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Precise determination of thermal parameters of a microbolometer

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ABSTRACT

Determination of microbolometer thermal properties such as thermal capacitance, conductance, time constant, and IR responsivity is of the utmost importance as they directly influence microbolometer performance. Here we show a technique to measure them by using a minimized self-heating effect, thus leading to their precise determination via measurements based on an AC-biased Wheatstone bridge containing a microbolometer. The bridge outputs were subtracted from each other by a differential voltage preamplifier with its output processed by a lock-in amplifier. The lock-in amplifier output as a function of the amplitude of AC bias provided an amplitude of microbolometer thermal conductivity. A microbolometer temperature response to pulse irradiation of its membrane provided the value of its thermal time constant and, thus, its thermal capacitance. Finally, we also extracted microbolometer responsivity using a blackbody IR source. The method was experimentally verified using a micromachined bolometer, which showed excellent agreement with the analytical solution.

1. Introduction

Midrange infrared (IR) with a wavelength range from (≈8 to ≈14) µm has a wide range of applications such as security and commercial uses. Among security applications, IR surveillance can help firefighters look for people in dense smoke or to identify fire hot spots to extinguish. IR devices can also help police identify cars recently arrived in a parking area. Typical commercial applications are as an aid for driving in poor visibility, looking for hot spots in an electrical power distribution system, finding heat leakages from buildings to conserve energy, precise tumor identification during surgery, and many others. The development of midrange IR detectors dates back to 1947 with the invention of a pneumatic IR detector, called the "Golay cell [1]". In 1984 [2], and following an improvement in 1986 [3], a new concept of a microbolometer as part of a microelectromechanical system (MEMS) device was introduced. This allowed the integration of an array of microbolometers with read-out integrated circuits into a focal plane array, i.e., a true IR imager. The microbolometer, operating in a vacuum, consists of an IR-absorbing thermally isolated membrane integrated with an embedded temperature sensor. Most commonly, the resistive temperature detector (RTD) is made of metal such as Ti [2], phase transition materials such as VO_x [4], or semiconductors such as amorphous Si [5]. Their resistance amplitude R changes with temperature change ΔT as per the equation

$$R = R_0(1 + \alpha{\cdot}\Delta T) \tag{1}$$

where R_0 is sensor resistance at ambient temperature T_0 and α is its temperature coefficient of resistance. Microbolometer membrane ΔT expressed as change of sensor resistance change (ΔR) is:

$$\Delta R = R{-}R_0 = R_0{\cdot}\alpha{\cdot}\Delta T \tag{2}$$

The ΔT value is linearly proportional to the amplitude of absorbed IR radiation (P_{IR}) and inverse to the value of the microbolometer thermal conductance (G) [6], making the G amplitude the parameter of utmost importance

$$\Delta T = \frac{P_{IR}}{G} \tag{3}$$

Other important parameters are thermal capacitance (H) and the thermal time constant (τ), which determine the rate of the microbolometer response as

$$\tau = \frac{H}{G} \tag{4}$$

Thus, all three parameters G, H, and τ have to be determined to optimize the microbolometer performance.

A well-established technique to determine specific heat and thermal conductivity of thin film materials and structures based on 3ω method were proposed earlier [7,8]. The structures were thermally modulated

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making this method especially suitable for thin film materials, less for slow MEMS devices such as IR microbolometers. A single measurement-based method to determine parameters G, H, and τ was proposed and demonstrated by biasing an unbalanced Wheatstone bridge, including a microbolometer with an RTD sensor made of Ti, by a single voltage pulse with a bias amplitude (V_B) with time period $\ll\tau$ at a pressure of $\approx 7.7 \times 10^{-4}$ Pa [9]. The microbolometer behavior is governed by a differential heat balance equation

$$H\frac{d\Delta T}{dt} + G\cdot\Delta T = P_J - P_R = \frac{V_B^2}{4R_0} - P_R, \tag{5}$$

where $P_J = \frac{V_B^2}{4R_0}$ is dissipated joule heat in the microbolometer resistor with an actual value of R_0. At a constant pressure of ≤ 5 Pa, heat convection due to energy transfer by the movement of gas molecules surrounding the membrane and radiation losses P_R at ambient temperature of 25 °C are also negligible [10]. The Eq. (5) with neglected amplitude of P_R can be solved as

$$\Delta T = \frac{V_B^2}{4G\cdot R_0}\left[1 - \exp\left(-\frac{t}{\tau}\right)\right], \tag{6}$$

where t is time. The researchers expressed the Wheatstone bridge output in simplified form as function of time [9]

$$\Delta V = \frac{\alpha\cdot V_B^3}{16G\cdot R_0}\left[1 - \exp\left(-\frac{t}{\tau}\right)\right] \tag{7}$$

With knowledge of V_B, R_0 and α of ≈ 1 V, ≈ 3.9 kΩ, and ≈ 0.0025 K^{-1}, respectively, researchers extracted the value of G from Eq. (7) at steady-state and the value of H from the pulse response slope for $t = 0$ s. The thermal time constant was calculated using Eq. (4). The proposed method was simple; however, during the measurement the P_J amplitude was ≈ 64.1 μW causing the microbolometer membrane with calculated G value of $\approx 7.8 \times 10^{-7}$ W K^{-1} warming by the excessive value of $\Delta T \approx 82.2$ K affecting the R_0 value, which was considered to be constant. The modulated amplitude of R_0 value due to ΔT resulted in a measurement error as Eq. (7) assumes R_0 to be constant. Lowering the V_B amplitude does lower the error due to smaller variation of R amplitude, but the measurement precision suffered due to the low output voltage of the system and signal-to-noise ratio (SNR) because the system response is linearly proportional to the amplitude of V_B.

