Next Generation Nickel-Based Bond Pads Enable Copper Wire Bonding

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Abstract

Copper wire bonding has huge cost advantages over gold wire bonding. As a result, low pin count, heavy wire applications have already been converted to copper wire and many companies are in high volume production. Recently, with the price of gold skyrocketing, conversion of high pin count (>250 I/O), high performance applications to Cu has dramatically accelerated.

These high performance devices are increasingly relying on low-k materials under the bond pads. Unfortunately, the 33% greater hardness of Cu compared to gold places even greater stress on these inherently fragile materials. This can result in difficulties with pad damage and cratering of the underlying structures. Advancements have been made to copper wire bonders, tools, and wire that have resolved many of these issues and made fine pitch copper wire bonding feasible.

Ni-based bond pads have emerged to solve the pad damage problem. Nickel is about 50% harder than copper and four times harder than aluminum so that it provides greater protection against the higher stress resulting from Cu ball bonding, as well as damage during probe. This is especially beneficial for devices with low-k active circuitry under the bond pad. NiPd, NiPdAu, and/or NiAu have demonstrated their great robustness to receive the Cu wire bonding with a huge wire bonding window without any splash and with excellent reliability.

INTRODUCTION

Gold wire bonding has overwhelmingly predominated in the industry for more than twenty years because of its high reliability and performance. Other types of wire bonding, such as copper or aluminum, on the other hand, are more popular for heavy wire, low cost applications in consumer products or discrete semiconductor products. As gold prices have risen to historical highs, copper wire bonding has again gained attention for its advantages of low density, high stiffness, low cost, high electrical and thermal conductivities and excellent (intermetallic) reliability with aluminum pad metallization. Fundamental understanding and the infrastructure for fine pitch copper wire bonding has been steadily maturing.

Because of its oxidation sensitivity, a special copper bonding kit is necessary to apply an inert or reducing environment when forming a ball through melting prior bonding. Such copper kits have now matured and conversion of gold process to copper is readily achievable. Copper's high modulus relative to Au could also ease the requirements of long, skinny wire for ultra-fine wire applications. High electrical and thermal conductivities and excellent Cu-Al intermetallic reliability further enhance the appeal of copper wire bonding.

However, the high stiffness of copper also introduces difficulties during bonding. A higher bonding force is required to respond to its greater work hardening in order to deliver satisfactory bonding integrity. While applying ultrasonic energy during bonding, shear forces add to the already applied normal bonding force. Such shear stress can transmit through bond pad metallization to the brittle, easily fractured dielectrics underneath, leading to pad peeling and bond failure. High hardness of copper could also smear off the soft aluminum during bonding along the ultrasonic direction, which is commonly called 'Al splash'. Significant effort has been focused on optimizing the bonding parameters, such as ultrasonic energy and bonding force, to reduce such pad damage and Al splash with some level of successes. However, as the device technology progresses to finer bond pad pitch and thinner pad metallization, pad management deserves much more attention, not only for copper wire bonding but also for ultra-fine gold wire bonding.

BOND PAD STRUCTURE

Current bond pad structure migration

When the submicron technologies were introduced, multiple metal layer structures were developed to accommodate the demands for complex device functions. In order to structure such multiple metal layers, a planarization process including CMP (chemical-mechanical polishing), via and via filling (typically W or TiW) were adopted. The bond pad structures therefore include varieties of a sea of tungsten vias underneath the Al pads for better current carrying capability. 0.5% or higher Cu was added into the Al or Al-1%Si metallization for better electromigration resistance in ever shrinking geometries. The bond pad design rules at the time restricted any active structure underneath the bond pad to prevent any destructive action from wafer probe testing and/or wire bonding. However, a strong desire of form factor shrinkage led to aggressive BOAC (bond over active circuitry) development [1], pushing wire bonding and probing improvements in addition to robust bond pad structures to minimize concerns for device integrity.

For deep submicron technologies beyond 0.27 µm, 0.13 um feature sizes were demanded for further performance with faster, more powerful devices with reduced RC (resistance/capacitance) delays. Cu interconnect and low-k dielectrics were therefore introduced and have now matured. Lower dielectric constant dielectrics are typically porous composite materials that can only tolerate low stresses from bonding or probing. Therefore, Cu interconnect and low-k dielectrics are being used in the lower levels of devices where RC concerns are critical, but medium-k dielectrics such as FSG (fluorosilicate glass) with Al cap finish are used for the top one or two metal layers for power carrying capability and good probing/bonding robustness.

