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MICRO ELECTROSTRICTIVE ACTUATOR WITH METAL COMPLIANT ELECTRODES FOR FLOW CONTROL APPLICATIONS

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ABSTRACT

A micro synthetic jet actuator driven by electrostrictive diaphragm actuator was developed for flow control applications. Metal concentric ring electrodes were employed in order to obtain large out-of-plane deformation. It is found that the deformation strongly depends on the gap/width ratio of the ring electrode. The maximum deformation for 2mm-diameter actuators is as large as 30μm, which is 3 times larger than that of the plain metal electrode actuator. A prototype synthetic jet actuator was fabricated by using the present electrostrictive actuator, and the jet flow issued from a 0.5mm orifice was visualized.

1. INTRODUCTION

Since fluid flow is highly-nonlinear phenomena and sensitive to external disturbances, efficient control systems for both micro and macro flows using micro actuators have received significant attention in the last few decades [1]. However, actuators for flow control should have large deformation, fast response, low energy consumption, and robustness in a harsh environment. Thus, it is not straightforward to develop such devices using conventional micro actuation principle.

Recently, Glezer et al.[2] proposed so-called synthetic jet actuator having an oscillating diaphragm beneath an orifice as shown in Fig. 1. The synthetic jet actuator requires neither external fluid reservoirs nor moving parts in the flow domain, but can induce a jet flow above the orifice. Glezer et al.[2] showed that it operates effectively in jet and flow separation control. However, they employ bulky PZT devices as the driving mechanism and use its resonant frequency to enlarge the actuator deformation. Therefore, MEMS diaphragm actuators having large out-of-plane deformation are required for more flexible and/or distributed control system.

The objective of the present study is to design a micro fabrication method of electrostrictive diaphragm actuators having large deformation, and to develop a synthetic jet actuator driven by the electrostrictive principle.

2. PRINCIPLE AND DESIGN

Electrostrictive actuator consists of an elastomer film sandwiched between two compliant electrodes. When voltage is applied to the electrodes, the elastomer is subjected to compressive stress by the applied electrostatic force, and stretches in the tangential direction [3]. Figure 2 shows the principle of the diaphragm actuator, of which periphery is constrained. When the voltage applied, the diaphragm buckles and moves in the out-of-plane direction.

It is reported that giant deformation can be obtained at the cost of large applied voltage when conductive powder or polymer is used for the electrodes [3,4]. But, those materials are incompatible with the MEMS technologies. On the other hand, if plain metal electrodes are used, the deformation is significantly reduced due to its large Young's modulus. To attack this problem, we employ metal concentric ring electrodes connected with bridges as shown in Fig. 2 in order to reduce the stiffness of the electrode.

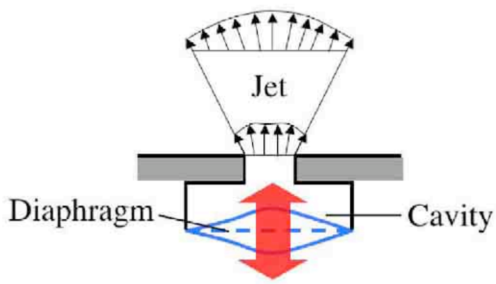


Figure 1: Synthetic jet actuator.

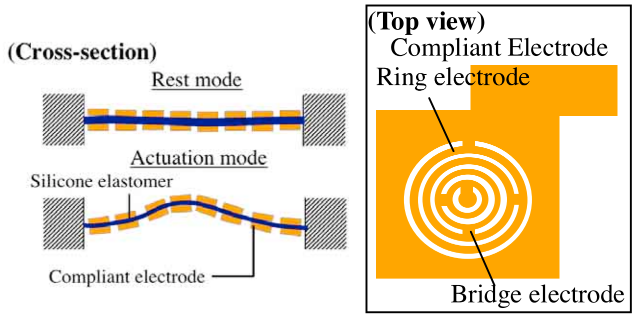


Figure 2: Out-of-plane electrostrictive actuator with patterned electrodes.

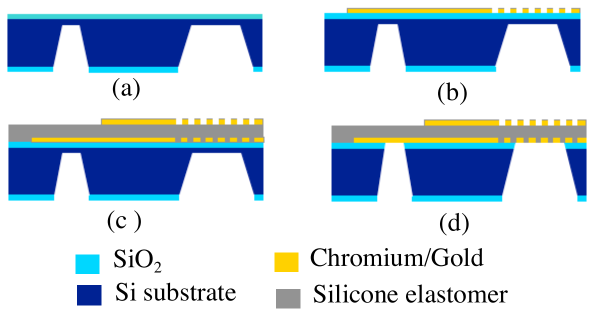


Figure3: Fabrication process.

