Design of Silicon-Monolithic Flexure Stage with Selective Compliance*

Nobuyuki MORONUKI*

This paper describes a design procedure of the linear-motion stage that has silicon monolithic structure and flexure beams suspend the stage. Single crystal silicon is appropriate for the structural material of miniaturized mechanism. However, the anisotropic properties and cleavage should be taken into account at the design stage. In addition, the manufacturing process has strong effects on the final strength because silicon is brittle material and sensitive to the flaw such as chipping. The design consideration is concluded as that the cleavage plane, $\{111\}$ plane, should be arranged apart from the direction of the tensile stress to compromise both the fracture strength and compliance to achieve accurate motion. Also, the crystal direction $\langle 100 \rangle$ should be aligned along the tensile stress to obtain long stroke. The prototypes, size of 30×30 mm, were prepared with deep reactive ion etching (DRIE) and its compliance was examined.

Key Words: Micromachine, Motion Stage, Flexure Hinge, Compliance, Silicon, Anisotropy

1. Introduction

Single crystal silicon is an appropriate material for microscopic mechanical applications because of its low inherent defect density and homogeneity. However, its brittleness and anisotropy make the design difficult because special attention should be paid to avoid the cleavage and also the Young's modulus varies with the crystal orientation.

Linear-motion stage suspended by flexible beams or hinges is one of the popular mechanisms in macroscopic world. Such stage can be miniaturized using so-called silicon process in which unnecessary part of the silicon substrate is etched away. This type of monolithic stage is preferable in micro-mechanism design because the assembly or adjustment process is eliminated and the properties of single-crystal silicon are fully utilized. Some of these designs are already in use^{(1),(2)}. However, the design methodology has not been optimized in spite that the anisotropic characteristic of silicon has been already pointed out⁽³⁾. Also, the selective compliance of the guide mechanism is important since the stage should be suspended stiff

perpendicular to the direction of guidance while keeping the motion along the direction of guidance as free as possible. Thus, this item should be added to the criterion of the design.

This paper aims to propose a comprehensive design methodology of the flexure stage that compromises the anisotropy, brittleness and the consideration of compliance.

2. Anisotropic Properties of Silicon

Figure 1 shows the rough specifications considered in this study. The stage is suspended by flexure hinges that deflect flexibly and support the motion. The whole structure is made of one silicon substrate by removing unnecessary part, thus this structure is monolithic. The problem is not only the small size of the stage but the directionality of the compliance to achieve accurate motion.

Single crystal silicon is brittle material that has strong anisotropy. The Young's modulus differs depending on the crystal orientation as mentioned above. The effect of crystal orientation was examined first with three-points bending tests. Table 1 shows the specifications of the testpieces used. Figure 2 shows the results, which shows the relationship between stress and strain. The results show the one cycle of loading and unloading process. It is seen that the relationship has good linearity without

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** Graduate School of Engineering, Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji, Tokyo 109-0397, Japan. E-mail: moronuki-nobuyuki@c.metro-u.ac.jp

Table 1 Specifications of the testpieces

Orientation	Direction	Processes	Width [μm]	Thickness [μm]
(100)	$\langle 100 \rangle$	Only diced	1808	458
		Anisotropically etched after diced	1772	458
		Isotropically etched after diced	1738	384
(110)	$\langle 111 \rangle$	Only diced	1808	457
		Anisotropically etched after diced	1787	457
		Isotropically etched after diced	1690	351

Table 2 Etching conditions

Type	Anisotropic	Isotropic
Etchant	KOH	HF: HNO_3 : CH_3COOH
Concentration or composition	35wt%	8:75:17 vol%
Temperature	60°C	20°C
Additive	IPA (saturated)	-
Etching time	1 hour	10 min

Fig. 1 Rough specifications of the stage

hysteresis. The Young's modulus, the gradient of the relationship, strongly depends on the crystal orientation.

The machining process also has strong effect on the fracture strength because the silicon is brittle material and sensitive to the flaw such as chipping. Figure 3 shows the effect of the machining process on the fracture strain. The testpieces were prepared with dicing, isotropic etching after dicing, or anisotropic etching after dicing. The etching conditions are shown in Table 2. The fracture mainly originated from the flaw at the intersection of the bottom surface where tensile stress works and the sidewall. Thus, the size of the flaw is defined here as the maximum vertical length of the flaw on the sidewalls. It was quantified using scanning electron microscope (SEM) for the testpiece as diced or profilometer for the testpiece after etching respectively. In the case of anisotropic etching, it was difficult to quantify the flaw size and the length of the flaw is shown with extent or variance. In the figure, the SEM photos of the edge that has the orientation of $\langle 111 \rangle$ are shown.

