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Finite Element Analysis of Optically Controlled MIS Slow Wave Line using High Frequency Structure Simulator

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***Abstract*-In this paper we have proposed and studied a method of characterization of propagation behavior of an optically controlled Metal-Insulator-Semiconductor (MIS) slow wave line. The propagation behavior of such line under optical illumination has been studied by finite element method using ANSOFT's High Frequency Structure Simulator (HFSS). We have compared our results with analytical calculated one dimensional wave analysis. In this new method a wider MIS line advantageously approximated as a parallel plate waveguide structure. The MIS line has been simulated for perfect electric conductor (PEC) and non-perfect electric conductor Indium-Tin-Oxide (ITO) and in both cases the simulation results compare well with analytical results. The proposed structural analysis can be used as easy and time saving tool for optically controlled delay line and phase-shifter for different RF signal processing schemes.**

***Index Terms*- Lossy Silicon, MIS, HFSS, β/β_0.**

I. INTRODUCTION

The effect of substrate conductivity on propagation behavior of RF signals in MIS microstrip line has been widely studied to understand the planar lines and high speed interconnects in VLSI circuits [1]. Initially Guckel, Brennan, and Paloz [2] have observed that, when substrate conductivity is greater than a specific conductivity σ_{min}, the MIS line is dominated by series loss, and when the substrate conductivity is less than σ_{min}, the MIS line is dominated by shunt loss. They used σ_{min} to define two regions of operation and developed different equivalent

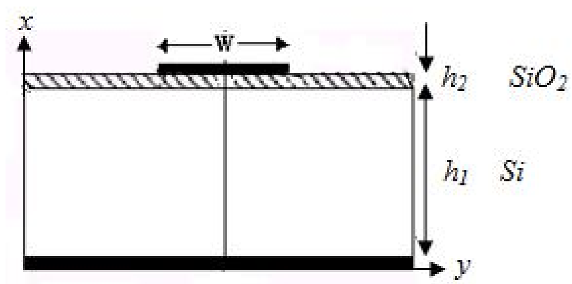

Fig.1(a). Optically controlled MIS slow wave line

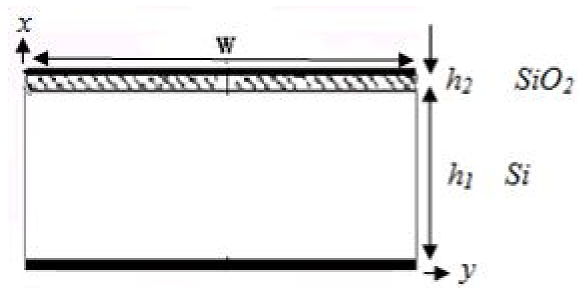

Fig.1(b). Equivalent Parallel plate model of optically controlled MIS slow wave line

Circuit models for each region. Hasegawa, Furukawa, and Yanai [3] divided the propagation behavior into three regions of operation, namely, dielectric quasi-TEM mode, slow-wave mode and skin-effect mode. The each region was described by its own distinct equivalent-circuit models. Initially the slow-wave mode in MIS lines was regarded as a drawback which needed to be avoided in high speed interconnects to circumvent delays and distortion in signals [4]. But now it is possible to exploit the slow wave phenomenon to realize new kind of devices like phase shifters [5], semiconductor traveling-wave amplifier [6], delay lines [7], antennae [8], filters [9,10,11] and many other signal processing devices. A Bhadoria [12] gives an analytical method for calculation of propagation constants. In all the above analysis, they do not give easy to model 3-D simulation of these devices. In this paper we have proposed a method of characterization of propagation behavior of an optically controlled Metal-Insulator-Semiconductor (MIS) slow wave line under optical illumination by finite element method based ANSOFT's High Frequency Structure Simulator (HFSS). In this simulator a wider optically controlled MIS line can be realized as parallel plate wave guide. In the previous analytical approach when boundary condition and the properties of strip conductor change the entire calculation become lengthier. In our new method one can easily changes the device dimensions and material properties and the boundary conditions will automatically adjust.

