Influence of Metallic Primers on the Attenuation of CPW in the Millimeter- and Submillimeter Range

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Short Abstract—A metallic primer is often used between a conductor and a substrate to build up coplanar waveguides (CPW). These primers influence the attenuation of the CPW line and planar structures in general. The exact influence of metallic primers is described and a frequency-independent description to avoid uneligible primers is presented.

Keywords: primer; attenuation; CPW

I. INTRODUCTION

CPW lines are built by depositing a conductive layer on a dielectric substrate. The conductive layer is often regarded to be of electrically thick thickness. This approximation is sufficiently accurate, if the layer is thicker than 3 d, where d means skin depth. The conductor often does not cling to the chosen substrate, so that a primer has to be used in between. One possibility is to use another conductor as a metallic primer.

In the MEMSTIC-project [1], [2], CPW lines are built for the millimeter- and submillimeter wave region as shown in Fig. 1. The conductive layer is made of gold and the substrate of a 4 µm thin dielectric membrane. This dielectric membrane is made of Hexamethyldisilazan (HMDS-N) and mounted on a mechanical carrier [2]. Titan is used as primer. (Optionally e.g. Wolfram would also be possible.) In the production process, 4 µm thin HMDS-N is deposited on top of a silicon wafer. A thin layer of titan as primer to the thick layer of gold is sputtered above. These CPW lines achieve a simulated (using Agilent HFSS) effective relative permittivity of \( \varepsilon_{\text{eff,r}} \approx 25.1 \). Dispersion is expected to not occur for frequencies below 500 GHz.

Examples of measurements, especially for transitions of CPW to D-Band waveguides, can be found in [3].

II. ATTENUATION

Using these thin dielectric membranes as substrate results in low dielectric attenuation. The dielectric attenuation of CPW lines can be estimated as [4]:

\[
\alpha_{\varepsilon}[\text{dB/mm}] = 0.091 \cdot q_{\tan} \delta_{\varepsilon} \cdot \tan \delta_{\varepsilon} \cdot f \cdot \sqrt{\varepsilon_{\text{r,eff}}} \cdot \sin f \cdot \frac{\varepsilon_{\text{r,eff}}}{\sin f}, \quad (1)
\]

where the frequency \( f \) has to be inserted in GHz, \( \tan \delta_{\varepsilon} \) is the dielectric loss factor, and \( q_{\tan} \) is a filling factor due to dielectric losses. It is defined as

\[
q_{\tan} \delta_{\varepsilon} = \frac{\varepsilon_{\text{f}}(\varepsilon_{\text{r,eff}} - 1)}{\varepsilon_{\text{r,eff}}(\varepsilon_{\text{r}} - 1)}. \quad (2)
\]

If the thickness \( t \) of the conductive layer fulfills \( 3d < t < s \) (\( s \) means stripe width and \( d \) skin depth), the attenuation due to the ohmic losses of the conductor layer is [4]

\[
\alpha_{\rho}[\text{dB/mm}] = \frac{8.686 \cdot R_F \cdot \sqrt{\varepsilon_{\text{r,eff}}}}{2 \cdot \eta_0 \cdot g \cdot K(k) \cdot K(k') \cdot (1 - k^2)} \cdot \left[ \frac{1}{k} \left[ \pi + \ln \left( \frac{4\pi w(l-k)}{t(l+k)} \right) \right] + \left[ \pi + \ln \left( \frac{4\pi w(l-k)}{t(l+k)} \right) \right] \right], \quad (3)
\]

where the wave impedance in free space is \( \eta_0 = 120\pi \Omega \), \( g = s + 2w \) with \( s \) stripe width and \( w \) gap width of the CPW line, \( t \) means conductor thickness, \( k = s / (s + 2w) \), \( k' = \sqrt{1-k^2} \), and \( K(k) \) is the complete elliptic integral of first order. \( R_F \) is the surface resistance, including the skin effect. Formula (3) shows that the attenuation due to ohmic losses is directly proportional to the surface resistance \( R_F \), which is the only variable being affected by the existence of a metallic primer. Hence the influence of the primer on \( R_F \) shall be regarded in the following.

The ohmic attenuation due to ohmic losses is the dominant part of the total losses for CPW lines on dielectric membranes in the millimeter and submillimeter wave range. This can be deduced from formulas (1) and (3). Hence the influence of the metallic primer on this attenuation is not necessarily negligible.
in the balance of the total losses and should be described and studied in detail.

