

[Document name]
Specification

[Title of the invention]
An Aluminum Alloy Wire for Connection to Semiconductor Devices

[Relevant field of technology]
[0001]

The present invention relates to an aluminum alloy wire used for connecting an electrode on a semiconductor device to an external electrode by means of ultrasonic wave, and especially to an aluminum alloy wire made of a solid solution formed by forcibly dissolving iron (Fe) in aluminum (Al) of a purity of 99.99 mass % or higher.

[Background technology]
[0002]

An ultrasonic bonding method applicable to this aluminum alloy wire is such that a cemented carbide tool is first pressed against the aluminum alloy wire laid on an aluminum pad to cause a bonding between the aluminum alloy wire and the aluminum pad by means of the pressure and the ultrasonic wave vibration from the cemented carbide tool. The effects of the application of the ultrasonic wave include an expansion of the bonding area for the purpose of promoting the deformation of the aluminum alloy wire, and destroying and removing a surface oxide film having a thickness of 5 – 10 nanometers formed over the aluminum alloy wire so that metallic atoms such as aluminum (Al) are caused to expose in the connection side face to thereby create a plastic flow across the interface formed with the bonding pad and by thus expanding gradually these newly created faces forming the interface of each other, an inter-atomic bonding between the two are established.

Conventionally, there have been aluminum alloy wires described below which are made of a solid solution of aluminum (Al) in which iron (Fe) is dissolved, but on account of the fact that the purity of the aluminum (Al) was so low that chipping occurred when subjected to ultrasonic waves; also, if a conditioning heat treatment was wrought at a high temperature in order to prevent the chipping, the strength of the aluminum alloy wire lowered so much that when used in a power semiconductor device after the ultrasonic bonding, there occurred a problem of wire breakage due to thermal shock.

[0003]

A first example of these is described in Japanese Patent application publication S48-026611 (1973) (hereinafter referred to as IP Publication 1). It reads "Table 1 shows results of practical examples regarding a typical aluminum-iron alloy (2.5 % Fe) having an Al-Al₆Fe structure, in terms of mechanical properties as of (i) as-cast (growth rate $R = 2500$ micrometers/second, temperature gradient $G = 10$ degrees C/minute) and (ii) under cold working condition (area decrease 94 %), (see right-lower column of Page 3), so that this invention tries to industrially utilize the particles of the Al₆Fe structure shown in Fig. 3(a) through extremely slow cooling.

However, in the case of a grain structure like this, the aluminum-iron alloy matrix becomes so hard that it is impossible to use a wire of this make in an ultrasonic wave bonding operation onto a semiconductor device with the application of ultrasonic wave and load.

[0004]

Also, there is Japanese Patent Application Publication H08-8288 (1988) (hereinafter referred to as IP Publication 2). This utilizes the ultrasonic wave wire bonding method, according to which a large load and ultrasonic wave are applied to deform an Al-0.02wt% Fe alloy wire having a diameter of 500 micrometers and to thereby cause the wire to be bonded upon an aluminum pad or an electrode pad clad with an Al-Si alloy film, strongly; by virtue of the inclusion of Fe in aluminum it is possible to heighten the temperature at which the recrystallization occurs, so that the recrystallization does not initiate upon the passing of electricity, and since the crystal grain size is as large as 50 micrometers or more, the thermal stress that works upon the crystal boundary becomes low and as a result the development of cracks is restricted – and such is enjoyed by this method (part 0010 of the specification).

However, with the increase in the crystal grain size, the mechanical strength of the bonding wire itself is lowered correspondingly, and thus the magnitude of the plastic deformation which the wire undergoes during the heat cycle test is increased. As such, the effect of reduced grain boundaries and the effect of increased deformation magnitude off set each other so that the reliability in thermal shock resistance of a bonding wire having a large crystal grain diameter like this is not as improved as

expected in reality.

[0005]

Also, Japanese Patent Application Publication 2008-311383 (hereinafter referred to as IP Publication 3) discloses (at part 0017) a wire having a diameter of 300 micrometers, which is prepared by making a 99.99 wt% (4N) high-purity Al-0.2 wt% Fe alloy ingot, drawing a wire from the ingot, annealing the wire at 300 degrees C for 30 minutes, slowly cooling it, removing the residual strain caused by the wire drawing, and softening the wire to a level suitable to the ultrasonic wave bonding operation applicable to power module, and this wire is bonded by ultrasonic wave bonding, and is let to age for one minute to one hour at 100 – 200 degrees C, and as the result it becomes possible to restrict the progress of a crack that is caused at the juncture part by a repetition of passage of large electricity, even when the temperature reaches the highest operation temperature of 200 degrees C (according to parts 0012 and 0015).

This bonding wire does not receive a solution heat treatment either, but simply undergoes “gradual cooling after annealing for 30 minutes at 300 degrees C” (which corresponds to the “conditioning heat treatment” of the present invention), so that even though its object is to improve the reliability in thermal shock resistance of the bonding wire through enlargement of the crystal grain size like in the case of the wire of Japanese Patent Application Publication H08-8288 (1988) (hereinafter referred to as IP Publication 2), the reliability does not improved so much because the strength of the wire is lowered.

On the other hand, in the case of an Al-Cu alloy, the wire is so hard that it is necessary to increase the bonding load, and in the case of a Si chip for high temperature semiconductor devices, chip cracking is liable to occur during the ultrasonic wave bonding operation.

