Microwave Filters on a Low Resistivity Si Substrate with a Polyimide Interface Layer for Wireless Circuits

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Abstract

Novel low-pass and band-pass filter designs on low resistivity silicon substrate (1 Ω-cm) with a polyimide interface layer are presented for the first time. The filters utilize the Finite Ground Coplanar (FGC) line technology, and operate from 10-30 GHz with very good insertion loss. The latter is possible by using a 20 μm thick polyimide on top of the silicon wafer, and a line geometry that minimizes field interaction with the lossy Si substrate. The attenuation of the FGC lines is comparable with that of thin film microstrip lines on similar substrates. Experimental and full-wave analysis results are provided. These filters can be used as part of a wireless microwave interconnect system.

I. Introduction

The possibility of low cost RF and microwave circuits integrated with digital and analog circuits on the same chip is creating a strong interest in silicon as a microwave substrate, especially with the development of SiGe Heterojunction Bipolar Transistors with a high frequency of oscillation [1]-[3]. The operation, however, of traditional microwave circuits, such as transmission lines, filters and antennas is problematic, due to the high loss that these circuits exhibit on low resistivity, CMOS grade Si wafers.

To overcome this problem researchers have used two different approaches. In the first approach, high resistivity Si wafers are used (ρ>2500 Ω-cm) [1]-[2] and traditional microwave components have a performance similar to those on insulating substrates, such as GaAs. In the second approach, dielectric layers such as polyimide are used on top of the CMOS substrate to create an interface layer that can host low loss microwave components. Both microstrip and coplanar waveguide transmission lines fabricated in this way have exhibited low attenuation for an optimum polyimide thickness [4]-[5].

This paper presents for the first time the development of low-pass and band-pass Finite Ground Coplanar (FGC) filters, operating from 10-30 GHz on a CMOS grade silicon substrate with a polyimide interface. Results from experimental measurements and 2.5-D Method of Moments (MoM) analysis are presented. The filters are part of a planar wireless communication system being developed to transmit data from one chip to another, as an alternative to traditional conductor-based interconnects for future systems.

II. Filter Design

a) *FGC line technology*

Finite Ground Coplanar technology was chosen for the design of the low-pass and band-pass filters. FGC lines are similar to Coplanar Waveguide (CPW) lines, with the exception of electrically narrow ground planes. The main advantages of FGC lines are that they do not support parallel-plate modes, thus eliminating the need for via-holes, and that the line loss is mainly ohmic [6]. Experimental results have shown that a nearly TEM mode propagates over a wide frequency range (2-118 GHz), and that the total line loss depends mainly on the line geometry rather than the substrate material and thickness [6]. FGC lines are, therefore, ideal candidates for microwave filter design on low resistivity Si wafers, where the conducting nature of the substrate severely limits line performance.

To design low-pass and band-pass filters on low resistivity (1-20 Ω-cm) Si wafers, the FGC electric fields must have minimum interaction with the lossy substrate. For this reason a thick layer (20 μm) of polyimide (DuPont WE 1111) is utilized on top of the silicon wafer (see Fig. 1). Previous studies have shown that it is possible to minimize the electromagnetic interaction between the FGC line and the substrate if

$$(S+2W) < 3\,H_p \qquad (1)$$

where S is the center conductor width, W the slot width and H_p the polyimide thickness [7].

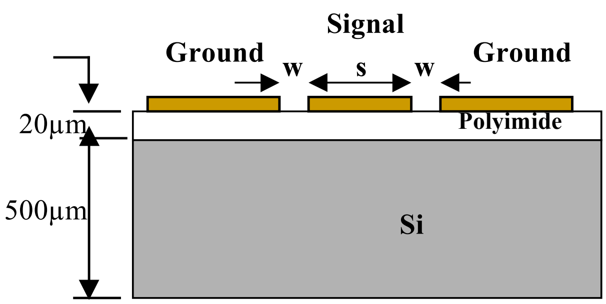

Figure 1: Schematic of FGC line on low resistivity Si wafer with a polyimide interface layer.

