

Measurement of thermal expansion coefficient of poly-Si using microgauge sensors

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Abstract

We present a micro electromechanical system (MEMS) structure to study the thermal expansion coefficient of polycrystalline silicon (poly-Si) thin film. Under conventional optically levered laser beam techniques, it is important to know some physical values, namely the thermal expansion coefficient of the substrate and $E/1 - \nu$ of the thin film, in order to measure the thermal expansion coefficient of the thin film. Also, an expensive optically levered laser beam system is needed. But in the microgauge method, other physical values are not needed and the thermal expansion coefficient of thin film could be observed only with an optical microscope and a current–voltage measurement system. The microgauge can be fabricated in situ along with active microsensors or actuators on the same chip for monitoring the thermal expansion coefficient of the thin film. A bias was applied across the microbridge anchors. Current–voltage characteristics and the displacement at the microgauge were measured at the same time when the microgauge was driven in vacuum chamber. After thermal analysis and mechanical analysis, the thermal expansion coefficient of poly-Si thin film was calculated. The experimental values for the thermal expansion coefficient of poly-Si thin film was $2.9 \times 10^{-6}/\text{K}$ with the standard deviation of $0.24 \times 10^{-6}/\text{K}$. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Thermal expansion coefficient; Poly-Si; Microgauge; Microbridge; Thin film; Measurement

1. Introduction

The thermal expansion coefficient of poly-Si thin film is an important parameter in the design of thermally driven microactuators [1–3] and in measurement of measuring intrinsic stress originated from deposition processes [4,5]. Murarka [4] and Retajczyk [5] reported using optically levered laser beam techniques to measure the thermal expansion coefficient of thin film. These authors determined the film stress by measuring changes in the curvature of the wafers induced by the deposited films. By analyzing stress as a function of temperature and doing the same experiments on identical thin film on a different substrate with known thermal expansion coefficient, the value of the thermal expansion coefficient of the thin film was calculated. But optically levered laser beam techniques to measure the thermal expansion coefficient of poly-Si thin film requires the knowledge of the thermal

expansion coefficient of the substrate and $E/1 - \nu$ of the thin film, where E and ν are the elastic modulus and Poisson's ratio of the thin film respectively. So, if we do not know exactly those physical values, we cannot get the exact value for the thermal expansion coefficient of the thin film. In this paper, we describe a new method which can be used to measure the thermal expansion coefficient of conductive thin film, this does not need other physical parameter values.

Fig. 1 shows a schematic diagram of the microgauge in our experiments. To thermally drive the microgauge, a large current should be applied so that enough Joule heating could be generated at the microgauge. For the microgauge to have enough conductivity, phosphorus was used to heavily dope the poly-Si microgauge structure by PSG (phosphosilicate glass) source.

When the current is applied to the microgauge, the test beam of the microgauge heats up. As the temperature of the test beam rises, thermal expansion of the test beam occurs. The idea is to magnify the tiny displacement caused by thermal expansion of the test beam. The thermal

