Electromechanical Reliability Testing of Flexible Hybrid Electronics Incorporating FleX Silicon-on-Polymer ICs

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***Abstract*—Flexible Hybrid Electronics combine the best characteristics of printed electronics and silicon ICs to create high performance, ultra-thin, physically flexible systems. New static and dynamic tests are being developed to evaluate the performance of these systems. Dynamic radius of curvature and torsional test results are presented for a flexible hybrid electronics system with a FleX Silicon-on-Polymer operational amplifier manufactured in an 180nm CMOS process with 4-levels of metal interconnect mounted on a PET substrate.**

Keywords—flexible hybrid electronics; silicon-on-polymer; reliability testing

I. INTRODUCTION

Flexible Hybrid Electronics (FHE) exist at the intersection of two industries: the electronics industry and the high performance printing industry [1]. Ultra-thin, conformal and even physically flexible electronic products have been under development for years, but have recently seen increased focus. One example is the recent investments in creation of NextFlex the U.S. Government's Manufacturing Innovation Institute supported by industry and academia [2]. FHE will enable novel products with form factors as shown in Fig. 1 and will support applications that include:

- Wearable health monitoring for lifestyle and fitness
- Medical health monitoring for improved health care
- Soft robotics for the elderly or wounded soldiers
- Sensor monitoring for structures, aircraft, or automotive
- Light-weight rugged sensors for harsh environments [1]

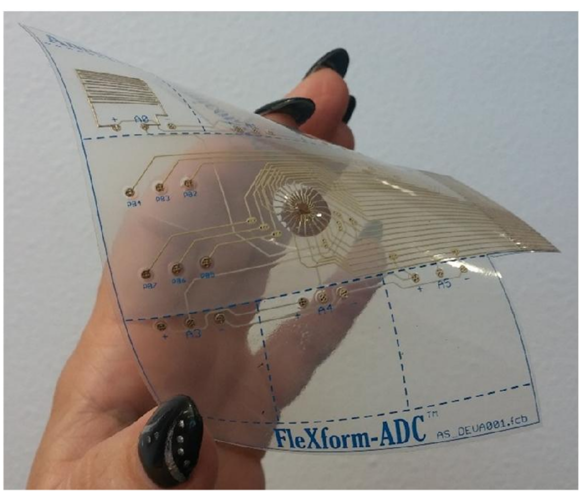

Fig. 1: Flexible Hybrid Electronics

Flexible printed electronics and silicon IC technologies each have properties and characteristics that are desirable for conformal and physically flexible products. However, neither can meet the full set of requirements alone. The flexible printed electronics deliver large form factor elements such as sensors, interconnects, and antenna elements. Silicon-based technologies are needed to meet the high performance logic, memory and mixed-signal requirements. Conventionally packaged ICs and even thinned die are generally too thick and rigid for aggressive bending. These limitations have been addressed by the FleX™ Silicon-on-Polymer™ process where standard full thickness Silicon On Insulator (SOI) wafers are transformed into flexible wafers and subsequently ultra-thin, physically flexible singulated die. Fig. 2 illustrates the advantages of FleX ICs to traditionally thinned die.

