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Study on Enhancing Adhesion and Reliability in Wafer-Level Fan-Out Packaging

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Abstract: Wafer-level Fan-out packaging (FOWLP) with multi-layer redistribution layers (RDL) emerges as a pivotal technology in 3D integration. Polyimide (PI) as an insulation layer in the construction of RDL is essential for FOWLP. The adhesion of PI has become a focal point of multi-layer RDL. This study focuses on solving the adhesion technologies for PI photoresist lithography to achieve four layer RDL. The adhesion of PI to both the complex substrate and varying RDL layouts is investigated as a significant determinant of package reliability, characterized predominantly by surface free energy (SFE). It reveals that improving the substrate morphology by flattening can significantly enhance the PI adhesion, thereby addressing fluctuations caused by temporary bonding defects. Techniques such as CF4 dry etching and optimization of the temporary bonding process were found effective in mitigating substrate imperfections. Furthermore, various surface treatments applied to the RDL layers were investigated to boost the interface adhesion between the RDL and PI. Notably, after subjecting the plated copper to a 180W, 3-minute Argon plasma atmosphere, we observed an increase in roughness to 12 nm and an elevation in SFE to 80.82 mN/m, markedly improving copper surface adhesion. Additionally, employing Plasma-Enhanced Chemical Vapor Deposition (PECVD) to deposit SiO2 on the surface of the RDL layer substantially increased the SFE to 83.1 ± 0.7 mN/m, demonstrating the most significant enhancement in PI adhesion. These advancements propose promising pathways to improve the structural integrity and reliability of FOWLP.

1. Introduction

With technological advancements, the integration level of Integrated Circuits (ICs) is continually increasing to meet market demands for smaller, high-performance electronic products. In this context, 3D Fan-Out packaging technology has emerged, significantly increasing the number of I/O ports without enlarging the package size, particularly crucial for high-performance computing devices like CPUs and Chiplet technologies. By stacking and interconnecting multiple chip layers, 3D Fan-Out packaging achieves higher functional density within limited space.

To attain higher density in 3D Fan-Out packaging, multi-layer Redistribution Layer (RDL) technology is essential. RDL allows complex inter-layer connections; however, it requires organic polymers or passivation layers as insulators, making the adhesion between multi-layer RDLs a critical issue for packaging reliability.[1-3] Multi-layer Polyimide (PI) technology faces adhesion challenges, which severely restrict the further development of 3D Fan-Out packaging technology. Recent studies in this field have focused on enhancing I/O port density and packaging reliability. Research by John H. Lau et al. (2019)[4] Fanout is more effective than traditional wire bonding. Additionally, Kim G et al. (2019)[5] shows the Curing Conditions on the Interfacial Adhesion of Cu RDL for Fan-Out Wafer Level Packaging

Internationally, research by Patel, A., and Yamanaka K [6] explored The copper wiring structure on the rewiring has a great influence on the adhesion of polyimide. Moreover, Liu (2023)[7] examined the effects of plasma treatment on wafer-level packaging interface bonding.

Despite these advancements, the adhesion issues in multi-layer PI structures in higher-level packaging remain unresolved. Therefore, this study builds on prior research to explore new materials and processes aimed at addressing the adhesion challenges in multi-layer PI structures within high-density 3D Fan-Out packaging applications. Although existing research has achieved the manufacturing of dual-layer PI structures, the adhesion problems become more pronounced with an increase in layer count, and currently, there is no effective solution to the adhesion issues within multi-layer PI structures.

This research aims to explore and address the adhesion issues in multi-layer PI photolithography integrated technologies to advance Fan-Out packaging technology towards higher density. By investigating the surface properties of PI materials, adhesion mechanisms, and influencing factors, this paper will propose new material handling methods or modification strategies to enhance the adhesion performance of multi-layer PI structures, meeting the requirements of high-performance electronic devices for packaging technology.

