OPTIMIZATION OF A CAPACITIVE MEMS POWER SENSOR FOR RADIO FREQUENCY APPLICATIONS

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Abstract — A novel, so called 'through', power sensor for radio frequency (rf) signals, based on capacitive measurements, was presented at MME 2003. We showed the design, fabrication and preliminary measurements. Here we describe further characterization and improvements on the design and fabrication with focus on increase of stability, resolution and bandwidth of the sensor.

Key Words: radio frequency, power sensor, capacitive readout

I INTRODUCTION

The available technology for power detection of rf signals is based on thermistors, thermocouples and diodes. All these are terminating devices, i.e. the signal is dissipated and therefore lost during the power measurement. At the MME conference 2003, a novel rf power sensor where the signal is not consumed but almost completely transmitted was presented [1]. It is based on the detection of the movement of a grounded membrane suspended above a coplanar transmission line (CPW) where the signal is traveling (see Figure 1).

Figure 1. Drawing of the top and cross section view of the sensor.

Due to the difference in voltage between the signal line and the membrane, an electrical force will appear between the capacitor plates, resulting in a displacement of the membrane. The movement is detected as a capacitance change between a measuring electrode and the movable plate, and the power of the signal can then be deduced.

The fabrication was done with surface micromachining [1] using special glass substrates for rf applications (AF45) [2]. The CPW was fabricated by sputtering a 1 μm thick layer of aluminum. Then a 1.7 μm thick sacrificial layer of photoresist was deposited, and a second 1 μm thick layer of aluminum was sputtered to create the membrane, which forms the capacitive sensor. SEM pictures of the devices are presented in Figures 2 and 3.

Figure 2. SEM picture of the sensor (top view).

Figure 3. SEM picture of the sensor (close up).
S-parameters characterization of the rf power sensor, as well as preliminary measurements using dc and rf signals were reported [1]. In this paper, we propose a number of improvements in order to arrive at an rf power sensor with significantly better performance.

II SENSOR MEASUREMENTS AND IMPROVEMENTS

II.1 IMPROVEMENT OF THE MEMBRANE FLATNESS

As can be seen in Figure 3, the shape of the CPW electrodes gives a curvature of the membrane. The sacrificial photoresist layer does not completely planarize the substrate and the shape of the CPW is still visible in the membrane. In combination with a temperature dependent, tensile residual stress this causes an unwanted deflection of the membrane. Furthermore, the membrane could touch the edge of the CPW electrodes. Changing the fabrication process as shown in Figure 4 can reduce the problem significantly.

![Figure 4. Schematic of the fabrication process.](image)

As a first step, photoresist is deposited and patterned, this is used as a mask for etching of the substrate, creating cavities where the CPW lines are going to be located. Aluminum is then deposited filling the cavities. By removing the photoresist, a lift-off technique is used for the patterning of the CPW lines. In this way, a thin polymer can be used as sacrificial layer ending with much flatter surfaces. As a last step, an layer of aluminum is deposited and patterned in order to create the sensing membrane.

II.2 IMPROVEMENT OF THE TRANSMISSION LOSSES

For the characterization of the rf response of the power sensor, measurements of S-parameters were done [1]. Transmission losses were reported to be 0.04 dB/mm when a 3 μm thick aluminum layer is used for the fabrication of the CPW [1], [3]. Due to difficulties in the etching of the AF45, no thicker layers than 1 μm could be easily achieved, which could introduce higher transmission losses than expected. Nevertheless, CPW length of 1 mm is sufficient for the fabrication of the sensor. Simulations done with Sonnet confirm that losses in the order of 0.05 dB can be achieved even with a 1 μm thick CPW.

II.3 IMPROVEMENT OF THE REFLECTION LOSSES

A good agreement between theory and experiments was reported in the reflection parameter; therefore, any $S_{11}$ response can be achieved (always above of the CPW limitation) by using the correct capacitance value. The final goal for reflection characteristics of the sensor is to obtain reflection losses lower than ~26 dB at 4 GHz. In order to reach this value, no higher capacitance values than 80 fF can be introduced to a standard transmission line. This small capacitance value limits the resolution of the sensor, since measuring capacitance changes on such a small capacitor is very difficult to do with high resolution. In order to solve this problem, two different approaches are presented.