The surface impedance of a single conductor layer is [5]

\[
Z = \sqrt{\mu_0 \frac{\varepsilon_0}{\varepsilon_r}} = \varepsilon_r = e^{j \left( \frac{\kappa}{\omega_0 \varepsilon_0 \tan \delta} + \varepsilon_r \tan \delta \right)}.
\]  

(4)

Good conductors are characterized by a dominating imaginary part of the relative permittivity. As shown in equation (4), this condition is approximately fulfilled, if the conductivity \( \kappa \gg \varepsilon_0 \omega \). In this case, \( \varepsilon_r \tan \delta \) is negligible, too. In the following considerations, only good conductors are regarded to be used as possible primers.

In the case of a good conductor and assuming \( \mu_r = 1 \), the surface impedance is calculated by (shown in formula (4),[6])

\[
Z = 1 + j \frac{d}{\kappa} \quad \text{with skin depth} \quad d = \frac{2}{\sqrt{\omega_0 \cdot \kappa_0 \cdot \mu_0}}.
\]  

(5)

The surface impedance of a layered conductor, made of an electrically thin layer (metal 1) of a primer and an electrically thick layer (covering metal 2) \( (3d < l << s) \) of gold as original conductor layer can be calculated as [5], [7]

\[
Z_{\text{layered}} = \frac{Z_{\text{Au}} \cosh(\gamma l) + Z_{\text{primer}} \sinh(\gamma l)}{Z_{\text{Au}} \sinh(\gamma l) + Z_{\text{primer}} \cosh(\gamma l)}
\]  

where \( l \) means thickness of metal 1 (or the primer in this case) and \( \gamma \) is calculated as:

\[
\gamma = k_0 \sqrt{-\varepsilon_r \mu_r} , \quad k_0 = \omega_0 \varepsilon_0 \mu_0.
\]  

(7)

where \( \varepsilon_r \) is given in formula (4).

\( R_F \) equals the real part of the surface impedance \( Z \). The influence of the dielectric HMDS-N-membrane on \( R_F \) is negligible.

The thickness \( l \) of the primer can be varied. In the manufacturing process of the used CPW lines, the height of the conductor layer made of gold has to be galvanically increased [2]. The thickness of the primer was set to \( l = 300 \text{ nm} \) in the beginning [2]. This was due to that the wafer has to be biased at a single point during the galvanic step of the manufacturing process. The sputtered metallic cover of the wafer results in a feeding resistance of the galvanic procedure. This resistance has to be kept sufficiently low in order to enable an uniform galvanically grown structure.

The influence of metallic primers of various thickness at a frequency of \( f = 150 \text{ GHz} \) is shown in Fig. 2 as a function of the conductivity of the primer layer (compared to a single electrically thick gold layer in the case of a vanishing primer with \( l = 0 \text{ nm} \)). For comparison, the influence of an electrically thick layer of the primer without coating gold layer is shown in Fig. 3. \( R_F \) is directly proportional to the attenuation due to the ohmic losses of the CPW line. As is well known, the graph in Fig. 3 belonging to the pure and electrically thick primer layer is strictly monotonically decreasing, if it is regarded as function of the primer conductivity. Fig. 2 shows that the surface resistance (and herewith the ohmic attenuation) always increases by adding a layer of a primer which has a lower conductivity than the covering gold layer. Additionally, the surface resistance (the ohmic attenuation) increases by adding thicker layers of a primer with fixed conductivity. These results are in good agreement with general expectations.

A point of intersection must appear in Figs. 2-5, at which the primer conductivity and that of the covering gold layer are equal \( (\kappa_{\text{primer}} = \kappa_{\text{Au}}) \). On the other hand, the graphs converge to another intersection point, if primers of relatively low conductivities are considered. This can be explained by the electric field behaviour when penetrating into a metal. As is well known, the current density decreases in
the metal in the direction perpendicular to the surface. At a distance of the skin depth $d$ below the surface, the current decreases by the factor $e^{-1}$. As already described in formula (5), the skin depth $d$ is inversely proportional to the conductivity of the regarded layer. A relatively low conductivity of the primer layer leads to a larger skin depth, which means that the electrical field is less influenced by the existence of this layer of fixed thickness. If the primer has a lower conductivity, the fixed thickness appears electrically thinner. Regarding a relatively low conductivity, the current density decreases less along the direction perpendicular to the metal surface than in the case of a higher conductivity. At low primer conductivities, the current density at the intersection to the gold layer is similar to the current density at the top of the gold, if no primer layer were used at all. This leads to an intersection point at low conductivity values.

