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Design and Development of MEMS Based Weather Monitoring System

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Abstract: The continued demands for better monitoring and control of environmental conditions have led to the need of precise means for measuring temperature, pressure and relative humidity with the technology of MEMS. This has been utilised to develop a temperature sensor which works on thermal expansion of a bimorph cantilever with a piezoelectric PZT-5A insertion in-between the active layers. A humidity sensor is made according to the principle of variable dielectric with change in moisture leading to change in overall capacitance. The pressure sensor is made up of piezoresistors with a 2 turn configuration. The pressure and temperature sensors have been simulated using COMSOL Multiphysics. A prototype of the entire system has been demonstrated to measure atmospheric pressure with a BMP180 and the humidity & temperature is measured with a DHT22, both being MEMS based sensor. The transmission to the base station from a remote weather balloon is done with Radio Frequency (RF) by a reliable XBee Module on a light weight and water-resistant Microcontroller. The data remotely acquired by the sensors is transmitted and logged at a base unit.

Keywords: *MEMS , Temperature, Pressure, Humidity, Sensor, Weather, Monitoring, Microcontroller.*

1. INTRODUCTION

Present systems for weather monitoring involve sensor arrays to measure parameters such as gas flow, temperature etc, however they are limited to usability for the atmospheric ranges alone. This research has been done with the main focus being on temperature, pressure and relative humidity for the measurement in the ranges of stratosphere and their usability in weather balloons. Three sensor systems were made as a part of a single package with options of expandability without replacement of the microcontroller and transmission systems. The hardware prototype has been demonstrated in this paper. The three sensors are proposed with the aim of having utmost accuracy along with sensitivity and optimisation in the measurable ranges. The hardware prototype involves an Arduino Lilypad microcontroller board with XBee module respectively for processing and transmission. The power requirements have been kept minimal supplemented with a light weight design such that the entire setup can be used as a part of weather balloons with ease. The proposed sensor structures were verified using COMSOL Multiphysics®. The simulation results of the temperature and pressure sensor have been stated below.

2. SIMULATED SENSORS

The three sensors to measure temperature, pressure and relative humidity have been redesigned and simulated to accommodate higher efficiency and accuracy with the technology of MEMS. The three sensors measuring temperature, pressure and relative humidity are designed to persist their highest levels of sensitivity from the atmosphere right till the areas of stratosphere, where weather balloons monitor environmental conditions. Hence the ranges of individual parameters are described below in the sensor explanations.

2.1. Pressure Sensor

The sensor has been designed to work in the pressure range of 0-1.1 bar. There are several principles that could be used for pressure sensing, a few of them being capacitive, piezoresistive, piezoelectric and resonant. Piezoresistive sensing principle is usually more preferred over the others because it provides high gain factor, high reliability, high sensitivity and good linear relation between output resistance change and applied stress. The basic working principle behind piezoresistance is the change in resistance of material when it is subjected to stress or strain. Piezoresistive pressure sensors are normally made from Silicon (Si) because it has excellent material property. This nature helps in measuring the strain in the silicon diaphragm. The silicon diaphragm has been made up of n-type silicon material and the 4 piezoresistors are of p-type silicon. When a pressure is applied on the diaphragm consisting of 4 piezoresistors a stress is induced in the diaphragm. This stress will result in change in the resistance of the piezoresistors. Two piezoresistors are subjected to longitudinal stress and their resistance increases whereas the other two resistors are subject to transverse stress and their resistance decreases. Thus, the balanced Wheatstone bridge becomes unbalanced and the sensor gives a voltage output. The silicon diaphragm used is a square shaped diaphragm because it has maximum induced stress for a given pressure. The piezoresistors are placed at the centre of each edge of diaphragm because that is a high stress region within the diaphragm. Length and thickness of the diaphragm and length of piezoresistors are important factors. The piezoresistive pressure sensor diagram has been presented below.

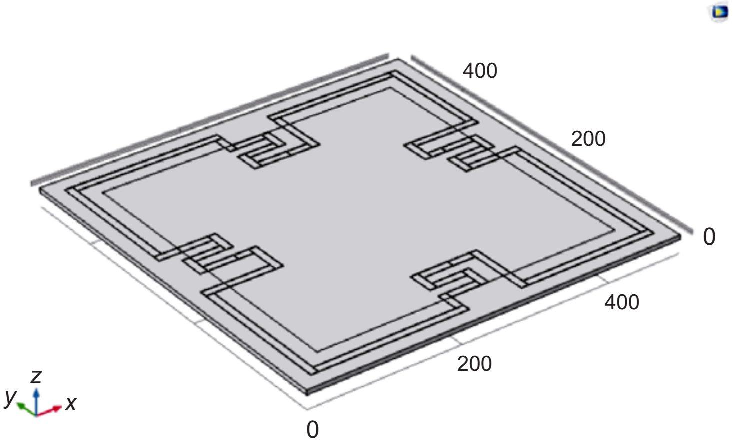

Figure 1: Piezoresistive pressure sensor with 2 turn configuration

Specific measurements are chosen and simulated to find out the best configuration for high sensitivity and good linearity. The dimensions of the components used have been mentioned below.

