

Ball-Bond Arrangement

The invention relates to a ball-bond arrangement comprising an aluminum bond pad of a semiconductor device and a copper alloy wire which is ball-bonded to the aluminum bond pad.

The use of bonding wires in electronics and microelectronics applications is well-known state of the art. While bonding wires were made from gold in the beginning, nowadays less expensive materials are used such as copper. While copper wire provides very good electric and thermal conductivity, bonding of copper wire has its challenges.

It has turned out that a ball-bond arrangement of a copper wire ball-bonded to an aluminum bond pad of a semiconductor device like, for example, an integrated chip tends to weaken over time as a consequence of an undesired formation and growth of an interfacial layer of copper aluminide within the ball-bond contact area between the aluminum bond pad surface and the surface of the ball-bonded copper wire, or, in more simple words, at the junction or at the ball-bond interface.

The term "aluminum bond pad" is used herein. It means bond pads, in particular bond pads of semiconductor devices, consisting of aluminum or of an aluminum alloy with an aluminum content of, for example, at least 98.5 wt.-% (weight-%). An example of an aluminum alloy very common for aluminum bond pads is aluminum alloyed with 1 wt.-% of silicon and 0.5 wt.-% of copper (Al1Si0.5Cu) or alloyed with 0.5 wt.-% of copper (Al0.5Cu). The aluminum bond pads have an overall thickness of, for example, 0.6 to 4 μm . The term "aluminum bond pad" also means bond pads of a metal other than aluminum or aluminum alloy which have an outer aluminum top layer of, for example, 0.5 to 1 μm thickness.

The term "copper aluminide" is used herein. It shall mean Cu_9Al_4 (68.3 atom-% Cu and 31.7 atom-% Al) and CuAl_2 (34 atom-% Cu and 66 atom-% Al) phases and $\text{Cu}_{0.01}\text{Al}_{0.99}$ (9.11 atom-% Cu and 90.88 atom-% Al), $\text{Cu}_{0.78}\text{Al}_{0.22}$ (78.2 atom-% Cu and 21.84 atom-% Al), $\text{Cu}_{0.84}\text{Al}_{0.16}$ (82.6 atom-% Cu and 17.4 atom-% Al), $\text{Cu}_{0.85}\text{Al}_{0.15}$ (84.5 atom-% Cu and 15.5 atom-% Al) and $\text{Cu}_{0.96}\text{Al}_{0.04}$ (97.3 atom-% Cu and 2.7 atom-% Al) metastable phases. The atom-% values stem from SEM-EDX measurements made at the respective copper-aluminum phases.

The formation and growth of the afore mentioned interfacial layer of copper aluminide is an ageing phenomenon. Apparently, a solid-state reaction occurs, i.e. diffusion of copper from the ball bond or the wire and aluminum from the bond pad. The more time flies or the older the ball-bond arrangement becomes, the more copper aluminide is formed as can be observed as growth of the copper aluminide layer not only in thickness but also in area. In other words, the more time the ball-bond arrangement has been in operation, the more copper aluminide is formed. There is also an influence of temperature, which means the higher the junction temperature in operation, i.e. the higher the temperature at the ball-bond interface during operation, the faster the growth of the copper aluminide layer. The junction temperature of a ball-bond arrangement in operation is believed to lie in the range of 100 to 300 °C or of 100 to 250 °C.

The nature and the thickness of such interfacial copper aluminide layer can be determined or characterized by color contrast imaging of a cross-sectioned sample of a ball-bond arrangement of copper wire ball-bonded to an aluminum bond pad observed in high power optical microscope (50 to 1200X magnification). It is expedient to choose a magnification in the range of 500 to 1000X. When looked at such cross-sectioned ball-bond arrangement under such microscope, such copper aluminide layer appears as regions in grey color of 80 to 100 area-% and in yellow color of 0 to 20 area-% of both regions' total area.

The characterization of the interfacial copper aluminide layer can be performed in even more detail as is outlined in the following.

The presence of the elements copper and aluminum in the interfacial copper aluminide layer and its quantitative ratio can be determined by using scanning electron microscope - energy dispersive X-ray analysis (SEM-EDX). This method is well-known to the skilled person and does not require further explanation. For example, a sample of 20 μm x 10 μm x 100 nm can be Focus-ion-beam (FIB) cut from the ball bond interface containing grey and/or yellow colored copper aluminide phases. FIB cross-sectioning and SEM imaging may be performed using a Helios Nanolab 450S Dual Beam FIB instrument from FEI (at a voltage of 2 to 30 kV with a beam current of 23 pA to 21 nA), for example.

