

Microspring Characterization and Flip Chip Assembly Reliability

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Abstract

Electronics packaging based on stress-engineered spring interconnects have the potential to enable integrated IC testing, fine-pitch, and compliance not readily available with other technologies. We describe new spring contacts which simultaneously achieve low resistance (<100 mohm) and high compliance (>30 micron) in dense two-dimensional arrays (180 x 180 micron pitch). Mechanical characterization show individual springs operate at ~0.015 gm force. Electrical measurements and simulations imply the interface contact resistance contribution to a single contact resistance is < 40 mohms. Daisy chain test die consisting of 2844 contacts are assembled into flip chip packages with 100% yield. Thermocycle and humidity testing suggest packages with or without underfill can have stable resistance values and no glitches through over 1000 thermocycles or 6000 hrs of humidity. This work suggests that integrated testing and packaging can be performed with the springs, enabling new capabilities for markets such as multi-chip modules.

I. Introduction and motivation

Compliant interconnects have the potential to dramatically improve integrated circuit flip chip packaging. They can absorb large thermal expansion mismatches between silicon chips and substrates, simplifying packaging design as current solder based approaches are not flexible. The high stresses of lead free solder can be avoided, facilitating integration of fragile low-K dielectrics. If the compliant interconnect enables bare die testing, then integrated at-speed testing of chips before bonding to a final substrate is possible, alleviating needs for expensive known good die. Such capability could reduce the cost of multi-chip module (MCM) and system-in-package (SIP) solutions by enabling both test and packaging functions.

Stress-engineered microsprings are compliant interconnects which can be scaled to achieve a variety of properties. Previous stress-engineered springs have been designed for probe cards for probing of aluminum pads [1]. For flip chip packaging, multiple packages have been demonstrated. Silicon die with large springs (>500 μm pitch) have been assembled directly to organic substrates [2]. Because they are photolithographically defined, stress-engineered springs can offer tighter pitches than other compliant packaging approaches such as polymer bumps [3] or plated wire bonds [4]. Dense linear arrays of stress

engineered springs at both 20 μm pitch [5] and 6- μm pitch [6] have been assembled into flip chip packages.

This work describes a new stress engineered contact design for dense two-dimensional (2d) array applications such as processors. The springs achieve low resistance (<100 mohm), high compliance (>30 μm), and high yield for dense 2d arrays (thousands of contacts, 180 μm $\times$ 180 μm pitch). In Section II, spring fabrication and yield is described. Section III summarizes single spring mechanical and electrical characterization. Simulations are used to estimate the interface contact resistance (<40 mohms). In Sections IV and V, various package assemblies and their reliability testing are described. Air gap packages using spacer layers or self aligning ball and pit [7, 8] mechanisms are described, as well as packages with springs embedded in adhesive.

II. Spring fabrication

The micro-springs are fabricated with stress-engineered thin film processing. The key step is the deposition of a 1 μm thick alloy of molybdenum-chromium (MoCr) with a large stress gradient (GPa per micron). After being lithographically patterned into cantilever beams (100 μm long, 30 μm wide) and subsequently released, the spring stress relaxes, lifting the tips out of the plane, forming a 3D compliant spring interconnect. Extra metal such as gold can be electrodeposited after release to provide conductivity

and strength. Figure 1 shows a closeup of a contact, consisting of two springs in parallel, and 2D array contacts. The fabrication process uses wafer-scale processing and requires only two masks. Routing and redistribution can be performed without extra masks by using traces which are not released. The process is low temperature and has been integrated at a wafer scale onto post-cmos devices [9]. See ref [10] for other fabrication details.

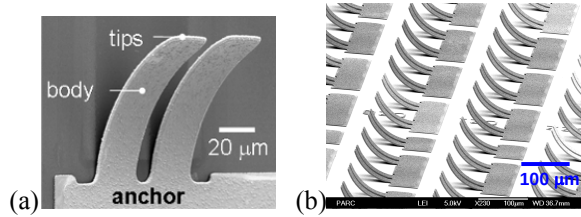


Figure 1. a) SEM of a contact and b) 2D array contacts.

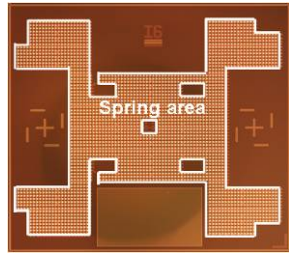


Figure 2. Spring chip die with 2844 contacts and an area of 14 mm × 16 mm.

