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Classification and Applications of Humidity Sensors: A Review

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Abstract: This review introduces an overview of importance of humidity, methods of their measurement. It gives Detailed description of humidity sensors; their types and properties have been discussed. It explains role of humidity in human life and need of humidity. It also deals with the experimental techniques for the development of humidity sensors and the water adsorption mechanism. Humidity sensors such as resistive type, optical, and ceramic humidity sensors etc. have been described.
Keywords: Humidity, Humidity Sensors, Sensing Mechanism, Applications.

I. INTRODUCTION

A. *Humidity*

Humidity is the presence of water vapour in atmosphere and this affects human comfort as well as many manufacturing processes in industries. The presence of water vapour also influences various physical, chemical, and biological processes [1-4]. Humidity measurement in industries is critical because it may affect the business cost of the products and the health and safety of the personnel. Hence, humidity sensing is becoming very important, especially in the control systems for industrial processes and human comfort. Since humidity is expressed in diverse ways, it is very difficult to come up with a reliable, consistent, and repeatable humidity measurement approach. In contrast to other sensors employed for measuring other parameters like temperature and pressure, a humidity sensor should be in contact with the processing environment and hence is difficult to implement.

Many processes in production and manufacturing industries need humidity measurements. The increasing importance of measuring humidity has caused researchers to search for more reliable and cost-effective humidity sensors and related control systems. There have been many approaches carried out to come up with a possible humidity measurement technique [5-6]. This section deals with the basic concepts in humidity and the various approaches and developments carried out in this field. Humidity in environment can be defined by several ways.

B. *Relative Humidity*

In an air-water mixture, it is the ratio of partial water vapour pressure to the saturation vapour pressure of water at the same temperature. In other words, the relative humidity is the ratio of the actual amount of moisture in the atmosphere to the amount of moisture that it can hold [7]. Therefore, a relative humidity of 100% means the air can hold no more water (rain or dew is likely) and a relative humidity of 0% shows that there is no moisture in the atmosphere.

C. *Absolute Humidity*

The mass of water vapour in each volume of air; i.e. density of water vapour in each sample, usually expressed in grams per cubic meter.

D. *Specific Humidity*

The mass of water vapour in a parcel divided by the total mass of the air in the parcel (including water vapour). It can also be defined as the mass of water vapour per unit mass of humid air.

E. *Dew point*

The temperature to which air would have to be cooled for saturation to occur. The dew point temperature assumes that there is no change in air pressure or moisture content of the air.

F. *Dry-Bulb Temperature*

The air temperature (usually paired with wet-bulb for measurement) that is used to derive the relative humidity.

G. Wet-Bulb Temperature

The lowest temperature that can be obtained by evaporating water into the air at a constant pressure. The name comes from the technique of putting a wet cloth over the bulb of a mercury thermometer and then blowing air over the cloth until the water evaporates. Since evaporation takes up heat, the thermometer will cool to a lower temperature than a thermometer with a dry bulb at the same time and place. Wet bulb temperatures can be used along with the dry-bulb temperature to calculate the dew point or relative humidity.

H. Saturation Of Air

The condition under which the amount of water vapour in the air is the largest possible at the existing temperature and pressure. Condensation will begin if the temperature falls or water vapour is added to the air.

I. Actual Vapour Pressure

The partial pressure exerted by the water vapour present in a parcel. Water in a gaseous state (i.e. water vapour) exerts a pressure just like the atmospheric air. Vapour pressure is also measured in milli bars.

J. Saturated Vapour Pressure

The largest partial pressure that water vapour molecules would exert if the air were saturated with vapour at a given temperature. The saturated vapour pressure is directly proportional to the temperature. In other words, it is the largest pressure of water that can exist at a given temperature.

Table-1 Various humidity sensing approaches and their operation mechanisms

Principle	Operating Mechanism
Capacitance	The dielectric constant of the material varies with the amount of water absorbed.
Coulometer	An electrolyte is formed by absorption of water and the current level obtained is proportional to the moisture content.
Dew Point	The temperature corresponding to the condensation evaporation equilibrium at a cooled surface varies with the amount of water present.
Gravimetric	A volume of moist air is exposed to a drying agent and subsequently weighed. The weight corresponds to the moisture.
Infra-red	The amount of absorption between the infrared range (1.5 to 1.93µm), which is computed for a reference cell and then for the sample cell.
Microwave	The radiation at the receiving end attenuates as the amount of water content increases.
Psychrometric	The introduction of humid air on the wet-bulb evaporation cools the wet bulb and the temperature is measured. The temperature change varies with the amount of water present in the humid air introduced.
Radio-frequency sensor	Radio-frequency current produced due to the dielectric change is a function of moisture content.
Resistance	The conductivity of the sensor depends on the amount of water vapour adsorbed.
Thermal conductivity	Self-heated thermistors are connected in a Wheatstone's bridge circuit. Due to the moisture present, there is an imbalance in the bridge as the heat dissipation in the reference and measuring thermistors.

K. Moisture Content

This is one more term that expresses humidity, which is usually used for the general description. It also refers to the proportion of water present in liquids or solids.

This review discusses the various approaches carried out before to develop a humidity sensor. Some of the types of humidity sensors and their working mechanism are tabulated above in table 1. Designing the humidity sensors and their respective applications are discussed in detail in next section. Humidity, temperature, and light play key role in the environment, which influence human comfort, industrial process, and agricultural activities. Among these three cases, agricultural activities may be the furthermost elementary level of production in which environmental monitoring devices are used. Agriculture is still generally run by the domestic unit whether the area of farming is small or large. In some republics, various machines have been introduced in cultivation irrespective of the size of cultivated areas and the workforce. The machines are, however, mainly used to decrease substantially focused tasks. Food products such as fruits, grains, and vegetables available to customers at supermarkets have appreciated an enhancement in quality over the years. This may have accomplished because of good fertilization, effective biological methods, advances in seed quality, water regulation, temperature control and so on. The experience of farmers mainly decides these factors. Meanwhile microtechnology has become progressive in strategy and developments, ecological monitoring sensor technology may help in growing crops, fruits, and vegetables in the so called quantitative way.

The benefits that the sensors offer include:

1) Remote monitoring of the environment
2) Data logging and storing sensor data for reference and future modelling
3) Automation of some workload
4) As an aid for the quantitative determination of types of tasks

This may result in better quality control, a reduction of agricultural producers' workloads and a better understanding of the correlation of growing conditions and environmental influence. To achieve these benefits, some issues should be discussed, namely cost, sensor size, sensor installment and sensor disposal. The cost has a significant impact because of the enormous number of sensors needed to check the environment in a useful way. The sensor cost is decided by the sensor size, fabrication processes, and packaging method. To meet some of these requirements for improved environmental monitoring, some novel strategies were developed throughout this research. Humidity, temperature, and wind speed/direction sensors were incorporated in the environmental sensors.

II. REQUIREMENTS OF HUMIDITY SENSORS

For a good humidity sensor following qualities are required:

A. Good Reproducibility

Reproducibility is a significant characteristic in regard to reliability. For a sensor to be useful, its output should be consistent with time.

B. High Sensitivity

If the sensitivity is low, large signal amplification and many parts are required to meet a satisfactory sensor output. In relation to output signal quality, the signal-to-noise ratio may also degrade.

C. Small Hysteresis

Hysteresis is the alteration of sensor output among increasing and decreasing humidity. Sensors with small hysteresis are useful for precise analyses.

D. Good Linearity

Linearity may not be a key issue because compensation is possible with a microprocessor. However, good linearity cuts the demand for additional electronic circuits, fragments, and programming effort.

