Development of New Ultra-high Stiffness Gold Bonding Wire

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Abstract

Driven by package performance, form factor, and cost, packaging trends are pushing pad pitch and therefore gold bonding wires diameters ever smaller. Pad pitch at 50μm and below implies wire diameters at 20μm and below. It is challenging to develop new bonding wires for such applications that have very high stiffness to resist sway and sweep, yet maintain very robust bondability. Concerns about impedance effects of bonding wire typically make a preference for 4N gold bonding wire with a resistivity essentially equal to pure gold.

In this paper, efforts in developing new high stiffness gold bonding wire will be summarized. Stiffness (elastic modulus) in 4N gold bonding wire is correlated to the wire microstructure and measured wire texture. Mechanical properties for new, ultra-high stiffness 4N gold wire are presented in perspective to existing alloys.

Recognizing that the bonding wire industry demands robust wire bonding solutions, this paper also presents data on bondability, looping capability and moldability as well as bond aging data on ultra-high stiffness 4N bonding wire compared to conventional wires.

Introduction

K&S has a research center in Singapore which focuses on the product and process development for gold bonding wire. The cost and reliability of gold wire bonding make it the preferred packaging solution today for over 80% of all semiconductor devices made[1]. Relentless pressures to reduce cost and increase performance push the bonding wire industry toward aggressive product development and continuous improvement of the bonding wire process. New alloy development is discussed here via study of interactions between mechanical, microstructural, and electrical properties of the wire to the wire composition, wire manufacturing process, and most importantly, test wire bonding applications. An understanding of these interactions provides insight into alloy micro-doping mechanisms, and a means for engineering new alloys with the best possible combination of properties for robust and economical wire bonding solutions.

Bonding Wires Serving the Market Today

The demands of higher speed bonding, finer pitch bonding, and economical molding of IC packages place increasing performance demands on gold bonding wires. Smaller diameter wires, lower loop heights and complex CSP, stacked die, and staggered bonding require excellent bondability and moldability over a wide range of applications. The industry demands robust performance of an alloy for multiple, diverse applications. The distinguishing features of a state-of-the-art gold bonding wire required for the spectrum of today's packages is given in Table I in terms of the corresponding benefits and value to the bonding application.

Table I. Features of state-of-the-art gold bonding wire in term of benefits and value.

Distinguishing features	Benefits	Bonding application value
Ultra High E	Stiffness	Low sweep
High BL	Hi pull	Strongest wire
Neck strength	Low loop	Thin pkgs, sensitive pad packages
Soft ball	Adhesion	Robust 1st bond
Ductility	Easy 2nd bond	Robust 2nd bond/tail bond
Be-free	Be-free	No Be issue
Universal use	Multiple applications	Fewer quals, few part numbers

Commercial gold bonding wire alloys can be classified into 2 compositional categories. Gold alloys >99.99% pure (<100ppm non-gold) are called "4N". Gold alloys >99% pure (<1% non-gold) are called "2N". The 1% dopant is typically some combination of Pd, Pt, or Cu. Table II compares general properties of 2N and 4N gold bonding wire alloys.

2N alloys have significantly declined in their use recently in part due to concerns with the ~30% higher resistivity and harder FAB on delicate bond pads. 2N alloys have shown slower intermetallic growth at the die pad/gold ball interface. However, this intermetallic has an insignificant effect on the lead impedance or reliability. 2N alloys are no longer higher in strength or modulus as compared to 4N alloys. For these reasons, as well as a well-established "tradition" in gold ball bonding, 4N alloys are expected to remain the preferred alloy choice.

A new 4N alloy has been developed for the latest fine-pad-pitch applications. The combination of features from Table I gives it great potential for a wire variety of bonding applications, especially those with complex looping or reduced wire diameters for either wire cost reduction or ultra-fine pad pitch bonding. This alloy is discussed in light of 4N technology development.

