

Parameter Extraction of Resistive Thermal Microsensors by AC Electrical Method

Mang Ou-Yang, Chin-Shown Sheen, and Jin-Shown Shie

Abstract—Obtaining device parameters of thermal microsensors is essential for evaluating their performances and simulation modeling. We report an ac electrical method for extracting these parameters experimentally with relatively simple instrumentation. The basic parameters of resistive microsensors, the resistance, temperature coefficient of resistance, thermal capacitance, and conductance, are derivable from the second harmonic signal of the output voltage induced by a sinusoidal driving current. The results are compared with other methods.

Index Terms—AC electrical method thermal variables measurement, electrothermal effect, parameter extraction, thermal microsensors.

I. INTRODUCTION

RECENTLY, microfabricated resistive thermal microsensors have shown great potential in measurement technology [1]–[6]. These devices transduce certain kinds of physical quantities into electrical signals by means of temperature-sensitive resistors. Sensors with a microstructure can improve their thermal performances effectively yielding faster speed and better responsivity. To evaluate these performances [7] and to facilitate the design simulation [8], [9], it is essential to extract the sensor parameters, both thermal and electrical, for device modeling.

A microbolometer is used as the example to interpret the extraction method. There have been some related works describing parameter measurements of thermal microsensors [10]–[12]. In Mather's method [10], an ac electrical technique was described without experimental proof. In addition, his analysis is not thorough, because the fundamental frequency response he proposed to use is believed to have a larger error, as will be explained in the following. Deep *et al.* [11] had used time-domain fitting of the transient response on a conventional bolometer, which also resulted in increasing the error due to the nonlinear behavior of the bolometer. Recently, a dc electrical method and a bolometric method have been utilized in our laboratory for extracting microbolometer parameters [12]. However, these methods require an accurate measurement of both temperature and

the irradiated optical power. In addition, it is very time consuming and tedious because of the bolometric measurement.

A new ac electrical method for parameter extraction of thermal microsensors is proposed in the present study. With a driving current containing dc and sinusoidal ac components, the experiment becomes easier and more accurate by considering the induced second-harmonic response. The details will be described in the following analysis.

II. THE WORKING PRINCIPLE

The temperature of a resistive microbolometer is increased due to the irradiated power and the self-heating power of its bias current. For the present ac electrical method, the bolometer to be evaluated is shielded from radiation and driven by a bias current containing a constant dc average, I_o , plus a small sinusoidal variation of $i(t) = i_m \cos(\omega t)$. In the steady-state condition, the microsensor then works at an operating temperature T_o with a fluctuation $\theta(t) = T(t) - T_o$, which is the difference of the instantaneous temperature and the dc operating temperature.

In a small range of temperature variation around T_o , the resistance of a microbolometer can always be approximated as a linear function of temperature, i.e.,

$$R(T) = R_o[1 + \alpha_o(T - T_o)] \quad (1)$$

where R_o and α_o are referred to the sensor resistance and temperature coefficient of resistance (TCR) at T_o , respectively. One should note that $R_o\alpha_o$ is an invariant quantity for the linear relation between temperature and resistance, which is an useful relationship for the following analysis.

The bias Joule heating on the bolometer reads

$$P_e(t) = [I_o + i_m \cos \omega t]^2 \cdot R_o[1 + \alpha_o(T(t) - T_o)] \quad (2)$$

and the heat-flow equation governing the sensor behavior follows [13]

$$H \frac{d}{dt} T(t) + G[T(t) - T_a] = P_e(t) \quad (3)$$

with G and H the thermal conductance and capacitance of the sensor, respectively, and T_a the instantaneous ambient temperature.