The tangential stiffness is decreased with increasing the gap between the concentric electrodes, while the effective electrode area is decreased. Therefore, the gap/width ratio of the ring electrodes is a crucial design parameter that needs detailed analysis in order to optimize the performance of the present actuator.

For the electrostrictive actuator, the effective pressure is twice that of a conventional parallel-plate electrostatic actuator, and can be expressed as,

$$p=\varepsilon\varepsilon_0 E^2, \qquad (1)$$

where ε_0 is the free-space permittivity (8.85 x 10^{-12} F/m), ε is the relative dielectric constant, and E is the electrical field. Thus, the strain in the thickness direction is given by

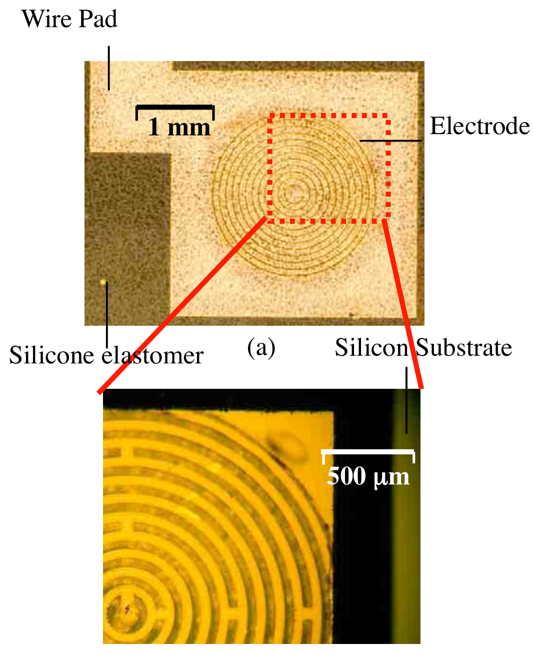
$$s_z=-\ \varepsilon\varepsilon_0 E^2/Y, \qquad (2)$$

where Y is the Young's modulus of silicone elastomer.

As can be seen from Eqs. 1 and 2, electrostrictive elastomer should have high breakdown voltage, large dielectric constant, and small Young's modulus in order to obtain large deformation. In the present study, SYLGARD 186 (Dow Corning Corp.) is employed because of its high breakdown voltage of more than 50 V/μm, relatively large dielectric constant of 3.1, and low Young's modulus of less than 10 MPa. It can also be spin-coated to a thickness of 42 ± 2 μm at the rotation speed of 6,000 rpm.

3. Fabrication Process

The fabrication process for the electrostrictive actuator is outlined in Fig. 3. The process starts with 3" Si wafer having 2 μm thermal oxide on both sides. Firstly, the oxide layer on the backside is patterned for the cavity opening and the wire connection pads. The Si substrate is then etched anisotropically using TMAH solution at 70°C until a 70 μm-thick diaphragm is left (Fig. 3a). Then, a Cr/Au/Cr layer having 10nm/180nm/10nm in thickness is deposited using an EB evaporator on the topside of the Si wafer, followed by a wet etching for patterning the bottom electrode (Fig. 3b). Subsequently, 42μm-thick SYLGARD 186 silicone is spin-coated, and cured at 65°C for 4 hours, before leaving it for 3 days to completely drive off the solvent. After the silicone is fully cured, another Cr/Au/Cr layer is deposited and patterned for the topside electrode (Fig. 3c). Finally, the diaphragm is released from the backside by etching Si and oxide layers using DRIE and BOE, respectively (Fig. 3d).



(b)

Figure4: Magnified view of the electrostrictive actuator. (a) topside electrode, (b) backside electrode.

Figure 4 shows the magnified view of the actuator. Due to the mismatch in the thermal expansion coefficients, cooling of the silicone after the metal deposition creates compressive stress in the metal film and results in the wavy pattern [5]. In the present study, the wavelength and the amplitude are respectively 10-20 μm and 1μm.

