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Static characteristics calibration of Pt/Au thin-film thermocouple by means of laser heating and temperature extrapolation method

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ABSTRACT

Thin-film thermocouples (TFTCs), owing to their fast response, show promise for use in temperature measurements with high spatial and temporal resolution. Because of the huge difference in the temperature profiles in the calibration and application, in the strictest sense, the standardised thermocouple calibration method is no longer suitable for TFTCs. However, this issue is always ignored in some TFTC research literature. To realise accurate calibration of a TFTC, a novel method is proposed in this article. The highlight of this method is the use of a laser to heat the hot junction of the TFTC. Then, according to the surrounding calibrated platinum resistance thermometers and the temperature distribution model, the temperature of the hot junction is calculated with an extrapolation method. Finally, the static characteristics of the TFTC are calibrated through establishing the function between the calculated temperatures and the electromotive forces (EMFs). In order to verify the applicability of this method, a Pt/Au TFTC sensor is designed on a thin cylindrical substrate. Through numerical simulation, a logarithmic model is obtained to describe the temperature distribution regularity of the sensor under laser heating. With screen-printed sensor fabrication and experimental setup realisation, the EMFs and resistances of the platinum resistors are recorded simultaneously. The results leads to the following three conclusions. First, this method can calibrate the Seebeck coefficient of the legs of the TFTC, where the temperature gradient is concentrated in applications. Second, the method shows good repeatability and stability in three repeated experiments. Third, the value of the calibrated temperature and the EMF curve of the TFTC are similar to those of bulk Pt/Au thermocouple. This signifies that the proposed calibration method is reliable and effective.

1. Introduction

Thin-film thermocouples (TFTCs), with the advantages of fast response and small physical size, have become a promising choice for the temperature measurements in high spatial and temporal resolution. Owing to these advantages, TFTCs have been developed on different materials with several types of fabrication techniques (magnetron sputtering [1–3], vacuum evaporation [4], and screen printing [5,6]) and applied in various transient-temperature measurement fields, including battery thermal runaway detection [7,8], chip calorimeters [9], and aeronautics propulsion systems [10]. Regardless of what fabrication method is adopted or what field the TFTCs are used in, the principle of almost all metal-based TFTCs is the Seebeck effect [11]. In order to measure the transient temperature accurately, the relationship between temperatures and electromotive forces (EMFs) of the TFTC should be calibrated first.

For the conventional wire-style thermocouple, the static characteristic calibration procedure is standardised [12]. The tested thermocouples are placed, together with a standard thermometer in a tubular furnace, and the function between the EMF of the tested thermocouple and the temperature measured by the standard thermometer is set up. In many small-size TFTC studies, this standardised calibration method is still widely adopted [8,13–15]. In the literature, authors use the main body of the TFTC and the extension wires to compose the temperature sensor. The whole TFTC is put in a temperature-controlled furnace for calibration. In this case, there is no temperature gradient on the TFTC. The TFTC itself generates no EMF. The recorded EMF signal doesn't reflect the thermoelectric properties of the TFTC, but those of the extension wires. The standardised calibration method is not suitable for TFTCs, especially for the small-size ones. This standardised method can only work under the following two conditions. First, the thermocouple and compensation wires are homogeneous. This is not

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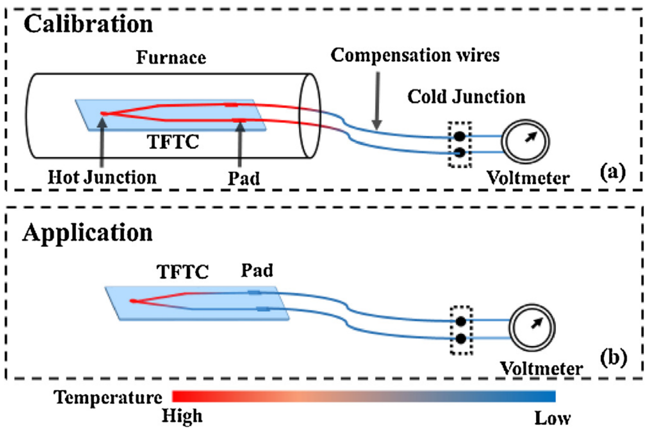

Fig. 1. The temperature distribution of the TFTC in calibration and application. The colour bar indicates the temperature. The red colour means high temperature. The blue colour means low temperature. (a) In the calibration, the temperature gradient is distributed on the compensation wires. (b) In application, the temperature gradient is distributed on the TFTC. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

