Propagation Characteristics of Finite Ground Coplanar Waveguide on Si Substrates With Porous Si and Polyimide Interface Layers

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Abstract- Measured and modeled propagation characteristics of Finite Ground Coplanar (FGC) waveguide fabricated on a 15 Ω-cm Si substrate with a 23 µm thick, 68% porous Si layer and a 20 µm thick polyimide interface layer are presented for the first time. Attenuation and effective permittivity as function of the FGC geometry and the bias between the center conductor and the ground planes are presented. It is shown that the porous Si reduces the attenuation by 1 dB/cm compared to FGC lines with only polyimide interface layers, and the polyimide on porous silicon demonstrates negligible bias dependence.

I. Introduction

The use of Radio Frequency and Microwave Monolithic Integrated Circuits (RFICs and MMICs) fabricated on silicon substrates is increasing for a wide range of applications, including personal communications devices, GPS receivers, television digital to analog converters, and wireless PDA. This shift to Si circuits from GaAs circuits is a direct result of the larger wafer sizes that CMOS product lines use, which results in reductions in circuit cost. In addition, because Si MMICs are fabricated on CMOS product lines, Si high frequency analog circuits may be monolithically integrated with digital CMOS circuits, which reduces packaging cost and improves reliability. However, passive components on 0.1 to 20 Ω–cm Si wafers, which is the common range for CMOS and BiCMOS circuits, results in higher loss [1], or lower quality factor, than placing the same element on GaAs, and this higher loss may limit the wider use of Si at microwave frequencies.

The obvious solution to this problem is to use high resistivity Si substrates [1], but this may limit the ability to manufacture circuits on high volume, CMOS product lines. A second solution that has been proposed is to use polyimide interface layers between the Si and the transmission lines and passive circuit components [2,3] to insulate the electromagnetic fields from the lossy substrate. Finally, a third alternative to decrease circuit losses is to selectively create regions of the substrate that are highly porous. Porous Si that is as much as 65-70% air dramatically lowers the interactions of the electromagnetic fields with the Si, therefore, circuit losses are reduced [4,5].

In this paper, the two alternatives to insulate fields from a finite ground coplanar (FGC) waveguide with the lossy Si substrate are combined. Specifically, we present for the first time the characteristics of FGC waveguide fabricated on a 15 Ω-cm Si wafer with a 23 µm thick porous Si region and a 20 µm thick polyimide interface layer as shown in Figure 1 (FGC-PPS). Measured and 2.5D Method of Moments characteristics of the transmission lines are presented without bias. Then, it is shown that the characteristics are bias independent.

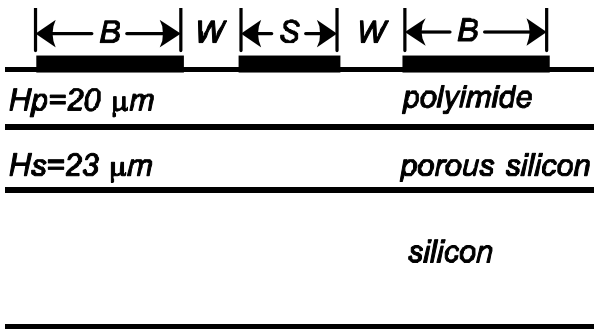


Fig. 1: Schematic of finite ground coplanar waveguide on Si substrate with porous Si and polyimide interface layers (FGC-PPS).

II. Circuit Fabrication and Characterization

The porous silicon film is formed by anodization using a conventional single-tank etch cell described in [6]. Lightly doped 12-17 Ω-cm p-type (boron) silicon wafers with (100) crystal plane orientation and a thickness of 525 µm are anodized at 10 mA/cm^2 in an HF mixture (22% HF:pure ethanol). Prior to anodization, titanium and aluminum is evaporated on the wafer backside, and then it is annealed to provide a good ohmic contact. This also ensures film uniformity across the wafer. The resulting film sample has a porosity of 68% (determined gravimetrically) and a film thickness of approximately 23 µm (determined by scanning electron micrograph). Passivation is performed by rapid thermal oxidation (RTO) for 30 minutes at 350°C. The oxidation terminates the dangling silicon bonds with a few monolayers of oxygen to make the material chemically stable in ambient [7].

