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Fine-Pitch Wire Ball Bonding Technology

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Abstract:

Advancing performance and diminishing size of semiconductors have increased the density of semiconductor packaging year by year. Wire bonding is in widespread use as technology for connecting semiconductor chip electrodes to external terminals. With development efforts expended to meet the higher packaging density requirements, wire bonding is now commercialized at a wire pitch of up to 90 μm. Wire bonding technology for a 50-μm wire pitch will be under development by the year 2000. This article presents the results of research conducted concerning the reduction in the diameter of the ball formed on the end of the wire, decrease in the tip radius of the capillary, and increase in Young's modulus of the wire. These study results verify the feasibility of wire bonding at pitches of 70 and 60 μm. The concept of wire bond reliability is also clarified.

1. Introduction

A general semiconductor package is illustrated in **Fig. 1**. The semiconductor chip has its electrode leads wire bonded to terminals of the lead frame, called inner leads, and is then packaged in plastics, excluding the external leads of the lead frame. With the size reduction and performance improvement of electronic equipment, the demand for semiconductor packages of smaller thickness and higher density has been mounting yearly. The pitch of wire bonding has rapidly decreased as a result. Wire bonding technology has been developed and implemented to meet a chip electrode pitch of 90 μm. Now that the internal wiring width of devices is rapidly diminishing from 0.5 to 0.35 and to 0.25 μm, wire bonding at a chip electrode pitch of 80 μm or less is being studied. Given the perceived limits of wire bonding, some semiconductor manufacturers are moving to tape automated bonding (TAB). TAB

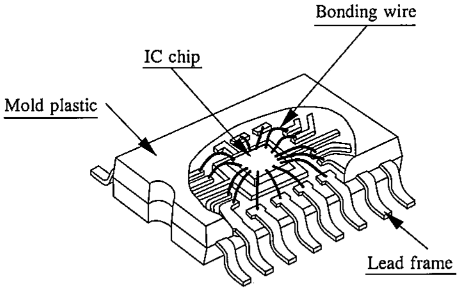

Fig. 1 Internal structure of LSI

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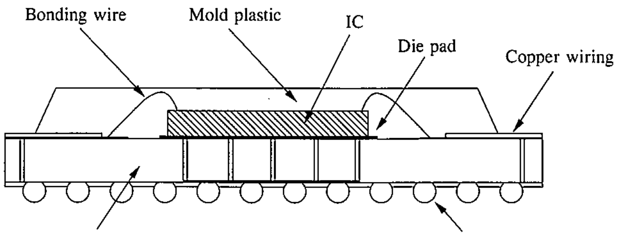


Fig. 2 Example of BGA structure1)

involves forming a wiring pattern on a polyimide film with copper foil, forming copper leads at the ends of wiring, and connecting the copper leads to bumps formed on electrode pads. TAB is reported to be capable of 60-μm pitch connections.

Currently components of wire bonding technology, or the wire, lead frame, wire bonder, and capillary, are now more actively being developed. Development of such a wire bonding technology that can meet the requirements for chips of smaller size and higher density without changing the existing packaging process is desired. The 1994 roadmap of the Semiconductor Industry Association (SIA) of the United States predicts that wire bonding at a pitch of 50 μm will be accomplished in 2001 and that bonding wires of higher strength will be required for the 50-μm pitch wire bonding technology. Ball grid array (BGA) packaging with solder balls placed in an array pattern at the back side of a plastic or tape substrate as shown in **Fig. 2** is beginning to take the place of lead frames for multipin devices with well over 300 pins1). Wire is used to connect chips and substrates in predominantly many BGA designs. Fine-pitch connections between chips and substrates are also increasing in demand.

This paper first describes problems with fine-pitch wire bonding, then presents the evaluation results of 70- and 60-μm pitch ball bonding using Type T and U bonding wires developed for the fine pitches, and identifies the problems to be solved for achieving the 50-μm pitch2).

2. Problems with Fine-Pitch Wire Bonding

The first problem with fine-pitch wire bonding is to deposit small-diameter gold balls with sufficient strength and without contact with adjacent balls on small-pad and fine-pitch electrodes. To make small-diameter balls stable, the ball diameter that is about 1.8 times as large as the wire diameter is necessary for the latest bonding equipment. This means that the diameter of the wire must also be reduced. The second problem is that the adjacent wires should not contact as the wire span increases. The leads of lead frames are difficult to machine to meet the decreasing pitch of pads, and the smallest possible lead pitch is now about one hundred and a few tens of micrometers now. For this reason, the wire bonding span is increasing. If the chip is square and the pads are arranged at equal spacings on each side of the chip, the maximum wire length L is

$$L = \sqrt{2}\, N\, (L_p - P_p)/8$$

where L_p = lead pitch; P_p = pad pitch; and N = total number of pads. The maximum wire length L is 4.2 mm for 300 pads, 80-μm pad pitch, and 160-μm lead pitch. The straightness of the bonding wires is as important as the prevention of wire sweep during plastic molding.