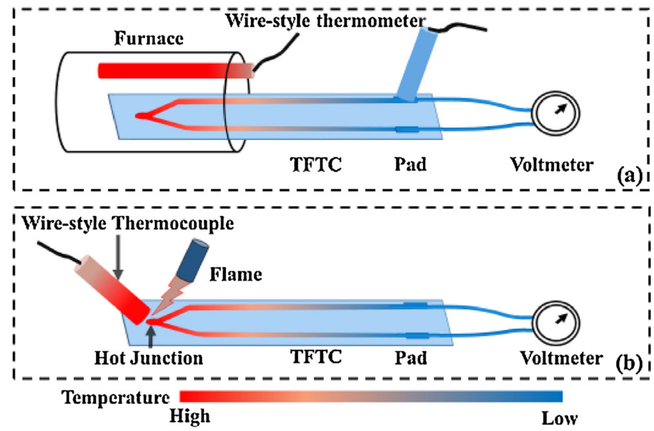

Fig. 2. Improved and nonstandard method for TFTC calibration. The colour bar indicates the temperature. (a) In the improved calibration method, the TFTC is long enough to span the length of the furnace. One standard thermometer is put in the furnace to record the hot-junction temperature, while the other one is put on the cold junction. (b) In the non-standard method, the hot junction of the TFTC is heated by a flame. In fact, the standard thermometer is much wider than the hot junction of the TFTC.

easy to achieve in TFTC calibration and application. The main body of TFTCs and junctions are fabricated by sputtering, evaporation or screen printing. However, their compensation wires that connect the pads and cold junctions are bulk wires. The materials of TFTCs and compensation wires can remain the same. Nevertheless, with different manufacture processes, they are essentially inhomogeneous, because the Seebeck coefficient of the metals depends not only on the material's chemical properties but also on its physical properties, and even the substrate. Wunderlich et al. found that the EMF differs when Pt/Pd TFTCs are fabricated on a substrate of alumina and mullite [16]. Cattani et al. reported that the Seebeck coefficient of TFTC is degraded with decreasing junction thickness because of the classic size effect based on the free electron conduction model [17]. Chen fabricated a very long S-type TFTC with sputtering technology. The calibration results showed that the EMF of the sputtered TFTC was smaller than that of the standard S-type bulk thermocouple [18]. Yang studied the size effect on the sensitivity of a T-type thermocouple. She found that the sensitivity of a Cu/CuNi TFTC is higher than that of the bulk T-type thermocouple [19]. Second, the temperature profile in the calibration is identical to the temperature profile in application. This is also difficult to implement. In transient temperature measurement conditions, the temperature gradient is distributed around the hot junction. However, in the calibration, the temperature gradient is distributed on the compensation wires, as shown in Fig. 1. Using the conventional calibration method to calibrate the TFTC, it just calibrates the Seebeck coefficient of the compensation wires, not of the TFTC itself.

To calibrate the Seebeck coefficient of the TFTC itself, the temperature gradient should move to the TFTC, as shown in Fig. 2. Jiang and his colleagues prepared a long-size Pt-10%Rh/Pt TFTC. The main body of the TFTC was long enough to lie across the furnace. In this calibration, the hot junction of the TFTC was in the furnace, while the pads were out of the furnace [18,20]. The temperature gradient on the TFTC can reach approximately 1000 K. However, this improvement still cannot satisfy the second condition of the conventional calibration method. Moreover, this long-size TFTC is not acceptable in many transient-temperature measurement applications. There are also some non-standard methods adopted in TFTC studies. Their main concept is attaching one reference wire-style thermocouple to the hot junction area of the TFTC and heating this area with an electric element [21] or flame [10]. If the heat is supplied by an electric element, the temperature rise is small, usually about 100 K. If the heat is supplied by a flame, the temperature rise can reach 1000 K, whereas the value of the temperature cannot be controlled easily and stably. Moreover, in these non-standard calibrations, the size of the hot junction of the wire-style thermocouple is much larger than that of the TFTC, and the temperature difference between these two hot junctions is large and non-negligible. Consequently, the temperature measured by the reference thermocouple is not equal to the temperature of the TFTC's hot junction. Recently, Sinha et al. designed a self-calibration thermocouple probe for intracellular temperature measurement and studied a suitable calibration method in a vacuum environment [22]. In their studies, an on-chip resistance heater was integrated to generate the temperature rise. A Au resistance thermometer and the hot junction are located symmetrically on the two sides of the heater. Nevertheless, limited by the resistance value of the heater, the temperature rise was about 10 K. The covers the temperature ranges of biological temperature measurements. However, for many industrial applications, it is insufficient.

To realise an accurate static characteristic calibration of a small-size TFTC, a method based on laser heating and temperature extrapolation is proposed in this study. The highlight of this method is using a laser to heat the hot junction of the TFTC. Then according to two calibrated platinum resistance thermometers (PRTs) located around the hot junction and the temperature distribution model, the temperature of the hot junction is calculated with the extrapolation method. The static characteristics of the TFTC are calibrated through establishing the function between the extrapolated temperatures and recorded EMFs. In order to verify this calibration method, a Pt/Au TFTC sensor was fabricated using screen printing technology, and the temperature distribution regularity of the sensor under laser heating was analysed by numerical simulation. An experimental setup that can record the EMF and PRT temperature simultaneously was built using a digital quadrature detection algorithm. The static characteristics of the TFTC were investigated experimentally and compared with the standard Pt/Au thermocouple. Additionally, the uncertainty of this calibration method was analysed. All the details will be described in the following sections.

2. Sensor design and fabrication

To obtain the temperature distribution model simply, the TFTC was designed on a thin cylindrical Al_2O_3 ceramic substrate, as shown in Fig. 3(a). The nominal value of the thermal conductivity