2.1.1. Diaphragm dimensions

The most important factor is to choose the thickness of the diaphragm to obtain finest output characteristics from the sensor. A thinner diaphragm will have a better sensitivity whereas on the other hand thicker diaphragm gives better linearity. To get a sensitive structure, diaphragms with various thicknesses is simulated at atmospheric pressure 101325Pa and the results are plotted below.

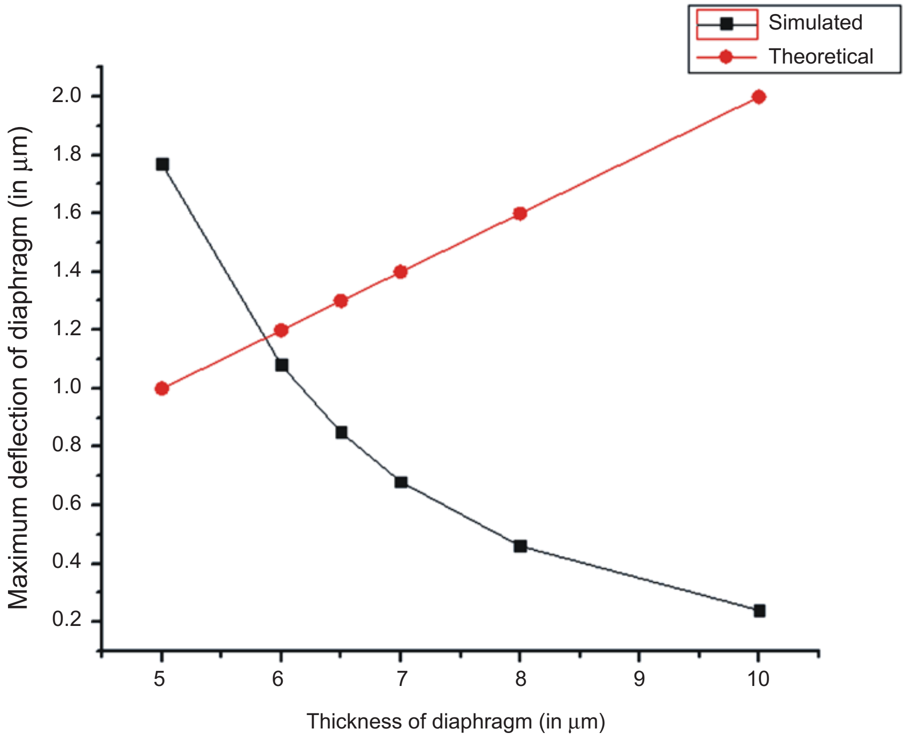

Figure 2: Graph between deflection of diaphragm and altitude

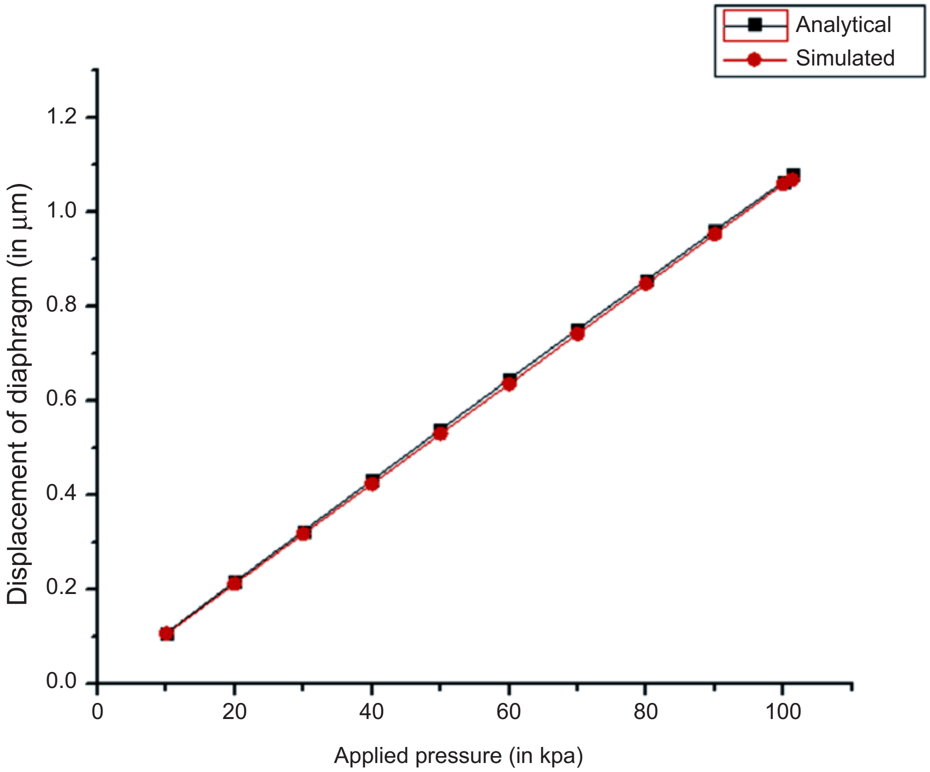

Figure 3: Graph between displacement of 6µm diaphragm vs applied pressure

The theoretical calculation of maximum deflection of diaphragm is measured by small deflection theory for bending of thin plates. This theory assumes that the deflection of midpoint of surface of the diaphragm must be small compared to the thickness of the plate and the maximum deflection must be less than 1/5th of the thickness of the diaphragm [4]. On the other side, the simulated deflection output is obtained by executing the pressure sensor structure in COMSOL Multiphysics for different diaphragm thickness. The simulated values are obtained and plotted and the most suitable thickness is chosen to obtain finest output characteristics from the sensor. According to the data obtained 6μm is chosen as the thickness of the diaphragm for given range. The maximum deflection at the midpoint of the diaphragm of 6μm thickness can be 1.2μm or less. But according to simulation results maximum displacement obtained at 101325Pa is 1.08μm. Therefore we choose the thickness of the diaphragm as 6μm in order to have a trade-off between sensitivity and linearity. A diaphragm can be considered as a thin diaphragm, if the ratio of thickness to the length of diaphragm is less than 1/20. Therefore in our case the length of the diaphragm must be 400μm. The graph between displacement of diaphragm and applied pressure is plotted above.

2.1.2. Geometry of Piezoresistors

