Dispersive Effects of a Thin Metal-Insulating Layer in MMIC Structures *

Anastasis C. Polycarpou, Michael R. Lyons and Constantine A. Balanis

Department of Electrical Engineering
Telecommunications Research Center
Arizona State University
Tempe, AZ 85287-7206

ABSTRACT

A full-wave finite element analysis is used to examine the dispersive effects of a thin metal-insulating layer in CPW and microstrip MMICs. This layer is often encountered in the MMIC manufacturing process residing on top of a semiconducting substrate. The effects of metallization thickness are also examined.

I Introduction

Since many monolithic microwave integrated circuits (MMICs) are currently realized on multilayer semiconducting substrates, the frequency dependent effects due to a thin metal-insulating layer must be accounted for. At present, the most common transmission line used in microwave circuit technology is the microstrip line. However, MMIC technology is also showing trends toward more coplanar waveguide (CPW) configurations [1]. The addition of a thin metal-insulating layer is often introduced in the semiconductor manufacturing process as a passivation layer, electric isolation between two metal layers and realization of MIM capacitors [2],[3]. Since this layer is generally very thin compared to neighboring substrates, its effects on wave propagation are usually ignored and not well known. It is important to characterize the frequency dependent effects of these thin layers using more rigorous analyses, such as full-wave techniques, in order to optimize microwave circuit performance and design. Planar structures, such as microstrips and CPWs, have been studied using a variety of computational methods including the Spectral Domain Approach (SDA) [1] and Finite Element Method (FEM) [4]. While the SDA is a popular choice for analyzing simple planar configurations, the FEM is the most generally applicable and versatile technique, since it allows modelling of arbitrary geometric and material complexities.

This paper examines the effects of a thin metal-insulating layer of Silicon Nitride (Si_3N_4) on the effective dielectric constant and characteristic impedance of two MMIC transmission line configurations. This layer of Si_3N_4 is commonly found in the semiconductor process residing on top of a Gallium Arsenide (GaAs) substrate. Two common planar structures, microstrip and CPW, are investigated with and without a thin metal-insulating layer of Si_3N_4; the effect of finite conductor thickness in conjunction with such a layer is also considered. The effective dielectric constant and characteristic impedance of the dominant mode is examined as a function of frequency.

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II Theory and Formulation

A full-wave analysis of shielded planar waveguide structures, which incorporates arbitrary materials and geometries, is formulated using the FEM applied to the electric field vector wave equation:

$$\nabla \times \left(\mu_r^{-1} \nabla \times \mathbf{E}\right) - k_o^2 \, \epsilon_r \, \mathbf{E} = 0 \qquad (1)$$

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It is assumed that the dependence of the electric field in the longitudinal direction is $e^{-jk_z z}$, where k_z is the corresponding propagation constant in the z-direction. The formulation involves representing the longitudinal fields using nodal basis functions and the transverse fields using vector basis functions [4].

After solving the eigenvalue problem at each frequency point, the propagation constant in the z-direction and the corresponding normalized transverse and longitudinal fields inside the structure can be obtained. Although the definition of the characteristic impedance is not unique for inhomogeneous waveguide structures, the voltage-power definition was chosen for the current analysis.

III Numerical Results

Two commonly used structures in MMIC designs, the CPW and microstrip, whose geometries are shown in Figure 1, were modelled using the FEM. In practical circuit designs, it is important that finite conductor thickness be accounted for. This was incorporated in the analysis at values of $t = 0.5\mu$m and 3μm for both CPW and microstrip configurations. The dispersion characteristics of the dominant mode are examined as a function of frequency for configurations with and without a thin metal-insulating layer.

The method implemented in this paper was validated by comparing results with the SDA. Figure 2 illustrates the comparison between the two methods in the case of a CPW with no conductor thickness. The effective dielectric constant obtained using the two methods are in excellent agreement for cases with and without the Si_3N_4.