2. Experimental and Method

2.1 Principles of Adhesion Characterization

In this paper, the surface free energy (SFE) is calculated to characterize the adhesion. Molecules on the surface layer of liquids and solids are more sparsely arranged compared to those inside, creating surface tension δ_f due to intermolecular forces[8]. When the surface area of a liquid increases by a unit δ_s, the work done by surface tension δ_f, called the surface free energy δ_γ, which can be calculated by measuring the material's surface tension. At the liquid-solid-gas interface, surface tensions reach an equilibrium of stress, according to Young's equation:

$$\gamma_s - \gamma_{sl} = \gamma_l \cos\alpha \tag{1}$$

Foukes, in studying the formation of intermolecular forces, suggested that surface free energy could be divided into dispersive and polar components:

$$\gamma^d + \gamma^p = \gamma \tag{2}$$

where γ represents the surface free energy of a liquid or solid, γd is the dispersive component generated by intermolecular interactions, and γp is the polar component of surface free energy, constituted by Lewis acids ($\gamma+$) and Lewis bases ($\gamma-$).The polar component of surface free energy is the geometric mean of $\gamma+$ and $\gamma-$, $\gamma^p = 2\sqrt{\gamma^+\gamma^-}$

$$\gamma = \gamma^{d} + 2\sqrt{\gamma^{+}\gamma^{-}} \tag{3}$$

Introducing polar components and acid-base interactions into equation (1) yields an expression for the solid-liquid interface tension:

$$\gamma_{sl} = \gamma_{s} + \gamma_{l} - 2\sqrt{\gamma_{s}^{p}\gamma_{l}^{p}} - 2\sqrt{\gamma_{s}^{d}\gamma_{l}^{d}} \tag{4}$$

According to thermodynamics, the surface binding energy and surface free energy parameters of biphasic and triphasic substances relate as follows:

$$W_{ls} = \gamma_{l} + \gamma_{s} - \gamma_{sl} \tag{5}$$

$$W_{lsk} = \gamma_{sk} + \gamma_{sl} - \gamma_{lk} \tag{6}$$

Wls represents the interfacial binding energy between two phases; Wlsk represents the interfacial binding energy between three phases; γs is the surface free energy of substance s, and γl is the surface free energy of substance l, with γij being the interfacial free energy between substances i and j.

Combining equations (3) and (4) provides:

$$W_{sl} = 2\sqrt{\gamma_{s}^{+}\gamma_{l}^{-}} + 2\sqrt{\gamma_{s}^{-}\gamma_{l}^{+}} + 2\sqrt{\gamma_{s}^{d}\gamma_{l}^{d}} \tag{7}$$

From equation (7), it is evident that testing the surface free energy allows the calculation of its adhesion work.

2.2 Silicon-copper substrate

In this study, we utilized a silicon-copper substrate, which comprises a silicon base, bare die, and copper. Chips were embedded onto the etched silicon substrate, followed by the application of a temporary bonding adhesive, WaferBond@ HT10.11, via spin coating. The substrate was then temporarily bonded with the carrier wafer before proceeding to the copper plating phase, as Fig 1. However, residual temporary bonding adhesive on the sidewalls resulted in poor edge flatness of the plated copper, as highlighted by the red circle in Fig 2. Consequently, this led to suboptimal surface flatness of the base substrate.

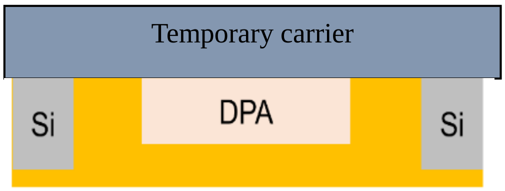


Figure 1: Schematic Diagram of Silicon-Copper Substrate.

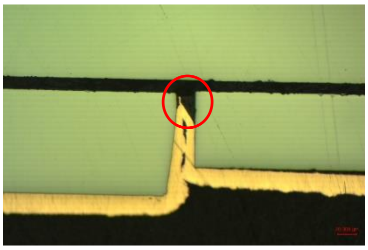


Figure 2: Silicon-copper baseplate before optimization.

2.3 Experimental procedure

The adhesion issue of RDLs in fan-out packaging involves two main aspects: the adhesion between the substrate and the redistribution layer, and the adhesion between different RDLs.

