

Design and Fabrication of Compact MEMS Electromagnetic Micro-Actuator with Planar Micro-Coil Based on PCB

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Abstract

This paper reports a compact design of electromagnetically driven MEMS micro-actuator utilizing planar electromagnetic coil on PCB (Printed Circuit Board). The micro-actuator device consists of an NdFeB permanent magnet, thin silicon membrane and planar micro-coil which fabricated using simple standard MEMS techniques with additional bonding step. Two planar coils designs including planar parallel and spiral coil structure with various coil geometry are chosen for the study. Analysis of the device involves the investigation of electromagnetic and mechanical properties using finite element analysis (FEA), the measurement of the membrane deflection and functionality test. The measurement results show that the thin silicon membrane is able to deform as much as 12.87 μm using planar spiral micro-coil. Reasonable match between simulation and measurement of about 82.5% has been revealed. The dynamic response test on actuator driven by parallel planar coil shows that silicon membrane effectively deformed in 40 s for an input electrical power of only 150 mW. It is also concluded that planar parallel coil is considered for the simple structure and easy fabrication of the actuator system. This study will provide important parameters for the development of compact and simple electromagnetic micro-actuator system for fluidic injection system in lab-on-chip.

Keywords: MEMS, electromagnetic micro-actuator, printed circuit board (PCB), silicon membrane, planar micro-coil

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1. Introduction

MEMS micro-actuators have recently attracted research interest in the fields of biomedical and chemical analysis due to their simple and compact structures [1], low and controllable power consumption [2] and fast response time [3]. Especially silicon based micro-actuator driven by electromagnetic field is the key component of microfluidic pumping system that finds its important role for biological sample injection in lab-on-chip system [4] and drug delivery system applications [5, 6] where accurately delivery of small quantity of liquid is required [7].

Electromagnetic actuator is driven by magnetic forces generated by current carrying conductive spiral coil, such as solenoid, toroid and planar coil. Among all the coil types, planar coils have been found as the simplest and most suitable structure for used in multilayer structure. Planar coil reduces the device volume as much as 10 times as compared to solenoid model [8].

Several techniques to fabricate planar micro-coils have been reported before. Some of standard microelectronic mechanical system (MEMS) fabrication technique such as metal deposition using vacuum evaporator or DC-sputtering [9], deposition of conductive polymer implementing SU8 micromolding [10], metal electroplating and electroless plating on silicon substrate [11], are preferred to fabricate the coil structure because of the familiarity of the process adopted from IC technology.

Nevertheless, the above mentioned techniques are complex and expensive. Planar micro coil produced by Kohlmeier, et al., [10] requires complicated processes, such as SU8 coating, patterning and molding process. Other techniques that have been done by Amato, et

al., [9] and Woytasik, et al., [11] require expensive metal target and equipment. On the other hand, it has been reported previously that microfluidic chip is packaged on printed circuit board (PCB) platform to reduce cost and enable effective integration between the lab-on-chip system with other electronics parts [12-14].

Therefore, we report in this paper the development of silicon based micro-actuator with planar micro-coil structure developed on PCB. Utilization of existing copper on the PCB layer used to fabricate micro-coil structure can reduce fabrication costs and ease of fabrication. The study is focused on exploring the PCB based coil design and geometry that is able to generate uniform and optimum magnetic flux density to produce optimum membrane displacement. The fabrication technology of the actuator system and the functionality test of the fabricated structure are also presented.

2. Basic Principle of Electromagnetic Micro-actuator

The basic structure of electromagnetic micro-actuator consists of three main parts namely an electromagnetic micro-coil, a permanent magnet and a mechanical membrane, as schematically shown in Figure 1. Basically, the working principle of electromagnetic actuator is depending on magnetic force acting on a flexible membrane that is produced by the interaction between magnetic fields generated by current carrying micro-coil with permanent magnet.

