行政院國家科學委員會專題研究計畫　成果報告

銅內導線晶片之金凸塊與銅銲墊熱音波接合製程研究

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計畫編號：nsc-93-2212-E-040-001
執行期限：2004.09.01 至 2005.07.31
主持人：莊正利　中山醫學大學職業安全衛生學系
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For high performance and miniaturized microelectronics packaging, flip chip assembly is an attractive solution. In this study, thermosonic bonding technique is adopted for wafer bumping. This kind of bump forming procedure is a mechanical-single point bumping technology derived from the conventional thermosonic wire bonding process. The research approach is to develop a process for thermosonic gold stud bump bonding (SBB) to copper pads for chip with copper interconnects using the design of experiment (DOE).

In order to enhance the bondability and bonding strength, a silver film first deposited on the surface of copper pads as a bonding layer due to excellent bonding property between silver layer and gold ball. In addition, a titanium diffusion barrier layer was deposited between copper pads and silver bonding layer to prevent copper atoms out-diffusion. Integration of silver bonding layer and titanium diffusion barrier layer on copper pads, one hundred percent bondability of gold bumps bonding to copper pads can be achieved. Bonding strength of gold bumps bonded to copper pads far exceeded the minimum requirements stated in JEDEC specifications. It implied that deposition of silver bonding layer and titanium diffusion barrier layer was an efficient scheme to obtain perfect bondability and sufficient bonding strength for gold bump bonding to chip with copper interconnects. From the simulation of leveling, the expansion of leveled bump will be lower than 10% with proper parameters. Hence, the leveling process should not be a serious concern on short circuit.

Keywords：Stud bump bonding, chips with copper interconnect, silver bonding layer, titanium diffusion barrier layer.

隨半導體製程技術日益成熟與元件不斷小型化，覆晶接合技術已成封裝製程之主流技術，本研究沿用傳統熱音波銲線製程於銅銲墊晶片上植金凸塊(gold stud bump)**，而銅銲墊於熱音波銲線製程中易形成氧化膜，致使金球無法成功銲著於銅銲墊上。為克服銅銲墊易於氧化，故於銅銲墊表面鍍著銀膜接著層與鈦膜擴散阻絕層，藉由鈦膜擴散阻絕層阻止銅銲墊原子擴散至銀表面形成氧化膜，進而提高金凸塊與銀膜接著層之銲著率**(bondability)**與銲著強度**(bonding strength)**。**

由實驗結果顯示，銅銲墊表面鍍著銀膜接著層與鈦膜擴散阻絕層後，金凸塊與銀膜之銲著率可達 100**%，且銲著強度遠高於電子封裝業界之要求，突破同銲墊晶片因高溫氧化而難以銲著之缺陷。此外，經由軟體模擬金凸塊受力整平**(leveling)**後之體積膨脹量遠小** 10**%，亦即經整平步驟後，相鄰金凸塊應無接觸，進而影響銅晶片電性的問題。**

本研究結果除提高金凸塊與銅銲墊晶片之高銲著率與高接合強度外，同時也對銅銲墊與金凸塊接合機理及最佳條件做一系統探討，更有助於下年度將陣列金凸塊覆晶接合(flip chip bonding)**於氧化鋁** Al_2O_3 **陶瓷基板，完成銅晶片上板**(chip on board; COB)**之製程開發。**

關鍵詞：金凸塊、銅內導線晶片、銀接著層、鈦膜擴散阻絕層

Introduction

Stud bump bonding (SBB) for flip chip process is different from conventional flip chip (FC) process. In the conventional FC process, it applies solder paste on the UBM using stencil print process, and subsequently applies reflow process to form solder balls for traditional process. Another approach is using photolithography and etching process to deposit solder, then reflow process is applied to form solder balls [1]. Both of the above mentioned processes to form solder bumps need spin coating, lithography and etching. Therefore, they are also called wet process. Thermosonic stud bump bonding process is using thermosonic wire bonding process to form first ball bond on the bond pad and subsequently break the wire instead of forming the second bond. After forming gold bumps on the bond pads, these bumps together with the chip flip bonding to substrate to form the chip on board. Therefore, it is also called dry process. In comparison with conventional solder bump forming process, thermosonic stud bump bonding process can meet the requirements for green industry.

