Excerpt from the Proceedings of the 2011 COMSOL Conference in Bangalore

Design of High Sensitivity and Fast Response MEMS Capacitive Humidity Sensor using COMSOL Multiphysics®

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Abstract: This paper presents the simulated model of capacitive humidity sensor, which predicts transient response for various humidity ranges applicable for breath analysis. The structure consists of parallel plate electrode with dielectric polymer film, simulated using COMSOL Multiphysics® based on molecular diffusion. This finite element simulation is carried out for various upper electrode structures with different type of polymer for better sensitivity and response time. It is found that structure with smaller upper electrodes width (2/2 structure) provides short response time (2.5 µsecs) and structure with electrode width twice of the gap (40/20 structure) provides high sensitivity (29.96 nF /%RH).

Keywords: MEMS, Capacitive Humidity sensor, COMSOL.

1. Introduction

A sensor is a device that converts one form of energy into another and provides the user with a usable energy output in response to a specific measurable input. For example thermister, a temperature sensor converts heat to resistance. If resistance could be read out, the temperature which has a relation to the resistance is found. The important considerations of modern sensors are low cost, small size, low power and high precision.

Measuring humidity, the presence of moisture in air, plays an important role in a wide and various range of practical measurement situations. Relative humidity refers to the ratio of the moisture content of air to the saturation moisture level at the same temperature which is often needed for many applications. Humidity sensors which measures humidity range 0% to 100% are widely used in Electronic chip manufacturing industry, Air conditioners, Artificial respiration units[1]. Humidity sensor is of three types, namely resistive, capacitive and displacement.

Modern sensor requirements can be fulfilled by Micro Electro Mechanical Systems (MEMS) technology, which was coined in the United States in the late 1980s. MEMS are made up of components between 1 to 100 micrometres in size (i.e. 0.001 to 0.1 mm) and MEMS devices generally range in size from 20 micrometres (20 millionths of a metre) to a millimetre. MEMS with its batch fabrication techniques enables components and devices to be manufactured with increased performance and reliability, combined with the obvious advantages of reduced physical size, volume, weight and cost[2]. MEMS based sensors are built to sense the existence and the intensity of certain physical, chemical, or biological quantities, such as pressure, force, humidity, light, temperature, nuclear radiation, magnetic flux, and chemical composition [3],[4].

The MEMS based capacitive humidity sensors due to its advantages over the others are modeled earlier using the softwares like Coventorware® [5], MATLAB [6] and ANSYS 7.0[7]. The structure was subjected to various analysis using modules in these Coventorware®, MATLAB and ANYSYS. Various regions of operation of the sensor were notified. The resulting sensor showed promising response in these regions. The linearity of the sensor is between 10-40% RH [4] and 80% of value reached in 1 sec ANSYS 7.0[7].

In this paper we focus on capacitive humidity sensor based on MEMS simulated using COMSOL Multiphysics®, which is an emerging engineering software environment used for modeling and simulation of any physical based structure.

This paper consists of five sections. Section 1gives the introduction, section 2 deals about types and parameters of humidity sensor, section 3 deals with COMSOL Multiphysics® software, section 4 elaborates MEMS based sensors, section 5 deals with Modeling of Humidity Sensor using COMSOL Multiphysics®, section 6 deals with optimization of the humidity sensor for better response time and sensitivity and section 7 elaborates the conclusion.

2. Humidity Sensors

Humidity sensors are used to senses and measure the Relative Humidity (RH) for various applications. Different humidity sensors exist for miscellaneous applications. The requirements that humidity sensors must meet in order to satisfy a wide range of applications are good sentivity over a wide range, short response time, reproducibility, small hysteresis, good durability and long life, resistance against contaminant and low cost [8].

Types of humidity sensors are resistive humidity sensor, displacement humidity sensor and capacitive humidity sensor.

Resistive humidity sensors mainly use ceramics and polymers as humidity sensitive materials, including TiO_2, $LiZnVO_4$, MnWO4,C_2O and Al_2O_3 [9]. In general, ceramics have good chemical stability, high mechanical strength and resistance to high temperature [9]. Due to the extremely high resistance at RH values of less than 20%, this sensor is generally better suited to the higher RH ranges.

Perhaps the oldest type of RH sensor still in common use is the displacement sensor. These devices use a strain gauge or other mechanism to measure expansion or contraction of a material in proportion to changes in relative humidity. The advantages of this type of sensor are that it is inexpensive to manufacture and highly immune to contamination. Disadvantages are a tendency to drift over time and hysteresis effects are significant.

