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FABRICATION AND TESTING OF ELECTROMAGNETIC MEMS MICRO-ACTUATOR UTILIZING PCB BASED PLANAR MICRO-COIL

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ABSTRACT

An electromagnetic MEMS actuator with planar electromagnetic micro-coil on a PCB (Printed Circuit Board) is reported. The microactuator device consists of permanent magnet made of NdFeB, silicon based membrane and planar micro-coil electroplated on PCB. Each part of the system was fabricated using simple MEMS technique and bonded together using epoxy material. The performance of the fabricated device was tested by measuring the deflection capability of the silicon membrane. The measurement results showed that a planar spiral micro-coil is able to generate magnetic flux density and to deform a 20 µm thin silicon membrane with a maximum deflection height of 12.87 µm. The functionality of the actuator system was tested by measuring the dynamic response in a period of 50 seconds. Test on planar parallel round micro-coil resulted in a maximum membrane displacement in 40 s for all tested input power from 100 to 1000 mWatt. The results from this study will benefit the future development of electromagnetic MEMS actuator for integrated micropump.

Keywords: electromagnetic actuator, PCB, planar micro-coil, MEMS fabrication.

INTRODUCTION

Electromagnetic micro-actuators driven by magnetic forces present significant improvement in its operating mechanism due to low power consumption (Sutanto *et al.* 2006), simple structures (Lv *et al.* 2015) and fast response time (Yin *et al.* 2007). They are already developed since decade for the use in various applications, such as microspeaker (Kwon and Hwang, 2007), micropump (Ni *et al.* 2014), gyroscope (Feng *et al.* 2013), micro-mirror (Sasaki and Hane, 2011), and micro-relays (Miao *et al.* 2011).

Furthermore, electromagnetic micro-actuator has been the key component in micro-pump which enable drug delivery or biological sample injection in lab-on-chip system for biomedical applications (Johari *et al.* 2011; Nisar *et al.* 2008).

Several types of electromagnetic micro-coil have been used to generate magnetic forces such as solenoid, toroid and planar. Among those types, planar micro-coils have been found as the simplest and most suitable structure to be used in multilayer structure since it reduces the device volume up to 10 times lower than the solenoid micro-coil (Yunas and Majlis, 2008).

The planar micro-coils have been fabricated using various MEMS method such as s such vacuum deposition of metal layer using evaporator or sputtering (Amato *et al.* 2013), micromol;ed conductive polymer (Kohlmeier *et al.* 2004), and electroplating process of metal layer on silicon substrate (Woytasik *et al.* 2008). The above mentioned process were preferred because of the good metal pattern results. However, they are expensive and need complex process steps.

Here we report a simple process fabrication of micro-actuator that utilizes planar micro-coil structure electroplated on PCB. The geometrical and structure consideration of the planar coil are also discussed to find appropriate design for optimum magnetic flux density and membrane displacement.

Theory

The schematic of electromagnetic micro-actuator design used in this study is shown in Figure-1.

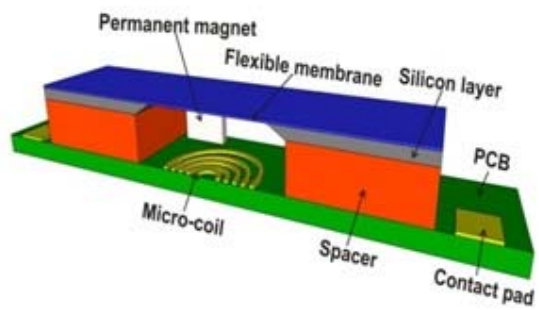

Figure-1. 3D schematic drawing of the MEMS micro-actuator.

The magnetic field H(z) is generated by a circular electromagnetic coil and can be referred from the Biot-Savart law.

