Advances in Flexible Hybrid Electronics Reliability

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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. Tests and methods are being developed to evaluate the reliability of these systems. Initial results are presented for flexible hybrid electronics systems.*

Keywords: FleX; flexible; flexible hybrid electronics; FHE; Silicon-on-Polymer

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, and recent advances in materials and methods have improved the capability to manufacture FHE systems as shown in Fig. 1. The next industry concern is showing FHE products are reliable.

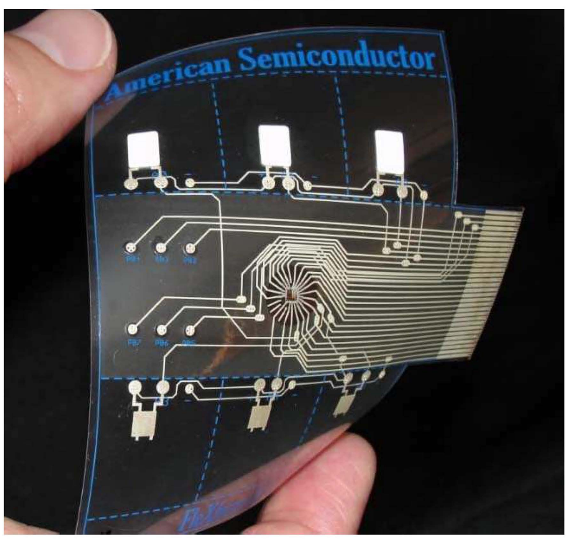

Fig. 1: Flexible Hybrid Electronics

Rather than try to develop new test methodologies and standards from scratch, we have attempted to draw from other, related industries where applicable. We have completed extensive research of the smart card industry, semiconductor industry, and U.S. military to identify a variety of relevant test standards and procedures that can be used as guidance for forming FHE test methods. This list includes, but is not limited to:

- JESD22-A110E (HAST)
- JESD220A102E (Accelerated Moisture Resistance)
- JESD22-A108D (Temperature Bias and Operating Life)
- ISO/IEC 7810 (Identification cards – Physical characteristics)
- ISO/IEC 7816-1 (Identification cards – integrated circuit cards)
- ISO/IEC 10373-1 (Identification cards – Test methods)
- IPC-TM-650 (Flexural fatigue life for a given bend radius)
- ASTM D522/D522M (Mandrel Bend Test of Attached Organic Coatings)
- MIL-STE-883K 1010.9 (Temperature Cycling)
- MIL-STD-883K 2018.6 (SEM Inspections)

This project included a review of over 30 relevant standards, procedures, and specifications for FleX FHE reliability assessment. A prioritization and down selection from this review resulted in identification of 13 relevant test procedures for this initial reliability investigation.

Radius of Curvature: FleX-ICs

One question commonly asked of flexible systems, but not of traditional electronics, is how far they can bend. As shown in Fig 2, even relatively small 2.5mm X 2.5mm ICs are not suitable for non-flat applications. The traditional die on the right would have interconnect failures at a significantly larger radius than the 5mm curve shown.

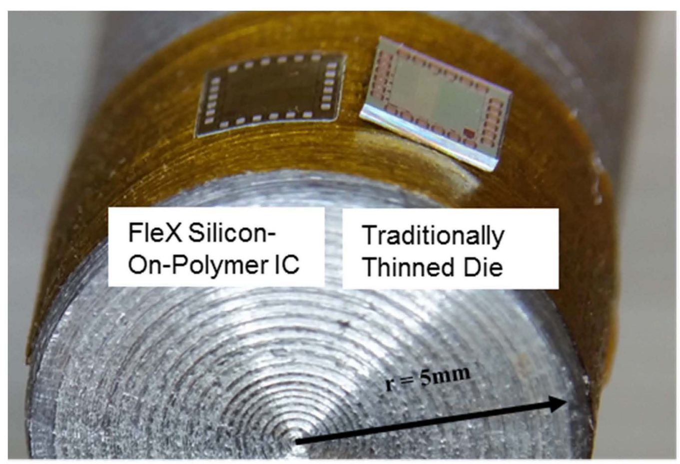

Fig. 2: FleX IC and Thinned Die on 5mm Radius Mandrel

We first performed a series of radius of curvature (RoC) tests in which individual FleX™ Silicon-on-Polymer™ die were bent around precision mandrels until mechanical failure. Testing was performed at 5, 2.5 and 1mm radius of curvature with the die in both concave and convex bend orientations. Three (3) AS_ADC1004 die were used for this test. Two of these samples had first experienced 168 hours of thermal stress testing, one (LTOL) at -30°C, the other (HTOL) at 125°C. The die were tested after each individual test for electrical functionality. The results shown in Table 1 demonstrate all FleX-ICs passed even at 1mm radius.

