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Micro-Ball Bumping Technology

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Abstract

With the latest performance enhancement of mobile facilities typically such as notebook size PCs, mobile telephones, etc., down-sizing and performance enhancement of the semiconductor devices for general use have been accelerated, resulting in demands for semiconductor device assembly in increasingly higher densities. In the high density assembly of high performance semiconductor devices, the bonding wire method using lead frames hitherto widely applied is being substituted with the flip chip method wherein a chip is directly connected to a substrate by forming bumps on the chip. This paper introduces a newly developed bump forming method, the micro-ball bumping technology, and describes advantages of the developed method compared with alternative technologies such as plating and printing methods.

1. Introduction

The increasing density, improving functionality, and decreasing size of semiconductor devices in recent years have increased the number of input and output pins and decreased the electrode size and pitch, making it imperative to make technology innovations in semiconductor packaging. Wire bonding technology, which connects the terminals of semiconductor chips to lead frames or substrates has accumulated performance results. It has also shown improvements in package design flexibility while enjoying widespread acceptance. It has also achieved commercial wire bonding pitches of about 70 μm or smaller.

However, contact between wires and inductance of wires sometimes becomes a problem for still higher densities and speed. The wire bonding technology is partly being supplanted by the tape automated bonding (TAB) technology and flip-chip (FC) technology in which bumps are formed on chips and make interconnections to the bumps. The bumps used in the TAB technology usually comprise gold formed by electroplating. A well controlled plating process offers many excellent advantages, such as high productivity and a fine bonding pitch. Since this process is relatively complicated, however, it has drawbacks such as requiring large initial investments and lack of flexibility in accommodating wafer size changes and product type variety. The construction of new electroplating lines is sometimes restricted by environmental -related reasons like the disposal of the waste plating solution.

The FC technology has attracted attention in terms of high density packaging and excellent electric properties, among other things, and the bumping technology has been studied for various FC packages[1-3]. The typical bump technology in use today allows the under-bump metal (UBM) to be first formed on aluminum electrode pads and then solder bumps to be formed in the position of electrode pads on a wafer using shadow masks or photo-resist by means of physical vapor deposition (PVD), such as evaporation and sputtering. Although this vapor deposition process has a proven track record with respect to reliability, a large vacuum chamber and photo-masks are required. Consequently, the cost becomes too high. In addition, it is pointed out that the majority of vapor-evaporated metals are not used as bumps and eventually they become waste. The technology of electroplating solder bumps has been studied and achieved to the stage of practical application.

The electroplated solder bumping process is suited for fine-pitch bumping, but is complicated like the gold plating process and is not environmentally friendly. Its lack of freedom as to selection of alloy plating compositions is also pointed out in the study of Pb-free solder material. The method of forming solder bumps by printing sol-

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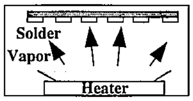
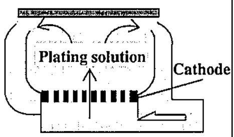
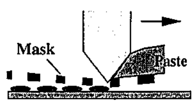
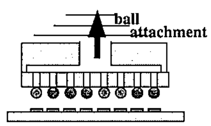
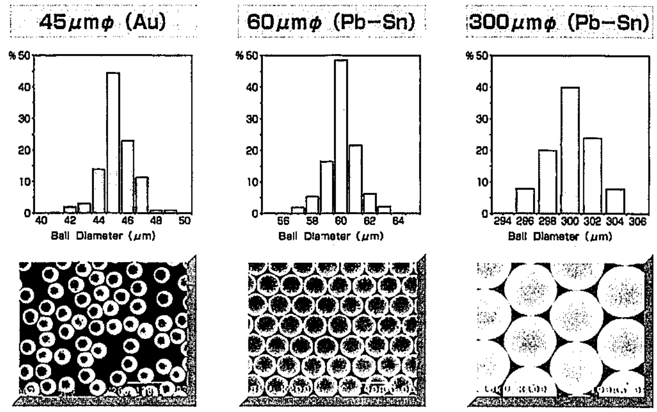
Table 1 Comparison of flip chip bumping technologies

