Design and development of an electrostatic-based micropump

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Abstract: Growing need for variety of micro-electro-mechanical systems necessitates advances in manufacturing technologies for high volume production at low cost. In the bio-medical field, drug delivery is one of the areas that attract the most attention for MEMS because of its potential to make drug delivery less invasive, more precise and less painful. A typical micro pump is a MEMS device, which provides the actuation source to transfer the fluid, in this case, the drug from the drug reservoir to the body (tissue or blood vessel) with precision, accuracy and reliability. Micro pumps are therefore an essential component in the drug delivery systems. In this study, a mechanical micro pump (with moving mechanical parts) will be modelled using MEMS module of COMSOL simulation tool. The micro pump will be based on electrostatic actuation which in-turn is based on the Coulomb attraction force between oppositely charged plates. The objective of this study is to determine the performance characteristics of electrostatic diaphragm driver for a range of applied voltages.

Keywords: MEMS; micropumps; drug delivery; electrostatic actuation; Coulomb attraction.

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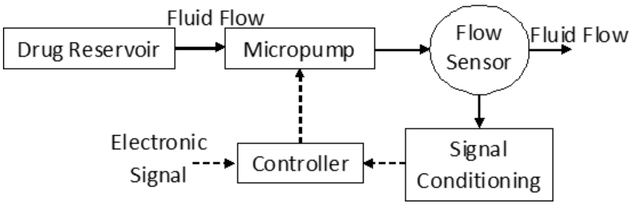
1 Introduction

A micro electromechanical system is a rapid growing field which helps in manufacture of small scale devices using micro fabrication techniques. The MEMS for biological purposes (bio MEMS) is emerging as a critical research area. MEMS fabrication technologies are increasingly being applied in medical fields for fabrication of drug delivery systems (DDSs), developing pumping mechanism for polymerase chain reaction in DNA analysis (PCR), lab-on-a-chip, micro total analysis systems (µTAS) (Zhang et al., 2007). The controlled micro scale fluid transport at flow rates ranging from nl/hrs to µl/min can be used to sample, trap, separate, sort, treat, detect, analyse biological materials and administer drugs using microfluidic devices.

An integrated DDS consists of drug reservoir, micro pumps, valves, micro channels, micro sensors and necessary related circuits, Figure 1. A typical micro pump is a MEMS device, which provides actuation source to transfer the fluid (drug) from drug reservoir to the body (tissue or blood vessel) with precision, accuracy and reliability. Micro pumps are therefore an essential component in DDSs. With controlled DDS appropriate and effective amount of drug can be precisely calculated by controller and released at appropriate time by the micro actuator mechanism such as micro pump. Several actuating mechanisms were studied and evaluated by Iverson and Garimella (2008).

Figure 1 Schematic illustration of DDS



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Micro pumps for drug delivery applications must satisfy some basic requirements, which are drug biocompatibility, actuation safety, desired and controllable flow rate, small chip size and less power consumption.

The electrostatic principle is used for sensing and actuating in devices of MEMS. Electrostatic deformation or pull-in of diaphragm or beam is used for many MEMS structures. Some of examples of sensing devices are capacitive accelerometer and the capacitive pressure sensor for measuring blood pressure gradients inside the coronary artery of the heart. The actuating devices are comb driver, the electrostatically driven micro elastic joints, the rotary electrostatic actuator, the electrostatically actuated MEMS power switch, and the electrostatically actuated micro pump. Commercial examples include static electricity actuated inkjet head applied in inkjet printers and the digital micro mirror array applied in optical scanner and digital light projector.

Finite element method has been established as a powerful tool for modelling in engineering. It has also been applied for electrostatically actuated systems. There are many FEM packages for modelling and analysis of MEMS, like ANSYS, COMSOL, MEMSPro, CoventorWare, etc. We are using COMSOL 4.3 for our study here. The main advantage of finite element method is the closer to reality. The limitation of FEM is that inexplicit physical meaning and requiring massive numerical calculations.

2 Device characteristics

A mechanical displacement micro pump is proposed in this paper and the performance characteristics of the diaphragm driver are investigated. Mechanical displacement micro pumps use the motion of a solid (diaphragm) or a fluid to generate the pressure difference needed to move a fluid. In particular, a diaphragm micro pump is considered, which comprises of a pumping chamber connected to inlet and outlet valves necessary for flow control.

Microfluidic devices widely use electrostatic actuation. Since this choice show some relevant advantages, such as low power consumption fast response time and full MEMS compatibility.

