Study on the effect of substrate material on the mechanical strength of Cu bonds bonded through flip chip bonding

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ABSTRACT

The application of flip-chip bonding utilizing copper (Cu) pillars has increasingly gained prominence for low-temperature chip-to-chip and chip-to-wafer integration in micro-electromechanical systems (MEMS). A critical factor influencing the bonding efficacy of Cu pillars is the thermal conductivity of the base substrate or chip material. This study aims to systematically assess the bonding strength of Cu-Cu pillar bonds fabricated on silicon (Si) and glass substrates. Employing Hertzian contact theory and Fick's laws, analysis of the operational parameters pertinent to the experimental evaluation of the impact of substrate material on bonding strength. The experiments show that better bonding of Cu pillars held at bonding temperatures of 180°C and 200°C with the shear strength of 0.0129 GPa and 0.00544 GPa for Cu-Cu pillars bonded through flip chip bonding with silicon and glass substrates, respectively.

1. Introduction

Micro-electro-mechanical systems (MEMS) have revolutionized modern engineering due to their miniature size, versatility, and adaptability across various applications such as aerospace, biotechnology, automotive, and consumer electronics. Ejeian et al. (2019); Errando-Herranz et al. (2020) MEMS technology integrates mechanical and electrical components on a micro-scale, allowing for the development of highly efficient systems that respond to physical stimuli like pressure, temperature, and acceleration. The technological advancements in MEMS packaging ensure that the device maintains its functionality and performance by efficiently integrating the sensing unit and the electronic circuitry. This integration is critical to connecting the two chip-unit to a substrate, where data integrity is paramount. Traditionally, these interconnects are done using the wire-bonding technique (Javed et al., 2019; Shah et al., 2019).

Wire bonding is a widely used, cost-effective technique in the semiconductor industry, where fine wires connect the die's I/O pads to larger-pitch substrate pads. This method has been a cornerstone for high manufacturing efficiency and yield, simplifying the adaptation of semiconductor pad spacing to the larger dimensions of printed circuit boards (PCBs). Being a simple technique, there is still some problem that prevails the use in high-performance applications. Problems like metal pad peeling, bonded wire failures and stiffness, which are material properties, are difficult to optimize for a particular application. However, the introduction of Flip-chip bonding can resolve these problems to some extent (Schwizer et al., n.d.; Zhong et al., 2007).

In contrast, flip-chip bonding is increasingly favoured for high-density interconnections due to its ability to offer superior thermal and electrical properties. Instead of using wires, flip-chip technology employs solder bumps or copper pillars to connect the die to the substrate. The small bumps of flip-chip interconnection provide short electrical paths, which yield excellent electrical properties with low capacitance, inductance, resistance, self-alignment, better heat dissipation through the back of the die and a smaller footprint. Kang et al. (1995); Pedder (1988); Wang and Lee, (2010) this area-array technique reduces the need for extensive connection areas and facilitates higher I/O counts, supporting smaller and more compact packages compared to traditional wire bonding. Flip-chip bonding is highly suited for applications where low-temperature processes are required, such as in

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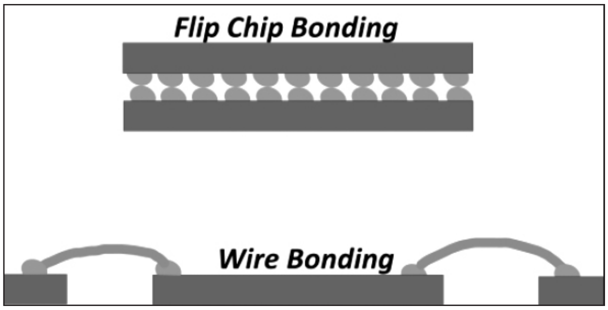

Fig. 1. Illustration of flip chip bonding and wire bonding.

displays, sensors, and optical devices, where reflow of solder alloys is not desirable. Clauberg et al. (2016); Ng and Abas (2022); Schwizer et al. (n.d.) Thus, to analyse the process parameter's effect on bonding strength, the current study emphasis on the structural integrity of the contact pillars/ bumps to overcome various process failures.

