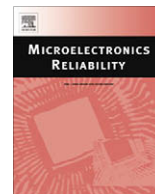




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## Nickel–palladium bond pads for copper wire bonding

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## ABSTRACT

The semiconductor packaging industry is undergoing a step-change transition from gold to copper wire bonding brought on by a quadrupling of gold cost over the last 8 years. The transition has been exceptionally rapid over the last 3 years and virtually all companies in the industry now have significant copper wire bonding production. Among the challenges to copper wire bonding is the damage to bond pads that had been engineered for wire bonding with the softer gold wire. This paper presents an extensive evaluation of electroless NiPd and NiPdAu bond pads that offer a much more robust alternative to the standard Al pad finish. These NiPd(Au) bond are shown to outperform Al in virtually all respects: bond strength, bond parameter window, lack of pad damage and reliability.

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## 1. Introduction

The past 3 years have seen a very rapid transition from gold to copper wire bonding, mainly driven by the large cost savings of copper in light of skyrocketing gold prices. At current gold prices (\$1200 per troy oz), it is estimated that the wire bonding cost savings is 75% for a typical 300 I/O package bonded with 25  $\mu\text{m}$  wire [1]. These cost savings have driven the industry to solving multiple technical challenges caused by copper's sensitivity to oxidation, corrosion and greater hardness. Along with cost savings for copper, also come the advantages of higher electrical and thermal conductivity.

Technical improvements, know-how and manufacturing infrastructure are improving at a breathtaking speed. The current status of copper wire bonding from a technical and marketing point of view have been recently presented [1,2]. A review of the technical literature for copper wire bonding has also been published [3].

Among the technical challenges in copper wire bonding are excessive deformation of the bond pad aluminum ("Al splash") and damage to sensitive structures under the pads caused by the greater hardness of copper [2,4,5]. This paper presents recent studies that demonstrate the advantages of NiPd and NiPdAu ("NiPd(Au)" for short) bond pad structures (Fig. 1) over the more standard Al bond pads with respect to pad damage and reliability.

## 2. Bond pad metallization

## 2.1. NiPd and NiPdAu pad structures

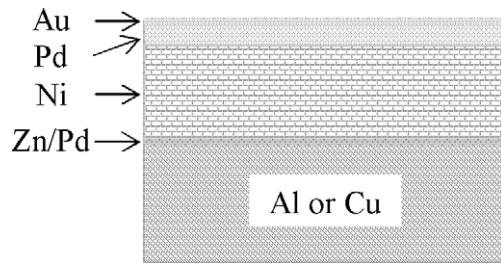
Aluminum bond pads have been the standard in the wire bonding industry for decades. It is inexpensive and, thanks to a thin, frangible passivating oxide layer, easily wire bondable. Its hardness is well matched to that of gold wire (Fig. 2) [6,7], but it is less well suited for copper wire bonding. One of the most significant drawbacks of aluminum pads for gold wire is Kirkendall voiding that results from extensive intermetallic formation [8]. The wire bonding industry has spent great effort to minimize Kirkendall voiding by engineering the bonding process, the bond pads and, most significantly, the gold wire bonding alloys. NiPd(Au) bond pads also offer an advantage in this respect and lack of Kirkendall voiding is one of the reason why some companies have already adopted them for gold wire bonding [9–11].

Not only is pure copper about twice as hard as pure gold [6], copper is also more susceptible to work hardening and the deformation associated with wire bonding can increase its hardness by another 50% [12,13]. In addition to this work hardening, copper wire bonding also requires approximately 20% more ultrasonic energy, exacerbating the problem of aluminum pad damage and cracking of fragile dielectrics under the pad [2,1].

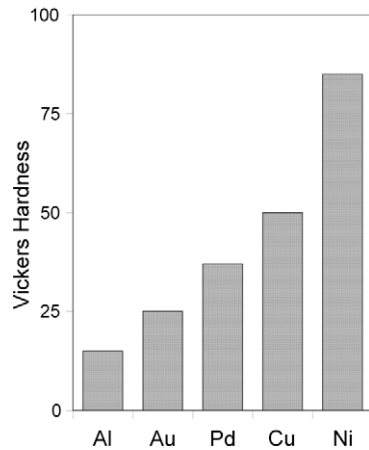
Nickel offers an attractive alternative to aluminum, since it is several times harder than aluminum and also harder than copper (Fig. 2). Inexpensive electroless plating processes have been well developed and have now been re-optimized for plating bond pads on integrated circuits [14,15]. An excellent overview of the status of Ni plating for wire bonding applications has just been published [16]. Ni itself is actually not wire bondable due to a hard, infrangible

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**Fig. 1.** NiPd(Au) pad stacks: 0.03  $\mu\text{m}$  Au (optional), 0.1–0.3  $\mu\text{m}$  Pd, 1–3  $\mu\text{m}$  Ni. Pre-treatment is zincation for Al bond pads or Pd for Cu device metallization.