Technology	Features
Evaporation (C4) 	○ Reliability (performance proven) × Bumping cost (large loss and high equipment cost) △ Material composition difficult to change △ Solder alone △ Wafer alone × Fine pitch × Initial investment (vacuum system)
Plating 	○ Reliability (performance proven for gold bumps) ○ Bumping cost △ Material composition difficult to change △ Solder/gold bumps both formable △ Wafer alone × Fine pitch × Initial equipment investment (equipment also required for spent solution disposal, etc.)
Paste printing 	○ Bumping cost ○ Material composition easy to change △ Solder alone ○ Wafers and substrates can be handled × Uneven bump height × Fine pitch ○ Initial investment
Micro-ball bumping 	○ Bumping cost ○ Material composition easy to change ○ Solder/gold bumps formable ◎ Wafers, chips, and substrates can be handled ○ Even bump height ○ Fine pitch ○ Initial investment The technology in this paper

der pastes has started to be applied commercially. This technology is high in productivity and excellent in solder material selectivity, but is claimed to be unsuited for fine-pitch bumps[3] (see **Table 1**).

Each of the above-mentioned bumping processes is wafer bumping and is not suited for diced chips. The stud bumping process cuts a bonded ball at the neck and forms a bump by using a conventional wire-bonder. It can form bumps on diced chips and chips on wafers. The gold bump-forming process using gold wires is made practical by some manufacturing. One advantage is the ability to form bumps on wire bonding chips without the UBM formation step. Among its disadvantages are the need for leveling bumps to the same height after cutting bonded balls at the neck and poor productivity for multi-pin devices because it is single-point bonding. The impact of bonding also makes the gold wire bumping process unfit for bumping on device circuits or area bumping.

This paper introduces a new bumping process for TAB and FC packages by using highly accurate and truly spherical micro-balls. This process can form bumps with high accuracy and efficiency by transferring and bonding micro-balls to pads. It also provides flexibility as to bump metal selection and at the same time, can bump diced chips and chips on wafers. It also can be applied to the formation of bumps on the substrate pads of TAB tape substrates and PCB substrates to which chips are TAB or FC interconnected.



(a) Gold micro-balls (45 μm) (b) Eutectic Pb-Sn balls (60 μm) (c) Eutectic Pb-Sn balls (300 μm)

Fig. 1 Size distributions and SEM images of three types of balls

2. Micro-Balls

Micro-balls can be made from various lead-tin (Pb-Sn) solder alloys, lead-free (Pb-free) alloys, and metals of relatively high melting point like gold alloys. The ball material is precut in a solid condition by controlling to a constant weight, heated to a temperature much higher than the melting point of the metal, and melted into balls. The surface tension of the molten metal allows balls to be formed to good sphericity. A vacuum, gas, or reducing atmosphere is selected as atmosphere by considering the melting point and oxidizability of the material to be melted.

The size of balls to be used is determined by considering the height and pitch of bumps to be formed on bond pads. At present, gold alloy balls for TAB and FC applications are formed in the diameter range of about 35 to 100 μm, and solder alloy balls for FC applications are formed in the diameter range of about 60 to 300 μm. Solder alloy balls in the diameter range of 250 to 760 μm are also prepared as ball bumps for ball grid array (BGA) and fine-pitch BGA applications. **Fig. 1** shows SEM images and size distributions of three types of balls.

3. Micro-Ball Arranging Technology

In the micro-ball bump formation technology, the balls are attached to the locations of the through-holes on one side of the arrangement plate by reducing the pressure in the other side so positioned as to match the points where bumps are to be formed. These balls are transferred to the points where electrode pads are located so that bumps can be formed efficiently[4-7]. **Fig. 2** shows the process flow whereby micro-balls are transferred and bonded to the pads on the chip or substrate.