Table II Comparison of 4N and 2N alloy properties.

Parameter	4N	2N
Micro-dopant[2]	Be, Ca, RE, others	Be, Ca, RE, others
Major dopants	Nil	Pd, Pt, or Cu
Resistivity (μΩcm)	2.3	3.0-3.5
Modulus (GPa)	75-100	80-95
Stength (MPa)	140-340	250-340
FAB grain size	Larger	Finer
Neck grain size	coarse to fine	Fine
Neck strength (% wire)	70-95%	80-90%
Intermetallic growth[3]	Slow	Slower
Low-loop capability	Good	Very good
1st bond	lower w/ larger bonding window	higher w/ smaller bonding window
2nd bond	Large, robust bonding window	Smaller bonding window

4N Gold Dopant Effects on Mechanical Properties

Engineering of new 4N alloys is based on an understanding of how dopants effect the wire properties within the gold bonding wire process. Gold is an anisotropic material, since the elastic modulus is dependent on the crystallographic orientiation[4]. The average modulus value for gold is 79GPa, however, the elastic modulus varies with direction as given in Table III.

Table III. Gold elastic modulus vs. gold cyrstallographic direction[4].

Direction	Modulus (GPa)
<100>	42
<101>	81
<111>	115

The continuous casting process is very capable of producing chemically uniform alloy with excellent drawability. The continuous casting process transforms liquid gold alloy directly to axially solidified rod. The as-cast rod therefore has axially oriented grains with a <100> texture, which is the natural solidification direction for gold. Fig. 1 below shows the microstructure and inverse pole figure for an as-cast rod.

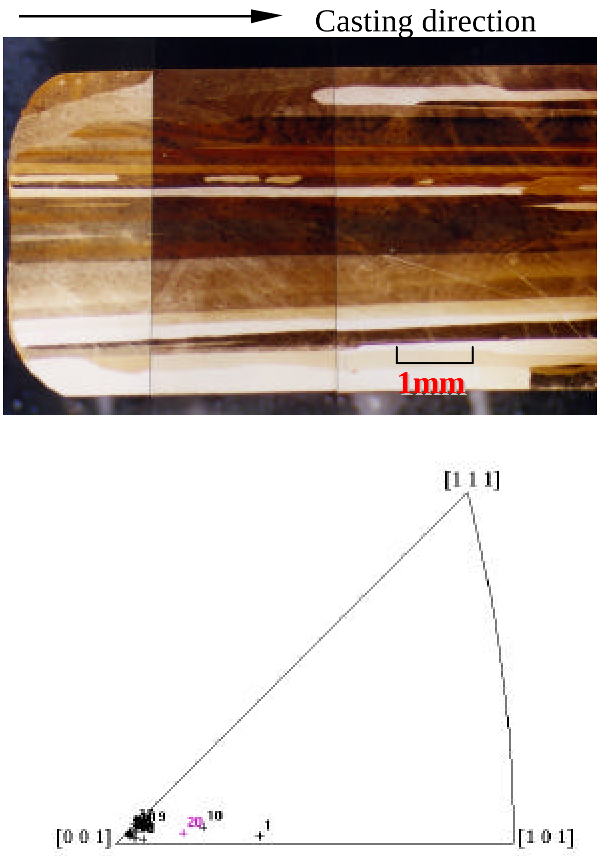

Fig. 1. Longitudinal cross section of as-cast gold bonding alloy (top) and its inverse pole figure showing a <100> axial texture (bottom).

Fortunately, the preferred wire drawing texture of gold, as with other face centered cubic (FCC) metals such as copper[5-7], is the <111> direction (high modulus direction). Due to deformation mechanisms, a double fiber texture of <111> and <100> may be present. Fig. 2 shows a longitudinal section of a drawn and partially annealed gold bonding wire at nominally 25µm diameter as well as the inverse pole figure for that section.

