Electrostatic Micro Actuator with Distributed Ciliary Electrodes (E-Macel)

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We have proposed and developed Electrostatic Micro Actuator with Distributed Ciliary Electrodes (E-Macel). This actuator consists of two fixed electrodes having many oblique ciliary electrodes distributed on a plate, which like foxtail grass, and a moving electrode that is sandwiched by the fixed electrodes. When the voltage is applied between the fixed electrode and the moving electrode, the electrostatic force is generated at the gap between the moving electrode and the ciliary electrodes, and the moving electrode sticks to the ciliary electrodes and is attracted to the fixed electrode. The moving electrode moves parallel to the fixed electrode as well as perpendicularly to it. The E-Macel was fabricated by micromachining. The ciliary electrodes were made of two-layer polyimide film. The 4382 ciliary electrodes, each of which was 3 μm thick, 300 μm long and 150 μm wide, were fabricated on a 20 mm x 20 mm Pyrex glass plate. The fabricated E-Macel was driven, and the movement of 9.6 μm/cycle was observed at the driving voltage of 150 V.

Keywords: micro actuator, electrostatic, ciliary electrodes, distributed electrode, polyimide structure

1. Introduction

Various types of micro actuator have been developed. Among them, electrostatic micro actuators have the advantage of the simple structure, and are easy to be distributed and integrated on/in the machines or robots. It means that this actuator is suitable for realizing soft machine/robot and related structure like an animal, and integrated actuators for scanning probe array.

Several electrostatic micro actuators were developed[1-3]. One of the authors has developed the electrostatic actuators[4-6] that use the electrostatic force perpendicular to the electrode because of large force generation capability. However, they could not generate the large force and long displacement because of small electrode area and the restriction by the elastic suspension of the moving part.

In this paper, we propose a novel electrostatic micro actuator, Electrostatic Micro Actuator with Distributed Ciliary Electrodes (E-Macel)[7]. The E-Macel has the many oblique ciliary electrodes distributed on the plate, which like foxtail grass. The actuators having cilia or legs have been also developed[7-9]. These used the cilia or legs for rectifying the bending motion or vertical vibration into the lateral motion. The E-Macel uses the cilia in order to have the large electrode area as large as possible, and also to rectify the electrostatic force perpendicular to the electrode plate into the driving force parallel to it. In addition, the moving part of E-Macel has no elastic suspension. The structure of the E-Macel, the driving principle, the fabrication process and the fundamental characteristics of the fabricated E-Macel are described.

2. Structure and Principle

Fig. 1 shows the schematic diagram of the structure of E-Macel to be fabricated. This consists of two fixed electrodes having distributed ciliary electrodes on a plate, and the moving electrode. The moving electrode is sandwiched by two fixed electrodes. In the vicinity of the contact point of the ciliary electrodes with the moving electrode, their electrodes make narrow gaps and the large electrostatic force can be generated in it. In addition, all the generated electrostatic force is used as the force of the actuator at the same time. So, the more distributed ciliary electrodes generate the larger force of this actuator. This is one of the reasons why the ciliary structure is applied to the electrostatic microactuator.

Fig. 2 shows the driving principle. The driving steps are as follows:

Step 1: The moving electrode (C) is sandwiched by the fixed electrodes (A), (B).

Step 2: The driving voltage is applied between the electrode (B) and (C), and the electrostatic force is generated.

Step 3: The ciliary electrodes on the electrode (B) stick to the electrode (C), and the electrode (C) is attracted to the electrode (B). The electrode (C) moves laterally (forward) and perpendicularly (downward) because of the elastic deformation of the ciliary electrodes.

Step 4: The voltage is applied between the electrode (A) and (C), too. The ciliary electrodes on the electrode (A)
move and stick to the electrode (C) by the electrostatic force.

Step 5: Applying a voltage between the electrode (B) and (C) stop. The electrode (C) is released from the electrode (B), and move to the electrode (A) (upward and forward).

Step 6: The electrode (C) contacts with the electrode (A).

Step 7: The voltage is applied between the electrode (C) and (B) again, the ciliary electrodes on the electrode (B) move and stick to the electrode (C) again (similar condition to step 4).

Step 8: Applying a voltage between the electrode (A) and (C) stop, and the electrode (C) is released from the electrode (A), and move to the electrode (B) (upward and forward). This is the same condition with Step 2.

By repeating the step 2 to step 8, the actuator can be driven continuously. The example of the sequence of applying the driving voltage is shown in Fig. 3.

If it stops in the step 3 or 6, the large electrostatic force can lock the moving electrode (C). It is another feature of the E-Maccel, and this is important and useful for the application of the actuator.

Although the ciliary electrodes are formed on the rigid plate in Figs. 1, 2, that is not always necessary. The ciliary electrodes are made of thin polymer and metal flexible films, and they can be also fabricated on the flexible sheet. In this case, the whole actuator has flexibility. This type of the E-Maccel is useful for driving the soft and flexible machines, which work with the changing the shape itself. E-Maccel has other features as follows:

1. E-Maccel has simple structure and is easy to be fabricated and integrated in micro/nano devices, especially, is suitable for nanoscale actuator.

