DEVELOPMENT OF MEMS BASED MICROPUMPS FOR MEDICAL APPLICATIONS

BY

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CONTENTS

INTRODUCTION

- MEMS is termed as Micro-Electro-Mechanical Systems.
- MEMS have been an important aspect in different domains of technological advancements.
- Application of MEMS in medical domain has been elevated in recent years for sensing and actuation purposes.
- But, there has been a **dearth of MEMS based devices** for fast and **effective treatment of wounds** and also for **real time treatment of glaucoma.**

http://www.eeherald.com/section/design-guide/mems_medical.html

This modified MEMS endoscopy is very small in nature of

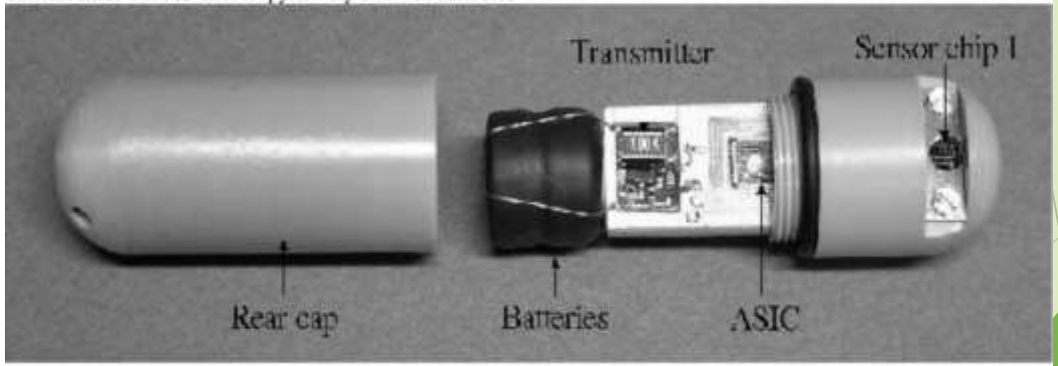


Figure 2: Lab on a pill

Abba, Ibrahim A.. "Role of Microelectromechanical Devices in Improving Human Health." (2015).

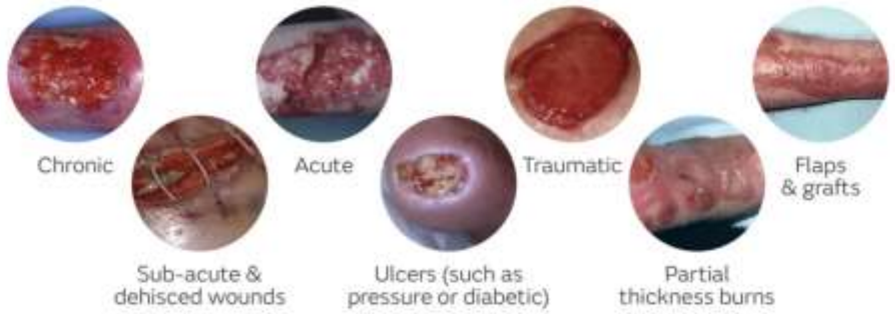
WOUND THERAPY

- **Vacuum Assisted Closure or Negative-pressure wound therapy.**
- **How does it work?**

i. Device **decreases air pressure** on the wound. The gases in the air around us put pressure over the area of the wound.

ii. Induce mechanical **stress** to tissues and stimulate the **division of cell (Mitosis)**

iii. Speed of the **growth of new blood vessels** can be enhanced by **removing excess exudates** and wound will be drawn **closed toward the center point.**



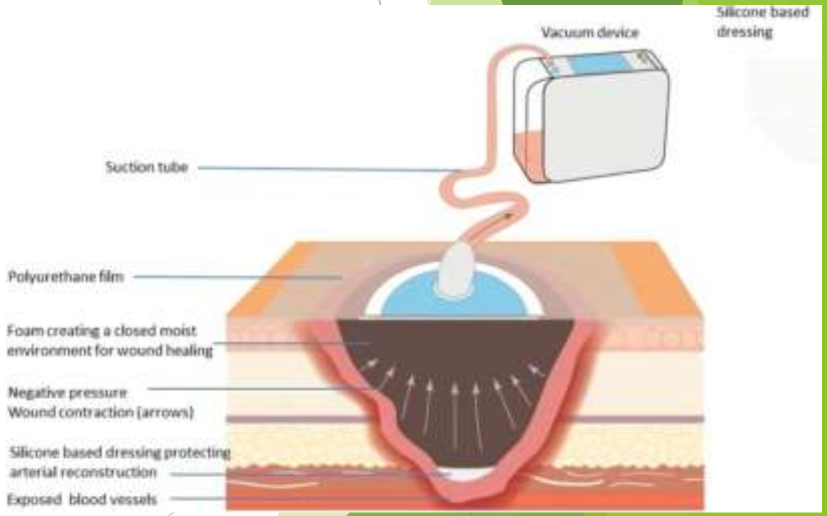
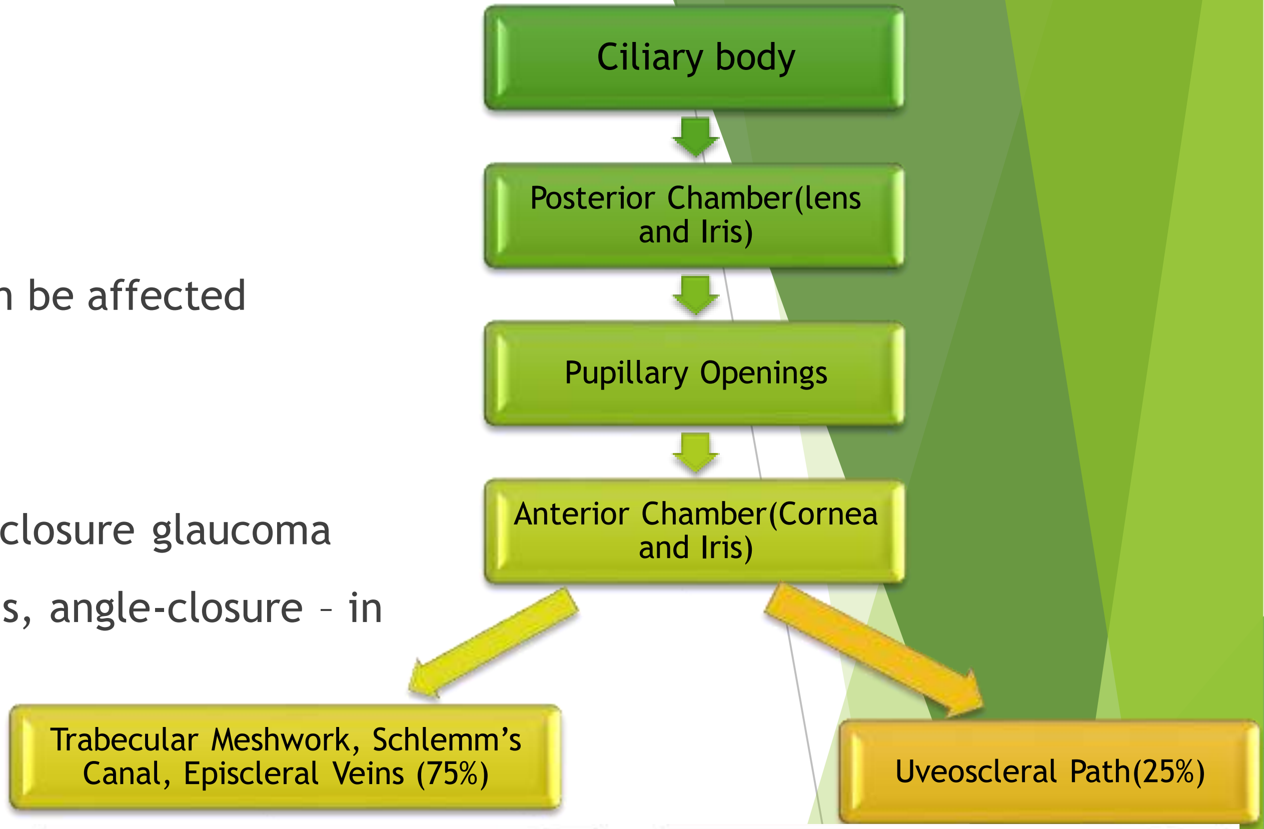


Figure : NPWT Wound Types and treatment.
Credit: https://www.smith-nephew.com/

Figure: Operation of NPWT
Credit: S. Andersson, C. Monsen, S. Acosta, Outcome and Complications Using Negative Pressure Wound Therapy in the Groin for Perivascular Surgical Site Infections after Vascular Surgery, 2017

GLAUCOMA

- Worldwide 6 – 9% blindness is caused by glaucoma.
- In 2020, 76 million people to 111.8 million in 2040 can be affected
- Normal range of IOP ~ 18-21 mm Hg for human eye
- Increased IOP damages optic nerves.
- Two types of glaucoma – open-angle glaucoma, angle-closure glaucoma
- Implantation – open-angle - in between cornea and Iris, angle-closure – in between Iris and Lens



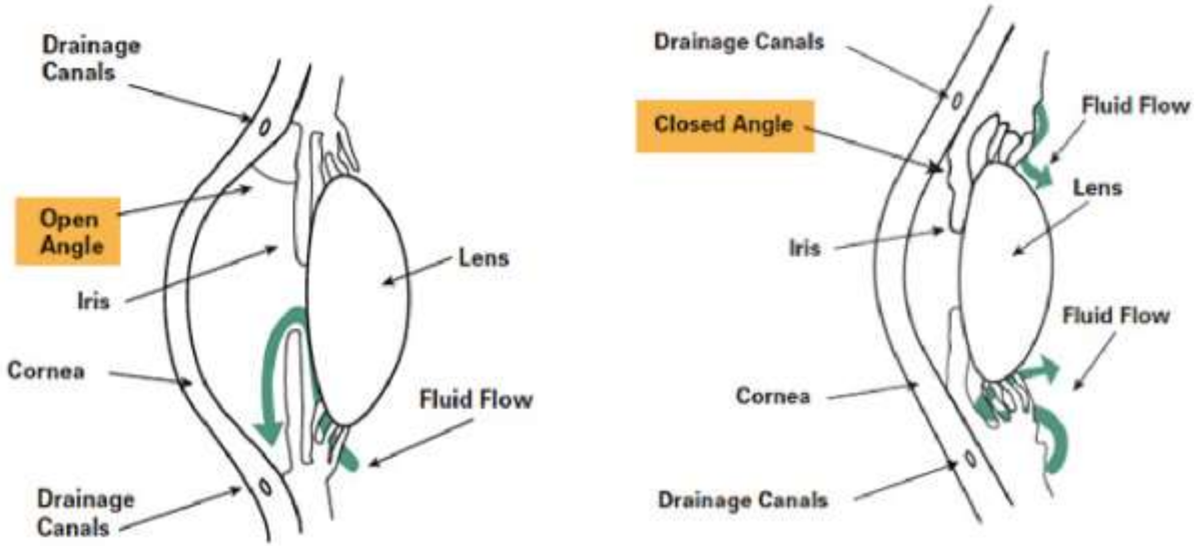


Figure: Open Angle and Closed angle Glaucoma
Credit: http://www.glaucoma.org/glaucoma/.