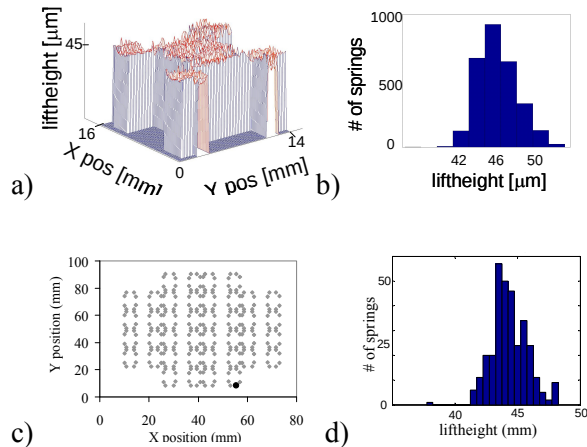


Figure 3. Spring liftheight uniformity measurements, across a chip of 2844 contacts (a,b) and across a wafer (c,d). Out of 319 measured springs spaced evenly across the wafer, only one spring on the wafer edge (dark circle) is outside of 42-48 μm (the measurement error is ± 3 μm).

The spring process is uniform and high yield. A key parameter is the liftheight, defined as the vertical distance of the tip above the substrate. Each test chip is 14 mm × 16 mm and has 2844 contacts (Figure 2). A commercially available tool (Nikon VMR-3020) was used to automatically measure the liftheights using pattern recognition. The repeatability of the measurement technique is ± 3 μm. Measurements of every spring in the chip give an average height of ~ 45 μm, with a variation equal to or less than the measurement error (Figure 4 a, b). Measurements across a 4inch wafer give similar results (Figure 4 c, d). Release yields $>99.9\%$ have been demonstrated (based on $\sim 10^5$ springs per wafer), and 100% yield has been achieved for more than half of the 20 die per wafer.

III. Single spring characteristics

Chips consisting of single spring test structures are used to measure single spring mechanical and electrical properties. The measured force versus compression of a spring is directly measured by a force scale (see [11] for setup description). Figure 4 shows the force curve is repeatable as the spring is repeatedly compressed to just under 30 μm. After full compression (not measureable), negligible liftheight change is observed. This suggests the spring is operating below its elastic regime. A typical compression in a package is 25 μm, corresponding to 0.015 gm. While this force is significantly less than many other pressure contacts, the pressure is similar (~ 15 MPa, see [12]), and thus we believe adequate for gold to gold pressure contacts.

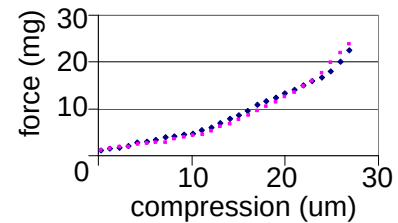


Figure 4. Measured force of a single spring

A resistance test structure was measured and modeled to study the resistance constituents. A single contact (2 spring) device in a four-wire configuration was measured as function of compression (Figure 5). Figure 6 shows a plateau of ~ 70 mohms is repeatedly achieved by 10-20 μm compression against a large gold pad.

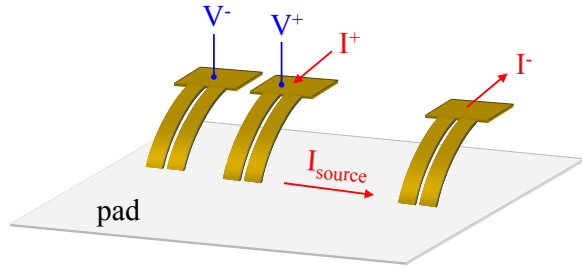


Figure 5. Four-wire resistance measurement of a contact (middle contact). I_{source} is forced from I^+ to I^- , electrical potential drop V_{sense} ($V^+ - V^-$) is monitored during compression. Electrical resistance of the middle contact is V_{sense}/I_{source} .

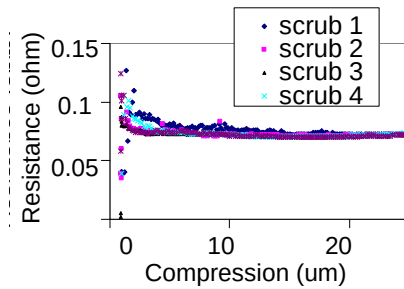


Figure 6. Four-wire resistance is monitored while spring is compressed. The plateau value is ~ 72 mohm.

