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Effect of Interfacial Characteristics of Metal Clad Polymeric Substrates on Electrical High Frequency Interconnection Performance

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EFFECT OF INTERFACIAL CHARACTERISTICS OF METAL CLAD

POLYMERIC SUBSTRATES ON ELECTRICAL HIGH FREQUENCY

INTERCONNECTION PERFORMANCE

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SUMMARY

Etched metallic conductor lines on metal clad polymeric substrates are used for electronic component interconnections. Significant signal losses are observed for microstrip conductor lines used for interconnecting high frequency (above 20 GHz) devices. At these frequencies, the electronic signal travels closer to the metal-polymer interface due to the skin effect. Copper-teflon interfaces were characterized by SEM and AES to determine the interfacial properties. Data relating roughness of the copper film to signal losses was compared to theory. Films used to enhance adhesion were also found, to a lesser extent, to contribute to these losses.

INTRODUCTION

Metal clad polymeric substrates have provided a suitable media for the printing of conductor lines used to interconnect electronic devices and components for several decades (ref. 1). The use of these substrates is being further extended for the interconnection of high frequency/high speed devices by designing the conductor lines as microstrip transmission lines (refs. 2 and 3). At high frequencies, the electrical signal propagates closer to the metal-polymer interface due to the skin effect. For example, at 10 GHz, the skin depth (δ) for copper is 6600 Å whereas at 1 GHz the skin depth is in excess of 2 μm. Contributing to the signal power losses are conductor loss, dielectric loss and radiation. Theoretical calculations by Morgan (ref. 4) have shown that the conductor surface roughness increases the conductor loss contribution to the total signal loss at higher frequencies. The increase approaches 100 percent as the value of the root mean square (rms) roughness (R_a) becomes twice that of the skin depth at the frequency of interest.

Several investigators have experimentally determined the effect of roughness on ceramic substrates for values of $R_a/\delta < 1$ (refs. 5 and 6). The copper-polymer interface provides data in the saturated region of Morgan's curve where $R_a/\delta \gg 1$. This effect in metal clad polymeric substrates at higher frequencies had not been experimentally evaluated.

This paper presents such an experimental investigation into the effect of asperities at the metal-polymer interface on high frequency signal power loss. Commercially available copper-clad teflon substrates were used. The results are compared with theory.

EXPERIMENTAL PROCEDURES

Copper clad teflon substrates were etched in a ferric chloride solution to obtain a teflon surface for analysis. The copper conductor surface was obtained by heating the substrates at 200 °C for 4 hr and then peeling back the copper for various measurements.

The copper and teflon samples were analyzed by SEM at 1000 and 3000 magnification. The copper surface was analyzed by AES to determine the composition and thickness of films used for adhesion. The AES sputter depth profiling was done with 3 KeV Ar ions at 25 mA current.

To obtain quantitative measurements of roughness, a Sloan profilometer, model DEKTAK II-A, was used. Root mean square (rms) roughness (R_a), and maxiumum roughness (R_T) were obtained.

The attenuation constant (α_T) of the microstrip transmission line is related to the Q of the line as below:

$$\alpha_T = \frac{8.686\pi}{Q_0} \frac{dB}{\lambda} \tag{1}$$

where "Q_0" is the unloaded Quality factor and λ is the wavelength (ref. 3). To determine the effect of surface finish on total loss, linear open circuit $\lambda/2$ microstrip resonators were fabricated on 10 mil thick electrodeposited and electroless copper-clad teflon substrates. The nominal impedance of all lines was 50 ohms. For frequencies below 20 GHz, a conventional coaxial-to-microstrip transition was used to feed the R.F. signal to the resonator via a symmetrical $\cong 4$ mil gap. Measurements from 28 to 34 GHz were performed using a novel waveguide-to-microstrip transition in line with the resonator via a similar gap (fig. 1). Both techniques utilized HP network analyzers to provide the swept measurements. The raw data yields the loaded quality factor, Q_L, as shown in fig. 2. Q_0 is then derived from the measured reflection coefficient at resonance and a Smith Chart impedance plot (ref. 7).

RESULTS AND DISCUSSION

In figure 3, the SEM micrographs of the copper conductor surfaces for samples A and B and the corresponding etched teflon surfaces are shown. Two different morphologies for the copper conductor surfaces were observed. In fig. 3 (top) the nodules are smaller than in fig. 3 (bottom). The teflon surfaces are an exact replica of the conductor surfaces and show no voids. In fig. 4, the SEM micrographs of the copper conductor surface and the corresponding teflon surface are shown. The copper surface is smooth when compared to the surfaces of samples A and B.

