FIELD THEORY ANALYSIS OF SLOW-WAVE PROPAGATION ON SILICON BASED COPLANAR MIS TRANSMISSION LINES

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ABSTRACT

This paper presents a rigorous field theory analysis of the slow-wave propagation characteristics on semiconductor based coplanar waveguide MIS transmission lines with ion-implantation doping profile by using the frequency-domain TLM method (FDTLM). Two types of coplanar MIS transmission line structures, namely bulk silicon and semiconductor-on-insulator (SOI) with a Gaussian profile of the doping depth and optimized lateral width of the doping region have been investigated. It was found that both structures exhibit much better slow-wave characteristics at lower losses than traditional thin-film MIS transmission lines.

INTRODUCTION

It is well known that coplanar waveguide (CPW) metal-insulator-semiconductor (MIS) transmission lines support slow-wave mode propagation. This phenomenon and the attractive features of CPW are of increasing interest in the design of monolithic microwave integrated circuits (MMIC) in the wireless communication frequency bands and for high speed digital integrated circuits. Unfortunately, the low Q-factor (high losses) of these structures is a major problem and has prevented the widespread use of CPW MIS. To reduce losses and at the same time maintain a high slow-wave factor, this paper investigates different doping profiles. In this investigation the electromagnetic field in the various layers is calculated rigorously by using the frequency-domain transmission line matrix (FDTLM) method [1~2].

The size of the problem is best appreciated by reviewing the basic layout of a CPW MIS. The structure consists essentially of a multilayered coplanar transmission line on a thin or thick-film of homogeneously doped semiconductor layer whereby an insulating layer is used to separate the CPW electrodes form the semiconductor layer. Such conventional structures have been studied theoretically and experimentally by several researchers, i.e. [3~7]. It was found that thin-film CPW MIS show generally lower losses than thick-film structures, but that the latter can sustain a slow-wave mode over a wider frequency range than the former. This, however, comes at the price of higher losses. To reduce losses the electric field must be pushed up into the insulating layer. This can be achieved to some extend by carefully controlling the doping level thickness. An alternative technique to reduce losses was proposed by Wu and Vahldieck [8] and employs a lateral gradually inhomogeneous doping (Gaussian-like) profile. However, this scheme is difficult to realize with epitaxial technology.

In this paper, we investigate numerically the effect of an ion-implantation technique in thin-film CPW MIS in which the lateral doping profile changes abruptly rather than gradually (Fig.1). This is technologically easier to control, and as will be shown, leads also to lower losses and higher slow-wave factor if the lateral extend of the doping region is optimized. Two types of structures will be investigated: bulk silicon and semiconductor-on-insulator (SOI) with a Gaussian profile of the doping level depth. In both cases, the p^+-doping layer is realized by implanting boron ion (B^{2+}) through the mask window whereby the size of the window determines the lateral extend of the doped region. To investigate numerically the effect of such a laterally inhomogeneous doping profile, which shows also a doping depth profile with Gaussian distribution, is very challenging for a numerical technique. In this work we are utilizing the FDTLM method because of its numerical efficiency and its capability to use nonequidistant discretization with second order accuracy. The latter point is very important for the analysis of CPW MIS because small and large circuit dimensions are in close neighborhood. Some numerical results are compared with the results from a method of lines (MoL) analysis for verification purposes. Excellent agreement between both numerical techniques is obtained.

THEORY

The geometrical layout of the two types of coplanar MIS structures investigated in this paper is shown in Fig.

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1a and b, respectively. Both structures consist of a thin p^+-doping region separated from the silicon substrate by a thin insulating layer of SiO_2. While in conventional CPW MIS the semiconductor is doped homogeneously over the entire cross-section of the structure, we limit the doping range in lateral direction to the area below the center conductor and the two slots, because this is the area in which the electric field of the fundamental mode is most prominent. The p^+-doping region is fabricated by B^{2+} implantation into the silicon substrate. According to the LSS (the unified theory of atomic stopping by Lindhard, Scharff and Schiott) range theory for amorphous targets, the implanted B^{2+} concentration in silicon is approximately a Gaussian distribution function of depth, which may be expressed as

$$N(x) = \frac{D}{\sqrt{2\pi}\Delta Rp}\exp\left[-(x-Rp)^2/\Delta Rp^2\right] \qquad (1)$$

