Microwave Coplanar Filters on Si Substrates

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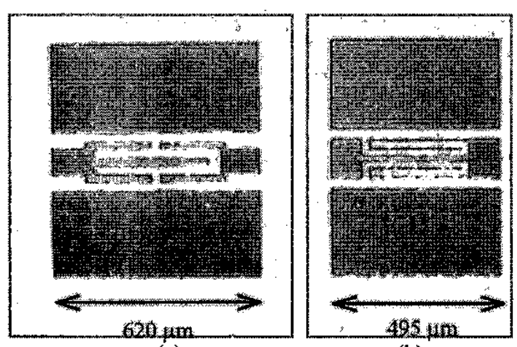
Abstract — **High performance band-pass and band-stop microwave coplanar filters operating from 22 to 94 GHz have been realized on Si substrate using proton implantation process. Very good insertion loss and filter characteristics close to ideal E-M simulation are measured that demonstrates the excellent filter performance to 91 GHz.**

I. INTRODUCTION

There is increasing interest to integrate filter with CMOS MMICs on Si substrate because of the low cost and compact system consideration. This requirement becomes even more urgent as the rapid increasing operation frequency of Si communication ICs. However, the microwave filter integrated on Si suffers poor performance from the high loss and cross-talk of the low resistivity (10 Ω-cm) Si substrate [1]-[5]. To overcome this problem, we have previously developed an ion implantation technology that can convert the conventional Si substrate (10 Ω-cm) into semi-insulating (10^6 Ω-cm) [1]-[5]. In this paper, we have further optimized the implantation process for better compatibility with VLSI process. Using this modified technology, we have achieved excellent RF performance close to E-M simulation for coplanar band-pass and band-stop filters from 22 to 91 GHz. This good result suggests that the microwave coplanar filters can be further integrated with CMOS MMICs on Si substrate.

II. EXPERIMENTAL PROCEDURE

The broadband filters were designed by IE3D using the coplanar waveguide (CPW) structure because it can be well integrated into the existing RF ICs on Si substrates without via holes. The filters have 50 Ω input impedance using the 150-μm GSG coplanar transmission line for a good RF impedance match. The picture of designed and fabricated band-pass filter is shown in Fig. 1(a), where the values of the equivalent capacitance and inductance depend on the gap spacing between couple lines and the width of the central line. We have utilized coupled line with coplanar structures to form series resonators, and the total length of the filter is about λ/2 with each stub finger width of 25 μm. Fig. 1(b) shows the photograph of band-stop filter. The width of the central conductor is 20 μm, and each stub width is 10 μm with gap of 15 μm. The band-stop filter designed here is a folded short-end stub form [6], which reduces the filter size from $\lambda_g/4$ to $\lambda_g/8$ by folding stubs and slots in the filter structure.



(a) (b)

Fig. 1. The photographs of fabricated (a) band-pass and (b) band-stop filters designed at 94 and 53 GHz, respectively. The respective band-pass and band-stop filters at 40 and 22 GHz are also designed and studied.

Then the filters were fabricated using 4-μm thick Al metal layer and patterning on conventional Si substrates with additional top 1.5-μm isolation SiO_2. The proton implantation is improved from previous process [1]-[5], which is applied after the whole device fabrication with implantation energy of ~ 4 MeV. This can ensure no contamination to the VLSI process line and can be masked by commercial available thick photoresist easily. The fabricated filters were characterized using HP 8510C Network Analyzer and a probe station up to 110 GHz without any de-embedding procedure.

III. RESULTS AND DISCUSSION

A. Band-pass Filter

We have first measured the RF performance of transmission line using the optimized proton implantation. Fig. 2 shows the measured power loss of 1000 μm-long CPW transmission lines with or without proton implantation. It is observed that the optimized proton implantation not only significantly improves the high loss from Si substrate but also keeps a low loss level, less than 0.6 dB, up to 110 GHz. The good loss performance indicates that the modified proton implantation process can be further used for microwave filters integrated on Si.