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

I = Applied current
r = Mean radius of the coil turn
z = Vertical distance along the z-axis

The magnetic force is produced due to the interaction between electromagnetic coil and permanent magnet, that can be described as follow,

$$F_z(z) = B_r A_g \int_{h_g} \frac{\delta H}{\delta z} dz \quad (2)$$

B_r = Remanence induction of the permanent magnet
A_g = Surface area
h_g = Thickness of the permanent magnet
$\frac{\delta H}{\delta z}$ = Magnetic field gradient from the coil

On the other hand, the correlation between applied magnetic force and mechanical defomation d_z can be derived from the equation (3) (de Bhail´ıs *et al.* 2000):

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

F_z = Applied magnetic force on the membrane
l_m = Membrane length
c = Constant that depends on the boundary conditions at the outer edges and the shape

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

E = Young's modulus of the material
v = Poisson's ratio
h_m = the thickness of the membrane

Actuator design

Electromagnetic micro-actuator is formed by three main parts namely electromagnetic micro-coil, permanent magnet and flexible mechanical membrane. When the magnetic force generated by electromagnetic coil is applied on a flexible membrane, it consequently produces attractive or repulsive forces.

The permanent magnet has the diameter size and thickness of 3mm and 2mm respectively that is glued on the silicon membrane using epoxy material.

The silicon membrane is made of silicon material having the surface area of 6mm x 6mm while the chamber has the size of 6mm x 6mm with 2mm depth which is designed to accommodate the required area space for the permanent magnet.

The electromagnetic coil consists of planar round Cu coil with two structure types including parallel round micro-coil and spiral micro-coil as shown in Figure-2a and 2b, respectively. The geometrical variation of both types of the planar micro-coil is listed in Table-1.

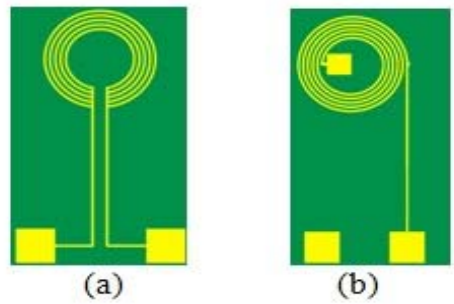

Figure-2. Types of planar micro-coil. (left) parallel round micro-coil. (right) spiral micro-coil.

Table-1. Geometrical parameter of both planar microcoil types.

Parameters	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 turns	5	5	5	5

Fabrication

In this work, the micro-actuator's membrane and chamber was fabricated using silicon MEMS process. The membrane was fabricated by anisotropic etch stop technique of 375 µm thick silicon wafer <100> using KOH solution at 75 ºC. Another alternative technique was HNA etching (Hamzah *et al.* 2012).

The planar electromagnetic micro-coil was fabricated by using metal etch process of electroplated copper on a PCB substrate using 70% $FeCl_3$ for 1 hrs 20 minutes. The detailed process for the fabrication of the membrane, chamber and planar coil are schematically shown in Figure-3(a) and 3(b) respectively.

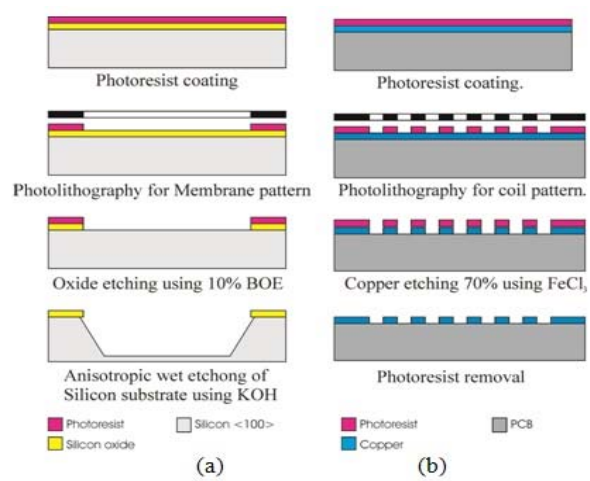

Figure-3. Detailed fabrication process of micro-actuator parts:(a) Membrane and chamber fabrication. (b) Planar coil fabrication.

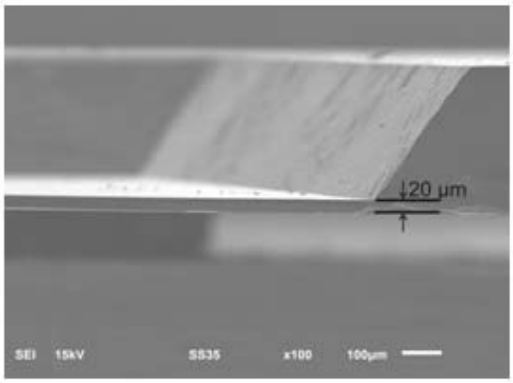

Figure-4. SEM images of the fabricated silicon membrane having the thickness of 20 µm.

