Comparison of high-frequency transmission characteristics of transmission lines on copper-plated cycloolefin polymer using directly sputtered copper seed layer and electroless copper plating seed layer

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Abstract
We have developed a technology to form a copper plating layer using a directly sputtered copper seed layer without an adhesion layer on cycloolefin polymer (COP) film for application in antenna circuits for 6G communications. This study compared the high-frequency transmission characteristics up to 100 GHz in coplanar transmission lines on copper-plated COP films using either a directly sputtered copper seed layer (sputtered type) or an electroless copper plating seed layer (electroless type). Our findings indicate that the sputtered type exhibits superior transmission loss characteristics compared to the electroless type, particularly beyond 60 GHz. This difference is attributed primarily to the skin effect at high frequencies, where current primarily flows through the copper plating layer for the sputtered type, compared to the electroless type, where it flows through the electroless copper plating layer, which has significantly lower conductivity.

Key words
cycloolefin polymer, electroless copper plating seed layer, high-frequency transmission characteristics, sputtered copper seed layer

I. Introduction
Millimeter-wave technology, which utilizes a wide bandwidth in the 30-300 GHz frequency range, is a promising solution for 6G wireless communication systems, offering significantly faster speeds, higher capacity, and lower latency compared to current 5G systems [1-2]. However, it faces challenges related to coverage area limitations due to propagation characteristics such as high propagation loss and susceptibility to blockage [3-5]; therefore, the implementation of small-cell technology is being explored. Small cells involve deploying numerous compact base stations to cover smaller areas, in contrast to the large-scale cell towers known as macro cells [5-6]. The increased number of small cells introduces challenges related to power consumption, making it crucial to mitigate transmission losses in the transmission lines of antenna circuits used in these base stations.

These transmission lines consist of copper (conductor) wiring patterns on resin (dielectric) substrates, meaning that transmission loss mainly comprises dielectric and conductor losses [7]. To reduce dielectric loss, it is important to utilize a resin substrate characterized by lower relative permittivity and dielectric tangent, with cycloolefin polymer (COP) [8] identified as a suitable candidate. Conductor loss primarily arises from an increase in the effective resistance of the copper conductor owing to the skin effect [9] and surface roughness. To minimize conductor loss, it is imperative to form a copper seed layer without roughening the resin surface before electrolytic plating of a conductive layer.

We focused on the dry process utilizing sputtering to form a copper seed layer on the COP surface without inducing roughness. This approach contrasts with the wet process using electroless copper plating, which also requires surface modification through ultraviolet (UV) or vacuum ultraviolet (VUV) irradiation [10-13]. Previous study [14] achieved a peel strength of 1 kN/m between the COP film and the copper plating layer by forming a copper seed layer on an adhesion layer of copper nitride (CuN) using sputtering. However, the use of an adhesion layer introduces challenges owing to its lower conductivity compared to the copper seed layer, exacerbating conductor loss. Additionally, the process complexity is increased by requiring separate etching of the copper seed and adhesion layers during wiring pattern formation.

To solve the abovementioned problems, we developed a novel dry process to form a copper seed layer directly without requiring an adhesion layer. This process employs a plasma-integrated sputtering machine incorporating various surface modification techniques [15-20]. Our research findings demonstrated that VUV irradiation followed by oxygen plasma treatment as pretreatment for copper seed layer formation resulted in a peel strength of 1 kN/m between the COP film and the copper plating layer was achieved solely with a copper seed layer, omitting the need for an adhesion layer [20].

In this study, we investigated the high-frequency transmission characteristics of a sputtered seed layer up to 100 GHz and compared them with those of a conventional electroless copper seed layer.

