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Effects of Dielectric Material, Aspect Ratio and Copper Plating on Microvia Reliability

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ABSTRACT
This paper documents test data on the effects of materials and processes on microvia structures. Thirteen sets of experiments were carried out to evaluate the effects of dielectric material, aspect ratio, via morphology, surface preparation, temperature and copper plating type and thickness on microvia reliability. Reliability was assessed by subjecting boards and coupons to thermomechanical stress using four test methods: hot oil immersion, thermal shock, oven reflow simulation and Interconnect Stress Test (IST).

INTRODUCTION
Past studies have shown that, when fabricated with proper materials and processes, printed circuit board (PCB) microvias are more reliable structures than plated through holes (reference 1). However, microvias have narrower material/process windows which can lead to quality and reliability issues. The most commonly-cited failure mode for microvias has been intermittent or open connections, and failure mechanisms include adhesive failure at the base of the microvia, or plating fractures (reference 2).

A large number of variables contribute to microvia adhesive failures, including temperature excursions and z-axis material expansion/contraction effects; via aspect ratio and morphology; copper plating quality and thickness; via fill; cleanliness and surface roughness of the capture pad. Many incidences of interface separation have been caused by impurities in the copper plating or incomplete cleaning of residues from laser drilling (reference 4). Reference 5 states that the base material and lamination quality have an overriding influence on microvia interconnect defects, relative to electroless copper. Past studies have shown that the most reliable microvia structures have depth-to-width aspect ratios less than 0.7:1, and a bowl shape rather than cylindrical shape (references 1, 6). In the past, the prevalent upper temperature limit for IST has been 150°C, but reliability testing has shown that higher test temperatures, up to 190°C, may be needed to simulate the stresses seen in oven reflow and bring about microvia failures in IST (reference 3). This is especially relevant for printed wiring boards that are subjected to lead-free processing temperatures.

The purpose of this study was to determine the compatibility and relative reliability of different dielectric materials and processes used in the fabrication of microvias.

TEST METHODS
Variables in the testing included

- PCB dielectric material
- Dielectric material thickness (microvia aspect ratio)
- Laser drilling process sequence
- Board/coupon bake out vs. no bake out
- Type of copper at capture pad: electroless vs. electrolytic
- Via fill: copper vs. epoxy
- Type of thermal stress test
- Temperature of stress test

The tests were conducted on either unpopulated PCBs or representative coupons from the board fabrication panels. The board stack up consisted of 14 layers with plated through holes, buried vias and blind vias, including 6 mil diameter laser drilled microvias between layers 1-2 and 13-14.

Four different modified-FR4 type dielectric materials were used. They will be referred to as materials A through D. Their properties are shown in Table 1. The materials were all modified epoxy-glass; they were chosen to test differences in Z-axis CTE, Tg and Td.

Table 1. Dielectric Materials

Material	Description	IPC spec	Z axis CTE Alpha1 (ppm/°C)	X-Y axis CTE (ppm/°C)	Tg (°C)	Td (°C)	Moisture absorption (weight %)
A	High speed, low loss enhanced epoxy	4101/29	70	10-14	200-210	350	0.1
B	High performance FR4/e-glass	4101/21, 24, 98, 99, 101, 126	55	16	200-230	360	0.24
C	Low dielectric constant, high heat resistant	4101/24, 32, 97, 99, 101, 126	35-45	NA	180-190	370-390	0.03-0.04
D	High speed multifunctional epoxy	4101/29	65	10-14	200-240	350	0.1

Two different processes were used for laser drilling the microvias and preparing the capture pad surface for electroless copper deposition. Most of the microvias were fabricated using the following "baseline" process:

UV laser - CO2 laser - UV laser - high pressure rinse - plasma clean - electroless copper

One set of microvias was fabricated using an "enhanced" process that roughened the capture pad and provided a slightly concave capture pad surface. Both of these factors enhance adhesion. The "enhanced" laser drill process is shown below:

UV laser - CO2 laser - UV laser - high pressure rinse - plasma clean – chemical clean - electroless copper.

Figure 1 illustrates microvias made with the different processes.

