

"SEMICONDUCTOR DEVICE AND
METHOD OF MANUFACTURING THE SAME"

The present invention relates to a semiconductor device, and a method of manufacturing such a device, and is more particularly concerned with the provision of a bonding wire for the electrical connection between
5 the bonding pad of a pellet and a conductive portion for external lead-out.

In producing a semiconductor device, a gold (Au) wire is used which electrically connects the aluminum bonding pad of a semiconductor pellet and a base plate
10 such as the base of a lead frame or a ceramic package. Usually, the gold wire is formed with a ball at an end thereof and then subjected to ball bonding by thermo-compression.

Utilizing aluminum as the material of the
15 wire can be considered in order to eliminate the disadvantage of the high cost of gold. It is disclosed in Japanese Laid-open Patent Application No. 51-140567 that a ball may be formed at an end of the aluminum wire by an electric torch or the like, whereupon ball
20 bonding is performed.

The present inventors have discovered the problem that, when ball bonding an aluminum wire, separation of the bonding wire occurs particularly

at an aluminum bonding pad on a pellet, with the result that bondability is reduced. The inventors researches have revealed that a hardness of the ball formed at the end of the aluminum wire has a great influence on the bonding property. As to the relationship between the hardness of the ball and bondability, the inventors have discovered the following:

When the ball formed has become too soft due to annealing, ultrasonic energy fails to act sufficiently on a bonding part when using ultrasonic bonding between the aluminum film of the bonding pad and the ball part of the aluminum wire by way of example. In consequence, a surface of aluminum having an active surface energy state does not occur, so that separation of the bonding wire takes place.

In contrast, when the hardness of the aluminum ball is too high, great stresses arise in a silicon layer or silicon dioxide layer etc. under the aluminum pad on account of the force obtained in the bonding operation. Therefore, bonding damage such as cracks occurs in these layers.

The inventors have also discovered the following as to the relationship of bondability with the hardness of the whole aluminum wire, rather than that of only the ball:

When the hardness of the aluminum wire is too low, the aluminum ball collapses excessively or a capillary wire feed gets clogged with the wire when using bonding equipment, for example an ultrasonic wire bonder.

Conversely, with an aluminum wire whose hardness is too high, it is sometimes the case that the height of a wire loop becomes much greater than the rated value thereof. When, with the intention of preventing this drawback, a back tension is exerted on the wire, the wire fails and breaks.

The inventors have found that the heat treatment conditions of a raw wire, namely the wire as it is formed and not yet subjected to any treatment, have an important relation to the aforementioned problems, and that the loop height of the wire can be restrained within the desired rating by controlling the heat treatment conditions.

According to the present invention there is provided a semiconductor device having a bonding wire which consists of aluminum or aluminum and an alloying substance and is ball-bonded to a metal bonding pad formed on a semiconductor pellet so as to connect the pad and a conductive layer formed outside the semiconductor pellet, the part of the wire ball-bonded to the bonding pad having a Vickers hardness in the range of 30 to 50 before bonding to the pad.

Since the parts involved are very small, by Vickers hardness we refer to a micro-hardness test performed by the Vickers method.

The invention in this aspect provides that the hardness of a ball part is set within an optimum range in the case of ball bonding with a wire that is made of aluminum including an alloying substance, thereby achieving good bondability.

According to the invention in another aspect there is provided a method of manufacturing a semiconductor device having a bonding wire which consists of aluminum or aluminum and an alloying substance and which connects
5 a bonding pad formed on a semiconductor pellet and a conductive layer formed outside the semiconductor pellet, comprising:

- (a) annealing said bonding wire;
- (b) forming into a ball a part of said bonding
10 wire to be connected to said bonding pad and obtaining a Vickers hardness of said ball in the range of 30 to 50; and
- (c) ball-bonding said ball to said bonding pad and connecting the wire to said conductive layer.

15 The invention can provide a technique which can restrain the loop height of a bonding wire within the desired rating thereof, and also a technique which can prevent the occurrence of wire break, thereby increasing the success rate of manufacture. Good bond-
20 ability can be attained by selecting in a specified range the hardness of a ball part which is formed on an aluminum wire or aluminum composition wire.