For samples A, B, and C, the average root mean square surface roughness values were 0.452, 0.770, and 0.270 μm, respectively. These values varied within 0.1 μm from area to area on the sample. The adhesion strength of samples A and B is close to 15 lb/in; For sample C it is approximately 4 lb/in (ref. 9).

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Figure 5 shows the Auger depth profile of the copper surface of Sample A, having a thickness of approximately 360 Å. The thickness value, based on sputter time, was deduced from the predetermined sputter rate. In figure 6, the profile data of sample C shows that no adhesion metals are present at the interface.

High resistivity intermediate films typically introduce negligible loss even at high frequencies if their thickness does not exceed $\cong 0.4$ δ, for which the increase in loss should not be more than 2 or 3 percent (ref. 6).

The relative attenuation is obtained from a comparison of the theoretical (smooth interface) quality factor, Q_T, to the experimental Q_0 values from the microstrip resonators. Q_T values were obtained using equation (1) where α_T is actually:

$$\alpha_T = \alpha_c + \alpha_d + \alpha_r \tag{2}$$

The conductor loss (α_c) was calculated using Pucel's (ref. 9) formulation, and the dielectric loss (α_d) was obtained from Edwards (ref. 3). Although it is known that the dielectric loss tangent increases slightly with frequency, an accurate description of its behavior was unavailable. Hence, the loss tangent was assumed constant and the manufacturer's reported value at 10 GHz was used. The effect on Q_0/Q_T is minimal. The resonators were enclosed in waveguide-type structures below cutoff, hence the radiation loss (α_r) was $\cong 0$. The ratio of experimental attenuation to theoretical attenuation versus the root mean square surface roughness is plotted in fig. 7 for microstrip resonators at several frequencies. The experimental data was further compared with a curve fit formula obtained by Hammerstad and Bekkadal (ref. 10). Their formula, based on Morgan's theory, is given below:

$$\text{Relative attenuation} = 1 + \frac{2}{\pi} \arctan \left\{ 1.4 \left(\frac{R_a}{\delta} \right)^2 \right\} \tag{3}$$

The skin depth, δ, at a particular frequency (f) is equal to $[\pi f \mu \sigma]^{-1/2}$ where μ is the permeability and σ is the conductivity of the metal film.

The results show a reasonable correlation of the experimental data to the theory for the lower frequencies where R_a is <0.5 μm. The higher frequency points, however, all fall below the predicted values. Especially noteworthy are the high frequency data at $R_a \cong 0.77$ μm which show the relative attenuation significantly below the curve postulated by Morgan. This discrepancy may be due to the differences in the effective path length between the assumed geometry of the theory and the real structures of the cones observed in SEM pictures. The net effect results from the fact that as the frequency increases, the skin depth decreases, and the apparent roughness and effective path length in terms of wavelength also increase. See figures 3 and 4.

CONCLUSIONS

The characteristics of the metal-polymer interface can affect the electrical performance of high frequency interconnections. In essence, the results show that it is desirable to keep R_a less than 0.25 μm so that the percentage increase in loss is kept below 10 percent for frequencies up to 30 GHz.

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The influence of conductor surface roughness on high frequency power loss in microstrip transmission lines can be predicted once the root mean square roughness is known. The experiments have shown that Morgan's theory, which was developed for idealized suface morphologies, overestimates the increased loss by $\cong 20$ percent as R_a/δ becomes $>>1$. An accurate effect, therefore can only be obtained by considering the total surface topography. Reduced roughness can effect the adhesion at the metal polymer interface and the consequences must be carefully evaluated prior to any application.