All gold bonding wire must be strand annealed at the final diameter to put the wire in the proper elongation and break-load state for sound bonding wire use. The anneal removes internal stresses that may cause irregular wire loops, and also can contribute to a robust 2nd bond/tail bond formation. This anneal also causes recovery in the gold along with some degree of recrystallization and grain growth. Grain growth typically causes some reduction of the <111> texture from the hard-as-drawn condition.

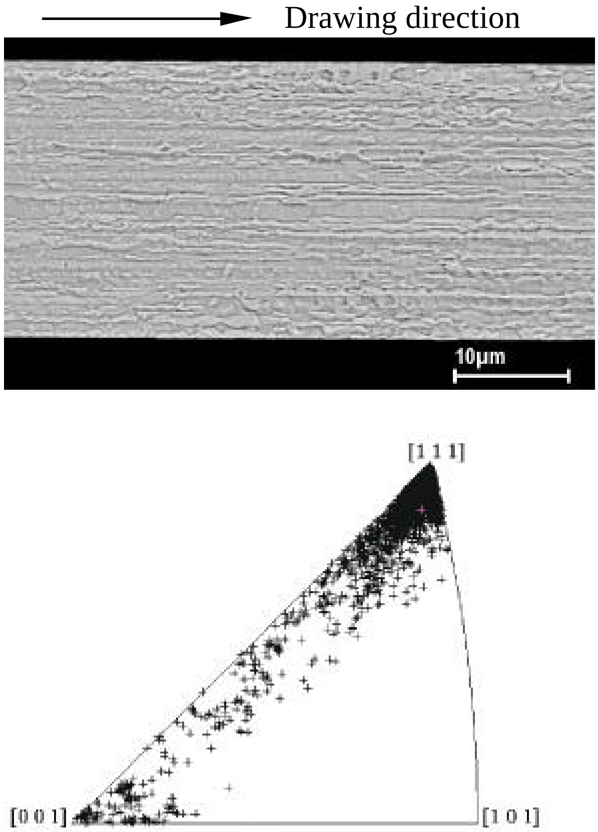

Fig. 2. Longitudinal cross section of drawn and partially annealed bonding 25µm wire (top) and its inverse pole figure showing a <111> axial texture (bottom).

Wire stiffness is a very important property of bonding wire, so it is desirable to have the highest possible elastic modulus. Very fine grain sizes ≤1µm are required for uniform deformation of wire as small as 15µm diameter used in ultra-fine pitch bonding. The anneal applied to bonding wire therefore is a partial anneal and is an optimization to achieve the highest modulus and strength, with a very fine grain size, and negligible residual stresses.

4N gold bonding wire alloys are engineered materials to give the best combination of grain size, modulus, drawability and strength both at room temperature and also high temperature. Dopants promote the formation of the <111> texture and raise the recrystallization/grain growth temperature. This allows retention of texture (high elastic modulus) and smallest grain size in the proper bonding wire annealed state.

Several elements have been utilized for bonding wire dopants, and they can be generally be classified as either solid solution dopants, such as Ag, Pd, Pt, Cu, or interstitial dopants, such as Be, Ca, and rare-earths. Optimization of dopant types and concentration levels are determined empirically and based on extensive experience. Beryllium has been a common bonding wire dopant for many years. While the environmental risks for ppm levels of Be in gold bonding wire are nil, new alloys today can be engineered without the use of Be.

Higher dopant levels generally give higher strength and higher elastic modulus, however, each dopant has a saturation effect as shown in Table IV. Dopants may also interact positively or negatively with other dopants with respect to mechanical properties. Commercial gold bonding wire alloys are proprietary combinations of typically 2 or more dopants.

The properties of gold bonding wire depend not only on the dopants, but also the wire manufacturing process. The casting, intermediate annealing and wire drawing process details also have an effect on the properties of the final wire. Fig. 3 shows the elongation (EL) vs. break load (BL) response of the same alloy with differences early in the bonding process. For a given composition, the final wire EL versus BL responses and the elastic modulus are significantly affected by the variation in process.