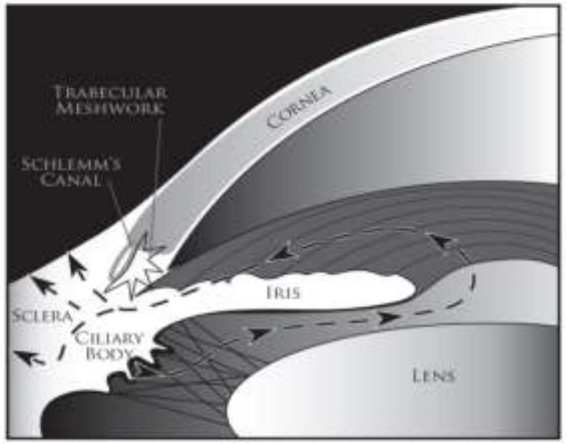


Figure: trabecular meshwork path
Credit:*Aqueous Humor Dynamics Manik Goel*

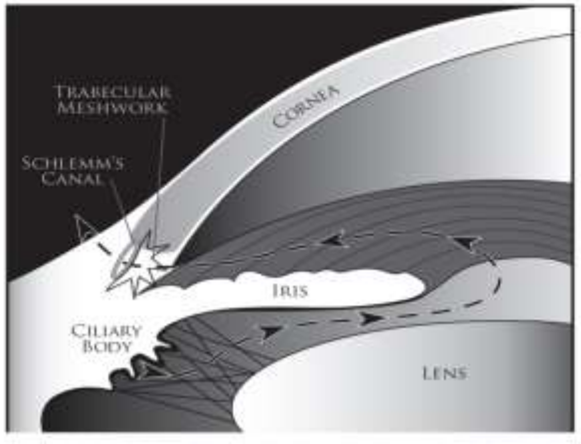


Figure: Uveoscleral path
Credit:*Aqueous Humor Dynamics Manik Goel*

TARGET OF THE PROJECT

- There are **no devices** to mitigate or heal the wounds inside the body.
- There are **no devices** to measure real time pressure and self actuate to pump out intraocular fluid to relieve IOP causing Glaucoma.
- To strike the problem of **in-vivo wounds** a **micropump is to be designed**, which will remove the exudates and to keep the wound clean and help fast healing of the wound.
- A **sensor** will also be incorporated to check the **real-time vitals** of the patient.
- For Glaucoma, **micropump** with **integrated pressure sensor** to be designed which **self-actuates**.
- The **micropumps** should be of **compact size** in the order of millimetres to centimetres.
- **Fabrication** of the devices will be done to be ready for implementation.

DESIGN OF MEMS BASED WOUND THERAPY SYSTEM

- The **schematic** of the design of MEMS based wound therapy system is shown.
- A **power source** is applied to the system. The whole pumping mechanism is **controlled** by a **control system**.
- **After pumping** the exudates are taken out of the system for further operations.

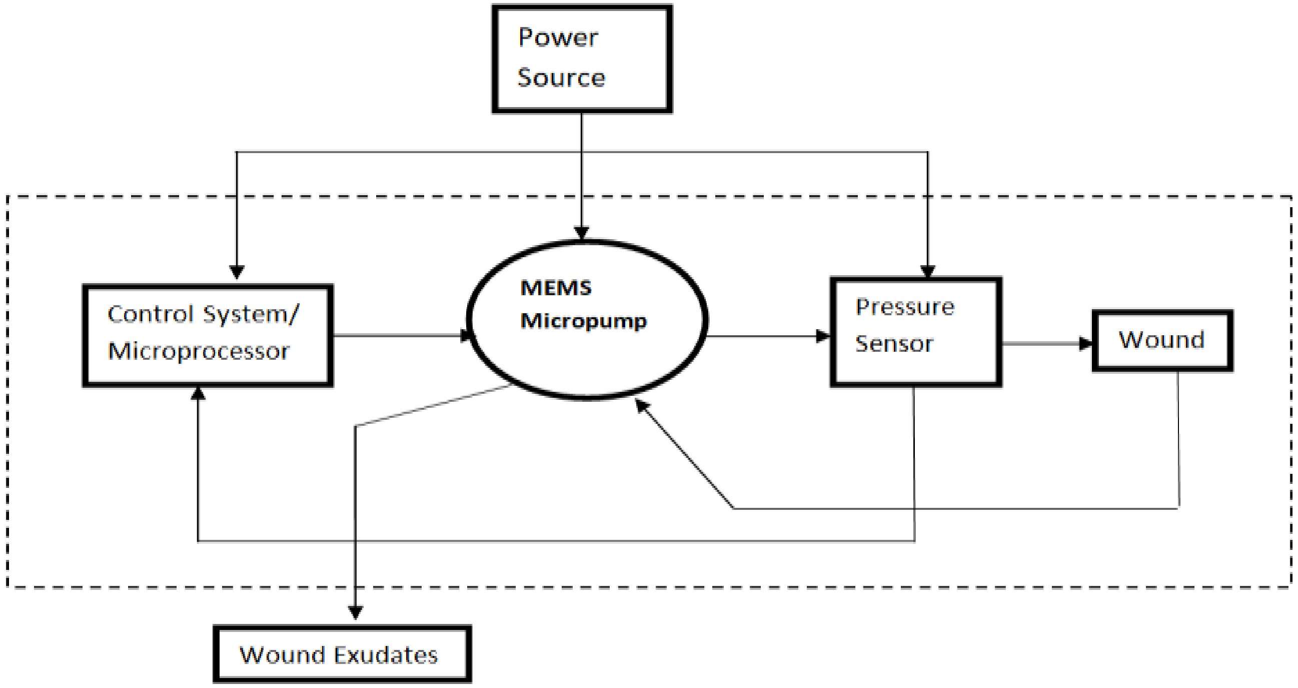


Figure : overall design of the system

DESIGN OF NOZZLE DIFFUSER MICROPUMP

Structure Schematic

- The structure shows **two conical diffuser elements** with **fully developed inlet chamber**.
- The fluid goes in the inlet, through the chamber and gets pumped out through the outlet
- The chamber is covered by a actuator

which changes the pressure inside the chamber thus actuating the pumping action.

- The designed micropump is shown below.
- The micropump is of size **1.2cm*0.6cm**.

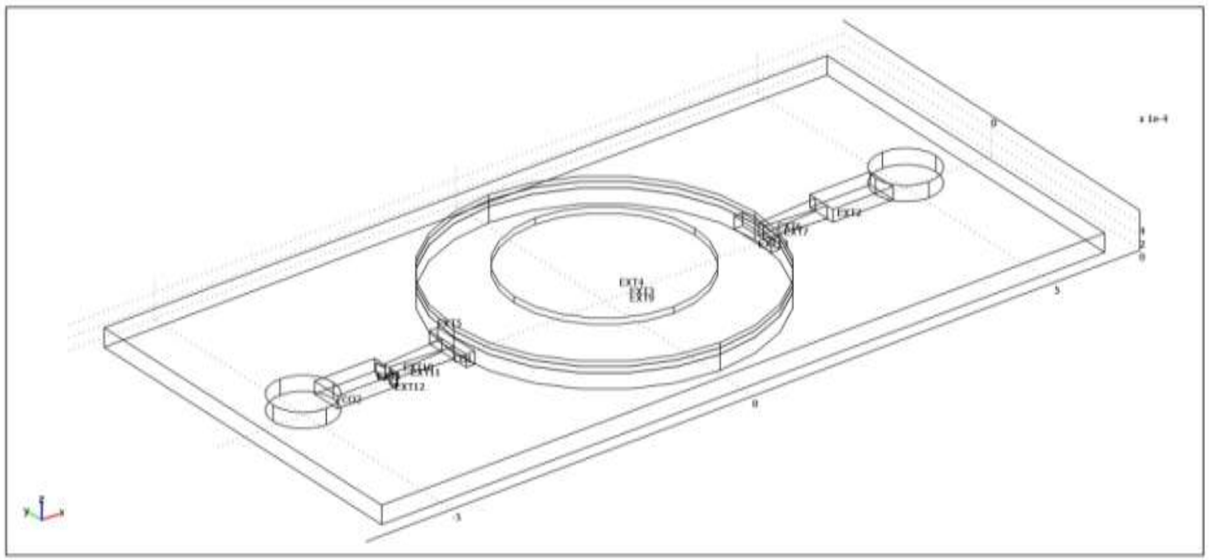


Figure: Design of the micropump

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NOZZLE DIFFUSER MICROPUMP

Working Principle

- There are **two modes** of operation of the pump-**expansion mode**, **contraction mode**.
- In **Expansion mode,** the **volume** of the pumping section **increases more fluid enters** the pumping chamber from the diffuser than the nozzle.
- In the **Contraction mode**, more **fluid goes out** of the element on the left which now acts as a diffuser, while the element on the right acts as a nozzle.

