Journal of Sensor Science and Technology
Vol. 22, No. 5 (2013) pp. 333-337
http://dx.doi.org/10.5369/JSST.2013.22.5.333
pISSN 1225-5475/eISSN 2093-7563

A Simple Plane-Shaped Micro Stator Using Silicon Substrate Mold and Enamel Coil

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Abstract

This study proposes a simply fabricated micro stator for higher output power than previously reported micro stators. The stator has been fabricated by inserting enamel coil in silicon mold formed by micro etching process. The most merits of the proposed micro stator are the simple fabrication process and high output power. Previously reported micro stators have high resistance because the micro coil is fabricated by relatively thin-film-based deposition process such as sputtering and electroplating. In addition, the previously reported micro coil has many electrical contact points for forming the coil structure. These characteristics of the micro stator can lead to low performance in output power. However, the proposed micro stator adopts commercially available enamel coil without any contact point. Therefore, the enamel coil of the proposed micro stator has low junction resistance due to the good electrical quality compared with the deposited or electroplated metal coil. Power generation tests were performed and the fabricated stator can produce 5.4 mW in 4000 RPM, 1 Ω and 0.3 mm gap. The proposed micro stator can produce larger output power than the previously reported stator spite of low RPM and the larger gap between the permanent magnet and the stator.

Keywords : Power generator, Turbine generator, Stator, Magnet, Coil

1. INTRODUCTION

Recently, various portable devices such as smartphone use sensors as key elements, those are battery-powered and operate on economic energy budget, and so low power management concern is significantly increasing. As a result of that, many studies about low power consumption system have been reported [1-3]. Also, researches on the power generator and the reducing the power consumption of the sensor have been reported in many papers. Therefore, many kinds of the power generation devices, such as thermoelectric device, piezoelectric device and solar cell, were reported [4, 5]. Especially, revolving field type micro generators have been widely reported [6-8]. The revolving field type micro generator convert mechanical torque into electrical energy on the basis of electromagnetic induction law. The revolving field type micro generators composed of disk shape permanent magnet for generating magnet filed and fixed planar type stator of around 10 mm diameters. The micro stator is generally fabricated by deposition and electroplating process for thick metal layer on the substrate. However, previously reported the micro stators have significant drawback such as complex fabrication process due to the complex structure, much manufacturing time for thick metal electro plating, low output power and expensive production expense. Also, the design of the stator is very hard and structurally limited because the stator must be fabricated as small size and planar type.

In this paper, simple micro stator was fabricated by inserting enamel coil into the silicon substrate to overcome the shortcomings. The enamel coil of the proposed micro stator is made by well optimized and commercialized fabrication technology. Moreover, the enamel coil is composed in one wire form without any disconnected parts and defects. Therefore, the enamel coil of the proposed micro stator has low junction resistance due to the good electrical quality compared with electroplated metal coil.

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(Received : Aug. 26, 2013, Accepted : Sep. 27, 2013)

The proposed fabrication process of stator is easy and simple and can produce more power than the previously reported stator by reducing contact resistance. In addition, the power generation experiment was conduct for comparing performance of the proposed micro stator with previously reported micro stators.

2. DESIGN AND FABRICATION

Figure 1 shows the schematic of the proposed stator applying enamel coil to silicon substrate mold. The silicon substrate was etched to a depth of 110 ㎛ and the 110 ㎛ width. And enamel coil was inserted in the silicon substrate. The diameter of the enamel coil is 110 ㎛.

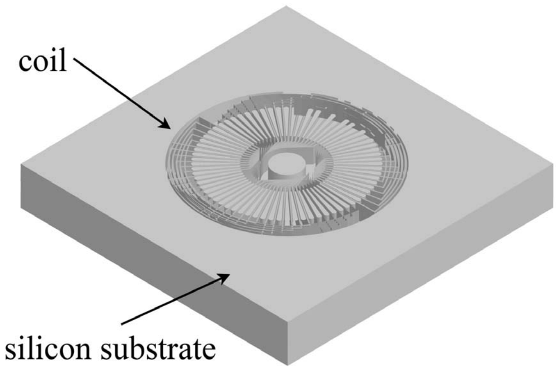


Fig. 1. Schematic of the proposed stator.

The previously reported micro stator was generally fabricated by deposition and electroplating metal layer on the silicon substrate. However, the proposed stator was fabricated by inserting the enamel coil into the micro etched silicon substrate. By using the proposed fabrication process, the complex fabrication process to form a micro coil can be simplified and the fabrication time and cost can be saved. Furthermore, the stator has low resistance due to good electrical characteristics of the enamel coil. The previously reported fabrication process of the micro coil repeats patterning, deposition and plating process to forming micro coil in three-dimensional structure on flat silicon substrate. In this case, the contact resistances of the micro coil increased because of many contact areas and electrical defect due to the many fabrication process. However, the proposed stator has good conductivity and low internal resistance because the enamel coil formed as single line without any contact areas.

