NEW GOLD BONDING WIRE

The present invention relates to bonding wires consisting of gold, platinum, yttrium and at least one component selected from the group consisting of calcium, cerium, germanium and palladium. The invention further relates to a process for manufacturing, the use and a ball-bond arrangement comprising such a wire.

The use of bonding wires in electronics and microelectronics applications is well-known state of the art. Even though nowadays less expensive materials than gold are available, such as copper, copper alloys, silver or silver alloys, gold wires are still applied for certain applications. Especially wires containing high-purity gold of purity not lower than 99.99 weight-% ("4N") are still used when high reliability and corrosion resistance is mandatory.

With respect to wire geometry, most common are bonding wires of circular cross-section and bonding ribbons which have a more or less rectangular cross-section. Both types of wire geometries have their advantages making them useful for specific applications.

Gold bonding wires are especially suitable for wire ball-bonding. The first step of wire ball-bonding is FAB (free air ball) formation at the tip of a round bonding wire. FAB formation is then followed by the actual ball-bonding procedure. The FAB is brought into contact with the surface to be bonded to establish a 1st bond (ball bond). The surface is typically a bond pad of a semiconductor device. Ball bonding of a FAB to a bond pad of a semiconductor device results in formation of a so-called ball-bond arrangement, or to be more precise, a ball-bond arrangement comprising a bond pad of a semiconductor device and a wire ball-bonded to the bond pad. The single-side bonded wire is then guided in a loop to a second position, where a 2nd bond is established, typically via stitch bonding (as a wedge bond), for example by ultrasonic compression.

It is well known in the art, that the geometry and characteristics of the FAB influence the resulting bond. Among others, the roundness of the FAB influences the quality of the resulting ball-bond. It has been found that a spherical FAB without any surface indentations, commonly called "dimples", improves the bonding process as well as the quality of the formed bond. A dimple in the FAB is likely to lead to an unbound region of the ball to the bond pad, which weakens the formed bond and its reliability and furthermore increases the electrical resistance of the bond.

Driven by the ongoing miniaturization of semiconductor devices, the density of bond wires on the devices needs to increase. The behaviour of the wire during the bonding procedure, also referred to as looping behaviour, significantly influences the suitability for the procedure. To avoid shortcuts or other failures, the bonded wires need to be as straight as possible, i.e. have a high linearity. The linearity of a bonded wire hereby refers to two aspects: The straightness of the bonded wire and the tilting of a loop formed by the wire with respect to neighbouring loops in an arrangement. Especially for thin bonding wires with a diameter between 10 to 80 µm, this linearity is significantly influenced by the doping composition of the wire material.

It is an object of the invention to provide a bonding wire suitable for use in wire bonding applications. Apart from satisfying fundamental requirements like wire softness, conductivity, as well as oxidation resistance, the bonding wire shall also be outstanding in particular in terms of the sphericity of the FAB during the bonding process under air atmosphere as well as in stable looping behaviour with regard to the linearity of the bonded wire. Furthermore, the bonding wire shall exhibit an overall well-balanced spectrum of properties which are relevant with regard to wire bonding applications including, for example, a wide stitch bonding window, low FAB hardness, high stitch pull strength, soft wire, low electrical resistivity and the like.

Gold is chosen as a wire material because of superior corrosion reliability. Different dopants to the gold material have been searched for in order to optimize the mechanical strength of the wire. For example, CN 112086365 A discloses a wire composition designed to be utilized for particularly thin wires, comprising in addition to gold 5 – 50 ppm of one or two alkaline earth metals and 2 to 20 ppm of one or two rare earth metals. EP 1830398 A1 also discloses several 4N gold compositions intended for semiconductor bonding wires, which are claimed to provide bonded balls with a high roundness.

The final properties of a wire are dictated by a delicate balance of the doping elements and not foreseeable. Thus, even though there are gold bonding wires available, there is an ongoing need for further improving bonding wire technology with regard to the bonding wire itself.

Accordingly, it is an object of the invention to provide improved gold bonding wires.

It is a further object of the invention to provide a gold bonding wire which exhibits FABs without indentations with a simultaneous high linearity of bonded wire loops.

It is a further object of the invention to provide a bonding wire which exhibits excellent bondability with respect to a stitch bonding.

It is a further object of the invention to provide a bonding wire which exhibits an improved bondability with respect to a ball bonding.

It is a further object of the invention to provide a bonding wire which exhibits an improved bonded ball roundness and concentricity with respect to ball-wedge bonding.

Further, a process for manufacturing these wires shall be found.

A contribution to the solution of said object is provided by the subject-matter of the category-forming claims. The dependent sub-claims represent preferred embodiments of the invention, the subject-matter of which also makes a contribution to solving the objects mentioned above.

In a first aspect, the invention relates to a gold bonding wire consisting of

(a) 20 to 50 wt.-ppm platinum (Pt),
(b) 10 to 40 wt.-ppm yttrium (Y),
(c) 2 to 40 wt.-ppm of at least one element selected from the group consisting of calcium (Ca), cerium (Ce), germanium (Ge) and palladium (Pd),
(d) 0 to 10 wt.-ppm further components other than platinum, yttrium, calcium, cerium, germanium, palladium and gold and
(e) gold (Au) as the remainder,

wherein the sum of the amounts of components (a), (b), (c) and (d) is from 32 to 100 wt.-ppm,
the sum of the amounts of Pt and Y is in the range of 30 to 90 wt.-ppm,
the sum of the amounts of Ca and Ce is below 20 wt.-ppm and
wherein all amounts in wt.-% and wt.-ppm are based on the total weight of the gold bonding wire.

Surprisingly, it has been found that a gold bonding wire with a certain relationship between doping elements provides a bonding wire with an indentation-free FAB and a high linearity of the bonded wire loops, leading to stronger and more reliable ball-bonds. Under linearity, the

aspects of the straightness of the bonded wire as well as the absence of a tilting of the wire loop are summarized.