Capacitive technique is the most widely used technique for humidity sensor, where the RH change is detected by the humidity induced dielectric constant change of thin films. The most widely used materials as humidity-sensitive dielectrics are polymer films, as they provide high sensitivity, linear response, low response time and low power consumption [10].

Table 1: Comparison between three types of humidity sensor

Parameters	**Capacitive**	**Resistive**	**Displacement**
RH range	0-100% possible	Only at higher RH range	Fair below 25%
Sensitivity	High even at low RH	Moderate at low RH	Low at low RH
Temperature range	Upto 200˚c	-40˚c to 100˚c	10˚c to 100˚c
Response time	Fast	Moderate	Moderate
Resistive to contamination	High due to film coating	Low	Low
Accuracy	±2%	±2%	±4%
Hysteresis	Minimum	Comparatively more	more

Capacitive humidity sensors are suited for high temperature environments because the temperature coefficient is low and the polymer dielectric can withstand high temperature [10].

MEMS based capacitive humidity sensors are interesting because their small physical size allows them to be less intrusive. MEMS sensors have the advantage of being sensitive and accurate with minimal amount of required sample substance. These sensors are suitable for applications requiring a high degree of sensitivity at low humidity levels, where they will provide a relatively fast response [10].

3. COMSOL®: A simulation tool for MEMS

COMSOL Multiphysics® is a software package which is widely used for modeling. This software not only helps to define the geometry, meshing, defining physics but also helps to visualize the end results.

The mathematical structure in COMSOL Multiphysics® is a system of partial differential equations. There are three ways of describing PDEs through the following mathematical application modes:

1. Coefficient form, Suitable for linear or nearly linear models
2. General form, suitable for non-linear models
3. Weak form, for models with PDEs on boundaries, edges or points, or models using terms with mixed space and time derivatives

Using these applications modes, you can perform various types of analysis including:

1. Stationary and time-dependent analysis
2. Linear and non-linear analysis
3. Eigen frequency and modal analysis

When solving the PDEs, COMSOL Multiphysics® uses the proven Finite Element Method (FEM).

MEMS module is a part of the COMSOL Multiphysics® software. This module helps in designing any type of MEMS device and do further analysis. The complete details can be taken from [11].

4. MEMS based humidity sensor

The sensor is a parallel plate capacitor with the sensitive layer. Sensitive layer is sandwich in between the electrodes. The lower electrode is a full plate, the upper electrode is a grid which allows the vapour to penetrate into the sensitive layer [12],[13].

When the water vapour blows over the surface, it is adsorbed on the surface. Then the adsorbed molecule diffuse in the polymer inducing a variation of its permittivity.

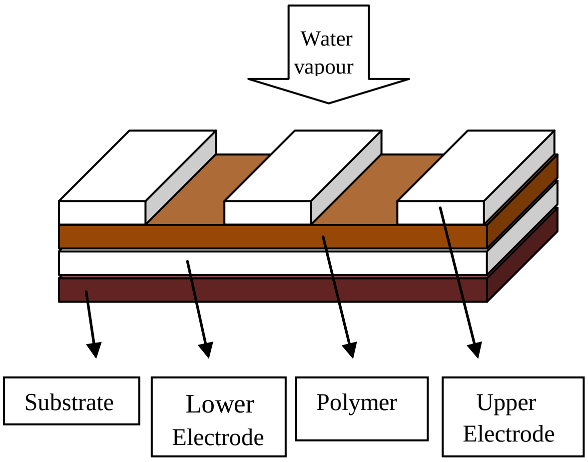

Figure 1. Structure of sensor

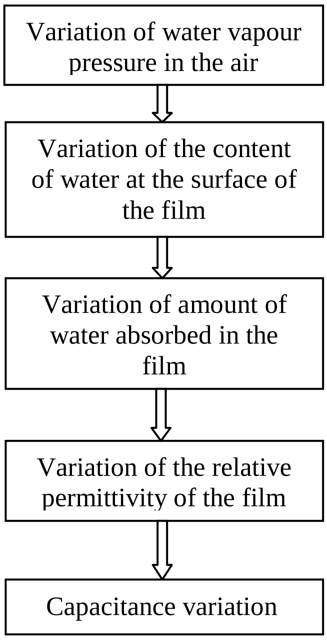

Figure 2. Working principle

The variation in permittivity causes variation in capacitance.

$$C = \frac{\varepsilon_0 \varepsilon_r A}{T} \qquad (1)$$

ΔP_i is the variation of water vapour partial pressure in the air. ΔC_{surf} is the variation of the concentration of water at the surface of the film, resulting from $\Delta P_{i.}$ ΔQ is the variation of the amount of water adsorbed in the film (expressed in mol). $\Delta \varepsilon_r$ is the variation of the relative permittivity of the film, and $\Delta \Gamma$ is the capacitance variation (in pF) [14].

