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NON-CONTACT ELECTROSTATIC MICRO-BEARING USING POLYMER ELECTRET

Yukinori Tsurumi, Yuji Suzuki, and Nobuhide Kasagi
Department of Mechanical Engineering, The University of Tokyo
Hongo, Bunkyo-ku, Tokyo 113-8656, Japan

ABSTRACT

We propose a passive gap-spacing control method in order to avoid stiction between top and bottom structures for in-plane sensor/actuator applications. Patterned electret using a high-performance perfluoro polymer material is employed to induce repulsive electrostatic force. Out-of-plane repulsive force is successfully demonstrated with our early prototype both in air and liquid.

1. INTRODUCTION

For in-plane sensors and actuators, sensitivity and efficiency are strongly dependent on the gap spacing. Various gap control methods for these applications have been investigated. Ramakrishnan et al. [1] propose a toroidal-shaped slider using DLC-coated low-wear interface. Their slider has low static coefficient of friction (COF) of about 0.3. Lin et al. [2] and Modafe et al. [3] employ microball bearings with micro grooves etched into the Si substrate. They found that static COF of the microball bearing is as low as 0.01. However, since most passive methods previously reported rely on mechanical contact, sticking and/or relatively short wear life are of concern especially for applications requiring extremely-large operation cycles.

The objective of the present study is to develop a passive non-contact gap-spacing control method using electrets. Electret is dielectric material with semi-permanent trapped charges [4], and used for microphones and power generators [5-7] in the MEMS field. Chang et al. [8] tried to realize repulsive force using planar electrets, but only attractive force was observed. In our preliminary tests, we duplicated their results and found that the attractive force can be explained with electrostatic potential theory assuming one-dimensional field. In the present study, we employ patterned electrets, and examine the electrostatic field and the force using systematic numerical simulations. In addition, we microfabricate an early prototype of non-contact electrostatic micro-bearing.

2. PRINCIPLE OF ELECTRET MICRO-BEARING AND DESIGN

Figure 1 shows the principle of the present device. Upper substrate is supported with flexures and moves parallel to the lower fixed substrate. Both substrates have patterned electret films with trapped charges. In order to keep the gap spacing, the electrostatic force between the substrates should be always repulsive independently of the overlapping area between the top and bottom electrets.

We made a series of numerical simulations of electrostatic fields between the substrates with ANSYS Ver. 11.0. As shown in Fig. 2, patterned electret films with backside electrodes are assumed. In between neighboring two electret films, guard electrodes are located on the substrates, which are electrically grounded. Only one pitch in the in-plane direction is solved with the periodic boundary condition. Width, thickness of the electrets and the gap between the electret surfaces are respectively set to 150 μm, 20 μm and 50 μm. Surface charge density and relative permittivity of the electret are assumed to be –1.0 mC/m^2 and 2.1, respectively. In Fig. 2, electrostatic vectors from the top and bottom electrodes are facing each other, and spread in the in-plane direction near the corners of electrets.

Figure 3 shows the electrostatic force between the electrets versus the overlap ratio, which is the percentage of overlapping area of the top and bottom electret surfaces. When charges are assumed to be located at the electret surface, large repulsion force is obtained for the relative permittivity of unity (ε_r=1). However, under realistic conditions, charges are located not at the electret surface, but some depth from the surface [4]. When charges are assumed to be at 1 μm depth, the force is markedly changed; the electrostatic force becomes attractive for ε_r=1. The force is also strongly dependent on the relative permittivity of the gap space ε_r, and the force become repulsive again for $\varepsilon_r > 5$. Note that the force is insensitive to the overlap ratio. From these results, repulsive force can be possible with patterned electrets, especially when medium with high permittivity is introduced into the gap.

Although most fluids with high permittivity are liquid, charges trapped in electrets are often lost when the electret surface is in contact with liquid. Therefore, in order to develop electrets that withstand in the liquid environment, we employ a parylene protection layer on the top of CYTOP electrets. Parylene-C is non-permeable against various kinds of liquid, and it can be deposited in room-temperature vacuum environment. In our preliminary tests, we found that the charges in CYTOP are intact after the parylene deposition. In addition, we can implant charges through the parylene layer after its deposition, since parylene-C is not charged.