[0006]

Also, there is Japanese Patent Application Publication 2011-252185 (hereinafter referred to as IP Publication 4). This relates to an Al alloy electrically conductive wire which consists of aluminum doped with silicon (Si) and copper (Cu) as well as iron (Fe), wherein the length in the long-axis direction of the substance consisting of iron that separates from the Al-Si-Cu alloy matrix is controlled so that an Al alloy conductive wire excellent in extensibility and tensile strength is obtained while the

electrical conductivity required as a conductive wire is maintained, which wire is applied as wire harness, battery cable and the like (part 0013, etc. of the specification).

According to an example of IP Publication 4, after drawing an Al alloy cast to a wire of diameter 5.65 mm, the wire was subjected to a solution heat treatment for three hours at 550 degrees C, and after this solution heat treatment, the wire was cooled by water and was further drawn cold to a diameter of 0.33 mm. And it is described that this Al alloy wire was thermally treated at 230 – 240 degrees C.

However, this Al-Si-Cu alloy matrix tends to make an over-hard wire, like Al-Cu alloy matrix, so that if it is used as a bonding wire for bonding to high-temperature semiconductor device, chip cracking occurs during the ultrasonic wave bonding. Furthermore, since its conductivity (by IACS [International Annealed Copper Standard]) decreases to as low as 55 – 61 % from the proper range of 62 % or higher, it is feared that the heat generation would be so great as to shorten the life of the semiconductor devices.

[0007]

As is seen from the above examples, the conventional bonding wires for high temperature semiconductor devices have been designed to avoid chip cracking during ultrasonic wave bonding operation through magnification of crystal grain boundaries in the aluminum (Al) matrix, and thus to avoid wire breakage starting from the bonding interface triggered by a thermal shock. The bonding part between the electrode pad on the semiconductor device and the alloy wire is constituted by a combination of silicon having an extremely low thermal expansion coefficient (3.5×10^{-6} /degrees C) and aluminum having a high thermal expansion coefficient (243×10^{-6} /degrees C), and is exposed to a very high temperature due to a heat generation caused by the strong electric current started at the time of the operation of the semiconductor device, so that a large thermal stress is piled up at the bonding interface between the electrode pad and the aluminum alloy wire.

As a result, a crack would develop from the vicinities of the bonded wire and hence a problem arises that the wire would come off in a short time.

[0008]

On the other hand, there is a desire to apply aluminum alloy wire to particular semiconductor devices which are required to have resistance

against heat of 100 – 200 degrees C, especially to power semiconductor devices such as ones used in air conditioner, solar power generation system, hybrid vehicle, and electric car, and thus the application field for the aluminum alloy wire is expected to expand progressively in the future especially to include where the operational temperature is higher than conventional. The operational conditions for such power semiconductor devices include temperatures higher than those for conventional semiconductor devices, and in particular it is necessary for the wire to withstand the temperature of 150 – 180 degrees C at the bonding juncture.

The aluminum alloy wires described above have not been utilized in such high temperature circumstances. The reason for this is that when the aluminum alloy wire is retained in a high temperature environment, the cold-drawn tissue (structure) in the aluminum alloy wire turns from a recovery state to a recrystallization state, and eventually grain growth would start and the whole body of the aluminum alloy wire would soften.

Also, with the conventional aluminum alloy wires, even when an aluminum matrix with large crystal grain size is used, sub-grains are formed in the aluminum matrix as a result of thermal shock distortion, which is caused by the difference in thermal expansion coefficient between the aluminum alloy wire and the silicon chip, and along these sub-grains cracks propagate in the aluminum alloy wire, and hence the problem of detachment of silicon chip from the aluminum alloy wire has not been solved.

[Prior Art Publications]

[IP Publications]

[0009]

[IP Publication 1] (Japanese) Patent Application Publication S48-026611 (1973)

[IP Publication 2] (Japanese) Patent Application Publication H08-8288 (1988)

[IP Publication 3] (Japanese) Patent Application Publication 2008-311383

[IP Publication 4] (Japanese) Patent Application Publication 2011-252185

[Non-IP Publication]

[0010]

[Non-IP Publication 1]

Light Metal (1980) Vol. 30, No. 11, P626 – 633 “Softening by Machining and Recrystallization of Al-Fe Alloy” Hiromi Takei and 2 others

[Summary of the Invention]

[Problems the Invention seeks to solve]

[0011]

It is an object of the present invention to provide an aluminum alloy wire which, when bonded to an aluminum pad by ultrasonic wave bonding, does not incur chip cracking, does not invite instability in the after-bonding strength of the bonding interface between the aluminum alloy wire and the aluminum pad even during a long time continuous operation, and especially has such a strong crystal tissue that, when it is subjected to a high temperature thermal shock test, the aluminum alloy wire does not come off from the aluminum pad due to thermal fatigue failure of the bonded aluminum alloy wire.

[Means to solve the problem]

[0012]

The inventors studied carefully the detachment phenomenon that occurs during the thermal shock test at the bonding interface coupling the aluminum (Al) of the aluminum pad and the aluminum (Al) of the bonding wire, and they found that the cause for the breakage of the bonding interface was a fatigue failure. They investigated further for the cause of this fatigue failure, and discovered that the problem existed in the solid solution behavior of the iron (Fe), which dissolves in the aluminum (Al) matrix by no more than 0.052 % (520 ppm) at 650 degrees C. In other words, in the process of casting an alloy ingot from aluminum (Al) and iron (Fe), the iron (Fe) would separate on the side of aluminum (Al) during the slow cooling for ingot solidification, because the iron (Fe) has extremely low solid solubility limit. As the result, the iron (Fe) does not dissolve in the solid solution to its solid solubility limit, and hence the strength of the aluminum alloy wire turns weak.

