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MEMS Humidity Sensors

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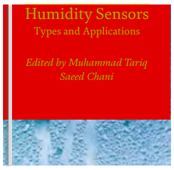

Humidity Sensors

Edited by Muhammad Tariq Saeed Chani, Abdullah Mohammed Asiri and Sher Bahadar Khan

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Abstract

This chapter reviews MEMS humidity sensors fabricated using microfabrication technologies. It discusses the operation principle, different designs, and the fabrication technologies for the different sensing mechanisms. Sensing humidity using capacitive sensors is first reviewed with a highlight on the different sensing materials and how their permittivity and physical parameters affect the sensor performance. Then the chapter discusses the piezoelectric humidity sensing method, wherein piezoelectric sensors the dynamic mode measurement is used. In these sensors, the mass changes corresponding to the humidity, resulting in resonance frequency shift and amplitude change. Finally, the chapter reviews the resistive humidity sensors where the change in the resistivity of various materials is used as an indication of humidity change in the environment.

Keywords

Humidity sensors | MEMS | capacitive sensors | piezoelectric sensors | resistive sensors

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Chapter sections

1. Introduction

Miniaturizing devices and systems are the key factors of today's technology advancement. Humidity sensor developments in all its categories are tightly related to micromachining technology development. Such developments allow the advantages of high performance, low power consumption, cost reduction, and the capability to fabricate batches of devices and systems that are needed for today's technology [ ].

Micro Electro Mechanical Systems (MEMS) are miniature devices fabricated using micro fabrication processes that are used for both sensing and actuation. When used in sensing, their mechanical properties are employed to generate electrical signals that indicate the measured parameter. When used in actuation, the electrical signal is used to produce micro movements. MEMS have been widely used in different sensing applications ranging from environmental sensing, e.g., temperature, to motion and position and detection, e.g., accelerometers [ ].

Humidity, in general, can be measured using absolute humidity, dew point, mixing ratio, and relative humidity. Among these measurements, relative humidity is the most common measure used in the literature [, , , ,]. In a closed system, relative humidity (RH) is defined as the total vapor pressure in volume to the pressure where the water vapor saturated at a given temperature, and its formula is generally expressed as:

$$\%RH = \frac{P_t}{P_s} \quad \text{E1}$$

where P_t is the total pressure and P_s is the saturated pressure [ ].

This chapter will review the three main sensing schemes usually used for humidity sensing in MEMS devices, starting with capacitive sensing with its sensing principle and fabrication process. The piezoelectric sensing method is then detailed, followed by a description of the resistive sensing. In each part, the sensing mechanism will be briefly reviewed with a glance at the fabrication method. The chapter is then concluded by a comparison between the three sensing schemes.

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2. Capacitive humidity sensing technology

depicts the basic design of a capacitive humidity sensor. This sensing method depends mainly on changing the permittivity of a sensing material due to its absorbance of water vapor molecules leading to a change in the capacitance value. As the sensing materials are exposed to the environment, water vapor molecules enter their pores resulting in a change of the sensing materials' permittivity. This change occurs because the water molecules have high permittivity due to their polar structure compared to the permittivity of the sensing materials. The sensitivity of the used layer can be attributed to several parameters, e.g., pores sizes, layer thickness, and area exposed to the environment [ ]. Capacitive sensing has several advantages over other sensing methods. It has a simple readout circuit, low power consumption, and nonmoving structure [ ].

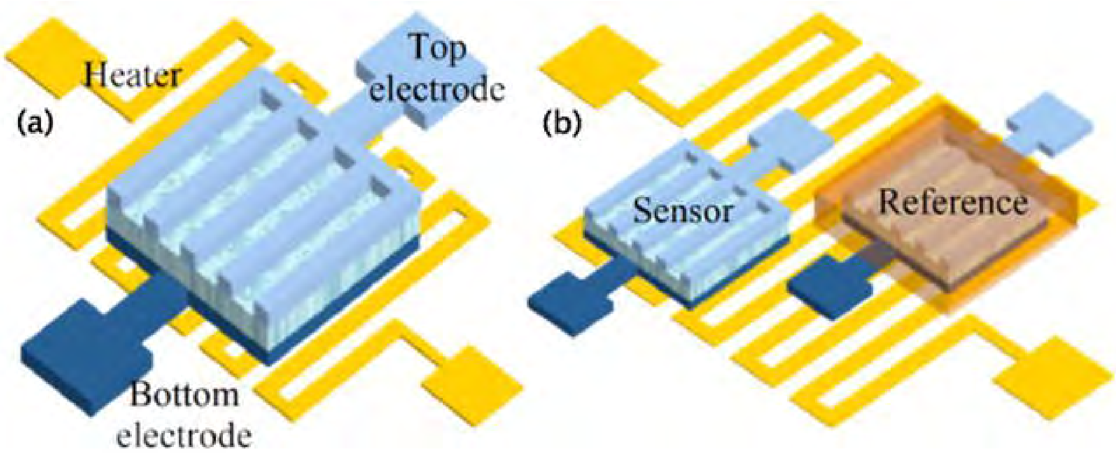

Figure 1.