The gold bonding wire is preferably a bonding wire for bonding in microelectronics. The bonding wire is preferably a one-piece object. Numerous shapes are known and appear useful for wires of the invention. Preferred shapes are – in cross-sectional view – round, ellipsoid and rectangular shapes. For the invention, the term “bonding wire” comprises all shapes of cross-sections and all usual wire diameters, though bonding wires with circular cross-section and thin diameters are preferred.

Preferably, the average cross-section of the gold bonding wire is in the range of for example from 50 to 5024 µm² or preferably 110 to 2400 µm². Accordingly in case of the preferred circular cross-sections, the average diameter is in the range of, for example, from 8 to 80 µm or preferably 12 to 55 µm.

The average diameter or, simply stated, the diameter of a wire can be obtained by the “sizing method” (ASTM Standard F205). According to this method the physical weight of the gold bonding wire for a defined length is determined. Based on this weight, the diameter of a wire is calculated using the density of the wire material. The diameter is calculated as arithmetic mean of five measurements on five cuts of a particular wire.

Unless otherwise noted, all standards cited herein are the current version at the time of the filing date.

The gold bonding wire in the present context is defined as a homogenous region of bulk material. Since any bulk material always has a surface region which might exhibit different properties to some extent, the properties of the wire are understood as properties of the homogeneous region of bulk material. The surface of the bulk material region can differ in terms of morphology, composition (e.g. sulfur, chlorine and/or oxygen content) and other features.

The gold bonding wire comprises “gold as the remainder”. It shall mean that gold is the main component in the gold bonding wire. The sum of the amounts of the other components of the gold bonding wire (a), (b), (c) and (d) ranges from 32 to 100 wt.-ppm. In other words, the bonding wire consists of at least 99.99 wt.-% gold. Put differently, the gold bonding wire consists of a 4N doped gold.

Within the present application, all amounts in wt.-% (weight-%) and wt.-ppm are based on the total weight of the gold bonding wire if not stated otherwise. The composition of the wires may be determined by ICP analysis as described below.

In line with the aforementioned, the gold bonding wire consists of (a) platinum, (b) yttrium, (c) at least one component selected from the group consisting of calcium, cerium, germanium and palladium, (d) optional further components and gold as remainder in the afore disclosed proportional ratio. The components (a) to (c) may also be referred to as doping elements. The sum of the amounts of doping elements is at least 50 wt.-ppm, preferably at least 60 wt.-ppm. For example, the sum of the amounts of doping elements is in the range of 50 to 95 wt.-ppm, preferably in the range of 60 to 90 wt.-ppm.

The gold bonding wire consists of (a) 20 to 50 wt.-ppm, preferably 25 to 45 wt.-ppm or even more preferred 28 to 42 wt.-ppm platinum.

The gold bonding wire consists of (b) 10 to 40 wt.-ppm, preferably 15 to 35 wt.-ppm or even more preferred 18 to 32 wt.-ppm yttrium.

It is essential, that the the sum of the amounts of platinum and yttrium is in the range of 30 to 90 wt.-ppm, preferably in the range of 50 to 70 wt.-ppm. It has been found that a combination of platinum and yttrium in this range is in particular advantageous for a bonding wire with an indentation-free FAB during the bonding process.

The gold bonding wire consists of (c) 2 to 40 wt.-ppm, preferably 3 to 35 wt.-ppm or even more preferred 5 to 30 wt.-ppm of at least two elements selected from calcium, cerium, germanium and palladium.

It is further essential, that the sum of the amounts of Ca and Ce is below 20 wt.-ppm, preferably below 15 wt.-ppm, even more preferred below 10 wt.-ppm. It has been discovered that the amount of calcium and cerium influences the grain size in the bonding wire formed, and with this the mechanical strength of the bonding wire.

The gold bonding wire of the invention may comprise (d) 0 to 10 wt.-ppm further components. It is to be understood, that 0 to 10 wt.-ppm is the total amount of these further components, often

also referred to as inevitable impurities. In other words, the sum of all inevitable impurities present is in the range of 0 to 10 wt.-ppm. In the present context, these further components are minor amounts of chemical elements and/or compounds which may originate from impurities present in the raw materials used or from the wire manufacturing process, i.e., the presence of further components of the (d) type may for example originate from impurities present in one or more of the platinum, yttrium, calcium, cerium, germanium, palladium and gold. In any case such inevitable impurities are not deliberately added or introduced into the bonding wire or the bonding wire precursors. Examples of such further components are, among others, silver (Ag), copper (Cu), iron (Fe), silicon (Si), manganese (Mn), chromium (Cr), magnesium (Mg), lanthanum (La), aluminium (Al), boron (B), beryllium (Be), zirconium (Zr), titanium (Ti) or sulfur (S). The low total amount of 0 to 10 wt.-ppm of the further components ensures a good reproducibility of the wire properties. Preferably, the bonding wire comprises less than 8 wt.-ppm of the further components, even more preferred less than 6 wt.-ppm.

Preferably, the gold bonding wire comprises Be in an amount below 5 wt.-ppm, more preferred below 3 wt.-ppm, even more preferred below 1 wt.-ppm.

In an embodiment, the gold bonding wire of the invention comprises the following amounts of inevitable impurities (d):

(i) any one of Ag, Cu, Fe, S below 10 wt.-ppm each;

(ii) any one of Si, Cr, Mg, La, Al, Be, In, Mn, Ti, Pd, Pt below 5 wt.-ppm each, preferably below 3 wt.-ppm, most preferred below 2 wt.-ppm.

In preferred embodiments, the gold bonding wire consists of

(a) 20 to 50 wt.-ppm, preferably 25 to 45 wt.-ppm or even more preferred 28 to 42 wt.-ppm platinum,

(b) 10 to 40 wt.-ppm, preferably 15 to 35 wt.-ppm or even more preferred 18 to 32 wt.-ppm yttrium,

(c) 2 to 40 wt.-ppm, preferably 3 to 35 wt.-ppm or even more preferred 5 to 30 wt.-ppm of at least two elements selected from calcium, cerium and germanium and

(d) 0 to 10 wt.-ppm, preferably 0 to 8 wt.-ppm, even more preferred 0 to 5 wt.-ppm further components other than platinum, yttrium, calcium, cerium, germanium and gold and

(e) gold (Au) as the remainder.