E. High Durability

Durability can be classified in terms of mechanical and chemical features. Mechanical durability is figured out by the type of substrate, sensor assembly and packaging process.

F. Negligible Temperature Dependence
Negligible temperature dependence is useful to simplify the sensor design, support electronics and programming for compensation.

G. Resistance Against Contamination
Contaminations such as smoke, oil, organic solvent, other chemicals and so on degrade the performance of sensor, resulting in misleading sensor outputs. Recovery methods from contamination may be employed in certain applications for more reliable sensors.

H. Low Cost
Although performance of sensor may be excellent, if the production cost is very high, this may become a disincentive to entering markets.

I. Fast Response
Response time may become important in the applications requiring fast response time such as industrial processes and medical facilities.

III. TYPE OF HUMIDITY SENSORS
Sensors are key elements in the rapidly evolving fields of measurements, instrumentations, and automated systems. The recent signs of progress made in improving the reliability and lowering the cost of microprocessors and interface circuits have resulted in a higher demand for sensors, which convert physical or chemical quantities in various environments into electrical signal. Distinct functions and materials have been investigated, and several devices have been put on the market or have become part of sophisticated instrumentations. The following section describes some of the most used methods of humidity measurements based on sensing materials.

A. Ceramic Humidity Sensors
Among all the sensing materials, functional ceramics have played a leading role because of their intrinsic characteristics: they are superior in mechanical strength and chemical resistance in most environments and in the reproducibility of the electrical properties. They have also been widely used to satisfy diverse needs for sensing devices, and consistent results have been obtained in the field of atmospheric sensors, i.e. temperature [8], humidity [9-15], and gas sensors [16-20]. It is well known that bulk ceramics are prepared by a relatively effortless process consisting of mixing raw materials, forming the part, and sintering. Ceramics are characterized by their unique structure consisting of crystal grains, grain boundaries and when they are porous, by large surface intra and intergranular pores. Individually high density and porous ceramics are effortlessly produced by controlling the compact forming and sintering conditions. Additionally, in ceramic materials, solid, solution or doping can be simply formed and improved properties are relatively easy to obtain [21-22]. Sensitive thick ceramic films can have obtained by the screen printing and firing technique [23-24], while the radio frequency sputtering [25], chemical vapour deposition [26] and sol-gel processes [27] enable one to deposit thin ceramic films on different substrates. In the following table, several ceramic materials with their sensing properties and functions are depicted.
In porous ceramics, the surface and open pores tend to collect water vapour and gases through chemical and physical adsorption and through condensation [28-31]. Especially in semiconductor ceramics, electrical properties are largely related to the grain size and size distribution of the open pores. The pore surface conductivity changes with even small variations in the humidity or with the adsorption of various gases. Porosity-controlled ceramics are suitable for atmospheric sensing's such as humidity and gas sensors. As we know that humidity or gas sensors are typically exposed to atmospheric surroundings, which has many other components. They tend to drop their intrinsic sensitive properties through use because of some complicated physical and chemical processes that arise among these components and the material. Major research efforts are directed towards developing highly reliable functional ceramic materials. In addition, most ceramics are not single functional but multifunctional. Thus, the key to achievement in developing a single functional material is the technology of concealing undesired functions. The nonappearance of the selectivity is considered too restrictive for the employment of some ceramics as sensors. Nowadays, the electronic technology is making full use of the intrinsic manifold function of the sensor and multifunctional devices are now being set up. These devices can complete many functions with a single element. For example, in atmospheric-type devices, there is a huge demand for multifunctional sensors that can independently measure both the humidity and another gas, or the humidity and the temperature, at the same time.

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TABLE-2 **Ceramic sensors: Properties, Materials, and Functions**

Sensors	Ceramic materials	Sensor function
Temperature	(Mn, Cu) (Mn, Co, Ni)$_2$O$_4$ CoAl$_2$O$_4$; NiAl$_2$O$_4$; SiC Mg (Al, Cr, Fe)$_2$O$_4$; BaTiO$_3$ VO$_2$, (Mn, Zn)Fe$_2$O$_4$	NTC Thermistor PTC Thermistor Temperature Switch
Gas	SnO2; ZnO; γ-Fe$_2$O$_3$; α-Fe$_2$O$_3$; WO$_3$ In$_2$O$_3$ Perovskite type: XYO$_3$ (X:Ca,Ba,Mg, Sr) (Y: Zr,Sn,Ti,Ce) TiO$_2$;CoO-MgO;MgO; Y$_2$O$_3$	CH$_4$; C$_4$H$_{10}$; CO; SO$_2$; NO; H$_2$S; NH$_3$; Ozone Air/Fuel Ratio O$_2$
Ion	AgX (X: Cl, Br, I, CN, SCN) PbS-Ag$_2$S; CdS-Ag$_2$S CuS-Ag$_2$S; LaF$_3$	Ion selective electrode
Position-Velocity	Pb(Zr, Ti) O$_3$	Piezoelectricity
Optics	PbTiO$_3$; LiTaO$_3$ LiNbO$_3$; Pb(Zr,Ti) O$_3$ CaF$_2$; Li$_2$B$_4$O$_7$	Pyroelectricity (Infrared detection) Thermoluminescence

B. Resistive Type

Resistive sensors work on the principle of conduction [32]. The sensor material used is sensitive to humidity (hygroscopic), and its resistance varies with the change for moisture present. From the open literature written in the last 25 years, those materials are acetates, fluorides, chlorides, iodides, nitrates, sulphate, carbonates, phosphates, and oxides, as well as polymeric materials. These materials can also be used to design a capacitive humidity sensor.

This type of humidity sensors show the variation in electrical resistance of a humid medium for example a conductive polymer, salt, or dried substrate [33-38]. Fig.1 show the typical characteristic of resistive humidity sensor. The variation in resistance is normally an inverse exponential connection to the humidity. Resistive type sensors usually hold noble metal electrodes either placed on a substrate by photoresist system or wire-wound electrodes on a plastic or glass hose. The substrate is encrusted with a salt or conductive polymer. On the other hand, the substrate may be treated by activating elements such as acid. The sensor adsorbs the water vapour, and ionic functional groups are dissociated, resulting in an increase in electrical conductivity. Mostly, resistive type humidity sensing devices consume regular AC excitation voltage with no DC bias to avoid polarization of the sensor. The resulting current is rehabilitated and rectified to a DC voltage signal for the other scaling or strengthening.