A 3D model of a capacitive humidity sensor as a (a) standalone, and (b) next to a capacitive reference [8].

To calibrate the capacitance of the sensing element, another capacitive structure is fabricated next to it as a reference, . The sensing materials in this reference capacitor are completely covered by the top electrode and are not exposed to the environment. Hence, its permittivity can be referenced as it does not absorb any water vapor. The performance of the humidity sensor can be improved by adding a heating element beneath it. The heating element increases the sensing materials' temperature, which increases the humidity diffusion constant and hence the response time. It can also be used to reset the sensor faster to the dry state [ ]. Notice that heating the sensor will affect its dielectric constant, so compensation must be made to the readings to account.

2.1 Design and operation

Humidity can be sensed using a capacitive scheme by using two parallel electrodes with a material sensitive to water vapor as the insulating layer between the two electrodes, . The device capacitance is given by [ ]:

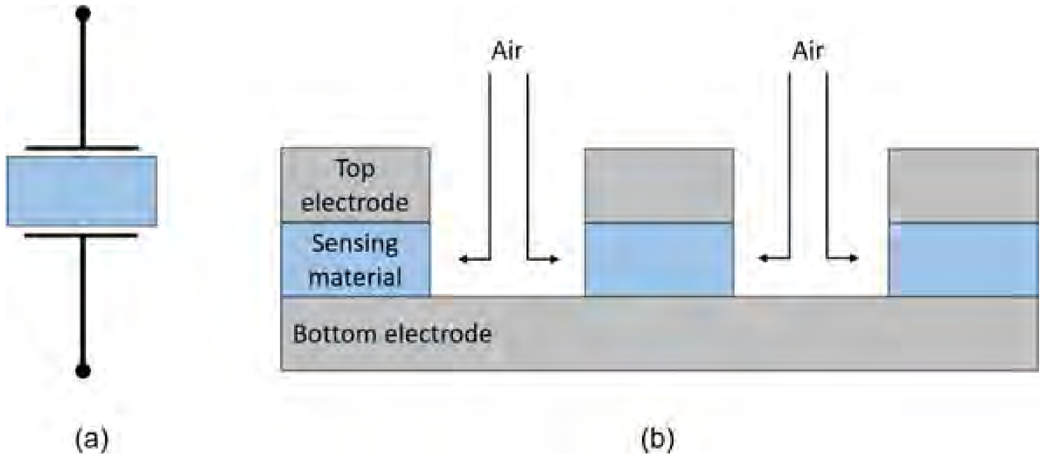

Figure 2.
(a) Capacitive humidity sensor sensing scheme; and (b) a cross-section of the fabricated sensor [9].

$$C = \varepsilon_0 \varepsilon_r \frac{A}{d} \qquad \text{E2}$$

where ε_0 is the air permittivity, ε_r is the relative permittivity of the sensing material, A is the capacitive area, and d is the capacitive gap, i.e., sensing material thickness.

It is important that the device structure exposes the sensing material from its side surfaces in order to allow the sensing material between the electrodes to absorb moisture effectively, . If the sensing material is left without patterning, most of the moisture will be absorbed in the part that is not sandwiched between the electrodes, leading to low sensitivity [ ].

There are several parameters that are used to characterize the capacitive sensor performance, e.g., response/recovery time, range, sensitivity, etc. The sensitivity of these sensors is usually linear and largely determined by device design structure design, and it can be expressed as [ ]:

$$S = \frac{\Delta C/C}{\Delta\, RH} \qquad \text{E3}$$

where ΔC is the capacitance change due to humidity, C is the nominal capacitance, and $\Delta\, RH$ is the relative humidity variation.

For a quick response time and better sensitivity, the sensing material thickness should be minimized. Furthermore, the thickness of the electrodes should be minimized for better sensitivity and to reduce the parasitic capacitance, but that means additional fabrication steps that are needed to form the bonding pads [, ,]. Capacitive sensors can measure the humidity over the er ange from 0–100%, which makes them preferable in most applications [ ].

2.2 Fabrication

Simple capacitive humidity sensors can be easily fabricated in a 3-mask process [ ], . The process starts with a handle silicon wafer covered with a thin layer of silicon dioxide to create an insulation layer that prevents short circuiting the capacitive electrodes when they are deposited later. Then a metallic layer, e.g., aluminum, is deposited on the wafer to form the bottom electrode. If the same layer will be used to create the pad for the wire bonding then its thickness should be around 300 nm to be able to stand the bonding step without punching through the layer and losing the signal connection. This metallic layer is then patterned using the first photolithography mask. Next, the sensing materials were deposited and patterned using the second photolithography mask. If the sensing materials are a polymer, e.g., polyimide, it can be spun and then cured before patterning it using a hard mask and an oxygen reactive ion etching step. The thickness of the sensing materials determines the performance of the device, which makes it critical to be controlled accurately, especially for the mass production of these sensors. The top electrode is then deposited and patterned using the third mask. If the same layer is to be used for the top electrode wire bonding, then the layer should be around 300 nm thick as well and the material must be a metal that can be wire bonded to, e.g., aluminum. In the last step, the sensing material is then etched in anisotropic etching step to expose the sensing surfaces and form the final structure.