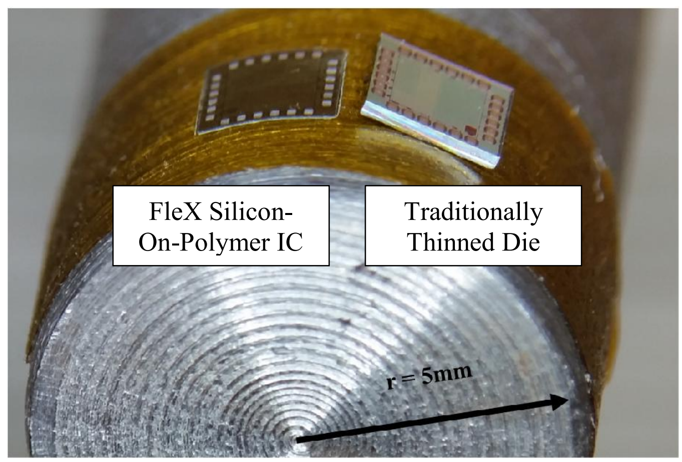

Fig. 2: FleX IC and Thinned Die on 5mm Radius Mandrel

II. FLEX SILICON-ON-POLYMER

FleX Silicon-on-Polymer is a proprietary and patented process to convert standard silicon wafers into flexible wafers [3,7]. American Semiconductor has demonstrated the FleX process by creating flexible, ultra-thin, single-crystalline CMOS with multi-layer metal interconnect [3,5]. CMOS is first fabricated using a standard SOI process on 200mm wafers and then the silicon substrate is removed. The FleX process completely removes the handle silicon and adds a polymer substrate to create ultra-thin flexible wafers as shown in Fig. 3 [6]. The resulting FleX wafers are singulated into individual FleX ICs.

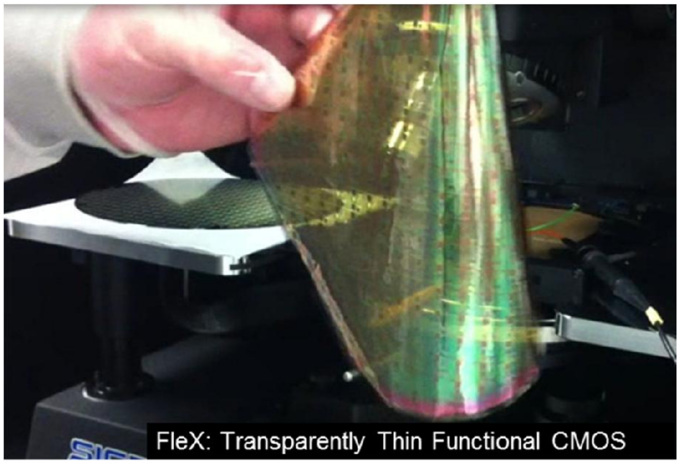

Fig. 3: 130nm CMOS FleX Silicon-on-Polymer Wafer

III. Flexible Hybrid Electronics Test Vehichle

The Rainbow™ test coupon shown in Fig. 4 was specifically designed to support reliability testing of FleX ICs. The base of the 150mm x 23mm Rainbow is a 127um thick PET substrate. The electrical traces are screen printed using a silver nanoparticle ink. A masked overcoat is applied to protect the silver inks. The traces are left exposed where the FleX IC will be attached and at the edges where connection is made through a zero-insertion force (ZIF) connector.

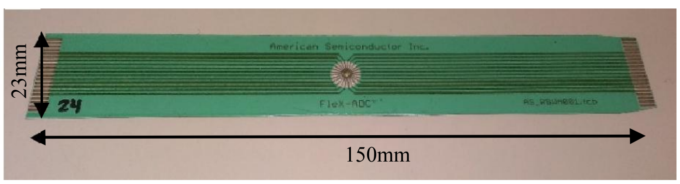

Fig. 4: Rainbow FHE Test Vehicle

The FleX-OpAmp is fabricated in the TowerJazz CS18 180nm partially depleted silicon-on-insulator (PD-SOI) CMOS process with 4-levels of aluminum interconnect and converted to a flexible form factor using the FleX Silicon-on-Polymer process. Each FleX-OpAmp die has two identical general purpose operational amplifiers. The die area is 2.4 X 2.4mm with 160um pad openings on a 300um pitch. The dimensions of the pad openings and pitch were selected to facilitate easy integration with screen-printed electronics in FHE systems.

The FleX-OpAmp die is first attached to the Rainbow PET substrate with a non-conductive, UV cure adhesive. A silver flake conductive adhesive is dispensed to connect the FleX-OpAmp die pads to the silver traces on the PET substrate to make electrical connections between the IC and the substrate. The conductive adhesive is thermally cured. After electrical testing, a thin protective UV cure encapsulate is applied over the FleX-OpAmp die and electrical interconnect area to complete the assembly process. Fig. 5 provides the profilometry data from a completed assembly. Maximum thickness was 119um.

American Semiconductor has previously demonstrated FleX ICs operating when statically deformed to a 5mm radius of curvature in both concave and convex directions and with die orientations of 0 and 90 degrees. In the following section, we will discuss the first extensive dynamic reliability testing of these flexible hybrid electronics systems.

