Sensitivity Optimization of Microfluidic Capacitance Sensor using COMSOL Multiphysics®

S. Satti, M.Shojaei Baghini
Indian Institute of Technology
Bombay, Mumbai, Maharashtra, India

1. Introduction

There is an increasing demand for affordable and accessible healthcare around the world in light of the increasing population. Diagnostics is a major aspect of healthcare, wherein certain measurements on body parameters need to be performed. Recent innovations in miniature chips that are cheap, low power and highly sensitive bring us closer to this goal. These lab on chips have many different components, which can be broadly divided into sample preparation, sample mixing/reaction and output characterization. To retain all the aforementioned benefits it is of utmost importance that all these components or sub systems are on a single chip.

In this paper, we analyze and optimize a capacitance sensor for microfluidic channels. Many of the reactions in such chips happen in the fluid phase in miniature channels fabricated by a lithography process. Putting a configuration of metal electrodes around the channel containing the fluid, one can measure the capacitance and hence the dielectric constant of the fluid [1]. Sensitivity of this measurement is however highly dependent on the geometry of the device, which we seek to optimize through simulations in COMSOL. Moreover to change a geometric parameter in an actual device, one needs to go through the whole sequence of fabrication steps, which takes multiple days and requires a clean room. Hence COMSOL studies offer a clear benefit in terms of flexibility as well as exploration of the model.

2. Methods

We first used COMSOL to analyze the dependence of the sensitivity metric on the various geometrical parameters in two dimensions. This gave us some insights into the optimal placement of electrodes around the channel. Then, we simulated an accurate model of a device fabricated in the CEN, IIT-Bombay to compare the results from simulated device and real device. Later, we studied the effect of using interdigiated electrodes instead of straight ones, by modelling in 3D.

2.1 Geometry

Fabrication of the device is constrained by the lithography process. For example, planar electrodes and rectangular cross section channels are easy to fabricate, while circular channels are difficult. We have used the standard microchannel fabrication method to finalize the geometry of the device.

Figure 1 shows the cross section view of the device consisting of planar electrodes on a glass surface, separated by a small distance. An insulating layer of PDMS separates the substrate from the rectangular microchannel which is made of the same material. The fluid flows through the rectangular channel, as shown in Fig. 1. We have enumerated the geometrical parameters that could be optimized as follows.

1. Aspect ratio (r), scaling ratio of channel width and channel height

2. Channel height (d/r)
3. Channel width (w*r)
4. Electrode separation (s)
5. Electrode thickness (e)
5. Thickness of the insulating layer (t)

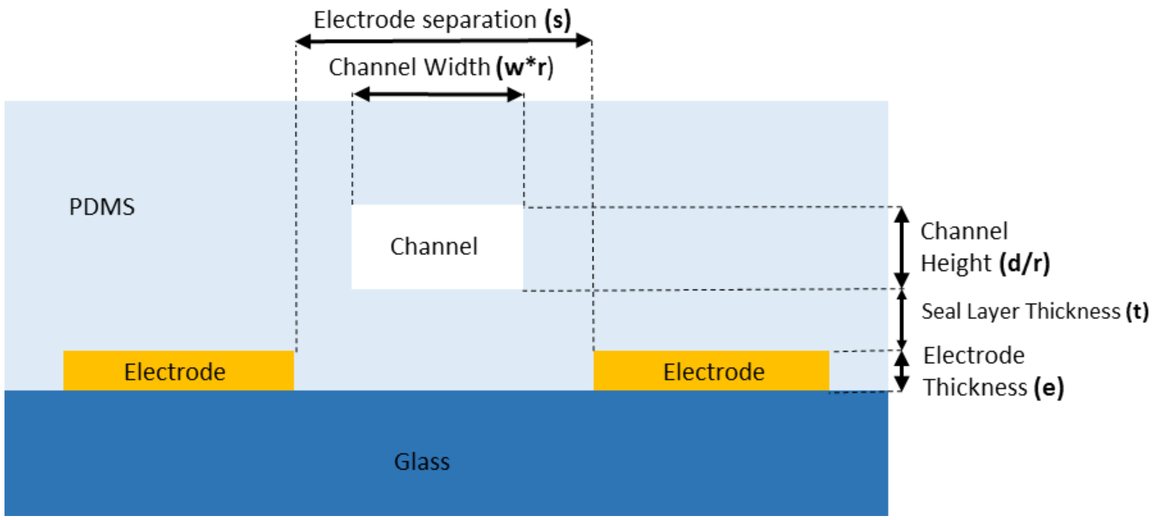


Figure 1 Two dimensional cross section of the capacitive sensor with channel

Assuming that we would like to work with as little volume of fluid as possible (and hence the minimum possible cross section), the problem is reduced to moving the rectangle and changing its aspect ratio in space, trying to maximize the sensitivity.

