A novel symmetrical microwave power sensor based on MEMS technology*

Wang Debo(王德波) and Liao Xiaoping(廖小平)†

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

Abstract: A novel symmetrical microwave power sensor based on MEMS technology is presented. In this power sensor, the left section inputs the microwave power, while the right section inputs the DC power. Because of its symmetrical structure, this power sensor provides more accurate microwave power measurement capability without mismatch uncertainty and temperature drift. The loss caused by the microwave signal is simulated in this power sensor. This power sensor is designed and fabricated using GaAs MMIC technology. And it is measured in the frequency range up to 20 GHz with an input power in the 0–80 mW range. Over the 80 mW dynamic range, the sensitivity can achieve about 0.2 mV/mW. The difference between the input power in the two sections is below 0.1% for an equal output voltage. In short, the key aspect of this power sensor is that the microwave power measurement is replaced with a DC power measurement.

Key words: symmetrical; MEMS; GaAs MMIC; power sensor
DOI: 10.1088/1674-4926/30/5/054006 **EEACC:** 2575; 8460

1. Introduction

Microwave power measurement is an important part of microwave wireless applications such as modern personal communication systems and radar systems. Thermocouple-based power sensors are the most widely used tool for microwave power measurements[1]. The traditional power sensors based on thermocouples[2] are subject to several error sources. Besides the error caused by the return loss resulting from a mismatch between the coplanar waveguide (CPW) and its load resistor, the thermal losses are main error sources, which include the heat conduction to the substrate, the convection loss and the radiation loss of the CPW, the load resistor and the thermopile. In order to reduce these thermal losses, it is of interest to remove the substrate directly underneath the thermal and microwave structures[3]. To achieve this, a complex fabrication process is needed. Though thermal and electromagnetic losses are minimized by removing the bulk silicon located beneath the device through micromachining, the improvement is limited and the fabrication cost is increased.

In order to eliminate the error caused by the thermal losses and to simplify the fabrication process, a novel symmetrical microwave power sensor based on MEMS technology is presented, as shown in Fig. 1. The operation of the power sensor is based on the differential principle. The right section of this power sensor has the same CPW, load resistor and thermopile as the left section. So it eliminates the error caused by thermal losses, since the two sections have equal thermal losses. In this power sensor, the left section inputs the microwave power while the right section inputs the DC power. When the temperature of the left thermopile increases as a result of the left load resistor absorbing the microwave power, the temperature of the right thermopile is increasing simultaneously as a result of the right load resistor absorbing DC power from the voltage source E. The DC voltage source E is adjusted until the output voltages of the two sections are equal. In this way, the microwave power is done by a DC power measurement, which is achieved easily. To better equalize the temperature of the cold junctions to that of the substrate, the cold junctions are covered with a second-layer metal. Compared with the traditional power sensors based on thermocouples[2, 3], the key aspect of this power sensor is that the microwave power measurement can be replaced with a DC power measurement.

2. Simulation

Compared with the DC source of the right section, the left section of the power sensor would produce additional losses which are caused by the microwave signal. The losses are mainly due to the transmission loss of the CPW and the parasitic loss of the load resistor. So it is necessary to analyze these two kinds of losses and to put forward a corresponding

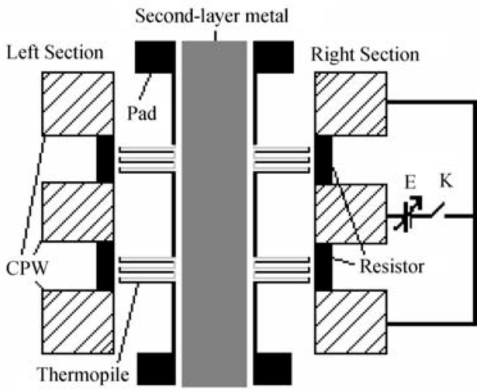

Fig. 1. Novel symmetrical microwave power sensor.

* 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 17 October 2008, revised manuscript received 25 November 2008

Table 1. Structural parameters.

Element	Parameter	Value
Center width of CPW	s	100 μm
Slot width	w	58 μm
Thickness of CPW	t	2 μm
Resistance	R	50 Ω
Characteristic impedance	Z_0	50 Ω
Effective permittivity	ε_r	12.9

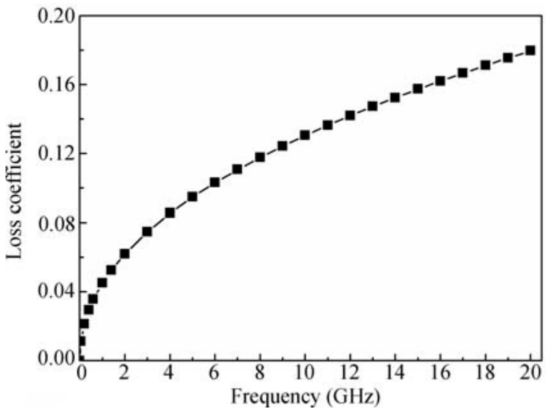

Fig. 2. Loss coefficient versus microwave frequency.

loss model. The structural parameters of the loss model are the same as the structural parameters of the physical model, as shown in Table 1.

