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Aluminium alloy wire for bonding applications

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The invention is related to a bonding wire, comprising:

A core with a surface, wherein the core comprises aluminium as a main component, wherein the core contains scandium as a component in an amount between 0.05% and

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1.0 %.

The invention further relates to a system for bonding an electronic device with a wire according to the invention and a method for manufacturing a wire according to the invention.

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Bonding wires are used in the manufacture of semiconductor devices for electrically interconnecting an integrated circuit and a printed circuit board during semiconductor device fabrication. Further, bonding wires are used in power electronic applications to electrically connect transistors, diodes and the like with pads or pins of the housing.

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While bonding wires were made from gold in the beginning, nowadays less expensive materials are used such as aluminium. While aluminium wires provide very good electric and thermal conductivity, bonding of aluminium wires has its challenges.

Generally, bonding wires in the sense of the invention are optimized for the use with high speed bonding tools, wherein typically ball-bonding or second bonding (wedge bonding) is used to connect an end of the wire with a surface like a bond pad. In the case of aluminium based wires, wedge-wedge-bonding is predominantly used. Bonding wires have to meet specific demands in order to be compatible with bonding tools at least within practicable process windows.

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For the present invention, the term bonding wire comprises all shapes of cross-sections and all usual wire diameters. Bonding wires with circular cross-section and thin diameters are possible as well as thick bonding wires with circular cross sections or flatted

cross sections for high power applications. Bonding wires with flattened cross sections are also called ribbons.

5 Some recent developments were directed to bonding wires having a core material based on aluminium as a main component due to its lower price compared with gold and other materials. Nevertheless, there is an ongoing need for further improving bonding wire technology with regard to the bonding wire itself and the bonding processes.

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

Thus, it is another object of the invention to provide a bonding wire, which has good processing properties and which has no specific needs when interconnecting, thus saving costs.

15 It is also an object of the invention to provide a bonding wire which has excellent electrical and thermal conductivity.

20 It is a further object of the invention to provide a bonding wire which exhibits an improved reliability.

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

25 It is another object of the invention to provide a bonding wire which shows an improved bondability with respect to a second bonding or wedge bonding.

It is yet another object of the invention to provide a bonding wire having a high tensile strength at least during a drawing of the wire.

30 It is yet a further object of the invention to provide a bonding wire having a low electrical resistivity.

35 It is another object to provide a system for bonding an electronic device, which system provides a reliable connection between bonding pads of means likes an electronic device and/or a packaging means.

It is another object to provide a method for manufacturing an inventive bonding wire, the method basically showing no increase in manufacturing costs compared with known methods.

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Surprisingly, wires of the present invention have been found to solve at least one of the objects mentioned above. Further, a process for manufacturing these wires has been found which overcomes at least one of the challenges of manufacturing wires. Further, systems comprising the wires of the invention were found to be more reliable at the interface between the wire according to the invention and other electrical elements.

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A contribution to the solution of at least one of the above objects is provided by the subject matters of the category-forming claims, whereby the dependent sub-claims of the category-forming independent claims representing preferred aspects of the invention, the subject matter of which likewise makes a contribution to solving at least one of the objects mentioned above.

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A first aspect of the invention is a bonding wire, comprising:

A core with a surface,

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wherein the core comprises aluminium as a main component, characterized in that

the core contains scandium as a component in an amount between 0.05% and 1.0 %.

If not particularly defined different, all contents or shares of components are presently given as shares in weight. In particular, component shares given in percent are meant to be weight-%, and component shares given in ppm (parts per million) are meant to be weight-ppm. For percentage values concerning denumerable objects like grains or particles, the given values are shares of a total number of the objects.

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Preferably, the wire according to the invention has no coating layer covering the surface of the core. This provides for a simple and cost saving manufacturing of the wire. This does not exclude that for specific applications, there might be an additional coating layer provided on the surface of the core of an inventive wire.

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It is to be understood that at least some thin layer is expected on the core of a finished wire, as the wire according to the invention is based on aluminium and hence almost instantaneously forms some oxide layer even if exposed to air for just a short time. For definition purposes, the given features and properties of the core of the wire are related to the unaffected core material below such unintentional surface region.

A component is a "main component" if the share of this component exceeds all further components of a referenced material. Preferably, a main component comprises at least 50% of the total weight of the material.