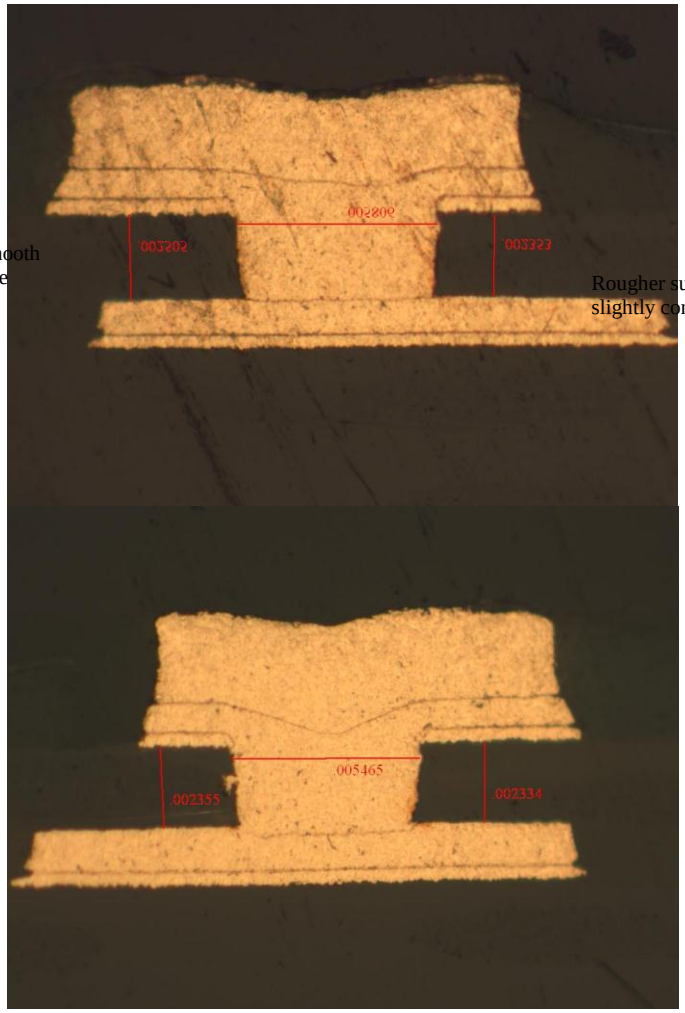


Figure 1. Microvias made with the "baseline" surface preparation process (left), and the "enhanced" process (right).

Figure 2 shows microvias with different height to width ratio, aka the aspect ratio. In this study, the width of the microvias was held relatively constant; the target being a 6 mil diameter laser drilled hole. The height of the via was determined by the amount of prepreg, both the number of plies and ply thickness.