To solve the above problems, it is indispensable to (1) develop a high-strength wire, (2) design a small-diameter capillary for fine pitches, and (3) optimize wire bonding conditions for higher bond reliability.

3. Development of High-Strength Wires

The properties required of bonding wires are (1) decrease in diameter by increase in strength, (2) formation of small balls, (3) prevention of wire sweep during plastic molding, and (4) bond reliability. **Fig. 3** shows the relationship between the elongation and load of bonding wires in tensile test. When its microstructure is as worked after drawing, the wire will curl to a great extent due to working strain during bonding. For this reason, the wire is used in the slightly recrystallized condition after heat treatment. **Fig. 4** shows the tensile strength and diameter of gold wires T and U. Wire U has gold purity of 99%, wire T has gold purity of 99.99% or more, and wire K is hard gold wire in conventional use and has gold purity of 99.99% or more. Each wire is heat treated after drawing and adjusted to a total elongation of about 4%. The diameter at which high-strength wires T and U are as strong as 25-μm diameter conventional bonding wire K is 22 and 20 μm for wires T and U, respectively.

Young's modulus of each type of wire is shown in **Fig. 5**. Young's modulus was obtained from the slope of the stress-strain curve of the wires in the elastic deformation region in the tensile test. The cross-sectional structures of the ball and nearby heat-affected zone of wires T, U, and K are shown in **Photo 1**. The recrystallization temperature decreases for wires K, T, and U in that order. The length of the recrystallization (grain growth) region from the end of the ball is about 140, 80, and 70 μm for wires K, T, and U, respectively. This recrystallization length is related to the loop height after ball bonding. Particularly with fine-pitch bonding, it is desirable that the recrystallization length and

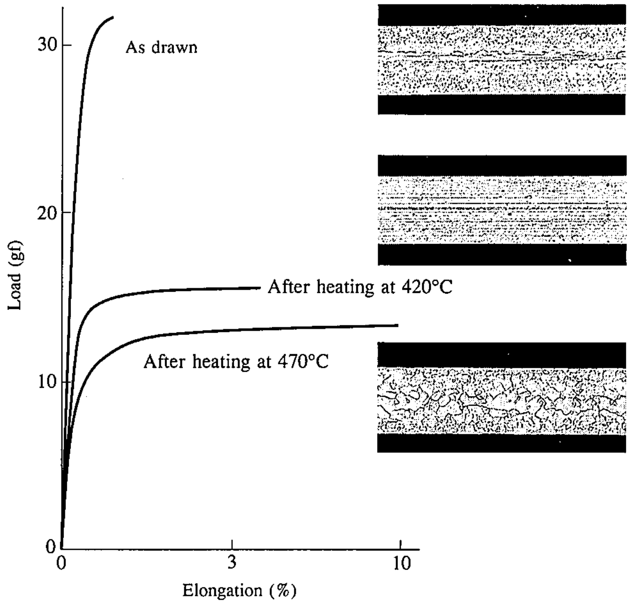


Fig. 3 Changes in strength, elongation, and microstructure of gold wires with heat treatment after drawing (cross-sectional microstructures of 30-μm gold wires shown)