The scandium content according to the invention is selected such that beneficial effects are present without disadvantageous effects becoming dominant. If a scandium content of more than 1% is chosen, high amounts of large grains of scandium or scandium containing phases are present in the core material. If the amount and size of such grains exceed certain limits, the mechanical properties of the wire are impaired. If a scandium content of less than 0.05 % is chosen, beneficial properties added by the scandium are no longer significant.

In case of a preferred embodiment of the invention, the scandium content is optimized to be in a range between 0.1% and 0.35%. In a most preferred embodiment, the scandium content of the core is in the range between 0.12% and 0.25%.

In a generally preferred embodiment of the invention, the core contains between 0% and 0.5% of silicon. It surprisingly turned out that, although silicon is a standard component of conventional aluminium based bonding wires in typical amounts of 1%, a low silicon content of an inventive wire has beneficial impacts. A good tensile strength could be reached even without any silicon, while the electrical conductivity is excellent at the same time. Even more preferred, the silicon content is maintained to be between 0% and 0.2%. In a most preferred embodiment of an inventive wire, no silicon apart from unavoidable traces, in particular less than 100 ppm, is contained.

As a general advantageous feature of an inventive wire, a total of components of the core other than aluminium and scandium is between 0% and 1.0%. More preferably, the content of such other components sums up to less than 0.5%, most preferred to

less than 0.2%. This provides for a high conductivity as little disturbance in the aluminium crystal is caused by further components.

5 In order to enhance a corrosion resistance of the wire, the core preferably contains at least one selected from the group comprising copper and nickel in an amount between 10 ppm and 100 ppm. Most preferred, the nickel content or the copper content is between 30 ppm and 80 ppm.

10 For reasons of low thermal losses due to resistive heating, an inventive wire preferably has a conductivity of at least $32.0 \cdot 10^6 \text{ Ohm}^{-1} \cdot \text{m}^{-1}$. Most preferred, the conductivity is at least $33.0 \cdot 10^6 \text{ Ohm}^{-1} \cdot \text{m}^{-1}$. The conductivity of an inventive wire can be influenced not only by selecting its elemental composition, but also by defined treatment like annealing or homogenization. Although in principle the conductivity is a material dependent constant, there might occur some dependency on the wire diameter at least for very small diameters. For definition purposes, the conductivity given herein is measured
15 with thick bonding wires of about 100 μm diameter.

In a specific embodiment of the invention, at least 30% of the scandium in the core is present in a phase separate to the aluminium main component. It is understood that up
20 to a certain extent, scandium can be completely dissolved in the aluminium matrix. Such state of dissolved scandium does not identify a separate phase. Under certain conditions, the scandium can at least partially be present in a different phase. Such phase is usually identified by crystalline or even amorphous grains which are separate to the main aluminium phase. The properties of such scandium containing phase like
25 grain size, grain size distribution, composition etc. depends on specific heat treatment and/or on the presence of further components.

Preferably, the scandium containing phase is an intermetallic phase comprising mainly Al_3Sc . Intermetallic phases are presently defined as homogenous chemical compounds
30 comprising two or more metals, the intermetallic phases having a lattice structure different from the lattices of the constituting metals.

Most preferably, at least two thirds of a total number of crystallites of the intermetallic phase have a diameter of less than 25 nm. It surprisingly turned out that once the wire

core is adjusted to such parameters, an optimum combination of electrical and mechanical properties is achieved.

5 In one possible embodiment of the invention, the wire has a diameter in the range of 80 μm to 600 μm . Such wires are defined as "thick wires" in the sense of the invention. In this respect, the cross sectional shape of the wire is considered to be circular. Independently of the cross sectional shape, thick wires in the sense of the invention are wires which have a cross sectional area of at least about 5000 μm^2 , which is about the cross sectional area of a circular wire of 80 μm diameter.

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In other embodiments of the invention, the wire has a diameter in the range of 8 μm to 80 μm . Such wires are defined as "thin wires" in the sense of the present invention. In the case of thin wires, circular cross sections are usually preferred, though flat cross sections are possible.

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It is pointed out that for all types of bonding wires, and specifically in the case of thin wires, there are high demands on the tensile strength of the wire material at least when drawing the wire to the final diameter. For conventional wires this means that certain aluminium alloys had to be chosen which allowed for the demanded tensile strength. In the case of the present invention, sufficient tensile strengths even for drawing of thin wires are achieved by the addition of scandium and a controlled heat treatment of the wire. This is true even for wires containing no other components than aluminium and small amounts of scandium.