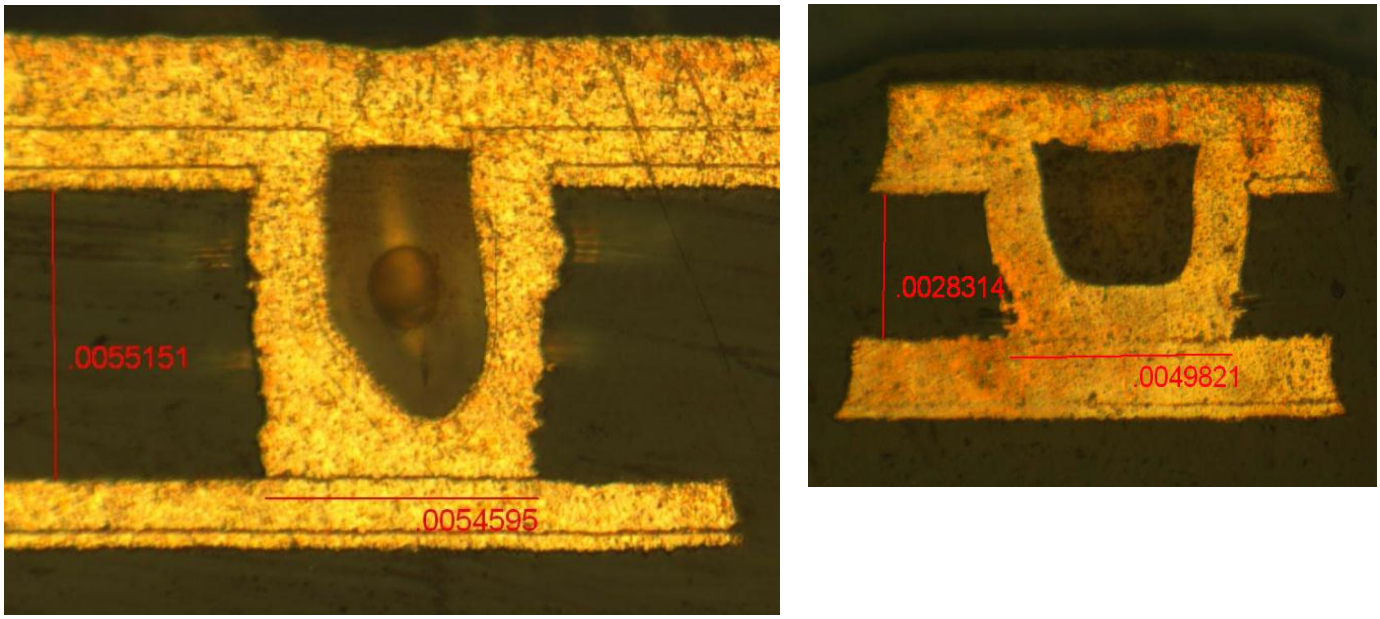


Figure 2. Examples of microvia morphology and aspect ratio. Microvias were filled with nonconductive epoxy. (left) High aspect ratio microvia made with 2 plies of prepreg. The height:width ratio is approximately 1:1 -- width 5.5 mil, depth 5.5 mil. (right) Lower aspect ratio microvia made with 1 ply of prepreg. These microvias had aspect ratio less than 0.6:1 -- width 5 mils, depth 2.8 mils. The higher aspect ratio resulted an a more cylindrical-shaped via, whereas the shorter via had more of a bowl shape.

Four different thermal stress methods were used to evaluate the robustness of microvias: hot oil immersion, thermal shock test, oven reflow simulation and Interconnect Stress Test.

Hot oil immersion is a thermal shock test that gives fast and useful qualitative data on the robustness of boards or coupons. It is an accelerated stress test, similar to a solder float test commonly performed on board coupons that mimics the temperature extremes of a solder reflow oven without the controlled ramp up. The test procedure used in this study was a modified version of IPC-TM-650 method 2.4.6. The entire board, initially at room temperature, was completely immersed in a hot oil bath for a minimum of 10 seconds. Normally used for reflow of electroplated tin-lead, the oil bath was maintained at 425 ± 5º F (218ºC). The boards were allowed to cool at room temperature for a minimum of 10 minutes prior to the next immersion. Boards were electrically tested by flying probe before the first cycle and after each subsequent set of 5 cycles, with pass/fail criterion for continuity at 10 ohms. The IPC test method 2.4.6 does not specify a pass/fail criterion on number of immersion cycles for high reliability applications, but in this study, robust board constructions survived 30 hot oil immersion cycles.

The second type of stress test was thermal shock. Coupons were cycled from -65 to 125°C, consistent with IPC-TM-650, method 2.6.7.2, for 400 cycles. Thermal shock testing in a chamber had a slightly slower transition, but more extreme lower temperature, than hot oil immersion. The total temperature difference was about the same as hot oil immersion, but the chamber cycling did not surpass the Tg of the dielectric materials.

Oven reflow simulation is similar to "pre-conditioning" used in IST or thermal shock testing. It mimics the thermal stress experienced by a PWB during solder reflow in a multi-zone oven. Thermal ramp up and down are controlled so that the device under test is not thermal shocked.

IST was the primary test method used in this study. IST coupons were pre-conditioned with 3 simulated oven cycles up to 230°C peak temperature. Coupons were cycled from room temperature to either 150°C or 190°C.

RESULTS

Hot Oil Immersion. Fifteen complete, bare boards made with dielectric material A were subjected to hot oil immersion testing. Each board contained 3,595 microvias. Nine of the boards were constructed with microvia aspect ratio 1:1, and six of the boards were constructed with microvia aspect ratio 0.6:1. Microvias were filled with nonconductive epoxy or copper. The boards had not previously been exposed to any assembly processes or bake out, with the exception of 2 boards which were baked at 250°F (121°C) for 8 hours. Boards were electrically tested after every set of 5 or 10 immersion cycles. Table 2 shows the test results, up to 30 immersion cycles.

