Assembly Technology for Fine Pitch Bumps Using Photodefinable Wafer-Level Underfill

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Photodefinable wafer-level underfill (PWLUF) has been developed to avoid the underfill entrapment which causes mechanical and electrical reliability issues with fine bumps. In this paper, firstly, we report the appropriate stacking profile to obtain void-free stacks, explaining the PWLUF process flow and the melt viscosity after patterning. Secondly, the lower pressure soldering on thermal compression and collective reflow soldering without any underfill entrapment were demonstrated. It means that this PWLUF was designed to have enough low viscosity after photo-curing for patterning. The stacked sample has enough high adhesive strength even after moisture absorption and passed moisture sensitivity level 2 (JEDEC MSL2). Finally, we demonstrated the compatibility with Cu-Cu bonding application comparing with conventional no-flow type underfills (NUF).

Key Words: Underfill, Reflow Soldering, Cu-Cu Bonding, Through Silicon Via, Interposer

1. Introduction

Three-dimensional integration technology using through silicon via (TSV) enables lower power and high bandwidth due to shorter interconnection length. The applicable electrical interconnection pitch for TSV and flip chip becomes narrower. Underfill materials are filled between organic/inorganic substrate and chip for stress relief and reinpressurement of bump soldering. The conventional capillary underfill is difficult to apply to the package with fine pitch bumps because there are unfilled areas and voids by the capillary process after stacking. Therefore pre-applied wafer level underfill (WLUF), which is formed to the whole wafer by lamination or spin coating, has been investigated. During the bonding process, WLUF material must flow not to be trapped between bump and pad. The underfill entrapment worsens the reliability of device by interference of intermetallic compound growth between bumps. As the bump numbers increase and the pitch narrows furthermore, it will be more difficult to push out the underfill on the top of bumps. Also it is needed to achieve good bump soldering with lower bonding pressure to reduce the stress and adapt to chip-to-wafer and wafer-to-wafer stacking method. Furthermore, the control of overflowed underfill is key point for multi-die stacks with fine pitch bumps. In order to solve above issues, photodefinable wafer level underfill (PWLUF) was developed and its design concept was verified, that is, the removal of underfill on the top of bumps enables the excellent quality of bump connection without underfill entrapment. It also can control the amount of overflowed underfill. Pre-applied underfill has productivity issue due to high temperature bonding one by one. In this paper, we report reflow soldering assembly results and moisture absorption reliability to improve the productivity and also Cu-Cu direct bonding results using PWLUF.

2. Assembly structure and experimental materials

Table 1 shows the test vehicle design for assembly evaluation. Fig.1 shows the overview of test chip and detailed bump structure. The top chip has 38 μm square bumps with solder and the bottom chip has 58 μm square pads. The 42 μm thick PWLUF was evaluated from underfill volume calculation after stacking. PWLUF was laminated on the top wafer at 80 °C and it covered the bumps. The underfill resin on bumps was removed completely. The top chips with patterned PWLUF were stacked with the bottom chips. The electrical yield, voids or delamination inspection from constant-
depth mode scanning acoustic microscope (SAM) and soldering quality from cross-sectional scanning electron microscope (SEM) were observed as assembly evaluation.

Another test vehicle was designed by IMEC for Cu-Cu assembly evaluation (Table 2). The top chip has Cu bumps with 15 μm diameter and the bottom chip has Cu bumps with 25 μm diameter. 8,250 bumps were designed in full area. Fig.3 shows schematic cross-section of bumps and the overview of stacked sample. Fig.4 shows Cu-Cu bonding assembly process flow using NUF and PWLUF. In the case of NUF evaluation, the appropriate amount of NUF was dispensed on the bottom chips. In the case of PWLUF evaluation, PWLUF was laminated at 80°C on the bottom wafer. PWLUF on bumps and dicing line was removed by lithography process. The wafer was diced to obtain the chips with patterned PWLUF.

PWLUF is designed as negative tone photosensitive material including polyimide as base polymer, acrylate as photocuring agent, epoxide as thermal curing agent and some additives. From the viewpoint of productivity, the thermal compression bonding time should be within 10 s. It is desirable that the underfill is cured pushing the voids out of chips. The voids are generated by outgas due to rapid heating. The outgas compositions during heating measured by gas chromatography were mainly TMAH and epoxide. For pre-applied underfill, it is important to control outgas, thermal curing and underfill flow by bonding profile to reduce the remaining voids between chips. To fix the appropriate
bonding temperature profile, the relationship between PWLUF viscosity after patterning and temperature was measured (Fig.5). The curve shows the lowest viscosity range from 150 °C to 180 °C and increase of viscosity over 160 °C by the thermal reaction. The thermal curing kinetic at each temperature was simulated by Kamal and Souerour phenomenological model using differential scanning calorimetry (DSC)\(^5\)\(^,\)\(^6\). Fig.6 shows the conversion ratio of thermal curing in PWLUF at 150, 180, 200 and 210 °C. The conversions over 200 °C reached higher than 50 % within 5 s. The rapid thermal reaction at high temperature tends to generate some voids. We decided to set the step temperature profile at lower than 200 °C.