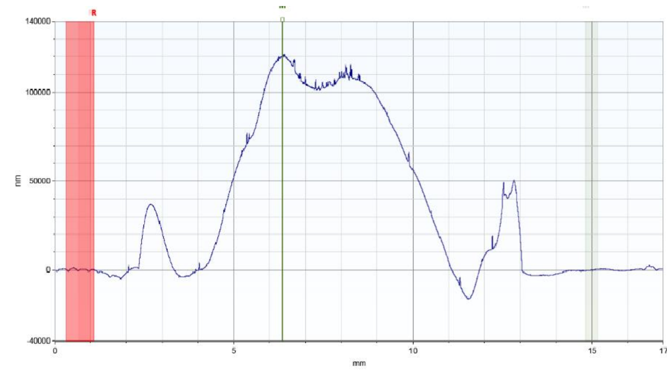

Fig. 5: Rainbow Test Sample Overcoat Profile

IV. Test Configurations

Tests were performed on American Semiconductor Flexible Hybrid Systems containing a FleX-OpAmp IC. Prior to any testing, each Rainbow test strip was examined for functionality and any indicators of damage. All samples were fully functional and defect free.

The Rainbow FHEs were subject to repeated physical stressing in three distinct configurations: Convex Radius of Curvature (RoC), Concave RoC, and Torsional. In each configuration, the FleX-OpAmp was configured as a voltage follower, and fed a 1.0 kHz with variable 0-800mV peak-to-peak square wave (Fig. 6). The samples were considered to have failed a test if at any point the input waveform was not correctly reproduced at the output due to failure of the FleX IC or FHE printed interconnects.

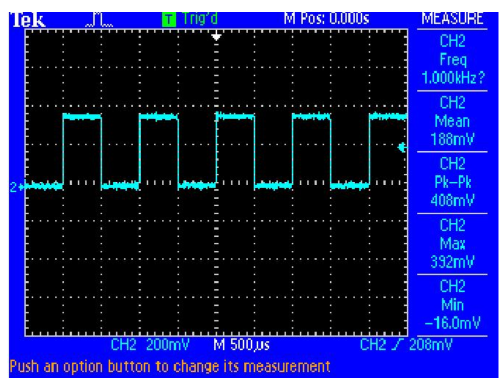

Fig. 6: Input Waveform for FleX Testing

Convex RoC testing was performed as shown in Fig. 7, with the die side of the test strip face up, causing tensional stresses on the die and printed interconnects. Concave RoC testing was also performed in order to determine the resilience of the FleX Silicon-on-Polymer IC and printed interconnects under compressive stresses. Concave RoC testing was performed with the die side of the test strip down, facing the mandrel. Both concave and convex testing utilized a mechanical arm which forced the sample to repeatedly conform to the curvature of a 15mm RoC mandrel.

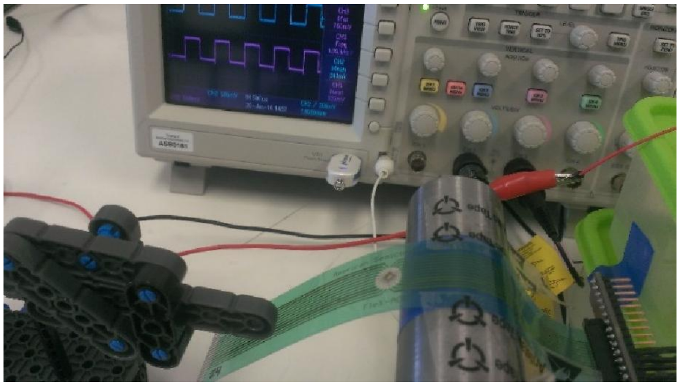

Fig. 7: 15mm Convex RoC Testing of FHS

Following the completion of the initial 15mm RoC testing, both the concave and convex samples were subjected to the opposite test from that which they had originally been designated. The sample that was initially tested for convex reliability was tested for concave reliability, and vice-versa. With the exception of the inversion of each sample for continued testing, the test setup remained identical.