The fabrication process of the silicon mold is shown in Fig. 2. The silicon was fabricated using micro electro mechanical systems (MEMS) technology for realization of micro scale structure. A silicon oxide was grown on 6-inch silicon wafer by wet oxidation. After photolithography process, the oxide layer was patterned by wet chemical etching process. And the silicon was etched to a depth of 110 ㎛ by deep reactive-ion etching (DRIE) process. Finally, photoresist and oxide layer was removed from the silicon substrate. Figure 3 shows the fabricated silicon substrate.

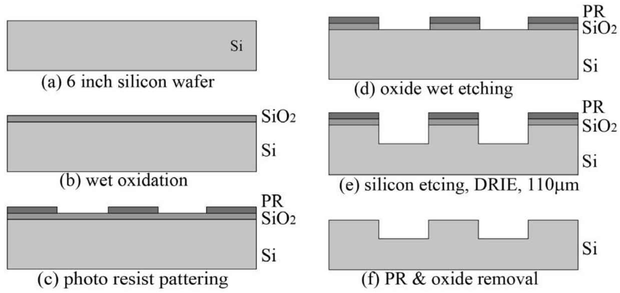


Fig. 2. Fabrication process of the silicon substrate.

Fig. 3. Fabricated silicon substrate.

The schematics of the stator windings are shown in Fig. 4. Figure 4(a) shows single phase stator winding. Along the dotted line, the enamel coil is wound. The ring-shaped permanent magnet was used for applying magnet field to the proposed micro stator. The permanent magnet has four poles on same surface. Therefore, the stator should be design into quarters according to the number of pole of permanent magnet. The enamel coil passes between the quarters of circle shown in Fig. 4(a).

The enamel coil was wound up 6-times. In part of the overlapped electrodes, the coil is perfectly insulated by the coated enamel.

Normally, previously reported micro stators are required complicate processes repeating for the making insulation layer and three dimensional coil structures of the stator such as thin film deposition, patterning and etching. However, in this paper, the proposed stator is simply fabricated by winding the enamel coil into the silicon substrate without the complicated process. The induced current by the permanent magnet is generated in the inner and outer directions depending on the direction of magnet rotation and type of pole. Overall, the current is induced to the one direction. Figure 4(b) shows the three phase stator winding.

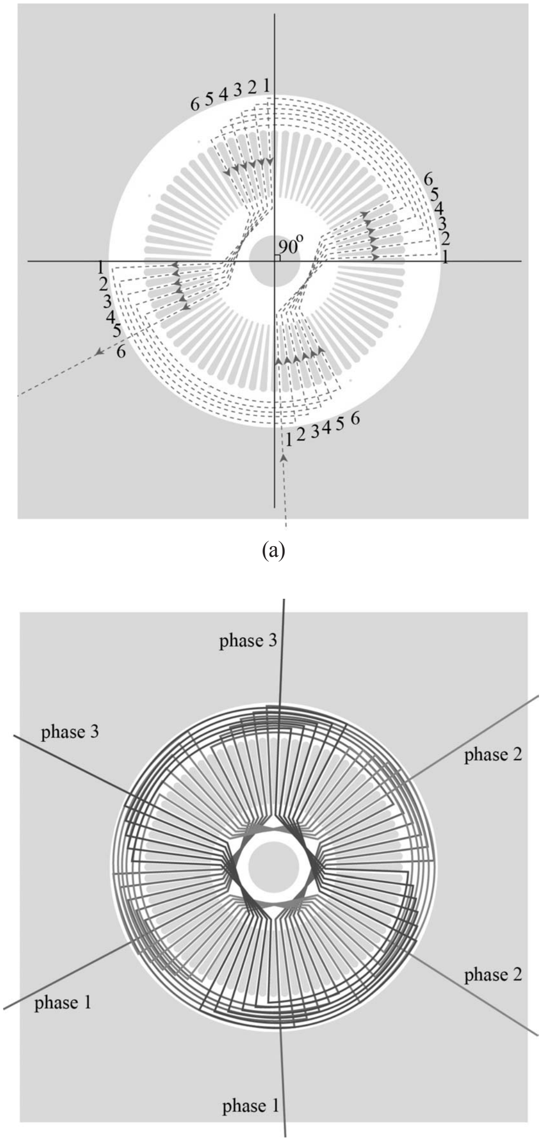


Fig. 4. Schematics of the stator windings; (a) Single-phase stator winding and (b) three-phase stator winding.