Two FGC line geometries for feeding the low-pass and band-pass filters are designed, that satisfy the goals of low loss and a characteristic impedance close to 50 Ω. The characteristic impedance, Zo, and effective dielectric constant, ε_{eff}, of these lines are evaluated numerically with a Method-of-Moments based software simulation tool (*Sonnet*). The substrate is low resistivity silicon (σ=100 S/m, tanδ=0.018, ε_r=11.7) with a 20 µm polyimide interface of ε_r= 2.8. Results for a frequency of 20 GHz are summarized in Table I (W_g is the ground plane width).

Dimensions (µm)	Zo (Ω)	ε_{eff}
S=25, W=5, Wg=95	69	2.14
S=50,W=10,Wg=100	60	2.69

Table I. Simulation results for FGC lines.

As seen in Table I, the effective dielectric constant in both cases has a value close to 2.4, indicating that the field interaction of the FGC lines with the lossy Si is reduced significantly. For minimal interaction (ideal case) an ε_{eff} of 1.9 is expected, while ε_{eff} would be 6.35 if the polyimide interface is not present.

b) Low-Pass Filter Design

A fourth order stepped-impedance low-pass filter is designed for a maximally flat response with a 10 GHz cut-off frequency. The low- and high-impedance sections are chosen to be 35 Ω and 105 Ω, respectively, due to the FGC line geometry limitations set by the fabrication capabilities. The characteristic impedance of the filter is set to 60 Ω. The characteristics of the low- and high-impedance sections are first evaluated with *Sonnet*, and then [8] is used to calculate their lengths for the desired response. Table II, summarizes the characteristics and lengths of the different line sections, while the filter schematic is shown in Fig.2.

Section #	Dimensions (µm)	ε_{eff}	Length (µm)
1	S=20,W=30	2.64	1280
2	S=150,W=5	3.53	2720
3	S=20,W=30	2.64	3100
4	S=150,W=5	3.53	1100

Table II. Characteristics of low- and high-impedance sections of the maximally flat low-pass filter.

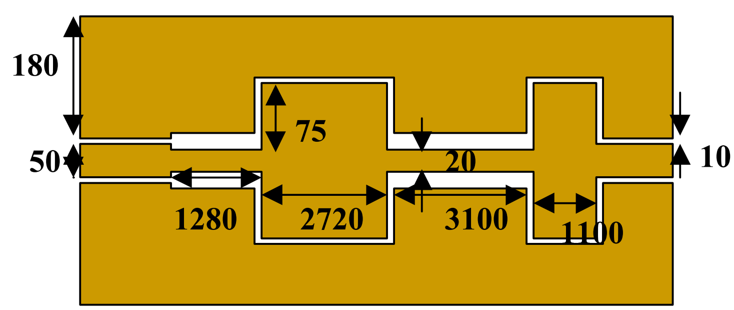

Figure 2: Schematic of the stepped-impedance low-pass filter (Dimensions in µm, not drawn to scale).

The simulated results for the low-impedance sections show that loss will be higher in those sections since the effective dielectric constant (3.53) deviates more from the ideal value of 1.9, and equation (1) is violated. Simulations for the overall filter response are also performed with *Sonnet* and the results are presented in section IV.

c) Band-Pass Filter Design

A two-pole FGC band-pass filter that utilizes quarter-wavelength long open-end series stubs is designed with a center frequency of 30 GHz, as shown in Figure 3. The stub is formed by printing a center conductor with a narrow slot. At the resonance, the $\lambda_g/4$ slot translates an open into a short. The filter impedance is 69 Ω, and the effective dielectric constant is 2.14 (from Table I). Based on this value, the stub lengths ware found to be 1.7 mm long. The width of each "stub-finger", as well as the slot width is 5 µm. The filter response is simulated with *Sonnet*, and is shown in section IV.

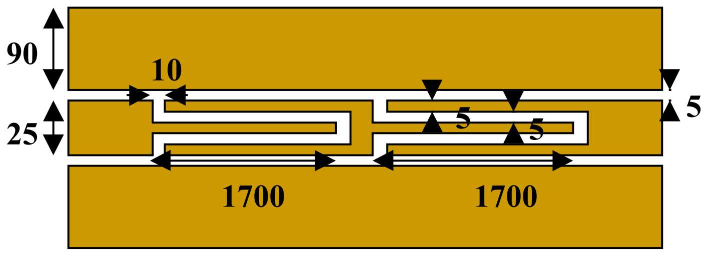

Figure 3: Schematic of the two-pole band-pass filter (Dimensions in µm, not drawn to scale).