Bond Pad Design for Cu wire bonding

More than a decade of experience with copper wire bonding has now led to a set of generic bond pad design rules. Ideally, a bond pad with thicker and/or higher yield strength bonding material is desired. As reported in the past [2,3], either alloying Al metal with different dopant types or dopant levels, or designing the Al pad structure differently can increase the composite pad strength and significantly reduce the risk of cratering or other damage to the underlying structures. However, changing the Al metallization or stacking metallization in wafer fab process is not trivial due to the complex process integration and stringent process reliability qualification requirements.

Therefore, a minimum Al pad thickness of 1µm is required irrespective of the alloy types (1%Si or 1%Si0.5%Cu). Typically when the Cu layer under the Al is thinner than 1 µm, the Cu wire bonding process has to be well-optimized to achieve a suitable bonding window without pad damage. In contrast, an underlying Cu thickness of more than 1 µm is very robust and generally delivers a good Cu wire bonding process. However, when Al pad thickness is thinner than 7000 Å or even approaching 5000 Å, pad damage is almost always found during Cu wire bonding irrespective of the type of dielectric.

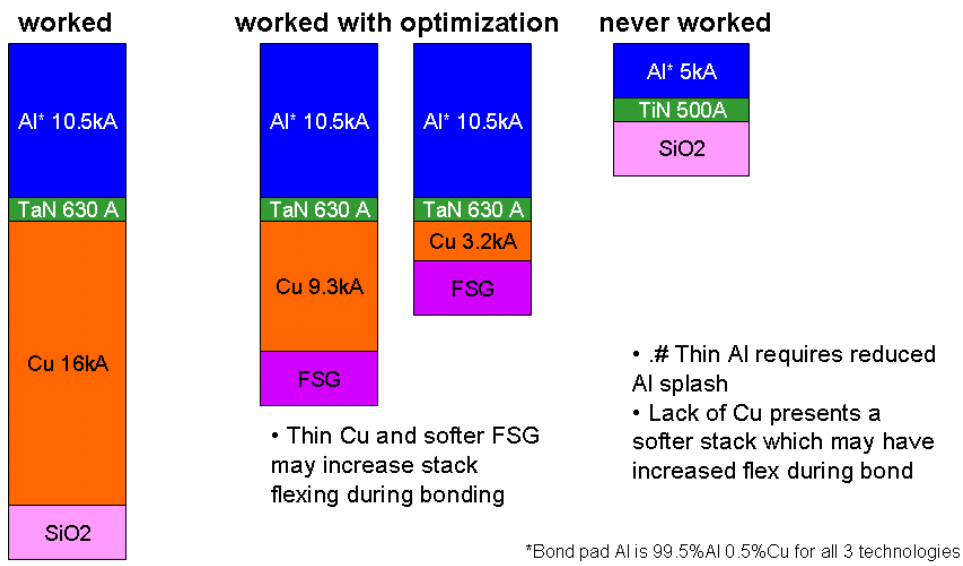

Figure 1. Pad Finish Stack Acceptable for Cu Wire Bonding

Dielectrics with a medium k, say above 3.2, such as FSG or TEOS SiO_2 typically have much stronger fracture resistance compared to low-k dielectrics. Bonding directly on top of low-k dielectric with either gold or copper wire bonding or even just probe testing such devices without pad damage has typically been found to be impossible [4, 5]. A tougher dielectric layer, either ILD (inter-layer dielectric) or passivation, has to be placed underneath the pad finish to enable robust wire bonding.

The use of a sea of via pad structure in conjunction with Cu wire bonding has been found to be detrimental. The tungsten vias in such W-SiO_2 composite structures serve as stress concentrators, causing cracks to propagate along the shortest distance between vias to release the pressure. Therefore, vias should not be placed under any high-stress areas of the bond pad. A peripheral via design for interlayer connection is much more desirable.