A similar effect of increasing the skin depth in resonant cavities with the help of certain layered material in order to avoid losses due to the skin effect has been mentioned in [8]. Another comparable effect is the existence of a minimum in the function of the resistance of a metal plate versus the thickness of this plate [9].

In between the two points of intersection, there exists a maximum, as is shown in Figs. 2-5. Fig. 4 depicts results at a frequency of $f = 450$ GHz. Regarding a frequency of $f = 1$ THz, the maximum of $R_F$ increases as shown in Fig. 5. (The introduced CPW lines would suffer from dispersion at $f = 1$ THz and the requirements of formula (3) would not be fulfilled. Nevertheless, the effect may be regarded in general and in case of a usage of other substrates.) In conclusion, a metallic primer with medium conductivity can lead to a greater increase of the attenuation of CPW lines than a primer with lower conductivity. The primer has to be chosen carefully, depending on the desired thickness of the primer layer and on the frequency range.

Regarding CPW lines on 4µm thin dielectric HMDS-N-membranes, the effect of increasing the attenuation is not negligible in the desired frequency range for a primer thickness of $l = 300$ nm and titan as primer. By decreasing the thickness to $l = 30$ nm, however, the additional losses can almost be eliminated. Moreover, at this thickness, metallic primers of any conductivity can be used. Even at a frequency of $f = 1$ THz, the influence of the primer almost disappears, as shown in Fig. 5. The reduction of the thickness of the titan layer to $l = 30$ nm is possible during the manufacturing process. The application as a primer is not disturbed. To achieve a low feeding resistance to the galvanic manufacturing process, it is possible to add another structured layer on top of the first gold layer, which is completely removed after the galvanic manufacturing step.

### III. Design Considerations

The maxima in the surface resistance versus the conductivity curve have to be considered when selecting a primer. Depending on the desired frequency and the desired thickness of a primer, there exist regions of conductivity, which have to be avoided for the primer. Those primers would cause a non-negligible influence on $R_F$ resulting especially in an increase of the attenuation of the CPW lines.

Regarding relatively thick primer layers, the influence of the maximum of $R_F$ appears at a conductivity for which the skin depth has approximately the same value as the layer thickness, even though it does not converge against it. This is shown in Fig. 6. On the other hand, the maximum cannot appear at conductivities greater than half of the conductivity of the gold:

$$\kappa_{\text{Primer,Max}} \leq \frac{\kappa_{\text{Au}}}{2}. \tag{8}$$

This leads to the effect that the maximum in $R_F$ appears at more and more smaller fractions of the skin depth, if relatively thin primer layers are regarded. It also means, that the maximum in $R_F$ appears at relatively high primer conductivities, if very thin layers are regarded. This is shown in Fig. 6, too.
The appearance and consequences of the maximum in $R_F$ can be described independent of frequency $f$. This is shown in Fig. 7 and Fig. 8.

The conductivity of the primer which leads to a maximum in $R_F$ is described as a function of the value of the thickness of the primer layer divided by the skin depth. As normalizing skin depth, that of the metal with conductivity taken at the location of the maximum, has been chosen. Then those primer conductivity values which have to be avoided can be found independent of frequency.

Being able to use electrically thin layers of a primer (namely a small fraction of the skin depth), the maximum in $R_F$ appears at higher values of the primer conductivity, but the effect can be neglected. If thicker layers of the primer cannot be avoided due to the manufacturing process, the maximum appears at lower values of the primer conductivity and the influence on the attenuation of the structures is significant. (see Figs. 7 and 8).

IV. CONCLUSIONS

Depending on the thickness of a required primer layer, metallic primers gain an influence on the attenuation of planar structures. To avoid this effect, the primer has to be highly thinned or the conductivity of the primer has to be chosen carefully. A metallic primer with medium conductivity can lead to a greater increase of the attenuation of planar structures than a primer with lower conductivity. A description of the primers which have to be avoided and their detailed consequences have been formulated independent on frequency.

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