Said FIB cut sample can be utilized for further transmission electron microscopy (TEM) study. Transmission imaging and diffraction pattern of the FIB cut may be performed using a JEOL JEM2100 TEM at an accelerating voltage of 200 kV with an emission current of 105 μA , for example. The nano sized grains and grain boundaries of the copper aluminide can be observed with the JEOL TEM, for example. In addition the diffraction pattern of a grain can be recorded. From the diffraction pattern the crystal lattice type and atomic parameters can be identified using the Hanawalt search method using the powder diffraction file from Inorganic Crystal Structure Database (ICSD) and International Centre for Diffraction Data (ICDD) reference files. Basically, three strong peaks reported in the powder diffraction file have to match to the reported plane of diffraction of the compound crystal structure documented by ICSD or ICDD. The composition analysis of the copper aluminide phases can be performed with a FEI Titan 80-300 TEM equipped with an EDX detector at an accelerating voltage of 200 kV with an emission current of 89 μA , for example. Transmission electron-microscopy (TEM) diffraction pattern analysis identifies mainly Cu_9Al_4 , CuAl_2 and $\text{Cu}_{0.01}\text{Al}_{0.99}$ in grey color regions and $\text{Cu}_{0.78}\text{Al}_{0.22}$, $\text{Cu}_{0.84}\text{Al}_{0.16}$, $\text{Cu}_{0.85}\text{Al}_{0.15}$ and $\text{Cu}_{0.96}\text{Al}_{0.04}$ in yellow color regions.

The formation of the copper aluminide layer over time may be monitored over the service life of the ball-bond arrangement of the invention. However, there is an accelerated ageing test method which allows for simulating formation of the copper aluminide layer over time by subjecting a freshly formed ball-bond arrangement to a continuous or discontinuous heat treatment of a total of, for example, 500 to 2000 hours at an object temperature of 125 to 250 $^{\circ}\text{C}$ or, in an embodiment, 2000 hours at an object temperature of 250 $^{\circ}\text{C}$. The skilled person knows such thermal ageing test as so-called high temperature storage test or high temperature reliability test. This high temperature storage test correlates quite well with the reality since the junction temperature during normal operation, as has already been said, is believed to reach or to lie in the range of 100 to 300 $^{\circ}\text{C}$ or 100 to 250 $^{\circ}\text{C}$. A so artificially thermally-aged ball-bond arrangement can then be qualitatively and quantitatively analyzed with regard to interfacial copper aluminide.

It has now been found that the above mentioned undesired formation and growth of an interfacial copper aluminide layer can be remarkably slowed down by replacing the copper wire in the above mentioned ball-bond arrangement by a wire of a copper alloy consisting of 0.05 to 3 wt.-% of palladium and/or platinum with copper as the remainder to make up 100 wt.-%. Palladium is preferred as the alloying noble metal.

Therefore the invention relates to a ball-bond arrangement comprising an aluminum bond pad of a semiconductor device and a wire ball-bonded to the aluminum bond pad, wherein the wire has a diameter of 10 to 80 μm and comprises a core consisting of a copper alloy consisting of 0.05 to 3 wt.-%, preferably 1 to 2 wt.-%, most preferably 1.2 to 1.3 wt.-% of palladium and/or platinum with copper as the remainder to make up 100 wt.-%. Palladium is preferred as the alloying noble metal.

The invention relates also to a process for the manufacture of the ball-bond arrangement of the invention.

In the following, the phrase "copper alloy consisting of 0.05 to 3 wt.-% of palladium and/or platinum with copper as the remainder to make up 100 wt.-%" is also called "copper alloy" for short.