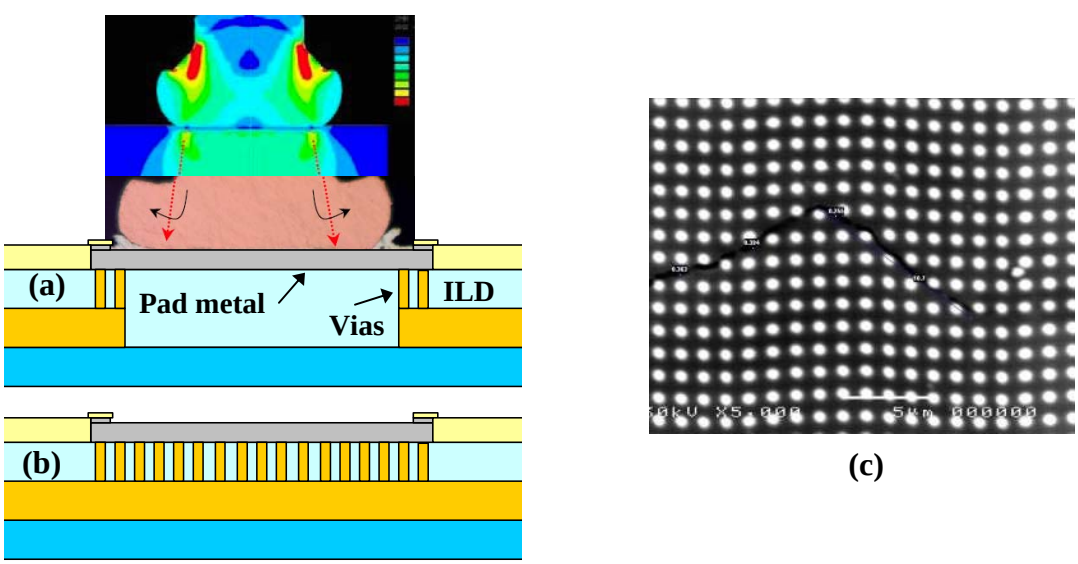

Figure 2: (a) workable bond pad via structure; (b) bond pad design with the sea of vias; (c) crack propagates between vias (top view, after pad metal stripped);

BOND PAD SOLUTIONS – NEXT GENERATION NI-BASED BOND PAD

The ideal next generation bond pad would address the needs of all of the emerging technologies, including copper wire bonding, ultra fine pitch gold wire bonding, ultra low-k dielectrics with rapidly shrinking BPP (bond pad pitch), as well as allowing probing and bonding on the same pad real estate.

Ni based bond pad introduction

From a mechanical viewpoint for bonding and probing, bringing two materials with distinct material properties together obviously causes a higher amount of deformation in the softer material. As a result, aluminum splash is much more severe in Cu wire bonding than in gold wire bonding. Simultaneously, this deformation thins down the Al metallization underneath the bond, potentially inducing device damage and possibly reducing the bond reliability as the intermetallics grow.

Therefore, a harder pad metallization is desirable to protect the underlying structures. Nickel, with a hardness 50% and 70% higher than Cu and Au, respectively, is receiving increasing attention as the predominant alternative to aluminum metallization. It addresses all of the requirements of higher reliability, higher bonding load, protection of fragile structures, compatibility between probing and bonding, and compatibility with Au and Cu wire bonding [4, 5, 6].

Typically, 1 µm to 3 µm thick Ni is deposited on either Al or Cu base metallization. However, as a thin oxide rapidly forms on Ni, a thin noble layer of Au and/or Pd should be used on top of Ni for more robust manufacturability, bondability, and reliability. The combinations of NiAu, NiPdAu, NiPd structures have been matured and are used in many other semiconductor or electronic applications. The layer thickness and stack structure combination may just need to be optimized to be suitable for the next generation bond pad structure of each specific application requirements.

Electroless plating bond pad

Electrolessly plated Ni-Pd and immersion plated Au has become an established technology in electronic component manufacturing. Recently it has become popular for wafer level, low cost flip chip under bump metal application because of it is low cost, maskless deposition and compatibility with Cu and Al substrates.

In this study, a test vehicle with Al pad finish was used. The bond pad pretreatment has to remove any residues or oxide layer from the aluminum alloy deposition process, followed by an alkaline etching to remove the top pad surface layer. Then, an immersion zincation process can provide the required surface protection as well as the necessary roughness characteristics for the subsequent electroless metal deposition. By replacing aluminum elementary with an immersion zinc layer, the surface is protected from forming any oxide layer.

