Vol. 30, No. 5 Journal of Semiconductors May 2009

A capacitive membrane MEMS microwave power sensor in the X-band based on GaAs MMIC technology*

Su Shi(苏适) and Liao Xiaoping(廖小平)†

(Key Laboratory of MEMS of Ministry of Education, Southeast University, Nanjing 210096, China)

Abstract: This paper presents the modeling, fabrication, and measurement of a capacitive membrane MEMS microwave power sensor. The sensor measures microwave power coupled from coplanar waveguide (CPW) transmission lines by a MEMS membrane and then converts it into a DC voltage output by using thermopiles. Since the fabrication process is fully compatible with the GaAs monolithic microwave integrated circuit (MMIC) process, this sensor could be conveniently embedded into MMIC. From the measured DC voltage output and S-parameters, the average sensitivity in the X-band is 225.43 μV/mW, while the reflection loss is below –14 dB. The MEMS microwave power sensor has good linearity with a voltage standing wave ration of less than 1.513 in the whole X-band. In addition, the measurements using amplitude modulation signals prove that the modulation index directly influences the output DC voltage.

Key words: MEMS; microwave; power sensor; GaAs MMIC technology; power handling

DOI: 10.1088/1674-4926/30/5/054004 **EEACC:** 2575; 8460

1. Introduction

Microwave power detection plays an important role in millimeter wave wireless applications and measurement technology in modern personal communication systems, radars, and wide-band tracking receivers. The MEMS technique has an excellent microwave sensing characteristic and a lower power consumption[1]. Traditional methods for measuring microwave power are usually based on thermistors, thermopiles, and diodes. The problems of these methods are, that they destroy the continuity of the coplanar waveguide (CPW) transmission line and they have a relatively narrow bandwidth or increased reflection losses[2, 3]. Compared with the conventional microwave detecting method, the capacitive membrane MEMS microwave power sensor couples only to a certain percentage of the microwave power and does not destroy the continuity of the CPW line; therefore, the microwave signal can still be used in a later stage.

2. Principle

Figure 1 shows a schematic drawing of the capacitive membrane MEMS microwave power sensor structure. The CPW transmission line and the pads are both fabricated by gold. A MEMS membrane is suspending over the CPW transmission line, thus creating a capacitance between them. Port 1 serves as the input port and Port 2 is the direct port, while Port 3 and Port 4 are the coupled ports located besides the capacitive membrane. If a microwave signal is applied on Port 1, a certain percentage of the microwave power is coupled out by the capacitive membrane and then transmitted to the coupled ports. The coupled microwave power is then converted into heat by the load resistor, which causes the temperature to increase around it. The thermopiles near the load resistors then detect the resulting temperature increase and convert the temperature difference into a DC voltage output, making it possible to measure the microwave power.

3. Modeling

3.1. Modeling of the thermopiles

According to the Seebeck effect, the total output DC voltage is expressed as[4]

$$V_{\text{out}} = \alpha \sum_{i}^{N_i} (T_{\text{h}} - T_{\text{c}}). \tag{1}$$

The sensitivity can be obtained by

$$S_{\text{total}} = V_{\text{out}}/P_{\text{total}} = \alpha \sum_{i}^{N_i} (T_{\text{h}} - T_{\text{c}})/P_{\text{total}}, \tag{2}$$

where α is the Seebeck coefficient and P_{total} is the total microwave power transmitting on the CPW line. Since the output

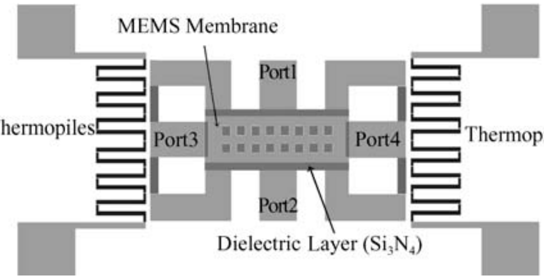


Fig. 1. Schematic drawing of the MEMS microwave power sensor structure.

---

* Project supported by the National Natural Science Foundation of China (No. 60676043) and the National High Technology Research and Development Program of China (No. 2007AA04Z328).

† Corresponding author. Email: xpliao@seu.edu.cn

Received 19 November 2008, revised manuscript received 13 January 2009

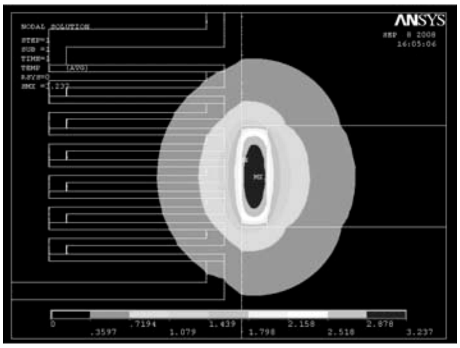


Fig. 2. Temperature distribution between the thermopiles and the load resistors.

