COMPARATIVE ANALYSIS OF CANTILEVER TYPE MEMS DEVICE FOR HUMIDITY MEASUREMENT

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Abstract
This paper presents research on water content present in transformer oils. Online moisture measurements were analyzed by using different designs of MEMS humidity sensor. The measurement of humidity is of great importance in transformer oil maintenance. This is especially essential for the continuous monitoring of oil in order to have safe operation of transformer without insulation breakdown. This paper presents the simulated model of a cantilever type humidity sensor. The structure consists of a cantilever beam made up of polyimide which is the sensing element and the water molecules are formed as a spherical structure over the polyimide beam. In the structure, the expansion of the polymer in the presence of water vapors forces the cantilever to bend resulting in a change of the device stress. The stress induced in the cantilever due to the polyimide swelling is proportional to the relative humidity. The model is simulated using COMSOL Metaphysics. This finite element simulation is carried out using different structures of cantilever for better sensitivity and response time. Static analysis were performed for the polyimide cantilever and the output is taken as displacement over the cantilever.

Keywords:
MEMS, Cantilever Humidity Sensor, COMSOL Metaphysics.

1. INTRODUCTION

Over the past decade, there is a dramatic increase in sensor research and developments and applications. There are tremendous advances made in the technology such as micro and nano sensors. Measuring humidity plays an important role in a wide range of practical measurement situations and in industries to control the environmental conditions. High humidity environment causes the fungus and bacteria growth which affects the stored materials in food processing industries. So proper sensing and control of humidity is important. [7]. Relative humidity refers to the ratio of the moisture content of air to the saturation moisture level at the same temperature. Accurate measurement of water level is an important factor for the maintenance of transformer. The presence of moisture in the transformer does actual harm to insulation which causes permanent damage. Moisture enters the transformer either through the external contaminants or generated internally by the oxidation or ageing of insulants. Power transformers utilize oil as a heat transfer medium and a dielectric material together with cellulose. Dielectric strength is most important parameters of transformer oil. Water affects the insulating properties of both the liquid and paper insulation of the transformer and thus leads to ageing. Moisture in insulating oil under fast decreasing temperature forms free water that can cause electrical breakdown of the insulating oil. Water content in the oil increases electrical conductivity and dissipation factor. It is measured when the transformer is in use. The main purpose of measuring the moisture content is to calculate the breakdown voltage of transformer oil. The breakdown voltage is affected by the moisture content present in the oil. It is proved that the breakdown voltage remains constant when the relative moisture saturation is below 20%.

The proposed Micro Electro Mechanical Systems (MEMS) device looks to solve the CMOS compatibility issue and avoid the use of any external components for actuation and read out. The MEMS devices are small, reliable and inexpensive platform in which a humidity sensor is developed. The device is a cantilever beam based Humidity sensor. The induced pressure in the cantilever produced by the surrounding moisture causes the displacement which is measured by the simulation.

Current MEMS based Relative Humidity sensor uses various types of sensors each offer distinct advantages. According to the principles of humidity sensors measurement, humidity sensors are classified into capacitive-type [10], resistive-type [9], Cantilever type and ion sensitive-type, etc. Cantilever relative humidity sensors are widely used because of the simpler structure, easier production process and higher sensitivity. Resistive sensors are interchangeable, usable for remote locations, and cost effective. Capacitive sensors provide wide relative humidity (RH) range and condensation tolerance. Thermal conductivity sensors perform well in corrosive environments and at high temperatures. For most applications, therefore, the environmental conditions dictate the sensor choice.

Many previous researches reported attempts made to improve the cantilever sensitivity using micro cantilevers comprises of either a polysilicon piezoresistor integrated with silicon / silicon-nitride cantilever or a doped single-crystalline silicon piezoresistor on a silicon cantilever. Investigations made to improve the sensor sensitivity by optimizing the geometrical dimension of the cantilevers and incorporated stress concentration regions were reported.

The proposed MEMS humidity sensor is analyzed for various designs of cantilever such as Rectangular, V-shape and paddle shaped. It is proved that the paddle shaped cantilever type of humidity sensor is more sensitive.
2. PRINCIPLE OF HUMIDITY MEMS SENSOR

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

$$ RH\% = \frac{P_a}{P_s} $$ (1)

Where $P_a$ is the absolute vapour pressure. $P_s$ is the saturation vapour pressure. $P_s$ depends on temperature.