Table 1: FleX-IC Radius of Curvature Test Results

Orientation	Radius (mm)	LTOL	Heat Neutral	HTOL
Convex (Die Out)	5	PASS	PASS	PASS
	2.5	PASS	PASS	PASS
	1	PASS	PASS	PASS
Concave (Die In)	5	PASS	PASS	PASS
	2.5	PASS	PASS	PASS
	1	PASS	PASS	PASS

Radius of Curvature: FHE Systems

Next, we repeated the (RoC) tests on FHE systems using IC die of various thicknesses mounted to 5 mil PET substrates that have been screen printed. We first performed a series of radius of curvature (RoC) tests in which individual FleX™ Silicon-on-Polymer™ die were bent around precision mandrels until mechanical failure. This test used progressively smaller radii of 40, 30, 25, 20, 15, 12, 10, 8, 7, 6 and 5mm. We tested 725um thick die without thinning, traditionally thinned die at thicknesses ranging from 20 to 300um, and FleX™ Silicon-on-Polymer™ die. We also tested die ranging from 2.2 x 2.2mm up to 5.0 x 5.0mm.

The test results are shown below in Table 2. Failure was noted when the die delaminated from the substrate and/or there were cracks in the materials system. As expected, the FleX-ICs provided the best results with no failures above 5mm radius. For the FleX-IC based FHE systems, the limit was the materials system for die attach and overcoat, not the FleX-ICs themselves.

As FHE RoC testing progressed to smaller radii, it became apparent the radius was limited by the substrate as shown in Fig 3 and that the thickness of the overcoat material contributed to the die cracking. Radius of curvature testing was performed on the FleX die only to evaluate flexibility.

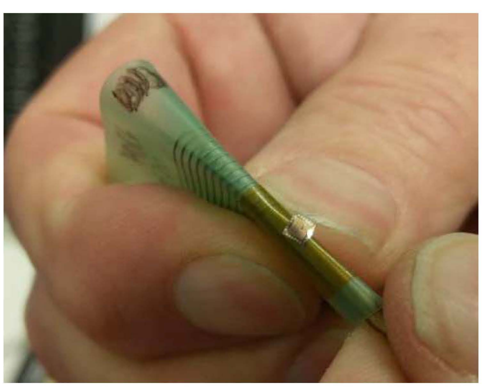

Fig. 3: Substrate Failure at 2.5mm RoC

The mechanical failures identified in this testing establish a baseline for performance, but we would fully expect to see electrical failures before these gross mechanical failures become evident. Figure 4 provides sample images of the failures.

Table 2: FHE Radius of Curvature Test Results

	Die Thickness (um)	Die Size (mm)	Sample	RoC Failure (mm)	Failure Mode	Notes
No Thinning	725	2.5 x 2.5	1	7	Delamination	
			2	8	Delamination	
			3	12	Delamination	
		5 x 5	1	20	Delamination	
			2	20	Delamination	
			3	20	Delamination	
Traditionally Thinned Die	300	2.5 x 2.5	1	12	Delamination	
			2	12	Delamination	
			3	12	Delamination	
		5 x 5	1	30	Delamination	
			2	30	Delamination	
			3	30	Delamination	
	40	2.2 x 2.2	1	10	Materials Crack	
			2	7	Delamination	
			3	8	Materials Crack	
			1*	8	Delamination	No Overcoat
			2*	8	Delamination	No Overcoat
			3*	12	Materials Crack	No Overcoat
	20	2.2 x 2.2	1	5	Materials Crack	
			2	12	Materials Crack	
			3	10	Materials Crack	
			1*	8	Materials Crack	No Overcoat
			2*	7	Materials Crack	No Overcoat
			3*	10	Materials Crack	No Overcoat
FleX-ICs	FleX	2.5 x 2.5	1	None	NA	
			2	5	Materials Crack	
			3	5	Materials Crack	

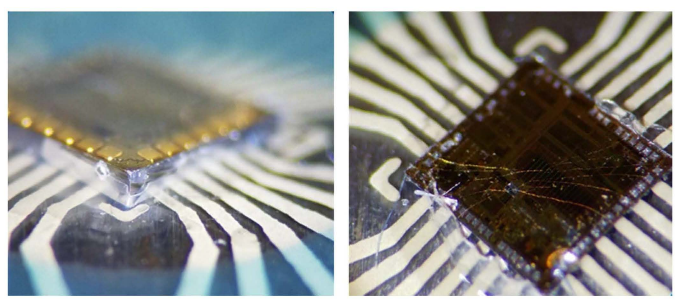

Fig. 4: 300um Die Delamination (L), 20um Materials Cracking (R)

Dynamic Radius of Curvature: FHE

Previous RoC testing was performed based on physical inspection or with pre- and post-test electrical testing. We devised testing to test radius of curvature with electrically active samples.

