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Non Leaky Conductor-Backed CPW Based on Thin Film Polyimide on CMOS-grade Silicon for Ku-band Application

Sang-No Lee*, Joon-Ik Lee, Jong-Gwan Yook* and Yong-Jun Kim****

Abstract - This paper reports a miniaturized conductor-backed CPW (CBCPW) bandpass filter based on a thin film polyimide layer coated on CMOS-grade silicon. With a 20 μm-thick polyimide interface layer and back metallization on the CMOS-grade silicon, the interaction of electromagnetic fields with the lossy silicon substrate has been isolated, and as a result a low-loss and low-dispersive CBCPW line has been obtained. Measured attenuation constant at 20 GHz is below 1.2 dB/cm, which is compatible with the CPW on GaAs. In addition, by using the proposed CBCPW geometry, miniaturized BPF for Ku band application is designed and its measured frequency response shows excellent agreement with the predicted value with validating the performances of the proposed CBCPW geometry for RFIC interconnects and filter applications.

Keywords: Band Pass Filter (BPF), CMOS-grade silicon, Conductor-backed CPW (CBCPW), Radio Frequency Integrated Circuits (RFICs), Thin film polyimide.

1. Introduction

Radio frequency integrated circuits (RFICs) technology based on the CMOS-grade silicon substrate for recent microwave and RF mobile communication systems possess appeal due to its low-cost and relatively simple fabrication process. However, the substrate loss in the lossy silicon (1 to 30 Ω·cm) poses problems when the lossy silicon is used as a microwave passive component. To overcome substrate loss due to low resistivity, the elevated thin film microstrip (TFMS) line based on the polyimide layer of CMOS-grade silicon has been used to provide compatibility with monolithic microwave integrated circuits (MMICs) processing and is useful for low-loss miniaturized circuits [1]. However, an additional process should be applied to form the passageway openings for on-wafer probing by etching the thin film. Also, low-loss CPW on low-resistivity silicon with a micromachined polyimide interface layer has been used for radio frequency integrated circuit interconnects [2]. However, the attenuation of the line on CMOS-grade silicon is very sensitive to the polyimide thickness, the strip, and the slot width.

In this paper, to overcome the limited performances of CPW on CMOS-grade silicon, the interaction of electromagnetic fields with the silicon substrate has been isolated by placing a conducting ground plane under the polyimide layer. This conductor-backed structure provides mechanical strength for a thin fragile wafer and can also be used as a heat sink for active devices and circuits [3]. Moreover, just one mask layout is required to fabricate the proposed CBCPW, thus making it a cost effective structure as well as compatible with the CMOS process. The parasitic leakage effects in CBCPW geometry, which is a troublesome issue in MMIC packages [4], is quite negligible up to 50 GHz owing to the smaller effective lateral dimensions and lower effective dielectric constant, which means the minimum resonant frequency of CBCPW based on a simple rectangular patch theorem [5, 6] shifts to higher frequency regime. After thoroughly investigating the proposed CBCPW characteristics on attenuation constant, effective dielectric constant and leaky resonant frequency, a miniaturized BPF geometry is designed and its measured frequency response is compared well with the simulated data. Moreover, the lumped element equivalent circuit model of the designed BPF including lossy components as well as inductive and capacitive components is also introduced and shows a good agreement with the measured data compared to the equivalent circuit [7], which only modeled the inductive and capacitive elements and therefore was not in accordance with the measured data. In addition, an on-wafer TRL calibration procedure is performed to obtain appropriate effective dielectric constant as well as attenuation constant, which are both necessary for accurate BPF design.