Three 6-times wound enamel coils were inserted each had been separated by 30 degrees to every 90 degree for form the three phase micro stators. Figure 5 shows the fabricated micro stator that inserted enamel coil in the fabricated silicon mold. Finally the enamel coil was fixed with epoxy.

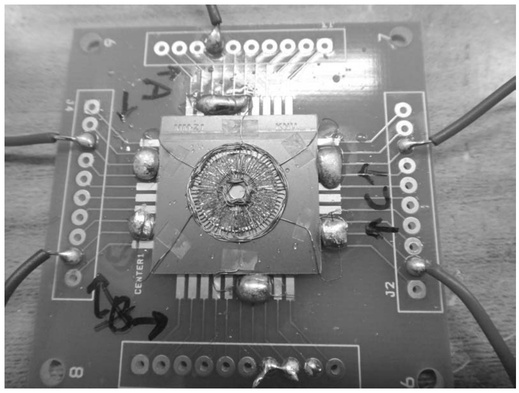


Fig. 5. Fabricated stator.

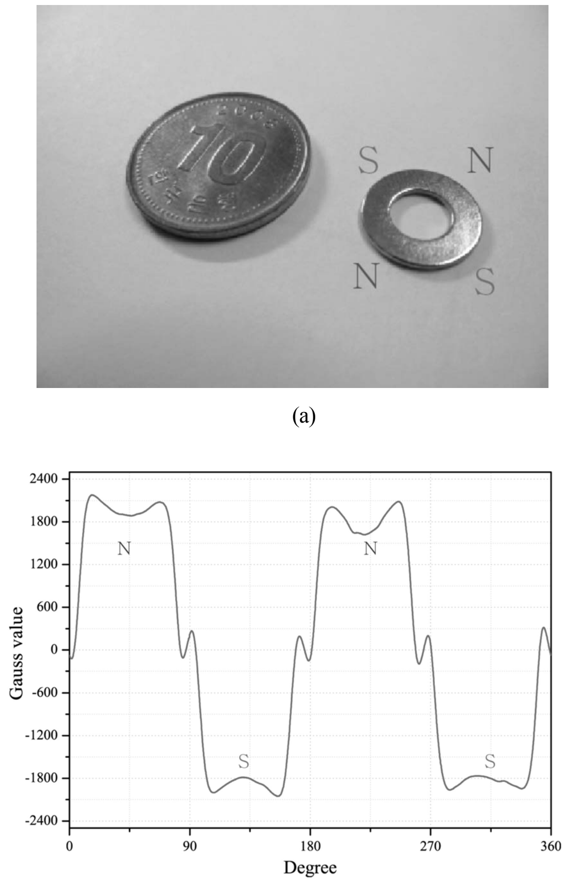
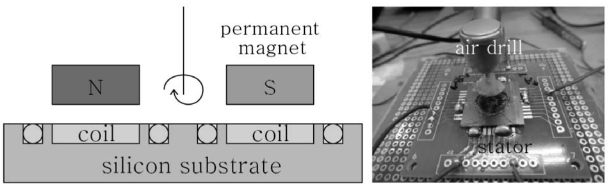


Fig. 6. (a) The permanent magnet (NdFeB) and (b) the gauss value of the magnet as a function of degree.

The four pole permanent magnet for applying magnetic field to stator is shown in Fig. 6(a). The polarities of four pole permanent magnet applying magnetic field to stator change every 90 degrees. Neodymium (NdFeB) permanent magnets (inner diameter × outer diameter × thickness : 5 mm × 10 mm × 0.7 mm) were used in this research. Figure 6(b) shows the measurement result in gauss value of the permanent magnet as a function of degree.

3. RESULTS AND DISCUSSIONS

Figure 7 shows schematics of the power generation measurement system of the proposed micro stator. The torque was obtained by fixing the permanent magnet to the dental drill. The rotation speed of dental drill can be adjusted by input air pressure. By installing the moving stage at the bottom of stator, the gap between the stator and stage can be adjusted. Therefore, the changes of power generation as a function of the gap between permanent magnet and stator can be observed by using the measurement system.



(a) (b)

Fig. 7. Power generation measurement system; (a) Schematic and (b) photograph.

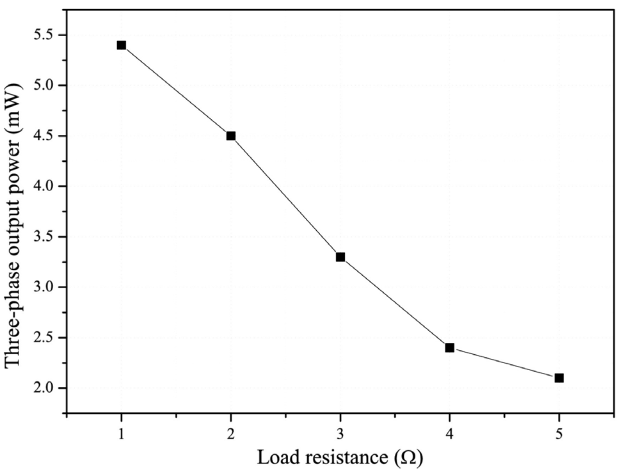


Fig. 8. Three-phase output power of the stator as a function of load resistance, at 4000 RPM for a 300 μm gap.