The phrase "copper as the remainder to make up 100 wt.-%" is used herein. It shall mean that copper is the main component in the copper alloy. To avoid misunderstandings, this shall not be understood to exclude other elements which are not expressly named and which due to prevailing technical conditions may have found their way into the copper alloy, for example, as a consequence of an unintentional but inevitable incorporation during manufacture. In other words, such other elements may be present in the alloy as inevitable impurities, however only in a very minor total amount of, for example, > 0 to 100 wt.-ppm. In any case such inevitable impurities are not deliberately added or introduced into the copper alloy forming composition. Insofar, the phrase "copper as the remainder to make up 100 wt.-%" means that the wt.-% proportion which is missing to make up 100 wt.-% of the copper alloy consists of copper plus said inevitable impurities, if the latter are present.

The copper alloy can be prepared by conventional processes known to the person skilled in the art of metal alloys, for example, by melting together the copper and the palladium and/or platinum in the desired ratio. In doing so, it is possible to make use of conventional copper-palladium-platinum, copper-palladium or copper-platinum master alloys. The melting process can for example be performed making use of an induction furnace and it is expedient to work under vacuum or under an inert gas atmosphere. The materials used can have a purity grade of, for example, 99.99 wt.-% and above. The copper alloy melt is typically cast in a mold of room temperature in which it cools down and solidifies.

The ball-bond arrangement of the invention can be made by a process comprising the subsequent steps:

- (1) providing a semiconductor device having an aluminum bond pad and a wire having a diameter of 10 to 80 μm and comprising a core consisting of an alloy of 0.05 to 3 wt.-% of palladium and/or platinum with copper as the remainder to make up 100 wt.-%, and
- (2) ball-bonding the wire to the aluminum bond pad.

The copper alloy wire having a diameter of 10 to 80 μm and comprising a core consisting of the copper alloy can be made by a process comprising the steps:

- (a) providing a precursor of the copper alloy,
- (b) drawing the precursor until a final diameter of 10 to 80 μm , preferably 15 to 50 μm of the wire is reached;
- (c) annealing the drawn wire, and
- (d) quenching the annealed wire.

In step (a) of the process a precursor of the copper alloy is provided.

Typically, such precursor is in the form of a rod having a diameter of, for example, 2 to 25 mm and a length of, for example, 5 to 100 m. Such rod can be made analogously or in accordance with the afore disclosed process for the preparation of the copper alloy, i.e. by casting copper alloy melt in an appropriate mold of room temperature, followed by cooling and solidifying.

In step (b) of the process the precursor is drawn in several steps until a final diameter of 10 to 80 μm , preferably 15 to 50 μm of the wire is reached. Such wire drawing process is well known to the person skilled in the art. Conventional tungsten carbide and diamond drawing dies may be employed and conventional drawing lubricants may be employed to support the drawing.

In step (c) of the process the drawn wire is annealed (finally annealed, strand annealed), for example, at an object temperature of 570 to 750 $^{\circ}\text{C}$ for 0.2 to 0.4 seconds. The annealing is typically performed by pulling the wire through a conventional annealing oven, typically in the form of a cylindrical tube of a given length and with a defined temperature profile at a given speed. In so doing the annealing time/object temperature parameters can be defined and set. The annealing oven is purged with a 90 to 96 vol.-% inert gas : 4 to 10 vol.-% hydrogen mixture. A 95 vol.-% inert gas : 5 vol.-% hydrogen atmosphere is a preferred atmosphere. The inert gas may be nitrogen and/or argon; typically, it is nitrogen. Purging is preferably performed at a gas exchange rate (= gas flow rate [liter/min] : inner oven volume [liter]) lying in the range of 43 to 125 min^{-1} , more preferably 43 to 75 min^{-1} , most preferably 50 to 63 min^{-1} .

In step (d) of the process the annealed wire is quenched, for example, in water. In an embodiment, the water may contain a surfactant, for example, 0.01 to 1 volume-% of surfactant. Quenching in water means immediately or rapidly, i.e. within 0.2 to 0.4 seconds, cooling the annealed wire from the object temperature it received in step (c) down to room temperature.