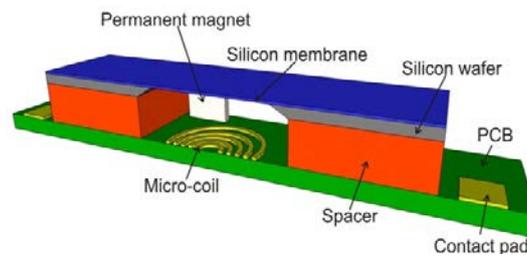


Figure 1. Schematic Structure of the MEMS EM Actuator

The analytical equation for the magnetic field generated by a circular coil is given by the Biot-Savart law. For a single turn circular coil, with radius r , the magnetic field at a distance z along its central axis, is given by Equation (1):

$$H(z) = \frac{I r^2}{2(r^2 + z^2)^{\frac{3}{2}}} \quad (1)$$

Where I is the current, r is the mean radius of the turn and z is the distance along the z -axis. To obtain the magnetic field of a coil with N turns, the total generated magnetic field is the sum of all magnetic fields generated by each turn. Meanwhile, the magnetic force produced for the system in Figure 1 is described in Equation (2):

$$F_z = B_r A_g \int_z^{z+h_g} \frac{\partial H_z}{\partial z} dz \quad (2)$$

Where F_z is the magnetic force, B_r is the remanence of the magnetic material, A_g and h_g are the surface area and thickness of the magnet, respectively. The correlation between magnetic force applied on the membrane and the resulting membrane displacement dz can be derived from Equation (3):

$$d_z = c \frac{F_z l_m^2}{D} \quad (3)$$

Where F_z is the force l_m is the length of the membrane. The constant c depends on the boundary conditions at the outer edges and the shape of the membrane. D is the flexural rigidity of the membrane material which is defined by:

$$D = \frac{E h_m^2}{12(1-\nu^2)} \quad (4)$$

Where E is the Young's modulus of the material, ν is Poisson's ratio and h_m is the thickness of the membrane.

3. Design of Electromagnetic Micro-actuator

3.1. Permanent Magnet

Bulk permanent magnet used for this proposed device is made of NdFeB material with diameter and thickness of 3 mm and 1.5 mm, respectively. The magnet is attached to the silicon membrane using epoxy material. The magnetic force is dependent on the magnetic field strength, magnetic material volume and the distance between the magnet and the electromagnetic coil along the z-axis.

3.2. Mechanical Membrane

In this study, silicon material is used as the membrane due to the best material strength and simplest fabrication process compared to other materials such as polyimide and polydimethylsiloxane (PDMS). Furthermore, silicon material has high thermal conductivity that prevents the release of permanent magnet attached on the membrane due to the heat concentration. However, silicon material is more rigid than polyimide or PDMS, due to its high modulus elasticity of approximately 169 GPa [15].

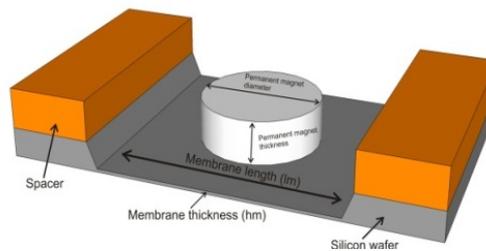


Figure 2. The Schematic of Membrane Geometry with Attached Permanent Magnet



Figure 3. Types Of Studied Micro Coil Structure: (a) Planar Parallel Circular Micro-Coil. (b) Planar Spiral micro-coil

Table 1. The Geometrical Parameter of Planar Micro-Coil used in the Study

Sample type	Coil 1	Coil 2	Coil 3	Coil 4
Width (μm)	100	200	150	100
Space (μm)	150	100	100	100
Thickness (μm)	30	30	30	30
Inner diameter (mm)	2.5	2.5	2.5	2.5
Number of Turn	5	5	5	5

The geometry of the membrane and silicon chamber used in this work is shown in Figure 2. In terms of space requirements, the membrane area should be large enough to accommodate the surface area of the magnet. Therefore In this work, the membrane surface area was set to $6 \times 6 \text{ mm}^2$ with total chamber volume including spacer of $6 \times 6 \times 2 \text{ mm}^3$ to provide enough space for a free movement, meanwhile the glass material was used for the spacer.

3.3. Planar micro-coil

Two types of planar micro-coil are investigated in this study including planar parallel circular micro-coil and planar spiral micro-coil, as shown in Figure 3. The geometry of the planar micro-coil is varied as listed in Table 1. The micro-coil parameters that are kept constant are inner diameter, thickness and the number of coil turns of 2.5 mm, 30 μm and 5, respectively.