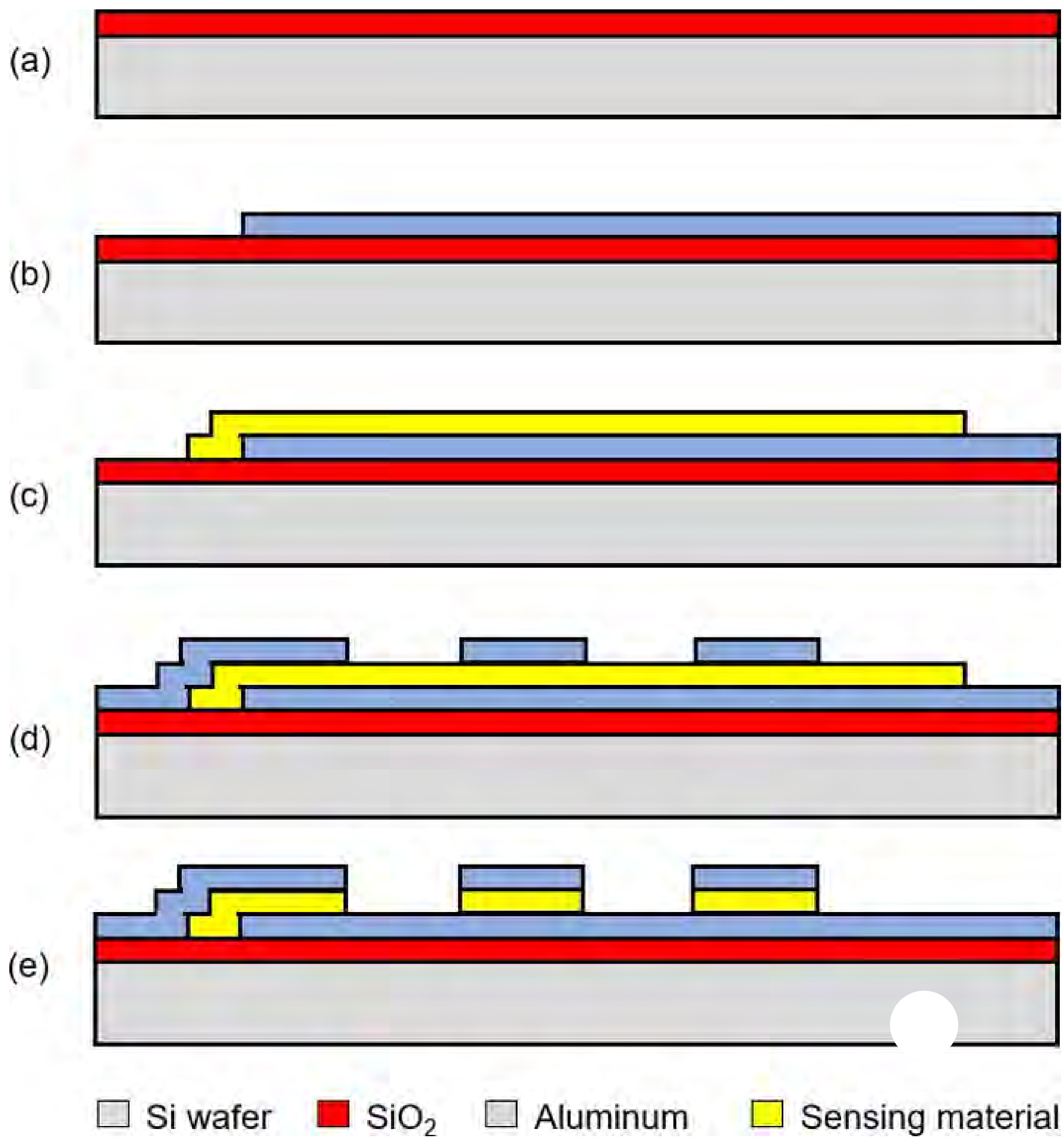

Figure 3.

Cross-section of a simple capacitive sensing fabrication process flow [9], depicting the silicon wafer after (a) being covered with silicon oxide, (b) depositing and patterning the bottom electrode, (c) spinning and patterning the sensing material, (d) depositing and patterning the top electrode, and (e) etching the sensing materials to create the final structure.

