

Research Article

Reduced Energy Loss via Wetting–Adhesion Relationship in Copper/Prepreg Interfaces for High-Frequency Communication Systems

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Received 14 May 2025; Revised 31 October 2025; Accepted 8 November 2025

Academic Editor: Sivaraj Durairaj

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This study analyzes the chemical bonding mechanism between conductive Cu foil and dielectric prepreg (PPG) substrate using a silane coupling agent to improve adhesion and optimize signal integrity for high speed printed circuit board (PCB). The silane coupling agent reacts with Cu foil to form Si–O–Cu bonds, and the organic functional groups simultaneously bond with PPG to form strong adhesion. Compared to conventional etching methods, this method provides high adhesion without increasing the roughness of the copper foil surface. Its nonetching characteristic minimizes reflection and attenuation during high-frequency transmission. Surface energy analysis shows that specific PPG had the lowest polar surface energy, indicating the best interaction with the silane coupling agent. Wetting coefficient analysis shows that PPG with optimized composition had the most balanced interfacial adhesion behavior, which was experimentally verified by peel test results with the highest adhesion due to the formation of strong Si–O–Cu bonds. Consequently, return loss testing showed that the optimized PPG-based PCBs maintained good signal integrity upto 40 GHz, an improvement of about 30% over conventional etching. This suggests that the selection of PPG for nonetching silane coupling agents is effective in high-speed signal transmission applications.

Keywords: adhesion; prepreg; printed circuit board; signal loss reduction; wetting coefficient

1. Introduction

The rapid development of electronic devices requiring high data rates and increased integration density has placed stringent demands on the performance of printed circuit boards (PCBs) [1]. PCBs ensure low signal loss and mechanical reliability in high-frequency applications. Among key structural elements of multilayer PCBs, Cu foil is the primary conductor for signal transmission and power supply. Copper substrates are widely used in electronic devices owing to their excellent electrical and thermal conductivity. These properties make Cu foil ideal for fabricating fine circuits required for high-density

interconnect (HDI) designs [2, 3]. Generally, PCBs are manufactured with adhesives primarily because of poor adhesion between Cu foil and prepreg (PPG) [4]. Nothdurft et al. [4] used a phosphonate adhesive between copper and PPG. They used phosphonic acid as an adhesion promoter on the copper surface, and pH control was required to enhance adhesion with the epoxy PPG. This method is highly complex, and suitable amino-functional phosphonic acids are expensive and unsuitable for PCB applications. Ding et al. [5] used a material cured by mixing phenol and epoxy between copper and PPG as an adhesive. This increases the substrate's moisture absorption rate and, due to the lack of hydroxyl groups, has the problem

of weak intermolecular interactions. Furthermore, the grafting modification process is complex because it requires an O₂ plasma process, and cost limits its commercial application. In addition, various studies have been conducted, including the introduction of organo-silanes, the use of vapor phase deposition to promote adhesion, and process control to reduce signal loss [6–12]. However, the presence of these adhesives can limit the thickness of the circuit board, which poses a reliability problem. To overcome this, various approaches, such as laser bonding and the formation of micro/nano-scale surface structures, have been investigated [13–17].

Cu foil is becoming increasingly important for interfacial adhesion between insulating materials, such as PPG [18–23]. Using silane coupling agents for interface engineering chemically links the PPG and Cu surfaces via organic resins. Silane coupling agents form silanol groups (Si–OH) through hydrolysis to enhance adhesion and covalently bond Cu and epoxy resin to the surface. In other words, silane materials contain functional groups (amino groups, thiol groups, phosphonic acids, etc.) that react with silanol groups on one side and epoxy groups on the other. Several studies have been reported on bonding copper and epoxy using silanes. However, the adhesion varies depending on the length of the alkyl chain, the type of functional group, and the surface condition [24–26]. Additionally, precisely controlling the surface of copper foil and epoxy resin is challenging, and it is sensitive to the degree of hydrolysis of the silane coupling agent. Hence, it needs to be understood more quantitatively [27–30].

This study systematically investigates various PPG materials and evaluates their adhesive behavior with copper foils and silane coupling agent through wetting coefficient analysis, peel strength tests, and signal integrity measurements. The wetting coefficient theory is introduced to quantify the interfacial properties and provide a practical indicator. The wetting coefficients for various types of PPGs can be calculated to predict the interfacial compatibility and wettability with copper foils. High wetting coefficients are generally associated with improved adhesion and reduced signal loss, providing measurable parameters for material selection and process optimization. This work suggests a comprehensive design strategy for low-loss, high-reliability PCBs optimized for high-speed applications by integrating chemical surface modification and quantitative adhesion measurements.

2. Experimental Section

2.1. Silane Treatment Process. The Cu foil was cleaned with deionized water to remove contaminants and then treated with the silane coupling agent (GliCAP, Shikoku Glicap). Four pre-commercial grades PPGs (labeled A–D) and Cu foil supplied by Isu Petasys were used. PPGs (labeled A, B, C, and D) are polyphenylene ether (PPE)-based resin composites that contain a variety of materials, including a hardener, plasticizer, stabilizer, glass fiber, flame retardant, and SiO₂. All grades are within typical PPE-based PPG windows, with glass content 20–40 wt% and resin 60–80 wt%. Four types of PPGs were laminated on top of the processed Cu foil using a hot press, followed by hydrolysis for 120 min at 220°C under 0.8–1.2 MPa.