The SEM image of the fabricated silicon membrane is shown in Figure-4. Thin layer of approximately 20 µm was remained while smooth and flat membrane surface was revealed after anisotropic etching of silicon for 8 hours.

Figure-5(a) and 5(b) show the fabrication result of the planar parallel metal coil and spiral coil pattern, respectively after etching process with an etch rate of about ±0.3 µm/min. It is shown that the planar parallel round micro-coil with 30 µm thickness was successfully fabricated. For the planar spiral coil type, the inner planar spiral coil was connected with the output pad using wire interconnection at the bottom side of PCB.

The final step in the fabrication of electromagnetic micro-actuator is the attachment of the permanent magnet to the silicon membrane using epoxy material and the bonding of each part of the system including electromagnetic coil, membrane and the chamber, to complete the structure as shown in Figure-6.

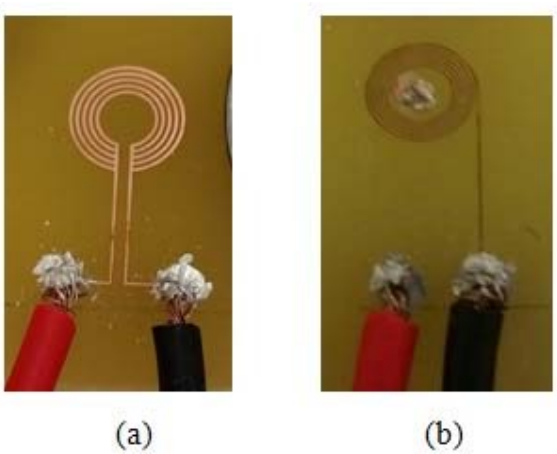

Figure-5. The fabricated planar micro-coils. (a) parallel round micro-coil. (b) spiral micro-coil.

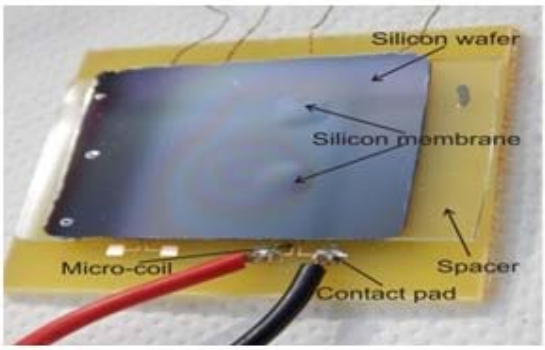

Figure-6. The complete structure of the micro-actuator.

Measurements and functionality test

The deformation capability of the silicon membrane was measured using Keyence LC-2400 laser displacement meter. Figure-7 illustrates the setup used to measure the membrane displacement.

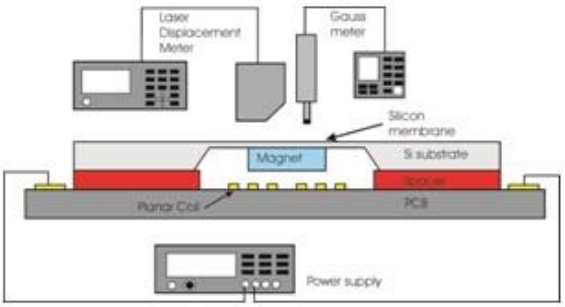

Figure-7. Schematic set up for measurement of membrane displacement.

Figure-8 and Figure-9 show the displacement of the membrane at the center when various continuous currents are applied to both micro-coil types. It is clearly shown that the membrane displacement increases with the applied power. Micro-actuator of both coil types with the lowest dimension (width= 100 µm and space= 100 µm) will produce the highest magnetic field hence maximum membrane displacements are achieved.

Meanwhile, the micro-actuator with planar spiral micro-coil 4 produces a maximum membrane displacement of approximately 12.87 µm in 40 s, for a power consumption of approximately 1 Watt. From this study, it can be concluded that planar spiral micro-coil produces 300% higher membrane displacement and higher magnetic field than planar parallel round micro-coil. This is due to the better current distribution along the micro-coil and more efficient electrical power consumption to generate magnetic forces.