**Fig. 2.** Vickers hardness of the metals of the bond pad stacks and bonding wires [5,6]. These values are for the pure, annealed metals and would differ somewhat depending on specific alloy and annealing state.

surface oxide layer. To provide a wire bondable surface, a thin layer of another metal needs to be applied to the surface. On many substrates, this layer is gold at a thickness of 0.3–0.5  $\mu\text{m}$ . While providing an excellent bondable surface, it is necessarily somewhat expensive. Electroless Pd is a more cost-effective solution that is easily wire bondable with both gold and copper. Diffusion of Ni, Cu or Au into Pd is very slow, which provides highly stable metal–metal interfaces. Mostly for cost considerations, NiPd(Au) surface finishes have already seen accelerated acceptance for substrates in the marketplace. This technology is now well established, although still being fine-tuned.

As shown in Fig. 1, NiPd(Au) pad metallizations can be applied either to existing Al pads or directly to the Cu conductors in the semiconductor die. NiPd(Au) on Al pads would be used for devices that are being converted from Au to Cu wire bonding, especially in cases where the existing pad structure is too fragile to withstand the additional stresses of Cu wire bonding. NiPd(Au) directly on Cu conductors would likely be the preferred choice for devices that are designed directly for Ni-based bond pads. Given the efficient electroless plating processes, these bond pads can actually be more cost-effective than Al bond pads. Since electroless plating processes selectively deposit on the metal, either pad structure can be created without the need for photoresist masks.

The pad structures consists of 1–3  $\mu\text{m}$  of electroless Ni, followed by 0.1–0.3  $\mu\text{m}$  electroless Pd. Both thicknesses are chosen to ensure complete and uniform coverage of all bond pads. As would be expected, thicker Ni provides additional mechanical protection for underlying structures. The Pd thickness needs to be sufficient to avoid Ni diffusion to the surface. The optional immersion Au layer is only about 0.02  $\mu\text{m}$  thick.

## 2.2. Electroless plating of bond pads

For this study the NiPd(Au) plating was applied to existing Al pads. However, as mentioned above, NiPd(Au) pads can also be applied to Cu conductors in the semiconductor die. The only difference between the two processes is the pre-treatment of the surfaces before the electroless nickel/palladium plating.

### 2.2.1. Pre-treatment of aluminum bond pads

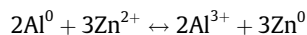
Immersion zincing is the industry-standard process in which the thin oxide layer on Al is first removed and then replaced with a thin layer of zinc. This zinc layer provides the surface protection and the necessary roughness characteristics for the subsequent electroless metal deposition.

In preparation for the zincation, any residual surface passivations and Al oxides are first removed by an acid cleaning and alkaline etching process. This exposes the Al metal and increases the pad roughness for improved mechanical and chemical reactivity for zincation. The etching system is specifically formulated for homogeneous and linear aluminum surface removal.

Uniform and controlled surface removal in the cleaning and etching process ensures a maximum remaining pad thickness. Any unnecessary surface removal would reduce the bond pad thickness and could potentially cause reliability drawbacks, like pad deformation or damage of underlying structures.

The devices in this study were prepared using an acidic zincation process, rather than the more traditional alkaline, cyanide-based process. Latest environmental regulations and restrictions on the use of hazardous components (ROHS, WEEE) as well as customer-specific requirements are driving the zincation process towards cyanide-free, fine-grain layer formation and more robust process control. Acidic zincation was developed in order to be environmentally friendly and simplify the handling. Additionally the acidic process conditions minimize the attack of the polyimide passivation layer relative to the alkaline process conditions.

Mechanism for formation of a zincate immersion layer:



### 2.2.2. Pre-treatment of copper metallization

Pre-treatment of copper pads also involves cleaning, etching and activation, but the details are different. The cleaning step improves the pad surface tension and increases the chemical activity for subsequent process steps. Cleaning is followed by a mild surface etch to remove any residual copper oxide. Any remaining oxide would weaken the adhesion of Ni to Cu and thus would negatively influence the bonding performance. Finally the activation process deposits a thin palladium layer on the surface. It acts as the surface catalyst for the subsequent electroless nickel deposition.