Electromagnetic force generated is strongly affected by the dimension of planar micro coil. Therefore, planar micro coil simulation with various dimensions was necessary. In this simulation, constant electrical current of 500 mA was applied. The simulation result shown in Figure 4 reveals that the optimum magnetic force was generated at the coil width and space with the range between 80 μm to 100 μm . This optimum generated electromagnetic force was uniformly distributed on the surface of planar micro coil as show in Figure 5.

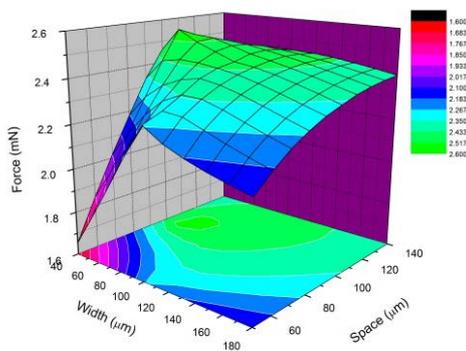


Figure 4. The Simulation Result of Electromagnetic Force

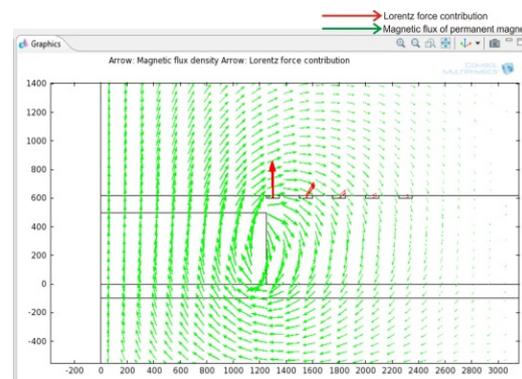


Figure 5. Distribution of Magnetic Flux

From Equation (1), it can be estimated that the smaller the area radius of the planar micro-coil, the higher magnetic field can be generated. Therefore, the design should consider the variation between space and width of the coil in order to obtained optimal geometry.

4. Actuator Fabrication

The important components of electromagnetic micro-actuator are the membrane, chamber and the electromagnetic coil. In this work, the micro-actuator membrane and the chamber is made of silicon material that is fabricated using standard silicon process. Here, the silicon membrane was fabricated by anisotropic etch of 375 μm thick silicon wafer $\langle 100 \rangle$ using KOH solution at 75 $^{\circ}\text{C}$ with controllable slow etch rate of 78 nm/min. Another etchant solution such as HNA is able to create the chamber however large under etch and unpredicted etch rate was observed [16].

Anisotropic etching technique is used due to the cost effectiveness and simplicity of the process compared to the deep reactive ion etching (DRIE) or others isotropic etching. The advantage of microcoil fabricated on the PCB is simpler than fabricated microcoil on silicon substrate, because it does not need metal deposition process. Nevertheless, the space geometry of fabricated microcoil below than 100 μm is hard to achieve due to the fabrication limitation such as low photolithography mask resolution.

The process step of silicon membrane fabrication is very simple requiring only one masking process (see Figure 5). Firstly, photoresist AZ 4620 was spin coated on planar silicon wafer (a), UV- exposure for 80 seconds to open the oxide window and PR development using

1:2 AZ 400 K dilution with DI water (b), Opening the oxide layer using 10 % BOE for 100 minutes (c) and follow with photoresist removal using acetone. The silicon substrate was then anisotropically etched using KOH etchant to produces silicon chamber and membrane (d).

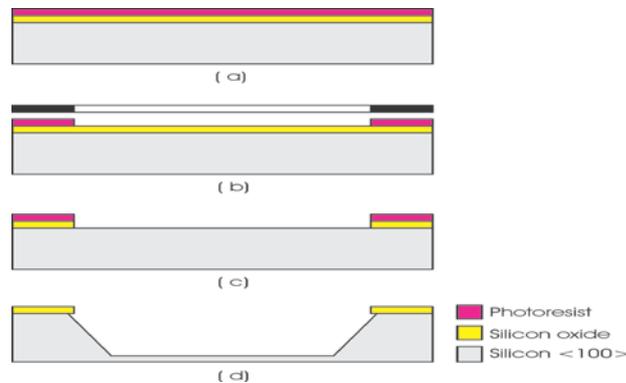


Figure 5. Membrane Fabrication Step, (a) Photoresist Coating, (b) Membrane Patterning, (c) Oxide Etching, (d) Silicon Etching