Thickness of the electret and the Parylene-C layers are

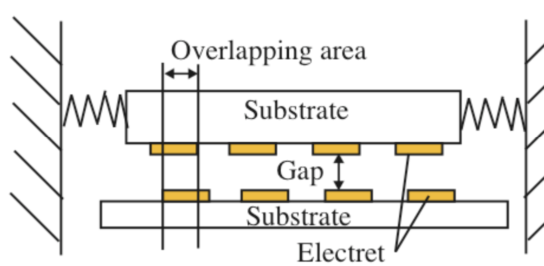

Figure 1: Principle of electrostatic micro-bearing using polymer electret. Vertical repulsive electrostatic force regulates the gap distance.

respectively 15 µm and 5 µm, and the other conditions are the same as mentioned above. The location of the charges is at 1 µm depth from the electret surface (i.e., 6 µm deep from the protection layer surface). As shown in Fig. 4, the electrostatic force is changed from attractive to repulsive when the relative permittivity is increased. If compared with the data shown in Fig. 3, the force for electrets with the parylene-C layer becomes repulsive at lower relative permittivity (ε_r>2.7) than electets without a protection layer.

It is now clear from the numerical simulation that repulsive force is possible using patterned electret, although the force strongly depends on various parameters.

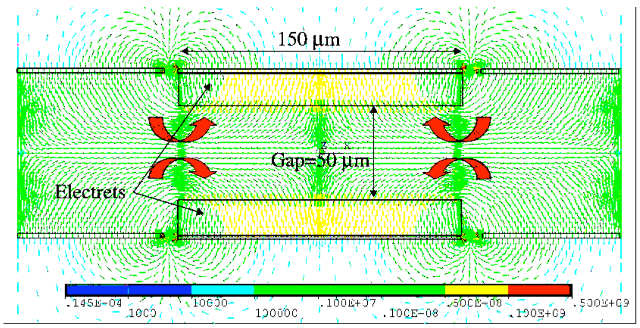

Figure 2: Numerically-simulated electrostatic field vectors between electrets for the overlap ratio of 100%.

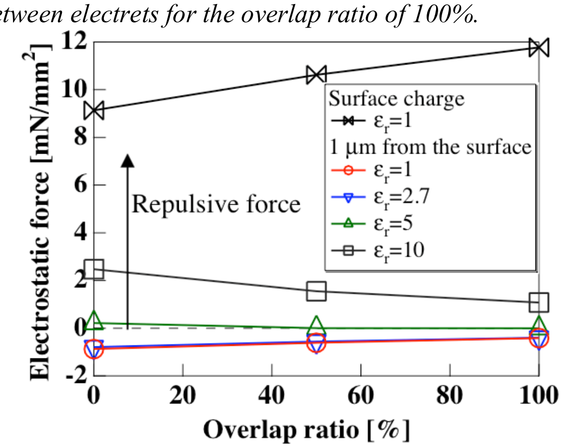

Figure 3: Computational results of electrostatic force for different relative permittivity of the gap space.

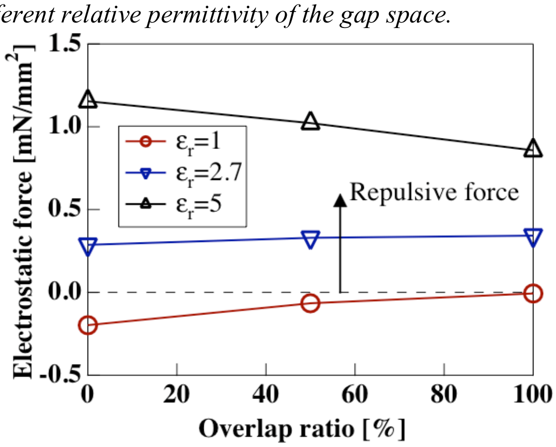

Figure 4: Computational results of electrostatic force for electrets with 5-µm-thick parylene-C as a protection layer.