Four piezoresistors are placed on high stress region at the centre of the four edges of the diaphragm. The piezoresistors are connected in two turn configuration. According to the simulation results it was observed that as the length of the piezoresistor increases sensitivity decreases. Therefore different lengths of the piezoresistors are simulated. A 50μm piezoresistor is used to get a superior sensitivity. The connecting arms connect the piezoresistors with each other. The connected arms are formed by using copper metal lines and the connecting wires are formed by using aluminium metal because they do not contribute to the piezoresistive effect.

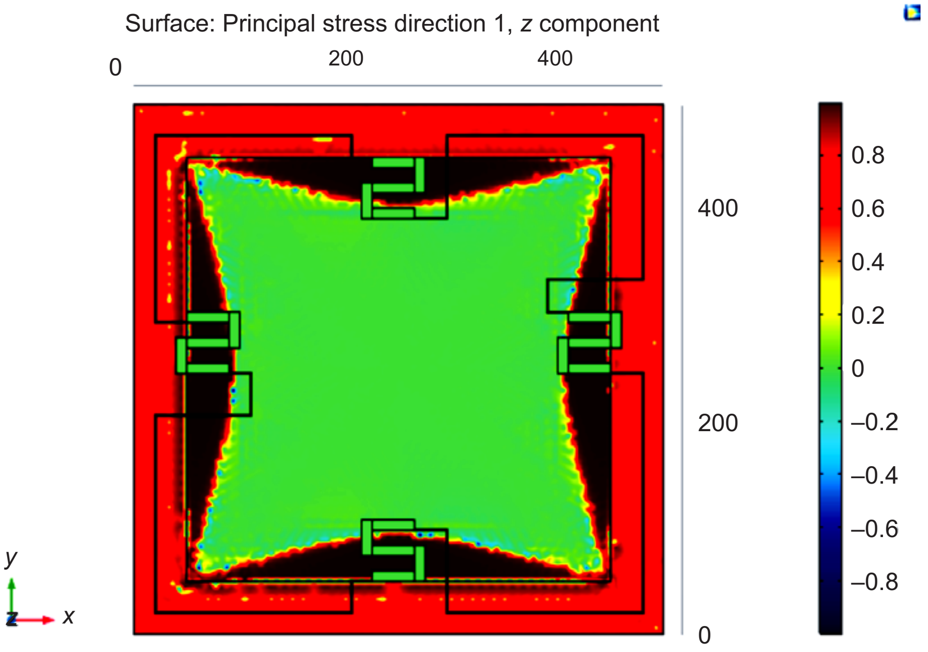

Figure 4: Application of stress on the geometry of piezoresistors

2.1.3. Parameter properties

In this design, an *n*-type silicon as a diaphragm material has been used for obtaining a better accuracy. Above the *n*-type silicon semiconducting material *p*-type piezoresistors are placed, because of high gauge factor of *p*-type silicon. Copper and aluminium metals are used as connectors because these metals will not contribute to the piezoresistive effects.

Table 1
Lists the different material properties of piezoresistive pressure sensor

Material	*Density (kg/m^3)*	*Young's Modulus*	*Poisson's Ratio*
Silicon	2330	170	0.27
n-type & *p*-type silicon	2330	160	0.22
Copper	8960	120	0.34
Aluminium	2700	70	0.25

2.1.4. Performance Parameters

The following parameters are used to analyse the designed pressure sensor model:

Total Displacement: When the pressure is applied on the diaphragm it tends to get displaced. The maximum displacement occurs at the centre of the diaphragm and it decreases near the fixed ends. The deflection at the centre of the diaphragm is measured by using the following equation [8]

$$D = [0.0151\,(1 - v^2)\,Pa^4] \div El^3 \tag{1}$$

Where V : Poisson's ratio
P : Pressure applied
E : Young's modulus
a : Side length of diaphragm.
l : Thickness of diaphragm.

Sensitivity: Sensitivity is a very important parameter. It is defined as the ratio of relative change in the output voltage with respect to per unit change in the pressure applied.

$$S = \Delta V/\Delta P * 1/V_{in} \tag{2}$$

Where ΔV is the change in output voltage, ΔP is Change in pressure.