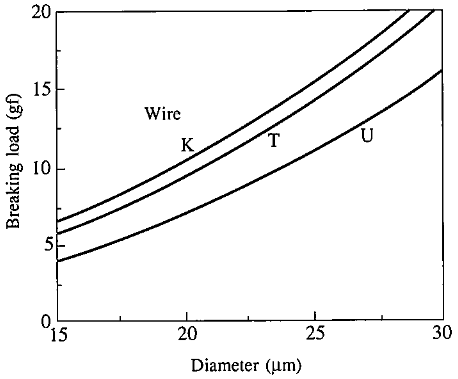


Fig. 4 Relationship between diameter and breaking load of gold wires

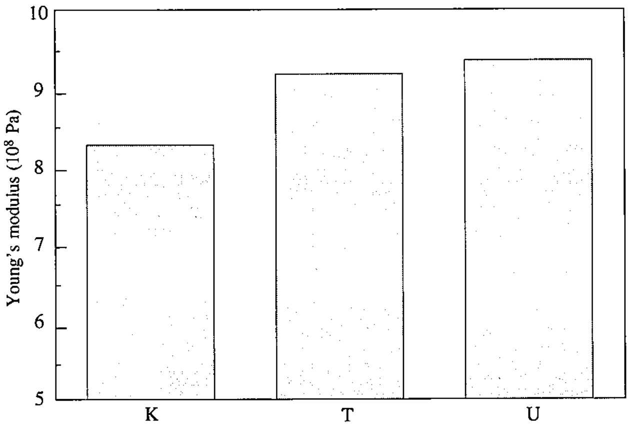


Fig. 5 Young's modulus of gold wires

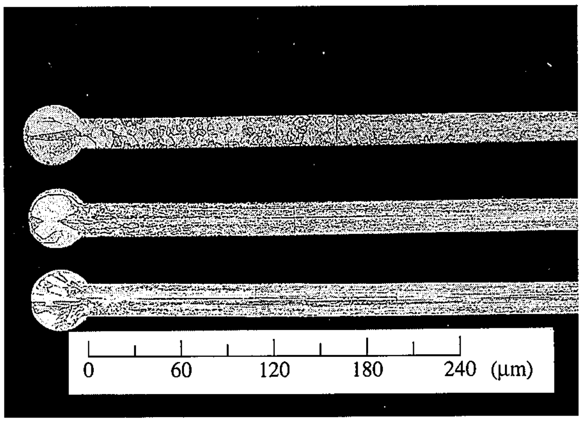


Photo 1 Cross-sectional microstructures of ball and heat-affected zone of gold wires K, T, and U (wire diameter of 22 μm and initial ball diameter of about 40 μm)

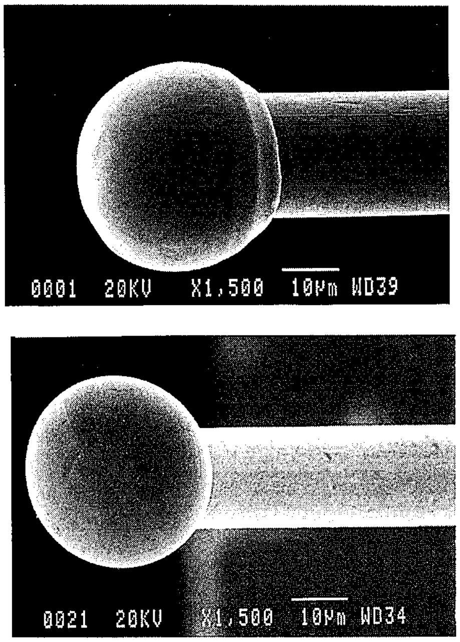


Photo 2 SEM images of balls formed on end of gold wires (top: 38-μm diameter ball formed on end of 22-μm diameter gold wire T, bottom: 33-μm diameter ball formed on end of 18-μm diameter gold wire U)

loop height should be both reduced to avoid the contact between the capillary and adjacent wire (as discussed in the next chapter). The ball hardness is 38, 39.5, and 40 Hv for wires K, T, and U with increasing strength. As compared with the high strength of the parent wires, the hardness of once molten balls rises only slightly. Chip damage during wire bonding, which was highlighted as a problem for copper wire, is not considered to occur with gold wire. (The ball hardness of high-purity copper wire is about 47 Hv.)

Photo 2 shows scanning electron microscope (SEM) images of a 38-μm diameter ball formed on the end of 22-μm diameter gold wire T and a 33-μm diameter ball formed on the end of 18-μm diameter gold wire U. The alloying elements added to increase the strength of gold wire are sometimes oxidized during ball formation, affecting the solidification behavior of the ball and causing voids in the ball or degrading the sphericity of the ball. It was confirmed that both wires T and U can stably form balls of high sphericity irrespective of the bonder model if the ball diameter is at least 1.8 times the wire diameter.

4. Capillaries and Bonders Used for 60-μm Pitch Wire Bonding

The bonders used are Shinkawa UTC200BI Super and Kulicke & Soffa 1488 Turbo. The capillaries used each have a bottle-neck tip. An optical micrograph of the tip of such a capillary is shown in **Fig. 6**, and the dimensions of the capillary are given in **Table 1**. The conditions under which the capillary does not touch the adjacent wires are given by

$$T < 2P_p - 2h\tan(\theta/2) - W_d$$

where P_p = pad pitch; h = loop height just above the ball; θ = bottle neck angle of the capillary; and W_d = diameter of the wire.

