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50 μm Fine Pitch Ball Bonding Technology

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Abstract

Importance of fine pitch bonding technology for high-density assembly of semiconductor devices is increasing in the background of rapidly advancing downsizing and performance enhancement of the devices. Presently, the wire bonding method is dominant as a method of electric interconnection between pad electrodes on Si chip and external electrodes, wherein demands are increasing for connection in narrower pitches between adjacent wires. 70 μm-pitch bonding has been applied to mass-produced devices and 40 μm-pitch bonding is expected to come to commercial use by 2005. This paper describes technology developments of 50 μm-pitch bonding involving high strength thin bonding wire, optimum relationship between the capillary shape and ball diameter, optimization of bonding conditions, etc.

1. Introduction

With the advent of the full-fledged multimedia age in recent years, the high performance and the downsizing of cellular phones, notebook personal computers, and other electronic equipment are truly phenomenal. Semiconductor devices have increasingly higher standards to meet for higher density and integration. Semiconductor package structures have been increasing in diversity and functionality on a yearly basis. For example, smaller and thinner packages, higher pin counts, and higher interconnect density are always in demand. Fine-pitch bonding technology is an important technological issue to meet demands for more pins, finer lead pitch, and finer pad electrode pitch .

An example of internal structure of an LSI package is shown in **Fig. 1**. Semiconductor device interconnections and pads are formed by aluminum alloy films of about 1 μm thickness. Wire bonding is a mainstream process for connecting the pads to external terminals, and gold wires, 18 to 40 μm in diameter, are the most popular bonding wire materials. The end of gold wire is melted by an arc discharge and formed into a ball. This ball is thermo-compression bonded to an aluminum pad while applying ultrasonic vibration, using a cylindrical tool called the capillary. The wire-bonded IC is molded with epoxy resin for protection from the external environment.

As far as package structures are concerned, the quad-flat package (QFP) that uses conventional lead frames has increased in pin count and decreased in thickness, and the ball grid array (BGA) in which the semiconductor chip is mounted on a resin or tape substrate, the chip scale package (CSP) has started to be utilized. Wire bonding is most commonly used for connecting chips to substrates in these new packages. The new packages have increased the demand for fine-pitch wire bonding.

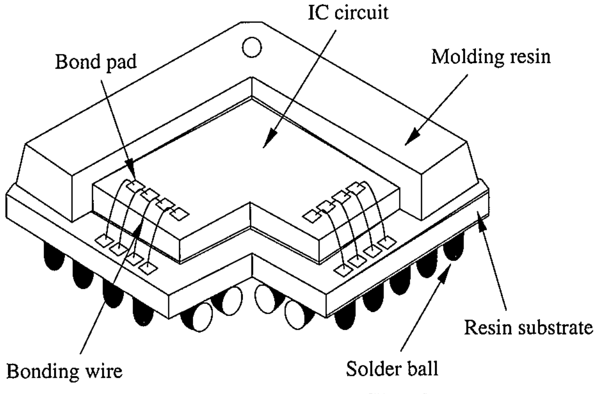

Fig. 1 Internal structure of LSI package

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According to the 2000 roadmap of the Semiconductor Industry Association (SIA) of the United States about wire bonding technology, the pad pitch is predicted to decrease from the present mainstream pitch of 70 μm and to reach the 40 μm pitch in 2005. Now that the mass production of the 60 μm pitch has started, it is urgent to establish early 50 μm pitch wire bonding technology.

This article organizes wire bond problems with finer-pitch wire bonding and mainly reports on the selection and optimization of high-strength wires, capillaries, wire bonding conditions, and high-temperature reliability required to achieve the 50 μm pitch interconnects.

2. Problems with Fine-Pitch Wire Bonding

In semiconductor packaging, the limit to the reduction in the pitch of wire bonding is partly recognized, and the tape automated bonding (TAB) process that uses metal bumps suited for finer-pitch interconnections and the flip chip (FC) process are put to practical use. The wire bonding technology that excels in productivity, interconnect freedom, and reliability has ever increasing requirements to meet. Coupled with the ongoing development of lead frames, substrates, capillaries, and bonders, the development of finer-pitch wire bonding materials and methods is strongly demanded. The environment surrounding the wire bonding technology is changing, for example, with an increase in the frequency of ultrasonic vibration to increase bondability, use of a bottleneck capillary suited for finer-pitch wire bonding, reduction in the wire length by reduction in the size of inner lead to restrain the wire sweep during resin molding, and study of molding resins to improve flowability.

