Gold Wire Bonding To Nickel/Palladium Plated Leadframes

by C. Fan, C. Xu, J.A. Abys, A. Blair & V. Chinchankar

Gold wire bonding on palladium pre-plated leadframes was investigated. This surface finish demonstrates excellent wirebonding performance meeting industry requirements and is comparable with gold surface finishes.

Palladium pre-plated leadframe (Pd PPF) surface finishing has been increasingly utilized by the semiconductor packaging industry since the mid 1980s.[1-6] This technology replaces the traditional surface finishing, *i.e.*, selective silver plating on die attach and wirebonding areas, and solder plating on external leads after encapsulation (Fig. 1). A number of substantial advantages can be achieved by using Pd PPFs:

- Plating process improvements
  - -Elimination of selective plating
  - -Completion of all wet processes prior to packaging
  - -Increase in throughput and production yields
- Quality improvements
  - -Improvement and maintenance of coplanarity
  - -Reduction of solder bridging
  - -Elimination of silver migration
- Environmental Improvements
  - -Elimination of cyanide from plating
  - -Elimination of lead from plating
- Overall packaging cost reduction
  - -Simplification of plating operation
  - -Elimination of post-plating
  - -Reduction of waste treatment
  - -Extension of shelf-life of leadframes

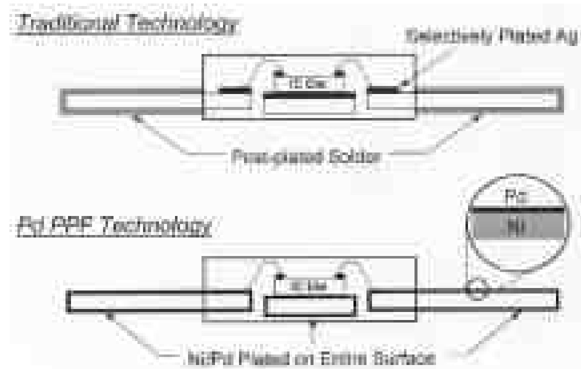

Fig. 1—Schematic cross sections of the leadframes plated with silver and solder or nickel/palladium, after die attach, wirebonding and encapsulation and before trimming-and-forming.

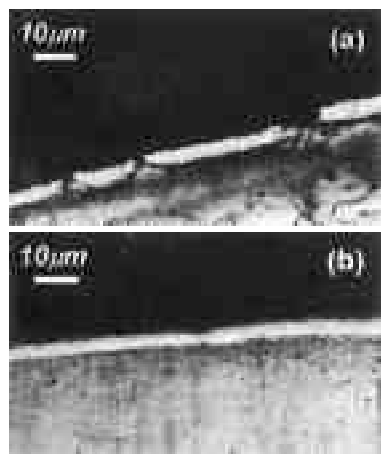

Fig. 2—Microscopic images, cross sections of (a) typical nickel/ and (b) conformable nickel/palladium surface finishes plated on alloy 194 leadframes after 90-degree bend with a radius of 0.25 mm.

Recent development of strengthening environmental protection and legislative requirement of using lead-free materials have generated tremendous pressure on the electronics industry.[7] Engineers are making considerable effort to search for alternative materials to tin-lead solders and finishes. In semiconductor leadframe packaging, the tin-lead post-plating will be completely replaced by environmentally friendly finishing processes. While thinking of tin and some tin alloy finishes, the industry has increased interest in the application of Pd PPFs. Nickel/palladium finishes should not be dismissed simply because of higher raw material costs. There are considerable cost savings to be factored when assessing the overall cost of integrated circuit packaging. Higher production speed, higher yields, less waste and lower disposal costs all contribute to reducing the total cost impact of converting to nickel/palladium PPFs.

