ANALYSIS OF ELECTROMAGNETIC WAVE PROPAGATION ON COPLANAR WAVEGUIDES ON DOPED SEMICONDUCTOR SUBSTRATES

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Abstract

High resistivity silicon substrates demonstrated strong potential for applications as a microwave and millimeter wave substrate. A method to simulate a coplanar waveguide (CPW) on a doped semicoductor substrate is presented. Its salient point is the inclusion of a voltage dependent depletion width and built-in voltage due to the metal-semiconductor (Schottky) contact. The attenuation, effective dielectric constant, and characteristic impedance are determined for different modes and applied biases.

1 Introduction

A high resistivity silicon has recently demonstrated strong potential as a microwave substrate. Experimental research shows that using schottky contacted coplanar waveguides (CPW) with HR silicon rivals semi-insulating Gallium Arsenide (GaAs) as an interconnect in microwave monolithic integrated circuit (MMIC) technology [1]. In the microwave band, the coplanar waveguide's role as an interconnect increases in importance because of its lower parasitics as compared to microstrip. Interest in minimizing costly MMIC test models can be pursued using computer simulations. Past numerical research concerning the CPW on a doped substrate inadequately considered the solid state physics of the Schottky contact. Previous models either ignored resistivity changes between the surface and bulk Fig.(1), or used a roughly estimated circuit model. The modeling and understanding of the Schottky contact and its effects on the wave propagation highlights this research.

2 The Model

This problem involves both the electromagnetic wave propagation characteristics on the CPW as well as the physics of the semiconductor material used in the substrate. The semiconducting aspects of the substrate are taken into account by coupling Poisson's equation with the continuity equation to describe the electrons response to the applied electric field.

$$\nabla^2 V = \frac{\rho}{\epsilon_s \epsilon_0} \quad (1)$$

$$\frac{\partial \rho}{\partial t} = \frac{1}{q} \nabla \cdot J \quad (2)$$

A drift-diffusion current model is utilized, where the mobility and diffusion constants are kept constant.

$$J_{total} = -q\mu \nabla V + qD\nabla n \quad (3)$$

The electric and magnetic fields inside the transmission line are calculated. To analyze the CPW on a semiconductor substrate, two main issues must be considered:

1. The various electromagnetic modes that can be excited on the line. These include the even and odd modes that may exist at the frequency range of interest to this study (i.e. up to 10 Ghz).

2. The influence of the bias condition on the propagating modes. To understand the significance of this point, let us consider the even (fundamental) mode on the CPW, which means that the two ground planes are held at the same potential and the center conductor is held at a different one. This mode can be obtained by keeping the ground conductors at zero DC potential. One would obtain two different depletion widths by assigning either a negative or a positive potential to the center conductor. Hence, two different wave

propagation characteristics may be obtained for the same even mode. To take the effects of the DC into account while analyzing the electromagnetic modes, the even mode is further classified as an assertive one or assertive zero mode, determined by the placement of the signal.

In this study, the CPW modes on a semiconductor substrate will be investigated as functions of the applied DC voltage and frequency. Results showing the effective-dielectric constant, the attenuation, and the characteristic impedance will be presented.

3 Parameter Extraction

3.1 Effective Dielectric Constant

The effective dielectric constant is defined using the ratio of the energy stored in the transmission line to the total energy stored when the transmission line is filled with air, as shown in the following expression.

$$\epsilon_{eff} = \frac{\frac{1}{T}\sum_{i,j=1}^{n} \epsilon_{Ri,j}\epsilon_0 E_{0i,j}^2 dt}{\frac{1}{T}\sum_{i,j=1}^{n} \epsilon_0 E_{0i,j}^2 dt} \quad (4)$$

where ϵ_R is the dielectric constant, ϵ_0 is the permittivity constant, and E_0 is the magnitude of the electric field.

3.2 Characteristic Impedance

The characteristic impedance is defined as the voltage across the conductors divided by the total current. Instantaneous values for voltage and current are found through the following equations:

$$V = -\int \vec{E} \cdot dl \quad (5)$$

$$I = \oint \vec{H} \cdot dl \quad (6)$$

$$Z_0 = \frac{V_{peak-to-peak}}{I_{peak-to-peak}} \quad (7)$$

Hence, it should be noted that the characteristic impedance of the line can also be calculated from the analytical power relation.

