International Journal of u- and e- Service, Science and Technology
Vol.8, No. 7 (2015), pp.347-356
http://dx.doi.org/10.14257/ijunesst.2015.8.7.35

Comparative Analysis between Multi-grid MEMS Structure and Inter-digital Electrodes for Moisture Measurement

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Abstract

This paper describe design of novel sensor for moisture measurement that can be used in agriculture, automotive industries. In the present scenario moisture is measured by calculating change in relative permittivity which in turn depends upon change in capacitance of polymer layer sandwiched between electrodes. In this paper a new design is presented in which IDC sensor is used instead of Grid electrodes to calculate change in capacitance. Further, Comparative analysis has been done between these two topologies; device modeling has been carried out using COMSOL Multi-physics suite with MEMS approach.

Keywords: *MEMS modelling, Humidity Sensors, Inter Digital Capacitive Sensors, Grid sensors*

1. Introduction

Moisture measurement basically refers to the quantification of the amount of water vapors present in a gas that can be a mixture like air or a pure gas like nitrogen, helium. Capacitive detection is the most commonly used technique for measurement of humidity content in sensors these days. Capacitive detection has shown great results in comparison to other sensing technologies like resistive sensor technologies due to their good linear response. A capacitor is a two terminal electrical device that stores electric energy when a voltage difference is applied across the terminals. The stored energy is proportional to the applied voltage squared and is measured by the capacitance of the device. Hence these sensing devices work on the same basic principle of measuring the change in capacitance as a response to the change in moisture content on the surface of the sensor.

There are two technologies that can be implemented to design such sensors that give us an approximation or estimation of the moisture content present around. These are either grid structure sensors or IDC. The grids like structures are now-a-days being used to measure the moisture content on any surface. These are sandwich like structures which have a sensitive layer sandwiched between the two terminals of the capacitor that is responsible for the change in dielectric constant of the layer which in turn effects the capacitance [9].

The technology that this paper proposes is the development of a MEMS sensor using an Inter digital capacitors more commonly known as IDCs. These are elements for producing a capacitor like, high pass characteristics using micro-strip lines. A comb like structure of the IDCs will be placed over a sensitive layer for the calculation of moisture content in the surroundings. IDCS are being implemented in various field operations for estimation of properties of dielectric material for dairy products, humidity and gas sensors, biosensor applications and detection of dangerous toxins in contaminated sea-food. The application of these sensors depends on both the characteristics of the chosen sensor as well as the characteristics of the MUT [10, 15]. This paper focusses on bringing

ISSN: 2005-4246 IJUNESST

out a novel sensor design for the calculation of moisture content in the surroundings and the comparative analysis of the proposed and the pre-existing technology. It also highlights the design and working of the new proposed sensor technology and how it proves more efficient in performing the same task. This task is performed efficiently using the COMSOL Multiphysics Suite.

2. Simulation and Working

2.1. Grid Sensors

Grid sensor can produce variation in capacitance of a parallel plate electrode due to variation in moisture content which in turn varies with different environmental factors. Such a MEMS technology is required to be fast in response, highly sensitive to change in any parameter and very reliable.

These sensors have a structural composition like a sandwich and contain a sensitive layer between two terminals of the capacitor. The upper terminal is an array of electrodes, each electrode about 2µm thick distanced 10µm from each other placed over the sensitive layer. The sensitive layer is kept 1.5µm thick and below it is a plate like electrode of the capacitor. These electrodes are made of Aluminum and placed over an insulating layer of SiO_2 and a substrate of silicon. Figure 1 shows the simulation of this sensor in COMSOL Multiphysics 5.0.

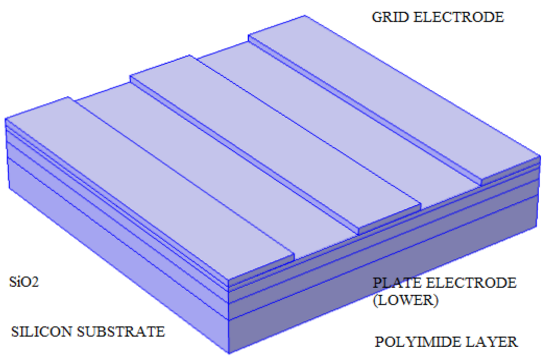

Figure 1. 3-D structure of Grid Like Sensor

This type of sensor works on the principle of response of the sensitive layer due to the analyte. The space between the grid electrodes leaves an accurate amount of space for the water to reach the sensitive layer between the electrodes. These water molecules are adsorbed into the sensitive layer changing the electrical properties of sensitized layer which is acting as the dielectric between two terminals of the capacitor. This in turn changes the *capacitance* on the surface of the sensor, hence giving the measure of moisture content [4, 18].