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Substituting (2) in (3), one can obtain the relationships for dc and ac parts

$$G(T_o - T_a) = I_o^2 \cdot R_o + \frac{1}{2}i_m^2 \cdot R_o \quad (4)$$

$$H \frac{d}{dt} \theta(t) + \{G - [I_o + i_m \cos(\omega t)]^2 \cdot \alpha_o R_o\} \theta(t) = 2i_m I_o R_o \cos(\omega t) + \frac{1}{2}i_m^2 R_o \cos(2\omega t) \quad (5)$$

respectively. Equation (5) can be solved analytically as

$$\theta(t) = H^{-1} \cdot e^{-k(t)} \int e^{k(t)} \{2i_m I_o R_o \cos(\omega t) + \frac{1}{2}i_m^2 R_o \cos(2\omega t)\} dt + c_o e^{-k(t)} \quad (6)$$

with

$$k(t) = \left\{ \frac{G - I_o^2 \alpha_o R_o - 1/2 \cdot i_m^2 \alpha_o R_o}{H} \right\} \cdot t - \left\{ \frac{2i_m I_o \alpha_o R_o}{H\omega} \right\} \cdot \sin(\omega t) - \left\{ \frac{i_m^2 \alpha_o R_o}{4H\omega} \right\} \cdot \sin(2\omega t). \quad (7)$$

The integration constant c_o depends on the initial condition. It vanishes quickly in over several thermal time constants, which, in general, takes only tens of milliseconds for microsensors [9]. Therefore, a steady-state condition is always assumed for the experiment, and the last term of (6) equals zero.

Equation (6) is nonlinear and difficult to calculate. However, if $I_o \gg i_m$, the terms containing i_m in (7) can be neglected and $k(t) = t/\tau$, with $\tau = H/G_{\text{eff}}$ and $G_{\text{eff}} = G - I_o^2 \alpha_o R_o$, called the effective time constant and thermal conductance, respectively. Therefore, (6) becomes

$$\begin{aligned} \theta(t) &= H^{-1} \cdot e^{-t/\tau} \cdot \int e^{t/\tau} \{2i_m I_o R_o \cos(\omega t) \\ &\quad + \frac{1}{2}i_m^2 R_o \cos(2\omega t)\} dt \\ &= \frac{2i_m I_o R_o}{G_{\text{eff}}} \frac{\cos(\omega t + \phi_1)}{\sqrt{1 + (\omega\tau)^2}} + \frac{i_m^2 R_o}{2G_{\text{eff}}} \frac{\cos(2\omega t + \phi_2)}{\sqrt{1 + (2\omega\tau)^2}} \\ &= \theta_1 \cos(\omega t + \phi_1) + \theta_2 \cos(2\omega t + \phi_2) \end{aligned} \quad (8)$$

where $\phi_1 = \tan^{-1}(\omega\tau)$ and $\phi_2 = \tan^{-1}(2\omega\tau)$.

The voltage across the microsensor

$$\begin{aligned} V(t) &= I(t) \cdot R(t) \\ &= (I_o + i_m \cos \omega t) \cdot R_o \{1 + \alpha_o [\theta_1 \cos(\omega t + \phi_1) \\ &\quad + \theta_2 \cos(2\omega t + \phi_2)]\} \\ &= V_o + V_\omega \cos(\omega t + \varphi_\omega) + V_{2\omega} \cos(2\omega t + \varphi_{2\omega}) \\ &\quad + V_{3\omega} \cos(3\omega t + \varphi_{3\omega}) \end{aligned} \quad (9)$$

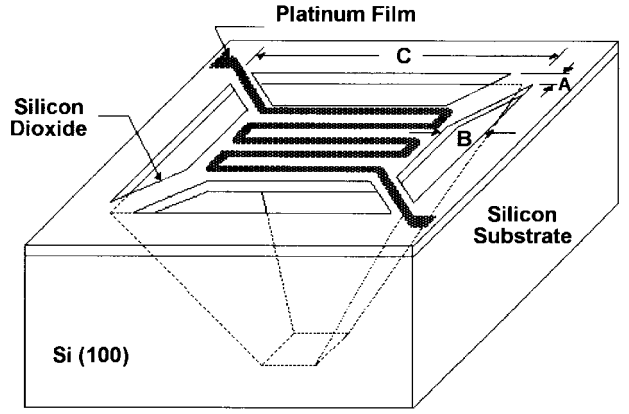


Fig. 1. The schematic of the experimental microsensor fabricated with micromeching technology [13].