In addition, at ambient temperature, the radiation determined by the Stefan–Boltzmann law can no longer be neglected. The amplitude of P_J is then split between power loss due to thermal conduction (P_C) and amplitude of P_R:

$$P_J = P_C + P_R = G\cdot\Delta T + A\cdot\varepsilon\cdot\sigma\cdot T^4 \tag{8}$$

where $A = 2a^2$ is the total area of a microbolometer membrane with square shape and side length of a with neglecting its sidewalls area, ε is the emissivity of the microbolometer membrane material, σ is the Stefan–Boltzmann constant with value of $\sigma \approx 5.6704 \times 10^{-8}$ W m^{-2} K^{-4}, and T is the thermodynamic temperature. This situation becomes even worse once the microbolometer membrane is heated up by $\Delta T \approx 82.2$ K as the P_R amplitude increases by a factor of ≈ 2.7.

A method to determine all thermal parameters, such as G, H, and τ, based on a short voltage pulse with duration of ≈ 60 μs was proposed [11]. This technique allowed employment of V_B with amplitude up to ≈ 5 V, resulting in an improved SNR. Due to short pulse duration, the self-heating effect was negligible as it resulted in minimal influence by variation of R. Modern microbolometers use two [12,13] or three-level membrane configurations or carbon nanotubes as IR-sensitive materials [14] and their responses to the P_J are more complicated. Therefore the short pulse technique [11] cannot be utilized and the long pulse method [9] does not provide results with sufficient precision.

Here we show a technique of precise determination of G, H, and τ of an AC-powered Wheatstone bridge containing a microbolometer device with the bridge output signal processed by lock-in amplification technique. The colossal SNR of a lock-in amplifier allowed us to perform the microbolometer testing using a V_B value as low as ≈ 10 mV root mean square (RMS). This low amplitude of V_B resulted in P_J of ≈ 26 nW, leading to marginal microbolometer membrane temperature increase of ≈ 59 mK and allowing precise determination of the value of G with P_R having a minimized effect on the measurement. The value of τ was then extracted by observing the transient response of the microbolometer output to modulated external power supply and calculated H using Eq. (4) as $H = \tau\ G$.

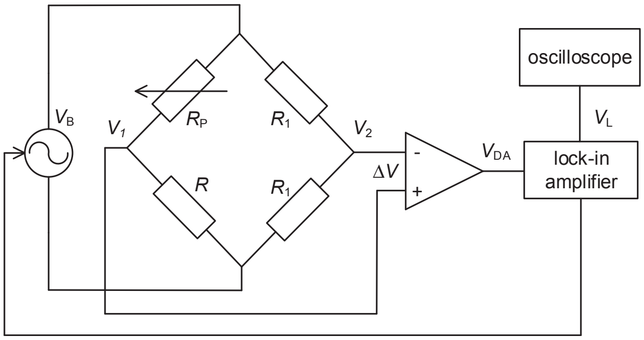

Fig. 1. Schematic of the system used for microbolometer testing. The microbolometer was connected into a Wheatstone bridge powered by an AC signal supplied by a lock-in amplifier. The balancing resistor R_P represents two potentiometers with maximum resistance value of 20 kΩ and 100 Ω, respectively, each with 20 turns for fine-tuning of the bridge balance. The R_1 represents two resistors with the fixed value of 20 kΩ and R stands for microbolometer resistance. The voltage difference of the bridge outputs was amplified by a differential voltage preamplifier with gain B set to 1000, its output voltage processed by a lock-in amplifier, and its output recorded by an oscilloscope.

2. Results and discussion

2.1. Theory and analytical solution

Let us consider the microbolometer connected to a Wheatstone bridge powered by an AC voltage with an amplitude of V_B RMS with its outputs processed by a differential amplifier with a gain factor of B and its output signal processed by a lock-in amplifier with gain of S (Fig. 1). The lock-in amplifier output voltage (V_L) can be expressed as function of ΔT and V_B (see Supplementary S1 for derivation of the equation) as

$$V_L = 10\frac{\left[\frac{R_0(1+\alpha\Delta T)}{R_0(1+\alpha\Delta T)+R_0} - \frac{1}{2}\right]V_B\cdot B}{S} \tag{9}$$

defining transfer function of entire system. For small values of ΔT the value of $\alpha\Delta T \ll 1$ the Eq. (9) can be simplified as

$$V_L = 10\frac{\alpha\Delta T\cdot}{4\cdot S}V_B\cdot B \tag{10}$$

The bridge was power by an AC voltage frequency ≫ than the one corresponding to the τ of the microbolometer. As the microbolometer membrane cannot be modulated by the AC, the total P_J can be considered as $P_J = \frac{V_B^2}{4\cdot R_0}$ warming up the membrane by $\Delta T = \frac{P_J - P_R}{G}$. Assuming the microbolometer membrane had the size of (25 × 25) μm^2 and ε of 0.48 (as per Ref. [15]), the amplitude of P_R at T_0 would be ≈ 251 nW. This P_R would cause the microbolometer membrane with G value of 180.4 nW K^{-1} (in Ref. [16]) to increase its membrane temperature only by ≈ 1.39 K. Nevertheless, as the ΔT during the microbolometer measurement is minimal, the P_R does not significantly change; thus, Eq. (8) can be simplified to $G = P_C/\Delta T$ as the P_R only causes an offset of the ΔV. We can then express V_L as function of G (Supplementary S1) as