II. SILICON UNDER OPTICAL ILLUMINATION

In Figure1when silicon is illuminated by a radiation corresponding to photon energy above the band gap leads to optically induced electron-hole plasma. This electron-hole plasma changes the dielectric behavior of silicon and gives rise to a complex dielectric constant. The imaginary part of complex dielectric constant corresponds to optically induced conductivity in the silicon substrate [1].

The complex dielectric constant in terms of optically generated carrier can be written as

$$\varepsilon_r^* = \varepsilon_L - \frac{\omega_p^2}{\omega^2 + \nu^2} - j\frac{\nu}{\omega}\frac{\omega_p^2}{\omega^2 + \nu^2} \qquad (1)$$

where, the plasma frequency ω_p is defined as

$$\omega_p^2 = \frac{ne^2}{\varepsilon_0 m^*}$$

which depends on the density of optically generated charge carriers $n_{op,}$ the effective mass of charge carriers $m*$. The v is the collision frequency of charge carriers and responsible for dissipation. Further, the optical generation rate of charge carriers can be related with optical incident power in the silicon substrate as

$$G = \frac{S\lambda_p}{hc}\frac{P}{A}(1 - R)\exp(-\alpha\, y) \qquad (2)$$

where, P is incident optical power, S is relative spectral response, λ_p is optical wave length, h is plank constant, c is velocity of light, R is the reflection coefficient , α is absorption coefficient and A is the illumination area. The variations of real and imaginary part of the complex dielectric constant with optically induced carrier concentration have been plotted in Figure 2(a) and 2(b). Figure 2(c) shows the variation of optically induced conductivity with carrier concentration.

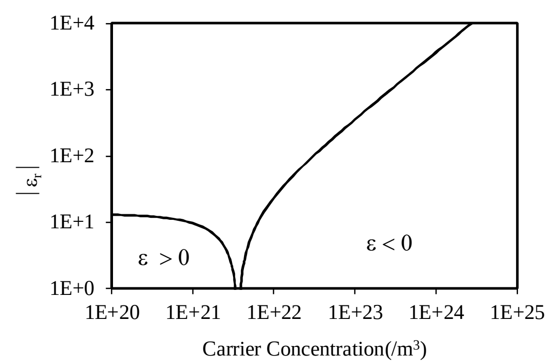

Fig.2(a). Variation of real part of optically induced dielectric constant

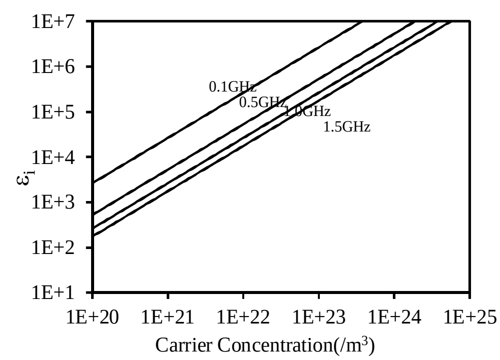

Fig.2(b). Variation of imaginary part of optically induced dielectric constant

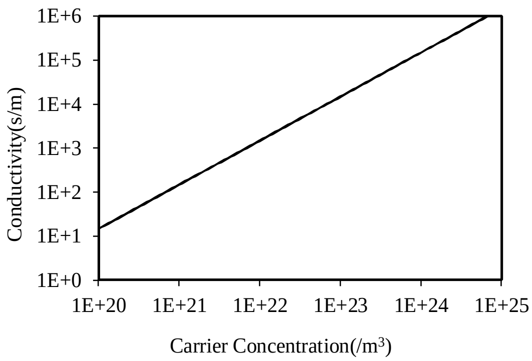

Fig.2(c). Variation of optically induced conductivity

III. ANALYTICAL ONE DIMENSIONAL WAVE ANALYSIS

To study the propagation behavior of an optically controlled MIS structure, we have assumed that the strip width is sufficiently wide and can be approximated as a two-layer parallel plate waveguide structure with dielectric constants ε_1 and ε_2^* as shown in Figure 2(a, b).The dielectric layers are covered with the two perfectly conducting planes. Using Maxwell equations, the magnetic field corresponding to TM mode in the structure satisfies the following wave equation

$$\frac{d^2H_y}{dx^2} + \beta_0(\varepsilon^*(x) - \beta^{*2}/\beta_0{}^2)H_y = 0 \qquad (3)$$