Further simulations were performed on 3 dimensional models to get the accurate geometry and capacitance values. Simple interdigiated electrodes were replaced in the 3D model.

2.2 Materials

Standard materials were chosen for the study, as the physics of the sensor mainly relies on the permittivity of the material. Practical dielectric constant of 2.5 for PDMS was taken from literature [2]. We assumed that quartz glass with minimal impurities is used as the substrate.

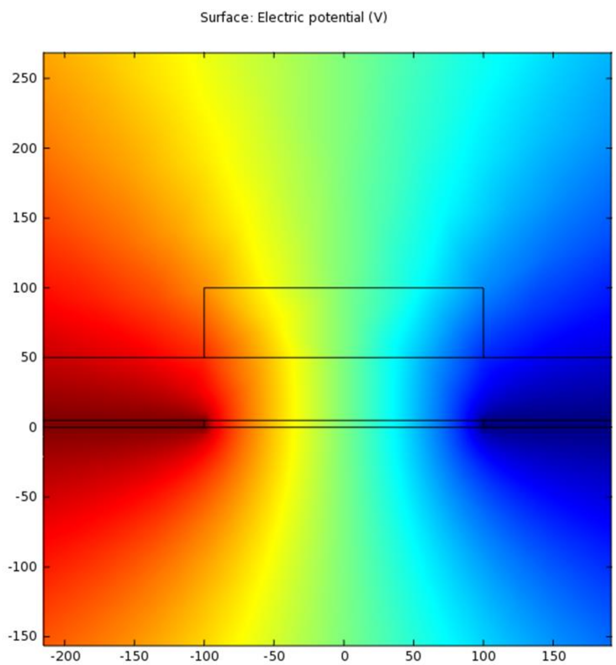
2.3 Studies performed

The simulations were performed using the AC/DC module in COMSOL. All studies were stationary. The geometrical parameters were varied during study using the parameter sweep feature for each variable. A global evaluation of capacitance (es.C11, a parameter from the COMSOL library) was done, and the result stored in tables for later plotting.

3. Results and discussion

3.1 Varying Dielectric Constant

The dielectric constant of the fluid was varied for a fixed geometry and 2D graphs in color were generated to indicate the distribution of electric potential in the space. To get a better idea of the field distribution the electric field lines were also generated. Two such images for a configuration at a fluid dielectric constant of 50 are shown in Figure 2. Note that the field lines are perpendicular to voltage contours and pass through both the channel as well as the PDMS.



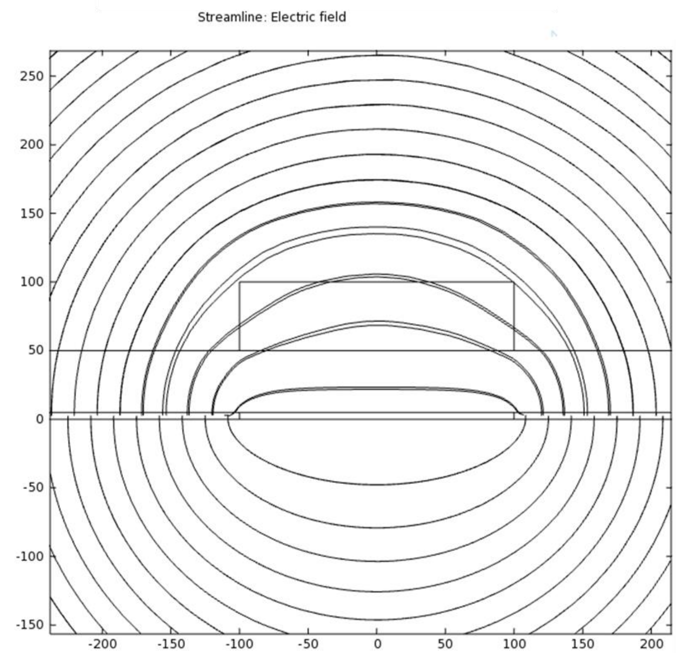


Figure 2 Left: Voltage potential graph. Red and blue regions correspond to 1V and 0V, respectively. Right: Electric field lines.