where D is the total number of ions implanted per unit area, x is the distance measured along the axis of incidence, $N(x)$ is the density of the implanted B^{2+} that stop at the plane x, Rp is the projected range which estimates the depth at which the concentration of implanted dopant reaches its maximum value and ΔRp is the average fluctuation in the projected range. After taking account of the diffusion effects that may occur during implantation or during annealing, Fig. 2 displays the relative conductivity depth profile of the very thin p^+-doping region (about 2 μm thickness) in silicon substrate. The parameters of both CPW's structures in Fig. 1 are: W = 40 μm, G = 25 μm; SiO_2 layer: t_a = 1000Å, ε_r = 3.9, σ = 0; SOI structure: t_d = 1 μm, ε_r = 11.8, ρ (SOI resistivity) = 10 Ω-cm, t_o = 2μm; Si substrate: t_{sub} = 525 μm, ε_r = 11.8, ρ (Si substrate resistivity) = 20 Ω-cm.

The conductivity depth profile given in Fig. 2 is used as material parameter in the full wave FDTLM analysis. Since the FDTLM method has been described in detail in the literature, i.e. [1~2], only some highlights will be given here that are relevant to the current analysis. The FDTLM models the electromagnetic field in a structure by discretizing its cross-section with transmission line cells. The interaction between the transmission lines for each space direction in each cell is described by the scattering matrix of the symmetrical condensed node (SCN). Other nodes are possible and are described in numerous publications. In contrast to the time-domain TLM (TDTLM) method, in which an impulse excitation leads to a time iterative procedure, the FDTLM algorithm works entirely in the frequency domain. That is the FDTLM network is considered to be in steady-state. The advantage of this approach is that time synchronism (required in the TDTLM) is not needed, that a graded mesh layout with arbitrary grading ratio can be chosen and that for most linear and narrow band analysis problems the network response can be found in a computationally efficient manner.

The electromagnetic field in the FDTLM network is represented by voltages and currents. The network is characterized by the intrinsic scattering matrix, S_{ism}, which represents all the internal branches of a network by the network branches pointing in propagation direction of the wave. For a two-dimensional propagation problem this has the advantage that the guided wave structure can be considered as a periodic network with periodicity of Δz. Based on Floquet's theorem the periodic structure can be reduced to a single unit cell and the intrinsic scattering matrix S_{ism} is constructed from one slice of the waveguide which contains only as many SCN's as needed to discretize the cross-section of the structure. The propagation constant γ and its corresponding eigenvectors (voltages) can be determined by solving the following eigenvalue equation:

$$\cosh(\Upsilon\Delta z)\cdot V = A\cdot V \qquad (2)$$

where V is the vector containing voltages at the exterior branches of the waveguide slice (the cross-section of the waveguide); Δz is the length of the slice (the node dimension along the propagation direction). Then, the current can be found as:

$$I = -\sinh(\Upsilon\Delta z)\cdot C\cdot V \qquad (3)$$

Matrix A and C are found from the S_{ism} of the waveguide slice [2]. Eqs. (2) and (3) yield the transverse electromagnetic field distribution and the propagation constants γ of the propagating modes supported by the structure at a given frequency.

NUMERICAL RESULTS AND DISCUSSION

The CPW MIS transmission line structures investigated in the following are shown in Fig.1. They are made from bulk silicon (Fig. 1a) or SOI (Fig. 1b). For both structures the doping depth profile is assumed to be Gaussian. Four different lateral doping widths have been investigated as shown in Fig.3. Fig. 4 illustrates the propagation constant, loss factor and Q-factor of the bulk silicon CPW MIS for the four different lateral doping widths. Fig. 5 shows results for the SOI CPW MIS. For verification purposes some results have been compared with the method of lines. In both cases it was found that the structure in Fig. 3c shows the lowest loss slow-wave mode propagation over the frequency range between 0.7 to 5.0 GHz. The highest slow-wave factor, however, can only be obtained from the structure in Fig. 3d.

Fig. 4a and b illustrate that a compromise exists between maximum slow-wave factor and minimum losses. For structure Fig. 3c the maximum attenuation is less than 0.75 dB/mm at 5 GHz and less than 0.3 dB/mm at 2 GHz. At the same time the slowing-factors λ_0/λ_g is between 12.5 ~ 13 with very little dispersion over the frequency range of 0.7 to 5.0 GHz. This slowing factor corresponds to an effective dielectric constants of 156.3 ~ 169.0, which is much larger than the dielectric constant of either the Si substrate or the SiO_2 insulating layer. The losses found with structure Fig. 3c are less than for other MIS CPW structures investigated in the literature [5~8]. Also the quality factor, Q, shown in Fig. 4c, reaches a higher value compared to the much larger MIS CPW structures on GaAs [3] or other microstructure CPW MIS transmission lines [6]. To verify the numerical results, measurements for the structure of Fig. 3b are found in Fig. 4. A comparison between the MoL, the FDTLM and measurements shows very good agreement.

