Proceedings of the Eurosensors XXIII conference

Investigation on Lifting Angle of Polyimide Self-assembly
Surface Micromachined Structure

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Abstract
This study presents a polyimide (PI) self-assembly technique for the development of three-dimensional surface micromachined structures. The effects of the geometric factors and the curing temperature of the PI elastic joints on the lifting angle of such microstructure are investigated. Under the optimized curing condition (380°C), a maximum 74° lifting angle of a 5.2×10^{-11} kg-weight polysilicon microplate can achieved utilizing the large surface-tension force of a single PI joint. The lifting angle of the thermally actuated 3-D microstructures can be demonstrated in nearly directional proportion to the length/width-thickness ratio of PI joint and the temperature difference temperature.

Keyword: Polyimide; Self-assembly Technique; Lifting angle; Surface Micromachined Structure.

1. Main text

1.1. Introduction

Surface-tension is an important force used in the micro scale domain for the development of various self-assembled 3-D microelectromechanical systems (MEMS) or micro-opto-electromechanical system (MOEMS) [1-8]. The major materials of the elastic joints adopted in the self-assembled 3-D microstructures or microsystems are photosensitive polymer, borophosphosilicate glass (BPSG) and Pb/Sn solder, respectively. Compared with solder ball-joint, the photosensitive polymer and BPSG thin film-joints have the advantages of higher fabrication yield and alignment accuracy, higher IC compatibility, smaller dimension, and lead pollution free. However, the processing temperature of the BPSG thin films deposited by conventional thermal furnace or plasma-enhanced chemical vapor deposition (PECVD) systems can reach up to 850–1100°C, which will limit its application. In 1998, T. Ebefores and his co-workers [8] firstly presented a 30 µm-thick PIs self-assembly bulk micromachined 3-D microstructure. The static bending angles of such microstructure between 0° and 200° for different numbers of V-grooves and curing temperatures have been achieved with a maximum bending of 35° per V-groove.

In contrast, this research presents a simple and high-yield PI based self-assembly technique for the implementation of 3-D surface micromachined structures. To obtain a large surface-tension force and to enhance further the lifting angle of the self-assembly microstructure, a specific photosensitive PI joint material with high modulus of elasticity (~3.5 GPa) and large elongation (45% at 380°C) was adopted in this research. The effects of the geometric factors and the curing temperature of the PI elastic joint on the lifting angle of PI self-assembled 3-D microstructure were investigated. Besides, the experimental and theoretical results were compared and discussed.
1.2. Theoretical Derivation

Even though the PI self-assembly technology has been developed for 3-D bulk micromachined structures for more than one decade, the theoretical formula for investigating the lifting angle of PI self-assembled surface micromachined structure has not been published yet. Figs. 1(a) and 1(b) illustrate the cross-sectional diagrams of the PI self-assembled 3-D microstructure before and after curing process. In this study, the 3-D surface micromachined structure is constructed by a moveable part and a stationary part of the low-stress polysilicon and PI elastic joint. Once the sacrificial layer (phosphosilicate glass, PSG) under the moveable part removed, a free-standing microstructure can be obtained as Fig. 1(a) depicts. The PI joint will thermally shrank during the moderate curing process and generate a sufficient surface-tension force to lift the moveable part and implement a 3-D microstructure. A simple force model of PI self-assembled microstructure was established in Fig. 1(b). The $\sigma$, $F_C$ and $F_\eta$ represent the surface-tension force, the top-side and bottom-side traction forces of the molten PI joint, respectively. The bottom-side of the PI joint is adhered tightly to the moveable and stationary parts of polysilicon layer since the viscosity of the PI layer is very high. Therefore, as the temperature varies from room temperature to curing temperature, the variation of $F_\eta$ is limited. Based on our observation, the length of the bottom surface of cured PI joint (denoted as $L_{\text{PI}}^\prime$) is almost equal to the original length of uncured PI joint (denoted as $L_{\text{PI}}$). In contrast, the $F_C$ presents an obvious variation from low temperature to high curing temperature since the top-side of the PI joint is not adhered to any surfaces of the polysilicon layer. Therefore, a non-zero $\sigma$ of the cured PI joint exists due to the non-zero difference of $F_C$ and $F_\eta$, which further results in the polysilicon microplate lifted out-of-plane with a specific angle (denoted as $\theta$).