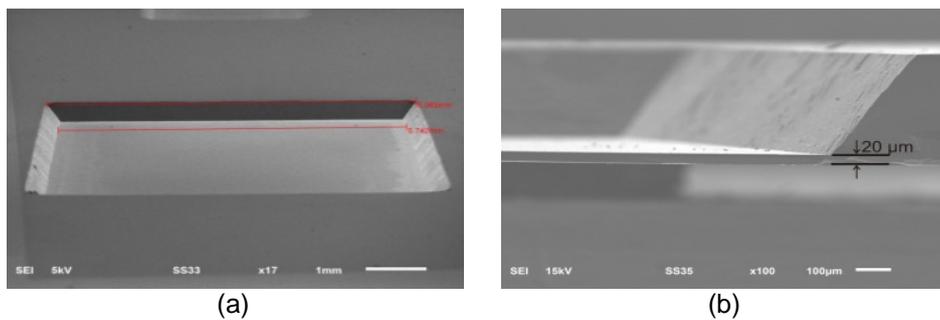


Figure 6. The result of fabricated silicon membrane and chamber, (a) SEM image of silicon trench for the actuator chamber after anisotropic etching, (b) SEM image of fabricated membrane having the thickness of 20 μm

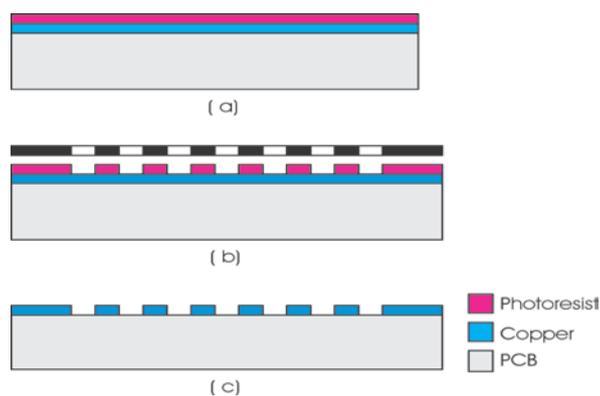


Figure 7. Fabrication Process of Planar Coil, (a) Photoresist Coating, (b) Photoresist Patterning, (c) Copper Etching and Photoresist Removing

The fabrication result of silicon membrane is shown in Figure 6a and Figure 6b. These results show that a silicon thin membrane with the thickness of approximately of 20 μm is

successfully fabricated after etching the silicon substrate. A side slope of about 54° with smooth and flat membrane surface were also observed.

Figure 7 shows the fabrication step of planar electromagnetic micro-coil. The planar coil is made of $30\ \mu\text{m}$ copper material electroplated on PCB substrate. The process step of the micro-coil fabrication is simple requiring only 1 lithography process.

Initially, photoresist AZ 4620 was spin coated onto PCB surface to form the coil pattern (a). UV light was then exposed for 80 seconds when the exposure energy is $250\ \text{mJ}/\text{cm}^2$ and developed in AZ 400k 1:2 for 50 seconds (b). Finally, the micro-coil structure was produced after copper etching process by 70 % FeCl_3 for 1 hour 20 minutes with an etching rate of about $0.375\ \mu\text{m}/\text{min}$ to etch $30\ \mu\text{m}$ copper (c).

Figure 8 shows the result of the coil fabrication for the both coil types, namely (a) planar parallel circular micro-coil and (b) planar spiral micro-coil. (c) SEM of micro coil thickness.

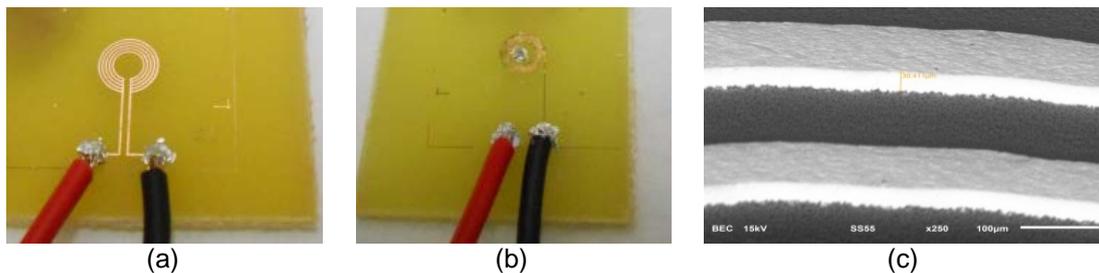


Figure 8. The Fabrication Result of Micro-Coil. (a) Planar Parallel Circular Micro-Coil. (b) Planar Spiral Micro-Coil. (c) SEM Image of Micro Coil Thickness