2.2. Proposed – IDC Sensors

The design procedure is based on the quantity that is to be measured by the sensor created. Hence after looking at various results and the requirements of the concept, moisture content was chosen. There is need of development of a sensor that can produce highly effective results in comparison to the existing technology. The proposed sensing device as you will find in the comparative analysis has proved more reliable and more effective. It has a tendency to measure even slightest of changes in the surroundings. Such a MEMS will be fast in response, highly sensitive to change [8]. There are so many converters which are used in electronics like buck converters for which we can build MEMS sensor and same analogies can be applied for signal conditioning [12].

The IDC sensor works on the same principle of operation as the parallel plate or co-axial cylinder permittivity sensor. Voltage is applied to the IDC electrodes and the impedance across the capacitor electrodes changes due to variation of frequency and capacitance. The IDC is specially designed on PCB to transform the permittivity differences in moisture content into capacitance variation. For ionic sensing materials, if the moisture content increases, the conductivity decreases and the dielectric constant increases. Hence a polymer layer is placed beneath the comb drive to increase the sensitivity of the sensor. The capacitance is related to charge on two conductive plates and the voltage across those plates. Figure 2 shows a flow chart discussing the working sequence of the sensor in COMSOL step by step.

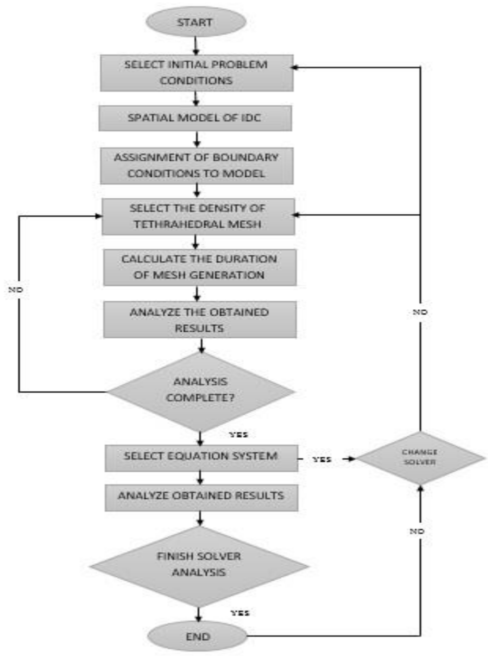

Figure 2. Working Sequence of the Proposed Sensor

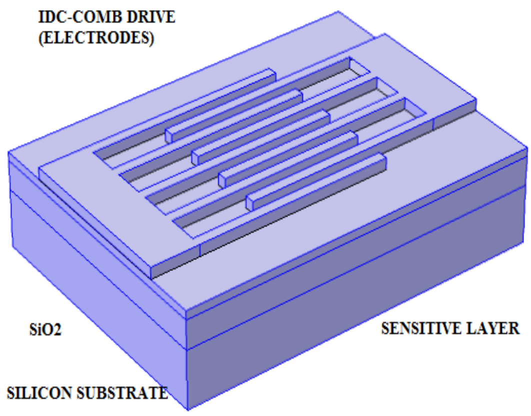

Figure 3. 3-D Structure of the Proposed Sensor

Figure 3 shows the simulation of the proposed structure of the sensor. The 2µm thick aluminum electrodes are placed in a comb like structure to develop an IDC. They are placed on 1.5µm thick sensitive layer which is placed over an insulating layer of SiO_2 which covers the substrate of silicon.

2.3. Different Materials of Sensitive Layer

The sensors that have been developed till now have used polymer based layers with capacitive sensing technologies due to their excellent response. It has been seen materials like polyimide, PVC, nylon *etc*., can all be implemented in the sensor to check for the best response. There is difference in electrical properties of each layer which effect the sensitivity if the sensor. Sensors based on these materials can perform well on room temperature due to their high sensitivity to heat. The change in dielectric constant of polymer layers is directly proportional to the amount of water adsorbed by the layer. The effect of different materials on measurement of capacitance in both designs can be found in Table 1 and Table 2 below in the comparative analysis section.