For the wire bonding technology to accomplish a finer pitch, it is important to realize finer wire, smaller balls, smaller bond area, less wire sweep, and higher bond reliability. To meet these requirements, there are many problems that cannot be solved by simply reducing the wire diameter, ball diameter, and capillary size, and it is necessary to arrange the technical issues of fine-pitch wire bonding. First, it is desirable to develop bonding wire with such strength and elastic modulus that when reduced in diameter, it does not contact the adjacent wires during resin molding. Second, it is indispensable to search for such wire bonding technology as to be able to simultaneously make both the bonded ball smaller and the bond stronger , prevent each wire from contact with the adjacent wires, and provide sufficient strength. Third, it is important to reduce the bond area, achieve low-temperature bonding on the resin substrate, and provide bonds with sufficient long-term reliability in a severe environment where the amount of IC heat generation is increased by higher frequency, for example.

To date, 70 and 60 μm pitch wire bonding methods have been reported[1]. With conventional relatively coarse-pitch interconnections, there has been relative leeway in capillary tip machining, wire diameter, and optimum wire bonding condition range, so that many applications have been addressable by experiential selection of wire bonding conditions. Mass production and reliability of 50 μm pitch interconnections are difficult, however, to achieve with the combination of latest wire bonding materials, equipment, and conditions, based on the conventional fine-pitch design criteria. Especially with small-ball bonding, it is all the more difficult to accomplish a smaller bond area and a stronger bond at the same time. To improve this situation, it is necessary to clarify the optimum relations between the surface condition, hardness, and structure of the ball and pad, among other things, and to optimize the capillary design and bonding conditions to make the best of these material properties to their fullest extent. It is important to establish the 50 μm pitch interconnection technology and clarify the considerations about micro-ball bonding.

3. High-Strength Fine Wire

In response to diversifying package structures, bonding wire has requirements of increasing severity to meet for longer length, lower loop height, smaller diameter, and higher reliability. Conventional wire quality was based on the high purity 4N (> 99.99%), and wire properties were mainly improved by adding trace elements of 100 ppm or less and optimizing fabrication technology. To satisfy the requirements for higher strength, smaller diameter, and higher bond reliability, alloy wire with elements added to 2N (> 99%) in excess of the 4N region has been developed and commercially used in some packages in recent years.

The NT series developed as 4N high-strength fine wire is high in strength and elastic modulus, and is advantageous in precluding the wire loop deformation and reducing the wire diameter. **Fig. 2** shows the relationship between the breaking load and diameter of representative wire products, including NT5 compatible with 50 μm pitch interconnections. The NT5 wire features strength about 30% higher than that of the conventional T1 wire and can be reduced in diameter by about 2 μm while maintaining the same strength. Despite its higher strength, the NT5 wire provides bondability, loop controllability, and electric conductivity equivalent to those of the conventional T1 wire, and can offer excellent mass producibility using latest high-speed wire bonders.