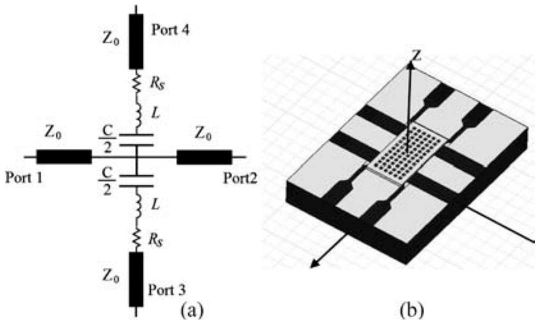


Fig. 3. (a) Lumped element model of the MEMS microwave power sensor; (b) HFSS model.

DC voltage is proportional to the coupled microwave power, the relationship between the input power and the output DC voltage can be calculated.

The temperature distribution near the load resistor and the thermopiles is simulated by Ansys and shown in Fig. 2. With an input voltage of 1 V applied on the CPW line, the temperature difference is about 3.2 K. Balancing the requirements between the sensitivity and the process complexity, the number of thermopiles and the gap between them are chosen to be six thermocouples and 10 μm, respectively[5].

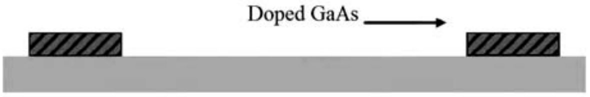
3.2. Microwave equivalent circuit

The lumped element model extracted from the MEMS microwave power sensor is given in Fig. 3[6].

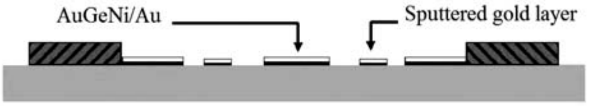
The capacitance C couples a certain percentage of the microwave power and transmits it to the load resistors Z_0 which are located at the end of the coupled port. R_s and L represent the resistance and the inductance of the MEMS membrane, respectively. The dimensions and element parameters of the sensor are shown in Table 1. Following a simulation done using Agilent's ADS software, the CPW is designed to have a center frequency $f = 10$ GHz in the X-band. The capacitance C is calculated from the parallel plate capacitor formula taking the fringing effect into account, l_e represents the width of the CPW center line and g is the height of the air gap. Simulated using Coventor, the values of the parameter are shown in Table 1.

Table 1. MEMS microwave power sensor dimensions and parameter values.

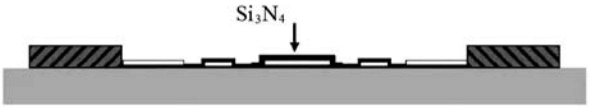
Element	Parameter	Value
CPW	G/W/G	58/100/58 μm
Dielectric layer thickness	t_d	1000 Å
Gold layer thickness	d	2 μm
Air gap	g_0	1.6 μm
Membrane width	b	100 μm
Resistance	R_s	4.323 Ω
Capacitance	C	62.91 fF
Characteristic impedance	Z_0	50 Ω



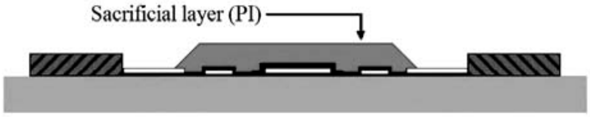
(a) Doped n^+ GaAs



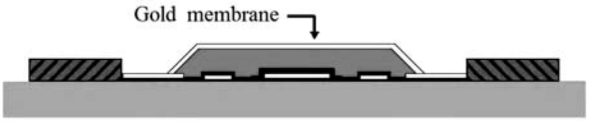
(b) Evaporate AuGeNi/Au layer



(c) Deposite SiN layer



(d) Pattern sacrificial layer



(e) Sputter Ti/Au/Ti seed layer

(f) Remove the polymide layer

Fig. 4. Fabrication process of the MEMS microwave power sensor.

4. Fabrication

Figure 4 shows a summary of the fabrication scheme, which is compatible with the GaAs MMIC process. The thermopiles were made out of gold and n^+ GaAs with a Seebeck coefficient of 100 μV/K. The CPW line and the pads were made by sputtering of a 0.3 μm thick gold layer, and the n^+ GaAs was made out of a 0.25 μm thick epitaxial layer. The loaded resistance was made by using a liftoff process through depositing of a TaN layer with a square resistance of 25 Ω/□. The CPW transmission line was fabricated by using a liftoff process through evaporating the 800/300/2200 Å Au/GeNi/Au layer. A dielectric Si_3N_4 layer of 1000 Å was then patterned and deposited. Following these steps, a 1.6 μm thick polyimide sacrificial layer was deposited. The thickness of the polyimide layer determined the initial height of air gap. The MEMS membrane was designed to be 270 × 146 μm^2 with a thickness of 2 μm. Finally, the 500/1500/300 Å Ti/Au/Ti