Thermosonic stud bump bonding process can not only form area array package and lower signal delay but also be employed without lithography and etching process. On the other hand, gold bumps do not contain lead which may pollute our environment, so it can satisfy the high standard required for green technology. Gold bumps need not to be reflowed, which means there is no thermal stress took place on the bonding interface. The bonding strength and reliability are much better than traditional solder bumps. Thermosonic wire bonding technology is the most adopted bonding technology to the present day. However, with the increasing demand of high frequency and miniaturized devices, flip chip bonding technology might replace wire bonding technology in the decade to come.

In order to improve performance of semiconductor devices, the feature size of ULSI technology continue to scale down, the intrinsic semiconductor gate performance is improved through higher drive current and low junction capacitance. However, the RC delay time constant increased rapidly because the resistance of interconnect metal increases with decreasing line width, and interconnect capacitance increases with decreasing spacing [2, 3]. When feature size is scaled down to submicron range, the interconnect delay becomes a major limiting factor for chip performance. The electrical performance of copper is approximately three times more than aluminum, and allows higher frequencies to be used with smaller line width. Many fabricators are converting to copper not just for speed, but also for cost reduction. Thinner conductors allow closer spacing and small chips. The switch to copper allows more dies per wafer, and this is where the saving from. Therefore, several major semiconductor companies including IBM announced to use copper interconnects in 1997. A large number of studies on the characterization and reliability issues for copper interconnect and low K materials have been carried out during this decade [4-7]. Results from these basic studies have provided considerable knowledge and guideline for Cu/low-K integration.

Copper pad easily oxidizes when exposed to the atmosphere environment at elevated temperature during thermosonic bonding process. Unlike aluminum pad, it does not form a stable self-passivation oxide layer to prevent copper surface from oxidizing. As a result, copper oxide on the copper pads grows rapidly at elevated bonding temperature during thermosonic bonding process and the bonding strength for gold ball bonding to copper pad was significantly deteriorated [8].

According to our previous research, three schemes prevent copper pad from oxidizing during thermosonic wire bonding process have been proposed [9-11]. The silver was selected to be deposited on the surface of copper pads as a bonding layer. The silver bonding layer could improve the bondability and bonding strength for gold stud ball bump bonding to copper pad due to their excellent bonding property for silver-gold bonding system. The resistance of silver bonding layer is lower than copper pad, which could not degrade the electrical performance of chip with copper interconnects.

Specimen preparation and experimental methods

Finite element model setup

A 3-D finite element model of bump is shown in Figure 1. This model is with tail diameter of 25 µm, tail length of 40 µm, ball height of 35 µm and ball diameter of 90 µm. The total height of the bump is 75 µm. There are 15762 elements in the tail and 12399 elements in the ball. The element type is tetragonal with 4 nodes per element.

The finite element analysis software used in this study is ABAQUS which includes three parts. The first part is ABAQUS/CAE, is to build finite element model and then define initial and boundary conditions. The second part is ABAQUS/Standard and ABAQUS/Explicit, which is the main part of calculation. The third part is ABAQUS/Viewer and ABAQUS/Post. This part can do post-processing and analysis for the results.

The analysis mode used in this study is elastic-plastic analysis mode. And therefore the definition of material properties is required. The flow curve is shown in Figure 2 [12]. In this study, the friction effect will be ignored due to its minor affection.

The flat leveling tool is to be set as a rigid plate. The height of the plate is set to 100 µm. The flat leveling tool gives a certain displacement or load to accomplish the leveling process within 2 seconds.

The desired bump height after leveled is considered to be 35 ~ 45 µm to fit the feasibility of underfill dispensing.

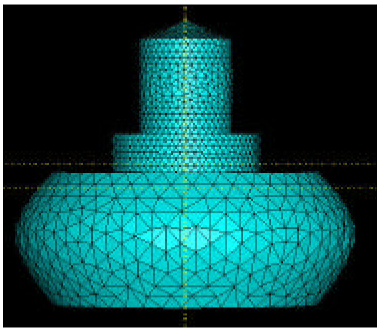

Figure 1 A 3-D finite element model of bump.