Analysis of the CPW structure has been further investigated for various heights (h_2) of a thin metal-insulating layer. Figures 3 and 4 illustrate the corresponding dominant mode dispersion characteristics (ϵ_{reff} and Z_c, respectively) for a conductor thickness of 0.5μm. While holding the total substrate height ($h_1 + h_2$) constant, the thickness of the Si_3N_4 layer (h_2) is varied from 0.2μm to 2.0μm. It is observed that both the ϵ_{reff} and Z_c of the dominant mode change quite significantly when the Si_3N_4 layer is varied from 0.2 to 2.0μm. Specifically, at low frequencies the ϵ_{reff} changes from ≈ 6.75 to ≈ 5.35, whereas the Z_c changes from $\approx 50.0\Omega$ to $\approx 56.0\Omega$. In many MMIC applications and designs, such significant variations in the effective dielectric constant and characteristic impedance must be accounted for; otherwise, unnecessary dispersion and/or reflections due to transmission line missmatch will result.

The same CPW configuration, shown in Figure 1, was considered this time using an increased conductor thickness of 3μm. The dispersion characteristics, ϵ_{reff} and Z_c, are illustrated in Figures 5 and 8, respectively. Both these figures show a similar trend to the ones presented for the previous case; however, both ϵ_{reff} and Z_c are now shifted to lower values due to the increased conductor thickness. In addition, the wave propagation becomes slightly more dispersive.

Results for the microstrip structure, as shown in Figure 1, are also computed using the same conductor thicknesses (0.5μm and 3.0μm) and the same thin insulating layer of Si_3N_4 previously used for the CPW. The dominant mode dispersion characteristics for both cases are shown in Figures 6, 7 and 9, 10. Similar observations are seen for the microstrip as were noted for the CPW configuration. Increasing the height of the insulating layer results in a decrease in ϵ_{reff} and increase in Z_c. On the other hand, increasing the conductor thickness results in a decrease in both ϵ_{reff} and Z_c.

IV Conclusions

A full-wave analysis using a finite element formulation of two common MMIC transmission lines has been presented. It has been shown that the addition of a thin metal-insulating layer, such as Si_3N_4, can significally change the propagation characteristics in CPW and microstrip structures. In addition, an increase in the conductor thickness results in lower values of the effective dielectric constant and characteristic impedance as well as higher dispersion.

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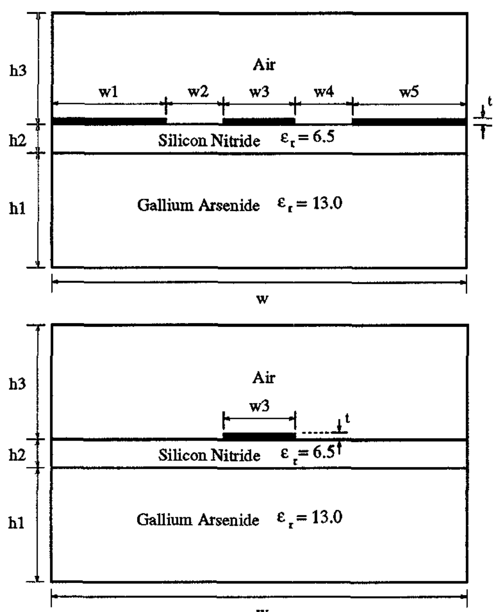

Figure 1: Geometries for the CPW and microstrip. The dimensions are the following: W=100 μm, $W_1 = W_5$=25 μm, $W_2 = W_4$=20 μm, W_3=10 μm, $h_1 + h_2$=20.2 μm, h_3=20 μm.

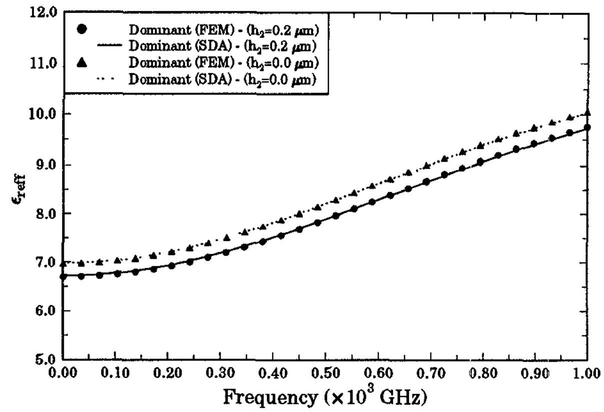

Figure 2: FEM and SDA dispersion curve comparison for the dominant mode of a CPW assuming no conductor thickness.