In an even more preferred embodiment, the gold bonding wire consists of

(a) 20 to 50 wt.-ppm, preferably 25 to 45 wt.-ppm or even more preferred 28 to 42 wt.-ppm platinum,

(b) 10 to 40 wt.-ppm, preferably 15 to 35 wt.-ppm or even more preferred 18 to 32 wt.-ppm yttrium,

(c) 2 to 40 wt.-ppm, preferably in the range of 3 to 35 wt.-ppm or even in the range of 5 to 30 wt.-ppm of a combination of calcium, cerium and germanium,

(d) 0 to 10 wt.-ppm, preferably 0 to 8 wt.-ppm, even more preferred 0 to 5 wt.-ppm further components other than platinum, yttrium, calcium, cerium, germanium and gold and

(e) gold (Au) as the remainder.

Even more preferred, the gold bonding wire consists of

(a) 20 to 50 wt.-ppm, preferably 25 to 45 wt.-ppm or even more preferred 28 to 42 wt.-ppm platinum,

(b) 10 to 40 wt.-ppm, preferably 15 to 35 wt.-ppm or even more preferred 18 to 32 wt.-ppm yttrium,

(c) 1 to 10 wt.-ppm calcium, 1 to 10 wt.-ppm cerium and 1 to 20 wt.-ppm germanium,

(d) 0 to 10 wt.-ppm, preferably 0 to 8 wt.-ppm, even more preferred 0 to 5 wt.-ppm further components other than platinum, yttrium, cerium, germanium and gold and

(e) gold (Au) as the remainder.

In an alternative embodiment, the gold bonding wire consists of

(a) 15 to 45 wt.-ppm, preferably 25 to 45 wt.-ppm or even more preferred 20 to 40 wt.-ppm platinum,

(b) 10 to 40 wt.-ppm, preferably 15 to 35 wt.-ppm or even more preferred 18 to 32 wt.-ppm yttrium,

(c) 2 to 40 wt.-ppm, preferably 3 to 35 wt.-ppm or even more preferred 5 to 32 wt.-ppm palladium,

(d) 0 to 10 wt.-ppm, preferably 0 to 8 wt.-ppm, even more preferred 0 to 5 wt.-ppm further components other than platinum, palladium and gold and

(e) gold (Au) as the remainder.

Preferably, the average grain size of the crystal grains of the gold bonding wire, measured in longitudinal direction, is in the range of from 0.2 to 1.0 µm, preferably 0.4 to 0.8 µm, most preferred 0.6 to 0.8 µm. The grain size may be determined by EBSD characterization with the linear intercept method.

The linear intercept method for determining the average size of crystal grains is a standard metallographic practice. There, a wire is cut perpendicular to the direction of the wire and the cross-section generated thereby is etched. The size of a crystal grain in the present context is defined as the longest of all sections of straight lines which can be passed through the grain. The average size of crystal grains is the arithmetic mean of at least seven measurements of crystal grains in the core/bulk material. The testing is performed according to ASTM E112-96 – 13 (2019) standard.

In an embodiment, the average diameter of the gold bonding wire is in the range of from 15 to 28 µm. In this case, the average size of crystal grains is preferably in the range of from 0.6 to 3 µm.

In another embodiment, the average diameter of the gold bonding wire is in the range of from > 28 to 38 µm. In this case, the average size of crystal grains is preferably in the range of from 0.8 to 4 µm.

In another embodiment, the average diameter of the gold bonding wire is in the range of from > 38 to 50 µm. In this case, the average size of crystal grains is preferably in the range of from 1 to 5 µm.

In another embodiment, the average diameter of the gold bonding wire is in the range of from > 50 to 80 µm. In this case, the average size of crystal grains is preferably in the range of from 1.2 to 8 µm.

Preferably, 35 to 70 %, preferably 40 to 65 % of the crystal grains in the gold bonding wire are oriented in <111> direction, and 0 to 20 %, preferably 5 to 18 % of the crystal grains of the bonding wire are oriented in <100> direction, each % with respect to the total number of crystal grains with orientation parallel to the drawing direction of the gold bonding wire. The grain orientation may be determined by EBSD characterization.

In a preferred embodiment of the invention, the hardness of the gold bonding wire (i.e. the hardness prior to bonding) is less than 90 HV, preferably in the range of from 65 to 80 HV. In addition, hardness of a FAB processed using the gold bonding wire prior to bonding is less than 80 HV, preferably in the range of from 55 to 70 HV. Such hardness or, more precisely, softness

of the gold bonding wire and FAB helps to prevent damage of a sensitive substrate in the course of bonding. Experiments have also shown that such soft wires according to the invention exhibit very soft FAB properties. Such limitation of FAB hardness (or better to say softness) is particularly helpful if mechanically sensitive structures are aligned below a bond pad. This is particularly true if a bond pad consists of a soft material like aluminum or gold. The sensitive structure can, for example, comprise one or several layers of porous silicon dioxide, in particular with a dielectric constant of less than 2.5. Such porous and hence weak material is becoming increasingly common as it can help to increase the device performance.

Therefore, the mechanical properties of the gold bonding wire of the invention are optimized to avoid cracking or other damaging of such weak layers.