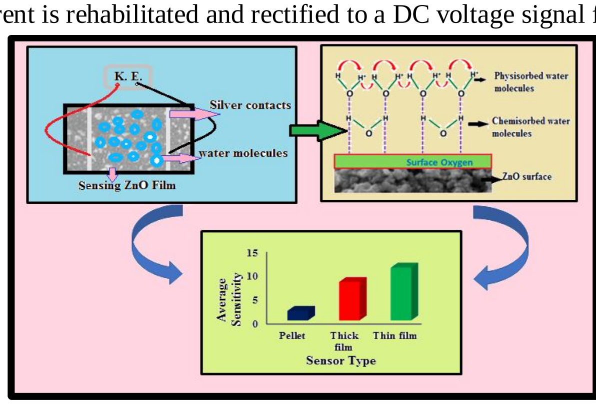

Fig.1 Resistive type humidity sensor

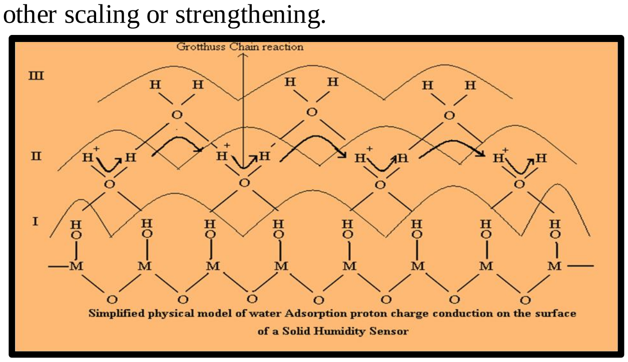

Fig. 2 Humidity sensing mechanism for resistive type humidity sensor

A discrete benefit of resistive humidity sensor is its repeatability, usually within ±2% RH, which consents the electric signal circuit board to be regulated by a WAQ controller at a fixed RH value. This cuts the necessity for humidity calibration standards, so these sensors are mostly field replaceable. The accuracy of the specific sensors may be set up by investigating in an RH regulator chamber or by a computer-based data acquisition (DA) system referenced to homogenous humidity controlled environment. Nominal operating temperature of resistive sensors ranges from –40°C to 100°C.

In housing and commercial surroundings, the life expectation of these sensors is larger than 5 years, but exposure to chemical vapors and other chemicals such as oil mist may lead to untimely failure. Additional downside of some resistive sensors is their tendency to shift values once exposed to condensation if a water-soluble coating is used. Resistive humidity sensors have significant temperature dependencies when installing in an environment with large (>10°F) temperature fluctuations. Simultaneous temperature compensation is incorporated for accuracy. The small size, low cost, interchangeability, and long-term stability make these resistive sensors suitable for use in control and display products for industrial, commercial, and residential applications.

First mass-produced humidity sensor was the Dunmore type which was fabricated by NIST in the 1940s and still it is in use [39]. It contains a twin winding of palladium wire on a plastic tube which is coated with a mixture of polyvinyl alcohol and either lithium bromide (LiBr) or lithium chloride (LiCl). Changing the concentration of LiBr or LiCl outcomes in a high-resolution sensor that cover humidity extents of 20% to 40% RH. For a smaller RH, control function in the range 1 to 2% RH, accuracies of 0.1% can be achieved.

The modern growth in resistive type humidity sensors uses a ceramic layer to overcome limitations in surroundings where condensation happens. The sensor has a ceramic substrate with noble metal electrodes placed by a photoresist method. The surface of the substrate is layered by a conductive polymer or a ceramic mixture, and the sensor is fitted in a protecting plastic cover with a dust filter. The binding material is a ceramic powder suspended in liquid form. After the surface is coated and air-dried, the sensors are heat treated. The process results in a clear non-water-soluble thick film coating that fully recovers from exposure to condensation. The engineering procedure yields sensors with a repeatability of better than 3% RH over the 15% to 95% RH range. The precision of these sensors is confirmed to ±2% RH by a computer-based DA system coupled to a standard reference. The recovery time from full condensation to 30% is a few minutes. When used with a signal conditioner, the sensor voltage output is directly proportional to the ambient relative humidity.

There are several types of humidity sensors [40-45] checked by the different type of adsorption mechanism. But resistive type humidity sensors are based on the variation in conductivity/resistivity of materials with the amount of water adsorbed by them. This principle is employed for the measurement of humidity for all such type of humidity sensors. Although this type of sensor can be subdivided into two parts depending upon their conduction mechanism;

(i) Ionic-type humidity sensor

(ii) Electronic-type humidity sensor.

1) *Ionic Type:* This type of sensor uses the change of ionic conductivity resulting from water adsorption and desorption. The humidity sensitive characteristics depend on the intrinsic conductivity of the materials used and microstructure of specimen. Ionic category oxides are associated equally to the chemisorption and physisorption of the water molecules on the oxide surface along with capillary condensation in the micro pores of ceramics. These sensors mostly work at low temperatures. W. J. Fleming [46,79] has shown that the physical mechanism operating for ionic type humidity sensors is the same for both the capacitive and resistive types.

a) *Identification of the Charge Carriers:* Experimental studies [47-48] have shown that humidity enhanced conduction on nonconducting surfaces is entirely due to electrical charges residing on the external surfaces. The simultaneous measurement of surface charge and conduction charge by means of Kelvin probe and an integrating ammeter, has proved that humidity enhanced conduction must be the result of an ionic charge flow on the external surface of the solid.

b) *Adsorption and Dissociation Mechanism of Water Molecules:* Since water is a polar molecule, the negatively charged oxygen of the water molecule is electrostatically attracted to the positively charged cationic side of the metal oxide surface. If the charge density of the cationic side is low then water remains physically adsorbed at the surface by weak electrostatic field. When the cationic charge density is high, as in the case of alkali salts, the electrostatic force is high enough to form a chemical bond between hydrogen and oxygen of water molecule, which in turn break the bond between oxygen and one of the hydrogen atoms. Mostly the force is high enough to break the bond in the initially adsorbed water vapour layer. Therefore, the initial monolayer in generally chemisorbed. This chemisorbed layer can be removed thermally by increasing the ambient temperature. The irreversible reaction of the first layer can be given as:

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$$M^{+} + H_2O \rightarrow M-OH + H^{+}$$

The complete water adsorption is schematically depicted in the following Figure. The subsequent water layer is physically adsorbed (shown as layer II in Fig. 2) on the first chemisorbed layer. This physisorbed water layer is bound by weak electrostatic force (known as hydrogen bonding) on the underlying chemisorbed layer and can be reversibly removed by decreasing humidity. Therefore, this layer is mostly contributed for the humidity sensitive conduction of ceramic materials. The chemisorbed water molecule exerts electrostatic field, which not only attract water molecule. It was concluded that the weakening action of the surface electrostatic field promotes the dissociation of physisorbed water molecule in the following manner:

$$2H_2O \rightarrow H_3O^{+} + OH^{-}$$

2) *Electronic Type:* In the electronic type of humidity sensor, the major charge carriers are electrons whose concentrations and mobility are influenced by adsorbed water. In the above-mentioned mechanism of ionic based humidity sensor, the physisorbed layer present is always in equilibrium with the atmospheric humidity as the rate of adsorption is equal to the rate of desorption. Since the ambient temperature increases, the thickness of the physisorbed water layer decreases because of the rate of desorption increases. The sensors now work as a semiconductor gas sensor, where electronic conductivity changes with ambient gas concentration [49]. Operating temperatures of this type of sensor is usually greater than 100°C. The observed change in this type of sensor is based on the chemisorption of the water molecule on the semiconducting oxide. The resistivity increases or decreases according to the type of semiconducting oxide. i.e. p or n-type. This indicates that electrons are apparently transferred from water molecule to oxide. The surface of the semiconductor is adsorbed with oxygen ions in the air, which reduces the conductivity of the base material. The reaction of reducing gas with this adsorbed oxygen removes the oxygen ion and the conductivity again increases.

C. Capacitive Type

Capacitive sensors are the most popular amongst all the existing humidity sensors [50-53]. The capacitive humidity sensor works on the principle of change in the dielectric of the capacitor due to the absorption of water in the atmosphere. Fig. 3 stands for a setup for capacitive type humidity sensor. The dielectric material is a hygroscopic material that responds to the humidity after meeting the water content.