It is clear from these results that the process that

Fig. 2 Young's modulus of silicon and effect of crystal orientation

left no flaw is preferable to permit larger strain or long stroke. Also, it is necessary to align the $\langle 100 \rangle$ direction along the tensile deformation to permit large strain because the permissible strain is obviously larger. The reason is that the cleavage plane is arranged apart from the plane that works the maximum tensile stress as shown in the figure. It is found from these results that permissible strain can reach more than 1%, if the substrate is properly orientated and proper finishing process are adopted.

3. Designs and Analysis

The primary cleavage plane of silicon is crystal plane $\{111\}$ and the arrangement of this plane in the structure has strong effect on the fracture strength as already shown in Fig. 3. Another study has also shown the strength differs 50% depending on the arrangement of cleavage plane though the process is kept same⁽³⁾. Thus, the arrangement of this plane in the structure is key issue at the design stage.

The design principle is summarized as follows:

- (1) The cleavage plane should be arranged not to coincide with the direction of tensile deformation
- (2) The orientation $\langle 100 \rangle$ should be aligned with the tensile deformation to obtain long stroke

Fig. 3 Effect of flaw after process on fracture strain

Fig. 4 Location of cleavage planes

- (3) The flaw at the edge of the structural member should be avoided

In order to achieve long stroke, the principle (1) described above should be taken into account. Figure 4 shows the location of cleavage planes of the structure. The structure deforms in the plane of the substrate surface and the principal stress work in the plane normal to the surface. Thus, the plane of maximum principal stress can be arranged apart from the cleavage plane by choosing the both the substrate orientation and the direction on it. One of the design solutions is adoption of (100) substrate.

In addition, the corner should be rounded to avoid the stress concentration at the fixed ends of the beam structure. Such profile can be obtained using deep reactive ion etching (DRIE), which is not affected by the anisotropy of the silicon.

Figure 5(a) and (b) show the design examples of the case of (100) substrate. Removing or blanking unnecessary part with specific pattern from a silicon substrate, stages can be obtained. In the figure, the stages are intentionally magnified compared with the substrate size and does not shows the actual size. The "Case A-1" is based on the principle (2). The "Case A-2" has different compliance from Case A-1 because

of the difference of the Young's modulus.

In some applications, accurate motion may be required at the sacrifice of the limited stroke. To respond this requirement, the profile accuracy of the structure is essential. Anisotropic etching is one of the candidates for such processing because this process produces regular profiles that consist of specific crystal planes due to the difference of the etching rate against each orientation. Silicon substrate with (110) orientation has {111} planes normal to the surface, thus, parallelogram structure as shown in Fig. 5(c) can be obtained (Case B). However, the final shape after anisotropic etching has sharp corners and they deteriorate the strength due to stress concentration.

The stress and strain in the structure were analyzed using finite element method (FEM). Table 3 shows the analytical conditions. The material was assumed as isotropic to simplify the calculation and linear elastic deformation under plane-stress state was also assumed. The mechanical properties such as Young's modulus was assumed as the average value along all direction on (110) plane⁽⁴⁾. The boundary conditions were set as follows: The nodes along the lower end of the structure were fixed both in X and Y direction. Forced displacement was applied to the nodes along

Table 3 Conditions for finite element analysis

Material properties	Isotropic / Linear elastic material	Young's modulus ⁽⁴⁾	170Gpa
		Poisson's ratio ⁽⁴⁾	0.25
Geometric properties	Planar / Plane stress	Thickness	300 μ m
	Permissible strain ⁽⁵⁾		0.80%

Fig. 5 Case studies corresponding to each crystal orientation

Fig. 6 Stress and strain analyzed with FEM (left: Case A-1/2, right: Case B)

the upper end.

Figure 6 shows the results of analysis for the “Case A” and “Case B”. In both cases, the principal strain distribution is shown at the moment when the principal strain exceeds the permissible value somewhere in the structure and brittle fracture occurs. It is found that the “Case A” can permit large stroke because the stress at the corner is well dispersed due to the rounded corner. In “Case B”, on the other hand, there observed stress concentration and thus the stroke is limited.