2. Methodology

Bonding of two bumps or terminals or similar or dissimilar material includes the diffusion of material into one another. Diffusion bonding is generally an action of localised melting of material due to compression and heat. The general steady-state diffusion follows Fick's first law of diffusion states (Muir et al., 2011; Van Milligen et al., 2005)

$$J = -D\left(\frac{d_c}{d_x}\right) \quad \text{.................(1)}$$

Where "*J*" is diffusion flux (mol m^{-2} s^{-1}); "*D*" is diffusion coefficient (m^2 s^{-1}), and "$\frac{d_c}{d_x}$"is a concentration gradient. Another form of Fick's first law includes material and dimensional information.

$$J = \frac{M}{(At)} \quad \text{.................(2)}$$

Where "*M*" is the molecular mass of the element, "*A*" is the cross-sectional area of bump(m2), and "*t*" is the time(s) required to diffuse the material.

$$D = D_0\, e^{-\frac{Q_d}{RT}} \quad \text{.................(3)}$$

Where, "D_0" is temperature - independent pre-exponent, "Q_d", is the activation energy (kJ mol^{-1}), "*R*" is the universal gas constant ($J{\cdot}K^{-1}{\cdot}mol^{-1}$) and "*T*" is the temperature (K). Derby and Wallach, (1982); Guo and Ridley (1987).

Three parameters are required for diffusion bonding: compression load, timer duration for compression, and the induced temperature during the process. From equations 1,2 and 3, the time required to join a particular specimen and temperature condition is calculated as it includes material and physical parameters. The compression force is a physical quantity and depends upon the characteristics of the asperities to be fractured to increase the contact area. Gourgiotis et al. (2019); Li and Mi (2019); Yang et al. (2020) The asperity level fracture analysis can be done by utilizing the Hertzian contact theory for deformation asperities, assuming that asperities are hemispherical and in non-conformal contact. The general expression for plastic deformation (equation 4) is (Jia et al., 2018; Li & Mi, 2019).

$$U\,(x,y) = \frac{2\pi}{E'} \iint \frac{P(x,y)}{\sqrt{(x-x')^2+(y-y')^2}}\, dxdy \quad \text{............(4)}$$

$$\frac{1}{E'} = \frac{1-\upsilon_1^2}{E_1} + \frac{1-\upsilon_1^2}{E_2} \quad \text{................(5)}$$

$$P(x,y) = P_0\,\left(1-\frac{r^2}{a^2}\right)^{1/2} \quad \text{.................(6)}$$

Where "U" is the deformation in (m), "E" is the Youngs modulus of elasticity, "P" is the contact pressure (Pa), "r" is the radius of hemispherical asperity, and "a" is the radius of the aperture of the deformed section the contact. "x, y" is the plane orthogonal to the applied force. Equations 4, 5 and 6 are utilized to calculate the required force for compression depending on the average surface roughness height. The deposition surface quality analysis for bumps or terminals is tedious as their number is high and the area of cross-section is less for miniaturization

2.1. Mechanism of diffusion bonding

Diffusion bonding involves multiple chemical and physical changes during the process. In general, the mechanism can be characterised by three significant steps (Derby & Wallach, 1984; Guo & Ridley, 1987; Hill-F & Wallach, 1989).

Step 1, micro asperity deformation: the terminal or bumps have rough surfaces due to the deposition technique involved in their formation. While the compression stage in bonding occurs, the asperities mating is crushed and forms a smooth