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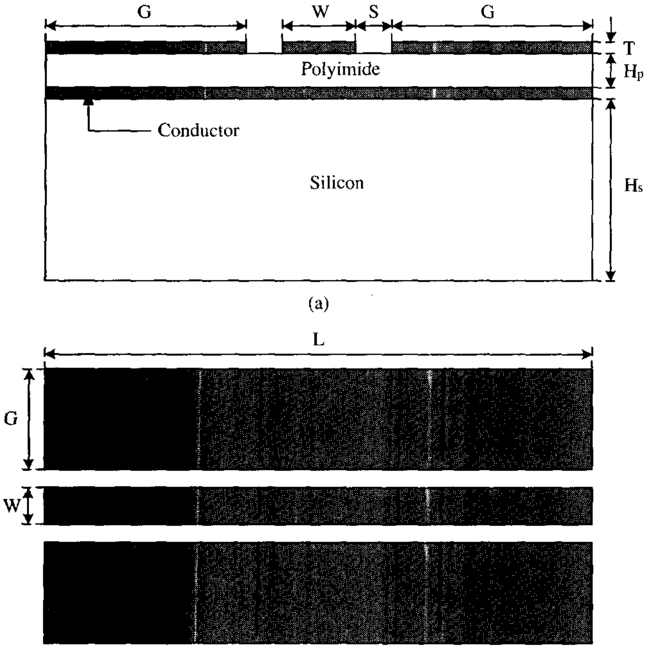
2. Design and Modeling

Fig. 1 shows the geometry of the proposed CBCPW on CMOS-grade silicon. This structure is more robust and simpler to fabricate than membrane-supported CPW lines on COMS-grade silicon [8, 9].



(a)

(b)

Fig. 1 Schematic of the proposed CBCPW with thin film polyimide on CMOS-grade silicon. (G = 2.0 mm, W = S = 50 μm, L = 5.0 mm, T = 10 μm, Hp = 20 μm, Hs = 500 μm) (a) side view (b) top view.

This geometry does not support the leaky parallel plate mode up to 50 GHz by directly calculating the resonance frequency of the equation (1),

$$f_{mn} = \frac{c}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{G}\right)^2 + \left(\frac{n}{L}\right)^2} \tag{1}$$

where c is the velocity of light, ε_r is the relative permittivity, and G and L are the width and the length of the ground patch, respectively. By utilizing the de-embedded effective permittivity into the above equation, the calculated lowest order mode resonance frequency f_{11} of 50.1 GHz is obtained, which agrees well with the simulated result of 51.1 GHz. Since the relative permittivity of the polyimide at 100 MHz is utilized, a slight difference of resonance frequency is observed. With the proposed CBCPW geometry it is possible to provide very low effective dielectric constants, thus low-dispersion transmission line for high-speed circuits is possible. To maintain 50 Ω characteristic impedance for feed lines, polyimide thickness of H_p is fixed as 20 μm. Also considering on-wafer measurement with 200 μm pitch G-S-G probe, 55 Ω structure with W = S = 50 μm is selected to minimize reflection loss between the CBCPW and probe structure. The optimized condition of $(W + 2S) / H_p \leq 3$ for minimum attenuation constant and dispersion loss [2] is not an issue in the CBCPW geometry because of the back metallization, thus making the flexible design rule possible in RF integrated circuits. Based on the CBCPW line a miniaturized bandpass filter for Ku-band application is designed with two $\lambda_g/4$ bended stubs inside the signal line and parallel stubs within the ground planes, where λ_g represents guided wavelength at center frequency. Basically, bended stubs are chosen for a sharper cutoff and narrower bandwidth due to the associated parasitic capacitive and inductive effects, which also slightly change the total length of bended stub structure when compared with the straight $\lambda_g/4$ stub [10].

A schematic view of designed BPF with 4.15 × 3.52 mm^2 size is shown in Fig. 2 with the following dimensions : L_1 = 0.5 mm, S = W = W_1 = 0.05 mm, L_2 = 0.4925 mm, L_3 = L_5 = 0.2925 mm, L_4 = 0.25 mm, W_2 = 0.15 mm, G_1 = 0.865 mm, G_2 = 1.075 mm, G_3 = 0.2 mm, and G = 2.0 mm. In this figure, black and white areas represent the plated conductors and deposited polyimide, respectively. The lumped element equivalent circuit model of the designed BPF including lossy components as well as inductive and capacitive components is also introduced in Fig. 3.