It may be expedient to equip the wire with an outer circumferential single-layer metal coating or a multi-layer coating of adjacent layers of different metals wherein the metal(s) is/are selected from the group consisting of palladium, platinum, gold and silver. In such embodiment the core of the copper alloy wire has a surface, wherein a 2 to 500 nm thin circumferential single-layer metal coating or a multi-layer coating of adjacent layers of different metals is superimposed over the surface of the core, wherein the metal or the different metals are selected from the group consisting of palladium, platinum, gold and silver and wherein the total mass of the single- or multi-layer metal coating is 0.09 to 2.5 wt.-% with respect to the total mass of the core. In order to superimpose the single-layer metal coating or the multi-layer coating of adjacent layers of different metals to the core of the copper alloy wire it is expedient to interrupt the wire

drawing process step (b) once a certain wire diameter in the range of, for example, 80 to 200 μm is reached. Then the circumferential single-layer metal coating or multi-layer coating of adjacent layers of different metals may be applied, for example, by electroplating. Thereafter the wire drawing process step (b) is continued until the final wire diameter of 10 to 80 μm is obtained.

The copper alloy wire is ball-bonded to an aluminum bond pad of a semiconductor device. The ball-bonding procedure as such is well-known to the person skilled in the art and comprises no methodological peculiarities. The usual ball-bonding equipment can be used. The bonding process parameters may be: bonding force in the range of, for example, 22 to 30 g; ultrasonic energy in the range of, for example, 78 to 94 mA; temperature in the range of, for example, 170 to 250 $^{\circ}\text{C}$; contact velocity in the range of, for example, 6 to 10.5 $\mu\text{m}/\text{ms}$.

The so produced ball-bond arrangement of the invention exhibits a much reduced tendency to develop an interfacial copper aluminide layer within the ball-bond contact area between the aluminum bond pad surface and the surface of the ball-bonded copper alloy wire, i.e. a slower growth of such copper aluminide layer compared to the same ball-bond arrangement produced with a ≥ 99.99 wt.-% pure copper wire.

With the afore mentioned analytical methodology it has been found, that the undesired interfacial layer of copper aluminide within the ball-bond contact area between the surface of an aluminum bond pad and the surface of a ball-bonded ≥ 99.99 wt.-% pure copper wire having a diameter of 20 μm grows rapidly to a thickness in the range of 10 to 15 μm on thermal ageing at 250 $^{\circ}\text{C}$ for 2000 hours. 100% yellow color phases form, wherein TEM diffraction pattern analysis identifies mainly $\text{Cu}_{0.84}\text{Al}_{0.16}$, $\text{Cu}_{0.85}\text{Al}_{0.15}$ and $\text{Cu}_{0.96}\text{Al}_{0.04}$ phases. In contrast to that, the same evaluation performed with a ball bond arrangement of the invention reveals an only 2.5 to 4 μm thin interfacial layer of copper aluminide which comprises Cu_9Al_4 , CuAl_2 and $\text{Cu}_{0.01}\text{Al}_{0.99}$ in grey color regions and $\text{Cu}_{0.85}\text{Al}_{0.15}$, $\text{Cu}_{0.84}\text{Al}_{0.16}$ and $\text{Cu}_{0.96}\text{Al}_{0.04}$ in yellow color regions. A $\text{Cu}_{0.96}\text{Pd}_{0.04}$ (99.14 atom-% Cu and 0.85 atom-% Pd) phase may here also be observed in the ball-bond contact area.

The following non-limiting examples illustrate the invention.

Examples

Copper rods of 99.99 wt.-% purity were melted in a vacuum induction furnace and continuously cast into rods of 8 mm in diameter. In further examples small amounts of Cu-15wt.-%Pd master alloy were added to the melt to cast Cu-Pd alloys: Cu0.01Pd, Cu0.05Pd, Cu0.5Pd, Cu1.0Pd, Cu1.25Pd, Cu2.0Pd, Cu3.0Pd, Cu5.0Pd.

Further, these continuous cast rods were cold wire drawn at room temperature (25 °C). A tungsten carbide die was used to draw heavy wire and a diamond die was used for further reduction. Drawing was performed in four steps at different drawing speeds: heavy wire drawing from 8 mm to 4 mm at 0.5 m/s and 4 mm to 0.8 mm at 1 m/s, intermediate wire drawing from 0.8 mm to 0.16 mm at 4 m/s and fine wire drawing from 0.16 mm to 0.02 mm at 6 m/s. Drawing was supported by making use of a water-based lubricant. The die reduction ratio was 14 % for thick wires (diameter of > 200 µm) and 8 % for fine wires (diameter of < 200 µm).

The alloyed Cu-Pd wires were intermediate annealed at a diameter of 45 µm at 600 °C. The 99.99 wt.-% pure copper wire was not intermediate annealed.

