Insertion Bonding: A Novel Cu-Cu Bonding Approach for 3D Integration

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Abstract

A novel low temperature Cu-Cu bonding approach called the insertion bonding technique has been developed. This technique leverages on the initiation of high shear stresses at metal-metal contact interface, thus resulting in high plastic deformation, which is essential for strong bond formation. Through finite element studies, it is observed that the insertion bonding technique result in significantly larger plastic deformation in comparison to the conventional bonding technique under the same bonding conditions. Experimental studies of the insertion bonding technique were performed and it is observed that a seamless bond interface is achieved, even at a low bonding temperature of 100°C. Bonding at room temperature (RT) in the presence of a surface cleaning agent resulted in an improved bond interface.

Resistance measurement of the samples bonded at 100°C revealed that an electrical contact is achieved between the stacked dies. This shows that the insertion bonding techniques holds much promise for low temperature Cu-Cu bonding.

Introduction

3D integration of devices with via first or 3D Stacked IC (3D SIC) type of through silicon via (TSV) integration has been one of the more recent focus of the semiconductor industry for miniaturization and performance enhancement. While there are different techniques for achieving interconnection between the different chip tiers, Cu-Cu thermo-compression bonding of Cu-TSVs to landing pads is one of the low cost approaches previously explored [1]. Cu-Cu thermo-compression bonding process is a solid state diffusion bonding process by which two nominally flat surfaces are joined at elevated temperature by applying an interfacial pressure [2]. Thus, bonds are formed by the inter-diffusion of atoms and grain growth between the two surfaces that are in contact [3]. However, different parameters influence bond formation such as, the bonding time, bonding surface roughness, bonding temperature, annealing temperature, annealing time, bonding pressure and the contamination level of the contacting surfaces [3-6].

In recent times, a lot of studies have been conducted on the achievement of Cu-Cu bonds. K. N. Chen et al [5] developed a morphology and strength map that shows that the minimum temperature required to achieve a strong Cu-Cu bonding is at about 300ºC. Figure 1 shows a Cu-Cu bonding of Cu-TSV on a flat landing pad of the bottom die at a bonding temperature of 350°C. The bonding interface is invisible, this shows that good bond has been achieved at this bonding temperature.

However, this high temperature budget could be detrimental to the performance of advanced devices. Y. I. Kim et al [7] showed in his studies that such high temperature degrades the performance of DRAMs.

Thus, there is a need for low temperature solutions for Cu-Cu bonding for 3D chip stacking.

In order to achieve this, one needs to understand not only the afore mentioned bonding parameters, but also the operating mechanisms that initiate bond formation. These operating mechanisms- surface diffusion, plastic deformation, creep, grain boundary diffusion and interface diffusion have been shown to be interlinked [2, 8].

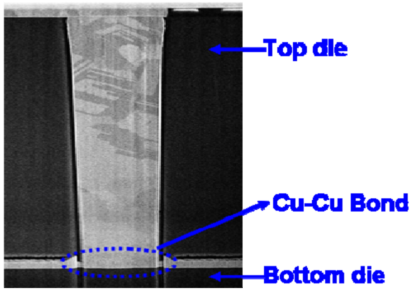


Figure 1: 3D chip stacking at a bonding temperature of 350°C achieved by the conventional Cu-Cu bonding technique

Thus, optimization of the operating mechanisms and the bonding parameters could lead to a low temperature solution for Cu-Cu bonding in 3D chip stacking. Based on this premises, we developed a novel low temperature Cu-Cu bonding approach called insertion bonding, which is the focus of this present paper.

The Insertion Bonding Technique Concept

The concept of insertion bonding technique hinges on the introduction of high shear stresses at metal-metal interface, thus resulting in a high localized plastic deformation, which aids bond formation.

In this technique, a top chip having extruding metal bump structure mates with the bottom chip which has sloped metalized hole (see figure 2).