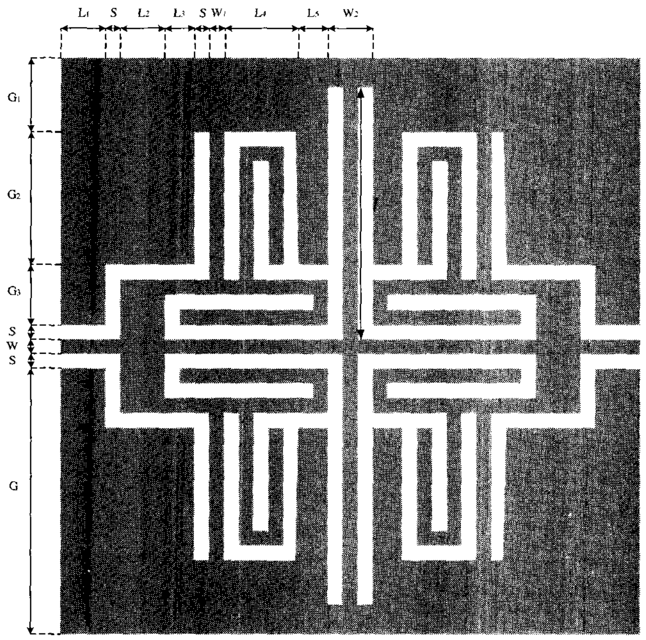


Fig. 2 Schematic top-view of proposed CBCPW BPF.

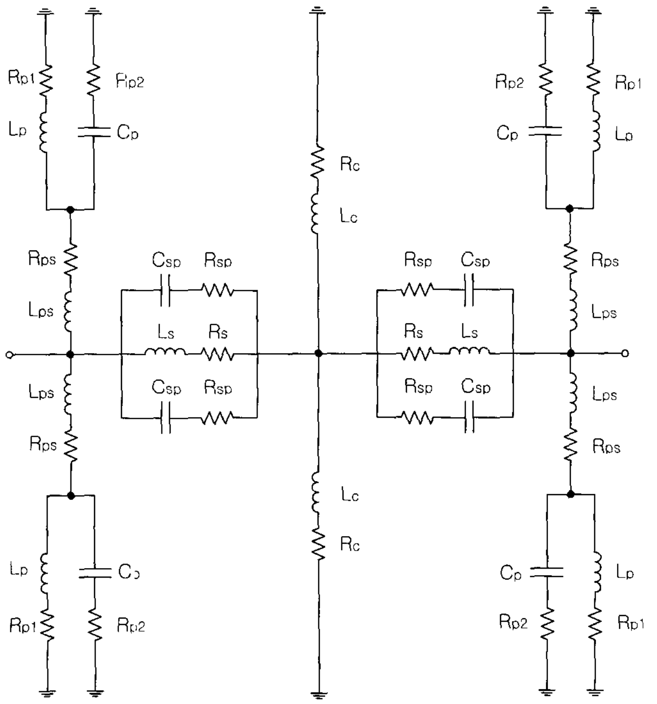


Fig. 3 Equivalent circuit of proposed CBCPW BPF (L_s = 0.22 nH, R_s = 1.7 Ω, C_{sp} = 0.42 pF, R_{sp} = 0.55 Ω, L_{ps} = 0.4 nH, R_{ps} = 1.0 Ω, L_p = 0.4 nH, R_{p1} = 0.2 Ω, C_p = 0.25 pF, R_{p2} = 1.0 Ω, L_c = 0.7 nH, R_c = 0.3 Ω).

Note that the parallel components L_p and C_p within the ground planes make resonant circuits. The L_{ps} and C_p combination introduces the upper band attenuation pole of the BPF, while the series elements of L_s and C_{sp} within the signal line contribute to the lower side attenuation pole. By varying the inductive stub length *l* having inductance value L_c in the equivalent circuit, the amount of coupling between resonators can be adjusted. In this paper, the inductive stub length is chosen as 1.625 mm for optimum response of the filter.

3. Experimental Results

For the fabrication of the proposed miniaturized BPF on the CBCPW structure, 5000 Å SiO_2 is deposited first on top of the silicon substrate, and then 200 Å Cr and 1 μm Cu layers are thermally evaporated as an underside ground plane. For improved adhesion of polyimide promoter (VM652) is applied on the metal layer and a 20 μm thick polyimide layer (Dupont PI-2611) of ε_r = 3.1 and tan δ = 0.003 is spin-coated and cured at 350°C for one hour. To form CBCPW line and BPF, positive PR (AZ 4620) is used as an electroplating mold and sacrificial layer. Finally, the sacrificial layer is removed by wet etching technique and dried in an 80°C convection oven.