Output voltage: The output voltage of the Wheatstone bridge depends on the input voltage applied to the bridge circuit and also the resistance values of all the four piezoresistive materials. As the resistance of the piezoresistors changes with pressure applied, the output voltage changes correspondingly. The output voltage across a Wheatstone bridge:

$$V_{out} = Pa^4/\,h_2\,(1 - v^2)\,\pi LV_{in} \tag{3}$$

Where, πL : Longitudinal coefficient of piezoresistors
V_{in} : Input voltage
a : Side length

For the mentioned application, the required range of sensing is between 0 to 1.1bar *i.e.* 0 to 110000 Pascal. Under ambient conditions, 101325 is the atmospheric pressure and as the altitude increases, the pressure decreases. Therefore, the suitable range for the sensor stands from 0 to 110000Pascal. As the diaphragm becomes thinner, the sensitivity increases.

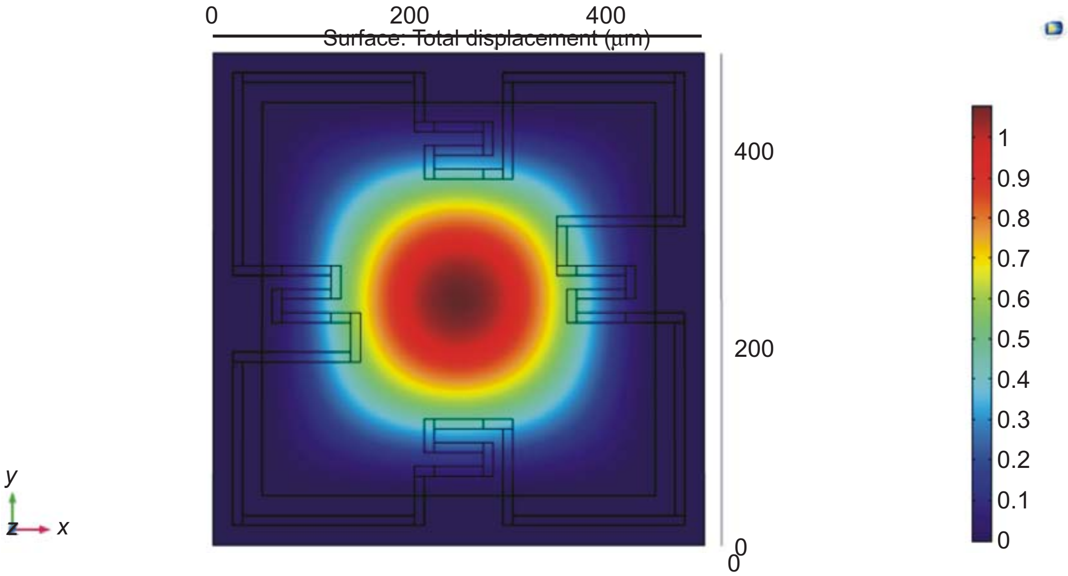

Figure 5: Simulation of Piezoresistive Pressure Sensor

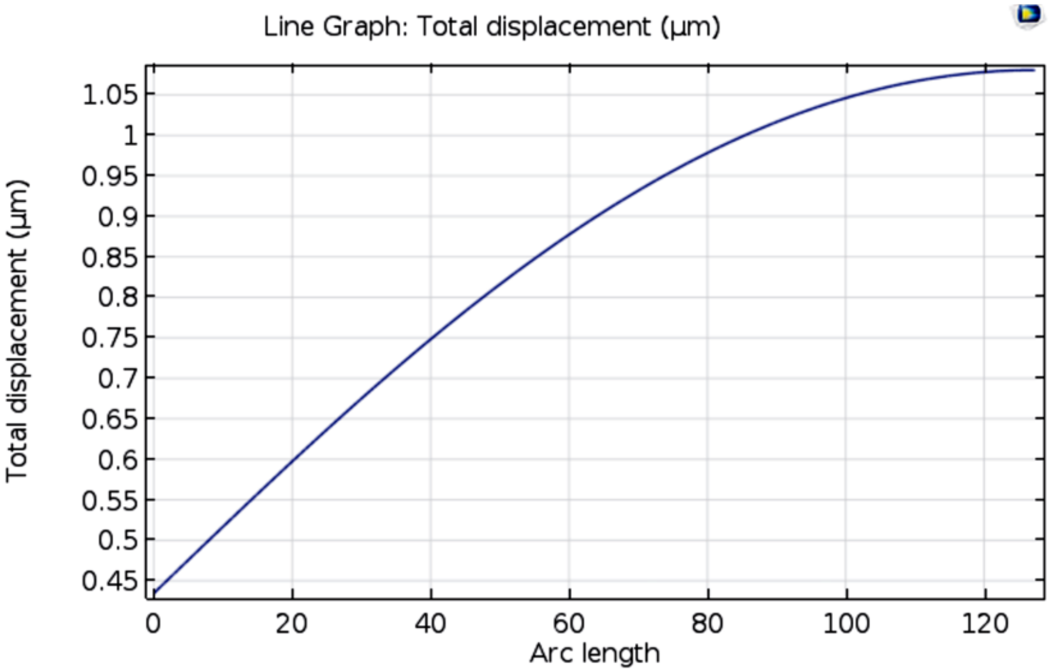

Figure 6: Maximum Displacement of diaphragm at 101325Pa

2.2. Temperature Sensor

A bimorph is used for implementing the principle of bending of cantilever beam. The functionality of expansion or contraction of any metal when subjected to a particular temperature can be taken advantage of. This is a very well-known and reliable method of temperature sensing than other existent methods such as optical sensors which may have difficulties in accurate sensing with presence of high interferences in varying atmospheric conditions and capacitive sensors which may show output alterations with a variable dielectric in unknown weather conditions. Thus, an entirely solid state sensing principle has been used. The cantilever structure is said to be the simplest model and the most common one used for sensing and actuation[1] which will in turn provide ease of fabrication. There can be an optional passive layer between two active layers[1] or just two active layers attached to each other. Silicon is specifically used for the bottom layer of the bimorph as there are advantages of its low damping[2] characteristic and an ability to recover. A major breakthrough was made in 1954 for temperature sensing by Charles S Smith who experimented and investigated piezoresistance in Silicon and Germanium[2]. Masya Toda et al. proposed that the use of Silicon as a part of a bimetallic cantilever highly increases the sensitivity of the structure and as compared to single metal cantilevers as these change only when there is a wide variation of temperature. Even small changes in temperature cause a deflection the beam from its free end[2] thereby proving a good resolution. The upper layer of the bimorph is made up of Magnesium. For an output, a piezoelectric material is inserted between the two elements which would provide a positive or negative voltage output depending on the temperature. The structural description of each material used has been explained below:

2.2.1. Cantilever Beam