There are a variety of materials that can be used to sense humidity; however, polymers and ceramics are the most common materials in MEMS humidity sensors [ ]. Porous semiconductors have been demonstrated to sense humidity. However, they have poor linearity and operate efficiently only in the range of relative humidity higher than 10–20%.

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3. Piezoelectric humidity sensing technology

RF MEMS is one of the MEMS categories used to transmit radio frequency signals that operate in ultra-high frequency. A micromechanical resonator can be used as a sensor to couple the energy in and out the resonator's mechanical structure by actuating and sensing motion out of the mechanical resonator. The piezoelectric transduction mechanism is used to transfer the energy between the mechanical/electrical domains in the micromechanical system. Piezoelectric materials like ZnO can generate an electrical charge in response to applied external mechanical stress (force). This happens because the internal reticular electric polarization from piezoelectric materials is perturbed by mechanical means, and an electrical response can be generated because of the induced dielectric displacement. This behavior is called the direct piezoelectric effect [ ].

On the contrary, the converse piezoelectric effect appears after applying an external electric field to a material that generates a mechanical deformation across the piezoelectric materials, which is directly proportional to both the electric field's strength and the equivalent acoustic velocity (V_{eq}) within the bulk piezoelectric material layer. The piezoelectric layer's internal electric polarization is affected by the mechanical deformation of the resonance frequency, and the piezoelectric effect can be calculated from the output current i_o. The piezoelectric effect can be closely governed by the following Equations [ ]:

$$T = e^S \cdot S - p \cdot E \qquad \text{E4}$$
$$D = p \cdot S + \varepsilon^S \cdot E \qquad \text{E5}$$

where S, T, D, and E represent the strain, stress, electric displacement, and electric field, respectively. Also, e^S is the elastic stiffness at a constant electric field, ε^S is the permittivity at a constant strain, and p is the piezoelectric constant [ ].

MEMS sensors based on metal oxide semiconductors such as zinc oxide (ZnO) and aluminum oxide (Al_2O_3) have become one of the most attractive sensors for gas detecting applications [ ]. Thin-film piezoelectric-on-substrate (TPoS) resonators based on ZnO have a considerable prospect to be used in mass or gas sensing applications. TPoS resonators are strategically coupled with low loss substrates like Si to have higher acoustic velocities and to store more energy which results in i[illegible]sing the equivalent acoustic velocity to be higher than typical piezoelectric resonators [ ]. Based on a previous study [ ], the effects of mass loading on TPoS based resonators have shown high sensitivity of the first and fourth-order contour mode ZnO-on-Si MEMS resonator-based mass sensor, which provides massive potential in mass sensing applications.

3.1 Piezoelectric MEMS mass resonator

Piezoelectric MEMS mass resonator consists of top and bottom electrodes sandwiching a structural layer (resonator body) that can be silicon, nickel, diamond, or any other low acoustic loss structural material. The equivalent acoustic velocity can be found by [ ]:

$$V_{eq} = \sqrt{\frac{E_1T_1+E_2T_2+\ldots+E_mT_m}{(\rho_1T_1+\rho_2T_2+\ldots+\rho_mT_m)(1-\sigma^2)}} \qquad E6$$

where m is the number of the stacked layers; T is the thickness of each material; ρ, E and σ indicate the density, Young's Modulus, and Poisson's ratio of the stacked piezoelectric resonator structural materials [ ]. The piezoelectric sensor is designed to be operated by applying a mechanical force to the body of the sensor which will excite the resonator system into the designed frequency mode. MEMS resonator sensor is extremely sensitive and can probably provide the most accurate measurement comparing with other technology. The piezoelectric MEMS resonator's output is a frequency that can be easily measured and monitored with very high accuracy using a vector network analyzer (VNA), as shown in . The frequency of the device all depends on the geometrical parameters as well as the material properties of the structure. The piezoelectric resonator can be used in gas sensing and humidity sensor applications. This resonator is sensitive enough to detect and sense any slight mass changes [ ].

