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Design and Simulation of Microactuator using Phase Change Liquid for Drug Delivery System

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Abstract: This paper aims to design and simulate a MEMS based microactuator for drug delivery applications. A diaphragm type microactuator is designed and simulated using Intellisuite CAD tool. In this paper, the proposed system consists of two reservoirs i.e., one for the phase change liquid and other for the drug storage. The two reservoirs are split by a thin silicon diaphragm coated with polymer material. The efficiency of the micro actuator is analyzed by applying pressure to the diaphragm which causes displacement as a result of the vapor pressure exerted by the phase change liquid. The reservoir filled with phase change liquid is equipped with heater elements to produce a relative temperature to produce acute change in the phase state of the fluid. The diaphragm is deflected to its maximum so the drug stored in its counter reservoir is pumped out in the fluidic channel to the target system. The designed microactuator is proposed to use with microneedles to study the utilization of drug delivery system.
Key words - MEMS, microactuator, drug delivery, Intellisuite, phase change liquid, diaphragm, microneedles.

1. Introduction

Micro-Electro-Mechanical Systems is an integration of sensors, actuators, and integrated circuits on a common substrate with micro fabrication technology. According to MEMS, miniaturized pumping devices fabricated by micromachining technologies are called micropumps (1). In general, micropumps can be classified as mechanical and non-mechanical pumps, by which kinetic energy is obtained to drive fluid flow (2). Mechanical micropumps have been developed using several conventional actuation methods such as piezoelectric, electrostatic, thermo pneumatic, shape memory alloy, bimetallic etc.

The impact of MEMS inbiological domain (BioMEMS) has attracted the attention of many researchers. There is a growing trend to fabricate MEMS based drug delivery systems with newly well-developed fabrication technologies and are widely applied in medical fields. An integrated Drug Delivery System (DDS) consists of drug reservoir, micropumps, micro valves, microsensors, microchannels and necessary related circuits (3).

The two main functional components of the MEMS are Sensors and Actuators(4). In MEMS, an actuator works by converting electrical, optical, magnetic or chemical energy into mechanical energy (5). The resultant state variables include displacement, velocity and force that regulate the flow created in the fluidic channel. In this paper, the microactuator using Phase Change Liquid is designed and simulated for drug delivery applications. The micro actuator is based on the Phase behavior property of the electronic fluids that causes deflection of thesilicon diaphragm coated with polymer material.

2. Micropump

Micropump provides actuation mechanism to vibrate the membrane. Reservoir is used to store the drug and microneedle array provides interface between the drug delivery system and the patient's body for releasing the drug as shown in Figure 1.The most common types of mechanical micropumps are displacement pumps involving a pump chamber which is closed with a flexible diaphragm (6). Under pressure in the pump chamber results in the flow of fluid inside the pump chamber through the inlet valve. The pressure in the pump chamber transfers the fluid out of the pump chamber through the outlet valve. Micro pump consists of a pump chamber with a thin silicon diaphragm coated with polymer material. The diaphragm is actuated by the use of phase change liquid made availablein another small reservoir.The designed microactuator is proposed to use with microneedles to study the utilization of drug delivery system (7),(8),(9).

