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Modeling and Simulation of a Micropump Chip using Dielectric Elastomer

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Abstract— This paper aims to simulate dielectric elastomeric (DE) diaphragm for a micropump. First a theoretical study is done to compare the different actuation methods that are currently being used in this field. Then a circular DE diaphragm is modeled for a micropump. The material assumed for the micro diaphragm is 3M's VHB^{TM} 4910 (polyacrylic tapes available in the market). The thickness of the micro actuator (diaphragm) is 30μm and the diameter is 5mm. This material is simulated on FEA software using linear material model and out-of-plane deflections are measured. The pre-stretch effects are not considered during the simulation of DE diaphragm. The simulated diaphragm data are compared to the experimental data available in the literature for validation. The deflections are then used in the empirical formulas to calculate maximum actuation pressure, stresses in diaphragm and discharge of the pump.

Index Terms— **Actuators, Dielectric Elastomer, FEA, Microfludics, Micro pump.**

I. INTRODUCTION

A microelectromechanical system (MEMS) is a rapidly growing field which enables the manufacture of small devices using microfabrication techniques. In the last three decades, MEMS technologies have been used in biomedical industries which give rise to a new emerging field known as Microfluidics. Microfluidics deals with design & development of miniature devices which can sense, pump, mix, monitor and control small volumes of fluids [9]. It deals with design and development of miniature devices which manipulate small amounts of fluids (10^{-9}–10^{-18}l), using channels with dimensions of tens to hundreds of micrometers [6]. Principal applications of Microfluidic systems are for chemical analysis, biological and chemical sensing, drug delivery, molecular separation such as DNA analysis, amplification, sequencing or synthesis of nucleic acids and for environmental monitoring [9]. Microfluidics is also gaining popularity in areas like automobile, aerospace, and machine tool applications. Miniaturization and fine control is one of the recent requirements of microstructures [8].

A. Micropumps

Micropump is the beating heart of microfluidics. A typical micropump is a MEMS device which is the actuation source through which a fluid sample is transferred with precision, accuracy and reliability from a reservoir to the target [5].

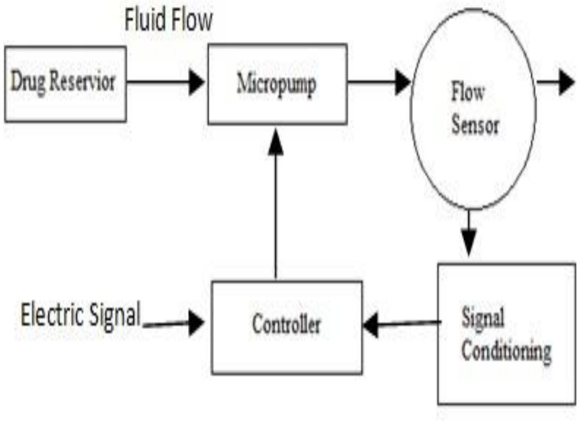

Fig 1: Microfludic System

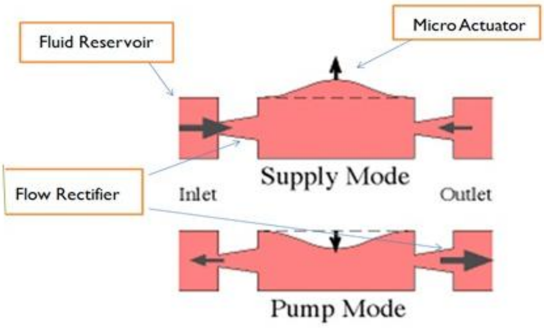

Fig 2: Components of a typical Micropump

Micropumps offer important advantages because they are compact and small in size and provide precise dosing and rapid response time. It is thus very useful in biological and engineering micro-systems where small sample consumption and rapid analysis is most important feature to be considered [8]. Such applications are drug delivery systems for high precision flow control, microchips integrated in computer to circulate coolant for cooling, micro pumping systems in portable fuel cells, as well as impeller system for blood flow regulation and pressurization [6].