ε^* is complex dielectric constant of illuminated silicon, β_0 is free space propagation constant and β^* is complex propagation constant in MIS line. The solution of Equation 3 with appropriate boundary condition leads to a magnetic field distribution in the structure as

$$\begin{aligned} H(y) &= H_0\cos(\kappa_1 x) & 0 < x < h_1 \\ &= H_0\frac{\cos(\kappa_1 h_1)}{\cos(\kappa_2 h_2)}\cos[\kappa_2(x-h)] & h_1 < x < h \end{aligned} \qquad (4)$$

The h_1, h_2 in the Figure 1 are the thickness of the silicon and SiO_2 layers respectively. The other field component E_x and E_z of the TM mode can be given as

$$E_x = \frac{\beta^*}{\omega\varepsilon_0\varepsilon(x)}H_y \qquad (5)$$

$$E_z = \frac{1}{j\omega\varepsilon_0\varepsilon(x)}\frac{dH_y}{dx} \qquad (6)$$

The boundary conditions for E_z is defined as $E_z=0$ *at* $x=0$ and $x=h$ along with the continuity of H_y at the interface $x=h_1$. With above boundary conditions we can find the eignvalue condition for complex propagation constant β^* as

$$f(\beta^*) = \frac{\kappa_1}{\varepsilon_1}\tan(\kappa_1 h_1) + \frac{\kappa_2}{\varepsilon_2^*}\tan(\kappa_2 h_2) = 0 \qquad (7)$$

To obtain complex propagation constant β^*, the newton-raphson method is a convenient tool as $f'(\beta^*)$ can be obtained analytically, We carried out calculations for a typical MIS line on a silicon substrate of thickness h_2=190µm and dielectric constant 11.8 with an insulating layer of SiO_2 of thickness h_1=0.3µm and dielectric constant 4.5.

The optically induced conductivity can be expressed in terms of optically generated charge carries as

$$\sigma_{opt} = n_{opt}(\mu_e + \mu_p)e \qquad (8)$$

where, e is the charge of electron while μ_e and μ_p are the mobilities of electron and holes respectively.

IV. FEM ANALYSIS USING HFSS

Further to analyze the transmission behavior of the proposed structure more accurately, we have carried out a 3-D simulation using finite element method (FEM) based tool HFSS. To verify our one dimensional earlier analysis we have taken MIS structure with very wide strip width which can be approximated as a parallel plate waveguide (w/h ratio =60) assuming conducting strip and ground are perfect conducting. The 3-D model of MIS structure used in HFSS is shown in Figure 3. The wave port has been used for excitation with 1mW input power. The port width has been chosen as 100 times of structural height to couple the maximum field to the structure. The air box of height 10 times of structural height has been created in the model. In the simulation optically induced conductivity σ_{opt} has been varied at different frequencies by setting the material properties. Using above model, a parametric driven model analysis for two cases with conductivity sweep of 1S/m to 1E+5 S/m has been done. The conductivity of ITO strip has been chosen as $4x10^5$ S/m while the thickness is 1µm.