4.1. Theoretical modeling

Relative humidity is the ratio of actual vapour pressure of the air at any temperature to the maximum of saturation vapour pressure at the same temperature. Relative humidity in percent is defined as

$$RH\% = \frac{P_a}{P_s} \qquad (2)$$

P_a is the absolute vapour pressure; P_s is the saturation vapour pressure. P_s depends on temperature. By determining P_s at particular temperature, we can derive P_a for various humidity [15].

4.2. Measuring saturation vapour pressure

The maximum partial pressure (saturation pressure) of water vapour in air varies with temperature of the air and water vapour mixture. A variety of empirical formulas exist for this quantity; the most used reference formula is the Goff-Gratch equation for the SVP over liquid water.

$$\log_{10}(p) = -7.90298\left(\frac{373.16}{T} - 1\right) + 5.02808\log_{10}\frac{373.16}{T} - 1.3816 \times 10^{-7}\left(10^{11.344\left(1-\frac{T}{373.16}\right)} - 1\right) + 8.1328 \times 10^{-3}\left(10^{-3.49149\left(\frac{373.16}{T}-1\right)} - 1\right) + \log_{10} 1013.246 \qquad (3)$$

where T, temperature of the moist air, is given in units of Kelvin and p is given in units of millibars(hectopascals).

4.3.Converting P_a to water vapour concentration

P_a can be converted to concentration by using the formula

$$\frac{kg}{m^3} = 0.02166 * \frac{P_a}{(t+273.16)} \qquad (4)$$

derived from $PV=nRT$. To get in mols/m^3 divide the equation by 18.02 which is the molecular weight of water vapour[16].

Table 2: Comparison of absolute pressure and vapour condensation

RH%	Absolute pressure millibar	Vapour concentration Mols/m^3
10	6.27	0.2429
20	12.55	0.4863
30	18.83	0.7297
40	25.11	0.9731
50	31.39	1.2164
60	37.67	1.4598
70	43.95	1.7032
80	50.23	1.9466
90	56.19	2.1899
100	62.79	2.4333

4.4. Diffusion modeling

Diffusion of water in the film is described using Fick's law.

$$\frac{\partial c}{\partial t} = \frac{D\partial^2 c}{\partial x^2} \qquad (4)$$

Where c is the concentration (mols/m^3), t is the time(sec), D is the diffusion coefficient, x is the position. For more than one dimension

$$\frac{\partial c}{\partial t} = D\delta^2 c \qquad (5)$$

$$\frac{\partial c(x,y,z,t)}{\partial t} = \frac{D_x \partial^2 c(x,y,z,t)}{\partial x^2} + \frac{D_y \partial^2 c(x,y,z,t)}{\partial y^2} + \frac{D_z \partial^2 c(x,y,z,t)}{\partial z^2} \qquad (6)$$

Fick's law predicts how diffusion causes the concentration field to change with time. It mainly depends upon diffusion coefficient [6],[17].

4.5. Permittivity of sensing film

The permittivity of the sensing film should be

$$\Delta\varepsilon_r = \varepsilon_{r(RH)} - \varepsilon_{r(0)} \qquad (7)$$

Where $\Delta\varepsilon_r$ is the variation in permittivity, $\varepsilon_{r(RH)}$ is the permittivity after absorption, $\varepsilon_{r(0)}$ is the permittivity before absorption. $\varepsilon_{r(RH)}$ can be calculated from Clausius-Mossotti's equation.

$$\frac{\Delta Q \alpha A}{3V\varepsilon_0} = \left(\frac{\varepsilon_{r(RH)}-1}{\varepsilon_{r(RH)}+2}\right) - \left(\frac{\varepsilon_{r(0)}-1}{\varepsilon_{r(0)}+2}\right) \qquad (8)$$

Where ε_0 is the permittivity in free space, A is the Avogadro's number. ΔQ derived from ΔC by integrating over the volume [18].