2.2. Characterization. Contact angle measurements were performed using a contact angle analyzer (Phoenix-10, Surface Electro Optics.) to determine the surface energy characteristics of the copper foil and PPG formulations. Water and diiodomethane (DIM) were used as probe liquids, and contact angles were measured at five different locations for each sample. Surface energy components were calculated using the Owens–Wendt method. The sample was cut into sheets after lamination of Cu foil and PPG sheets. Peel-off tests were conducted using a tensile tester (NK-200, MiSUMi) following the ASTM D1876 standard. Copper–PPG laminated samples were prepared with a 10 mm width, and a peel force was applied at an angle of 90°. Scanning electron microscopy (SEM) (S-3400 N, Hitachi) was performed to analyze fracture surfaces of the PPG samples after peel-off tests. X-ray photoelectron spectroscopy (XPS) was performed with a K-Alpha + spectrometer (Thermo Fisher Scientific). Signal integrity of PCBs fabricated with PPG A was evaluated through return loss measurements using Delta-L method by UL Verification Services Inc. Measurements were taken over a frequency range of 0.1–40 GHz.

3. Results and Discussion

This study aims to understand the chemical bonding mechanism between copper foil and PPG substrate through the silane coupling agent. In PCB manufacturing, silane coupling agent is essential to form a strong chemical bond between the inorganic copper surface and organic PPG substrate [31, 32]. This interface is important for the mechanical strength and electrical integrity of the final PCB product.

As illustrated in Figure 1, silane coupling agent forms covalent bonds with both materials through a two-step process. First, the silanol groups of the coupling agent undergo hydrolysis to form silanol groups (Si–OH) [33–35]. These silanol groups then condense with hydroxyl groups present on the copper oxide surface, forming stable Si–O–Cu linkages [36]. Simultaneously, the organo-functional group of the silane molecule interacts with the PPG substrate owing to the catalytic action of copper, creating a robust interfacial bond [37]. This bonding mechanism is particularly advantageous compared with conventional etching processes because it creates a uniform surface without the fluctuation associated with etched copper [38]. The nonetching method provides excellent adhesion to the PPG substrate while maintaining the roughness of the copper foil. Surface irregularities cause signal reflections and scattering, resulting in signal loss and electrical performance degradation. Therefore, the uniform interface from the nonetching process is important for high-frequency signal transmission.

Each PPG reveals different types of monomers, chain lengths, chemical bonding, and mixing ratios. Depending on the type of organic bonding group that constitutes PPG, the degree of bonding reaction with the silane coupling agent differs, which determines the reactivity and adhesive properties between PPG and silane. PPGs (labeled A through D) are a mixture of glass fiber and resin composite, which is composed of 20–40 weight % of glass fiber and 80–60 weight % of

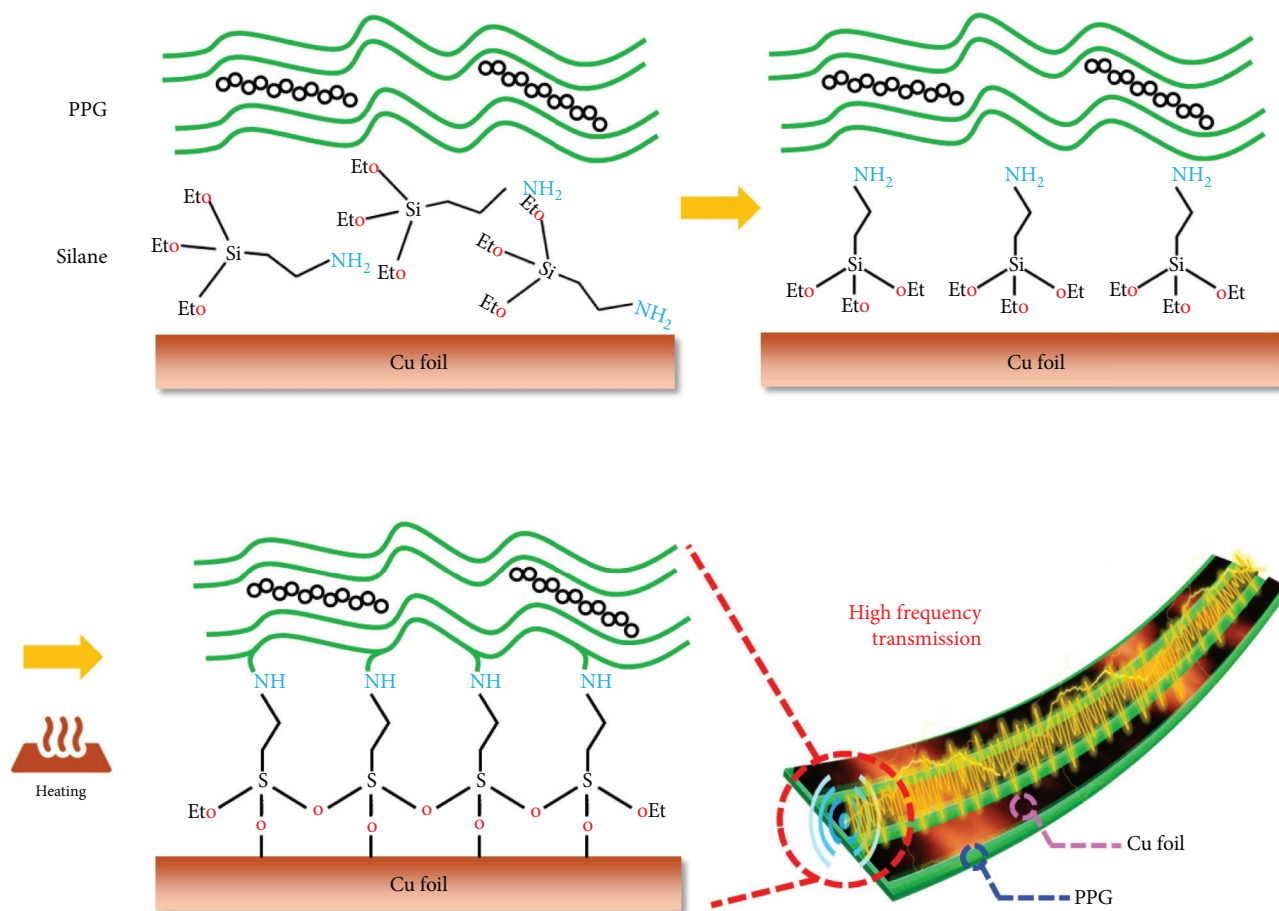


FIGURE 1: Schematic of the chemical bonding mechanism of the silane coupling agents between Cu foil and PPG.