[0013]

In order to solve this problem, the inventors of the present invention re-dissolved the iron (Fe), which had separated from the aluminum (Al) matrix of the aluminum alloy wire, to its solid solubility limit of 0.052 % (520 ppm) at 650 degrees C, and thereby they could increase the strength of the aluminum alloy wire. They rendered the tissue of the aluminum (Al) matrix after drawing into a wire to have a uniform infinitesimal recrystallization tissue of several-micrometer-order, and dispersed the iron (Fe) which had remained without re-dissolving in the form of Fe-Al

inter-metallic compound particles in the grain boundaries and the grains having the infinitesimal recrystallization tissue, and as the result it was possible to have the thermal shock distortion, caused during the operation of the high temperature semiconductor device, absorbed not by the alloying element but by the boundaries having the infinitesimal recrystallization tissue.

A characteristic of the present invention lies in that the amount of iron (Fe) which dissolves in the aluminum (Al) matrix is increased to the solid solubility limit, which is 0.052 % at 650 degrees C, through a process of solution heat treatment and rapid cooling treatment conducted before the conditioning heat treatment, and thereafter by conducting ordinary continuous cold wire drawing followed by the conditioning heat treatment, it is made possible to minimize the crystal grain size of the Al-Fe alloy wire, and in that by adopting highly purified aluminum a dynamic recrystallization is occasioned during the bonding operation whereby the chipping damage is circumvented.

By virtue of this, it has become possible to satisfy the self-contradicting demand of (i) lowering the amount of plastic deformation of the wire at the bonding interface coupling the bonding wire and the aluminum pad which deformation is caused by thermal shock during a heat cycle test through increasing of the mechanical strength of the bonding wire, and of (ii) enabling a bonding under low load during the ultrasonic wave bonding without incurring chip cracking.

[0014]

The wire bonding caused by ultrasonic wave proceeds as the wire is made to deform whereby new bonding area is created between the wire and the pad under the application of the ultrasonic wave thus increasing the bonding face area and forming mutual inter-atomic bonds; the chip cracking that occur on the occasion of the formation of these bonds is generally caused when the hardness and the strength of the bonding wire are great, as there is a need to increase the load inflicted by the bonding tool and also as the load inflicted upon the chip by the wire is increased too.

On account of this, it is said in general, that when the wire is softer and easier to deform, the load upon the chip is more mitigated and in effect the occurrence of chip cracking is more restricted.

However, the present inventors thought that there must occur some work hardening during the wire deformation and this ought to have some effect.

In other words, on the occasion of wire bonding the pad is preheated, and upon the application of ultrasonic wave the temperature of the wire as well as that of the pad rise to some degree, but the rise is only such that the work hardening occurs accompanying the deformation without softening, so that it is thought that this excessive load imposed on the chip is one of the causes for the occurrence of chip cracking.

[0015]

Now, metals and alloys in general are known to harden when wrought, which is called work hardening, but in the cases of pure Al and metallic alloys such as Al-Fe alloy it is known that work softening phenomenon takes place whereby softening proceeds accompanying the working (ref. non-IP Publication 1).

These metals and alloys are regarded to have the feature of softening more when they receive stronger working under the same conditions, and it is known with respect to Al-Fe alloy that the recrystallization behavior varies profoundly with the difference in the state of existence of Fe in Al.

It was postulated that in the case of Al-Fe alloy, the sample in which Fe is dissolved as a result of these annealing treatments undergoes a stationary deformation as a result of saturation of work hardening, that as the deformation occurs the recovering strain energy contributes to recrystallization, and that by utilizing this so-called dynamic recrystallization, the excessive load upon the chip which accompanies the wire deformation is mitigated.

As mentioned above, the present invention seeks to improve the wire strength in order to restrict the breakage of the bonding interface that is caused by the thermal fatigue, so that the softening of the bonding part which deforms at the time of bonding would have an opposite effect, but so long as the work hardening does not occur at the time of the deformation the excessive load on the chip can be avoided, and the present inventors identified the conditions that bring about such state in the case of Al-Fe alloy.

An aluminum wire of the present invention, in which iron (Fe) is forcibly

dissolved into the aluminum (Al) matrix to the solid solubility limit, is capable of occasioning a dynamic recrystallization simultaneously as the deformation of the bonding wire at the time of the ultrasonic wave bonding, so that even in the case of a bonding wire having a large diameter, it is possible to keep the bonding load low.

[0016]

The aluminum alloy wire for semiconductor device according to the present invention is defined as an aluminum alloy wire for ultrasonic wave bonding applicable to a semiconductor device, the wire being made of 0.2 – 2.0 mass % of iron (Fe) and the balance aluminum of a purity of 99.99 mass % or higher, wherein iron (Fe) is dissolved by 0.005 – 0.05 % in an aluminum (Al) matrix of the aluminum alloy wire, and also the after-drawn matrix tissue as seen in cross section of the aluminum alloy wire has a uniform fine recrystallization pattern of an order of several micrometers, and iron-aluminum (Fe-Al) intermetallic compound particles are uniformly crystallized in the boundaries and interior of the fine recrystallization tissue.

