SLOW-WAVE COPLANAR WAVEGUIDE ON PERIODICALLY DOPED SEMICONDUCTOR SUBSTRATE

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Abstract

A metal-insulator-semiconductor (MIS) coplanar waveguide with periodically doped substrate is described. Reduction of attenuation and enhancement of the slow-wave factor are observed, compared to the uniform MIS coplanar waveguide. The structure is experimentally simulated and shows good agreement with theory.

Introduction

Recent studies of planar transmission lines on semiconductor substrates show the existence of slow-wave propagation[1,2]. These transmission lines have either metal-insulator-semiconductor (MIS) configurations or Schottky-contacts on semiconductor substrates. The latter structures have applications as variable phase shifters.[3] For applications in monolithic microwave integrated circuits, coplanar structures are preferred and the coplanar waveguide is the most suitable structure because of the feasibility of connecting series and parallel components. To obtain slow-wave propagation over a wide frequency range, it is necessary to raise conductivity of the semiconductor substrate to a large finite value. This, however, causes a high attenuation and makes practical applications difficult. The present structure introduces loss-less sections periodically to reduce the attenuation. By doing this, the important phase-shift property of the Schottky-contact coplanar waveguide is still preserved. Theoretical study shows a possibility to extend the frequency range of the slow-wave propagation.

Theory

The basic theoretical treatment of the MIS periodic coplanar waveguide consists of using Floquet's theorem for the periodic transmission lines. Fig. 1 shows a schematic view of the structure. A coplanar waveguide is placed on the semi-insulating semiconductor substrate which is periodically doped to form highly conductive regions. Each periodic section is characterized by a propagation constant and a characteristic impedance, which are computed by a hybrid-mode analysis. For this purpose, a technique proposed by Yamashita and Atsuki[4] is modified and introduced. The conductivity of the doped region is incorporated into a complex dielectric constant. Then an integral equation for the slot field and the current density is formulated:

$$\int_s E_x(x_o)\, k_1(x|x_o)\, dx_o + \int_c J_z(x_o)\, k_2(x|x_o)\, dx_o = 0 \qquad (1)$$

where s indicates the integration over the slot region, and c the conductors. This equation is solved by the point matching method (N_p matching points), which yields the complex propagation cosntant. The characteristic impedance of each section is easily calculated by using the solution of the integral equation.

The overall propagation constant of the MIS periodic coplanar waveguide is then calculated by applying the Floquet's theorem:

$$\cos(\gamma \ell) = \cos(\gamma_a \ell_a)\cos(\gamma_b \ell_b) - \frac{1}{2}\left[\frac{Z_a}{Z_b} + \frac{Z_b}{Z_a}\right]\sin(\gamma_a \ell_a)\sin(\gamma_b \ell_b)$$

(Parameters are shown in Fig. 1) (2)

Gamma (γ) is a complex propagation constant. The slow-wave factor and the attenuation constant are obtained from its real and imaginary part respectively.

Numerical Results

Numerical solution of the integral equation is very efficient and successful. An example of the convergence of the solutions is shown in Fig. 2, which is calculated for a typical MIS coplanar waveguide. The figure shows error relative to the values of $N_p = 30$. Convergence becomes faster for the waveguide with a thicker insulator or narrower slots.

The computed slow-wave factors and attenuation constants for MIS periodic coplanar waveguide are presented in Fig. 3. Two typical cases are shown in the figure. For the case $\sigma=10^5$ mho/m (solid curves), the extension of the frequency range of the slow-wave propagation is observed (Fig. 3a). Namely, the slow-wave factor of the periodic structure becomes greater than that of uniform MIS coplanar waveguide at frequency higher than 10GHz. This crossover of the slow-wave factor occurs for conductivities larger than a certain critical value. For instance, no crossover point exists for $\sigma=10^4$ mho/m (dotted curves). The reduction of attenuation is also more pronounced for the case $\sigma=10^5$ mho/m compared with the other case (Fig.3b). Therefore adjustment of the conductivity of the doped regions is very important to obtain these advantageous characteristics.

