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COMPARATIVE STUDY OF HOMOGENEOUSLY AND INHOMOGENEOUSLY DOPED MIS COPLANAR TRANSMISSION LINES

By

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ABSTRACT

This paper presents a hybrid mode analysis of slow-wave modes in microsize MIS CPW's on heavily doped thin- and thick-film semiconductor wafers. It was found that in homogeneously doped MIS CPW's a slow-wave mode can be maintained up to 40 GHz if the center conductor strip width is in the order of 0.5μm. To circumvent fabrication and interconnection problems associated with such small line dimensions, a gradually inhomogeneous doping profile has been introduced, resulting in much wider strip dimensions which are in the range of 50μm. In this case a slow-wave mode can be maintained up to 20 GHz. The study was carried out by using alternatively the spectral domain approach and the method of lines.

INTRODUCTION

Unilateral coplanar transmission lines are of growing interest for the design of monolithic microwave integrated circuits. In particular the coplanar Metal- Insulated Semiconductor (MIS CPW) structure, which allows low-loss slow-wave propagation, finds potential application in the design of electronically controlled phase shifters and filters or to reduce cross-coupling in high speed digital integrated circuits, to name a few examples. Slow-wave propagation along coplanar MIS structures has been studied theoretically and experimentally by a large number of authors (i.e. [1] - [15]). The basic structure which supports a slow-wave mode is shown in Fig. 1 and consists of a multilayer coplanar transmission line on a thin semiconductor substrate which is separated from the metal plane by a low-loss or lossless insulating layer of silicium-dioxide or GaAs. The low-impedance semi-conductor is virtually invisible to the magnetic field while the electric field is highly concentrated between the semiconductor and the center strip of the coplanar transmission line. This field distribution corresponds to a separate storage of electric and magnetic energy in space which is the well known condition for a low-loss slow-wave mode to propagate. For thin film MIS transmission lines this effect occurs significantly in the frequency range up to 1 GHz. Typical data are 0.2dB/mm losses at 0.5 GHz and a slow-wave factor of 40 while losses increase at 4 GHz up to 10dB/mm combined with a reduced slow-wave factor of 10. Extrapolating these results towards higher frequencies, the obvious conclusion is that those structures are not suitable for millimeter wave application.

To achieve low-loss slow-wave propagation also at higher frequencies, Kwon, Hietala and Champlin [8] proposed, therefore, another version of the CPW structure, the so-called "micrometer-size coplanar MIS transmission line" which is fabricated on a heavily doped thick N^+ silicon surface where a thin layer of S_i0_2 is grown as insulator.

The geometry of the conductor, slots and insulator layer in a micro-size MIS line is very small (several μm). While in a conventional thin-film MIS CPW the ratio between semiconductor layer and the insulator thickness is typically in the range of 2:1 to 100:1, the micro-size MIS CPW is grown on a thick semiconductor and the insulator thickness ranges between 0.1μm to 0.53μm (ratio more than 1000:1). At the same time the strip width ranges from 5.-10.μm which is significantly smaller than in a conventional thin-film MIS CPW. It was found in [8] that by optimizing the line dimensions and the doping level a moderate slow-wave mode can exist at frequencies higher than 5 GHz showing very little dispersion (quasi TEM propagation) combined with low losses. To determine the upper frequency limits of the micro-size MIS CPW, we have applied the spectral domain approach (SDA, [9]), for which numerical results are presented in this paper.

It was found that in contrast to traditional thin-film MIS CPW's, which are homogeneously doped, thick-film, heavily (homogeneously) doped MIS CPW's show superior performance in that a low-loss slow-wave mode

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can propagate up to 40 GHz with very little dispersion over a wide frequency range. Unfortunately, this performance can only be achieved at the expense of very small conductor dimensions which are in the order of $0.5\mu m$. Therefore, fabrication cost may be high and interconnections with common circuit geometry may be difficult.