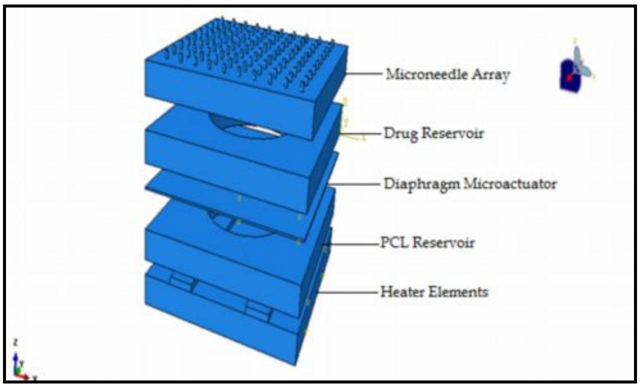

Figure 1. Proposed MEMS Based Drug Delivery System

2.1. Phase Change Liquid

The phase change is one of the unique properties associated with electronic liquids produced by 3M solution in commercial market. The phase change liquids used in our system is of two way phasing change liquid capable of changing from vapour and liquid phase. The phase change liquids used in the system reservoir is 3M HFE7000 Phase change liquid of relatively higher vapor pressure. Such phase change liquid will vaporize readily at its boiling point producing considerable vapor to actuate the diaphragm attached with drug reservoir of the system. The phase change liquids in the chamber can produce an acute pressure of about 0.089 to 2MPa which can relatively produce the displacement of about 29µm to maximum. Several3M liquids with low boiling points are listed in Table I

Table I: Summary of Boiling point of 3M liquids

Liquid	Boiling Point	Vapour Pressure
3M FC3284	50ºC	267.77 Torr
3M HFE7000	34ºC	484.53 Torr
3M HFE 11PA	56.8ºC	109Torr
3M HFE 7100	61ºC	202 Torr

2.2. Microactuator

The core part of the actuator in the micropump is the thin silicon diaphragm coated with polymer material which is displaced as a result of the vapor pressure created in the reservoir due to the 3M electronic phase change solutions. From Table I, it can be observed that solution 3M HFE 7000 at a temperature of about

34ºC canable to create a pressure of about 484.53 Torr that is almost 0.0895 MPa pressure in equivalent to the Intellisuite CAD softwaretool. This pressure is enough to deflect the silicon diaphragm which in turn pumps the fluid out of the drug reservoir.

Table II. Material specification for silicon

Name of the material property	Specification value
Young's modulus	130-180GPa
Poisson ratio	0.064 - 0.28
Band gap energy at 300 K	1.12 eV

The diaphragm suspended over the walls of substrate is subjected to stress when pressure is applied by the phase change liquid chamber. A rectangular shaped diaphragm is used instead of Conventional Circular Diaphragm as the rectangular shaped diaphragm is easy to suspend from the walls of the chamber. The patterning of the rectangular diaphragm is also easy compared to the conventional system. Table II summarizes the material specification for silicon.

2.3. Heater Elements

The drug reservoir filled with chemotherapy drugs such as epirubicin, durorubicin is built above the diaphragm. The volume of drug storage is $50mm^3$. The dosage of drugs such as epirubicin required for the chemotherapy is 50mg. To prevent back flow and other losses in the fluidic channel the storage chamber capacity is increased to ~$60mm^3$. The heater elements are used to achieve a proper fluid outflow with an ambient pressure of ~485 Torr that requires ~34°C by providing low voltage. To achieve such a temperature, the thermocouple material is used as heater elements.

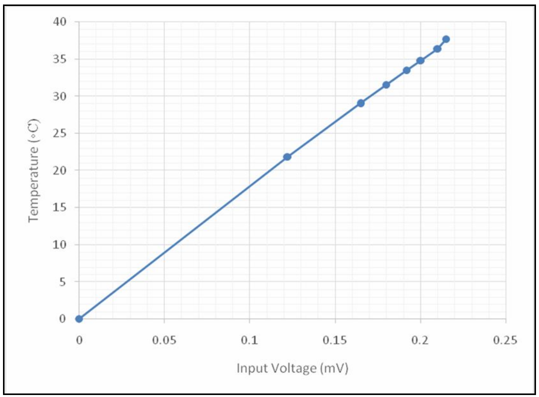

Figure 2 Characteristics of Type R Heater Element

Type R Thermocouple is selected which is an alloy combination of Platinum and Rhodium. Type R thermocouples (Pt/Rh 87%/13% by weight) are used up to 1600 °C. The Type R element produces a temperature of ~34°C for an applied voltage of about ~0.19mv as shown in Figure 2. So, with respect to the ambient response the Type R element is used. The heater elements are provided with low input voltage that generates required temperature to evaporate and condense the phase change liquid (3M HFE7000) in the reservoir. The pressure in the PCL reservoir deflects the diaphragm microactuator which inturn pushes the drug from the drug reservoir into the array of microneedles.