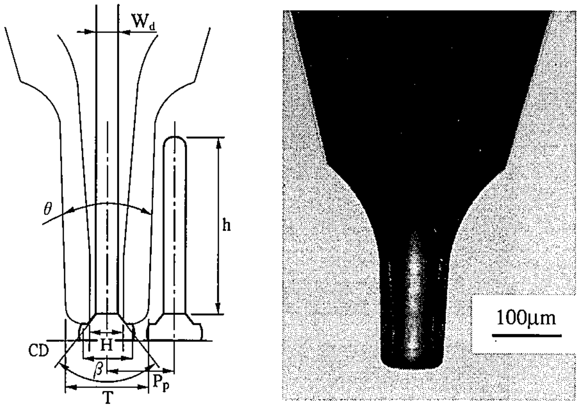


Fig. 6 Example of capillary used (right) and relationship between capillary geometry and adjacent wire (left)

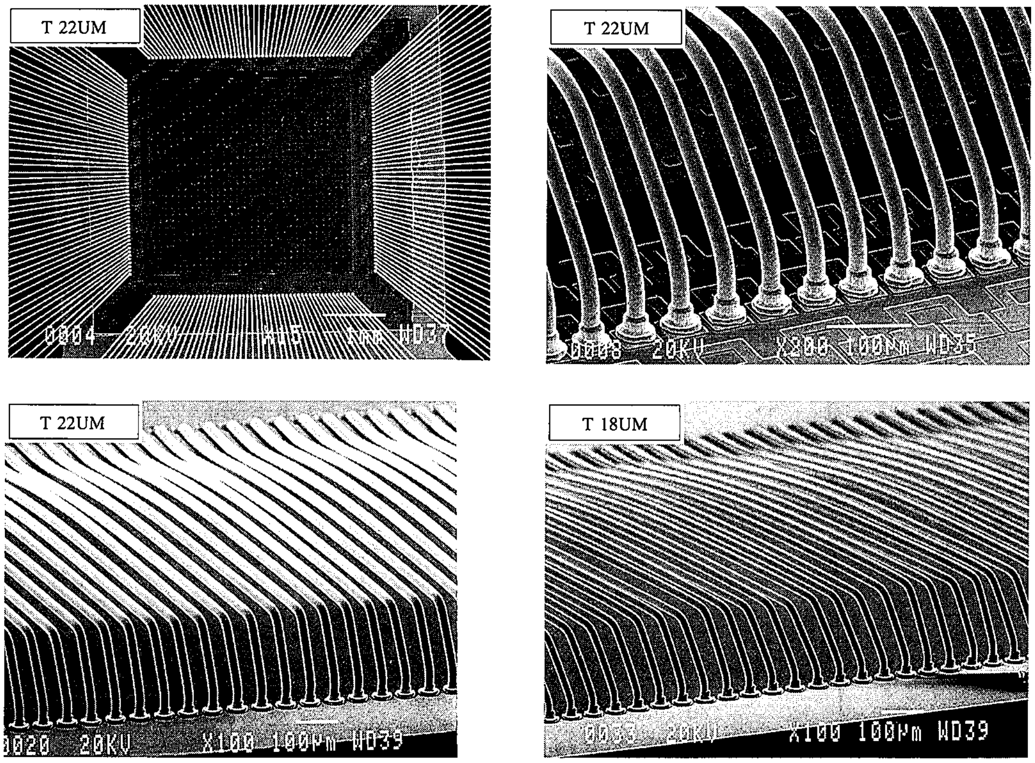
Table 1 Dimensions of capillary used (example)

Symbol	Name	Dimension (μm)
H	Ball diameter	31
CD	Chamfer diameter	40
T	Tip diameter	83
θ	Bottle neck angle	5°
β	Chamfer angle	90°

When $T = 83$, $P_p = 60$, $W_d = 22$, and $\theta = 5$, the loop height right above the ball must be controlled to 172 μm or less. Given the positional accuracy of wire bonding, the loop height must be reduced further (refer to **Fig. 6**). **Photo 3** shows SEM micrographs of wire bonds. For 60-μm pitch bonding, 18-μm diameter wire (initial ball diameter of about 33 μm) and 22-μm diameter wire (initial ball diameter of about 38 to 40 μm) were used. The dimension T of each capillary was not greater than 85 μm, and it was confirmed that none of the capillaries touched the adjacent balls and wires.