Experiments

A model of the MIS periodic coplanar waveguide was fabricated and tested in the frequency range of 40MHz - 1GHz. Instead of a doped semiconductor substrate, graphite powder was used as a resistive material. The graphite powder was sandwiched by two adhesive plastic sheets, and placed periodically on the coplanar waveguide etched on a circuit board. Measurements were performed for simulated MIS periodic coplanar waveguide and simulated uniform MIS coplanar waveguide. The dimensions and other parameters are as follows:

Common parameters

length of line ... 212 mm
$a = 1.0$ mm, $b = 5.0$ mm
$\varepsilon_1 = \varepsilon_2 = \varepsilon_4 = 2.5$ ($\varepsilon_2 = 1.0$ for section b)
$\varepsilon_3 = \varepsilon_5 = 1.0$, $\sigma \simeq 20$ mho/m (estimate)

MIS periodic coplanar waveguide

$d_1 = 0.13$ mm, $d_2 = 0.02$ mm, $d_3 = 3.0$ mm

$\ell_a = \ell_b = 8.0$ mm (12 periods)

Uninform MIS coplanar waveguide

$d_1 = 0.18$ mm, $d_2 = 0.02$ mm, $d_3 = 3.0$ mm

The input impedances of the lines with open and short end were measured and the results were converted into the slow-wave factors and attenuation constants. The results are shown in Fig. 4. These are in reasonably good agreement with the theoretical curves in spite of nonuniformity of the thickness and densities of the graphite layers. The crossover of the slow-wave factor does not occur in this case since the conductivity of the graphite powder is small. However this experiment justifies the theoretical calculation, and the extension of the slow-wave propagation range is expected for higher conductivities.

Conclusions

MIS periodic coplanar waveguide is analyzed and the idea is tested by experiment. The result shows the reduction of attenuation and the extension of the frequency range of the slow-wave propagation.

The present structure can also be used as a variable phase shifter if MIS sections are replaced by Schottky-contact coplanar waveguides. In this case, reduced attenuation is also expected and therefore operation of such a voltage controlled phase shifter at higher frequency may be possible.

Acknowledgement

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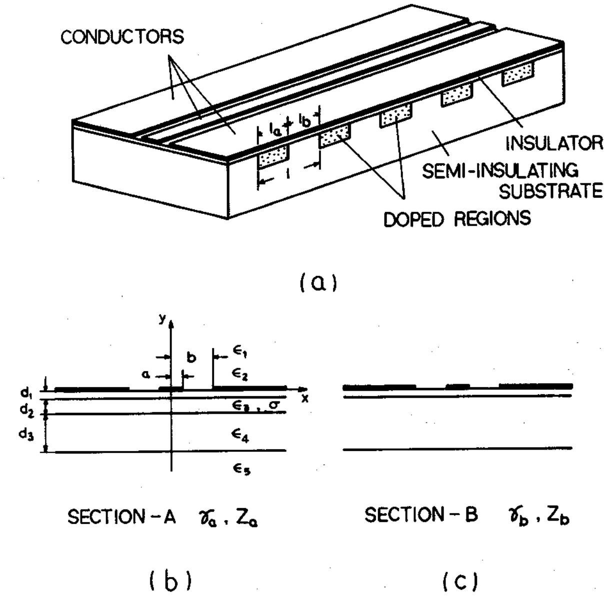

Fig.1 Schematic view of the structure
(a) MIS periodic coplanar waveguide
(b) section a ... MIS coplanar waveguide
(c) section b ... coplanar waveguide