The compliance can be estimated using the analyzed relationship between the applied force and displacement. The compliance perpendicular to the applied force can also be estimated based on the analysis. The ratio of these compliances suggests the achievable motion accuracy because it shows the ratio of compliance in necessary motion to that in unnecessary motion. Figure 7 shows the design candi-

dates together with the compliance ratio. “Case A” has simple beam structure and estimated to have high compliance ratio as $X:Y=50:1$. On the other hand, “Case B” has complicated and regular structure that consists of $\{111\}$ planes. The compliance ratio is estimated as low as $X:Y=11:1$. It is found that the “Case A” is preferable from the standpoint of compliance ratio.

4. Production and Evaluation

Some case studies in Fig. 7 that have high compliance ratio were selected and produced. The selected designs are shown in the section of which back is shaded. In order to investigate the effect of the design independently of the process, DRIE was selected for all cases. Applying this process, deep and vertical walls can be made.

Figures 8 and 9 show the SEM photos of the prototypes. The substrates of 300 μ m thickness were

Table 4 Summary of the experimental results

	Case A-1		Case A-2		Case B	
	Analysis	Experiment	Analysis	Experiment	Analysis	Experiment
Fracture load [mN]	5340	2330	4780	2370	2240	443
Stroke [μm]	29.4	24.7	20.2	17.1	7.22	8.82
Compliance [$\times 10^{-3} \mu\text{m}/\text{mN}$]	C_x	5.51	4.22	7.22	3.22	19.9
	C_y	0.111	-0.539	0.0832	0.307	0.286
$C_x : C_y$	50:1	20:-1	51:1	8.8:1	11:1	70:1

Fig. 7 Analyzed compliance

Fig. 9 SEM photo of the "Case B"

Fig. 8 SEM photo of the "Case A"

blanked with fine profile such as the round shape at the corner. However, the side etching could not be precisely controlled and the cross section is not rectangle but almost triangle as shown in the figure. The amount of side etching varies with many conditions and even the position on the same wafer affects the results. Thus, it is not easy to obtain the precise geometry^{(6),(7)}. In addition, there observed stripe grooves on the sidewall as shown in the figure. This pattern is considered as the result of the directed ion-beams bombardment during the process. These grooves will weaken the strength of the member and the stroke will be limited.

Fig. 10 Experimental setup for measurement of compliance

The relationship between the force that act on the stage and displacement was examined with the setup shown in Fig. 10. Motor-driven stage applied force at a part of the stage and the corresponding displacement of both the stage and the base were measured. The force was quantified with the strain gages and an amplifier, and the displacement was measured with a laser-type micrometer (resolution 0.01 μm). The whole equipment was set on a vibration isolation table. The stage is fixed at the outside of the base-part as shown in the figure, thus, not only the stage but the base-part deforms according to the applied force. To evaluate the relative motion between the base and stage, both of the displacements of the stage δ_x and the base δ_{bx} were measured together with the load F_x . The stage was fixed at the position rotating 90 degrees

Fig. 11 Compliance property of the "Case A-1"

in the figure and the displacement δ_y and δ_{by} were measured together with the load F_y using the same equipments. The compliance ratio was calculated from these results.

Figure 11 shows the results of the "Case A-1". It is found that the relationship between the force and the displacement has good linearity. However, the base displaced much more than the expectation. The actual displacement of the stage from the base can be calculated by subtracting the displacement of the base from that of the stage. In other experiments, the stages were deformed until the fracture though these data points are not plotted in the figure.

Table 4 summarizes the results of all cases. In every case, the experiments coincide with the analysis qualitatively. The obtained stroke is almost same with the analysis; silicon substrate can permit large strain as about 0.8% as assumed. However, the fracture load is smaller than the analysis. This might be caused by the geometrical error in the cross section described above, error in estimating the Young's modulus, and/or the assumption that the material is isotropic. The compliance was larger than the analysis in most cases. In addition, there observed the negative compliance. This means that the stage moved in the opposite direction of the force applied. This fact suggests that the non-uniform elastic deformation of the structure might occur and/or the boundary conditions might be different with the ideal ones.

It was also found that the "Case B" has larger compliance ratio than the "Case A" differently from the analysis. This means that precise motion is

available with this design though the stroke is limited. The selection of the "Case A" or "Case B" depends on the requirements.

5. Conclusions

The design criteria of monolithic-silicon flexure-stage was discussed and examined with experiments. The results are summarized as follows:

- (1) The effect of the finishing process on the permissible strain of the silicon structure was experimentally made clear. It can reach 1% if the stress concentration is eliminated.
- (2) Design criteria were made clear as follows.
 - (a) The cleavage plane should be arranged not to coincide with the direction of tensile stress.
 - (b) Large compliance can be obtained by the alignment of orientation $\langle 100 \rangle$ to the tensile stress.

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