with

$$V_o = I_o R_o + \frac{1}{2}i_m \alpha_o R_o \cos \phi_1 \quad (10a)$$

$$\begin{aligned} V_\omega &= i_m R_o \gamma^2 \sqrt{\frac{1 + (\omega\tau/\gamma)^2}{1 + (\omega\tau)^2}} \\ &= i_m R_o \gamma^2 \sqrt{\frac{1 + (\omega\tau')^2}{1 + (\omega\tau)^2}} \end{aligned} \quad (10b)$$

where $\gamma^2 = G + I_o^2 \alpha_o R_o / G - I_o^2 \alpha_o R_o$ and $\tau' = (\tau/\gamma)$ as shown in (10c) and (10d) at the bottom of the page.

The dc response, V_o , is weakly related to the thermal conductance in its phase term ϕ_1 , hence is not very useful. While in the V_ω term, γ is not much different from unity for small I_o . This makes it also weakly dependent of G_{eff} , since $G_{\text{eff}} \gg I_o^2 \alpha_o R_o$. Besides, it is difficult to extract the thermal capacitance from the cutoff frequency of the V_ω spectral response, because the pole and the zero in (10b) are close to each other. Large errors will result in experimental data fitting with the equation. This explains why Mather's proposed method cannot be useful for the purpose of parameter extraction. Finally, $(V_{3\omega}/V_{2\omega}) \approx (i_m/6I_o) \ll 1$, thus $V_{3\omega}$ is not as important as $V_{2\omega}$. We therefore, conclude that the second harmonic response, $V_{2\omega}$, is the best choice for our purpose. This is obvious from a physical point of view, because $V_{2\omega}$ is directly responsible for the Joule heating, which is proportional to the square of the ac bias current. Therefore, from (10c) and for $\omega \ll \tau^{-1}$, one obtains the thermal conductance

$$G = \alpha_o R_o I_o^2 + G_{\text{eff}} = \alpha_o R_o I_o^2 + \frac{3 \alpha_o R_o^2 I_o i_m^2}{2 V_{2\omega}}. \quad (11)$$

$$V_{2\omega} = \frac{i_m^2 I_o \alpha_o R_o^2}{G_{\text{eff}}} \sqrt{\frac{1}{4[1 + (2\omega\tau)^2]} + \frac{1}{1 + (\omega\tau)^2} + \frac{1 + 2(\omega\tau)^2}{[1 + (2\omega\tau)^2][1 + (\omega\tau)^2]}} \quad (10c)$$

$$V_{3\omega} = \frac{i_m^3 \alpha_o R_o^2}{4G_{\text{eff}} \sqrt{[1 + (\omega\tau)^2]}} \quad (10d)$$