In an embodiment, the gold bonding wire is characterized by at least one of the following intrinsic properties (determined according to the methods as described below):

- The percentage of crystal grains in the wire oriented in <100> direction is less than 20 %, for example in the range of from 1 to 20 %, preferably in the range of from 5 to 18 %,
- the percentage of crystal grains in the wire oriented in <111> direction is less than 90 %, for example in the range of from 50 to 90 %, preferably in the range of from 65 to 85 %,
- the wire twin boundary fraction is not more than 10 %, for example in the range of from 0.5 to 10 %, preferably in the range of from 1 % to 8%,
- the FAB exhibits a combination of two types of grain structure: equi-axed grains (grains are nearly rounded with non-uniform boundaries) and columnar grains (grains are elongated),
- the FAB average grain size is in the range of from 0.5 to 18 µm, preferably in the range of from 1 to 15 µm,
- the percentage of crystal grains in the FAB oriented in <100> direction is less than 80 %, for example in the range of from 5 to 80 %, preferably in the range of from 10 to 75 %,
- the percentage of crystal grains in the FAB oriented in <111> direction is less than 80 %, for example in the range of from 5 to 80 %, preferably in the range of from 10 to 75 %,
- the FAB twin boundary fraction is not more than 15 %, for example in the range of from 0 to 15 %, preferably in the range of from 1 to 12 %.

and/or at least by one of the following extrinsic properties (determined according to the methods as described below):

- The yield load of the wire is not more than 20 gF, for example in the range of from 3 to 20 gF,
- the average bonded ball concentricity for a gold bonding wire with an average diameter of 18 µm has a value of not more than 0.0006µm, preferably not more than 0.0005 µm, most preferred not more than 0.0004 µm,
- the resistivity of the gold bonding wire is not more than 3.0 µΩ·cm, for example in the range of from 2.0 to 2.6 µΩ·cm, preferably in the range of from 2.2 to 2.4 µΩ·cm.

The terms “intrinsic property” and “extrinsic property” are used herein with regard to a gold bonding wire or a FAB formed at a tip of the gold bonding wire. Intrinsic properties mean properties which a bonding wire or a FAB has of itself (independently of other factors), while extrinsic properties depend on the gold bonding wire’s or FAB’s relationship with other factors like a measuring method and/or measuring conditions employed.

A second aspect of the invention is a process for manufacturing a gold bonding wire in any of its embodiments disclosed above. In its most general embodiment, the process comprises at least the process steps of

(1) providing a precursor item consisting of
   (a) 20 to 50 wt.-ppm platinum (Pt),
   (b) 10 to 40 wt.-ppm yttrium (Y),
   (c) 2 to 40 wt.-ppm of at least one element selected from the group consisting of calcium (Ca), cerium (Ce), germanium (Ge) and palladium (Pd),
   (d) 0 to 10 wt.-ppm further components other than platinum, yttrium, calcium, cerium, germanium, palladium and gold and
   (e) gold (Au) as the remainder,
   wherein the sum of the amounts of components (a), (b), (c) and (d) is from 32 to 100 wt.-ppm,
   the sum of the amounts of Pt and Y is in the range of 30 to 90 wt.-ppm,
   the sum of the amounts of Ca and Ce is below 20 wt.-ppm and
   wherein all amounts in wt.-% and wt.-ppm are based on the total weight of the gold bonding wire,
(2) elongating the precursor item to form a wire precursor, until the desired diameter of the gold bonding wire is obtained; and
(3) annealing the elongated wire precursor obtained after completion of process step (2) to form the gold bonding wire.

A precursor item as provided in process step (1) can be obtained by doping gold with the desired amount of platinum, yttrium and calcium, cerium, germanium and/or palladium. The doped gold itself can be prepared by conventional processes known to the person skilled in the art of metal alloys, for example, by melting together gold, platinum, yttrium and calcium, cerium, germanium and/or palladium in the desired ratio. 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, 99.999 wt.-% and above. The so produced melt can be cooled to form a homogeneous piece of gold-based precursor item. Typically, such a precursor item 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 by casting said doped gold melt in an appropriate mold of room temperature, followed by cooling and solidifying.

For example, such a rod can be made by casting a doped gold melt consisting of (a) 20 to 50 wt.-ppm platinum, (b) 10 to 40 wt.-ppm yttrium, (c) 2 to 40 wt.-ppm of at least one element selected from the group consisting of calcium, cerium, germanium and palladium, (d) 0 to 10 wt.-ppm further components other than platinum, yttrium, calcium, cerium, germanium, palladium and gold and (e) gold as the remainder in an appropriate mold of room temperature, followed by cooling and solidifying, wherein all amounts in wt.-ppm are based on the total weight of the doped gold melt.

In process step (2) the precursor item is elongated to form a wire precursor, until the desired final diameter of the gold bonding wire is obtained. Techniques to elongate a precursor item to form a wire precursor are known to the skilled person. Preferred techniques are rolling, swaging, die drawing or the like, of which die drawing is particularly preferred. In the latter case the precursor item is drawn in several process steps until the desired and final diameter of the wire core is reached.

The desired and final diameter of the gold bonding wire may be in the range of from 8 to 80 µm or, preferably, in the range of from 15 to 50 µm. Such wire die 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.

Step (2) of the process of the invention may include one or more sub-steps of intermediate batch annealing of the elongated precursor item at an oven set temperature of from 300 to 800 °C for an exposure time in the range of from 50 to 150 min and/or one or more sub-steps of intermediate strand annealing of the elongated precursor item at an oven set temperature of from 400 to 800 °C for an exposure time in the range of from 0.4 to 1.2 s. The one or more steps of intermediate annealing of the elongated precursor item may be performed between two or more of multiple elongation or drawing steps. To illustrate this by example, there may be performed two intermediate annealing steps at three different stages during drawing, for example, a first intermediate batch annealing of a rod drawn to a diameter of 2 mm and coiled on a drum at an oven set temperature in the range of from 400 to 800 °C for an exposure time of 50 to 150 min and a second intermediate strand annealing of the precursor item drawn to a diameter of 47 µm at an oven set temperature in the range of from 300 to 800 °C for an exposure time of 0.4 to 1.2 s.

The term “oven set temperature” is used herein. It means the temperature fixed in the temperature controller of the annealing oven. The annealing oven may be a chamber furnace type oven (in case of batch annealing) or a tubular annealing oven (in case of strand annealing).