Electrostatic micro pumps involve electrostatic forces for actuation mechanism. Electrostatic force is defined as the electrical force of attraction and repulsion induced by an electric field. The like charges repel each other and unlike charges attract each other. The electrostatic force applied on the electrostatic plates can be expressed by the equation (1).

$$F = dW / dx = \frac{1}{2} \varepsilon_0 \varepsilon_r A V^2 / x^2 \qquad (1)$$

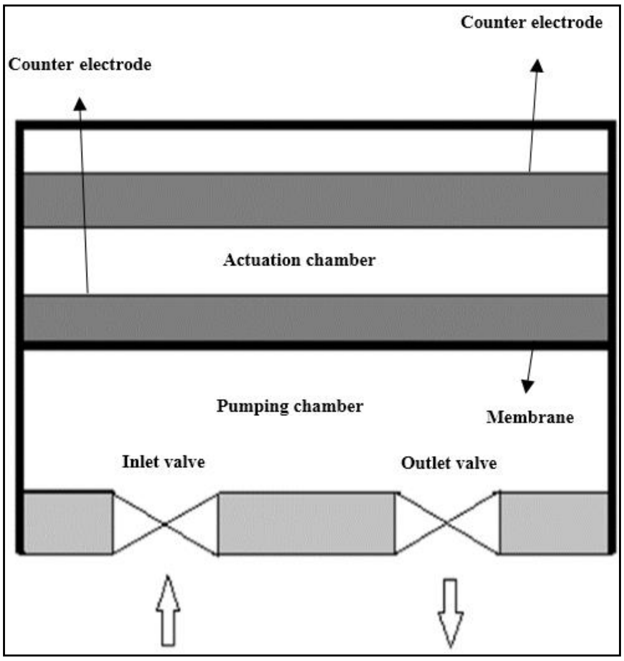
where F represents electrostatic attraction force, W is energy stored, ε is dielectric constant, A is electrode area, x is electrode spacing and V is the applied voltage.

The first electrostatic micro pump was fabricated by Judy et al. (1991) through surface micromachining technology. It consists of active check valve, chamber and active outlet valve. Actuation voltages of approximately 50 V were required for valve closure and membrane deflection. However, no pumping action was reported. The first experimental results of electrostatic micro pump were reported by Zengerle et al. (1992). Cabuz et al. (2001) presented dual diaphragm electrostatic micro pump using injection moulding technique. Thin electrodes were deposited by evaporation and thin dielectric material was deposited by ion beam sputtering. The micro pump was capable of bidirectional operation but was applicable only for gases. Teymoori and Sani (2005) designed and simulated an electrostatic peristaltic micro pump for drug delivery. The flow rate of designed micro pump was quite suitable for drug delivery application such as chemotherapy. A low voltage electrostatic micro pump for drug delivery applications were reported by Bourouina et al. (1997). The total size of the micro pump was 5 mm × 5 mm. Machauf et al. (2005) were first to attempt fabrication of membrane micro pump electrostatically actuated across working fluid. High electric permittivity of the working fluid was utilised as well as low conductivity for the design.

The actuator proposed by Zengerle et al. (1992) consisted of two silicon chips that embody the flexible pump diaphragm and a rigid counter electrode in a capacitor like configuration. The application of an increasing voltage to the capacitor electrodes causes the electrostatic attraction of the pump diaphragm, which deflects towards the counter electrode. After the discharge of capacitor, the pump diaphragm returns to its rest position. The major disadvantage of that solution resulted from the small stroke volume, partially balanced by high operation frequencies. Moreover, high voltages were required for actuation, with a consequent charge build-up and efficiency loss in long-term operation (Liu, 2010; Lil et al., 2010; Nisar et al., 2008; Bertarelli et al., 2009).

The geometry proposed for the micro pumping device is illustrated in Figure 2.

Figure 2 Schematic illustration of electrostatic micro pump



In the filling phase, voltage is applied to the counter electrode and the diaphragm deflects under the electrostatic force acting on it. The pumping chamber gets expanded, resulting in a corresponding decrease in chamber pressure (expansion stroke). When the pressure at inlet becomes higher than the chamber pressure, the inlet valve opens and the expanding chamber will be filled with liquid. When the voltage is cut off, the membrane bounces back. Thus, pressure in the pumping chamber increases (compression stroke), thereby liquid is discharged through the outlet valve. Thus, the driving force in the emptying phase is given by the elastic recovery of the membrane.