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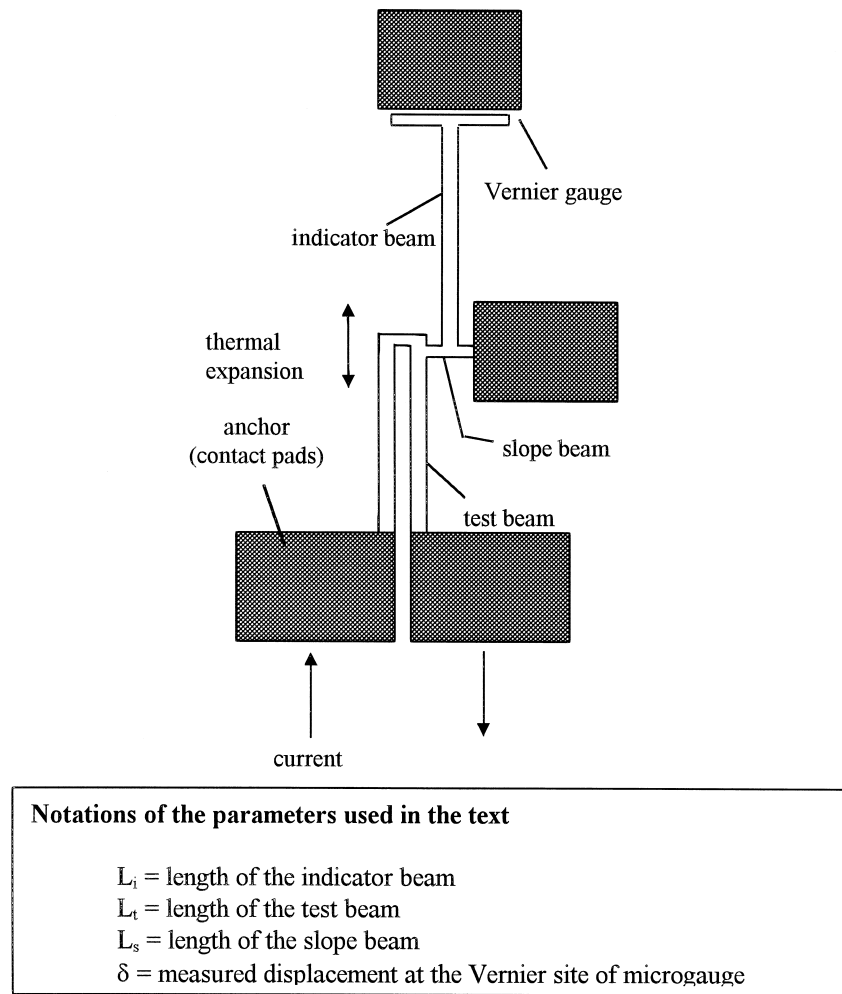


Fig. 1. Schematic illustration of microgauge structure.

expansion of the test beam due to Joule heating effect causes the movement of the slope beam and then creates tiny rotations at the indicator beam. The indicator beam magnifies the slope and a large displacement is generated at the site of the vernier gauge. The amount of displacement at the vernier gauge is measured with optical microscope. The average temperature of the microgauge, when current is applied, is calculated with known experimental parameters such as design parameters of the microgauge, and measured current, applied voltages. The microgauge equation relates the thermal expansion of the thin film as a function of the average temperature of the microgauge and measured displacement at the microgauge. The thermal expansion coefficient of poly-Si was calculated from the microgauge equation with calculated average temperature and measured displacement at the microgauge.

2. Fabrication

The fabrication process for the devices started with 4-in. (100) silicon wafers. 1000 Å thick silicon oxide was

grown as a stress buffer layer for the next silicon nitride layer. After the growth of silicon oxide, 1000 Å thick LPCVD silicon nitride layer was deposited. The nitride layer acted as an isolation layer between devices and the substrate. 2 μm thick PSG layer was then deposited on the silicon nitride layer. This PSG layer was used both as a sacrificial layer and the phosphorus diffusion sources for poly-Si layer. 3 μm thick LPCVD poly-Si was then deposited. Again, 2 μm thick PSG layer was deposited on the poly-Si layer as a phosphorus diffusion source. This step was followed by a high temperature phosphorus diffusion step at 1000°C for 10 h which also annealed out intrinsic stress in the deposited poly-Si. Upper PSG layer was stripped out in buffered oxide etch (BOE) solution and 6000 Å thick APCVD silicon oxide layer was deposited on the poly-Si layer. This APCVD oxide layer was used as a hard mask for defining poly-Si devices. After patterning APCVD silicon oxide, poly-Si layer was dry etched with APCVD silicon oxide hard mask and then device structures were defined. APCVD silicon oxide hard mask was removed by dry etching. Conventional aluminum metalization followed, and a second patterning process defined

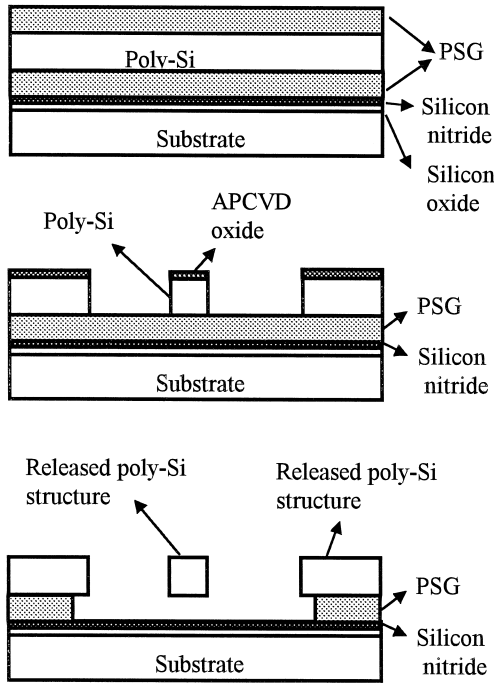


Fig. 2. Schematic sequence illustration of device fabrication.