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25 A further aspect of the invention is a system for bonding an electronic device, comprising a first bonding pad, a second bonding pad and a wire according to any of the preceding claims, wherein the wire is connected to at least one of the bonding pads by means of wedge-bonding.

30 For a preferred embodiment of such system, a structure underlying the bonding pads comprises at least one layer of porous silicon dioxide. Inventive wires can be adjusted concerning their hardness in order to meet requirements of mechanically sensitive structures being aligned below the bond pad. This is particularly true if the bond pad consists of a soft material like aluminium or gold. The sensitive structure can, for example, comprise one or several layers of porous silicon dioxide, in particular with a

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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 inventive bonding wire are optimized to avoid cracking or other damaging of the weak layers. The optimization can be achieved by specific annealing procedures dependent on the respective demands.

A wire according to the invention can advantageously be used in a system with high operating temperatures. Preferably, standard operating temperatures are permanently up to 175 °C, preferably up to 250°C. It is also possible to use a wire according to the invention with very high permanent operating temperatures up to 300 °C. It has turned out that such high temperatures do not interfere with the demanded behaviour of the alloyed scandium in the wire.

For some embodiments of a system for bonding an electronic device, it might even be provided that a controlled formation of a scandium containing phase, in particular an intermetallic Al_3Sc phase, is achieved during the bonding procedure or even during a first operation of the bonded device.

A further aspect of the invention is a method for manufacturing a bonding wire according to the invention, comprising the steps of

- a. providing an aluminium core precursor with the demanded content of scandium; and
- b. drawing and/or rolling the precursor until a final diameter of the wire core is reached.

A precursor of the wire core is defined to be any structure which has to be further deformed in order to obtain the final wire shape. Such precursor can, for instance, be provided by extrusion of a raw material into a cylindrical shape, wherein the raw material already comprises the desired composition. Such precursor can be simply obtained by melting a defined amount of aluminium, adding the further components in the defined amounts and taking care of a homogenous mixture. The wire core precursor can then be cast or formed in any known manner from the molten or solidified alloy, e.g. by casting or by extrusion.

The forming of the precursor into the final wire shape is usually done by a series of drawing steps. In cases of wires with circular cross section, drawing may be the only forming steps. In other cases, in particular for ribbons, the method might include alternative or additional rolling steps. It is to be understood that there might be further steps of different deformation methods included.

In a generally preferred embodiment, a step of homogenization of the core precursor or the final wire is comprised. Homogenization of the aluminium based material is understood as a heating procedure in which at least a major share of the contained scandium is dissolved in the aluminium. Most preferably, the entire scandium share is dissolved in the aluminium. This allows for a controlled adjustment of the crystal structure. Dependent on the demands, the final wire may even be fed to a bonding tool with all of the scandium remaining in a dissolved state. In such case, a scandium containing intermetallic phase may be formed later in the bonding process, or even after the bonding, or even during the operation of the bonded device.

Most preferably though, the homogenization is followed by some defined treatment step in order to modify the crystal structure and particularly in order to form a defined scandium containing phase.

Generally preferred, the step of homogenization is performed prior to a final drawing step. This might help improving the wire properties as lattice defects are added in the final drawing step which can support the formation of a specifically fine scandium containing intermetallic phase later on.

In order to achieve a sufficient dissolution of the scandium, the step of homogenization preferably comprises heating of the core precursor or the final wire to a homogenization temperature of at least 450 °C, more preferred at least 550 °C, for a defined time. Even more preferred, the heating is followed by a rapid cooling at a rate of at least 10 K per second, more preferably at least 100 K per second. Such rapid cooling might be achieved by simple measures like e.g. dipping the wire into a cold liquid like water.

In a most preferred embodiment, a step of precipitation hardening of the wire is comprised. Precipitation hardening is defined as an annealing step in which crystal grains condense and grow in a controlled manner in order to enhance a mechanical strength

of the wire. This leads to an increase of the wire hardness and in particular to an increase of the tensile strength of the wire. A preferred temperature range for precipitation annealing is between 250 °C and 400 °C, wherein an exposure time of the wire is typically at least 30 minutes. In a most preferred embodiment, the precipitation hardening leads to the formation of a finely dispersed Al_3Sc intermetallic phase. The finely dispersed Al_3Sc intermetallic phase has a grain size of preferably less than 500 nm, more preferably less than 300 nm, even more preferably less than 150 nm and most preferably less than 25 nm. A particularly preferred range of the grain size is 20 – 200 nm.