The speed of a capacitive humidity sensor [54] can be changed by using a more humidity-sensitive material or by a change in the shape/geometry of the sensor film. The conventional parallel plate-structured sensors have only one side of the sensing layer exposed to the moisture. The newly developed cylindrical sensor has polyimide columns of a very small diameter available, which allows extreme adsorption of the humidity. Polyimide is used as the hygroscopic material, and it is deposited on a polysilicon material, which acts as a heater. The heater prevents condensation, which is the key factor in the recovery period of the sensor. The sensor shows high speed because of the application of the moisture around the circumference of the sensor film. This shows a response time of 1.0 second for a polyimide diameter of 5µm. Further speed enhancement can be achieved by using polyimide film columns with lesser diameters.

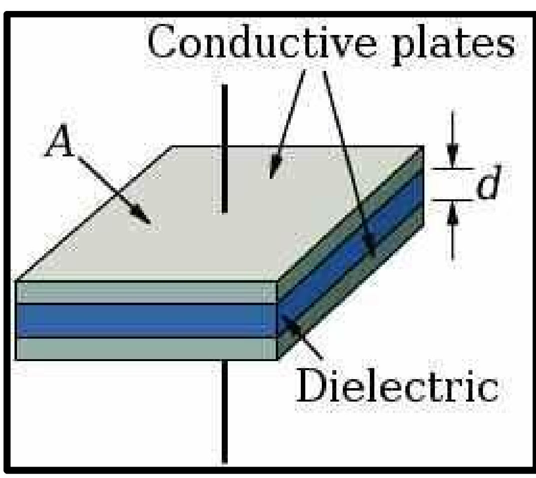


Fig.3 Capacitive Humidity Sensor

Fig.4 Solid-Electrolyte Humidity Sensor

D. Solid-electrolyte Type

Solid-electrolyte type humidity sensors as shown in Fig. 4, have also been investigated for elevated temperature applications [55]. This type of sensor uses mainly the protonic conductivity of materials. Electromotive force (e.m.f.) is the measure o3f the proton conductor type of solid-electrolyte because of variation of water vapour pressure. The proton transfer occurs from higher vapour pressure side, which is the negative pole on lower vapour pressure side. The reactions at each electrode are given as under [56]:

·Electrode with higher vapour pressure

$$H_2O\ (g) \rightarrow 2H^+\ (\text{electrolyte}) + 1/2O_2\ (g) + 2e^-$$

· Electrode with lower vapour pressure

$$2H^+\ (\text{electrolyte}) + 1/2O_2\ (g) + 2e^- \rightarrow H_2O\ (g)$$

E. Polymer-based Humidity Sensors

Polymer-based humidity sensors have a longer history than that of ceramic sensors, and one of them was demonstrated using a plastic in the 1960's [57]. A variety of polymers has also been investigated and continues to be studied. Some polymers used as humidity sensing materials are listed in the following table no. 3:

1) *Polyelectrolyte Type:* Polymers with ionic monomers are classified as polyelectrolyte type humidity sensors. Ionic type materials exploit ionic conductivity, which increases as the humidity increases. Ionic mobility and/or charge carrier concentration handles this type of mechanism. These types of humidity sensors are also called "humistors" [58]. When the polyelectrolytic material meets to the water, the electrostatically held ions in the material start moving freely, and the resistance decreases accordingly. In other words, the polyelectrolyte electrical resistance variation depends upon the varying conduction of the ions within the hygroscopic polyelectrolyte material. The sensor has a polyelectrolytic film deposited over it and connected to the measuring circuitry through metal electrodes. In the presence of humidity, the electrical impedance/resistance of the sensor decreases and a change in the humidity is reported in terms of the voltage. The typical response of the system is such that the resistance of the sensor element decreases by several orders for a change in the relative humidity from 20% to 90%.

TABLE-3 Polymers as humidity sensors

Sensing type	Sensing materials
Polyelectrolyte type	• Sodium sulphonated polystrene + cellulose-based polymer • Styrene sulphonated monomer • Sulphonated polystyrene branch grafted on tetrafluoroethylene film • Various copolymers of ionic and nonionic monomers
Dielectric type	• Polyimide • Polymethyl methacrylate (PMMA) • Poly(ethyleneterephthalate) (PET) • Polysulphone (PSF) • Cellulose acetate butyrate (CAB) • Polyethynylfluorenol (PEFI)

Polyelectrolyte sensors are not so popular since the stability is an issue. Also, they are not so useful in dry conditions since resistance rapidly increases as dry conditions are met. Moreover, an upward drift in the electrical resistance is observed with time, which is not so useful in the long run as far as the stability issues are concerned.

2) *Dielectric Type:* In dielectric type sensors, water molecules are bound at suitable sites in the polymeric network during adsorption and desorption processes. The polymer sensor is made up of two electrodes separated by a polymer film, which is a humidity-sensitive material [59]. Since the dielectric constants of water and polymers are about 80 and 5 respectively, the water molecules in polymer influence their dielectric constant. It can be expected that the dielectric constant increases with the

content of water molecules in the polymers. If electrodes consist of a parallel plate, the principle of operation of the capacitive type humidity sensor is based on the following expression:

$$C = \varepsilon_0 \varepsilon_r A/d$$

Where C is the capacitance, A is the area; d is the thickness of polymer film and ε_r is the relative permittivity of the polymer.

Polymeric humidity sensors are commercially successful because of their bulk phenomenon (rather than the surface phenomenon) and their low cost of production. It is **seen** that these sensors exhibit slow response, and the temperature compensation is required to avoid the change in the capacitance due to temperature. Amongst all humidity sensors commercially available, capacitive sensors are the most preferred. Despite so much development in these kinds of sensors, they offer disadvantages like slow response and less accuracy.

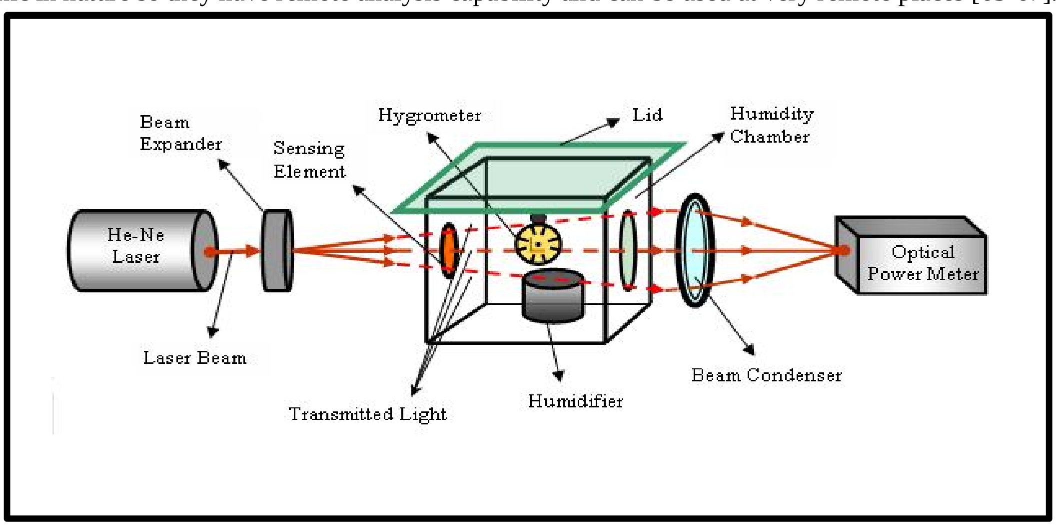
F. SAW Type Humidity Sensor

In preference to sensing capacitance as a straight alteration of dielectric constant other humidity sensing methods based on the surface acoustic waves (SAW) detection principle and piezo resistive transduction principle have been showed. The SAW detection technique has been used to measure humidity with aid of the hygroscopic nature of the polymer. The change in the transmission of sound in air or any other material can show the changes in humidity levels [60-62].