contact pads of the devices. A time controlled PSG etch freed the microgauge. The PSG etch was stopped when the poly-Si microgauge was freed completely. At this time, the anchors of the microgauge were only slightly undercut because of their larger size. For the last step, 25.4 μm (1-mil) thick Al wires were bonded between contact pads of the devices and copper lead frames. The fabrication process flow is shown in Fig. 2.

3. Theory

3.1. Mechanical theory

Fig. 1 is the schematic diagram of the microgauge structure. Dark parts are anchors which are attached to the substrate. Clear parts are movable free standing structures. Ohmic dissipation is used to heat the test beam. When

current is applied to the test beam, thermal expansion of the test beam occurs. This causes the movement of the slope beam and creates tiny rotations. The indicator beam magnifies the slope, and a large displacement is generated at the site of the vernier gauge. The microgauge has a fine resolution of 0.2 μm at the vernier gauge.

From beam analysis for the slope beam, the displacement at the vernier gauge can be represented as [6]

$$\delta = \frac{3L_i L_t c_f \varepsilon}{2L_s} \quad (1)$$

L_s is the length of the slope beam, δ is measured displacement at the microgauge, L_i is the length of the indicator beam, L_t is the length of the test beam, and ε is thermal strain due to thermal expansion of the test beam. Fig. 1 shows parameters used in Eq. (1). If thermal expansion of the test beam occurs, the slope beam cannot deflect continuously as beam theory expects. The nonzero width of the indicator beam affects the deflection of the slope beam as seen in Fig. 3. c_f is a correction factor for the presence of the slope beam and can be derived as [6]

$$c_f = \frac{1 - d^2}{1 - d^3} \quad (2)$$

where d is the ratio of the width of the indicator beam, w_i , over the length of the slope beam, L_s . The thermal strain at the test beam due to thermal expansion can be represented as

$$\varepsilon = \alpha \Delta T = \alpha (T_{\text{avr}} - T_s) \quad (3)$$

where α is a thermal expansion coefficient of thin film, T_{avr} is average temperature of the microgauge when current is applied, T_s is the temperature of the substrate. Substituting Eqs. (1) and (2) into Eq. (3), we have

$$\alpha = \frac{2L_s \delta}{3L_i L_t c_f (T_{\text{avr}} - T_s)} \quad (4)$$

It is clear that if we measure the displacement at the vernier gauge (δ) and calculate the average temperature of the microgauge when current is applied, we can calculate

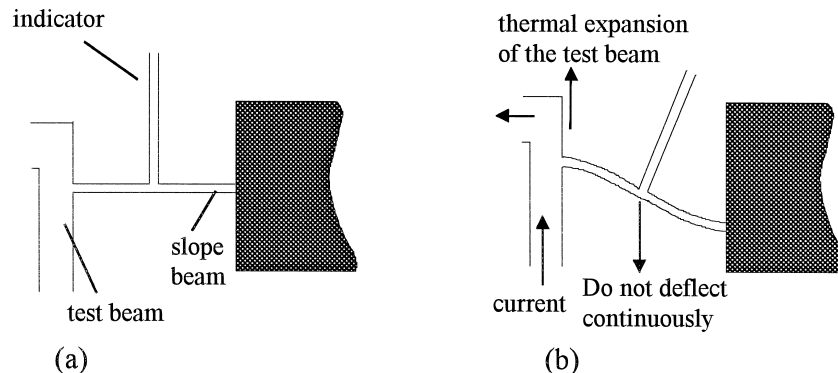


Fig. 3. Deflection of the slope beam due to thermal expansion of the test beam. (a) No applied current. (b) With applied current. The slope beam does not deflect continuously as beam theory expects due to the presence of the indicator beam.