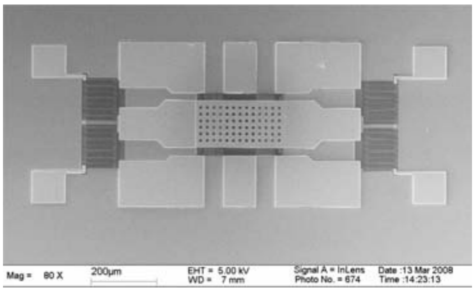


Fig. 5. SEM photo of the MEMS microwave power sensor.

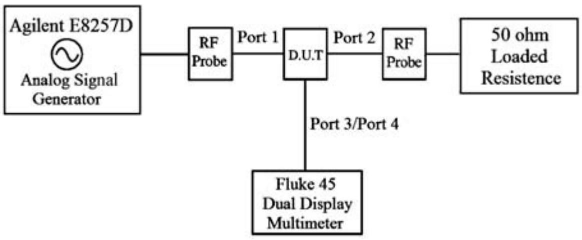


Fig. 6. Experimental setup of the MEMS microwave power sensor.

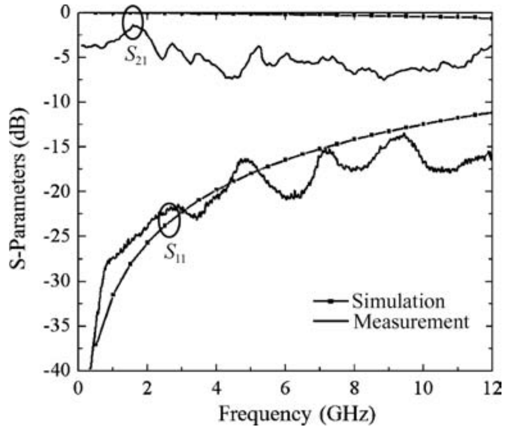


Fig. 7. S-parameters of the MEMS microwave power sensor.

seed layer was sputtered onto the polyimide layer. To remove the top Ti layer, the membrane was electroplated with a 2 μm thick gold layer in a 55° cyanide-based solution. The sacrificial layer of polyimide was removed using a developer, and the alcohol was utilized to get rid of the residual water during the process[7].

An SEM photo of the fabricated sensor is shown in Fig. 5.

5. Measurements

Figure 6 shows the experimental setup for the capacitive membrane MEMS microwave power sensor. The measurement requires a reflection loss and an insertion loss, when the microwave signal is applied onto the sensor. In addition, the coupled power values obtained from the sensor have to be calculated by the coupling coefficient measurements deduced from the S-parameters. The microwave characterization involves the measurements of the S-parameters with an Agilent 8719ES network analyzer and a Cascade Microtech 1200 probe station. The measurement frequency range is from 250 MHz up to 12 GHz.

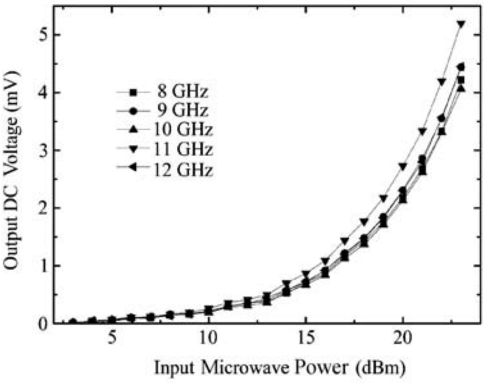


Fig. 8. Output voltage at different frequencies.

Table 2. Measurement results of the MEMS microwave power sensor.

Frequency (GHz)	VSWR	Sensitivity (μV/mW)
8	1.453	211.47
9	1.509	225.73
10	1.352	209.27
11	1.437	260.9
12	1.513	219.78

From Fig. 7, the reflection losses of the sensor are below –14 dB up to 12 GHz. Because of the buckling during the wet-etch and release process, the capacitance between the MEMS membrane and the CPW line is higher than in the simulation results. In addition, the error in the fabrication process also causes a deterioration of the S-parameters. As a result, the S_{21} parameter of this sensor deviates from the design, which is around –8 dB in the X-band. From the S-parameter measurement results from the experiments and the simulation, it can be concluded that the coupled power is equal to about 5% of the total microwave power that is transmitted to the CPW line, and the sensor demonstrates an acceptable microwave detection characteristic.

The sensitivities S_{th} and the voltage standing wave ratio (VSWR) of the MEMS microwave power sensor are shown in Table 2. The VSWR of the MEMS microwave power sensor has a maximum value of 1.513 which is only slightly higher than the theoretical VSWR value, which is simulated by HFSS software to be 1.338.