Dupont adhesion promoter and two, 10 µm thick layers of Dupont PI-2611 polyimide were spun onto the wafer to yield a total polyimide interface layer thickness of 20 µm. Each layer of polyimide was fully cured at 340 °C for 120 minutes before the next layer was added. PI-2611 polyimide has a relative dielectric constant of 3.12 measured at 1 MHz [8] and a loss tangent of 0.002 measured at 1 kHz [9]. The metal FGC circuit consists of 200 Å Ti and 1.45 µm of evaporated Au, both of which are defined by a liftoff process.

The circuits for measuring the propagation constant, $\gamma = \alpha + jk_0\sqrt{\varepsilon_{eff}}$ where α is the attenuation constant and ε_{eff} is the effective permittivity, consist of Thru-Reflect-Line (TRL) calibration standards with four delay lines of 850, 1700, 3500, and 10000 µm to cover the frequency band of 1 to 50 GHz. The TRL calibration was implemented with MULTICAL [10], a TRL software program that computes the propagation constants of the lines by using the difference in the measured magnitude and phase between the thru and delay lines. The measurements were performed on a vector network analyzer and a microwave probe station.

Table 1: Dimensions of FGC-PPS lines

S (µm)	W (µm)	B=3S (µm)	S+2W (µm)	Zc (f=25 GHz)
34	5	102	44	63
46	7	138	60	62
56	10	168	76	63
66	12	198	90	62
78	16	234	110	63
86	20	258	126	64
100	25	300	150	64

Sonnet 2-D simulation software was used to analyze the FGC-PPS lines. For the simulations, the porous Si thickness, relative dielectric constant, and resistivity are 23 µm, 3.3, and 100 Ω-cm respectively. These parameters are based on prior experience with the materials. The Si substrate resistivity is 15 Ω–cm, and the polyimide is fully described above. FGC lines with dimensions given in Table 1 were analyzed, and the characteristic impedance of the lines is nominally 63 Ω.

III. Results

Because the structure is complicated and the porous Si material properties are not accurately known, the Sonnet simulations and the measured results are compared first to verify the results. In Figure 2, the measured and simulated attenuation of three lines with zero bias are compared. The agreement is very good for narrowest and widest lines, but there is approximately 12 percent error for the S = 66 µm line. The measured and modeled effective permittivity is shown in Figure 3. The agreement is excellent for all three lines, approximately 4%, which indicates that the measurements to be presented are accurate, the characteristic impedance of the lines is nominally 63 Ω as determined by the simulations, and the material characteristics of the porous Si used in the model is accurate enough for engineering design purposes.

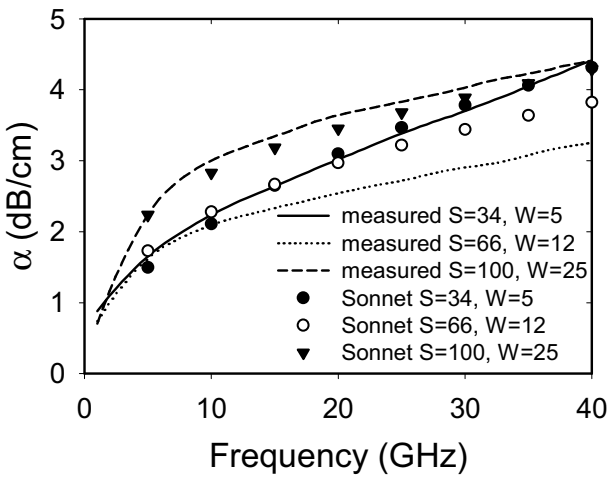


Fig. 2: Measured and Sonnet determined attenuation of FGC-PPS lines with no bias.

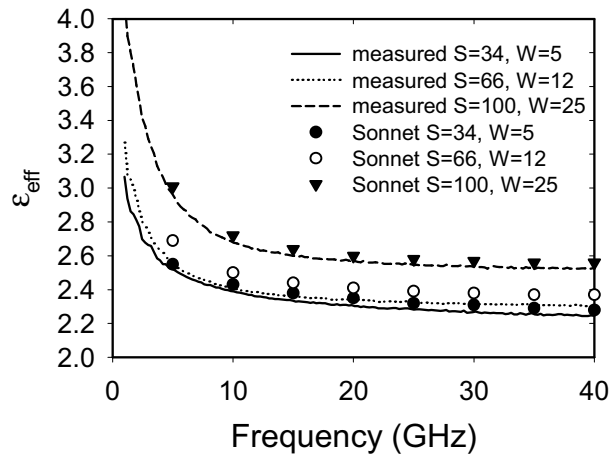


Fig. 3: Measured and Sonnet determined effective permittivity of FGC-PPS with no bias.