For the adhesion issue between the substrate and the redistribution layer, the flatness of the substrate and the cleanliness of the substrate should be considered:

The flatness of the substrate directly impacts the uniformity and adhesion of the Polyimide (PI) coating. An uneven substrate surface can lead to an inconsistent thickness of the PI layer, which, during drying and curing, results in varying shrinkage forces. This variation can cause uneven stress within the coating, weakening its adhesion to the substrate. To improve the edge flatness, this paper attempts 1. CF4 gas flowing at 100 sccm for 5 minutes on the sidewalls of the silicon-copper baseplate; 2. Optimization of bonding processes to reduce bonding pressure.

The cleanliness of the substrate is another significant factor affecting PI adhesion. The presence of dust, particles, or other organic substances on the substrate surface can severely obstruct effective contact between the PI and the substrate, leading to decreased adhesion. Before the PI coating process, substrates typically undergo cleaning, pickling, or plasma treatments to ensure good adhesion between the PI and the substrate.

The adhesion issue between RDLs are another important aspect to consider. The layout and wiring of the Redistribution Layer (RDL) significantly influence the adhesion of the upper RDLs. When the RDL has different areas and widths of copper wiring, the adhesion of PI significantly decreases. When the copper area of the substrate is large, the Polyimide (PI) lifting or peeling before full development, shows in Fig 3**.**

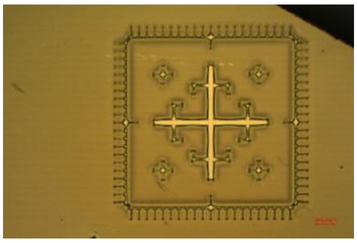


Figure 3: Photolithography with Polyimide (PI) on copper substrates

Since the micro-topographical structure of the substrate surface can increase the contact area between PI and the substrate, thereby enhancing adhesion, we compared the roughness and surface free energy of copper with 200nm deposited by Physical Vapor Deposition (PVD), electroplated 1 μm thick layer of copper at a current density of 1 ASD, copper after Ion Beam Etching (IBE) for 15 minutes, and copper treated with Ar plasma for 3 minutes at 180W.

Since PI materials can form strong chemical bonds with SiO2 surfaces, mainly because polar groups in the PI structure can form hydrogen bonds with the hydroxyl groups (-OH) on the SiO2 surface. Additionally, the high surface energy of SiO2 helps to form strong adhesion with the PI layer through van der Waals forces and possible chemical bonds. Therefore, depositing a 10 nm thick layer of SiO2 by Plasma Enhanced Chemical Vapor Deposition (PECVD), which transforms the adhesion issue between the RDL and PI into a problem of adhesion between SiO2 and PI.

In the final step, uniformly apply the AR300 adhesion promoter on the SiO2 layer deposited by PECVD, spinning at 3000 rpm for 2 minutes. To complete the process, treat again with O2 plasma for 5 minutes at 300W and with CF4 at a flow rate of 100 sccm for 5 minutes.

3. Results and Discussions.

3.1 Substrate Effects on Redistribution (RDL)

3.1.1 Impact of Substrate Surface Modifications on Adhesion

To improve the edge flatness, this paper attempts 1. CF4 treatment on the sidewalls of the silicon-copper baseplate; 2. Optimization of bonding processes to reduce bonding pressure. After applying CF4 Treatment to the Sidewalls of the Silicon-Copper Substrate, the edge void ratio reduced from 12.6% to 4.7% indicating an improvement in edge flatness, which is shown in Fig 4. Optimizing the Bonding Process to Lower Bonding Pressure is likely contributed to the reduction in edge void rates and enhanced surface uniformity, subsequently improving the adhesion quality by applying less mechanical stress to the PI layer. Following these interventions, the surface free energy of the silicon-copper substrate increased from 31.3 ±1.15 mN/m to 43.7 ±2.45 mN/m. This change suggests that the surface became more conducive to adhesion, as higher surface free energy typically leads to better wetting and stronger adhesive bonds.