Electroless nickel is then plated onto this zinc layer on top of the Al. The stress in the nickel layer is mainly influenced by the phosphorous co-deposit. Typical mid-phosphorous nickel layers can range from 7 to 9.5 %P and generate a tensile stress. Alternative electroless nickel types with a high P content of between 10% and 11% generate a compressive stress.

A rather new approach is an additional palladium intermediate layer between Nickel and gold or pure palladium as top metal layer. Acting as an additional protective barrier, the palladium significantly improves the bond pad stability, the corrosion resistance of the nickel and the stress impact of the metallization stack. The complete metal stack is more resistant to metal diffusion during thermal processing steps. Especially the stress impact can be minimized as the individual metal layer can be thinned down without risking nickel corrosion. Palladium not only allows minimizing the thickness of the nickel layer from 5 µm to less then 3 µm, but also eliminates the necessity of gold as the bondable pad surface finish.

COPPER WIRE BONDING ON NICKEL/PALLADIUM/GOLD PADS

Experimental

Nickel/palladium/gold layers were plated onto 1 µm thick Al pads (Al-1%Si-0.5%Cu) of test wafers. An identical test wafer without any Ni/Pd/Au served as a reference. Bonding tests were performed using 0.8 mil Heraeus Maxsoft wire on 50 µm pitch pads at a 165 ºC bond temperature. All bonding was performed using a K&S Max µm Ultra wire bonder with a Microenvironment Copper Kit to provide forming gas (5% / 95% H2 / N2) cover gas during ball formation. The bonding tool was a K&S CuPRAplus capillary with 1.25 mil CD and 60º ICA. All devices were plasma cleaned in a March plasma cleaner for 5 min in Ar at 200 mtorr. Shear and pull measurements were performed using a Dage 4000 tester.

Bonding Results

Screening study. In an initial screening experiment, devices with eight combinations of Ni/Pd/Au pads and an Al reference device (see Table I) were wire bonded with the same wire bonding parameter set. The bonding parameters were optimized on the Al reference and then applied without further changes to the Ni/Pd/Au pads. As Figure 3 shows, the shear/area response on all of the Ni/Pd/Au-plated devices was essentially the same with average shear per area between 12 and 14 g/mil^2 in each case. These shear/area values were about 6 g/mil^2 higher than those on the Al reference pads. The shear failure mode was through the Cu ball in all cases on the Ni/Pd/Au pads, but failure at the Al-Cu interface for the Al reference device. Top-of-loop pull strengths were between 9 and 9.5 g on all devices, including the Al reference. All wires broke at the neck of the balls.

Table I: Ni-Pd-Au Surface Finishes

Sample	Ni (µm)	Pd (µm)	Au (µm)
Al Ref	0	0	0
A	3	0.3	0.03
B	3	0.3	0
C	3	0.1	0.03
D	1	0.1	0
E	1	0.1	0.03
F	1	0.3	0.03
G	3	0.1	0
H	1	0.3	0

