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Effect of Finite Metallization and Inhomogeneous Dopings on Slow-Wave-Mode Propagation

Jakub J. Kucera and Ronald J. Gutmann

***Abstract*— A finite-element simulation has been implemented to evaluate the slow-wave-mode propagation characteristics in metal–insulator–semiconductor (MIS) waveguiding structures. Particular emphasis has been placed on coplanar waveguides compatible with silicon integrated circuits (IC's), with an objective of evaluating the effect of inhomogeneous doping on propagation characteristics. The simulator has been successfully benchmarked against a number of cases presented in the literature, including MIS coplanar waveguides. The effect of inhomogeneous doping and finite metallization in maintaining a large slowing factor while reducing the attenuation constant and increasing transmission-line Q is presented, and constraints on slow-wave-mode passive components are discussed.**

***Index Terms*—Coplanar waveguides, slow-wave mode.**

I. INTRODUCTION

There is continued interest in slow-wave-mode propagation in silicon integrated circuits (IC's), both in preventing such propagation in digital IC's and in utilizing such propagation in microwave-analog IC's for passive components. In the latter application, maintaining a high slowing factor and achieving a low attenuation factor are critical. Work to date indicates that adjusting dimensional and electrical parameters with uniform semiconductor doping does not result in propagation characteristics useful for passive components [1]–[4], although simulation results obtained with nonuniform doping profiles indicate that more attractive characteristics can be obtained [5], [6].

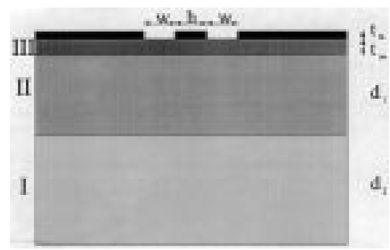
In this paper, a two-dimensional (2-D) electromagnetic simulator is developed to determine the propagation characteristics of metal–insulator–semiconductor (MIS) structures with arbitrarily doped substrates based upon the finite-element method (FEM). Since the propagating modes within an inhomogeneous structure are hybrid, quasi-static approaches can only be used in limited cases. In particular, when dealing with arbitrary substrate dopings, a quasi-static approach is insufficient and a full-wave analysis is required. With our FEM simulator, the advantages of lateral doping profiles on propagation characteristics of coplanar waveguide (CPW) structures have been evaluated. The influence of line parameters such as the finite metallization on the propagation characteristics of the slow-wave mode is presented, and upper bounds of achievable transmission-line quality factors are discussed.

II. EFFECT OF FINITE METALLIZATION AND INHOMOGENEOUS DOPINGS

The effect of quantities such as center strip or slot width, oxide thickness, and substrate resistivity on the slow-wave-mode propagation in MIS CPW's has been extensively studies [3], [5], [7], but the effect of imperfect conductors generally has been neglected. While the finite thickness of the metallization has a minor effect, the conductivity is of great importance. It is known that with decreasing linewidth, the metal conductor losses increase and can constitute the dominant loss mechanism [4]. In the lower gigahertz range, the slowing factor is also affected to a large extent since the current penetrates deep into the metal surface so that the metal behaves like a very lossy dielectric. The surface-impedance approach based on the skin depth becomes questionable, because the effect of the lossy metal on the slowing factor is ignored and the current is not necessarily confined to the surface of the conductor. In our FEM approach the metal losses and the field penetration within the conductor are precisely handled by treating the metal layers as lossy dielectrics with a dielectric constant of unity. We estimate the contribution of the metal losses to the overall losses for a particular waveguide by calculating the attenuation for both a perfect and a lossy metal conductor. The metal losses dominate the overall losses at 1 GHz even for a wide center strip (100 μm), and even at 10 GHz they cannot be neglected for narrow strips, as shown in Table I.

TABLE I
PERCENTAGE OF THE CONDUCTOR LOSS TO THE OVERALL LOSS FOR A MIS COPLANAR WAVEGUIDE ($w = 50$ μm, $t_{ox} = 0.1$ μm, $d_1 = 150$ μm, $d_2 = 660$ μm, $\sigma = 3.7$ S/mm, $t_m = 2$ μm, and $\sigma_m = 2.7 \cdot 10^4$ S/mm)