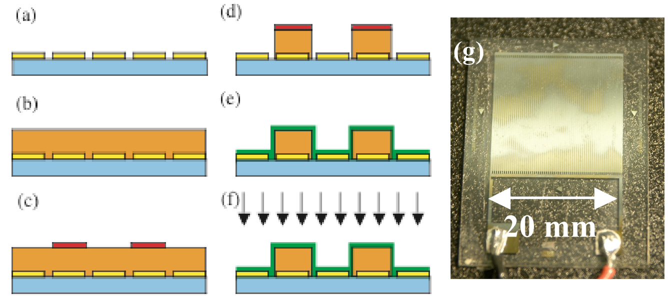

Figure 5: Fabrication process for patterned electret plate.

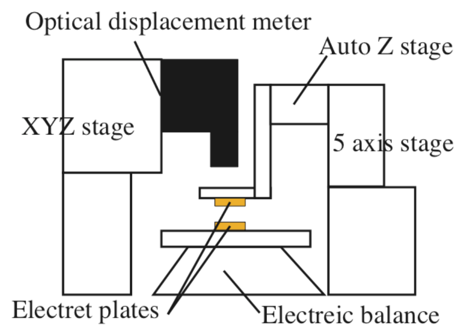

Figure 6: Schematic of the force measurement set-up.

3. FABRICATION PROCESS AND EXPERIMENTAL SET-UP

We employ CYTOP CTL-809M (Asahi Glass Co., Ltd.) for the electret material. CYTOP is amorphous perfluoro polymer. We previously found that CYTOP can provide three times larger surface charge density than Teflon AF [7]. Figure 5 shows the fabrication process of the patterned electrets with the parylene-C protection layer. At first, Cr/Au/Cr films are evaporated on a 4" Pyrex wafer and patterned with standard photolithography and wet etching process. CYTOP is then spun on at 800 rpm for 20 second and soft baked 100 ºC for 10 minutes. This process is repeated 7 times to obtain 15-µm-thick film, and cured at 185 ºC for 1.5 hour. As the metal mask layer, copper is evaporated and patterned on the CYTOP surface, followed by O_2 plasma etch with 100 W RF power for 60 minutes. Finally, 5-µm-thick parylene-C is deposited, and charges are implanted using corona charging. Figure 5g shows the electret substrate with 150-µm-wide interdigitized electrets and electrodes.

Figure 6 shows the experimental set-up for the measurement of electrostatic force between electret substrates. One of the substrates is fixed on an electric balance, and the other is mounted on a 5-axis alignment stage with an automatic z-axis stage, by which the gap between the two substrates is adjusted. The gap is measured with a high-precision laser displacement meter.

4. EXPERIMENTAL RESULTS

Table 1 summarizes surface voltage of the electrets used in the present experiments. Firstly, we measured the electrostatic force in the air environment (ε_r=1) for electrets without the parylene-C protection layer. Cases 1 and 2 correspond to different samples with different surface voltage. As shown in Fig. 7, magnitudes of the electrostatic force are increased with decreasing the gap. Repulsive force is obtained when the overlap ratio is 100 %, whereas attractive force appears for the 0% overlap ratio. The attractive force is twice as large as the repulsive force. These experimental data exhibit different trends from the numerical results assuming surface charges shown in Fig. 3, in which large repulsive force is obtained both for 0 % and 100 % overlap ratios. It is conjectured that the charge depth is a cause of difference between numerical results and the experimental data.

Figure 8 shows electrostatic force in air using four different pairs of electet substrates with the protection layer (Cases 3-6). Surface voltages are much higher for these cases as shown in Table 1. For 100 % overlap, repulsive force is obtained for all the cases examined. The repulsive force is increased with decreasing the gap, and reaches 0.33 mN/mm^2 (3.3g/cm^2) at the gap of 100 μm for Case 4. On the other hand, for 0 % overlap, attractive force is obtained for Cases 3 and 5, while repulsive force for Cases 4 and 6. It is conjectured that repulsive force is obtained when the difference of surface voltage between the top and bottom electrets is small (10 % or less for Cases 4 and 6). On the contrary, the force becomes attractive when the surface voltage difference is large. Note that the minimum gap in air is chosen as 100 μm, to avoid discharge in air.