The capacitance arising in each case was plotted as a function of the dielectric constant. Figure 3 shows that this capacitance is a nonlinear function of the dielectric constant with a decreasing slope, implying that the sensitivity reduces as dielectric constant increases. This effect can be better understood by approximating the complex geometry using a lumped capacitance model as shown in Figure 4. The lumped capacitor model also helps us to correlate the later results seen.

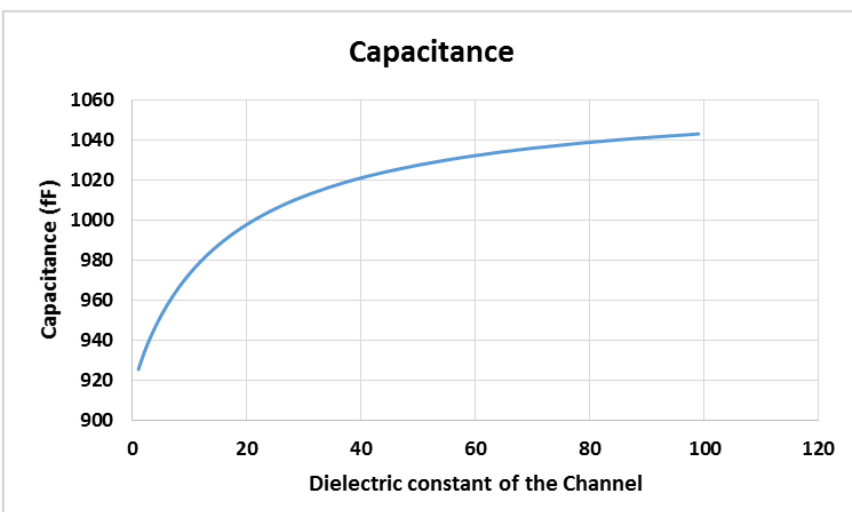


Figure 3 Capacitance as a function of the varying dielectric fluid in the channel

3.2 Definition of sensitivity

For a given configuration, we define the sensitivity metric as the percentage change in capacitance between air being present in the channel and a liquid of dielectric 50 being present, Equation 1. A configuration with a greater number is thus more sensitive.

$$Sensitivity = \left(\frac{Capacitance_{dielectric\ of\ 50}}{Capacitance_{air}} - 1\right) \times 100$$

Equation 1

3.3 Straight Electrodes

The first results were obtained by sweeping a geometrical parameter in the simple electrode configuration keeping the other ones constant. Figure 5 has all these results in a graphical format. Increasing the thickness of the insulating layer monotonically decreased the sensitivity of the configuration. This can be explained by observing that as distance from the electrodes increases, the series capacitances, C_{pdms} begin to substantially add up to $C_{channel}$, reducing its influence on the overall capacitance.

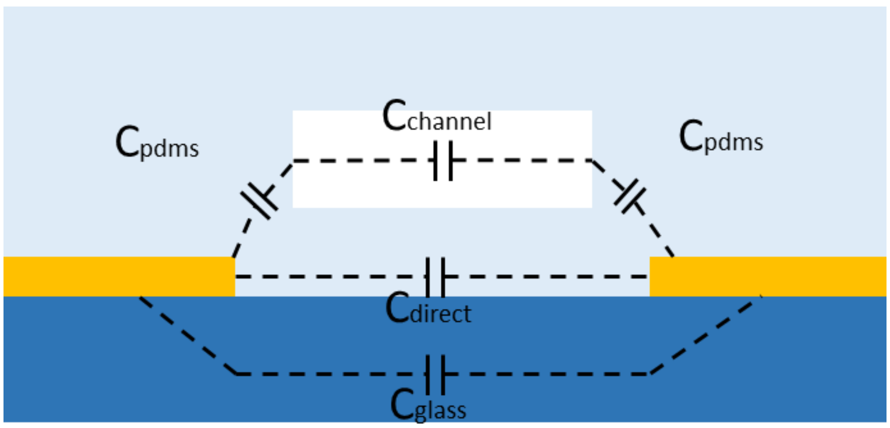


Figure 4 Lumped capacitance model

As shown in the figure increasing the channel width increases the sensitivity as majority of the field lines pass through the channel region. However, varying the electrode separation has a non monotonic effect on the sensitivity. At very small or very high separations the sensitivity is low and hence there exists a particular aspect ratio corresponding to the maximum sensitivity. This can be explained qualitatively by the lumped capacitor model. At very small separations all of the field lines are between the electrodes, and there is very little fringing field. As the distance between the electrodes increases the field passes through the channel due to fringing. However at very high separations C_{pdms} dominates $C_{channel}$ and sensitivity reduces.