The measured attenuation of the FGC-PPS lines with no applied bias is shown in Figure 4. It is seen that the frequency dependence of the attenuation is complicated and highly dependent on the FGC line dimensions. To better illustrate the relationship between attenuation and the FGC line dimensions (S+2W), the data from Figure 4 is replotted in Figure 5. In Figure 5, it is seen that there is a minimum attenuation for S+2W=90, or (S+2W)/Hp=4 for aspect ratio normalized to polyimide thickness, which agrees with the design rule presented in [3] that was derived for FGC lines on Si wafers with a polyimide interface layer. Also plotted in Figure 5 is the attenuation of FGC lines on three Si wafers with different resistivities and a 20 µm polyimide interface layer [3]. The lines from [3] have approximately a 50 Ω characteristic impedance and were fabricated and characterized the same as the lines in this paper. It is noted that the lines have the same minimum in attenuation for S+2W=90 µm. More importantly though, it is shown that the porous Si reduces the attenuation across the entire range of S+2W.

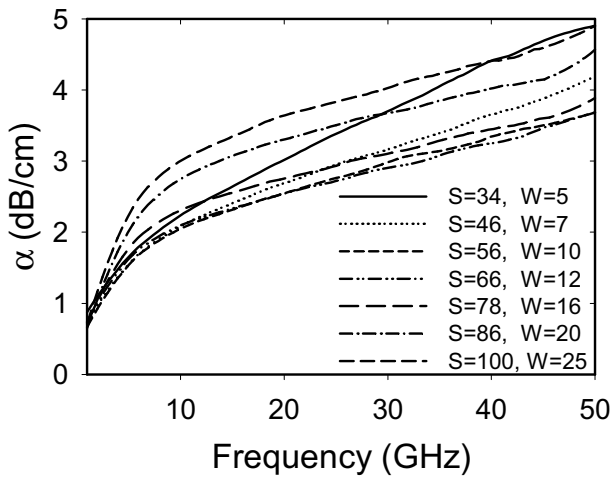


Fig. 4: Measured attenuation of FGC-PPS lines with no bias.

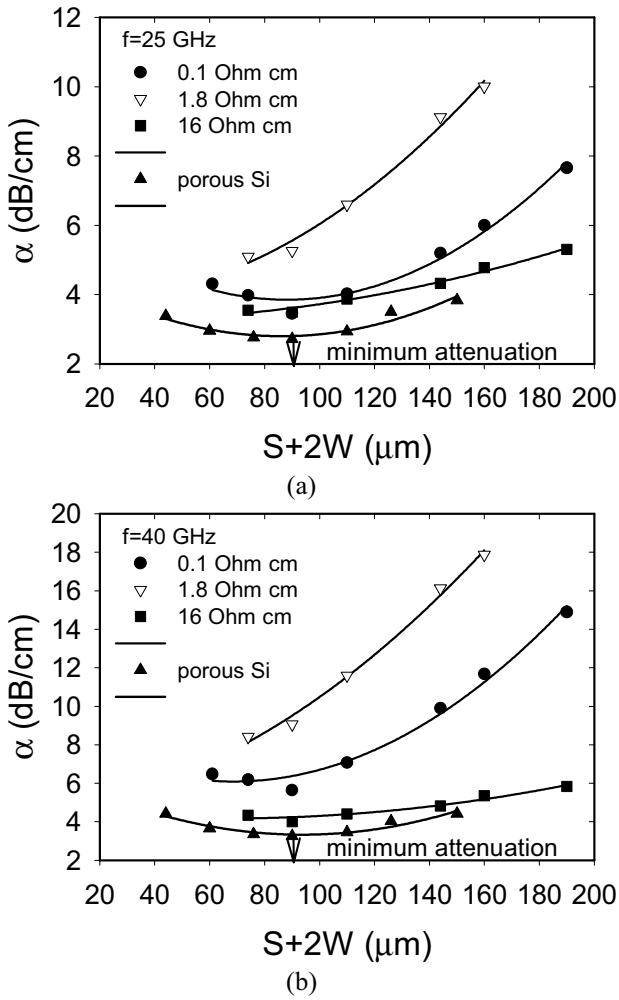


Fig. 5: Measured attenuation of FGC-PPS lines as a function of the FGC dimensions.

The measured effective permittivity of the same lines is shown in Figure 6. ε_{eff} increases as S+2W is increased, which is evidence that the electric field strength in the porous Si is stronger for wider FGC lines. For W/(Hp+Hs)>3, the field dependence is also further impacted by the presence of the silicon substrate, which causes a stronger increase in ε_{eff} as the slot width increases. This observation supports the explanation that the dielectric attenuation increases as S+2W increases.