II. Experimental methods

A. Copper-plated COP film

The fabrication process for the copper-plated COP film (ZF-16, t100 μm, Zeon Corporation) with a sputtered copper seed layer (referred to as the sputtered type hereinafter) followed the steps outlined in Fig. 1. The fabrication parameters were based on conditions that obtained a peel strength of 1 kN/m, as detailed in [20]. First, the COP film was baked in an oven at 80°C for 1 h to remove moisture. Next, the COP film was irradiated with VUV light using an excimer transfer device (SVS3 series, Ushio Inc.) in clean, dry air conditions, with a VUV irradiation dose of 600 mJ/cm^2. Subsequently, the COP film underwent oxygen plasma treatment immidiately using a medium-vacuum plasma-integrated sputtering machine (LPP-450, Shibaura Machine Co., Ltd.) at a pressure of less than 100 Pa for a plasma treatment time of 120 s. Following oxygen plasma treatment, a copper seed layer with a thickness of approximately 200 nm was continuously formed onto the COP film under argon flow at a pressure of less than 1 Pa. Then, the copper plating layer, with a target thickness of 10 μm was deposited onto the copper seed layer in a copper sulfate bath. Finally, the copper plating and copper seed layers were annealed at 100°C for 1 h in the oven.

The other copper-plated COP film (same material as above) with an electroless copper plating seed layer (referred to as the electroless type hereinafter) and a copper plating layer with a thickness of 10 μm, was also prepared. The fabrication process involved surface modification, chemical treatment, application of a palladium catalyst, electroless copper plating, electrolytic copper plating, and annealing. The target thickness of the electroless copper plating layer was approximately 300 nm.

Baking (80 °C, 1 h)

↓

VUV irradiation (CDA, 600 mJ/cm^2)

↓

Oxygen plasma treatment (<100 Pa, 120 s)

↓

Cu sputtering (<1 Pa, 200 nm)

↓

Electroplating (25 um)

↓

Annealing (100 °C, 1 h)

Fig. 1 Fabrication procedures for the sputtered type

The average surface roughness (Sa) parameters in 10 × 10 μm area after oxygen plasma treatment for the sputtered type and after chemical treatment for the electroless type were evaluated using atomic force microscopy (AFM; SPM-9600, Shimadzu Corporation) in the dynamic (tapping) mode.

B. Transmission line fabrication

The coplanar transmission line [21] was designed using simulation software (COLMINA CAE Signal Integrity, Fujitsu Limited), with the signal line width and gap between the signal and ground set at 30 μm and 200 μm, respectively, resulting in a characteristic impedance of approximately 50 Ω, as shown in Fig. 2.

The coplanar transmission lines were fabricated using widely employed subtractive method [22]. Two types of copper-plated COP films, as described in the previous section, were laminated with a dry film resist (DFR). The DFR was then exposed to ultraviolet light in areas intended to remain as wiring patterns, thereby curing it. Subsequently, the uncured areas of the DFR were removed using a sodium hydroxide aqueous solution. Then, copper in the areas where the DFR had been stripped was etched using a ferric chloride aqueous solution. Finally, the DFR was stripped using a sodium hydroxide aqueous solution, resulting in the formation of the wiring patterns. The surface of the transmission lines was examined using scanning electron microscopy (SEM; JSM-IT100, JEOL Ltd.).

C. Transmission characteristics evaluation

The scattering parameters (S-parameters; S11: reflection coefficient, S21: transmission coefficient) at frequencies from 10 MHz to 100 GHz were measured using a network analyzer (N5245B, Keysight Technologies), calibrated via the Through–Reflect–Line (TRL) method, with a frequency extender (N5295AX53, Keysight Technologies) and an air coplanar probe (ACP110-A-GSG-150, FormFactor Inc.). The characteristic impedance was determined by analyzing

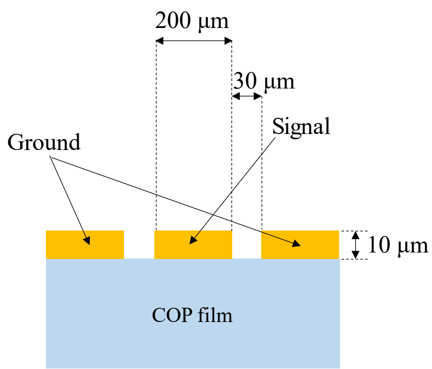


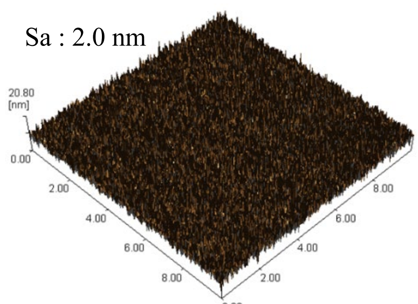
Fig. 2 Specifications for the design of the coplanar transmission line

the S11 parameter using the Physical Layer Test System (N1930B, Keysight Technologies) through the Time Domain Reflectometry method. The S-parameters were measured twice for each coplanar transmission circuit of the sputtered and electroless types.