Wirebonding performance and solderability are the most critical functional properties of leadframes. A thin palladium layer is usually applied over a nickel (Ni) electrodeposit underlayer (Fig. 1, inset). The palladium protects the nickel from oxidation and can provide the required wirebondability and solderability. The nickel, functioning as a barrier layer, ensures the integrity of the palladium finish by preventing diffusion and migration of substrate metals, such as copper, to the surface. This eliminates the formation of oxides and other corrosion products that are detrimental to wirebonding and soldering. However, the nickel electrodeposits typically used in the industry tend to crack when elongated during the forming operation (bending leads) of package manufacture (Fig. 2a). Poor solderability results from this operation.[8] In order to maintain the solderability of Pd PPFs, a "conformable" nickel electrodeposit has recently been developed, which is highly ductile, soft and conformable with the deformations of the leadframe surface during the forming operation (Fig. 2b).[9,10] The conformable nickel/palladium PPFs have superior solderability after forming and a long term steam aging even when using a non-activated flux.[10] However, the conformable nickel has a significantly different structure and material properties, such as grain size and hardness, from the typical nickel plated in the industry (Table 1 and Fig.

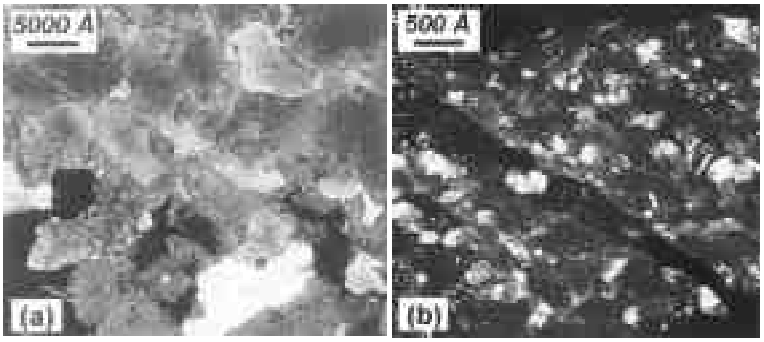

Fig. 3—TEM dark field images of (a) conformable and (b) typical nickel coatings showing different grain sizes.

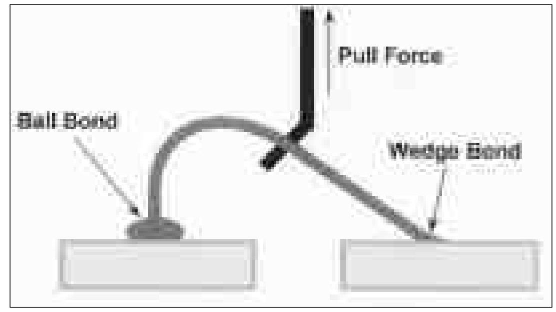

Fig. 4—Schematic gold wire bonding and pull test.

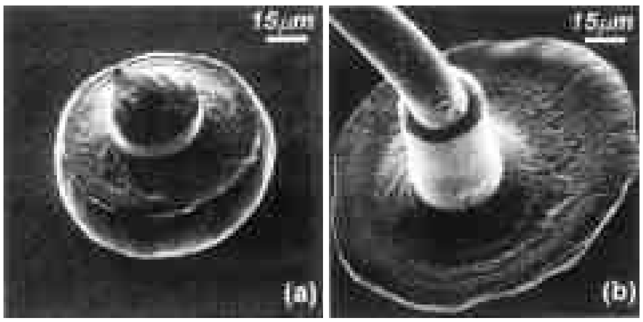

Fig. 5—SEM images showing ball bonds after pull test. Wire bonding at 180°C under (a) appropriate and (b) excessive force and power.

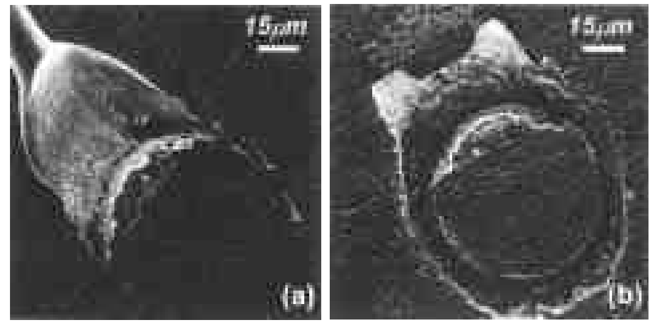

Fig. 6—SEM images showing wedge bonds after pull test. Wire bonding at 180°C under (a) appropriate and (b) excessive force and power.