Table 2. Hot Oil Immersion Test Results

					Hot oil immersion cycles					
Sample	Material	µvia fill	Baked prior to test?	Microvia aspect ratio	5x	10x	15x	20x	25x	30x
1	A	Epoxy	N	1:1	Pass					
2	A	Epoxy	N	1:1	Pass	Pass	Pass	Pass		
3	A	Epoxy	N	1:1	Pass	Pass	Pass	Pass	Pass	Pass
4	A	Epoxy	N	1:1	Pass	Pass	Pass	Pass	Pass	Pass
5	A	Epoxy	N	1:1	Pass	Pass	Pass	Pass	Pass	1 open
6	A	Epoxy	N	1:1	Pass	Pass	Pass	1 open	2 opens	3 opens
7	A	Epoxy	N	1:1	Pass	Pass	2 opens	2 opens	2 opens	5 opens
8	A	Epoxy	N	1:1	Pass	Pass	3 opens	11 opens	12 opens	15 opens
9	A	Epoxy	Y	1:1	Pass	Pass	Pass	Pass	Pass	Pass
10	A	Epoxy	N	0.6:1	Pass	Pass	Pass	Pass	Pass	Pass
11	A	Epoxy	N	0.6:1	Pass	Pass	Pass	Pass	Pass	Pass
12	A	Epoxy	N	0.6:1	Pass	Pass	Pass	Pass	Pass	Pass
13	A	Epoxy	N	0.6:1	Pass	Pass	Pass	Pass	Pass	Pass
14	A	Epoxy	N	0.6:1	Pass	Pass	Pass	Pass	Pass	Pass
15	A	Epoxy	N	0.6:1	Pass	Pass	Pass	Pass	Pass	Pass
16	D	Copper	Y	0.7-0.8:1	Pass	Pass		Pass		Pass
17	D	Copper	N	0.7-0.8:1	Pass	Pass		Pass		Pass
18	D	Copper	N	0.7-0.8:1	Pass	Pass		Pass		Pass
19	D	Copper	N	0.7-0.8:1	Pass	Pass		Pass		Pass
20	D	Copper	N	0.7-0.8:1	Pass	Pass		Pass		Pass
21	D	Copper	N	0.7-0.8:1	Pass	Pass		Pass		Pass
22	D	Copper	N	0.7-0.8:1	Pass	Pass		Pass		Pass
23	D	Copper	N	0.7-0.8:1	Pass	Pass		Pass		Pass

Observations from the hot oil immersion testing:

- 4 out of the 7 boards tested to 30 immersion cycles, constructed with aspect ratio 1:1, and not baked prior to immersion, failed at least one location.
- One board constructed with aspect ratio 1:1 and material A, and baked prior to immersion, passed after 30 cycles.
- 6 out of 6 boards constructed with aspect ratio 0.6:1 and material A, and not baked prior to immersion, passed after 30 cycles.
- 8 out of 8 boards constructed with aspect ratio 0.7-0.8:1 and material D passed after 30 cycles.
- A low percentage of microvias failed. The largest number of failed microvias on any one board was 15 out of 3595 (0.4%) after 30 cycles.
- Location of the failures on the board was random.
- No delamination or blisters were observed on any boards.

Thermal Shock. Thermal shock testing was completed in a dual chamber oven per IPC-TM-650, method 2.6.7.2, on 30 "D" type coupons fabricated per IPC-2221. The coupons were built on the same panels as boards, with material A, from 2 separate lots. The temperature extremes were -65°C to 125°C and the transfer time was less than 2 minutes. A previous study concluded that 100 cycles of thermal shock testing from -65 to 125 °C induced the same level of fatigue stress damage as 300 IST cycles from room temperature to 150°C (reference 9).

Each coupon contained 30 microvias, constructed with aspect ratio 0.5 to 0.6:1, and filled with nonconductive epoxy. The coupons were not pre-conditioned. The coupons were electrically tested after every 100 thermal shock cycles. There were no failures of any microvias in the thermal shock test. No delamination or blisters were observed on any boards

Reflow Oven Simulation. 72 coupons were subjected to repeated oven reflow cycles. The oven cycles had peak temperature 260°C and controlled ramp up /down to avoid thermal shock. This method was designed to avoid thermal shock but to reach the highest peak temperature of any of the thermal stress methods and surpass the Tg of the dielectric materials with

comfortable margin. Twelve coupons from 6 different lots, constructed with material D, were tested. Each coupon contained 90 daisy-chained microvias with aspect ratios 0.7-0.8:1 and plated shut with copper. A total of 42 oven cycles was completed on each coupon, plus one set of 5 hot oil immersion cycles at the end. Coupons were probed for electrical resistance before and after each set of 6 cycles. Failures were observed on 2 of the 6 lots, and the failures were observed early in the test. No delamination or blisters were observed on any boards.