To overcome this problem we propose a modified MIS monolithic structure in which the high doping region of the semiconductor is limited to the region just below the central conductor instead of over the full cross-section. For optimum results it is suggested to introduce a gradually inhomogeneous doping (Gaussian-like) profile which reaches a maximum level just below the center conductor (Fig. 2). This measure is potentially suitable to reduce the losses of the slow-wave mode which are to a large extent due to the electric field emerging from the strip area and its tangential component along the semiconductor interface. In the homogeneously doped micro-size MIS CPW this component was reduced by virtue of a reduced slot and strip width. The same effect is achieved by introducing the inhomogeneous doping profile without changing strip and slot dimensions to the extreme. This is due to the fact that the inhomogeneous doping profile reduces the effective lossy interface area between the insulating layer below the conductor plane and the doped semiconductor itself, by reducing the lateral expansion of the doped region.

In other words, the semiconductor-insulator interface under the strip changes very rapidly to an insulator-insulator interface with progressing distance from the strip area and hence the tangential component of the emerging electric field has less influence on the circuit losses. Therefore, the slot width need not be reduced. This solution still guarantees the relaxation of charge in the partial active region but at the same time allows larger strip-slot dimensions which lead to lower costs in fabrication and better interconnections to other circuits.

To analyze inhomogeneously, gradually doped MIS CPW's, the SDA is not suitable. Alternatively, we have applied the method of lines (MOL) using non-equidistant discretization, [16]-[19]. The MOL has never been used before to analyze cross-sections as shown in Fig. 2. Extensive modifications are required and details of this procedure will be given elsewhere [20].

RESULTS

I. Homogeneously doped thick-film structure

Fig. 3 shows a detailed analysis of slow-wave propagation in a micro-size thick-film MIS CPW for different slot and strip widths. In comparison to the conventional thin-film MIS CPW it is obvious from the figures, that relatively low-loss slow-wave propagation can be achieved up to 40 GHz when the slot and line widths are chosen very small ($w = 100.\mu m$, $h = 0.5\mu m$, Fig. 3a,b). The slow-wave factor remains above a moderate value of 15 with virtually no dispersion for the micro-size strip width. The same observation can be made for the real part of the characteristic impedance which shows only slight variations over the frequency but changes from $Z_r = 0.3\Omega$ for a strip width of $h = 50.\mu m$ to $Z_r = 18\Omega$ for $h = 0.5\mu m$. This effect is even more pronounced when the slot width decreases from $w = 100.\mu m$ in Fig. 3a,b to $w = 50.\mu m$ in Fig. 3c,d. In this case losses of 5.dB/mm can be observed at 30 GHz together with a slow-wave factor of $\lambda_o/\lambda_g = 13$. The real part of the characteristic impedance varies now from $Z_r = 0.6\Omega$ for $h = 50.\mu m$ to $Z_r = 108.\Omega$ for $h = 0.5\mu m$. At the same time the imaginary part of Z_o can change from $Z_i = 0$ to $10.\Omega$. An obvious disadvantage of this structure is that the common impedance range of 50 Ohms requires ultra fine line dimensions which could impose serious manufacturing problems.

II. Inhomogeneously doped thin-film structures

Inhomogeneous doping of the semiconductor in a thin-film MIS CPW does not result in improved slow-wave factors. This is shown in Fig. 4 which illustrates the slow-wave factor versus frequency in a thin-film MIS CPW with homogeneous ($k_o = 0$) and gradually inhomogeneous doping profile ($k_o = 0.5$ - 2). As expected, the slow wave factor reduces significantly with increasing frequency and becomes a dielectric mode beyond 2 GHz. This effect becomes more pronounced by narrowing the shape of the doping profile. At the same time a narrower doping profile improves the loss factor significantly (Fig. 5). Both phenomena can be explained by the fact that a sharp doping lobe cannot grasp the electric field sufficiently because of a considerably reduced effective active surface area below the center conductor. In other words, the electric field is dispersed into the cross-section in a similar way as the magnetic field and hence the condition for a slow-wave mode to propagate, namely the separate storage of magnetic and electric energy in space is no longer satisfied.