There are three basic components in the micropumps (Fig 2):

1. A micro actuator, device which converts electrical, thermal, magnetic chemical/biological or optical energy into mechanical motion to provide the necessary driving force to fluid.
2. Flow rectifiers, the devices which regulate the flow of fluid by opening and closing various micro channels and these are connected to inlet and outlet valves.
3. A fluid chamber in which the fluid is stored and pressurized by the actuating member to flow to the outlet valve.

II. ACTUATION SCHEMES

There are different types of actuation principles are being currently used these days in micropumps. These include piezoelectrics, thermo-pneumatics, electrostatics, electromagnetic, shape memory alloys and magnetostrictive principles. There are various research papers which have done a nice comparative study of micropumps using these technologies [5]-[10]. These papers mainly focus on key features of micropumps such as actuation methods, construction, fabrication methods, performance parameters and their practical applications. All these papers had compared the advantages and disadvantages of different micropump technologies.

Researchers have classified micropumps in two main categories - Mechanical and Non-mechanical micropumps [8]. Mechanical type micropumps need a physical actuator (oscillating membranes or turbines) to perform pumping [10]. The most common type of mechanical micropumps piezoelectric [12], thermopneumatic [13]-[14], shape memory alloy (SMA) [15], bimetallic and ionic conductive polymer film (ICPF) [16]. Non-mechanical type of micropumps transforms non-mechanical energy into kinetic momentum to drive fluid in the micro channels. These include Magneto-hydrodynamic (MHD) pump, electro-hydrodynamic (EHD) pump, electro-osmotic pump, electro wetting pump, bubble type and flexural planar wave (FPW) pump. Electro wetting, electrochemical and ion-conductive polymer film (ICPF) actuator micropumps seems to be the most promising and provide adequate flow rates at very low applied voltages [16]. An Electro-osmotic micropump consumes high voltages but exhibit high pressure and is very small in size [17]. Bimetallic and electrostatic micropumps are smaller in size but exhibit high self-priming frequency. Piezoelectric pumps are most widely used in practical applications due to easily availability of actuation material. These are simple in structure, provide high actuation force, fast response, and provide a displacement of 1µm at 100V. But requirement of high actuation voltage, smaller stroke length and difficult mounting process on membrane gives certain disadvantages [16]. Thermopneumatic pumps have long thermal time constant and the working frequency limits upto approx. 50Hz [14].

These disadvantages have given rise to work on a new material which can provide a higher actuation force, large stroke, quick response, low thermal losses and should be accurate. It must be biocompatible, the most important feature of a micropump. Dielectric elastomers have shown all these properties.

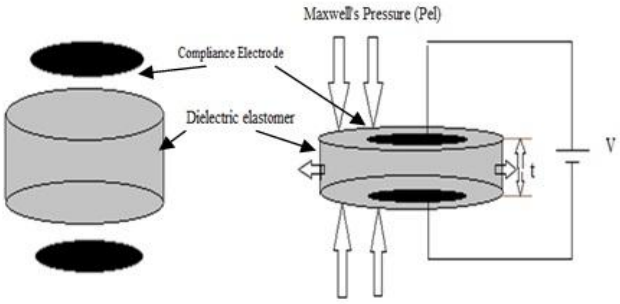

Fig 3: Working mechanism of Dielectric Elastomer

III. DIELECTRIC ELASTOMER

Dielectric Elastomers (DEs) belongs to a class of materials known as electroactive polymers (EAPs), which is soft, flexible and commonly known as “Artificial Muscles” [1]. These are capable of converting electrical energy to mechanical energy and thus imparting a force and/or motion [3]. Due to their versatile properties, robust behavior and low cost DEs have become the material of choice for an increasing number of technologies. DEs exhibit the most promising properties that mimic natural muscle for use in advanced robotics & smart prosthetics, as well as in haptic and microfludic device [3].