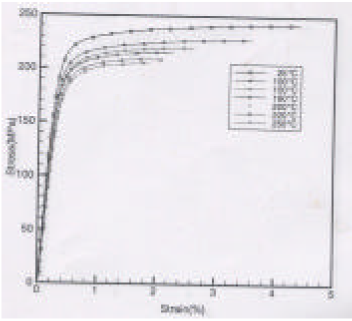

Figure 2 Flow curve of Au wire

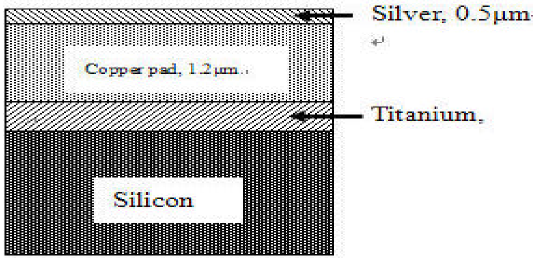

Figure 3 Schematic stacking structure of bond pad with silver bonding layer

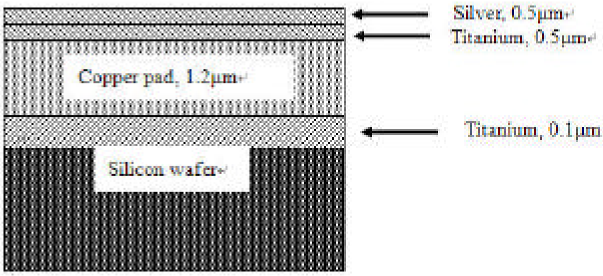

Figure 4 Schematic stacking structure of bond pad with silver bonding layer and Ti diffusion barrier layer.

Experimental materials and specimen preparation

Three categories of specimen were prepared using an E-gun evaporating film system. The first categories test chip was a bare copper pad (without silver bonding layer and titanium diffusion barrier layer) and the second was the test chips with silver bonding layer but without titanium diffusion barrier layer barrier layer deposition. The third test chip was to deposited silver on the surface of copper pad and titanium diffusion was deposited between the copper bond pad and silver cap layer to obstacle out-diffusion of copper. In order to enhance the adhesion between copper pad and silicone wafer, a titanium film of l00 nm in thickness was first deposited on the P type [111] bare silicone wafer by E-gun evaporation process prior to deposit copper film. Sliver bonding layer, titanium diffusion barrier layer and copper film were then successively deposited using thermal evaporation on the adhesive layer of titanium film without breaking the vacuum of chamber. The stacking sequences of deposited layers on the blank wafer were Cu/Ti/Si, Ag/Cu/Ti/Si and Ag/Ti/Cu/Ti/Si, respectively. The thickness of sliver layer is 0.5μm, titanium barrier layer and copper film are 0.5μm and 1.2μm approximately. Figure 3 and Figure 4 show schematically stacking structures of test chips with and without titanium diffusion barrier layer deposited in this study, respectively. The parameters for titanium film, copper film and sliver film were listed in table 1.

Table 1 Parameters for films deposition

	Power (KW)	E-Gun Base pressure (Torr)	film deposition pressure (Torr)	Deposition rate (Å/s)
Ag	1.0	$9.8x10^{-8}$	$2.3x10^{-6}$	7.0
Ti	0.7	$9.8x10^{-8}$	$9.5x10^{-7}$	5.0
Cu	250	$9.8x10^{-8}$	$4.7x10^{-6}$	10.2

Experimental procedure

Thermosonic stud bump bonding was conducted using a K&S 8098 automatic stud bump bonder and a gold wire diameter of 1.3mil was used for experimentation. The parameters of thermosonic stud bump bonding were listed in table 2. Subsequent ball-shear test was carried out using a Royce 552 tester according to EIA/JEDEC JESD22-B116 [13]. The shear tool was set at a height of 3.5μm above the surface of bond pad.

Scanning electron microscopy (SEM) was used to verify the morphology of the bumps. To roughly identify the out-diffusion of copper, energy dispersive spectrometer (EDS) was conducted. Furthermore, Auger depth profile was used to determine the atomic distribution at different depth.

Table 2 Parameters for stud bump bonding process

	Bonding Time (ms)	Bonding Temperature (℃)	Bonding Force(gf)	Ultrasonic power (mA)
A	12	125~200	45	240
B	12	175	45	200~320

A. parameters for investigation of bonding temperature
B. parameters for investigation of ultrasonic power

Results and discussions

1. Bondability of stud ball bump bonding to Cu pad

Figure 5 is the SEM micrographs of gold bumps bonded onto copper pad deposited a silver bonding layer without titanium diffusion barrier layer under different bonding temperatures. In figure 5(a), the gold stud ball bump bonding to silver bonding layer without titanium diffusion barrier layer exhibited a good bondability and repeatability at bonding temperature 125℃. Gold stud ball bump bonding to silver bonding layer without titanium diffusion layer layer resulted in a poor bondability and repeatability as shown in figure 5(b). Only very limited number of gold stud ball bumps were able to be bonded on to silver bonding layer. For gold stud ball bump bonding to silver bonding layer with titanium diffusion barrier layer under different bonding temperatures, all stud ball bumps were successfully bonded on copper pads as shown in figure 6 It implies that silver bonding layer with titanium diffusion barrier layer provided an excellent bonding property for gold stud ball bumps bonding to copper pad under different bonding temperatures.