The wires were finally strand annealed by running them through a conventional annealing oven and using conventional equipment (including reels, spools, pulleys). Annealing time was 0.3 s. The strand annealing temperature was 600 °C (pure copper), and 700 °C (Cu-Pd alloy). The oven was purged with forming gas (95 vol.-% N₂ : 5 vol.-% H₂).

Immediately after leaving the oven, i.e. within 0.3 s, the hot wires were quenched in deionized water.

The wires were ball-bonded (bonding force 26 g; ultrasonic energy 86 mA; temperature 220 °C; contact velocity 7.6 µm/ms) to 1 µm thick Al1Si0.5Cu bond pads of integrated chips and the ball-bond arrangements so produced were artificially thermally aged, cross-sectioned and evaluated under an optical microscope at 500X magnification. Tables 1a and 1b show the ageing conditions (time, object temperature) and the thickness and area fraction of yellow and grey phases of the copper aluminide layer observed at the ball bond interface for pure copper wire and Cu1.25Pd wire.

Table 1a

	Pd content (wt.-ppm)	Thickness of copper aluminide layer (μm) after thermal ageing						
		130 °C, 500 h	175 °C			250 °C		
			500 h	1000 h	2000 h	500 h	1000 h	2000 h
99.99 wt.% Cu	1.2	0.20	1.00	1.17	1.21	4.99	7.51	12.83
Cu1.25Pd alloy	12490	0.17	0.72	0.90	0.94	2.81	3.08	3.36

Table 1b

	Pd content (wt.-ppm)	Area-% of yellow (Y) and grey (G) color phases after thermal ageing													
		130 °C, 500h		175 °C						250 °C					
				500h		1000h		2000h		500h		1000h		2000h	
		Y	G	Y	G	Y	G	Y	G	Y	G	Y	G	Y	G
99.99 wt.% Cu	1.2	0	40	0	40	10	90	15	85	100	0	100	0	100	0
Cu1.25Pd alloy	12490	0	20	0	30	5	95	10	90	5	95	10	90	15	85

Comment: The yellow and grey phases may not total 100 area-%; area-% formed by Al₁Si_{0.5}Cu are not mentioned in the table.

Table 2 shows the area fraction of the grey and yellow color copper aluminide phases' total area at the ball-bond interface of thermally aged (250 °C for 500 hours) ball-bond arrangements made with 20 μm $\geq$ 99.99 wt.-% pure copper and Cu/Pd wires with varying Pd content.

Table 2

	Pd content in wt.-%								
	0.001 [#]	0.01	0.05	0.5	1.0	1.25	2.0	3.0	5.0
Yellow Phase	100	100	85	10	5	0	0	0	0
Grey Phase	0	0	15	90	95	100	100	100	100

[#]: $\geq$ 99.99 wt.-% pure copper

TEM imaging and diffraction pattern analysis of the grey and yellow color phases were performed with the above disclosed analytical methodology. From the diffraction pattern, zonal plane of diffraction, atomic parameters and composition, the different copper aluminide phases were identified by the Hanawalt search method. The results are provided in Table 3 obtained with pure Cu wire and with Cu1.25Pd wire.

Table 3

	Hanawalt Search	Powder diffraction file (PDF)	Composition measured using SEM-EDX, atom-%			At Ball Bond Interface		Thermal ageing			Phase Color	
			Cu	Al	Pd							
						pure Cu wire	Cu1.25Pd wire	130°C, 500h	175°C, 1000h	250°C, 500h	Yellow	Grey
$\text{Cu}_{0.96}\text{Al}_{0.04}$	Matched	ICDD 04-003-7051	97.29	2.70	-	X	X	-	X	X	X	-
$\text{Cu}_{0.84}\text{Al}_{0.16}$	Matched	ICDD 04-008-2100	82.62	17.37	-	X	X	-	X	X	X	-
$\text{Cu}_{0.85}\text{Al}_{0.15}$	Matched	ICDD 04-006-2624	84.51	15.48	-	X	X	-	X	X	X	-
$\text{Cu}_{0.78}\text{Al}_{0.22}$	Matched	ICDD 04-006-6355	78.15	21.84	-	X	X	-	X	X	X	-
$\text{Cu}_{0.01}\text{Al}_{0.99}$	Matched	ICDD 04-003-7063	9.11*)	90.88*)	-	-	X	X	-	-	-	X
Cu_9Al_4	Matched	ICSD 01-071-0307	68.27	31.72	-	X	X	X	X	X	-	X
CuAl_2	Matched	ICDD 04-007-5167	33.96	66.03	-	X	X	X	X		-	X
$\text{Cu}_{0.96}\text{Pd}_{0.04}$	Matched	ICDD 04-008-6249	99.14	-	0.85	-	X	-	X	-	-	X