Similar characteristics can be observed for the SOI structure (Fig. 5). In comparison with the silicon bulk structure, the slow-wave factor is generally approximately 15% higher and shows somewhat less dispersion. The attenuation is only 3.5% higher. The introduction of a lossless SiO_2 layer between the ion-implantation doping layer and the high resistivity Si substrate plays an important role in confining the electric field in the insulating layer beneath the coplanar conductors. This may be the reason why SOI structures with selected B^{2+} ion-implantation doping exhibit reasonably large slow-wave factors with little dispersion. The analysis results indicate that the SOI structure with a lateral doping width as shown in Fig. 3 (c) not only provides a better slow-wave factor but the Q-factor is also improved over that of the bulk structure.

CONCLUSIONS

A numerical analysis of slow-wave propagation, losses and Q-factor in bulk silicon and semiconductor-on-insulator (SOI) CPW MIS has been presented. The analysis is based on the frequency-domain TLM method. It was found that large slowing factors at low losses can be achieved by optimizing the lateral extend of the semiconductor doping region. It was furthermore found that SOI structures show better Q-factor with less dispersion than the bulk silicon structures.

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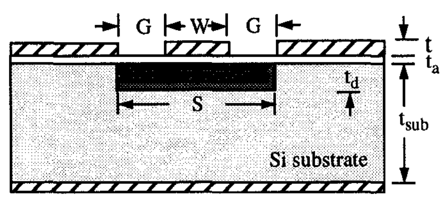
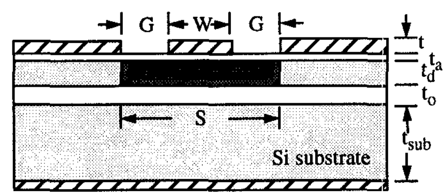


(a) Bulk Silicon with Gauss Dope Profile structure



(b) SOI (Silicon-On-Insulator) Structure

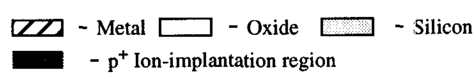


Fig. 1 Two types of cross-sectional structure of micron-sized coplanar waveguide MIS transmission line: (a) Bulk silicon and (b) SOI. The doping region is obtain by baron dopant ion implantation at energy 200 keV.

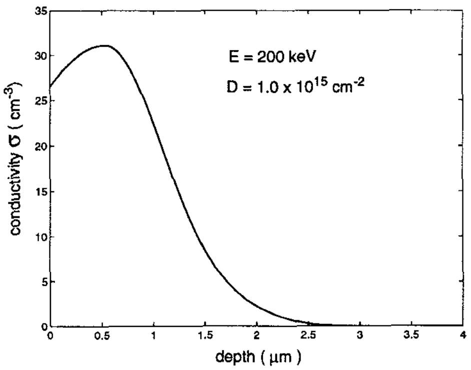


Fig. 2 The conductivity profile in silicon obtained by boron ion-implantation with doses of 1×10^{15} B^{2+} ions/cm^2 at energy of 200 keV (After anneal)

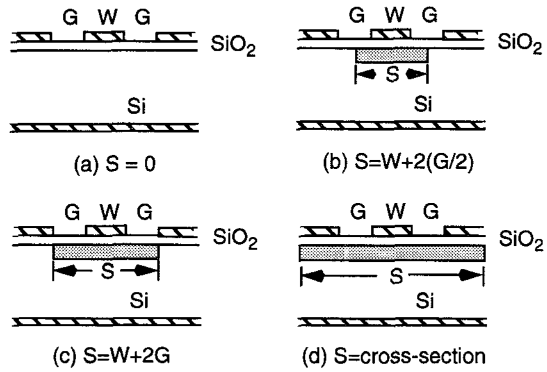


Fig. 3 Four kinds of lateral doping region configuration for bulk silicon and SOI CPW MIS transmission lines: (a) S=0; (b) S=W+2*(G/2); (c) S=W+2*G; (d) S=cross section.