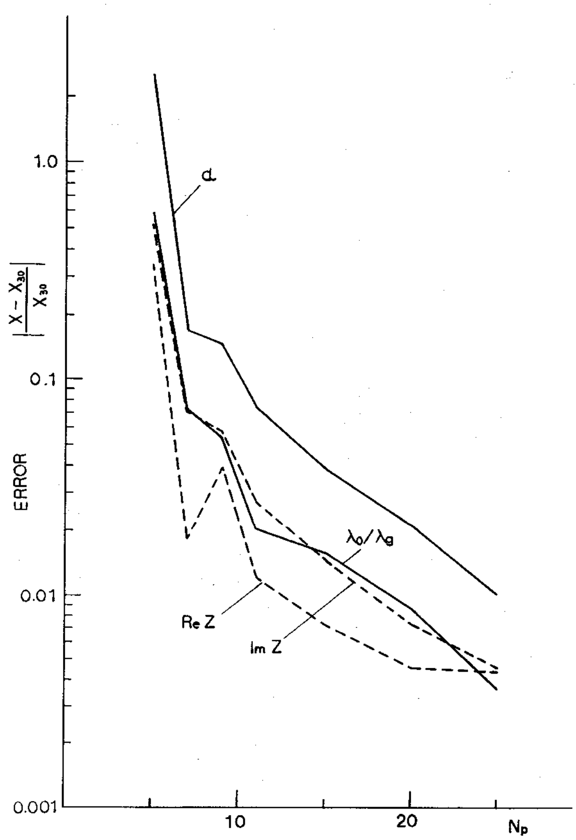

Fig.2 Convergence of the solutions
$a = 0.05$mm , $b = 0.5$mm
$d_1 = 1.0\mu$m , $d_2 = 3.0\mu$m , $d_3 = 1.0$mm
$\varepsilon_2 = 8.5$, $\varepsilon_3 = \varepsilon_4 = 13.0$, $\sigma = 10^4$ mho/m
$f = 0.1$ GHz
$(N_p = 30)$ $\lambda_0/\lambda_g = 22.321$, $\alpha = 0.01759$ dB/mm
$Z_c = 9.733 + j0.3901\ \Omega$