h [μm]	@ 1 GHz	@ 10 GHz
1	99.5	83.5
5	97.6	49
100	57.3	2.2



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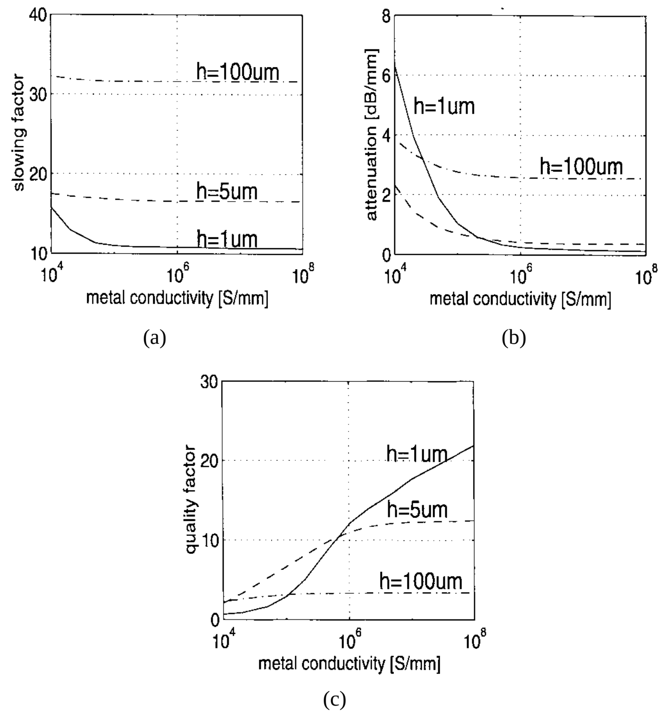

Fig. 1. (a) Slowing factor, (b) attenuation, and (c) quality factor at 3 GHz of a MIS coplanar waveguide ($w = 50\ \mu$m, $t_{ox} = 0.1\ \mu$m, $d_1 = 150\ \mu$m, $d_2 = 660\ \mu$m, $t_m = 2\ \mu$m, and $\sigma = 3.7$ S/mm) as a function of metal conductivity for different strip widths.

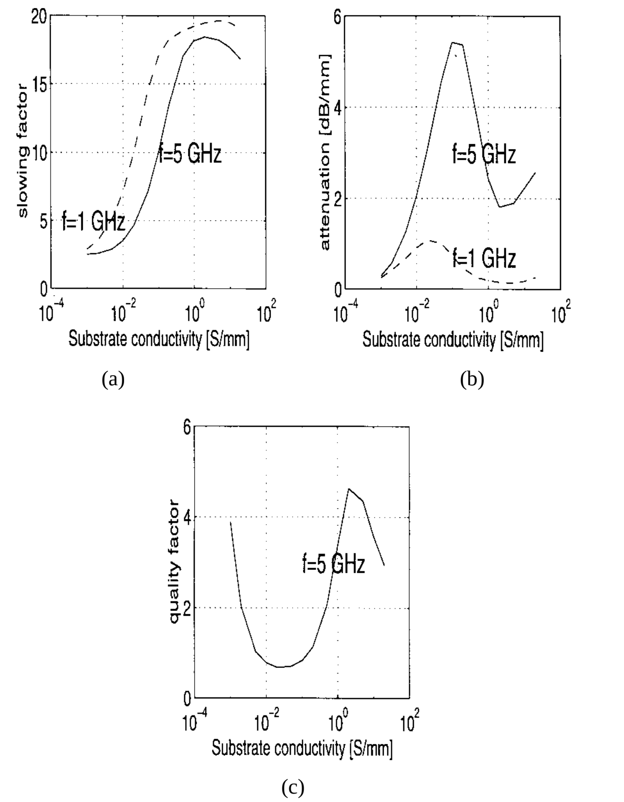

Fig. 2. (a) Slowing factor, (b) attenuation, and (c) quality factor for a MIS coplanar waveguide ($h = 50\ \mu$m, $w = 50\ \mu$m, $t_{ox} = 0.2\ \mu$m, $d_1 = 150\ \mu$m, and $d_2 = 660\ \mu$m) with a perfect metallic conductor as a function of substrate conductivity for two frequencies.

The influence of the finite metal conductivity on the slowing factor and the attenuation for a MIS coplanar waveguide ($w = 50\ \mu$m, $t_{ox} = 0.1\ \mu$m, $t_m = 2\ \mu$m, $d_1 = 150\ \mu$m, $d_2 = 660\ \mu$m, and $\sigma = 3.7$ S/mm) with different strip widths is shown in Fig. 1. The slowing factor is affected most with narrow center strips and at lower frequencies. As can be seen, high quality factors can only be achieved for narrow and extremely high conductivity conductor strips. Increasing the metal thickness can further reduce the attenuation. Thus, thick metals (several μm) with high conductivity (copper, silver) must be used to minimize the conductor loss and improve the Q of the line. Wider strips reduce the conductor loss but also increase the dielectric losses.