The first approach is illustrated by Figure 5, where the capacitance to the measuring electrodes is increased, without affecting the capacitance to the central line of the CPW. In this way, a much larger sensing capacitor (in the order of 1 pF) is used for
the detection of the displacement, while keeping the capacitance to the CPW at 80 fF. As a second approach, a redesign of the sensor circuit dimensions is proposed. Whereas theory predicts that reflection losses below -26 dB up to 4 GHz can only be achieved for capacitor values below 80 fF, simulations done with Sonnet show that much better results can be obtained by numerical optimization of the dimensions of the sensor. Figure 6 shows the S-parameter characteristics of an optimized sensor design together with the theoretical performance when only the added capacitance of 80 fF to ground is considered. Clearly, the reflection losses are much lower for the optimized design. In this case the improved performance is reached by simply enlarging the area in the ground lines where the sensing electrodes are located (see Figure 1). In the optimal situation this area starts 280 μm before the sensor membrane and has a width of 150 μm. Further optimization involving more design parameters could result in an even better performance.

From Figure 6 we clearly see the significant reduction of the reflection losses due to the optimization, allowing the use of higher capacitance values than theoretically predicted to stay within certain reflection losses, or to increase the bandwidth of the sensor for a certain value of capacitance.

II.4 IMPROVEMENT OF MEASURING READOUT

Movement detection of the membrane measured capacitively was reported when a dc voltage was applied between the central line of the CPW and the membrane [1]. The capacitance detection needed for this configuration was difficult due to the fact that the membrane was grounded, resulting in high parasitic capacitances added to the measuring capacitor. In the new design, a floating membrane is created, which allows elimination of parasitic capacitance and provides a much more accurate capacitance measurement. We expect to gain a factor of 10 in the power resolution due to this change. The rf voltage level on the floating membrane can be kept very small by designing a sufficiently large overlapping area with the ground lines.

Figure 5. Reshape of the membrane design in order to increase capacitance measuring electrodes without affecting the capacitance introduce to the CPW.

![Graph showing reflection losses improvement](image)

Figure 6. Improvement of the reflection losses by optimization of the sensor dimensions.

II.5 IMPROVEMENT OF TEMPERATURE DEPENDENCE

A temperature dependent effect in the sensor was found which was due to the difference in the thermal expansion coefficient of the substrate material (5.4 × 10⁻⁶ /K) and the aluminum used for the fabrication of the membrane (22.6 × 10⁻⁶ /K). Furthermore, a temperature difference between the membrane and the substrate can easily arise due to self-heating of the sensor due to ohmic losses. The latter was demonstrated by feeding a current through the CPW, which indeed resulted in a capacitance change.
In the new generation of sensors, the membrane is suspended by meander shaped springs, as indicated in Figure 7. With such a suspension the membrane can freely shrink or expand with respect to the substrate, thus eliminating the temperature effect. In parallel we are studying the use of other materials with an expansion coefficient more close to that of the glass substrate (4.5 $10^6$/K), like molybdenum (4.8 $10^6$/K) or tungsten (4.3 $10^6$/K).

![Figure 7. Meander shape springs created to absorb deformation of the membrane caused by temperature dependence.](image)

II.6 IMPROVEMENT OF SENSITIVITY

The power resolution of the rf sensor was also limited by the spring constant values as a result of the two sided supported configuration. With the new spring design mentioned in the previous section, we expect to reduce the spring constant of the sensor by a factor of 100 [4], [5], giving an improvement of the sensitivity and resolution by the same factor.

III CONCLUSIONS

In this paper we have presented and discussed the possible improvements that should result in a significantly better performance of a capacitive rf power sensor. We expect to increase the linearity of the sensor by creating flatter membranes, to reduce the transmission losses by designing a shorter CPW, to improve the reflection characteristics by numerical optimization of the sensor dimensions, to increase the sensitivity by changing from grounded to floating capacitor measurement, to reduce significantly the temperature dependence and to increase the resolution by introducing meander-shaped springs. In this way, we expect to create a power sensor with power resolution in the order of microwatts, with transmission losses lower than −0.1 dB and reflection losses lower than −26 dB (up to 4 GHz).

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