Finite element modeling (FEM) was used to study the resistance components of the test structure. Using commercial software (COMSOL), a geometric model was constructed. The electrical potential distribution of the entire structure is calculated by setting I_{source} (1mA) and calculating V_{sense} (Figure 7). The simulated total resistance value equals V_{source}/I_{source} .

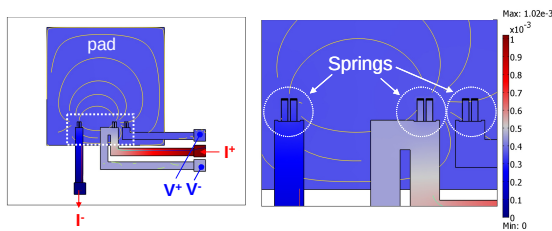


Figure 7. Electrical potential with current density arrows of single contact four-wire resistance test structure. Constant current I_{source} is forced from I^+ to I^- and potential drop V_{sense} ($V^+ - V^-$) is calculated.

Several potential-drops constitutes contribute to V_{sense} , including the lead traces, spring body, tip-pad interface and pad spreading (Figure 8). All of them are defined as effective resistance components that contribute to total measured resistance (V_{source}/I_{source}). FEM was used to determine all of these components based on measured sheet resistance and geometric

values, except for the tip-pad resistance. The tip-pad interface resistance physically consists of asperities and constriction resistance. While models for this resistance exist [13], they require assumptions concerning multiple variables, such as the effective contact area, asperity dimensions and local conductivity. We instead modeled the tip-pad interface resistance as a simple resistor and swept the value of this resistor to fit the total measured resistance.

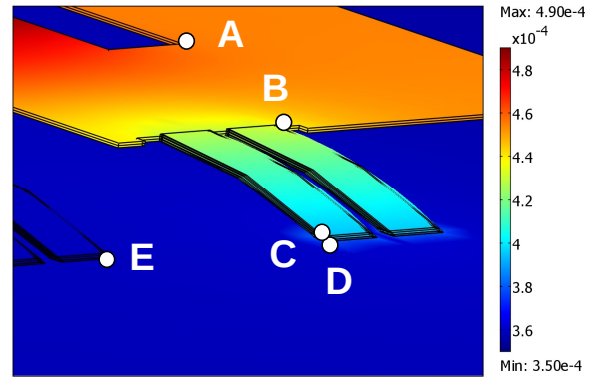


Figure 8. Electrical potential distribution of middle contact. Measured V_{sense} equals V_{A-E} , and is composed of effective lead trace V_{A-B} , spring body V_{B-C} , tip-pad interface V_{C-D} , and pad spreading V_{D-E} .

Table 1 show that 16-41% of the resistance is due to the tip-pad interface. This is an estimate of the low resistance limit for a gold-gold pressure contact with this contact area and force (11-41 mohms). This is similar to other reported values [13]. The spring body contributes another third of the resistance. This value can be lowered by changing the spring dimensions. For example, if less liftheight or compliance is required, then the spring can be shorter. The trace resistance contributes 23-33%. This routing exists to enable the measurement, and would be much less for the typical case of a spring on via (with no routing). The spreading resistance was found to be relatively negligible.

Table 1. Resistance components of one contact.

Resistance Component	Value (mohm)
Lead trace R_{A-B}	23
Spring body R_{B-C}	36
Tip-pad R_{C-D}	11-41
Pad spreading resistance R_{D-E}	~ 0
Total	70-100

IV. Package Assembly

To study reliability and packaging options, flip chip packages are assembled by placing a die with springs (see Figure 9) onto a corresponding pad chip using a variety of approaches.