3). The wirebonding performance of the conformable Ni/Pd PPFs, which can be affected by the structure and properties of the nickel underlayer, needs study. Wirebonding is reportedly the major cause of failure in integrated circuit packaging and one of the most expensive steps in the assembly process.[11] To reduce processing cost and production of unreliable devices, wirebonding performance of the leadframes should be optimized and wirebonding failures must be eliminated.

In this work, gold (Au) wire bonding performance of the conformable Ni/PPFs was evaluated and optimized. The optimization was achieved by using appropriate bonding conditions and palladium plating conditions which provide suitable structure and material properties to the finish for wirebonding. The gold wire bondability and bond strength on the nickel/palladium surface finish were compared to those on gold surface and to industry requirements.

Experimental Procedure

Surface Finishes

For wirebonding, 2.5–3.0 µm-thick conformable nickel and 0.125–0.175 µm-thick palladium were plated on Olin 194 copper alloy leadframes using proprietary chemistries developed at Lucent Technologies. The coating thickness was controlled by adjusting plating time at a fixed plating current density and measured via X-ray fluorescence. The palladium coatings with different grain sizes and hardness were produced by adjusting plating conditions. The grain size of the nickel and palladium coatings was determined by transmission electron microscopy (TEM) and the coatings were plated 0.3 µm thick for the TEM investigation. The hardness of the coatings was measured by micro-hardness indentation on cross sections using a 50 grams load and 50 µm thick coatings were plated for the measurement.

Two types of gold surfaces were also prepared for wire bonding: (1) a 1.25 µm-thick pure gold layer plated, using a proprietary chemistry, over a nickel underlayer[12] on the leadframes and (2) the gold plates provided by Kulicke and Soffa Industries Inc. (P/N 19090-2523-000).

Wirebonding

Gold wire bonding and destructive pull tests were carried out to determine the bondability and bond strength on the conformable Ni/PPFs. The wirebondings on the leadframes including a ball bond and a wedge bond (or called a crescent bond, Fig. 4) were made by using a manually controlled thermosonic bonder (Kulicke and Soffa, Model 4124). The bonding temperature set for the workholder was chosen from 100 to 180°C and the sample preheating time on the holder was 5 minutes. An alumina capillary (Micro-Swiss, P/N 40472-0010-320) was set up on the bonder and the gold wire (American Fine Wire) had a diameter of 25 µm, an elongation of 3-6% and a breaking load of 8-10 grams. Wirebondability is determined based on the number of bonding failures resulting from non-adhesion of either the ball bonds or the wedge bonds on the leadframe surface. A computer controlled pull tester (Dage, Model BT22PC) was used for the destructive pull tests to assess the strength between the bonds and the surface finish. During the pull test, a force was applied to the wire by pulling it with a metallic hook in the center of the loop (Fig. 4). The force was increased until the wire broke or either of the ball and wedge bond lifted off from the surface. The force needed to break the bonding is defined as pull force.

It should be noted that wirebonding in production is used to connect integrated circuits to the leadframes. The ball bonds are formed on the contacts of the circuits and the wedge bonds are on the leads. The strength of the wedge bonds is significantly lower than that of ball bonds. Since the issue in this work was to study the wirebonding performance of the leadframes, the wirebondability and wedge bond strength on the surface finish were of concern. The destructive pull test is typically used to evaluate the strength of wedge bonds and it is a suitable test in this study.