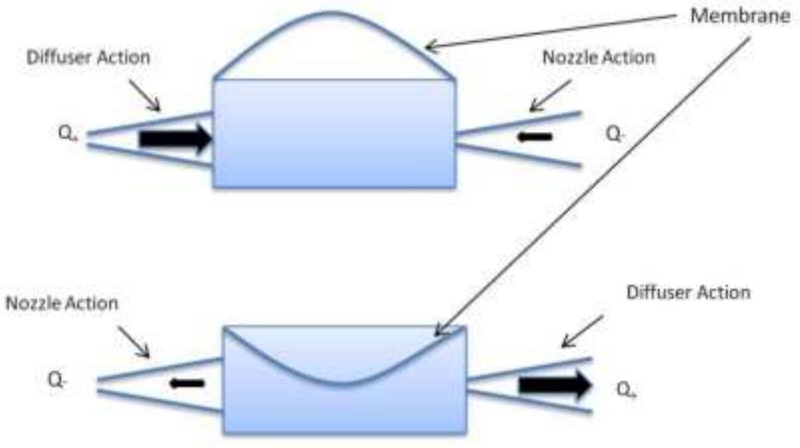


Figure: Modes of operation

Theoretical Analysis

- To analyze the working of the diffuser element, **pressure loss coefficient, flow rectification efficiency** and **diffuser efficiency** was taken in consideration.
- The pressure loss coefficient is defined- $K_d = 1 - \frac{d_a^4}{d_b^4} - C_p$ $\quad K_n = \frac{\Delta p_n}{\rho v_b^2/2}$
- The flow rectification efficiency (ε)is given by- $\varepsilon = \frac{Q_+ - Q_-}{Q_+ + Q_-}$
- The nozzle efficiency of the diffuser is – $\eta = \frac{K_{n,t}}{K_{d,t}}$
- **Diffuser angle** should be of **9°**.
- Less the K_d, more is the efficiency.

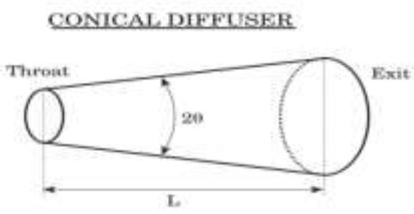


Figure: Conical Diffuser

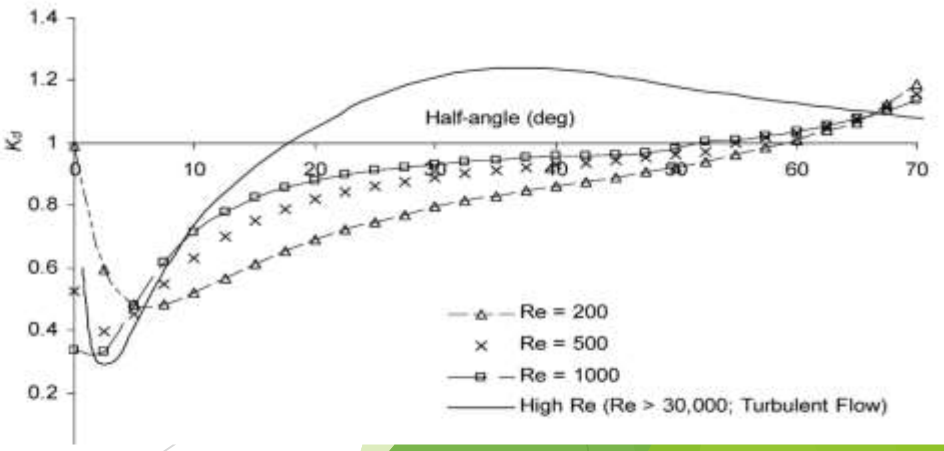


Figure: pressure loss coefficient with half angle

DEVICE FOR GLAUCOMA TREATMENT

The device can be segregated in two part- Piezoelectric Pressure Sensor and Peristaltic Micropump.

Peristaltic Micropump

- Dimension of the micropump is 3mm * 0.25mm.
- Consists of three pumping cells, Microchannels, moving membrane

and electrodes.

- Electrostatic force pulls down the diaphragm.
- Fluid chamber expands and fluid starts to flow.
- ***Piezoelectric Pressure Sensor-***
- Consists of Stacked layers.
- Size of device is 350µm*100µm*1.3µm

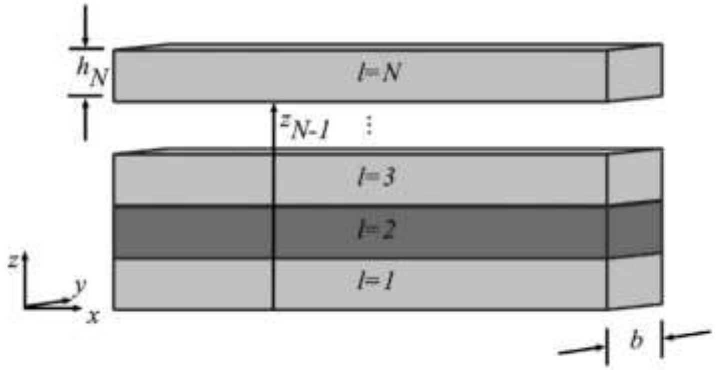


Figure: Piezoelectric laminate beamlayer

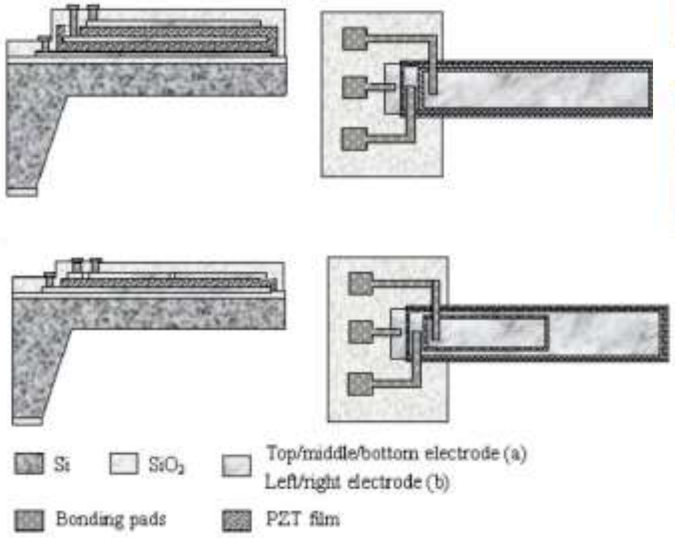


Figure: Bimorph Piezoelectric Sensor

Credit: M. Liu *et al.*, "Piezoelectric Microcantilevers with Two PZT Thin-Film Elements for Microsensors and Microactuators," *2006 1st IEEE International Conference on Nano/Micro Engineered and Molecular Systems*, 2006, pp. 775-778.

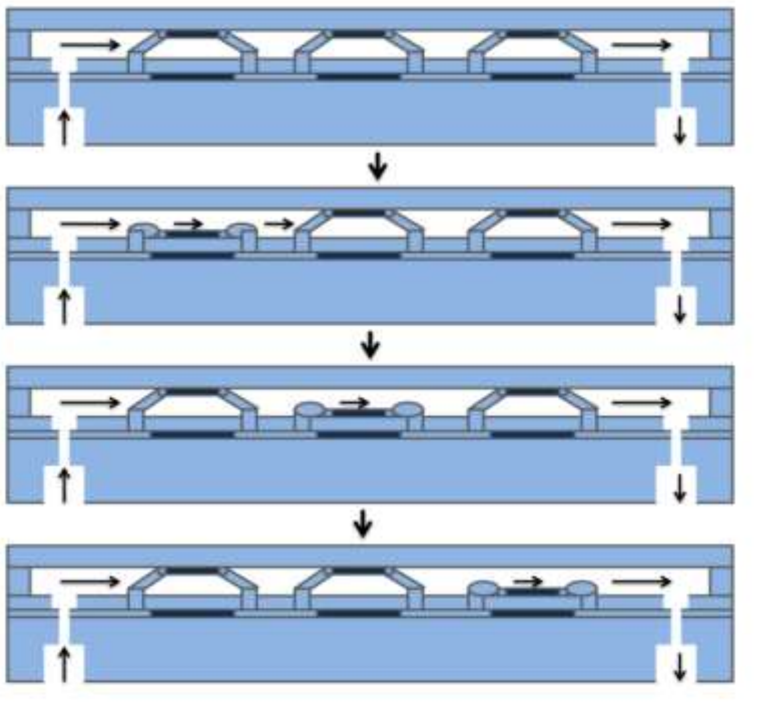
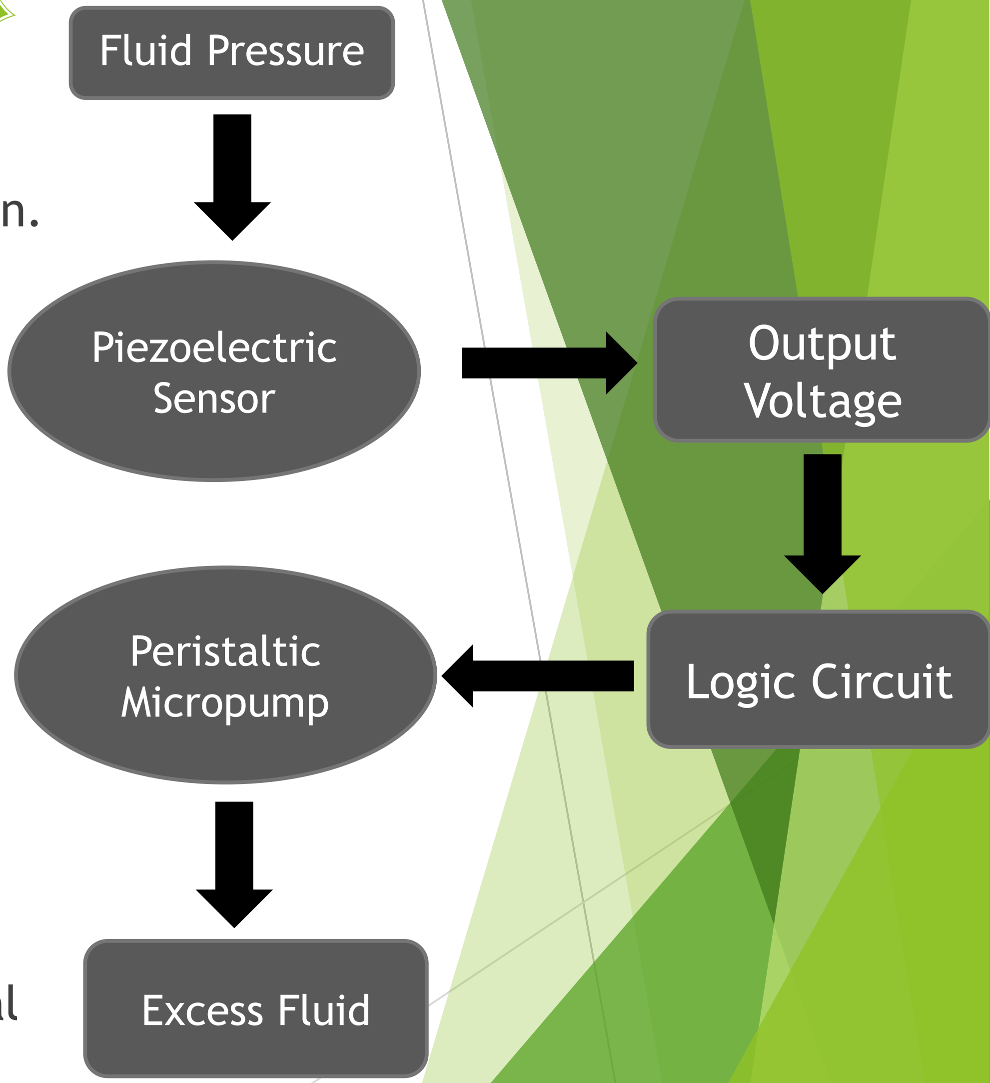


