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Analysis and experiment of temperature effect on the thermoelectric power sensor

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ABSTRACT

In this paper, a numerical model is established to describe the effect of temperature on the packaged thermoelectric power sensor in different environments. The thermal conductivity of the GaAs substrate and the Seebeck coefficient of the thermopiles both change with the surrounding temperature and then influence the output voltage of the sensor. The return loss of the packaged power sensor is measured to be −20 dB at 10 GHz and close to −12 dB at the edge of X-band. The temperature experiment is performed from 273 K to 363 K in the temperature chamber. An agreement between the measured results and the presented model is obtained and the temperature dependence factor is close to 0.15 mV/K at 10 GHz under the incident power of 50mW. Furthermore, calibration of the output voltage is accomplished from 273 K to 363 K and the compensated power with respect to the surrounding temperature is also recorded under 50mW.

1. Introduction

Power detection is an important part of microwave and millimeter-wave wireless applications [1]. Recently, two different kinds of power sensors have been researched based on the micro-electromechanical systems (MEMS) technology. As a typical one, the thermoelectric power sensor has been extensively researched [2–6]. The incident microwave power is dissipated completely by the loaded resistors and the produced heat is converted to dc voltage by several thermopiles based on Seebeck effect. This power sensor has various advantages such as low return loss, good linearity and high sensitivity. In our group, the thermoelectric power sensor has been researched on the GaAs substrate and its frequency-dependent characteristic has been presented [7–10]. For a long time this power sensor is usually tested at room temperature in the lab. However, as it gradually moves towards practical application, the thermoelectric power sensor has to work in outdoor environments with different temperatures. Consequently, the output voltage is easy to be affected and the accuracy of the power sensor degrades as the surrounding temperature decreases. Furthermore, up to now, there is little experiment of temperature effect on the thermoelectric power sensor in the literature [11].

It is therefore the purpose of this paper to research the temperature effect on the thermoelectric power sensor. Moreover, a theoretical numerical model is developed so as to provide an insight into the operation of the sensor in different environment.

2. Theoretical model

Fig. 1 shows the schematic view of the thermoelectric power sensor. The left side is used to measure the incident power and the right side is the frequency calibration port and eliminates the frequency-dependent characteristic [7]. When a microwave signal is fed by the CPW transmission line in the left side, the incident power is dissipated completely and converted to heat by the loaded resistors. The metal block is used to maintain the temperature of the cold junction of thermopile same as that of the GaAs substrate. As shown in Fig. 2(a), the produced heat transfers in the substrate and a temperature gradient between the hot junctions and clod junctions is formed. Therefore, the temperature difference between two junction leads to output DC voltage based on Seebeck effect. In this design, several thermocouples are connected in series in order to increase the output voltage and improve the sensitivity of the sensor. As a result, the incident power of the microwave signal can be deduced by the voltage measurement. The output voltage can be expressed as

$$V = N \times (\alpha_1 - \alpha_2) \times (T_1 - T_2) \quad (1)$$

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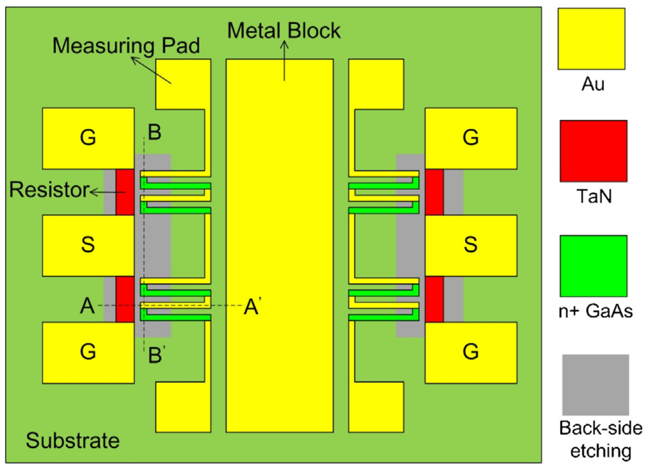

Fig. 1. Schematic view of the thermoelectric power sensor.

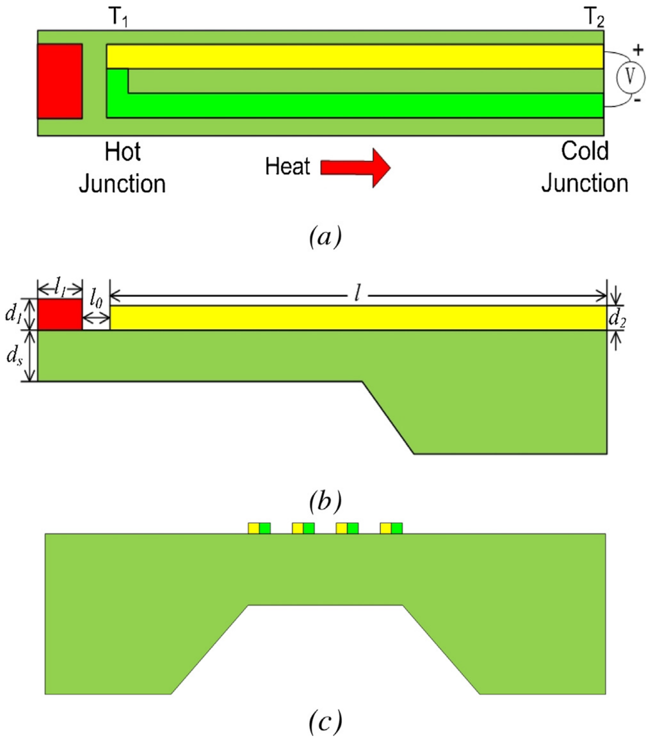

Fig. 2. Schematic view of the thermocouple of the power sensor (a) top view, (b) cross-section of AA′ and (c) BB′.