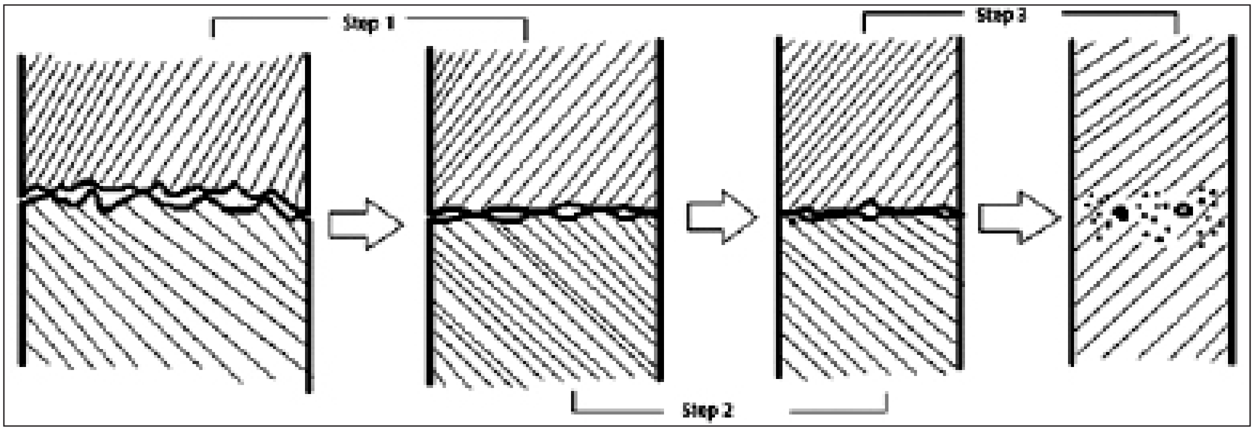

Fig. 2. Illustration of the mechanism of the diffusion process.

Table 1
Cu pillar dimension on the sample.

Bump Material	Substrate material	Bump height (um)	Diameter of Cu pillar (µm)	Die Dimension (mm)
Cu pillar	Silicon (thickness 275 micron)	10	200	5×5
Cu pillar	Glass (thickness 500 micron)	6	200	5×5

surface, which also increases the contact area for the bonding.

Step 2, the diffusion-controlled mass transport: the crushed asperities fill in the troughs of the other terminal. The frictional heat generated during the crushing and movement of material in the microcavities develops a localised melting effect, which enhances the material fill-up in the cavities and increases the surface contact area.

Step 3, the interface migration: Further, under high compression force and temperature, activate the atoms at the interface. These activated atoms at the interface communicate with each other by exchanging the ions formed. The localised melting of the interface material enhances the ion exchange and formation of ionic bonding between the interfaces.

2.2. Experimentation

The current experimentation involved the bonding of copper (Cu) pillars and bumps on both the substrates and the chip. Identical samples were utilized for both the substrate and the chip, which were fabricated through a photolithography process. Two types of substrate materials were employed: glass and silicon. Each substrate was coated with a 20 nm layer of platinum, followed by a 50 nm seed layer of gold. This sequence was essential to establish a conductive pathway for the subsequent copper deposition (Kulkarni et al., 2022). The deposited copper formed cylindrical structures or pillars.

Table 2
Flip chip bonding parameters.

Sr. No	Temperature (°C)	Compressive Force (kg)	Time (sec)
1	150 - 200	4	500
2	150 - 300	20	500

Table 1 presents the materials and dimensions of the copper pillars utilized in this study. The detailed experimental investigation of the parameters listed in Table 2 was deduced through the analysis of the mathematical equations (Equations 1-6). The flip chip bonding machine, specifically the FC150 bonder, available at the STDC laboratory, CMTI Bangalore, was utilized for the experimental procedures.

The thermo-compression bonding process was utilized to join the Cu-Cu pillars. Clauberg et al. (2016); Suppiah et al. (2017); Xie & Lee, 1993) For the bonding procedure, identical samples were used, with the substrate placed on the chuck while the chip was positioned in the chip cassette. Both the chip and substrate contain Cu pillars.

Table 3
Experimental trials conducted to bond Cu-Cu pillars through the flip chip bonding technique with the thermo compression process.

Sr no.	Material	Temperature (°C)	Force (kg)	Time (sec)	Status
1.	Si	150	4	500	Not Bonded
2.	Si	160	4	500	Bonded
3.	Si	165	4	500	Bonded
4.	Si	170	4	500	Bonded
5.	Si	175	4	500	Bonded
6.	Si	180	4	500	Bonded
7.	Si	185	4	500	Bonded
8.	Si	190	4	500	Bonded
9.	Si	195	4	500	Bonded
10.	Si	200	4	500	Bonded
11.	Glass	150	20	500	Not Bonded
12.	Glass	160	20	500	Not Bonded
13.	Glass	170	20	500	Not Bonded
14.	Glass	190	20	500	Not Bonded
15.	Glass	200	20	500	Not Bonded
16.	Glass	210	20	500	Not Bonded
17.	Glass	220	20	500	Not Bonded
18.	Glass	230	20	500	Not Bonded
19.	Glass	240	20	500	Not Bonded
20.	Glass	250	20	500	Bonded
21.	Glass	260	20	500	Bonded
22.	Glass	270	20	500	Bonded
23.	Glass	280	20	500	Bonded
24.	Glass	290	20	500	Bonded
25.	Glass	300	20	500	Bonded