Figure: working of peristaltic micropump
Credit: MSppt

DESIGN OF MEMS BASED DEVICE FOR GLAUCOMA TREATMENT

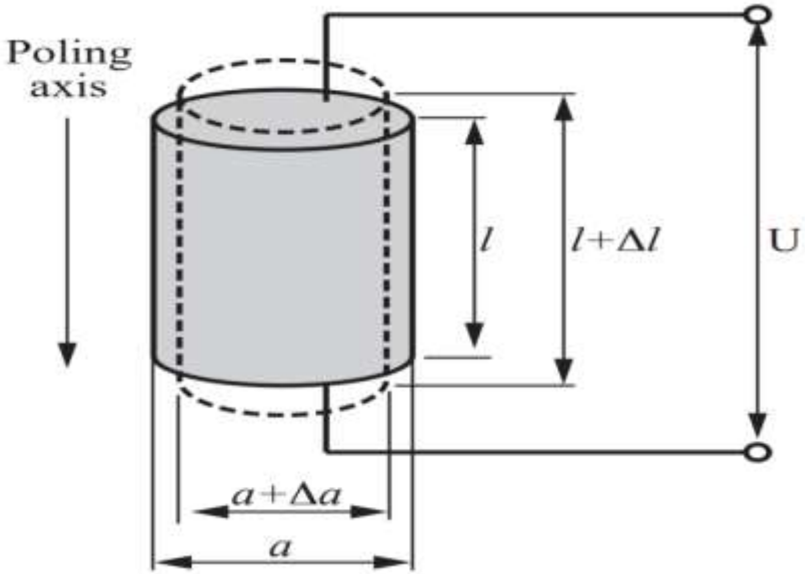
- The **schematic** and flow chart of **working** of the device is given.
- The device **self actuates** by the **output voltage** of the **piezoelectric sensor**.
- A **logic circuit** applies voltage **sequentially** to the different electrodes for operation.

- **How to know the pump will actuate after the pressure increases than a certain range?**
- The **output voltage** of sensor for 25mm Hg and also the **threshold voltage** of membrane known.
- We thus modulate the output voltage to be greater than the threshold voltage when the pressure increases from the normal limit.



COMSOL SIMULATION

- **Actuation Principles**
- Special crystals were subject to mechanical tension, they became electrically polarized and the polarization was proportional to the extension – **direct piezoelectric effect.**
- The same phenomenon occurs when an electrical voltage is applied, the material gets deformed – **inverse piezoelectric effect.**
- This serves as the main actuating phenomenon for the pumping mechanism for the micropump.



Thorsén, Anders. (1998). Valveless Diffuser Micropumps.

COMSOL SIMULATION

- Piezoelectric Actuator

Description	Value
Diameter and thickness of the Diaphragm	6mm, 100µm
Diameter and thickness of Brass	6mm, 100µm
Diameter and thickness of the Piezo Material	4mm, 100µm

Description	Material Used
Diaphragm	PDMS
Piezoelectric Actuator	PZT-5H
Substrate	Brass

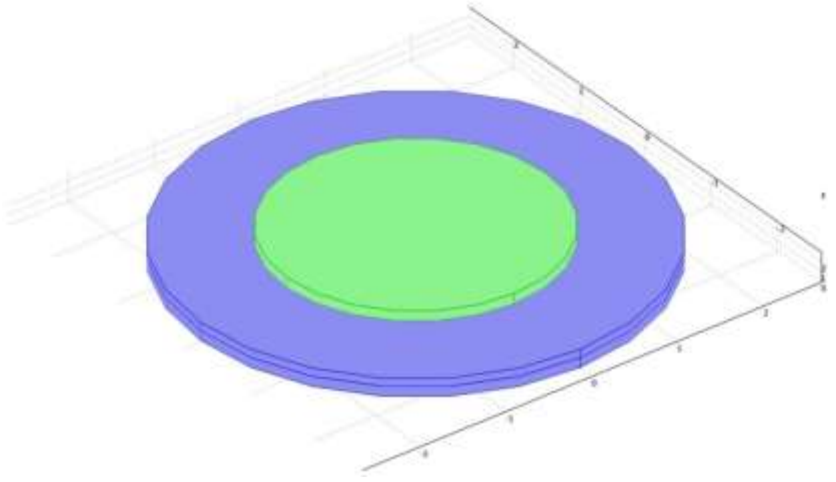
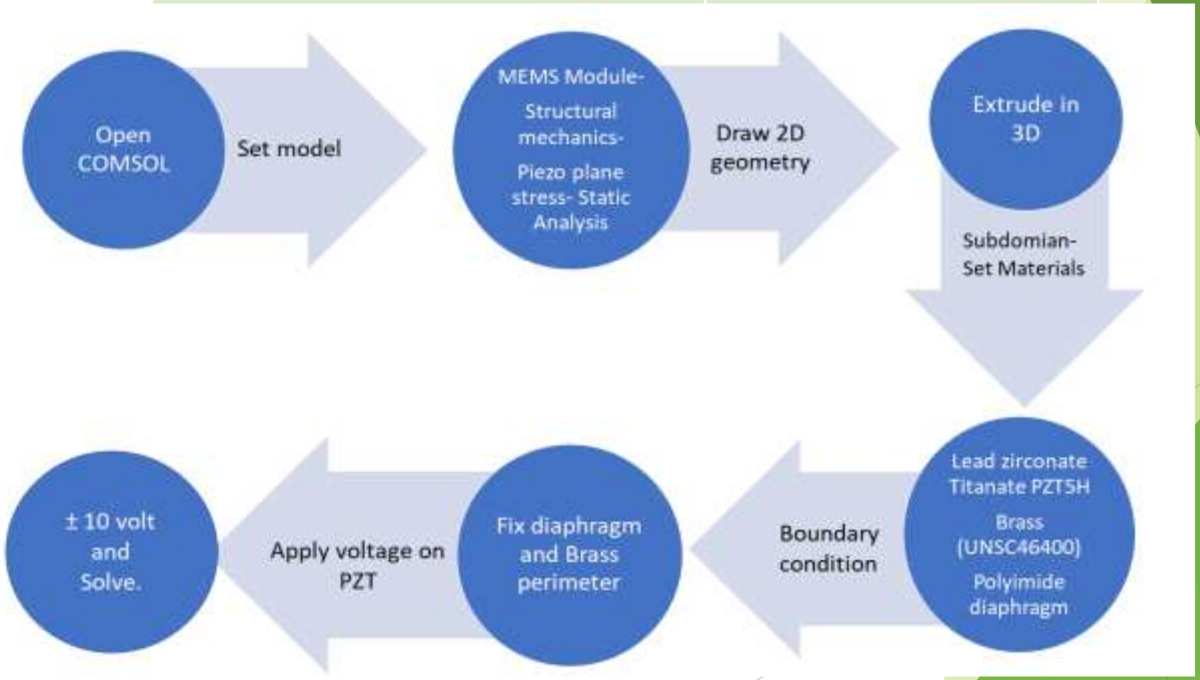


Figure : Design of actuator



COMSOL SIMULATION

Fluid Transport Geometry

Description	Value
Length of the inlet chamber(l_1)	1mm
Length of the diffuser(l_2)	1mm
Chamber Diameter(D)	5mm
Actuator Diameter	3mm
Neck width(l_3)	100µm
Neck width-outflow(l_4)	260µm
Width of chamber	300µm
Top plate thickness	100µm

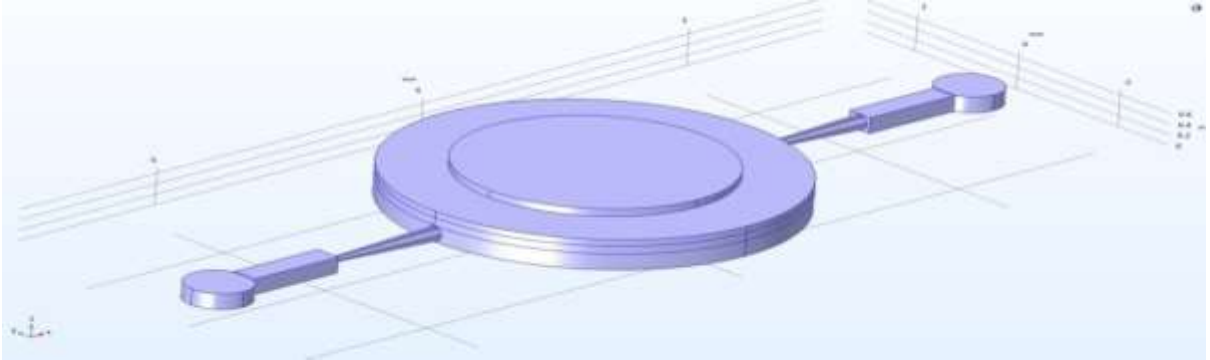


Figure: Design of Fully Developed Nozzle/Diffuser Micropump
Credit: COMSOLmultiphysics

Problem formation (Design variable and performance characteristics)

Computational formulation (Pump modeling using pzd and fsi module, governing equations and boundary constraints)

Simulation and parametric studies (study of influence of different design parameters on net flow rate)

Optimal design (Identification of optimal designed parameters)

Characterization of micropump (Flow characteristics)

