Investigation into the Role of Different Substrate Ni Compositions and Plating Methods on Die Attach Reliability

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Abstract

Nickel is a commonly used diffusion barrier for direct bond copper (DBC) substrates used in high temperature, high power applications. The Ni can be deposited by electroless or electrolytic plating and may be pure Ni, Ni:P, Ni:B or Ni:Co. The reactivity of these different Ni layers with AuGe and BiAgX® solder is explored. Specifically the reaction to form Ni-Ge intermetallics and $NiBi_3$ during high temperature storage and the impact on die shear strength and failure mode are discussed.

Keywords: Ni finish, Die attach, High temperature

Introduction

Nickel is widely used as a diffusion barrier in surface finishes (Ni/Au, Ni/Pd/Au, Ni/Ag) for copper metallization. Surface finishes are of particular importance for high temperature electronics exposed to the atmosphere to prevent oxidation of the Cu. Plating is most often used to deposit the Ni layer. The actual composition of the "Ni" is a function of the plating chemistry and process. Pure Ni, Ni:Co and Ni:P can be electroplated, while Ni:P and Ni:B can be plated using an electroless process.

During solder assembly, the Au, Pd and/or Ag layers are dissolved into the molten solder and the solder wets to the Ni, forming an intermetallic. With high temperature aging, further intermetallic growth occurs. The composition of the "Ni" layer has been shown to impact the aged reliability of the solder joint. Yoon, et al. [1] has shown that Ni:(7-10%)P was more reliable than Ni:(1-3%)B after high temperature (150^o) aging of Sn-3.5Ag BGA solder spheres as determined by ball shear analysis. The brittle Ni_3Sn_4 intermetallic grew faster on the Ni:B compared to the Ni:P layer. At higher temperatures, Johnson, et al. have shown degraded die shear strength for SiC die attached with AuSn liquid transient phase (LTP) bonding to an electroless Ni:P/electroplated Au finish on Cu with aging at 400^{o}C due to Kirchendall voiding. No degradation was observed with an electroplated Ni/Au surface finish.

In this work, AuGe preforms and BiAgX® (Indium Corporation) solder paste were evaluated. The "X" in BiAgX® contains Sn. Shen, et al. have shown that the aged (200^{o}C) die shear strength of SiC die assembled with BiAgX® is higher on Cu with a Ag finish than on Cu with a Ni:B/Au finish [3, 4]. The Bi reacted with the Ni to form $NiBi_3$ intermetallic with high temperature aging. Cu does not form intermetallics with Bi. Egelkraut, et al. have shown that die attached with AuGe had higher initial and aged (200^{o}C and 250^{o}C) die shear strength on bare Cu compared to Ni/Ag plated Cu [5]. Both Ni_2Ge and NiGe intermetallics were identified in cross sections of initial Ni/Ag plated assemblies. For the Cu samples, a Au – Cu interdiffusion layer and a ζ-phase $(Cu,Au)_5Ge$ intermetallic layer were observed. Tanimoto, et al. [6] and Lang, et al. [7] have both shown a significant decrease in die shear strength with AuGe die attach and Ni:P with aging in air at 300^{o}C and 330^{o}C, respectively. NiGe intermetallic was observed along with oxidation of the underlying Cu.

Since diffusion and intermetallic formation play an important role in solder joint strength and reliability, the influence of different Ni plating processes and compositions on intermetallic formation and die shear strength with BiAgX® and AuGe were studied.

Test Vehicles

Die:

The die for the BiAgX experiments were fabricated from 0.38 mm thick SiC wafers with backside Ti/Ni/Ag (50nm/200nm/50nm) e-beam metallization layers. The wafers were diced into 2mm x 2mm die for the 200^{o}C aging test.

The die for the AuGe die attach studies were fabricated from SiC wafers with deposited Ti/Ti:W (10:90 wt%)/Au (25nm/50nm/50nm) metallization. After thin film deposition, 3µm of Au was electroplated. The wafers were diced into 2mm x 2mm die for the 300°C aging test.

Substrates:

The substrates were 96% aluminum oxide direct bond copper (DBC) from Stellar Industries (Millbury, MA, USA). The nominal thickness of the Al_2O_3 was 0.635 mm and copper was 0.2032 mm.

Finishes:

For the BiAgX® studies, the DBC Cu was plated with a 1.8µm Ni layer and a 0.17 µm Au layer except for the Ni:Co samples, which were not Au plated. A thicker Ni layer (5µm Ni and 0.17 µm Au) was used on the AuGe test substrates. The Ni plating compositions are shown in Table 1.

Table 1. Nickel Composition as Provided by the Plating Suppliers

Plating	Ni Percentage (at.%)
Pure Ni - electroplated	100%
Ni:P - electroplated	80%~85%
Ni:Co - electroplated	95%~97%
Ni:B - electroless	75%~80%
Ni:P - electroless	80%~85%

Assembly Processes and Characterization

BiAgX® Assembly Process:

The BiAgX® solder paste was printed on the DBC substrate with a 0.127mm thick stainless steel stencil. Then, a Palomar Model 3500 automated die placement machine was used for die placement. The solder reflow was performed in a nitrogen environment using a PEO 601 furnace. A 3 min. ramp from room temperature to 321°C was used for assembling. A thermocouple was attached to the DBC substrate with Kapton tape and the measured temperature profile is shown in Figure 1.

BiAgX® Die Shear:

The die shear strength was measured with a Dage PC2400 using a 100kg shear module. The BiAgX® samples had average shear strengths of 4.8kg/mm^2 (see Table 2) for all Ni finishes.