### 2.2.3. Electroless plating

Typical nickel layers are 1–3  $\mu\text{m}$  thick and are the main structural element of the pad stack. This layer provides the protection for fragile structures below the pad. The amount of phosphorous that is co-deposited must be carefully controlled to manage the stresses that typically occur in electroless plating processes. Mid-phosphorous processes (7–9.5% P) generate tensile stresses, while high phosphorous (10–11% P) produces compressive stress in the layer. The optimal combination of process conditions and thickness of the individual metal layers enables an almost stress free bond pad metallization. Such stress management is especially important to reduce the warpage of thin wafers.

Palladium, with or without an additional very thin immersion gold layer, replaces the more traditional and much more costly

**Table 1**

Sample description and bonding results for 0.8 mil Cu wire.

Sample	Ni ( $\mu\text{m}$ )	Pd ( $\mu\text{m}$ )	Au ( $\mu\text{m}$ )	XY Avg ( $\mu\text{m}$ )	Ball Z ( $\mu\text{m}$ )	Shear	SHR/area (g/mil <sup>2</sup> )
Al – ref	1 $\mu\text{m}$ , Al, reference die			39.4	8.1	15.0	7.9
A	3	0.3	0.03	39.2	9.2	24.6	13.2
B	3	0.3	0	39.5	9.4	25.9	13.6
C	3	0.1	0.03	39.1	9.3	24.3	13.1
D	1	0.1	0	39.3	8.8	24.5	13.0
E	1	0.1	0.03	39.5	8.9	25.7	13.5
F	1	0.3	0.03	39.3	8.4	25.9	13.8
G	3	0.1	0	39.2	9.2	26.0	13.9
H	1	0.3	0	39.3	8.4	25.0	13.3

thick, electrolytic gold finish. Being a relatively hard, noble metal, the Pd layer is corrosion-resistant and mechanically strong.

### 3. Experimental

#### 3.1. Materials

NiPd and NiPdAu layers (Table 1) were plated onto 1  $\mu\text{m}$  thick Al pads (Al–1%Si–0.5%Cu) of test wafers using the Atotech Xenolyte<sup>®</sup> process outlined above. An identical test wafer without any NiPd(Au) served as a reference. All devices were cleaned with Ar gas in a March plasma cleaner for 5 min before use.

#### 3.2. Cu wire bonding

Devices were bonded on 50  $\mu\text{m}$  pitch pads with 20  $\mu\text{m}$  Heraeus Maxsoft copper wire at 165 °C. The Cu bonding process was performed using a K&S Max $\mu\text{m}$  Ultra wire bonder with a Microenvironment Copper Kit. Forming gas (5%/95% H<sub>2</sub>/N<sub>2</sub>) protected the free-air ball during formation. The bonding tool was a K&S CuPRA-plus capillary with 1.25 mil chamfer diameter (CD) and 60° inner chamfer angle (ICA).

#### 3.3. High temperature storage test

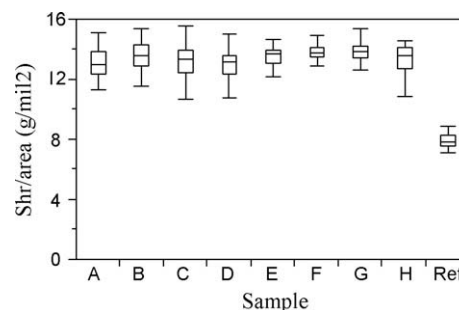
A subset of the wire bonded samples (A, B and C in Table 1) along with an Al reference were bake tested unmolded at 175 °C up to 1000 h. To minimize oxidation of the copper wire, the baking was carried out under a nitrogen atmosphere. At each interval, samples were shear and pull tested using a Dage 4000 tester. Pull tests were conducted at top-of-loop.

### 4. Copper wire bonding results

#### 4.1. Screening study

Bonding parameters were first optimized for the Al reference device and then applied without modification to the eight combinations of NiPd(Au) pads listed in Table 1. These optimized bonding parameters on a K&S Max $\mu\text{m}$  Ultra wire bonder are: 0.30 mil/ms impact velocity, 14 g force, 80 mA ultrasonic energy, 70% pre-impact (pre-bleed) ultrasonic energy, 12 ms bond time. The bonding occurred without any non-sticks on pad and top-of-loop wire pull tests resulted in wire breaks above the ball in all cases, including the reference device.