This mating hole is characterized by a sloped metal sidewall, in which the diameter of the bottom of the sloped hole ($\varnothing_b$) is less than the diameter of the top chip metal bump ($\varnothing_t$). And the top diameter of the hole ($\varnothing_{bt}$) is slightly larger than the diameter of the metal bump ($\varnothing_t$), with an amount that compensates for the alignment tolerances in placing the bumped top chip in the mating bottom chip.

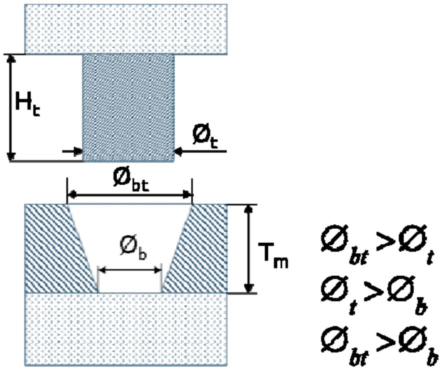
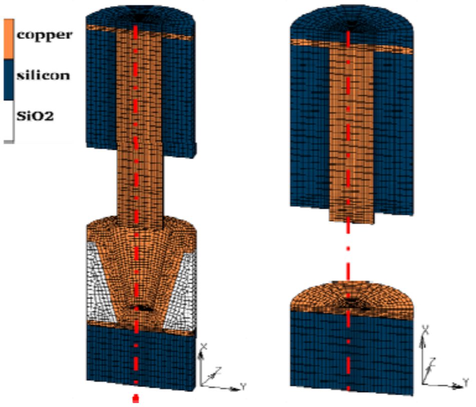


Figure 2: A schematic drawing of the insertion bonding technique.

Where,

- Diameter top bump = $\boldsymbol{Ø_t}$
- Height of the top metal bump = $\boldsymbol{H_t}$
- Diameter at bottom of the substrate “hole” = $\boldsymbol{Ø_b}$
- Diameter at top of the substrate “hole” = $\boldsymbol{Ø_{bt}}$
- Height of bottom metal = $\boldsymbol{T_m}$



(a) (b)

Figure 3: Axisymmetric model description; (a) Insertion bonding (b) Conventional bonding techniques.

Therefore during bonding, the metallic bump first makes contact with a small part of the sloped sidewall of the mating metal substrate. Due to the contact with the sloped surface, the perpendicular applied force, translates into a high shear stress along the bump/pad metal interface, allowing for more easy plastic deformation at the contact area. As the bump is pushed deeper in the mating substrate, the contact area will gradually increase and the bump will further deform plastically. The result is a more effective bonding than the conventional thermo-compression bonding approach, with however a smaller final contact area.

To verify the insertion bonding concept for Cu-Cu bonding, first of all, a feasibility study is performed by finite element modeling (FEM). Based on the FEM results, experimental studies are conducted.

Finite Element Modeling Study

FEM using MSC Marc software is used to prove the merits of insertion bonding over the conventional bonding technique where a flat bonding pad is used. An axisymmetric model is used with the contact analysis feature. In order to avoid singularity and convergence errors due to large deformation, element remeshing feature is implemented. Additionally, the frictional force between the two mating parts is accounted for; a coefficient of friction of 0.35 is used.

While silicon and silicon oxide materials are modeled as elastic materials, copper is modeled as an elastic-plastic material having temperature dependent yield strength from [9].

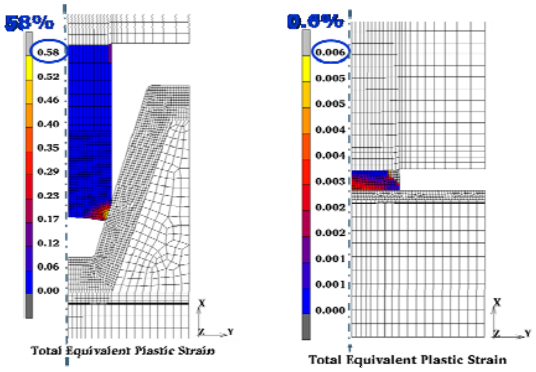
The values of the used material properties for FEM modeling are shown in table 1.