Figure 8 shows the three-phase output power of the proposed micro stator as a function of load resistance. The gap between the stator and permanent magnet is 0.3 mm and the torque is 4000 RPM. The fabricated micro stator can produce 5.4 mW with 1 Ω load resistance.

Figure 9 shows three-phase output power of the proposed micro stator as a function of rotation speed. The experiment was performed from 2000 to 4000 RPM with 1 Ω load resistance. The fabricated stator produced maximum power of 5.4 mW at 4000 RPM and the production of power is linearly proportional to the number of rotation speed. Above 4000 RPM, the larger output power is expected.

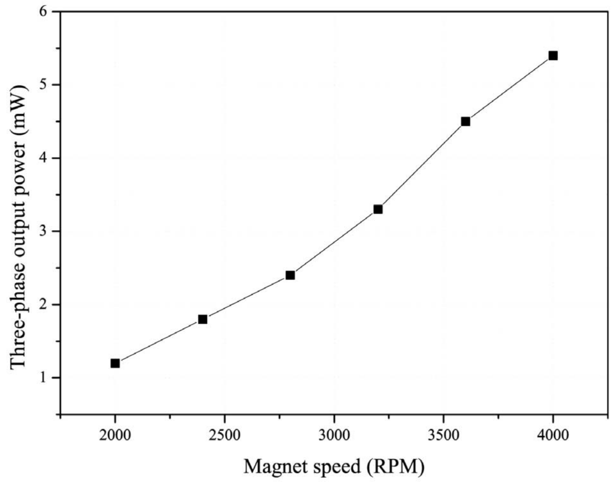


Fig. 9. Three-phase output power of the stator as a function of a rotation speed at 300 μm gap for a 1 Ω.

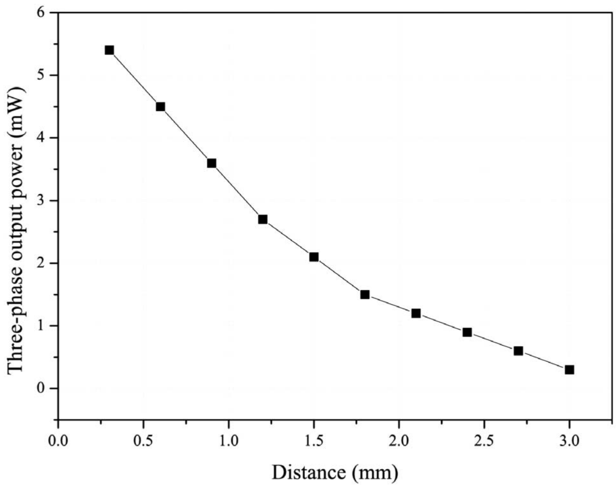


Fig. 10. Three-phase output power of the stator as a function of the gap at 4000 RPM for a 1 Ω.

Figure 10 shows three-phase output power of the proposed micro stator as a function of gap between permanent magnet and the stator. The output power is inversely proportional to the gap between permanent magnet and stator because the magnetic field affecting the stator is reduced.

Table 1. Performance comparison of variable stators [6-8]

Reference	Gap (μm) (magnet-stator)	RPM	Output Power (μW)
A. S. Holmes [6]	120	7000	60
C. T. Pan [7]	1	13000	1800
F. Herrault [8]	50	392000	6600
J. C. Choi (This work)	300	4000	5400

The comparisons of output power of the previously reported micro stators and the proposed micro stator are shown in Table 1. The proposed micro stator can produce larger output power than the previously reported stators despite of low rotational speed and the larger gap between the permanent magnet and the stator.

4. CONCLUSIONS

In this paper, simple micro stator with inserting enamel coil into the silicon substrate is proposed. The previously reported micro stator has disadvantages such as complicated fabrication processes, long time and expensive cost. But the proposed stator has simple fabrication process and can save cost and time. Also, the proposed stator has superior performance in terms of resistance of materials because of good electrical characteristics of the enamel coil. The proposed micro stator shows higher power production efficiency than the previously reported stator. The proposed micro stator produced 5.4 mW at 4000 RPM, 1 Ω load resistance and 0.3 mm gap between the stator and the permanent magnet.

ACKNOWLEDGMENT

This research was financially supported by a grant to MEMS Research Center for National Defense funded by DAPA/ ADD.

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