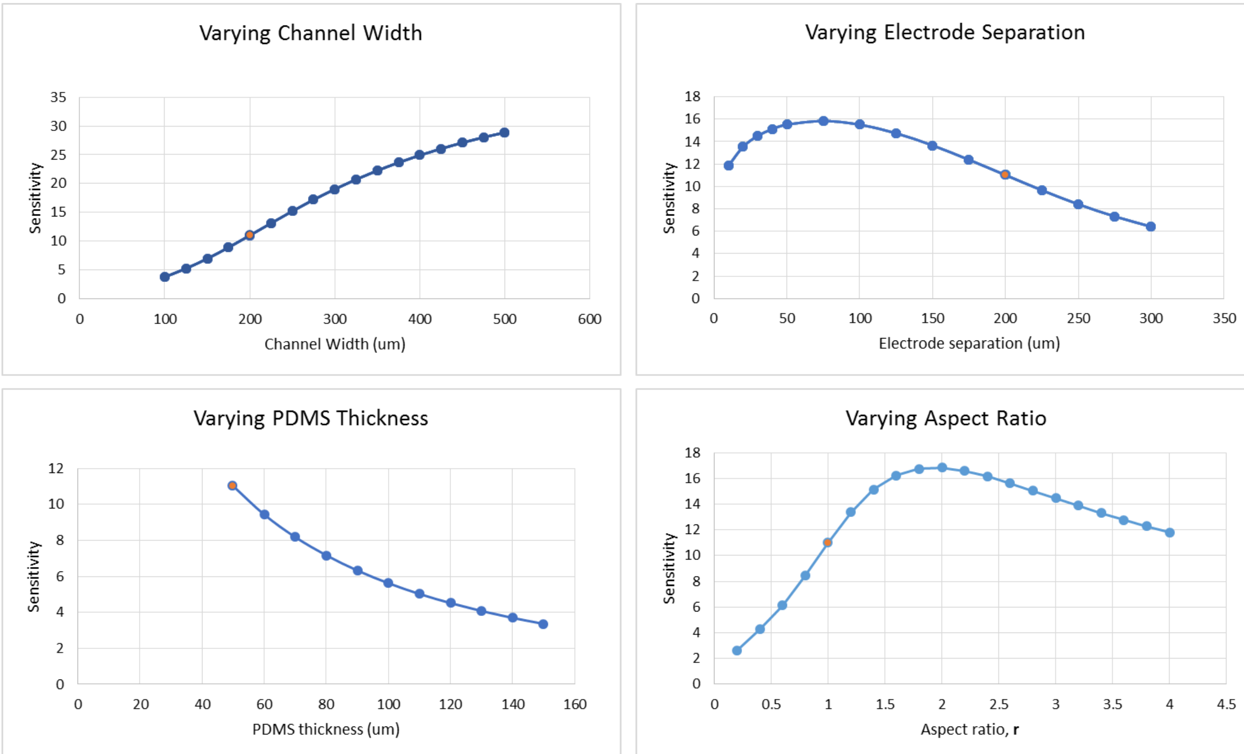


Figure 5 various graphs plotted on solely varying specified geometric parameters. The base case is marked as an orange point in all the graphs.

The electrode separation at which sensitivity is maximized is found to depend on the thickness of the PDMS insulating layer too. At thinner layers this peak occures at smaller separations.

By holding the electrode separation and insulating layer thickness constant, the aspect ratio of the channel was varied, holding the area of the channel constant. The constraint of using small volume is a realistic consideration in view of extremely small amount of output in some chemical reactions. A maximum was attained at an intermediate value of aspect ratio.

3.4 Interdigiated Electrodes

3D simulations have been performed while replacing straight electrodes with interdigiated ones. Similar studies were performed in the two dimensional case. A Voltage (parameterized by color) plot in 3D is shown in figure 6. The geometry of these electrodes is characterized by the following, parameters as denoted in figure 7.