2.1. Loss model of the CPW

Due to electromagnetic coupling, the microwave signal will produce losses[4] when it moves through the CPW. The loss coefficient (α) can be expressed as

$$\Delta t = \frac{1.25t}{\pi}\left[1 + \ln\frac{4\pi s}{t}\right], \quad (1)$$

$$k_t = \frac{s + \Delta t}{s + 2w - \Delta t}, \quad (2)$$

$$b = 0.183(t + 0.464) - 0.095{k_t}^{2.484}(t - 2.595), \quad (3)$$

$$a = \sqrt{\frac{\varepsilon_r + 1}{2}}\left[\frac{45.152}{(sw)^{0.410}e^{2.127\sqrt{t}}}\right], \quad (4)$$

$$\alpha = af^b, \quad (5)$$

where s is the center width of the CPW, w is the slot width, t is the thickness of the CPW, f is the input microwave frequency, and ε_r is the substrate effective permittivity.

The relationship of the loss coefficient to the microwave frequency is shown in Fig. 2. The loss coefficient increases with microwave frequency, which shows that the power loss of the CPW also increases with microwave frequency.

2.2. Loss model of the load resistor

In the microwave frequency range[5], the film load resistor does not act as a pure resistor but is subject to parasitic effects, which includes parasitic capacitances and inductivities. These capacitances and inductivities will store some power. The power is thus not completely dissipated in the film load

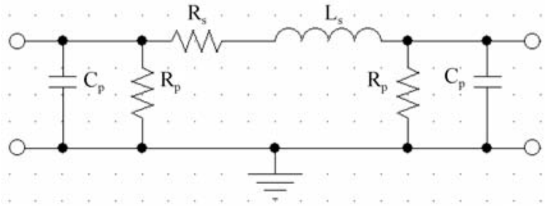

Fig. 3. Equivalent circuit of the film load resistor.

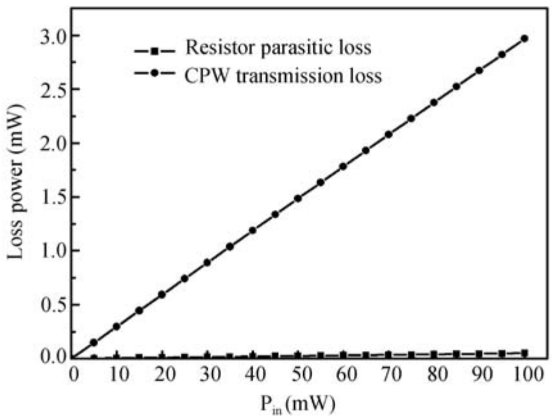

Fig. 4. Two kinds of power loss versus input power.

resistor. The parasitic equivalent circuit of the film load resistor in the microwave frequency range is shown in Fig. 3.

The circuit elements shown in Fig. 3 can be expressed as

$$R_S = R\left(1 - \frac{\omega^2\varepsilon_{\text{eff1}}l_1^2}{3c^2}\right), \quad (6)$$

$$L_S = \frac{Z_{01}\sqrt{\varepsilon_{\text{eff1}}}l_1}{c}\left(1 - \frac{\omega^2\varepsilon_{\text{eff1}}l_1^2}{6c^2} + \frac{R^2}{6Z_{01}^2}\right), \quad (7)$$

$$C_p = \frac{\sqrt{\varepsilon_{\text{eff1}}}l_1}{2cZ_{01}}\left(1 + \frac{\omega^2\varepsilon_{\text{eff1}}l_1^2}{12c^2}\right), \quad (8)$$

$$R_p = \frac{24c^2Z_{01}^2}{\omega^2\varepsilon_{\text{eff1}}l_1^2R}, \quad (9)$$

where R is the low frequency resistance, Z_{01} is the characteristic impedance of the resistor in the lossless case, $\varepsilon_{\text{eff1}}$ is the effective relative permittivity of the load resistor, and c is the velocity of light.

The losses in the CPW and in the load resistor vary with the input power at 10 GHz, as shown in Fig. 4. The parasitic loss in the load resistor is much lower than the loss in the CPW; so mainly the loss in the CPW is considered in this power sensor.