For the balls to be attached and held, without excess or shortage, to the through-holes in the ball arrangement plate, (1) the ball container is vibrated to cause the balls to jump to a certain height. (2) The bonding head with the ball arrangement plate attached at its end is brought down closer to the jumping balls, and vacuum-sucks them to the through-holes (suction holes) in the ball arrangement plate. The smaller the diameter of the micro-balls, the more excess micro-balls tend to adhere to positions other than the suction holes. Since the micro-balls are small in diameter, a few more micro-balls readily adhere to the area around each suction hole due to the air sucked through the very small clearance between the normally attached ball and the suction hole. In addition, micro-balls adhere to the ball arrangement plate due to their surface contamination or adsorbed mois-

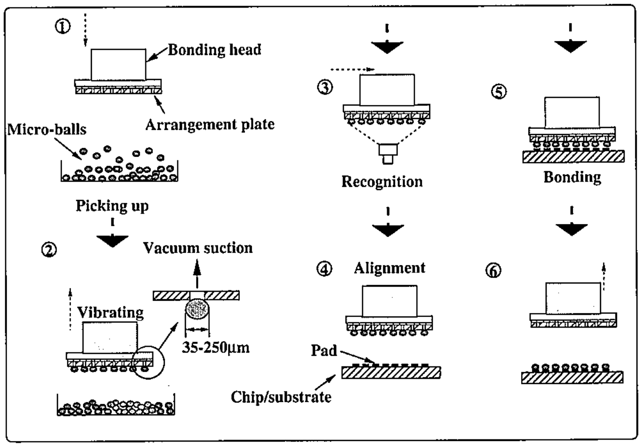


Fig. 2 Process of transferring and bonding micro-balls to pads on chips, etc.

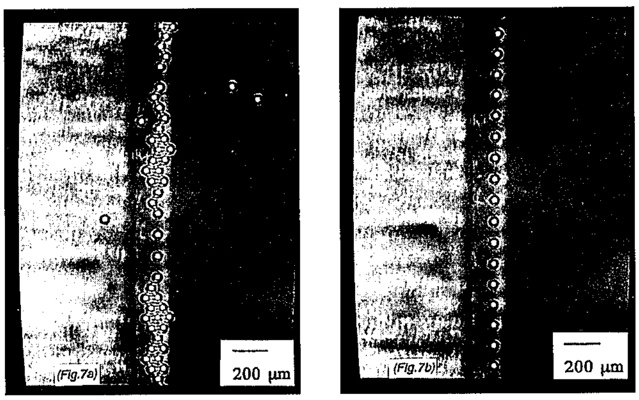


Fig. 3 Example of excess balls attached to arrangement plate (left) and example of balls normally arranged on arrangement plate after ultrasonic vibration (right) (ball diameter: 45 µm)

ture. (3) The head is given ultrasonic vibration of optimum frequency and amplitude to remove the excess balls and continue to hold the normally attached balls. (**Fig. 3** shows an example in which excess balls are attached to the ball arrangement plate and an example in which balls are arranged in normal positions alone after application of ultrasonic vibration.) (4) The balls attached and arranged on the ball arrangement plate are checked by imaging processor to see if they are arranged on the ball arrangement plate without excess or shortage. If there is any arrangement problem, the balls are all removed from the arrangement plate, and the ball arranging procedure is repeated. (5) When the normal ball arrangement is confirmed, the head is moved to the bonding stage, and the ball positions are aligned with the chip or substrate pads to which are the balls are to be transferred. (6) The head is lowered and transfers the balls to the pads under a preset pushing load. When the head is raised, the suction pressure on the side opposed to the ball holding side of the ball arrangement plate is decreased or increased above the atmospheric pressure to prevent any balls from remaining attracted to the ball arrangement plate.

When thermo-compression bonding gold balls, either or both of the chip stage and the bonding head are heated and pressed. When reflow bonding a low-melting point metal like solder, flux is applied to pad positions before transfer of balls to pads, and the balls are temporarily fixed to the pads by the adhesive force of the flux. The temporarily fixed balls are heated in a furnace to a temperature above their melting temperature and bonded to the pad metal. The details will be discussed in a later section.

We have developed a unit for performing these steps fully automatically. The bumping cycle time of the unit is now about 20 s per head.

4. Formation of Gold Ball Bumps for TAB and FC Interconnections

Gold wire-to-LSI chip aluminum pad bonding is widely used practically in wire bonding, and many studies have been conducted of the reliability of these bonds[8-10]. The results of high-temperature heating test indicate such problems as the formation of voids by the growth of gold-aluminum intermetallic compounds and the corrosion of the intermetallic compounds in the molding resin. It is demonstrated that if the initial bond condition and operating environment are appropriately controlled, high reliability can be accomplished. When forming gold bumps, therefore, the under-bump metal (UBM) formed for bumping by plating is not always required.