2.1 ABSOLUTE VAPOUR PRESSURE

By determining $P_s$ at particular temperature, we can find the value of $P_a$ for various humidity. The saturation vapour pressure defines the maximum amount of humidity that the air can hold. Beyond this limit, condensation occurs to form fog or water droplets. So the variation of %RH can be considered to be the change in the vapour pressure exerted onto the sensing layer in real environmental conditions. This variation in pressure causes the deflection due to stress. The relationship between vapour pressure and concentration is given by the equation

$$ p = nRT/V $$ (2)

Where $p$ is the pressure in Pa, $V$ is the volume in cubic meters, $T$ is the temperature in degrees Kelvin (degrees Celsius +273.16), $n$ is the quantity of gas expressed in molar mass (0.018 Kg in case of water). $R$ is the gas constant (8.31 Joules/mol/ m³). Water vapour pressure can be converted into concentration in Kg/m³ by the equation

$$ Kg/m^3 = \frac{0.002166*p}{t+273.16} $$ (3)

Where $p$ is the actual pressure. Thus if there is an increase in %RH then the vapour pressure exerted over the beam also increases, resulting in increase in deflection of the beam.

2.2 SATURATION PRESSURE

For the calculation of Saturation pressure, the temperature variation has to be considered. Saturation vapour pressure increases strongly with increasing temperature. The relation between Temperature ($t$) and Saturation pressure ($P_s$) is given by the equation

$$ P_s = 610.78 * \exp\left(\frac{t}{t+23.83} * 17.2694\right) $$ (7.2) (4)

The values of saturation vapour pressure is given in the Table 1 as follows

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Saturation Vapour pressure (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.61</td>
</tr>
<tr>
<td>10</td>
<td>1.23</td>
</tr>
</tbody>
</table>

2.3 POLYMIDE MICRO CANTILEVERS

Cantilever sensors are based on relatively well known and simple transduction principle. [9]. A simple Cantilever beam is used for various applications such as chemical, Biomedical and other environmental monitoring applications. [14]. figure.1 and figure.2 shows the water vapours adsorbing on functionalized surface of the cantilever beam.

The changes in the surface properties of the micro cantilever through absorption or adsorption of water molecules will influence its surface stress. This causes the deflection of micro cantilever and it is proportional to the amount of water vapour present in the environment.

3. POLYMIDE AS A HUMIDITY SENSITIVE MATERIAL

Polyimide films are developed for electronic industries. The polyimide is chemically inert in its cured form and a thermally stable material upto temperatures around 450°c. In addition it is a perfect planarizer used to planarize irregular surfaces. It also has a low relative permittivity and high breakdown voltage, which makes it desirable for high speed applications. Of all which the important parameter is its high humidity sensitivity. Humidity responses of polyimide films have been investigated in many works [5], [8]. Investigation show that the dielectric constant of polyimide films change from about 3 to 4 as the relative humidity changes from 0%RH to 100%RH. Moreover, the dielectric constant change with respect to the humidity change is almost linear especially within the 20% RH to & 70% RH range.
4. MOISTURE SORPTION AND TRANSPORT IN POLYIMIDES

The absorption of moisture in a material modifies many physical properties such as dielectric constant, conductivity, modulus, impact strength, ductility, and toughness. Water has a high dielectric constant of 80. The equilibrium is reached when moisture is exchanged between the material and the environment. The equilibrium moisture content is a function of humidity, temperature, type of material and the moisture history of the material. The absorbed water exists in several different forms such as chemisorbed, physisorbed and condensed states. In Chemisorbed type, water molecules are chemically bound to the constituents of the material, in the second type, they are held by surface forces and in the third state, Water is condensed inside the small pores [6].

The radius of the pores is given by the equation

\[ r_k = \frac{2\gamma M_n}{\rho R T \ln \frac{P_s}{P}} \]  

(5)

Where \( \gamma \), \( M \), \( \rho \), \( R \), \( T \), \( P_s \), and \( P \) are the surface tension, molecular weight of water, density, universal gas constant, temperature, saturated water vapour pressure and water vapour pressure respectively. In polyimides, water molecules are condensed in micro voids depending on the humidity level.

5. DESIGN OF HUMIDITY SENSOR

The schematic of the humidity sensor structure is shown in figure.3.