[0017]

The impurity elements that coexist with the aluminum of a purity of 99.99 mass %, according to the present invention, include transition metal elements such as silicon (Si), copper (Cu), manganese (Mn), magnesium (Mg), zinc (Zn), titanium (Ti) and alkaline earth metal elements as well as alkaline metal elements.

It is preferable that the purity of aluminum (Al) is 99.995 mass % or higher and more preferably 99.998 mass % or higher for the promotion of dynamic recrystallization of aluminum (Al) matrix.

[0018]

In the present invention, it is preferable that iron (Fe) is dissolved in the matrix by 0.01 – 0.05 %. More preferably, iron (Fe) is dissolved in an amount of 0.02 – 0.05 %. And this is because the closer to the solid solubility limit by which iron (Fe) is dissolved, the finer the crystal grains would be.

Also, in the present invention, it is preferable that the wire diameter of the aluminum alloy wire is 50 – 500 micrometers. If it is smaller than 50 micrometers it cannot be used with large current power semiconductor

devices for electric vehicle, and if it is greater than 500 micrometers, the ultrasonic bonding to the aluminum pad becomes difficult. The diameter of the aluminum alloy wire is selected responsive to the semiconductor device in which it is used. Also, in the present invention, it is preferable that the average grain diameter (D_{average}) of the fine recrystallization tissue is 0.5 - 5 % of the wire diameter from the viewpoint of thermal shock distortion. The ratio of 0.5 - 5 % was determined by defining the drawing ratio by which the cross sectional area of the wire is decreased as it is drawn continuously from the aluminum alloy preform wire to make the end aluminum alloy wire, with the consideration of the diameter of the drawn wire and the size of the fine recrystallization tissue. It is more preferable that the average grain diameter is 0.5 - 2 % of the wire diameter.

The fine recrystallization tissue is preferably such that it is obtained by conducting a cold continuous wire drawing of a drawing rate of 90 % or greater from the preform wire. More preferably the rate is 99 % or greater.

[0019]

Also in the present invention, it is preferable that the continuous wire drawing operation is conducted cold after the solid solution heat treatment. The continuous wire drawing operation is preferably die drawing, and use of diamond die is especially preferred; this is because it is easy to create a concentrically aligned thin and lengthy fine recrystallization tissue.

[0020]

Incidentally, it is alright to subject the continuously drawn aluminum alloy wire to a heat treatment while it is tensed by a constant force so as to remove the strain or distortion caused by the wire drawing. A constant tension is basically applied during the continuous wire drawing as the wire runs from the exit of the final diamond die to the entrance of the winding spool, but by using a dancer roller to thereby preventing the vibration originating at other stages from reaching the aluminum alloy wire, it is possible to maintain the tension strictly constant between the heat treatment stage and the cooling stage, and thus it is possible to impart to the aluminum alloy wire a predetermined strain removal thermal energy by adjusting the final heat treatment temperature and the heat treatment distance.

However, this heat treatment is absorbed into the conditioning heat treatment, which uses far greater thermal energy.

The solution heat treatment meant by the present invention comprises heating at a temperature slightly lower than the solidus line temperature of Fe-lean Al-Fe alloy (655 degrees C), re-solutionizing the iron (Fe) which has separated from the aluminum (Al) matrix and thus uniformly dissolving the iron into the matrix, and thereafter conducting a rapid cooling, preferably water cooling, to thereby effect forced solidification. The heating time is normally several tens of hours. This solution heat treatment is conducted for the purpose of increasing the mechanical strength to outdo the thermal shock distortion of the soft aluminum (Al) matrix by miniaturizing the recrystallized grains.

[0021]

Also, in the present invention, iron-aluminum (Fe-Al) intermetallic compound particles separate as a result of conditioning heat treatment. As the wire is continuously drawn cold before the conditioning heat treatment, a uniform fine recrystallization tissue is also formed in consequence of the conditioning heat treatment. The size of the grain boundary of the fine recrystallization tissue is determined by the drawing rate of the wire drawing, and it was designed to be several micrometers or so, so that the size of the average boundary of the polygonal fine recrystallization tissue, as shown in Fig. 1, was set to be within the range of 0.1 to 10 micrometers. The wire diameter of the aluminum alloy wire is preferably such that is obtained as a result of continuously drawing from the aluminum alloy preform wire at a drawing rate of 80 % or higher, and it is more preferable if the rate is 95 % or higher.

The size of the grain boundary of the fine recrystallization tissue is also variable with the temperature and duration of the conditioning heat treatment, and also the temperature and the duration of the conditioning heat treatment vary with the drawing rate of the wire drawing, and hence there is no ambiguous determining method. As such, it is preferable ordinarily to adopt a temperature range of 350 – 500 degrees C, in the case of a batch processing, for the recrystallization of the aluminum alloy wire, and a range of 380 – 430 degrees C would be more preferable. As for the possible heating method for the heat treatment, there are heating by electric furnace, electrical heating, photo irradiation heating, steam heating, etc.

Also, if the aluminum alloy wire after wire drawing is cooled with water at the end of the conditioning heat treatment (the final heat treatment), pores and the like are formed in the surface of the aluminum alloy wire and on the occasion of ultrasonic wave bonding the ultrasonic wave gives rise to heat generation around the pores and the like, so that it becomes easier for the aluminum alloy wire to be bonded on the aluminum pad by the ultrasonic wave. If ethanol is mixed in the cooling water, the result of the ultrasonic wave bonding becomes better. On the other hand, the crystallized iron-aluminum (Fe-Al) intermetallic compound particles are uniformly and finely dispersed in the aluminum (Al) matrix as the result of the wire drawing, and contribute to the increment of the mechanical strength of the aluminum (Al) matrix and also prevent the coarsening of the fine recrystallization tissue caused by heat by virtue of their pinning effect. The iron-aluminum (Fe-Al) intermetallic compound particles are thought to be FeAl_3 or FeAl_6 .