Table 1: *Material Properties implemented in FEM*

Material	**Young’s Modulus (GPa)**	**Poisson Ratio**	**CTE (ppm/°C)**
Silicon	169	0.26	2.3
SiO_2	75	0.17	0.5
Copper	117	0.35	16.7

A parametric study of the bonding temperature (RT-350ºC) and bonding force (0.5-2.5mN) is done for both insertion bonding and the conventional bonding techniques. The nominal values of 300ºC, 1mN respectively is used for the bonding temperature and force, while a sidewall slope angle of 18º is used for the insertion bonding technique.

A bonding criterion of 1% plastic deformation is assumed as the threshold for bond formation to occur between the recessed Cu-TSV and the sloped bond pad. This criterion is used to calculate the plastically deformed volume.



(a) (b)

Figure 4: Shows the plastic deformation achieved in the Cu-TSV at the nominal bonding temperature (300°C) and force (1mN per bond) for (a) the insertion bonding technique (b) the conventional bonding technique.

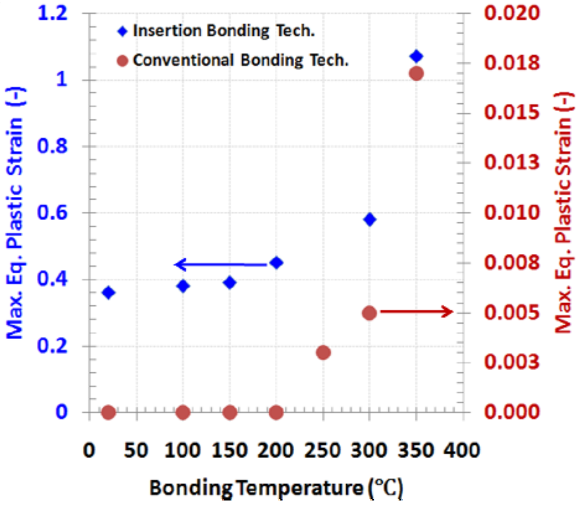


Figure 5: Shows the plot of the maximum equivalent plastic deformation achieved in the Cu-TSV at a nominal bonding force of 1mN for different bonding temperatures.

Figure 4 shows the results of the plastic deformation in the Cu-TSV for both the insertion bonding and the conventional bonding techniques at the nominal bonding temperature (300°C) and force (1mN). It could be observed that under the same applied temperature and force that maximum achieved plastic deformation for the insertion bonding (58%) is about two orders of magnitude larger than the conventional bonding technique (0.6 %). This is because in the insertion bonding technique, the use of a sloped landing pad that is tangential to the Cu-TSV results in the initiation of deviatoric stresses which are the stress components that are responsible for plastic deformation. Since the Cu-TSV is perpendicular to the landing pad in the conventional bonding technique, little deviatoric stresses are achieved, thus resulting in low plastic deformation.

A parametric study of the effect of bonding temperature on the achieved maximum plastic deformation in the Cu-TSV (figure 5) at a nominal force of 1mN shows that the increase in bonding temperature aids plastic deformation. This is true for both bonding techniques. However, the insertion bonding technique shows considerable plastic deformation even at room temperature (36%). This is not true for the conventional bonding technique for which below a bonding temperature of 250°C the maximum plastic deformation is below 0.1%. This finding for the conventional bonding technique correlates well with experimental works reported by [5] in which the authors observed that Cu-Cu bond formation below 250°C greatly deteriorates.

However, a better yardstick for quantifying bond formation is looking at the plastically deformed volume instead of the maximum plastic deformation values. Figure 6 shows the calculated plastically deformed volume of the Cu-TSV for the two bonding techniques assuming a 1% plastic deformation criterion for bond formation.