Fig. 3 shows a SEM micrograph of a free air ball (FAB) formed

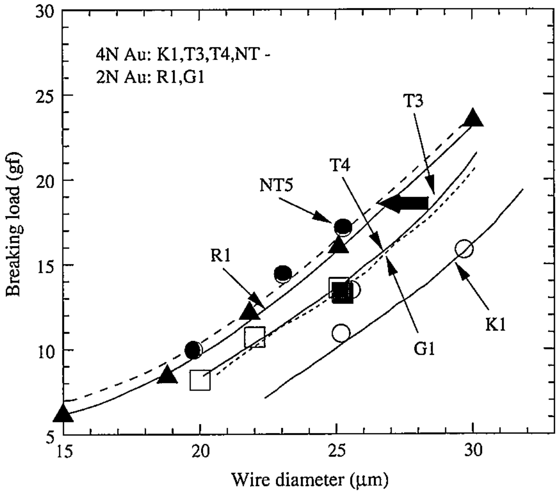


Fig. 2 Strength of bonding wire products

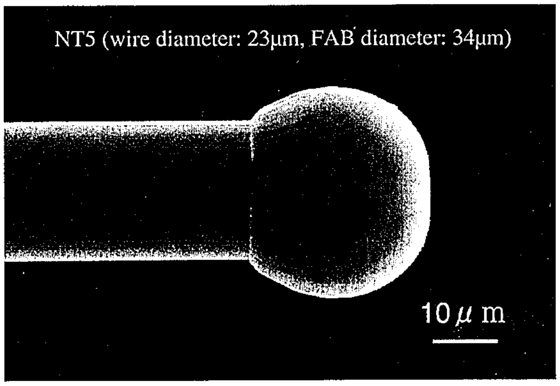


Fig. 3 SEM micrograph of ball formed at end of wire

at the end of NT5 wire (wire diameter of 23 μm and ball diameter of 34 μm). Elements added to obtain higher strength are feared to cause oxidation during ball melting or adversely affect the solidification structure, giving rise to such problems as shrinkage cavity formation and sphericity deterioration. The NT5 wire is free from such problems and allows good conditions, such as stable sphericity and high surface cleanliness, to be obtained with balls whose diameter is not more than 1.5 times the wire diameter.

Fig. 4 shows the cross-sectional microstructures of balls and heat-affected zone (HAZ). When the NT5 and T1 wires are compared, the HAZ length is about 40 and 70 μm for the NT5 and T1 wires, respectively, and the HAZ grain size is slightly smaller for the NT5 wire. The HAZ length is related to the loop height just above the ball. This means that the NT5 wire is suited for lower loop height. Usually, the strength of the HAZ is lower than that of the wire, so that when a loop is formed, tilt or damage in the HAZ becomes a problem. When tested for tensile fracture strength in the HAZ portion, the NT5 wire was confirmed to have about 10% higher strength than that of the T1 wire. Because HAZ damage and contact with adjacent wires are prevented by HAZ grain reduction and HAZ strength increase, the NT5 wire can be appropriately used for making fine-pitch interconnections.

Fig. 5 shows a general view of wire bonds formed at a fine pitch of 50 μm using NT5 wire with a diameter of 23 μm. Good ball bond shape, necks without contact with adjacent wires, proper loop shape, and good linearity were obtained. The wire sweep during resin molding was reduced for the NT5 wire to a smaller degree than observed for conventional gold wires.

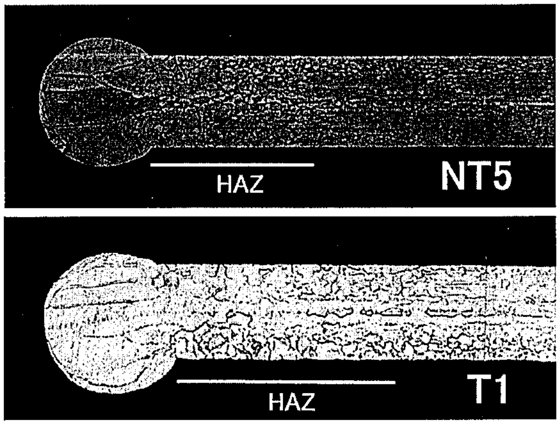


Fig. 4 Microstructures of wire ball and heat-affected zone (HAZ) (wire diameter: 23 μm, FAB diameter: 34 μm)

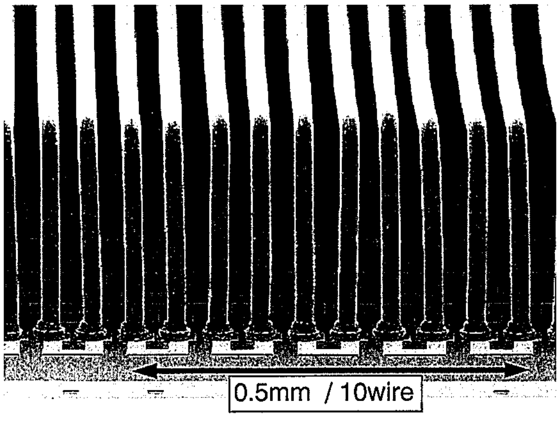


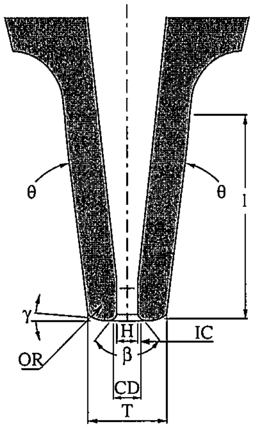
Fig. 5 SEM micrograph of 50 μm fine-pitch wire bonds (wire diameter: 23 μm, wire length: Approx. 5 mm)

