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Fabrication and Characterization of Dome-Shaped Actuator Membrane for Peristaltic Valveless Electromagnetic Micropump

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ABSTRACT

This paper discusses the method of fabrication and characterization of a peristaltic micropump with a dome-shaped electromagnetic (EM) actuator membrane by pouring Polydimethylsiloxane (PDMS) on top of the glass master mould. The peristaltic micropumps have three membranes separated by a spacer of 2 mm. The structure of the mould consists of three pillar-shaped glasses that have a dome-like structure at the top. The border on the edge of the mould functions as a barrier to prevent the spill of the PDMS. When the PDMS is poured on top of the glass mould, a thin membrane will be formed and it will automatically overflow to form a chamber and spacer. The fabricated membrane structures were characterized using Scanning Electron Microscopy (SEM), while the mechanical and electrica properties were analysed by observing the deformation of the membrane. The SEM images show that a hanging PDMS membrane with a thickness of 77.5 μm was established. The permanent magnet connected to the lever and attached to the membrane will interact with the magnetic field generated by the EM coil. The measurement results show that a coil of 275 turns carrying a current of 600 mA produces a magnetic field of 11 mT causing a membrane deflection of 1.5 mm. The resulting dome-shaped membrane will have its potential application for the use as the actuator for the EM peristaltic micropumps.

Keywords: *dome-shape, multi membrane, PDMS, peristaltic, micropump, valve less*

1. INTRODUCTION

MEMS-based micro pump technology utilizes the displacement of movable membrane to create pressure difference enabling the transport of medium. Various control mechanisms are commonly used to move the membrane, either mechanically or non-mechanically [1]. Micro-mechanical controllers use propulsion mechanisms such as electric, magnetic, thermal, optical, and chemical or biological forces. The actuation of this type of pump includes electrostatic [2], electromagnetic [3], and piezoelectric [4] techniques. Meanwhile, non-mechanical pumps include magnetohydrodynamic, electrohydrodyamic, and electroosmotic [5]. The technology for making micro pumps is modified in order to get high flow rates with small pump sizes. Modifications will be done based on the shape of the membrane [6], the number of membranes in one pump [7], and the number of pumps [8]. Based on the number of pumps, peristaltic technology is created. In this report, a peristaltic pump is made using EM actuation.

The working principle of the EM peristaltic pump follows the principle of the EM pump by flowing an electric current through a coil of wire which will produce a magnetic field around the coil. The interaction between the magnetic force from the coil of wire and the magnetic force on the permanent magnet attached to the membrane causes attraction or repulsion.

In operating a peristaltic micropump, there are several stages of pumping conditions [9]. Subsequently, the movement of each pump membrane was set using a microcontroller [10]. Meanwhile, the operation of the pump is based on synchronous compression of microfluidic channels [11]. The movement will be adapted to two functions, namely as a pump and as a valve.

The structure of the micropump consists of a flexible membrane, a driver, a chamber, a spacer, and a movable one. The membrane used must be selected based on the properties of the material which are flexible, ease of fabrication, and the economic aspect. Owing to their flexibility, membranes with polymeric materials are widely used, including PMMA [12] and PDMS [6] [13]. Membrane with PDMS polymer material has the best elasticity properties with a Young's modulus of 0.4-0.9 MPa [13]. Besides, PDMS materials also are compatible with biomedical instrumentation, and easy to fabricate.

Most of the micro peristaltic pumps that have been developed so far still use a flat membrane. This results in a low fluid flow velocity [3]. Therefore, to obtain a high fluid flow velocity, the membrane section can be made in the form of a dome. The advantage of dome membranes over flat membranes is that they have much higher structural rigidity. Thus, dome membranes can exert greater forces than flat membranes [14]. The disadvantage of using a membrane dome is that a large force is required to move the membrane. To overcome this, EM drives that usually use planar wire windings must be replaced with cylindrical wire windings by including a ferrite core [15].

In this study, a dome-shaped membrane by pouring PDMS directly onto a substrate was successfully fabricated and its mechanical properties were characterized.

2. MATERIALS AND METHODS

To achieve the objectives of this study, several steps must be carried out, including design, material collection, fabrication, and testing. The first step is to design the structure of the EM actuator, which includes EM wire coils, membranes, and spacers. The second step is to choose the material of the membrane followed by fabrication and characterization.

Materials

The materials used for the manufacture of EM actuators are a glass rod, a borosilicate glass plate, PDMS along with a curing agent, Polyacrylic Acid (PAA), copper wire, and ferrite core.

Electromagnetic Actuation and Structure

The structure of the EM actuator is illustrated in Fig. 1. The EM actuation system is divided into two main parts: electromagnetic/pneumatic actuation and magneto-mechanic/magnetic actuation. The current passing through the wire creates a magnetic field concentrated in the centre of the coil [16]. To obtain high magnetic strength, the wire must be wrapped around a core made of a ferromagnetic material such as iron that concentrates the magnetic flux [15].