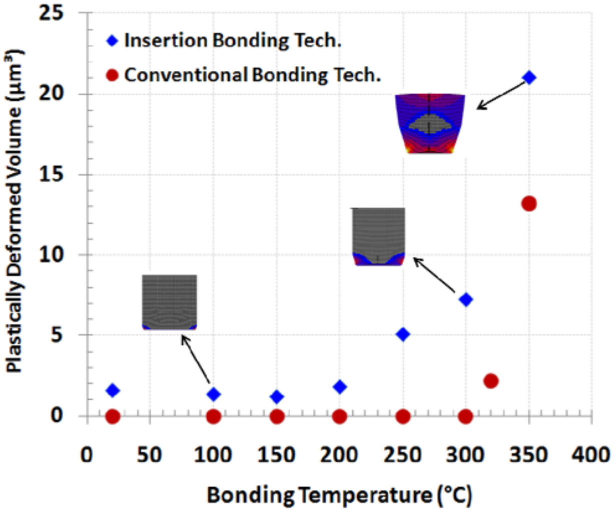


Figure 6: Calculated plastically deformed volume at different bonding temperatures assuming a 1% plastic deformation criterion.

From figure 6, it is observed that for the conventional bonding technique, 1% plastically deformed volume threshold is only achieved at bonding temperatures above 300ºC, while for the insertion bonding technique even at room temperature (RT) more than 1% plastic deformation is achieved.

Another bonding parameter of interest is the bonding force. A parametric study of impact of the applied bonding force on plastic deformation for the two bonding techniques is studied in figure 7. The plastically deformed volume is shown to scale with increasing bonding force. At a bonding force of 0.5mN about 5μm³ plastically deformed volume of the Cu-TSV in the insertion bonding technique attains the set 1% plastic deformation criterion, while it is only after 1.5mN bonding force that we observe a significant deformation volume for the conventional bonding technique. The differences observed between the two techniques for the bonding force could be attributed to the fact that the contact area between the mating parts is much smaller for the insertion bonding technique than the conventional bonding technique.

This leads to higher pressure, thus, higher plastic deformation in the former technique. Thus, insertion bonding technique seems to be a promising technique for both low temperature and force Cu-Cu bonding.

Further simulation studies are performed to optimize the insertion bonding technique, in which the slope of the landing pad is varied (figure 8). It is observed that steeper sidewall landing pad resulted in larger plastically deformed volume. This is because steeper sidewall results in larger mating area, which leads to an increase in the deformed area.

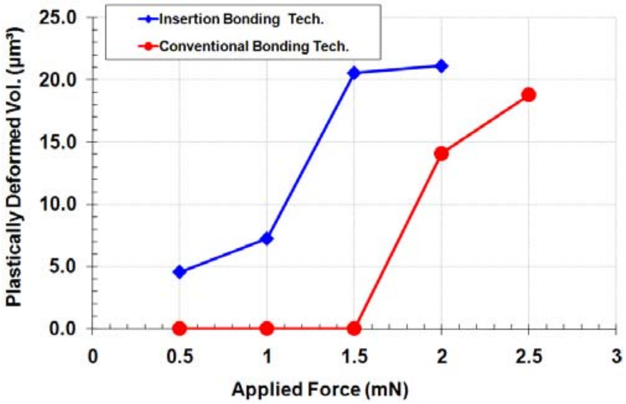


Figure 7: Calculated plastically deformed volume for different bonding forces at a bonding temperature of 300°C, assuming a 1% plastic deformation criterion.