The next part of the micro-actuator fabrication is the attachment of permanent magnet on to the silicon membrane using epoxy. The permanent magnet is cylinder type with diameter and thickness of 3 mm and 1.5 mm, respectively.

The electromagnetic micro-coil, silicon chamber and membrane including permanent magnet are then finally integrated by bonding all micro-actuator parts using epoxy completing the structure as shown in Figure 9.

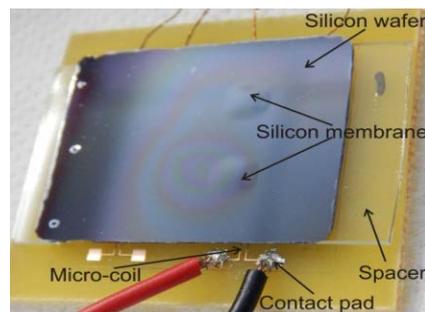


Figure 9. The Micro-Actuator after Integration of All Parts

5. Results and Discussions

5.1. Measurement Results

Figure 10 illustrates the setup for the measurement of actuator performances. The measurement system consists of Keyence LC-2400 displacement meter with the laser probe, measurement stage and power supply.

Figure 11 and Figure 12 show the displacement of the membrane at the center when DC currents are applied to the both micro-coil types. It is clearly shown that the $20\ \mu\text{m}$ thin silicon membrane can reach its maximum deflection after 40 seconds. This is because of the

relaxation time characteristic of silicon membrane to adjust the plastic deformation capability of the material for bending.

It is also observed that after 40 sec, the membrane displacement decreases slightly which is due to the heat effect of the coils reducing the generation of electromagnetic field and the efficiency of the energy transfer.

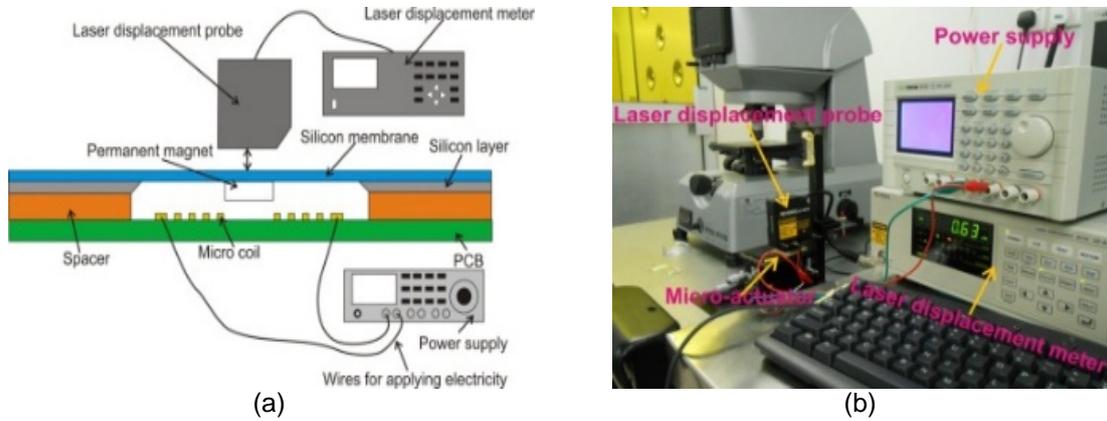


Figure 10. (a) The Schematic of the Set Up for the Measurement of Membrane Displacement, (B) Photography of the Measurement System