4. Selection of Capillary for Fine-Pitch Interconnections

The capillary has an important role to play in the fine-pitch interconnection technology as it guides the wire and is closely related to the shape of the compressed ball of the first bond and the loop profile, among other things. **Fig. 6** illustrates an example of bottleneck capillary narrowing toward the tip. Tip shape, micro-fabrication, durability, and other characteristics are required of the capillary to make the fine-pitch interconnections. To make effective use of high-strength fine wire, it is imperative to select a capillary suited to the wire diameter, quality, and characteristics.

Table 1 lists the wire diameter, free air ball or FAB diameter, bonded ball diameter, and recommended values of representative capillary shape parameters suitable for each pad pitch. Optimum values are determined after fully considering the geometrical relations between the wire and capillary, the capacity of the wire bonder, and the reliability of wire bonding.

The setup criteria to be satisfied at least are stable FAB formation and ball deformation, sufficiently high bond strength without the ball bond protruding from the pad opening and ball bond formation without the capillary coming into contact with the adjacent wire and ball. For the 50 μm pitch in the table, two wire diameters of 23 and 20 μm are studied. Some of the reasons are that W = 23 μm is



Symbol	Name	Dimension*
H	Ball diameter	28 μm
CD	Chamfer diameter	33 μm
T	Tip diameter	65 μm
θ	Bottleneck angle	10°
γ	Face angle	11°
β	Chamfer angle	90°

*Used in this experimental study

Fig. 6 Capillary tip shape and dimensions of capillary used

Table 1 Wire and capillary dimensions and shapes suited for fine-pitch interconnections

Bond pad pitch (μm)	80	70	60	50		45	40
Wire							
Wire diameter (μm)	27	25	25	23	20	20	20
FAB diameter (μm)	55	48	36	34	32	30	27
Bonded ball diameter (μm)	60	55	47	42	38	35	32
Capillary tip geometry							
Tip diameter T (μm)	110	95	75	65	65	56	48
Hole diameter H (μm)	38	33	30	28	25	26	24
Chamfer diameter CD (μm)	50	45	35	33	31	29	26

more effective in preventing the wire sweep during resin molding and that W = 20 μm facilitates stable FAB formation and affords an appropriate margin during mass production. Recommended conditions based on the present wire bonding technology are also given for the next-generation target or 45 μm ultra-fine-pitch wire bonding. This comprehensive finer-pitch interconnect approach is important in promoting the acceptance of developed wire and bonding technology.

5. 50 μm Pitch Wire Bonding Technology

If the bond area gets larger to increase the bond strength in fine-pitch interconnections, the possibility of the ball bond coming into contact with the adjacent ball bond increases. When ball bonds are formed at a pitch of 50 μm, they sometimes come within 3 to 5 μm of each other. In such a case, average bonded ball diameter control is not enough, and the control must be exercised over the deformation variability of individual balls as well. Since it is difficult to eliminate this variability, however, it is desirable that the ball deformation should be made as isotropic as possible. This deformation behavior cannot be properly controlled simply by adjusting the FAB dimensions, bonding load, and ultrasonic vibration individually. It is important to optimize the wire bonding conditions after understanding the relationship between the complicated shape parameters of the capillary tip and the ball deformation behavior. An example is introduced below.

Fig.7 shows the changes in the bonded ball diameter and height of ball bonds formed at the end of 23 μm diameter wire. A K&S Model 8028 was used as the wire bonder. It is a normal change that the bonded ball diameter along the vertical axis increases as the ultrasonic output along the horizontal axis increases. When average FAB diameters of 34 and 33 μm are compared, the smaller 33 μm FAB provides larger bonded ball diameter and smaller bonded ball height. This is opposed to the frequently observed change that the bonded ball diameter decreases with decreasing FAB diameter. The 33 μm FAB is conspicuous as to deformation anisotropy and is confirmed to produce irregular ball deformation in random directions. This random deformation is presumed to be closely related especially to the magnitude relationship between the chamfer diameter, a principal capillary dimension, and the FAB diameter.