III. Inhomogeneously doped thick-film structures

Fig. 6 shows the behaviour of the slow-wave mode in a inhomogeneous, gradually doped thick-film MIS CPW over a range of 40 GHz. Two observations can be made: Firstly, the slow-wave mode is less dispersive than in a thin-film MIS CPW and can be maintained beyond 30 GHz; secondly, the doping profile has less influence on the slow-wave mode. Only a very narrow doping profile ($k_o = 4.0$) reduces the slow-wave mode significantly. The reason for this phenomenon is the same explained previously in conjunction with the thin-film MIS CPW. At the same time, however, the line losses are more sensitive to the doping profile. Loss reductions of 5 dB/mm can be achieved if the doping profile index, k_o, is changed from $k_o = 0$ (homogeneous doping distribution) to $k_o = 4$ (very narrow doping profile). A comparison between Fig. 6 and Fig. 3c, shows clearly that by using a relatively wide center conductor (50μm), the inhomogeneous doping profile supports a low loss slow-wave mode ($\alpha > 10$ dB/mm) up to 20 GHz. For the structure in Fig. 3c, this was possible only by reducing the center strip width to 10μm or less which may cause fabrication difficulties.

CONCLUSION

We have presented a numerical analysis of homogeneous and inhomogeneous, gradually doped thin- and thick-film MIS CPW. The study has shown that for a thick-film MIS CPW the inhomogeneous doping distribution allows a low-loss slow-wave mode to propagate up to 20 GHz having significantly larger line dimensions than in the case of homogeneously doped semiconductor in thin-film CPW's. Therefore, this type of transmission line is more convenient to fabricate and much easier to interconnect with other circuits. Furthermore, it was shown that the method of lines is a very versatile numerical tool to analyze transmission line cross-sections of complicated shape.

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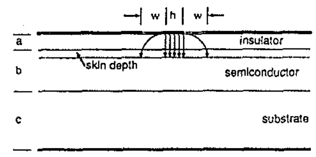

Figure 1: Cross-section of the thin- and thick-film MIS CPW structure deposited on RT/Duroid or GaAs substrate.

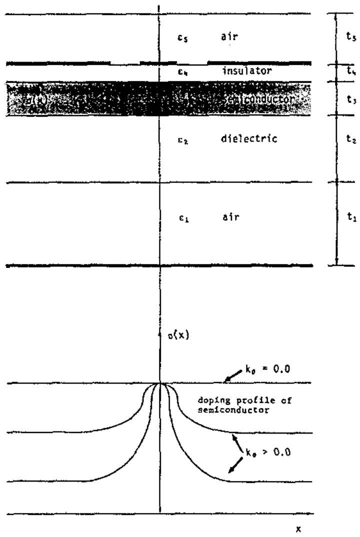

Fig. 2 A cross-section of low-loss MIS coplanar lines with a gradually inhomogeneous doping (Gaussian-like) profile.

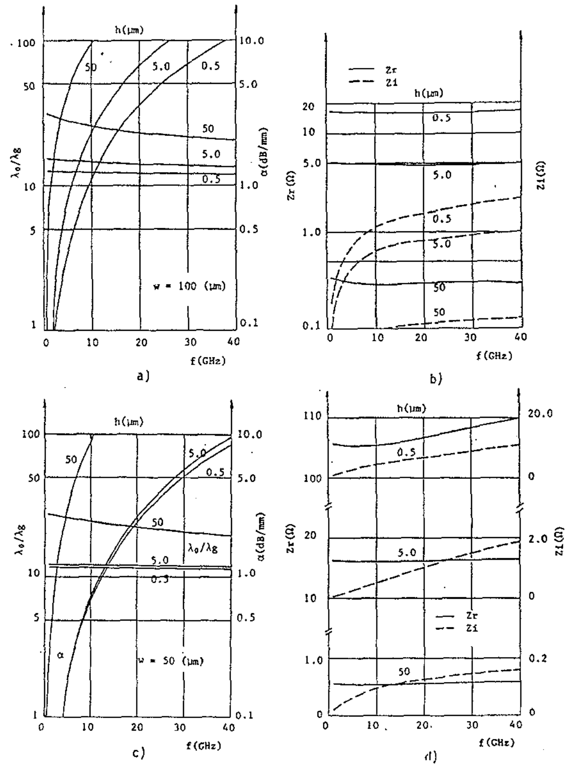

Figure 3: Slow-wave factor and loss characteristics in a thick-film MIS CPW grown on RT/Duroid substrate ($\epsilon_c = 2.22$, $t_c = 660\mu m$) ($t_a = 0.1\mu m$, $t_b = 150\mu m$, $\sigma = 3703.7\Omega m^{-1}$).