For on-wafer measurement, TRL de-embedding procedure using Multical [11] software is performed by employing a vector network analyzer with G-S-G high frequency coplanar probes having a 200 μm pitch. Each calibration standards consists of a thru line of 200 μm long, two delay lines of 5200 μm and 12000 μm long, and a reflect standard with an open circuited CBCPW line.

Measured attenuation constant and effective permittivity of the designed CBCPW with G = 2.0 mm, W = S = 50 μm, L = 5.0 mm geometry are shown in Fig. 4. The measured attenuation constant at 20 GHz is below 1.2 dB/cm, which is compatible with the CPW on GaAs, while the de-embedded effective dielectric constant versus frequency is below the dielectric constant of the thin film, which validates the very low-dispersive characteristic of the proposed CBCPW transmission line.

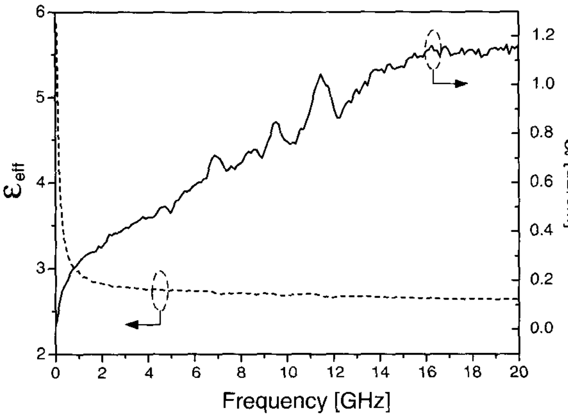


Fig. 4 Measured characteristics of the CBCPW.

Fig. 5 shows a measured frequency response of the designed CBCPW BPF as well as simulated data based on IE3D and modeled data derived from Fig. 3, which reveals excellent agreement with the predicted value having center frequency of 15.92 GHz, insertion loss of 2.4 dB and bandwidth of 23%.

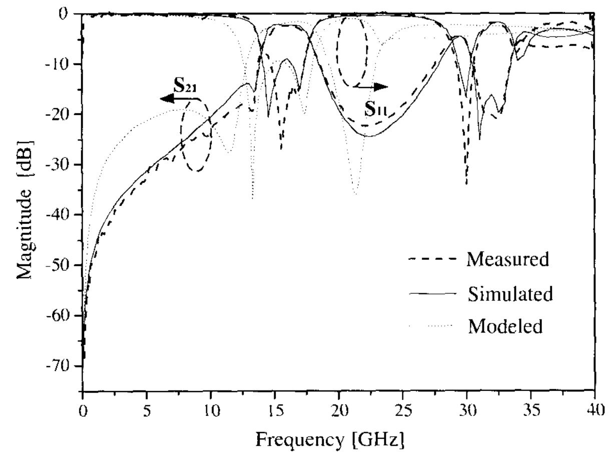


Fig. 5 Measured frequency response of the fabricated BPF.

4. Conclusion

In this paper, a miniaturized conductor-backed CPW bandpass filter based on thin film polyimide layer coated on CMOS-grade silicon is described. Proposed geometry effectively isolates the interaction of electromagnetic fields with the lossy silicon substrate by using a thin film polyimide interface layer and back metallization. By de-embedding the CBCPW using TRL calibration standards, low-dispersive property is demonstrated. Also, measured attenuation constant up to 20 GHz is below 1.2 dB/cm, which is compatible with the CPW on GaAs. Measured frequency response of the designed CBCPW BPF using bended stubs for miniaturization has excellent agreement with the simulated data having center frequency of 15.92 GHz, insertion loss of 2.4 dB and bandwidth of 23%. Proposed CBCPW geometry using CMOS-grade silicon and thin film polyimide can be applied for RFIC interconnects and filter application without exciting leaky waves up to 50 GHz.

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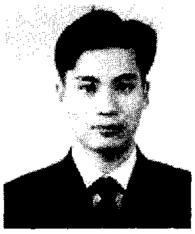

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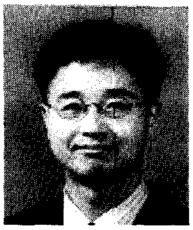

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