resin composite, and their physical and electrical properties are changed depending on the mixing ratio. It has a glass transition temperature of 170–200°C and has thermosetting polymer properties. The surface energy characteristics of copper foil and different PPG formulations (labeled A through D) are deterministic in adhesion behavior and PCB performance. Figure 2c,d present a comprehensive analysis of these surface energy parameters through contact angle measurements (Figure 2a,b) using water and DIM, allowing the calculation of polar and dispersive surface energy components. Water contact angle measurements (Figure 2a) reveal significant variations across the tested materials, with PPG A exhibiting the highest angle at approximately 88.2°, indicating relatively higher hydrophobicity. Moreover, copper foil has a water contact angle of approximately 97.8°, demonstrating its inherent hydrophobicity. DIM contact angles (Figure 2b) provide information about the dispersive energy component of each material surface. The calculated polar surface energy components (Figure 2c) demonstrated that PPG A possessed the lowest polar component at approximately 0.98 mJ/m², suggesting a weak capacity for polar interactions [39, 40]. This characteristic is important for bonding with the organofunctional group of the silane coupling agent, as polar hydrolyzed silanol groups are linked with the hydroxyl group of Cu foil.

The dispersive surface energy components (Figure 2d) ranged from approximately 34–38 mJ/m² according to the PPE-backbone formulations, whereas the copper foil exhibited a substantially higher dispersive component of approximately 45 mJ/m² [39, 40].

This detailed surface energy analysis provides the foundation for understanding wetting behavior and adhesion mechanisms at the copper–PPG interface, which directly impacts the uniformity of the surface and, subsequently, the signal transmission characteristics of the final PCB product [41]. The wetting coefficient (k_w) is a quantifiable predictor of adhesion strength at the copper–polymer interface, impacting signal integrity in high-frequency applications [42]:

$$k_w = \frac{\gamma_{ij} - \gamma_{jk}}{\gamma_{ik}}, \quad (1)$$

where γ_{ij} , γ_{jk} , and γ_{ik} represent the interfacial surface energies of the different interfaces from the harmonic equation; the components i , j , and k correspond to the Cu foil, silane coupling agent, and PPG, respectively. The interfacial energy is obtained by following equation from Owens, Wendt, Rabel, and Kaelble (OWRK) method [43]:

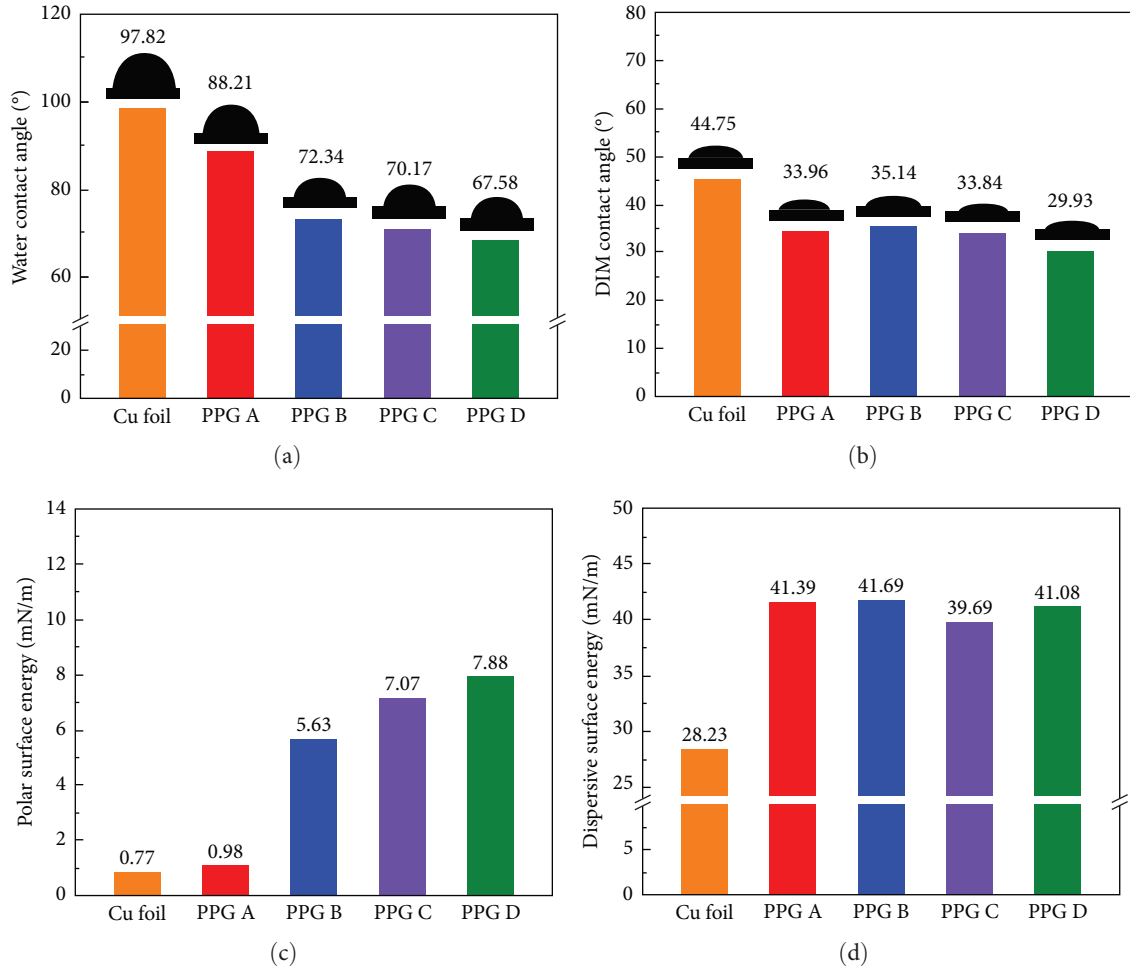


FIGURE 2: (a) Water contact angles, (b) DIM contact angles, (c) polar surface energy, and (d) dispersive surface energy of Cu foil, PPG A, B, C, and D. The water and DIM contact angles were measured three times and the average values were provided.