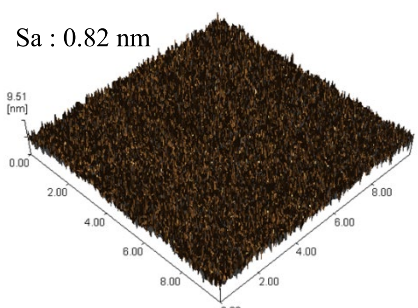
III. Results and discussion

A. Surface roughness

The Sa parameters before copper seed layer formation were approximately 2.0 nm for the sputtered type (Fig.3 (a)) and 0.82 nm for the electroless type (Fig.3 (b)). Thus, although the surface roughness of the sputter type was slightly larger than that of the electroless type, both were not significantly different from 0.42 nm of the untreated [18].



(a) Sputtered type



(b) Electroless type

Fig. 3 Sa parameters before copper seed layer formation

B. Transmission line characteristics

Fig. 4 shows SEM image of the transmission line surface for the sputtered type. Based on SEM length measurements, the signal line width was 190 µm, and the gap between the signal and ground was 40 µm, aligning closely with the design specifications. Similar results were confirmed for the electroless type as well. Thus, coplanar circuits were successfully fabricated using the subtractive method.

The S-parameters were consistent across two measurements, confirming their reproducibility. The S11 parameter indicates the proportion of the input signal reflected back at the input port after TRL calibration. Across all frequencies from 10 MHz to 100 GHz, the S11 parameters remained below −20 dB for the sputtered and electroless types. Thus, the reflectance at the input port is less than 1%, indicating that over 99% of the signal is transmitted. This confirms the absence of issues with the overall quality of design, fabrication, and measurements concerning the transmission line. Furthermore, the characteristic impedances for both the sputtered and electroless types were found to be 50 Ω ± 3 Ω, aligning with the design value of 50 Ω.

The S21 parameter denotes the proportion of the input signal transmitted to the output point, also called as insertion loss. Fig. 5 illustrates the relationship between frequency and insertion loss for signal line lengths of 30 mm for the sputtered and electroless types up to 100 GHz. At 30 GHz and 60 GHz, the insertion losses were −0.945 dB and −1.51 dB for the sputtered type and −1.02 dB and −1.64 dB for the electroless type, respectively. Thus, the sputtered type exhibits slightly lower insertion losses compared to the electroless type, suggesting a marginal advantage for the sputtered type below 60 GHz.

For the sputtered type, the insertion loss exhibited a gradual decline, maintaining this trend beyond 60 GHz and reaching −2.45 dB at 100 GHz. In contrast, the insertion loss for the electroless type began to rapidly decrease beyond 60 GHz, registering −2.93 dB at 100 GHz. These findings indicate that the sputtered type demonstrates superior transmission loss characteristics compared to the electroless type, particularly beyond 60 GHz.

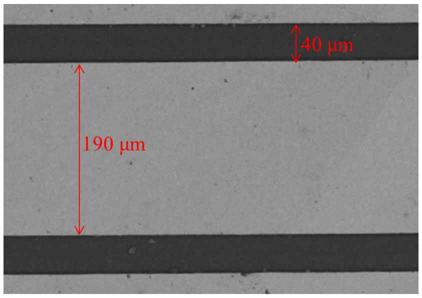


Fig. 4 SEM image of the coplanar transmission line for the sputtered type

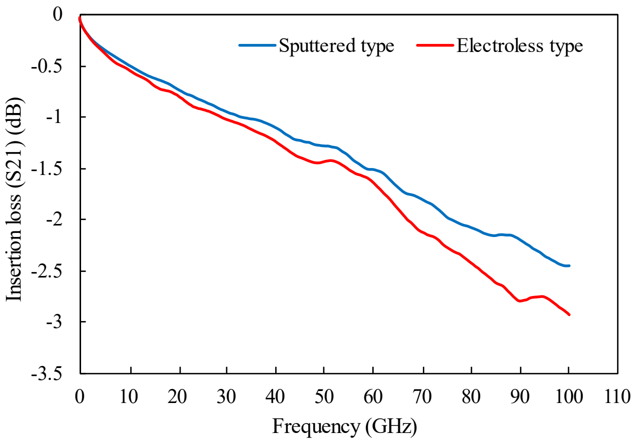


Fig. 5 Relationship between frequency and insertion loss for the sputtered and electroless types at 30 mm of signal length