3 Modelling

Both 2D and 3D models are used in this investigation to determine the performance characteristics of the diaphragm. There are two chambers mainly for modelling, actuation chamber and pumping chamber. Actuation chamber consists of counter electrode and diaphragm. Pumping chamber consists of inlet and outlet valve. Inlet valve is modelled like a diffuser and outlet valve like a nozzle, for regulating pressure and velocity (Rochus et al., 2005; Wang and Soper, 2007; Tang et al., 1989; Osterberg et al., 1994; Lee and Kim, 2000; Artz and Cathy, 1992).

Diaphragm membrane is made of polysilicon material, which is modelled as isotropic linear elastic material (Young's modulus E = 160 GPa, Poisson's ratio υ = 0.22, density ρ = 2,320 Kg/m^3). Large deformation formulation is used. The space between electrodes is assumed to be filled of a dielectric, air. The pumped fluid is assumed to be water (density ρw = 1,000 Kg/m^3, viscosity μw = 0.001 Pa·s), and modelled as an incompressible laminar flow.

The mesh movement is described by the arbitrary Lagrangian-Eulerian method. Time dependent solution is obtained by an implicit solver (backward Euler integration).

Suitable boundary conditions are defined between adjacent domains where required, in terms of electrostatic force and displacements for the electro-mechanical interaction, as well as boundary velocity and fluid load for the fluid structure interaction. Ideal valves are taken into account, since there should not be any pressure drop across fully open structure and no leakage if valve is closed.

The diaphragm is modelled as a linear elastic material with both ends fixed (fixed constraint). Electric potential is applied on counter electrode and diaphragm is grounded. Results give the displacement of diaphragm and potential distribution.

4 Results and simulations

The study of an electrostatic-based micro pump results in coupled partial differential equations in electrical, mechanical and fluid solid domain. These lack an analytic solution due to complexity of the boundary conditions and cannot be solved analytically. Thus, finite element method is used for solving this problem. COMSOL which is commercially available FEM-based software used to simulate micro pump. Simulation is done separately for static analysis of actuation unit and dynamic analysis of pumping chamber.

Both 2D and 3D models of actuation unit was modelled and simulated. In 2D modelling, actuation unit is modelled with rectangular geometries. The thickness of diaphragm membrane, electrode spacing and voltage is varied to get optimum deflection and pump flow rate. The deflection of a diaphragm membrane in 2D after application of electric potential is shown in Figure 3.

Figure 3 Deflection of diaphragm (see online version for colours)

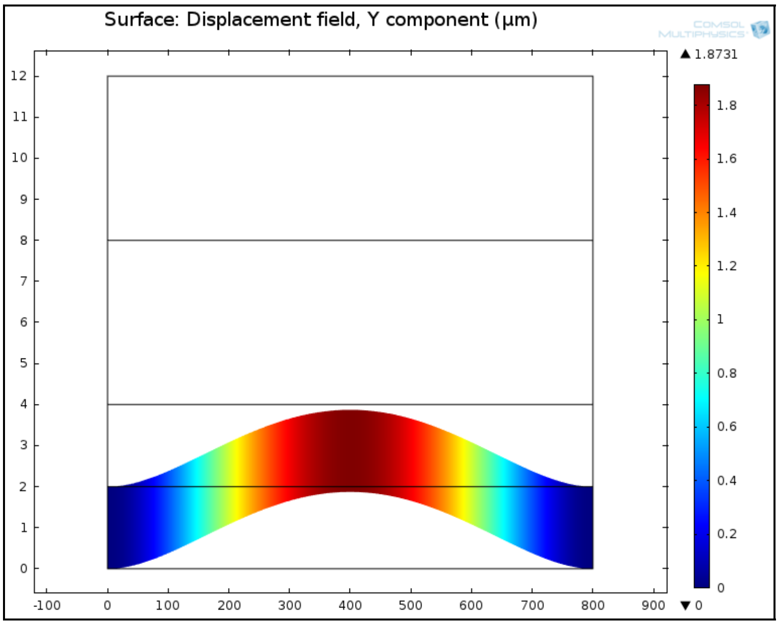


Figure 4 shows graph showing effect of electrode spacing, Hc and membrane thickness. From this graph, we are fixing value of membrane thickness and electrode spacing as 2 µm. Again, a 'voltage versus deflection' graph is plotted and it is found to be linear from 5 V.

Figure 5 shows variation of deflection of membrane with different voltage. Thus, sensitivity of diaphragm is determined.