$$\gamma_{ij} = \gamma_i + \gamma_j - 2 \left(\sqrt{\gamma_i^d \gamma_j^d} + \sqrt{\gamma_i^p \gamma_j^p} \right), \quad (2)$$

where γ_i is the total surface energy, γ_i^d is the dispersive surface energy, and γ_i^p is the polar surface energy. Each interfacial energy is obtained from Figure 2c,d and Tables 1 and 2. Based on this Equation (1) and (2), the interfacial energy and wetting coefficient are strongly affected by the dispersive surface energy and polar surface energy of each surface. Figure 3a illustrates the precise relationship between wetting coefficient values and corresponding adhesion behaviors, establishing three distinct regions: selective wetting to PPG ($k_w < -1$, Zone I), interactive wetting without selective separation of coupling agents ($-1 < k_w < 1$, Zone II), and selective wetting to Cu foil ($k_w > 1$, Zone III) [42]. The calculated wetting coefficients for PPG formulations A through D, displayed in Figure 3b, reveal that all four formulations fall within the partial wetting region, with PPG A exhibiting the highest wetting coefficient at 0.78, followed by formulations B (2.12), C (2.42), and D (2.48). This superior wetting coefficient of PPG A can be attributed to its optimized balance between polar and dispersive surface energy components. Since the

TABLE 1: Results of surface energy of Cu foil and various PPG samples.

Sample	Contact angle from water (°)	Dispersive surface energy (mJ/m ²)	Polar surface energy (mJ/m ²)	Total surface energy (mJ/m ²)
Cu foil	97.82	28.23	0.77	23.01
PPG A	88.21	41.39	0.98	42.37
PPG B	72.34	41.63	5.63	47.37
PPG C	70.17	39.39	7.07	46.77
PPG D	67.58	41.08	7.88	48.94

PPE-backbone of the PPGs induces similar dispersive surface energy, the polar surface energy from the ratio of each component decides the adhesion behavior based on the interfacial energy and wetting coefficient. Figure 3c plots the relationship between these energy components for each PPG formulation, demonstrating that PPG A achieves the most favorable combination with lower polar energy (0.98 mJ/m²) and similar dispersive energy (41.39 mJ/m²) compared with that of Cu foil. This specific energy profile enhances compatibility with

TABLE 2: Results of surface tension of silane coupling agent.

Sample	Contact angle of liquid from dispersive surface (°)	Dispersive surface tension (mJ/m ²)	Polar surface tension (mJ/m ²)	Total surface tension (mJ/m ²)
Silane coupling agent	75.69	35.49	20.26	55.75