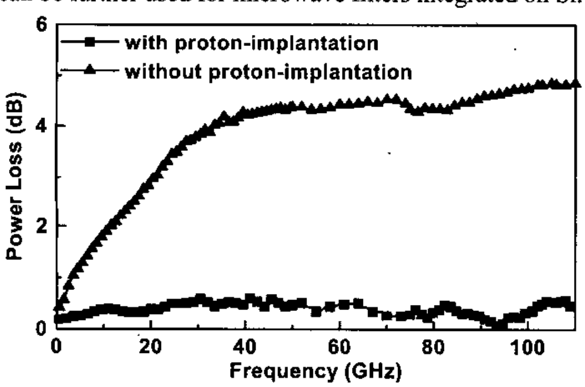


Fig. 2. Measured power loss for 1 mm-long CPW transmission lines fabricated on 1.5-μm SiO_2/Si substrates with or without proton implantation.

Figs. 2(a) and 2(b) present the RF characteristics of 40 GHz band-pass filters on conventional SiO_2 isolated Si substrates, with and without the optimized proton implantation respectively. At the peak transmission of 40 GHz, the filter with proton-implantation exhibits a S_{21} of -3.4 dB that is much better than the large -10 dB loss for filter Si without proton implantation. This 7 dB difference of peak transmission is equivalent to gain improvement by two technology generations of MOEFET scaling [7]. In addition, the large return loss for filter without proton implantation prohibits this filter useful in RF ICs.

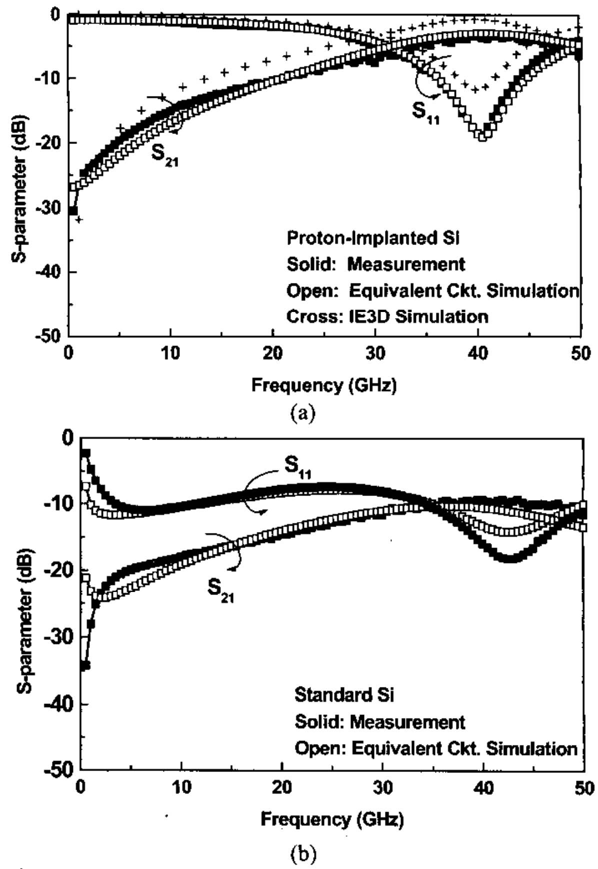
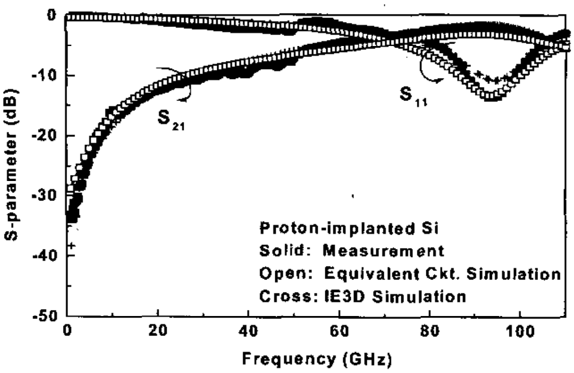
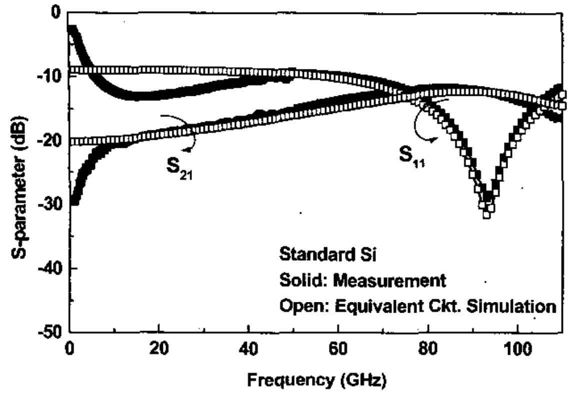


Fig. 3. Measured and equivalent-circuit simulated 40 GHz band-pass filter characteristics on 1.5-μm SiO_2/Si substrates (a) with and (b) without proton implantation. The IE3D simulated characteristics are also shown in (a).