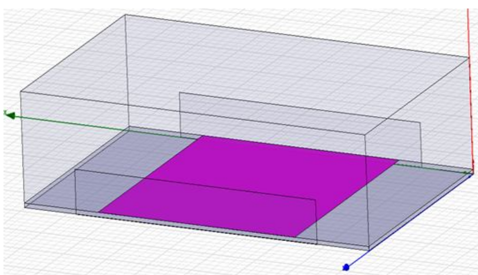

Fig.3. HFSS generated 3-D model of MIS LINE

Next the similar structure has been studied considering strip is made of transparent conducting ITO while ground is perfect conductor. The typical values of various parameters for silicon substrate used are as $\varepsilon_l = 11.8$, $P_e = 0.14 n_p$, $P_h = 0.86 n_p$, $m_e^* = 0.259 m_0$, $m_{pl} = 0.16 m_0$, $m_{ph} = 0.49 m_0$, $\mu_p = 600\, cm^2/V.s$ $\mu_e = 1500\, cm^2/V.s$, $\tau_p = 1.3X10^{-12} s$, $\tau_e = 2.2X10^{-13} s$

V. RESULTS AND DISCUSSION

The propagation behavior like slowing factor and loss has been plotted in Figure 4 using PEC as strip conductor. Figure 5 shows the variation of slowing factor with conductivity at different frequencies when strip conductor made of ITO. It can be seen in Figure 4(a) that the slowing behavior with optical conductivity at a single frequency can be divided in three regions. In first region the slowing factor β/β_0 increases with increase in conductivity and reaches to a maximum value of ~53.

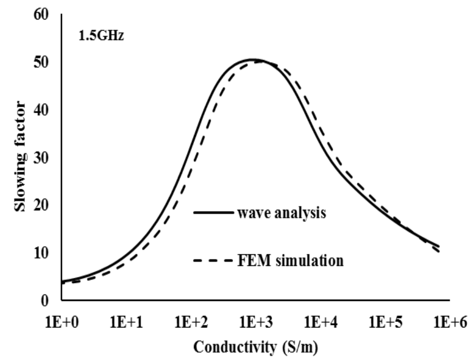

Fig.4(a). Variation of slowing factor with optically induced conductivity when the strip conductor is made of PEC

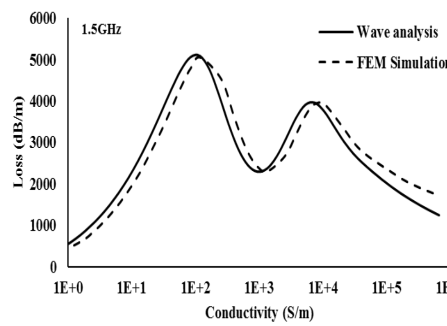

Fig.4(b). Variation of loss with optically induced conductivity when the strip conductor is made of PEC

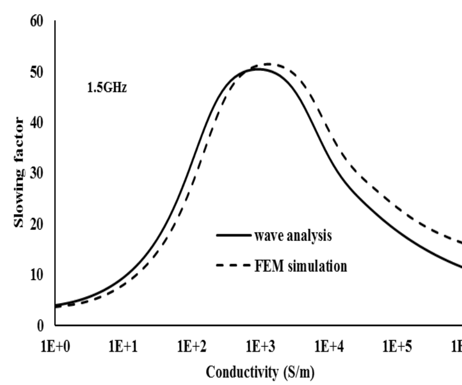

Fig.5(a). Variation of slowing factor with optically induced conductivity when the strip conductor is made of ITO

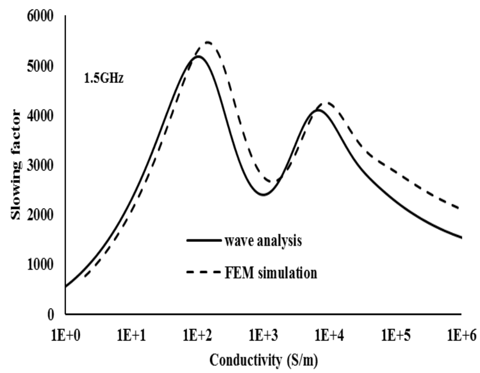

Fig.5(b). Variation of loss with optically induced conductivity when the strip conductor is made of ITO