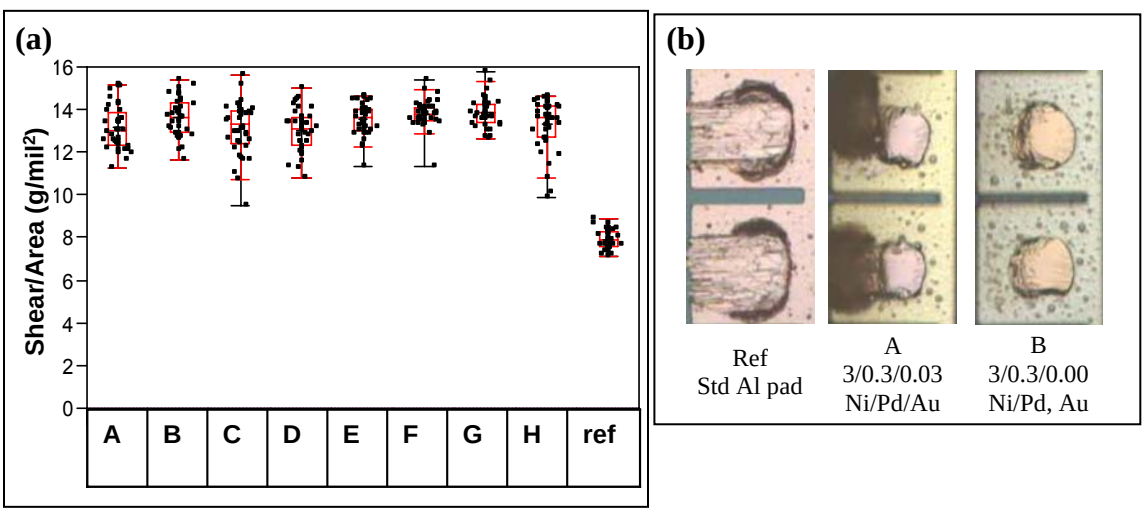

Figure 3: (a) Shear/Area for plating finishes in Table I (b) optical images of failure mode in shear test

The higher strength of the Ni allowed bonding without any of the pad splash (Figure 4(a)) that is normally seen in Cu wire bonding on Al pads. Clearly visible in Figure 4(b), such splash can add several microns to the effective ball diameter. The cross sections in Figure 5 of bonded devices demonstrate that there is minimal to no deformation of the Al layer under the Ni layer. For the thinner, 1 µm Ni plating, a slight deformation of 0.2 µm of the underlying Al pad is seen. The thicker, 3 µm Ni plating completely protected the Al from any deformation. In contrast, the thickness of the Al under the Cu ball is often reduced by 80% or more on standard Al pads.

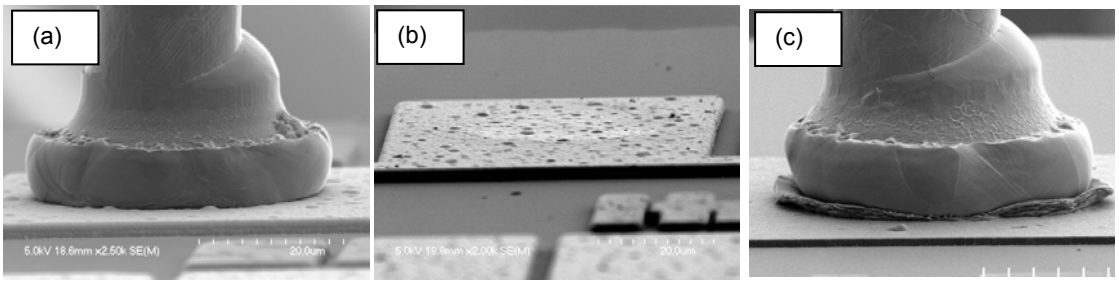

Figure 4: (a) Cu ball on Sample F (1um Ni) bonded at 85 mA USG, (b) after acid removal of Cu ball from Sample F, (c) Cu ball on Al ref pad bonded at 80 mA. Note lack of deformation of Ni/Pd/Au pad.

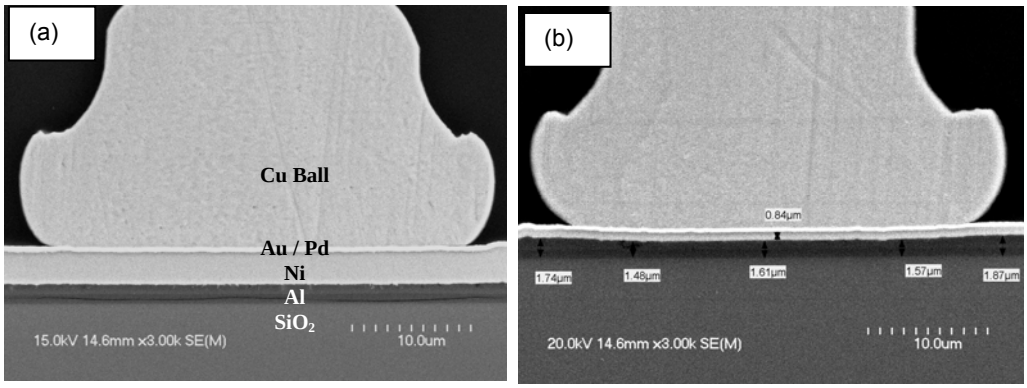

Figure 5: Cross-sections on Cu ball on (a) Sample A – 3 um Ni, 0.3 um Pd, 0.03 um Au and (b) Sample F – 1 um Ni, 0.3 um Pd, 0.03 um Au.