The longitudinal cross-sections of the PI joint can only provide a much smaller torque to lift the polysilicon microplate than the transversal cross-sections, since the pivot location of the former is not on the center line of polysilicon microplate. What mainly contributes to the lifting angle is the deformation difference between the length of the top surface and bottom surface of the cured PI joint (denoted as $\Delta L_{\text{PI}}$). Based on the expansion theory, before over-shrinkage takes place, the $\Delta L_{\text{PI}}$ can be expressed as Eq. (1).

$$
\Delta L_{\text{PI}} = L_{\text{PI}}^\prime - L_{\text{PI}}' \approx L_{\text{PI}}(\alpha \Delta T) \tag{1}
$$

Where the $\alpha$ is the average coefficient of linear expansion of the PI thin-film along the length direction of PI joint and the $\Delta T$ is the difference of the curing temperature and room temperature. Based on the rotational mechanics, if we neglect the torque contributed by the variation of width and thickness of PI joint, then the effective torsional torque (denoted as $\tau_{\text{eff}}$) is approximately equal to the longitudinal lifting force ($\sigma \Delta L_{\text{PI}}$) times the moment arm ($\Delta L_{\text{PI}}/2$) as Eq. (2) expresses.

$$
\tau_{\text{eff}} = k \theta = \left(\sigma \Delta L_{\text{PI}}\right) \times \frac{L_{\text{PI}}}{2} \Rightarrow \theta \alpha \Delta L_{\text{PI}} L_{\text{PI}} \tag{2}
$$

Where the $k$ is a torsional constant of the PI joint. Consequently, Eq. (2) also reveals that the lifting angle of the polysilicon microplate is not only in directional proportion to the length difference between the top surface and bottom surface of the cured PI joint but also the original length of PI joint. On the other hand, increasing the volume of the PI joint will shift the effective center of mass (denoted as $\text{CM}_{\text{eff}}$) of the moveable part (including the suspending PI part and the polysilicon microplate) forward to the stationary part and will shorten the $D_{\text{CM}}$, which is defined as the distance between the $\text{CM}_{\text{eff}}$ and the $C_{\text{PI}}$. A smaller $D_{\text{CM}}$ represents a shorter moment arm and results in a smaller lifting angle, so the lifting angle of the microplate will be inversely to the volume of PI joint. Combined the above-mentioned conclusions and substituted Eq. (1) into Eq. (2), the formula of lifting angle can be further expressed as follows.
\[
\theta = k \left( \frac{\Delta L_{pl}}{L_{pl} W_{pl} T_{pl}} \right) = k' \frac{\Delta L_{pl}}{W_{pl} T_{pl}} = k'' \Delta T \frac{L_{pl}}{W_{pl} T_{pl}}
\]

(3)

Where the \( k' \) and \( k'' \) are two material constants of the adopted PI joint. Consequently, as presented in (3), the lifting angle of the PI surface tension-powered microstructure is in direct proportion to the curing temperature and the PI joint.