Another approach to reduce the attenuation is to use wider strips and an inhomogeneous substrate doping to minimize the dielectric loss. The idea is to limit the higher doping region of the semiconductor to the area just below the center strip, rather than extending over the full transverse dimension. Dielectric loss due to the electric field emerging from the strip area and causing transverse currents may be reduced by reducing the effective lossy interface area between the insulating oxide layer and the doped semiconductor itself. In [5], Wu and Vahldieck predict a promising improvement of the quality factor of thick-film MIS coplanar waveguides ($h = 50\ \mu$m, $w = 50\ \mu$m, $t_{ox} = 0.2\ \mu$m, $d_1 = 150\ \mu$m, $d_2 = 660\ \mu$m, and $\sigma_0 = 10$ S/mm) in the lower gigahertz range by reducing attenuation using a lateral Gaussian-like doping distribution as follows:

$$\sigma(x) = \begin{cases} \sigma_0 \cdot \cosh^{-k}\left(\frac{x}{h}\right), & |x| < h/2 + 2w \\ \sigma_0 \cdot \cosh^{-k}\left(\frac{h/2+2w}{h}\right), & \text{elsewhere.} \end{cases} \quad (1)$$

However, conductor loss was not taken into account, while our results show that for the particular line dimensions conductor loss is significant for frequencies below 10 GHz. Furthermore, by reducing the conductivity of the substrate, the dielectric loss does not necessarily decrease as is illustrated in Fig. 2. Slowing factor and attenuation are shown as a function of substrate conductivity at 1 and 5 GHz, respectively, assuming a perfect metallic conductor. We find a highest slowing factor together with lowest attenuation for this waveguide for a conductivity of about 5 S/mm. Therefore, we anticipate that the attenuation will increase when we use Gaussian-like dopings, although detailed optimizations with such profiles have not been performed. Fig. 3 shows disagreement of our results with those from [5] when nonuniform doping is included.

The behavior for a thin-film structure ($h \gg d_1$) is different. The dielectric loss increases monotonically with increasing substrate conductivity. Thus, we expect reduced attenuation when using the inhomogeneous profile. We use the waveguide with dimensions and parameters $h = 280\ \mu$m, $w = 410\ \mu$m, $t_{ox} = 0.3\ \mu$m, $d_1 = 0.7\ \mu$m, $d_2 = 360\ \mu$m, $t_m = 1\ \mu$m, $\sigma_0 = 12.8$ S/mm, and $\sigma_{Al} = 2.7 \cdot 10^4$ S/mm to illustrate the different behavior. Both slowing factor and attenuation are reduced using inhomogeneous doping, because there is not enough free charge in the substrate to prevent the electric field from penetrating into the bulk. The electric and magnetic field are no longer separated and the propagating mode becomes a less lossy dielectric mode. In this case, our simulation results agree well with [5], as can be seen in Fig. 4.

In order to avoid the contribution of the lossy substrate regions, we introduce an abrupt lateral doping profile as follows:

$$\sigma(x) = \begin{cases} \sigma_0, & |x| < x_0 \\ 0, & \text{elsewhere} \end{cases} \quad (2)$$