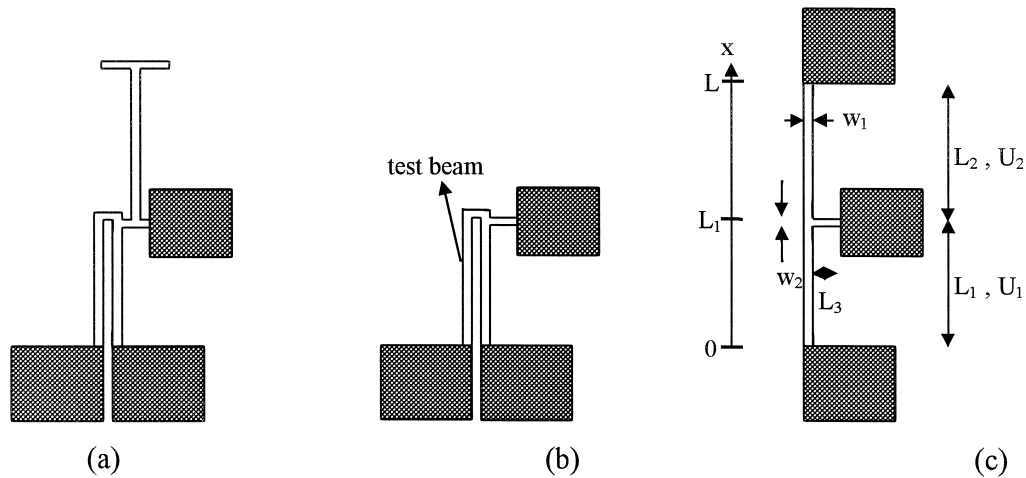


Fig. 4. Simple modeling of the microgauge as a T-shaped microbridge. (a) Initial feature of the microgauge. (b) The indicator beam can be neglected in heat conduction equation because it is floated with respect to heat flow. (c) T-shaped microbridge is equivalent to the microgauge with respect to the heat conduction equation.

the thermal expansion coefficient of thin film because other parameters are known.

3.2. Thermoelectrical theory

According to the Eq. (4), the average temperature of the microgauge, when the current is applied, is needed in order to calculate the thermal expansion coefficient of thin film. The average temperature of the microgauge was calculated by the following sequences.

First, the temperature profiles of the microbridge along the test beam length was induced from the differential heat conduction equation. In this step, the microgauge was modeled as T-shaped microgauge as shown in Fig. 4.

Second, the temperature profiles were integrated along the test beam length, and then divided by its total length, resulted in average temperature of the microgauge.

In order to get the temperature profiles of the microgauge, the microgauge is simply modeled as a T-shaped microbridge. Fig. 4 shows T-shaped microbridge. U_1 is the

temperature profile along the bridge region $0 < x < L_1$, U_2 is the temperature profile region $L_1 < x < L$.

If the power is applied to the microgauge, it heats up. There are three heat dissipation mechanisms for the power applied to the microgauge. First, the heat is directly conducted through the beam itself to the contact pads of the microgauge and then to the substrate. Second, the heat is dissipated by conductive and convective mechanism through the air. Third, the heat is dissipated into the environment in the form of infrared radiation. If the microgauge is driven in vacuum chamber, we can assume that heat is transported only by conduction through the heavily doped poly-Si microgauge arms because the amount of free molecule air conduction is negligible compared with the amount of heat generated in the microgauge by Joule heating [7,8]. If the average temperature of the microgauge does not exceed 600°C (in this experiment it was 200°C) heat loss by radiation is also negligible. The amount of heat loss by convection, conduction through the air and radiation loss was calculated in the same way as done by Mastrangelo et al. [7,8].