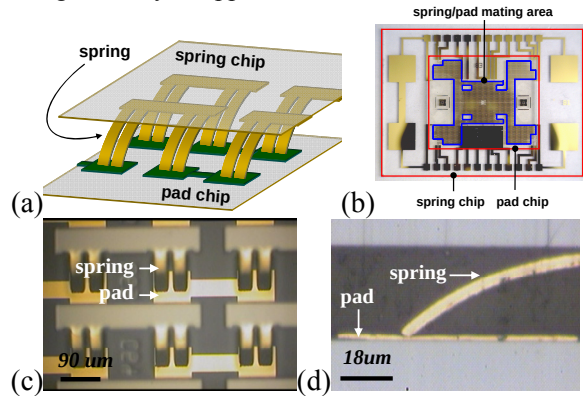


Figure 9. a) Schematic of a flip chip package with aligned springs and pads. b) Top view and closeup c) of a glass on glass package with 2844 springs landing on 2844 pads in spring/pad mating area. d) Cross section of a silicon on silicon flip chip package.

Generally two types of packages were built: springs in air and springs embedded in adhesive (Figure 10). Other important parameters include how the gap between the chips is controlled and the bonding method. The gap should insure the springs are compressed $>15 \mu\text{m}$ to operate in the resistance plateau region (Figure 6). For springs with initial liftheights of $45 \mu\text{m}$, our target gap was $20 \mu\text{m}$, corresponding to a $25 \mu\text{m}$ compression. The gap was defined by using a polyimide spacer wall on the pad chip, a precise ball and pit scheme [8], or precision assembly. The bonding methods used were either adhesive on the edges/corners, corners only, adhesive all along the edges, or adhesive everywhere. Note that for the adhesive everywhere case, the adhesive can be applied onto the spring chip before assembly, or after assembly by wicking from the edges (underfill). An activator can be mixed with adhesive to cure or UV cure can be used for the adhesive on the edges. Note the spring and pad substrates were either silicon or glass. The glass substrates aid inspection during development and have the same thermal expansion coefficient as silicon.

The relative merits of each assembly approach depend on the application requirements. Springs in air are easier to rework. In previous work we showed springs in air with no adhesive, as they were bonded through a clamping mechanism [8]. Such an approach could be appropriate for large high-end multichip modules, where easy rework is particularly important. Springs in adhesive can have lower profiles (no clamp on top),

and have extra protection from the environment. These cannot be readily reworked, but at speed testing can be performed before bonding. Gap control based on a spacer layer is substrate independent, while the ball and pit approach requires silicon substrates.

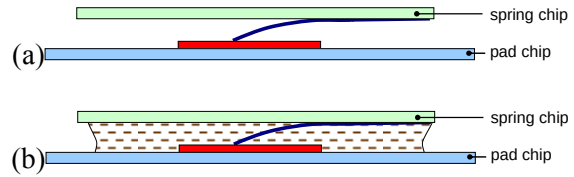


Figure 10. Schematic of two package types. a) Spring and contact are in air or b) springs embedded in adhesive.

V. Package Testing

Thermocycle testing consisted of cycling between $0-100^\circ\text{C}$ with 10 min dwells. The packages were wired to an event detector so that any momentary resistance increase in any one of the 2844 contacts longer than 200 nsec is detected as a glitch. For humidity testing the packages were stored in an 85°C , 85% RH oven. Periodically the packages were removed from the thermocycle and humidity ovens and 4-wire resistance measurements of the daisy chains were taken (Figure 11). The measured resistance is comprised of the spring resistance (body, tip-pad interface, spreading) and significant amounts of spring trace and pad trace. These measurements used an automated pogopin setup which had a system repeatability of approximately $\pm 5\%$, corresponding to $\pm 10-20$ mohm for the 2 contact chains.

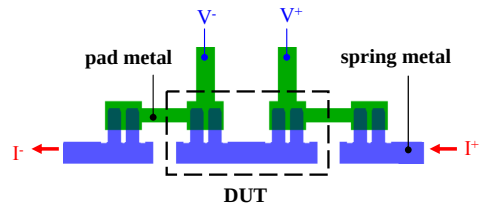


Figure 11. I_{source} is forced from I^+ to I^- , electrical potential drop V_{sense} ($V^+ - V^-$) is measured. DUT (device under test) resistance equals to $V_{\text{sense}}/I_{\text{source}}$.

Table 2 summarizes the reliability testing. None of the packages have shown glitches during thermocycling. The majority of resistances were stable or decreased from initial values through over >1000 thermocycles and 2000-6500 hrs in humidity. No increases over 15% were observed, unless noted by an obvious defect.