[0022]

The hardness of the bonding wire in the present invention is preferably 25 – 40 Hv in terms of Vickers hardness, and 28 – 35 Hv would be better. From the viewpoint of chip cracking during the ultrasonic wave bonding, it is preferable that the wire hardness is as low as possible in general. However, the aluminum alloy according to the present invention undergoes dynamic recrystallization simultaneously as the deformation of the wire during the bonding operation, and does not undergo work hardening even when the wire undergoes plastic deformation, so that it is possible to use a harder bonding wire which makes the handling for the bonding work easier. The higher the purity of the aluminum (Al) in the aluminum matrix is, the more extensively the dynamic recrystallization proceeds. Therefore, the purity of the aluminum (Al) is preferably 99.998 mass % or higher, and more preferably 99.999 mass % or higher.

[Effects of the Invention]

[0023]

In the case of the aluminum alloy wire for connecting semiconductor devices according to the present invention, even when a wire of a large diameter is subjected to ultrasonic wave bonding, the wire being bonded is bonded while undergoing a stationary deformation without experiencing work hardening by virtue of the occurrence of the dynamic recrystallization, so that there occurs little chip cracking. Also, even

when the inventive wire is subjected to a number of fatiguing repetition of thermal shock test consisting of a 3-minute heating at a high temperature (such as 200 degrees C) followed by a 3-minute cooling at a below-zero temperature (such as -50 degrees C), it shows a thermal shock resistance comparable to that of the aluminum alloy matrix by virtue of the fine recrystallization tissue in the aluminum (Al) matrix and the pinning effect of the intermetallic compound particles.

More specifically, the number of the repetition of the thermal shock resistance test consisting of 3-minute heating at the high temperature (200 degrees C) followed by 3-minute cooling at the low temperature (-50 degrees C), as described in the examples, that is required to cause the initial shear strength to fall by 20 % to 30 % (0.8 to 0.7), that is, the ratio obtained by dividing the after-test shear strength by the initial shear strength, has increased so many as about twice the conventional number. The effect of this is felt greater in the case of a 5-nine pure aluminum alloy wire than in the case of a 4-nine pure aluminum alloy wire, but when a price is a higher priority a 4-nine-8 or so pure aluminum alloy wire is appropriate, and thus the aluminum alloy wire of the present invention passes as an aluminum alloy wire for ultrasonic wave bonding suitable to power cycle semiconductors for electric automobiles, etc. where high temperatures are experienced.

[Examples]

[0024]

Aluminum alloys consisting of iron (Fe) and balance aluminum (Al) having compositions as shown in Tables 1 and 2, respectively, namely Examples 1 – 20 and Comparative Examples 1 – 28, were melt and continuously cast into aluminum alloy ingots having a diameter of 300 mm. After being rolled in a grooved rolling mill, each of these ingots was drawn to be an aluminum alloy preform wire of a diameter of 5 mm.

Next, this preform wire was subjected to the solution heat treatment. This solution heat treatment was applied for 48 hours at three temperature levels in the range of 650 – 450 degrees C, and thereafter the wire was rapidly cooled in water or slowly cooled in the atmosphere (Comparative Examples 20 – 24). Then, the wire was continuously drawn in water until the wire diameter became a predetermined size and thus a bonding wire was completed. One hundred pieces of each wire were bonded by ultrasonic wave bonding upon an aluminum pad of Al-Si alloy (1.0 % Si),

using a fully automatic ultrasonic wire bonder REBO 7, manufactured by ULTRASONIC ENGINEERING CO., LTD., under conditions that the frequency was 120 kHz, the load 8000 mN, the ultrasonic power 15 W, and bonding period 180 ms. As Conventional Example, a wire of Al-Ni alloy (50 ppm Ni) was adopted.

Incidentally, the temperature for conditioning was 380 degrees C in the cases of Examples and Comparative Examples, and 330 degrees C only in the case of Conventional Example.

[0025]

(Conditions for ultrasonic wave bonding)

The wire diameters of the aluminum alloy wire were 0.1 mm, 0.3 mm and 0.5 mm, the loop length was 10 mm, and the loop height was 1.5 mm. Using the fully automatic ultrasonic wire bonder REBO 7, manufactured by ULTRASONIC ENGINEERING CO., LTD., the aluminum alloy wire was bonded by ultrasonic wave bonding upon a film of Al-Si (1.0% Si) (4 micrometers in thickness) coated on an Si chip (0.5 mm in thickness). The bonding conditions were such that the frequency was 120 kHz, the load and the ultrasonic wave quality were arbitrarily controlled such that the width of the collapsed wire at the first bonding part becomes 1.3 times the wire diameter, and that for the 100 pieces each of all samples were subjected to the ultrasonic bonding at the first bonding and the second bonding under the same conditions. The cemented carbide tool and bonding guide used were ones manufactured by ULTRASONIC ENGINEERING CO., LTD., which were suitable to the wire size.

[0026]

Next, the thus bonded aluminum alloy wire was subjected to a chip cracking observation test and a thermal shock test.