We have also designed a 94 GHz coplanar filter using the topology in Fig. 1(a) with reduced filter length of 620 μm than the 40 GHz devices. Measured and simulated RF characteristics for this filter are shown in Figs. 4(a) and 4(b), with and without the optimized proton implantation respectively. The simulations from both IE3D and the equivalent circuit model are plotted for comparison. For the filter with proton implantation, .excellent RF performance is achieved with only −1.6 dB S_{21} loss at peak transmission of 91 GHz. The measured transmission and bandwidth are close to those of the ideal filter designed by IE3D, which is the first demonstration of high performance filter at W band on Si substrates with process compatible to current VLSI technology. In contrast, much poorer peak transmission of -12 dB is measured for the same filter without implantation. The large return loss also makes this filter failed for circuit applications.



(a)



(b)

Fig. 4. Measured and equivalent-circuit simulated characteristics on broadband band-pass filter at 94 GHz on 1.5-μm SiO_2/Si substrates (a) with and (b) without proton implantation. The ideal IE3D simulated characteristics are also shown in (a).

We have further used the equivalent circuit model to analyze the substrate loss effects of the band-pass filter. Fig. 5 shows the equivalent circuit model. The series LC represents the resonator realized by the coupling lines, while the shunt resistor and capacitor to ground are used to model the Si substrate loss. The series R is the signal loss by parasitic resistor and the R_1 expresses the RF loss between couple structures. Good agreement between measured and simulated S_{21}, S_{11}, and bandwidth shown in Figs. 3 and 4 is obtained at all frequencies in both cases that suggests the excellent accuracy of these models. The extracted R_s for filter on conventional Si without the implantation is only 200 Ω, which is increased by ~two orders of magnitude to 10,000 Ω for the same filter implanted with proton. Therefore, the poor peak transmission and large return loss for filters without implantation are due to the small impedance shunt pass to ground, which is typical but fatal for RF devices on the lossy Si substrate.

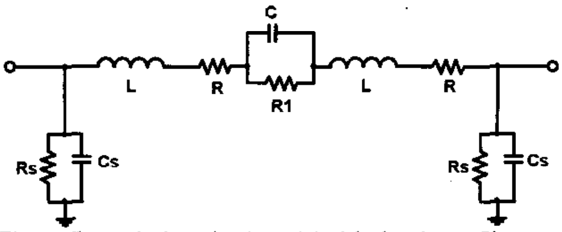
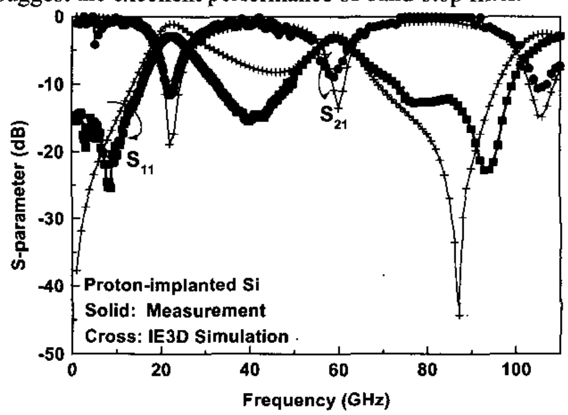


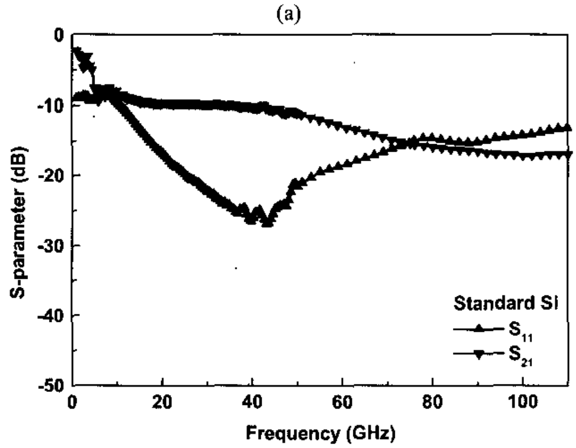
Fig. 5. The equivalent circuit model of the band-pass filter.