The Axial Torsion Test (ATT) was designed to test the resilience of the flexible hybrid system to rotational stresses. As shown in Fig. 8, this test was performed by holding the anterior edge of the rainbow board in a fixed position and rotating the posterior about the anteroposterior axis. The initial test was to sweep the deflection angle 60 degrees in both clockwise and counterclockwise directions. This deflection angle was increased to ±90 degrees for further testing as well.

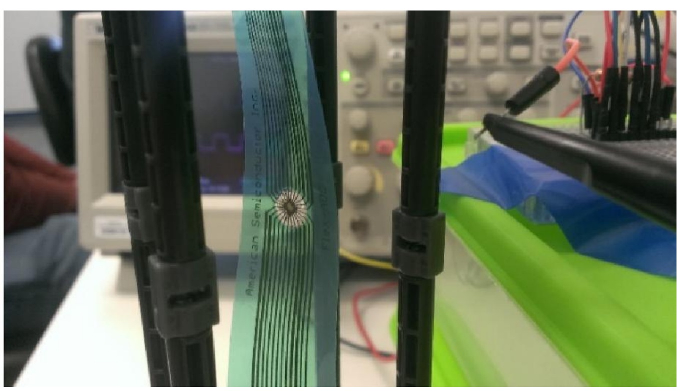

Fig. 8: Axial Torsion Test

V. Results

The sample that was initially used for convex testing survived 10,000 convex test cycles and an additional 13,600 concave test cycles. This sample completed all testing with no failures. As can be seen in Fig. 9, the pre-test and post-test waveforms show no signal degradation.

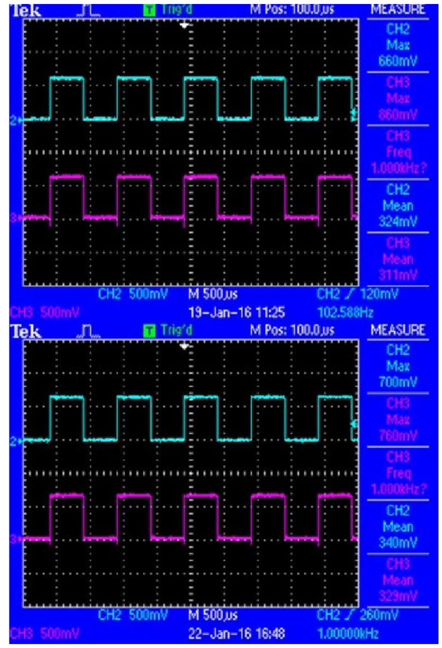

Fig. 9: Pre (top) and Post (bottom) Test I/O Waveforms

The concave test sample endured 11,100 concave test cycles before being tested in the convex mode. At 15,800 cycles into the convex test, this test sample began to enter a pre-failure state. This pre-failure state was characterized by intermittent signal degradation as seen in Fig. 10. This signal degradation occurred only for extremely short durations at specific points in the flex cycles and only every 2-5 cycles.

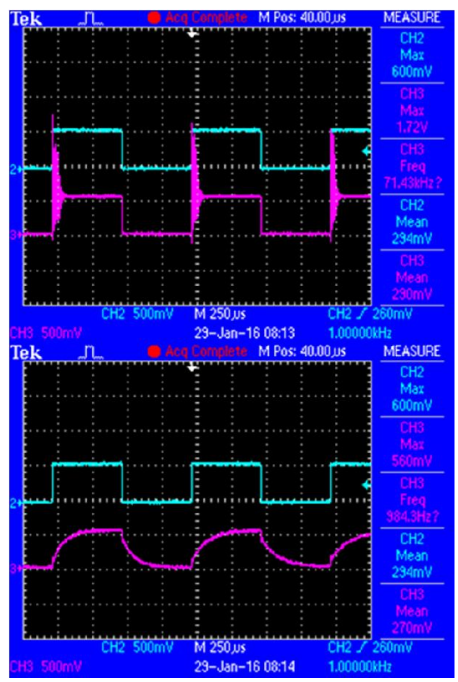

Fig. 10: Signal Distortions in Pre-Failure State

Over the following 610 cycles, the signal degradation increased steadily to become both more frequent and severe. The sample was, however, still properly functional in both the fully extended and fully conformed states.