2.4. Operation Specifications

The proposed system consists of the two reservoirs, one for the phase change liquids and the other for the drug storage. The two reservoirs are split by the thin silicon diaphragm coated with polymer material, the core part of actuator meant for pumping outdrugthrough the microneedle. The reservoir filled with phase change liquid is equipped with heater elements to produce a relative temperature of about 35ºC which is enough to change the phase of the fluid to vapor pressure and the diaphragm made of silicon coated polymer material is deflected to its maximum deflection so the drug stored in the reservoir is pumped out in the fluidic channel to the target area.

3. Simulation of the Diaphragm

The Intellisuite CAD tool is used for the simulation of the silicon diaphragm actuated by the phase change liquid. The efficiency of the micro actuator is analyzed by applying the pressure to the diaphragm which deflects as a result of the vapor pressure exerted by the phase change liquid. The simulation scenario uses the pressure application in MPa. The 3D simulation output is shown as a response of the applied pressure.

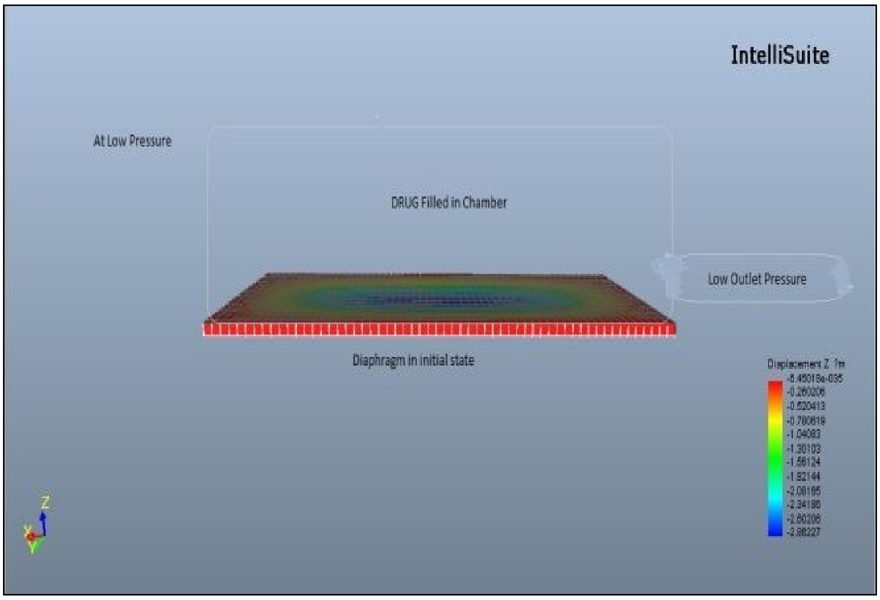

Figure 3. Diaphragm in initial state

This simulation model uses the diaphragm of 2µm thickness with its supporting substrate of increased thickness is shown in Figure3. This diaphragm thickness of 2µm is used only for the system that exhibits the temperature to a maximum of about 50˚C. An increased amount of the temperature will result in the creation of increased vapour pressure resulting in the deformation of the diaphragm as shown in Figure 4. The deflection of the diaphragm at its maximum pressure causes the drug at its reservoir to flow through the channel. The designed micro actuator is proposed to use with micro needles at its output to study the utilization in drug delivery system.