These are electrically actuated devices consisting of an elastomer sandwiched between two compliant electrodes as shown schematically in Fig.3. When a voltage is applied to the electrodes, an electrostatic pressure P_{el} is generated, which is given by the equation [4]:

$$P_{el} = \varepsilon_0 * \varepsilon_r * (V/t)^2 \qquad (1)$$

Where, ε_0 is the vacuum permittivity ε_r is the relative permittivity and V is the applied electric voltage, t is the thickness of the elastomer and P_{el} is known as Maxwell’s Stress. This equation is also known as Pelrine’s equation. The pressure adds compressive stress to the membrane.

Recently some research works have been done in this field [5]. Xuanming Pang et al. has used 3Ms’ VHB^{TM}4910 acrylic elastomer as the actuating membrane as it shows a large out-of-plane deformation, high electro-mechanical efficiency and very small response time as compared to any other materials. This paper had presented a valveless micropump using DE diaphragm as its driving component. The planar DE actuator was designed and the diaphragm actuating performances were characterized. Then the micropump, containing a chamber and a pair of nozzle/diffuser, was fabricated on SU-8 (a photosensitive polymer). The diaphragm and the SU-8 was sealed by adhesive tape and finally covered by a PMMA. The pumping and flow rate was tested and measure under high AC supply. But due to the undesirable durability, micropump fails and was able to give a maximum flow rate of 0.078ml/min was achieved under 4000V, 0.5Hz sine wave. The possible reasons for the failure of the pump were not discussed in the paper. Due to the lack of studies in the field of DE at micro and nano-levels made the task more complicated.

This paper provides a computation model of a dielectric elastomer diaphragm valveless micropump. As discussed earlier DE can provide large out-of-plane deformation [22]. Hence this property can be easily used to design a diaphragm that can generate much higher driving pressure (P_a) higher discharge (Q) with compact size and within much lower cost as compared to piezoelectric micropumps.Firstly, the out-of-plane deflections were calculated using FEA software ANSYS 13.0 at different voltages and operating frequencies. Then using empirical relations of driving pressure, stress and discharge are being calculated.

IV. SIMULATION

For simulation of a DE membrane we had modeled a circular membrane of diameter 5mm and thickness 30µm. This is the thickness of elastomer when stretched upto 300% in radial direction. Rather using a hyper elastic model of the material as used in previous work [2][23][24], linear material is used with Young’s modulus of elasticity as 2.1×10^6, Poisson’s ratio as 0.499 (it has to be taken as 5 but due limitation of software it has to be taken as 4.99) and

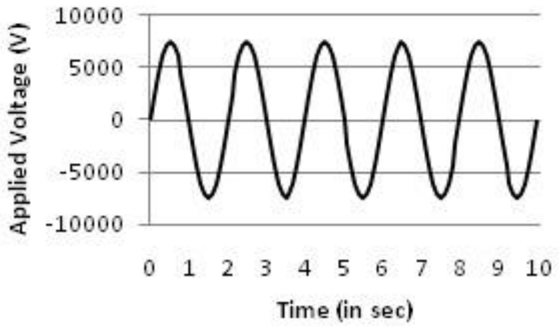

Fig 4: Applied Voltage (7500V) onto the elastomer with the frequency of 0.5Hz.