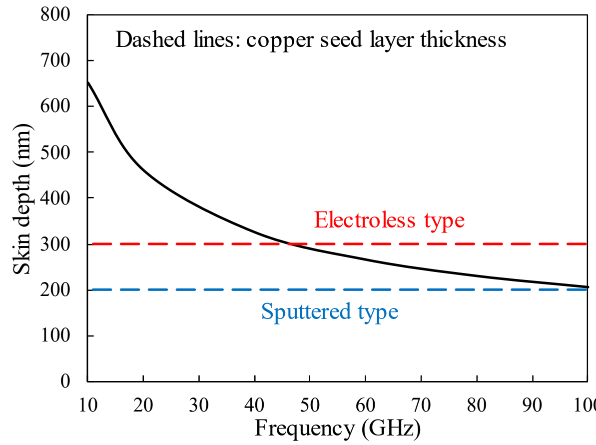


Fig. 6 Relationship between skin depth for copper, with dashed lines representing the thickness of the seed layers for the sputtered and electroless types.

C. Factors contributing to the difference in insertion loss

The observed variance in insertion loss between the sputtered and electroless types at high frequencies prompted an investigation into potential contributing factors.

Given that both types utilize the same dielectric material, consistent dielectric loss is expected. Moreover, because the surface roughness before seed layer formation was nearly identical for both types, conductor loss attributed to surface roughness should also be comparable. Therefore, it is reasonable to assume that the difference in insertion loss between the sputtered and electroless types is influenced by conductor loss owing to the skin effect.

The skin effect refers to the phenomenon where, at higher frequencies, the current primarily propagates along the surface of the conductor rather than through its center. The skin depth, determined by the following equation [9], represents the depth from the surface through which the current flows.

$$d = \sqrt{\frac{1}{\pi f \mu \sigma}}$$

Where d is the skin depth, f is the frequency, μ is the absolute magnetic permeability of the conductor, and σ is the conductivity of the conductor. For copper conductors, with permeability of 1.257×10^{-6} (H/m) and conductivity of 59.77 $\times\ 10^{6}$ (S/m), the relationship between frequency and skin depth is shown in Fig. 6. Additionally, Fig. 6 shows the seed layer thicknesses for the sputtered and electroless types. At 10 GHz, the skin depth is approximately 650 nm, decreasing to about 290 nm at 50 GHz and around 200 nm at 100 GHz. For the sputtered type, the current is expected to predominantly flow through the copper plating layer even at 100 GHz. for the electroless type, since the thickness of the electroless copper seed layer is approximately 300 nm, the current is expected to mainly flow through this seed layer above 50 GHz. Given that the conductivity of the electroless copper plating layer is known to be less than 1/10 that of the copper plating layer [23], the effective resistance of the conductor for the electroless type is expected to be higher than that of the sputter type. Consequently, it is expected that the insertion loss of the electroless type would increase more rapidly than that of the electroless type, particularly above 50 GHz, aligning generally with the results shown in Fig. 5. While other factors may influence insertion loss, differences in seed layers are considered to be dominant at high frequencies.

IV. Conclusion

In this study, we evaluated and compared high-frequency transmission characteristics up to 100 GHz in coplanar transmission lines fabricated with either a sputtered copper seed layer (sputtered type) or an electroless copper plating seed layer (electroless type). The sputtered type consistently outperformed the electroless type across all frequencies, exhibiting notably superior transmission loss characteristics, particularly in the high-frequency range above 60 GHz. This difference in transmission loss was primarily attributed to the skin effect at high frequencies. For the sputtered type, the current flows through the copper plating layer in the sputtered type. In contrast, it predominantly flows through the electroless copper plating layer, known for its significantly lower conductivity compared to the copper plating layer, for the electroless type.

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