4.6. Capacitance modeling

For an unequal parallel electrode capacitor, the capacitance variation of sensor should be

$$\Delta\Gamma = \Delta\varepsilon_r \varepsilon_0 A/th \qquad (9)$$

Where $\Delta\Gamma$ is the capacitance variation, A is the area of the upper electrode, $\Delta\varepsilon_r$ is the variation permittivity, ε_0 is the permittivity in free space, th is the thickness of the film.

4.7. Geometrical modeling

Parallel plates consist of upper electrode and lower electrode, upper electrode in the form of grid with a sensitive layer in between which act as a dielectric.

Electrode plates width is 20µm, spacing between plates is 20µm, thickness of plates is 1µm, thin film thickness is 1.5µm (DVS-BCB) [19], [20].

5. Results and observation

5.1. Simulation of test structure

A structure was modeled in COMSOL Multiphysics®. Its accuracy was checked through finite-element simulation and experiments on structure 20/20 (width of the upper electrode 20 µm and spacing between the electrodes 20 µm) with a film thickness of 1.5 µm. The electrodes are made up of aluminium of thickness 1µm and the sensitive layer is DVS – BCB in between them. The simulation was based on the assumption that diffusion in the polymer film was quit ideal because water vapour sorption in DVS – BCB follows Henry's law, which suggests free diffusion of water molecule in film. First the structure is simulated with humidity variation from 0 to 100% to analyze transient response and sensitivity of the structure. Then the structure is modeled with different polymer sensitive layer to find the optimal sensitive layer. Finally the structure is analyzed for small humidity variation in the range of 3%. The following figure shows simulated structure in three dimensions.

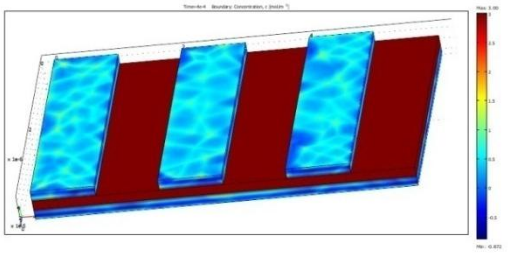

Figure 3. Structure in 3D

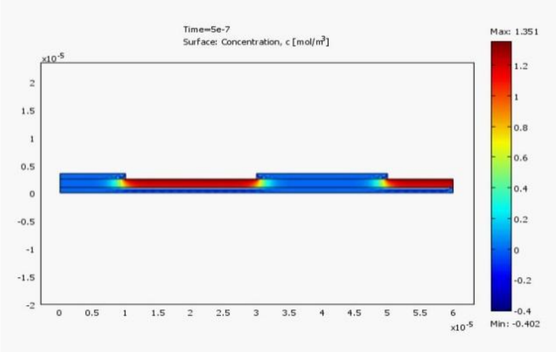

Figure 4. Simulation at time t=0.5µs

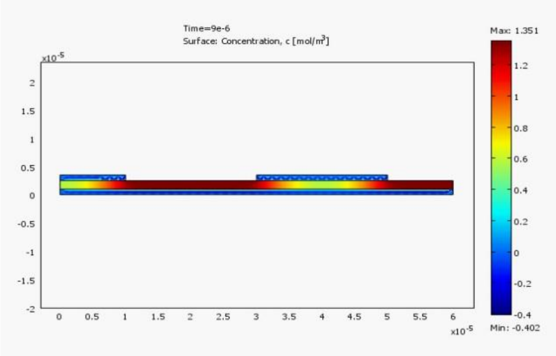

Figure 5. Simulation at time t=9µs

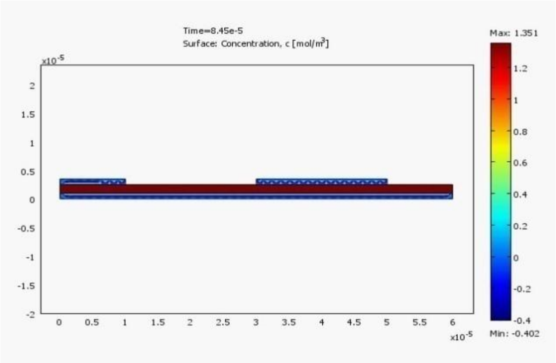

Figure 6. Simulation at time t=45µs

5.1.1 Capacitance variation with time

To check the linearity of structure the test structure is simulated with humidity variation from 0 to 100 % at 26°C, the sensor shows linear response for the variation in humidity as shown in the graph.