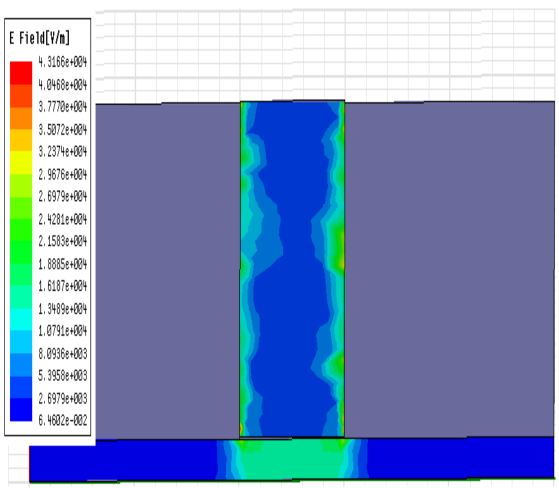

Fig.6(a). E field distribution in MIS slow wave line

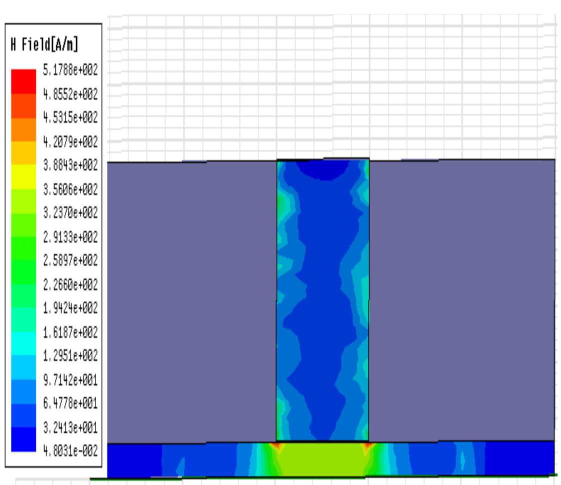

Fig.6(b). H field distribution in MIS slow wave line

In second region, slowing factor remains constant at maximum value. Further increase in conductivity the slowing factor starts to decrease where the third region starts. Similarly these regions can be seen distinctly in loss curves. In first region the losses are very high and dominated by the dielectric losses. The second region where the slowing effect is maximum the values of losses go very low and attains a minimum value at a critical conductivity (~1290S/m for our structure) which is in agreement with the value of conductivity, σ_{min} for minimum attenuation given by Guckel [2]

$$\sigma_{\min} = \sqrt{\frac{3\varepsilon_0\varepsilon_1}{\mu_0 h_1 h_2}} \tag{9}$$

When third region starts the losses are again starts increasing to very high values where conductor losses (series losses) are dominant as the skin effect starts playing the role. These all three regions strongly depend on frequency of operation. The results for slowing factor and losses from HFSS simulation using PEC boundaries(assuming the Strip and ground are Perfect Electric Conductor) have been compared in Figure 4(a) and 4(b). The similar propagation behavior can be seen in 1-D wave analysis. In this case σ_{min} for minimum attenuation was found to be 1250S/m which is also close to the value obtained by 3-D simulation. Further the simulation results for propagation behavior have been plotted in Figure 5(a) and (b) assuming the strip is transparent conductor ITO with finite conductivity. Form the Figures we can say that the variation of slowing factors and losses are slightly higher than the case where strip is PEC which is due to finite conductivity of ITO.

VI. CONCLUSION

A 3-D full wave analysis using finite element method by HFSS tool has been carried out to study the propagation behavior of an optically controlled MIS microstrip line considering the strip is made of transparent conductor ITO with finite conductivity. The results have been compared with the results obtained by HFSS simulation considering strip conductor is perfect electric. We have also compared these simulation results with 1-D wave analysis. It is also found that using ITO as a strip conductor losses are within tolerance and can be used for device applications at low frequencies. This study proposes a new class of optically controlled device which can be used as delay line, phase shifters, having features like ultrafast response, high isolation between controlling and controlled devices, high power handling capacity and easy to fabricate.

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