COMSOL SIMULATION

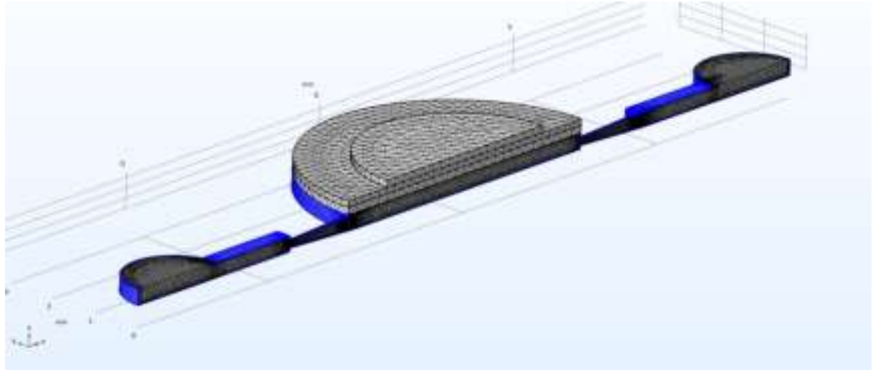


Figure: Mesh formation
Credit: COMSOL Multiphysics

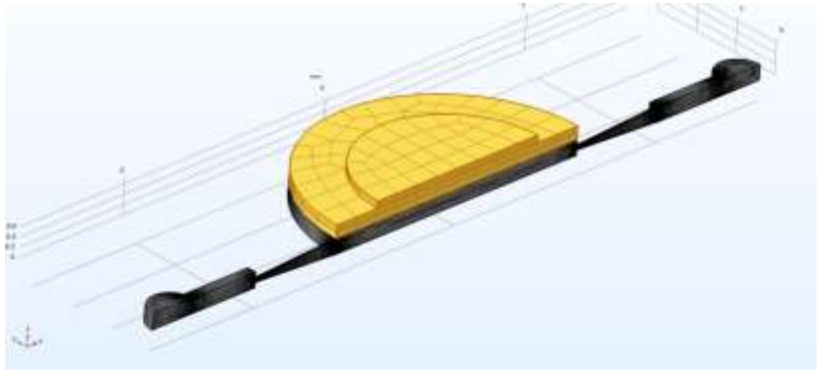


Figure: Swept mesh
Credit: COMSOL Multiphysics

- **Boundary Conditions**
- The side walls of the diaphragm, membrane and the Piezo disc were fixed.
- For inlet/outlet we have used pressure inlets as boundary conditions.

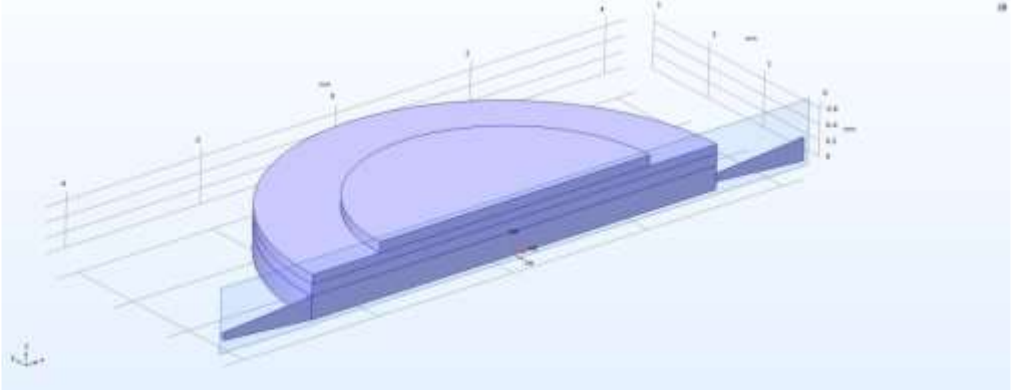


Figure: work / symmetric planes
Credit: COMSOL Multiphysics

COMSOL SIMULATION

- *Peristaltic Pump 2D Geometry*

Description	Value
Thickness of Actuation Membrane	2µm
Height of Actuation gap	4µm
Thickness of Electrodes	0.5µm
Inlet/Outlet Length	20µm
Height of Microchannel	6µm

- *Piezoelectric Sensor*

Material	Thickness
SiO2	0.5µm
Aluminum	0.1µm
PZT	0.5µm
Si3N4	0.1 µm
Length of the sensor	350µm
Breadth of the sensor	100µm

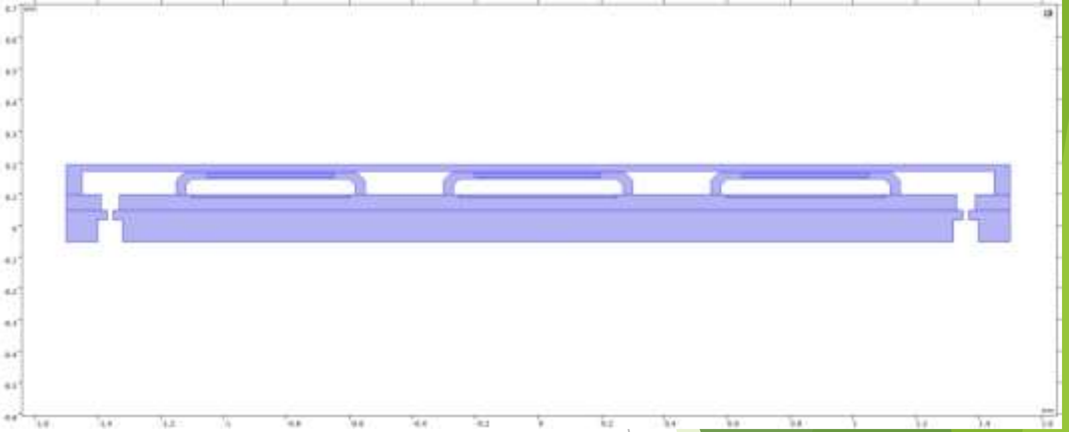


Figure: Design of Peristaltic Micropump
Credit: COMSOL Multiphysics

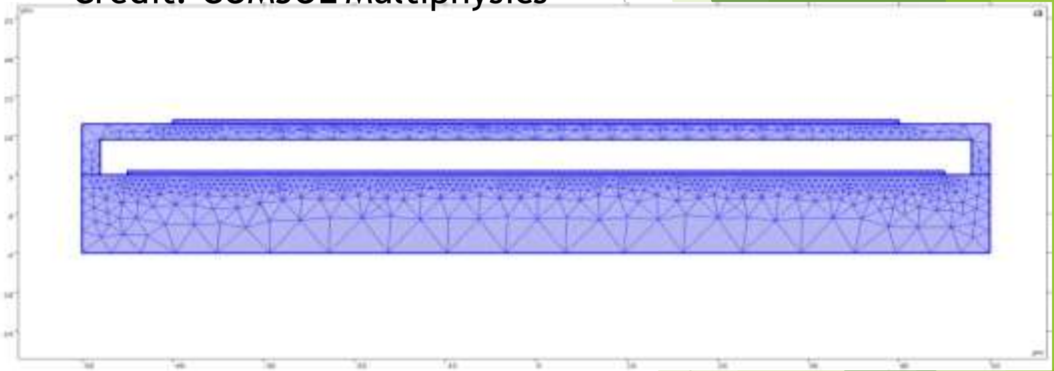


Figure: Mesh Formation

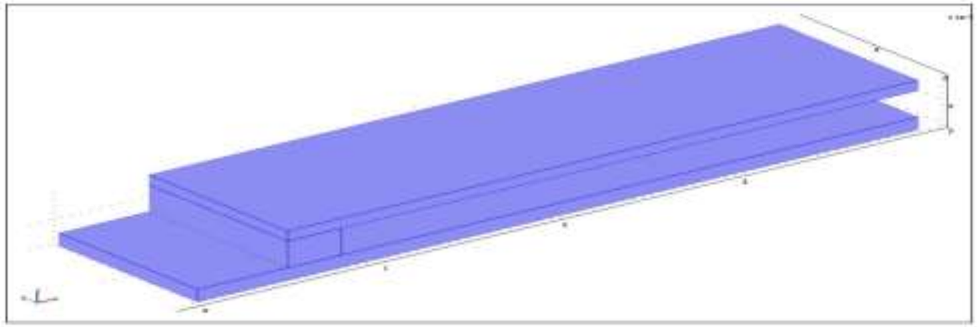


Figure: Piezoelectric Sensor

RESULTS

Piezoelectric Simulation-

- Applying +10volt to the actuator forms a concave surface and bends upwards.
- Applying -10volt the actuator bends inwards as shown.
- The graph shows a **linear curve**, thus depicting linear Increase of the diaphragm with the change in voltage.