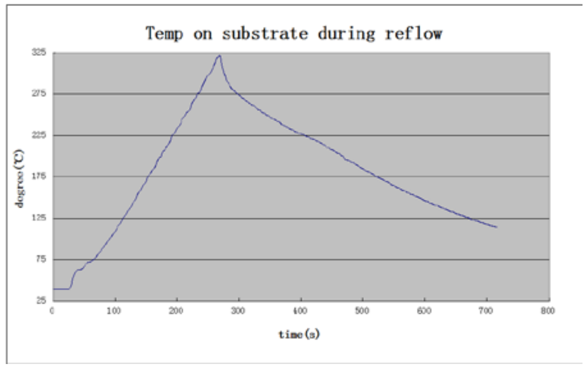


Figure 1. BiAgX® Solder Paste Reflow Profile.

Table 2. BiAgX® Initial Average Shear Strength

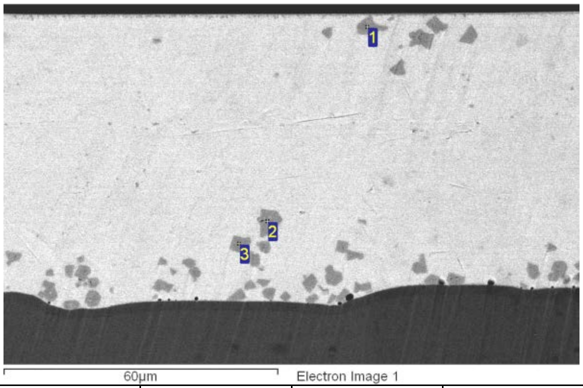
Plating	Initial Average Shear Data (kg/mm^2)
Pure Ni - electroplated	4.84
Ni:P - electroplated	4.83
Ni:P - electroless	4.80
Ni:Co - electroplated	4.80

BiAgX® Cross Sections:

Figure 2 shows SEM images of cross sections of an as-built BiAgX® sample with electroplated Ni:P. In the solder region of the die attach, the ζ-phase $(AgAu)_{0.86}Sn_{0.14}$ was found in a Bi matrix. The ζ-phase contains Sn in the range from 11.8 at.% to 18 at.% Sn at 200°C. The ζ-phase was observed in all samples (Figures 3-6). In the Ni:Co samples, the ζ-phase did not contain Au, since the substrates were not Au plated (Figure 6). The EDS spot size did not allow exact determination of the Ni-Sn intermetallic composition as Bi was always included. The Ni-Sn intermetallic had less protrusions into the Bi solder for the electrolytic Ni and Ni:P platings (Figures 3-4), compared to the electroless Ni:P and electrolytic Ni:Co platings (Figures 5-6).

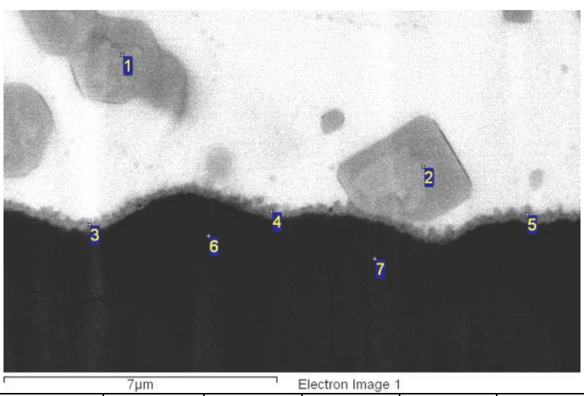
BiAgX® Failure Analysis:

Fracture surfaces were examined after die shear. The fracture surfaces for the electrolytic Ni:P are shown in Figure 7. Based on the fracture surface analysis and the cross sections, failure occurred in the solder near the Ni-Sn intermetallic layer (Ni, Ag, Sn, Bi on substrate side and Bi and Ag on the die side). The electroless Ni:P also had Bi and Ag on the die side and Ni, Ag, Sn and Bi on the substrate side. The electrolytic Ni and Ni:Co failed in approximately the same region with both having Bi, Ag and Sn on the die side and Ni, Ag, Sn and Bi on the substrate side. Similar failure locations are consistent with nearly identical initial shear strengths measured for the different Ni finishes.



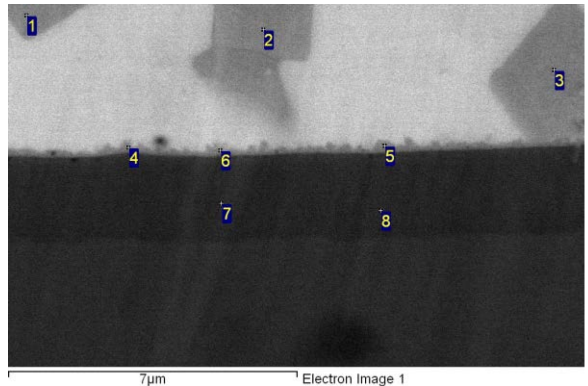
Locations	Ag	Sn	Au
1	78.2	14.2	7.6
2	77.9	14.0	8.1
3	80.6	14.0	5.4

Figure 2. As-built BiAgX® on Electrolytic Ni:P Cross Section and Elemental Analysis (at.%).