4. Experimental Results

In the present study, actuators having 2mm in diameter are fabricated. Detailed parameters of the electrodes such as width and gap are summarized in Table 1. The coverage area ratio γ is defined by the electrode area dividing by the total area of the elastomer film. The plain electrode actuator has γ of unity, while patterned electrode actuators have γ less than 1. Laser displacement meter (Keyence, LC-2440) having a resolution of 0.2 μm is employed to measure the static and dynamic responses of the actuators.

Figure 5 shows the out-of-plane deformation of the actuators with 45μm-wide electrodes. With increasing the electric field, the deformation is increased with a nonlinear manner as expected from Eq. 2. For the W45G15 actuator, of which electrode width and gap are respectively 45μm and 15μm, the maximum deformation of 30.6μm is achieved at 50V/μm, which is 3 times larger than the plain electrode actuator. For the cases of W45G10 and W45G40, the deformation is much smaller than W45G15.

Figure 6 shows the out-of-plane deformation for all the actuators listed in Table 1. Horizontal axis is the coverage area ratio γ, while the vertical axis is the deformation at an electric field of 50V/μm. For both sets of actuators having 45μm- and 60μm-wide electrodes, the deformation exhibit similar trends, and have a maximum deformation at around γ=0.7-0.8. As mentioned above, increase of the gap has two opposite effects. The first one is the reduction in the effective area of the electrode, which leads to a reduction in the electrostatic force. The second one is the reduction in the tangential stiffness of the actuator, which results in larger deformation for the same applied force.

The dynamic response to a sinusoidal driving voltage is examined for the W45G15 actuator, which has the optimum coverage area ratio. The driving voltage V_d [kV] is given by

$$V_d=0.9(\sin 2\pi ft + 1), \qquad (3)$$

Gain is defined as the ratio of the maximum dynamic amplitude to the static deformation. It is found in Fig. 7 that gain is rapidly decreased to about 0.9 at the frequency less than 1Hz. With further increasing the frequency, gain is gradually decreased with some fluctuations and becomes about 0.8 at 2kHz. The resonance frequency of the diaphragm is estimated to be 4 kHz, and no marked peak is observed in the frequency range examined, although a small peak is found at 550Hz.

Table 1:List of actuators fabricated.

Case	Width (μm)	Gap (μm)	Gap /Width Ratio	Coverage Area Ratio (γ)
PLAIN	-	-	-	1
W45G10	45	10	0.22	0.81
W45G15	45	15	0.33	0.74
W45G40	45	40	0.89	0.51
W60G10	60	10	0.17	0.85
W60G20	60	20	0.33	0.77
W60G50	60	50	0.83	0.52

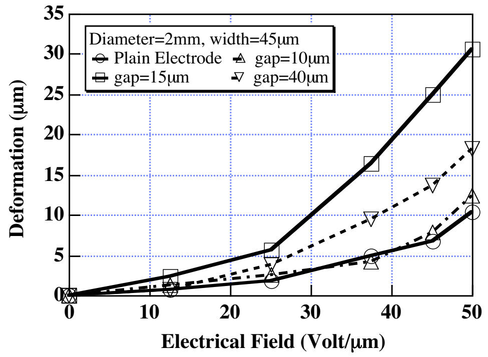


Figure 5: Out-of-plane deformation versus applied electric field for actuators having 45μm-wide electrodes and different gaps.

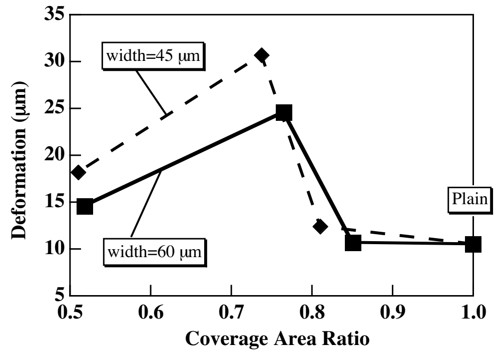


Figure 6: Out-of-plane deformation at 50 V/μm versus the coverage ratio.

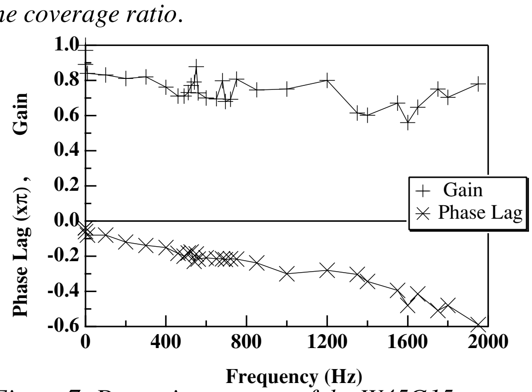


Figure 7: Dynamic response of the W45G15 actuator.

