Microstrip Circuits on Micromachined Silicon

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Abstract — **Fully monolithic integration of a millimeter wave system on silicon requires low loss passive circuitry. Transmission line elements are needed to interconnect active devices and to realize distributed passive components. Using bulk micromachining and high resistivity silicon on insulator (SOI) wafers, well defined thin silicon membranes can be manufactured. This allows the use of microstrip circuits on silicon substrate at frequencies beyond 100 GHz. Full wave simulation results accompanied by measurements are presented for coplanar to microstrip transitions, microstrip lines and two simple test circuits.**

I. Introduction

In recent years, radar sensors for distance and speed measurement have become attractive to a wide range of industrial and automotive applications [1]. However, cost and size constraints impede the use of such sensors in large numbers or for more price conscious applications. Reducing size and cost simultaneously can be achieved by monolithically integrating the radar sensor. Increasing the operation frequency further reduces the size, resonant circuit lengths get well below one millimeter on silicon for frequencies above 100 GHz.

Ideally, for an integrated solution, all millimeter wave signals remain on the integrated circuit or are radiated. No external millimeter wave signal connection is necessary. This requires the realization of components like oscillators, mixers, filters, signal distribution and antenna elements directly on chip.

Coplanar waveguide transmission lines are frequently used for monolithic integration on silicon [1]. However, with increasing frequency the inner conductor width and gap size have to be decreased, in order to avoid excitation of higher modes. Also the coupling of modes into the electrically thick wafer has been observed. Finally air bridges are necessary to suppress slot modes at discontinuities.

The use of microstrip transmission lines can eliminate these drawbacks. To achieve good performance, the substrate thickness for a microstrip transmission line has to be less than one tenth of the wavelength inside the substrate. Therefore, a silicon membrane thickness of less than 100 µm for applications above 100 GHz is required. To study the feasibility of such an approach, millimeter wave microstrip circuits on high resistivity silicon have been simulated, manufactured and measured.

II. Micromachining Technology

A small substrate thickness of 100 µm, or even below, can be achieved by mechanically thinning the wafer. This is often done in GaAs technology microwave circuits. However, this approach leads to very fragile wafers, where handling and mounting of the devices gets very difficult. The proposed alternative is the thinning of only a small specified area of the wafer by micromachining, where the microstrip circuitry is to be placed. Figure 1 shows a schematic cross section view of such a micromachined wafer. Only below the microstrip circuit element, the backside of the wafer is thinned.

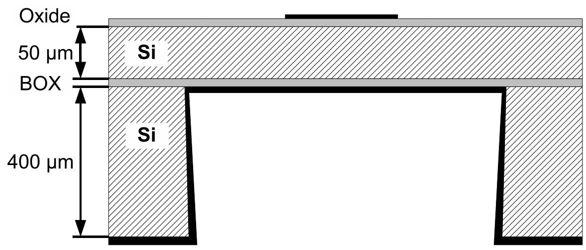

Fig. 1: Schematic cross section view of a micromachined wafer with additional backside metallization

The SOI wafer used for micromachining has a thickness of 450 µm. The top and bottom silicon layers are separated by a thin intermediate oxide layer. An additional top oxide layer has been added as an option. The conductive circuit elements on top are made of 1 µm thick aluminum.

Because of the wafer manufacturing process, the upper silicon layer can be specified having a thickness of 50 µm with only a few microns tolerance, typically less than 10 percent. This is critical for obtaining reliable high frequency characteristics, when mass producing monolithically integrated microstrip components.

Backside micromachining is performed utilizing the so called *Bosch Process*, a high performance anisotropic plasma etch process [2]. The thin silicon oxide layer in between the two silicon layers acts as an etch stop, so in the etching step only the the bottom silicon layer will be removed. After the etching, the wafer backside is metallized by sputtering an aluminum layer with a thickness of a few microns. The metallization will be used as ground for the microstrip elements.

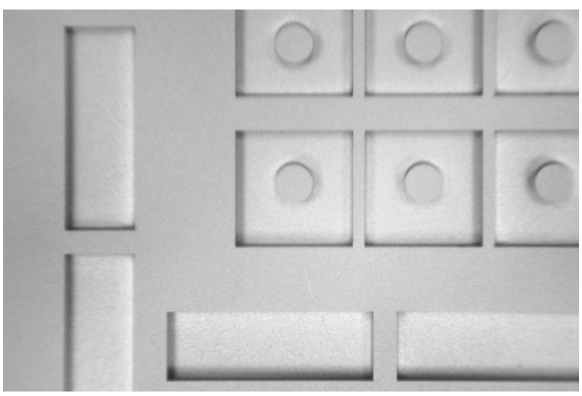

Fig. 2: Backside photograph showing micromachined areas of the wafer

Figure 2 shows the backside view photograph of such a micromachined wafer. Several rectangular areas which have been micromachined can be seen. On the top side of the wafer, microstrip circuits have been placed on these areas.