The wirebonding performance was checked on both as-plated and cured leadframes. The cure was carried out in an oven at 175°C for two hours in uncontrolled air. This reproduces the process conditions used in industry during die

Table 1
Grain Size & Hardness of Nickel Electrodeposits

Observables	Conformable Nickel	Typical Nickel
Grain size, Å	3000–10000	100–500
Hardness, KHN_{50}	160–230	250–500

Table 2
Gold Wire Bonding to Conformable Ni/PPFs
With Different Temperatures

Observables		100°C	120°C	150°C	180°C
Pull Force, g	mean	3.81	4.76	6.99	7.72
	STD dev	1.33	1.48	1.05	0.83
	minimum	1.72	1.97	3.38	5.90
	maximum	7.75	7.67	9.74	9.61
Pull force above 5.00 g, %		17	42	95	100
Break above the ball, %		6	12	65	95
Break at the wedge, %		94	88	35	5

Table 3
Grain Size & Hardness of the Palladium Finishes

Observables	Group 1	Group 2	Group 3
Grain size, Å	600 - 2000	500 - 1200	60 - 150
Hardness, KHN_{50}	120 - 170	400 - 430	500 - 530

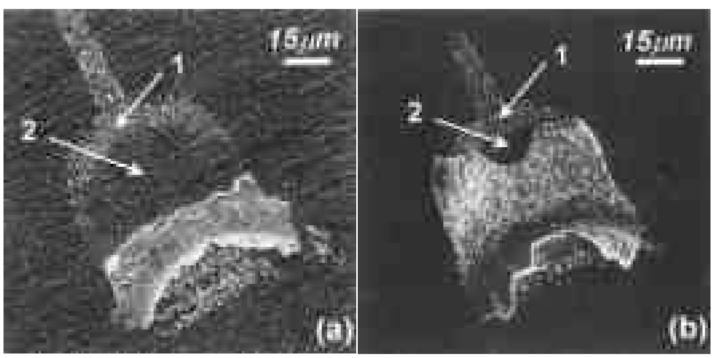

Fig. 7—SEM images showing broken wedge bonds made at (a) 100°C and (b) 180°C after pull test.

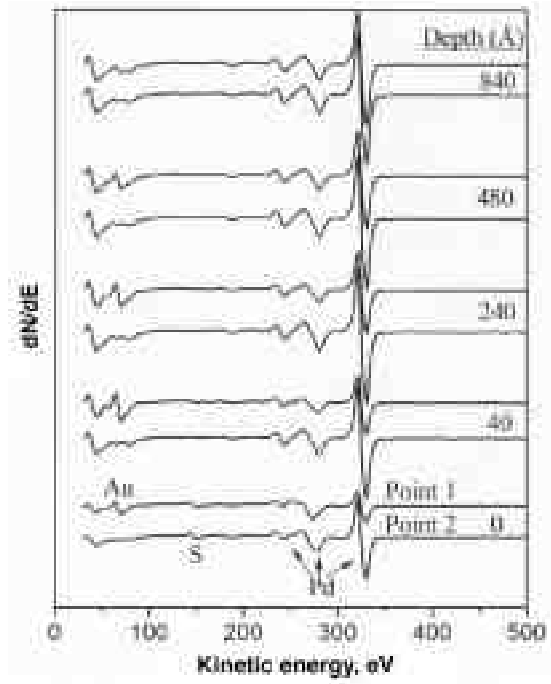

Fig. 8—AES spectra showing a typical surface composition at the perimeter (point 1) and inner part (point 2) of a broken wedge bond at different sputtering depths.

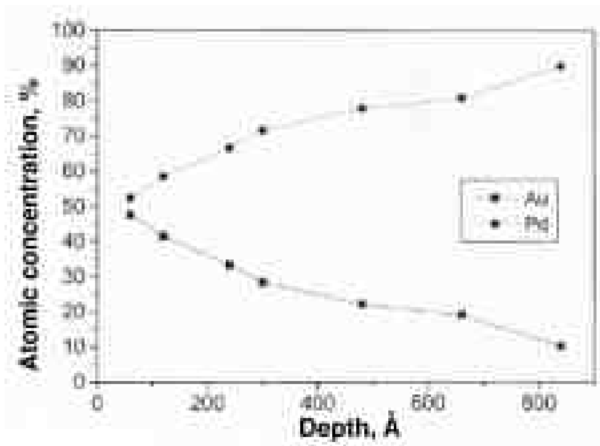

Fig. 9—A typical AES depth profile at the perimeter of a broken wedge bond.

attach on leadframes before wirebonding. In this study, one hundred experiments were carried out under each condition in wirebonding/pull tests to evaluate the wirebonding performance. Statistical results were obtained from the experiments for each test condition and compared with industry requirements, which demand a mean pull force higher than 7.00 grams and minimum higher than 5.00 grams with the wire used in this work.