During the bonding process, the Universal Bonding Arm (UBA) picks up the chip and precisely aligns its diagonal pillars with those on the substrate. The bonding parameter range as shown in Table 2 are utilized to select the parametric setting levels for experimentation. Throughout the procedure, the bonding tool undergoes multiple heating and cooling cycles as it picks up the chip and attaches it to the substrate or another die. The controllable parameters for flip chip bonding are temperature, force, and time, which are varied to achieve the optimal setting level for a particular bonding material.

A number of experimental trials were conducted by varying the parameters setting level, as shown in Table 3, to achieve the proper adhesion of the chip and substrate. In the investigation of copper pillar bump bonding using flip chip technology, a series of systematic trials were conducted to evaluate the effects of applied force, temperature, and bonding duration on two distinct substrates: silicon and glass. The experimental trials of substrate samples were bonded with varying bonding temperatures between 150°C and 200°C while maintaining constant applied force of 4Kg and bonding time of 500 seconds.

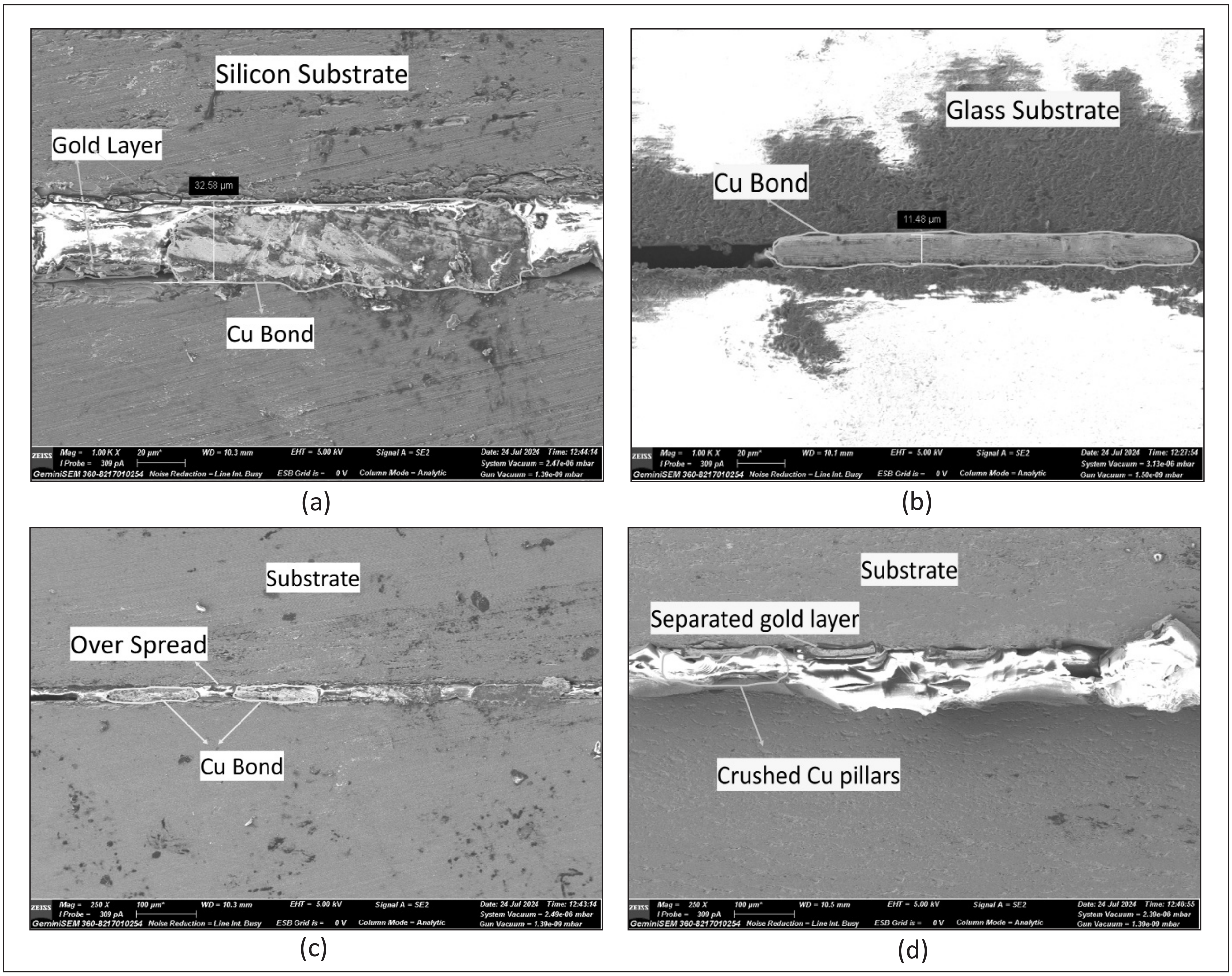

Fig. 3. (a) SEM image of bonded Cu pillars on silicon substrate having pillar to pillar bond
(b) SEM image of bonded Cu pillars on glass substrate having pillar to pillar bond
(c) SEM images of spread Cu pillars bond formed (d) SEM images of pillar crushed during bonding.

This preliminary phase aimed to establish a baseline for effective bonding conditions. Ultimately, a combination of 4 kg of force and a temperature exceeding 160°C was applied for a bonding duration of 500 seconds, resulting in successful adhesion of the silicon samples.

Further trials were performed with copper pillars electroplated on glass substrates. However, applying the same parameters used for silicon did not yield successful bonding in the glass samples (ref. Table 3). Recognizing the need for adjustments, the experimental conditions were modified to improve adhesion. Specifically, the bonding temperature was systematically increased from 150°C to 300°C, while the applied force was elevated to 20 kg, with the bonding time held constant.