Within the air-gap packages, the resistance tended to decrease during testing if pre-scrubs were

performed (see Package C). To pre-scrub, the die is compressed and retracted five times after alignment, but before bonding. We believe this helps to clean the tips and pads as well as increase the effective contact area. Separate mate and re-mate tests show that scrubbing can reduce the resistances by 5 to 20%. Air gap packages with the pre-scrubs more consistently showed resistance decreases with time, possibly caused by an annealing of the interface contact or increase in the effective contact area during cycling. Thermocycle data for package similar to Package C is reported in reference [8], and shows similar results.

For the springs embedded in adhesive, very stable or decreasing resistance values were observed for both thermocycle and humidity testing. The package which was underfilled after assembly (E) showed stable or decreasing resistance values. These packages did not have pre-scrubs. Performing pre-scrubs might reduce the initial resistance values and improve reliability performance.

Table 2. Summary of package reliability tests.

Package	Springs	Adhesive	Gap Stop	Humidity (hours)	Thermocycle (cycles)	Resistance	Pre-scrubs
A	In Air	Edges and corners	spacer layer		1017	+/-15%	NO
B	In Air	Edges and corners	NONE	6474		mostly increasing, submerged	NO
C	In Air	Perimeter	balls/pits	2347		decreasing	YES
D	Embedd ed	Pre-mixe activator	spacer layer		1082	mostly decreasing	NO
E	Embedd ed	underfill pre-mixe activator	spacer layer		1112	stable or decreasing	NO
F	Embedd ed	Pre-mixe activator	spacer layer	7746		stable or decreasing	NO

Detailed reliability results for packages with springs in air and springs embedded in adhesive are given in Figure 12-Figure 19 and Figure 20-Figure 25 respectively. All 4wire measurements of contacts are reported for each package (2608 total). In general, the initial uniformity of the measurements within each contact chain type (highlighted) is < 5% within a package. Variations between packages are attributed to unintended variations between the spring trace and pad trace metal thickness.

Certain chains with relatively higher resistance are denoted with asterisks. Inspections showed that most were caused by clear assembly or spring fabrication defects, such as particles near the spring tips, lithography defects, or air bubbles in the case of adhesive. It is important to avoid these defects,

as during assembly process development, it was observed that these defects could also cause clear failures like large resistance increases or opens.

Air-Gap Package (Thermocycle)

Package A: Package gap is defined by a lithographically defined polyimide spacer. The UV adhesive holds the spring and pad chips together after UV curing. The adhesive is applied at four corners of the chip, see and Figure 12 and Figure 13.



Figure 12. Schematic of assembled Package A.

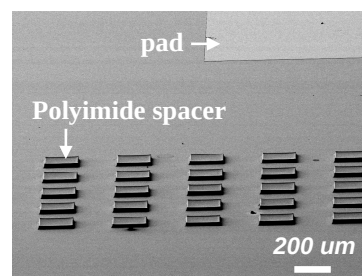


Figure 13. SEM of polyimide spacer.

contacts per chain	Four-wire resistance, ohms			% change
	initial	680 cycles	1017 cycles	
2	0.311	0.295	0.331	6.7
2	0.339	0.315	0.380	12.2
2	0.428	0.352	0.364	-15.0
2	0.359	0.307	0.331	-8.0
2	0.336	0.323	0.372	10.6
2	0.330	0.306	0.348	5.5
2	0.285	0.247	0.243	-14.8
2	0.256	0.223	0.252	-1.9
2	0.212	0.205	0.241	13.5
2	0.234	0.236	0.231	-1.2
134	34.169	32.647	35.721	4.5
134	33.939	32.441	37.052	9.2
246	78.243	74.439	82.067	4.9
246	76.159	73.245	80.273	5.4
384	115.130	95.642	102.313	-11.1
384	95.708	90.505	96.802	1.1
530	141.370	130.510	134.848	-4.6
530	132.800	128.357	136.344	2.7
total 2608				

Figure 14. Package A thermocycling measurements.

Air-Gap Package (Humidity)

Package B: Package gap control is performed by a precision flip chip assembler. The UV adhesive holds the spring and pad chips together after UV curing, see Figure 15.