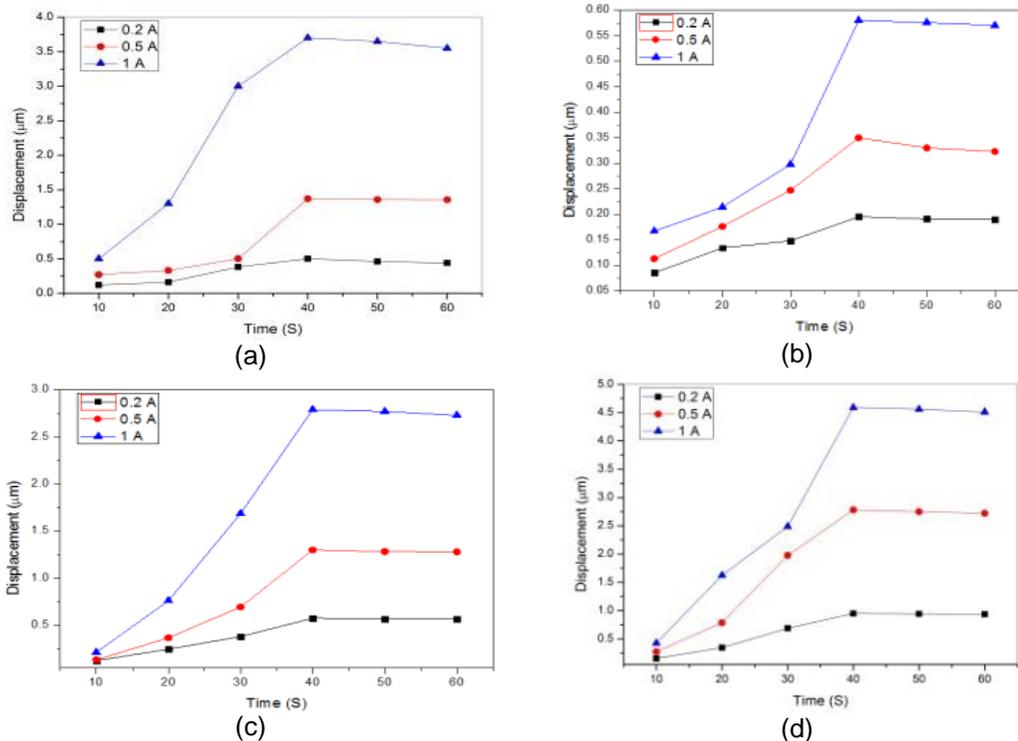


Figure 11. Relationship between deformation time and measured micro-actuator displacement of planar parallel circular micro coil at various applied input current. (a) coil 1 with $w=100 \mu\text{m}$, $s=150 \mu\text{m}$. (b) coil 2 with $w=200 \mu\text{m}$, $s=100 \mu\text{m}$. (c) coil 3 with $w=150 \mu\text{m}$, $s=100 \mu\text{m}$. (d) coil 4 with $w=100 \mu\text{m}$, $s=100 \mu\text{m}$