The shear test revealed the first substantial advantage of the NiPd(Au) pads. The shear-per-area strength on the NiPd(Au) pads was about 5 g/mil<sup>2</sup> (or more than 50%) higher than for the bonds to Al. As seen in Fig. 3, the shear strength of all the NiPd(Au) devices was approximately the same. No trend could be found between the shear strength or its standard deviation and the metal stack configuration.



**Fig. 3.** As-bonded shear/area for NiPd(Au) samples A–H (Table 1) and the reference Al sample.

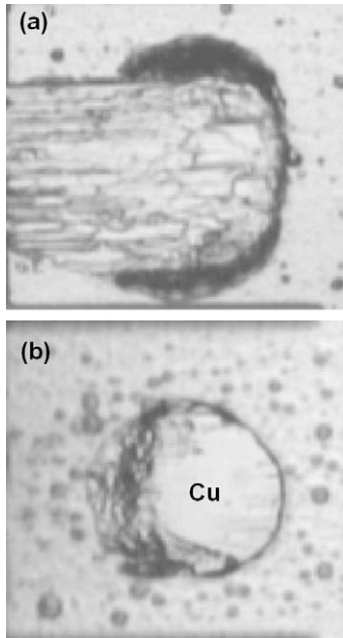
The shear failure mode was also completely different for the bonds to NiPd(Au) and Al. Since Cu is so much stronger than Al, the shear failure on Al is either at the Cu–Al interface or within the Al. Fig. 4a shows this failure mode. It should be noted that as-bonded, no failure at the Al–Si interface was seen in the reference samples. Such pad peeling can at times be a serious problem in Cu-to-Al ball bonding and requires very careful process optimization.

In contrast, on NiPd(Au) bond pads, the tool shears through most of the Cu ball, leaving a thin layer of Cu behind as in Fig. 4b. This failure mode was seen for all bonds on all of the NiPd(Au) devices. Clearly the Cu ball itself is weaker than the Cu–Pd bond. This means that the shear test actually measures the strength of the copper ball and the bond-to-bond variation in the shear data is as much if not more a reflection of differences in the work hardening of the Cu ball than variation in the strength of the bond.

#### 4.2. Lack of pad damage

Great resistance to pad damage is the main advantage of NiPd(Au) pad surface finishes. Deformation (“splash”) of the Al bond pad as seen in Fig. 5c is a serious concern in Cu wire bonding and cannot be eliminated. The amount of Al splash is directly correlated to the shear strength of the bond. Since it could cause shorts between adjacent bond pads, the target ball diameter for a copper wire bonding process is often reduced relative to the corresponding gold wire process to account for this splash. In addition, the copper wire bonding process must be carefully optimized so as to not completely remove all the aluminum under portions of the Cu ball.

NiPd(Au) pads are completely resistant to such pad splash as can be seen in the bonded ball of Fig. 5a. Removal of the Cu ball using nitric acid reveals that the bond pad is essentially unaltered by the bonding process (Fig. 5b).



**Fig. 4.** Shear failure mode after bonding for (a) the reference Al pad sample and (b) sample B (3  $\mu\text{m}$ /0.3  $\mu\text{m}$  Ni/Pd, no Au).

#### 4.3. Ultrasonic power bonding window

Since ultrasonic energy is the main factor responsible for both bond formation and pad damage in Cu-on-Al wire bonding, the effect of varying this bond energy was more closely examined. Fig. 6

shows the results of an ultrasonic power sensitivity study for sample A (3/0.3/0.03  $\mu\text{m}$  Ni/Pd/Au) and the Al reference device. A similar study was performed on sample F (1/0.3/0.03  $\mu\text{m}$  Ni/Pd/Au) with essentially identical results. Ultrasonic energy was incremented in steps of 5 mA while keeping all other bonding parameters fixed at the level used in the screening study. This type of experiments is typically used to establish the bonding window and measures the relative robustness of the bonding process.