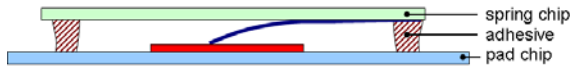


Figure 15. Schematic of assembled Package B.

contacts per chain	Four-wire resistance, ohms			% change
	initial	1015 hours	6474 hours	
2	0.405	0.420	0.448	10.8
2	0.418	0.419	0.459	9.9
2*	0.097	0.100	0.129	33.4
2	0.386	0.391	0.418	8.3
2	0.416	0.410	0.407	-2.2
2	0.407	0.407	0.406	-0.2
2**	0.310	0.345	0.401	29.4
2	0.357	0.366	0.407	14.2
2	0.307	0.312	0.317	3.3
2	0.360	0.379	0.392	9.0
132	40.448	41.252	43.118	6.6
132	38.554	39.707	38.602	0.1
246	82.412	84.219	88.270	7.1
246	77.789	79.157	78.930	1.5
384	108.800	113.265	119.071	9.4
384	109.931	109.782	113.748	3.5
530	152.799	157.965	161.965	6.0
530	159.962	161.684	159.326	-0.4
total 2608				

Figure 16. Package B humidity measurements. *Chain resistance is low initially, due to suspected electrical short **Chain increase cause unknown, though possibly water related as packages was accidentally submerged in water and then subsequently dried.

Package C: Package gap defined by self-aligned balls and pits. Adhesive on edges holds the spring and pad chips together after UV curing (Figure 17 and Figure 18)

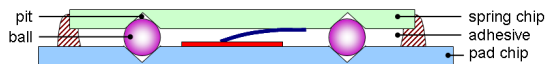


Figure 17. Schematic of assembled Package C.

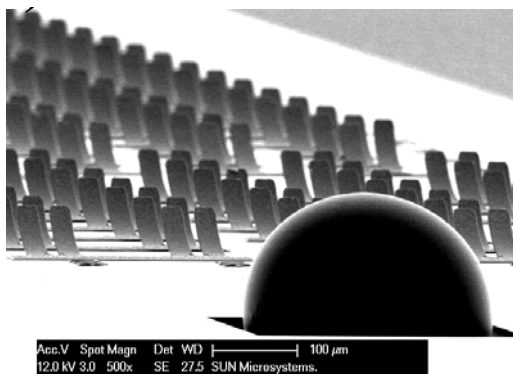


Figure 18. SEM of balls/pits with springs[8].

contacts per chain	Four-wire resistance, ohms			% change
	initial	909 hours	2347 hours	
2	0.352	0.349	0.352	0.1
2	0.367	0.358	0.360	-1.8
2	0.351	0.347	0.347	-1.1
2	0.371	0.356	0.355	-4.5
2	0.388	0.368	0.365	-6.0
2	0.390	0.366	0.363	-6.8
2*	0.234	0.242	0.263	12.2
2	0.243	0.245	0.245	0.7
2	0.262	0.251	0.247	-5.7
2*	0.258	0.271	0.283	9.6
134	46.012	44.551	44.359	-3.6
134	46.597	44.587	44.301	-4.9
246	90.377	89.284	89.090	-1.4
246	93.151	90.352	89.807	-3.6
384	128.603	127.055	127.238	-1.1
384	132.793	127.651	127.068	-4.3
530	177.211	177.477	178.036	0.5
530	185.669	180.171	179.276	-3.4
total 2608				

Figure 19. Package C humidity measurements. *Chains increasing; suspected gap issue because both on corner of package.

Embedded Package (Thermocycles)

Package D: Package gap is defined by polyimide spacer. Contact area is cured by activator which is activated/cured by activator. Non-contact area is cured by adhesive which is cured by UV light. , see Figure 20.

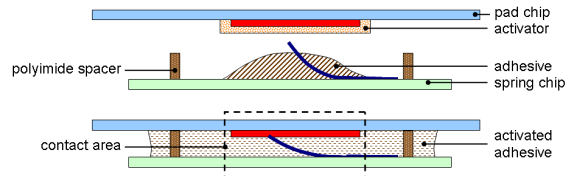


Figure 20. Adhesive near the contacts of Package D are cured by activator and edges are cured by UV light.

contacts per chain	Four-wire resistance, ohms			% change
	initial	435 cycles	1082 cycles	
2	0.232	0.222	0.217	-6.5
2	0.232	0.233	0.226	-2.7
2	0.240	0.255	0.247	2.8
2	0.230	0.247	0.246	6.9
2	0.230	0.219	0.216	-6.1
2	0.236	0.222	0.214	-9.2
2	0.191	0.189	0.201	5.3
2	0.206	0.190	0.190	-7.9
2	0.189	0.178	0.177	-6.3
2	0.194	0.198	0.193	-0.8
134	29.303	28.243	28.135	-4.0
134	29.579	28.474	28.240	-4.5
246	60.408	58.821	58.705	-2.8
246	60.539	58.866	58.658	-3.1
384	87.527	85.201	84.465	-3.5
384	87.801	86.363	86.353	-1.6
530	116.468	113.676	113.717	-2.4
530	119.233	115.577	114.736	-3.8
total 2608				

Figure 21. Package D thermocycle measurements.