Table 3. Reflow Oven Simulation Results

					Oven cycles							Hot oil
Lot	Material	µvia fill	Microvia aspect ratio	Electrolytic copper thickness (inch)	6x	12x	18x	24x	30x	36x	42X	5X
1	D	Copper	0.7-0.8:1	.0003-.0006	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
2				0-.00007	FailΔR 1/12	FailΔR 1/12	FailΔR 1/12	FailΔR 1/12	FailΔR 1/12	FailΔR 1/12	FailΔR 1/12	FailΔR 1/12
3				.00023-.0006	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
4				0-.0001	FailΔR 1/12	FailΔR 2/12	FailΔR 3/12	FailΔR 3/12	FailΔR 3/12	FailΔR 3/12	FailΔR 3/12	FailΔR 4/12
5				0	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass
6				.00014-.00034	Pass	Pass	Pass	Pass	Pass	Pass	Pass	Pass

Interconnect Stress Test. Fourteen sets of IST coupons were tested, including tests of different dielectric materials, microvia aspect ratios, and hole preparation. Table 4 shows a summary of the results. Each test set (row in Table 4) consisted of 6 IST coupons, and each coupon contained 99 microvias. All microvias were filled with nonconductive epoxy. Materials A, B, C and D were used, and the microvia aspect ratios varied between 1:1 and 0.5:1. The coupons were pre-conditioned with 3 simulated oven cycles to 230°C peak temperature. 190°C and 150°C were used for the IST peak temperatures. The pass/fail criterion was established at 10% resistance change.

Table 4. IST results

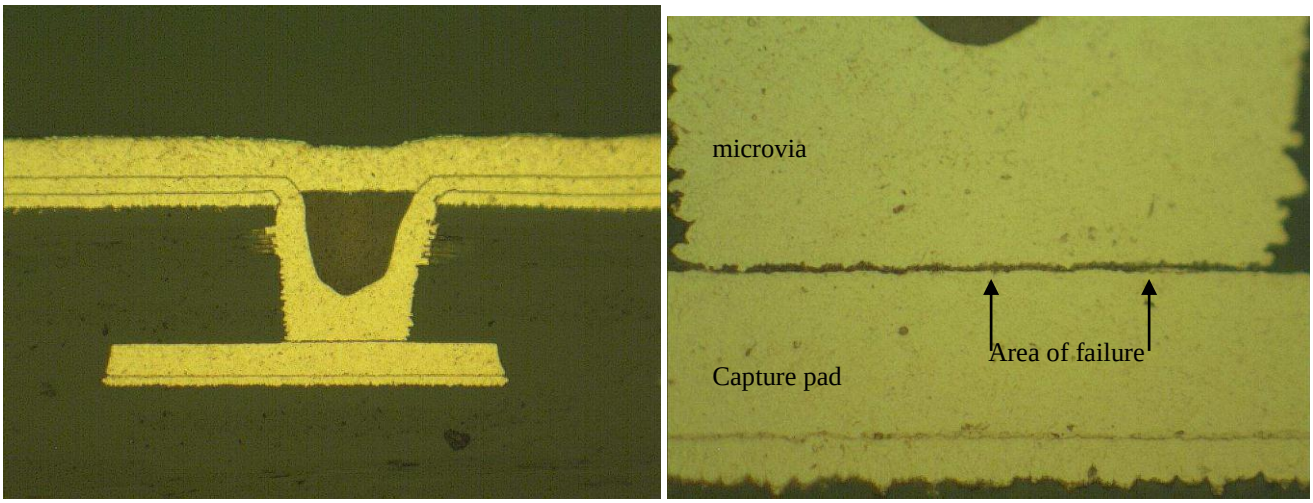
Round of test	Test temp	Material	µvia fill	µvia process	µvia aspect ratio	Preconditioning result	IST result
1	190°C	A	epoxy	Baseline	1:1	Fail >10% ΔR	Fail
		B		Baseline	1:1	Pass	Fail: >10% ΔR between 24th cycle and 89th cycle
		C		Baseline	1:1	Pass	Pass: 5 of 6 coupons had <10% ΔR after 500 cycles. 1 coupon had >10% ΔR after 446 cycles
2	190°C	A		Baseline	1:1	Fail >10% ΔR	Fail
		B		Baseline	1:1	Pass	Fail: >10% ΔR between 1 cycle and 61 cycles
		C		Baseline	1:1	Pass	Pass: <10% ΔR after 500 cycles
3	150°C	A		Baseline	1:1	Fail >10% ΔR	Fail
		B		Baseline	1:1	Pass	Pass: <10% ΔR after 1000 cycles
		C		Baseline	1:1	Pass	Pass: 4 out of 5 coupons had <10% ΔR after 1000 cycles. 1 coupon had >10% ΔR after 996th cycle
4	150°C	A		Baseline	0.5:1	Pass	Pass: <10% ΔR after 1500 cycles
		A		Enhanced	0.5:1	Pass	Pass: <10% ΔR after 1500 cycles
		B		Baseline	0.5:1	Pass	Pass: <10% ΔR after 1500 cycles
		C		Baseline	0.5:1	Pass	Pass: <10% ΔR after 1500 cycles
5	150°C	D		Enhanced	07:1	Pass	Pass: <10% ΔR after 600 cycles