Polyimide layer is the most commonly used sensitive layer because it always gives a linear response and a detection limit below 20%RH [1, 2].

2.4. Related Work

Both the sensing devices have been added with a thin layer of water for testing purposes beneath the air domain of the sensors. Multiple studies were performed on both the sensing designs. Stationary studies have been performed on the sensors under AC/DC module in the Electrostatics setting in COMSOL Multiphysics. Multiple parameters were changed during the testing especially geometrical to get the best of results. A global evaluation of capacitance eS.C11 has been performed to notice the characteristics of both the sensors on the surface due to different sensitive layers.

The capacitance has been calculated using the following formula in both the sensors:

$$C= \frac{\varepsilon o \varepsilon r A}{D}$$

Where ε_o is the relative permittivity of air, ε_r is the relative permittivity of substance, A is the area covered by the capacitor and D is the thickness of the polyimide film [5].

The value of capacitance as calculated under same circumstances for both the sensors has been compared and included in table 3 in the next section for reference.

3. Comparative Analysis

3.1. Capacitance Calculation Due To Different Sensitive Layers in the Grid Sensors

This section highlights the change in capacitance due to variation in material of the polymer layer used as the sensitive layer in the grid like structure. It also gives values of the surface charge density that also changes as the response to properties of the material. The following Table I also contains some pre-defined quantities like density and relative permittivity of the layer [17].

Table I. Variation in Capacitance due to Change in Sensitive Layer

POLYMER	DELECTRIC PROPERTIES			CAPACITANCE
Material	*Density (kg/m^3)*	*Relative Permittivity (1)*	*Surface Charge Density Range (C/m2) (MIN:MAX) *E^{-5}*	*Value(F) *E^{-14}*
PTFE	2200	2	-0.77 : 1.06	3.58
POLY-ETHYLENE	1900	2.4	-0.81:1.21	3.76
POLYIMIDE	1300	2.8	-0.87:1.46	4.02
PVC	1760	2.9	-0.88:1.51	4.07
NYLON	1150	4	-0.96:2.06	4.51

The variation in capacitance as tabulated in the above table has been plotted in Figure 4 in a bar chart in reference to the different polymer layers.

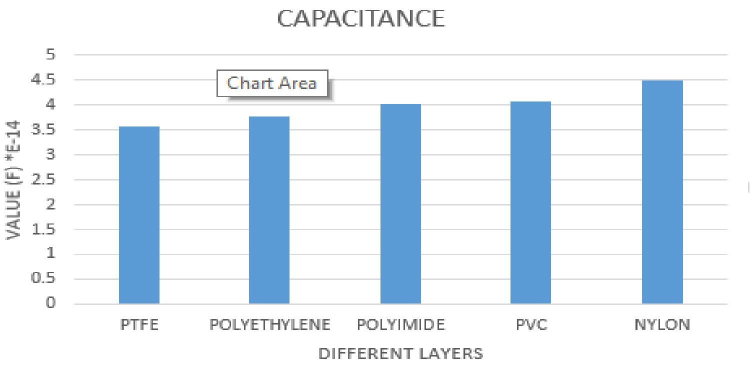

Figure 4. Bar Chart Showing the Different Values of Capacitance

The following Figures contain simulation Figures and evidence of variation in capacitance in the software.

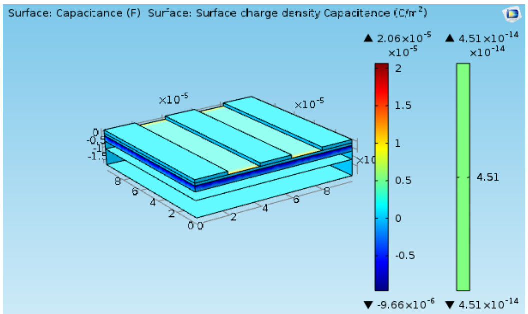

Figure 5. Picture shows the Graph of Capacitance and Surface Charge Density when the Sensitive Layer of Nylon is in Contact with a thin Water Layer Above the Grid Electrode

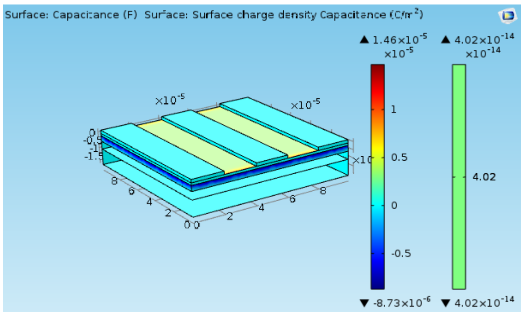

Figure 6. Picture shows the Graph of Capacitance and Surface Charge Density when the Sensitive Layer of Polyimide is in contact with a Thin WATER Layer Above the Grid Electrode

Figure 7 gives the 2-D view of the sensor in z-x axis whre you can spot the light shaded regions with different surface charge densities.