Fig. 8 shows the ball deformation behavior as classified by the magnitude relationship between the FAB diameter and the CD dimension. Depending on whether FAB is greater or smaller than CD, the ball deformation balance greatly changes between the capillary hole and periphery, which in turn is considered to make the ball deformation behavior different.

When FAB > CD, the ball deformation mainly occurs outside of the capillary hole. As a result of this essential bonding behavior, the ball is isotropically deformed. When FAB < CD, most of the ball deformation occurs inside the capillary hole and chamfer. The portion of the ball deformed in the periphery of the capillary is reduced in volume and subjected to the same load as peripheral part of the ball outside the capillary, increasing the bonded ball diameter. Consequently, the deformation anisotropy of the ball composed of many crystal grains is considered to be promoted. The dimension CD of the capillary used in the experimental study shown in Fig. 7 is nominally 33 μm. When FAB = 34 μm, the relation FAB > CD is always satisfied. When FAB = 33 μm, the relation FAB < CD is likely to hold in the vicinity of the lower limit of FAB.

This deformation anisotropy was traditionally considered to be greatly influenced by the wire material properties, bonding load, and ultrasonic conditions, among other things. Although these effects were confirmed, it was also made clear that the deformation anisotropy of the bonded balls also depends on the optimum relationship between the FAB diameter and the chamfer diameter of the capillary. This dimensional relationship is reflected in the finer-pitch design of Table 1.

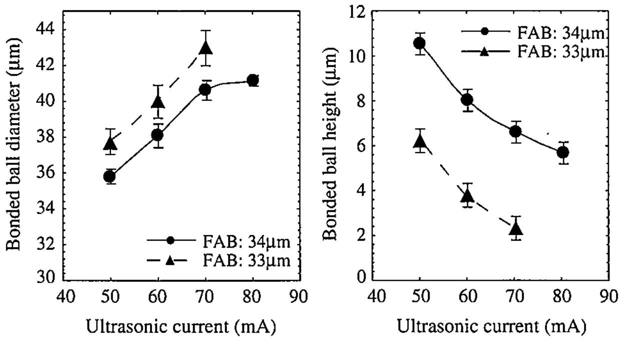


Fig. 7 Changes in bonded ball diameter and height (wire: NT5, wire diameter: 23 μm)

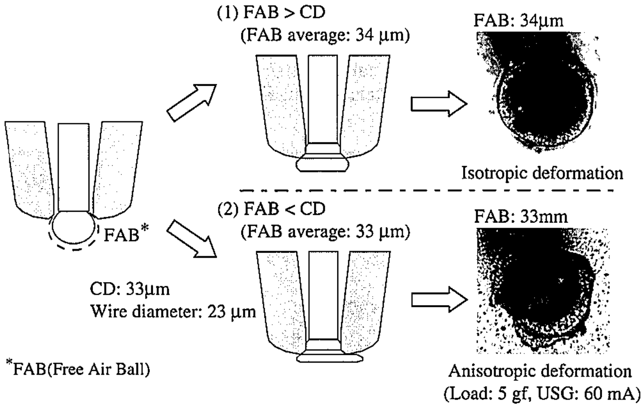


Fig. 8 Relationship between FAB diameter and capillary shape for fine-pitch interconnections

6. Reliability of Au/Al Bonds

The long-term reliability of the bonds between gold wire and aluminum pad is another important property required of gold wire bonding. Still higher bond reliability has been demanded with decreasing bond area, increasing IC heat generation, and increasing IC operating temperature in recent years. Decrease in the strength of Au/Al bonds after heating at high temperatures and increase in their electric resistance have been traditionally feared to cause semiconductor failures. The results of research by the authors indicate that the bond reliability is mainly reduced by void formation at the bond interface[2, 3] and by corrosion reaction between intermetallic compounds and molding resin components[4]. This reliability depends on many factors, such as the materials, bonding conditions, interface conditions, package strucure, and operating environment. It is important to clarify the considerations about improving the reliability of finer-pitch bonds.