A bimorph structure is made with a piezoelectric layer in between them. The overall dimension of the structure is (100μm × 15μm × 1μm) per layer. There's a piezoelectric insert in-between the two layers of Magnesium AZ31B and Silicon.

2.2.2. Upper Layer (Magnesium)

The layer has been made up of the alloy: Magnesium AZ31B. The use of Magnesium over other metals for the sensing layer has a variety of advantages. With a strength which is higher than Aluminium, it is 33% lighter, 60% lighter than Titanium and 75% lighter than steel. This adds to the convenience of a light weight and reliable sensor to be used in a weather balloon. Further, the Mg used here has a coefficient of thermal expansion of 26μm/mK which is higher than that of metals like Aluminium and Platinum used in conventional methods of temperature sensing[3]. With a high CTE, it can have a better response. It also has a higher shock absorption capacity than the other two metals. However, there are a few disadvantages of Magnesium which to be overcome. It has a likelihood of getting corroded. Hence, the Magnesium AZ31B alloy is used such that an initial dark film gets deposited on exposure to air. This prevents even the minimal amount of corrosion to take place. Further, the micro structure has an even lesser chance of corrosion as it increases with surface area. It's compatible with the bottom Silicon layer as it doesn't react within the temperature ranges and has an acceptable amount of stability. Further, the Young's Modulus is 45 which is lower than Al and Pt, this making it more reformable and contributing to an enhancement of its reusability. Its Poisson's ratio is 0.35 which is equal to that of Aluminium used for temperature sensing[3] layer.

2.2.3. Bottom Layer (Silicon)

Silicon is used as the bottom most layer of the bimorph. Silicon has been used in various temperature sensors previously[2] as the bottom layer of construction of a bimorph cantilever. The main advantage of Silicon is that it doesn't react with Mg. Silicon provides good sensitivity[2] and has a reliable coefficient of thermal expansion.

2.2.4. Piezoelectric Block (PZT)

This is a block structure embedded in the cantilever structure in between the active layers. The property of piezoelectricity makes it produce a voltage output when the entire cantilever bends. The block produces a positive voltage when the beam bends downwards for higher temperatures and a negative voltage when the beam bends upwards with lower temperatures in the range. For production of output, one end of the block is supplied with 5V and the other end is grounded as shown in the diagrammatic explanation. Dimensions are 20μm × 15μm × 1μm to maintain a 75-25% ratio with the subsequent elements in the structured.

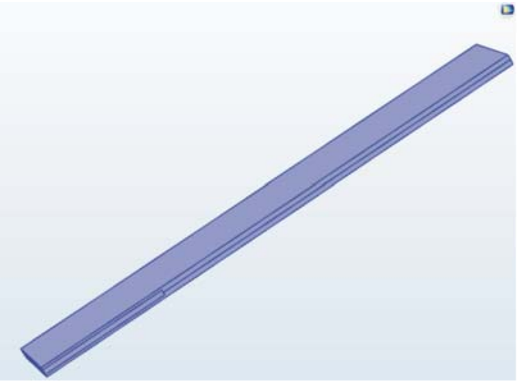

Figure 7: Structure of Temperature Sensor

The bending of the bimorph cantilever has been simulated to analyse the structural changes and check the voltage output from it using COMSOL Multi-Physics. The displacement of the entire structure is considered and the according voltage change in the piezoelectric layer is monitored. The results are posted below.