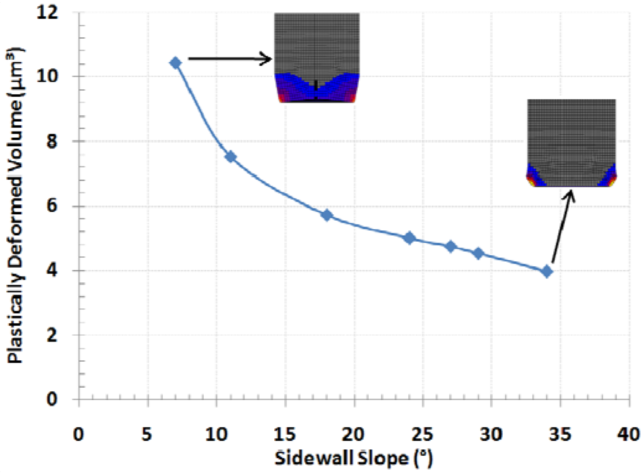


Figure 8: Influence of sidewall steepness on the achieved plastically deformed volume for the insertion bonding technique at a bonding temperature and force of 300°C and 1mN respectively, assuming a 1% plastic deformation criterion.

Therefore, the insertion bonding technique could be further optimized by varying the sidewall slope; however, the optimum point will be determined by the alignment tolerance of the pick-and-place tool used for the stacking process.

Insertion Bonding Technique: Experimental Results

Insertion bonding experiments are performed on post processed 5µm diameter Cu-TSVs. These samples are fabricated using IMEC's 3D-SIC approach [10]. Longer recess etch process is used to expose ~10µm Cu-TSV of the top die. The shape of the landing pad is modified such that the Cu-TSV can be inserted into the landing pad.

The sloped landing wafer is fabricated by depositing oxide on top of metal tracks. The oxide is then dry etched to get a tapered profile. Cu seed layer is sputter coated on the wafers followed by lithography and Cu electroplating. The samples are cleaned in a cleaning solution to remove Cu oxide and SET FC150 flip chip bonder is used for the die to die bonding. Table 2 shows the different conditions used for the bonding experiment. In this experimental set up the bonding force and the cleaning conditions are kept constant except for the second test set done at RT in which the bonding process is performed in the presence of a cleaning agent.

Table 2: Shows the bonding conditions used for the insertion bonding experiment.

Serial Number	Bonding Temp. (°C)	Applied Force per bond (mN)	Treatment
1	RT	2	Sample Cleaned
2	RT	2	Sample Cleaned + Bonding in the presence of cleaning agent
3	100	2	Sample Cleaned

Figure 9 and 10 shows a cross-sectional SEM image of the achieved bonding by insertion bonding at RT in which the sample is only cleaned in a cleaning solution before bonding. An obviously plastically deformed Cu-TSV is observed, whose diameter narrows down in the sloped landing pad. This is in agreement with the prior FEM studies for insertion bonding (figure 5 and 6) which showed that recessed Cu-TSV plastically deforms at RT. Cu-Cu bonding is achieved at RT conditions, however as could be seen in the inserted image in figure 10, the bond interface between the recessed Cu-TSV and the landing pad is still very visible.

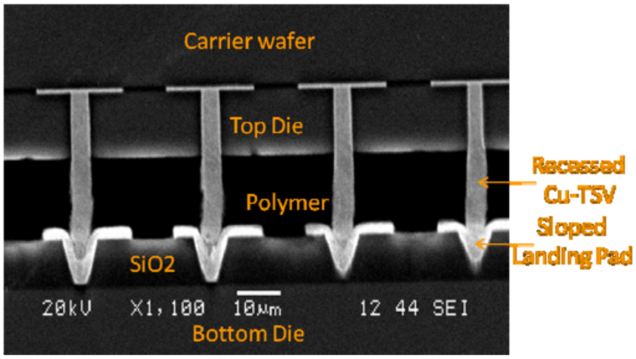


Figure 9: Cross-sectional SEM image of bonded dies achieved by insertion bonding at RT. (Low magnification)

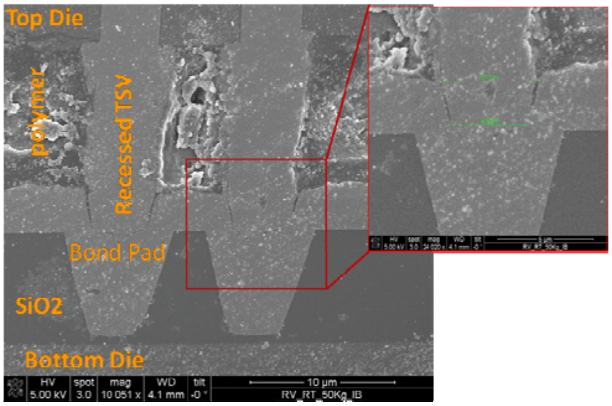


Figure 10: High magnification SEM image showing two stacked dies bonded at RT using insertion bonding technique after a sample cleaning.