Broken wedge bonds after pull test were examined with scanning electron microscopy (SEM, Hitachi Model 2500) and Auger electron spectroscopy (AES, Physical Electronics Model 595). AES was performed with a beam energy of 3 KeV and a beam size between 1-10 µm. The depth profile was obtained and the sputtering rate was calibrated using a silica thin film.

Results & Discussion

Effect of Bonding Conditions

In order to achieve high wirebonding yield and reliability on the conformable Ni/PPFs, bonding conditions were optimized. In thermosonic wirebonding, compressive force, ultrasonic energy and heat are the basic parameters.

When appropriate bonding force and power (energy) were used, high pull force was obtained and the wire broke mostly at the "ball neck" (just above the ball), this is related to the weakness of the wire at the heat affected zone (grain growth area) after ball formation.[13] Excessive bonding force and/or power, however, squashed the ball bonds and severely damaged the wire at the wedge bonds. Then, the pull force was low and the break position was mostly at the wedge bond. Figures 5 and 6 show the different shapes of the ball and wedge bonds, respectively, produced with different bonding force and power.

The effect of the bonding temperature on the pull test results is shown in Table 2. With 100°C, the pull force, mean and minimum values, was too low and unacceptable. Even though no bonding failure occurred, a very high percentage of wedge bond breaks appeared in the pull test with low pull force readings (Table 2, Fig. 7a), indicating low strength of the wedge bonds. As the temperature was increased to 120, 150 and 180°C, the pull force, mean and minimum values, gradually increased, eventually met the industry requirements. The break position occurred increasingly at the "ball neck" with increasing the temperature. With

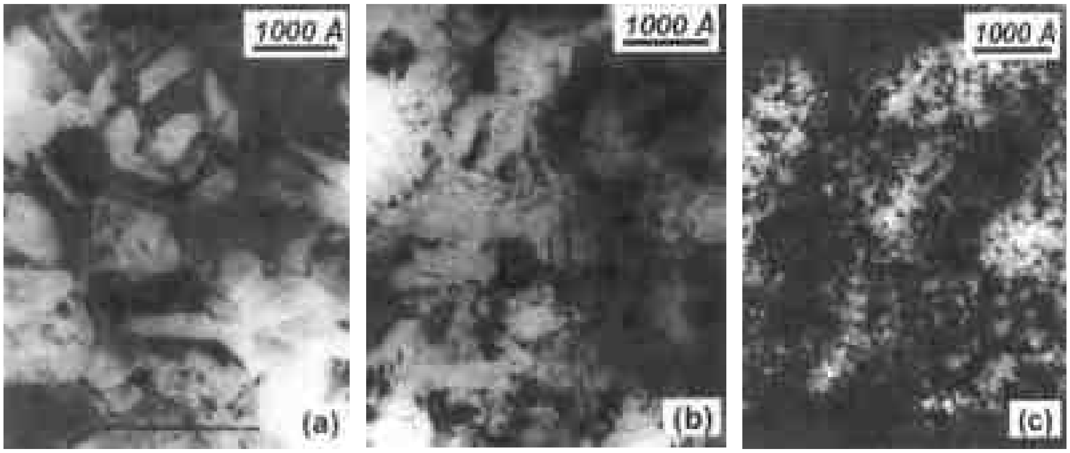

Fig. 10—TEM bright field images of (a) group 1, (b) group 2 and (c) group 3 palladium finishes showing different grain sizes.