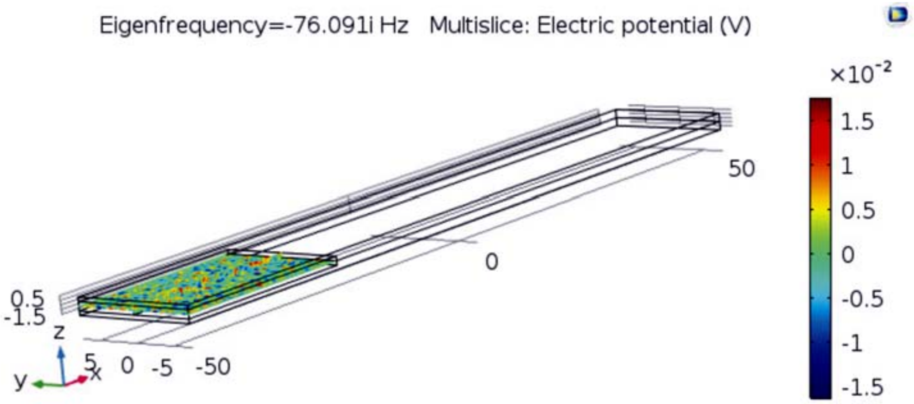

Figure 8: Voltage output from the PZT5A block

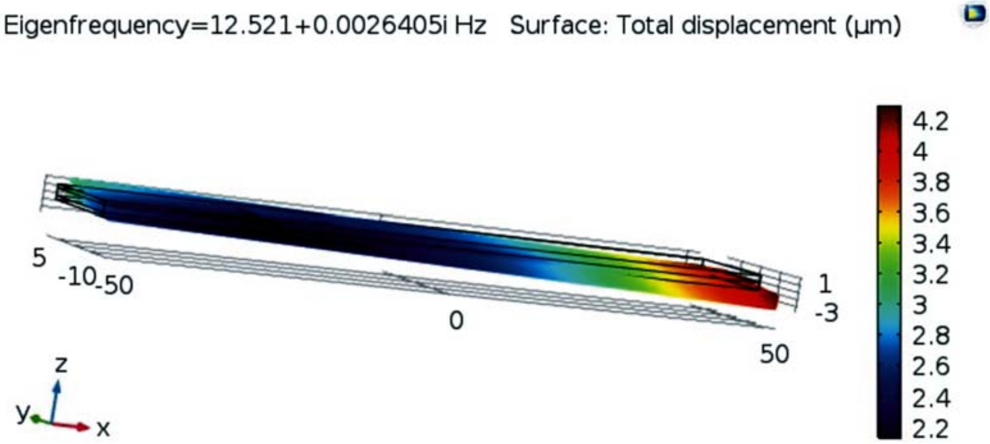

Figure 9: Displacement of the Bimorph

For a fixed beam, there's a large compressive stress which is introduced due to restrained increase of length. According to the beam theory, the stiffness is increased by a tensile stress and it is decreased by a compressive stress. This changes the frequency and hence the results are shown with respect to the temperature ranges.

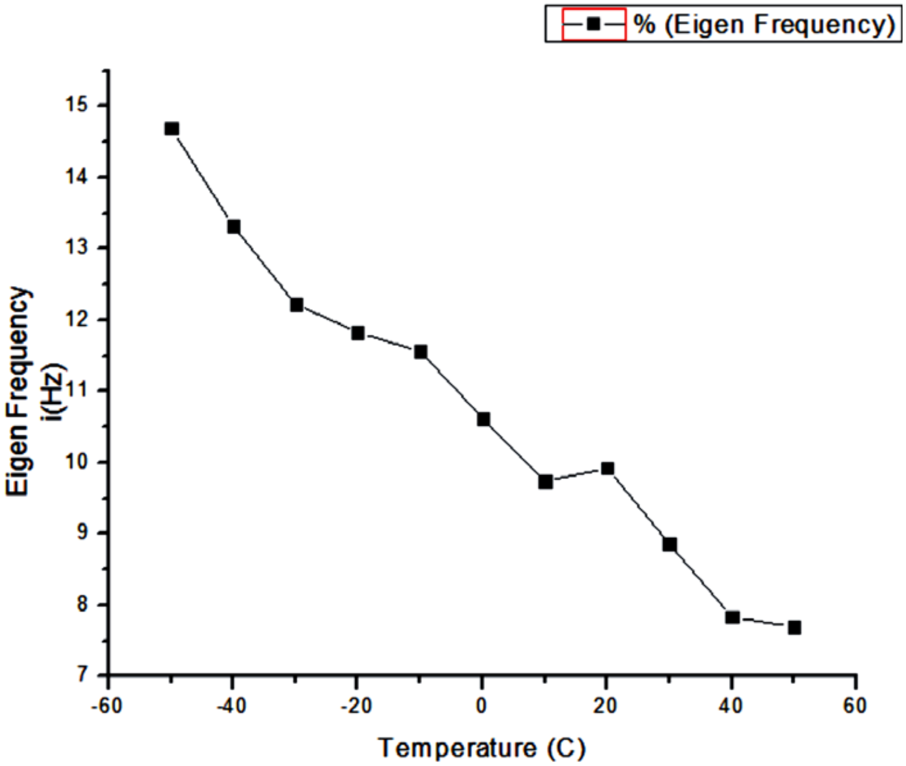

Figure 10: Plot versus Eigen Frequency from parts of the required temperature range