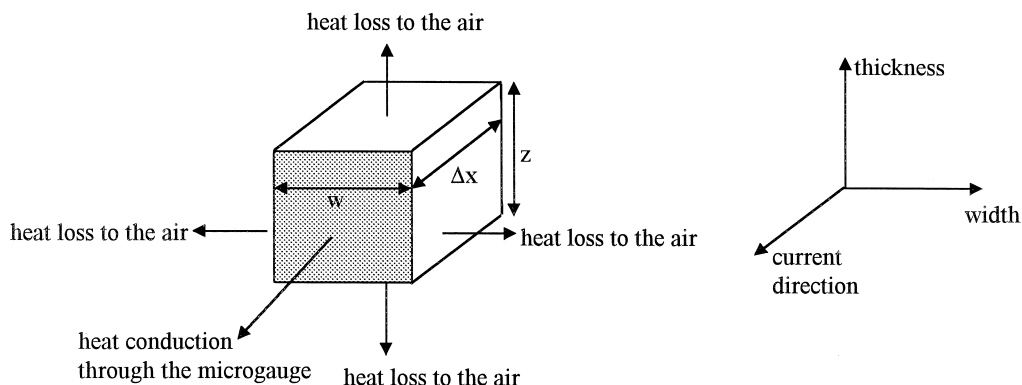


Fig. 5. Differential element of the microgauge structure.

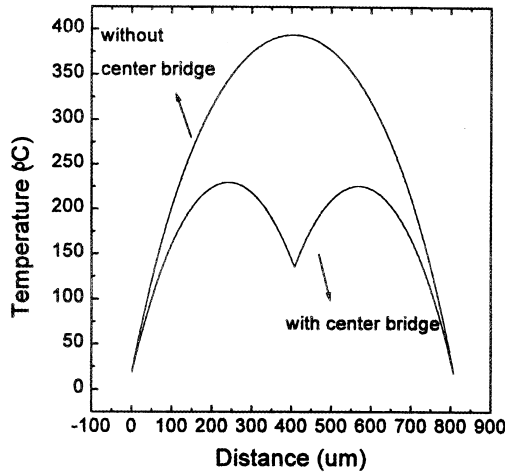


Fig. 6. Temperature profiles of microgauge along test beam. $L = 800 \mu\text{m}$, $L_1 = 407.5 \mu\text{m}$, $L_3 = 20 \mu\text{m}$, $z = 3 \mu\text{m}$ and applied current is 500 μA .

Now, we consider the differential element of the T-shaped microbridge of width w , thickness z and length Δx as shown in Fig. 5. The heat balance for the differential element is given by

$$Q_{\text{total}} = P_g + Q_{\text{conduction}} \quad (5)$$

where Q_{total} is the net rate of change of the internal energy of the element, P_g is the power generated inside the element and $Q_{\text{conduction}}$ is the heat loss mechanisms acting on the differential element. In Eq. (5), Q_{total} is given

$$Q_{\text{total}} = \rho_m c w z \Delta x \left(\frac{\partial u}{\partial t} \right) \quad (6)$$

where c and ρ_m are the specific heat and density of the microgauge material, respectively, and u is the average temperature of the element. The power generation term P_g is

$$P_g = J^2 \rho(u) w t \Delta x = J^2 \rho_0 w t \Delta x [1 + \xi(u - T_0)] \quad (7)$$

where J is the current density flowing through the element, ρ_0 is its resistivity at T_0 and ξ is temperature coefficient of the resistivity (TCR). The conductive component is

$$Q_{\text{conduction}} = -k w z \left(\frac{\partial u}{\partial x} \Big|_x - \frac{\partial u}{\partial x} \Big|_{x+\Delta x} \right) \quad (8)$$

This term represents the conduction through the beam itself, and k is the thermal conductivity of the microgauge material. If we arrange Eqs. (5)–(8), we obtain

$$c \rho_m w z \Delta x \left(\frac{\partial u}{\partial t} \right) = J^2 \rho_0 w z \Delta x [1 + \xi(u - T_0)] - k w z \left(\frac{\partial u}{\partial x} \Big|_x - \frac{\partial u}{\partial x} \Big|_{x+\Delta x} \right) \quad (9)$$

In a steady state condition, Eq. (9) can yield the linear second-order partial differential equation.

$$\frac{\partial^2 u_i}{\partial x^2} + \frac{J^2 \rho_0 \xi}{k} u_i + \frac{J^2 \rho_0}{k} [1 - \xi T_0] = 0 \quad (i = 1, 2) \quad (10)$$

Eq. (10) is solved subject to the boundary and initial conditions

$$u_1[x = 0] = u_2[x = L] = T_s \quad (11)$$

$$\begin{aligned} -k w_1 z \left(\frac{\partial u_1}{\partial x} \right) \Big|_{x=L_1} - k w_1 z \left(\frac{\partial u_2}{\partial x} \right) \Big|_{x=L_2} \\ = \frac{k w_2 z}{L_3} (u_1[x = L_1] - T_s) \end{aligned} \quad (12)$$

We assume that the temperature at the microgauge anchors ($x = 0$, $x = L$) is identical to that of the substrate T_s . According to Mastrangelo's calculation [7,8], this condition is true as long as the power conducted through the anchors does not exceed a few milliwatts. Second assumption in Eq. (12) is that the amount of heat conducted away through the slope beam is the sum of the heat conducted from the region $0 < x < L_1$ and $L_1 < x < L$ respectively. Eq. (10) is solved with the above boundary and the initial conditions.

