minimally affecting the yield.

5 Conclusion

We have presented a high-density superconducting flex fabrication process that significantly improves upon the process used for the ACTPol PA3 semihex flex both in terms of yield consistency and process time. The flex meets the requirements of AdvACT, including a superconducting critical current above 1 mA at 80 mK, the ability to withstand cryogenic cycling and mechanical stress, high electrical yield, and a robust wire bonding interface.

Acknowledgments This work was supported by the U.S. National Science Foundation through awards AST-0965625, PHY-1214379, and AST-1440226. The NIST authors would like to acknowledge the support of the NIST Quantum Initiative. The work of EG, BJK, BLS, SMS, and JTW was supported by NASA Space Technology Research Fellowship awards. We had helpful conversations with Marcel Bruijn about his experience with flex fabrication that helped us begin this research. We would also like to thank Bert Harrop and the rest of the Princeton University MNFL staff for their advice and guidance during the flex fabrication process development.

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