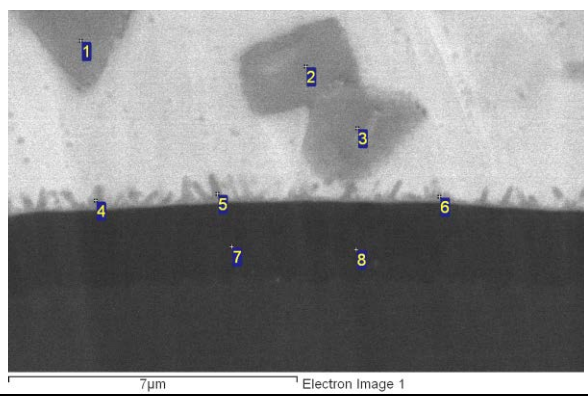
Location	Ni	Ag	Sn	Bi	Au
1	0.0	75.8	16.0	0.0	8.2
2	0.0	70.5	17.9	0.0	11.6
3	55.1	0.0	19.3	25.6	0.0
4	63.1	0.0	24.1	12.8	0.0
5	52.6	0.0	18.7	28.7	0.0
6	100.00	0.0	0.0	0.0	0.0
7	100.00	0.0	0.0	0.0	0.0

Figure 3. As-built BiAgX® on Electrolytic Ni Cross Section and Elemental Anaylsis (at.%).



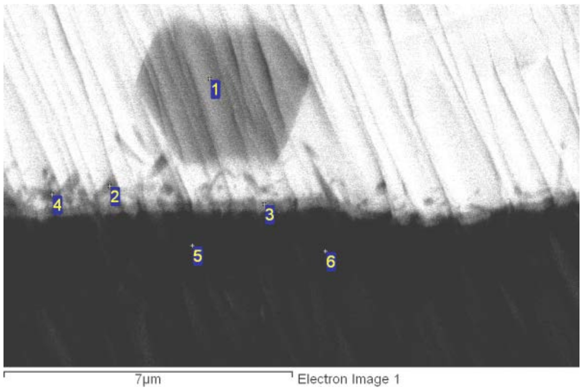
Location	Ni	Ag	Sn	Bi	P	Au
1	0.0	80.0	14.0	0.0	0.0	6.0
2	0.0	79.0	14.4	0.0	0.0	6.6
3	0.0	79.6	13.7	0.0	0.0	6.7
4	41.7	0.0	25.5	32.8	0.0	0.0
5	47.7	0.0	32.1	24.2	0.0	0.0
6	46.1	0.0	23.7	30.2	0.0	0.0
7	82.1	0.0	0.0	0.0	17.9	0.0
8	82.9	0.0	0.0	0.0	17.1	0.0

Figure 4. As-built BiAgX® on Electrolytic Ni:P Cross Section and Elemental Analysis (at.%).



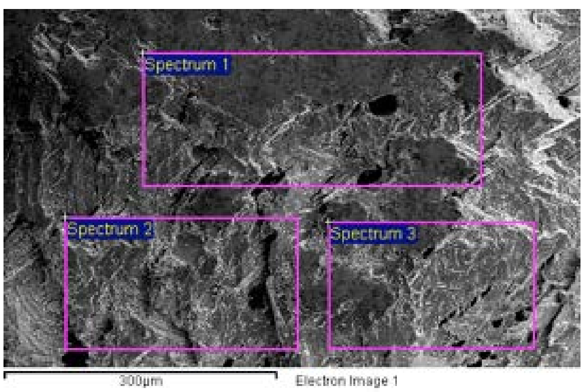
Location	Ni	Ag	Sn	Bi	P	Au
1	0.0	77.4	15.0	0.0	0.0	7.6
2	0.0	78.8	14.8	0.0	0.0	6.4
3	0.0	75.9	15.8	0.0	0.0	8.3
4	48.7	0.0	31.0	20.3	0.0	0.0
5	43.3	0.0	30.5	26.2	0.0	0.0
6	44.6	0.0	30.3	25.1	0.0	0.0
7	81.6	0.0	0.0	0.0	18.4	0.0
8	82.1	0.0	0.0	0.0	17.9	0.0

Figure 5. As-built BiAgX® on Electroless Ni:P Cross Section and Elemental Analysis (at.%).



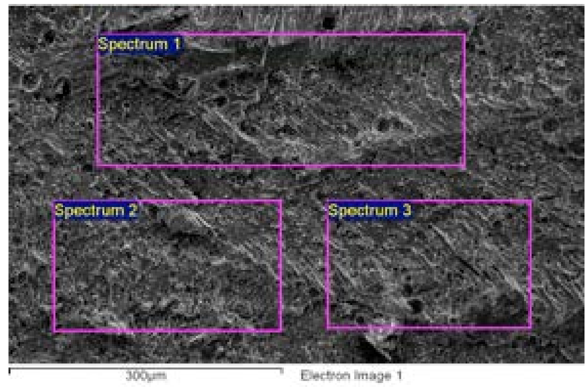
Location	Ni	Ag	Sn	Bi	Co
1	0.0	86.6	13.4	0.0	0.0
2	34.8	0.0	29.3	35.9	0.0
3	42.5	0.0	33.1	24.4	0.0
4	42.9	0.0	31.9	25.2	0.0
5	94.5	0.0	0.0	0.0	5.5
6	94.5	0.0	0.0	0.0	5.5

Figure 6. As-built BiAgX® on Electrolytic Ni:Co Cross Section and Elemental Analysis (at.%).



