DESIGN OF HIGH SENSITIVITY AND FAST RESPONSE MEMS CAPACITIVE HUMIDITY SENSOR

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ABSTRACT

This paper presents a model which predicts the temporal response of capacitive humidity sensors made of parallel electrodes and a polymer sensitive coating. This model is used for the simulation of the response of the sensor subjected to specific conditions. The model includes electrostatic and molecular diffusion calculation. As an application example, the model is used to simulate the response of several humidity sensor structures exposed to the conditions of a medical application related to breath analysis. The model may also be helpful to predict the effects of fabrication process uncertainties. Because the model used to describe water diffusion in Polyimide is based on Henry’s law and Fick’s law, it could be extended to the optimization of capacitive sensors for other vapours

KEYWORDS: MEMS, Capacitive Humidity Sensor, Sensor Transient Response Modeling, Intellisuite

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, a 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 measure 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].

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

This paper consists of six sections. Section 1 gives the introduction, section 2 deals about the sensor structure and
principle, section 3 deals with INTELLISUITE software, section 4 elaborates MEMS Humidity sensors, section 5 elaborates results and discussions, section 6 elaborates the conclusion.

**MEMS HUMIDITY SENSOR**

MEMS technologies are derived from integrated circuit batch fabrication techniques, in which a large number of components are manufactured concurrently such that the unit production cost is approximately reciprocal to the number of fabricated units.

Humidity is one of the most commonly measured physical quantities, and is a fundamental concern in a wide variety of commercial and industrial applications, including those associated with cleanrooms in the semiconductor industry, environmental chambers for the testing of electronics, automotive industries, building ventilation control, and process monitoring in the chemical, pharmaceutical, food/beverage, electronics, and biomedical analysis industries.

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 sensitivity 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.

Capacitive humidity sensors 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]

**STRUCTURE AND PRINCIPLE**

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 [1],[3].

![Figure 1: Sensor Structure](image-url)
Design of High Sensitivity and Fast Response MEMS Capacitive Humidity Sensor

Figure 2: Working Principle

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.

The variation in permittivity causes variation in capacitance.

\[ C = \varepsilon_0 \varepsilon_r A / D \]  

(1)

Theoretical Modelling

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

\[ \text{RH\%} = \frac{P_a}{P_s} \]  

(2)

Pa is the absolute vapour pressure; Ps is the saturation vapour pressure. Ps depends on temperature. By determining Ps at particular temperature, we can derive Pa for various humidity [5].

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.

\[ \log_{10}(p) = -7.90298 \left( \frac{373.16 - 1}{T} \right) + 5.02808 \log_{10} \frac{373.16 - 1.3816}{T} \]
10^{-7} \left(10^{11.344} \left(\frac{T - 373.16}{1} \right)^{1 - \frac{T}{373.16}} - 1 + 8.1328\right)x \\
10^{-3} \left(10^{3.49149} \left(\frac{27.13 - 1}{T} \right)^{-1} -1\right) + \log_{10} 1013.246 \\
\text{(3)}

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

**Diffusion Modeling**

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

\[ \frac{\partial c}{\partial t} = \frac{D \partial^2 c}{\partial x^2} \] \hspace{1cm} (4)

Where $c$ is the concentration (moles/m$^3$), $t$ is the time (sec), $D$ is the diffusion coefficient, $x$ is the position.

Fick’s law predicts how diffusion causes the concentration field to change with time. It mainly depends upon diffusion coefficient[6],[10].

**Permittivity of Sensing Film**

The permittivity of the sensing film should be

\[ \Delta \varepsilon_r = \varepsilon_{r(RH)} - \varepsilon_{r(0)} \]

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.

**Capacitance Modeling**

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

\[ \Delta \Gamma = \Delta \varepsilon_r \varepsilon_0 A \text{th} \] \hspace{1cm} (5)

Where $\Delta \Gamma$ is the capacitance variation, $A$ is the area of the upper electrode, $\Delta \varepsilon_r$ is the variation permittivity, $\varepsilon_0$ is the permittivity in free space, $\text{th}$ is the thickness of the film.

**Geometrical Modeling**

Parallel plates consist of upper electrode and lower 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.

**INTELLISUITE: A SIMULATION TOOL FOR MEMS**

Intellisuite 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 design process of the sensor is carried out using Intellisuite simulation software. The sensor is designed using both Intellimask and 3D builder tool. Using the fabrication process, the masks for the MEMS device were imported first, then a process table generated which included all of the process steps necessary to create the device and from which the resulting material property was determined.
During process design, the imported mask set was linked to the process, which provided the definition of the x-y geometry of the structure. Then the 3D model of the device could be visualized in 3D viewer, and the model exported to a thermoelectro mechanical analysis module to view the results.

RESULTS AND DISCUSSIONS

A structure was modeled in INTELLISUITE. Its accuracy was checked through finite-element simulation and experiments on structure 20/20 structure (width of the upper electrode 20μm and spacing between the electrodes 20μm) with a film thickness of 1.5μm.

![Figure 3: Sensor Structure](image)

The electrodes are made up of aluminium of thickness 1μm and the sensitive layer is polyimide in between them. The simulation was based on the assumption that diffusion in the polymer film was quit ideal because water vapour sorption in polymer film 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.

![Figure 4: Sensor Structure in INTELLISUITE TEM Analysis](image)
Simulation based on our model was performed to predict the behavior of different structures in order to fabricate the most optimal of them. Because the thickness of the film is a limiting factor of the response time of the sensor, we have chosen 1μm film thickness. Another limiting phenomena of the response time is diffusion under the upper electrode lines. Lines of small width provide short response time, but if the total surface of the upper electrode is small, the absolute capacitance variations of the structure.

CONCLUSIONS

A simple and powerful model was designed for the simulation of capacitive humidity sensor. The model is supported by finite-element simulation using INTELLISUITE software 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 the upper electrode, smaller the upper electrode structure faster response time. Future work will focus on the use of other polymer materials to design fast response capacitive humidity sensors, and the design of a monolithic system comprising the sensor, the capacitance measurement circuit and a signal processing unit. Note that this could be extended to the simulation of other chemical capacitive sensors if the polymer sensitive coating is in the glassy state, and if water sorption in the film follows Henry’s law.

REFERENCES