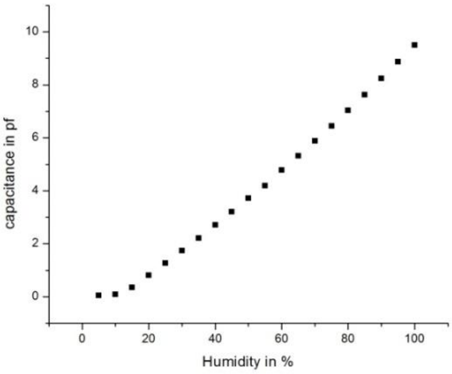

Figure 7. Capacitance Vs Time

5.1.2 Absorption and desorption

The Fig 8 show the variation of capacitance with time the curve shows a transient response and response time is of the order of 0.50 milisecs.

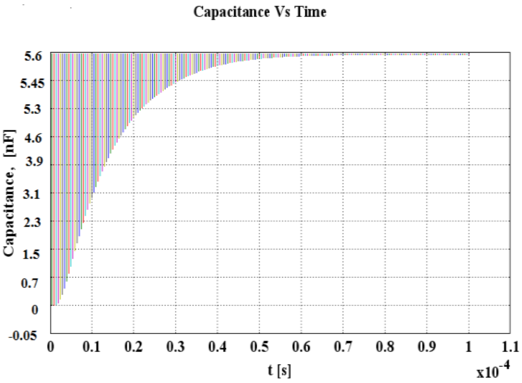

Figure 8. Capacitance variation with time due to absorption

Fig 9 shows the desorption of water as it is decreased from 100%RH to 0%RH. The desorption time was found to be 0.65 ms

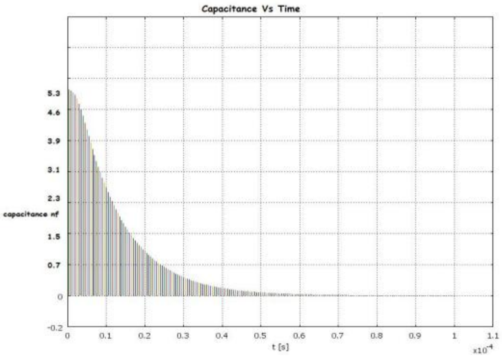

Figure 9. Capacitance variation with time due to desorption

5.1.3 Structure tested with various polymer films

According to sensing mechanisms, polymeric humidity sensors are divided into two fundamental categories: resistive-type and capacitive-type. The former responds to moisture variation by changing its conductivity while the latter responds to water vapour by varying its dielectric constant. Because of the excellent linear response, capacitive sensors are far more attractive than resistive sensors the change of the dielectric constant of the hygroscopic polymer is linearly proportional to the amount of water absorbed. The following table gives time response comparison of different polymers used in test structure.

Table 3: Comparison of response time and diffusivity of test structure with different polymers.

Polymers	**Diffusivity (µm^2/s)**	**Concentration (mols)**	**Time (sec)**
DVS-BCB	4.5e^{-6}	2.4374e^{-15}	0.003
PDMAA	8.7e^{-10}	1.7340e^{-15}	0.03
PDMAEMA	10e^{-10}	1.7783 e^{-15}	0.03
PAA	3.5 e^{-10}	1.5023 e^{-15}	0.03
POLYVINYL acetate	11 e^{-10}	1.8103 e^{-15}	0.03
POLYMIDE	2.81 e^{-13}	2.0850 e^{-16}	0.03

Table 3 gives that the DVS – BCB films shows good time response and high diffusivity. This polymer is one of the lower moisture polymer and highly suitable for parallel plate capacitive humidity sensor.

5.2. Optimizing for fast response time structure

Simulation based on fast response model was performed to predict the behavior of different structures in order to fabricate the most optimal of them. The transient response is reduced with increase in the sensing layer thickness, as theoretically expected. The minimum and maximum thickness of the sensing layer is often limited due to the thickness of the sensing layer that can be achieved in micro fabrication. Because the thickness of the film is a limiting factor of the response time of the sensor, hence film with 1µm thickness was chosen.

Another limiting phenomenon of the response time is diffusion under the upper electrode lines. A part of the surface of the film is directly exposed to moist air and the other part is covered by the upper electrode bars. Diffusion in the polymer film is bidimensional: in the exposed parts, water diffuses from the surface to the lower electrode quickly, and in the covered parts water diffuses on the sides under the upper electrode bars and diffusion rate quite limited.