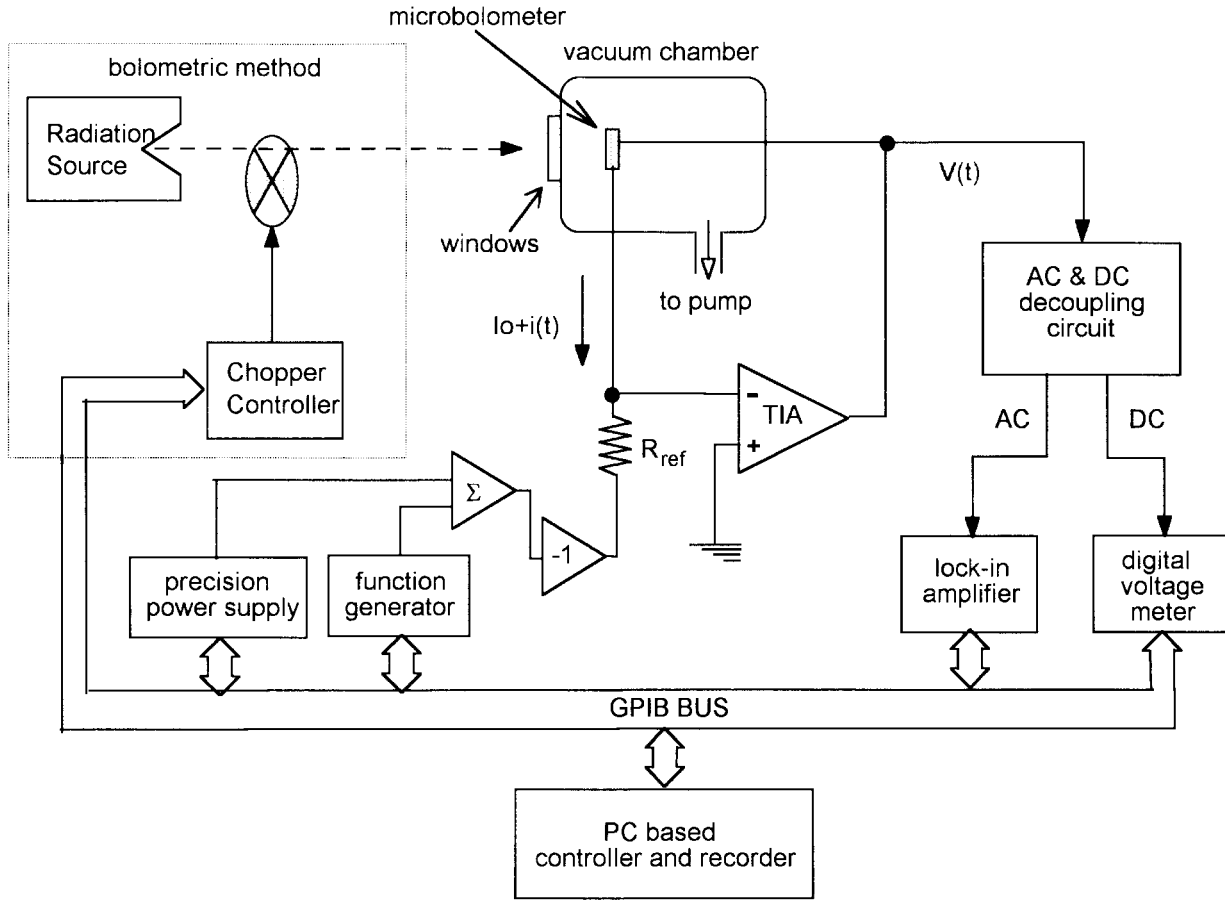


Fig. 2. Experimental setup for the measurements of response signal.

During the short-period measurement of $V_{2\omega}$, the V_o signal can also be read simultaneously to calculate the instantaneous value of R_o according to (10a). Since $\alpha_o R_o$ is an invariant, as stated before, (11) is independent of the ambient temperature and its variation.

In the dc electrical method reported previously [12], the thermal conductance is given by

$$G = \frac{I_o V_o \alpha_o R_o}{R_o - R_a} \quad (12)$$

where R_a is the resistance of the microbolometer at the ambient temperature, T_a . Here R_a and R_o differ only by a small amount due to a small TCR. The accuracy of (12), therefore, depends heavily on that of the measured ambient temperature, because of the small $R_o - R_a$ term in the denominator. The instantaneous value of R_a will be quite unstable without good environmental temperature control within $\pm 0.1^\circ\text{C}$ [12]. The advantage of the present method, which does not need to consider this ambient temperature variation, is obvious.

Also the thermal conductance in the previous bolometric method [12] is expressed by

$$\log(R_v^{-1} + \varepsilon^{-1} I_o) = -\log(I_o) + \log\left(\frac{G}{\varepsilon R_o \alpha_o}\right). \quad (13)$$

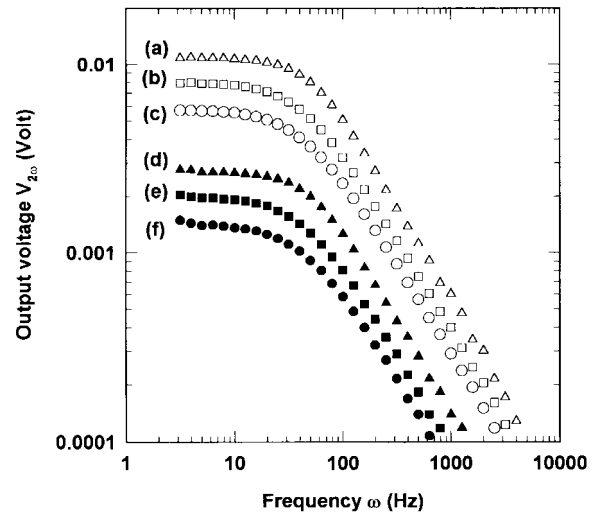


Fig. 3. The $V_{2\omega}$ frequency spectrum measured using the present ac electrical method.

