Design of a Nano-Displacement No-Wiring Solid Actuator*

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Abstract

In this paper, we considered a polymer-based piezoelectric stack actuator based on MEMS nano-positioning technology. A no-wiring structure was used for simplicity of fabrication and to avoid irregularity deformation under wiring. We selected the key parameters for actuation design, and a simulation was executed through FEM analysis of the electric field and deformation. From this simulation, we decided upon the appropriate parameters of the actuator.

Key words: Nano Displacement, Piezoelectric Actuator, Structure Design, Non-Wiring

1. Introduction

Head positioning of hard disk drives and precision devices requires micro-scale stroke and nano-scale positioning. To better achieve this, we propose a multi-resolution actuator system for nano-positioning. We selected a solid actuator built using MEMS technology because it offers fast response speed and stable deformation.

Piezoelectric actuators[1,2] for nano-positioning were developed using ceramic material. But they are usually used high temperature and high cost fabrication process. And polymer based piezoelectric actuators were developed using Polyvinylidene Fluoride (PVDF) and some related materials[3,4]. These actuators were fabricated using coating, molding and film adhesion[5,6].　In our development, low temperature and dry process are required for this fabrication to maintain the accuracy of the head positioning parts. Feng et al. succeeded to developed the piezoelectric transducer using parylene for electret and they were used CVD process[7]. Then, parylene can be used as a piezoelectric material[8]. A fabrication technology for vertical nano-sheets of SiO_2/Au embedded into PDMS has already been developed[9]. Therefore, we propose stacking the actuator by using vertical nano-sheets with parylene placed between the sheets.

The required specifications are a 10-nm displacement at a 1-mm actuator length, a 10-kHz movement at maximum frequency and a drive voltage of less than 100 V. In an earlier study [11], we investigated a piezo-electric analysis method for a parylene stack actuator and considered the wiring aspect. In this research, we consider the appropriate structure for actuation and fabrication. The prototype version used wiring with positive and negative electrodes placed alternatively and with each electrode being a thin vertical wall. We decided upon a suitable stack width of piezoelectric material and clarify the problems associated with this version. In the second version, we selected a simple structure to avoid

irregular displacement under the wiring and adopted a no-wiring structure for simplicity of fabrication. We designed the actuator and verified that the performance satisfies the specifications for drive voltage and actuator length. In addition, we simulated the displacement and resonance frequency of a computer model of the actuator.

2. Design and simulation method

2.1 Analysis method

The piezoelectric deformation is computed by following equations:

$$T = cS + eE \tag{1}$$

$$D = eS + \varepsilon E \tag{2}$$

$$\nabla^2 E = -\varepsilon^{-1} \rho \tag{3}$$

Here T is the stress, S is the strain, E is the electric field, c is the stiffness, e is a constant of the piezoelectric stress, D is the dielectric flux density, ε is a dielectric constant and ρ is the charge density matrix. Simultaneous equations were constructed on the basis of these three equations and solved by the finite element method. In this analysis, electric field is calculated and strain of each element is computed and finally whole deformation of actuator is obtained. We used MemsONE[TM] [10] and a two-dimensional model to simulate the piezoelectric displacement and resonance frequency.
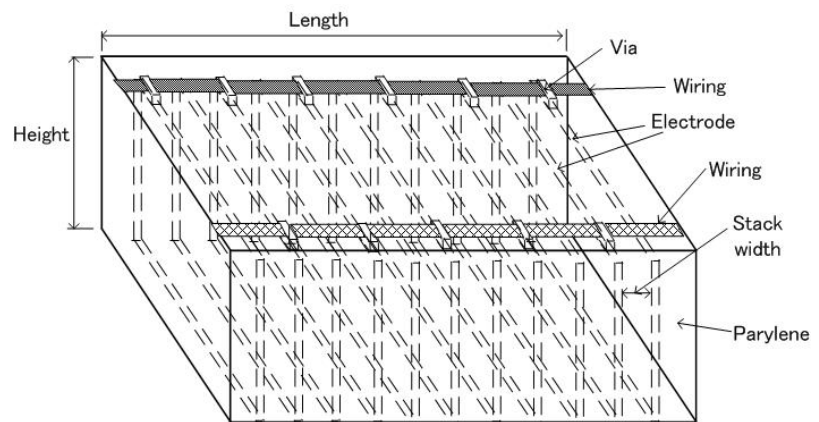
2.2 Wiring design

Fig. 1. Structure of nano actuator.