3.3 Attenuation

The attenuation constants are determined through power equations.

$$\alpha = \frac{P_{loss}}{2.0 P_{avg.transmitted}} \quad (8)$$

$$P_{loss} = \sigma E_0^2 \quad (9)$$

$$P_{transmitted} = Re\left[\int \frac{|E|^2}{\eta} \cdot ds\right] \quad (10)$$

Where η is the complex wave impedance:

$$\eta = \sqrt{\frac{j\omega\mu_0}{\sigma + j\omega\epsilon}}, \quad (11)$$

and σ is the conductivity:

$$\sigma = q\mu_{mobility} n. \quad (12)$$

4 Results

The previously described approach is used to analyze the structure. The following parameters are used:

- mobility: $\mu = 1400 \frac{cm^2}{V-s}$
- resisitivity: $\rho = 3 \frac{k-\Omega}{cm}$
- voltage (bi): $V_{built-in} = -0.5V$
- voltage (apl): $V_{applied} = 1V_{peak-to-peak}$
- dielectric c.: $\epsilon_{si} = 11.8$
- line width: $lw = 30\mu m$
- line spacing: $ls = 10\mu m$.

The attenuation, effective dielectric constant and characteristic impedance as functions of frequency are shown in Fig.'s (2),(3), and (4). Our generated results are compared with those developed by Reyes et al [2]. The attenuation constant is the most difficult to measure. There are many loss mechanisms in the structure. These include conductor losses (ohmic), dielectric losses from the substrate polarization and ohmic losses from the semiconductor. The attenuation constant of a lossy homogeneous substrate generated by our model is in excellent agreement with those developed by Reyes et al. [2] as shown in Fig.(2). It should be mentioned that lines (a) and (b) in Fig.(2) are generated neglecting the depletion region width. When the depletion region width is introduced, the attenuation is reduced by about 10 dB/m, as shown by line (c) in Fig.(2). Experimental and numerical values for the effective dielectric constant and characterisitic impedance are compared in figure (3) and figure (4). Reasonable agreement was obtained over the frequency range of interest.

Figures (5) through (7) show the CPW characteristics for the possible modes of operation. Lines (a) and (b), which indicate the assertive one and zero modes respectively, show no change in the three figures. The attenuation in Fig.(5) shows the odd modes attenuation to be significantly larger. An expected result due to deeper field penetration with the odd mode. The effective dielectric constants shown in Fig.(6) are accurate since they center around the predicted value of 6.40. The characteristic impedance is depicted in Fig.(7). The odd mode, due to an extra capacitance between the outer conductors, has a lower impedance. No significant dispersion in the CPW parameters was observed in the frequency range of interest. This study confirms the feasibility of using silicon as a microwave substrate for low cost commercial applications.

The final figures (8) and (9) show how the attenuation varies with the substrate resistivity and applied bias. As the resistivity increases the depletion width also increases, which reduces the attenuation, as shown in Fig.(8). Fig.(9) shows that higher attenuation is observed at low frequencies and higher bias.

5 Conclusion

A model for analyzing the wave propagation characteristics on high resistivity substrates was presented. It was used to investigate CPW on silicon substrates. Good agreement with experimental results was obtained. The modeling of the Schottky contact proves to be very valuable. The results presented in this paper support using a Schottky contacted CPW on HR silicon as a MMIC interconnect.

References

[1] A.C.Reyes and S.M.El-Ghazaly, "Coplanar waveguides and microwave inductors on silicon substrates," *IEEE Micro. Theory Tech.*, vol. 43, pp. 2016–2021, September 1995.

[2] A. C. Reyes, *Silicon as a Microwave Substrate.* M.S. Thesis, Arizona State University, 1995.

[3] D. M. Pozar, *Microwave Engineering.* Addison-Wesley,Menlo Park, Ca., 1990.