Figure 9 shows electrostatic force in silicone oil (Shinetsu Silicone, KF-96, ε_r=2.7). Even with the parylene-C protection layer, about half of charges are lost when the electrets are dipped into silicone oil (Cases 7 and 8). As expected from the numerical results shown in Fig. 4, repulsive force is obtained both for 100 % and 0 % overlap ratios. Note that smaller gap down to 50 μm is tested in silicone oil, because the dielectric strength of the silicone oil is higher than that of air. The magnitudes of the repulsive force are insensitive to the overlap ratio, and the force for Case 7 is as large as 1 mN/mm^2 (10 g/cm^2), which is 10 times larger than that for Case 8. This difference is also due to the difference in the surface voltages of the top and bottom electrets.

Figure 10 shows the electrostatic force of Cases 4 and 7 normalized with the electrostatic force between parallel plates with constant voltage $F_0=\varepsilon_r\varepsilon_0 E_0^2/2$. The electric field E_0 estimated with the gap and the surface voltage of electret is used. Repulsive force obtained in the present

Table 1: Surface voltages of electret samples.

	Surface Voltage [V]		Parylene thickness	Medium
	Top	Bottom		
Case 1	-520	-540	0 μm	air
Case 2	-500	-500	0 μm	air
Case 3	-1200	-950	5 μm	air
Case 4	-1100	-980	5 μm	air
Case 5	-1100	-1350	5 μm	air
Case 6	-860	-970	5 μm	air
Case 7	-600	-600	5 μm	silicone oil
Case 8	-540	-600	5 μm	silicone oil

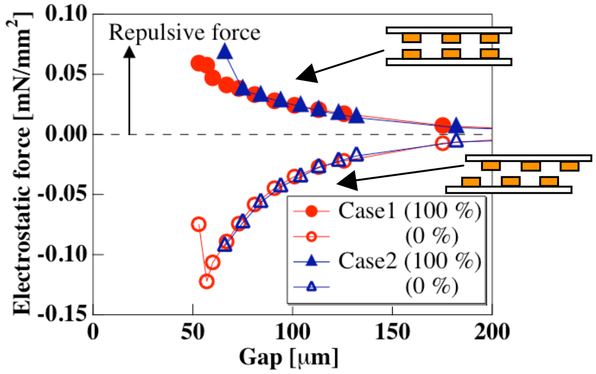

Figure 7: Experimental results of electrostatic force between electret substrates without the protection layer.

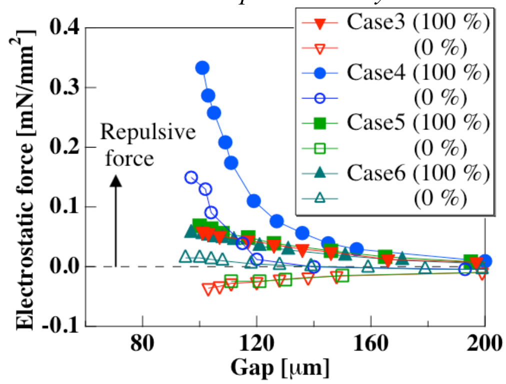

Figure 8: Experimental results of electrostatic force between electret substrates with a 5-μm-thick parylene-C layer.

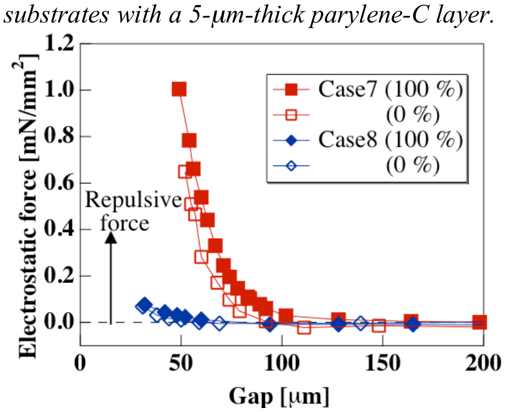

Figure 9: Experimental results of electrostatic force between electret substrates with a 5-μm-thick parylene-C layer in silicone oil.