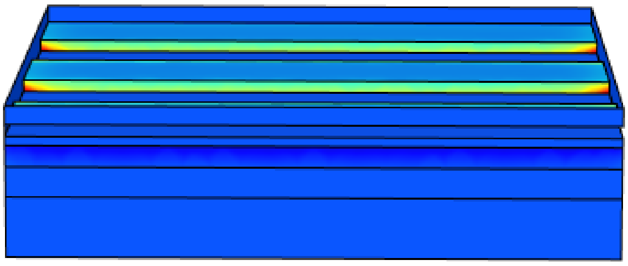

Figure 7. Picture shows the 2-D Structure in y-z Axis Showing Difference in Surface Charge Density and Capacitance at Different Points

3.2. Capacitance Calculation Due To Different Sensitive Layers in the Proposed Sensor

This section of the paper gives the values calculated for the capacitance change due to different moisture content in the proposed sensor under the same conditions as the existing grid sensors [14, 19] It highlights a more effective change of capacitance on change of parameters. Table II gives all the calculated values during the simulation of this sensor. Refer to Figure 8 for a graphical representation of the change in capacitance as tabulated below.

Table II. Variation in Capacitance Due to Change in Sensitive Layer in the IDC Based Sensor

POLYMER	DELECTRIC PROPERTIES			CAPACITANCE
Material	*Relative Permittivity (1)*	*Diffusivity ($\mu m^2/s$)*	*Surface Charge Density Range (C/m2) (MIN:MAX) *E^{-5}*	*Value(F) *E^{-14}*
PTFE	2	0124	-4.58:4.53	2.87
POLY-ETHYLENE	2.4	0.144	-4.58:4.54	2.87
POLYIMIDE	2.8	0096	-4.6:4.58	2.94
PVC	2.9	0.08	-4.58:4.54	2.88
NYLON	4	0.089-0.17	-4.59:4.55	2.89

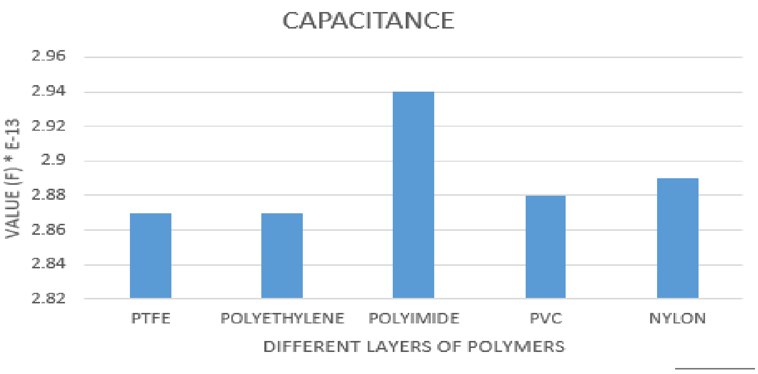

Figure 8. Bar Chart Showing the Different Values of Capacitance

The following Figures 9 and 10 will show the simulation for the proposed design of the sensor under the same physical conditions as tested for gird sensor to show variation in both.

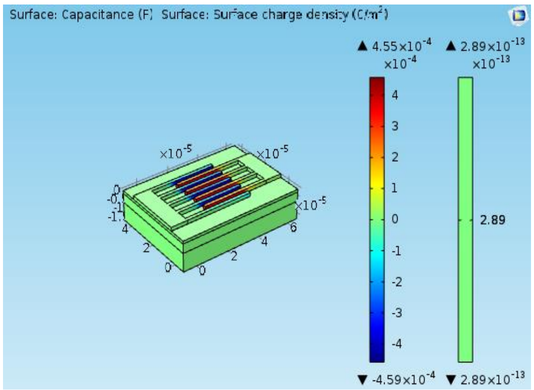

Figure 9. Picture shows the Graph of Capacitance and Surface Charge Density when the Sensitive Layer of Nylon is in Contact with a Thin Water Layer Above the Comb Drive