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10. E.O. Hammerstad, and F. Bekkadal, "Microstrip Handbook", ELAB Report STF44-A74169, University of Trondheim, Norway, 1975.
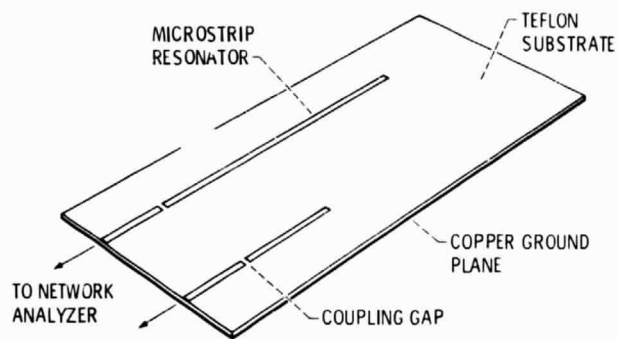
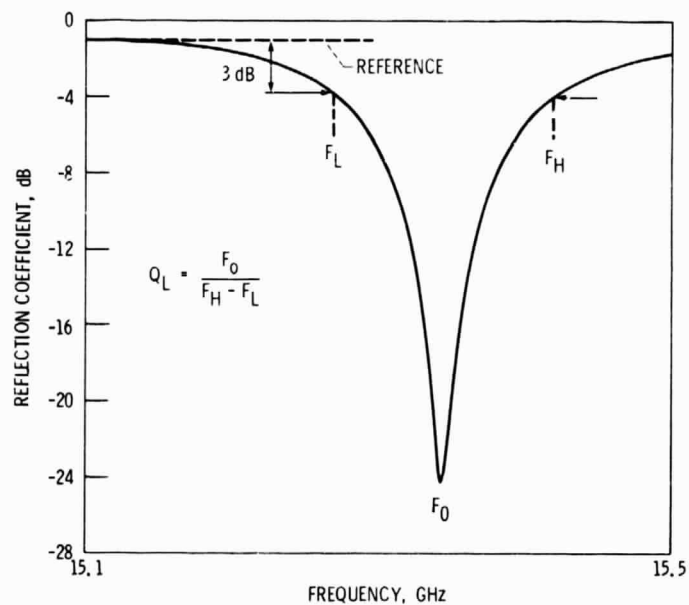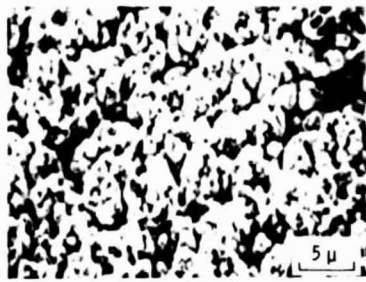Figure 1. – Schematic diagram of partial experimental setup to measure loaded quality factor.
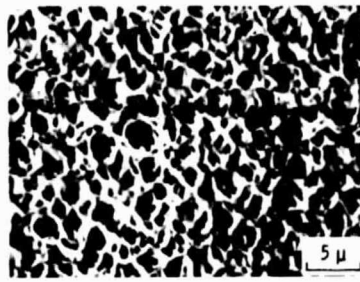

Figure 2. – Frequency response obtained for microstrip resonator designed at f = 16 GHz. The method to obtain loaded quality factor is also shown.
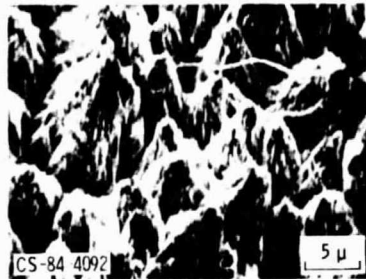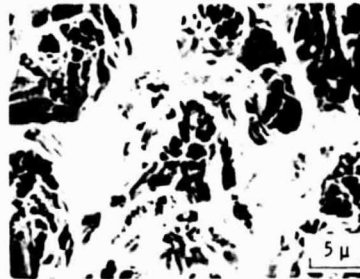
Copper surface 3000X

Etched PTFE - glass 3000X composite surface

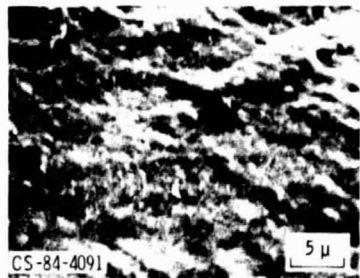Copper surface 3000X

Etched PTFE - glass 3000X composite surface

Figure 3. - Scanning Electron Micrographs (3000X) for samples A (top) and B (bottom).
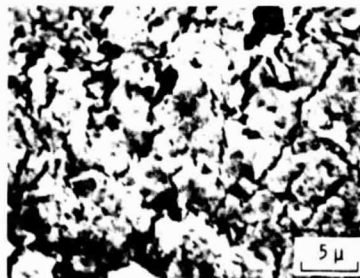Both samples show non uniform nodular morphology.