![Fig 3 Structure of Humidity Sensor](image)

It comprises of silicon substrate and polyimide as the sensing element. Silicon/polyimide bimorph microcantilever structures were designed. Silicon micro-cantilevers have been shown to be able to detect minute quantities of chemical species with sensitivity exceeding that of traditional quartz crystal microbalance (QCM) and surface acoustic wave (SAW) transducers[13]. In this work, finite element (FE) modeling has been used to approximate the Si/Polyimide bimorph behavior and to design and optimize the cantilever beams. Finite element simulations were performed using Comsol Multiphysics software. Cantilevers of various structures have been studied. For the Finite Element simulations, the dimension of the cantilever devices were constructed using the geometrical data and the material properties of polyimide were used as per the details given in the Table.2. All simulations were performed using the Comsol Multiphysics Software.

The material properties [4], [6] and geometry parameters are summarized in Table.2.

<table>
<thead>
<tr>
<th>Table.2. Material Properties and Geometrical Data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Material properties of Si</strong></td>
</tr>
<tr>
<td>Young’s modulus</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td><strong>Material properties of polyimide</strong></td>
</tr>
<tr>
<td>Young’s modulus</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td><strong>Geometry parameters</strong></td>
</tr>
<tr>
<td>Length</td>
</tr>
<tr>
<td>Width</td>
</tr>
<tr>
<td>Si beam thickness</td>
</tr>
<tr>
<td>Polymer thickness</td>
</tr>
</tbody>
</table>

Static Analysis was carried out by applying the pressure as the load and the Simulation setting set to displacement.

The Displacement profile for the given cantilever is shown in figure.4.

![Fig 4. Displacement Profile of Humidity Sensor](image)

6. RESULTS AND DISCUSSIONS

In order to suit intended applications of MEMS cantilever, there are many available designs for MEMS cantilever. These designs vary in terms of the shape and parameter of the MEMS cantilever such as length, width, and thickness. In this paper, different shapes of MEMS Cantilevers are designed and the sensitivity is analyzed. Figures shown below provide the different designs of MEMS Cantilever type of humidity sensor. The various types of designs such as Rectangular shape, V shape and Paddle shape has been designed.
First, the Rectangular type of Humidity sensor has been analyzed by applying static analysis. The result show that for 10% of RH, the value of displacement is 3000μm. The simulated result is shown in figure.5 as follows.

![Fig.5. Simulated Result of Rectangular Type Humidity Sensor](image)

Secondly, the V shaped type of Humidity sensor has been analyzed by applying static analysis. The result show that for 10% of RH, the value of displacement is 7000μm. The simulated result is shown in figure.6.

![Fig.6. Simulated result of V- Shaped Type Humidity Sensor](image)

Thirdly, the paddle shaped type of Humidity sensor has been analyzed by applying static analysis. The result show that for 10% of RH, the value of displacement is 20000μm. The simulated result is shown in figure.7 as follows.

![Fig.7. Simulated result of Paddle Shaped Type Humidity Sensor](image)

The various structures has been designed and analysed and the values of displacements for rectangular, V shape and Paddle shapes are given in table 3.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Displacement (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rectangular Shape</td>
<td>3,000</td>
</tr>
<tr>
<td>V Shape</td>
<td>7,000</td>
</tr>
<tr>
<td>Paddle Shape</td>
<td>20,000</td>
</tr>
</tbody>
</table>

7. CONCLUSION

The work is multidisciplinary and it combines microelectronic engineering and mechanical engineering. Finally, electrical engineering principles were employed to actuate, monitor and manipulate the electrical signal of the sensor based on absorption principles. In this paper, geometric dimensions of three types of cantilever type MEMS Humidity sensor has been designed and analyzed. Finite Element Analysis has been used for all the structures and the results show that paddle shaped design is more sensitive when compared to rectangular and V shaped structures. This humidity sensor may have potential for many applications, such as Industrial automation, Transformer oil testing and environmental monitoring.

REFERENCES


[2]. Firdaus, S.M.; Azid, I.A.; Sidek, O.; Ibrahim, K.; Hussien,M.; Enhancing the sensitivity of a mass-


[7]. Polyamic acid DurimideTM 100 from Arch Chemicals.


[9]. Recent achievement in miniaturized humidity sensors—a review of transduction techniques. Rittersma ZM.

[10]. RF MEMS and their application Vijay K Varadhan K.J. Vinoy K.A.Jose.


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