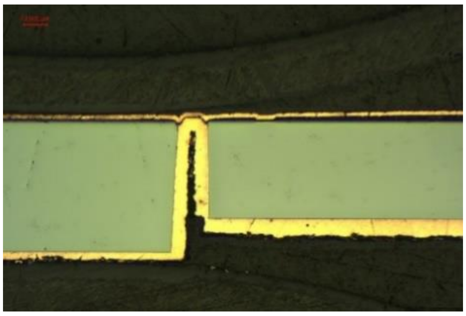


Figure 4: Silicon-copper baseplate after optimization.

3.1.2 Influence of Substrate Cleanliness

According to Table 1, various cleaning techniques significantly affect the substrate's surface free energy. Untreated Substrates show the lowest surface free energy of 42.5 ±1.71 mN/m. This lower value indicates that without any treatment, the substrate surface is relatively less favorable for adhesion, likely due to the presence of natural contaminants or oxides that reduce surface activity. O2 Plasma Treatment (5 min): This method significantly increases the substrate's surface free energy to 78.7 ±0.29 mN/m, the highest among the three methods. The O2 plasma treatment effectively removes contaminants and possibly introduces functional groups that increase the substrate's hydrophilicity, enhancing its adhesion capabilities. This suggests that O2 plasma treatment is highly effective for surface activation and cleaning, leading to improved surface properties for subsequent processing steps. After CF4 Plasma Treatment (5 min) the surface free energy increases to 50.6 ±2.37 mN/m, which is higher than the untreated substrates. While CF4 plasma treatment does improve the surface energy compared to the untreated case, it is not as effective as O2 plasma. This might be due to the nature of CF4 plasma, which could not introduce as many functional groups conducive to high surface energy.

The data clearly demonstrate that substrate flatness and surface cleaning significantly impact the surface free energy and thus the adhesion potential of substrates. Specifically, when substrate flatness improved by optimizing the temporary bonding process, surface adhesion is enhanced. O2 plasma treatment emerges as the most effective method for enhancing substrate adhesion properties, followed by CF4 plasma treatment, with untreated substrates showing the least favorable adhesion characteristics.

Table 1: Shows the surface free energy of substrates after different cleaning treatments:

Cleaning Method	Surface Free Energy (mN/m)
Untreated	42.5 ±1.71
O2 plasma 5min	78.7 ±0.29
CF4 5min	50.6 ±2.37

3.2 Effects of RDL Layout and Surface Roughness on PI Adhesion

3.2.1 Copper Surface Roughness analysis

This segment examined how the roughness of the RDL layer and enhancements to interface adhesion affect PI adhesion. The context of employing Atomic Force Microscopy (AFM) for research purposes, the primary focus of this study is to assess the variations in surface roughness, as Fig 5.

Table 2: Shows the roughness and SFE of substrates after different treatments

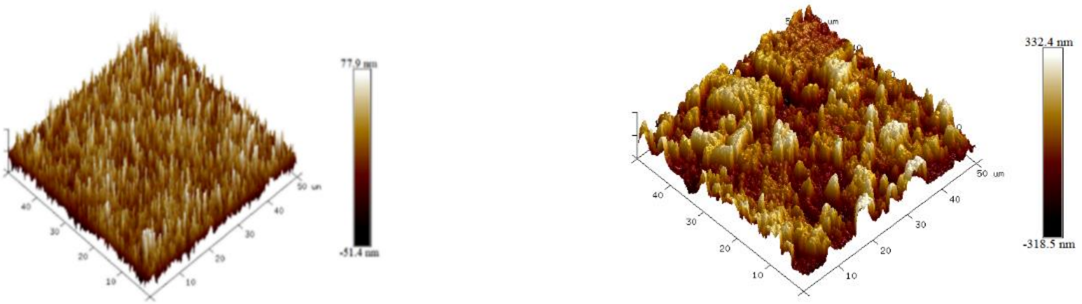
	Roughness(Ra1/Ra2)(nm)	SFE (mN/m)
PVD Deposited	3.61/3.24	44.45 ±1.15
Electroplated	7.96/8.09	51.09 ±2.99
IBE 15 min	90.27/9.7	67.4 ±2.66
Ar plasma 3min/180W	12.3/11.9	80.82