Location	Bi	Ag
1	10.00	0.0
2	94.3	5.7
3	95.7	4.3

(a) Die Side



Location	Ni	Ag	Sn	Bi
1	13.1	7.1	5.4	74.4
2	12.0	6.1	8.6	73.3
3	12.4	5.9	6.9	74.8

(b) Substrate Side

Figure 7. As-built BiAgX® on Electrolytic Ni:P Fracture Surfaces after Die Shear (at.%).

AuGe Assembly Process:

The Au88Ge12 preforms were purchased from Materion Advanced Materials Group (Buffalo, NY, USA). An SST vacuum furnace was used for the assembly. A 3 min ramping from room temperature to 385°C with a 3 min. peak hold time was used to achieve good wetting and flow.

AuGe Die Shear:

The die shear strength was measured with a Dage PC2400 using a 100kg shear module. For AuGe die attach, the initial shear strength for the Ni:P electroless samples was high, with an average shear strength of 13.31kg/mm^2 (see Table 3). Both the Ni and Ni:B samples had significantly lower shear strengths.

Table 3. AuGe Initial Average Shear Strength

Plating	Initial Average Shear Strength Data (kg/mm^2)
Pure Ni - electroplated	5.64
Ni:P - electroless	13.31
Ni:B - electroless	3.77

AuGe Cross Sections:

Figure 8 is a cross section of the AuGe die attach on electrolytic Ni. The Ge has precipitated out of the Au: there is very limited solubility of Ge in Au at room temperature. The appearance of the bulk solder was similar for all three Ni finishes.

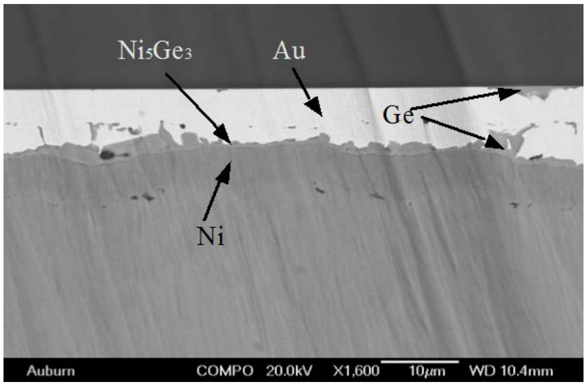
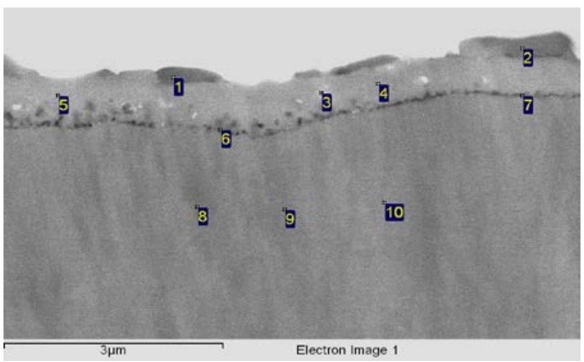


Figure 8. As-built AuGe on Electrolytic Ni Cross Section.

Figure 9 is an image and elemental analysis of the electrolytic Ni sample in the region near the substrate. The intermetallic (locations 3, 4 and 5) corresponds to Ni_5Ge_3. Interestingly, Au is detected at points 6 and 7.



Location	Ni	Ge	Au
1	8.2	88.3	3.5
2	5.3	90.0	4.7
3	61.5	38.5	0.0
4	64.5	33.6	1.9
5	64.4	35.6	0.0
6	59.4	35.2	5.4
7	39.8	55.2	5.0
8	100.0	0.0	0.0
9	100.0	0.0	0.0
10	100.0	0.0	0.0

Figure 9. As-built AuGe on Electrolytic Ni Cross Section and Elemental Analysis (at.%).

A high magnification image of the Ni_5Ge_3 intermetallic-to-Ni interface (Figure 10) reveals voiding. Surface analysis of the die shear sample fracture surfaces revealed Ni_5Ge_3 and a small amount of Au (~3 at.%) on the die side and only Ni on the substrate side. Formation of voids and failure at this interface is consistent with the significantly lower shear strength for the electrolytic Ni samples.

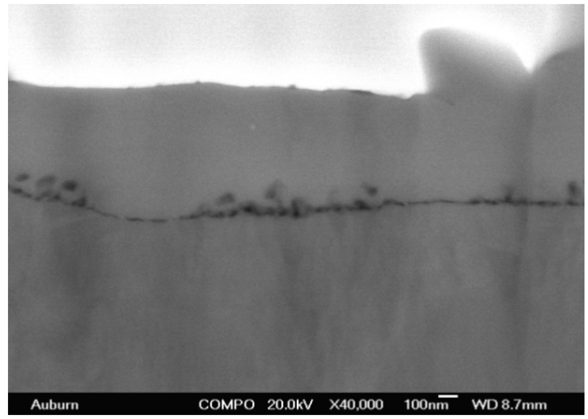
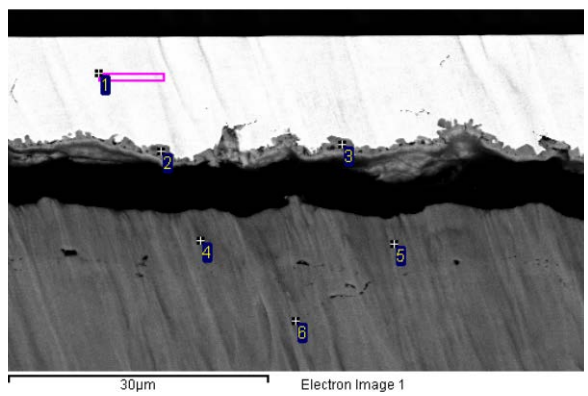


Figure 10. High Magnification Image of Ni_5Ge_3-to-Ni Interface Showing Voiding.