Table 4
Gold Wire Bonding to Conformable Ni/PPFs & to Gold Surfaces

Observables		Pd as-plated	Pd after cure	Au as-plated	Au (K&S)
Pull Force, g	mean	7.72	7.81	8.00	7.48
	STD dev	0.83	0.83	0.81	0.78
	minimum	5.90	5.66	6.41	5.97
	maximum	9.61	9.64	10.10	10.37
Pull force above 5.00 g, %		100	100	100	100

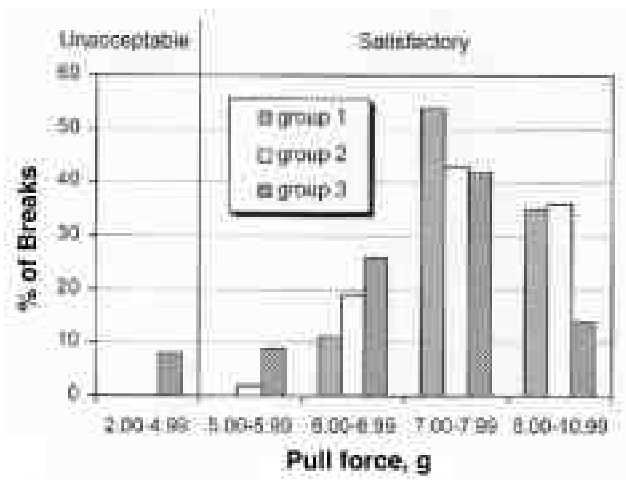

Fig. 11—Distribution of wirebonding breaks within different pull force ranges using the different palladium finishes.

a wirebonding temperature of 180°C, 95% of the break positions occurred at the "ball neck" (Fig. 5a) and only 5% of them occurred at the wedge bond (Fig. 7b).

Typical AES spectra showing the composition within the surface layer at different areas of a broken wedge bond, points 1 and 2 in Figs. 7a and b, are given in Figs. 8 and 9. As the spectra demonstrate, the perimeter (bright area) of the broken bond around point 1 consisted of both gold (wire) and palladium (surface finish), while no gold but palladium was found at the inner part (dark area) of the bond around point 2. At the perimeter, the extensive interdiffusion between gold and palladium occurred, gold could even be found at a depth of more than 800 Å (Figs. 8 and 9). These results indicate the formation of Au-Pd alloy at the wirebonding interface, which ultimately provides the strength to the bonding. It is believed that gold and palladium are completely miscible, and no intermetallic compounds exist between the two metals.[14] Apparently, the gold wire bonding was preferentially formed along the perimeter, which is consistent with the literature reported for ultrasonic aluminum wire bonding.[15]

It is noteworthy that the obtained AES surface compositions and depth profiles were virtually identical with different bonding temperatures used in this work at the perimeters and the inner areas, respectively, of the broken wedge bonds. Neither copper (leadframe material) nor nickel (underlayer material) was detected by AES on the surface of nickel/palladium finish and within the depth of bonding interface. This excludes the formation of copper and nickel oxides on the surface, which are detrimental to wirebonding. It seems that there is a correlation between the bonding area and bonding temperature, as shown in Figs. 7a and b. Higher temperature seems to result in a larger area of bonding between gold wire and palladium finish. With a low bonding temperature, however, the gold wire bonding was essentially confined to the perimeter and no bonding area was seen at the inner part. Therefore, low bond strength at the low temperature can arise from insufficient bonding area.

In production, an appropriate bonding temperature should be used, maintained and controlled. Excessive heat may damage electronic circuits and lower the adhesion between integrated circuit die and leadframe. A low temperature, however, may cause unreliable wirebonding.

Effect of Palladium Grain Size & Hardness

The leadframes plated with the conformable nickel and three groups of palladium finishes were studied for wirebonding. The palladium finishes were plated under different conditions and therefore have different structure and material properties. The grain size and hardness of the finishes are given in Table 3. Figure 10 shows the TEM images of the palladium deposits with different grain sizes. The palladium finishes in group 1 were composed of large grains and they had considerably lower hardness (Fig. 10a). The palladium finishes of group 2 composed of medium size grains had medium hardness (Fig. 10b), these finishes were used for optimizing the wirebonding conditions as mentioned in the previous section and also for comparing with the gold surfaces for wirebonding performance as reported in the following section. With one order of magnitude smaller grains than the others, the palladium finishes in group 3 had excessive hardness (Fig. 10c).