To obtain G , one will have to take a set of absolute voltage responsivity data (R_v) for different bias currents (I_o), and to evaluate the emissivity (ε) of the bolometer by other complex means. Hence, the method becomes very inconvenient and time-consuming compared with the electrical method.

TABLE I
PARAMETERS OF THE MICROBOLMETER DETERMINED WITH THE AC ELECTRICAL METHOD

	I_o	i_m	V_o	$V_{2\omega}$	ω_{3dB}	R_o	α_o	T_o	G	H
unit	mA	mA	Volt	mV	rad/s	Ω	%/°C	°C	W/°C	J/°C
(a)	4.0	0.2	4.28	10.8	268.4	1070	0.164	295.45	7.03×10^{-5}	1.19×10^{-7}
(b)	3.0	0.2	2.16	7.78	212.1	720	0.244	96.59	4.52×10^{-5}	1.06×10^{-7}
(c)	2.4	0.2	1.50	5.55	210.7	625	0.282	42.61	3.88×10^{-5}	1.04×10^{-7}
(d)	4.0	0.1	4.28	2.67	270.4	1070	0.164	295.45	7.03×10^{-5}	1.19×10^{-7}
(e)	3.0	0.1	2.16	1.94	210.0	720	0.244	96.59	4.52×10^{-5}	1.05×10^{-7}
(f)	2.4	0.1	1.50	1.38	209.0	625	0.282	42.61	3.88×10^{-5}	1.03×10^{-7}

According to (10c) the 3 dB cutoff of the $V_{2\omega}$ spectrum appears at $\omega_{3dB} = 0.757/\tau$. This provides the information on the thermal capacitance H through $\tau = H/G_{eff}$.

III. EXPERIMENTAL DETERMINATION

The structure of a microsensors that has been studied is shown schematically in Fig. 1. This device had been used previously for studying vacuum microsensors [13]. Its structure is characterized by the width ($\sqrt{2}A$) and length ($\sqrt{2}B$) of the supporting leads, and the cavity dimension (C). For this study, $A = 4 \mu\text{m}$, $B = 80 \mu\text{m}$, and $C = 325 \mu\text{m}$. The resistance and TCR of the Pt-film sensor on the floating membrane can be measured in a controlled oven at various temperatures as done in the paper [9]. For the experimental sample $\alpha_o = 0.32\%/^{\circ}\text{C}$ and $R_o = 550 \Omega$ at 0°C , thus, the invariant $\alpha_o R_o = 1.76 \Omega/^{\circ}\text{C}$.

Fig. 2 shows the experimental setup. It can be used for all three methods: the dc electrical, bolometric, and the present ac electrical method. The sensor is placed inside a chamber which can be evacuated to a low pressure, if necessary.

In the present ac electrical method the chamber window is shielded from radiation by covering it with a sheet of aluminum foil. A precision power supply and a function generator, both controlled by a PC through a GPIB interface, generate a sinusoidal voltage superimposed on a dc level. This summing voltage is used as a reference voltage for a transimpedance amplifier (TIA) to support the driving current, $I_o + i(t)$, for the microbolometer, as expressed in (4). The TIA output is connected to a lock-in amplifier by ac coupling it, to read the second-harmonic signal, which is then transferred to a PC through the GPIB.