A tensile strength of a preferred wire is chosen to be at least 140 MPa, more preferred 160 MPa and most preferably at least 180 MPa. Such tensile strength in particular allows for an easy and reliable drawing even of thin wires. For the case of thick wires, the tensile strength is less critical with respect to the manufacturing process. For definition purposes, the tensile strength of the material is measured with a circular wire of 100 μm diameter. It surprisingly turns out that the tensile strength of an inventive wire can be adjusted to values even in the range of conventional AISi1-alloy-wires.

Concerning more preferred detail embodiments of the method for manufacturing the wire, in particular with respect to optimized annealing parameters, reference is made to the above description of an inventive wire.

DESCRIPTION OF THE FIGURES

The subject matter of the invention is exemplified in the figures. The figures, however, are not intended to limit the scope of the invention or the claims in any way.

Figure 1 shows a diagram of a tensile strength and an elongation of a wire according to the invention.

Figure 2 shows a diagram of a method of manufacturing an inventive wire, in particular a thin wire.

EXAMPLE

The invention is further exemplified by an example. This example serves for exemplary elucidation of the invention and is not intended to limit the scope of the invention or the claims in any way.

An alloy is prepared by melting a predetermined amount of pure aluminium (purity >99.99%) and adding a predetermined amount of pure scandium in order to obtain a well-mixed composition as follows (in weight-%):

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Aluminium	Scandium	Rest / unavoidable Contaminants
99.8%	0.18%	<0.02%

The molten mixture is cast into an ingot and cooled. The ingot is extruded into a cylindrical shape. An optional drawing step may be performed on the extruded cylinder. A wire core precursor of about 1 mm diameter is obtained.

The 1 mm diameter wire core precursor is then homogenized in a homogenization step. In this step, the core precursor is inserted into an annealing oven preheated to a temperature of 640 °C. The core precursor remains in the oven at constant temperature of 640 °C for an exposure time of several hours. After this period, the entire amount of the Scandium is dissolved in the aluminium lattice.

After the exposure time, the hot core precursor is immediately quenched by dipping into cold water. A cooling rate of more than 100 K per second is achieved by the quenching. This rapid cooling prohibits a formation of larger grains of scandium containing phases.

After homogenization, the precursor is drawn or otherwise formed into a thick wire of typically between 80 µm and 600 µm. Performing the homogenization before drawing of the wire reduces the wear of the drawing tools and improves their lifetime.

In case the final wire is formed as a thick wire, the process can be terminated here or may be followed just by a final annealing step for adjusting the mechanical properties.

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In case the final wire is to be a thin wire, a controlled precipitation hardening is now performed on the thick wire, wherein the diameter after the first series of drawing and/or forming steps is considered an intermediate diameter. The precipitation hardening is done by exposing the wire to a temperature typically in the range of 250 °C to 400 °C, preferably about 300 °C, for several hours. Such temperature is typically lower than the temperature used for homogenization.

During the precipitation hardening, a finely dispersed intermetallic phase Al_3Sc builds up. Such precipitation of the previously dissolved scandium provides for an enhancement of the electrical conductivity of the wire. Furthermore, hardness and tensile strength of the wire are improved.

Good results are obtained if more than 30%, even better more than 70%, of the scandium precipitates in the Al_3Sc intermetallic phase. Most preferably, this phase is predominantly present in the form of very fine grains, wherein at least two out of three of the grains have an average diameter of preferably less than 500 nm, more preferably less than 300 nm, even more preferably less than 150 nm and most preferably less than 25 nm with a particularly preferred range between 20 – 200 nm. The diameter of a grain is presently defined in the ordinary way as the maximum diameter distance which can be laid through the grain.

Fig. 1 shows a diagram of tensile strength and elongation as a function of annealing time at a temperature of 300 °C. The tensile strength is given as breakload "BL" in units of cN (Centinewton). As the wire has a diameter of 100 μm , a breakload of 150 cN is equal to 191 MPa. It can be seen from the diagram that such value is easily reached.