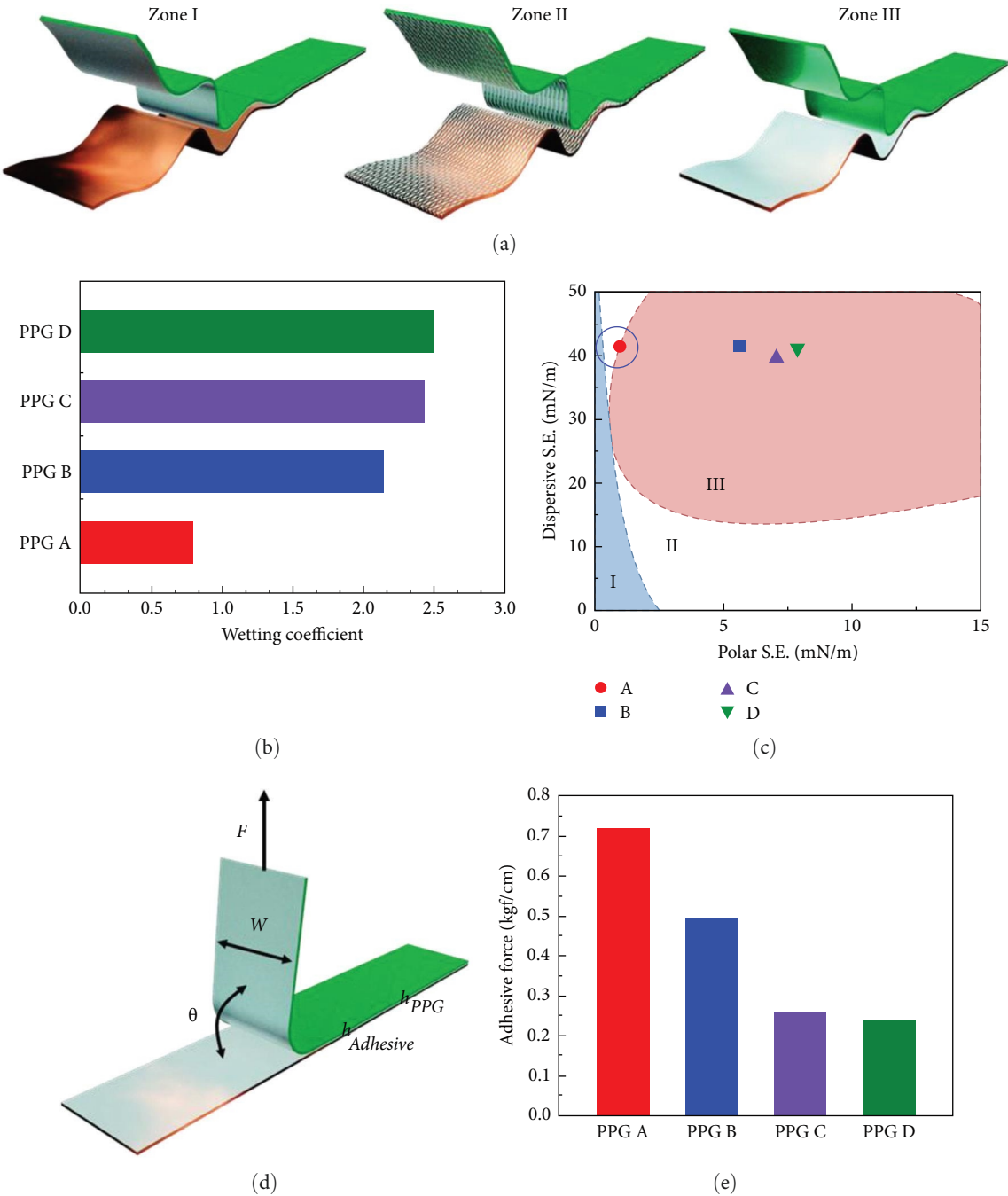


FIGURE 3: (a) Adhesion behavior depending on wetting coefficient regions. (b) Wetting coefficients of PPG A, B, C, and D. (c) Relation of dispersive surface energy (S.E.) versus polar S.E. of each PPG. (d) Schematic of peel-off test, and (e) adhesive force of PPG A, B, C, and D.

the silane-treated copper surface, promoting more uniform interfacial contact and stronger adhesion against shear strength. The wetting coefficient analysis provides a theoretical foundation for predicting adhesion performance between

Cu foil and PPG without etching. A wetting coefficient indicates interfacial contact behavior between the copper and PPG. The regime of interactive wetting without selective separation of coupling agents (Zone II) represents an ideal

TABLE 3: Results of wetting coefficient and adhesive force of various PPG samples.

Sample	Wetting coefficient	Adhesive force (kgf/cm)
PPG A	0.78	0.714
PPG B	2.12	0.490
PPG C	2.42	0.255
PPG D	2.48	0.235

balance, where strong adhesion is achieved without biased wetting that might compromise the distinct boundary between materials or introduce undesirable stress concentrations. Furthermore, efficient wetting property induced by PPG selection results in fewer air gaps or discontinuities that cause signal reflection and attenuation.

The correlation between surface energy components and wetting behavior highlights the importance of strong adhesive material formulation in high-frequency PCB manufacturing. By optimizing polar and dispersive components of the PPG substrate, we can enhance the effectiveness of silane coupling agents and achieve more uniform, strongly bonded interfaces that maintain signal integrity during high-frequency transmission and reduce signal loss.

To quantitatively evaluate the bond strength of different PPG formulations with Cu foil, peel-off tests were conducted following the methodology illustrated in Figure 3d. Results demonstrated adhesive force trends among PPG formulations A through D, related to wetting coefficient results (Figure 3e). PPG A exhibits the highest adhesive force at 0.714 kgf/cm, substantially outperforming the other formulations. PPG B shows moderate adhesion at 0.490 kgf/cm, whereas PPGs C and D demonstrate considerably lower adhesive forces at 0.255 and 0.235 kgf/cm, respectively (Table 3). We directly confirmed the bonded surface through cross-sectional SEM measurements (Figure S2). PPG A and B showed excellent bonding between Cu foils due to the silane coupling agent, but PPG C and D confirmed that the silane coupling agent was not evenly bonded to the surface. This clear differentiation in adhesive performance correlates strongly with the previously observed wetting coefficients, confirming theoretical predictions with empirical evidence. The superior adhesive force of PPG A is attributed to several factors. First, its optimized surface energy components promote better interfacial bonding with the silane-treated copper surface. Second, the specific molecular structure of PPG A likely facilitates stronger interactions with the organo-functional groups of the silane coupling agent. Third, processing conditions for PPG A may have been optimized to enhance cross-linking density at the interface, resulting in a more robust bond. This adhesion value was confirmed to be similar to the level of adhesion obtained through an additional surface modification process (Table S1) [5, 44, 45].

Morphology analysis of PPG surfaces after peel-off testing provides fracture mechanisms and interfacial bonding characteristics through SEM. Figure 4 presents SEM images of

PPG substrates from A to D, before and after the peel-off test, revealing distinctive morphological changes related to their adhesion performances. PPG A exhibits a surface with copper residue, indicating bonding fractures in the copper layer rather than silane at the interface. Thus, this shows the strong bond formation between copper and PPG A through the silane reaction. Conversely, PPG B, C, and D exhibit less copper residue and the shape of the destroyed resin, indicating a weak bond strength between copper and each PPG. This progression across the PPG substrates directly corresponds to the wetting property calculated from the surface energy.