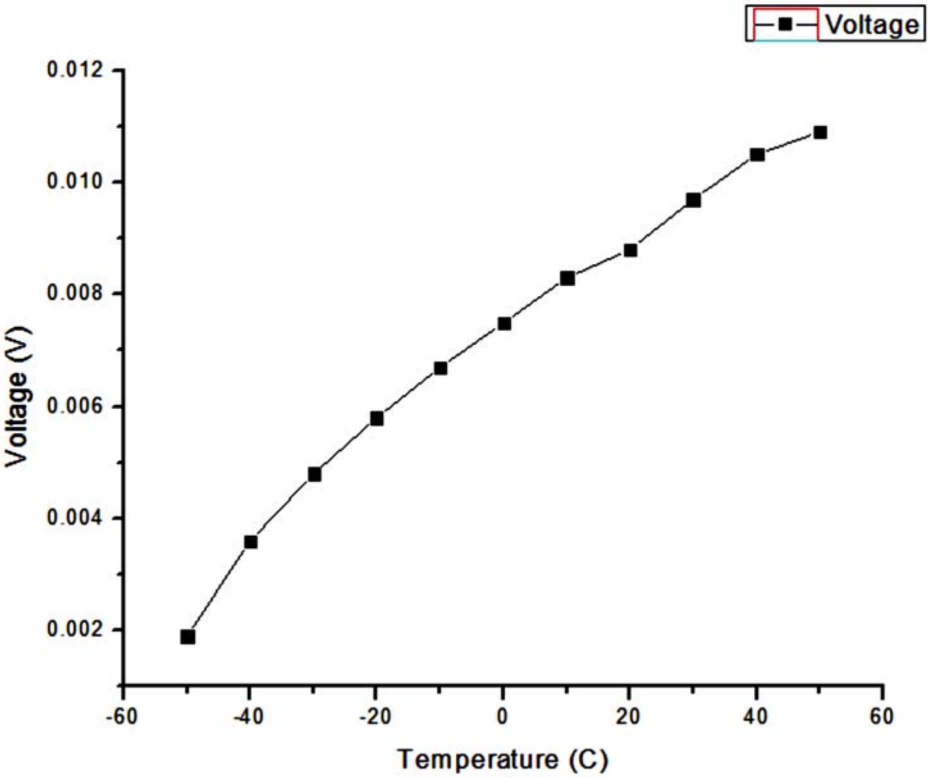

Figure 11: Plot between Voltage and Temperature

From the results, it can be inferred that with a change in temperature, there is a change in voltage output generated. the Eigen Frequency and Temperature relationship has been verified that with increase in temperature, the Eigen Frequency increases. As for the voltage output, it is noted that the output voltage increases with increase in temperature. Hence, a high sensitivity is achieved.

2.3. Humidity Sensor

Humidity measurement is one of the most important parameters to be measured at high altitudes. As the altitude increases the temperature decreases, the ambient temperature can be as low as –70◦C when the sensor reaches tropopause. The different types of humidity sensors are resistive humidity sensor, displacement humidity sensor and capacitive humidity sensor. Among all the three sensors, capacitive technique is the most widely used technique for humidity sensing, where the relative humidity change is detected by the dielectric constant change of thin films due to varying humidity. 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. Therefore a capacitive sensing principle is designed and proposed.