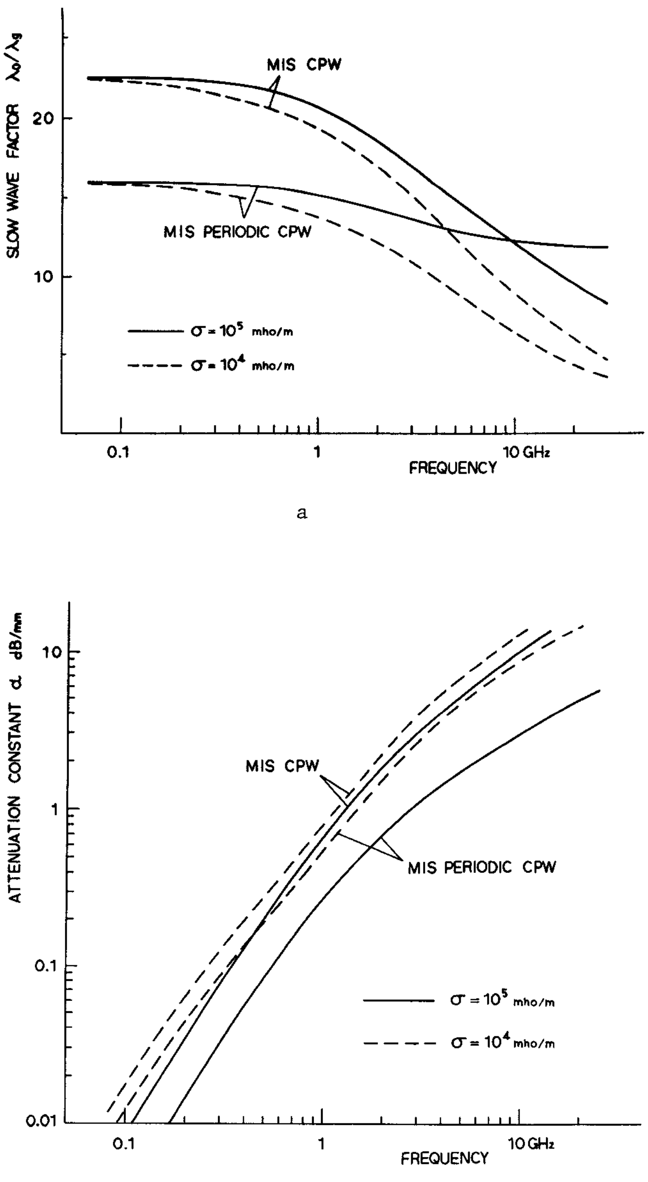

Fig.3 Comparison of MIS periodic coplanar waveguide with uniform MIS coplanar waveguide

a. slow-wave factor vs. frequency

b. attenuation constant vs. frequency

$a = 0.05\text{mm}$, $b = 0.5\text{mm}$
$d_1 = 1.0\mu\text{m}$, $d_2 = 3.0\mu\text{m}$, $d_3 = 1.0\text{mm}$
$\varepsilon_2 = 8.5$, $\varepsilon_3 = \varepsilon_4 = 13.0$
$\ell_a = \ell_b = 0.1\text{mm}$

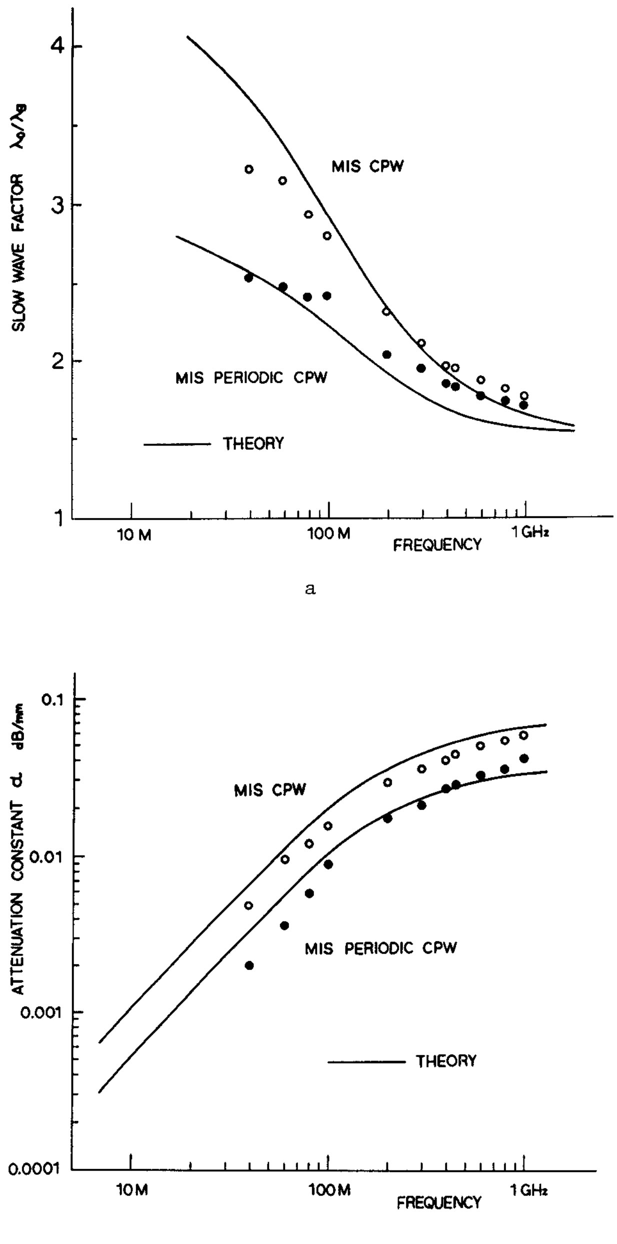

Fig.4 Experimental results

a. slow-wave factor vs. frequency

b. attenuation constant vs. frequency