XPS provides detailed chemical state information at the molecular level, offering bonding mechanisms between the Cu foil, silane coupling agent, and PPG substrate. Figure 5 presents comprehensive XPS results for C 1s, O 1s, and Si 2p core level spectra from PPG A and copper foil with and without silane treatment, enabling the identification of specific chemical bonds responsible for the superior adhesion observed in PPG A [46]. The functional group of the silane coupling agent was identified through fourier transform infrared spectroscopy analysis. (Figure S1) High-resolution C 1s spectra (Figure 6a,b) of PPG A and Cu foil with silane treatment revealed distinct carbon chemical environments, with precisely identified peaks at 284.8, 286.5, and 288.7 eV corresponding to C–C/C–H, C–O/C–N, and C=O bonds, respectively, compared with the spectra of the pristine PPG A and Cu foil, which indicates the formation of new carbon-containing bonds at the interface after silane treatment [47–49]. Particularly notable is the enhancement of the C–O peak in the copper foil, providing quantitative evidence of successful interaction between the silane coupling agent and the copper surface, which supports strong adhesion observed in previous peel-off tests. Analysis of the O 1s spectra (Figure 6c,d) of PPG A and Cu foil with silane treatment shows well-resolved peaks at 530.5, 531.8, and 533.2 eV, attributable to metal oxide (Cu–O), siloxane bonds (Si–O–Si/Si–O–Cu), and organic oxygen (C–O/C=O), respectively [50]. The prominent siloxane peak, comprising the main portion of the total O 1s signal in both samples, confirms the formation of Si–O–Si/Si–O–Cu bonds, constituting the primary chemical bridge between the copper and the organic substrate [49]. These siloxane bonds provide improved mechanical strength that prevents delamination under mechanical stress. The Si 2p spectra (Figure 6e,f) provided definitive evidence of successful silane coupling, with characteristic peaks at 102.5 and 103.4 eV corresponding to Si–O–Cu and Si–O–Si bonds, respectively [51]. The Si–O–Cu peak indicated that the silane coupling agent has successfully formed chemical bridges between the copper surface and the PPG substrate, and it underwent controlled self-condensation to form a robust siloxane network. Moreover, XPS spectra peaks of Cu 2p in the Cu foil with and without the silane treatment show two strong peaks at 934.7 and 954.6 eV, corresponding to Cu²⁺ 2p_{3/2} and Cu²⁺ 2p_{1/2}, respectively (Figure S3) [51, 52]. The state was further observed by satellite peaks at binding energies of 942.8 eV, which indicates the formation of Si–O–Cu for strong adhesion and uniform coverage.

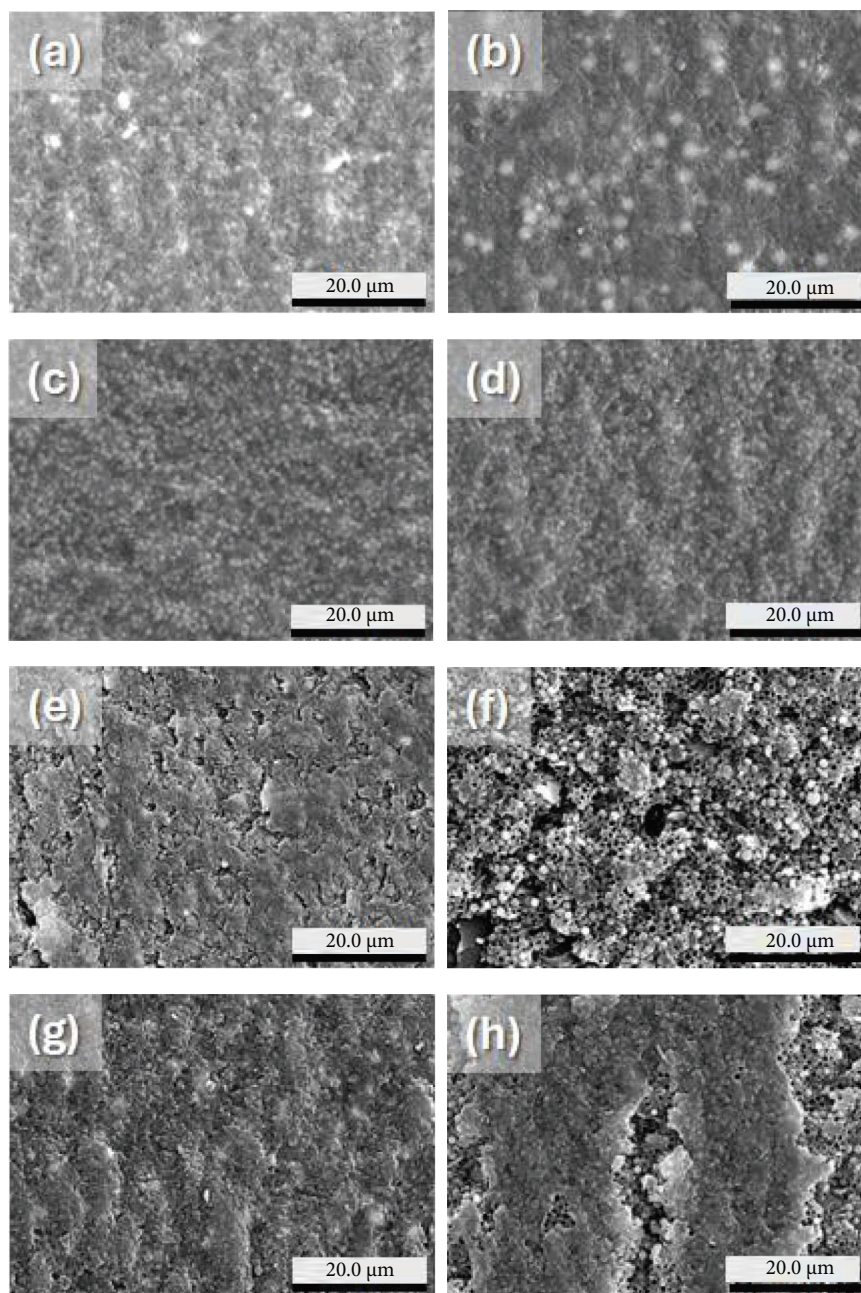


FIGURE 4: SEM images of PPG (a, b) A, (c, d) B, (e, f) C, and (g, h) D before and after the peel-off test.