Fig. 4 shows a SEM image of gold balls bonded to chip aluminum pads. The 45 µm diameter gold balls are thermo-compression bonded to the 80 µm pitch aluminum pads. The total of 300 aluminum pads were bonded at a time. The bonding conditions were a chip temperature of 370°C, a load of 10 gf/ball, a pressure application time of 2 s. The maximum displacement of the bonding position was ± 3 µm. Then these gold bumps are used as the bumps for TAB interconnection using thtermo-compression bonding, the reliable bonding between gold balls and aluminum electrode pads can be obtained through inner lead bonding process. If the Flip Chip interconnection is carried out without applying thermo-compression, that is , if anisotropic conductive adhesive filmes (ACF) or conductive adhesive pastes are used to bond bumps to a substrate[11], the quality of initial bonds between the gold balls and the aluminum electrode pads of a chip need to be sufficiently high.

Fig. 5 shows the relationship between the bonding force and the bond strength when gold balls are thermo-compression bonded to aluminum pads. A study[8] on the reliability of conventional wire bonding found that the deterioration of Au-Al bond reliability or the formation of voids is closely related to the initial bond condition. Void formation is not considered to occur if the initial shear strength of gold ball-to-aluminum pad bonds is 8 kgf/mm^2 or more per unit bond area as reliability criterion[12]. In Fig. 5, the shear strength exceeds the minimum value required for this reliability if the bonding force is 25 gf/ball or more. To form bumps constant in height, flat, and high in reliability, the vacuum attraction of balls is broken after

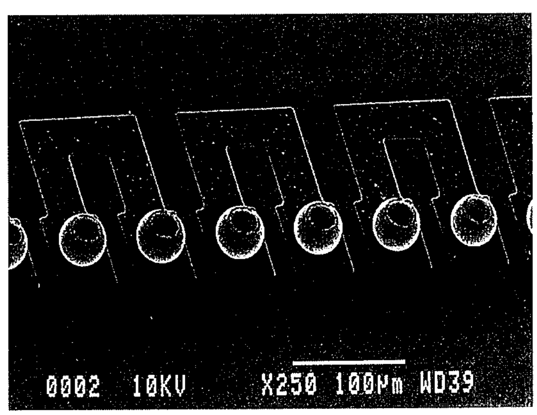


Fig. 4 Example (SEM image) of 45 µm gold balls transferred and bonded to pads

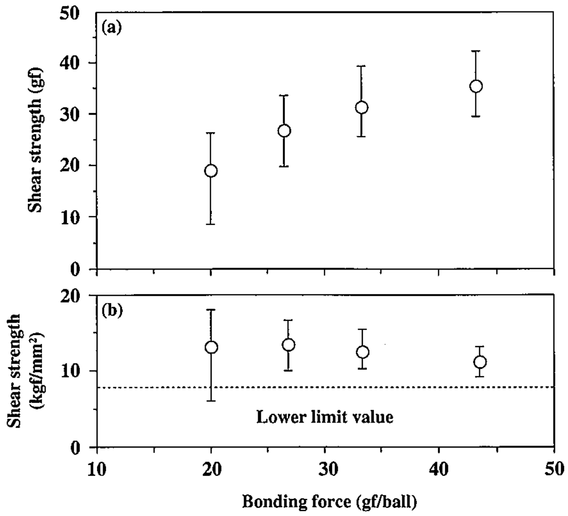


Fig. 5 Relationship between bonding force and shear strength of gold balls (ball diameter: 45 μm)

the transfer of balls and the formation of bumps. The ball arrangement plate then is slightly raised, shifted in the horizontal direction, and lowered again to press on the bumps. The height variability of the bumps thus formed is equivalent or superior to that of bumps formed by the conventional plating process.