1.3. Design and Fabrication

Fig. 2 shows the typical layout of the PI self-assembly surface micromachined structure. The dimension of moveable polysilicon microplate is fixed (the weight is about \( 5.2 \times 10^{-11} \) kg) and the ratio and the curing temperature of PI joint are varied. If we assume the \( L_{pl}/W_{pl} T_{pl} \) ratio is 125/75 \( \times 12 \) \( \mu \)m\(^{-1} \) and the \( \Delta T \) is 355°C, then calculated by conventional center of mass formula, the \( D_{CM} \) and the distance between CM\(_{eff}\) and the center line of PI joint equal to 95 \( \mu \)m and 125 \( \mu \)m, respectively. The major processing steps of the presented PI self-assembly technology are detailed as follows: (i) Deposit the 2 \( \mu \)m-thick low-stress PSG layer on a 4-inch (100) oriented p-type wafer by a commercial PECVD (SAMCO), (ii) Deposit the 1 \( \mu \)m-thick silicon-rich Poly-Si layer by a commercial low-stress low-pressure chemical vapor deposition system, (iii) Pattern the Poly-Si layer by photomask \#1 and an inductively coupled plasma etching system, (iv) Coat the 12 \( \mu \)m- or 18\( \mu \)m-thick PI joint layer and pattern it by photomask \#2, (iv) Release the microstructure by removal of the PSG sacrificial layer and, (v) Cure the PI elastic joint in a convective oven to lift the polysilicon microplate. In this research, the curing temperatures are varied from 360°C to 400°C with 10 °C interval and all the curing processes of this work start from room temperature (25°C) and with a constant heating rate (7°C/min).

1.4. Results and Discussion

Four mechanical characteristics of the PI material adopted in this paper are measured by a commercial stress measurement system under three different curing temperatures. Based on the report of the PI manufacturer, the elongation of the cured HD-4012 PI thin films will be decreased substantially at lower curing temperature (360°C) and the modulus of elasticity can be enhanced at higher curing temperatures (380–400°C). To enhance the lifting ability, the optimized curing temperature of the HD-4012 PI joint adopted in this work is equal to 380°C since the largest tensile strength, elongation and elasticity modulus and low residual stress can be obtained under such condition.

To study the influence of lifting angle on curing temperature, this work measured the realistic lifting angle of two types of PI self-assembled polysilicon microplate under five different curing temperatures. Fig. 3 demonstrates the optimized curing temperature of PI joint is 380°C. Lower curing temperature (such as 360°C and 370°C) can not provide enough deformation of PI joint and will cause a smaller lifting angle than that of the optimized condition. However, higher curing temperature (such as 390°C and 400°C) can not trigger a larger lifting angle of the self-assembled microstructure than that of 380°C curing temperature.

Fig. 4(a) demonstrates the PI joint cured at 380°C is adhered tightly to the polysilicon microplate. However, as Figs. 4(b) and 4(c) show, 390°C and 400°C cured PI joints present an over-shrinkage effect of the PI joint and further cause the deformed PI joint to peel off from the polysilicon microplate and present a smaller lifting angle than that of the 380°C cured PI joint.

Before the over-shrinkage takes place (cured at 390–400°C), the lifting angle of the 18 \( \mu \)m-thick and 12 \( \mu \)m-thick PI self-assembled 3-D microstructures varies almost in directional proportion to the temperature difference of curing and room temperatures (with linearity of 92.3%–97.6%). This experimental result matched very well with the theoretical prediction of Eq. (3).

Fig. 5 depicts the measured lifting angles of the same dimensional polysilicon microplate using six different \( L_{pl}/W_{pl} T_{pl} \) ratios of the PI joints designed in this research. Consequently, under the optimized 380°C condition, the lifting angle of the PI surface-tension-powered 3-D microstructures is in nearly directional proportion to the length/width-thickness ratio of PI joints (with linearity of 95.5%). Namely, the PI joint with higher \( L_{pl}/W_{pl} T_{pl} \) ratio can obtain a larger lifting angle of the microplate and a 74° maximum lifting angle can be achieved.
This experimental result matched very well with the theoretical prediction of Eq. (3). The slope \((555.77\times10^6 \text{ m})\) of the line of linear approximation line illustrated in Fig. 5 divided by the temperature difference \(\Delta T\) (355°C) is equal to \(1.565\times10^6 \text{ m/°C}\) and hence the experimental \(k\) constant of Eq. (3) can be calculated. Four SEM micrographs of the implemented PI self-assembled 3-D microstructures with the same dimension of the polysilicon microplate but with the different geometric layout of PI joints are shown in Fig. 6.