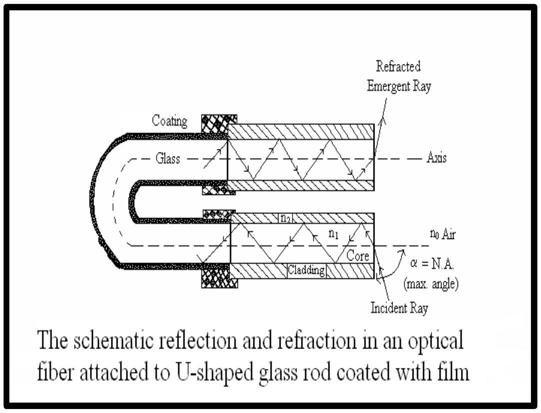
The advantages of acoustic-wave technology include a small footprint, shallow package size, enhanced linear phase, good rejection qualities, and stability over a wide temperature range. The physical structure of acoustic-wave devices also allows for highly reliable and robust designs that exhibit stability in a range of environments/temperatures. In addition, the wafer processing techniques used for these devices enable repeatable fabrication from high- to low-volume production. The fundamental operation behind both SAW and BAW devices is a piezoelectric material, which converts an electromagnetic (EM) signal into an acoustic signal. This physical effect can be used to enhance the filtering response of a device beyond the capabilities of purely electronic devices for the form factor. Mostly, SAW devices work with superior performance in the RF range, however BAW devices reveal higher performance features in the low microwave range.

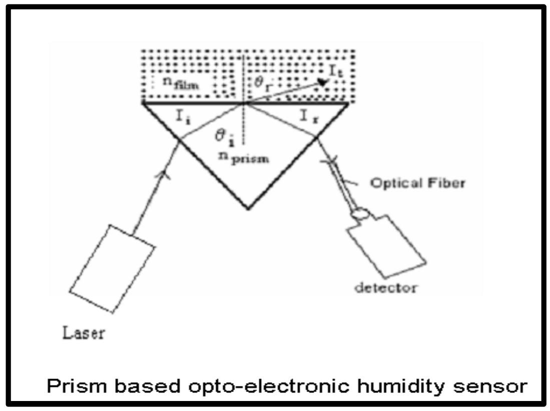
G. Optical Humidity Sensors

1) *Optochemical Humidity Sensors:* In recent years, optochemical sensors [63-64] have attracted attention because of their remote analysis capability, high sensitivity, and compactness. Most of the optochemical sensors are composed of a dye-dispersed polymer in which optical intensity of the absorption, florescence or phosphorescence peak depends upon the chemical species and their concentrations. Various researchers have used this effect for developing optical humidity sensors. Following figure show the proper experimental set-up for optical humidity sensor.
2) *Optoelectronic Humidity Sensors:* These sensors are based on variation in refractive indices of material coated on silica fibre, U-shaped glass rod or prism base as shown in Fig. 5. As the humidity of environment changes, adsorption takes place through the film and it results in the modulation in output intensity of light. Fresnel reflection or Evanescent losses regulate the reflected/transmitted output intensity. Interference or polarization may also be taken place in some cases. These sensors are opto-electronic in nature so they have remote analysis capability and can be used at very remote places [65-67].



(a)





(b) (c)

Fig. 5 (a) Set-up for optical humidity sensor, (b) U-shape optoelectronic sensor, (c) Prism shape optoelectronic humidity sensor.

H. Mechanical Humidity Sensors

This type of hygrometer uses the principle in which the change in the humidity can be measured with the expansion and contraction of some materials. The sensing elements that can be useful in this regard are human hair, catgut, cow's intestine, textile plastic, etc. These expand with the increase in humidity. This is a basic type of a mechanical humidity sensor. The sensing element (for example, human hair) is connected to the pointer of a dial or a pen of a recording chart through a lever. The expansion and contraction in the length of the sensing element due to an increase or decrease in the humidity can be recorded on the dial of a meter on a recording chart. These types of sensors are not so reliable in automatic humidity control in industries because of their inability to produce an electrical signal for measurement.

I. Piezoelectric Humidity Sensors

The change in the resonating frequency of a quartz crystal shows the mass of water absorbed from the air. the piezoelectric humidity sensors that can convert mechanical vibration energy into electrical power has showed unique advantages compared to the former versions because mechanical energy is ubiquitous in our environment. Thus, mechanical energy harvesting will be less affected by working conditions than optical and thermal energies. For instance, Xu *et al.* have demonstrated self-powered pH and UV sensors with a ZnO nanowire-based piezoelectric nanogenerator as their powering sources [68-69].

The working mechanism of such "active sensors" can be ascribed to the polarization screening effect, which was persuaded by the relocation of free charge carriers in the material below piezoelectric potential. As the free charge carrier density of the sensing material will be sensitive to the surface-absorption of chemicals such as hydrogen, ethanol, water, and glucose, then devices could be used for detecting the target subject by checking the difference in generated output voltage. Therefore, both the piezoelectric and chemical sensing properties of the materials are crucial for fabricating high-performance active sensors.

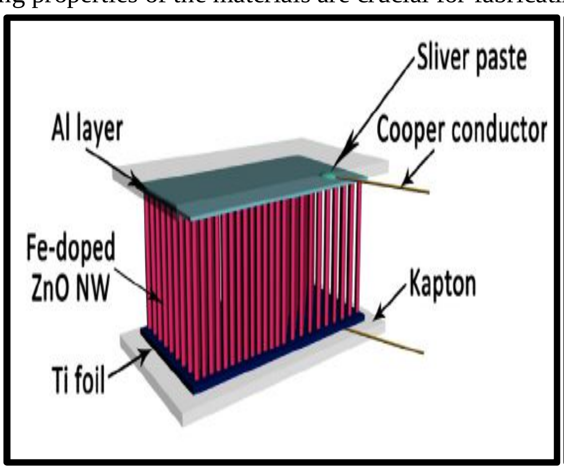


Fig. 6 Piezoelectric Humidity Sensor

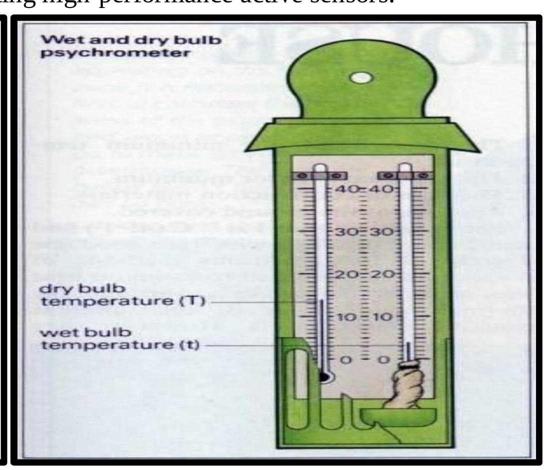


Fig. 7 Wet and Dry Bulb Psychrometer

J. Wet and Dry Bulb Psychrometer

This humidity sensor works on the principle of change in the temperature due to change in the humidity. The temperature difference of two bulbs (wet and dry) of a Psychrometer is affected by the surrounding atmosphere's nature; temperature, pressure, humidity, etc. If all the factors governing the change in temperature are kept constant, it is seen that the temperature changes with the variation in humidity [70-71]. The configuration of this type of hygrometer consists of two matched temperature sensors (wet-and-dry bulb, in this case). One sensor is covered with a porous medium at the bottom for example a wet sock, shoelace etc. Its wetness is maintained by a continuous flow of water on it from reservoir.