Observations from the IST data:

- 3 out of 3 sets of microvias made with material A and 1:1 aspect ratio failed after preconditioning. The resistance rapidly increased further with thermal cycling.
- 2 out of 2 sets of microvias made with material A and 0.5:1 aspect ratio passed 1500 IST cycles. Coupons with varying degrees of surface roughness at the via-to-capture pad interface passed 1500 cycles. This suggests that the microvia aspect ratio is a strong effect and surface preparation is a lesser effect.
- Material greatly impacted the reliability of microvias. Material C was most robust, and Material A was least robust.
- 3 out of 3 sets of microvia coupons made with material C and 1:1 aspect ratio passed 1000 IST cycles. The set of coupons made with material C and 0.5:1 aspect ratio passed 1500 cycles.
- 2 out of 2 sets of microvias made with material B and 1:1 microvia aspect ratio failed at less than 100 cycles at 190°C, but a third set passed 1000 cycles when tested to 150°C. Material B was more robust than Material A, but still marginal.
- Coupons made with material D and 0.7:1 microvia aspect ratio passed 600 cycles.
- No delamination or blisters were observed on any coupons.

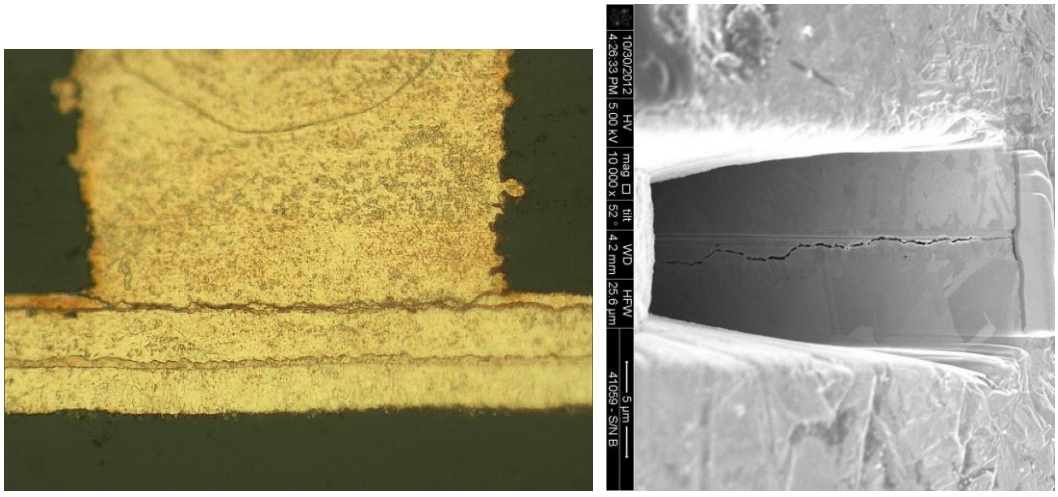
ANALYSIS

Board and coupon failures were isolated to discontinuities across microvias. Failed microvias were analyzed by cross section, FIB and SEM to determine the failure mechanism. In this study, all failures occurred at the interface between the microvia and the capture pad, as illustrated in Figure 3. In some cases, it was easy to see separation under a microscope, for example in Figure 3. However, in other cases, such as Figure 4, there was a line of demarcation at the base of the microvia but it was hard to tell at 1000X magnification whether or not there was separation between the microvia and capture pad. In those cases, cracks became visible 10,000X magnification, after the interface had been smoothed by Focused Ion Beam (FIB).



200X 1000X

Figure 3. Cross section images of failed microvia.



700X 10,000X

Figure 4. Cross section and SEM images of failed microvia

The FIB/SEM images showed separation within the electroless copper layer at the base of the microvia. The images led to these conclusions:

- Failure mechanism was brittle fracture of electroless copper. The most likely cause was fatigue stress brought about by the differential expansion and contraction between the dielectric and copper.
- Failures were cohesive rather than adhesive.
- Failures were not the result of residues or incomplete cleaning of the capture pad.
- Besides the microvia failures, there was evidence of thermal stress in the PWBs, but no evidence of thermal overstress.
- Any variation in the quality of electroless plating, such as voids or low density, weakened the copper and contributed to fractures.
- In some cases (discussed below), there was minimal electrolytic copper cap on the target pad at the base of failed microvias.