Au wire/Al pad bonds were heated in nitrogen at 473K and then pulled upward. The pull strength values thus measured are shown in **Fig. 9**. The comparison is made at the ultrasonic currents P of 50 and 70 mA. When P = 70 mA, the ball shear strength did not drop even after heating. When P = 50 mA, the ball shear strength declined. The

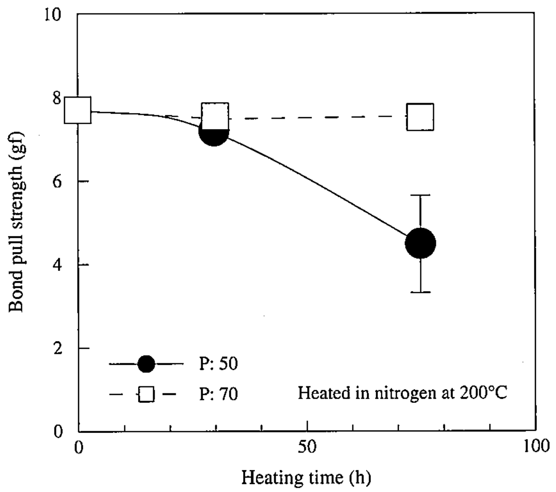
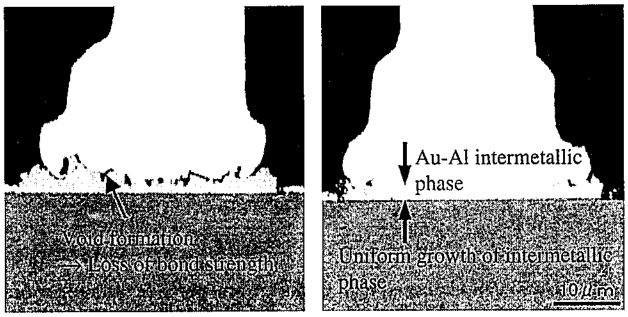


Fig. 9 Change in ball pull strength with heating (wire diameter: 23 μm, FAB diameter: 34 μm)



(a) Low ultrasonic output **(b) High ultrasonic output**

Fig. 10 Cross-sectional observation of ball after heating at 200°C for 75 h (wire diameter: 23 μm, FAB diameter: 34 μm)

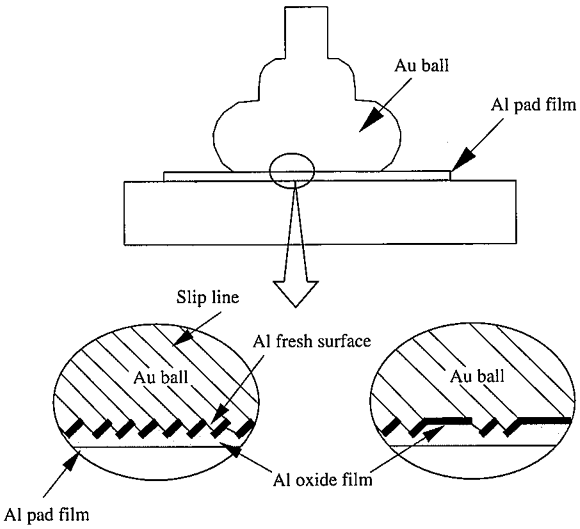


Fig. 11 Schematic of Au wire/Al pad bond interface

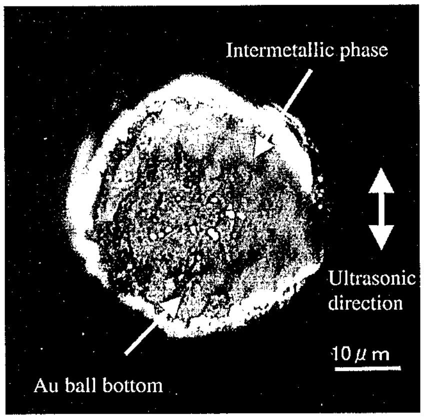


Fig. 12 Bottom view of ball after bonding (wire: NT5, FAB diameter: 34 μm)

cross-sectional views of bonds heated at 473K for 75 h are shown in **Fig. 10**. The Au-Al intermetallic compound non-uniformly grew and led to the formation of voids in the bond made with the ultrasonic current P of 50 mA as shown in Fig. 10 (a). In the bond made with the ultrasonic current P of 70 mA, the Au-Al intermetallic compound uniformly grew throughout the interface, and no voids formed as shown in Fig. 10 (b).