III. Contacting

Measuring microstrip components manufactured as described above, requires contacting using an onwafer probe tip. Millimeter wave probe tips are usually coplanar type, as shown in figure 3. For the measurements in the F band (90-140 GHz), we used a GGB probe with 50 µm pitch between the tips.

As the process offers no ground vias to the backside, an electromagnetically coupled coplanar waveguide to microstrip transition is needed. Several possible transitions have been investigated by others [3]. In our approach, we simply continue with the inner conductor and virtually short circuit the coplanar ground lines at the beginning of the micromachined area.

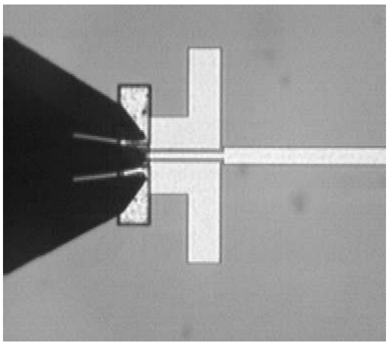

Fig. 3: Photograph of a coplanar onwafer probe tip contacting a coplanar transmission line leading to the microstrip transition

Figure 4 shows a transition for a center frequency of 24 GHz. The virtual short circuit for the coplanar ground lines is realized using a high impedance line over the thick silicon area as an inductor and a large pad over the micromachined area forming a conductor. Together they act as a series resonant circuit, shorting the ground lines.

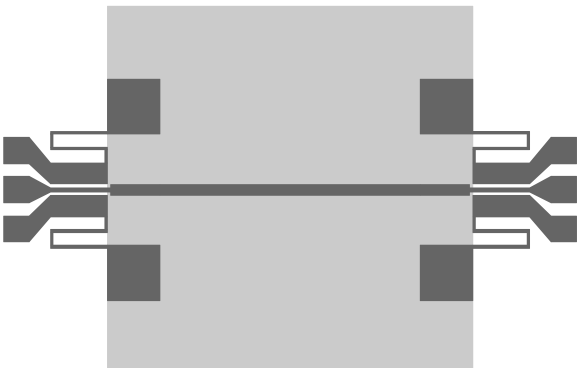

Fig. 4: Coplanar to microstrip transition designed for an operation frequency of 24 GHz

The simulated and measured frequency response of the 24 GHz transition is shown in figure 5. The match is better than 20 dB with an insertion loss of less than 1.5 dB for two consecutive transitions. The insertion loss of a single transition can be computed by taking into account only one transition and additionally removing the line losses between the two transitions. This yields an insertion loss of about 0.6 dB for a single transition.

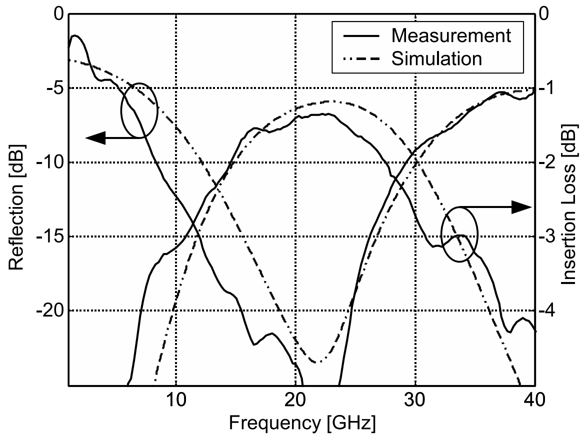

Fig. 5: Measured and simulated frequency response of the double coplanar to microstrip transition from figure 4

For a coplanar to microstrip transition in the F band (90-140 GHz), a design using a simple open stub is sufficient to provide the virtual ground connection. This is shown in figure 6.