Figure 7 illustrates the effect of bonding temperatures on the bondability for gold stud ball bump bonding to copper pads. The bondability in this study obtained from the gold stud ball bump bonded onto copper pads divided by the total number of bonding actions. The bondability of gold stud all bump bonding to silver bonding layer with titanium diffusion layer reaches 100% from low bonding temperature 125℃ to high bonding temperature 200℃. In contrast a perfect bondability for gold stud ball bump bonding to silver bonding layer with titanium diffusion bonding layer under different bonding temperatures, the bondabilty of gold stud ball bump bonding to silver bonding layer without titanium diffusion barrier layer decreases with increasing bonding temperatures. Increasing the bonding temperature to 200℃, however, resulted in no gold stud ball bmp can be bonded on silver bonding layer under the same bonding conditions. The unsatisfactory result of gold stud ball bump bonding to silver bonding layer without titanium bonding layer at high bonding temperature (200℃) is attribution to oxide layer formation on the surface of silver bonding layer. Oxides on copper pad prevent the interface from bonding. Oxides could not be removed or broken by ultrasonic power and obstructs diffusion between the gold stud ball bump and silver bonding layer during thermosonic bonding. Poor bondability is inevitable for gold stud bump bonding to silver bonding layer without titanium diffusion barrier layer at high bonding temperature.

In order to investigate the effect of oxide layer on bondability for gold stud ball bump bonding to silver bonding layer without titanium diffusion barrier layer, EDS was used to determined the oxide layer which appeared in the interface between silver bonding layer and gold stud bump. Figure 8 depicts the concentrations of copper increase with increasing the bonding temperature. This analysis result reveals that copper atoms could diffuse to the surface of silver bonding layer and the diffusion of atoms increase with increasing bonding temperature. To obtain more precise analysis on out-diffusion of copper atoms and effect of titanium diffusion barrier layer, Auger microscopy (SAM) was used to determine the profile of copper pads under different bonding temperatures. From depth of figure 9, it reveals that copper does out-diffuse with increasing temperature when silver bonding layer is no titanium diffusion barrier layer. According to the analysis results of depth profile, the copper diffused to surface of silver bonding layer and subsequently oxidized to obstacle the bonding formation between gold stud ball bump and silver bonding layer. This result can be used to explain why no one gold stud ball bump can not be boned onto silver bonding layer without titanium diffusion barrier layer at 200℃. With the assistance of titanium diffusion barrier layer, there is no copper out diffused under different bonding temperature, thus a perfect bondability can be achieved.

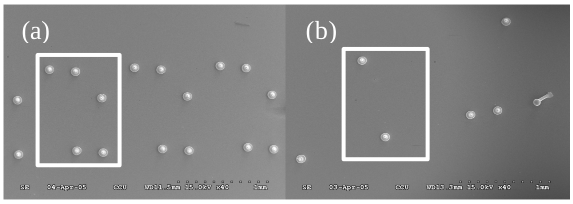

Figure 5 SEM micrographs of bumps bonded onto wafer without titanium diffusion barrier layer at different bonding temperatures, (a)125℃, (b) 150℃.

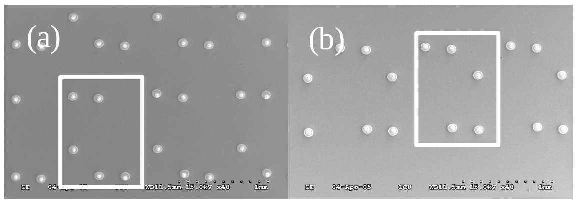

Figure 6 SEM micrographs of bumps bonded onto wafer with titanium diffusion barrier layer at different bonding temperatures, (a)125℃, (b) 200℃.