This test used American Semiconductor's FleX-OpAmp test coupons that 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 [7]. 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.

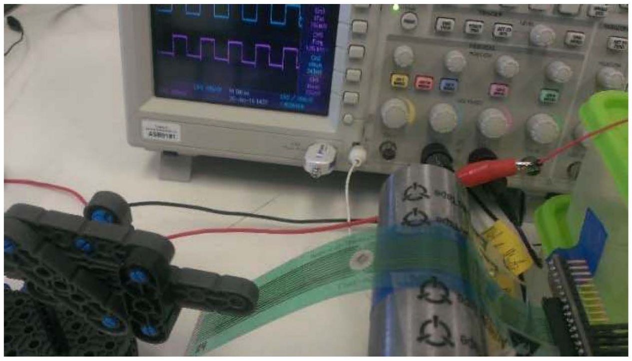

Fig. 6: 15mm Convex RoC Testing

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 [7].

The second 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 characterized by intermittent signal degradation that occurred only for extremely short durations at specific points in the flex cycles and only every 2-5 cycles. 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. Visual inspection of the sample revealed the cause of the failure of the aforementioned sample to be a crack in the printed Vdd interconnect [7].

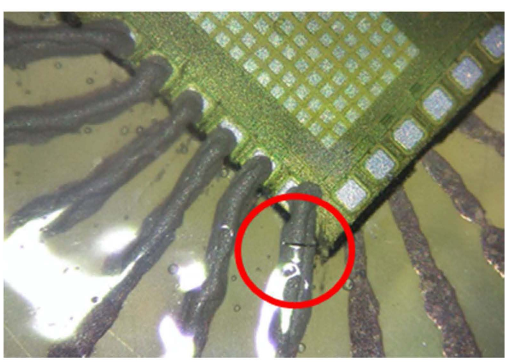

Fig. 7: Crack in Printed Interconnects on VDD Line

The Axial Torsion Test was designed to test the resilience of the flexible hybrid system to rotational stresses and complex curvatures. 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. This test 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 with indications of a severed interconnect line [7].

HTOL and LTOL: FleX-ICs and FHE

Standard testing for ICs includes High Temperature Operation Life (HTOL) and Low Temperature Operation Life (LTOL). The HTOL and LTOL tests are defined to run for 168 hours @ 125C (HTOL) and -25C (LTOL) in ambient air, under bias and electrically active where possible. The devices are tested for functionality before and after the stress test.

The initial HTOL and LTOL testing was focused on bare FleX-ADC die. The bare die were placed in the test chamber and removed at 1, 24, 48, 72, and 168 hours for test. The HTOL sample passed 168 hours at 125C without failure. The LTOL sample passed 168 hours at -25C without failure.

To facilitate comprehensive FHE testing we created flexible circuit board test coupons for compatible with HTOL, LTOL, and Highly Accelerated Stress Test (HAST) tests. The test coupons were printed on PET substrates using a roll-to-roll screen printing process. These reliability test coupons include 30-pin and 20-pin connector versions to support multiple FleX-ICs in both pad-up and flip-chip orientations. These test coupons are used with a PCB designed to support simultaneous testing of multiple devices while providing power and clock signals to electrically stress the devices under test as shown in Fig. 8.

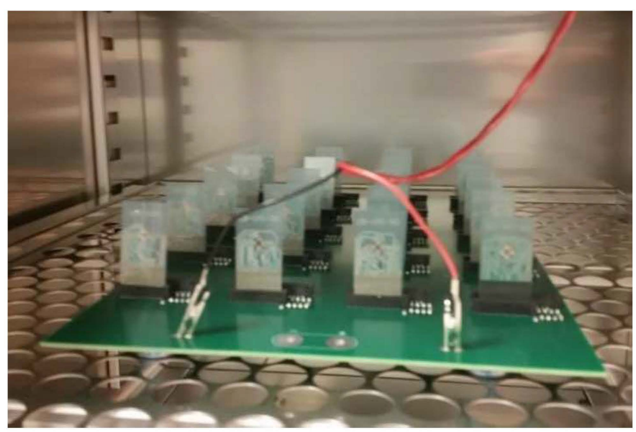

Fig. 8: FHE Test Configuration for HTOL and LTOL

At the time of writing the FHE HTOL and LTOL tests have not completed.