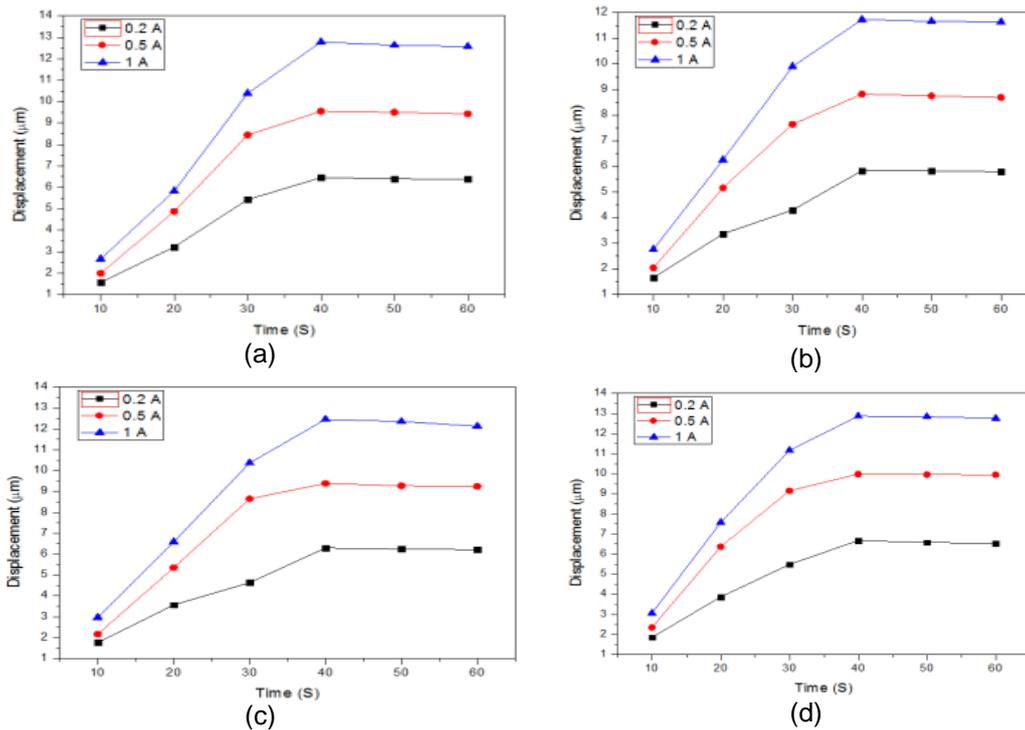


Figure 12. Relationship between Deformation Time and Measured Micro-Actuator Displacement of Planar Spiral Micro-Coil at Various Applied Input Current. (a) coil 1 with $w=100 \mu\text{m}$, $s=150 \mu\text{m}$. (b) coil 2 with $w=200 \mu\text{m}$, $s=100 \mu\text{m}$, (c) coil 3 with $w=150 \mu\text{m}$, $s=100 \mu\text{m}$, (d) coil 4 with $w=100 \mu\text{m}$, $s=100 \mu\text{m}$

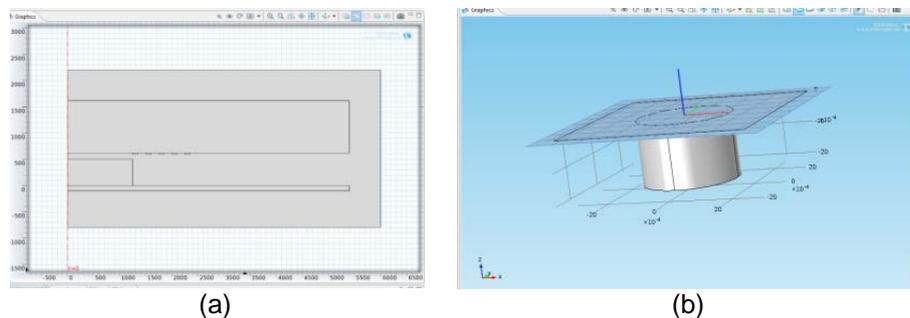


Figure 13. The Geometric Layout Design Model, (a) 2D Axisymmetric, (b) 3D Model

In Figure 12d it is shown that micro-actuator with planar spiral micro-coil 4 (width= $100 \mu\text{m}$ and space= $100 \mu\text{m}$) produces a maximum membrane displacement of approximately $10.1 \mu\text{m}$ for an input current of 500 mA , which is the highest deflection among all types. This is due to the better current distribution along the micro-coil and more efficient magnetic field generation at the coil center.

On the other hand the micro-actuator with planar parallel coil achieved maximum membrane displacement of approximately $2.75 \mu\text{m}$, which is almost 3 times lower than that of planar spiral coil type (see Figure 11d).

It is also shown in Figure 12 that the fabricated micro-actuator with planar spiral micro-coil types can achieve displacement height within the range of 4 to $13 \mu\text{m}$ for input current between 200 mA to 1 A .

To validate the analysis, the measurement results are compared with the simulation. Two dimension model of COMSOL (2D axisymmetric) simulation was used. Meanwhile, 3D

model used for displacement simulation as show in Figure 13 and the solid mechanics module was also applied. The micro-coil geometry and others micro actuator parameter were varied as shown Table 2. Furtehrrmore, air medium parameter is used for the boundary condition.