[4] A. Rosen, M. Caulton, P. Stabile, A. M. Gombar, W. M. Janton, C. P. Wu, and a. C. W. M. John F. Corboy, "Silicon as a millimeter-wave monolithically integrated substrate – a new look," *RCA REVIEW*, vol. 42, pp. 633–657, 1981.

[5] R. A. Pucel, "Design considerations for monolithic microwave circuits," *IEEE Micro. Theory Tech.*, vol. 29, pp. 513–534, June 1981.

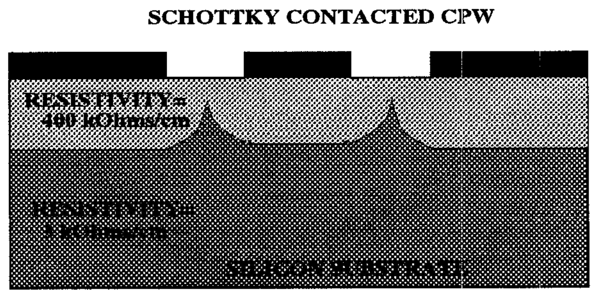

Figure 1: Schottky Contact with Depletion Width

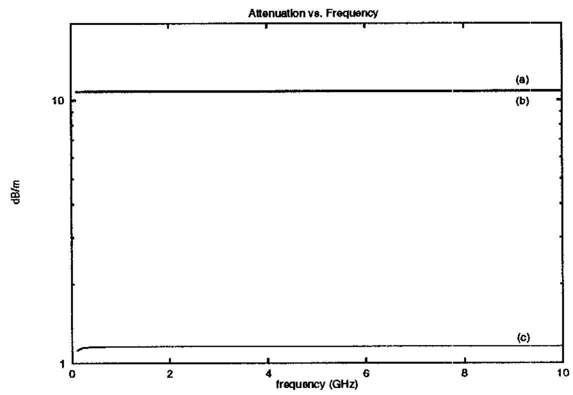

Figure 2: (a) Attenuation constant without a depletion width, (b) analytical attenuation without a depletion width, (c) attenuation with a depletion width.

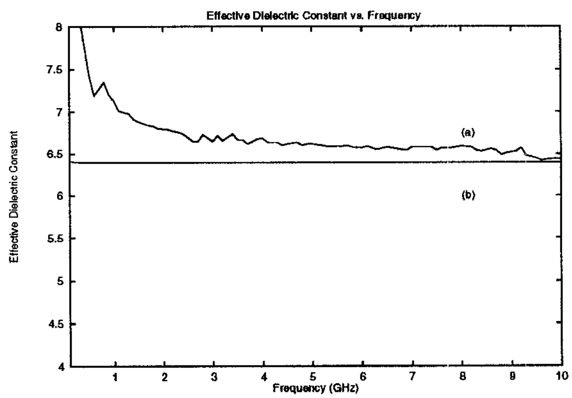

Figure 3: Effective Dielctric Constants (a) experimental, (b) calculated.

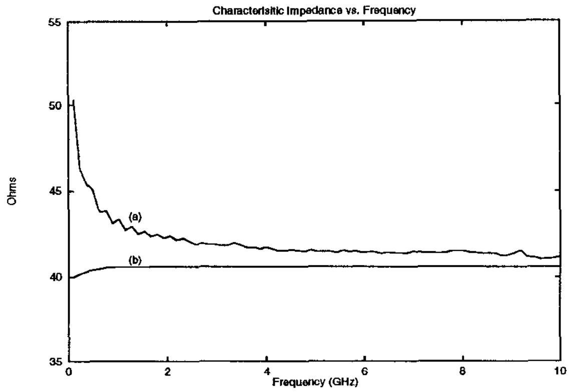

Figure 4: Characteristic impedance (a) experimental, (b) calculated.