(Chip cracking observation test)

The wire sample after bonding was isolated by dissolving away the Al-Si (0.1% Si) pad with a 20% NaOH solution, and using an optical microscope (STM6, a measuring microscope manufactured by OLYMPUS CORPORATION), the chip cracking was looked for at 100 magnifications. Observation was made at ten localities, and when even one locality was found to have a chip crack, the sample was given, a rating of "X", and none was found in any locality, the sample was rated "○".

[0027]

(Thermal shock test)

The thermal shock test equipment used was TSE-11, a small-sized hot-cold shock testing equipment manufactured by ESPEC CORP., and the temperatures were set at 200 degrees C at the higher side and -50 degrees C at the lower side, and each temperature was maintained for 3 minutes in each cycle and the cycle was repeated for 10,000 times.

The samples after the thermal shock test were subjected to the next shear strength test for evaluation.

(Shear strength test)

Using a tester type 2400, manufactured by DAGE CORPORATION, the shear strength of the first bonding part was measured after heat shock cycles of 1,000 times, 2,000 times, 5,000 times and 10,000 time, respectively, and each result was compared to the initial strength, that is, the result after zero time of heat shock cycle. When the number of cycles it took for the shear strength to decrease by 20 % (0.8) from the initial shear strength was less than twice the number in the case of Conventional Example, the wire was given a rating of "X", and when it was twice or more, the wire was given a rating of "○". As the sample for Conventional Example, a commercially available one of Al-Ni (50 ppm Ni) was used. The test height was 5 micrometers and the test speed was 500 micrometers per second.

[0028]

(Measurement of specific resistance)

The specific resistances at 77 K and 300 K of each wire were measured in accordance with the electric conductivity measurement by 4 probes method, using a direct current power source (type 2400 manufactured by Keithley Instruments Inc.) and a nanovolt-meter (type 2182 manufactured by Keithley Instruments Inc.).

[0029]

(Measurement of width of collapsed wire)

The width of a collapsed wire at the first bonding part was the width of the wire measured orthogonally to the wire axis, and the largest of such values was taken as the collapse width. For the measurement, an optical

microscope STM6 (a measuring microscope manufactured by OLYMPUS CORPORATION) was employed.

[0030]

(Measurement of 0.2 % yield strength)

A tensile test was conducted using a tensile strength tester (Autograph AG-X, manufactured by Shimadzu Corporation), and the stress measured when plastic deformation of 0.2 % occurred, and it was named 0.2 % yield strength.

[0031]

(Cross-sectional observation test)

Using a cross-section milling machine (type IM-4000, manufactured by Hitachi High-Technologies Corporation), a wire cross section was exposed and the tissue observation was done by using a focused ion beam processing and observation equipment (type JIB-4000 manufactured by JEOL Ltd.). A so-called method of cross section was used for the measurement of crystal grain diameter.

In Tables 1 and 2 the average fine recrystallization tissue size is an average of the diameters of the cross section of the wire measured along a horizontal line and along a line orthogonal to the horizontal line.

[0032]

(Measurement of Vickers hardness)

A Vickers hardness meter (MVK-G3 manufactured by AKASHI SEISAKUSHO CO., LTD.) was used to measure the Vickers hardness.

The details of the bonding wires and the results of the above-described various tests of Examples and Comparative Examples are entered in Table 1 and Table 2.

[Table 1]

[Examples]

	Fe content (wt%)	purity of starting Al (%)	temperature for solutionizing (°C)	wire diameter (mm)	average recrystallized grain diameter (μm)	(average recrystallized grain dia.)/(wire dia.)	Vickers hardness	specific resistance in liquid nitrogen (nΩm)	conductivity (%ACS) (%)	0.2% yield strength (MPa)	(collapse width)/(wire dia.)	chip cracking	thermal shock test
1	0.22	99.999	650	0.5	4.7	0.9%	25	2.88538	63.4	37.6	1.36	○	○
2	0.5	99.999	650	0.5	4.5	0.9%	26	2.94099	63.4	39.4	1.34	○	○
3	0.8	99.999	650	0.5	4.2	0.8%	28	2.97044	63.4	42.4	1.31	○	○
4	1.2	99.999	650	0.5	4.1	0.8%	29	2.89132	63.1	43.6	1.30	○	○
5	1.9	99.999	650	0.5	3.9	0.8%	32	2.9188	63.2	47.6	1.26	○	○
6	0.22	99.995	650	0.5	4.6	0.9%	26	3.00844	64.0	39.8	1.33	○	○
7	0.8	99.995	650	0.5	4.1	0.8%	29	2.94268	62.4	43.9	1.29	○	○
8	1.9	99.995	650	0.5	3.8	0.8%	32	2.95754	63.0	49.6	1.24	○	○
9	0.22	99.99	650	0.5	4.5	0.9%	26	3.07643	63.2	39.5	1.34	○	○
10	0.8	99.99	650	0.5	3.9	0.8%	30	3.01429	63.0	46.0	1.27	○	○
11	1.9	99.99	650	0.5	3.6	0.7%	32	2.99554	63.2	49.8	1.23	○	○
12	0.22	99.995	550	0.5	5.3	1.1%	25	2.61891	63.8	38.2	1.36	○	○
13	0.8	99.995	550	0.5	4.8	1.0%	29	2.61234	63.5	43.2	1.30	○	○
14	1.9	99.995	550	0.5	4.6	0.9%	33	2.6477	64.4	49.6	1.24	○	○
15	0.22	99.995	650	0.3	5.0	1.7%	26	2.93741	62.3	38.8	1.34	○	○