The ultimate measure of PCB performance for high-frequency applications is signal integrity, which can be quantitatively assessed through return loss testing. Figure 6a illustrates the return loss test following the IPC-TM-650 2.5.5.14. This setup measures the ratio of reflected signal power to incident signal power across a frequency spectrum from 0.1 to 40 GHz [53, 54]. The results for PCBs manufactured using PPG A with the silane coupling agent described in the previous section demonstrate exceptional signal integrity characteristics. The return loss curve for the PCB based on PPG A with nonetching coupling agents shows consistently

low reflection across the tested frequency range. This performance is significantly superior to conventional PCBs manufactured using conventional etching processes, which typically exhibit return loss values of -1.5 dB/inch or higher at frequencies above 20 GHz (Figure S4). This value was certified by UL verification services as shown in Figure S5. Low return loss values indicate that minimal signal power is being reflected owing to impedance discontinuities or surface irregularities, confirming the uniformity of the copper–PPG interface achieved through the nonetching oxide chemical approach and the siloxane bonds (Si–O–Cu) identified in the XPS

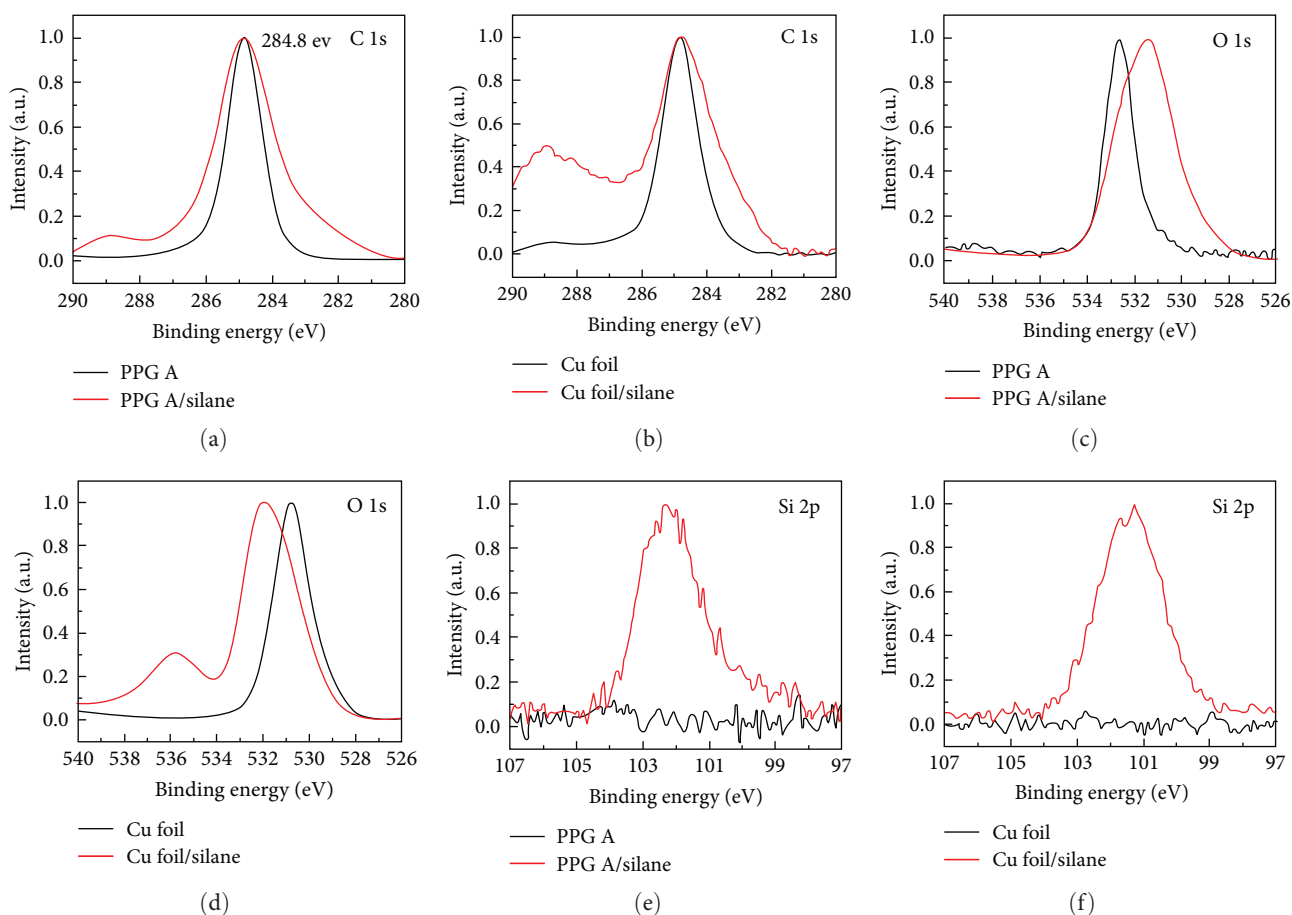


FIGURE 5: XPS results of (a, b) C 1s, (c, d) O 1s, and (e, f) Si 2p by PPG A and Cu foil with and without silane coupling agent.

analysis. At higher frequencies (above 10 GHz), the return loss gradually increases to approximately -1.08 dB/inch at 30 GHz but remains within acceptable limits for most high-frequency applications. Comparative analysis shows that the nonetched samples have an advantage over conventional etched samples even at these elevated frequencies. The exceptional signal integrity demonstrated by the return loss test results has profound implications for PCB applications in high-speed digital systems. The reduced signal loss contributes to longer transmission distances, higher data rates, and improved reliability in critical applications. Furthermore, the consistent performance across a wide frequency range makes these PCBs suitable for broadband applications where signal integrity must be maintained across multiple frequency bands, such as 6G infrastructure equipment.

4. Conclusion

This study quantified the surface energy of the Cu and PPG layers, deriving and validating a wetting coefficient for evaluating and predicting interfacial adhesion behavior. This

approach avoids the increased surface roughness associated with conventional etching techniques, thereby reducing signal reflection and attenuation during high-frequency transmission. Surface energy analysis revealed that certain PPG formulations exhibit lower polar surface energy, indicating superior compatibility with the silane layer. Among the tested samples, PPG A showed the most favorable wetting coefficient (0.78), which correlated well with the highest peel strength measured experimentally. This enhanced adhesion is attributed to the formation of robust chemical bonding at the Cu/PPG interface. As a result, return loss measurements confirmed that PCBs fabricated with PPG A maintained stable signal integrity up to 40 GHz, achieving approximately 30% improvement compared to etched counterparts. Thus, while this study primarily focused on room-temperature adhesion, these results are expected to extend the wetting coefficient model to dynamic and multilayer PCB structures and large-scale industrial lamination processes. Furthermore, implementing this nonetching silane-based adhesion method could provide a sustainable and cost-effective alternative to current roughness-based PCB manufacturing techniques.