By reducing the size of the upper electrode, the area under covered part gets reduced and hence rate of diffusion of the water vapour in the film is increased. Thus the width of the upper electrode is the limiting factor of sensor response time. Because lines of small width provide short response times, the following structures are chosen to simulate and compare to find optimal of them: 2/2 (Figure 11), 3/3 (Figure 12), 4/4 (Figure 13), and 5/5 (Figure 14). Dimensions lower than 1µm were not considered because they tackle the limits of the fabrication process.

Figure 11-14 shows 2D simulated in comsol ΔRH 3% at 26ºc

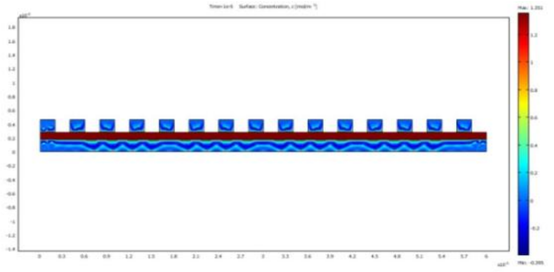

Figure 11. 2/2 Structure

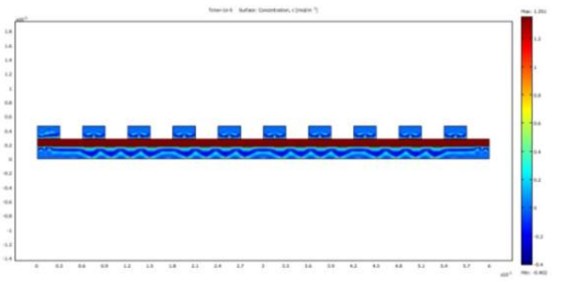

Figure 12. 3/3 Structure

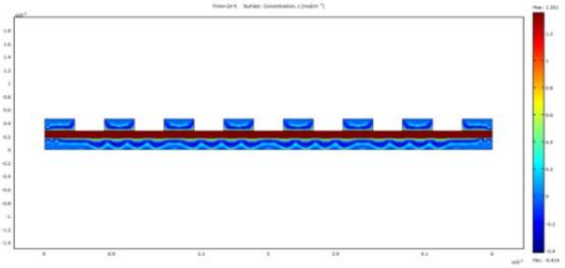

Figure 13. 4/4 Structure

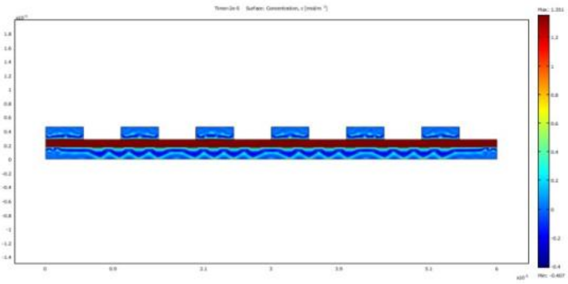

Figure 14. 5/5 Structure

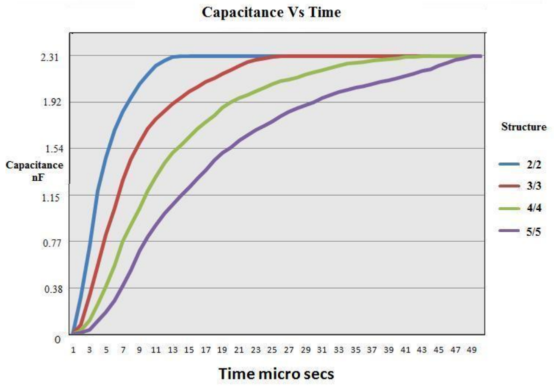

Figure15. The graph shows the response time comparison of optimized structures

Four different possible combinations of electrode width and gap are studied. In all the four designs the electrode width and electrode gap are equal as shown in Figure 14. These structures are simulated with variation in humidity of 3% at 26º c. The Figure 15 shows the capacitance versus time comparison of the designs, from the graph it is clear that the response time is faster in the case of structure with very small width and gap i.e. 2/2.

Table.4 shows the comparison of all the four designs with their response time and sensitivity, it shows that lines of small width provide short response time, but if the total surface of the upper electrode is small, the absolute capacitance of the structure is reduced.