Figure 11 is a cross section and elemental analysis of the as-built AuGe-Ni:B sample. The die and die attach separated from the substrate during sample preparation along the NiGe-to-Ni interface.

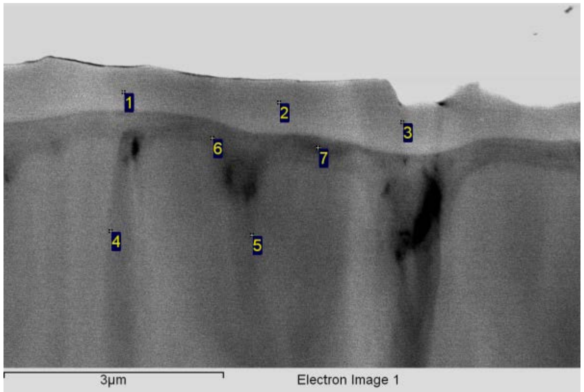


Location	Ni	Ge	Au	Cu
1	0.0	0.0	100.0	0.0
2	51.2	48.8	0.0	0.0
3	48.2	51.8	0.0	0.0
4	100.0	0.0	0.0	0.0
5	100.0	0.0	0.0	0.0
6	0.0	0.0	0.0	100.0

Figure 11. As-built AuGe on Electroless Ni:B Cross Section and Elemental Analysis at Ni Interface (at.%).

Figure 12 is a cross section and elemental analysis of the AuGe assembly on electroless Ni:P at the Ni:P interface. Locations 1, 2 and 3 correspond to approximately NiGe. Locations 6 and 7 indicate an increased P concentration due to the consumption of

Ni in the formation of NiGe. Analysis of the fracture surfaces after die shear indicates failure was at the NiGe layer: there was Ni, Ge and Au on both fracture surfaces, primarily Au on the die side and Ni and Ge on the substrate side.



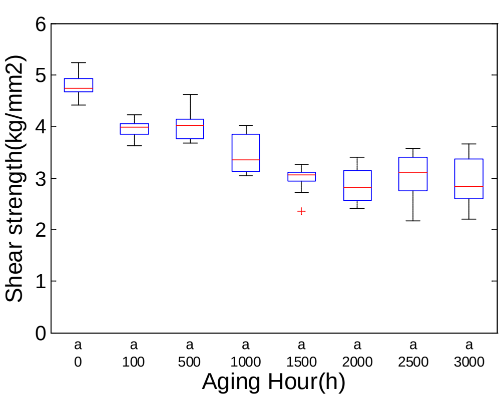
Location	Ni	P	Ge
1	53.8	0.0	46.2
2	50.4	0.0	49.6
3	52.0	0.0	48.0
4	86.7	13.3	0.0
5	85.5	14.5	0.0
6	68.4	19.2	12.4
7	68.9	20.5	10.6

Figure 12. As-built AuGe on Electroless Ni:P Cross Section and Elemental Analysis at Ni Interface (at.%).

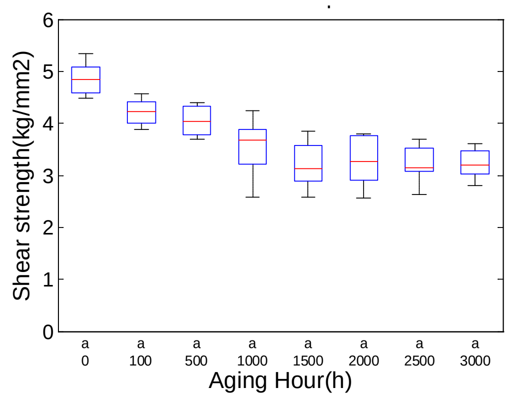
Aging Studies

BiAgX®:

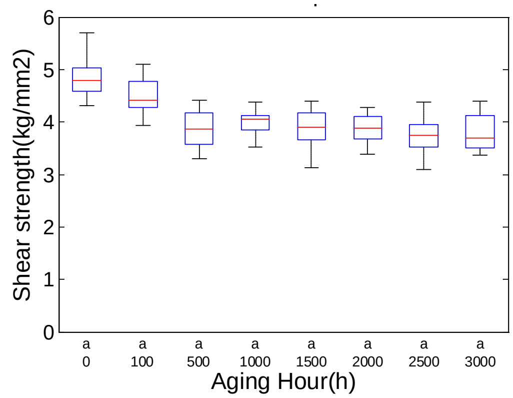
The BiAgX® samples with 2mm x 2mm SiC die were aging at 200°C in air. Samples were removed for shear testing at specified time intervals. The die shear results are shown in Figure 13.