The wirebonding/pull test results are shown in Fig. 11. With the groups 1 and 2 finishes, the leadframes showed high bondability and bond strength. Most breaks occurred at the wire above the ball. With the group 3 finishes, however, the wirebonding performance was poor. In the case, 1% bonding failure occurred, the wedge bond didn't stick to the surface. In addition, 8% of the pull force data were lower than the requirement (5.00 grams minimum) and the minimum pull force was only 2.00 grams (Fig. 11). All these low force breaks occurred at the wedge bonds indicating low wedge bond strength on the surface finish.

Based on the results, a palladium layer having relatively large grains and low hardness should be plated over the conformable nickel to meet the requirements of gold wire bonding on leadframes.

Comparison with Gold Wire Bonding to Gold Surface

Under optimized bonding and plating conditions, the gold wire bonding performance of the conformable Ni/PPFs, either as-plated or after the cure, was evaluated and compared with the gold wire bonding to gold surfaces (Table 4). No significant difference was found in the wirebonding performance on the leadframes as-plated and after the cure process. The nickel/palladium surface finish was reliable for wirebonding after the cure process. In literature, gold to gold wire bonds showed the highest interface reliability in high volume production.[16] In this study, gold wire bonds on both the nickel/palladium plated leadframes and gold surfaces showed comparable strength which meets industry requirement (Table 4).

Conclusions

1. The conformable nickel/Pd PPFs meet industry requirements for gold wire bonding and perform comparably with gold surfaces for the bonding.
2. To achieve the required bond strength, appropriate bonding force and power should be used. In addition, the bonding temperature should be sufficiently high. With a low temperature, the attachment area of a wedge bond to the leadframe surface can be insufficient.
3. If a ductile and soft nickel underlayer is plated on the leadframes to ensure minimal cracking during forming operations hence sufficient solderability, a palladium top layer with relatively large grains and low hardness should be plated to ensure high-quality gold wire bonding.

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References

1. Texas Instruments, European Patent Application 87305080.1 (1987).
2. Texas Instruments, European Patent Application, 89302939.7 (1989).
3. S. Shiga & A. Matsuda (Furukawa Electric), Japanese Patent 1,501,723 (1988).
4. C. Abbott, R.M. Brook, N. McLelland & J.S. Wiley, *IEEE Trans. on Components*, Hybrids, & Mfg. Technol., 14, 567 (September 1991).
5. J.A. Abys, I.V. Kadija, E.J. Kudrak & J.J. Maisano, U.S. Patents 5,360,991 (1994) & 5,675,177 (1997).
6. I.V. Kadija, J.A. Abys, J.J. Maisano, E.J. Kudrak & S. Shimada, *Plating & Surface Finishing*, **82**, 56 (February 1995).
7. IPC Roadmap for Lead-free Electronics Assemblies, 3rd Draft, IPC, Northbrook, IL (February 2000).
8. T. McGuiggan & E.E. Benedetto, *Circuits Assembly*, **8**, 32 (November 1997).
9. J.A. Abys, C. Fan & I.V. Kadija, U.S. Patents 5,916,696 (1999) & 6,090,263 (2000).
10. C. Fan, J.A. Abys & A. Blair, *High-Density Interconnect*, **1**, (1), 22 (May 1998).
11. S. Trigwell, *Solid State Technology*, **36**, 45 (May 1993).
12. G.A. DiBari, "Nickel Plating," in *Metal Finishing Guidebook*, **94**, Elsevier Science Inc., New York, NY, 1996; No. 1A, p. 251.
13. G. Harman, *Wire Bonding in Microelectronics*, 2nd edition, McGraw-Hill, New York, NY, 1997; pp. 50-52.
14. *ASM Handbook*, H. Baker, Ed., Vol. 3, Alloy Phase Diagrams, ASM International, Materials Park, OH, 1992; p. 2.74.
15. G. Harman, *Wire Bonding in Microelectronics*, 2nd edition, McGraw-Hill, New York, NY, 1997; pp. 18-23.
16. G. Harman, *Wire Bonding in Microelectronics*, 2nd ed., McGraw-Hill, New York, NY, 1997; p. 148.

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