Table 4: Comparison response time

Structure	Response time (µ secs)	Desorption time (µ secs)	Sensitivity nf/%RH
2/2	2.5	4	0.77
3/3	7	8	1.15
4/4	8.8	14	1.54
5/5	12	18	1.92

5.3. Optimizing for high sensitivity structure

As the capacitance is directly proportional to the area of the upper electrode, then reducing the size (area) of electrode will reduce the capacitance i.e. sensitivity. So it is necessary to increase the size i.e. area of the upper electrode to get higher order of sensitivity.

Influence of the electrode width and the gap on the sensitivity of the device was investigated. Three different possible combinations of electrode width and gap are modeled, as shown in table 5. In design- 1, the electrode width is half that of the electrode gap. In design-3, the electrode width and the electrode gap are equal. Design-2 has the electrode width twice that of the electrode gap. These three structures are subjected to a humidity variation of 3% at temperature 26ºc. The corresponding response time, desorption time and sensitivity are shown in table 5:

Table 5: Comparison of Sensitivity

Structure	Response time (µ secs)	Desorption time (µ secs)	Sensitivity nf/%RH
10/20	180	220	8.36
40/20	250	320	29.96
30/30	200	280	22.47

A comparison of the sensitivities of these designs is presented in the table.5. The results show that the sensitivity is highest for the case where the electrode width is twice the electrode gap, which may be because of higher capacitance due to higher electrode area. Therefore, the proposed design will have twice electrode width than the width of the gap. The results show that the sensitivity increases with increase in the electrode width.

5.4. Optimizing for sensitivity and response time

Influence of the electrode width and the gap on the sensitivity and the transient response of the device are investigated. Four different possible combinations of electrode width and gap are modeled to optimization for fast response and table 4. Shows the comparison of all the four designs with their response time and sensitivity, it shows that lines of small width provide short response time, but if the total surface of the upper electrode is small, the absolute capacitance of the structure is reduced.

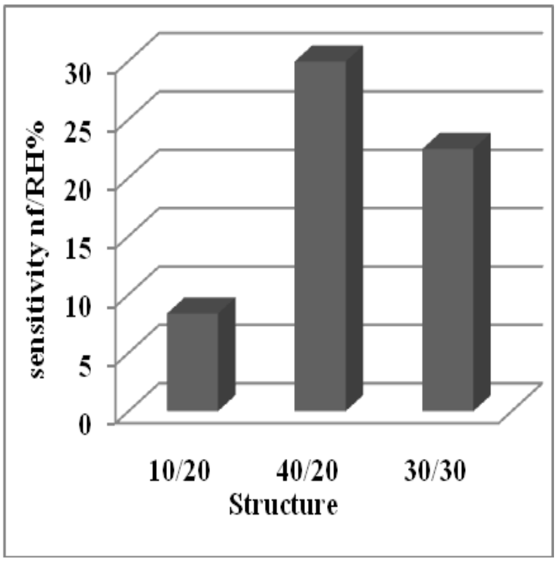

Figure 6. Comparison of sensitivity

The sensitivity and response time are inversely proportional, if the structure is optimized for faster response time then the sensitivity will be decreased and vice versa. The optimization of the structure should be made by taking into account that area of the upper electrode neither maximum nor minimum compared with the gap between the electrodes. Three models were considered for simulation with different electrode configurations (20/10, 30/15, 40/10) and compared to get optimal of them. Three models with different configurations are simulated and the results are shown table 6. The structures with unequal upper electrode configuration show good response time with good sensitivity.

Table 6: Comparison of sensitivity and response time at 26^0C ΔRH 3%

Structure	Response Time ms	Desorption Time in ms	Sensitivity nf/%RH
20/10	50	70	14.89
30/15	120	140	22.47
40/25	200	240	29.96

6. Conclusion

A simple and powerful model was designed for the simulation and optimization of capacitive humidity sensor. The model is supported by finite-element simulation using COMSOL Multiphysics®, First the simulation was carried out with a test structure of film thickness of 1.5µm and with top electrodes. The structure is optimized for faster response time by varying upper electrode, smaller the upper electrode structure faster response time. Structures with configurations 2/2, 3/3, 4/4 and 5/5 were simulated and the comparison study shows that smaller electrode structure 2/2 show faster response time. Optimization is also done for higher sensitivity which shows sensitivity is higher for the structure whose upper electrode width is twice the spacing between the electrodes.

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