Most of the microvias that failed in test showed acceptable plating quality, and would not have been flagged during final PWB fabrication inspection. Detachment of the microvias from the capture pad suggests a strong z-axis effect which explained the trends with different materials. Material A, with the highest z-axis CTE, showed the most defects in thermal stress testing, while Material C had the lowest CTE and failure rates. Figure 5 illustrates the strong effect of the dielectric material on microvia reliability in IST.

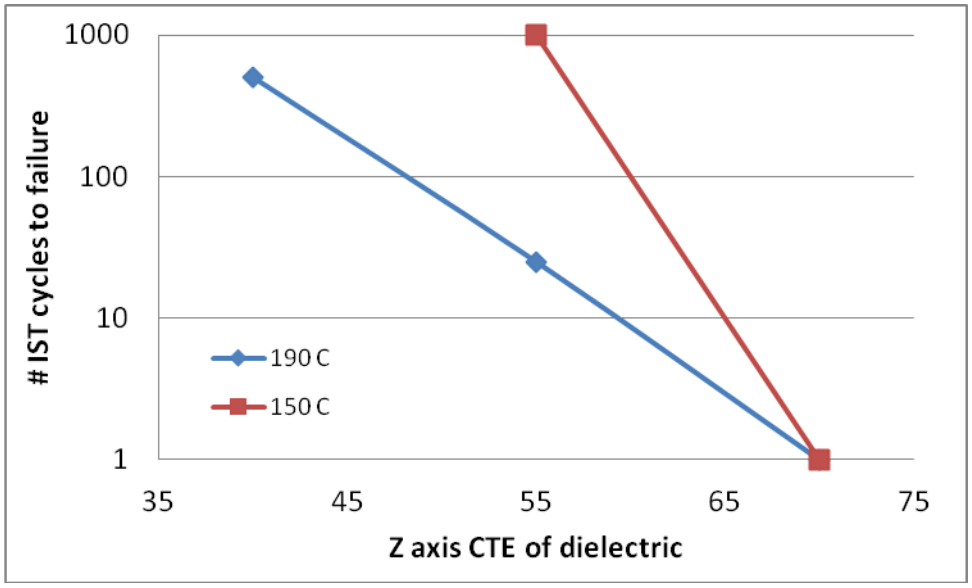


Figure 5. Effect of Z axis CTE on microvia IST reliability, for aspect ratio 1:1. The two lines represent IST peak temperatures, either 190°C or 150°C.

Another important factor in the failed microvias was the nature of the copper at the capture pad. References 7 and 8 cite thin copper at the capture pad as a problem with high aspect ratio (>1:1) microvias, but this study showed that under certain circumstances it can be a problem even with lower aspect ratios.

Figures 6 and 7 contrast a microvia deposited on a thick layer of electrolytic copper, and a microvia deposited on thin electrolytic copper. If the amount of electrolytic copper on the capture pad is thin to begin with, the resulting microvia will be susceptible to reliability issues. Laser drill and/or cleaning processes may further deplete the electrolytic copper, leaving behind an underlying layer of electroless copper, on which the microvia "seed" layer is deposited. The results of this study clearly showed that microvias with electroless-to-electroless connections failed at a higher rate than microvias on which the electroless copper was deposited onto a thick cap layer of electrolytic copper—see Figure 8.

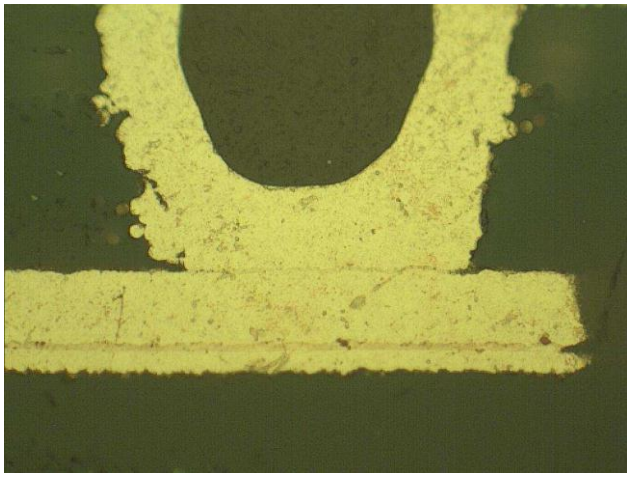


Figure 6. Microvia deposited on capture pad with 1 mil of electrolytic copper.