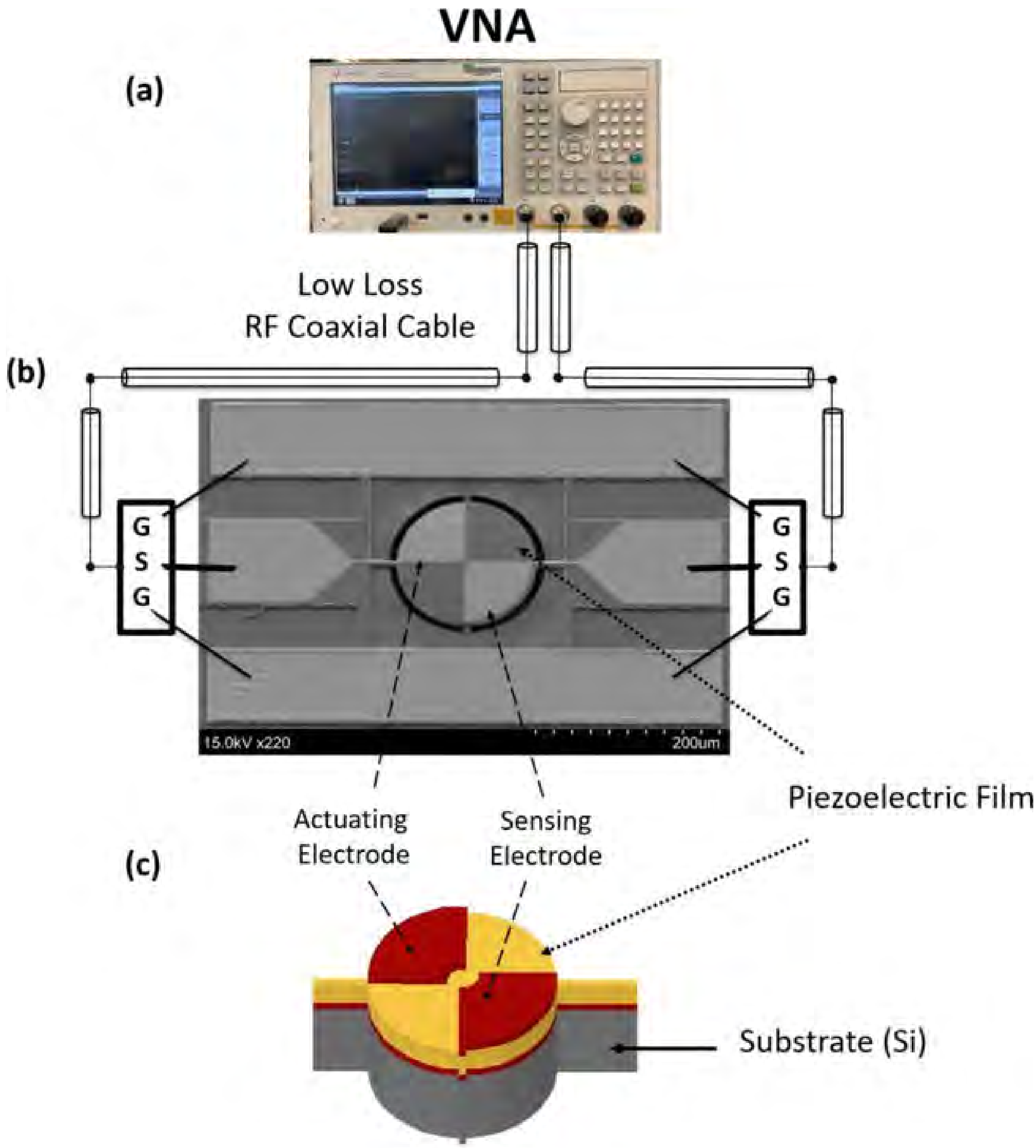

Figure 4.
(a) Illustration of RF measurement set-up for piezoelectric mass sensor device to measure the frequency response; (b) SEM image showing 2D illustration of the dynamic mass of a 1 st contour mode disk resonator for piezoelectric mass sensor device; (c) 3D illustration of sensing film, actuating and sensing electrodes for piezoelectric mass sensor device [14].

3.1.1 Design and operation

There are two modes of operation for MEMS sensors: static and dynamic modes. In the static mode, the resonator remains stationary where its deflection and actuation depend only on the variation of the surface stress. In the dynamic mode, the changes occur on the resonator's mechanical stiffness, and the mass variation results in resonance frequency shift and amplitude change [ ]. Dynamic mode is the most commonly used technique for gas and humidity sensing applications.

For humidity sensing application, MEMS resonator can be coated with a water or ga... ...bsorbing layer such as Metal–Organic Frameworks (MOFs). As the humidity increases, the value of the resonance frequency of the piezoelectric sensor will be shifted down due to the increase of the mass. The mass-loading effect can be calculated by monitoring the resonance frequency change of MEMS resonator, which is proportional to the ratio between the mode frequency and the equivalent mass given by [ ]:

$$\Delta f = \frac{f_n}{2m_e} \Delta m \qquad \text{E7}$$

where m_e is the effective mass of the resonator (also known as the equivalent dynamic mass of the resonator), Δf is the measurable resonance frequency shift due to the loaded mass, Δm is the change of mass, and f_n is the resonance frequency of the n-order contour mode [ ].

The piezoelectric MEMS resonator sensor's working principle depends on the change in the frequency of the resonator structure due to the mass loading effect. Air can only absorb a certain amount of water vapor. This amount highly depends on the temperature. Piezoelectric MEMS sensor measures humidity with a mass type sensor. The sensor uses a principle like the piezoelectric effect to measure frequency, force, or strain changes which is super sensitive for mass variation. The piezoelectric dielectric material absorbs water vapor proportionately to the ambient humidity, thus changing the frequency due to the increase of the MEMS resonator device's mass as the device becomes heavier. The humidity changes the mass of the sensor, which is proportional to the relative humidity in the air [ ].