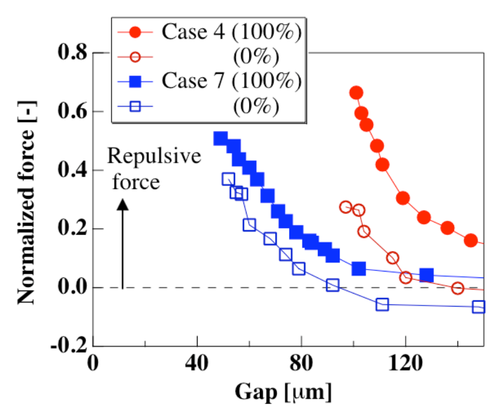

Figure 10: Electrostatic force normalized by the force between parallel plates with constant voltage difference.

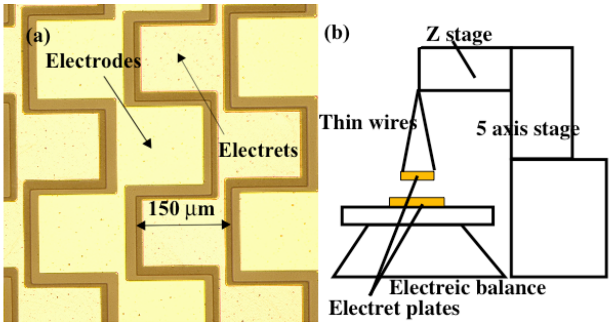

Figure 11: (a) Electret plates with checker-board pattern, (b)Experimental set-up.

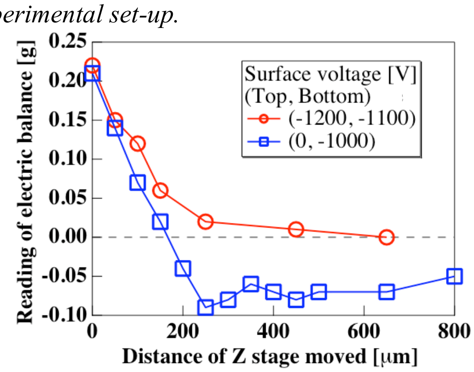

Figure 12: Experimental result for demonstration of electret levitation.

experiments is almost the same for air and silicone oil, and about 50 % and 30 % of the force acting between parallel plates for 100 % and 0 % overlap ratio, respectively. Note that the force in air acts further than that in silicone oil.

In the present experiments, repulsive force has been obtained both in the air and silicone oil environments with patterned electrets. However, the experimental data show different trends from the numerical results. This is probably because we assume uniform charges located at a depth of 1 μm from the electret surface. Detailed analysis including the charge density distribution in the depth direction is necessary for more accurate prediction.

5. DEMONSTRATION OF ELECTRET LEVITATION

Based on the experimental results shown above, we designed an early prototype of electret levitation using patterned electret. We employ a checker-board pattern in this prototype as shown in Fig. 11a, where 150 x 150 μm^2 square electrets and electrodes are patterned on the glass substrate. With this design, the device should become less sensitive to the alignment between the top and bottom plates. Fabrication process for this prototype is the same as the interdigitized electret shown in Fig. 5. The patterned areas of the top and bottom substrates are respectively 10 x 10 mm^2 and 20 x 20 mm^2. Figure 11b shows the experimental set-up for demonstration of electret levitation. The bottom substrate is fixed on the electric balance, and the top substrate is hanged with two thin copper wires for electrical connection to the ground. The top substrate is turned over and placed on the bottom substrate. Then, the top substrate is gradually moved upwards using a z-stage. If the attraction force acts between the top and bottom substrates, the reading should become negative, when the top substrate is moved.

Figure 12 shows the reading of the electric balance versus the traverse distance of the z-stage. Initial reading of the balance is about 0.2 g, because the weight of the top substrate is 0.21g. When only the bottom electret is charged, the balance reading is decreased with increasing the traverse distance, and shows negative values due to the attractive force. On the other hand, when both the top and bottom electrets are charged, no negative reading has been observed. The reading is also positive for large traverse distance because of the repulsive force. This is an evidence of the repulsive force between two electrets and thus the electret levitation of the top substrate is confirmed.

6. CONCLUSION

In the present study, we propose electrostatic micro-bearing with patterned polymer electret. Electrets with a protection layer of parylene-C are successfully micro-fabricated, and out-of-plane repulsive electrostatic force up to 1.0 mN/mm^2 has been achieved for the first time. An early prototype for electret levitation is also developed for proof of our concept.

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