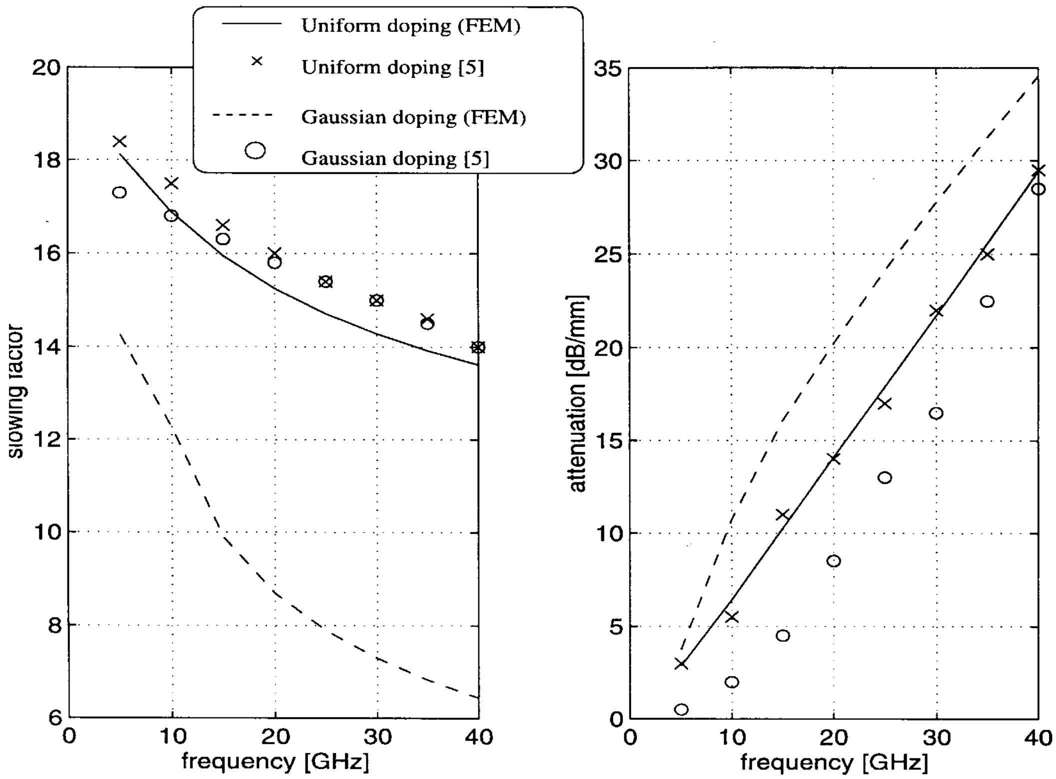

Fig. 3. Simulation results for a thick-film ($d_1 \gg h$) MIS coplanar waveguide ($h = 50$ μm, $w = 50$ μm, $t_{ox} = 0.2$ μm, $d_1 = 150$ μm, $d_2 = 660$ μm, and $\sigma_0 = 10$ S/mm). Uniform doping compared with Gaussian-like doping with $k = 4$. Discrete points ($\times$ and $\bigcirc$) are simulation results from [5].

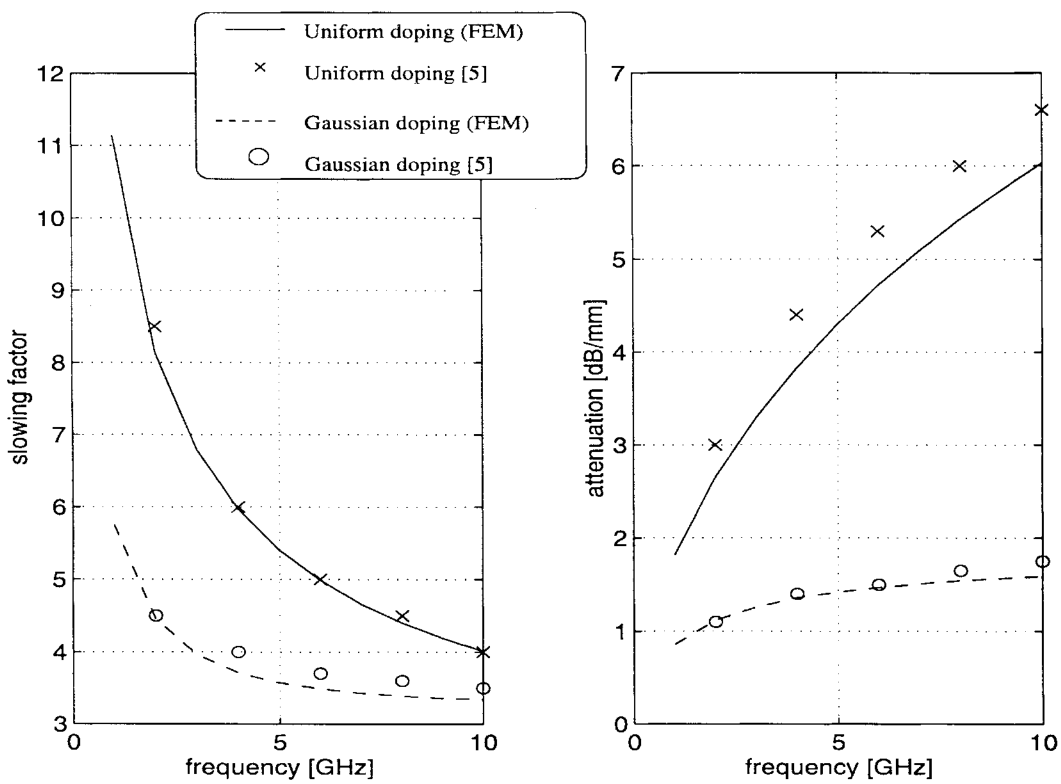

Fig. 4. Simulation results for a thin-film ($d_1 \ll h$) MIS coplanar waveguide ($h = 280$ μm, $w = 410$ μm, $t_{ox} = 0.3$ μm, $d_1 = 0.7$ μm, $d_2 = 360$ μm, and $\sigma_0 = 12.8$ S/mm). Uniform doping compared with Gaussian-like doping with $k = 4$. Discrete points ($\times$ and $\bigcirc$) are simulation results from [5].