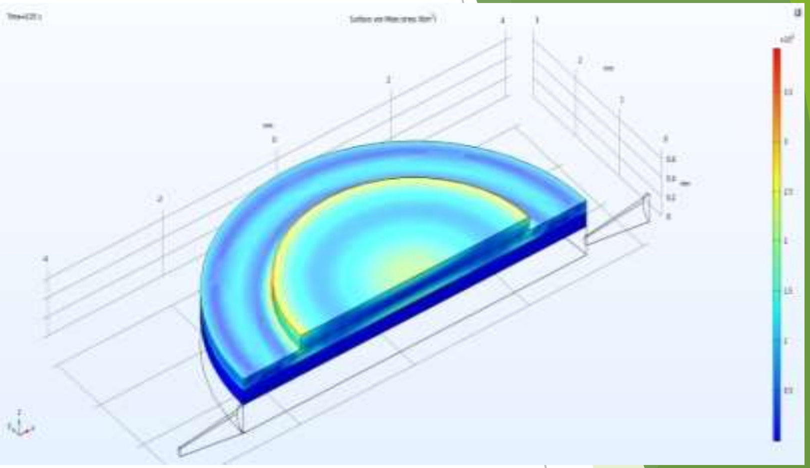


Figure: von-mises stress due to deformation
Credit: COMSOLmultiphysics

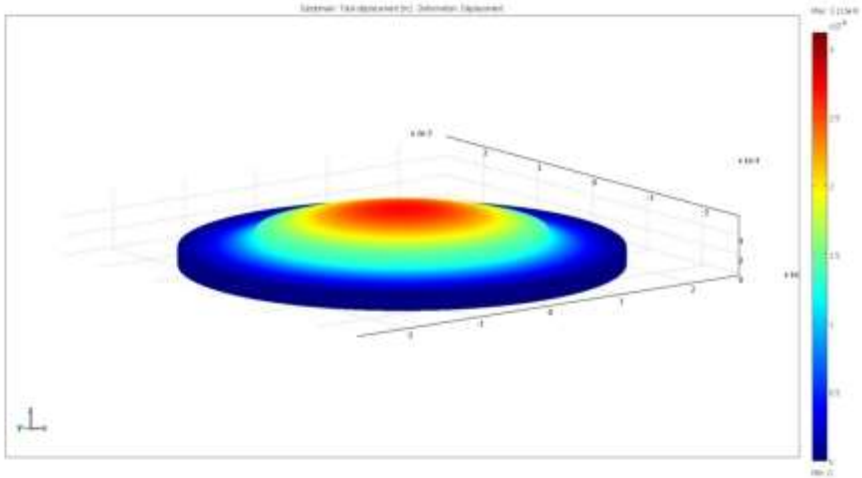


Figure: Piezoelectric actuator simulation
Credit: COMSOLmultiphysics

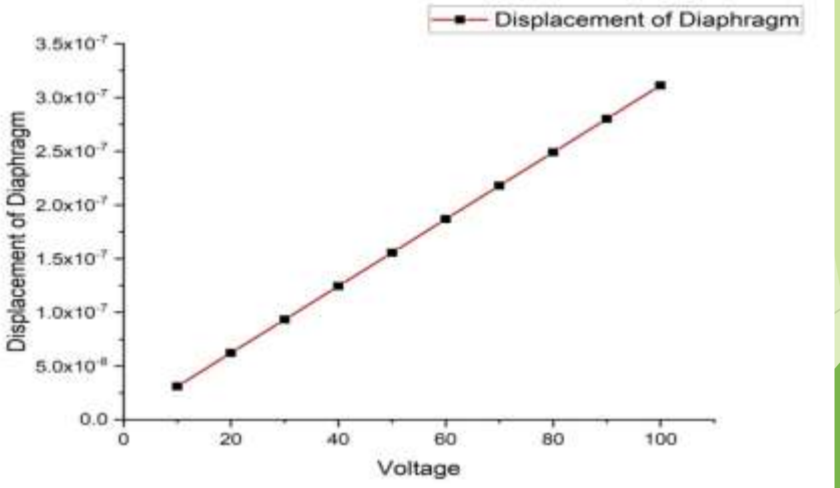


Figure: Diaphragm displacement(m) with voltage(V) plot
Credit: COMSOLmultiphysics

RESULTS

Fluid Transport Simulation-

- Inflow characteristics-

I. It is observed a maximum velocity of 1.43x 10-5m/s near the neck of the diffuser element. The inflow of the fluid is shown.

- Outflow characteristics-

i. As the top plate is pressed down, the fluid ejecting out of the chamber with a maximum velocity of 1.54x 10-5m/s.

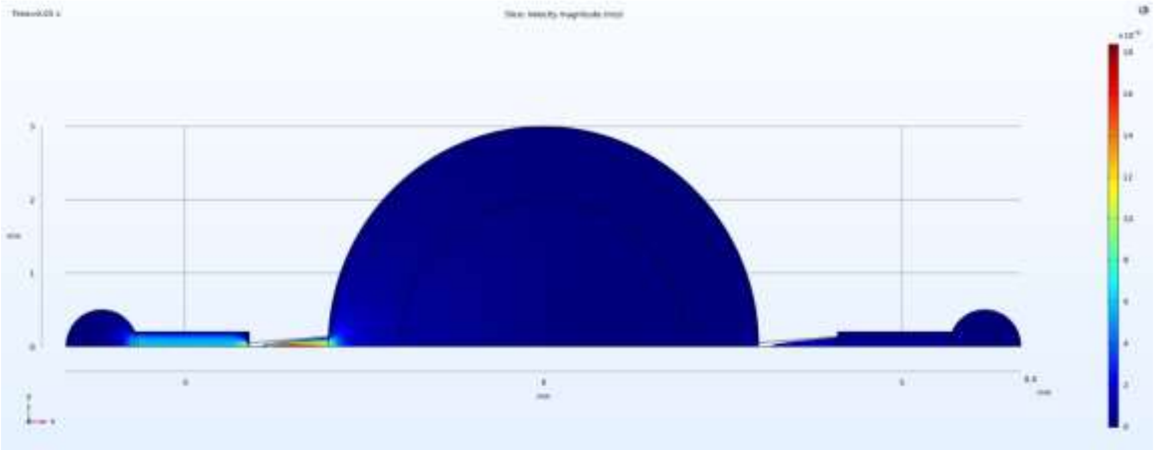


Figure: Simulation of inflow of fluid transport
Credit: COMSOLmultiphysics software

RESULTS

Fluid Streamlines and velocity fields

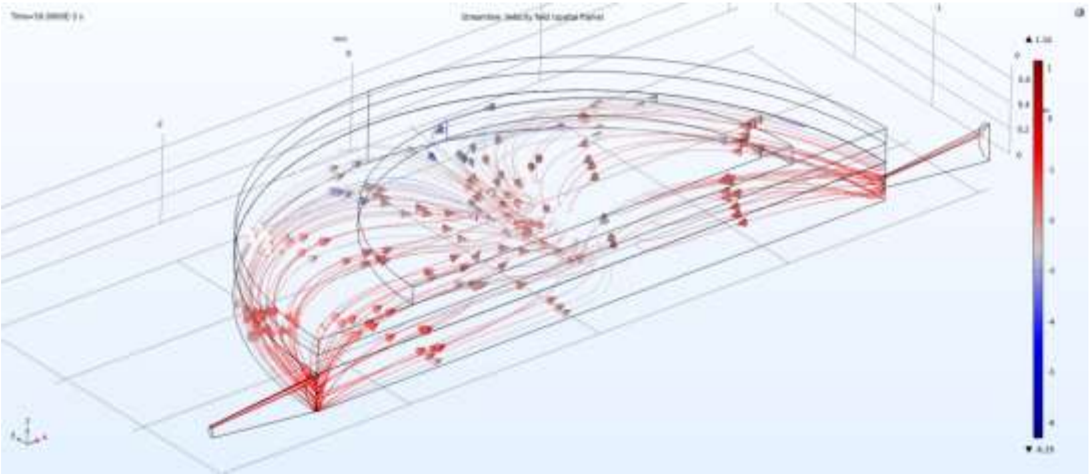


Figure: streamline at time 0.05s (inflow)
Credit: COMSOL Multiphysics

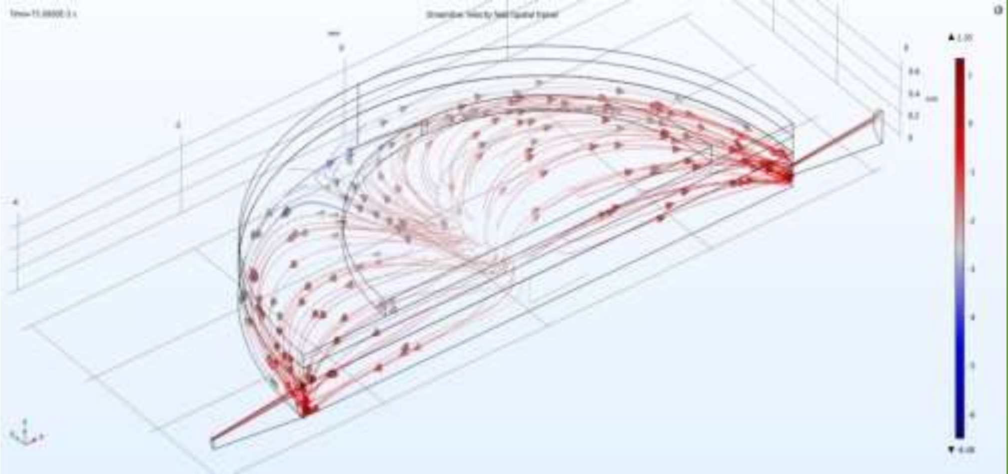


Figure: streamline at time 0.075s (outflow)
Credit: COMSOL Multiphysics

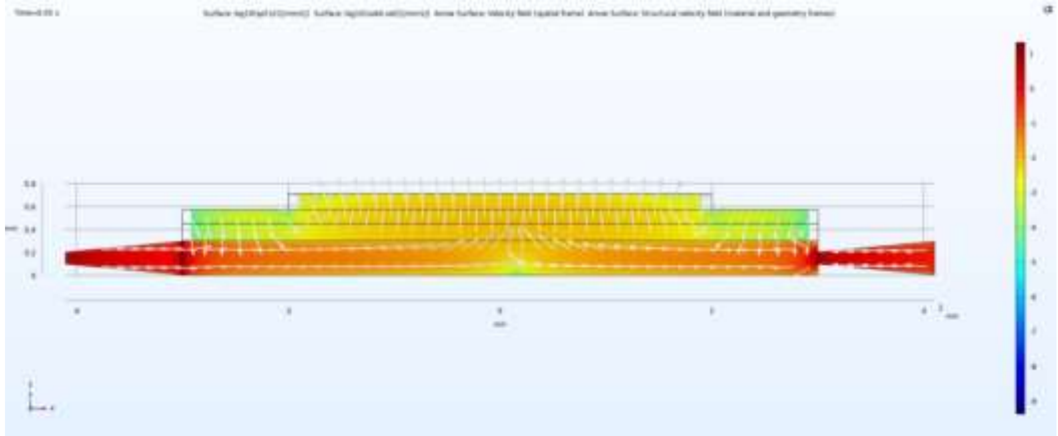


Figure: Flow velocity at time 0.05s (inflow)
Credit: COMSOL Multiphysics

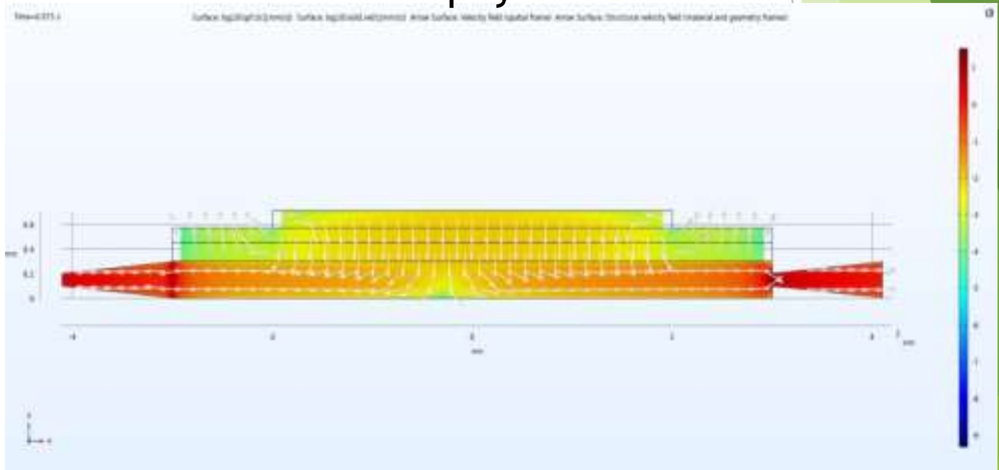


Figure: Flow velocity at time 0.075s (outflow)
Credit: COMSOL Multiphysics

RESULTS

Figure: Accumulated flow volume(μl) vs. time(s) for diffuser length 0.9mm [COMSOL Multiphysics]