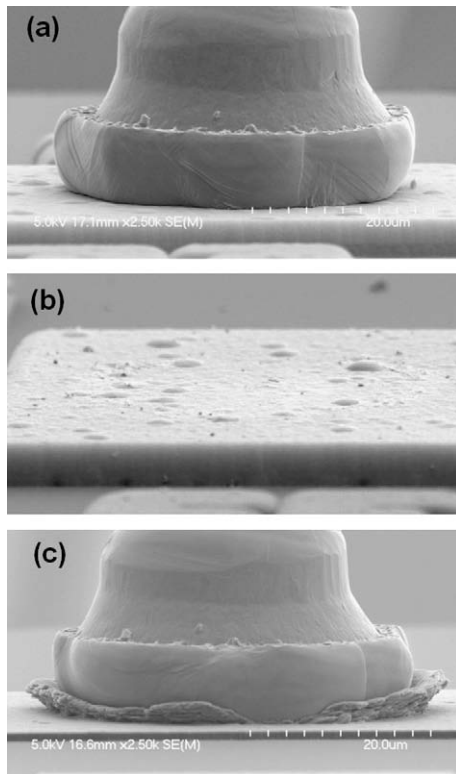
The diameter of the copper balls responds very similarly to the ultrasonic energy on both Al and Ni–Pd–Au pads. However, as mentioned previously, Al splash adds significantly to the effective ball diameter when bonding to Al. To avoid the risk of shorting to adjacent pads, the Al splash, not the actual bonded ball diameter, defines the upper limit for the ultrasonic energy. In this experiment, the splash exceeds the ball diameter by approximately 4  $\mu\text{m}$ , a value that is representative for many real-life applications. Setting an upper spec limit of 40  $\mu\text{m}$  for this 50  $\mu\text{m}$  pitch process, the splash limits the ultrasonic energy to below 85 mA on the Al pads.

In contrast, since there is no splash and no pad damage, ultrasonic energies as high as 115 mA can be used on the NiPdAu pad before the ball exceeds the upper spec limit. Even at 115 mA the bond pads remained completely undamaged.

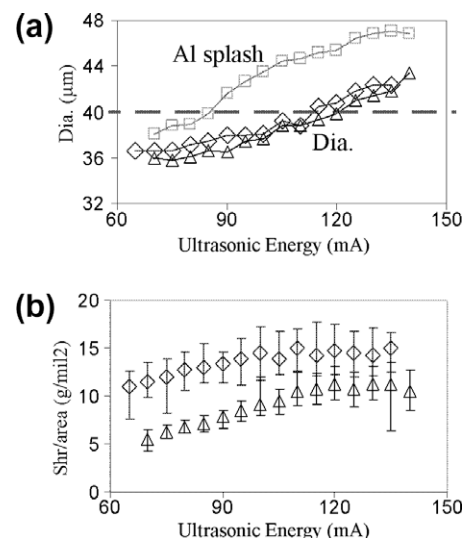
The lower limit of the bonding window is normally defined by the ultrasonic energy that results in shear/area at the lower spec limit. This limit is usually set to 5.5 g/mil<sup>2</sup>. On the Al pads, this lower ultrasonic limit is found to be 70 mA. The useable ultrasonic energy window on Al therefore extends only from 70 to 85 mA.

On the NiPd(Au) pads, shear/area is far above the shear/area spec for all ultrasonic levels. Instead, the lower limit of the bond window is set by the occurrence of NSOP (non-stick on pad). For both samples A and F, a single NSOP out of 120 wires occurred at 65 mA ultrasonic energy. No NSOP occurred at higher ultrasonic levels. An ultrasonic energy of 70 mA can therefore be set as the lower limit of the bonding window. The ultrasonic bond window for NiPd(Au) is therefore 70–115 mA, three times as large as on Al pads.

The behavior of the NiPd(Au) pads at the lower limit of ultrasonic energy is actually somewhat surprising. As can be seen by the range bars in Fig. 6b, even when ultrasonic levels are low enough for the occurrence of NSOP, the minimum shear values are quite high. The lower shear values typically correlate with a small-



**Fig. 5.** Electron micrographs of Cu ball bonds on (a) sample A and (c) Al pad, both bonded with 85 mA ultrasonic energy. (b) shows the bond pad in (a) after the copper ball was removed with nitric acid.



**Fig. 6.** Ultrasonic power sensitivity of (a) ball diameter and (b) shear/area. NiPdAu sample A (diamonds), Al reference (triangles) and Al splash (squares).



ler amount of copper remaining on the pads. Essentially the ball is first sheared with failure in the copper, but then the ball breaks off the pad. Since the shear tester measures the maximum in the shear-displacement curve, the values for balls that break off early are actually not much lower than those where most of the copper remains on the pad. This observation suggests that the amount of copper remaining may be a more useful quality measure than shear strength.