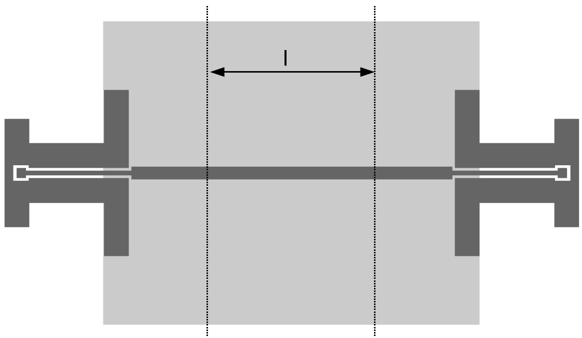

Fig. 6: Coplanar to microstrip transition designed for an operation frequency range of 90-140 GHz

The measured performance in figure 7 shows an insertion loss of less than 1.5 dB and a reflection coefficient better than 14 dB over the complete frequency range from 90-140 GHz. Computing the insertion loss for only a single transition gives a value of less than 0.7 dB.

IV. Calibration

When measuring microstrip components, the coplanar to microstrip transitions may not influence the measurements. Therefore, we used *TRL* calibration [4], where only a through line, an offset through line and an arbitrary reflection standard are needed. The through and offset through line are simply made of two microstrip lines with different length, an open ended microstrip line is used as reflection standard. The reference plane after *TRL* calibration can be seen in figure 6, in between these planes microstrip circuits

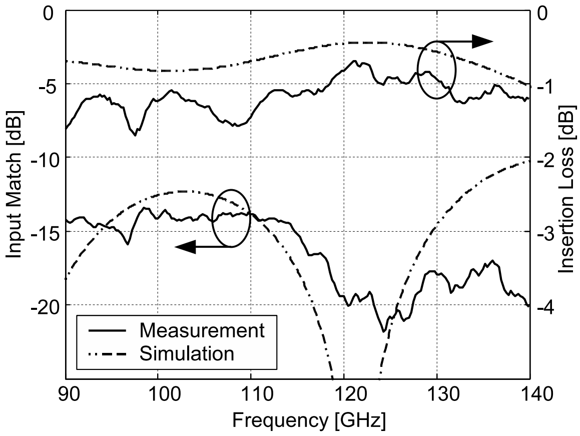

Fig. 7: Measured and simulated frequency response of the double coplanar to microstrip transition from figure 6

can be placed and measured, in case of figure 6 a microstrip line with a length of l.

V. Transmission Lines

As basic element, microstrip transmission lines with different lengths have been manufactured and their attenuation has been measured. A line width of 45 µm has been used, giving a characteristic line impedance of $50\,\Omega$.

For reference, the transmission lines have also been simulated using the time domain full wave simulator Microwave Studio. The results for the line losses are shown in figure 8.

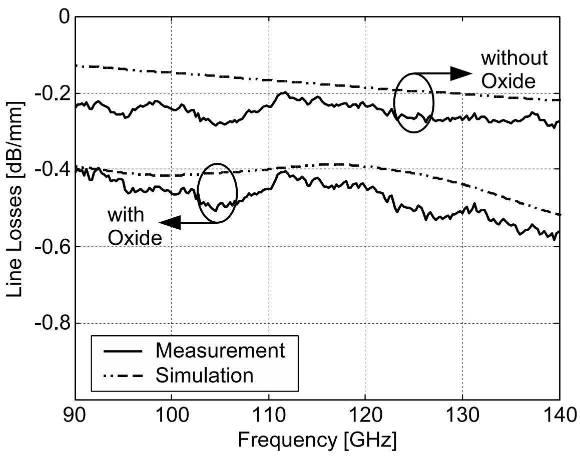

Fig. 8: Losses for a simple microstrip transmission line

Two variants of microstrip lines have been manufactured. One variant does not have the top oxide layer between the silicon and the top aluminum conductor, as shown in figure 1. The second variant is manufactured with a 500 nm thick thermal oxide layer. From the measurements, a significant difference in the line losses of about 0.2 dB/mm can be seen. This difference is most likely due to free surface charges accumulating at the interface between silicon and oxide. Similar findings have been reported in [5]. In our simulation models, we simply added a loss tangent to the oxide layer, to account for the observed losses. The losses are consistent with measurements we have made, using coplanar transmission lines on the same silicon substrate.

VI. Circuits

A large number of basic microstrip elements like bends, steps, tees, stubs and some more complicated circuits like filters, couplers and antennas were manufactured. Those elements were used to verify our computer simulation models. They allowed the creation of a microstrip design element library using the readily available commercial software ADS and its advanced model composer.

Two circuits will be presented below, they were manufactured and measured as described above, the simulation results were obtained using Agilent Momentum.

The first element is a simple meander line, shown in figure 9, that exhibits some coupling between it's adjacent lines. The length of the lines is 500 µm with a distance of 180 µm.

