Proc. of the 9th Intl. Conf. of Asian Society for Precision Engg. and Nanotechnology (ASPEN 2022)
15–18 November 2022, Singapore. Edited by Nai Mui Ling Sharon and A. Senthil Kumar
doi://10.3850/978-981-18-6021-8_OR-12-0113

Fabrication of Flexible Coil on PDMS for MEMS-based Electromagnetic Membrane Actuator

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KEYWORDS: MEMS, Electromagnetic membrane actuator, Flexible coil, Screen printing, PDMS

MEMS-based electromagnetic membrane actuators (EMMAs) play a significant role in driving micropumps due to their high response, environmental insensitivity, and low driving voltage. However, the development of conventional moving-magnet EMMA, consisting of a membrane/magnet structure and a planar coil, is limited by the time-consuming and costly fabrication process because of the indirect integration of high-temperature-deposited film-magnet and the polydimethylsiloxane (PDMS) polymer membrane. We propose a moving-coil EMMA consisting of a coil/membrane structure. The integration is simplified by screen-printing Ag-based conductive polymer composite (CPC) material having high elongation directly on the PDMS membrane as the coil. The magnet can be directly deposited on the heat-resist wafer, such as silicon or glass. This paper focuses on the feasibility verification of printing coil on PDMS membrane. The CPC is densely printed and has a solid shape for the printed pattern on the PDMS treated by oxygen plasma. The minimum line, average thickness, and resistivity of the printed CPC on treated PDMS are 100 μm, 6 μm, and 2×10^{-6} Ω·m, respectively. The tensile test shows that the printed CPC is still electrically conductive under a strain of 40%.

1. Introduction

MEMS-based membrane actuators have been used in various applications ranging from micropumps to vibrotactile displays. Until now, many types of membrane actuators utilizing different actuation mechanisms have been developed. Amongst them, electromagnetic membrane actuators (EMMA) have great potential for lithium battery-powered wearable devices because of their low-voltage actuation benefits.

To fabricate fully MEMS-based EMMA, Zhi realized a moving-magnet EMMA using high-performance NdFeB magnets and a coil fabricated by sputtering technology [1]. However, the development of this EMMA is limited due to an indirect complex integration process of NdFeB magnets with PDMS membrane through a Si sacrificial layer and dry etching. To simplify the integration process, our group fabricated a moving-magnet EMMA using bonded magnets composed of polymer matrix and NdFeB magnet powders [2]. We simplified the integration of magnets with PDMS membrane by a simple trench filling approach. However, due to the addition of non-magnetic components in the bonded magnets, the diluted magnet properties lead to a weak actuator performance under the same current.

Therefore, we propose a moving-coil EMMA using a flexible coil to achieve both simple fabrication and high-performance EMMA. In this EMMA, we integrate the coil and PDMS membrane instead of the permanent magnet and membrane. To achieve simple fabrication and flexibility of the coil, we print conductive polymer composite (CPC) material onto the PDMS membrane using the screen-printing technique to manufacture the flexible coil. This paper focuses on the feasibility verification of printing coil on PDMS membrane through screen printing.

2. Proposal of a Moving-coil EMMA

The schematic of the proposed moving-coil EMMA is shown in **Fig. 1**. The coil is printed on the membrane by the screen-printing technique using CPC-based ink. The magnet is a high-performance

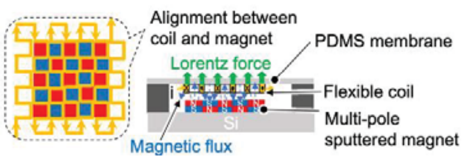


Fig. 1 Schematic of the proposed moving-coil electromagnetic membrane actuator using screen-printed flexible coil

NdFeB magnet fabricated by sputtering depositions. The multi-pole magnetization pattern of the magnet is achieved by laser-assisted magnetization developed by our group [3]. When we apply a current to

the coil, the coil is subjected to Lorentz force, which subsequently drives the PDMS membrane. Because the ink has conductive particles with a stretchable polymer matrix, the coil can still conduct electricity in the presence of deformation.

3. Fabrication

3.1 Printing preparation on a PDMS membrane

We conduct a preliminary experiment to print line/space patterns on a PDMS membrane to verify the feasibility of printing CPC.