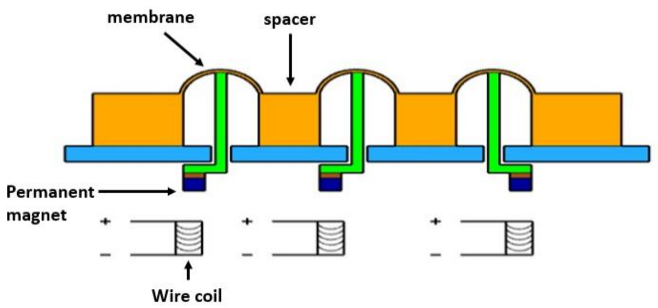


Figure 1. EM actuator structure

The resulting magnetic field interacts with the permanent magnet attached to the membrane. The magnetic force that is caused by the interaction between the EM coil and permanent magnet is known as the Lorentz force, which has the following equation [17]:

$$F_z = B_r A_g \int_z^{z+h_g} \frac{\partial H_z}{\partial z} dz \quad (1)$$

Here, B_r is the remanent induction of the permanent magnet, A_g is the surface area of the magnet, h_g is the thickness of the permanent magnet and z is the vertical distance along the z-axis. While $(\partial Hz)/\partial z$ is the gradient of the magnetic field generated from the EM coil. This force causes the membrane to be pushed up or pulled down, depending on the polarity of the input current.

The Fabrication of the Membrane Actuation

The master mould was made by simply sticking a glass rod to a flat glass. The first step involved the preparation of cylindrical rod-shaped glass with a diameter of 5 mm and a length of 5 mm at the end. The next step is to attach the other end of the glass rod to the flat glass. Three glass rods were placed in series; which are separated from each other by 2 mm, as shown in Figure 2. Then, a border in the shape of a cylinder at the edge of the substrate was made using glass or plastic. The margins are made to prevent the spill of PDMS liquid and as a high/low limit for the membrane.

After the master mould was made, the PDMS polymer was mixed with curing agent (Sylgard 184 (Dow Corning)) [18] at a ratio of 10:1. The mixture was stirred for 10 min to allow it to form. Next, the mixture was placed in a vacuum desiccator to remove air bubbles formed during stirring. Subsequently, the border was placed on glass using PDMS and heated on a hotplate at 120 °C for 10 min.

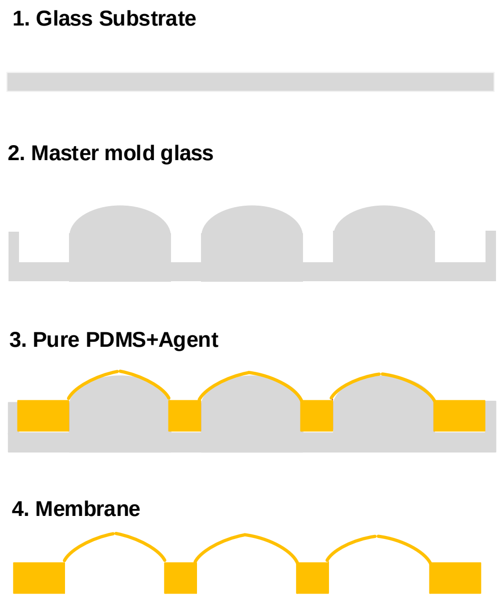


Figure 2. The Fabrication process steps

The next step was to mix 1 g of PAA with 100 ml of DI-H2O and then stir until it was evenly distributed. The mixed PAA was poured over the master mould and spun at 3000 rpm. Heat was applied to the hotplate until the PAA liquid had evaporated completely. Next, pour the PDMS liquid over the glass dome mould to create the membrane. The PDMS part that overflows form a spacer. The mixture was then heated at 60 °C for 10 min.

After those steps, pour the PDMS liquid over the PDMS 10 times to get the required membrane thickness. Pour PDMS again before it overflows over the rim. The spacer that is formed is not strong and is still a viscous liquid; therefore, it should be heated at 120o C for 30 min.

After the membrane and spacer are dry, the next process is to release the liquid to flow inside the channel. It was then placed in DI-H2O until the membrane and spacer were lifted. The resulting membrane binds tightly to the PDMS spacer because the pouring process does not have a time lag between pouring. All fabrication steps are shown in Figure 2.

Characterization Methods

Characterization was performed to determine the profile, thickness, and height of the membrane deflection. The fabricated structure was cut to determine membrane thickness. Then, a cross-sectional view of the structure was observed using SEM (Philips XL20-series Scanning Electron Microscope).

A constant current was applied to the coil wire to determine the membrane deflection height, as shown in Figure 3. The height of the deformation was photographed when there was a push-and-pull action of the membrane.