Where N is the number of the thermocouples, α_1 is the Seebeck coefficient of n$^+$ GaAs, α_2 is the Seebeck coefficient of Au, T_1 is the temperature of the hot junctions of the thermopile and T_2 is the temperature of the cold junctions.

Based on [12,13], one dimensional Fourier equivalent model of the thermoelectric power sensor have been studied to describe the heat transfer in the substrate. As a result, the temperature difference between the hot junction and the cold junction can be expressed as [7]

$$\Delta T = T_1 - T_2 = \frac{P_{in}}{2\lambda_e p W d_e} \cdot \frac{\sinh(pl)}{\cosh(p(l+l_0))} \tag{2}$$

where P_{in} is the incident power, W is effect width of the heat-flux, l is the length of the thermopiles and l_0 is the distance between the resistors and the thermopiles. In Eq. (2), $p=(H/(\lambda_e \times d_e))^{0.5}$, d_e is equivalent thickness of thermopile, H is the total heat loss coefficient which is related to thermal convection and thermal radiation [7]. In Eq. (2), $d_{e'}$ is equivalent thickness of loaded resistors, λ_e is the equivalent thermal conductivity and they can be expressed as

$$d_e{}' = d_1 + d_s \tag{3}$$

$$\lambda_e = \frac{\lambda_s d_s + \lambda_2 \frac{d_2}{2}}{d_s + \frac{d_2}{2}} \tag{4}$$

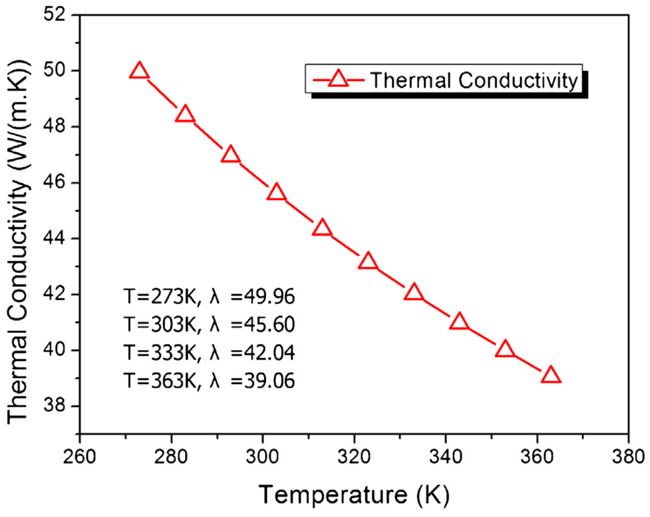

Fig. 3. Calculated thermal conductivity of GaAs substrate as a function of the surrounding temperature.

where d_1 is the thickness of the loaded resistors and d_s is the substrate, $\lambda_2=(\lambda_n+\lambda_p)/2$ is the average thermal conductivity of the thermopile, λ_n and λ_p are the thermal conductivity of n$^+$ GaAs and Au, respectively, λ_s is the thermal conductivity of the substrate, and d_2 is the thickness of thermopile. Therefore, inserting Eq. (2) into Eq. (1), the output voltage can be written as a function of the incident power,(5)$V = N \times (\alpha_1 - \alpha_2) \times \frac{P_{in}}{2\lambda_e p W d_e'} \cdot \frac{\sinh(pl)}{\cosh(p(l+l_0))}$

In different environments, the thermal conductivity of the GaAs substrate and the Seebeck coefficient of the thermopiles both change with the temperature, and therefore influence the output voltage of the power sensor.

2.1. *Thermal conductivity of GaAs substrate*

First, the thermal conductivity of the substrate changes with the surrounding temperature and have an effect on the temperature difference between the hot junctions and cold junctions. The first approximate relationship between the thermal conductivity of the substrate and the temperature can be expressed as [7,14]

$$\lambda_s \approx \frac{13800}{T} \tag{6}$$

where T is the surrounding temperature. Therefore, the thermal conductivity of the substrate decreases with the surrounding temperature, and therefore increases the temperature difference ΔT between the hot junctions and cold junctions of the thermopiles based on Eqs. (2) and (4).

Fig. 3 gives the calculated thermal conductivity as a function of the surrounding temperature. Obviously, the thermal conductivity decreases from about 50 W/(m × K) to 39 W/(m × K) while the surrounding temperature varying from 273 K to 363 K. As a result, the decrease of the thermal conductivity leads to the increase of the temperature difference between the hot and cold junctions. Fig. 4 shows and calculates temperature difference between the hot junctions and cold junctions varying with the surrounding temperature.