16	0.8	99.995	650	0.3	4.4	1.5%	29	2.89375	62.6	43.5	1.30	○	○
17	1.9	99.995	650	0.3	3.8	1.3%	33	2.98099	63.8	49.3	1.24	○	○
18	0.22	99.995	650	0.1	4.7	4.7%	26	2.9657	63.4	39.0	1.34	○	○
19	0.8	99.995	650	0.1	4.2	4.2%	29	2.98866	63.7	43.5	1.30	○	○
20	1.9	99.995	650	0.1	3.8	3.8%	33	2.96029	63.3	49.3	1.24	○	○
Conventional Example Al-50mmpNi		99.995	-	0.5	50.0	10.0%	20	2.32	62.2	31.6	1.33	○	X

[Table 2]

[Comparative Examples]

	Fe content (wt%)	purity of starting Al (%)	temperature for solutionizing (°C)	wire diameter (mm)	average recrystallized grain diameter (μm)	(average recrystallized grain dia.)/(wire dia.)	Vickers hardness	specific resistance in liquid nitrogen (nΩm)	conductivity (%ACS) (%)	0.2% yield strength (MPa)	(collapse width)/(wire dia.)	chip cracking	thermal shock test
1	0.07	99.999	650	0.5	12.5	2.5%	21	2.98005	63.6	31.6	1.42	○	X
2	0.15	99.999	650	0.5	7.3	1.5%	23	2.9507	63.3	34.7	1.38	○	X
3	2.5	99.999	650	0.5	3.5	0.7%	36	2.95366	63.6	54.1	1.19	X	-
4	0.15	99.995	650	0.5	7.3	1.5%	24	3.00855	63.3	35.5	1.38	○	X
5	2.5	99.995	650	0.5	3.4	0.7%	37	2.99787	63.5	55.2	1.18	X	-
6	0.15	99.99	650	0.5	7.2	1.4%	24	3.03404	63.2	37.8	1.35	○	X
7	2.5	99.99	650	0.5	3.3	0.7%	37	2.9739	63.2	55.0	1.18	X	-
8	0.15	99.9	650	0.5	3.9	0.8%	35	3.86024	61.9	50.3	1.21	X	-
9	0.22	99.9	650	0.5	3.4	0.7%	34	3.93758	60.3	49.0	1.22	X	-
10	0.8	99.9	650	0.5	2.9	0.6%	37	3.91742	60.7	55.3	1.18	X	-

11	1.9	99.9	650	0.5	2.4	0.5%	40	3.93728	60.9%	60.6	1.13	X	-
12	2.5	99.9	650	0.5	2.1	0.4%	43	3.91563	60.5	65.3	1.08	X	-
13	0.15	99.995	550	0.5	7.9	1.6%	24	2.6	64.3	35.1	1.38	O	X
14	2.5	99.995	550	0.5	4.3	0.9%	35	2.58118	63.6	55.1	1.18	X	-
15	0.15	99.995	450	0.5	12.7	2.5%	21	2.27621	64.1	31.8	1.41	O	X
16	0.22	99.995	450	0.5	10.1	2.0%	22	2.30644	64.6	33.2	1.40	O	X
17	0.8	99.995	450	0.5	9.2	1.8%	23	2.26179	64.7	34.7	1.38	O	X
18	1.9	99.995	450	0.5	8.7	1.7%	22	2.23492	65.1	33.0	1.40	O	X
19	2.5	99.995	450	0.5	9.0	1.8%	23	2.20892	65.1	33.8	1.39	O	X
20	0.15	99.995	650	0.5	10.2	2.0%	21	2.27015	65.4	31.5	1.42	O	X
21	0.22	99.995	650	0.5	7.0	1.4%	23	2.28313	65.0	33.9	1.39	O	X
22	0.8	99.995	650	0.5	6.2	1.2%	22	2.28758	64.4	33.3	1.40	O	X
23	1.9	99.995	650	0.5	6.6	1.3%	24	2.31058	64.7	36.0	1.37	O	X
24	2.5	99.995	650	0.5	5.6	1.1%	23	2.22284	65.7	34.3	1.39	O	X
25	0.15	99.995	650	0.3	7.7	2.6%	24	2.92414	63.4	35.7	1.37	O	X
26	2.5	99.995	650	0.3	3.2	1.1%	37	3.0168	63.3	55.9	1.17	X	-
27	0.15	99.995	650	0.1	7.3	7.3%	24	2.97184	62.8	35.9	1.37	O	X
28	2.5	99.995	650	0.1	3.7	3.7%	37	3.03435	63.4	56.1	1.17	X	-

[0033]

The following is the conclusion gained from the comparative study of the wire composition ranges, the conditions for the solution heat treatment and the results of the chip cracking and the thermal shock tests, as shown in Tables 1 and 2 with regard to Examples and Comparative Examples. In the cases of Comparative Examples 9 and 10, the purity of the starting aluminum (Al) was 99.9 mass % (the content of the impurities was 100 mass ppm), and the negative effect of this prevented the bonded wires from obtaining the goals of the present invention, which are improvement in strength through the solution heat treatment to dissolve Fe and prevention of chip cracking through work softening. In the case of Comparative Example 11, in addition to the lowness of the purity of the starting aluminum, the content of Fe exceeds the scope of the present

invention, and as the result Vickers hardness and the ratio of collapse width to wire diameter are such that the hardness is too high and the work softening effect is insufficient – hence chip cracking did occur.