Figure 1 shows the structure of the nano-actuator. Thin-plate electrodes for the power source and GND are placed alternately, and a piezoelectric material (parylene) is placed between these electrodes. A plate electrode mainly consists of SiO_2 and a thin Au layer, with a total thickness of 500 nm. The electrode connects the source and GND wiring, which are sited on the upper face of the actuator. The design parameter is the stack width. The total length of the actuator is 1 mm and its height is 50 μm.
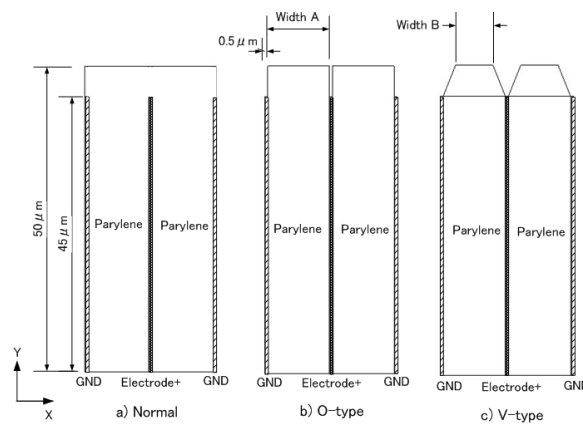
Fig. 2.   Simulation model.

Table 1. Parameter of analysis model in fig. 2.

Model	Width A （μm）	Width B （μm）	stacks number
Stack width is 10μm model	10	6	91
Stack width is 5μm model	5	3	182
Stack width is 2μm model	2	1	400

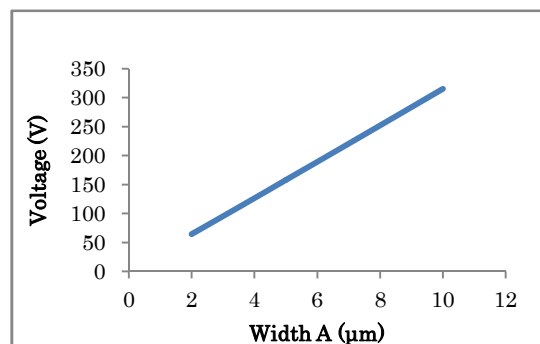### 2.2.1 Required voltage for 10-nm displacement

Fig. 3. Requirement voltage for 10 nm displacement of each model.

Figure 2 shows the structure of the actuator. It is a two-stack model, whereas an actual actuator needs more stacks. First we determined the required voltage for 10-nm displacement. We use the Normal model (a) in Fig. 2 and changed width A of the analysis model. Table 1 shows the design parameters of 10, 5, and 2 μm models and the number of stacks for a 1-mm-long actuator. Width A is the distance between the signal and GND electrodes. We used a quadratic element in the FEM analysis, and 4257 and 1089 elements for the 10- and 2-μm-stack-width models, respectively. The piezoelectric coefficients of the parylene used in the simulation were taken from Reference[9], and the coefficients depend on the electric field. The permittivity was 2.74×10^{-11} F/m. We neglected the thin Au layer. Figure 3 shows the requirement voltage for 10-nm displacement of each model. We use centre-area displacement. From this figure, the drive voltages are 315, 157.5, and 64 V for 10, 5, and 2 μm of width A. We found that a width A of 2 μm satisfied the drive voltage requirement of less than 100 V.

2.2.2 Improving upon irregular displacement

In this structure, a dead area of deformation is located at the upper part of the actuator. The dead area of a multi-stacked structure can generate irregular deformation. Therefore, we

consider three types of dead areas as shown in Fig. 2. Normal is not considered for a dead area. The O-type is etched straight over the entire electrode, and the V-type is etched as a V shape. Both the O-type and V-type require the embedding of insulating material on the opposite wiring. We simulated the piezoelectric displacement for each case.