This means that though there is an evidence of plastic deformation at the TSV/landing pad interface, it was not sufficient to establish inter atomic diffusion and grain growth across bond interface. Hence, the bonding parameters need to be further optimized.

To further optimize the bonding conditions, the bonding process is carried out at RT in the presence of a cleaning agent. The achieved bonding using this second test set is shown in the SEM image in figure 11. It can be observed that in the inserted image that the bond interface between the recessed Cu-TSV and the landing pad is partially invisible.

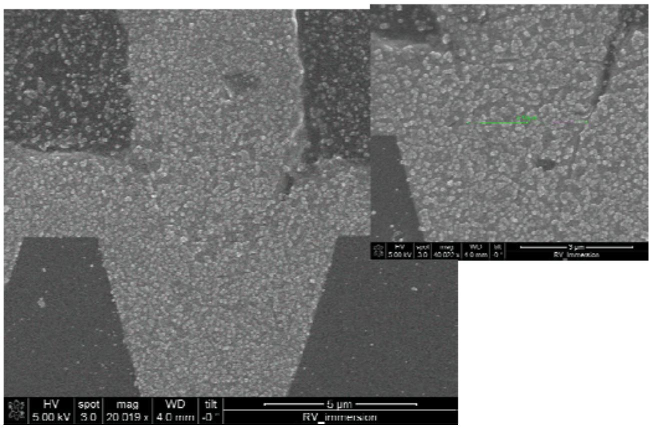


Figure 11: SEM image of stacked dies for which the bonding is done in the presence of a cleaning agent at RT. Inserted image shows that partial seamless bond interface is achieved.

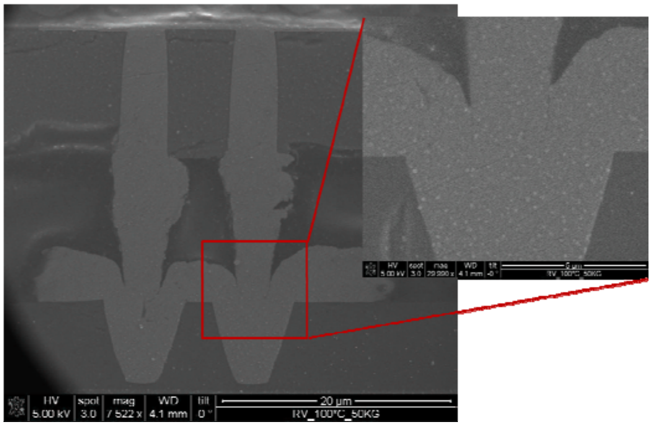


Figure 12: SEM image of insertion bonded stacked dies achieved at a bonding temperature of 100°C after prior cleaning. Inserted image shows a seamless bond interface between the recessed Cu-TSV and the sloped landing pad.

Thus, resulting in a better bond quality than that shown in figure 10, where the samples were only cleaned prior to bonding. This means that the presence of a cleaning agent during the bonding process enables improved bond formation. This is because it removes surface contaminates such as oxides, thus leading to an unhindered mating of the Cu-TSV and the sloped landing pad, that results in better Cu-Cu bond.

This showcases the importance of having a super clean surface for bonding which is in agreement with the findings of [3].

In the third experimental set shown in table 2, chip stacking is achieved at a bonding temperature of 100°C after the cleaning of the mating surfaces. As could be seen in figure 12, a more seamless bond is formed at the interface between the recessed Cu-TSV and the landing pad.