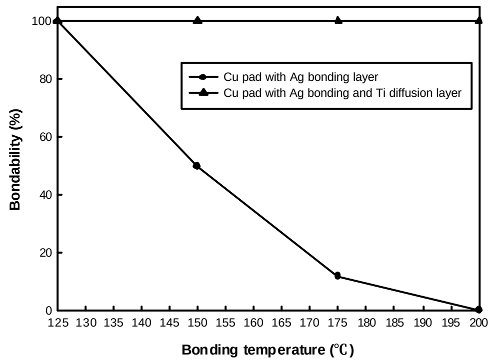

Figure 7 Influence of the bonding temperatures on the bondability, bonding parameters: bonding force: 0.4N, ultrasonic power: 240 mA and bonding time 12ms.

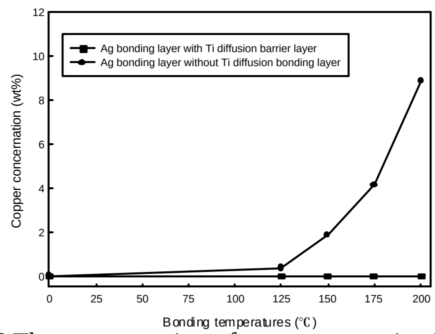

Figure 8 The concentration of copper atoms in silver bonding layer after heated at different temperature for 150 seconds.

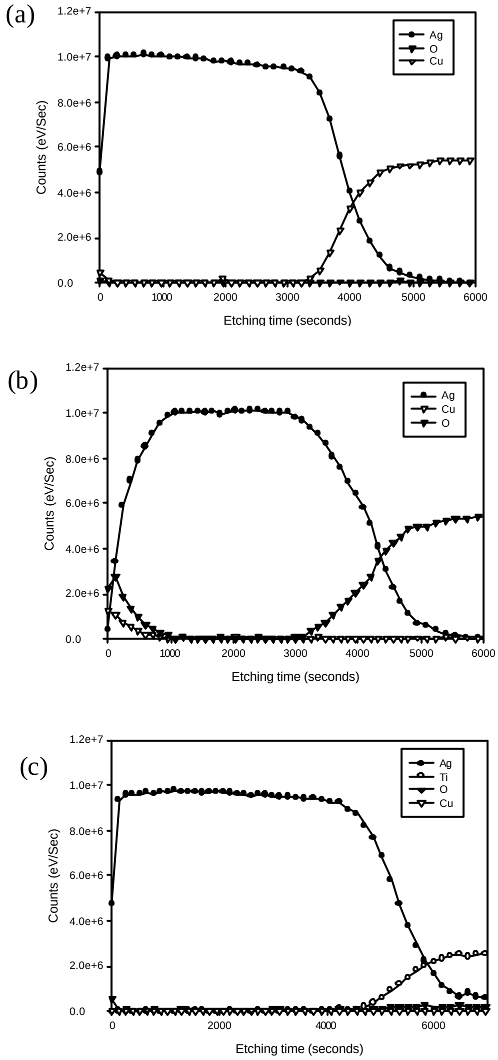

Figure 9 Auger depth profiles of silver bonding layer, (a) without Ti diffusion barrier layer at room temperature, (b) without Ti diffusion barrier layer at 200℃/150s under atmosphere, (c) with Ti barrier layer at 200℃/150s under atmosphere.

2. Evaluation of bonding strength

The influence of the bonding temperature on the stud ball bump bonding strength is illustrates in figure 10. The apparent diameter of stud ball bumps was in the rage between 85μm and 90μm. According to JEDEC standard [13], the minimum requirement on average bonding strength is 40.2g when the apparent diameter of stud ball bump is 95μm. For the stud ball bump bonded on silver bonding layer without titanium diffusion barrier layer under different bonding temperatures, all measured values of bonding strength are far below the minimum requirement stated in JEDEC standard. The bonding strength for stud ball bump bonding to silver bonding layer without titanium diffusion barrier layer was decreases with increasing bonding temperature form 125℃ to 175℃. This result is attribution to copper atom out-diffusion to the surface of silver bonding layer and further oxidized to form a copper oxide layer. The out-diffusion copper atoms increases with increasing bonding temperature as indicated in figure 8. This explains why bonding strength is very low if no titanium diffusion barrier is deposition between copper film and silver bonding layer. Since no stud ball bump bonded on silver bonding layer without titanium diffusion bonding layer at 200℃ as indicated in figure 7. Thus, no bonding strength obtained for stud ball bump bonding to silver bonding layer without titanium diffusion layer at 200℃ as shown in figure 10. In contrast to bonding onto silver bonding layer without titanium diffusion barrier layer, bonding of gold stud bump onto silver bonding layer with titanium diffusion barrier layer exhibits sufficient bonding strength for different bonding temperatures. All the bonding strength is much higher than that minimum requirement stated in JEDEC specification. The bonding strength is increase with increasing bonding temperature form 125℃ to 175℃. It is well know that higher bonding temperature provided more thermal energy to enhance the inter-diffusion between gold stud ball bump and silver bonding layer during thermosonic bonding. However, the bonding strength dramatically dropped further increase boning temperature to 200℃. Too much energy applied to bonding interface to form a golf shape bump as shown in figure 11. It presumes that some defects exhibited in golf shape bump, which results lower bonding strength. Deposition of a titanium diffusion barrier layer is effective to obstacle copper atoms out-diffusion, and the bonding strength of a gold stud ball bump bonding to silver bonding layer can be guaranteed.