III. Fabrication

On 1 Ω-cm silicon wafers, DuPont WE 1111 (now called PI-1111) polyimide is deposited and cured to a thickness, Hp, of 18 µm. FGC circuits are fabricated on top the polyimide using standard liftoff processing with the FGC made of 0.02 µm of Ti and 1.5 µm of Au. No backside ground plane or Si passivation layers are grown.

The FGC propagation characteristics are measured with a vector network analyzer and probe station. A quartz spacer between the Si substrate and the probe station wafer chuck is used to eliminate parasitic microstrip and parallel plate waveguide modes. The propagation constant, $\gamma=\alpha+j\omega\sqrt{\varepsilon_{eff}}/c$ where α is the attenuation constant, ω is the angular frequency, and c is the velocity of light in vacuum is deembedded through the Thru-Reflect-Line (TRL) calibration routine implemented in the software program MULTICAL [9]. For each FGC line characterized, four delay lines with the longest line being 1 cm are used in addition to the thru line to enhance accuracy from 1 to 50 GHz. The reference planes are set by the calibration to the edges of the filters.

IV. Results

Figure 4 shows the measured effective dielectric constant and attenuation for the FGC lines with s=25 µm, w=5 µm and s=50 µm, w=10 µm. The constant behavior of ε_{eff} in Fig. 4, indicates the propagation of a nearly pure TEM mode for both FGC line geometries. Values of the ε_{eff} are approximately 2.47 for the s=25/w=5 µm line and 3 for the s=50/w=10 µm line, indicating that the former interacts less with the Si substrate. Both of these values are in close agreement with the values of Table I. Regarding attenuation, the s=25/w=5 µm line has a much better behavior especially for frequencies above 22 GHz. At 20 GHz the s=25/w=5 µm line has an attenuation of 3.17 dB/cm, while the s=50/w=10 µm line has an attenuation of 3.45 dB/cm.

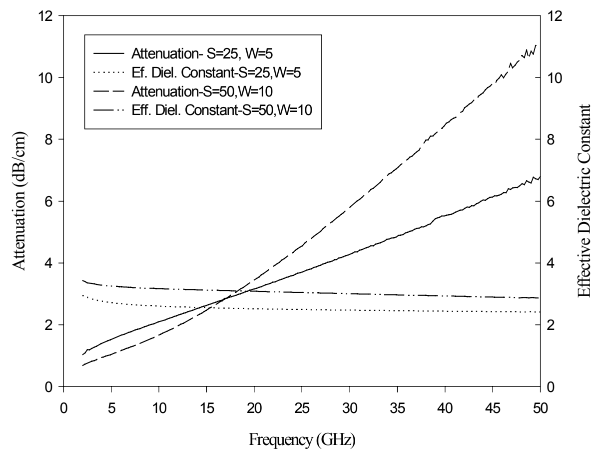

Figure 4: Measured attenuation and effective dielectric constant for FGC lines with s=25 µm, w=5 µm and s=50 µm, w=10 µm .

Measured and simulated results for the low-pass filter are shown in Fig. 5, and agree very well. The measured insertion loss is higher than the simulated loss for frequencies above 24 GHz, due to inaccurate loss modeling in the simulations and the relatively thin metalization thickness (1.5 µm). At 10 GHz the filter exhibits a loss of approximately 5.4 dB, while at 2 GHz the loss is only 0.74 dB.

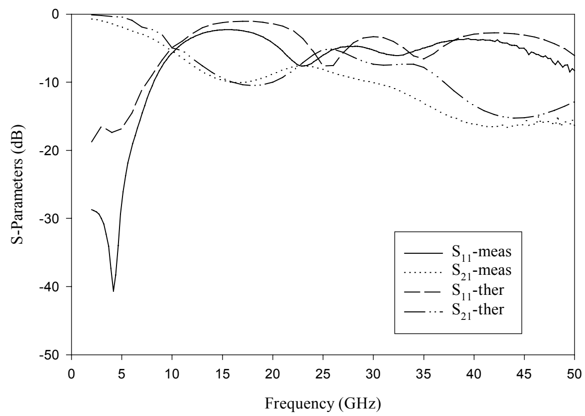

Figure 5: Measured and simulated results for the low-pass filter.