In process step (3) the elongated wire precursor obtained after completion of process step (2), is finally annealed. Process step (3) may be a strand annealing. By “strand annealing”, a continuous process allowing for a fast production of a wire with high reproducibility is to be understood. Strand annealing means that the annealing is done dynamically while an elongated wire precursor item or wire precursor to be annealed is moved through an annealing oven and spooled onto a reel after having left the annealing oven.

The strand annealing of process step (3) may be carried out at an oven set temperature in the range of from 400 to 600 °C for an exposure time in the range of from 0.4 to 0.8 s, or, in a preferred embodiment, 400 to 550 °C for 0.5 to 0.7 s.

This disclosure distinguishes between precursor item, wire precursor and gold bonding wire. The term “precursor item” is used for those wire pre-stages which have not reached the desired final diameter of the gold bonding wire, while the term “wire precursor” is used for a wire pre-stage at the desired final diameter. After completion of process step (3), i.e. after the final annealing of the wire precursor at the desired final diameter, a gold bonding wire in the sense of the invention is obtained.

The final strand annealing is typically performed by pulling the elongated wire precursor 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 annealing speed which may be chosen in the range of, for example, from 4 to 30 m/min, or from 14 to 16 m/min. In so doing the annealing time/oven temperature parameters can be defined and set.

In a preferred embodiment, the finally strand annealed gold bonding wire is quenched in water which, in an embodiment, may contain one or more additives, for example, 0.01 to 0.07 volume-% of additive(s). The quenching in water means immediately or rapidly, i.e. within 0.2 to 0.6 s, cooling the finally strand annealed bonding wire from the temperature it experienced in process step (3) down to room temperature, for example by dipping or dripping.

With respect to an embodiment of the invention, it was found that annealing at a temperature below the temperature of maximum elongation can result in beneficial wire properties as the wire morphology can be influenced in a positive way. Further, it has been found that selecting the annealing temperature to be higher than the temperature of maximum elongation while maintaining the annealing time constant, is of further advantage. For example, this manufacturing principle can be used to adjust the average grain size of the wire, e.g. to larger average grain sizes. By this adjustment, other properties like e.g. wire hardness, ball-bonding behavior etc. can be influenced in a positive manner.

Hence, in an embodiment, annealing is performed at a temperature below the temperature of maximum elongation wherein the elongation value of the wire after annealing is not more than 98% of the maximum elongation value.

For example, process step (3) may be performed at a temperature which is at least 10 °C, preferably at least 50 °C, or at least 80 °C lower than the temperature of maximum elongation $T_{\Delta L(max)}$. Preferably, the temperature in process step (3) is not more than 100 °C lower than $T_{\Delta L(max)}$. The temperature of maximum elongation $T_{\Delta L(max)}$ is determined by testing the elongation at break of a specimen (wire) at different temperatures. The data points are collected in a graph, showing the elongation (in %) as a function of temperature (°C). The resulting graph is often referred to as an “annealing curve”. In the case of gold-based wires, a temperature is observed where the elongation (in %) reaches a maximum. This is the temperature of maximum elongation $T_{\Delta L(max)}$. The elongation may be determined by tensile testing.

In an embodiment, the final strand annealing may be performed at a temperature which is at least 150 °C lower, for example 200 to 220 °C lower than a temperature at which the maximum elongation value is achieved by annealing; this may result in an elongation value of the wire after annealing being not more than 70 % of the maximum elongation value, for example 20 to 60 % of a maximum elongation value.

For example, process step (3) may be performed at a temperature which is at least 150 °C, preferably at least 180 °C, or at least 200 °C lower than the temperature of maximum elongation $T_{\Delta L(max)}$.

It is believed that the unique combination of the composition of the precursor item material (which is the same as that of the finished gold bonding wire) and the annealing parameters prevailing during process steps (2) and (3) is essential to obtain the wire of the invention exhibiting at least one of the above disclosed intrinsic and/or extrinsic properties. The temperature/time conditions of the intermediate and the final strand annealing steps allow for achieving or adjusting intrinsic and extrinsic properties of the bonding wire.

It is preferred that all process steps (1) to (3) as well as spooling and vacuum sealing are carried out under clean room conditions (US FED STD 209E cleanroom standards, 1k standard).

A further aspect of the invention is the use of the inventive gold bonding wire in a ball-bonding procedure.

A further aspect of the invention is a ball-bond arrangement comprising a bond pad of a semiconductor device and an inventive gold bonding wire ball-bonded to the bond pad.

The term “bond pad” is used herein. It means bond pads, in particular bond pads of semiconductor devices. Bond pads may consist of a metal M or of an alloy of > 90 wt.-% (% by weight) of a metal M or they may consist of a metal other than the metal M with an outer metal M (alloy) top layer. Such top layer may have a thickness of, for example, 0.5 to 1 µm. The metal M may be aluminum, gold, silver, copper, palladium, or nickel, in particular aluminum or gold. Bond pads may have an overall thickness of, for example, 0.2 to 4 µm.

The ball-bond arrangement of the invention can be made by a process comprising the subsequent steps (i) and (ii), as are disclosed in the following. Hence, in an embodiment, the invention relates to a process for the manufacture of a ball-bond arrangement comprising the steps:

(i) providing a semiconductor having a bond pad and a gold bonding wire according to any of its afore disclosed embodiments, and

(ii) ball-bonding the gold bonding wire to the bond pad.

In step (i) a semiconductor having a bond pad and a gold bonding wire according to any of the afore disclosed embodiments are provided. With regard to processes for the manufacture of such a gold bonding wire reference is made to the disclosure above.

In step (ii) the gold bonding wire is ball-bonded to the bond pad of the semiconductor device. To this end, first of all, an FAB is prepared at the tip of the gold bonding wire by performing electric flame-off (EFO) firing in air atmosphere.

