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In-situ determination of the coefficient of thermal expansion of polysilicon thin films using micro-rotating structures

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ABSTRACT

A simple method for *in situ* determination of the coefficient of thermal expansion (CTE) of polysilicon thin films by using micro-rotating structures is presented. The structures are heated electrically and deflect due to the thermal expansion. An analytical expression is derived to relate the CTE of the polysilicon thin film with the lateral displacement, geometrical parameters and the average temperature of the test structure. The lateral displacement is designed to be a constant value (2 μm), while the average temperature of the test structure can be obtained from the measurement of resistance of the test structure. Instead of an optical or visual readout, electrical input and electrical readout are utilized. In the experiments, a current–voltage measurement system only is required and all measurements can be carried out in atmosphere. Finite element analysis and experimental results with surface micromachined polysilicon thin films are used to demonstrate the effectiveness of the proposed method. The average value of the obtained CTE is $(2.76 \pm 0.09) \times 10^{-6}\ \mathrm{K}^{-1}$ with temperature ranging from 450 K to 500 K.

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1. Introduction

The coefficient of thermal expansion (CTE) of polysilicon thin film is an important material property in design and fabrication of micro-electro-mechanical systems (MEMS) devices. The mismatch of CTEs between attached films may introduce residual stresses which lead to shift of performance or even failure of MEMS devices. Besides, thermal expansion effect can be exploited to thermally drive MEMS devices [1,2]. Behaviors of MEMS devices are sensitive to variations in material parameters including the CTE which may vary with manufacturing conditions of fabrication process [3]. Therefore, it is important to ascertain the CTE of thin films from process line in order to predict device performances and obtain accurate compensation of device response to changing conditions. Moreover, the extracted parameter also provides direct quality-control information for fabrication process line.

A lot of works on the CTE of bulk materials have been reported [4–7]. However, these reported methods may not be appropriate for the measurement of the CTE of thin films in MEMS, since the dimension of thickness of the thin film is too small to meet the sophisticated preparation requirements of traditional methods. Because of the small size of thin film samples, deflections induced by thermal expansion is often too small to detect directly. Murarka et al. and Retajczyk et al. have deposited the thin film on two different substrates and optically measured the change in the curvature of wafer induced by the deposited thin film to determine the CTE of the thin film [8,9]. In this method, the CTE of the thin film is calculated with known Young's modulus, Poisson's ratio of the deposited thin film and the CTE of the substrates. Cetinorgu has improved this two-substrate method and developed a one-substrate method which is semi-empirical and has the advantage of requiring only one substrate in order to extract the CTE of the thin film [10]. Fang et al. and Tada et al. have utilized the out-of-plane deflection of micromachined cantilevers caused by the temperature change to determine the CTE of the thin films [11,12]. The deflection is measured by using the optical interferometric technique. Pan has reported a structure composed of a pair of cantilever beams with different lengths connected by a short tip beam to measure the CTE of the thin film [13]. When the temperature changes, a large displacement of the tip beam induced by different expansions or contractions between the two cantilever beams has been observed and measured with an optical microscope. The CTE of the thin film can be calculated by using this piece of information. Chae et al. have adopted microgauge structure, which is heating by applying a current into the structure and magnifies the tiny displacement caused by thermal expansion, to test the CTE of the thin film [14]. The structure is placed in a vacuum chamber and the displacement is measured by an optical microscope. Wang et al. have exploited tensile experiments at different temperatures to measure the CTE of the thin film [15]. The measurements are performed by a special testing device. Coster et al. have proposed a method that uses a laser Doppler vibrometer (LDV) for extracting the CTE of the thin film in vacuum [16]. With the knowledge of the CTE of the substrate and the measurement of the resonance frequencies with the LDV's laser pointed at the beam at different temperatures, the CTE of the thin film can be obtained.

Most extant extracting methods for the measurement of the CTE of thin films made use of an optical or visual readout, which render the

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test structures useless upon packaging. Some methods use expensive instruments or special testing devices. Some methods require knowledge of other physical properties of the thin film specimen or the substrate. Some of them are only available in a vacuum chamber. Although useful in a laboratory setting, the operations of such methods are inconvenient for high volume manufacturing, which prevents these methods from meeting the requirement for *in situ* measurement. Constitutive properties of the thin films, such as elastic constants, residual stress and thermal properties, may vary significantly depending on the precise process sequence. Hence, it is important for MEMS designers to have access to test data from appropriate test structures that document the constitutive properties, and these data must come from the actual process line where the devices are to be manufactured. It is therefore hoped that test methods can be operated in atmosphere and can be applied at the wafer level using ordinary wafer-probe test equipment. An electrical readout better conforms to standard integrated circuit (IC) test equipment and procedures. Moreover, an electrical readout permits the test structure to be co-fabricated or co-packaged with other devices, potentially giving rise to many conceivable applications. Therefore, the test methods, which exploit electrical readout and can be carried out in free air, are much more preferred by foundries. Parameters extracted in such methods could be directly used in quality control.