Embodiments of the invention will now be described by way of example with reference to the
25 accompanying drawings, in which:-

Fig. 1 is a sectional view of a semiconductor device which is one embodiment of the present invention;

Fig. 2 is an enlarged partial sectional view of a wire bonding portion in the semiconductor device of Fig. 1;

Figs. 3 and 4 are explanatory views showing the formation of a ball in an aluminum-based wire and the ultrasonic bonding state thereof, respectively;

Fig. 5 is a graph showing the relationships between on the one hand the Vickers hardness of an aluminum ball and on the other hand, the separation occurrence rate and the bonding damage;

Fig. 6 is a graph showing the relationship between the wire composition and the Vickers hardness;

Fig. 7 is a partial sectional view of another embodiment of the semiconductor device according to the present invention;

Fig. 8 is an enlarged partial sectional view showing a wire loop in the semiconductor device of Fig. 7;

Fig. 9 is a graph showing the relationships between on the one hand the heat treatment temperature of a wire, and on the other hand the broken load and the expansion percentage; and

Fig. 10 is a graph showing the same relationships as in Fig. 9 for another broken wire.

In a semiconductor device of Fig. 1, a pellet 3 of, for example, silicon is mounted on a tab 2 of,

for example a 42 alloy by a bonding layer 4 which is made of, for example, a gold-silicon eutectic or a binder such as silver paste. Fig. 2 shows a bonding pad 5 of aluminum on the pellet 3.

5 A bonding wire 6 is an aluminum-based wire which is made of aluminum or an aluminum composition. This bonding wire 6 is used for electrically connecting the aluminum pad 5 of the pellet 3 to an aluminum layer 14 formed on the inner lead part 7 of a lead 1 of,
10 for example a 42 alloy. After completion of the wire bonding, the pellet 3, bonding wire 6 etc. are encapsulated with a molded plastic resin 8.

 In order to perform the bonding of the bonding wire 6, as illustrated in Fig. 3, in the present
15 embodiment a ball 6a is formed at the end of the wire by electric discharge between the end of the wire 6 which is held by a wire bonder (not shown) and the electrode 9 of the wire bonder. By specifying the material of the wire as described later, the ball 6a
20 has a hardness adapted to the bonding.

 Immediately after the formation of the ball 6a, this ball may be quenched by blowing an inert gas, e.g. argon, against it at a low temperature. In this way, a preferred ball hardness is attained. Whatever
25 composition the wire may have, quenching is one of useful expedients for obtaining a predetermined desired hardness.

Using an ultrasonic bonding tool 10 as shown in Fig. 4 by way of example, the ball 6a is pressed against the aluminum pad 5 on the pellet 3 and is securely bonded thereto by ultrasonic vibrations.

- 5 An Al_2O_3 film produced at the surface of the ball 6a is destroyed during the bonding, and a good wire connection is obtained. When pressed down, the ball 6a forms a bonding part 6b. The bonding part 6b covers the aluminum pad 5 which is exposed through an opening
10 of a final passivation film 13.

- When the hardness of the ball 6a of the aluminum wire 6 is too low, an aluminum surface which has an active surface energy state does not appear, and the separation of the bonding wire from the pad occurs,
15 as described above. On the other hand, when the hardness of the ball 6a is too high, the force applied in the wire bonding operation may give rise to bonding damage e.g. that a silicon dioxide (SiO_2) layer 12 under the aluminum pad 5 is destroyed.

- 20 In order to attain good bonding, accordingly, the hardness of the aluminum ball 6a needs to be set within the optimum range.

- Fig. 5 shows results of experiments on the relationships of the hardness of the aluminum ball
25 part 6a to the occurrence rate (%) of peeling between

23

the bonding wire 6 and the aluminum pad 5 and to the occurrence rate (%) of bonding damage in which the silicon dioxide layer 12 under the aluminum pad 5 cracks. It can be seen from Fig. 5 that, when it is taken into account that a value permissible as the occurrence rate of inferior bonding is about 10%, the peeling occurrence rate (indicated by the solid line) is high at a Vickers hardness of below about 30, and the bonding damage occurrence rate (indicated by the broken line) is high at a Vickers hardness of above about 50. Especially preferred is the range of Vickers hardnesses of 35-42.

Fig. 6 shows results of a large number of experiments performed under the same conditions in order to obtain the composition of the material of a wire which can provide Vickers hardness within these optimum ranges.

In Fig. 6, the ordinate represents the Vickers hardness, while the abscissa represents the compositions of various materials. The Vickers hardness of each material is indicated by the bar height, for example, the value for Au is 40. In addition, "1 % Si - Al" indicates a wire which is made of Al containing 1 weight-% of Si, and "Au" indicates a wire which is made of 100 % Au.

Fig. 6 shows that, with a wire of a composition of aluminum containing 2 weight-% of silicon (2 % Si - Al) or a wire of a composition of aluminum containing 1.5 - 2 weight-% of magnesium (1.5 - 2 % Mg - Al),
5 a wire having Vickers hardness of 35-42 is obtained, so good aluminum ball bonding is possible.