To verify the influence of ultrasonic power on bonding strength, different ultrasonic powers were used to perform the gold stud ball bump bonding as shown in figure 12. The bonding strength of gold stud ball bumps bonded onto silver bonding layer with titanium barrier layer increases from 200mA to 240mA and decreases with further increasing ultrasonic power to 240mA. Higher ultrasonic power results in a dynamic strain softening effect on bonding area which eases plastic deformation of gold stud bump an thus a larger bonded area between gold stud bump and silver bonding layer can be achieved as shown figure 13. Larger bonded area generally ensures a higher bonding strength. However, too high an ultrasonic energy causes severe deformation as shown in figure 13(b). The severe deformation ball bump could exhibit some defects which resulting lower bonding strength at high ultrasonic power. The optimal ultrasonic power for gold stud ball bumps bonding to copper pads with silver bonding layer is approximately 240mA. The bonding strength of gold bumps bonded onto copper pads with titanium barrier layer appears much higher bonding strength than JEDEC standard requirement. It is a potential scheme that applied silver bonding layer and titanium diffusion barrier layer to packaging for chips with copper interconnects.

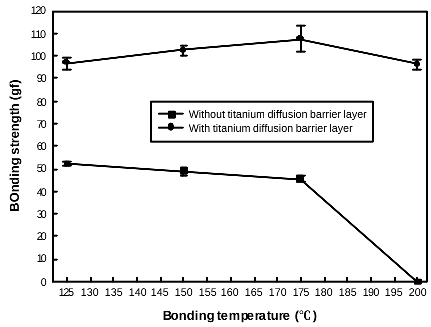

Figure 10 Bonding strength of gold stud bumps bonded onto silver bonding layer with titanium diffusion barrier layer and without titanium diffusion barrier layer under different bonding temperatures..

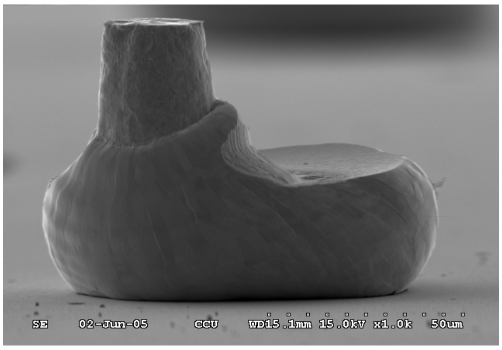

Figure 11 A SEM micrograph shows too high ultrasonic power input resulting a golf shape gold stud bump.

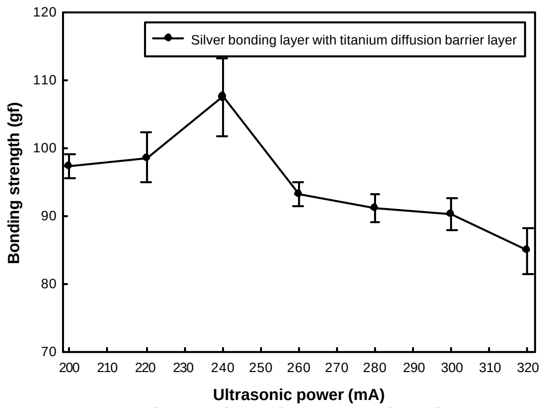

Figure 12 Relationship between bonding power and bonding strength of Au stud ball bump bonding to silver bonding layer with titanium diffusion barrier layer.