Figures 4 and 5 show the piezoelectric displacement of the side edge for 10- and 2-μm stack widths, respectively. This displacement was converted to whole-length displacement of the actuator. The displacement of the Normal type is asymmetric in shape and irregular in the multi-stack case. The displacement profile between the 0 and 45 μm positions in the Y direction are almost the same for the O-type and the V-type. Subsequently, we chose the O-type.
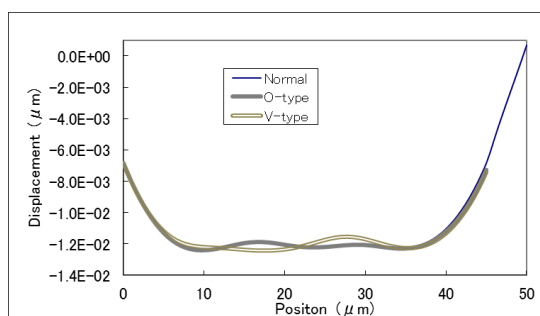

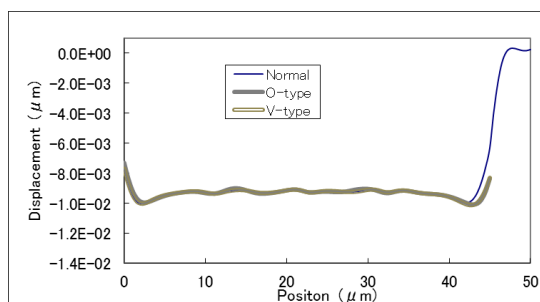Fig. 4. Piezoelectric displacemnet of side edge (Stack width is 10μm, Applied voltage is 315V).

Fig. 5. Piezoelectric displacemnet of side edge (Stack width is 2μm, Applied voltage is 64.0V).
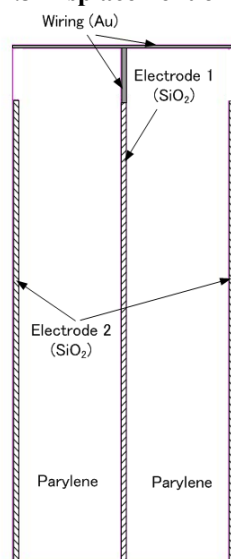
2.2.3 Displacement of interconnection wiring part
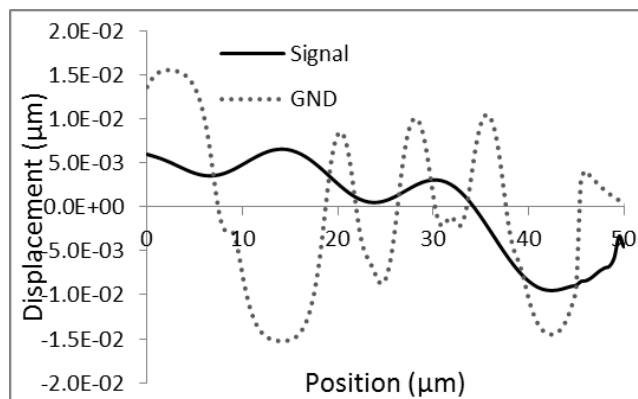

Fig. 6 Analysis model (Wiring case)

Fig. 7. Piezoelectric displacement of side edges for wiring is signal and GND. (Stack width is 10μm, Applied voltage is 315.0V).

In this structure, signal and GND wiring is needed, which is run over a dead area. Therefore, we simulated the displacements. Figure 6 shows the analysis model. Wiring is constructed using Au electrodes with a thickness of 0.3 μm. Figure 7 shows the piezoelectric displacement of the side edges for signal wiring and GND. In this figure, Signal represents wiring and electrode 1 is applied voltage, GND represents wiring and electrode 1 is GND. From this figure, centre-area displacement **is observed to** be very complex and the displacement is not uniform. Although if we were to design narrow-width wiring and place both ends, we could use this structure. The actuator would have irregular displacement due to the wiring.