The 3D simulation of actuation unit is also performed which shows a considerable variation from 2D. The results of 3D simulation of a diaphragm membrane 800 × 800 × 2 µm is shown in Figure 6.

Electric potential distribution was also plotted in 2D and it is shown in Figure 7.

Figure 4 Deflection versus membrane thickness (see online version for colours)

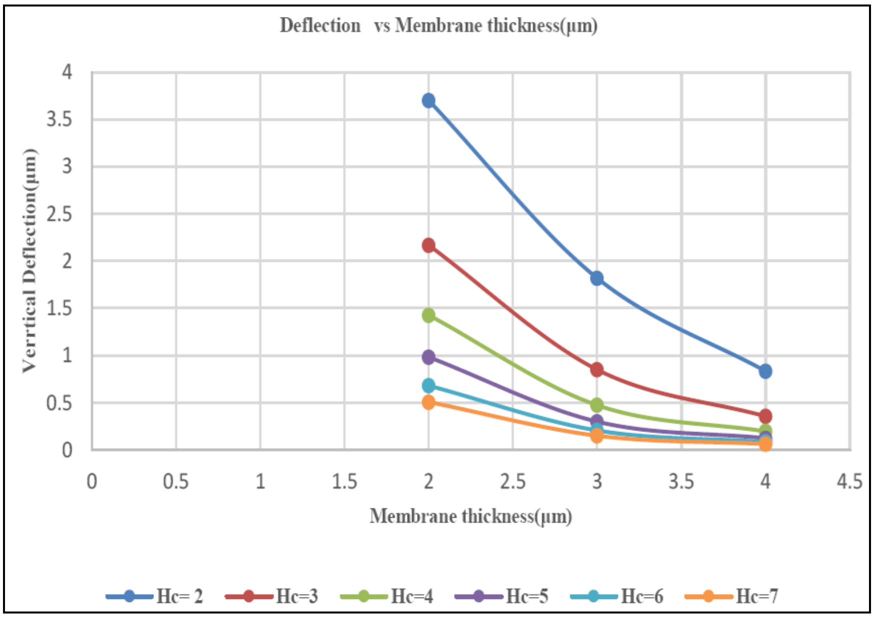


Figure 5 Voltage versus deflection of membrane (see online version for colours)

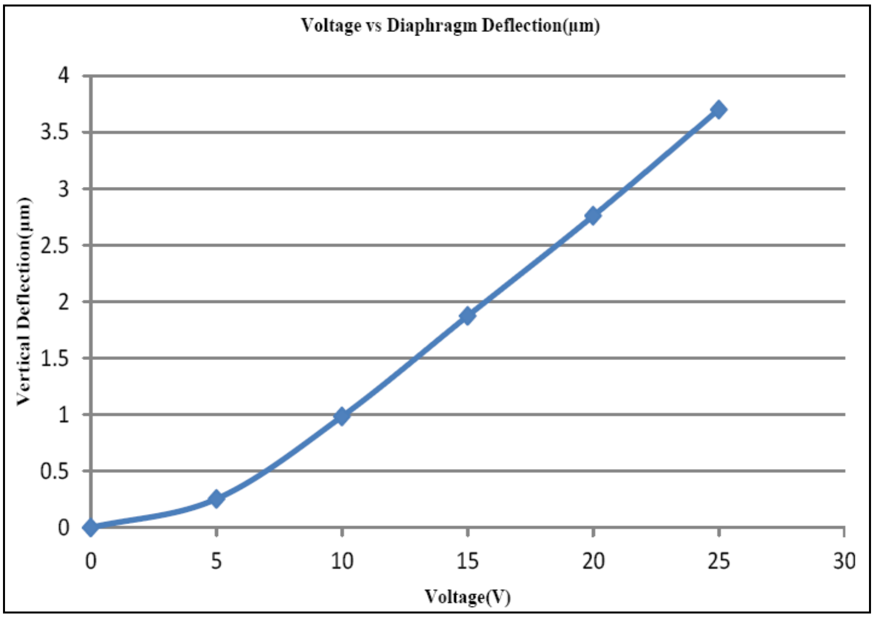


Figure 6 3D simulation showing deformation of membrane (see online version for colours)