The results demonstrated that effective bonding of CU pillars with glass substrate was achieved at temperatures above 250°C when a force of 20 kg was applied for 500 seconds. This marked improvement in bonding efficacy underscores the critical role that both elevated temperatures and increased forces play in optimizing the bonding process for electroplated copper pillars on glass substrates. These findings highlight the necessity for tailored bonding parameters that take into account the specific characteristics of the substrate materials to achieve reliable and robust bonding.

3. Results and Discussion

From Table 3, it is inferred that from 25 trails, only 15 trail samples, 9 of Si substrate and 6 of glass substrate, were bonded. But before considering them for shear analysis, the bond quality was verified through Scanning electron Microscope images, which were taken by made FESEM (Make: Carl Zeiss) available at the

Table 4
Calculated shear strength of Cu pillars.

Sample no.	Substrate Material	Bond Ultimate Shear Strength (GPa)
1.	Si	7.16E-03
2.	Si	1.00E-02
3.	Si	1.29E-02
4.	Si	8.59E-03
5.	Si	1.15E-02
6.	Glass	4.01E-03
7.	Glass	4.73E-03
8.	Glass	5.01E-03
9.	Glass	4.30E-03
10.	Glass	5.44E-03
11.	Glass	5.44E-03

Fig. 4. Illustration of shear test of bonded Cu pillars on bond tester (Make: Xyztec).

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Figure 3 (a) displays the SEM images of bonded Cu pillars at 180^{o}C on a silicon substrate having pillar-to-pillar bonds. The bonds formed are distinguishable and can withstand a huge shear force (ref Table 4). Figure 3 (b) displays the SEM images of bonded Cu pillars at 300^{o}C on glass substrate having pillar to pillar bond The bonding in glass samples as illustrated in Figure 3(b) is visually good with no spreading during slicing operating. Figure 3(c) shows the SEM images of bonded Cu pillars at 160^{o}C on silicon substrate weak bond and partial deformation of the copper pillars caused by applied non optimal force and temperature during the bonding process. Figure 3(d) shows the SEM images of bonded Cu pillars at 200^{o}C on silicon substrate deformed copper pillars, which may be crushed due to the excessive force applied, coupled with high temperature, resulting in mechanical failure. SEM analysis reveals deformation and smudging of copper pillars on both glass and silicon substrates, attributed to the application of excessive force and elevated temperature during the bonding process. On observing SEM images, 4 out of 15 samples were not considered for shear analysis as they were with some damages, as shown in Figures (c) and (d).