Furthermore, it is observed that the membrane requires time of about 40 seconds to adjust between the elastic properties of the membrane and electromagnetic force that imposed on the membrane. Therefore our tests with dynamic response were conducted by applying a square wave signal with period of about 50 seconds.

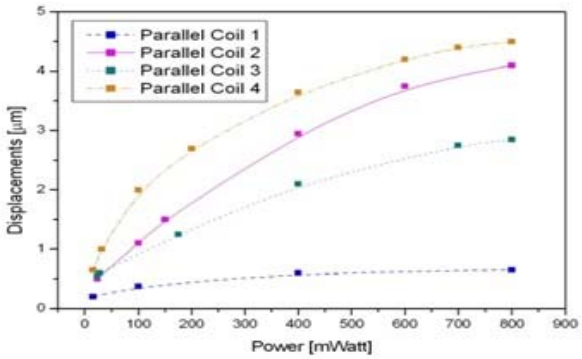

Figure-8. Measured micro-actuator displacement of planar parallel round micro coil for various applied input power.

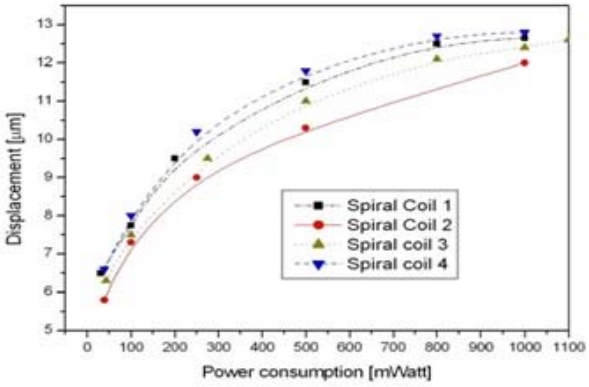

Figure-9. Measured micro-actuator displacement of planar spiral round micro coil for various applied input power.

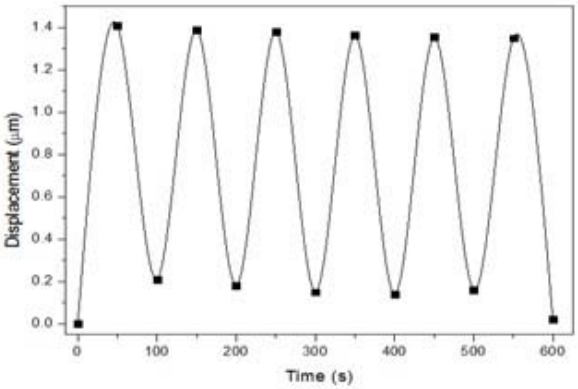

Figure-10. Dynamic response of fabricated micro-actuator for intermittent electricity input of 0.5 A at planar parallel round micro-coil 1.

Figure-10 shows the dynamic response of the micro-actuator when a square wave applied current signal of 0.5A at planar parallel round micro-coil 1 was intermittently turned ON and OFF with the period of 50 seconds. It is shown that the membrane was able to deform within 50 seconds. The maximum deformation of about 1.4 µ was achieved for a power consumption of 200 mwatt.

Furthermore, our analysis shows that the planar spiral micro-coil resulted in better magnetic properties than the planar parallel round micro-coil. However the fabrication process of the planar parallel round micro-coil is much simpler than the spiral one as it does not require interconnection between inner coil and output pads.

CONCLUSIONS

The electromagnetic micro-actuator based on PCB micro-coil has been investigated. It was demonstrated that a reliable electromagnetic micro-actuator can be designed and fabricated using standard MEMS process. Two types of planar micro-coil including planar parallel and spiral coils were chosen for the investigation. The micro-coil design with various parameters including variation of coil geometry were fabricated and characterized. The results show that planar spiral micro-coils produced the highest membrane displacement compared to the planar parallel round micro-coil. However the simple process step should be considered. The optimum displacement of approximately 12.87 µm was achieved within 40s with a 1 Watt electrical power. the proposed device can be fabricated in a simple manner that will benefit the development of compact micropump integrated in Lab on Chip.

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