40-GHz Coplanar Waveguide Bandpass Filters on Silicon Substrate

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***Abstract*—We report a very simple process to fabricate high performance filter on Si at 40 GHz using proton implantation. The filter has only −3.4-dB loss at peak transmission of 40 GHz with a broad 9-GHz bandwidth. In sharp contrast, the filter on 1.5-μm SiO_2 isolated Si has much worse transmission and reflection loss. This is the first demonstration of high performance filter at millimeter-wave regime on Si with process compatible to current VLSI technology.**

I. Introduction

SMALL SIZE and light weight are the two requirements for the bandpass filters [1] used in portable communication. Combining compact filters with Si VLSI technology, we can achieve high integrity and low cost for the commercial demands. However, the performance of integrated circuits on Si wafers is very poor at microwave frequencies due to the high loss coming from the low resistivity (10 Ω cm) of the substrate [2]–[7]. One of the most common solutions is to utilize VLSI backend dielectric layers on top of Si substrate to reduce the lossy effect. However, large loss from Si substrate is still unavoidable because of the limited oxide thickness provided by current VLSI technology. Other approaches are to use porous Si fabricated by anodic etching [8] or MEMS technology [9], but these nonconventional VLSI processes require further process integration and package considerations. Recently, we have developed a selectively formed ion implantation process [2]–[7] that can transfer the standard 10 Ω-cm Si substrate into a high resistivity of 10^6Ω cm and close to insulating GaAs. Good reliability is evidenced from the negligible resistivity degradation even after 400 °C annealing for 1 h [4], [5]. In this paper, we have successfully implemented a 40-GHz coplanar bandpass filter on proton-implanted Si with process compatible to current VLSI technology [3], [5]. Good filter characteristics are evidenced from the −3.4 dB transmission at 40 GHz, while the filter on conventional Si with 1.5-μm isolated oxide has a large transmission and return loss that is failed for circuit application.

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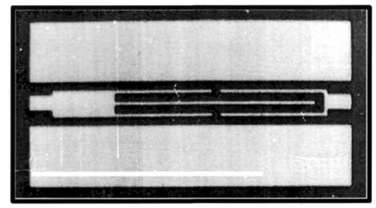

1000 µm

Fig. 1. Photograph of the fabricated broad-band filter on Si designed at 40 GHz.

II. Experimental Procedure

We have used the coplanar waveguide (CPW) structures because of its simple process without via holes and capability to be integrated with active devices. The bandpass filter of this work is shown in Fig. 1, 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 [1], and the total length of the filter is about $\lambda/2$ and the width of each stub finger is 20 μm. The filters were designed by IE3D with 50-Ω input impedance. The configuration of the coplanar transmission feed line is 150-μm GSG probe and is adjusted to achieve a good RF impedance match. Then the filters were fabricated on proton-implanted Si or conventional Si with additional 1.5-μm-thick top oxide. After depositing a 4-μm-thick aluminum (Al) layer and patterning, filter characteristics were measured using HP 8510C Network Analyzer and a probe station up to 50 GHz without any de-embedding procedure.

III. Results and Discussions

Fig. 2(a) and (b) presents the RF characteristics of filters on proton-implanted Si and conventional oxide isolated Si. For filter on proton-implanted Si, excellent RF performance is achieved with only −3.4-dB S_{21} loss at peak transmission of 40 GHz and a broad 9-GHz bandwidth. The measured transmission and bandwidth is close to the ideal filter designed by IE3D, which is the first demonstration of high performance filter at mm-wave regime on Si with process compatible to current VLSI technology [3], [5]. The slightly 3-dB lower S_{21} than the ideal case that may be due to the RF loss by skin effect or slight input impedance mismatch. In contrast, the filter on conventional Si shows much worse S_{21} transmission loss of −10 dB at center frequency, which is 7-dB less than proton-implanted Si. This extra 7 dB loss in S_{21} is equivalent to the gain improvement by two generations of MOEFET scaling [6]. The poor S_{11} return loss also prohibits its usability

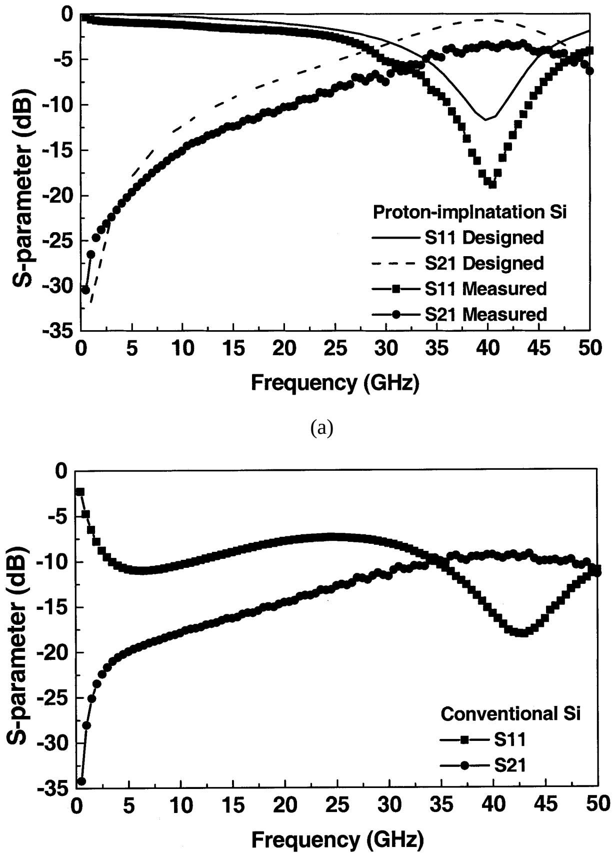

Fig. 2. (a) Designed and measured filter characteristics on proton-implanted Si and (b) measured s-parameters on conventional Si with additional 1.5-μm oxide isolation.