Table IV. Break load and Elastic modulus for 25µm wire as a function of nominal dopant level for one dopant.

Normalized dopant level	BL at 4.5%EL (g)	Elastic modulus (GPa)
X/2	11.4	84
X	12.1	87
1.5X	12.8	91
1.75X	12.6	89
2X	12.0	85
2.25X	12.4	85

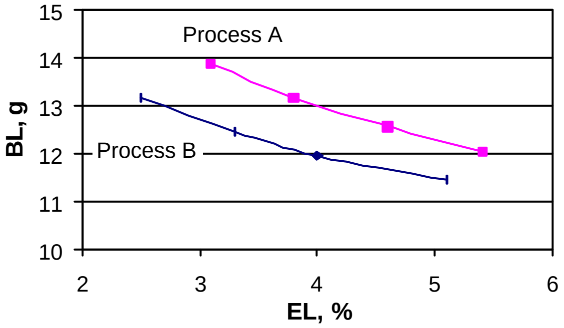

Fig. 3. EL vs. BL response of the same alloy with differences early in their processing.

4N Gold Dopant Effects on Microstructure Near the Free-Air Ball

Microstructural control of bonding wire is a key to its performance and is carefully controlled through the doping and the fabrication process. The microstructure near the Free-Air Ball (FAB) varies from an as-solidified microstructure in the ball to that of the as-received annealed wire. A heat-affected-zone (HAZ) has a continuously changing microstructure between the ball and unaffected wire. The HAZ length and grain size greatly affects the loop shape and strength of the wires during wire bonding.