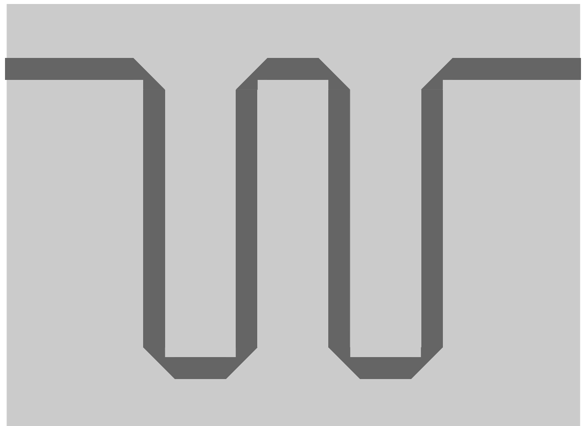

Fig. 9: Layout of a microstrip meander line

The frequency response shows two resonances for the input match at about 105 GHz and 115 GHz. The transmission losses increase above 120 GHz. There is a very good agreement between measurement and the simulation results, as shown in figure 10.

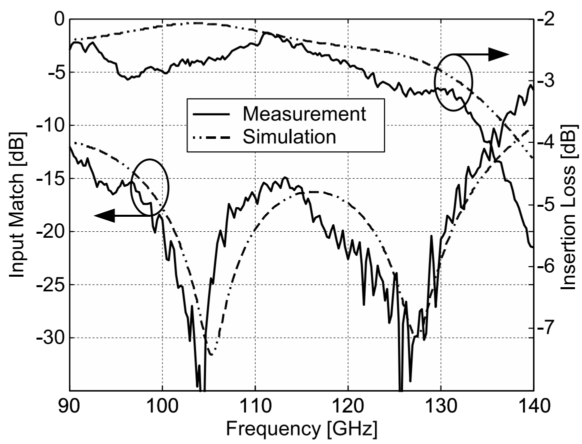

Fig. 10: Simulated and measured microstrip meander line performance

As second example, a side-coupled microstrip-bandpass-filter is discussed. It is designed as a single-pole Tchebychev filter with a center frequency of 122 GHz, a bandwidth of 3 GHz and a ripple of 0.1 dB. The design was performed using a commercial microstrip filter design tool [6]. Optimization was necessary, as first results deviated from the desired behavior. This was due to the neglect of fringing effects in the design process. Figure 11 shows the layout of the single-pole filter, the resonator line is 434 µm long.

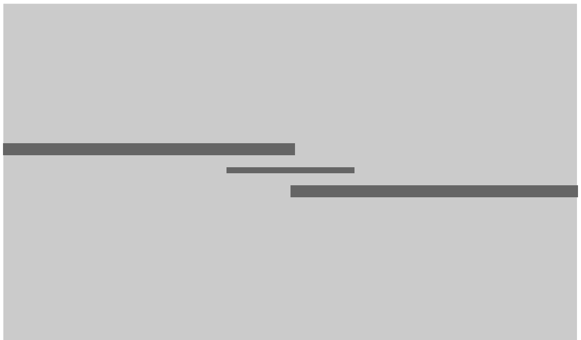

Fig. 11: Layout of the single-pole microstrip filter

A very good agreement between measurement and the simulation can be seen.

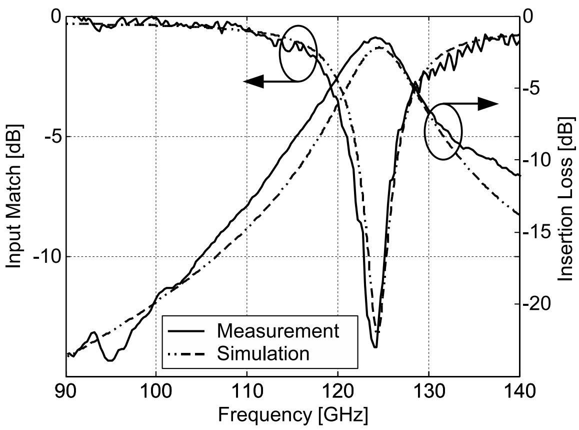

Fig. 12: Response of the microstrip filter

VII. Conclusion

Microstrip millimeter wave circuit elements on micro-machined, high resistivity silicon substrate have been investigated. Measurements up to 140 GHz show the good performance of microstrip transmission lines and permit their application in future monolithically integrated millimeter wave radar sensors.

VIII. Acknowledgments

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