As materials of which wire having Vickers hardness of about 30 - 50 is produced, there can be mentioned aluminum containing any of 0.5 weight-% of
10 magnesium, 1 weight-% of magnesium and 2 weight-% of palladium. Even with these materials, wire of low bonding failure rate illustrated in Fig. 5 can be obtained.

The hardness of the whole wire affects the bondability and the wire loop shape, as well as the
15 hardness of the ball discussed above.

The control of the shape of a wire loop becomes most important in a thin semiconductor device, for example a device for a timepiece, as shown in Figs. 7 and 8. A silicon pellet 3 is mounted in a recess
20 in a base 11 made of an insulating material such as glass epoxy, by a binding material 4, for example a silver (Ag) paste or gold - silicon (Au - Si) eutectic.

An aluminum bonding pad 5 on the pellet 3 and an electrically conductive layer 16 made of copper
25 or the like and arranged on the base 11 and around the cavity opposite the pellet are electrically connected

by a bonding wire 6 which is made of for example aluminum or an aluminum composition or gold. The conductive layer 16 is an external terminal for electrically connecting the pellet 3 to the exterior.

5 The part of the bonding wire 6 connected to the bonding pad 5 is subjected to ball bonding. After a ball 6a is formed in the manner shown in Fig. 3, it is bonded to the bonding pad 5 by the method shown in Fig. 4, whereby a bonding part 6b is formed.

10 The pellet 3 and the several wires 6 are encapsulated in a sealing member 15 by potting or molding a resin, for example a polyimide resin or epoxy resin, or a like process.

 Especially in a thin semiconductor device,
15 it is very important that the loop height of the bonding wire 6 is maintained at a fixed stable height within the desired rating thereof when the wire 6 is laid by a wire bonder (not shown). As stated above, a favourable loop height is not attained when the hardness
20 of the wire 6 is too high or too low.

 The inventors have found, by experimental researches, that the wire loop height can be optimally controlled by heat-treating the wire 6 under specified temperature conditions within a continuous annealing
25 furnace (not shown) before the wire bonding of the wire 6. Further, it has been found that the wire loop

height can be optimally controlled by recrystallizing the wire 6 when the wire once softened by the heat treatment is cooled and hardened again.

Fig. 9 shows the relationships of the heat treatment (annealing) temperature to the broken load and the expansion percentage for a wire having a diameter of 30 μ m and made of aluminum containing 1 weight-% of silicon (1 % Si - Al). The annealing was performed by moving a semiconductor device at a speed of 40 cm/min. in the annealing furnace held at a fixed temperature.

In Fig. 9, the abscissa represents the annealing temperature ($^{\circ}$ C), and the ordinate represents the broken load (gr.) of the wire and the expansion percentage (%) thereof. The solid and broken curves show the tensile load (g) at the rupture of a wire in dependence on annealing temperatures and the maximum expansion (elongation) percentage (%) of the wire before the rupture, respectively.

A wire giving a favourable wire loop height performance can be obtained by heat-treating the wire in a temperature range which is higher than the recrystallization starting temperature of the wire, namely the lowest temperature T_a permitting the recrystallization, and is not higher than a temperature T_b of maximum expansion percentage, i.e. in the range indicated by L_1 in Fig. 9 (about 400 - 470 $^{\circ}$ C). In this example

the recrystallization starting temperature T_a is a point of inflexion, and is about 400°C in the case of Fig. 9.

A wire annealed at a temperature above the
5 recrystallization starting temperature T_a , in other words a recrystallized wire, provides a good loop shape. The reason will be that the tension in the wire acts on the whole wire and is absorbed uniformly.

For a wire annealed at a temperature below
10 the recrystallization starting temperature T_a , particularly the wire annealed at a temperature in a range in which the expansion percentage curve exhibits a constant value, the loop shape is unfavourable because the height from the bonding plane is too low. Such
15 wire has a high broken load and has a high strength, but is liable to break for the following reason.

The size of the crystal grain of the wire changes abruptly near the ball 6a. The bonding part 6b, the ball 6a, and a part of the wire over a height
20 2 - 3 times as great as the height of the ball 6a from the bonding plane are heated to a temperature of 500°C - 600°C when forming the ball 6a. This temperature is higher than the recrystallization starting temperature of aluminum wire of any composition. Therefore, in
25 this temperature region the recrystallization of the aluminum is promoted and a grain diameter of several



tens μm is obtained. One grain can occupy a section of the wire having a diameter of 30 μm . On the other hand, the aluminum outside these regions undergoes only temperatures lower than the recrystallization starting temperature T_a . Accordingly, the grain size of the aluminum remains unchanged from that of the raw wire formed by drawing the ingot of aluminum, and the grain diameter is not greater than 1 μm .