ULTRASONIC POWER SENSITIVITY STUDY

Figure 6 shows the results of an ultrasonic power sensitivity study in which samples A (3 / 0.3 / 0.03 µm Ni/Pd/Au), sample F (1 / 0.3 / 0.03 µm Ni/Pd/Au) and the Al reference device were compared. Ultrasonic energy was incremented in steps of 5 mA while keeping all other bonding parameters fixed. This type of experiments is typically used to establish the bonding window of a process (Table I).

The diameter of the copper balls responds very similarly to the ultrasonic energy on both Al and Ni-Pd-Au pads. However, as can be seen from the top line in Figure 6(a), the Al splash adds significantly to the effective ball diameter when bonding on Al pads. Since this splash limits the available space for the ball, it defines the upper limit of useful ultrasonic energies. For this typical 50 µm pitch process with an upper spec limit of 40 µm for the diameter, the ultrasonic energy is limited to 85 mA when bonding on bare Al pads. In contrast, since there is no splash and no pad damage, ultrasonic energies as high as 110 and 115 mA can be used on pads with 1 µm and 3 µm Ni, respectively.

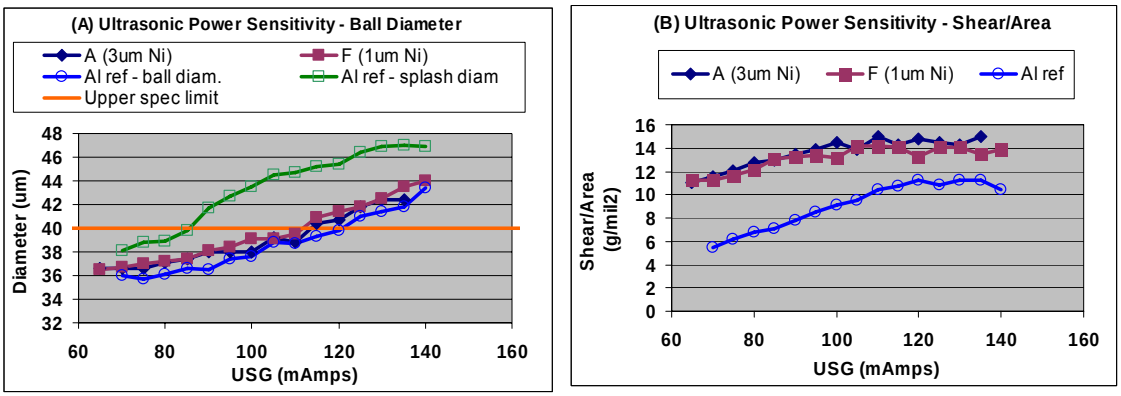

Figure 6: (a) Bonded ball diameter and Al splash diameter, (b) shear/area on sample A, F and Al reference

The lower spec limit of the bonding window is normally defined by the USG level that gives shear/area at the lower spec limit. This limit is usually set to 5.5 g/mil^2. On the Al pads, this lower ultrasonic limit was found to be 70mA. On the Ni-Pd-Au pads, shear/area was always far above the shear/area spec. Instead, the lower ultrasonic limit was set by the occurrence of NSOP (non-stick on pad). This limit was 70 mA for both of the Ni-Pd-Au samples.

The ultrasonic energy range between the lower and upper limits is the bond window. As seen in Table I, the bond window for the nickel pads is approximately three times larger than that on the aluminum pads.

Table II: Ultrasonic Bond Window (mA)

Sample	Min USG no NSOP	Min USG Shear > 5.5 g/mil^2	Max USG Dia. < 40 µm	Bond Window
A (3 µm Ni)	70		115	70 - 115
F (1 µm Ni)	70		110	70 - 110
Al ref		70	120 for ball 85 for splash	70 - 85

CONCLUSIONS

The advantages of nickel-palladium-gold surface finishes to protect Al pads from the greater stresses of copper wire bonding have been demonstrated. Improvements are seen in elimination of pad splash, elimination of pad damage and a large increase in the bonding window. These low-cost plating finishes can be readily applied to existing wafer designs and provide an alternative to redesigning sensitive pads for Cu wire bonding. Future experiments will test the reliability of these Ni-Pd-Au bond pads when used with Cu wire bonding. Reliability of such pads in Au wire bonding has been shown to exceed that of Au-to-Al wire bonding [7].

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