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THE ELECTRICAL AND MECHANICAL CHARACTERIZATION OF SILICON BASED ELECTROMAGNETIC MICRO-ACTUATOR FOR FLUID INJECTION SYSTEM

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Abstract

Electrical and mechanical properties of Electromagnetic (EM) micro-actuator with silicon membrane has been characterized. The study is aimed to see the effect of the geometry and the structure of the actuator system on the actuating performance of the silicon-based membrane for fluid injection purposes. The actuator system consists of two main parts, namely, the electromagnetic part that generates an electromagnetic field and the magneto-mechanical part that enable the membrane deformation depending on the magnetic force on the silicon membrane. A standard MEMS process was implemented to fabricate the actuator system with an additional bonding between the actuator part and microfluidic part to complete the system for fluid injection purpose. The simulation using COMSOL Multiphysics was done to see the generation of the magnetic force and to see its effect on the membrane deformation. It was found that the height of the generated magnetic force increases significantly with the applied power. The measurement of the membrane deformation done at a 20-µm silicon membrane showed a maximum deflection of 4.6 µm. The measurement results of the electrical characteristic of the device were compared with the simulation to validate the analysis. This study is very important to get the general insight of the silicon-based actuator membrane capability for the fluidic injection system in lab-on-chip.

Keywords: Electromagnetic micro-actuator, Fluid injection system, Planar micro-coil, Pilicon membrane.

1. Introduction

The MEMS-based deformable membrane has been an essential element in a fluids pump actuator driven by electromagnetic force. The micro-actuator is functioning to create a pressure difference inside the fluidic chamber for transporting the fluidic sample from the storage to the human body or to a biological analysis system. Some of the potential applications of such actuator system are the continuous insulin delivery, injection of a dialysate solution in portable dialysis machine as well as for fluid sample injection in the lab-on-a-chip system [1-3].

A compact and small micro-pump system for biomedical application is necessary to achieve a precise dosage of the sample injection and optimum fluid transport where a low sample volume with precisely controlled fluid injection flow and low energy consumption are demanded [4]

Therefore, there is a growing demand in the area of the actuator to reduce the dimension, to increase the performance of the injector with precise flow control with as low as possible energy consumption of the system. While in the point of view of the technological aspect, there is the trend to fabricate the device with a simple process and low fabrication cost as well as the integration possibility of the injector devices with other part of the microfluidic systems.

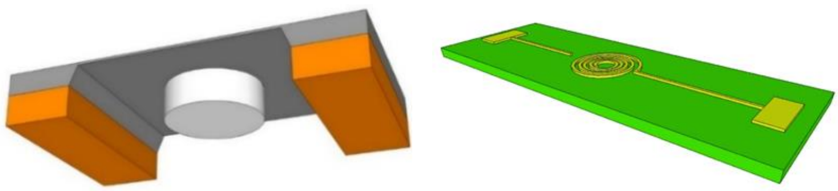
Several types of micro-actuators have been investigated, such as thermal pneumatic actuator [5], electrostatic actuator [6, 7] and piezoelectrically driven actuator [7]. The first two actuator types are implementing the material that directly attached to the flexible membrane. The continuous attacking of the physical such as heat or mechanical can cause damage and material crack that reduce the reliability of the actuator membrane. An electrostatically driven micro-actuator requires a high input voltage implementation to enable a sufficient membrane deformation, which is not suitable for a portable system where the low energy consumption is highly considered. While a piezoelectrically driven actuator has been the most implemented concept to drive the membrane actuation. However, the use of a wire connection between the metal electrode and the piezo material to the external electrode could reduce the deformation capability of the membrane.

Base on reasons as provided, the electromagnetically driven actuator seems to be the best alternative used as a micro-actuator for a portable micro-pump system due to its low power, precision in the flow control and higher membrane reliability as well [8]. Furthermore, the silicon is chosen as the membrane as it has a high surface strength to withstand the failure due to the continuous vibration. On the other hand, the fabrication of the silicon membrane is established many years ago that simplifies the fabrication process. Finally, the silicon monolithic based membrane concept opens the possibility of integration between the micro-actuator part and the CMOS based control circuitry.

Therefore, in this paper, we report the study on electromagnetic actuator with silicon-based membrane material and structure to find appropriate parameter suitable for the actuation purpose of the micro-pump system. This, includes the analysis of coil dimension producing a high magnetic force on to silicon membrane and its relationship with the mechanical deformation capability of the membrane. The effect of the coil and input power on the actuator performance will be also discussed in detail.

2. Actuation Concept and Micro-Actuator Design

The initial structure of the electromagnetic micro-actuator consists of the combination between magnetic and mechanical part called as Magneto-mechanic part, as shown in Fig. 1(a). This part includes the thin film deformable membrane, magnetic chamber and the permanent magnet. The second part of the system is called the electromagnetic part that includes the current carrying planar micro-coils on glass or PCB substrate lying perpendicular to the permanent magnet, as in Fig. 1(b)



(a) Magneto-mechanic part. **(b) Electromagnetic part.**

Fig. 1. Schematic of micro-actuator part.