A new 4N alloy, hereafter named AW99, has been engineered to have optimal

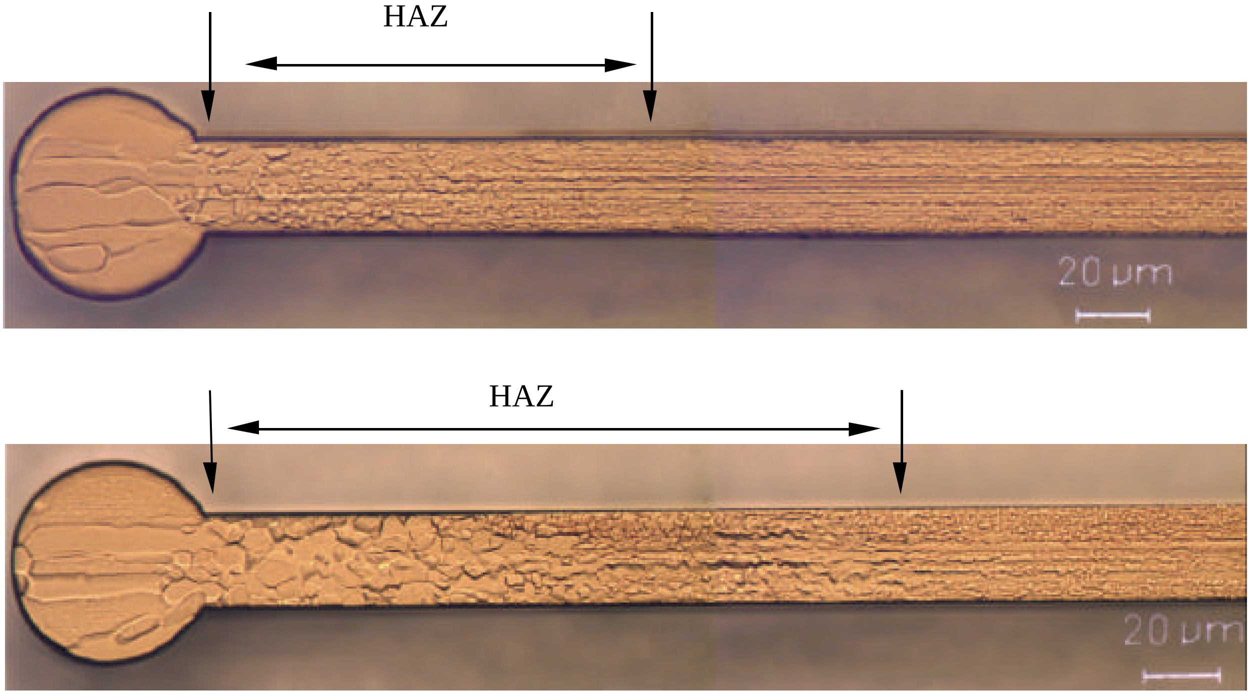

Fig. 4. Longitudinal section of FAB's of the new AW99 alloy (top) as compared to a standard 4N alloy (bottom).

properties of the wire, the HAZ, and the FAB. The dopants are carefully chosen not only to give high wire strength and elastic modulus, but also a very fine grain size in a short HAZ, and at the same time, a low hardness in the as-solidified FAB. Such a combination gives a strong and reliable 1st bond without damaging sensitive pads, a strong HAZ for a high 1st bond pull value, and very low loop capability. Fig. 4 is a longitudinal FAB section of the latest AW99 as compared to a standard 4N alloy. The hardness within balls in either of these alloys is 55-65 HV. Benefits in strength and modulus of the new 4N alloy do NOT come at the expense of ball hardness or 1st bond capability.

The properties of the new AW99 alloy are outlined in Table V in comparison to popular AW14 and AW88 4N alloys, all at 25μm diameter. The new alloy is markedly better in most parameters, without an increase in ball hardness, and these values are the state-of-the-art for gold bonding wire.

Table V. Comparison of 4N alloy properties at 20mil loop height with a 50μm ball size.

Parameter	AW99	AW88	AW14
BL (RT, g)	15.8	12.8	11.4
BL (250C, g)	15.2	12	9.5
EL (RT, %)	4	4	4
Modulus (GPa)	97	90	79
Ball hardness (HV)	55-65	55-65	55-65
HAZ length (±10 μm)	100	120	160
Average HAZ neck grain size (μm)	1.8	2.5	3.2
Neck Strength (Ball Pull, g)	9.4	8.9	8.8

AW99 alloy has been extensively tested in terms of manufacturing capability as well as bondability and bond aging performance and benchmarked to existing alloys. For bondability tests, an approach described in reference [8] was adopted to obtain 1st and 2nd bond process windows. Two different test vehicles were chosen to test the bonding process stability in terms of the 1st and 2nd bond. The test vehicles were chosen in order to simulate potential problems encountered during the bonding of extremely high strength wires. In the case of 1st bond, potential problems come from NSOP (Non Stick-On-Pad) and cratering for small balls at low temperature. For the second bond, it essentially comes from bonding on QFP devices at finer pitches of 70 µm and below.

Based on the criteria mentioned above, the following test vehicles were chosen:

i) 1st bond - 50µm pad pitch on BGA device with K&S test die. Wire span was 170 mils and bond temperature was set to 170 ^{0}C. The wire diameter used here is 20µm and capillary used was a K&S 414FF-2021-R33.

ii) 2nd bond - 70µm pad pitch on 208 lead QFP with K&S test die. Wire span was 230 – 250 mils and bond temperature set to 220 ^{0}C. The wire diameter used was 25µm and the capillary used here was 413FD-0110-R33.

First Bond

Using the method described in Ref [8], the following criteria were used to extract the process windows for first bond

i) Target ball diameter of (38 ± 2) µm

ii) Ball height (8 – 10) µm

iii) Shear per unit area ≥ 5.5 g/mils^2.

iv) No NSOP's and visually acceptable ball shape.

