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A bi-material microcantilever temperature sensor based on optical readout

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ABSTRACT

As one of the simplest MEMS sensors, microcantilever can sense temperature faster and more sensitively than traditional thermometers as its small size and low thermal mass. In this paper, an Au/SiN*x* bi-material microcantilever temperature sensor based on optical readout is presented. The deflection of the cantilever varies with the change of temperature due to the differences in thermal expansion coefficients between gold and silicon nitride. Then, the temperature could be accurately measured by detecting the deflection of the cantilever with optical lever method. By experiments, the theoretical model is verified and the temperature characteristics of the sensor are also determined. With a commercial microcantilever, the temperature resolution of the sensor is tested to be 0.02 K when 25 mm length of optical arm set. By optimizing the microcantilever parameters, the temperature resolution of the sensor could be 0.1 mK. High sensitivity makes it suitable for some special precise temperature measurements.

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1. Introduction

Temperature is an important physical quantity in industrial and agricultural production, exploration of energy sources, environmental monitoring, and scientific research, etc. Accurate temperature measurement is very important in some special fields. Currently, many kinds of temperature sensors have been manufactured [1], such as thermocouple temperature sensors, thermal resistance temperature sensors, bi-metal temperature sensors and so on. Although a vast selection of temperature sensors exists, there is no simple solution for all applications due to their respective characteristics and temperature measurement limitations. For example, the thermocouple thermometers need to provide a constant reference temperature environment; Thermal resistance temperature sensors have high temperature nonlinearity; Bi-metal temperature sensors response slowly, and their temperature resolution is not high. For these reasons, they are difficult to meet some special temperature measurement requirements, examples as observation of oscillations in the catalyzed reaction of hydrogen and oxygen on platinum [2] and the photothermal spectroscopy studies of amorphous silicon [3]. Development of a high resolution, fast response, and low cost temperature sensor is desired.

In recent years, MEMS sensing technology has been greatly developed [4–7] with improvement of micro-fabrication technology for integrated circuit and ultra-precision micro-machining technology. As one of the simplest MEMS sensors, microcantilever can sense temperature rapidly and sensitively, whose time constant and temperature resolution can be of the order of milliseconds (ms) and 10^{-5} Kelvin (K), respectively [3,8]. The deflection of the bi-material microcantilever varies with the change of temperature based on the differences in thermal expansion coefficients between the two materials (such as silicon nitride and thin gold film) [8–10]. Theoretical calculation and experimental results both show that there is a linear relationship between the deflection of the microcantilever and the temperature, so the temperature could be measured by detecting the deflection of the microcantilever.

The methods for monitoring the microcantilever deformation mainly include optical methods (optical

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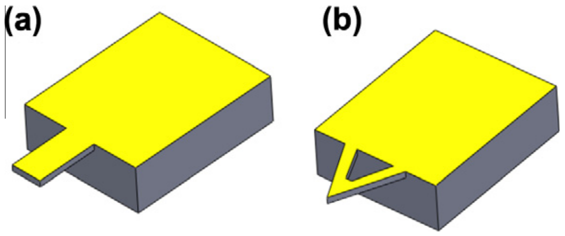

Fig. 1. The rectangular cantilever (a) and the triangular cantilever (b).

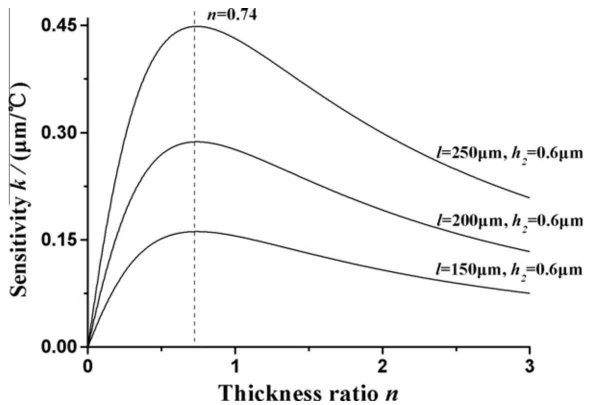

Fig. 2. Thermal response sensitivity curves of the triangular bi-material microcantilever. From the curves, it can be found that with the increase of n, k increases in the former halfway and then decreases in the latter halfway, and achieves the maximum when n is 0.74. In fact, no matter what values of l and h_2 are, this trend of k with n is unchanged.

interferometry [11] and optical lever [12]) and electrical methods (capacitance, piezoresistive, and piezoelectric) [13]. As one of these methods, optical lever method has advantages of simple structure, high sensitivity, refraining electrical noise, and can detect the displacement of the order of 10^{-11} m [13–15].