Another critical factor besides the process is the distance between the load resistance and the thermopiles. A decrease of the distance will lead to smaller temperature difference between the resistance and the thermopiles, and the response time will be shorter. The thermopile resistance is around 177 kΩ at 300 K. A theoretical signal-to-noise ratio SNR = $S_{\text{th}}/V_{\text{n}}$, where the noise voltage is given by $V_{\text{n}} = (4kTR_{\text{total}}B)^{1/2}$, was calculated to be 5.24×10^{6} W^{-1}. As the output DC voltage is proportional to the power coupled into the capacitive membrane, the sensitivity is also influenced by the efficiency of this power coupling. The main reason that the measurement deviates from the simulation is the error during the process and the decrease of the MEMS membrane.

Figure 8 shows the output DC voltage for the MEMS microwave power sensor under different input microwave power levels. From the curves at different frequencies, the MEMS microwave power sensor demonstrates a relatively good linearity and accuracy in the whole X-band. Because of the error

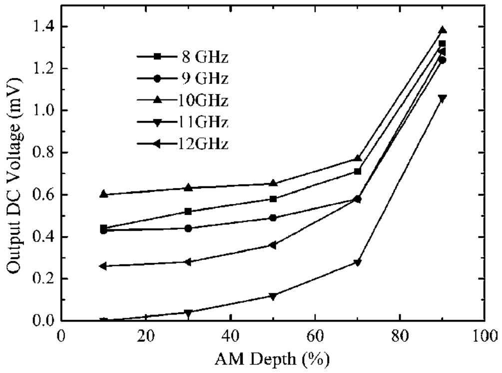


Fig. 9. Output DC voltage for different AM depths.

during the fabrication process, the sensitivity of the power sensor at 11 GHz deviates from the initial design, which should have a maximum at 10 GHz. In addition, the reduction of S_{11} at 11 GHz also leads to an augmentation of the coupled microwave power. As a result, the coupled power from the capacitive membrane results in an output DC voltage at 11 GHz that is higher than at other frequencies.

Because the influence of the frequency range on the thermopiles and the load resistors is limited, the output DC voltage has no direct relationship to the frequency range. However, the total coupled power varies together with the coupling coefficient fluctuation during frequency changes.

When the modulated signals are applied to the power sensor, the output DC voltage includes both the carrier signal and the sideband:

$$\begin{aligned} P_{\text{total}} &= P_{\text{signal}} + P_{\text{sideband}} = P_{\text{signal}} + \frac{1}{4}m_{\text{a}}^2U_{\text{mo}}^2 \\ &= P_{\text{signal}} + \frac{1}{2}m_{\text{a}}^2P_{\text{m}}. \end{aligned} \tag{3}$$

Figure 9 shows the output DC voltage in different modulation depths with a constant input power of 10 dBm. From Eq. (3), the AM depth determines the amplitude, which is directly related to the total output DC voltage. The measurement result shows that the output DC voltage increases when the modulation index m_{a} increases.

6. Conclusions

The design and modeling of a MEMS microwave power sensor has been presented in this paper. The sensor has been fabricated by using a GaAs MMIC process. From the measured S-parameters, the reflection loss is below –14 dB up to 12 GHz. The average sensitivity of the MEMS microwave power sensor in the X-band is 225.43 μV/mW, while the VSWR is less than 1.513. The measurements shows that the MEMS power sensor has a good linearity in the whole X-band. Finally, the result under modulated signals proves that the AM depth also directly influences the output DC voltage.

References

[1] Rebeiz G M. RF MEMS theory, design, and technology. New York: Wiley, 2003

[2] Dehe A, Klingbeli H, Krozer V, et al. GaAs monolithic integrated microwave power sensor in coplanar waveguide technology. Proceedings of IEEE MTT-S Symposium, 1996: 161

[3] Fernandez L J, Sese J, Flokstra J, et al. Capacitive MEMS application for high frequency power sensor. Proceedings of Micromechanics Europe, 2002

[4] Vaha-Heikkila T, Kyynarainen J, Dekker J, et al. Capacitive RF MEMS power sensor. Proc 3rd ESA Workshop on Millimeter Wave Technology and Application: Circuits, System, and Measurement Technology, Finland, 2003: 503

[5] Milanovic V, Hopcroft M, Zincke C A, et al. Optimization of CMOS MEMS microwave power sensor. Proceedings of IEEE ISCAS Conference, 1999: 144

[6] Fernandez L J, Wiegerink R J, Flokstra J, et al. A capacitive RF power sensor based on MEMS technology. J Micromechan Microeng, 2006, 16: 1099

[7] Han L, Huang Q A, Liao X P. A microwave power sensor based on GaAs MMIC technology. J Micromechan Microeng, 2007, 17: 2132