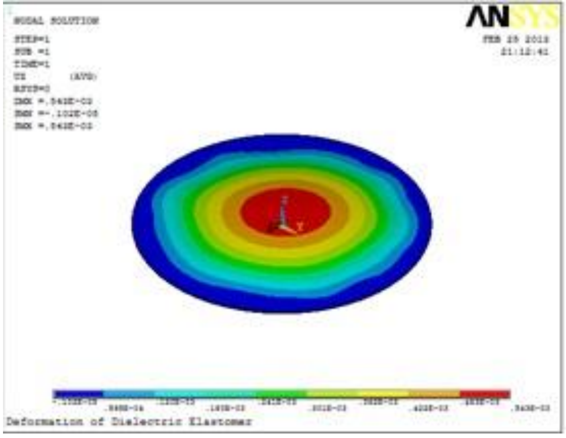

Fig 5: Deformation along Z-direction in the dielectric elastomer

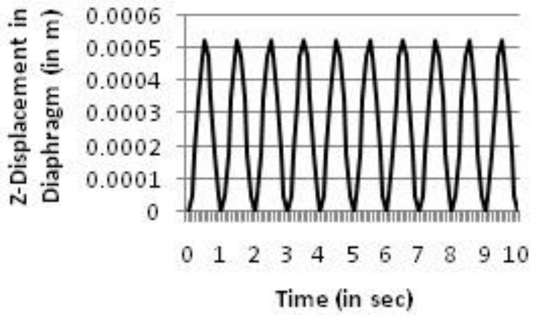

Fig 6: Graphical representation of z-direction displacement in elastomer along time.

The relative permittivity as 4.7 [23]. The element used for the simulation is a coupled field 10noded tetrahedron SOLID227. Voltage applied is 7500V at a frequency of 0.5 as used in the experiment [5]. hen simulated at this voltage the diaphragm has given a maximum out-of-plane deflection in Z-direction as 5.23×10^{-4} m. his displacement is higher as compared to the piezoelectric plate diaphragm. This displacement can be used in different formulas to calculate the uniform applied driver force per unit cross-sectional area of diaphragm, first mechanical resonance frequency and finally the maximum pressure differential. Since the DE would only actuate in one direction subject to any AC voltage, these out-of-plane deflection was generated twice in one sine wave cycle in the either direction, as showed in fig 6. The frequency of diaphragm $f=2*f_{sin}$. Practically the actuation of DE is dependent on the amplitude and frequency of sine wave [5]. As the amplitude is raised the deflection of diaphragm will increase, subject to the dielectric failure at much higher voltages. But as the frequency is increased the time taken for the actuation response will be much less hence the deflection per cycle will reduce. So the best operating frequencies are summarized by the experiment [5] as 0.5-2Hz.

V. DESIGN OF MICROPUMP

For the design and simulation of micropump the parameters are taken from [5], as the experimental results were also available. The micropump is mainly composed of three layers. The bottom layer is SU-8 photoresist (SU-8 50, MicroChem Corp™), on which a pump chambers of 5mm diameter and a pair of nozzle/diffuser are patterned to UV exposure with a mask. The top layer is PMMA, which has an opening for the out-of-plane displacement and two inlets and outlets holes where the rubber tubes were connected. The middle diaphragm layer is made of two pieces of acrylic elastomers, VHB 4910 and VHB F9473. VHB 4910, with 200% pre-strain, was coated of carbon grease on both sides and used to drive the flow through the pump. For assembly and sealing, VHB F9473, a similar acrylic tape withstanding solvent, was chosen to conglutinate the diaphragm to the bottom layer. All these layers were support by a piece of glass substrate. The overall dimension of the pump is given as 10mm×16mm×4.16mm. As the present study is concerned with valveless pump, so the valves will be replaced by the nozzle/diffuser assembly. The design values of the nozzle/diffuser elements, such as length, width, conical angles and the Reynolds number has been taken from [20]. As we know that the pressure and flow rate generated by reciprocating displacement pumps depends on the following factors [21]:

- (i) Stroke volume ΔV or the difference between the maximum and minimum volumes of the pumping chamber over the course of the pump-cycle.
- (ii) Pump dead volume V_0 or the minimum fluid volume contained between the inlet and outlet valves at any point during the pump cycle.
- (iii) Pump operating frequency, f.
- (iv) Properties of fluid.
- (v) Properties of valve.

For ideal valves ($\Delta p_{forward}=0$ and $\Delta p_{reverse} \rightarrow \infty$) and incompressible working fluid, according to the conservation of mass, the flow rate is simply the product of the stroke volume (ΔV) and the pump operating frequency, f.