Figure 2 shows the schematic view of the electromagnetic micro-actuator. The membrane deformation is produced due to the interaction between the permanent magnet and the electromagnetic field of the coil. Theoretically, when an electrical alternating current flows through the micro-coils, a generated magnetic field H_z will interact with the permanent magnet on the membrane with the magnetic induction of B_r and the area size of A_m at the vertical distance H_m above the coil. This interaction produces magnetic force F_z that periodically push and pull the flexible membrane.

The generated magnetic force F_z can be calculated as follows,

$$F_z = B_r A_m \int_{z}^{z+h_m} \frac{\partial H_z}{\partial z} dz \tag{1}$$

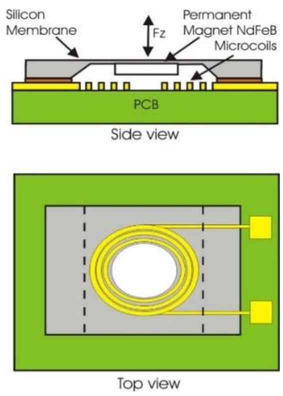


Fig. 2. Schematic of the electromagnetic micro-actuator structure.

The magnetic force causes the thin membrane to vibrate periodically. The membrane deformation W_{max} is depending on the mechanical property of the membrane, the shape and geometry of the membrane, and the magnetic force F_z

acting on to the membrane surface. The deflection height W_{max} for a square type membrane is calculated as follows [5, 9],

$$w_{max} = C\,\frac{F_z\ {L_m}^2}{(h^2)}\left(\frac{12(1-v^2)}{Eh^2}\right) \qquad (2)$$

where C is the constant depending on the shape and geometry, L_m is the membrane dimension, v is the Poison's ration, E is the Young modulus of the membrane material and h is the membrane thickness.

3. EM Actuator Fabrication

The micro-actuator parts can be fabricated separately, namely the fabrication of the electromagnetic part (1) and the fabrication of magneto-mechanic part (2), which is then finally followed with the bonding of both parts using epoxy (3). The detailed fabrication process of the micro-pump system is shown in Fig. 3.

Initially, the fabrication of the actuator starts with the creating of the planar Cu micro-coil wire (a). The planar coil is fabricated by etching the electroplated Cu metal sheet on PCB using $FeCl_3$. The coil pattern has three different widths such as 100, 150 and 200 µm with a space between the coils of 100 µm. The coil has 5 turns wounded side by side to form a planar parallel spiral coil.

Next is the fabrication of the magneto-mechanical part involving the patterning process of the chamber using standard Photolithography (b), the fabrication of the magnetic chamber and silicon membrane using anisotropic silicon etching using KOH solution (c) and the attachment of the permanent magnet magnetic NdFeB on to the membrane (d). The process is finally completed by bonding both fabricated structures using epoxy glue (3).

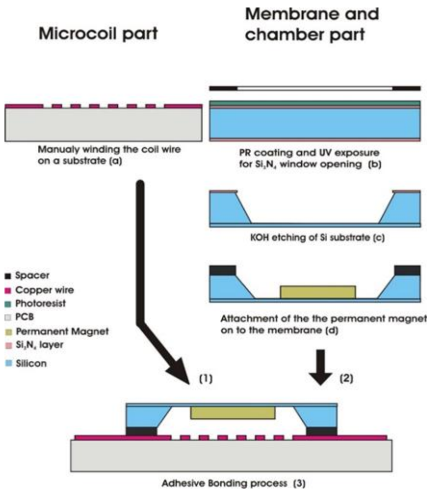


Fig. 3. Process flow for fabrication of electromagnetic actuator.

Table 1 lists the specification of the fabricated EM actuator, while Fig. 4 shows the complete fabricated fluid injection system including the electromagnetic actuator and attached microfluidic system.

Table 1. Geometrical and structural design specifications of fabricated micro-actuator.