This tensile strength allows for a further drawing of the wire down to thin wire diameters. A typical thin wire diameter which is easily reached is less than 50 μm .

After drawing to the final wire diameter, the wire is exposed to a further, final annealing step. Such step may be identical or similar to the precipitation heating. Alternatively, it may comprise exposure to rather moderate annealing temperatures below 250 °C. Such final annealing is done in order to reduce stress and lattice defects which have been introduced by the deformation of the material.

Scandium content	Homogenization 48h at 640 °C	Precipitation Annealing 7h at 300°C	Stress annealing 7h at 300°C	Conductivity [m/(Ohm*mm ²)]
0.18%	yes	no	no	33.15
0.18%	yes	yes	yes	35.42
0.25%	no	no	yes	35.62

Table 1

Table 1 above shows measured conductivities of two thick wires with a diameter of 300 μm and different scandium content. The measurement was performed on a 1.0m
 5 length of wire with an applied current of 10mA in a four-point-setup.

For the 0.25% scandium sample, homogenization was not performed, but the ingot as delivered are considered to be quite homogenized.

10 Generally, the data proves that conductivity is enhanced by precipitation of scandium containing phase because less disturbance is caused in the aluminium lattice by dissolved scandium. Further it is shown that conductivity values of more than $33.0 \cdot 10^6 \text{ Ohm}^{-1} \cdot \text{m}^{-1}$ are easily reached.

15 Concerning the fineness of the precipitated Al_3Sc phase, measurements using a FIB system (FIB = Focused Ion Beam) were made. The spatial resolution of the FIB system was at about 20nm. Several FIB-cuts of at least $100 \mu\text{m}^2$ have been made on wire sample and have been evaluated for grains. Due to the purity of the used materials, it is assumed that all grains belong to the Al_3Sc phase.

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Measurement with the FIB system and evaluation turned out the following results:

For the material as delivered, grains at an average diameter of 25 nm with a standard deviation of 7 nm are observed.

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No visible grains are present after homogenization over 48 hours at 640 °C.

After precipitation annealing at 300 °C for 7 hours, still no grains are observed.

Considering the resolution of the FIB system and the change of electrical and mechan-

ical properties, the precipitation of a fine Al_3Sc phase with grain sizes not bigger than 20 nm can be derived.

Claims:

1. A bonding wire, comprising:
a core with a surface,
5 wherein the core comprises aluminium as a main component, and
the core contains scandium as a component in an amount between 0.05% and
1.0 % and at least 30% of the scandium in the core is present in a phase
separate to the aluminium main component, wherein the phase is an
intermetallic phase comprising mainly Al_3Sc , wherein at least two thirds of a
10 total number of crystallites of the intermetallic phase have a diameter of less
than 25 nm, and wherein the wire has a diameter in the range of 80 μm to 600
 μm or in the range of 8 μm to 80 μm .
2. Wire according to claim 1, wherein the core contains between 0% and 0.5% of
15 silicon.
3. Wire according to any of the preceding claims, wherein a total of components of
the core other than aluminium and scandium is between 0% and 1.0%.
- 20 4. Wire according to any of the preceding claims, wherein the core contains at
least one selected from the group comprising copper and nickel in an amount
between 10 ppm and 100 ppm.
5. Wire according to any of the preceding claims, wherein the wire has a
25 conductivity of at least $32.0 \cdot 10^6 \text{ Ohm}^{-1} \cdot \text{m}^{-1}$.
6. System for bonding an electronic device, comprising a first bonding pad, a
second bonding pad and a wire according to any of the preceding claims,
wherein the wire is connected to at least one of the bonding pads by means of
30 wedge-bonding.
7. System according to claim 6, wherein a structure underlying the bonding pads
comprises at least one layer of porous silicon dioxide.
- 35 8. Method for manufacturing a bonding wire according to any of claims 1 to 5,
comprising the steps in sequence of

- a. providing an aluminium core precursor with the demanded content of scandium; and
 - b. homogenization of the core precursor, wherein the homogenization comprises heating of the core precursor to a homogenization temperature of at least 550 °C for a defined time, wherein the heating is followed by a rapid cooling at a rate of at least 10 K per second; and
 - c. drawing and/or rolling the precursor until a final diameter of the wire core is reached,
- wherein the method comprises a step of precipitation hardening of the wire.

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