### 3. Influence of the bonding profile on soldering quality

Fig.7(a) shows the four types of actual bonding temperature profile, which are 135 °C step (Profile 1), 150 °C step (Profile 2), 180 °C step (Profile 3), and non-step (Profile 4) as reference. The internal actual temperature between chips during thermal compression bonding was measured by putting in a thermocouple in advance. We have studied the influence of bonding temperature on soldering quality keeping 20 MPa bonding pressure per bump and 7s bonding time as shown in Fig.7(b). Fig.8 shows SAM images after bonding by four conditions. There were large areas of voids in Profile 4 and some voids in Profile 3. We assumed that higher step temperature or non-step bonding tend to generate

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**Fig.5** PWLUF viscosity curve after patterning. Temperature elevation rate for measurement is 10 °C/min.

**Fig.6** Simulated thermal curing kinetics by Kamal Sourour model at 150, 180, 200 and 210 °C.

**Fig.7** Four types of bonding temperature profiles, Profile 1, 2, 3 and 4 include 135 °C step, 150 °C step, 180 °C step and non-step, respectively. Soldering temperature is 280 °C (a). Bonding pressure per bump is 20 MPa (b).

**Fig.8** SAM images of stacked sample obtained by four types of bonding temperature profiles.
much more outgas from PWLUF by rapid thermal reaction. On
the other hand, in the case of Profile 1 and Profile 2, clear voids
were not observed. Fig.9 shows the cross-sectional SEM images
of soldering bumps obtained by Profile 2. The stacked samples
achieved excellent soldering quality without any underfill
entrapment between bumps and 100 % electrical yield. These
results indicate that PWLUF has been designed to have enough
low viscosity even after photocuring for patterning.
In the case of pre-applied underfills such as no-flow type
underfill (NUF) and non-conductive film (NCF), higher bonding
pressure than 20 MPa per bump is required to push out the
underfill on bumps. However, high bonding pressure is
incompatible for the increasing fine pitch bumps because of the
pressure limit and planarization issue of bonding instrument.
We have studied the influence of bonding pressure on soldering
quality to verify whether the patterned PWLUF enables lower
pressure bonding. Fig.10(a) shows three types of bonding
pressure profiles, which are 20 MPa as normal pressure (Profile 2),
7 MPa (Profile 5) and 3 MPa (Profile 6). The step temperature
and bonding time were fixed at 150 °C and 7s, respectively as shown
in Fig.10(b). Fig.11 summarizes the electrical yield, SAM images
of stacked samples and cross-sectional SEM of soldering bumps
obtained by each bonding pressure profile. The stacked samples
over 7 MPa achieved excellent electrical yield, no underfill
entrapment and no voids. On the other hand, the stacked samples
by 3 MPa showed no soldering. Fig.12 shows the underfill
fillet, which means flowed underfill out of chips, overview and
cross-sectional SEM image of stacked sample by Profile 5. The
underfill fillet showed ideal shape for the mechanical reliability
covering the corner of chip as shown in Fig.12(b). There were
less fillet length by lower bonding pressure as shown in Table 3.
This means that the low bonding pressure such as 3 MPa is not
enough to push out the underfill for bump soldering. From these
results, we have verified that PWLUF enables lower bonding
pressure such as 7 MPa (25 N per chip).

Fig.9 Cross sectional SEM image of soldering bumps obtained by Profile 2.

Fig.10 Three types of bonding pressure profiles, Profile 2, 5 and 6 are 20
MPa, 7 MPa and 3 MPa, respectively(a). Step temperature is fixed
at 150 °C (b).

Fig.11 Electrical yield, SAM images of stacked samples and cross-
sectional SEM images of soldering bumps obtained by Profile 2, 5
and 6, respectively.