3.1.2 Fabrication process of piezoelectric humidity sensor

The most crucial feature of the piezoelectric MEMS resonator is the capability to integrate effectively with other electrical components in semiconductor chips that are deemed as IC-compatible for on-chip applications integrated with IC electronics such as sensing, signal processing, and wireless communication systems. Piezoelectric MEMS resonator is a technology that can be easily fabricated using semiconductor materials on a silicon or silicon on insulator (SOI) wafer substrate and standard fabrication process of material layers such as metal deposition, etching, and patterning [ ]. The fabrication process of the piezoelectric mass resonator is described in .

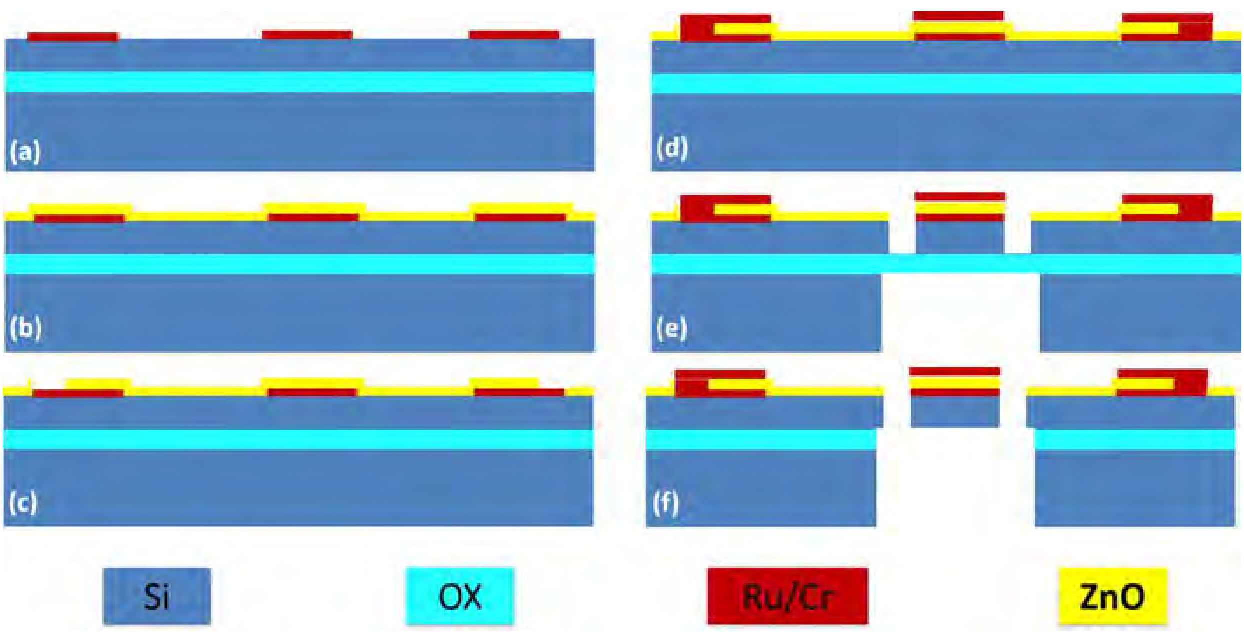

Figure 5.

The cross-sectional view illustrates the fabrication process flow of the ZnO piezoelectric resonator on an SOI wafer including: (a) bottom electrodes patterning; (b) ZnO sputtering; (c) ZnO etch; (d) to[ ]rodes patterning; (e) define the device body; (f) device release [14].

The fabrication process begins with a photolithography step using a positive photoresist and LOR to define a lift-off profile for the piezoelectric resonator's bottom electrode. After that, a bottom electrode metal layer is deposited following by sputtering the piezoelectric layer (ZnO) with optimized parameters to achieve a (002) c-axis-aligned crystal orientation, as shown in . Next, a photoresist is used to pattern the access to define the anchor points for the grounding, which will allow the ohmic contact between the bottom electrode and the subsequent top electrode after etching the ZnO from this anchor point by using ZnO wet etch solution. The top electrode process is performed using LOR and photoresist to have a lift-off profile for defining the piezoelectric resonator's top electrodes following by top electrodes metal layer deposition, as shown in . Then, the piezoelectric layer is etched to define the resonator body by performing ZnO dry etch using the DRIE tool for etching the ZnO and the Si anisotropically. Finally, backside etching technique is used to release the device after defining a selected area by patterning a photoresist on the backside of the wafer to allow etching and removal of Si in selected areas using HAR DRIE Si etch followed by SiO_2 anisotropic directional dry etch to suspend and fully release the device as shown in .