The microcantilever sensing technology based on optical readout has been used in infrared imaging of thermal deformation [16,17] and detection of biochemical reactions [18,19]. In this study, it is used for temperature measurement, and a high-resolution temperature sensor is designed and fabricated. Finally, the temperature characteristics of the bi-material microcantilever have been tested and verified by experiments.

2. Theoretical analysis

2.1. Thermal deformation of the bi-material microcantilever

By the knowledge of Material Mechanics, the thermal deformation formula of a rectangular bi-material cantilever can be expressed as [3,13]:

$$\delta = 3(\alpha_1 - \alpha_2)\left(\frac{n+1}{\beta}\right)\left(\frac{l^2}{h_2}\right)\Delta T \qquad (1)$$

where δ is the vertical deflection of the cantilever tip, α is the thermal expansion coefficient with the subscripts referring to the two layers of the cantilever, l is the length of the cantilever, ΔT is the change of the ambient temperature and β is given by

$$\beta = 4 + 6n + 4n^2 + \phi n^3 + \frac{1}{\phi n} \quad , \quad n = \frac{h_1}{h_2} \quad , \quad \phi = \frac{E_1}{E_2}$$

where h is the thickness and E is the Young's modulus for each of the two materials, n is the thickness ratio and Φ is the Young's modulus ratio of the two materials, respectively.

Eq. (1) is for the rectangular cantilever (Fig. 1a), however, a commercial triangular microcantilever (Fig. 1b) is used in the experiments, so there must be a transition between the vertical deflection of the two cantilevers. With the same physical parameters, their corresponding relationship is as follow [20]:

$$\delta_r = 1.15\delta_t \qquad (2)$$

where δ_r is the vertical deflection of the rectangular cantilever tip, and δ_t is the vertical deflection of the triangular cantilever tip.

For the Au/SiNx bi-material microcantilever, introducing the material parameters of gold and silicon nitride ($\alpha_1 = 14.2 \times 10^{-6}\,K^{-1}$, $\alpha_2 = 0.8 \times 10^{-6}\,K^{-1}$, $E_1 = 73$ GPa, $E_2 = 180$ GPa) into Eqs. (1) and (2), then the thermal response sensitivity k ($\delta/\Delta T$) of the triangular microcantilever can be written as:

$$k = \frac{34.96 \times 10^{-6} \times (n+1)}{4 + 6n + 4n^2 + 73n^3/180 + 180/(73n)} \times \left(\frac{l^2}{h_2}\right) \qquad (3)$$

By calculation, k can achieve the maximum $4.3 \times 10^{-6}\, l^2/h_2$ when n is 0.74. In order to directly observe the specific trend of k with n, the values of l and h_2 should be given. Usually, a cantilever is fabricated to be the typical dimensions of 100–200 μm in length, 20–40 μm in width and 0.6 μm in thickness [9,21]. Therefore, we set h_2 to 0.6 μm, l to 150 μm, 200 μm, 250 μm, and then draw the corresponding curves of k verses n, which are shown in Fig. 2.

For the Au/SiNx bi-material microcantilever, if the geometric parameters are defined, the thermal response sensitivity k will be a constant. Furthermore, the bending

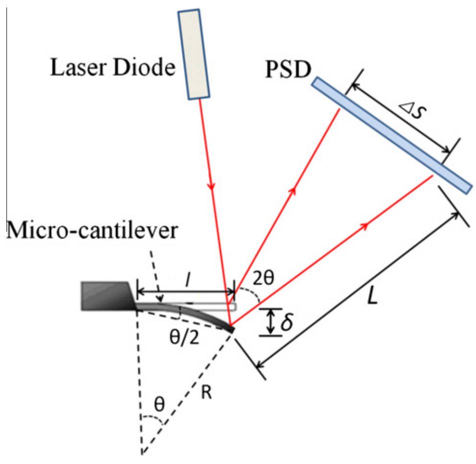

Fig. 3. Schematic diagram of optical lever.

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