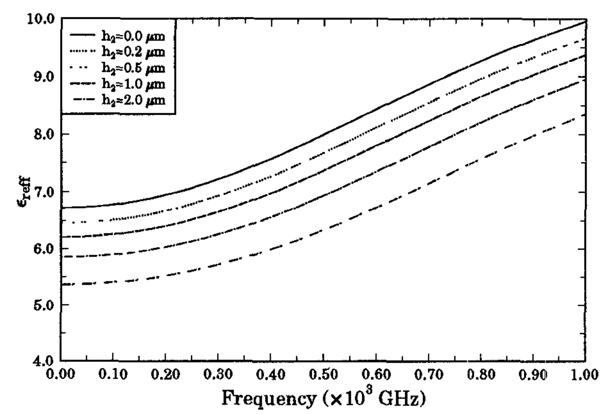

Figure 3: Effective dielectric constant curves for the dominant mode of a CPW with finite conductor thickness ($t = 0.5\mu$m).

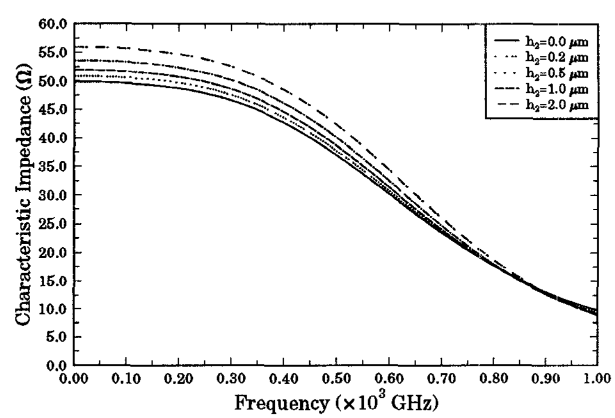

Figure 4: Characteristic Impedance curves for the dominant mode of the CPW with finite conductor thickness ($t = 0.5\mu$m).

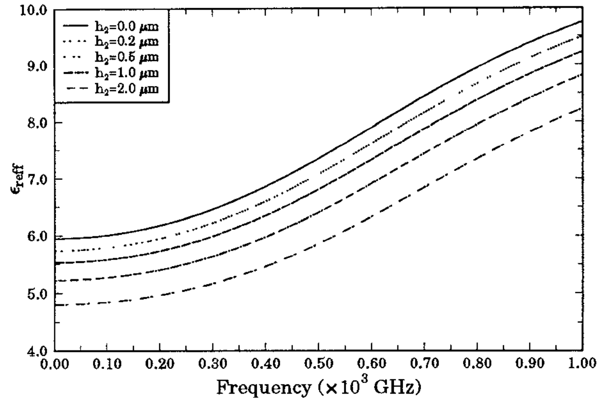

Figure 5: Effective dielectric constant curves for the dominant mode of a CPW with finite conductor thickness ($t = 3\mu$m).

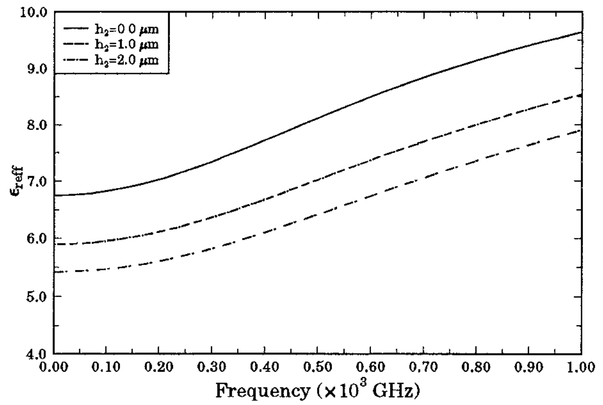

Figure 6: Effective dielectric constant curves for the dominant mode of a microstrip with finite conductor thickness ($t = 0.5\mu$m).