Package E: After assembly, UV adhesive on the corners only holds the package. The package is underfilled by the self-curing and UV curable mixture. Non-contact area on edge is cured by UV light, see Figure 22 and Figure 23.

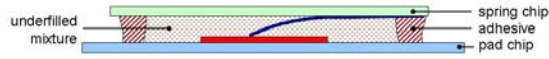


Figure 22. Schematic of Package E.

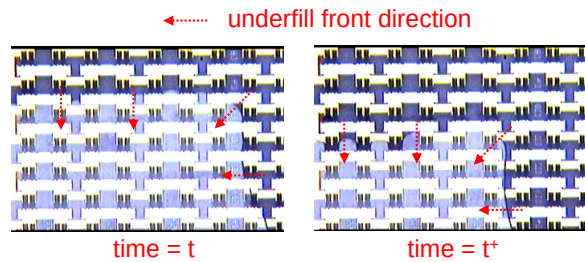


Figure 23. Image of Package E during underfill.

contact per chain	Four-wire resistance, ohms			% change
	initial	322 cycles	1112 cycles	
2	0.238	0.230	0.228	-4.1
2	0.233	0.229	0.228	-2.2
2	0.220	0.218	0.215	-2.4
2	0.229	0.227	0.225	-2.1
2	0.238	0.228	0.228	-4.3
2	0.242	0.227	0.225	-6.7
2*	0.181	0.173	0.201	11.0
2	0.173	0.164	0.162	-6.5
2	0.165	0.159	0.157	-5.2
2	0.171	0.182	0.172	0.8
134	28.836	28.066	27.848	-3.4
134	29.022	28.269	28.051	-3.3
246	59.129	57.584	57.054	-3.5
246	59.777	57.961	57.408	-4.0
384	82.418	82.069	81.327	-1.3
384	78.453	78.585	77.799	-0.8
530	117.680	113.601	113.111	-3.9
530	117.205	114.195	115.975	-1.0
total 2608				

Figure 24. Package E thermocycle measurements.
*Chain had a bubble contacting springs, caused by insufficient underfill supply.

Embedded Package (Humidity)

Package F: The assembly method is the same as package D.

contacts per chain	Four-wire resistance, ohms			% change
	initial	160 hours	7746 hours	
2	0.362	0.357	0.346	-3.1
2	0.364	0.357	0.348	-2.7
2	0.356	0.361	0.359	-0.4
2	0.365	0.371	0.360	-2.9
2	0.375	0.370	0.359	-2.9
2	0.146	0.374	0.360	-3.7
2	0.344	0.275	0.285	3.7
2	0.353	0.344	0.277	-19.4
2	0.258	0.262	0.248	-5.5
2	0.180	0.293	0.282	-3.7
134	44.753	44.406	43.434	-2.2
134	44.495	44.229	43.211	-2.3
246	90.561	93.858	89.506	-4.6
246	90.511	98.071	90.528	-7.7
384	127.219	128.525	125.921	-2.0
384	128.287	129.145	126.373	-2.1
530	177.553	175.475	172.228	-1.9
530	7799.544	180.266	176.815	-1.9
total 2608				

Figure 25. Package F thermocycle measurements.

VI. Summary and conclusion

A micro-spring capable of low resistance (<100 mohms), high compliance (>30 μm) and dense 2d array (180 μm $\times$ 180 μm pitch) has been demonstrated. Lower resistances are possible for different spring geometries, as the tip-pad interface is <40 mohms. High yield and uniform fabrication enabled 100% assembly yield flip chip packages with thousands of contacts. Springs in air and springs embedded in adhesive were shown to have stable or decreasing resistances during thermocycle and humidity testing. Pre-scrubbing the tips is a beneficial assembly step.

VII. Acknowledgements

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