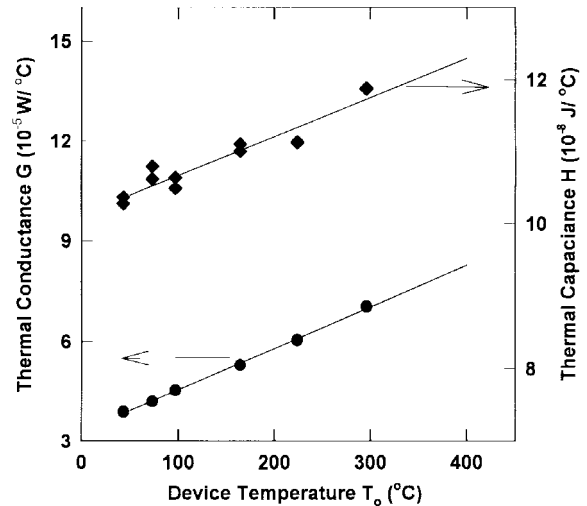


Fig. 4. Temperature dependences of the thermal conductance and capacitance derived from the experimental data.

The dc method and the bolometric method have been carried out in the same way, as before, in our laboratory [12].

Fig. 3 shows the results of the $V_{2\omega}$ spectrum measured by the ac electrical method. Six sets of data were taken under conditions of different I_o and i_m , labeled from a to f in the figure. The low frequency gains of $V_{2\omega}$, were evaluated from the average of 15 points between 2–20 Hz.

IV. RESULTS AND DISCUSSIONS

Table I lists the parameters extracted from the measurements. The thermal conductances are calculated by (11), while the thermal capacitances are computed according to $H = 0.757 \cdot (G_{eff}/\omega_{3dB})$ as stated before. The operation

TABLE II
COMPARISONS OF VARIOUS METHODS OF DETERMINING BOLOMETRIC PARAMETERS

	G(W/°C)	H(J/°C)	FREQUENCY TAKEN	COMMENTS
theoretical calculation	(a) 2.93×10^{-5}	(a) 5.89×10^{-8}	X	great uncertainty in assigning material parameters
A.C. electrical method	(b) 3.64×10^{-5}	(c) 1.02×10^{-7}	second-harmonic frequency	fast, simple and accurate
D.C. electrical method	5.57×10^{-5}	X	D.C.	requiring accurate ambient temperature measurement
bolometric method	(e) $1.2 \times 10^{-4} \epsilon$	7.90×10^{-8}	fundamental frequency	requiring accurate optical power calibration

(a) [2], [9], (b) by eq. (14) and (c) by eq. (15). All are calculated at 27°C.

(e) depends on the emissivity, ϵ , of the sensor surface.

temperature, T_o , of the microsensor is evaluated from the measured R_o according to (1). Based on those data, the temperature dependence of the thermal conductance as well as capacitance can be expressed empirically by the following equations:

$$G(T) \approx 1.2451 \times 10^{-7} \cdot (T - 273^\circ\text{K}) + 3.3022 \times 10^{-5} \quad (14)$$

$$H(T) \approx 5.4298 \times 10^{-11} \cdot (T - 273^\circ\text{K}) + 1.0130 \times 10^{-7} \quad (15)$$

as also shown in Fig. 4. These temperature-dependent information were not available by the previous methods [10]–[12] and is another advantage of the present technique.

Table II shows the comparisons among all methods mentioned above. Here, a cross symbol X means the parameter is not calculable by the corresponding method. The theoretical values are estimated from the equations in previous reports [2], [9]. Although the bolometric method gives the thermal capacitance value close to that of the ac method at 27 °C, the value is only the average at different device temperatures corresponding to different bias currents. The temperature-dependence behavior cannot be calculated from the bolometric method. Furthermore, the thermal conductance extracted with the bolometric method is incomplete, because of the unknown emissivity, ϵ . In previous work, the dc electrical method was used together with this method to find

out both G and ϵ [12]. But since the dc electrical data could have large error, the derived values could not be trusted completely.

V. CONCLUSIONS

In this study, a new ac electrical method is applied to a resistive thermal microsensor to perform the device parameter extraction. The second harmonic response is selected for the evaluation, which has been proved to be insensitive to the ambient temperature variation and is therefore, better than the previous dc electrical method. The simplicity of the instrumentation as well as the fast time of measurement make it superior to the other methods. It can also provides the temperature-dependent properties of the thermal conductance and capacitance. These data are useful for our electrothermal SPICE model [14]. The method obviously can be applied to other resistive thermal sensors without much modification.

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