5. Bond Strength and Reliability

The low reliability of gold ball-aluminum electrode bonds was considered as one cause for bond failures during long use and has been studied by various researchers. In the current actual manufacturing process, it is general practice to measure the initial bond strength (shear strength) of balls and to establish a lower limit. For fine-pitch bonding, the bond strength decreases with decreasing ball diameter. When the bonding load and ultrasonic output are increased, the shear strength rises, but the ball compressed diameter increases to increase the possibility of contact with an adjacent ball. It is important to clarify the concept of required initial bond strength and to select the optimum initial ball diameter and bonding conditions more strictly. The shear strength of balls formed using 22-μm diameter wires T and U at a pitch of 70 μm is shown in the as-bonded condition and after heating to 200°C in the upper and lower parts of **Fig. 7**, respectively. The average

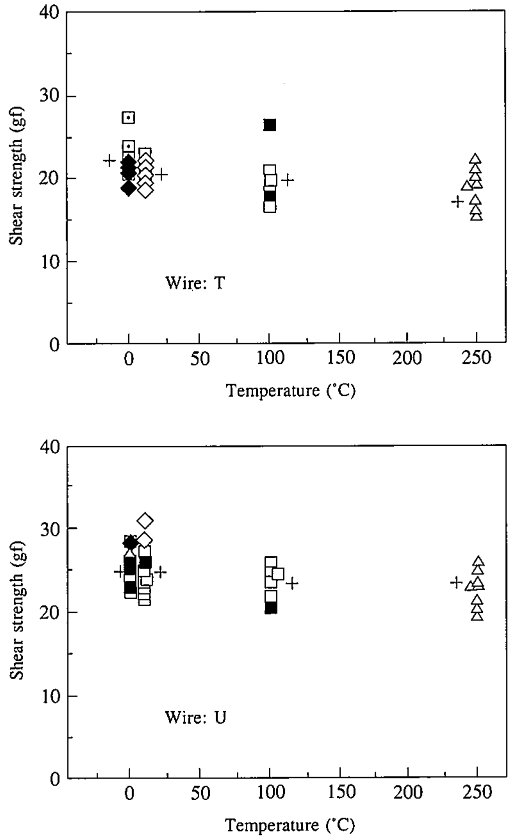


(a) Wire T: 22-μm diameter, Bonder: Shinkawa UTC200BI Super

(b) Wire T: 22-μm diameter (top)/Wire U: 18-μm diameter (bottom), Bonder: Kulicke & Soffa 1488 Turbo

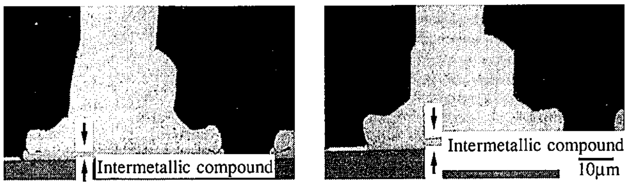
Photo 3 SEM images of wires bonded at pitch of 60 μm compressed ball diameter was about 55 μm in each case. The values measured in 20 positions under each set of bonding conditions are plotted, and the average values are each indicated by a plus (+) mark. The initial shear strength ranged from about 20 to 25 gf in each case. Heating up to 250 h did not reduce the shear strength of the wire bonds. As shown in **Photo 4**, the cross-sectional observation of a heated bond interface reveals the uniform growth of a gold-aluminum intermetallic compound and the formation of no voids.

The studies by the authors to date[3,4] indicate that voiding is related to the distribution of the aluminum oxide film formed at the interface between the gold ball and aluminum electrode. The oxide film formed on the aluminum electrode layer surface is broken by the compression force and ultrasonic vibration of gold wire bonding, allowing the gold and aluminum to make a metal-to-metal joint. If the oxide film is not broken small enough but remains at the bond interface, the initial bond strength is reduced. When such a wire bond is subsequently heated, the gold and aluminum do not uniformly diffuse into each other, giving rise to the formation of voids. To enhance bond reliability, therefore, any control standard established should be judged according to the distribution of the oxide film at the bond interface.