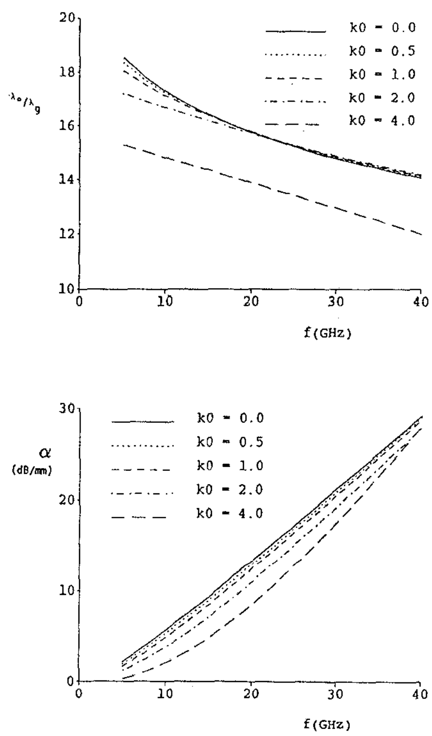

Fig. 6 Slow-wave factor of thick-film MIS structures versus frequency ($\sigma_0 = 5.0(\Omega mm)^{-1}$). Dimensions and parameters for all thick-film MIS structures: $\epsilon r_1 = 1.$, $\epsilon r_2 = 2.22$, $\epsilon r_3 = 11.8$, $\epsilon r_4 = 3.9$, $\epsilon r_5 = 1.$, $s_1 = 25\mu m$, $w = 50\mu m$, $s_2 = 50\mu m$, $C = 0.95mm$, $t_1 = 5.mm$, $t_2 = 0.66mm$, $t_3 = 0.15mm$, $t_4 = 0.2\mu m$, $t_5 = 10mm$

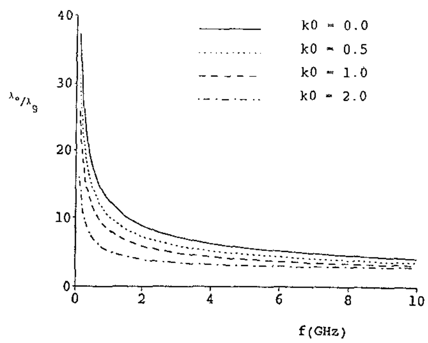

Fig. 4 Frequency-dependent slow-wave factor of thin-film MIS structures in case of $\sigma_0 = 12.8(\Omega mm)^{-1}$.

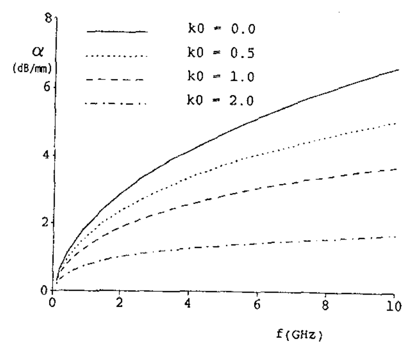

Fig. 5 Frequency-dependent loss behaviour of thin-film MIS structures in case of $\sigma_0 = 12.8(\Omega mm)^{-1}$. Dimensions and parameters for all thin-film structures: $\epsilon r_1 = 1.$, $\epsilon r_2 = 13.1$, $\epsilon r_3 = 13.1$, $\epsilon r_4 = 8.5$, $\epsilon r_5 = 1.$, $s_1 = 0.14mm$, $w = 0.41mm$, $s_2 = 0.41mm$, $C = 5.0mm$, $t_1 = 5.0mm$, $t_2 = 0.36mm$, $t_3 = 0.7\mu m$, $t_4 = 0.3\mu m$, $t_5 = 10.0mm$