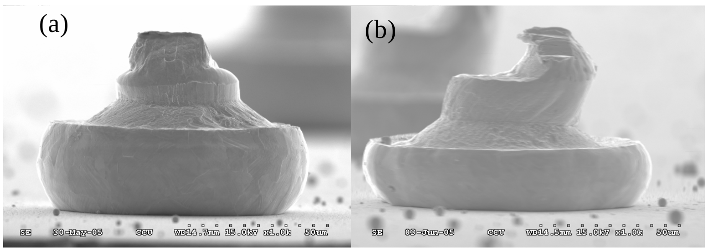

Figure 13 SEM micrographs show the morphology of gold stud bump bonding to silver bonding layer with titanium diffusion barrier layer under different ultrasonic powers, (a) 200mA, (b) 320Ma.

3. Evaluation of failure mode

The SEM micrographs in figure 14 show the failure modes of gold stud ball bump bonded onto silver bonding layer after ball-shear test. The figure 16(a) shows the residue of gold stud ball bump bonded onto silver bonding layer with titanium barrier layer left on the bond pad. The gold stud ball bump bonded firmly to the silver bonding layer with titanium barrier layer after ball-shear test. It is a "type 2" failure according to JEDEC standard [13]. This failure mode indicates that bonding strength between gold ball and silver bonding layer is even stronger than that of gold stud ball bump itself. However, the morphology of residue for gold stud ball bump bonded onto silver bonding layer without titanium barrier layer reveals a "type 1" failure mode according to JEDEC standard [13] as shown in figure 16(b). The bonded ball bump was peeling off from the bonding pad. This reflects the lower bonding strength obtained from ball-shear test. Thus, figure 16 explains itself the superiority of titanium barrier layer.

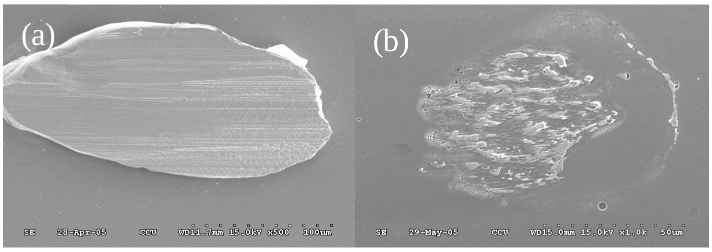

Figure 14 SEM micrographs show the failure mode of gold stud bump bonding to silver bonding to (a) with titanium diffusion barrier layer, (b) without titanium diffusion barrier layer.

4. Simulation of leveling

The bumps formed by thermosonic left a tail on the top of each bump and hence should be leveled to achieve co-planarity. The purpose of this simulation is to predict the transverse expansion of the bump after leveled. The desired height of bump after leveled is considered to be 35 ~ 45 μm to fit the following dispensing of underfill.

During leveling process, a flat leveling tool is required. In this study, we set a rigid plate as a flat leveling tool to press the bumps. And the material used for the bumps is considered to be gold wire manufactured by TANAKA Company. The wire diameter and type of the gold wire are 25μm and FA-type, respectively.

During simulation of leveling, we ignore the effect of friction between flat leveling tool (rigid plate) and bump due to its minor affection to bump deformation. And the whole leveling process is accomplished under room temperature.

Because the bottom surface of the bump is bonded on to bond pad, the bottom surface of the bump is considered constrained on any direction. So we set the BCs to U1 = U2 = U3 = UR1 = UR2 = UR3 = 0

The flat leveling tool should be completely horizontal to press the bumps to achieve co-planarity. Therefore, only vertical direction of the rigid plate is free to move.

The distance between the rigid plate and chip is set to 100 µm. This rigid plate can be controlled by applied force or given displacement.

(1) Given a downward displacement of 65 µm

The rigid plate moved downward for 65 µm. The bump was hence pressed to be 35 µm tall, as shown in Figure 15. The ball diameter after leveled is about 99.3 µm.

The transverse expansion of the bump after leveled is about 10.33%

(2) Given a downward displacement of 60 µm

The rigid plate moved downward for 60 µm. The bump was hence pressed to be 40 µm tall, as shown in Figure 16. The ball diameter after leveled is about 94 µm.

The transverse expansion of the bump after leveled is about 4.44%

(3) Given a downward force of 0 ~ 1 N during 1 second (ramp) to the rigid plate

The height of leveled bump is 46 µm. The cross section of the leveled bump is shown in Figure 17. the ball diameter after leveled is about 91 µm.

The transverse expansion of the bump after leveled is about 1.11%

(4) Given a downward force of 0 ~ 0.5 N during 1 second (ramp) to the rigid plate

The height of leveled bump is 54 µm. The cross section of the leveled bump is shown in Figure 18. the ball diameter after leveled is about 90.3 µm.