	Material	Value	Unit
Planar coil hickness	Cu	30	µm
Coil turn number	Cu	5	
Coil space s	Cu	100	µm
Coil width w	Cu	100; 150; 200	µm
Coil substrate thickness	PCB	2	mm
Membrane substrate thickness	Silicon	525	µm
Membrane thickness	Silicon	20	µm
Membrane dimension	Silicon	6×6	mm^2
Chamber depth	Silicon and PDMS	0.5	mm
Spacer thickness	PDMS	2	mm
Permanent magnet thickness	NdFeB	2	mm

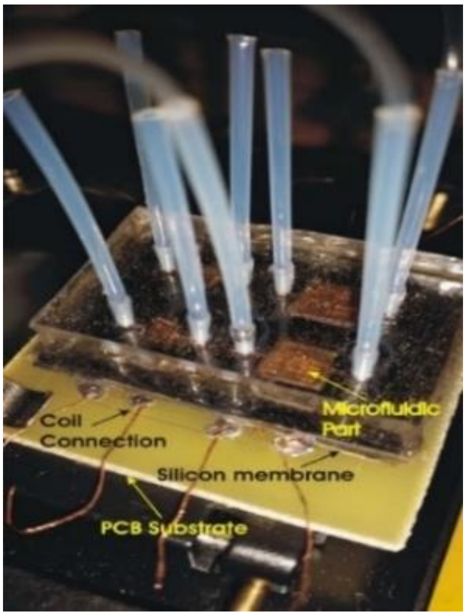


Fig. 4. Fabricated micro-actuator system with microfluidic part to complete fluid injection system.

4. Results and Discussion

The electrical and mechanical characteristics of the actuator membrane were studied using the FEM simulation of the proposed design and the measurement of the fabricated device.

4.1. Simulations results

The magnetic field and the magnetic force produced by the electromagnetic coil is simulated using COMSOL Multiphysics. The simulation results of the magnetic flux density at the distance from 0 to 1 mm above the coil plane surface can be seen in Fig. 5. It is clearly shown that the magnetic flux density increases with the applied current. On the other hand, the magnetic flux density reduces with the higher measurement distance from the coil surface. This means, that, the permanent magnet should be put as close as possible above the coil. However, the minimal distance should be considered to prevent the membrane crack due to the hit against the coil during vibration.

The results of the simulated membrane deflection at various input current are summarized in Table 2. It is shown that the applied input gives significant impact on the capability of the membrane deformation. A higher force is generated if the higher input current is applied resulting to the increase of the displacement height. However, low power consumption should be considered due to the heating effect of the microcoil causing the membrane damage.

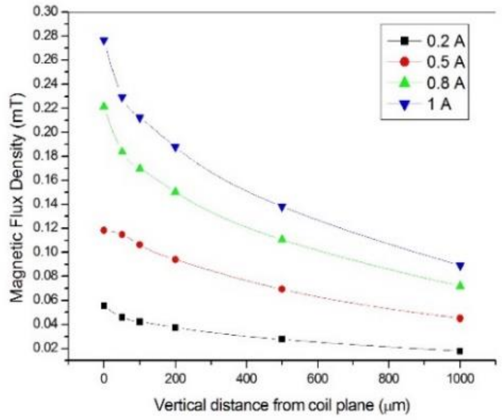


Fig. 5. Magnetic flux density at center of coil plane simulated with various input currents.

Table 2. Summary of simulation result.

Input current (A)	Force (mN)	Displacement (μm)
0.2	0.03069	0.485
0.5	0.105	1.66
0.8	0.18	2.83
1	0.23	3.6366

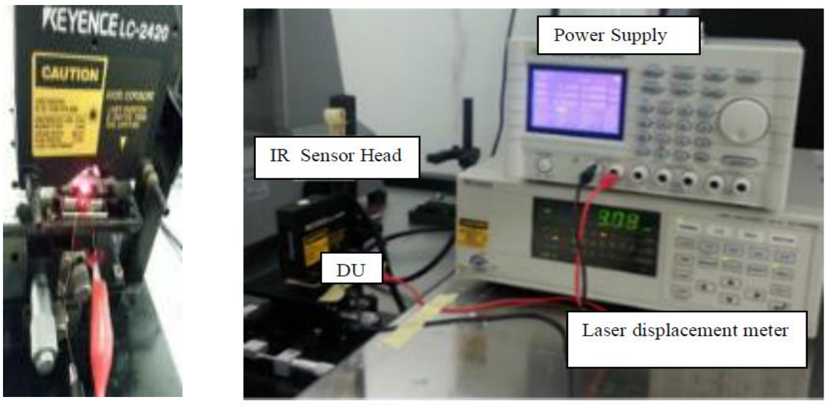
4.2. Measurement results

As shown in Figs. 6(a) and (b), the measurement setup for the characterization of the actuator consists of laser displacement meter to analyse the deformation height of the membrane lying perpendicular to the deforming membrane surface, Gauss meter to analyse the strength of the magnetic field density produced by the electromagnetic coil, ohm meter and power supply.

In the measurement process, the sample is put on a vibration free stage while the membrane deformation is driven by an input AC current supplied by a power supply and connected to the planar coil wire. The input current is varied from 200 mA up to 1 A. The resulted membrane deflection is measured by the laser displacement meter. The value of the Gauss meter is then calculated using Eq. (1) to get the generated magnetic force value.