Fig. 6 shows an example of the steady state temperature profiles when $L = 800 \mu\text{m}$, $L_1 = 407.5 \mu\text{m}$, $L_3 = 20 \mu\text{m}$, $z = 3 \mu\text{m}$ and the applied current is 500 μA . Also, the temperature profile at the same condition when no slope beam is presented in Fig. 6. If we integrate the temperature profile along the microgauge length and divide it by its total length, we can get the average temperature of the microgauge.

4. Experiments and results

4.1. Temperature characteristics of resistivity of poly-Si thin film

In Eq. (7) we assumed that the temperature characteristics of the resistivity is linear. We verified this relation-

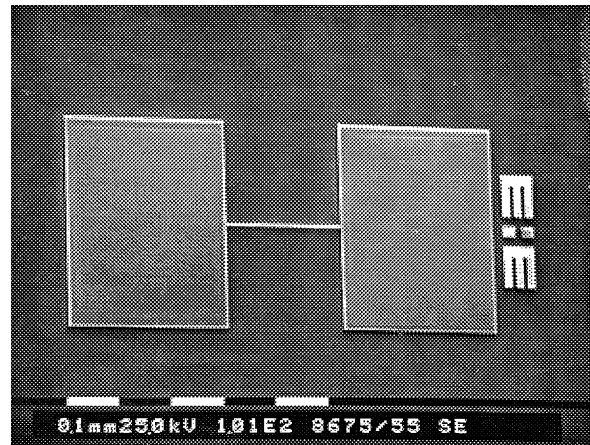


Fig. 7. SEM image of poly-Si microbridge. Bridge length = 300 μm , width = 3 μm , thickness = 3 μm .

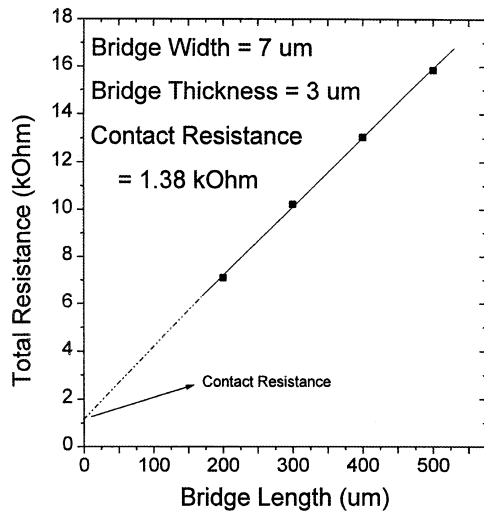


Fig. 8. Total bridge resistance as a function of microbridge length.

ship with microbridges. Because microgauges and microbridges were fabricated at the same time, they had same electrical properties. The fabricated microbridge is shown in Fig. 7.

We can get the value of resistivity of the poly-Si thin film by simply measuring the resistance of the microbridge because we know the dimensions of the microbridges. The resistance of the microbridge was measured by oil-bath method. All the poly-Si microbridges were first bonded to copper lead frames. The packages, containing the bridges and substrates, were filled with electrically insulating silicon oil. The oil acts as a heat exchanger, holding the microbridge temperature at a series of values T_{oil} , that was adjusted by a hot chuck used as an external heat source in contact with the packages. Uniform temperature of this system was controlled by a hot chuck from the room

temperature to 200°C. A small current less than 10 μA was applied to the microbridges to minimize Joule heating effect of the microbridges which could affect controlled temperature of the system. The I – V characteristics of the microbridges were measured by using an HP4145B semiconductor parameter analyzer. The temperature of the silicon oil was measured by a k-type thermocouple.