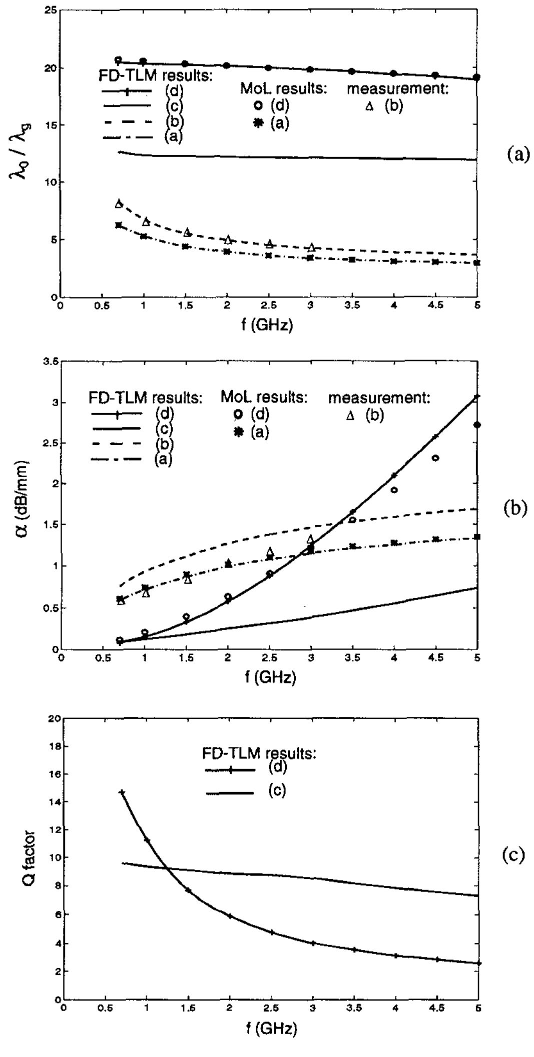


Fig. 4 Slow-wave propagation characteristics of ion-implantation bulk silicon MIS coplanar waveguide transmission line with different doping widths, *S*, *W = 40 μm* and *G = 25 μm*. (a) Slow-wave factor versus frequency. (b) Attenuation versus frequency. (c) Quality factor versus frequency.

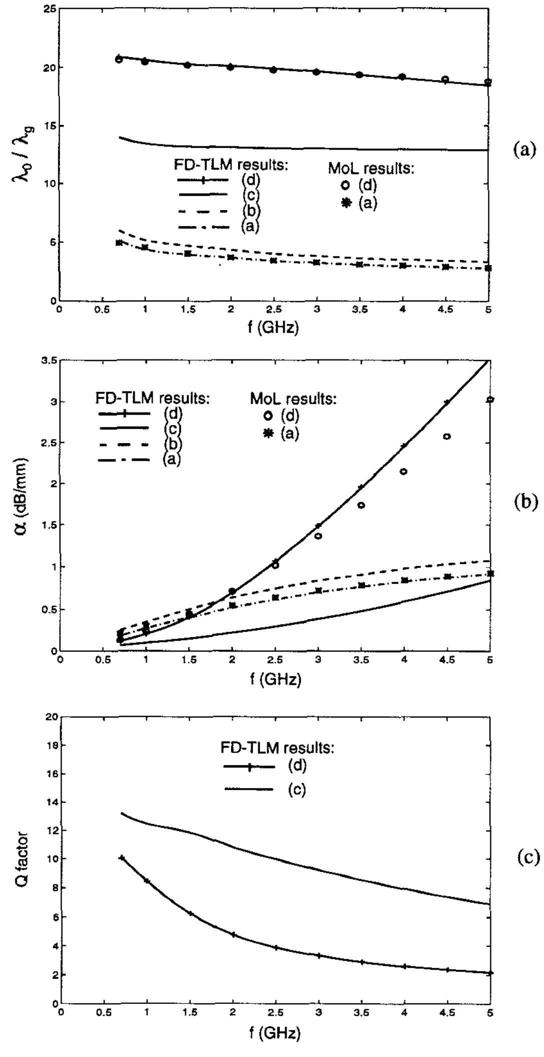


Fig. 5 Slow-wave propagation characteristics of ion-implantation SOI-MIS coplanar wave guide transmission line with different doping widths, *S*, *W = 40 μm* and *G = 25 μm*. (a) Slow-wave factor versus frequency. (b) Attenuation versus frequency. (c) Quality factor versus frequency.