1. Fin Length
2. Fin Width
3. Electrode separation
4. Fin Separation

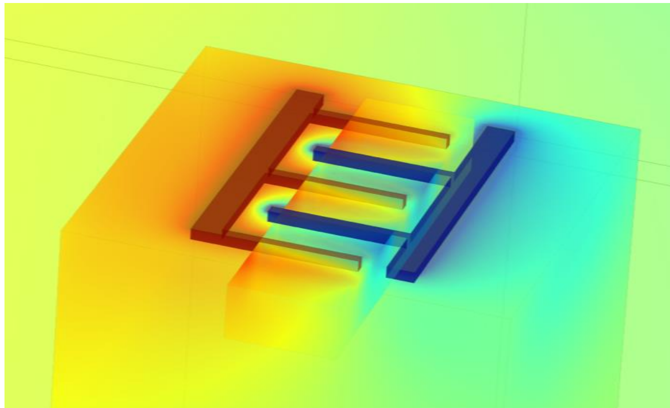


Figure 6 3D voltage graph of an Interdigiated electrode configuration

Another way of looking at interdigiated electrodes is to consider the electrodes straight, and the channel twisted. Thus, the effective length of the channel increases for the same electrode length and the sensitivity increases.

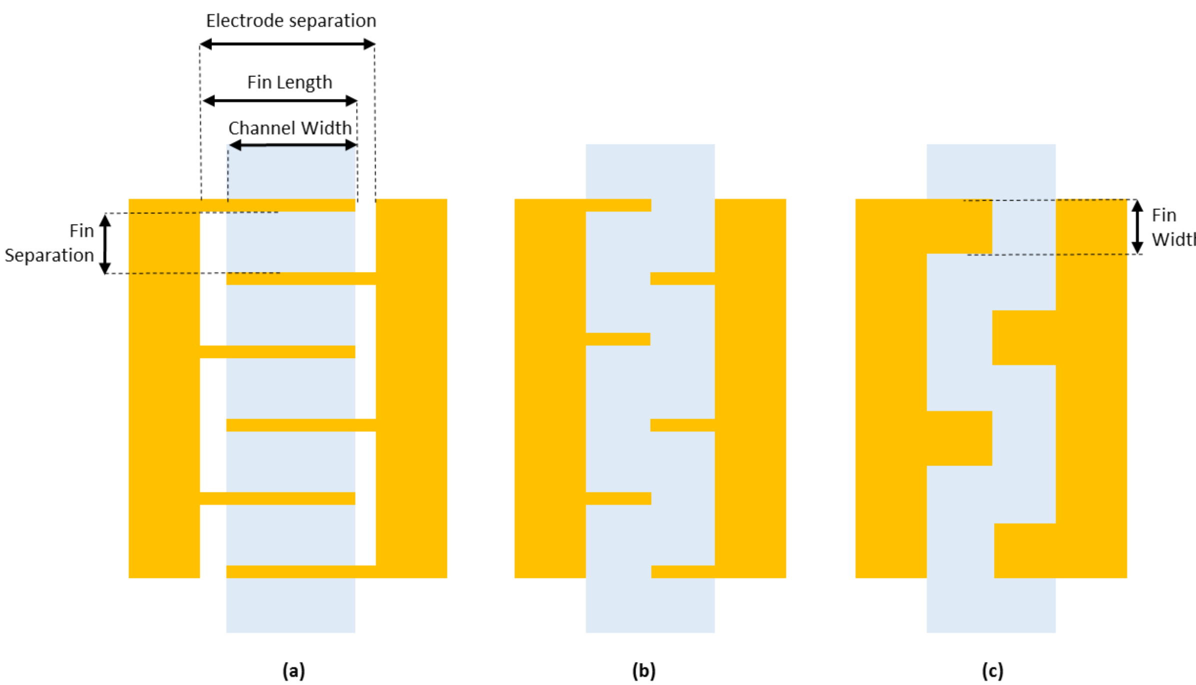


Figure 7 various configurations of Interdigiated Electrodes

In figure 7, starting off with configuration (a), it was found that decreasing the size of the fins, as in configuration (b), increases sensitivity from 17% to 30% as more field lines pass through the channel. Making the fins thicker, further increases sensitivity to 32%, shown in configuration (c).

Conclusions

In this paper, we have shown various optimized configurations for electrodes around a microfluidic channel, both straight and interdigiated. The electrode separation must be 2.6 times smaller compared to the channel width. Also, the Channel width must be 4 times smaller than the channel height for a given volume. We note that interdigitiation improves the sensitivity, though it comes at the cost of increased mask complexity. Also, an optimized aspect ratio of the channel for a given electrode separation and PDMS height has been calculated.

Acknowledgements

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Bibliography

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