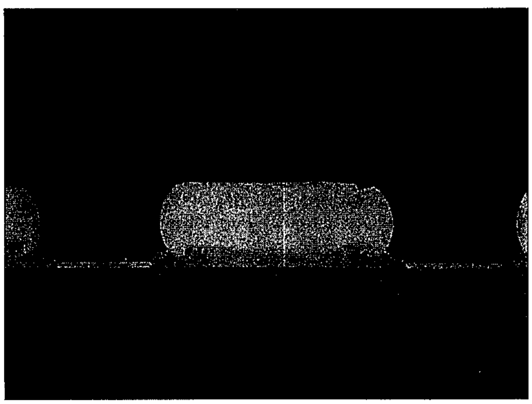


Fig. 6 Cross-sectional micro-graph of ball bond after accelerated heating test (heating temperature: 200°C, heating time: 100 h)

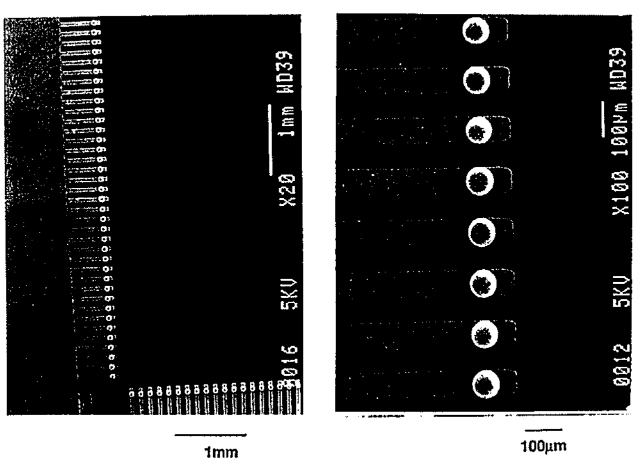


Fig. 7 Example of gold balls (diameter 65 μm) transferred and bonded to TAB leads

To test their reliability after high-temperature heating, bumps with an initial shear strength of about 12 kgf/mm² were formed and heated at 200°C for 200 h. **Fig. 6** shows the cross-sectional view of a bond after the heating test. The heating test confirmed that the bonds made by the ball bumping process are free from void formation and bond strength degradation and are as reliable as the bonds made by the conventional wire bonding process. **Fig. 7** shows an example of gold bumps formed at pad positions on the TAB tape. This technology is also applicable to the manufacture of TAB with bumps or bump sheets[13].

5. Formation of Solder Bumps for Flip Chips

Since the solder has poor wet-ability with the aluminum pads of a chip, it is necessary to form the UBM. **Fig. 8** illustrates the process of transferring solder balls and forming solder bumps. The UBM is deposited on the aluminum pads, and flux is applied to these electrode pads. Solder balls are then transferred to the electrode pads by the method illustrated in Fig. 2. The balls attached to the pads on the wafer are melted in a nitrogen atmosphere in a reflow furnace and bonded to the pads. The flux residue is removed by cleaning. Due to the adhesive strength of flux functions to retain in position, the portions of balls transferred to the chip pads, it is important to select the most appropriate viscosity of the flux. Since the success rate of transferring the balls to the pads is influenced by the grade of ball diameter distribution, it is necessary to use balls of small size variability. When forming solder bumps on diced chips, dedicated jigs are used to carry flux-coated chips.

Fig. 9 is a SEM image of solder bumps formed on a chip with 200 pads arranged at a pitch of 140 μm at the periphery. The passi-