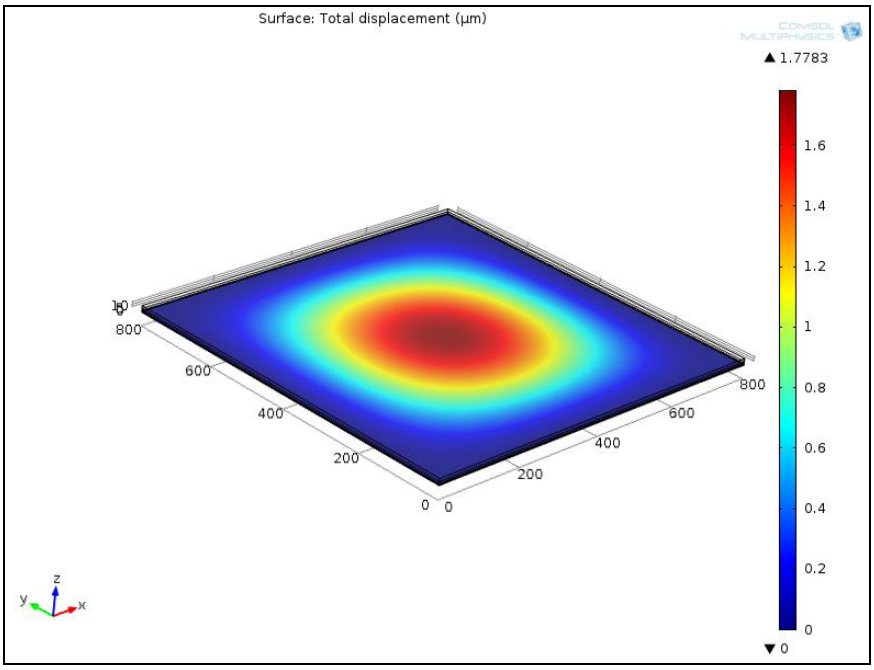
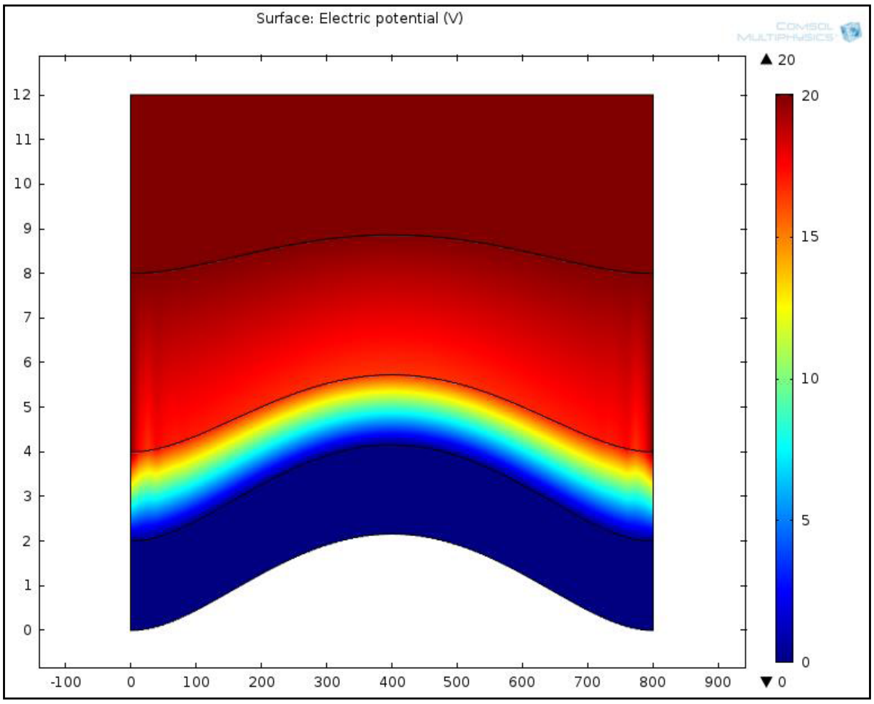


Figure 7 Electric potential distribution of actuation unit (see online version for colours)



5 Conclusions

The performance characteristics of the electrostatically driven diaphragm are investigated in the paper. The diaphragm which can be used in a micro pump is designed on the basis of electrostatic actuation. 2D as well as 3D models were created and analysed using COMSOL MEMS module. The results indicate that the deflection of actuator is linear with applied potential over electrodes. The maximum deflection observed was 3.7 μm at applied electric potential of 25 V. Though the volume that can be displaced by electrostatic diaphragm driver is limited, yet, a positive and accurate amount of liquid, drug in this case, can be pump through the proposed micro pump

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