Preferably, the FAB has at a BSR (ball size ratio; FAB diameter divided by the wire diameter) in the range of 1.5 to 2.2, preferably 1.6 to 2.0; hence, it may be worked at an EFO current in the range of, for example, 16 to 32 mA, preferably 18 to 25 mA, most preferred 20 to 22 mA, and at an EFO time in the range of, for example, 75 to 1400 µs, preferably 140 to 550 µs, most preferred 250 to 500 µs, and with a wand gap (distance between EFO electrode tip and fractured wire tip) in the range of, for example, 500 to 1125 µm, preferably 650 to 900 µm. Examples of well-known bonders, to name only a few, include the IConn - KNS bonder, the Shinkawa bonder and the ASM bonder.

As already mentioned above, the ball-bonding procedure as such, i.e. the descending of the formed FAB so as to touch the bond pad of the semiconductor device and to ball-bond the gold bonding wire, is well-known to the person skilled in the art and comprises no methodological peculiarities. A usual ball-bonding equipment can be used, in particular one of the three well-known bonders as disclosed above. The bonding process parameters may be: bonding force in the range of, for example, 10 to 25 g; ultrasonic energy in the range of, for example, 45 to 80 mA; temperature in the range of, for example, 25 to 220 °C; contact velocity in the range of, for example, 6 to 20 µm/ms.

Test methods:

All tests and measurements were conducted at T = 20 °C and a relative humidity RH = 50 %.

Chemical Composition:

The chemical composition of the wires was evaluated by ICP (inductively coupled plasma) analysis using a Perkin Elmer ICP-OES 7100DV model. The wires were dissolved in concentrated nitric acid and the solution was used for the ICP analysis.

Determination of grain size, grain orientation and twin boundaries of the wires:

The microstructures of the wires, the FABs and the heat affected zones (HAZ) after bonding were evaluated by EBSD (Electron Backscattered Diffraction) characterization.

The wires with or without FAB were first potted using epoxy resin and polished as per standard metallographic technique. Ion milling was applied in the final sample preparation step to remove any mechanical deformation of the wire surface, contamination and oxidation layer. The ion-milled cross-sectioned sample surface was sputtered with gold. Then ion milling and gold sputtering were carried out for two further rounds.

The sample was loaded in a FE-SEM (field emission scanning electron microscope, Zeiss Sigma) with a 70° angled holder to the normal FE-SEM sample holding table surface. The FE-SEM was further equipped with an EBSD detector (Nordlys S, Oxford Instruments). The EBSD patterns containing the wire crystallographic information were obtained.

The crystal grain size was measured using grain boundary delineation concept defining a critical misorientation angle (15°) with the EBSD software tool (AZtec version 3.3, HKL Channel5 system) according to the ASTM E2627 – 13 (2019) standards. The EBSD software calculated the area of each grain and converted it to equivalent circle diameter, which is defined as “average crystal grain size”. All the grains along the longitudinal direction of the wire within a length of ~100 µm were counted to determine mean and standard deviation of the average crystal grain size.

These patterns were further analyzed for the grain orientation fractions. Points of similar orientation were grouped together to form the texture component. To distinguish different texture components, a maximum tolerance angle of 15 º was used. The wire drawing direction was set as a reference orientation. The <100>, <101> and <111> texture percentages were

calculated by measurement of the percentage of crystals with <100>, <101> and <111> direction parallel to the reference orientation.

Twin boundaries (also called Σ3 CSL twin boundaries) were excluded in the average grain size calculation. The twin boundary was described by a 60° rotation about <111> direction between the neighboring crystallographic domains. The number of points depends on the step size, which was less than 1/5 of the average crystal grain size.

Linear Intercept Method for determination of the sizes of the crystal grains of the FABs:

FABs were prepared by performing conventional electric flame-off (EFO) firing by standard firing using an IConn - KNS bonder (single step, 18 µm wire, EFO current of 20 mA, EFO time 495 µs, BSR ratio 2.0 (Bonded Ball to wire diameter ratio)). It was worked according to the procedures described in the KNS Process User Guide for FAB (Kulicke & Soffa Industries Inc, Fort Washington, PA, USA, 2002, 31 May 2009) in ambient atmosphere.

The wires comprising the FABs at the tip were first potted using cold-mounting epoxy resin and then polished (cross-sectioned) by ion-beam etching. A multi-prep semi-automatic polisher was used with low force and optimal speed to grind and polish the sample with minimum deformation strain on the sample surface. Finally, the polished sample was ion beam etched to reveal the crystal grain boundary. The crystal grain size was measured using linear intercept method under optical microscopy with a magnification of 1000, according to the ASTM E112-12 standards.

Vickers Micro-hardness:

The hardness was measured using a Fischerscope H100C testing equipment with a Vickers indenter. A force of 10 mN indentation load was applied to a test specimen of wire for a dwell time of 5 seconds. The testing was performed on the center of the wires and the FABs.

Electrical Resistivity:

Both ends of a test wire of 0.5 m length were connected to a power source providing a constant current/voltage. The resistance was recorded with a device for the supplied voltage. The measuring device was a RESISTOMAT 2316 model, and the test was repeated with at least 10 test wires. The arithmetic mean of the measurements was used for the calculations given below.

The resistance R was calculated according to R = V / I.

The specific resistivity ρ was calculated according to ρ = (R x A) / L, wherein A is the mean cross-sectional area of the wire and L the length of the wire between the two measuring points of the device for measuring the voltage.

The specific conductivity σ was calculated according to σ = 1 / ρ.

Elongation, yield load, break load:

The tensile properties of the wires were tested using an Instron-5564 instrument. The wires were tested at 2.54 cm/min speed, for 254 mm gauge length (L). The load and elongation on fracture (break) were acquired as per ASTM standard F219-96 and ASTM standard F72-06. The elongation was the difference in the gauge length (△L) of the wire between start and end of the tensile test, usually reported in percentage as (100 · △L/L), calculated from the recorded load versus extension tensile plot.

The tensile strength and the yield strength were calculated from the break and yield load divided by the wire area. The average diameter of the wire was measured by the sizing method as described above.

The yield load corresponds to the change of the wire deformation behavior from elastic to plastic mode in the recorded plot.