Figure: Accumulated flow volume(μl) vs. time(s) for diffuser length 1.3mm [COMSOL Multiphysics]

Figure: Accumulated flow volume(μl) vs. time(s) for diffuser length 1.1mm [COMSOL Multiphysics]

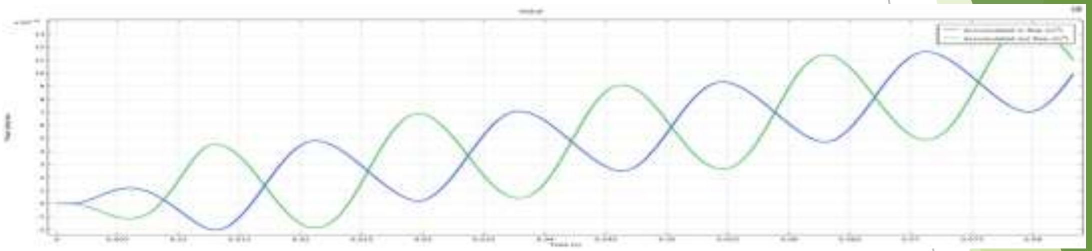


Figure: Accumulated flow volume(μl) vs. time(s) for diffuser length 1.5mm [COMSOL Multiphysics]

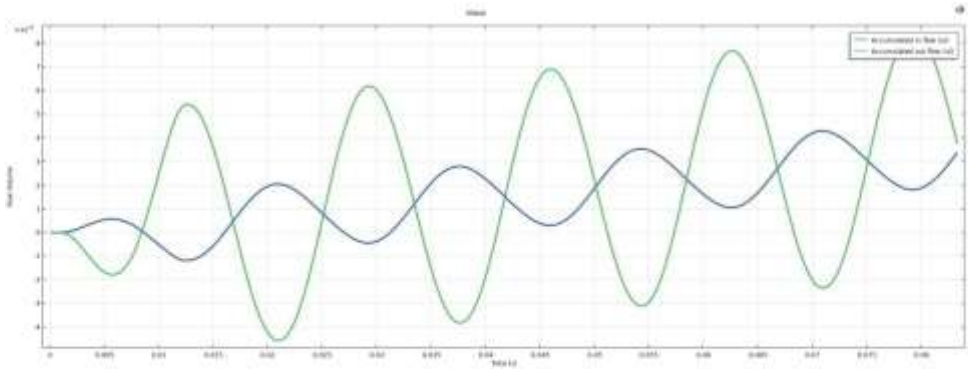


Figure: Accumulated flow volume(μl) vs. time(s) for diffuser angle 8° [COMSOL Multiphysics]

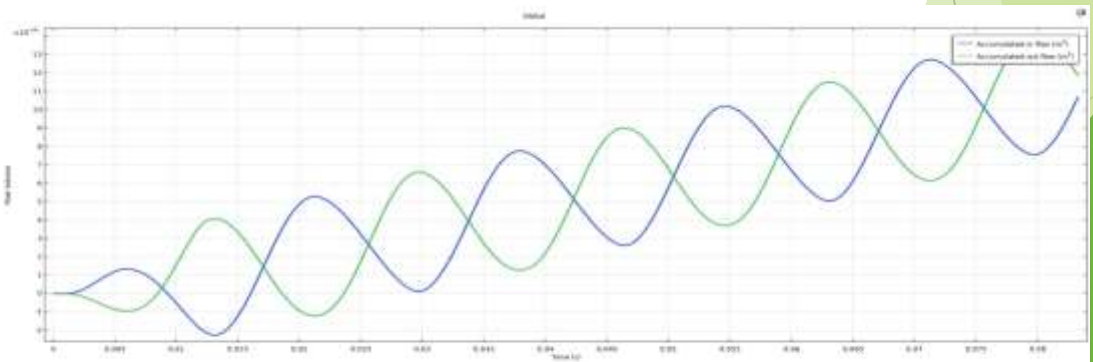


Figure: Accumulated flow volume(μl)vs time(s) for diffuser angle 9° [COMSOL Multiphysics]

RESULTS

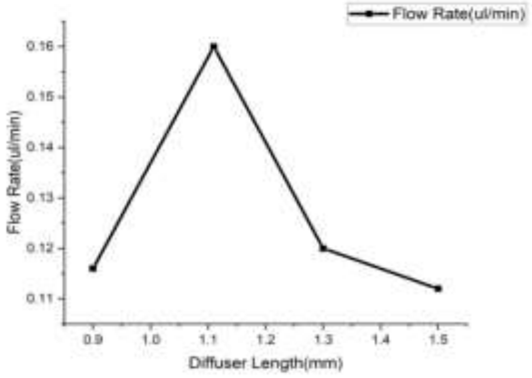


Figure: flow rate(μl/min) with diffuser length(mm) plot for blood
Credit: Origin

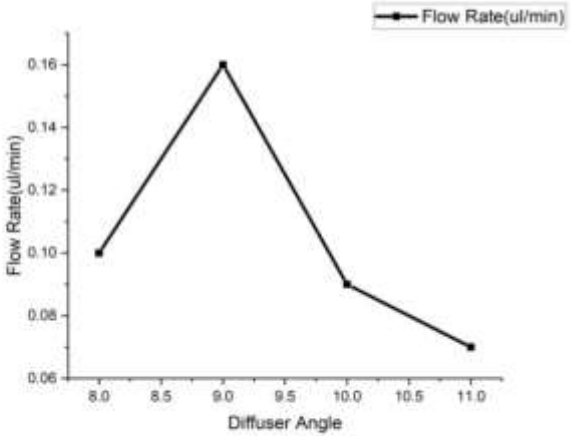


Figure: flow rate(μl/min) with diffuser angle(°) plot for blood
Credit: Origin

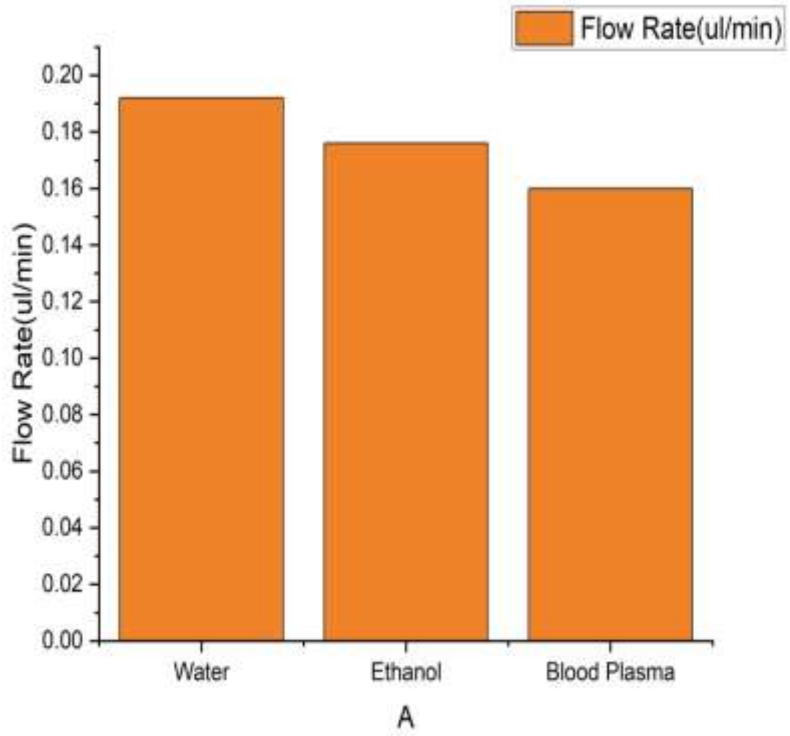


Figure: flow rate(ul/min) of different fluids for optimal geometry
Credit: Origin