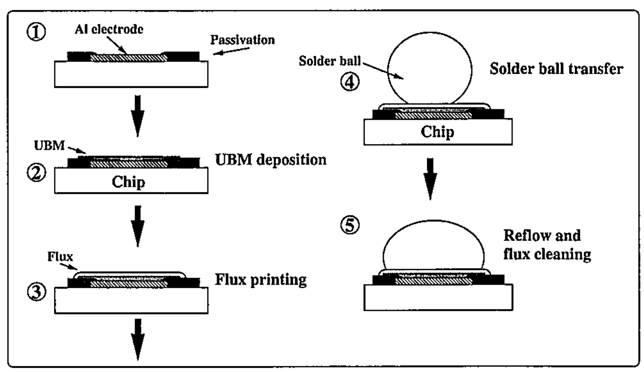


Fig. 8 Process of transferring solder balls and forming bumps

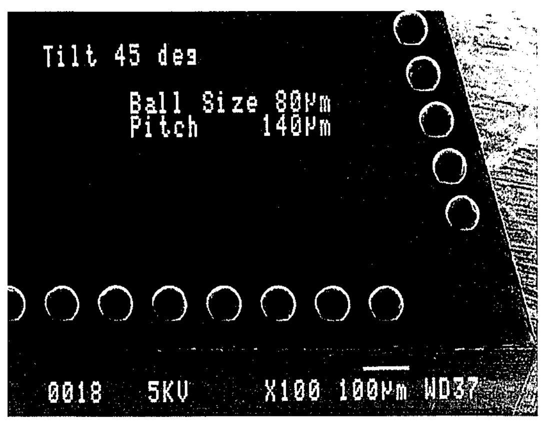


Fig. 9 Example of solder bumps formed

vation opening size is 60 × 60 μm. The UBM has the structure of Au/Cu/Cr layers and was formed on the aluminum pads with 1000 Å Cr, 2000 Å Cu and 1000 Å Au. The balls were composed of a Pb-63%Sn alloy and were 80 μm ± 2 μm in diameter. **Fig. 10** shows the cross-sectional view of the solder bumps. The height of the bumps was 65 ± 1.5 μm, and their shear strength was 23 ± 4 gf. When shear tested, the balls all were fractured only inside the solder balls.

Fig. 11 shows a SEM image of bumps formed on a chip with 45 × 45 or 2,025 pads placed at a pitch of 220 μm in an area array. The solder balls were 150 ± 2 μm in diameter. Since a load applied during transference is less than 10gf per ball, it is considered that the circuitry remains free of damage even if bumps are formed on the pads over active circuitry. Of the 2,025 bumps, 65 were arbitrarily selected and measured for shear strength and height. The shear strength and height are 61 ± 10 gf and 126 ± 2 μm, respectively. The height variations are equivalent or superior to that of other bumping methods, such as, plating, solder paste printing, and vapor deposition methods.

Fig. 12 compares the height variations of solder bumps formed by the solder paste printing process and solder bumps formed by the ball bumping process. The micro-ball bumping process displays its advantage in bump height uniformity. The formation of solder bumps at a pitch of 80 μm is confirmed to be possible by use of solder balls with a diameter of 60 μm. Defects, such as bump bridging and bump shape failure, were successfully avoided by the optimization of flux thickness and type, ball transfer conditions, and reflow conditions. The micro-ball bumping process is highly flexible in the selection of solder types and can form bumps by using high-temperature solder (95Pb-5Sn) and Pb-free solder like Sn-Ag-Cu alloy. As far as UBM formation is concerned, the electroless nickel plating process now

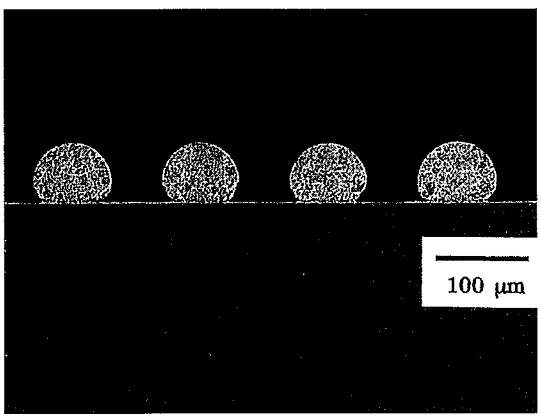


Fig. 10 Cross-sectional view of solder bumps (ball diameter: 80 μm)

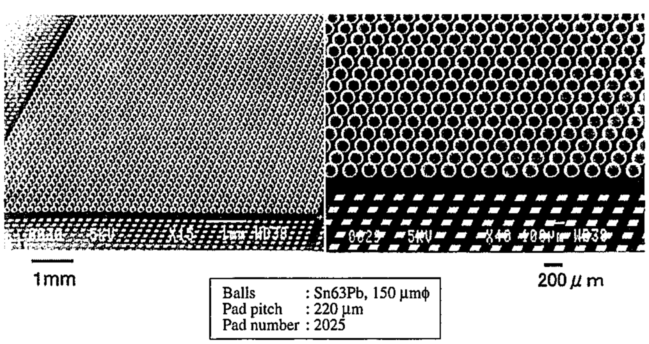
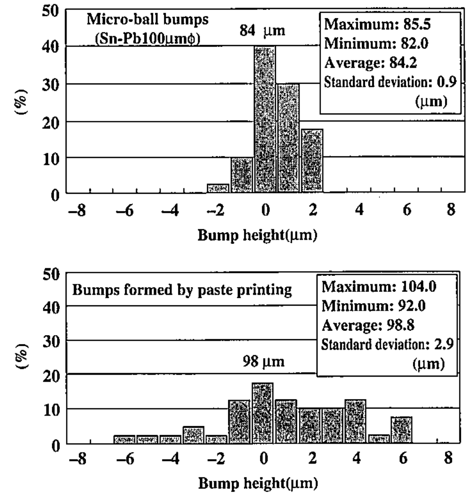