Figure 7 shows the measurement results of the magnetic field density generated by the coil. From this figure, the simulation result is moderately matched with the measurement that validates the results. The comparison between the simulation and measurement results shows that the simulation results reveal a higher value than that from the measurement. This is possibly due to the ideal case considered in the simulation parameter. On the other hand, several lost factor in the measurement process, such as inner resistance on Gauss meter and power supply contributes to the reduction of the measurement precision.

The characterizations of the electrical and mechanical property of the actuator were done to see the effect of the coil parameter and input power on the deformation characteristics of the membrane. Figure 8 shows that the membrane deformation increases with the input current, which is correlates with the strength of the generated magnetic force. It can be seen, that if, we use coil wire with a small current flow area, the resistance of the coil will be increasing hence the power consumption will be also higher. On the other hand, the larger cross-section area of the coil does not improve the generation of the magnetic field, which is probably due to the eddy current effect. Also, Fig. 9 shows that the maximum membrane displacement of approximately 4.6 µm for a power consumption of approximately 0.8 W was also revealed.



(a) Schematic of measurement set-up.

(b) Photograph of membrane measurement system.

Fig. 6. Set-up of measurement system.

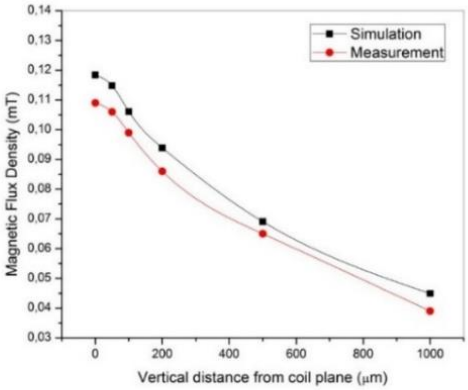


Fig. 7. Comparison of magnetic flux density between the simulation and measurement for input current of 500 mA.

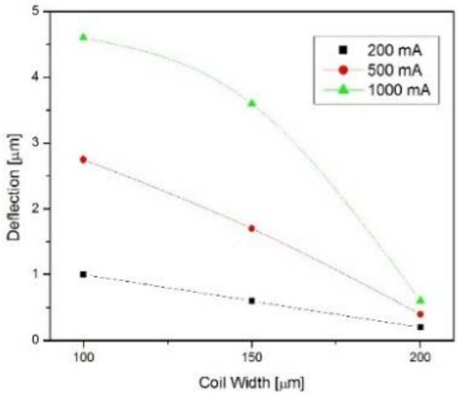


Fig. 8. Deflection characteristic of microactuator at various electrical applied powers for membrane thickness of 20 µm.

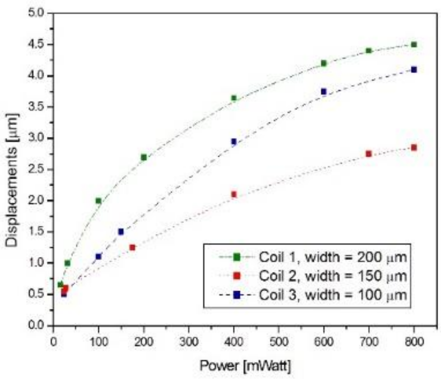


Fig. 9. Deflection characteristic of microactuator at various electrical applied powers for membrane thickness of 20 µm.

5. Conclusions

An EM actuator with the silicon-based membrane was designed, fabricated and characterized. The actuator consisting of an electromagnetic coil, silicon membrane and attached NdFeB permanent magnet was fabricated using standard MEMS process with additional bonding. The electrical characteristics of the EM actuator have been the important parameter for the generation of the magnetic force while the mechanical characteristics contribute to the deformation and the reliability of the actuator membrane. It is shown that the generated force increases significantly with the applied power on the coil. While the magnetic field generation on the coil was moderately matched with the simulations results. The analysis of the electro-mechanical characteristics of the actuator shows that the 20-µm silicon membrane was able to deform as high as 4.6 µm that reduces significantly with the input current. The dimension of the coil structure has no significant effect on the deformation capability of the membrane. However, a maximum deflection height was observed for an 800 mW of input power. The result of this observation would give the promising for the future development of silicon-based integrated electromagnetic micro-pump for continuous insulin drug delivery and lab on chip application.

Nomenclatures

A_m	Surface area size of the permanent magnet
B_r	Magnetic induction of the permanent magnet
E	Young modulus of the membrane material
F_z	Magnetic force
H_m	Vertical distance above the coil
Hz	Magnetic field generated by the EM coil
h	Membrane thickness
L_m	Membrane dimension
W_{max}	Maximum membrane deflection

Greek Symbols

ν	Poison's ratio

Abbreviations

CMOS	Complimentary Metal-Oxide-Semiconductor
EM	Electromagnetic
MEMS	Micro Electro-Mechanical System
PCB	Printed Circuit Board
PDMS	Polydimethyl Siloxane

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