In Table 2, it is showed that PVD Deposited has the lowest roughness among the treatments with a lowest SFE of 44.45 ±1.15 mN/m. The smooth surface resulting from PVD deposition may limit the adhesion of PI. Electroplated Cu shows increased roughness and higher SFE (51.09 ±2.99 mN/m) compared to PVD indicates better adhesion potential. The increased roughness from electroplating provides more surface area and opportunities for mechanical interlocking, enhancing adhesion. IBE 15 min treatment significantly higher roughness, indicating a highly textured surface, however its SFE (67.4 ±2.66 mN/m) is lower than Ar Plasma treatment, which shows that excessive roughness can decrease SFE and adhesion. Ar Plasma treatment (3 min/180W) increase roughness less than IBE but more than PVD and electroplating. The highest SFE (80.82 mN/m) among the treatments, indicating the best potential for adhesion.

When surface roughness increases (as observed with physical vapor deposition (PVD), electroplating, and ion beam etching (IBE) treatments), the surface free energy and adhesion usually improve. This is primarily due to enhanced mechanical interlocking and an increased surface area available for bonding. However, excessive roughness can decrease surface free energy and adhesion because the PI may fail to conform fully to a highly irregular surface, resulting in air gaps and weak bonding points. Ar plasma treatment seems to provide an optimal balance between surface texture and chemical reactivity, leading to the highest adhesion potential. This method enhances both mechanical interlocking and chemical bonding due to increased roughness and very high SFE, making it highly suitable for critical applications where superior adhesion is required.

(a) PVD Deposited Cu surface

(b) Electroplated Cu surface



(c) IBE 15min Cu surface (d) Ar plasma Cu surface

Figure 5: The AFM imagines of different treatment on Cu surface

3.2.2 Copper Surface Roughness analysis

After depositing 10nm of SiO2 on the redistribution layer, the surface free energy of the redistribution layer rose to 83.1±0.7 mN/m, suggesting that this approach significantly boosts adhesion capabilities compared to prior methods. Based on this, several surface treatments were also tried after depositing SiO2, as shown in the Table 3. Experimental results show that these surface treatments perform worse than the untreated group. The untreated group exhibited the highest surface free energy (83.1±0.7 mN/m).

Surface treatments, such as spin-coating with an adhesion promoter (AR300) and applying O2 plasma, slightly reduced the surface free energy but remained high, indicating that while they did not enhance the effect of the SiO2 layer, they did not significantly reduce the adhesion potential either.

The CF4 treatment decreased the surface free energy to 68.48±0.73 mN/m, showcasing a detrimental effect compared to no treatment, suggesting this particular treatment might not be suitable after SiO2 deposition for improving PI adhesion.

Table 3: Shows the surface free energy of substrates after Surface Treatment Methods

Surface Treatment Method	Surface Free Energy (mN/m)
Untreated	83.1±0.7
Spin-coating Adhesion Promoter (AR300)	77.75±0.11
O_2 Plasma	78.05±0.38
CF_4	68.48±0.73

4. Conclusions

The results demonstrate that substrate smoothness and cleanliness significantly contribute to improved PI adhesion. Cu layer with Ar plasma treatment can the highest SFE, indicating the best potential for multi-layer PI adhesion. Additionally, employing SiO2 deposition are effective in enhancing the adhesion of PI layer. Since polar groups in the PI can form hydrogen bonds with the hydroxyl groups (-OH) on the SiO2 surface, SiO2 can be an effective insulation layer to modify the surface energy. Additionally, high surface energy of SiO2 can further help to form strong adhesion with PI layer through van der Waals forces and chemical bonds. However, too thick SiO2 will result in extra stress. Therefore, depositing 10 nm of SiO2 on the PI surface in the intermedius layer between two PI layer solves the adhesion issue between the metal and PI in the different RDL layers.

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