The wire extending away from the ball 6a upright substantially vertically is subjected to a lateral tension to form the loop. This tension concentrates on the part of the wire at which the grain diameter changes abruptly, namely the part at a height is 2-3 times greater than the height of the ball 6a from the bonding pad 5. In consequence, the wire breaks.

Furthermore, even with annealing at a temperature above the recrystallization starting temperature T_a , a wire annealed at a temperature above the temperature T_b of maximum elongation percentage of the wire is not favourable. Since the whole wire is soft or the elongation percentage is great, the wire loop shape approximates the path of movement of the bonding tool. Therefore, the maximum height of the loop from the bonding pad 5, which is usually 200-300 μm , becomes as great as 600-700 μm .

A wire annealed above the temperature T_a and below the temperature T_b is difficult to break, and can provide a proper loop height. The grain diameter of aluminum becomes several μm , for example, 5 μm in
5 the whole wire. Furthermore, the grain diameter decreases gradually, not abruptly, from the part having a grain diameter of several tens μm .

The annealing described above needs to be carried out before performing the wire bonding, preferably
10 before the wire is loaded on the spool of the wire bonder or the like.

The recrystallization starting temperature T_a and the temperature T_b of maximum expansion (elongation) percentage differ, depending upon the wire materials.

15 Fig. 10 shows the relationships of the heat treatment temperature to the broken load and the expansion percentage for various wires subjected to continuous annealing treatments (at 40 cm/min.) as in the case of Fig. 9. In Fig. 10, the abscissa and the ordinate
20 represent the same quantities as in Fig. 9, and again solid lines and broken lines indicate the broken load and the expansion percentage, respectively.

The solid line a and the broken line a relate to a wire of aluminum containing 1.5 weight-% of
25 magnesium (1.5% Mg - Al), the solid line b and the broken line b to a wire of aluminum containing 2.9 weight-%

of magnesium (2.9% Mg - Al), and the solid line c and the broken line c to a wire of aluminum containing 4.9 weight-% of magnesium (4.9% Mg - Al). The diameters of all these wires is 30 μ m.

5 Similarly to the example illustrated in Fig. 9, the range L_2 of optimum annealing temperatures can be set for the wire of 1.5% Mg - Al. In this case, $T_a \approx 300^\circ\text{C}$ and $T_b \approx 400^\circ\text{C}$. With this wire, besides the favourable wire loop shape, ball bonding better
10 than with the wire illustrated in Fig. 9 is possible, because as Fig. 6 shows, this wire can provide the optimum hardness of the ball. It is therefore possible to prevent bonding defects such as the separation of the bonding wire and the cracks due to the bonding.

15 With the wire of 2.9% Mg - Al, the desired temperature range of annealing becomes 300°C - 420°C while the loop shape is good and the wire strength is held at or above a certain value. In this case, however, the hardness of the wire is high, and hence
20 results as good as that of the 1.5% Mg - Al wire are not attained. For the wire of 4.9% Mg - Al, a temperature range of annealing as wide as several tens $^\circ\text{C}$ cannot be set.

 When possible, however, a wire having the
25 favourable loop height property can be produced by

conducting the heat treatment in the temperature range (indicated by L_2 in Fig. 10) higher than the recrystallization starting temperature of the wire material and not higher than the temperature of maximum expansion percentage. That is to say, the loop shape of the wire can be controlled by recrystallizing the wire.

The embodiments described above can provide the following results:

Since bonding is carried out with a wire of aluminum or an aluminum composition, a sharp reduction in cost can be achieved, as compared with the use of gold.

By selecting the hardness of the ball in a specified range, the bonding property and the bonding strength of an aluminum wire can be remarkably enhanced.

By specifying a wire composition, a good bonding property can be stably attained.

By quenching a wire after forming its end with a ball, a ball having a predetermined hardness is obtained, so that favourable wire bonding can be performed.

The loop shape of a wire can be controlled well if the wire softened by heat treatment is recrystallized before wire bonding.

The loop height of a wire can be the optimum height if the wire is heat-treated in a temperature

range higher than the recrystallization starting temperature of the wire and not higher than a temperature maximizing the expansion percentage of the wire.

Particularly when the wire is an aluminum
 5 wire containing 1 weight-% of silicon or 1.5 weight-% of magnesium, a favourable loop height within the rating of the loop height can be attained.

Due to the control of a wire loop shape achievable by virtue of the heat treatment, the
 10 occurrence of a flaw of a wire due to a back tension is preventable, rupture etc. of the wire is preventable, and an inferior external appearance ascribable to an improper wire loop is preventable.