If we measure the resistance of the microbridge system, the measured resistance of the microbridge consisted of two factors. One was the resistance of the microbridge itself and the other was the contact resistance of the microbridge system. So we needed to know the contact resistance of the microbridge in order to measure exactly the resistivity of the poly-Si thin film. This value of the contact resistance was obtained by plotting the measured resistance values for resistors of varying length and extracting the intercept resistance corresponding to the length of zero.

Fig. 8 shows the measured resistance of the microbridge as a function of microbridge length. The y -intersection point means the resistance of the microbridge when the microbridge length equals zero, in other words, the contact resistance of the microbridge. Considering contact resistance of the microbridges, we obtained temperature characteristics of resistivity as shown in Fig. 9. This relationship could be fitted linearly as Eq. (13) and its parameter values were as shown below in temperature range from room temperature to 200°C.

$$\rho = \rho_0 [1 + \xi(T - T_0)]$$

$$\rho_0 = 5.7 \times 10^{-4} \sim 6.4 \times 10^{-4} [\Omega \text{m}] \text{ at } T_0 = 19^\circ\text{C}$$

$$\xi = -1.74 \times 10^{-3} / ^\circ\text{C} \quad (13)$$

From this oil-bath experiment, the ρ_0 values showed some deviations from one sample to another sample. But

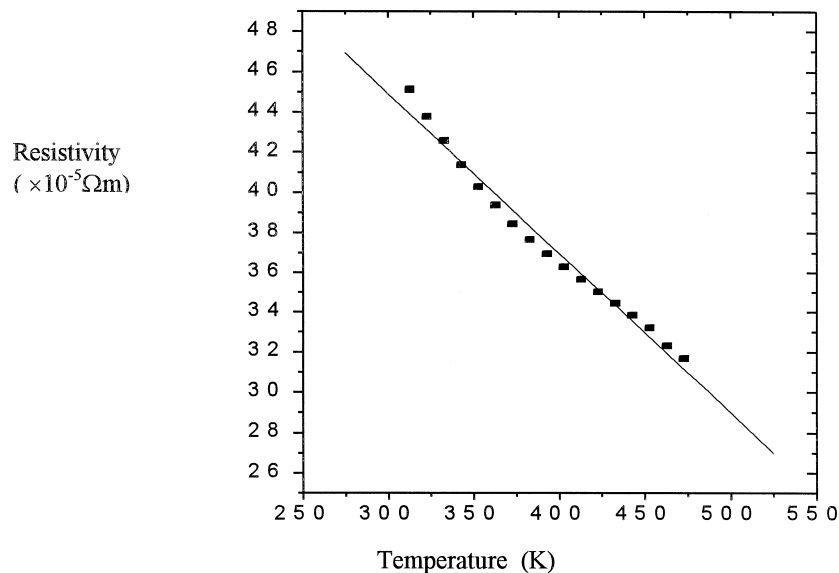


Fig. 9. Temperature coefficient of resistivity for poly-Si thin film.

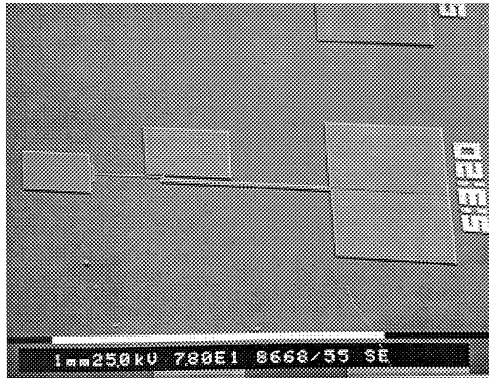


Fig. 10. SEM image of microgauge.

TCR, ξ , value was always measured as constant value, $-1.74 \times 10^{-3}/^{\circ}\text{C}$, independent of samples. The negative temperature coefficient of resistivity is due to barrier effect of the poly-Si grain boundary. If the temperature of the poly-Si thin film was raised, it is more easier for the carriers to surmount a given barrier, namely grain boundaries of the poly-Si thin film.