2. As the moving electrode has no elastic suspension, the travelling distance of the moving electrode is restricted only by the fixed electrode area and the electrical power supply method.

3. In principle, the speed and the generated force of E-Maccel can be changed by the gap between the fixed and moving electrodes.

3. Fabrication

The fabrication process is shown in Fig. 4. We applied the principle of the fabrication process of the ciliary structure

(1) Al (sacrificial layer) deposition and patterning

Pyrex glass plate

Al

(2) Coating of polyimide layers, A and B

Polyimide A

Polyimide B

(3) Al (mask) deposition and patterning

(4) O₂ ion etching of polyimide

O₂ ion

(5) Al etching (mask and sacrificial layer)

(6) Al (electrode) deposition

Fig. 4. Fabrication process of the ciliary electrodes.
Table 1. Size of the designed and the fabricated ciliary electrodes.

<table>
<thead>
<tr>
<th></th>
<th>Designed</th>
<th>Fabricated</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lower electrode</td>
</tr>
<tr>
<td>Length</td>
<td>300 μm</td>
<td>298 ± 3 μm</td>
</tr>
<tr>
<td>Width</td>
<td>150 μm</td>
<td>145 ± 2 μm</td>
</tr>
<tr>
<td>Thickness</td>
<td>3 μm</td>
<td>3.1 μm</td>
</tr>
<tr>
<td>Height</td>
<td>104 μm</td>
<td>143 • 158 μm</td>
</tr>
</tbody>
</table>

![Cross-section of A-A](image)

Fig. 6. The structure of the fabricated moving electrode.

Coated and cured. In this step, thermal stress is induced in the polyimide film.

3) Al (3 μm thick) was deposited and patterned for the mask of oxygen ion etching.

4) Polyimide layer was etched with oxygen ion by using ECR ion gun.

5) Al mask and sacrificial layer were etched away.

6) Al (30 nm thick) was deposited. After that, the conductive adhesive bonded the electrical wire on the contact pad.

![Fig. 5](image)

Fig. 5. The fabricated electrode with the ciliary electrodes. The ciliary electrode is 150 μm wide, 300 μm long and 3 μm thick.

![Fig. 5](image)

Proposed by Ataka et al.\(^7\). Two types of polyimide thin layer having low and high thermal expansion coefficients, respectively, were coated, and the tip of the cilia was lifted up due to the thermal stress in the polyimide film. The detail of the fabrication process is as follows:

1) Pyrex glass plate that was 20 mm x 20 mm and 1 mm thick was used for the substrate. Al (0.1 μm thick) was deposited by sputtering, and was patterned by photolithography.

2) Polyimide A (low thermal expansion coefficient, \(1 \times 10^{-5}/°C\), 2 μm thick) was coated and cured. Then polyimide B (high thermal expansion coefficient, \(5 \times 10^{-7}/°C\), 1 μm thick) was also coated and cured. In this step, thermal stress is induced in the polyimide film.

4. Experiment

4.1 Simple Measurement of Motion by Electrostatic Force  In order to confirm the driving principle, i.e., the motion by the electrostatic force, the motion with a pair of a fixed and the moving electrodes were measured. The experimental set up is shown in Fig. 7(a). The moving electrode is put on a fixed
electrode. The DC power supply is connected to both electrodes. Lateral and vertical displacements of the moving electrode are observed by using an optical microscope with a micrometer. The displacements perpendicular and parallel to the moving electrode are called a displacement by the electrostatic attraction and a displacement by the actuator movement, respectively, as shown in Fig. 7(b).

An example of the experimental result is shown in Fig. 8. It shows the dependence of the each displacement of the moving electrode on the applied voltage. The voltage larger than 250 V could not be applied because of electrical breakdown. It is seen that the ciliary electrodes could not lie down completely lower than 250 V. It means that this electrode cannot generate the ideal actuator motion shown in Fig. 2, but this actuator worked as mentioned below. This problem is due to the high stiffness of the ciliary electrodes. It seems that ideal operation can be achieved by optimising the elastic property of the ciliary electrode.

In the other hand, the complete stiction by the electrostatic force was observed when the moving electrode was pushed to the fixed electrode. Fig. 9 shows the experimental result of the displacement of the moving electrode when the applied voltage reduced after the stiction. The origin of the displacement was at the condition of the complete stiction, so the negative value means that the moving electrode rises. It is seen that the moving electrode was released suddenly at about 107 V. In general, electrostatic actuators that change the electrode gap have hysteresis in the applied voltage-displacement relation. Figs. 8 and 9 suggest that the fabricated actuator also have this hysteresis. The released voltage expected by the theory is 68 V because the theoretical spring constant of a ciliary electrode is 0.14 N/m and the bending radius, $r$, of the 150-$\mu$m-high ciliary electrode is estimated at 2.7x10^{-2} m. The
higher value in the experiment is seemed due to the larger distance between the fixed and the moving electrodes caused by the dust, particle and so on between the electrodes.