Void formation in Au/Al bonds is attributable to the Kirkendall effect due to the difference in diffusion rate between Au and Al atoms and is closely related to the growth behavior of the Au/Al intermetallic compound phase. According to the analysis of intermetallic phases growing in the Au/Al bond, Au_5Al_2 is the phase that grows preferentially in the initial stage and changes to the gold-rich phase Au_4Al after disappearance of the Al pad beneath the bond. With conventional broad pitch wire bonding, it is made clear that Au-Al intermetallic growth does not always lead to void formation but that when the Au-Al intermetallics grow non-uniformly, void formation is promoted to reduce the bond strength[2)].

The probable reason why the Au-Al intermetallic compound phase growth in the local region of the Au/Al bond interface was inhibited is the presence of Al surface oxide film and contaminant layer at the bond interface. The microstructure of the Au/Al bond immediately after wire bonding is schematically illustrated in **Fig. 11**. Usually, the Al surface oxide film is finely destroyed and dispersed by the bonding load and ultrasonic vibration. As a result, fresh Al surfaces are exposed to ensure a satisfactory Au/Al bond. When the oxide film is not fully destroyed and continuously remains at the Au/Al interface, this oxide film is considered to act as barrier against the interdiffusion of Au and Al atoms[3)].

Effective measures against this Kirkendall voiding are optimization of wire bonding conditions to fully destroy the aluminum oxide film and heating to promote the uniform growth of Au-Al intermetallic compounds. In the former case, if the Al oxide film is finely and uniformly dispersed by the load and ultrasonic vibration applied during bonding, the uniform growth of the Au-Al intermetallics is promoted in the next heating step. In the latter case, heating in a vacuum, for example, is found to encourage the uniform growth of the Au-Al intermetallics and hence to reduce the void formation.

As the bond area decreases, the proportion of the capillary hole area that does not come into direct contact with the ball increases to retard the growth of the Au-Al intermetallic phase in the central region. **Fig. 12** shows the bottom surface of a 50 μm pitch ball with the Al film removed by etching. The intermetallics are grown virtually throughout the interface, and spotty intermetallic growth is not recognized as initially feared. It is necessary to search for wire bonding conditions to promote the destruction of the Al oxide film and the diffusion of Au and Al atoms at the bond interface by considering the compression deformability of the ball and the surface condition and hardness of the bond pad material.

Besides the non-uniform intermetallic growth behavior discussed above, the addition of doping elements to the gold wire is another possible cause of void formation at the Au/Al bond. For instance, it is confirmed that a large addition of palladium (Pd) accelerates void formation and that the addition of silver (Ag) induces the growth of the intermetallic compound phase $AuAl_2$, which does not otherwise form, and reduces the bond strength[5]. In the development of wire for fine-pitch bonding, doping is important in increasing the wire strength, but material design must be conducted by ascertaining the effect of the dopants on the diffusion behavior at the bond. With the NT5 wire, it is confirmed that the formation of voids due to material causes is inhibited to provide long-term reliability equivalent to that of the commercial 4N wire.

7. Summary and Future Issues

The fine-pitch wire bonding technology that supports the latest semiconductor packages has been evaluated mainly for ball bondability and long-term reliability in 50 μm pitch interconnections. Adaptability to the 50 μm pitch interconnections has been confirmed to be achievable by use of high-strength wire, a bottleneck capillary narrowing toward the tip, and latest bonding technology. It has been clarified that the optimum relationship between the free air ball (FAB) diameter and the capillary chamfer diameter (CD) is important in attaining smaller bond area and higher ball shear strength. It has been also confirmed that optimization of wire bonding conditions can inhibit void formation due to high-temperature heating and improve bond reliability. The wire bonding materials and techniques developed as reported here are not only confined to the 50 μm pitch interconnections, but also are fully applicable to the next-generation finer-pitch interconnections.

The wire bonding materials and techniques to realize the next-generation 40 μm ultrafine-pitch bonding will have to be developed by selecting the optimum molding compounds and conditions to prevent wire sweep during resin molding, improving production yield by low-temperature and low-impact bonding, and studying applicability to the next-generation copper interconnections.

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