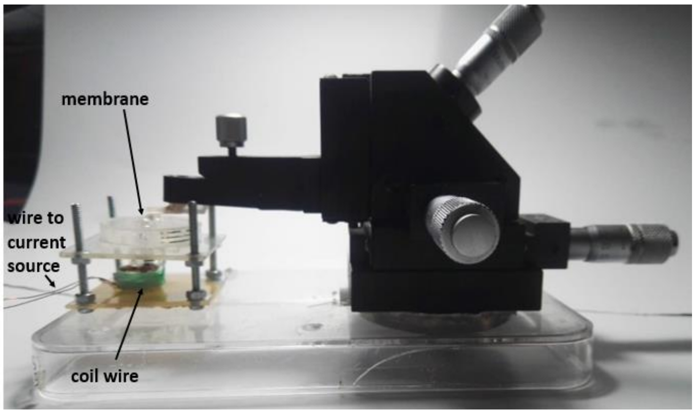
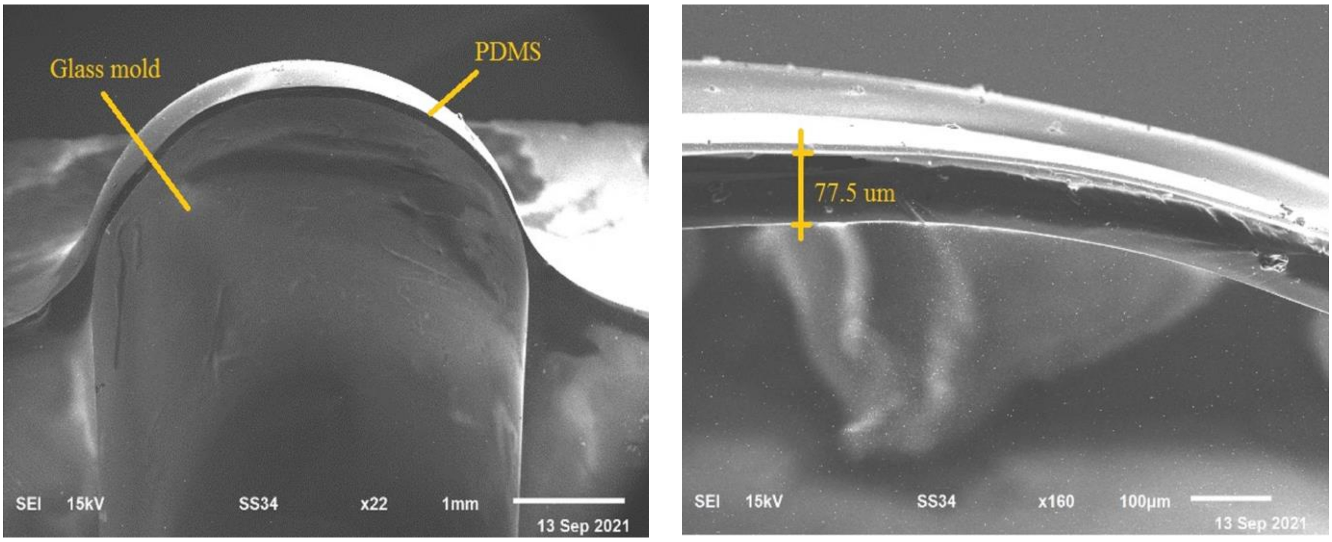


Figure 3. Membrane deflection measurement



(a) (b)

Figure 4. SEM image of the cross-section of the membrane: (a) overall view and (b) membrane thickness

3. RESULTS AND DISCUSSION

The fabricated structures were analyzed using SEM, and the magnetic properties of the membranes were measured using a Gauss meter. Finally, the mechanical properties of the fabricated membrane were analyzed by testing the membrane deformation when the magnet was induced by the EM coils.

The results of the SEM analysis are shown in Figure 4. It is seen in Figure 4a that the PDMS membrane with dome-shaped structure having a thickness of around 77.5 µm has been obtained. After releasing the master mould, the membrane can keep its structure in a normally deflected position that confirms the stability and reliability of the structure (Figure 4b).

Characterizations of the EM wire coil section was performed by varying the number of turns of the wire, the diameter of the core, and the current passing through the wire. A copper wire with a diameter of 300 µm was used. The electric current supplied to the wire coil produces a magnetic flux. The measurement results obtained using a Gauss meter at distances of 2 mm and 3 mm from the ferrite core are shown in Figure 5.

From Figure 5, it is shown that the current increases and the addition of wire turns can significantly increase the magnetic field. The resulting magnetic field is between 4.75 mT-11 mT with wire turns between 175-275 turns. The 275 turns of the wire coil produced a magnetic field of 11 mT, which is measured at a distance of 2 mm from the end of the ferrite core.