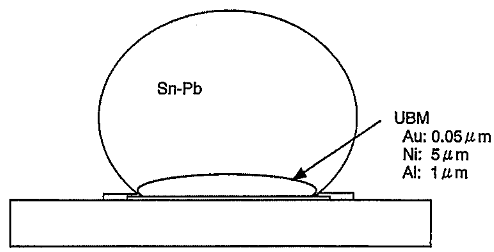
Fig. 11 Solder bumps formed in area array (bump quantity: 45 × 45, pitch: 250 μm)



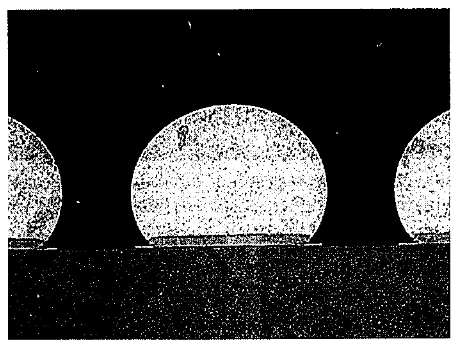
n=40

	Pad size (μm)	Pad pitch (μm)	Average bump height (μm)	Standard deviation
Micro-ball bumps	60	140	84.2	0.9
Paste printing	100	180	98.9	2.9

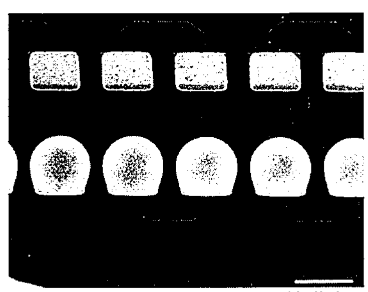
Fig. 12 Comparison of bump height variation



a) Schematic view: Nickel-gold UBM formed by electroless plating and solder bump formed by using 100 μmφ solder balls



b) Cross-sectional optical micro-graph



c) SEM micro-graph: UBM alone and balls bonded to UBM
Lower right line denotes 100 μm

Fig. 13 Micro-balls on electroless Ni UBM (ball diameter: 100 μm)

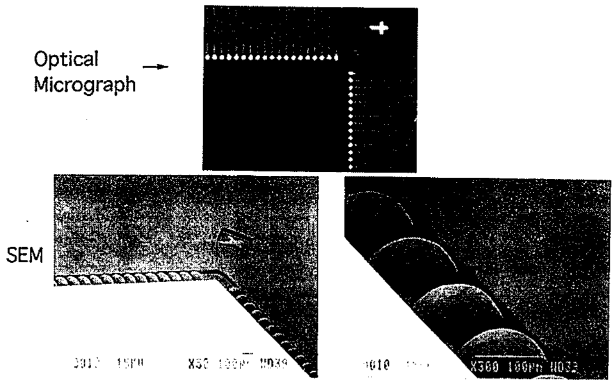


Fig. 14 Micro-ball bumps formed on FC substrate (ball diameter: 60 μm)

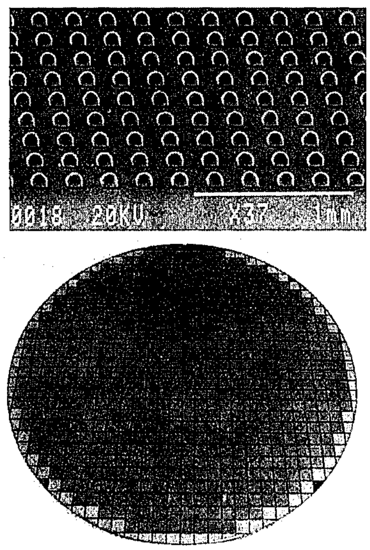


Fig. 15 Example of ball bumps formed at one time on 8-inch wafer (ball quantity: about 400,000, ball diameter: 100 μm)

under development can be adopted to form solder bumps at lower cost. Since this method can also form the UBM on aluminum pads on individual diced chips, it can be used in combination with the micro-ball bumping process to form solder bumps for wire bonding chips.