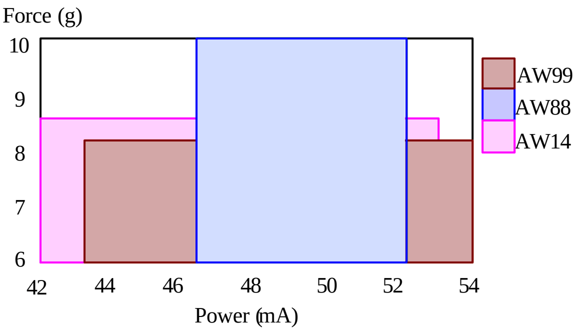

Fig. 5. First bond process window comparison for a 50µm pad pitch BGA device.

Fig. 5 shows the process windows that meet the criteria mentioned in the early part of this section. The size of the process windows ranks in descending order of AW14, AW99 and AW88. The results in Fig. 5 also show that the AW99 wire utilizes lower parameter settings in order to achieve the targeted values. The parameter window for the AW99 is similar to that of the lower strength/modulus AW14.

Table VI. Results for various wires at optimized settings.

Wire Type	AW14	AW88	AW99
Ball Diameter (µm)	37.4	37.80	38.1
Std Deviation	0.5	0.20	0.4
Min	36.2	37.40	37.5
Max	38.2	38.40	38.8
Ball Height (µm)	8.4	10.80	10.2
Std Deviation	0.3	0.40	0.6
Min	7.7	10.00	9
Max	9.1	11.50	11.2
Shear Strength (g/mil^2)	6.75	6.24	7.00
Std Deviation	0.44	0.23	0.32
Min	5.77	5.83	6.56
Max	7.49	6.73	7.72

The values for the optimized settings for AW88, AW14 and AW99 are shown in table VI. All the 3 wire types examined here meet the targeted criteria defined at the early part of this section. The shear per unit value for each of these wires greatly exceeds the 6 g/mils^2 criteria.

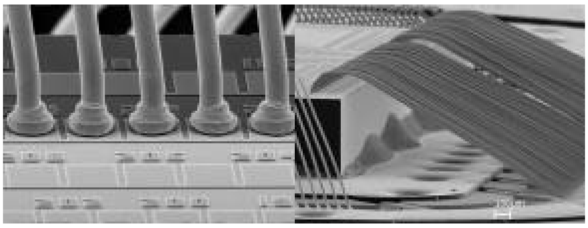

Fig. 6. Typical 1st bond SEM images of the AW99 wire at 50µm pad pitch.

The SEM images taken of the 1st bond for AW99 show no abnormality in terms of the ball shape nor ball formation (see Fig. 6).

Second Bond

The criteria established to obtain the second bond window are as follows:

i. Stitch pull strength greater than 5 g.
ii. No non-stick on lead (NSOL), no short tails, and visually acceptable tool mark/crescent bond.

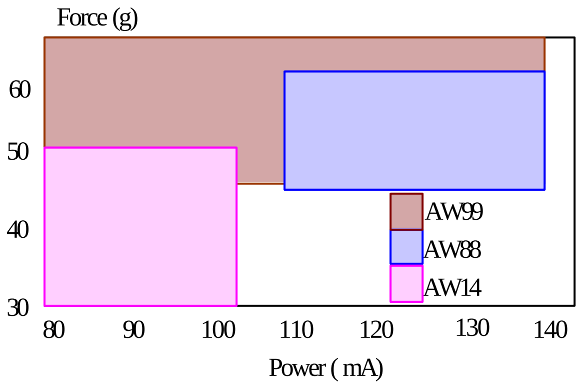

Fig. 7 Second bond process window for a 70µm pad pitch on 208 lead QFP device.

As shown in Fig. 7, AW99 has the largest second bond process window followed by AW14 and finally AW88. Although AW99 has the largest process window, AW99 requires higher parameters as compared to AW14. This points out that for the second bond a higher set parameters are needed when a stronger wire is used. This phenomenon is unlike the first bond (where the ball is as solidified and is softer than the rest of the wire) as there is no less change to the wire mechanical properties.