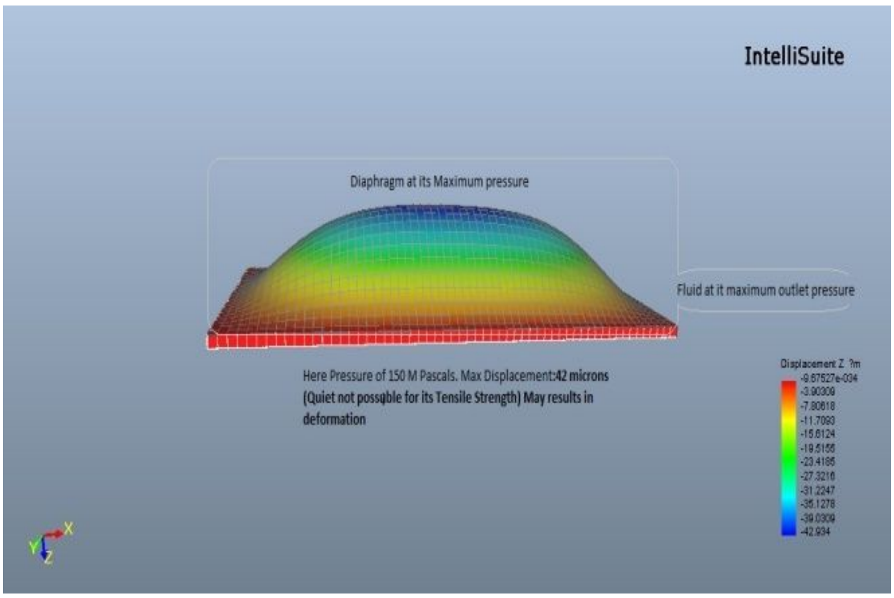

Figure 4. Diaphragm after deflection

4. Results & Discussion

The graphical plot in Figure 5,is obtained as a response of the diaphragm with respect to applied pressure. The 2D plot epics the applied pressure over diaphragm due to phase changes in X-Axis and Displacement of Diaphragm in the Y-Axis. The diaphragm displacement continues and linearly increases resulting in the drug outflow into the array of micro needles. The diaphragm can respond linearly with an applied pressure of 0.089 to ~1.8 Mega Pascal's unit. The diaphragm displacement for this range will be in order of 3 to 68µm which is almost the maximum pressure required to empty the entire chamber of drug. When the applied pressure is increased beyond 2MPa it results in the deformation of the diaphragm.

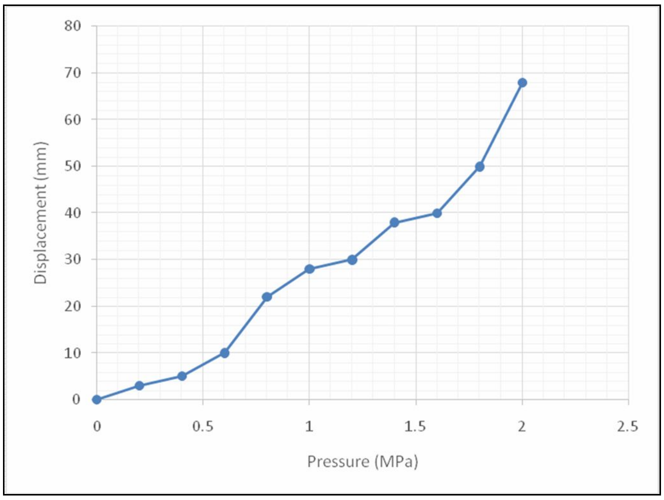

Figure 5. Pressure Vs Displacement of Diaphragm

A diaphragm actuated by phase change liquid in the micro pump has been designed and simulated. The data gathered regarding the boiling points of various 3M liquids is used to select a phase change liquid for the actuation of the diaphragm. The structure of mechanical micro pump proposed uses the simple principle of phase change which makes the displacement of the diaphragm. A thin silicon diaphragm coated with polymer material emphasises on lowering the manufacturing costs and increases the biocompatibility. It can be concluded that according to the pressure applied by the micro actuator using phase change liquid, it pumps the drug out into the target area with a desired flow rate.

6. Conclusion

According to the needs of biomedical industry, various micro pump concepts have been developed. A micropump capable of providing controlled and targeted drug delivery is very much essential for an effective drug delivery system. In the biomedical therapies, the major aspects concerned with the delivery of drugs to the patients are actuation safety and bio compatibility. The most promising feature of the micro pump is to provide an adequate flow rate at very low applied voltage.In the future, the microfluidic drug delivery system with an array of microneedles intended for the drug delivery will be analyzed.

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