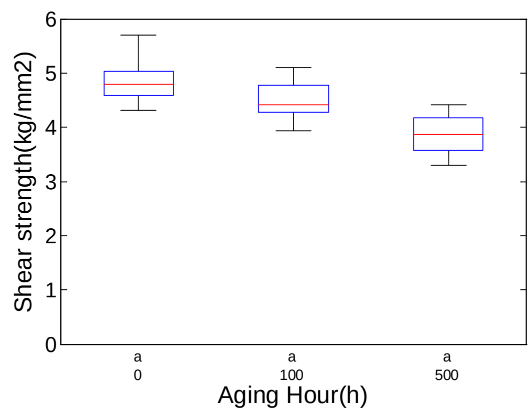
(a) Electroless Ni:P



(b) Electrolytic Ni



(c) Electrolytic Ni:P



(d) Electrolytic Ni:Co

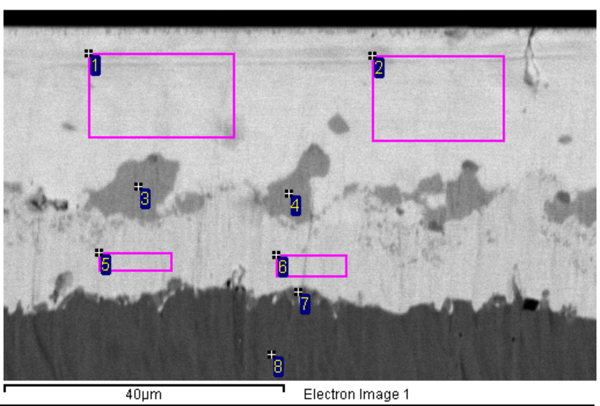
Figure 13. Die Shear Data for BiAgX® as a Function of Storage Time at 200°C. (a) Electroless Ni:P, (b) Electroplated Ni, (c) Electroplated Ni:P, and (d) Electrolytic Ni:Co.

There was a significant decrease in shear strength during the first 1500 hours for both the electroless Ni:P and the electrolytic Ni. The average shear strength dropped to approximately 3kg/mm^2 and was relatively stable through 3000hr. This was similar to the results with electroless Ni:B in [3]. The electroplated Ni:P samples showed less degradation.

After a decrease in shear strength during the first 500 hours, the shear strength of the electroplated Ni:P was stable with average shear strength of 3.8kg/mm^2. The electrolytic Ni:Co had a comparable decrease in die shear strength during the first 500 hours at 200^{o}C. Aging of this finish is ongoing.

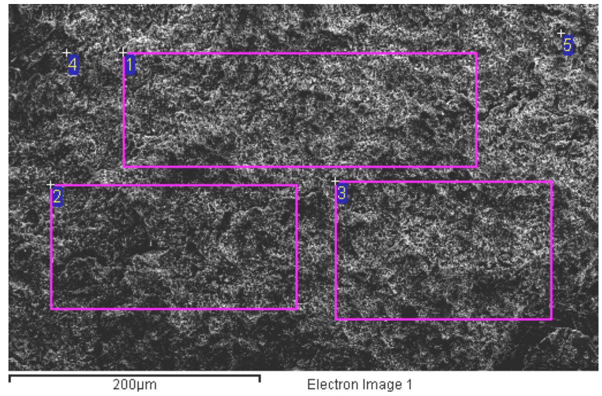
Figure 14 is a cross section of the BiAgX® die attach on electrolytic Ni after 2000 hours at 200^{o}C. A thick layer of $NiBi_3$ intermetallic has formed and the Ni has been consumed. Figure 15 is an analysis of the fracture surfaces from die shear of a 3000 hour aged sample. Examination of the fracture surfaces after die shear of 2000 and 3000 hour aged samples revealed Ni, Ag, Sn, Au and Bi on both the substrate and die fracture surfaces. The Ni-to-Bi ratio corresponded to $NiBi_3$. From the cross section, the fracture surface was in the $NiBi_3$ and ζ-phase Ag(Au)-Sn regions.

Figure 16 is a cross section of the electroless Ni:P after 500 hours aging at 200^{o}C. The Ni:P layer has started to spall from the Cu. After 3000 hours, it has completely spalled (Figure 17). Figure 18 is a higher magnification image and elemental analysis of the spalled region after 3000 hours. $NiBi_3$ has formed on both sides of the Ni:P layer. From elemental analysis of the 3000 hour aged die sheared fracture surfaces, the failure occurs near the spalled Ni:P-to-$NiBi_3$ and Ni-Sn intermetallic interface along the top side of the Ni:P layer.



Location	Ni	Bi	Ag	Sn	Au	Cu
1	0.0	100.0	0.0	0.0	0.0	0.0
2	0.0	100.0	0.0	0.0	0.0	0.0
3	0.0	0.0	85.8	9.6	4.6	0.0
4	0.0	0.0	89.0	5.9	5.1	0.0
5	24.9	75.1	0.0	0.0	0.0	0.0
6	24.4	75.6	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	8.5	91.5
8	0.0	0.0	0.0	0.0	0.0	100.0

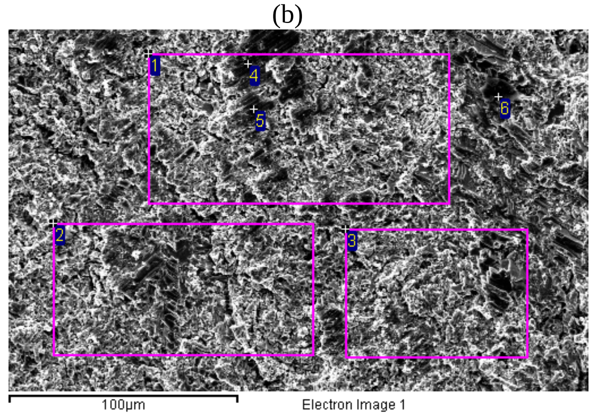
Figure 14. Cross section of the BiAgX® Die Attach on Electrolytic Ni after 2000 hours at 200^{o}C.