Humid air is blown over these sensors. Due to the presence of humid airflow, water evaporates from the wet sock/shoelace. This evaporation causes the wet sensor to be chilled, which reduces the temperature in the sensor. This is an indication of the humidity in the environment. Readings on both the temperature sensors are recorded and the humidity is calculated with the help of the psychrometric graph.

K. Thermal Conductivity Humidity Sensors

This method can be used for temperature above 212°F or for measuring very low humidity levels. It gives absolute humidity independent of ambient temperature. Water vapour, as well as other gases and the respective humidity affect the heat loss from a hot wire [72]. In this type of humidity sensor, a thin platinum film is used as the hygroscopic material. Using the temperature-resistance characteristics of this film and the detection of thermal conductivity in water and air, the amount of moisture present is showed.

Following table give the comparison of all type of humidity sensors based on their working principles, benefits and their disadvantage.

TABLE-4 Comparisons of humidity sensors

Humidity sensor	Principle	Advantage	Drawbacks
Humidity sensors using hygroscopic Materials	Mechanical property change (length, volume, stress)	No power requirement, Low sensitivity to temperature, Inexpensive, Simple	Non-linear output, Hysteresis, Drift over time
	Electrical property change (resistivity, capacitance, frequency)	Can be mass produced, Simple, Inexpensive, Small, Easy to maintain	Hysteresis, Sensitive to contamination
Psychrometer	Relative humidity estimation based on dry- and wet-bulb temperature measurements	No requirement of calibration	Requirement of regular replacement of wick and distilled water, Requirement of air-flow with high flow rate (3 m/sec)
Dew-point humidity sensor	Measurement of dew-point temperature by detecting dew formation on a cooler base	High accuracy, Wide dynamic range, No requirement of calibration	Large size, Expensive, Large power consumption, Regular cleaning of mirror surface
Infrared humidity sensor	Selective absorption of distinctive infrared spectrum by water vapor	Can be used with corrosive gases, Wide dynamic range	Expensive, Possibility of interference with other gas species

IV. APPLICATIONS OF HUMIDITY SENSORS

Humidity plays a leading role in human life in many subtle ways. Water, since present in all living organisms, from simplest to the most complex like a human being, drastically influences their life and working efficiency. Overall human discomfort is higher at both the extreme humidity levels. Throat and nose become dry at low humidity's which in turn decreases the resistance to infection. Therefore, they become susceptible to the disease. The evaporation rate of tear fluid in eyes is high at low humidity. Therefore, frequent blinking of the eyelid is required to keep the tear fluid sufficiently soaked. If the work demands eye concentration which allows occasional blinking of eyelids, then eyes become itchy due to cracks in the protective tear fluid. Skin roughens in dry conditions and can crack. Drying of perspiration is inhibited in wet conditions, thus clothes get to stick to the body causing cloth discomfort. The flexibility, permeability to perspiration and thermal insulation of cloth fabrics is strongly influenced by humidity. Low humidity can induce electrostatic shocks. Dry conditions can induce respiratory infections because it lowers the resistance power of the body. Wet conditions can enable house mites to flourish which can cause allergy to a susceptible occupant. Dust burden is higher in a dry atmosphere. The personal sensation caused by a pollutant is higher at low humidity.

Other than the living organism, humidity drastically influences the various processes also. Moulds in the form of fungus readily grow on materials such as food products, papers, leathers, fabrics and wood, in wet conditions. This causes an unpleasant smell and eventually destroys the materials. Corrosion of metals due to high humidity has been experienced from a long time. For engineering, classy integrated circuits in the semiconductor manufacturing, humidity or moisture levels are regularly checked in wafer processing. There are many domestic applications, such as intelligent control of the living environment in buildings, cooking control for microwave ovens and intelligent control of laundry etc. In medical applications humidity sensors are used in respiratory type of the equipment, sterilizers, incubators, pharmaceutical processing, and biological products. In agriculture fields, green-house air-conditioning, plantation, protation, soil moisture monitoring and cereal storage. In general manufacturing, humidity sensors are used for humidity controller in chemical gas distillation, dryers, ovens, film dehydrations, paper and textile productions and food processing. Because of these severe effects of humidity on mankind, directly or indirectly, it is necessary to measure and control humidity. Humidity measurement is having widespread uses in almost all fields of applications. Application of humidity sensors can be summarized as given Table number 5.

TABLE-5 Applications of humidity sensors and their operating ranges in terms of the relative humidity and temperature measurements

Industry	Industry application	Operating Temperature °C	Humidity range (%RH)
Domestic electric Appliance	Air conditioning system	5~40	40~70
	Drier for clothing	80	0~40
	Microwave oven	5~100	2~100
Automobile	Car window	20~80	50~100
Medical service	Medical apparatus	10~30	80~100
	Incubator	10~30	50~80
Industry	Textile mill (spinning)	10~30	50~100
	Drier for ceramic powder	5~100	0~50
	Dehydrate food	50~100	0~50
	ESD control	22	30~70
	Clean room	21	36~39
	Humidity control in factories	5~40	0~50
	Humidifier for industry	30~300	50~100
	Web printing	-	40~50
	Motor assembly line	17~25	40~55
	Electric device manufacturing	5~40	0~50
Agriculture	Forcing culture	5~40	0~100
	Cereal stocking	15~20	0~45
Measurement	Thermo-hygrostatic chamber	5~100	0~100
	Raido-sonde	50~40	0~100
	Hygrometer	5~100	0~100
Community safety	Nuclear power reactor	>80	80
	Humidity in boiler	100~400	50~100

V. CONCLUSION

This review article is deliver a diverse classification of humidity sensors, their types, working principles, sensing elements, transduction mechanisms, and manufacturing skills. Additionally, the characteristics of the different humidity sensors such as electrical and statistical data will be detailed and gives an added value to the report. Through comparison of global prospects of the sensors it was discovered that there are still disadvantages as to efficiency of sensing elements and conduction values. The flexibility offered by thick film and thin film processes either in the preparation of materials or in the choice of shape and size of the sensor structure offers advantages over other technologies. The resistive and piezoelectric humidity sensors show faster response than other types.