Electrostatic Discharge: FHE

Our procedure for ESD testing of FHE was adapted from ANSI-ESDA-JEDEC_JS-001 and JS-002. First, we established a baseline using rigid, full thickness die. Six (6) AS_ADC1004.pkg ADCs using full thickness die wire bonded to a lead frame. Three (3) parts were tested to 2kV and 3 parts were tested to 4kV using the Human Body Model test standard. After ESD testing, the parts were again tested for functionality and changes in pin leakage. The result was that the AD_ADC1004 passed all tests.

After the baseline testing, three (3) AS_ADC1004.fxd FleX-ADC die were mounted to PET substrates, inserted into packages and connected to the lead frame using conductive epoxy as shown in Fig 9. These devices passed the same 4kV Human Body Model test standard with FleX-ADC functional data.

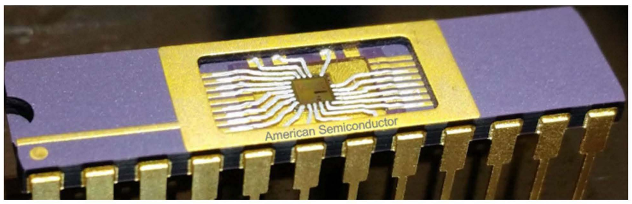

Fig. 9: FHE ESD Test Coupon

Materials Delayering Analysis: FleX-IC

Our procedure for Scanning Electron Microscope (SEM) inspection was developed from MIL-STD-883K, Method 2018.16. This test calls for layer by layer deconstruction analysis of all passivation and all 4 metal layers. The purpose of this analysis is to look for cracking, delamination, or other visual defects. For this test, six (6) thin, flexible FleX-ADC die, AS_ADC1003.fxd, were used. The devices passed the testing as no defects were attributed to the FleX SoP process. This was the expected result as it is consistent with functional testing of FleX-ICs before and after FleX conversion.

An example of the analysis results is shown in Fig. 10. This image shows the IC structures as drawn on the left and the SEM image on the right. This image is the metal 4 layer (purple) deposited on the top of the interlayer dielectric (ILD) covering metal 3 (orange). The lighter shading in the SEM image is the metal 3 layer faintly visible through the ILD.

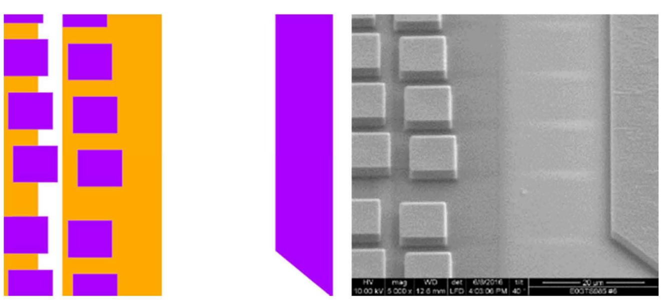

Fig. 10: FleX-IC Metal 4 Inspection Layout (L) and SEM (R)

This is a passing test with no defects present. A failure would have shown the metal or ILD layers with cracking or delamination resulting from bending or other movement allowed by the FleX process but not possible with traditionally thinned die.

Conclusions

Flexible Hybrid Electronics is a new, maturing industry that enables unique form factors and physically flexible product capability. Methods and procedures for reliability testing must evolve to evaluate these new capabilities. This paper has presented initial work that helps define new test requirements for FHE systems.

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References

1. "Flexible Hybrid Electronics Manufacturing Innovation Institute (FHE-MII)". http://www.manufacturing.gov/fhe-mii.html
2. "FlexTech Alliance Receives $75 Million Department of Defense Award to Create and Manage a Flexible Hybrid Electronics Manufacturing Facility," http://www.nextflex.us/flextech-alliance-receives-75-million-department-of-defense-award-to-create-and-manage-a-flexible-hybrid-electronics-manufacturing-facility/
3. R. Chaney, D. Hackler, "Semiconductor on Polymer Substrate," U.S. Patent 9 082 881, July 14, 2015.
4. R. Chaney, D. Hackler, "Performance Electronics Integration in Flexible Technology". GOMAC, March 2010. url: www.americansemi.com/GOMAC2010_28-18.pdf
5. R. Chaney, D. Hackler, "High Performance Single Crystal CMOS on Flexible Polymer Substrate" GOMAC, March 2011. url: www.americansemi.com/GOMAC2011_30-16.pdf
6. R. Chaney, D. Hackler, D. Wilson, B. Meek, "FleX Silicon-on-Polymer: Flexible (Pliable) ICs from Commercial Foundry Processes". GOMAC, March 2013. url: www.americansemi.com/GOMAC2013_31.2.pdf
7. D. Leber, et. al., "Electromechanical Reliability Testing of Flexible Hybrid Electronics Incorporating FleX Silicon-on-Polymer ICs". 2016 IEEE Workshop on Microelectronics and Electron Devices. April 2016. pp 38-41