The sample was temporarily removed from the influence of the actuator and allowed to fully straighten out, then the test was continued. It was found that this process of allowing the sample to straighten out would return the sample to 100% functionality for anywhere between 25-200 cycles. At 1200 cycles past the first signs of breakdown, the failure had become extreme, with the output signal being either completely distorted, railed to VDD, or non-existent.

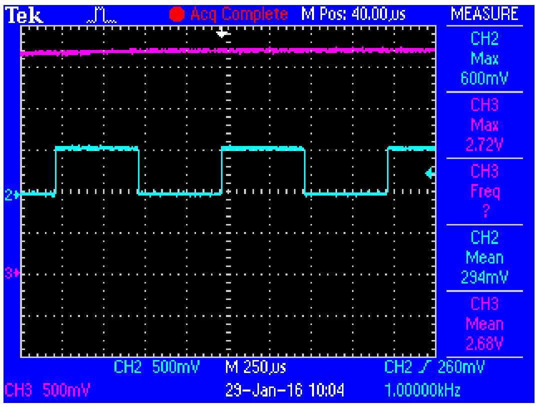

Fig. 11: Complete Interconnect Failure Signal

Despite this failure, allowing the sample to flatten out still returned full functionality for a short time. Furthermore, at this point, the sample still provided proper functionality if manually conformed to the mandrel. The test was stopped at 2500 cycles after the beginning of the first signs of failure (over 29,000 cycles total). Visual inspection of the sample revealed the cause of the failure of the aforementioned sample to be a crack in the printed Vdd interconnect.

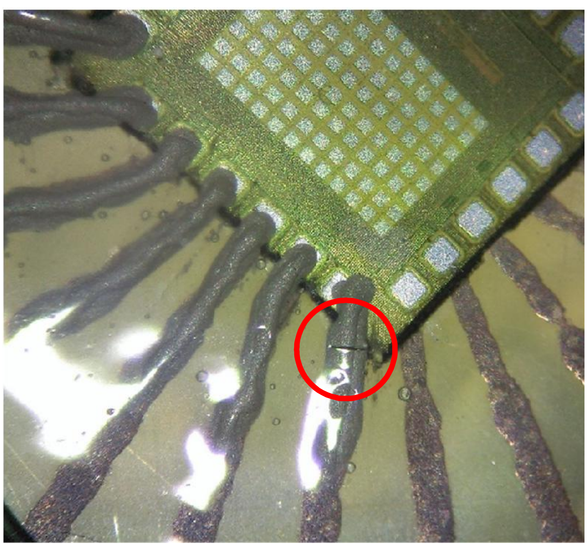

Fig. 12: Crack in Printed Interconnects on VDD Line

The Axial Torsion Test was performed as described in section IV. The sample exhibited full functionality through 10,000 cycles at 60 degrees deflection, and additional 92,000 cycles at 90 degrees. Shortly after 100,000 cycles into the ATT, the sample failed.

Similar to the failure of the concave test sample, the ATT sample could be returned to 100% functionality for a short time by manually flexing the sample. In this case it was found that if the sample was flexed to a RoC of approximately 20mm in either the convex or concave direction, the FHE would again function, indicating that the most likely cause of failure is a crack in the printed FHE interconnects.

VI. Conclusions and Next Steps

The reliability of FleX Silicon-on-Polymer ICs in flexible hybrid electronics systems under dynamic mechanical flexing has been demonstrated for both single-plane and multi-plane deformation. Altogether, the samples underwent over 400 hours of electrical testing with no failures of the FleX Silicon-on-Polymer ICs. The failure mechanism for these test samples was the conductive epoxy electrical interconnects between the FleX ICs and the printed substrate traces.

Future test plans include RoC testing at <10mm Radius of Curvature, Axial Torsion testing at >90 degrees rotation, hot/cold temperature testing, as well as humidity testing. Combination testing, such as Axial Torsion Testing in a hot, humid environment will be explored as well. In addition, we plan to evaluate different materials for die attach, electrical interconnects and overcoat for improved reliability of the FHE systems.

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