B. Band-stop Filter

Figs. 6 (a) and 6(b) show the measured and simulated results for 22 GHz band-stop filters on Si substrates, applied with and without the proton implantation respectively. Very low transmission loss, only -1.3 and -0.5 dB at respective 40 and 80 GHz, are measured on band-stop filters with proton implantation. Band stop at 22, 59 and 105 GHz are measured that is due to the odd (1, 3 and 5) harmonics of the filter. The combined results suggest the excellent performance of band-stop filter.



(a)



(b)

Fig. 6. Measured and simulated characteristics of band-stop filters at 22 GHz on 1.5-μm SiO_2/Si substrates (a) with and (b) without proton implantation.

In sharp contrast, very large transmission loss of -10 dB at 40 GHz is measured for the same filter without implantation, and becomes even worse to -15 dB at 80 GHz. The poor performance of transmission and return loss obviously limits the band-stop filter application on standard SiO_2/Si substrates.

Figs. 7(a) and 7(b) are the characteristics of 50 GHz band-stop filter using the folded single-end stub shown in Fig. 1(b), applied with and without proton-implantation respectively. At the pass band <40 GHz and >70 GHz, the transmission loss is smaller than 1 dB. The very low transmission loss over the broad microwave frequency range and filtering at 52 GHz indicate the excellent stop-band filter performance with proton implantation. Again, the stop-band filter on standard Si without implantation is completely failed due to the large loss from the substrate.

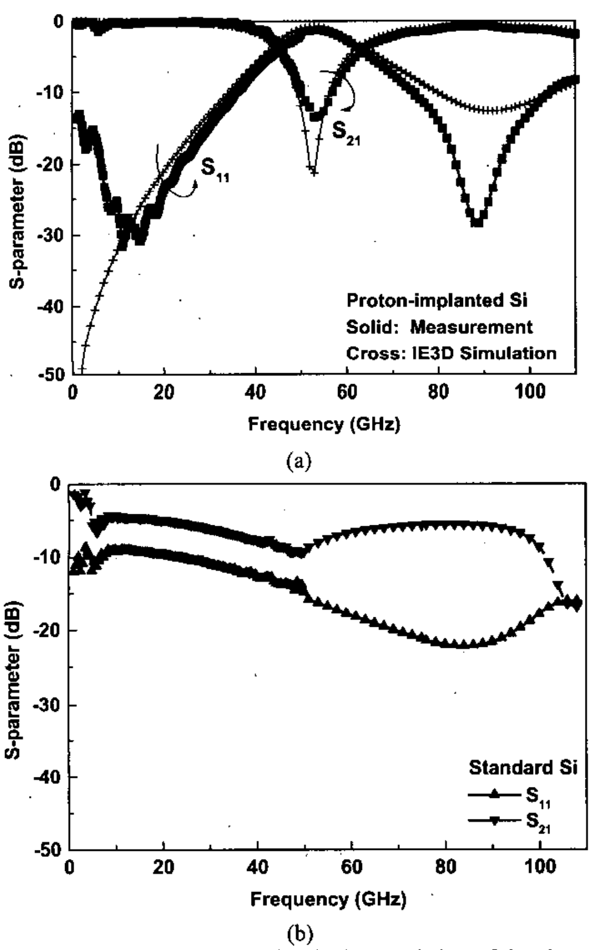


Fig. 7. Measured and simulated characteristics of band-stop filters at ~50 GHz on 1.5-μm SiO_2/Si substrates (a) with and (b) without proton implantation.

IV. CONCLUSION

We have achieved excellent RF performance for both band-pass and band-stop microwave coplanar filters at 22~94 GHz on Si substrates using an optimized proton implantation process. In contrast, much poor filter characteristics are measured or completely failed for filter devices without implantation. These results show high possibility to integrate microwave filters into MMICs on Si using the VLSI technology compatible proton implantation.

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