Evaluation of FAB quality (sphericity, tilt and dimple formation):

2,400 free air balls (FABs) were formed according to the procedure described above. The roundness of the FABs was evaluated by optical microscope and SEM inspections and categorized according to the following evaluation scheme:

- \+ molten drop of wire solidifies, but the ball size is smaller than the specification and/or pointed and/or with surface indentation
- ++ molten drop of wire solidifies with spherical shape, but the ball size is out of specification and/or tilted and/or with surface indentation
- +++ molten drop of wire solidifies with spherical shape and within the specification, but slightly tilted or with surface indentation
- ++++ molten drop of the wire solidifies with spherical and axi-symmetrical ball-like shape with no surface indentation

Fig. 1 shows FABs with a surface intendation (dimple, Fig. 1 A) and with complete sphericity (Fig. 1 B).

Evaluation of bonded ball concentricity, wire sway and wire straightness:

The FAB (formed as described above) was descended to an Al-0.5 wt.-%Cu bond pad from a predefined height (tip of 203.2 µm) and speed (contact velocity of 6.4 µm/sec). Upon touching the bond pad, a set of defined bonding parameters (bond force of 100 g, ultrasonic energy of 95 mA and bond time of 15 ms) took into effect to deform the FAB and formed the bonded ball. After forming the ball, the capillary rose to a predefined height (kink height of 152.4 µm and loop height of 254 µm) to form the loop. After forming the loop, the capillary descended to the lead to form the stitch. After forming the stitch, the capillary rose and the wire clamp closed to cut the wire to make the predefined tail length (tail length extension of 254 µm).

For each wire example 1024 bonded wires were optically inspected using a light microscope with a magnification of 1000.

Bonded ball (1st bond) morphologies were quantified by measuring the average concentricity. E-max software version 5.3 interlinked to the microscope predicted a theoretical circle by least square method and found the centre of the outer circle. Similarly, it predicted inner circle and its centre. 12 edges were marked along the outer circle. The difference in the centre between outer and inner circle for both X and Y direction were calculated, from which the concentricity was calculated as $\Delta C = \sqrt{\Delta X^2 + \Delta Y^2}$. A well concentric bonded ball showed a concentricity of 0.0001 µm, while the worst ball revealed a concentricity of 0.0009 µm.

The concentricity of the bonded ball was determined and categorized according to the following evaluation scheme:

+	≥ 15 % of the bonded balls had a concentricity of more than 0.0006 µm
++	≥ 10 % to < 15 % of the bonded balls had a concentricity of more than 0.0006 µm
+++	< 10 % of the bonded balls had a concentricity of more than 0.0006 µm.

The wire sway gives the percentage of wires which lean towards the neighboring wire. The occurrence of the bonded wires was evaluated and categorized according to the following evaluation scheme:

+	> 25 % of the wires deflect towards neighbor wire in the loop
++	> 5 % of the wires deflect towards neighbor wire in the loop
+++	wires show no loop deflections

The wire straightness gives the percentage of wires which exhibit kink or bend defects. The occurrence of the bonded wires was evaluated and categorized according to the following evaluation scheme:

+	> 20 % of the wires show straightness defects
++	≥ 10 % to ≤ 20 % of the wires show straightness defects
+++	< 10 % of the wires show straightness defect

The following non-limiting examples illustrate the invention. These examples serve for exemplary elucidation of the invention and are not intended to limit the scope of the invention or the claims in any way.

Preparation of wire samples

A quantity of platinum (Pt), yttrium (Y) and gold (Au) of at least 99.999 % purity (“5N”) in each case were melted in a crucible.

For the alloys of Table 1 the corresponding combination of the master alloys Au-0.0045wt.-%Pt-0.0015wt.-%Y, Au-0.0035wt.-%Pt-0.0030wt.-%Y and Au-0.0010wt.-%Y were first prepared. Further dopants of calcium (Ca), cerium (Ce), germanium (Ge) and/or palladium (Pd), according to Table 1, were then added to the melt and uniform distribution of the added components was ascertained by stirring.

Then a wire precursor item in the form of 12 mm rods was continuous cast from the melt. The wire precursor item was drawn in several drawing steps to form a wire precursor with a diameter of 18 ± 1.0 µm. The cross section of the wire was of essentially circular shape.

The rods drawn to a diameter of 2 mm and coiled on a drum were intermediate batch-annealed at an oven set temperature of 370 °C for an exposure time of 90 minutes. A final strand annealing of the 18 µm wire core precursors at an oven set temperature of 490 °C for an exposure time of 0.6 seconds was performed followed by quenching the so-obtained wires in

water containing 0.05 vol.-% of surfactant. All intermediate batch annealing and strand annealing steps were performed in ambient air atmosphere.

By means of this procedure, several different samples 1 to 6 of alloyed gold wires according to the invention and comparative alloyed gold wires of 4N purity, as shown in Table 1, were manufactured.

Table 1: Chemical composition of wires, all values given in wt.-ppm.

Sample	Au	Pt	Y	Ca	Ce	Ge	Pd
Inventive Example 1	Bal.	45	15	5	5	10	5
Inventive Example 2	Bal.	45	15	5	5	10	-
Inventive Example 3	Bal.	35	30	-	-	-	25
Comparative Example 4	Bal.	-	-	60	30	-	-
Comparative Example 5	Bal.	-	10	22	15	-	-
Comparative Example 6	Bal.	45	15	15	15	-	-

Table 2 summarizes the evaluation results of the different wire samples with regard to their intrinsic and extrinsic properties. The above defined wire samples 1 to 6 were bonded to Al-0.5 wt.-%Cu bond pads and tested according to the above disclosed test methods. All tests were carried out with 18 µm wires.

Table 2: Results of wire and FAB characterization.