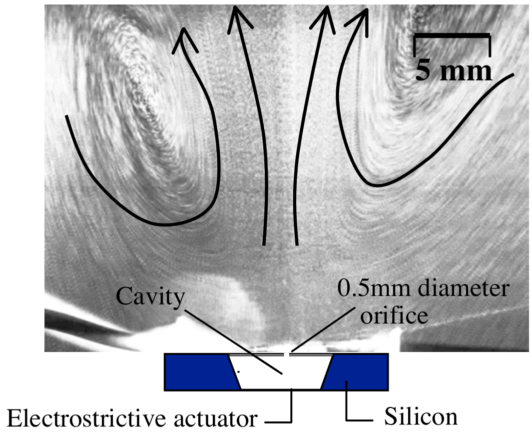


Figure 8: Flow visualization result.

The rapid decrease of the deformation at very low frequency can be explained by the frequency dependence of the electric field induced strain, which is especially found in high dielectric material. It was suggested that the strain induced by the electric field decreases when the driving frequency increases [6]. According to the phase lag, the absolute value monotonically increases with the frequency, and becomes about 0.6π at 2kHz.

5. SYNTHETIC JET ACTUATOR

A synthetic jet actuator is developed using an electrostrictive diaphragm actuator presently developed. A 50μm-thick copper plate with a 0.5mm hole is attached onto the backside opening of a 5mm-diameter actuator in order to make a cavity and an orifice. Sinusoidal voltage signal of 1.8kV amplitude is applied to the electrodes, which corresponds to out-of-plane deformation of 10μm. In the present flow visualization experiment, the actuator is fixed in a box filled with smoke, and two-dimensional plane contains the orifice axis is illuminated by using an 1mm-thick laser sheet of a pulsed Nd:YAG laser. Figure 8 shows the visualized smoke image, of which field of view is about 2x2 cm^2. Driving frequency of the actuator is chosen as 1.6kHz. A jet flow is clearly seen above the orifice, while a pair of counter flow toward the orifice is also observed. The jet flow velocity at the centerline and 10 mm above the orifice is about 50 mm/s.

6. CONCLUSION

Micro fabrication technology for out-of-plane electrostrictive actuators has been developed and applied to a synthetic jet actuator. The following conclusions can be derived.

1) Compliant metal electrodes using concentric ring patterns are successfully integrated on the electrostrictive actuator.
2) The deformation strongly depends on the coverage area ratio of the ring electrodes. Deformation 3 times larger than that of the plain electrode is achieved at the optimum condition.
3) Jet flow velocity of about 50mm/s is obtained using a 5mm-diameter actuator at a driving frequency of 1.6kHz.

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REFERENCES

[1] P. Moin and T. Bewley, "Feedback control of turbulence," *Appl. Mech. Rev.* Vol. 47, 1994, S3-S13.

[2] A. Glezer and M. Amitay, "Synthetic jets," *Annu. Rev. Fluid Mech.,* Vol. 35, 2002, pp. 503-529.

[3] R.E. Pelrine, R.D. Kornbluh, and J.P. Joseph, "Electrostriction of polymer dielectrics with compliant electrodes as a means of actuation," *Sensors Actuators A*, Vol. 64, 1998, pp. 77-85.

[4] Y. Suzuki, N. Kasagi, and T. Yoshino, "R&D study on micro sensors and actuators for active control of wall turbulence," *Proc. 2nd Symp. Smart Control of Turbulence*, Tokyo, 2001, pp. 19-26.

[5] N. Bowden, S. Brittain, A.G. Evans, J.W. Hutchinson, and G.M. Whitesides, "Spontaneous formation of ordered structures in thin films of metals supported on an elastomeric polymer," *Nature*, Vol. 393, 1998, pp. 146-149.

[6] J. Su, Q.M. Zhang, C.H. Kim, R.Y. Ting, and R. Capps, "Effects of transitional phenomena on the electric field induced strain-electrostrictive response of a segmented polyurethane elastomer," *J. Appl. Polymer Science,* Vol. 65, No.7, 1997, pp. 1363-1370.