During the bonding process, copper-copper pillar interconnects were bonded at temperatures ranging from 160°C to 200°C for silicon electro-plated samples. However, the bond quality varied significantly across this range. At 160°C, bonding occurred, but the resulting bond strength was suboptimal, indicating insufficient energy for proper adhesion. Ng and Abas (2022) The best bonding results were consistently achieved at 180°C, with strong and reliable bonds. It is observed that Cu pillars formed on silicon bonds at lower temperatures of 180^{0}C with a maximum applied force of 4 Kgf. However, the Cu pillars formed on a glass substrate were bonded at a temperature of 300C with a maximum applied force of 20 Kgf.

The bonded samples were sliced in half using a mechanical saw dicer. The dicing was done to use the samples for surface morphology analysis.

The bond shear tests were conducted by using a bond tester (Make: Xyztec), as shown in Figure 4, to measure the bond strength of the bonded copper pillars (Hong et al., 2023). Table 4 shows the calculated shear strength of the bonded Cu pillar. The strength was calculated by dividing the shear force, as shown in Figure 5(a), of the sample obtained by the destructive shear test and dividing it by the area in contact (number of pillars in contact × area of the individual pillar).

The bond test results reveal a discernible trend, indicating that materials with higher thermal

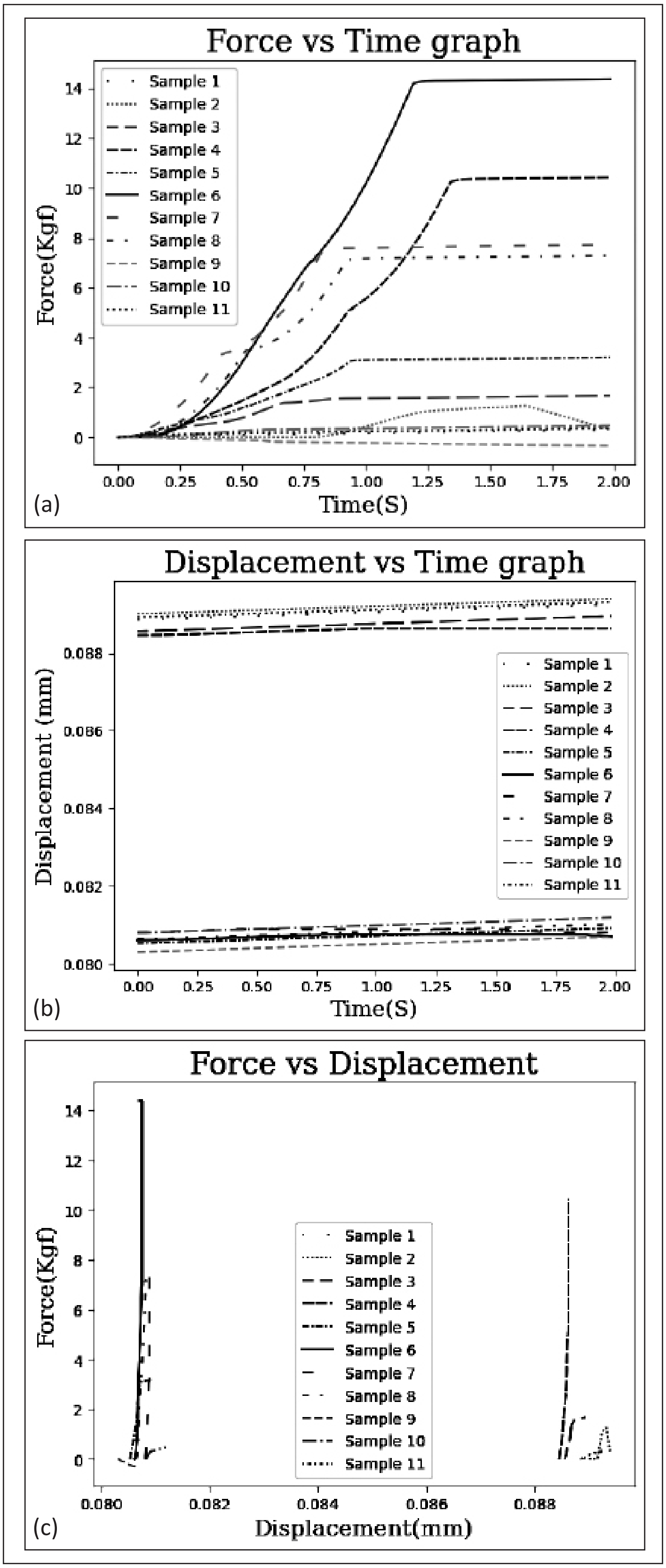

Fig. 5. Bond shear test for Cu-Cu pillar
(a) Force Vs time graph of bonded sample of glass and silicon substrate;
(b) Displacement Vs time graph showing the cluster of glass and silicon substrate
(c) Force Vs displacement graph.