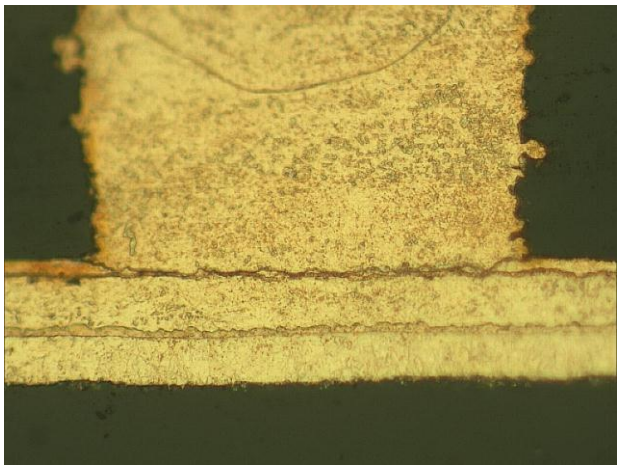


Figure 7. Microvia deposited on capture pad with minimal electrolytic copper cap.

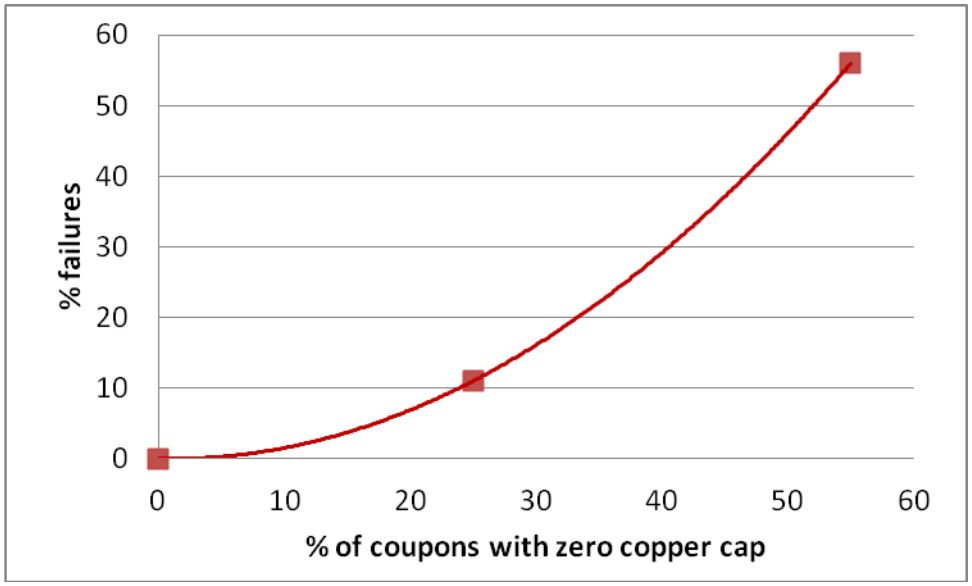


Figure 8. Microvia failure rate trend with copper cap thickness. As the number of samples with no electrolytic copper cap at the capture pad increased within a lot, the failure rate increased steeply. The trend illustrates that an electroless-to-electroless copper interface is less reliable than electroless-to-electrolytic.

CONCLUSIONS AND RECOMMENDATIONS

In this study, microvias were fabricated with different features and stressed to failure. The following is a list of contributing factors to the failures, ranked in order of most likely contribution:

- Microvias with higher aspect ratio are less reliable. Microvias with aspect ratio 0.7:1 or less survived accelerated life testing regardless of the dielectric material of construction. Microvias with 1:1 aspect ratio commonly failed after just a few thermal stress cycles.
- Dielectric materials. Microvias made with high z-axis CTE dielectrics failed at a higher rate, and it was found that dielectrics with higher z-axis CTE were more susceptible to material property variations.
- Capture pad copper composition. Processes that result in an electroless-on-electroless base layer for microvias is prone to premature brittle failure. 0.0003" minimum of electrolytic copper is recommended at the microvia capture pad.
- PWB fabricator laser drill and cleaning processes. Processes that yield a relatively flat capture pad will result in lower microvia adhesive strength, relative to roughened surface with some curvature.
- Board design and assembly. The more thermal stress cycles that a board sees during PWB and CCA fabrication, including lamination, bake out, oven reflow and rework, the more susceptible they are to microvia failure. For board designs with 3 or more laminations, or ROHS thermal profiles, dielectric material selection is crucial to reliability.
- Moisture absorption. Based on limited data, board bake out resulted in fewer failures even with zero blisters or delamination. A possible explanation is that moisture absorbed by the board causes an increase the Z-axis CTE, and stress on the microvia during oven reflow.

ACKNOWLEDGEMENTS

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