Wire diameter: 22 μm, Ball compressed diameter (interface diameter): 55 μm

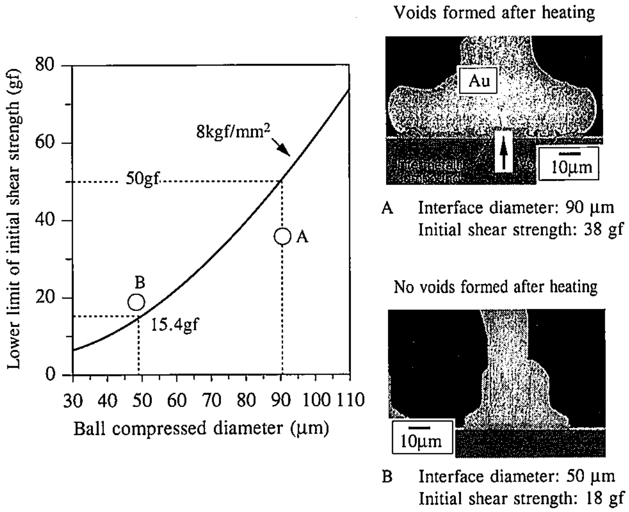
Fig. 7 Change in ball shear strength with heating



Wire: T

Wire: U

Photo 4 Cross sections of ball bonds of wires T and U after heating at 200°C for 10 h (ball compressed diameter of 55 μm, wire diameter of 22 μm)



A Interface diameter: 90 μm
Initial shear strength: 38 gf

B Interface diameter: 50 μm
Initial shear strength: 18 gf

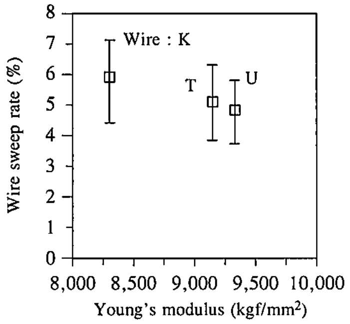
Fig. 8 Lower limit of initial shear strength as required to ensure bond reliability

If wire ball bonds are to be controlled according to their initial bond strength, it seems appropriate to evaluate them according to their bond strength per unit area. The relationship between the initial shear strength and void formation was investigated in general ball bonding (initial ball diameter of 75 μm and compressed ball diameter of 90 μm)[3]. It was found that voids that would otherwise result in a bond failure did not occur unless the initial shear strength dropped below 50 gf. The lower limit of the initial shear strength per unit area at which no voids are formed can be thus calculated to be about 8 kgf/mm² as shown in **Fig. 8**. **Fig. 8** shows the cross-sectional views after heating of a wire bond (A) with compressed ball diameter of 90 μm and initial shear strength of 38 gf and a wire bond (B) with compressed ball diameter of 50 μm and initial shear strength of 18 gf. Many voids were formed in the wire bond A, while no voids were observed in the wire bond B.

6. Wire Sweep during Molding

The wire sweep rate during molding decreases with increasing wire diameter, increasing wire Young's modulus, and decreasing wire span[5].

When 22-μm diameter wires were bonded over a wire span of about 4.5 mm and molded, the wire sweep rate decreased for wires K, T, and U in that order, or decreased as Young's modulus of the wire increased, as shown in **Fig. 9**. When 22-μm diameter wire T and 20-μm diameter wire U were bonded and molded at pitches of 70 and 60 μm, respectively, the wires did not contact each other and break. The dependence of wire sweep on the mold-



Wire sweep rate = ΔW/L where ΔW = wire sweep and L = wire span

Fig. 9 Relationship between Young's modulus and wire sweep rate after molding

ing conditions, molding plastics, and wire span will have to be studied further with respect to the lead frames and chips to be actually used.

7. Conclusions and Future Problems

The smallest possible pitches of wire bonding have been studied. Using wires of higher strength and capillaries of smaller tip radius, wire bonding was performed at pitches of 60 and 70 μm. The bond strength decreased with decreasing ball diameter, but the bond strength per unit area was higher than in the past. This means that bond reliability is satisfactory. It was confirmed that the wires do not break or touch each other due to their sweep, and the commercial feasibility of 60-μm pitch wire bonding was indicated. The durability of thinner capillaries, select optimum mold plastics and plastic molding conditions will be checked. The applicable range of wire bonding at pitches of 60 and 50 μm by ascertaining the smallest possible lead pitch of lead frames and the longest possible wire span will be clarified. Studies show it is also important to develop joining technology for 50-μm pitch wire bonding. Increasing the ultrasonic frequency to 120 kHz during wire bonding, a recently commercialized technique, is considered to be helpful in minimizing the compressed diameter of small balls and obtaining desired initial bond strength.

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