2.3 No-wiring design

To avoid the irregular displacement caused by wiring, we designed a no-wiring actuator. Figure 8 shows part of the no-wiring nano-actuator, in which the signal and GND wiring can connect directly to an electrode. In this design, a dead stacking area is produced because the electrode also acts as wiring. Design parameter W1 is the width of dead stacking and W2 is the width of active stacking. Length is related to stability against deformation, thus the length is fixed at 100 μm. In this simulation, parylene was used for the stacking material. The width of the electrode (made of SiO_2) is 0.5 μm.

2.3.1 Requirement length for 10-nm displacement

First, we determined the required length for 10-nm displacement. Table 2 shows the parameters, dead stacking width W1 and active stacking width W2 for each model. The applied voltage is 330 V. The piezoelectric coefficients of parylene used in the simulation were taken from Reference [2] and the coefficients depend upon the electric field. The permittivity was 2.74×10^{-11} F/m. We neglected the Au thin layer. Applied voltages were selected from a wiring voltage that results in a 10-nm displacement for stacking width.

Table 3 shows the required actuator length for 10-nm displacement. Although, the M5 model is nearly at the minimum limit of production, the required actuator length for 10-nm displacement is 2 mm. In this case, the voltage was set almost the same as that for the wiring case. Displacement used the centre area to obtain the required actuator length for 10-nm displacement.
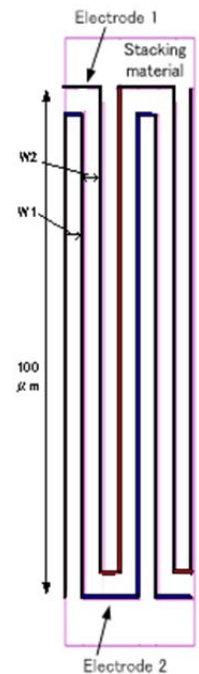

Fig. 8 Structure of non-wiring model

Table 2. Design parameter of non-wiring nano actuator.

Model name	W1 (μm)[Dead]	W2 (μm)[Active]
M1	5	5
M2	3	5
M3	3	3
M4	2	2
M5	0.5	2

Table 3.   Requirement actuator length for 10 nm displacement of each model.

Model name	Drive voltage	Requirement actuator length for 10nm deformation
M1	157.5V	2.9mm
M2	157.5V	2.2mm
M3	94.5V	2.8mm
M4	63V	3.6mm
M5	63V	2.0mm

2.3.2 Adjusting voltage

Although, 63 V was low enough to meet the voltage specification, the required length was nearly double the specification. Therefore, we determined the drive voltage which would satisfy the length specification. Table 4 shows the required actuator length for a 10-nm displacement of each model by adjusting drive voltages. By adjusting the voltage to a slightly higher value, the required actuator length was settled within the length specification of 1 mm.

Table 4. Requirement actuator length for 10 nm displacement of each model adjusting drive voltages.

Model name	Drive voltage	Requirement actuator length for 10nm deformation
M4	75V	0.9mm
M5	68V	0.78mm

Figure 9 shows the side edge displacement of the M5 model (stack number is 65). This displacement was converted to the whole length displacement of the actuator. Irregular displacement was reduced compared with the displacement for the wiring case shown in Fig. 7.
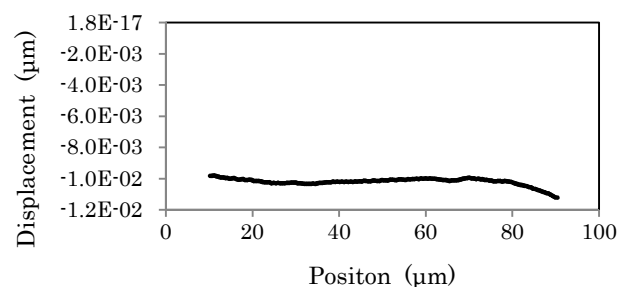

Fig. 9 Piezoelectric displacemnet of side edg
(Stack width is 2μm, Applied voltage is 68.0V).