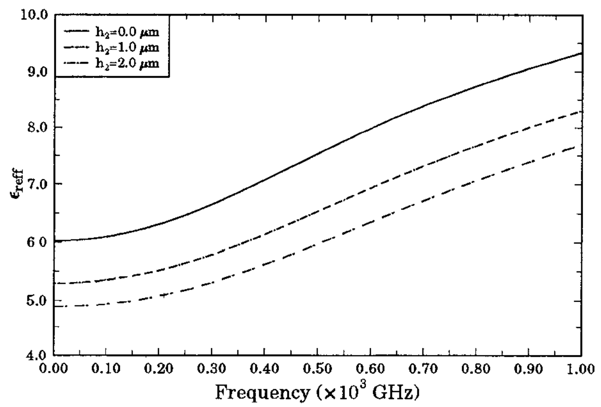

Figure 7: Effective dielectric constant curves for the dominant mode of a microstrip with finite conductor thickness ($t = 3\mu$m).

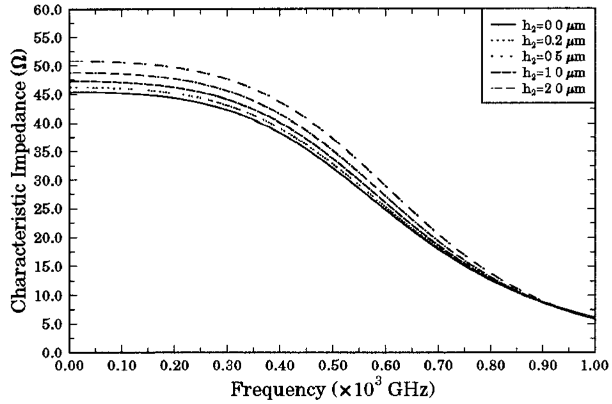

Figure 8: Characteristic Impedance curves for the dominant mode of the CPW with finite conductor thickness ($t = 3\mu$m).

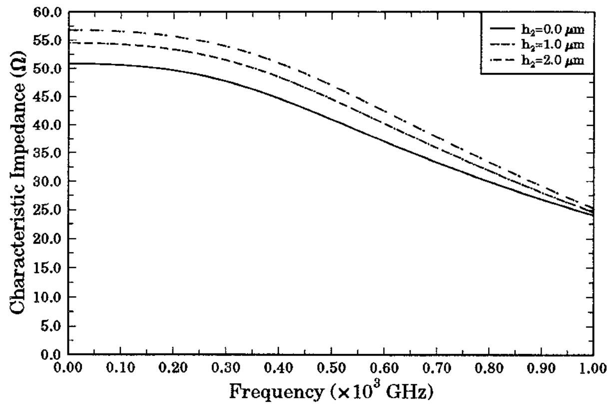

Figure 9: Characteristic Impedance curves for the dominant mode of a microstrip with finite conductor thickness ($t = 0.5\mu$m).

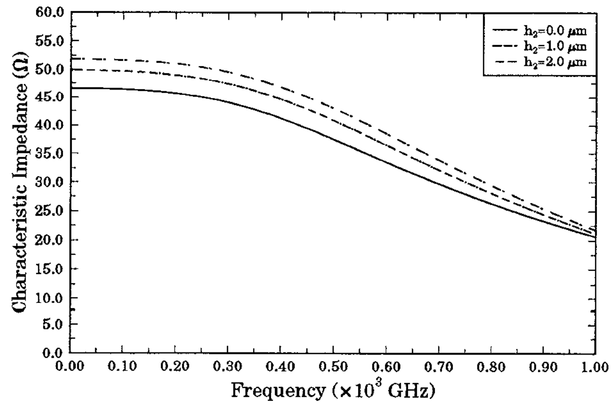

Figure 10: Characteristic Impedance curves for the dominant mode of a microstrip with finite conductor thickness ($t = 3\mu$m).