Figure 6 shows measured and simulated results for the band-pass filter, with very good agreement observed between the two of them. Measured insertion loss at 26.48 GHz is 2.76 dB, while the return loss is -22 dB. At 30 GHz the measured insertion loss is 3.17 dB, while the simulated loss is 1.2 dB. Again, the discrepancy is due to inaccurate loss modeling in the *Sonnet* simulations and the thin metalization thickness.

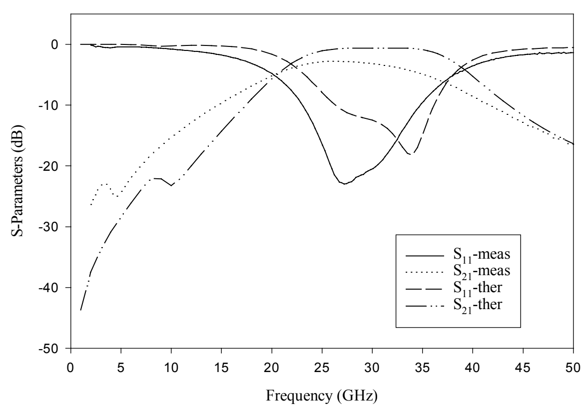

Figure 6: Measured and simulated results for the band-pass filter.

V. Conclusions

A low-pass and a band-pass filter, operating between 10 and 30 GHz, on a low resistivity silicon substrate with a polyimide interface layer have been designed, fabricated and tested. To the author's knowledge this is the first demonstration of such microwave circuits. The low-pass filter response agrees very well with simulated results and exhibits a 5.4 dB loss at 10 GHz. The band-pass filter shows an insertion loss of 2.76 dB at 26.48 GHz, and the measured response also agrees very well with simulated results. These circuits will be part of a wireless chip-to-chip interconnect system, as well as other wireless microwave systems built on CMOS grade wafers.

Acknowledgements

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References

[1] J.F. Luy et al, "Si/SiGe MMICs," *IEEE Trans. Microwave Theory and Techniques,* Vol. 43, No. 4, pp. 705-714, April 1995.
[2] J.S. Rieh et al, "X- and Ku-band amplifiers based on Si/SiGe HBTs and micromachined lumped components," *IEEE Trans. Microwave Theory and Techniques,* Vol. 46, No. 4, pp. 685-694, May 1998.
[3] A. Gruhle and A. Schuppen, "Recent advances with SiGe heterojunction bipolar transistors," *Thin Solid Films*, 294, pp. 246-249, 1997.
[4] G.E Ponchak and A. Downey, "Characterization of thin film microstrip lines on polyimide," *IEEE Trans. Comp., Packaging and Manuf. Technology-Part B*, Vol. 21, No. 2, pp.171-176, May 1998.
[5] G.E. Ponchak and L. Katehi, "Measured attenuation of coplanar waveguide on CMOS grade Si substrates with a polyimide interface layer," *IEE Electronic Letters*, Vol. 34, No. 13, pp. 1327-1329, June 25, 1998.
[6] J. Papapolymerou, J. East and L. Katehi, "GaAs vs. Quartz FGC Lines for MMIC Applications*,"* *IEEE Trans. on Microwave Theory and Techniques*, vol. 46, no. 11, pp. 1790-1793, Nov. 1998.
[7] G.E. Ponchak, A. Margomenos and L. Katehi, "Low loss CPW on low resistivity Si substrates with a micromachined polyimide interface layer for RFIC interconnects," *submitted to IEEE Trans. on Microwave Theory and Techniques.*
[8] *Microwave Engineering*, D.M. Pozar, J. Wiley & Sons, Inc., 2nd Edition, 1998.
[9] R.B. Marks and D.F. Williams, *Multical* v1.00, NIST, Boulder, CO, Aug.