Copper surface 1000X

PTFE surface 1000X

Copper surface 3000X

PTFE surface 3000X

Figure 4. - Scanning Electron Micrograph (1000X, 3000X) showing copper and etched
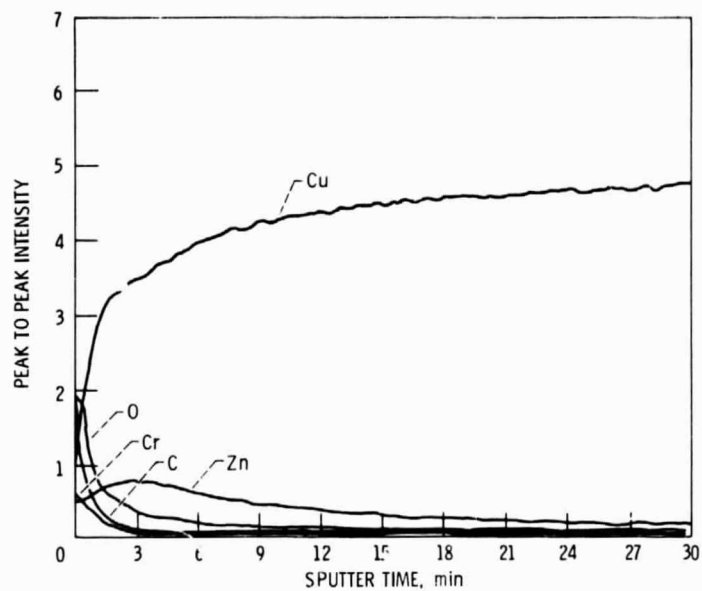teflon surface for sample C. The copper conductor surface is relatively smooth.

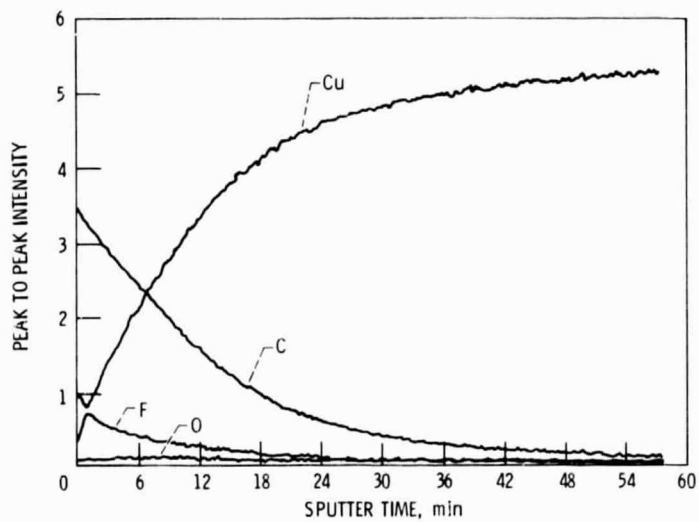Figure 5. - Sputter depth profile of copper surface sample A.

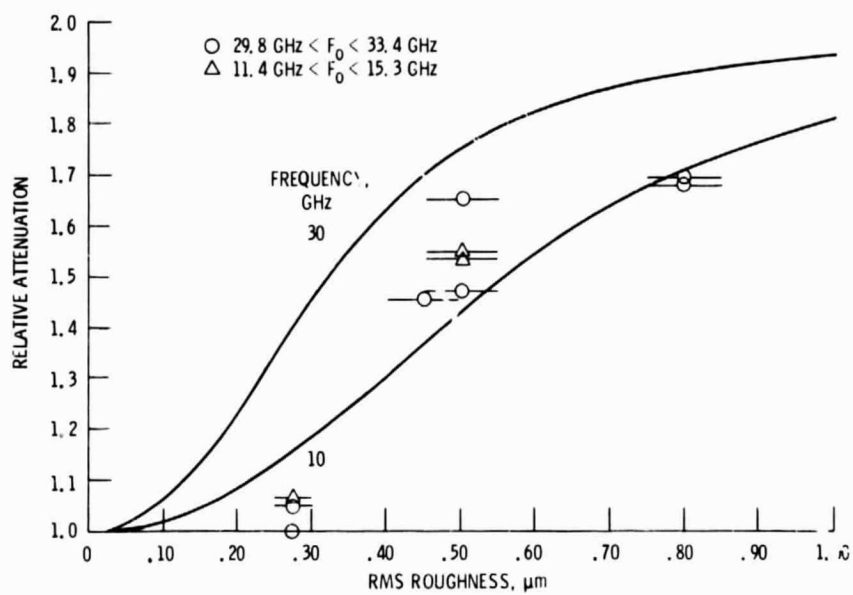Figure 6. - Sputter depth profile of copper surface sample C.

Figure 7. - Relative attenuation observed from 10 to 35 GHz for microstrip resonators vs. r. m. s. roughness at the copper-teflon interface. The solid curves at 10 GHz and 30 GHz are based on Morgan's Theory.