2.3. Simulation of loss

Considering the loss of the CPW, the power absorbed by the resistor is not equal to the input power (P_{in}). The relation between the loss coefficient (α) and the input power of the CPW (P_{in}) can be expressed as

$$\alpha = 10\ \lg(P_{\text{in}}/P_{\text{out}})\,(\text{dB/cm}). \quad (10)$$

The output power of the CPW (P_{out}) is obtained by Eq. (11).

$$P_{\text{out}} = P_{\text{in}}/10^{\frac{\alpha}{10}}\ (\text{W/cm}). \quad (11)$$

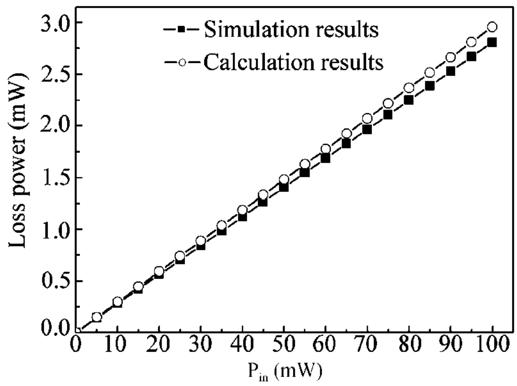

Fig. 5. Loss power from simulation and calculation.

The loss coefficient (α) can be obtained by Eq. (5). So the loss power ($P_{\rm loss}$) of the CPW is deduced as

$$P_{\rm loss} = P_{\rm in} - P_{\rm out} = P_{\rm in}(1 - 10^{-\frac{\alpha}{10}}). \tag{12}$$

The loss of the CPW is simulated at 10 GHz using the electromagnetic field solver HFSS from Ansoft Corporation and compared with the results from Eq. (12), as shown in Fig. 5. The difference between the results is below 4% for an input power below 100 mW.

3. Fabrication

The fabrication of this power sensor is compatible with the GaAs MMIC process[6]. In this power sensor, the CPW line was designed to have a 50 Ω characteristic impedance. The thermopiles are made of Au and n^+-GaAs with a Seebeck coefficient of 100 μV/K. The Au was made by using a lift-off process through evaporating the 300/1800/300 Å Au/GeNi/Au layer, and n^+-GaAs was made of a 2500 Å thick epitaxial layer. The load resistor was made by using a lift-off process through depositing a TaN layer with a square resistance of 25 Ω/□. Then a 500/1500/300 Å Ti/Au/Ti seed layer was sputtered and patterned. After removing the top Ti layer, the transmission lines of the CPW and the second-layer metal were formed through electroplating a 2 μm thick Au layer. Finally, the GaAs substrate was thinned down to 100 μm. In addition, since only a few, 80-μm short thermopiles are used, the area of the chip is not larger than the area of traditional thermocouple-based power sensors. The process steps of the power sensor are shown in Fig. 6. The SEM photo of the power sensor is shown in Fig. 7.

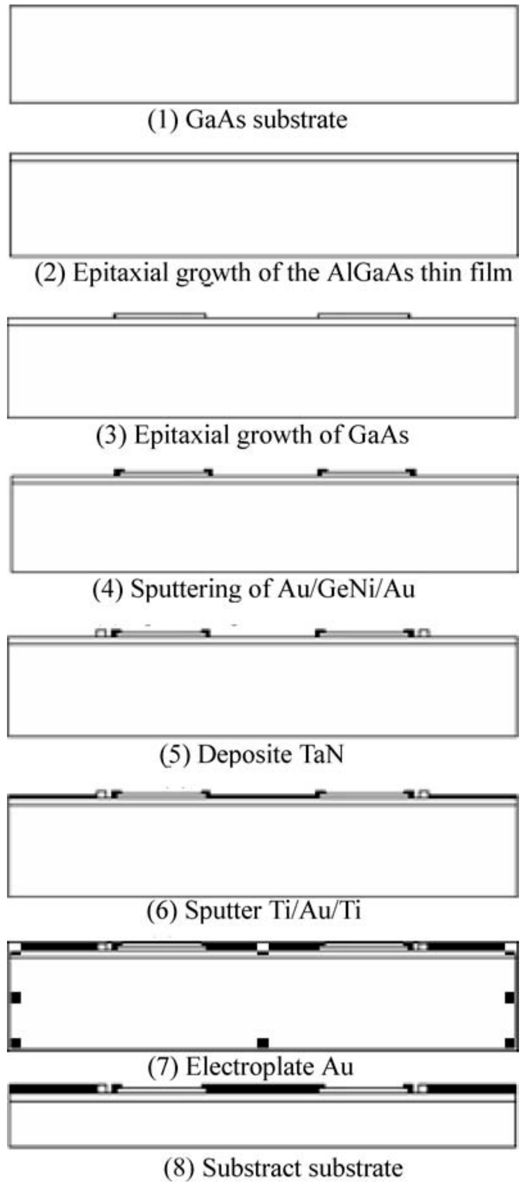

Fig. 6. Process steps during fabrication.