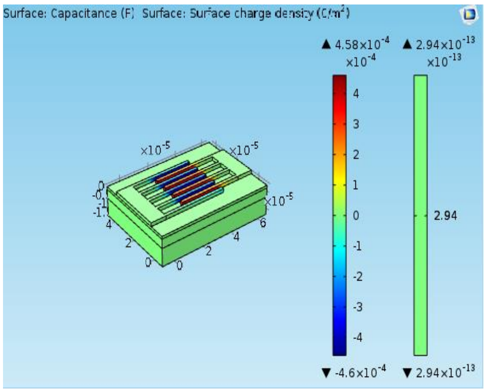

Fig 10. Picture shows the graph of Capacitance and Surface Charge Density when the Sensitive Layer of Polyimide is in Contact with a Thin Water Layer Above the Comb Drive

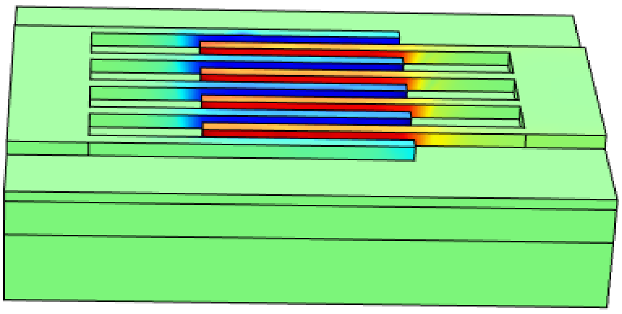

Figure 11. Picture shows the 2-D Structure in y-z axis Showing Difference in Surface Charge Density and Capacitance at Different Points

Figure 11 as shows above is the 2-D image of the sensor proposed by the research.

3.3 Comparison Table

This section highlights the difference in calculation and estimation of moisture content due to different design specification of the two talked about sensors in the paper above. Both the sensor designs have been compared in similar physical conditions in the software to show best results for analysis. You can find various capacitance values compared and analyzed in the Table III and graph in Figure 12 below.

Table III. Variation in Capacitance due to Change in Sensitive Layer in the IDC Based Sensor

POLYMER	DIELECTRIC PROPERTIES		
Material	***Relative Permittivity (1)***	***CAPACITANCE 1 (F) *E^{-14}***	***CAPACITANCE 2 (F) *E^{-13}***
TFE	2	3.58	2.87
POLY-ETHYLENE	2.4	3.76	2.87
POLYIMIDE	2.8	4.02	2.94
PVC	2.9	4.07	2.88
NYLON	4	4.51	2.89

a. Capacitance 1 is for grid sensor
b. Capacitance 2 is for the proposed new design sensor

Figure 11 below shows a comparative scattered line chart where Capacitance 1 is the capacitance from the grid sensor while capacitances 2 are the values from the new proposed design.

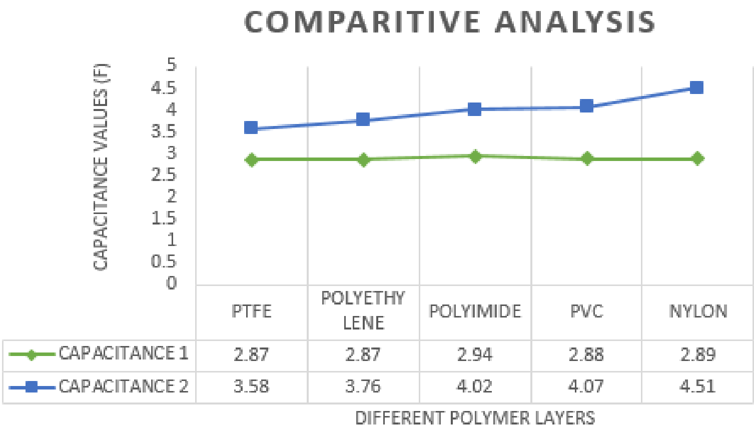

Figure 12. Comparative Analysis of Both the Sensors for Variation in Capacitance

4. Conclusion

This paper represents comparative analysis between GRID electrodes and IDC used for MEMS Moisture sensor. Various Microelectronic layers have been used for measuring change in capacitance due to relative motion between two combs in IDC. This is concluded from comparison tables that IDC gives more selective capacitance measurement as compare to GRID electrodes. Also, Solution time is less for IDC as compared to grid electrodes which are a good advantage in microelectronic and MEMS industry [7, 16].

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