Fig. 13 shows an example of micro-ball bump formation on the UBM formed by electroless nickel plating. The UBM was deposited as a 5 μm nickel layer and a 0.05 μm gold layer on the aluminum film. The balls were 100 μm in diameter and composed of a Sn-Pb eutectic solder. **Fig. 14** shows an example of solder bumps formed on a FC interconnection substrate. The technology of mounting all balls at a time on a wafer is developed to reduce the cost of FC solder bump formation. An example of about 400,000 balls with a diameter of 100 μm mounted simultaneously on pads on an 8-inch wafer is shown in **Fig. 15** (bump formation yield of 100%).

6. Application of Micro-Ball Bumps to 3D Packaging

As a multi-chip module (MCM) application example[14], a large chip was bonded to a small chip by micro-ball bumps with their pad faces opposed to each other, the bottom surface of the large chip was die bonded to the lead frame, the peripheral pads were connected to the inner leads on the lead frame, and the entire module was then molded (See **Fig. 16**[15]). The MCM was tested for reliability by using DRAM in the upper chip and was confirmed to operate normally. There also can be considered a bump structure repairable by the combination of low-melting point and high-melting point metals.

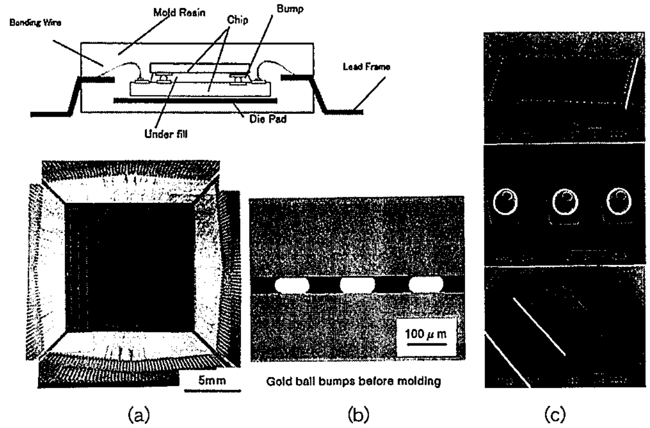


Fig. 16 (a) MCM structure using micro-ball bumps; (b) Cross section of bump connections; (c) General view of MCM

7. Conclusions

New technologies have been developed for forming gold bumps for TAB and FC packages and for forming solder bumps for FC packages. Their features may be summarized as follows: (1) Bumps are formed by making micro-balls with high accuracy and transferring all of them at a time. Micro-ball bumping is thus relatively high in productivity even for multi-pin devices. (2) Various pad arrangement patterns can be accommodated by changing the ball arrangement plate. Micro-ball bumping is thus suited for small-volume production of many different types of products. (3) Bumps can be formed on diced chips, wafers, printed circuit boards, and tape substrates, among other things. Micro-ball bumping is thus highly flexible. (4) As compared with the plating and vapor deposition processes, the equipment is simple, and the initial equipment investment is small. (5) There are no environmental problems like the disposal of spent plating solutions, and materials are not used wastefully, as is the case with vapor deposition. (6) Gold bumps can be formed directly on aluminum pads without UBM formation. The bonds are confirmed to be as reliable as those made by the wire bonding process. (7) Ball sizes can be selected to suit respective bump sizes. A minimum pitch of 60 μm or less can be accommodated. (8) The volume of solder bumps can be adjusted in a wide range by selecting an appropriate solder ball size. Solder bumps can be formed at a pitch of 80 μm or less. (9) Solder balls of almost any compositions can be fabricated, so that material selection is not restricted. (10) The bump height variation is smaller than that of the other bumping processes.

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