3.2 MOF-based functionalized mass sensors

Metal–Organic Framework (MOF) thin film-coated metal oxide layers have recently been exploited to implement ultra-high sensitivity gas sensors. A thin MOF layer is gradually coated on the ZnO surface to form an ultrahigh sensitive layer to further tune the newly integrated MOF and ZnO materials with desired properties to detect gas and humidity efficiently [, ,]. The piezoelectric sensor can be used in sensing applications based on the changes in the physical properties of the device, such as stress or the mass due to gas absorption at the surface of the device. This device can also be used for humidity sensing applications by coating MOF on ZnO on-Si resonators. The humidity is controlled by detecting the mass changes and monitoring the resonating structure's frequency changes due to the mass loading and surface stress changes (static mode) after absorbing the humidity in the air. Wang's group has grown MOF crystals on ZnO-on-Si resonators to develop a new ultrasensitive sensor for gas and humidity detection by combining the MOF crystals layer, which has excellent absorption and discrimination qualities, and the ZnO layer, which has excellent sensitivity. The sensor can reach a sensitivity of about 191 Hz pg-1after performing FIB- micro pellet depositions and measuring the frequency change per deposition. The frequency change Δf_0 was measured to be 726 Hz [ ].

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4. Resistive humidity sensing technology

Resistive humidity sensing technology depends highly on the water molecules' absorption into the sensitive material used in the system. Such exposure to humidity can cause either electrical or mechanical effects due to its interaction with the water molecules. Electrical effects, typically impedance change, are measured in standard resistive humidity sensors, while mechanical effects, typically mechanical deformation, are used in piezoresistive humidity sensors. Each of these sensors is designed differently based on the detection mechanisms [,].

4.1 Standard resistive humidity sensors

The standard resistive humidity sensing fabrication process is quite simple, using an insulator material as a starting substrate such as glass. Then, it follows with a metallic patterning of interdigitated electrodes covered by materials that are sensitive to humid environments, as shown in . The selection of the sensitive materials in these types of sensors determines the quality and the performance of the resistive humidity sensors [ ].

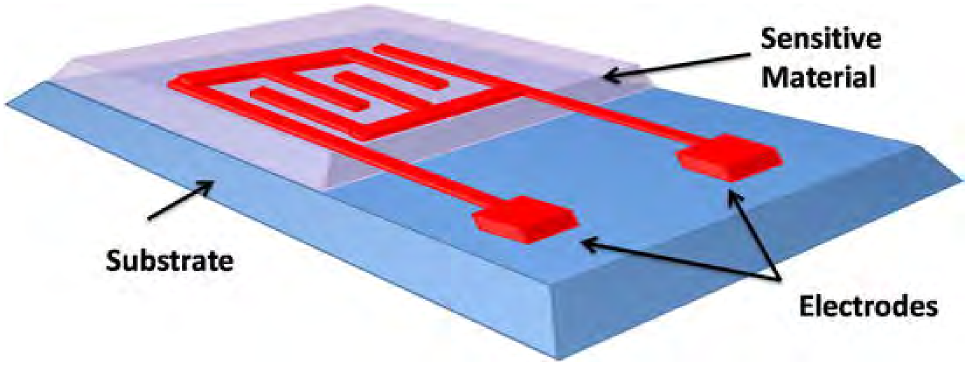

Figure 6.

General schematic of resistive humidity sensors [25].

The resistive humidity sensors are categorized by the sensitive materials. These materials are generally divided into four groups of materials; ceramics, polymer, electrolytes, and mixer of ceramic/polymer, also known as hybrid composites-based sensors.

Electrolytes based sensors, developed by Dunmore in 1938, are the first developed sensors for humidity detection [ ]. The lithium chloride (LiCl) was used by Dunmore as a sensitive material to the humid environment for circuit applications [ ]. The humidity can be detected in these types of sensors when the water molecules are absorbed by the electrolyte cells. The electrical effects can also be measured when the cell conductivity changes. The difficulty of working under harsh humid conditions and the low performance had led to developing sensors of other types of materials.

Polymer based humidity sensors are generally categorized into two classes of polymers: polyelectrolytes and conjugated polymers. Typically, polymer humidity sensors' performance depends on the polymer's chemical properties. Polyelectrolytes are hydrophilic and their conductivity is lower than conjugated polymers. Fabrication of polyelectrolytes polymers requires chemical reactions to change the polymers' water solubility without affecting their hydrophilicity, making them inconvenient in contrast with ceramics-based sensors due to their low sensitivity and poor impedance [ ]. Several polyelectrolyte materials have been investigated, such as ammonium salt and sulfonate salts [,]. The conductivity in most polymer-based sensors has an inverse relationship with the humidity level. This correlation was observed to be non-linear, unlike piezoresistive-based and capacitive-based humidity sensors [,]. Conjugated polymers are hydrophobic, and their conductivity can be significantly increased by doping metallic ions. By doping the polymer, the humidity decreases at a low level and thus increases the impedance change. Various polymers were doped with different metallic catalysts such as nickel and gold [,]. As a result, the conductivity of the sensors had enhanced as well as other performance parameters such as linearity, sensitivity, response time, etc. [,].