1.5. Conclusion

This paper investigates the lifting angle of the PI based self-assembly surface micromachined structure with theoretical and experimental methods. Increasing the \(L_{PI}/W_{PI}T_{PI}\) ratio of the PI joint from 0.033 \(\mu\text{m}^{-1}\) to 0.139 \(\mu\text{m}^{-1}\) has been demonstrated to effectively improve the lifting angle of 3-D microstructure and their linearity is very high (95.5%). Before the over-shrinkage occurs at 390°C–400°C, the lifting angle of the PI surface-tension-powered 3-D microstructure is nearly directional proportion to the temperature difference of curing and room temperatures with linearity of 92.3–97.6%. Under the optimized curing condition (380°C), a maximum 74° lifting angle of a 5.2×10^{-11} kg-weight polysilicon microplate can be achieved utilizing the large surface-tension force of single PI joint with dimensions of 125 \(\mu\text{m}(L)\times75 \mu\text{m}(W)\times12 \mu\text{m}(T)\). The manufacturing yield of the presented PI self-assembly technique is very high (91.6%) and very suitable for the mass production.

2. Author Artwork

Fig. 1. Cross-sectional schematic views of the PI self-assembly 3-D surface micromachined structure (a) before and (b) after curing process.

Fig. 2. Layout diagram of the self-assembly surface micromachined structure with a PI elastic joint (125 \(\mu\text{m}\)-length and 75 \(\mu\text{m}\)-width) connected with the moveable and stationary parts of polysilicon.
Fig. 3. Measured lifting angles of the 3-D microstructures actuated by two types of PI joints under various curing temperatures.

\[
\frac{L_{\text{PI}}}{(W_{\text{PI}}T_{\text{PI}})} = \frac{75}{(75 \times 18)} \, \mu\text{m}^{-1}
\]
\(T_{\text{curing}} = 380^\circ\text{C}\)

\[
\frac{L_{\text{PI}}}{(W_{\text{PI}}T_{\text{PI}})} = \frac{75}{(75 \times 18)} \, \mu\text{m}^{-1}
\]
\(T_{\text{curing}} = 390^\circ\text{C}\)

\[
\frac{L_{\text{PI}}}{(W_{\text{PI}}T_{\text{PI}})} = \frac{75}{(75 \times 18)} \, \mu\text{m}^{-1}
\]
\(T_{\text{curing}} = 400^\circ\text{C}\)

Fig. 4. Cross-sectional view SEM micrographs of the PI self-assembly polysilicon microplate under (a) 380°C, (b) 390°C and (c) 400°C curing temperatures.

Fig. 5. Measured lifting angles of the PI self-assembly surface micromachined structure versus six different ratio of the PI elastic joint cured under the same temperature 380°C.

\[
y = 555.77x - 0.069
\]
\(R^2 = 0.9547\)
\[ \frac{L_{pi}}{W_{pi}T_{pi}} = \frac{75}{(75 \times 12)} \mu m^{-1} \]

\[ \frac{L_{pi}}{(W_{pi}T_{pi})} = \frac{75}{(75 \times 12)} \mu m^{-1} \]

\[ \frac{L_{pi}}{W_{pi}T_{pi}} = \frac{125}{(125 \times 12)} \mu m^{-1} \]

\[ \frac{L_{pi}}{(W_{pi}T_{pi})} = \frac{125}{(75 \times 12)} \mu m^{-1} \]

Fig. 6. SEM micrographs of the 12 \( \mu m \)-thick PI microplate with different \( L_{pi}/W_{pi} \) ratios designs.

Acknowledgements

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