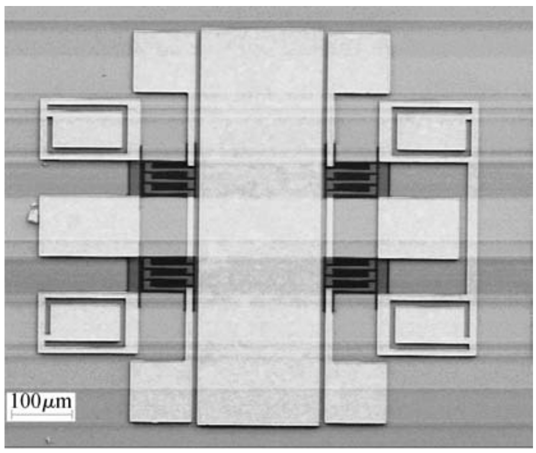

Fig. 7. SEM photo of the power sensor.

4. Measurement

The power sensor was measured at different input powers and different microwave frequencies. First, in order to obtain an estimate of the input mismatch error of the power sensor, the return loss was measured. Second, in order to obtain the sensitivity and the relative deviation of input powers between the two sections, the power was measured.

4.1. Return loss measurement

The return loss of this power sensor was measured using a network analyzer and a Cascade Microtech 1200 probe station. These were used to determine the input mismatch error over the entire frequency range (0–20 GHz) in the left section. The measurement results include the parasitic effects of the pad and underlying substrate. The return loss is below –26 dB over the entire frequency range, as shown in Fig. 8. This

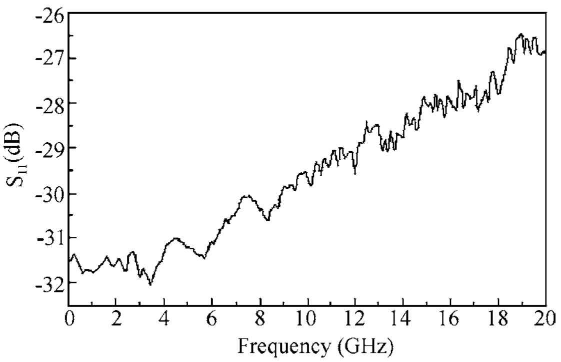

Fig. 8. Measurement results of the return loss.

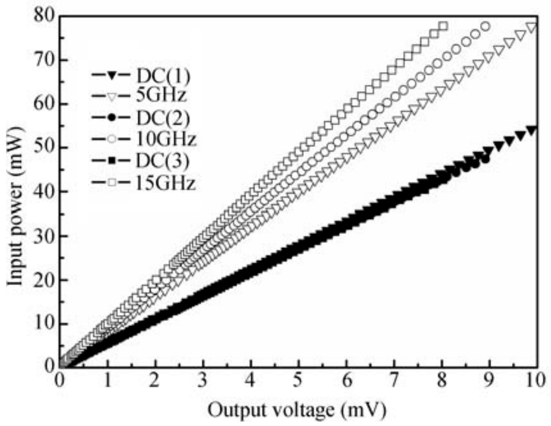

Fig. 9. Power measurement results before calibration.

reflects that the power sensor has a good matching characteristic.

4.2. Power measurement

The power measurement was accomplished with an Agilent E8257D signal generators, a Cascade Microtech 1200 probe station, a DC voltage source and two digital voltmeters.

For a power measurement[7], the microwave signals are applied to the left section with a power in the range of 0 to 80 mW at 5, 10 and 15 GHz respectively, and the output voltage is recorded. In the right section, the DC voltage source E is adjusted to make the output voltage of the thermopiles of the two sections equal. The DC power is recorded as DC(1), DC(2) or DC(3) for 5, 10 or 15 GHz, respectively. The microwave power measurement results at different frequencies before calibration differ significantly from the corresponding DC power, as shown in Fig. 9. Under ideal conditions, the DC power curves corresponding to different frequencies would coincide. But the second metal is not ideal enough to keep the microwave power from influencing the DC power, so the curves DC(1), DC(2) and DC(3) have different slopes. However, the errors are negligible. In addition, due to the electromagnetic coupling loss of CPWs at microwave frequencies, the input microwave power results in unwanted frequency-dependent losses. As the loss power increases with microwave frequency, the microwave power absorbed by the load resistor decreases. Therefore, the output voltage decreases as a function of the microwave frequency and the DC supply can achieve the same output voltage with less power. So for a power