REFERENCES

[1] B. C. Yadav, A. K. Srivastava, P. K. Khanna, "Synthesis of TiO_2-Nb_2O_5 and TiO_2-CuO Nano Co-Oxides and Their Application as Solid State Humidity Sensors", International Journal of Green Nanotechnology, vol. 3, no. 3, pp. 160-169, 2011.
[2] B. C. Yadav, M. Singh, "Morphological and Humidity Sensing Investigations on Niobium, Neodymium, and Lanthanum Oxides", IEEE Sensor Journal, vol. 10, no. 11, pp. 1759-1766, 2010.
[3] B. C. Yadav, R. Srivastava, A. Yadav, T. Shukla, "Synthesis and characterization of ZnO/$ZnNb_2O_6$ nanocomposite and its application as humidity and LPG sensor", International Journal of Green Nanotechnology, vol. 31, no. 1, pp. 56-71, 2011.
[4] B. C. Yadav, A. K. Yadav, "Synthesis of Nanostructured Cuprous Oxide and Its Performance as Humidity and Temperature Sensor", International Journal of Green Nanotechnology: Materials Science and Engineering, vol. 1, no. 1, pp. M16-M31, 2009.
[5] B. C. Yadav, R. C. Yadav, G. C. Dubey, "Optical humidity sensing behaviour of sol–gel processed nanostructured ZnO films", Optica Applicata, vol. 39, no. 3, pp. 617-627, 2009.
[6] A. K. Srivastava, B. C. Yadav, "Humidity sensing properties of TiO_2-Sb2O_5 nanocomposite", Materials Science-Poland, vol. 28, no. 2, pp. 491-502, 2010.
[7] C. Y. Lee and G. B. Lee, "Humidity sensors: A review", Sensors Letters, vol. 3, pp. 1-15, 2005.
[8] W. Heywang, H. Thomann, "Positive temperature coefficient resistors in Electronic Ceramics", edited by B.C.H. Steele, Elsevier, Amsterdam, pp. 29-47, 1990.
[9] N. Yamazoe and Y. Shimizu, "Humidity sensors: Principles and application", Sensors and Actuators B, vol. 10, pp. 379-398, 1986.
[10] T. Nitta, "Development and application of Ceramic Humidity Sensor," in Chemical Sensor Technology, Elsevier, Amsterdam, vol. 1, pp. 57-78, 1988.
[11] T. Yamamoto and K. Murakami, "Humidity sensor using TiO_2-SnO_2 ceramics", Chemical Sensor Technology, Elsevier, Amsterdam, vol. 2, pp. 133-149, 1989.
[12] H. Arai, T. Seiyama, "Humidity Sensors", Sensor a Comprehensive Survey, V.C.H. Weinheim, vol. 3, part II, pp. 982-1012, 1992.
[13] C. Cantalini and M. Pelino, Microstructure and Humidity-Sensitive characteristics of α-Fe_20_3 ceramic sensor", J. Am. Ceram. Soci., vol. 75, no. 3, pp. 546-551, 1992.
[14] B. C. Yadav, P. Sharma, P. K. Khanna, "Morphological and humidity sensing characteristics of SnO_2-CuO, SnO_2-Fe_2O3 and SnO_2-SbO_2 nanocooxides", Bulletin of Materials Science, vol. 34, no. 4, pp. 689-698, 2011.
[15] B. C. Yadav, A. K. Srivastava, P. Sharma, "Resistance based humidity sensing properties of TiO_2",Sens. Transducers, vol. 81, pp. 1348-1353, 2007.
[16] A. Yadav, B. C. Yadav, "A mechanochemical synthesis of nanostructured zinc oxide via acetate route for LPG sensing", Journal of Experimental Nanoscience, vol. 9, no. 5, pp. 501-511, 2014.
[17] A. Yadav, B. C. Yadav, Experimental Investigations on Solid State LPG Sensor Using $ZnFe_2O_4$ Nanocomposite Prepared by Co-Precipitation Method", Journal of Materials Science and Engineering B, vol. 5, no. 11-12, pp. 435-445, 2016.
[18] A. Yadav, B. C. Yadav, "A comparative LPG sensing study of bulk titanium oxide and nanostructured titanium oxide", Science and Engineering Applications, vol.1, no. 5, pp. 58-63, 2016.
[19] B. C. Yadav, S. Singh, A. Yadav, "Nanonails structured ferric oxide thick film as room temperature liquefied petroleum gas (LPG) sensor",Applied Surface Science, vol. 257, vol. 6, pp. 1960-1966, 2011.
[20] R. Lalauze, P. Breuil C. Pijolat, "Thin films for gas sensors." Sensors and Actuators B, vol. 3, pp. 175-182, 1991.
[21] A. Yadav, B. C. Yadav, "Synthesis and Characterization of Nanostructured Cobalt Zincate and Its Application as LPG Sensor", Advanced Science Letters, vol. 20, no. 5-6, pp. 939-945, 2014.
[22] B. C. Yadav, R. Dixit, S. Singh, A Review on Synthesis, Fabrication and Properties of Nanostructured pure and doped tin oxide Films", International Journal of Scientific and Innovative Research, vol. 2, no. 1, pp. 41-57, 2014.
[23] M. Prudenziati, "Thick film Technology." Sensors and Actuators A, vol. 25, no. 1-3, pp. 227-234, 1990.
[24] F. Forlani, "Film spesso nei sensori chimici e biochimici", Elettronica Oggi, vol. 145, pp. 62-69, 1992.
[25] T. Suzuki, T. Yamazaki, K. Takahashi, T. Kageyama and H. Oda, "Ion-beam sputtering apparatus for deposition of multilayered films." J. Mat. Sci. Lett., vol. 7, pp. 79-80, 1980.
[26] R. Lalauze, P. Breuil, C. Pijolat, "Thin films for gas sensors." Sensors and Actuators B, vol. 3, pp. 175-182, 1991.
[27] B. C. Yadav, "Sol–gel processed TiO_2 films on a prism substrate as optical moisture sensors", Sensor Transactions Journal. Vol. 79, pp. 1217-1224, 2007.
[28] T. Morimoto, M. Nagao and F. Tokuda, "The relation between the amounts of chemisorbed and physisorbed water on metal oxides", J. Phys. Chem., vol. 73, pp. 243-248, 1969.
[29] E. McCafferty, C. Zettlemoyer, "Adsorption of water vapour on α-Fe_2O_3", Discuss. Faraday Soc., vol. 3, pp. 239-255, 1969.
[30] Y. Shimizu, H. Arai and T. Seiyama, "Theoretical studies on the impedance-humidity characteristics of ceramic humidity sensors", Sensors and Actuators, vol. 7, pp. 11-22, 1985.
[31] J. H. de Bore, "The shape of capillaries, the structure and properties of porous materials" Butterworth, London, pp.68-94, 1958.
[32] B. C. Yadav, R. Singh, S. Singh, P. K. Dwivedi, "Humidity sensing investigations on nanostructured zinc stannate synthesized via chemical precipitation method", International Journal of Green Nanotechnology, vol. 4, no. 1, pp. 37-45, 2012.
[33] J. H. Andrson, G. A. Parks, "Electrical properties of silica gel in the presence of adsorbed water", JPC, vol. 72, pp. 3662-3668, 1968.
[34] M. Hijikigawa, S. Miyoshi, T. Sugihara, A. Jinda, "A thin-film resistance humidity sensor", Sens. Act. B, vol. 4, pp. 307-315, 1983.
[35] R. K. Nahar, V. K. Khanna and W. S. Khokle, "On the origin of the humidity sensitive electrical properties of porous alumina oxide", J. Phys. D: Appl. Phy. 17 (1984) 2087.
[36] S. Babu, S. Chatterjee, M. Saha, S. Banddyapadhyay, K. K. Mistry and K. Sengupta, "Study of electrical characteristics of porous alumina sensors for detection of low moisture in gases" Sens. Act. B, vol. 79, pp. 182-186, 2001.