Fig.12 Underfill fillet overview (a) and cross-sectional SEM image (b) of
stacked sample by Profile 5.
4. Collective reflow soldering method

Pre-applied underfill has faced the productivity issue because the chips with the underfill require bonding at high temperature over 260 °C for many times. This causes not only too long cycle time by heating up and cooling down of bonding tool but also thermal damage or Cu pad oxidation of bottom wafer in the case of chip on wafer stacking method. We have studied the process compatibility to verify whether the patterned PWLUF enables collective reflow soldering, which gives bump soldering by wafer level reflow process after temporary bonding of chip on wafer at 4s by 20 MPa pressure for alignment as shown in Fig.13. In the case that the top chip attached on the bottom wafer at 25 °C and 80 °C for the alignment, all chips are delaminated from the wafer. On the other hand, the alignment bonding at 120 °C and 150 °C afforded enough underfill flow for adhesion. The obtained samples passed through reflow oven which profile set as shown in Fig.14. Fig.15 shows the cross-sectional SEM images of soldering bumps after the alignment bonding and reflow process. Table 4 includes electrical yield of samples obtained by each alignment temperature and reflow process. The stacked sample by alignment bonding at 150 °C and reflow process achieved the excellent bump soldering and electrical yield though the sample by alignment bonding at 120 °C and reflow process has voids because of poor underfill flow. This collective reflow soldering process is quite suitable for the chip on wafer stacking method with good productivity due to no need of 260 °C bonding tools.

The obtained samples were put in the thermos-hygrostat at 85 °C, 60 %RH for 168 h for moisture absorption reliability evaluation. Table 5 shows the shear adhesive strength after reflow and moisture absorption using stacked bare silicon chips without bumps by alignment bonding at 150 °C and reflow process. PWLUF has quite high adhesion strength even after moisture absorption. Fig.16 shows the cross-sectional SEM and SAM images of stacked sample after moisture sensitivity level 2 (JEDEC MSL2)9. There were no delamination of bump soldering and voids. From these results, the stacked samples obtained by collective reflow soldering method passed MSL2.

5. Cu-Cu direct bonding application

As the bump pitch becomes narrower, the solder on Cu bumps become thinner to prevent the electrical short due to the overflowed solder. Furthermore Cu-Cu direct bonding is ideal connection from the view point of electrical performance. However the underfill entrapment becomes more critical issue for these bumps connection such as thinner solder on Cu or Cu-Cu. We have studied Cu-Cu direct bonding application of PWLUF. The bonding pressure was 50 MPa and the time was 300 s to
obtain good Cu connection. The step and maximum interface actual temperature were 150 °C and 300 °C, respectively. Fig.17 shows cross-sectional SEM images of Cu-Cu bonding bumps using two kinds of NUF without filler (a) and with filler (b). In the case there is enough solder on Cu, NUF can flow out from the parts of bump soldering together with solder during bonding. In the case of Cu-Cu bonding, the trapped NUF left between bumps as shown in Fig.16. We couldn’t achieve better connection by changing the bonding conditions such as the pressure, time and temperature. In contrast, cross-sectional SEM images demonstrate PWLUF achieved seamless Cu-Cu bump as shown in Fig.18. These results indicate PWLUF concept is suitable for Cu-Cu direct bonding because the stacked samples using NUF, which is liquid type and has enough low viscosity, have much underfill entrapment. The surface roughness and height variation of Cu bump before stacking need to be improved to achieve more excellent junction in the whole area.

6. Conclusion

We have evaluated appropriate bonding profile, collective reflow soldering and Cu-Cu bonding assembly using PWLUF. The stacked sample by 150 °C step profile obtained 100 % electrical yield and excellent bump soldering without any underfill entrapment between bumps. In addition we could verify that this PWLUF was designed to have enough low viscosity even after photocuring for patterning. The stacked samples show 100 % electrical yield with no underfill entrapment and no voids by low bonding pressure such as 7 MPa as well. The collective reflow soldering was successfully demonstrated by alignment bonding at 150 °C. This result indicates that PWLUF has good compatibility with high productive process of chip on wafer assembly. Finally the Cu-Cu bonding was demonstrated to take advantage of no underfill entrapment property. The conventional pre-applied underfill such as NUF showed no Cu-Cu bump because of the entrapment. The stacked samples with PWLUF achieved seamless Cu-Cu bump.

**Table 5** Shear adhesive strength at 260 °C after reflow and moisture absorption.

| Process | After reflow | After moisture absorption* |
|---------|--------------|---------------------------|
| Shear adhesive strength at 260 °C | 4.0 MPa | 2.3 MPa |

* 85 °C, 60%RH, 168 h

**Fig.16** Cross-section SEM (a) and SAM (b) images of stacked sample after MSL2.

**Fig.17** Cross-sectional SEM of bumps obtained by Cu-Cu direct bonding using NUF without filler (a) and with filler (b).

**Fig.18** Cross-sectional SEM of bumps obtained by Cu-Cu direct bonding using patterned PWLUF.

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