By specifying a wire composition, a ball
 15 of a hardness suited to bonding can be formed, and moreover, a wire loop height can be rendered the optimum value.

When the heat treatment is conducted at a specified temperature for a particular wire so as to
 20 render the hardness of the ball of the wire suitable for bonding, high bondability and good loop shape can be realized.

The present invention is not restricted to the foregoing particularly described embodiments.

25 For example, the material of the wire may be different from those mentioned ^{above.} ~~before, and the wire~~

~~may well be an Au wire etc. besides the Al based wire.~~

The preferred hardness of the ball can be attained by gradual cooling after the formation of the aluminum ball, not by quenching based on air cooling.

5 In addition, a favourable bonding property can be attained by varying the thickness of the aluminum film of the aluminum pad.

In the above, the invention has been principally described with application to a resin-molded semiconductor
10 device made by ball bonding of aluminum-based wires by ultrasonic bonding, but it is not restricted to this application. The invention is extensively applicable to thermocompression and other various bonding systems, as well as to ultrasonic bonding. It is applicable
15 to other semiconductor devices as well as the resin-molded type; generally the invention is applicable to any semiconductor device in which, at least, a semiconductor pellet and an external terminal for connecting this pellet and the exterior are connected by a wire.

CLAIMS

1. A semiconductor device having a bonding wire which consists of aluminum or aluminum and an alloying substance and is ball-bonded to a metal bonding pad formed on a semiconductor pellet so as to connect the
5 pad and a conductive layer formed outside the semiconductor pellet, the part of the wire ball-bonded to the bonding pad having a Vickers hardness in the range of 30 to 50 before bonding to the pad.
2. A semiconductor device according to claim
10 1, wherein there is an insulating film between the bonding pad and the semiconductor pellet.
3. A semiconductor device according to claim 1 or claim 2 wherein the Vickers hardness of the said part of the wire connected to the bonding pad is in
15 the range 35 to 42 before bonding to the pad.
4. A semiconductor device according to any one of claims 1 to 3, wherein said wire contains as alloying substance magnesium.
5. A semiconductor device according to claim
20 4 wherein the magnesium content is in the range 1.5 to 2 weight-%.
6. A semiconductor device according to any one of claims 1 to 4, wherein said wire contains as alloying substance silicon.



7. A semiconductor device according to claim 6, wherein the silicon content is about 2 weight-%.
8. A semiconductor device according to any one of the preceding claims wherein the wire composition is uniform.
9. A semiconductor device according to any one of the preceding claims wherein the said conductive layer is made of metal different from that of the bonding pad.
- 10 10. A semiconductor device according to any one of the preceding claims wherein the bonding pad is made of aluminum or an alloy thereof.
11. A semiconductor device according to any one of the preceding claims having a resin encapsulation enclosing the semiconductor pellet and the whole of the bonding wire.
12. A semiconductor device substantially as any such device herein described with reference to and as shown in the accompanying drawings.
- 20 13. A method of manufacturing a semiconductor device having a bonding wire which consists of aluminum or aluminum and an alloying substance and which connects a bonding pad formed on a semiconductor pellet and a conductive layer formed outside the semiconductor pellet, comprising:
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(a) annealing said bonding wire;
(b) forming into a ball a part of said bonding wire to be connected to said bonding pad and obtaining a Vickers hardness of said ball in the range of 30 to 50; and

(c) ball-bonding said ball to said bonding pad and connecting the wire to said conductive layer.

14. A method according to claim 13 wherein a Vickers hardness of said ball in the range 35 to 42 is obtained, before the bonding of the ball to the pad.

15. A method according to claim 13 or claim 14 wherein the annealing is performed at a temperature higher than the recrystallization starting temperature of said bonding wire and lower than the temperature of maximum elongation percentage of said bonding wire.

16. A method according to any one of claims 13 to 15 wherein said wire contains as alloying substance magnesium.

17. A method according to claim 16 wherein the magnesium content is in the range of about 1.5 weight-% to 2.9 weight-% and the annealing temperature is about 300°C to 420°C.

18. A method according to any one of claims 13 to 15 wherein said wire contains as alloying substance silicon.



19. A method according to claim 18, wherein the silicon content is about 1 weight-%, and the annealing temperature is in the range of about 400°C to 470°C.

20. A method according to any one of claims 13 to 19 wherein the ball is formed by an electrical discharge between the wire and an electrode.

21. A method according to any one of claims 13 to 20, wherein the ball is cooled by blowing a gas against it, prior to bonding of the ball to the bonding pad.



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