[37] S. K. Nandi, S. Chatterjee, S. K. Samanta, G. K. Dalapati, P. K. Bose, S. Varma, S. P. Patil and C.K. Maiti, "Electrical properties of Ta_2O_5 film deposited on ZnO", Bull. Mat. Sci., vol. 26, pp.365-370, 2003.
[38] A. K. Yadav, B. C. Yadav, K. Singh, "Solid state conductivity of sucrose and its applications as humidity and temperature sensors", Sens. Trans., vol. 88, pp. 66-73, 2008.
[39] F.V. Dunmore, An improved electrical hygrometer, J. Research of NBS, vol. 23, pp. 701-714, 1939.
[40] G. Gusmano, G. Montesperelli, E. Traversa, A. Bearzotti, G. Petrocco, A. D'Amico and C.Di. Natale, "Magnesium-aluminium spinel thin film as humidity sensor", Sens. Act. B, vol. 7, pp. 460-463, 1993.
[41] B. C. Yadav, K. Agrahari, S. Singh, T. P. Yadav, "Fabrication and characterization of nanostructured indium tin oxide film and its application as humidity and gas sensors",Journal of Materials Science: Materials in Electronics, vol. 27, no.5, pp. 4172-4179, 2016.
[42] J. Jawalkar, P. More, S. R. Damkale, R. Kumar, B. C. Yadav, A. K Vishwanath, S. H. Sonawane, P. K. Khanna, "Effect of Organic Chromophore on Nano-sized TiO2: Optical properties and humidity sensing", International Journal of Green Nanotechnology: Physics and Chemistry, vol. 1, no. 1, pp. P40-P50, 2009.
[43] P. M. Ajayan, C. R. Gautam, C. S. Tiwary, S. K. Biradar, R. K. Sonker,B. C. Yadav, Sujin Jose, Sehmus Ozden, "Synthesis and porous h-BN 3D architectures for effective humidity and gas sensors", RSC Advances, vol. 6, no. 91, pp. 87888-87896, 2016.
[44] A. Furlani, G. Iucci, M. V. Russo, A. Bearzotti and A. D'Amico, "Iodine doped polyphenylacetylene thin film as humidity sensor", Sens. Act. B, vol. 8, pp. 123-126, 1992.
[45] M. Singh, B. C. Yadav, "Physics and Technology of Humidity Sensing Through a Solid State Pellet of Cerium Oxide", Sensors & Transducers, vol. 186, pp.140-147, 2015.
[46] William J. Fleming, "A Physical Understanding of Solid State Humidity Sensors", SAE Technical Paper, no. 81043, pp. 1656-1667, 1981.
[47] W. Shokley. W. Hooper, H. Queisser and W. Schroen, "Mobile electric charges on insulating oxides with application to oxide covered silicon p-n junctions", SS2, pp. 277-287, 1964.
[48] C. Adat, D. Deresmes, D. Vuillaume and D. Stievenard, "Influence of surface defects on the electrical behaviour of aluminium porous silicon junctions", Appl. Phys. Lett., vol. 64, pp. 2827-2829, 1994.
[49] R Kumar, B. C. Yadav, "Humidity sensing investigation on nanostructured polyaniline synthesized via chemical polymerization method", Materials Letters, vol. 167, pp. 300-302, 2016.
[50] P. Thoma, J.O. Cola and R. Stewart, "Capacitance humidity sensing transducers", IEEE Trans. On Components Hybrids and Manufacturing Technology, vol. 3, pp. 21-323, 1979.
[51] H. Grange, C. Bieth, H. Boucher and G. Delapierre, "A capacitive humidity sensor with very faast response time and very low hysteresis", Sens. Act. B, vol. 12, pp. 291-296, 1987.
[52] M. Dokmeci, and K. Najafi, "A high-sensitivity polymide capacitive relative humidty sensor for monitoring anodically bonded hermetic micropackages", IEEE Journal of Microelectromechanical Systems, vol. 10, pp. 197-204, 2001.
[53] M. Matsuguchi, Y. Sadaoka, Y. Sakai, T. Kuroiwa, and A. Ito, "A capacitive type-humidity sensor using cross-linked poly(methyl methacrylate) thin films", J. Electrochem. Soc., vol. 138, pp. 1862-1865, 1991.
[54] U. Kang, and K. D. Wise, "A high speed capacitive humidity sensor with on chip thermal reset", IEEE Trans. Electron Devices, vol. 47, pp. 702-710, 2000.
[55] M. Zhou, A. Ahmad, "Sol–gel processing of In-doped $CaZrO_3$ solid electrolyte and the impedimetric sensing characteristics of humidity and hydrogen" Sens. Actuators B, vol. 129, no. 1, pp. 285-291, 2008.
[56] H. Iwahara, H. Uchida, K. Ono and K. Ogaki, "Proton conduction in sintered oxides based on $BaCeO_3$," J. Electrochem. Soc., vol. 135, no. 2, pp. 529-533, 1988.
[57] D. E. l. Nelson and E. J. Amdur, "A relative humidity sensor based on the capacitance variations of plastic film condenser", Humidity and Moisture: Measurement and control in science and industry, vol. 1, pp. 597-601, 1963.
[58] M. R. Yang and K. S. Chen, "Humidity sensors using polyvinyl alcohol mixed with electrolytes", Sens. Act. B, vol. 49, pp. 240-247, 1998.
[59] T. Zhang, "A polymer sensitive to humidity and its electrical properties analysis", J. Mat. Sci. Lett., vol. 19, pp. 1419-1422, 2000.
[60] D. C. Kim, H. D. Kweonm K. W. Kim, J. O. Jung, Y. S. Yoon, D. I. Kim, and I. H. Yoo, "A study on the humidity sensor using surface acoustic wave delay line", Ungyong Mulli., vol. 8, pp. 84-89, 1995.
[61] C. Caliendo, E. Verona, A. D'Amico, A. Furlani, G. Iucci and M.V. Russo, "A new surface acoustic wave humidity sensor based on a polyethylfluorenol membrane", Sens. Act. B, vol. 18-19, pp. 82-84, 1994.
[62] H. Wohltjen, "Mechanism of operation and design considerations for surface acoustic wave device vapour sensors", Sens. Act., vol. 5, pp. 307-325, 1984.
[63] M. Ando, "Recent advances in optochemical sensors for the detection of H_2, O_2, O_3, CO, CO_2 and H_2O in air", Trends in Analytical Chemistry, vol. 25, no. 10, pp. 937-948, 2006.
[64] A. Vijayan, M. Fuke, R. Hawaldar, M. Kulkarni, D. Amalnerkar, R.C. Aiyer, "Optical fibre based humidity sensor using Co-polyaniline clad", Sen. and Actuators B: Chemical, vol. 129, no. 1, pp. 106-112, 2008.
[65] B. C. Yadav, N. K. Pandey, A. K. Srivastava, P. Sharma, "Optical humidity sensors based on titania films fabricated by sol–gel and thermal evaporation methods", Measurement Science and Technology, vol. 18, no. 1, pp. 260-64, 2006.
[66] B. C. Yadav, R. C. Yadav, P. K. Dwivedi, "Sol–gel processed (Mg–Zn–Ti) oxide nanocomposite film deposited on prism base as an opto-electronic humidity sensor", Sensors and Actuators B: Chemical, vol. 148, no. 2, pp. 413-419, 2010.
[67] S. K. Shukla, G. K. Parashar, P. Misra, B. C. Yadav, R. K. Shukla, A. Srivastava, F. Deva, G. C. Dubey, "On exploring sol-gel deposited ZnO thin film as humidity sensor: an optical fiber approach", Chemical Sensors 20, pp. 546-547, 2004.
[68] S. Xu, Y. Qin, C. Xu, Y. Wei, R. Yang, and Z. L. Wang, Self-powered nanowire devices, Nature Nanotechnology vol. 5, pp. 366 – 373,2010.
[69] G. Gerlach, K. Sager, "A piezoresistive humidity sensor", Sens. Act. A, vol. 43, pp. 181-184, 1994.
[70] R. J. Taylor, "The response of Psychrometer fluctuation in vapor pressure: humidity and moisture", R. E. Ruskin, vol. 1, pp. 76-82, 1965.
[71] R. W. Worrall, "Psychrometer determination of relative humidities in air with dry-bulb temperature exceeding 212F: humidity and moisture", R. E. Ruskin, vol. 1, pp. 106-109,1965.