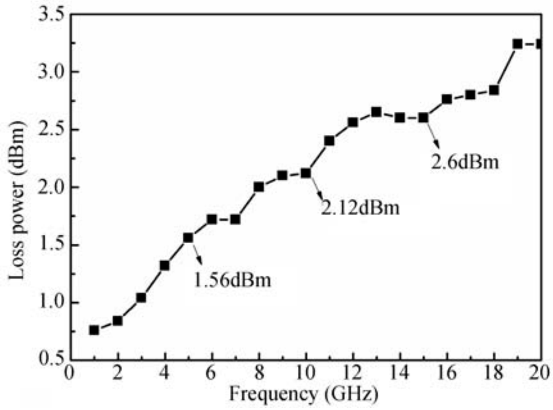

Fig. 10. Loss for different frequency levels.

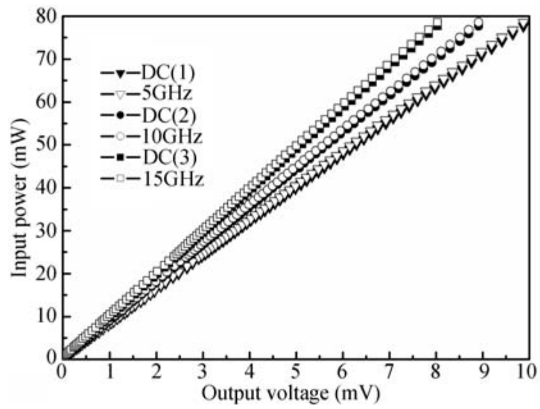

Fig. 11. Power measurement results after calibration.

measurement, the zero correction losses of the microwave signal must be determined. The zero correction losses at different frequencies are measured by comparing measured DC power values with the DC power values at 0 dBm when the output voltage is equal. The measurement result is shown in Fig. 10. The zero correction losses at 5, 10 and 15 GHz are 1.56, 2.12 and 2.6 dBm, respectively. If the output voltage of the thermopiles of both sides is equal, the DC power is equal to the output power of the CPW (P_{out}). Therefore, the zero correction loss needs to be added to the DC power in order to determine the input power of the CPW (P_{in}). The measurement results after calibration are shown in Fig. 11. At different frequencies, the relative deviation of the input power in two sections is below 0.1% at equal output voltages. The microwave power measurement can thus be replaced with a DC power measurement. The sensitivity is about 0.2 mV/mW with good linearity for the DC power measurement.

5. Conclusion

A novel symmetrical microwave power sensor based on MEMS technology is presented in this paper. The power sensor eliminates the error caused by the thermal losses and simplifies the fabrication process. The loss caused by the microwave signal is simulated. The measurement results show that this power sensor has good linearity and low return loss up to 20 GHz. The relative deviation of the input power in the two sections is below 0.1% with equal output voltage. So this power sensor is created to provide a more accurate microwave power measurement capability. However, the repeatability and reliability of this power sensor need to be studying in more detail in the future.

References

[1] Kinard J R, Hastings J R, Lipe T E, et al. AC–DC difference calibration. NIST Special Publ, 1989: 250

[2] Dehe A, Krozer V, Chen B, et al. High-sensitivity microwave power sensor for GaAs-MMIC implementation. IEEE Electron Lett, 1996, 32(23): 2149

[3] Milanovic V, Gaitan M, Bowen E D, et al. Thermoelectric power sensor for microwave applications by commercial CMOS fabrication. IEEE Electron Lett, 1997, 18(9): 450

[4] George E P, Mehran M, Linda P B, et al. A measurement-based design equation for the attenuation of MMIC-compatible coplanar waveguides. IEEE Trans Microw Theory Tech, 1999: 241

[5] Chramiec J, Adamski M E, Kitlihski M. Evaluation of chip resistor CAD models used in microwave circuit design programs. Proc Int Conf Signals and Electronic Systems, 2000: 369

[6] Dehe A, Klingbeil H, Krozer V, et al. GaAs monolithic integrated microwave power sensor in coplanar waveguide technology. IEEE Microw Millimeter-Wave Monolithic Circuits Symposium, 1996: 172

[7] Milanovic V, Gaitan M, Bowen E D, et al. Implementation of thermoelectric microwave power sensors in CMOS technology. Proceedings of IEEE International Symposium on Circuits and Systems, 1997: 2753