#### 4.4. Reliability

Samples A, B and C were chosen for a high temperature storage test at 175 °C up to 1000 h in a nitrogen atmosphere. All three had 3 µm of Ni, but provided tests for the effect of 0.1 µm vs. 0.3 µm Pd and the presence and absence of the immersion Au layer. The three samples behaved essentially identically in the bake test (Fig. 7). The shear strength increased slightly over the first 48 h, but then remained unchanged for the remainder of the test. The failure

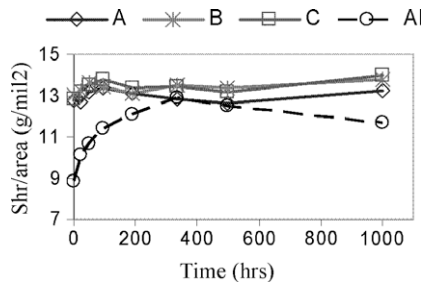


Fig. 7. Shear/area progression during a high temperature storage test at 175 °C. A: NiPdAu (3/0.3/0.03 µm), B: NiPd (3/0.3 µm), C: (3/0.1/0.03 µm).

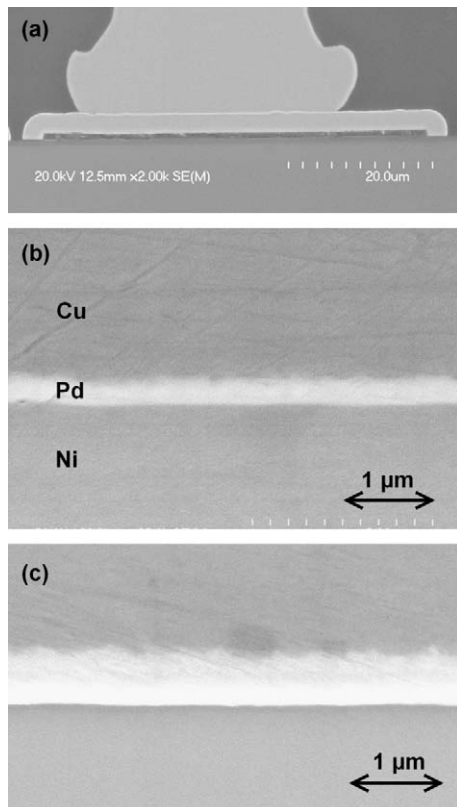


Fig. 8. Cross-sections after high temperature storage at 175 °C. (a), (b) sample C at low and high magnification after 1000 h, (c) similar sample after 5000 h.

mode was always shear through the copper. Top-of-loop pull tests resulted in wire breaks for all bake intervals. A separate 175 °C bake test with 1 mil Cu wire to 5000 h was also passed with similarly excellent results.

The Al reference samples failed this same reliability test. Although the shear strengths increased to eventually equal those of the NiPd(Au) devices, at 48 h and all subsequent intervals, the Al reference sample had 10–30% peels and craters during the pull tests and many shear tests also resulted in failure at the Al–Si interface. The shear strengths at 1000 h dropped because a few bonds failed with very low strength while others remained strong.

Cross-sections (Fig. 8) of the devices after 1000 h at 175 °C reveal only minimal changes at the Cu–Pd and Pd–Ni interface. Over the period of the bake test, the Pd diffuses less than 0.5 µm into the Cu. There is no noticeable diffusion layer between the nickel and palladium. Neither the Cu–Pd nor the Pd–Ni interface show any voids at all. The same is true for a sample from a similar study baked for 5000 h at 175 °C (Fig. 8b). These cross-sections are in agreement with a previous studies [17,18] and attest to the exceptional stability of these metal interfaces.

#### 5. Conclusions

NiPd and NiPdAu pad metallizations have been shown to be an excellent bonding surface for copper wire. They outperformed a standard Al pad with respect to bond window, shear strength, pad damage and reliability. Although not directly proven here, the lack of deformation of the pad also suggests that underlying structures would be much better protected with a Ni-based bond pad. In this study, neither the different Ni and Pd thicknesses nor the presence or absence of the immersion Au layer caused any difference in the bond quality measures or high temperature storage test. No voids formed at the interface even after 5000 h at 175 °C.

#### Acknowledgments

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