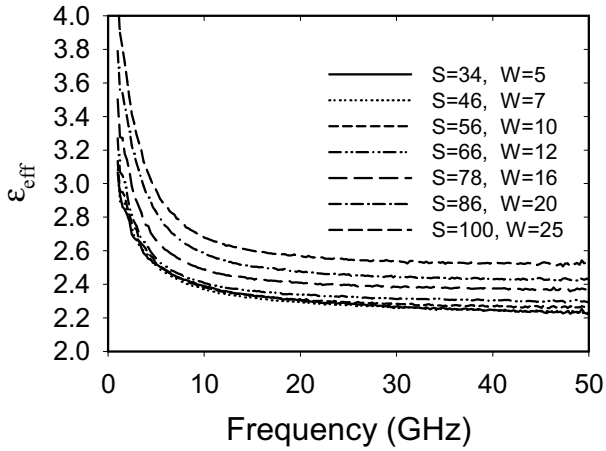
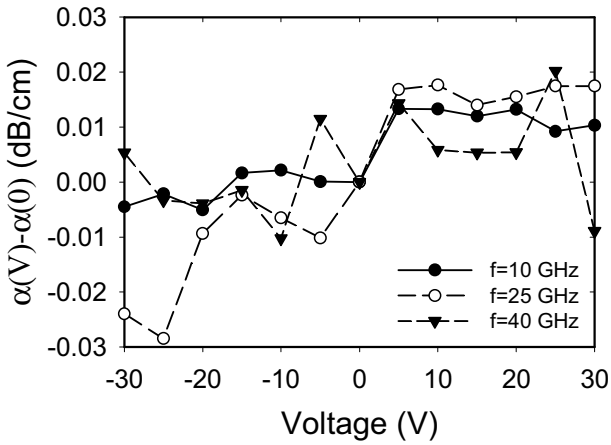


Fig. 6: Measured effective permittivity of FGC-PPS lines with no bias.

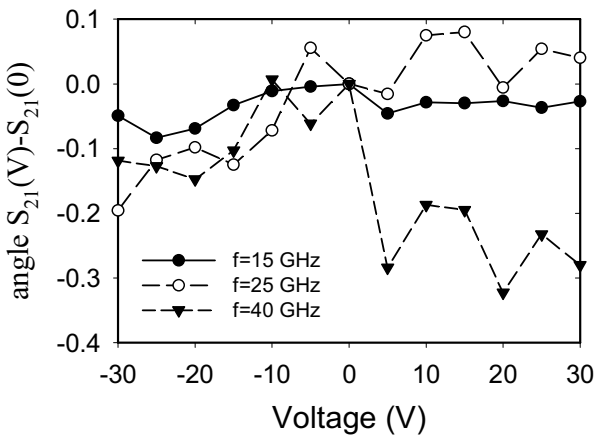
It has been shown that the attenuation of transmission lines on bulk Si substrates is dependent on the applied bias, and that the same transmission lines on porous silicon are bias independent [11]. To determine the bias dependence of FGC-PPS lines, a full TRL calibration was performed with zero bias. Then, the S-parameters of a 1 cm long line were measured as a function of bias. The difference in the attenuation and phase of the 1 cm line measured at an applied bias between the center conductor and ground planes to no applied bias is shown in Figures 7a and 7b respectively for the S=66 μm line. In Figure 7a, it is seen that the difference in attenuation as the bias is varied from –30 to +30 V is less than 0.015 dB, excluding two data points. Furthermore, it appears that the attenuation difference, while small, is higher for a positive applied bias. The phase of the 1 cm long FGC-PPS line varies less than 0.3 degree, which is within normal measurement error. The bias dependent characteristics of the S=100 μm line were measured and had similar results.

IV. Conclusions

For the first time, Finite Ground Coplanar waveguides fabricated on CMOS grade Si wafers with a porous silicon and a polyimide interface layer have been characterized. The measured attenuation is 1 dB/cm lower than previously reported FGC lines on CMOS grade Si. It is shown that this new transmission line follows the same design rules derived for FGC lines with only a polyimide interface layer. Furthermore, it is shown that the propagation characteristics are not dependent on applied bias.



(a)



(b)

Fig. 7: Measured attenuation and phase of a 1 cm long FGC-PPS line with S=66 μm as a function of applied bias between the center conductor and ground planes.

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