*) deviation from powder diffraction file because of SEM-EDX test limitation

Claims:

1. A ball-bond arrangement comprising an aluminum bond pad of a semiconductor device and a wire ball-bonded to the aluminum bond pad, wherein the wire has a diameter of 10 to 80 μm and comprises a core consisting of a copper alloy consisting of 0.05 to 3 wt.-% of palladium and/or platinum with copper as the remainder to make up 100 wt.-%.
2. The ball-bond arrangement of claim 1, wherein the core consists of a copper alloy consisting of 1 to 2 wt.-% of palladium and/or platinum with copper as the remainder to make up 100 wt.-%.
3. The ball-bond arrangement of claim 1, wherein the core consists of a copper alloy consisting of 1.2 to 1.3 wt.-% of palladium and/or platinum with copper as the remainder to make up 100 wt.-%.
4. The ball-bond arrangement of any one of the preceding claims, wherein the core has a surface, wherein a 2 to 500 nm thin circumferential single-layer metal coating or a multi-layer coating of adjacent layers of different metals is superimposed over the surface of the core, wherein the metal(s) is/are selected from the group consisting of palladium, platinum, gold and silver, and wherein the total mass of the single- or multi-layer metal coating is 0.09 to 2.5 wt.-% with respect to the total mass of the core.
5. The ball-bond arrangement of any one of the preceding claims, which subsequent to its manufacture has continuously or discontinuously been heat treated for a total of 500 to 2000 hours at an object temperature of 125 to 250 $^{\circ}\text{C}$.
6. The ball-bond arrangement of claim 5, wherein the heat treatment takes a total of 2000 hours at an object temperature of 250 $^{\circ}\text{C}$.
7. The ball-bond arrangement of claim 6, characterized in that it exhibits a 2.5 to 4 μm thin interfacial layer of copper aluminide formed within the ball-bond contact area between the aluminum bond pad surface and the surface of the ball-bonded wire.
8. The ball-bond arrangement of any one of the preceding claims forming part of an electronic assembly.

9. An electronic assembly comprising one or more ball-bond arrangements according to claims 1 to 7.

10. A process for the manufacture of a ball-bond arrangement comprising the subsequent steps:

(1) providing a semiconductor device having an aluminum bond pad and a wire having a diameter of 10 to 80 μm and comprising a core consisting of an alloy of 0.05 to 3 wt.-% of palladium with copper as the remainder to make up 100 wt.-%, and

(2) ball-bonding the wire to the aluminum bond pad.

11. The process of claim 10, wherein the core consists of a copper alloy consisting of 1 to 2 wt.-% of palladium and/or platinum with copper as the remainder to make up 100 wt.-%.

12. The process of claim 10, wherein the core consists of a copper alloy consisting of 1.2 to 1.3 wt.-% of palladium and/or platinum with copper as the remainder to make up 100 wt.-%

13. The process of any one of claims 10 to 12, wherein the core has a surface, and wherein prior to performing step (2) a 2 to 500 nm thin circumferential single-layer metal coating or a multi-layer coating of adjacent layers of different metals is superimposed over the surface of the core, wherein the metal(s) is/are selected from the group consisting of palladium, platinum, gold and silver and wherein the total mass of the single- or multi-layer metal coating is 0.09 to 2.5 wt.-% with respect to the total mass of the core.

14. The process of any one of claims 10 to 13, wherein after completion of step (2) a further step (3) of subjecting the ball-bond arrangement to a continuous or discontinuous heat treatment of a total of 500 to 2000 hours at an object temperature of 125 to 250 °C is performed.

15. The process of claim 14, wherein the heat treatment takes a total of 2000 hours at an object temperature of 250 °C.

16. The process of claim 14 or 15, wherein the heat treatment is performed as a high temperature storage test (high temperature reliability test).