Table 2. Micro Actuator Parameters

Sample type		Micro-coil 1	Micro-coil 2	Micro-coil 3	Micro-coil 4
Micro coil	Width (μm)	100	200	150	100
	Space (μm)	150	100	100	100
	Thickness (μm)	30	30	30	30
	Inner diameter (mm)	2.5	2.5	2.5	2.5
	Turn	5	5	5	5
	Material	Copper	Copper	Copper	Copper
Membrane	Material	Silicon			
	Width	6 mm			
	Thickness	20 μm			
	Form	Square			
Permanent magnet	Diameter	1.5875 mm			
	Thickness	0.3429 mm			
	Form	Disc			

The measurement results are summarized in Table 3. It is shown that the simulated membrane deflection is higher than that of measurement for all coil configurations which is due to the ideal simulation condition. On the other hand, there are several lost in measurement process such as resistances of the wires, Gauss meter and power supply that affect to the power efficiency delivered to the coils. However it can be seen that reasonable match between simulation and measurement of about maximum 82.5 % was obtained.

Table 3. Comparison between Measurement and Simulation Results of Membrane Deflection for 0.5 A Input Current

Sample Type	Type of micro-coil			
	Planar parallel micro-coil		Planar spiral micro-coil	
	Measured Displacement (μm)	Simulated Displacement (μm)	Measured Displacement (μm)	Simulated Displacement (μm)
Coil 1	1.37	1.66	9.55	9.63
Coil 2	0.35	0.358	8.82	8.91
Coil 3	1.3	1.39	9.39	9.46
Coil 4	2.78	3.46	9.978	10.13

5.2. Dynamic Response Test

Figure 14 shows the dynamic response of the micro-actuator for the functionality test purpose. An applied current of 500 mA at planar parallel circular micro-coil (1) was intermittently turned ON and OFF within a period of about 50 seconds. For the ON state condition, it is shown that the membrane is able to deform effectively within 40 seconds with the maximum deflection of 1.4 μm for only 150 mW electrical power consumption (see also Figure 10a). While at OFF state condition, it can be seen that the membrane cannot return to its starting position, which is due to the lack on membrane elasticity after deformation and loss of electromagnetic force hence requiring more time to release its surface stress

Although the planar spiral micro-coil resulted in better magnetic properties and higher deflection capability than planar parallel circular micro-coil, it should be considered that the fabrication process of the planar parallel circular micro-coil is simpler than the spiral one as it does not require interconnection between inner coil and output pads. Other advantages of planar parallel circular micro-coil type are that it does not need wire bonding process for connection, sacrificial layer or insulation layer to prevent short circuit between the interconnection and coil structure.

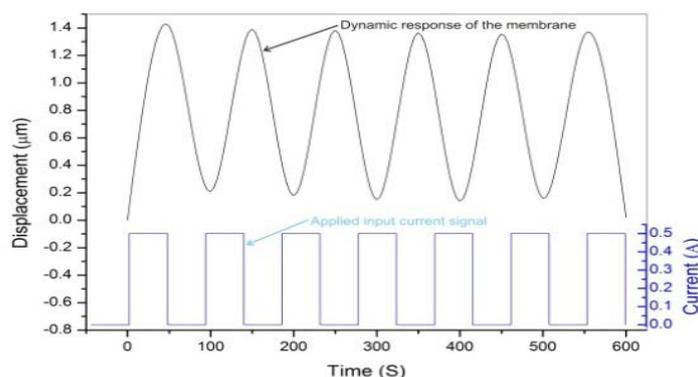


Figure 14. Dynamic Response of Fabricated Micro-Actuator for Intermittent Electricity Input of 0.5 A at Planar Parallel Circular Micro-Coil 1

4. Conclusion

The silicon based electromagnetic micro-actuator using planar micro-coil on PCB has been successfully fabricated and tested. Two types of planar micro-coil including variation of coil geometry were chosen for the investigation. The results showed that a reliable electromagnetic micro-actuator can be designed and fabricated using simple and cheap MEMS process. It was also shown that planar micro-coils are able to produce an optimum Silicon membrane displacement of approximately $12.87 \mu\text{m}$. Reasonable match between simulation and measurement of about 82.5% has been also revealed. It was also concluded that planar parallel circular coil is able to deform the silicon membrane effectively within 40 seconds with the maximum deflection of $2.75 \mu\text{m}$ for only 200 mW electrical power consumption. This actuator type is considered for the simple structure with easy fabrication that will benefit the development of compact micropump integrated in Lab on Chip. Provide a statement that what is expected, as stated in the "Introduction" chapter can ultimately result in "Results and Discussion" chapter, so there is compatibility. Moreover, it can also be added the prospect of the development of research results and application prospects of further studies into the next (based on result and discussion).

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