The electrostatic force pulling up the moving electrode is also evaluated. The experimental set up is shown in Fig. 10. The fixed electrodes are settled on the facing plates of the micrometer by double side adhesion tape. The distance of the fixed electrodes, or the electrode gap between the fixed and the moving electrodes can be adjusted by the micrometer. The evaluation method is shown in Fig.11, and only the upper fixed electrode is settled on the micrometer in this experiment. The experimental sequence is as follows:

1. The electrode gap is adjusted.
2. Voltage is applied between the upper fixed electrode and the moving electrode.
3. The distance of the facing plate of the micrometer is increased.
4. Checking the moving electrode sticking or not sticking to the fixed electrode.

The experimental result is shown in Fig.12. It is seen that the sticking always occur if the electrode gap is below the maximum height of ciliary electrode, i.e., the ciliary electrodes touch the moving electrode, over the voltage of 87 V. This critical voltage may depend on the deformation property of the ciliary electrode. Over the maximum height of ciliary electrode, i.e., when the ciliary electrodes don't touch the moving electrode, the critical voltage gets higher linearly according to the increase of the electrode gap. That is seemed to be due to the need of the higher voltage for deforming the ciliary electrodes to touch the moving electrode.

4.2 Driving Experiment The fabricated actuator was driven, and the distance of the actuator movement was measured. The experimental set up shown in Fig. 10 was used. The fabricated actuator is driven with the sequence shown in Fig. 3. The sequence was carried out by switching manually at about 0.25 Hz. The distance of the actuator movement per cycle depend on the gap of the moving electrode and the fixed electrode. The electrode gap, therefore, was changed by using the micrometer. The total electrode gap was defined as total electrode gap = electrode gap(a) + electrode gap(b), as shown in Fig. 13. It should be noticed that the upper ciliary electrodes don’t touch the moving electrode over the total electrode gap of about 310 μm. After 100 cycles, the distance of the movement was measured by the optical microscope. The experimental result was shown in Fig. 14. The distance of the movement has peak at each voltage. At the driving voltage of 150 V and the total electrode gap of 354 μm, the peak
value of the average distance of the movement was 9.6 μm/cycle, and the larger peak value is observed at the higher driving voltage.

At gap below the 300-320 μm, which is lower limit of the total electrode gap, the movement was not observed. Over the upper limits of the total electrode gap, which depend on the driving voltage, the distance of movement was not observed, but go and back motion of the moving electrode was observed. In later case, it seems that the ciliary electrodes on lower fixed electrode generate the actuator motion, in the other hand the ciliary electrodes on upper fixed electrode could not stick to the moving electrode any longer because of large gap, and they could not stop the backward motion of the moving electrode.

5. Discussion

As shown in Fig. 14, the fabricated E-Maccel starts moving at the gap larger than 300-320 μm. It seems to be the reason that the ciliary electrode already deforms at the low total electrode gap, and cannot deform further by applying voltage. The height of the ciliary electrodes is 143-158 μm as shown in Table 1. Theoretically, it is expected that the actuator starts moving at the gap of 272-302 μm according to Fig. 8, Table 1, and other experimental data. It is under consideration why the larger gap, i.e., the upper ciliary electrodes don’t touch the moving electrode, was needed in the experiment.

The maximum displacement may be related with the maximum displacement of the ciliary electrode, i.e., the displacement by the actuator in the movement in Fig. 8. The expected distance of the movement (Summation of the displacement by the actuator movement for the upper and the lower electrode) is 17 μm/cycle. It is seen that there is a large difference between the expected and observed value. It seems that all the ciliary electrodes don’t move with same behavior and some ciliary electrode may prevent the motion of the moving electrode. This problem should be also solved in the future work.

6. Conclusion

A novel electrostatic microactuator with the ciliary electrode, E-Maccel, was proposed and fabricated by micromachining.

The fundamental characteristics of the fabricated actuator were evaluated. The actuator did not work ideally because of the mismatch of the elastic property of ciliary electrode, and so on. At the driving voltage of 150 V and the total electrode gap of 354 μm, the peak value of the average distance of the movement was 9.6 μm/cycle was observed

Acknowledgement

We thank to Mr. Muntechika for his contributions on establishing the fabrication process.

This work was partly supported by the Grant-in-Aid for Scientific Research on Priority Areas (B), No. 12131210, The Ministry of Education, Culture, Sports, Science and Technology (MEXT), and the grant of SUZUKI Foundation, Japan.

(Manuscript received Dec. 9, 2003, revised May 17, 2004)

References


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386 IEEJ Trans. SM, Vol. 124, No.10, 2004