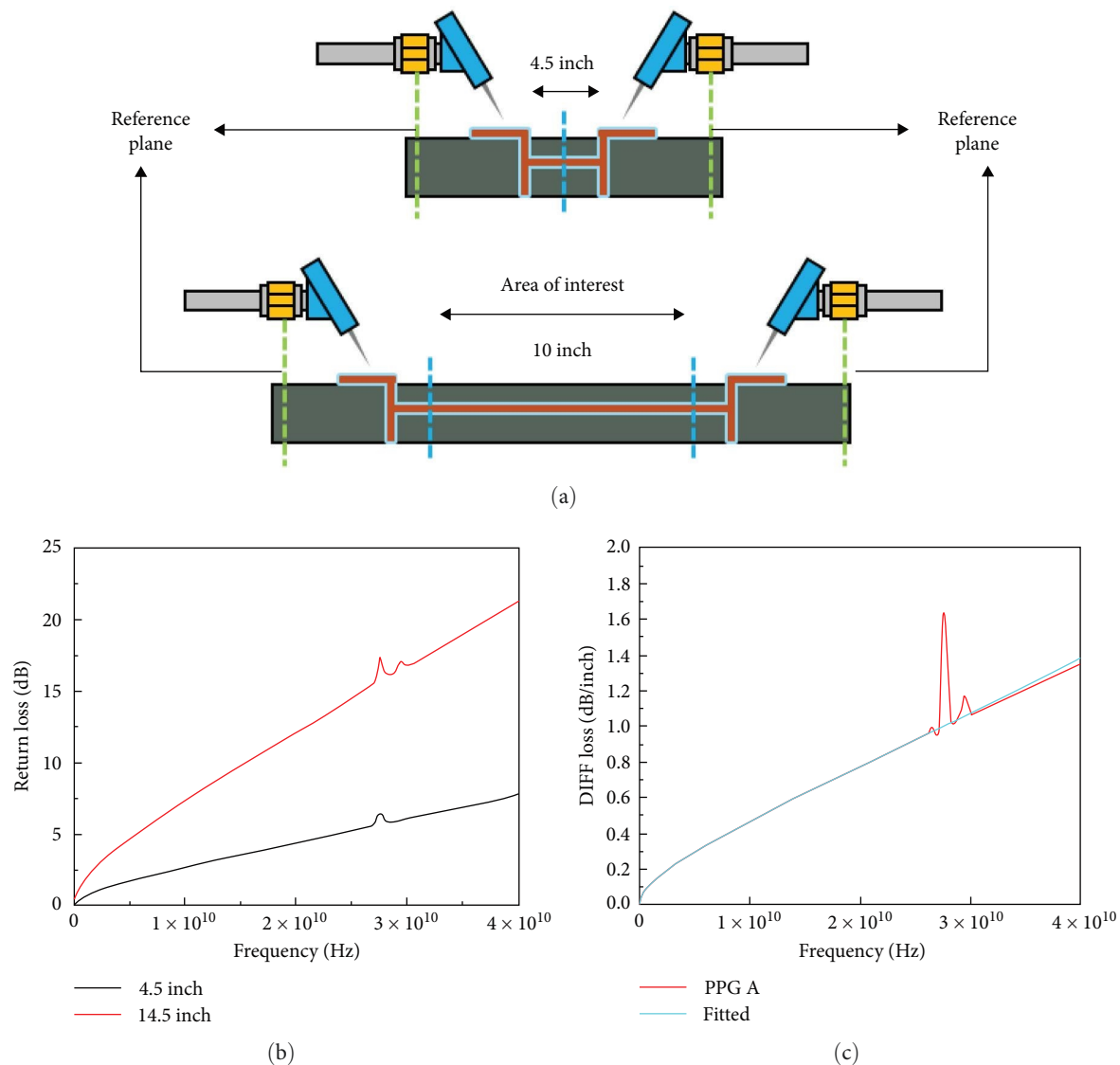


FIGURE 6: (a) Schematic of return loss test and (b, c) results of return loss and differential insertion (DIFF) loss by PCB from PPG A by using nonetching type silane coupling agent.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Woongsik Jang and Jin Young Kim contributed equally to this work.

Funding

This study was funded by the National Research Foundation of Korea (Grants NRF-2023R1A2C2008021, NRF-RS-2023-

00217270, and NRF-RS-2024-00394860) and the Ministry of Trade, Industry and Energy (Grant 20017439).

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) under the Ministry of Science and ICT (MSIT, Republic of Korea) (Grants NRF-2023R1A2C2008021, NRF-RS-2023-00217270, and NRF-RS-2024-00394860). This work was also supported by the Technology Innovation Program funded by the Ministry of Trade, Industry and Energy (MOTIE, Republic of Korea) (Grant 20017439, "Development of manufacturing process technique on high-speed signal transmission line for 6G device").

Supporting Information

Additional supporting information can be found online in the Supporting Information section. (*Supporting Information*)

Figure S1. It shows the FT-IR spectra of the silane coupling agent. Figure S2. It shows the cross-sectional SEM image. Figure S3. It shows the XPS results of Cu foil with and without silane coupling agent. Figure S4. It shows the return loss results measured from PPG A to PCB using conventional silane coupling agent. Figure S5. It shows the certificate of insertion loss results by PCB from PPG A using conventional silane coupling agent. Table S1. Comparison of adhesion with different surface treatment concepts.

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