instead of the gradually decreasing doping. Various simulations have shown that the optimum width x_0 of the doped region is $\frac{h}{2} + 2w$. Fig. 5 compares the propagation characteristics of the waveguides with the three different doping profiles. A significant reduction of the attenuation can be achieved with the abrupt doping profile while maintaining a high slowing factor. With increasing frequency,

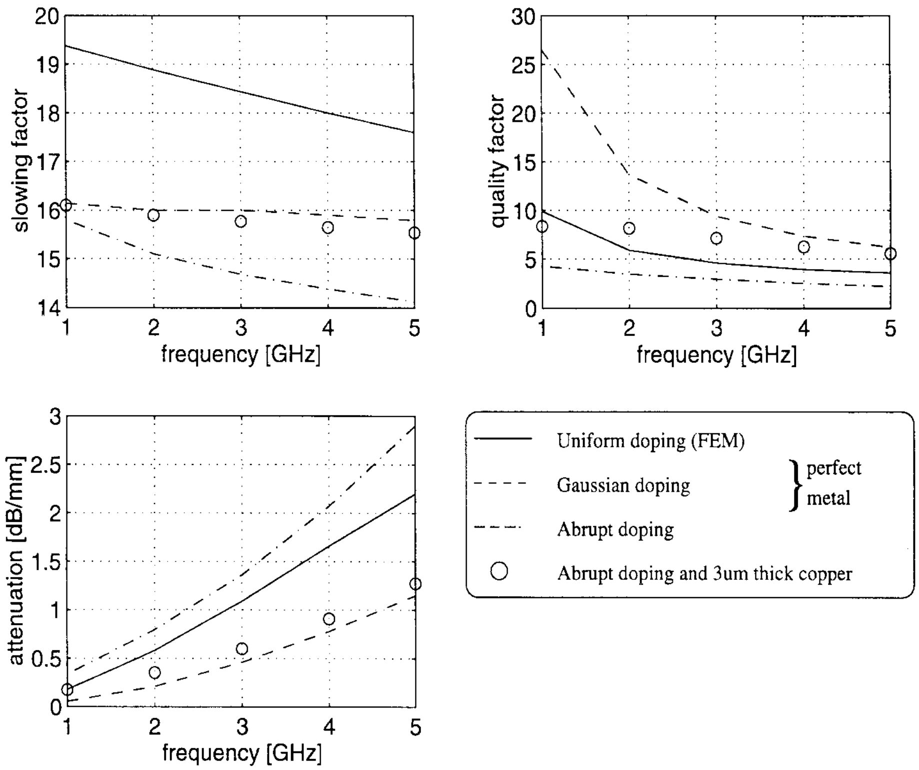

Fig. 5. Comparison of the three different doping profiles of a thick-film MIS coplanar waveguide ($h = 50$ μm, $w = 50$ μm, $t_{ox} = 0.2$ μm, $d_1 = 150$ μm, $d_2 = 660$ μm, and $\sigma_0 = 10$ S/mm). Uniform doping (–) and Gaussian-like doping (– –) with $k = 4$ and abrupt doping ($\cdots$ and ◯) with $x_0 = 125$ μm. A perfect metallic conductor is assumed except for (◯) where $t_m = 3$ μm and $\sigma_m = 6.25 \cdot 10^4$ S/mm.

the electric field is more confined under the conductor strip, and attenuation is less sensitive to the doping profile. The discrete points (◯) show the line characteristics when conductor loss is taken into account. Even for a thick ($t_{\text{metal}} = 3$ μm) high conductivity metal such as copper ($\sigma_{\text{metal}} = 6.25 \cdot 10^4$ S/mm), the attenuation is dominated by the dissipation in the metal.

We conclude that high quality factor $(Q > 20)$ transmission lines cannot be achieved in the low gigahertz region with inhomogeneous doping profiles because the losses are predominantly due to finite metal conductivity.

III. Summary

In this paper, we have presented the full-wave analysis results of MIS coplanar waveguides fabricated on an Si substrate. The losses of the metallic conductor as well as the semiconducting effect of the Si substrate were rigorously taken into account in the analysis. Generally good agreement with published measurements and simulations results has been found. We have investigated the impact of inhomogeneous doping profiles and finite thickness and conductivity of the metallization on reducing the losses. We have found that dielectric losses can be reduced while maintaining a relatively high slowing factor using abrupt doping profiles. However, in the lower gigahertz range, the overall losses are dominated by the conductor loss, which cannot be overcome by any substrate doping profile investigated to date.

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