Table VII. Stitch pull values at optimized settings for different wire types.

Wire type	**AW14**	**AW88**	**AW99**
Average (g)	5.10	6.20	6.36
Std Deviation	0.46	0.41	0.27
Min	4.00	5.27	5.56
Max	5.84	6.80	6.72

At 70µm pad pitch, the stitch pull values rank in ascending order of AW14, AW88 and final AW99 (see Table VII). Both AW99 and AW88 have an average stitch pull value of greater than 6 g, whereas AW14 wire has an average stitch pull value of about 5 g. SEM images of the fracture mode are shown in Fig. 8. Both AW88 and AW99 have similar fracture modes.

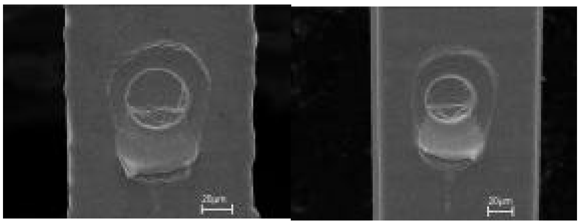

Fig. 8. SEM images of second bond fracture mode (AW88 (left) and AW99 (right))

Ultra-fine 35mm Pad Pitch bonding

The improved mechanical and bonding properties of the AW99 alloy have been applied to next-generation ultra-fine 35µm pad pitch bonding with ~15µm diameter wire. Wire processing to 15µm is already proven viable with good surface finish and 5.3g BL in the anneal condition, which normalizes to the same value as indicated in Table V.

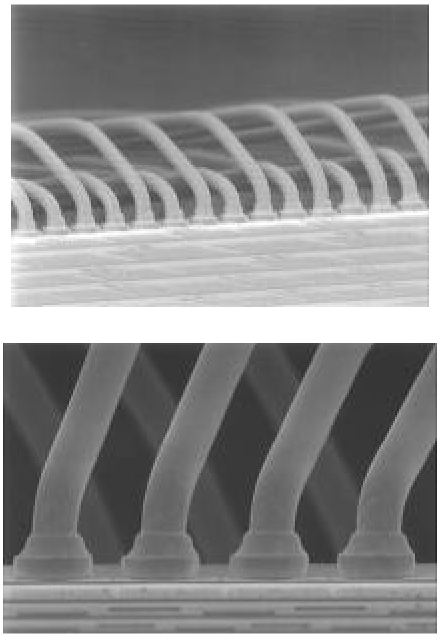

Fig. 9. Staggered (top) and in-line (bottom) 35µm pad pitch bonding using the new AW99 alloy.

Fig. 9 shows both in-line and staggered bonding for 35µm pad pitch. As can be seen, looping is stable and squashed ball size, bond pull as well as shear force are consistent. Follow-on work for 35µm pad pitch bond windows, molding, and aging effect is on going.

Summary

Gold bonding wire is an engineered material. The composition and fabrication processes are carefully chosen and optimized to give the best bonding wire performance.

The industry predominately uses 4N bonding wire for the majority of applications. A new alloy has been engineered to achieve the highest possible strength and elastic modulus, as well as a soft FAB and very fine grain size in the HAZ. These features in a Be-free wire provide robust bonding performance over a wide range of applications. Such an alloy is particularly outstanding for ultra-fine wire sizes and ultra-fine pad pitch applications and is in line with market trends in the future. These features are demonstrated in the supporting mechanical, microstructural, and process performance window of 1st and 2nd bonds.

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Biography

Jeffrey Seuntjens is Chief Technical Director for K&S Bonding Wire. He has more than 15 years of experience in product and process development for non-ferrous wire and cable. Mr. Seuntjens holds a Ph.D. in Metallurgical Engineering and has authored more than 50 publications. He can be reached at JSeuntjens @kns.com.