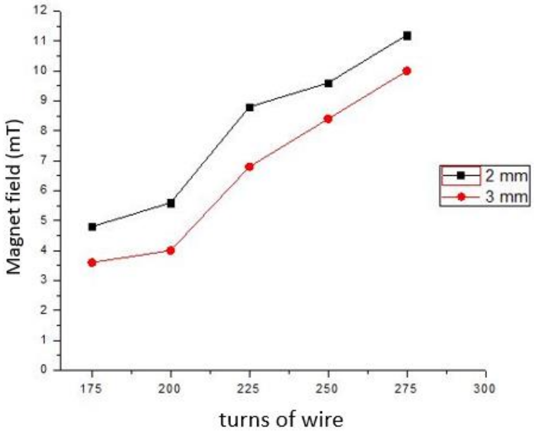
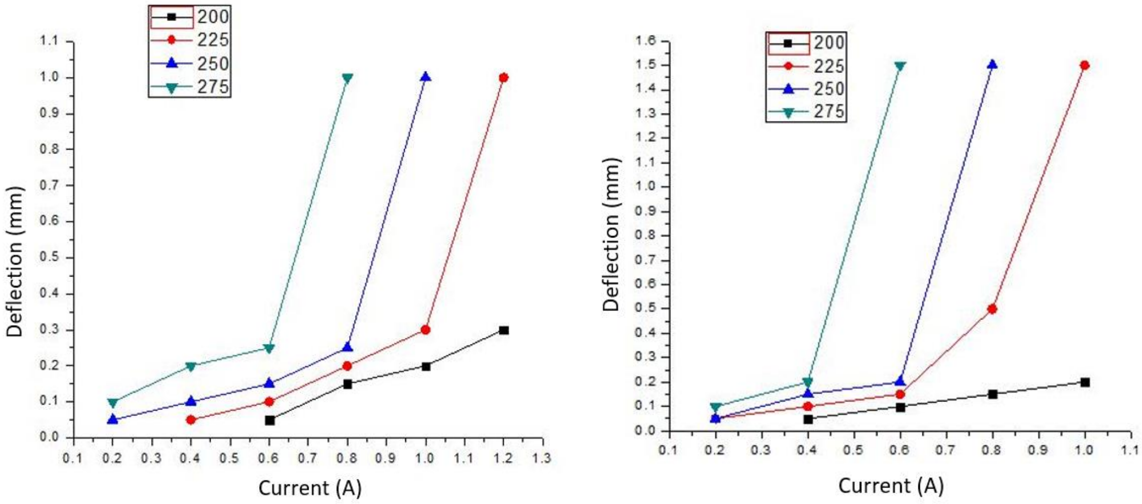


Figure 5. Results of magnetic field measurements, for several turns of wire at a distance of 2 mm and 3 mm to the Gauss meter

In micropumps, the greater the membrane deflection, the greater the fluid flow rate. Membrane deflection occurs due to the interaction between the magnetic fields generated from the EM coil and the permanent magnets attached to the membrane. The magnetic force is also determined by the magnetization intensity and cross-sectional area of the permanent magnet according to Equation 1 above. For this reason, magnetic field measurements for different sizes of permanent magnets were carried out. Figure 5 shows the results of membrane deflection measurement for wire windings between 200-275 turns, with currents flowing between 0.2 - 1 Amperes.



(a) (b)

Figure 6. The amount of deflection to current where the distance of the magnet to the ferrite core is 3 mm for: (a) 3x2mm^2 permanent magnet (b) 3x3mm^2 permanent magnet

In Figure 6, it is shown that the influence of the size of the permanent magnet is very significant. By using the same parameters, at a current of 0.6 Amperes with a total of 275 coil turns, a deflection of 0.2 mm is produced when a 3x2 mm^2 magnet and a 1.5 mm deflection for a 3x3 mm^2 magnet are used, respectively. The deflection height increases significantly due to the dome-shaped nature of the membrane. The flexibility of the membrane is influenced by the material property of the membrane and the shape of the dome itself. The size limit of the cross-sectional area of the dome which results in membrane deflection will increase significantly with the applied current. For example, a wire with 275 turns at a current of 0.4 A produces a deflection of 0.2 mm, and it increases significantly at a current of 0.6 A with a deflection of 1.5 mm.

4. CONCLUSION

In this paper, a three-chamber EM actuator with a dome-shaped membrane structure has been successfully fabricated and characterized. The fabrication process is carried out by dripping PDMS on the master mould several times to obtain the thickness of the membrane while forming a spacer. Meanwhile, the structure observed using SEM showed that the membrane having the dome shape structure with a thickness of about 77.5 um was established. The membrane deformation test showed that the actuator membrane obtains a deflection of 1.5 mm for an input current of 600mA which is suitable for high fluid flow micro-pumps.

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