4.2. Thermal expansion coefficient of poly-Si thin film

The thermal expansion coefficient of poly-Si thin film was measured with a microgauge shown in Fig. 10. The microgauges were driven in 10 mTorr vacuum chamber to avoid heat loss into the air. Current was applied to the microgauge via copper lead frame by a 4145B HP semiconductor parameter analyzer. The displacement at the microgauge was measured with an optical microscope equipped with a CCD camera and a color image printer. Fig. 11 (a) shows the vernier site of the microgauge when no current was applied. Fig. 11 (b) shows the same vernier site of the microgauge when current was applied, indicating some displacement at the vernier gauge due to applied current. The displacement of the microgauge due to the applied current was measured from the difference between

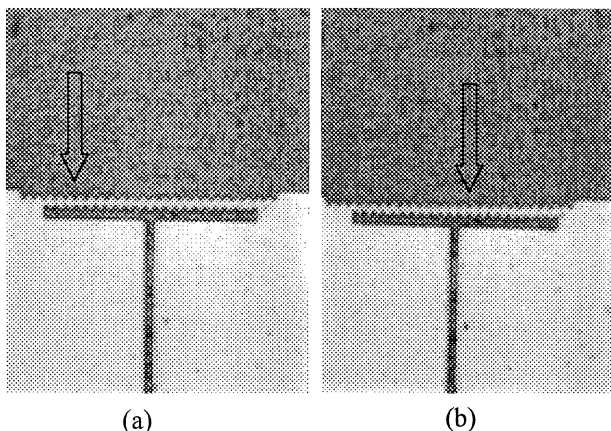


Fig. 11. CCD image of Vernier gauge of the microgauge. (a) no current was applied (b) current was applied.

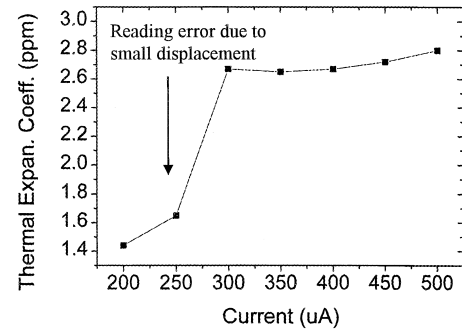


Fig. 12. Thermal expansion coefficient of poly-Si thin film.

its last and initial positions of the vernier gauge. Because of the intrinsic stress of the poly-Si thin film, the initial position of the Vernier gauge can be moved from its designed position. But this makes no problem because we need only the difference of the Vernier site when current was applied and no current was applied. The average temperature of the microgauge when current was applied was calculated from Eq. (10). The thermal expansion coefficient of poly-Si thin film was calculated from Eq. (4) with the measured displacement at the vernier gauge and the calculated average temperature of the microgauge. Fig. 12 shows the calculated thermal expansion coefficient of poly-Si as a function of applied current. The measured thermal expansion coefficient of poly-Si was measured as a constant value independent of applied current, in other words the average temperature of the microgauge.

If the current was small, 250 uA in Fig. 12, the measured displacement was so small that the exact displacement was not measurable. If the current was large, the average temperature of the microgauge can exceed 200°C . In this condition, the assumption made in Eq. (7) is no longer valid because we verified the linear relationship only from room temperature up to 200°C . So the heat conduction equation was not always correct if the current was large, 500 uA in Fig. 12. Therefore, the current was limited properly to avoid overheating above 200°C . From some sets of measurements, we calculated that the thermal expansion coefficient of poly-Si thin film was $2.9 \times 10^{-6}/\text{K}$ with a standard deviation of $0.24 \times 10^{-6}/\text{K}$.

5. Conclusion

Thermal expansion coefficient of poly-Si thin film was measured by the microgauge method. Microgauge method has some merits compared with commonly used optical methods. In the measurement process of the thermal expansion coefficient of the thin film, the Elastic modulus of the substrate and the thermal expansion coefficient of the substrate are no longer needed in the microgauge method. In the microgauge method, the thermal expansion coefficient of the thin film was expressed as a function of the

average temperature of the microgauge and the measured displacement at the vernier gauge. When the current was applied to the microgauge, a thermal expansion of the microgauge was produced by Joule heating effect and the average temperature of the microgauge rose. The amount of temperature rise was calculated from the second order differential heat conduction equation. The amount of displacement at the vernier gauge was measured with an optical microscope. From some sets of experiments, we measured that the thermal expansion coefficient of poly-Si thin film is $2.9 \times 10^{-6}/\text{K}$ with a standard deviation of $0.24 \times 10^{-6}/\text{K}$.

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