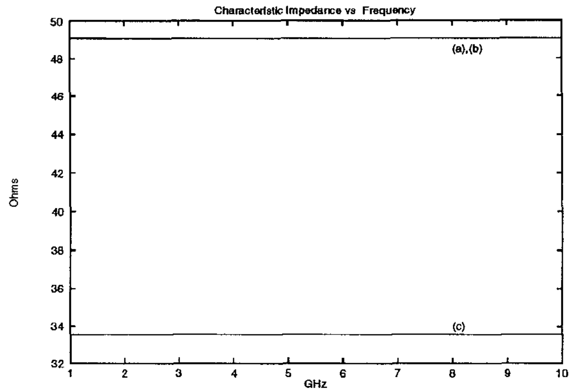

Figure 7: Characteristic Impedance (a) Assertive one mode, (b) Assertive zero mode, (c) Oddmode.

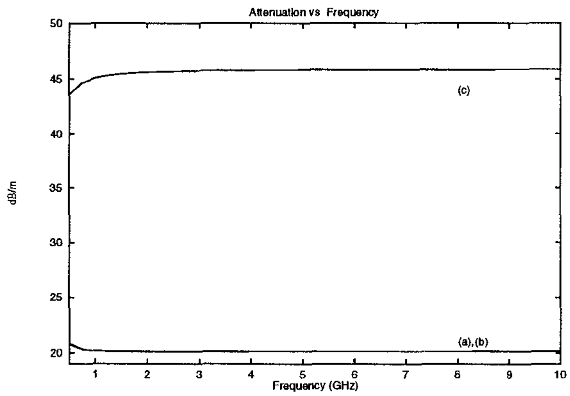

Figure 5: Attenuation (a) Assertive one mode, (b) Assertive zero mode, (c) Odd mode. $\rho = 500\Omega/cm$.

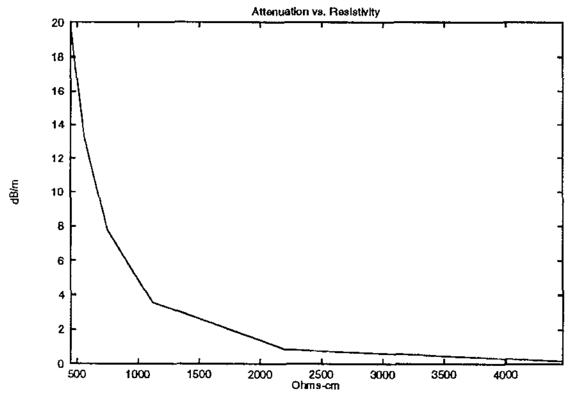

Figure 8: Attenuation versus Resistivity

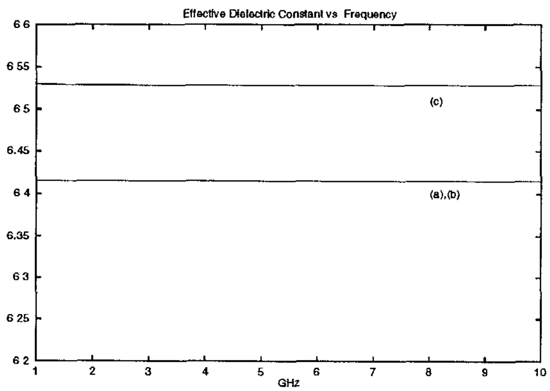

Figure 6: effective dielectric constant (a) Assertive one mode, (b) Assertive zero mode, (c) Odd mode.

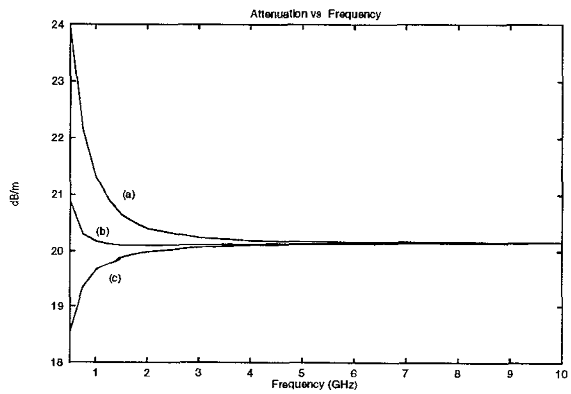

Figure 9: Attenuation constant versus frequency with different applied biases (a) 5, (b) 3 , (c) 1 $V_{peak-to-peak}$