Also, more plastic deformation of the recessed Cu-TSV is observed. This is attributed to the higher bonding temperature of 100°C that is used. Higher bonding temperature results in lower yield stress, and consequently more plastic deformation. This is in agreement with the FEM results discussed earlier in which it is observed that higher bonding temperature resulted in larger plastic deformation (see figures 5 and 6). Moreover, higher temperature allows for more inter-diffusion of atoms across the bond interface, which leads to a much better bond formation.

Electrical measurements were performed using a 4-point nano-prober on the samples that were bonded at 100°C. This measurement is done on the cross-sectioned surface. The resistance measurement for five Cu-Cu bonds are shown in figure 13, which confirms that an electrically yielding bond is formed by the insertion bonding approach. However, a high average resistance value of 584 mΩ is observed, as compared to the standard 5µm diameter Cu-TSV resistance of about 20 mΩ [11]. This high resistance is attributed to the limited contact area between the Cu-TSV and the sloped landing pad and to the fact that the nano-probe measurement is performed on cross-sectioned samples instead of full diameter Cu-TSVs.

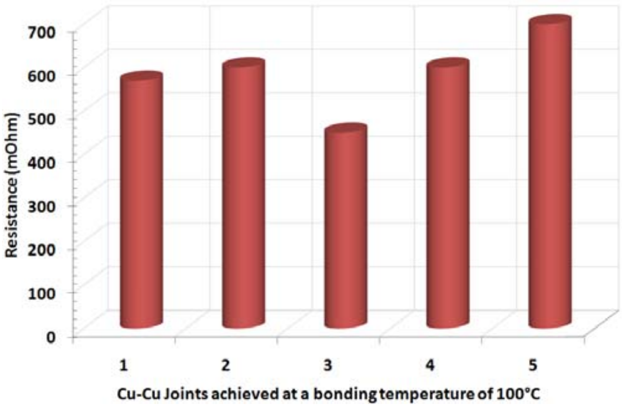


Figure 13: Shows the resistance measurement of bonds formed by the insertion bonding technique. (Resistance measurement is done on cross-sectioned sample).

Thus, further optimization of this bonding approach is required. This could be achieved by making the landing pad sidewalls steeper, thus resulting to larger contact area and by the use of a cleaning agent during bonding to avoid oxide formation at the interface during bonding at 100°C.

Conclusions

A novel bonding approach called the insertion bonding technique is proposed as a possible solution for low temperature and force bonding for 3D stacking of chips by Cu-Cu bonding. This bonding technique relies on the introduction of high shear stresses to yield large plastic deformation. This is achieved by the use of a sloped sidewall landing pad instead of the conventional flat landing pad.

FEM is used to study the feasibility of this technique. It is found that insertion bonding technique resulted in plastic deformation that is two orders of magnitude larger than the conventional technique. High plastic deformation is witnessed at low temperatures and forces, making it a potential candidate to low temperature and force Cu-Cu bonding. The insertion bonding technique could further be optimized by varying the slope of the landing pad sidewall; however the optimal point will be influenced by the alignment tolerance of the pick-and-place tool that is used.

Experimental studies were performed; they also confirm that insertion bonding technique is suitable for low temperature bonding. It is observed at a bonding temperature of 100ºC, that a seamless bond interface is achieved between the Cu-TSV and the sloped landing pad. This is about 200ºC lower than the required temperature for achieving Cu-Cu bonding based on the conventional bonding approach. For bonding done at RT, the interface between the Cu-TSV and the sloped landing pad could obviously be seen. However, when bonding is done at RT in the presence of a cleaning agent an improved bond interface is observed.

Resistance measurement of the single bonds achieved at a bonding temperature of 100ºC revealed that an electrically yielding connection exists between the stacked dies. This infers that insertion bonding technique is a potential solution for low temperature Cu-Cu bonding for 3D stacking of chips.

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