Printing ink consists of silver particles, acrylic polymer, and DEAC solvent. Silver particles act as the conductive filler for electrically conducting. The acrylic polymer acts as the polymer matrix for stretching. DEAC acts as a solvent to reduce the viscosity of the ink for better printing. Ag/acrylic polymer/DEAC solvent ratio is 54.3/13.6/32.1wt%. The substrate to be printed is PDMS (SIM260, Shinetsu Chemical, Japan) fabricated by spin coating with a thickness of 100 μm. The mesh count per inch, wire diameter, mesh thickness, and emulsion thickness of the screen mask (Sonocom, Japan) are 500, 16 μm, 20 μm, and 10 μm, respectively. A screen-printing machine (DP-320, NEWLONG, Japan) is used to fix the PDMS substrate to avoid its movement during printing. Clearance is set to 1 mm to make the mesh snap off the substrate after printing. After printing, the printed pattern is heated at 90 °C for 30 min to evaporate the solvent.

3.2 Results and discussion

3.2.1 Printing coverage ratio

The coverage ratio of the pattern (actual printed area printed/designed area) is an essential factor for printing. When the pattern coverage ratio is too low, the resistance of the coil can increase significantly or the coil will even malfunction. We compare the printed pattern on surface-untreated and surface-treated PDMSs, as shown in **Fig. 2**. We calculate their respective coverage ratio by thresholding. The coverage ratios of the pattern on the surface-untreated and surface-treated PDMSs are 55% and 95%, respectively, which shows that proper surface treatment is essential to obtain a pattern with high coverage ratio.

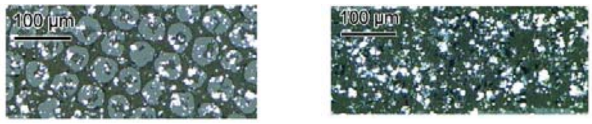
3.2.2 Printing tracks

The widths of the coils used for EMMA are in the micrometer range, so we print tracks of different widths to know their printing limits. The printing results show that a 100 μm wide track is successfully printed, as shown in **Fig. 3**. When the designed track width is too small, such as 30 μm, the considerable mesh opening length (35 μm) of the screen mask makes the printing incorrectly.

After measuring the thickness of a 6 mm long and 100 μm wide track, we find that the average thickness is about 6 μm. The resistance is 20 Ω measured by a multimeter. As a result, the resistivity is $2 \times 10^{-6}\ \Omega \cdot \mathrm{m}$.

3.2.3 Resistance under tensile force

To verify that the coil on PDMS is still electrically conductive during deformation, we measure the normalized resistance at different strains of a 6 mm long and 100 μm wide track. The results indicate that the track is still conductive at 40% strain, as shown in **Fig. 4**. The resistance increase contributes to the dimension and resistivity changes of the coil.



(a) (b)

Fig. 2 Printed pattern on: (a) surface-untreated PDMS; (b) surface-tre ated PDMS

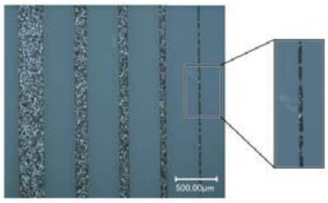


Fig. 3 Printed tracks with 400, 200, 150, 100, 30 μm

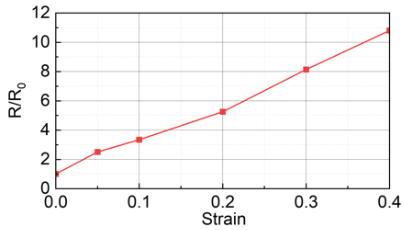


Fig. 4 Normalized resistance of a printed 100 μm wide track under tensile force

4. Conclusions and outlook

This paper presents a moving-coil EMMA based on screen printing technology. The minimum width of the printed track is 100 μm. The resistivity of the material is $2\times10^{-6}\ \Omega\cdot\mathrm{m}$. Tensile tests have demonstrated that the track is still conductive at 40% strain. This method of integrating coil and membrane by screen printing can significantly simplify the processing and improve the performance of EMMA. In the future, we will design and manufacture the actuator.

ACKNOWLEDGEMENT

This work was supported by JST SPRING, Grant Number JPMJSP 2106.

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