VI. CALCULATION OF PUMP PARAMETERS

The analysis of the mechanical properties of a general pump diaphragm is informative. For a micropump diaphragm with diameter d, and thickness t held fixed along its perimeter, and having a centerline defection as y, the diaphragm will be subjected to a uniform applied pressure; p is given as [21],

$$\frac{p.d^4}{16.E.t^4} = \frac{5.33}{(1-\vartheta^2)}(y/t) + \frac{2.6}{(1-\vartheta^2)}(y/t)^3 \qquad (2)$$

Where E is the Young's modulus of elasticity and ϑ is the Poisson's ratio of the material. Using this formula the maximum actuation pressure on the DE diaphragm is 1.835×10^4MPa. The maximum stress developed in the diaphragm, σ can be calculated as [21]:

$$\frac{\sigma.d^2}{4.E.t^2} = \frac{4}{(1-\vartheta^2)}(y/t) + 1.73(y/t)^2 \qquad (3)$$

Using this formula the stress is calculated as 28075MPa whereas the maximum stress in the simulated model is coming as 17240MPa, which is much below the theoretical value.

Table 1: Simulated results of the DE diaphragm at 7500V and 0.5Hz frequency

At 7500V		
Time (sec)	**Displacement (m)**	**Stress (MPa)**
0.1	4.99E-06	1644.95
0.2	1.81E-05	5956.73
0.3	3.42E-05	11283.2
0.4	4.73E-05	15595
0.5	5.22E-05	17240
0.6	4.73E-05	15594.9
0.7	3.42E-05	11283.3
0.8	1.81E-05	5956.62
0.9	4.99E-06	1645.11
1	-3.94E-10	0.196331

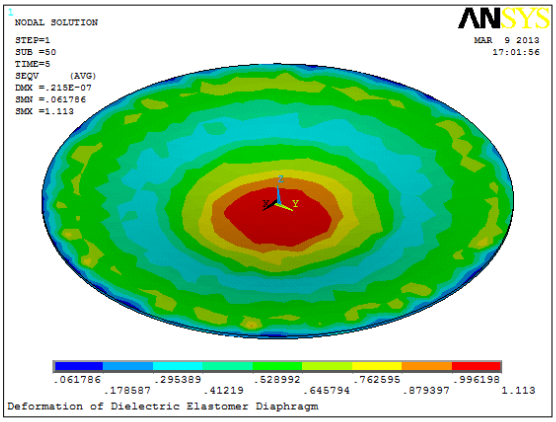

Fig 8: Stress Value in the DE diaphragm at 7500V and 0.5Hz (the image shows the stress at the end of the cycle).

Finally the discharge of the pump is calculated by the formula

$$Q_{max} = \Delta V \times f$$

Where, ΔV is the stroke volume and f is operating frequency. This equation is valid until the external fluid pressure differential is neglected and operation is considered as quasi-static. he value of ΔV is calculated by using the design data of the pump and the deflection of the diaphragm. So the calculated discharge is 0.086μl/min, which is very close to the experimental value (i.e. 0.078μl/min) at 4000V and 0.5Hz frequency.

VII. CONCLUSION

It has been observed from the study that numerical simulation is very close to the experimental results. This is a comparatively newer field of research so this paper can provide guidance for the numerical simulation of the DE micropump. The discharge of the pump is very much comparable to the other piezoelectric pumps. In this paper the effect of back pressure is being neglected so the deformation is completely based on the electrical actuation. The back pressure of the fluid will play an important role the pump operation. So we can conclude that DE can be a useful actuation material in field of micropumps, as it has a higher strain ratio than the piezoelectrics, SMAs, thermopneumatic etc. diaphragms, and it is cheap and easily available material. The only disadvantage with the material is its high power requirement for the actuation which makes it difficult to be used in bio-medical applications. But can be readily used in applications like microprocessor chip cooling and space-craft applications.

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