conductivity are effectively bonded at lower bonding temperatures. Furthermore, it was observed that a lower applied force corresponds to increased bonding strength. Specifically, the copper (Cu) pillars on the silicon substrate exhibited a maximum shear strength of 0.0129 GPa, while the Cu pillars on the glass substrate demonstrated a lower maximum shear strength of 0.00544 GPa.

It is inferred that the thermal properties of the substrates play a significant role in the bonding process, emphasizing the importance of considering the substrate material along with the analytical diffusion equation, which only considers the material properties of elements in contact. From Figure 5 (b) and (c), it is intuitive that the trend of toughness for the CU pillar is identical, but the range of energy absorption has a gap. Figure 5 (b) illustrates that the Si sample can be displaced in less time than the glass samples and similar results were inferred from Figure 5(c), which reveals that Cu pillar bonded with Si substrate were displaced by lower force as compared with Glass samples.

Beyond this temperature, up to 200°C, bonding was still possible, but the bond quality deteriorated, likely due to increased thermal stress and potential microstructural defects. Thus, while bonding was feasible from 160°C to 200°C, 180°C emerged as the ideal temperature for achieving optimal bond integrity and strength.

For the glass electroplated samples, proper bonding was achieved at temperatures above 250°C with an applied force of 20 kg and a bonding duration of 500 seconds. However, die shear test results indicate that samples bonded at 300°C exhibited superior bonding strength. This suggests that the adhesion between the chip and substrate bumps is robust. The results table above highlights the samples' ultimate die shear strength, confirming the bonding process's effectiveness at elevated temperatures. The results confirm that optimizing temperature and force is crucial for achieving high-quality bonds. By carefully adjusting these parameters, we can significantly improve bonding strength, ensuring that the flip-chip assemblies maintain their integrity under stress.

As the results are tabulated in Table 4 above, the strength of the bond was very good at the temperatures of 180°C and 300°C for Silicon and glass samples, respectively. But, below and above the optimal temperature also the adhesion of chip and substrate is happened but quality of the bonding was weaker and some bonds are get smudged due to the less temperature with high force the bumps didn't get melted properly, and some bumps got melted too much and smudged that can be observed in Figure.

The results confirm that optimizing both temperature and force is crucial for achieving high-quality bonds. By carefully adjusting these parameters, we can significantly improve bonding strength, ensuring that the flip-chip assemblies maintain their integrity under stress. This optimization process is essential for achieving reliable and durable bonds in flip-chip technology, particularly when working with challenging substrates such as glass.

These results highlight the importance of carefully optimizing temperature and force to achieve the desired bond strength. Properly balanced parameters ensure strong, reliable bonds, whereas deviation from these optimal conditions can compromise the mechanical integrity of the flip-chip assembly.

4. Conclusion

The conclusion of this study establishes the possibility of integration of Fick's First Law and Hertzian contact theory. It provides a solid foundation for determining optimal operating parameters in flip-chip bonding. A critical finding is that the heat conductivity of the base substrate is essential for effective terminal bonding. Additionally, the reliability of the theoretical equations presented (1-6) is significantly influenced by the height of the terminals; as this height increases, so does the risk of buckling and shearing of the pillars. Furthermore, the shear strength of the bond is closely linked to the adhesion between the copper pillars and the substrate, highlighting the importance of material compatibility. It is also inferred that Cu pillar formed on the substrate materials with high conductivity will bond at lower temperatures, achieving higher shear strength.

For future research, optimising the significant parameters, i.e. temperature, force, and time in the flip-chip bonding process, is important. Additionally, exploring the effects of pillar dimensions on bonding strength will provide valuable insights. This focused approach can enhance the reliability and performance of flip-chip technology, contributing to advancements in modern electronics.

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