2.3.3 Prototyping

We are trying to build the prototype of non-wiring actuator. Figure 10 shows the suspended vertical wall. Alternate walls are signal and GND electrode of non-wiring actuator. We succeeded in fabrication of 500nm width SiO_2 vertical walls. We are trying to optimize the CVD condition for low strain parylene fabrication.
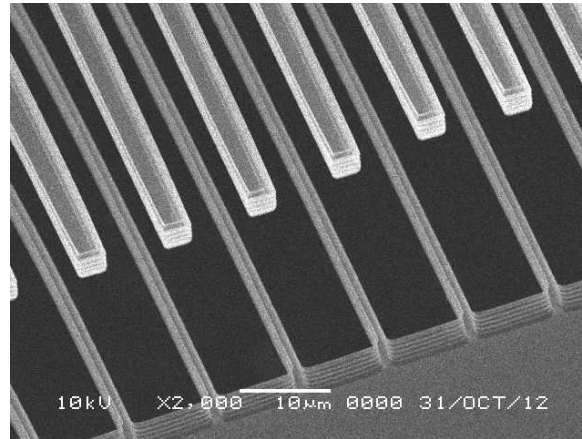
Fig. 10 Fabricated suspended vertical wall.

2.4 Resonance frequency

The maximum moving frequency is 10 kHz; therefore, a resonance frequency of more than 10 kHz is required. Figure 11 shows the model analysis of a resonance frequency constructed using parylene and SiO_2 electrode layers alternatively. The wiring and no-wiring models were the same as the simplified model used to analyse the resonance frequency. The drive direction is horizontal; however, we need to consider the vertical force on the cantilever because the structure is asymmetrical (the upper part has a dead area for the wiring actuator, as shown in Fig. 2). A total of 52850 elements were used for the 10-μm-stack-width model. Calculations were executed using the quadratic element at resonance frequency. The resonance frequency of the vertical actuation was lower than that of the horizontal actuation. Figure 12 shows the results of the vertical actuation for the 10-μm-stack-width model. The first mode frequency is 33760 Hz for the 10-μm-stack-width model. The resonance frequency of the 5-μm-stack-width model is 39800 Hz. Therefore, the resonance frequency was higher for the 2-μm-stack-width model than for the 10-μm-stack-model. Thus, it is a safe resonance frequency for the required moving frequency. The first mode frequency of the horizontal actuation is 232500 Hz for the 10-μm-stack-width model, which is also a safe resonance frequency for the required moving frequency.
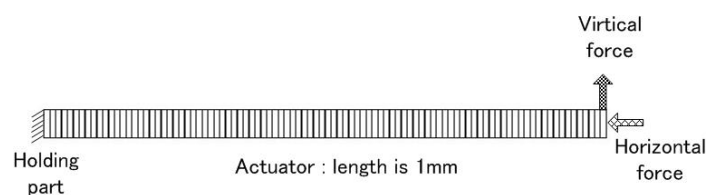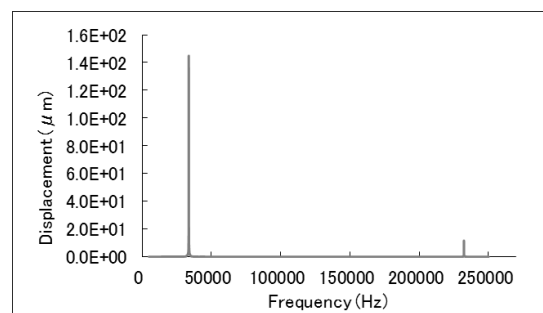

Fig. 11. Resonance frequency analysis model.

Fig. 12. Resonance frequency for vertical actuation

3. Conclusion

We designed a nano-scale positioning actuator using a polymer-based solid piezoelectric material. We considered two types of actuators: a wiring type and a no-wiring type. We designed a low-voltage structure to achieve 10-nm displacement within the specification length of the actuator. A actuation voltage was determined that satisfied the specifications for the 2-μm stack width for the wiring and no-wiring models, and a narrow dead staking width was found better adapted to a low-voltage drive in the no-wiring case. We also considered the displacement effect of the wiring part. The wiring model has an irregular displacement under the wiring. Therefore, we opted for the no-wiring model to avoid the irregular displacement of wiring. We also considered the resonance frequency of the actuator and found that it was high enough higher for the moving frequency. Thus, piezoelectric displacement and resonance frequency satisfied the requirements. In a future study, we need to confirm the performance and durability of an actuator by constructing a prototype using this design.

Acknowledgements

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