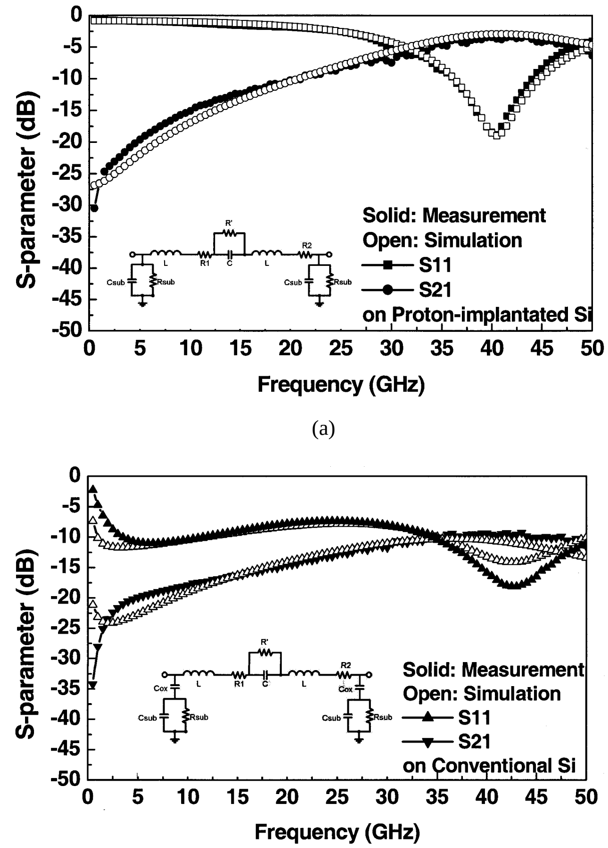

Fig. 3. The simulated results and measured filter characteristics on (a) proton-implanted Si and on (b) the conventional Si substrate with additional 1.5-μm oxide isolation.

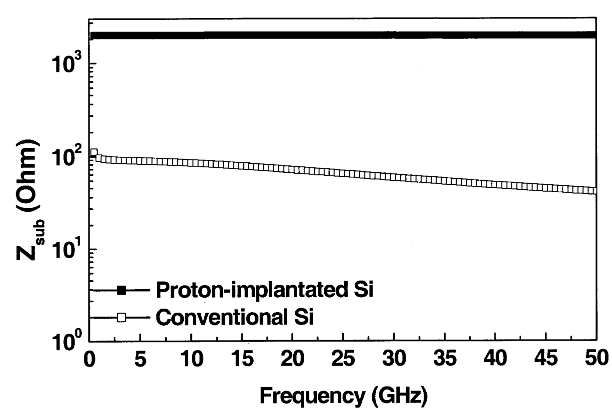

Fig. 4. Extracted shunt impedance for filters with proton-implantation and conventional Si substrate with additional 1.5-μm oxide isolation.

for connecting to RF circuit or dual band application at both 20 and 40 GHz. The small difference of resonant frequencies between filters on two substrates may be due to the slightly different dielectric constants as Si is implanted by proton.

We have further used the equivalent circuit model to analyze the substrate lossy effects of RF filters. Fig. 3(a) and (b) is the simulated frequency responses of the fabricated filters on both substrates, respectively. The equivalent circuit models are also inserted in each respective figure. The series LC in models indicates the resonator realized by the coupling lines, while the shunt resistor and capacitor to ground are used to model the substrate loss. The oxide capacitors are included at standard Si case to model the top 1.5-μm oxide layer [10]. To consider the signal loss between two coupling lines, a resistor R' is also added to shunt with series C between two ports. The series resistor between two ports is used to simulate the skin effect of the 4-μm-thick Al line. Good agreement between measured and simulated S_{21}, S_{11}, and bandwidth, shown in Fig. 3(a) and (b), are obtained at all frequencies in both cases that suggest the excellent accuracy of these models and can be used for the further parameter extraction [3], [6].

The extracted substrate shunt impedance from the matched models is shown in Fig. 4. The shunt impedance of conventional Si with top 1.5-μm-thick oxide decreases as increasing frequencies, and at 50 GHz reaches 1/3 of its original value at 1 GHz. In sharp contrast, the filter substrate shunt impedance on proton-implanted Si is improved by $>$ one order of magnitude with a flat shunt impedance curve with negligible frequency dependence. These results indicate its low loss performance and explain the good RF performance of filter on proton-implanted Si.

IV. Conclusion

We have developed a very simple process to fabricate high performance RF filter on Si up to 40 GHz by proton implantation. The filter on proton-implanted Si has only -3.4-dB loss at peak transmission of 40 GHz with a 9-GHz bandwidth, while the filter on 1.5-μm SiO_2 isolated Si has much worse transmission and reflection loss. The large improvement is due to the much larger resistivity of Si substrate after implantation, which is extracted from the equivalent circuit. Therefore, the proton-implanted Si shows a great potential for compact, low loss, and low-cost passive circuits in the future applications at high frequencies.

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