Location	Ni	Ag	Sn	Bi
1	0.0	0.0	0.0	100.0
2	23.6	4.5	3.1	68.8
3	22.0	0.0	0.0	74.0

(a) Die Side

(b)



Location	Ni	Ag	Sn	Bi
1	22.3	13.3	9.6	54.8
2	27.6	15.5	12.9	44.0
3	24.3	14.9	11.0	49.8

(b) Substrate Side

Figure 15. Die Shear Fracture Surfaces of BiAgX® on Electrolytic Ni Sample Aged for 2000 Hours at 200^{o}C (at.%).

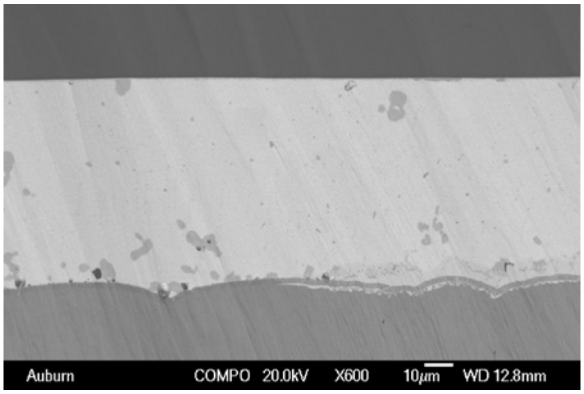


Figure 16. Cross Section of the BiAgX® Die Attach on Electroless Ni:P after 500 hours at 200°C

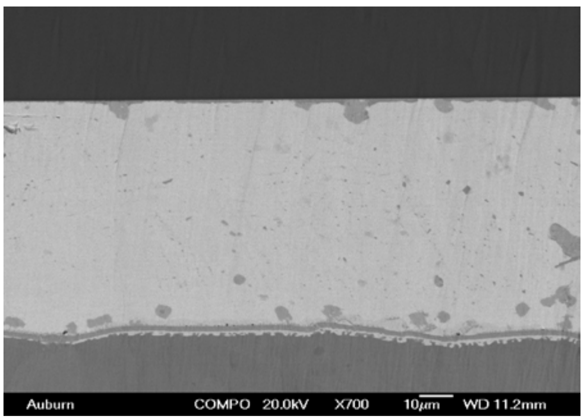
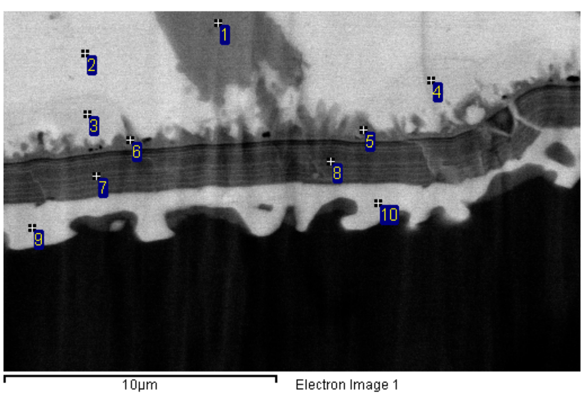


Figure 17. Cross Section of the BiAgX® Die Attach on Electroless Ni:P after 3000 hours at 200°C.



Location	P	Ni	Au	Ag	Sn	Bi
1	0.0	0.0	5.4	91.1	3.5	0.0
2	0.0	0.0	0.0	0.0	0.0	100.0
3	0.0	22.5	0.0	0.0	0.0	77.5
4	0.0	22.2	0.0	0.0	0.0	77.8
5	0.0	35.7	0.0	0.0	48.1	16.2
6	0.0	40.8	0.0	0.0	41.7	17.5
7	32.3	67.7	0.0	0.0	0.0	0.0
8	33.1	66.9	0.0	0.0	0.0	0.0
9	0.0	23.6	0.0	0.0	0.0	76.4
10	0.0	24.6	0.0	0.0	0.0	75.4

Figure 18. BiAgX® on Electroless Ni:P Cross Section and Elemental Analysis (at.%) after 3000 hours at 200°C.

Figure 19 is a cross section of the electrolytic Ni:P after 3000 hours at 200°C. The Ni:P layer remains intact and no $NiBi_3$ has formed. This is consistent with the higher shear strength for electrolytic Ni:P after 3000 hours aging. The failure interface remained at the solder-to-Ni-Sn intermetallic region.

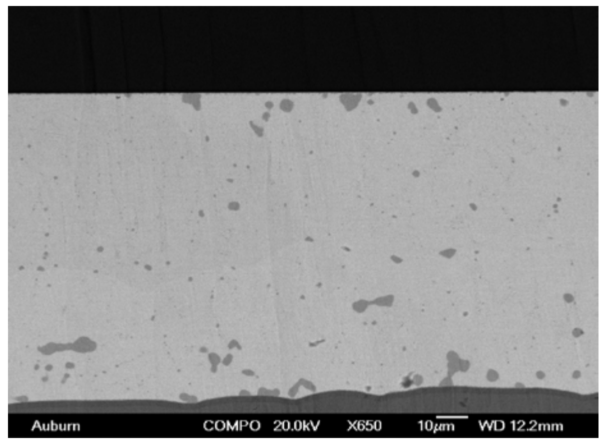
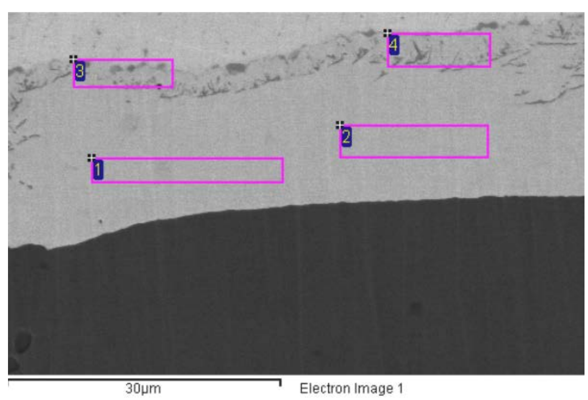


Figure 19. Cross Section of the BiAgX® Die Attach on Electrolytic Ni:P after 3000 hours at 200°C.