	Sample	1	2	3	4	5	6
Mechanical properties	Elongation [%]	4.0	4.4	3.9	3.9	4.0	4.0
	Yield Load [g]	4.7	4.5	4.5	3.8	4.7	4.5
	Break Load [g]	5.3	5.1	5.3	5.7	5.4	5.5
	Micro-hardness FAB; HV [10 mN/5 s]	80.8	81.2	73.7	74.6	71.0	75.1
	Micro-hardness wire; HV [10 mN/5 s]	90.9	89.5	88.1	89.9	91.3	90.3
Electrical properties	Resistivity [µΩ·cm]	2.285	2.283	2.301	2.341	2.320	2.315
Microstructure properties	Grain size wire [µm]	0.95	0.90	1.09	1.15	1.08	1.01
	Grain size FAB [µm]	4.0	3.7	2.4	8.0	7.0	6.5
HAZ length	[µm]	70	68	75	72	71	73
FAB quality	Sphericity, tilt and dimple formation	++++	++++	++++	+	++	++
Bonding properties	Bonded Ball	+++	+++	+++	+	++	++
	Sway	++	+++	++	+++	++	++
	Straightness	++	+++	++	+++	+++	+++

The inventive wires exhibit superior properties with regard to their bonding properties in comparison to the comparative examples, especially, no dimples were observed during FAB formation.

Claims

1. A gold bonding wire consisting of
   (a) 20 to 50 wt.-ppm platinum (Pt),
   (b) 10 to 40 wt.-ppm yttrium (Y),
   (c) 2 to 40 wt.-ppm of at least one element selected from the group consisting of calcium (Ca), cerium (Ce), germanium (Ge) and palladium (Pd),
   (d) 0 to 10 wt.-ppm further components other than platinum, yttrium, calcium, cerium, germanium, palladium and gold and
   (e) gold (Au) as the remainder,
   wherein the sum of the amounts of components (a), (b), (c) and (d) is from 32 to 100 wt.-ppm,
   the sum of the amounts of Pt and Y is in the range of 30 to 90 wt.-ppm,
   the sum of the amounts of Ca and Ce is below 20 wt.-ppm and
   wherein all amounts in wt.-% and wt.-ppm are based on the total weight of the gold bonding wire.

2. A gold bonding wire according to claim 1, wherein the average cross-section of the gold bonding wire is in the range of from 50 to 5024 µm².

3. A gold bonding wire according to claim 1 or 2, wherein the average diameter is in the range of from 8 to 80 µm.

4. A gold bonding wire according to any of the preceding claims, wherein the sum of platinum, yttrium and at least one component selected from the group consisting of calcium, cerium, germanium is at least 50 wt.-ppm.

5. A gold bonding wire according to any of the preceding claims, wherein the gold bonding wire comprises Be in an amount below 5 wt.-ppm.

6. A gold bonding wire according to any of the preceding claims, wherein the average grain size of the crystal grains of the gold bonding wire, measured in longitudinal direction, is in the range of from 0.2 to 1.0 µm.

7. A gold bonding wire according to any of the preceding claims, wherein 35 to 70 % of the crystal grains in the gold bonding wire are oriented in <111> direction.

8. A gold bonding wire according to any of the preceding claims, wherein the gold bonding wire consists of

(a) 20 to 50 wt.-ppm, preferably 25 to 45 wt.-ppm or even more preferred 28 to 42 wt.-ppm platinum,

(b) 10 to 40 wt.-ppm, preferably 15 to 35 wt.-ppm or even more preferred 18 to 32 wt.-ppm yttrium,

(c) 2 to 40 wt.-ppm, preferably 3 to 35 wt.-ppm or even more preferred 5 to 30 wt.-ppm of at least two elements selected from calcium, cerium and germanium and

(d) 0 to 10 wt.-ppm, preferably 0 to 8 wt.-ppm, even more preferred 0 to 5 wt.-ppm further components other than platinum, yttrium, calcium, cerium, germanium and gold and

(e) gold (Au) as the remainder.

9. A gold bonding wire according to any of claims 1 to 7, wherein the gold bonding wire consists of

(a) 15 to 45 wt.-ppm, preferably 25 to 45 wt.-ppm or even more preferred 20 to 40 wt.-ppm platinum,

(b) 10 to 40 wt.-ppm, preferably 15 to 35 wt.-ppm or even more preferred 18 to 32 wt.-ppm yttrium,

(c) 2 to 40 wt.-ppm, preferably 3 to 35 wt.-ppm or even more preferred 5 to 32 wt.-ppm palladium,

(d) 0 to 10 wt.-ppm, preferably 0 to 8 wt.-ppm, even more preferred 0 to 5 wt.-ppm further components other than platinum, yttrium, palladium and gold and

(e) gold (Au) as the remainder.

10. A process for manufacturing a gold bonding according to any of claims 1 to 9, comprising the steps of

(1) providing a precursor item consisting of

(a) 20 to 50 wt.-ppm platinum (Pt),

(b) 10 to 40 wt.-ppm yttrium (Y),

(c) 2 to 40 wt.-ppm of at least one element selected from the group consisting of calcium (Ca), cerium (Ce), germanium (Ge) and palladium (Pd),

(d) 0 to 10 wt.-ppm further components other than platinum, yttrium, calcium, cerium, germanium, palladium and gold and

(e) gold (Au) as the remainder,

wherein the sum of the amounts of components (a), (b), (c) and (d) is from 32 to 100 wt.-ppm,

the sum of the amounts of Pt and Y is in the range of 30 to 90 wt.-ppm,

the sum of the amounts of Ca and Ce is below 20 wt.-ppm and

wherein all amounts in wt.-% and wt.-ppm are based on the total weight of the gold bonding wire,

(2) elongating the precursor item to form a wire precursor, until the desired diameter of the bonding wire core is obtained; and

(3) annealing the elongated wire precursor obtained after completion of process step (2) to form the bonding wire.

11. Use of a gold bonding wire according to any of claims 1 to 9 in a ball-bonding procedure.

12. A ball-bond arrangement comprising a bond pad of a semiconductor device and a bonding wire according to any of claims 1 to 9 ball-bonded to the bond pad.