The transverse expansion of the bump after leveled is about 0.33%

(5) Given a downward displacement of 55 µm

The rigid plate moved downward for 55 µm. The bump was hence pressed to be 45 µm tall, as shown in Figure 19. The ball diameter after leveled is about 90.9 µm.

The transverse expansion of the bump after leveled is about 1%

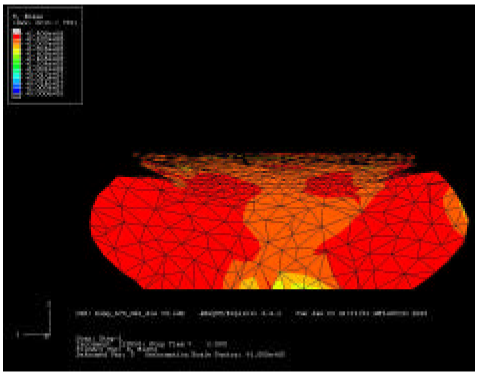

Figure 15 Cross section of leveled bump (35µm, displacement control).

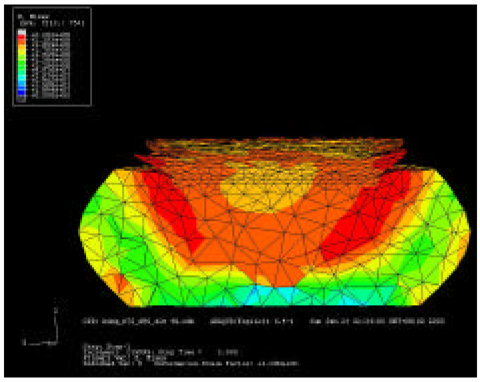

Figure 16 Cross section of leveled bump (40µm, displacement control).

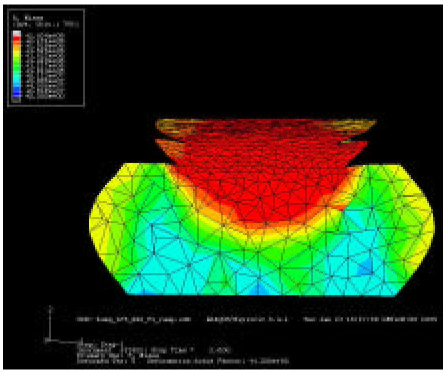

Figure 17 Cross section of leveled bump (46µm, force control, 0-1N with ramp profile).

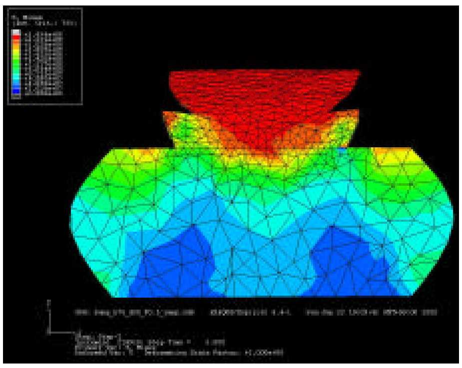

Figure 18 Cross section of leveled bump (54µm, force control, 0-0.5 N with ramp profile).

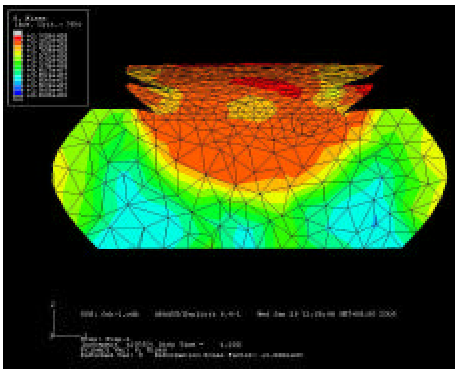

Figure 19 Cross section of leveled bump (45μm, displacement control).

Conclusions

One hundred percent bondability of gold stud bumps bonding to silver bonding layer with titanium barrier layer can be achieved. Bonding strength of gold bumps bonded to silver bonding layer with titanium barrier layer far exceed the minimum requirements stated in JEDEC specifications. As above results on bondability and bonding strength study, deposition of a titanium diffusion barrier layer between the copper pad and silver bonding layer has been proved to be an effective way in achieving superior bonding quality for thermosonic stud bump bonding of gold bumps onto chips with copper interconnects.

From the simulation of leveling, the expansion of leveled bump will not be higher than 10% with proper parameters. Hence, the leveling process can be conducted without concern of short circuit when bump height after leveling is controlled.

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