Figure 20 is a cross section of the electrolytic Ni:Co assembled with BiAgX® after 100 hours at 200°C. There is significant $NiBi_3$ intermetallic formation. The fracture surface was between the Bi (solder) and the $NiBi_3$.



Location	Ni	Ag	Sn	Bi
1	21.8	0.0	0.0	78.2
2	24.7	0.0	0.0	75.3
3	19.4	11.6	4.4	64.6

4	27.8	7.8	2.5	61.9

Figure 20. Cross Section of the BiAgX® Die Attach on Electrolytic Ni:Co after 100 hours at 200°C.

AuGe:

Based on the as-built die shear results, only the AuGe on electroless Ni:P samples were aged at 300°C. Figure 21 presents the shear strength as a function of aging time at 300°C. The shear strength is starting to decrease at 1000 hours. This aging test is ongoing.

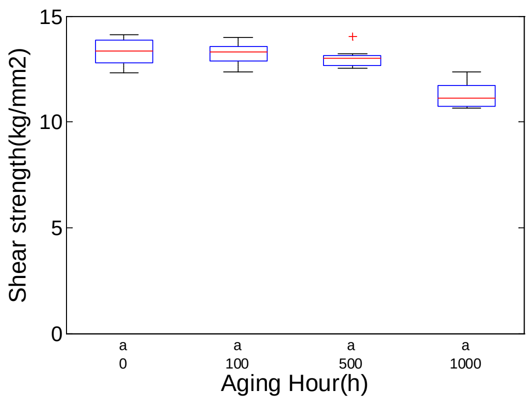
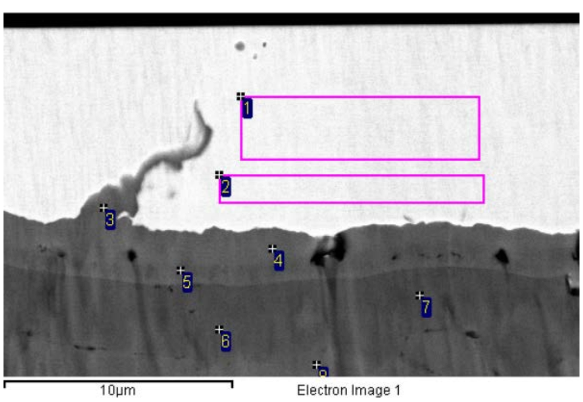


Figure 21. Die Shear Strength with AuGe Die Attach on the Electroless Ni:P Surface Finish.

Figure 22 is a cross section and elemental analysis of a AuGe on electroless Ni:P sample after 1000 hours at 300°C. The Ni-Ge intermetallic is consistent with Ni_2Ge at locations 3 and 4 and with Ni_3Ge at location 5. The P content in the Ni finish layer has increased due to the consumption of Ni. Also, Ni has diffused into the Au layer. Elemental analysis of the fracture surfaces showed Au with Ni (~5%) on the die side and Au with Ni (10-20%) and Ge (0-6.5%) on the substrate side. This indicates that the fracture occurred in the Au near the Ni-Ge intermetallic.



Location	Ni	Ge	Au	P	Cu
1	2.7	0.0	97.3	0.0	0.0
2	5.4	0.0	94.6	0.0	0.0
3	67.4	32.6	0.0	0.0	0.0
4	67.6	32.4	0.0	0.0	0.0
5	74.1	25.9	0.0	0.0	0.0
6	82.9	0.0	0.0	17.1	0.0
7	76.0	0.0	0.0	24.0	0.0
8	0.0	0.0	0.0	0.0	100.0

Figure 22. Cross section of the AuGe Die Attach on Electroless Ni:P after 1000 hours at 300°C.

Conclusions

The BiAgX® solder paste assemblies had acceptable die shear strengths after 3000 hours at 200°C with electrolytic Ni, electrolytic Ni:P and electroless Ni:P. $NiBi_3$ intermetallic formed with both electrolytic Ni and electroless Ni:P samples during aging. These assemblies had a lower average die shear strength than did the electrolytic Ni:P samples, which did not form $NiBi_3$. The Ni:Co samples are still in test, but after 100 hours at 200°C a significant $NiBi_3$ intermetallic layer has formed.

AuGe die attach with electrolytic Ni and electroless Ni:B resulted in relatively low initial die shear strength. Voids were observed at the Ni_5Ge_3-to-Ni interface of the electrolytic Ni samples. Cross sectioning of the Ni:B samples resulted in failure between the NiGe intermetallic and the Ni layer. High initial shear strength was measured for the electroless Ni:P samples. A Ni-Ge intermetallic layer was formed, but no voids were observed. After 1000 hours at 300°C, a 15% decrease in die shear strength was observed. Ni was observed in the Au layer and failure was in the Au(Ni) layer, not the intermetallic after 1000 hours of aging. This aging test is ongoing.

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