Rotating technique is usually adopted to measure residual stress [17,18]. In this study, an electrical test structure combined with rotating technique for measuring the CTE of surface micromachined polysilicon thin films is proposed [19]. The test structure is heated by applying direct voltage current and a displacement caused by thermal expansion occurs. An analytical expression is derived to relate the CTE of the polysilicon thin film with the lateral displacement, geometrical parameters and the average temperature of the test structure. The displacement is designed to be a constant value (2 μm) and the average temperature can be extracted from the measured polysilicon resistance. The finite element software ANSYS is used to verify and modify the model. The simulation also provides guidelines for structure design. Instead of an optical or visual readout, an electronic readout is utilized. All measurements are operated in free air. The average value of the obtained CTE is $(2.76 \pm 0.09) \times 10^{-6}\ \mathrm{K}^{-1}$ with temperature ranging from 450 K to 500 K.

2. Analytical model

The schematic view of the micro-rotating structure for measuring CTEs of polysilicon thin films is illustrated in Fig. 1. In Fig. 1(b), the clear parts are movable structures and the dark parts are anchors. The structure consists of one rotating beam and two test beams. The test beams are connected off-center to the opposite sides of the rotating beam. As shown in Fig. 1, L_1 is the length of the top side of the rotating beam; L_5 is the length of the bottom side of the rotating beam; W_1 is the width of the rotating beam; L_2 and W_2 are the length and width of the test beam, respectively; L_3 and W_3 are the length and width of the connecting part between test beams, respectively; and L_4 and W_4 are the length and width of the connecting part between the test beam and the anchor, respectively. The initial gap between the tip of the rotating beam and the contact electrode is designed to be a constant value (2 μm). The test structure is heated with Joule heat by forcing a current through two test beams and the thermal expansion of the test beams occurs. Since the length of the test beam is much larger than its width and thickness, thermal expansion mainly occurs along the length direction of the test beams. The thermal strain is

$$\varepsilon = \alpha \cdot (T_{avr} - T_0) \quad (1)$$

where ε is the thermal strain along the length direction of the test beam, α is the CTE, T_{avr} is the average temperature of the test beam when the current is applied, and T_0 is the initial temperature of the test beam. It is obvious that $\Delta T = T_{avr} - T_0$ is the temperature change of the test beam.

The thermal expansion of the test beam due to the thermal strain causes the movement of the rotating beam. The rotating beam

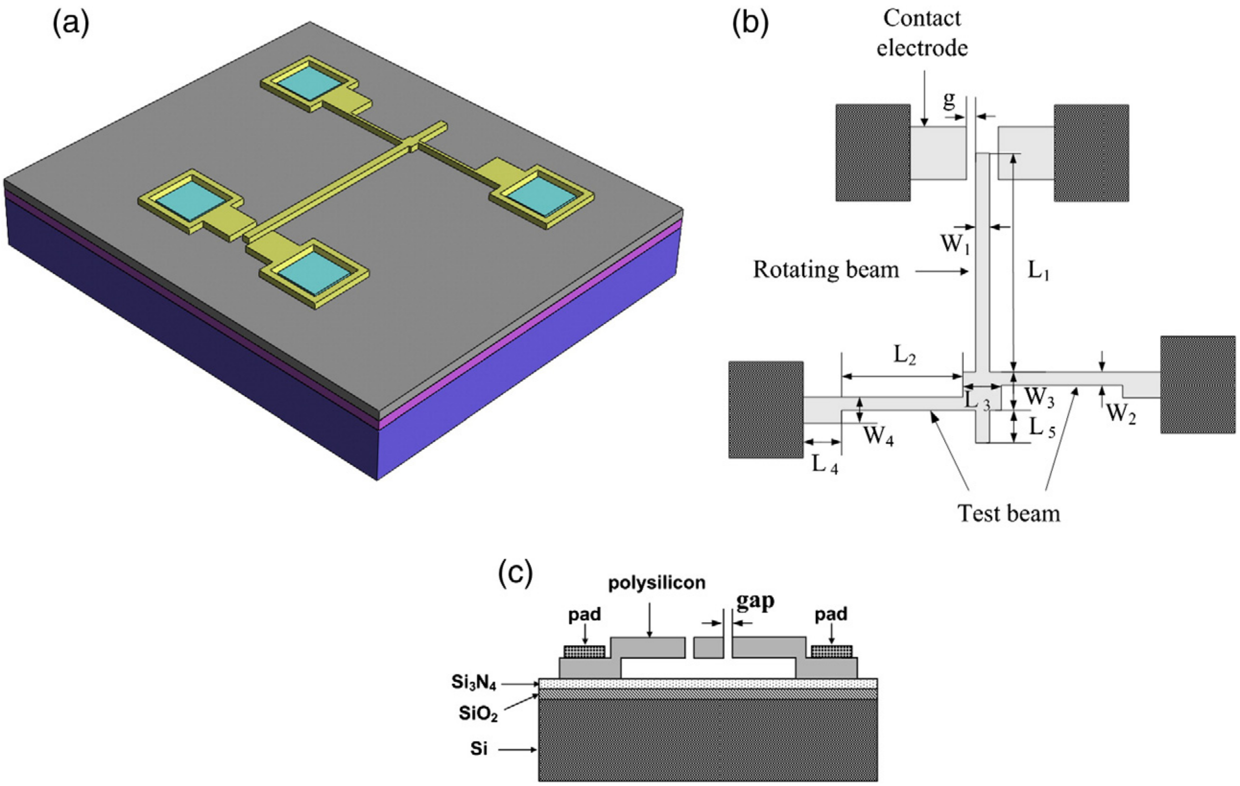

Fig. 1. Schematic view of the micro-rotating structure for measuring CTEs of polysilicon thin films. (a) Overall view; (b) top view; (c) cross section view.

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