[0034]

Also, although Comparative Examples 16, 17 and 18 could achieve the prevention of chip cracking through work softening, by virtue of the composition being within the scope of the present invention, sufficient solutionizing did not occur since the temperature for the solution heat treatment was so low as 450 degrees C, and hence the strength of the basis metal was insufficient and the result of the thermal shock test was not good.

In the cases of Comparative Examples 15 and 19, the composition of the wires were off the scope of the present invention and similarly as the preceding cases the temperature for the solution heat treatment was so low that solutionizing did not occur and the strength was not improved, so that the result of the thermal shock test was not good, although chip cracking did not occur thanks to the lowness in hardness and strength.

[0035]

In the cases of Comparative Examples 21 and 22, the compositions were within the scope of the present invention so that hardness is low and thus chip cracking did not occur; however, since the cooling after the solution heat treatment was done with cold air so that the solutionizing was not followed by a rapid cooling and consequently the re-dissolving of Fe, which is a feature of the present invention, was not occasioned and thus the strength of the metallic tissue was not sufficient and the result of the thermal shock test was not good.

The cases of Comparative Examples 20 and 24 experienced the similar consequences as the preceding for the reasons that the compositions were off the scope of the present invention and the cooling after the solution heat treatment was conducted by cold air.

[0036]

In the cases of all the other comparative examples, the purity of the starting aluminum (Al), the temperature for the solution heat treatment, and the cooling condition (water cooling) are the same as the present invention, but the alloy compositions are off the scope of the present

invention.

In the cases of comparative examples in which the Fe content was smaller than the scope of the present invention, it was found that the hardness became too low and the ratio of (collapse width)/(wire diameter) was too large so that although chip cracking did not occur, the result of the thermal shock test was not good on account of the insufficient strength.

On the other hand, in the cases of comparative examples in which the Fe content was larger than the scope of the present invention, it was seen that the hardness became too high and the ratio of (collapse width)/(wire diameter) was too small so that chip cracking did occur and the result of the thermal shock test showed that the number of cycles was short of the minimum predetermined threshold number and thus the rating was no good.

From the above results, it is confirmed that the wire of the present invention must have a composition within the specified scope and must undergo the kind of solution heat treatment and the thermal treatment process as specified by the scope of the present invention.

[Possibility of industrial usefulness]

[0037]

The wire of the present invention is useful as a bonding wire for power semiconductor devices which are used in hybrid vehicle, electric vehicle, as well as electric train, wind power generator, and industrial robot for the reason that its shear strength does not undergo much lowering during the repetition of thermal shock test.

[Brief description of drawings]

[0038]

Fig. 1 is a photo showing a sectional tissue of an aluminum alloy wire.

Fig. 2 is a graph showing the variation rate in shear strength of aluminum alloy wires.

Fig. 3 is a photo showing a sectional tissue of a wire having cracks after the thermal cycle test.

[Document name]

Scope of the claims for patent

[Claim 1]

An aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices, said alloy being made of iron (Fe) in an amount of 0.2 – 2.0 mass % and balance aluminum (Al) of a purity of 99.99 mass % or higher, characterized in that some of the iron (Fe) is dissolved in an aluminum (Al) matrix of the aluminum alloy wire in an amount of 0.01 – 0.05 % and that the rest of the iron (Fe) is included in an iron-aluminum (Fe-Al) intermetallic compound particles, which are dispersed in a form of crystal in a fine recrystallization tissue of the matrix tissue of the wire when viewed in a cross section of said aluminum alloy wire after being drawn.

[Claim 2]

The aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices as claimed in Claim 1 characterized in that the iron (Fe) is dissolved in said aluminum (Al) matrix in an amount of 0.02 – 0.05 %.

[Claim 3]

The aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices as claimed in Claim 1 characterized in that said balance aluminum (Al) is of a purity of 99.995 mass % or higher.

[Claim 4]

The aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices as claimed in Claim 1 characterized in that said balance aluminum (Al) is of a purity of 99.998 mass % or higher.

[Claim 5]

The aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices as claimed in Claim 1 characterized in that the diameter of the aluminum alloy wire is 50 – 500 micrometers.

[Claim 6]

The aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices as claimed in Claim 1 characterized in that the

mean particle size of the fine recrystallization tissue is 3.6 – 5.3 micrometers.

[Claim 7]

The aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices as claimed in Claim 1 characterized in that said fine recrystallization tissue is obtained after conducting a cold continuous wire drawing of a drawing rate of 90 % or higher from a preform wire after a solution heat treatment.

[Claim 8]

The aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices as claimed in Claim 1 characterized in that said fine recrystallization tissue is obtained after conducting a cold continuous wire drawing after a solution heat treatment.

[Claim 9]

The aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices as claimed in Claim 1 characterized in that said fine recrystallization tissue is obtained after conducting a solution heat treatment, a cold continuous wire drawing and a conditioning heat treatment in this order.

[Claim 10]

The aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices as claimed in Claim 1 characterized in that said fine recrystallization tissue is obtained after conducting a solution heat treatment, a cold continuous wire drawing and a conditioning heat treatment, which is done at 300 – 500 degrees C for 60 minutes, in this order.

[Claim 11]

The aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices as claimed in Claim 1 characterized in that said aluminum alloy wire has a Vickers hardness of 25 – 40 Hv.

[Claim 12]

The aluminum alloy wire for ultrasonic wave bonding for use in semiconductor devices as claimed in Claim 1 characterized in that the conductivity of the aluminum alloy wire is 62 % or higher by IACS.