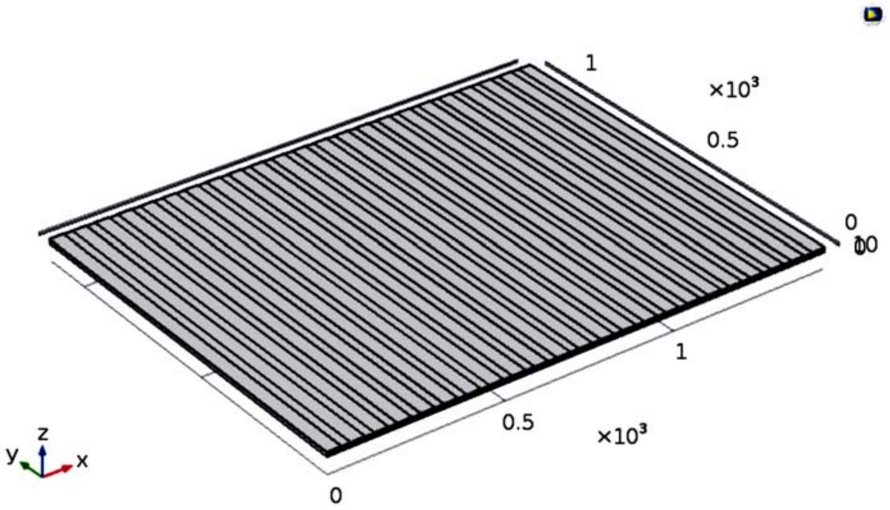

Figure 11: Structure of Humidity Sensor

2.3.1. *Design of humidity sensor*

Capacitive relative humidity sensor consists of a moisture sensitive dielectric material sandwiched between two metallic electrodes. In order to allow moisture into the dielectric layer the top electrode is split into 23 fingers. Each finger is 40μm wide and 1150μm long, in order to facilitate rapid moisture diffusion into and out of the film [8]. As an upper electrode, the top of the sensing surface is coated with a thin layer of evaporated gold to protect it from ambient contamination or dust and help ensure better condensation. In the sandwich configuration, the upper porous electrode is always a water vapour permeable film. Under these striped top electrodes there is a 3μm thick polyimide layer deposited, on top of bottom electrode. Polyimide layer is chosen because it has excellent mechanical and dielectric properties, good dimensional stability, high temperature resistance, radiation resistance, easy modification, processing morphological diversity, and synthetic diversity. As the dielectric constant of the polyimide is about 2.93 and the dielectric constant of water is about 80, the dielectric constant of the polyimide will be increased when it absorbs water molecules. As the dielectric constant of the polyimide changes, there is a corresponding change in the capacitance value. The capacitance is directly proportional to dielectric constant, as dielectric constant increases capacitance value also increases. Also, capacitance is directly proportional humidity. With the proposed structure, the simulation for getting an accurate and optimised output from the environmental ranges is currently in progress and is planned for a reveal in the future.

3. HARDWARE PROTOTYPE

The prototype is made with a Microcontroller, BMP180 sensor to measure the atmospheric pressure and DHT11 sensor to measure the relative humidity and temperature. For transmission and acquisition of data, an XBee S2 module has been used. To facilitate power supply, a light weight 3.7V Lithium Polymer battery has been used in the setup. The entire system is to be attached to a weather balloon and is monitored from a ground base station where the signals are communicated by a XBee module's efficient and reliable RF transmissions. The purpose of these components has been explained below.

3.1. Components used in the Prototype

Arduino Lilypad Microcontroller has been used as it is a very simple and fast prototyping platform. It has an additional advantage of being water resistant which makes it perfect for outdoor use and capable of monitoring in wet weather conditions. It has a diameter of 50mm and weighing just 9g, it can be readily used in a weather balloon. With a clock frequency of 8MHz, it is ideal for optimized data acquisition from the sensor with minimal power requirements.

BMP 180 is an atmospheric pressure sensor which works on the lines of barometric sensors. Barometric pressure sensors measure the absolute pressure of the air around them and provide an accurate reading. The main advantage lies in having the capability of ultra-low power consumption (of 3 micro Amps) along with high levels of mobility. It is known to have a very stable behaviour with regard to the independency of the supply voltage.

DHT11 is used for humidity and temperature sensing. A single sensor can be used for dual purpose. Having an ultra- low cost, it is highly affordable. It uses a maximum current of 2.5mA while requesting data. The humidity is sensed with 5% accuracy and temperature is sensed with $\pm 2^0$C. Additionally, it has a small body size of 15.5mmx12mm x5.5mm[9].

XBee Module is used for communication between the set of sensors and the monitoring devices. The shield uses RF transmission and is easily programmable. Its modular structure adds to the convenience. The low power usage also complements the set of benefits. Two XBee modules are attached at the two ends for the purpose of transmission and receiver.

The hardware is made to acquire data in real time to monitor the temperature, relative humidity with DHT11 and the atmospheric pressure with BMP180. The entire set up is used with a Arduino Lilypad thereby keeping the set-up light in weight of approximately 100g and fairly water resistant.

The setup is demonstrated below. The entire system of sensors and microcontroller is arranged and attached to each other such that it takes up minimal space (60 × 60mm). The choice of components makes the system fairly resistant to water.

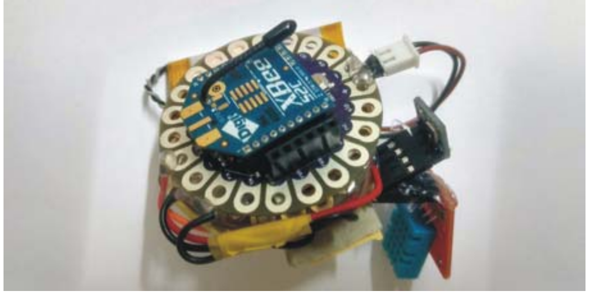

Figure 12: Arduino Lilypad XBee Module (for transmission) coupled with the microcontroller and attached to BMP180 and DHT11 sensors

The receiving end is connected to the monitoring system via an USB cable and the data is received in the XBee shield.

This system is adaptable for future improvements as it can sense up to 26miles by using XBee-Pro 900 XSC S3B module without affecting the size and weight of the system.

Figure 13: The receiver module (base station) with XBee shield which can be easily interfaced with a data logging and computing device with an USB cable.

4. CONCLUSIONS

The relative humidity, pressure and temperature sensors have been structured using the technology of MEMS with the focus highly being on accuracy, sensitivity and the range starting from the atmosphere and spanning till the stratosphere. Hence they can be easily blended into a module and sent with the weather balloons for reliable environmental weather monitoring. The entire system has been demonstrated with a prototype and real time data transmission and receivable equipment for logging of data. A microcontroller is coupled with a transmission module to send the data from the sensors at intervals with no loss of information. Hence, the three sensors have been developed to be a part of a single package.

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