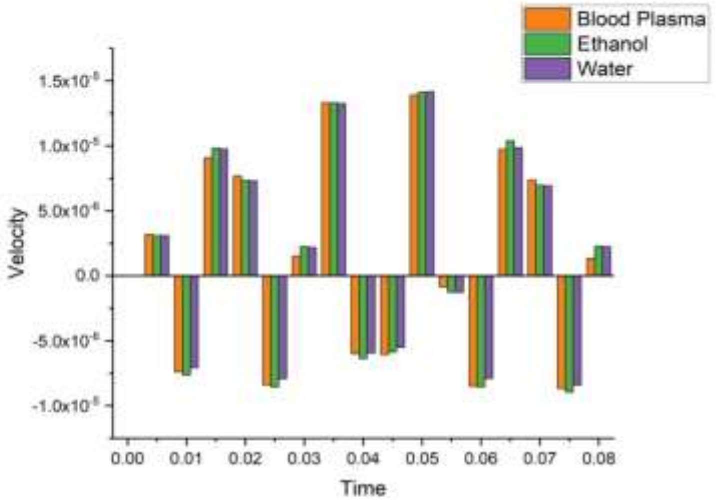


Figure: inlet velocity(m/s) with time(s)
Credit: Origin

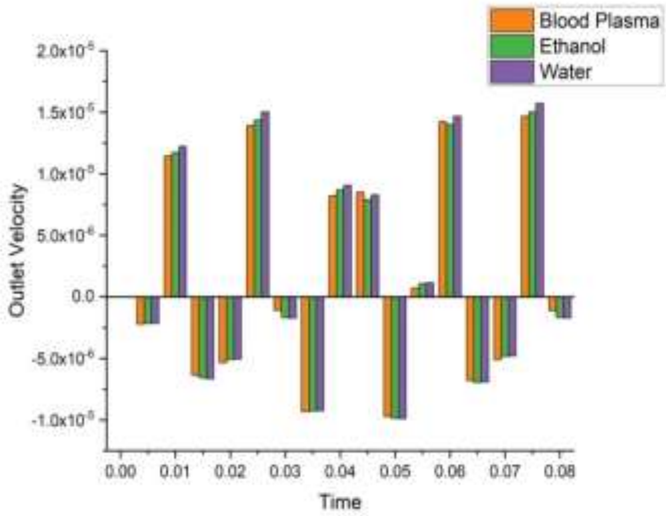
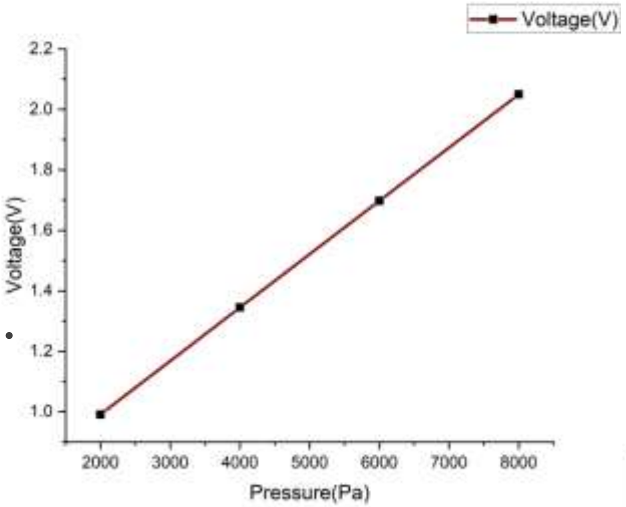


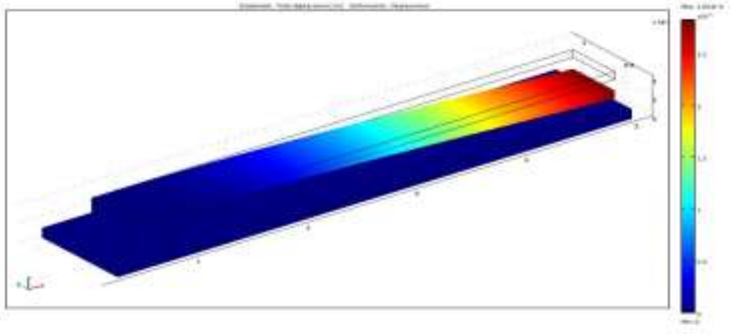
Figure: outlet velocity(m/s) with time(s)
Credit: Origin

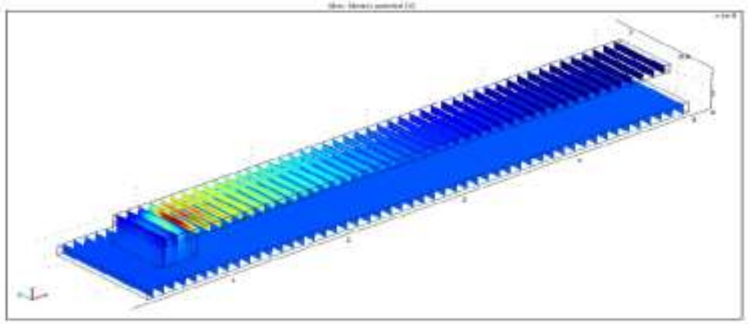
RESULTS

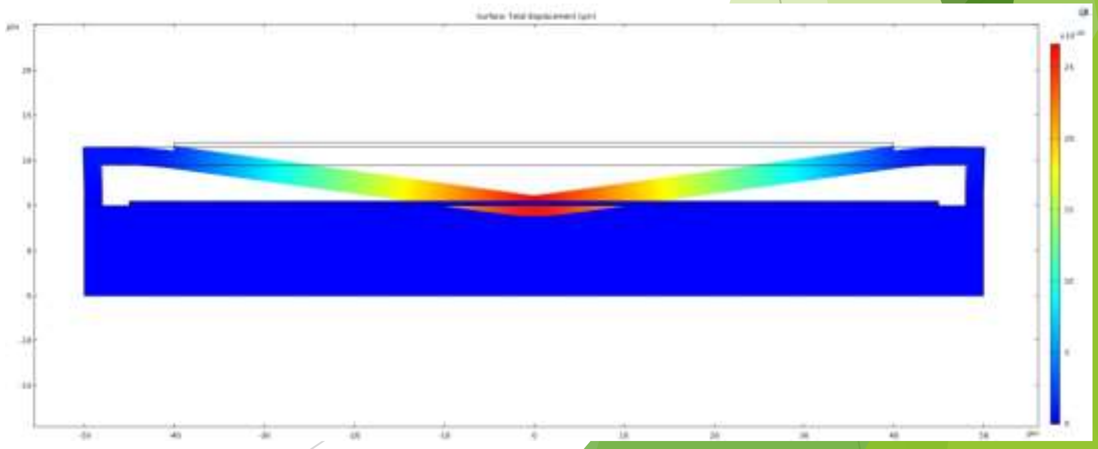
- ***Piezoelectric Sensor***
- The stacked pressure sensor was simulated and characteristics were studied for PZT-5H.
- Output voltage vs. applied pressure characteristics were measured.

- ***Peristaltic pump***
- The most important part of the pump is the **moving diaphragm** as actuation depends on its **threshold voltage.**
- The **threshold voltage** of the membrane was seen at **18.5**V, thus voltage of **20 V** was applied on top electrode.









FUTURE CONSIDERATIONS

- **Design Improvement**
- As we finish designing a single micropump, the design of such can be extended for modifications to increase the flow rate of the pump.

  One such design modification is shown.

- **Fabrication of Structures**
- The **process flow** of the fabrication of the MEMS micropump can be given as-
  - Firstly, the a 300µm silicon wafer is **patterned** in the shape of the micropump with the corresponding chamber and two diffuser, inlet-outlet channels using **photolithography**.
  - Then, it was **etched out** to form the required geometry. **Isotropic etching** is to be done for the **conical diffusers** and the **chamber** and the **inlet boundary** will be **anisotropically etched**.
  - Then, the **PDMS diaphragm** was deposited on the wafer and patterned to give the specific shape.
  - Then, the **piezoelectric actuator** with the **brass base plate** was kept on the diaphragm and joined with epoxy/glue resin.

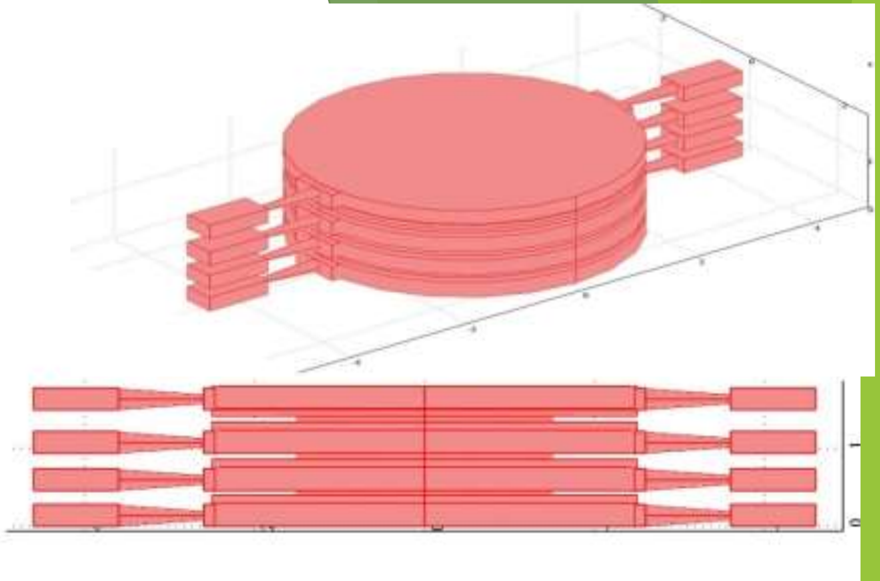


Figure: Design of alternating action micropump
Credit: COMSOLmultiphysics

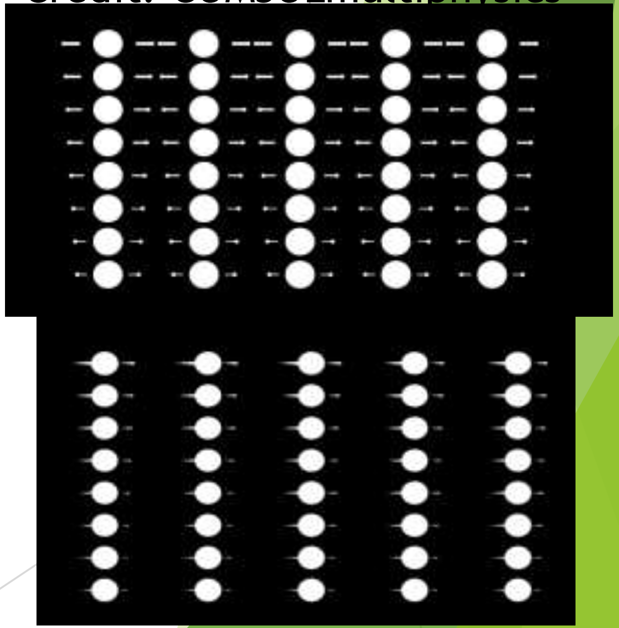


Figure: Masks for fabrication
Credit: Autocad

APPLICATION RANGES

Nozzle/Diffuser Micropump

- The whole system can have **several application** in medical domain including wounds on outside and inside human body.
- This device can be attached with the front of the imaging probe for **endoscopy**, and can attach to cuts inside the body after taking samples.
- For **laparoscopy**, cuts of **1-1.5cm** is made. Our device's dimension is sufficient enough to mitigate the cut for such purpose.

Peristaltic Micropump with Pressure sensor

- The integrated device can be used to lower down the intraocular pressure thus reducing the chance of glaucoma.
- The peristaltic micropump alone can also be used for drug delivery purpose specially for glaucoma treatment.

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Thank You