Ceramics based sensors proved to have advantages over polymer-based sensors in terms of mechanical strength, ability to operate at elevated temperature, effectiveness in absorbing water molecules on the surface, and better chemical stability [,]. Several materials have been studied in literature at different humidity levels and different temperature ranges, such as $MnWO_4$ and SnO_2

[,]. Most of the ceramic based sensors' materials utilize compounded materials to overcome the deficiency issues found in typical materials, such as poor sensitivity and inability to work in harsh environments [ ]. On the other hand, ceramic based sensors have incompatibility problems with IC fabrication technology due to their surface contamination [ ].

Another type that utilizes the advantages of both polymer sensors and ceramic sensors is the formulation of the composite/compound of the two materials. Recently, such a method has shown its capability to produce sensing elements that offer better performance since they gained the polymer and ceramic materials advantages. Several composites have been investigated in the literature, such as polyaniline and tungsten oxide (PANI/WO_3), TiO_2 nanoparticle/polypyrrole, iron oxide-polypyrrole (Fe_3O_4-PPY) nanocomposite, etc. These hybrid sensors have shown high performance behaviors in response time, mechanical strength, and hysteresis features [, ,].

4.2 Piezoresistive humidity sensors

Unlike standard resistive based humidity sensors where only one material controls the sensor operation of sensing and detection, piezoresistive based humidity sensors require two materials for their operation. As a result, the humidity sensors' performance was improved, especially that they do not exhibit non-linearity problems at low humidity like standard humidity-based sensors [ ]. The two materials in these types of sensors are: humid sensitive materials and mechanical sensitive materials or piezoresistive materials. The sensitive materials sense the water molecules and the piezoresistive materials detect the stress changes due to the expansion caused by absorbing the water molecules in the sensitive layer. Piezoresistive based sensors are MEMS devices that are compatible with pre-CMOS and post-CMOS technologies [ ]. The fact that the Si has large piezoresistive coefficients has allowed it to be widely used as piezoresistive material over other materials such as metals. It also enabled these sensors to be used in miniaturized devices since Si is the based material in surface and bulk micromachining technologies [,].

The piezoresistive effects were noticed in the 19thcentury by Wiliam Thomson [ ]. He noticed in his experiments that resistivity is related to the mechanical loads in metals, which he used as piezoresistive materials [ ]. In the 20thcentury, the piezoresistive behavior was studied intensively by many scholars in the field and was pioneered by Smith SC [ ]. The piezoresistive coefficient in piezoresistive materials relates the resistivity with the mechanical stress as follow:

$$\frac{\Delta\rho}{\rho} = \pi\sigma \qquad \text{E8}$$

where, ρ, π, σ are resistivity, piezoresistive coefficient and stress, respectively [ ].

Piezoresistive humidity sensors have been developed and miniaturized using micromachining technology. Early designs of piezoresistive sensors were fabricated using bulk micromachining process where SOI wafers are typically utilized as starting wafers and wet bulk etching of the back-side of the wafer leading to some limitation of the process precision. Surface micromachining was also used to develop these types of sensors. J-Q Huang et al. reported a successful method that is compatible with pre-CMOS and post-CMOS technologies using microcantilever as humidity sensors. Such a technique has exhibited better sensors' performance in terms of sensitivity and linearity [ ]. A comparison between the three types from examples of published work in humid sing technologies in terms of sensitivity and response time is presented in .

Sensing Technology	Materials	Humidity Range %	Response Time	Sensitivity (/%RH)	Ref.
Capacitive	PI, CU1512, DuPont	30–70	3s	0.86	[ ]
	BCBa, 4024–40, Dow Chemical	50–90	0.5s	0.025	[ ]
Piezoelectric	ZnO/PI	5–87	50s	34.7	[ ]
Resistivity	Si (Piezoresistive)	30–70	1s	4.4	[ ]
	PAMPS doped salts	20–90	60s	0.026	[ ]
	TiO2 NP3/PPy/PMAPTAC	30–90	30s	0.065	[ ]

Table 1.

Comparison of humid sensing technologies.

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5. Conclusion

This chapter reviewed three types of MEMS humidity sensors: capacitive, piezoelectric, and resistive sensors. While the capacitive sensing depends on the changing permittivity of the sensing material, the humidity can be determined in the piezoelectric sensors by measuring the shift in the resonance frequency. The resistive sensors use the change in resistivity to detect the humidity change. Capacitive sensors in general exhibit higher linearity, faster response and temperature compensation but are sensitive to gas contaminations compared to the resistive sensors [ ]. Piezoelectric sensors, on the other hand, do not require external power source which is needed for both capacitive and resistive. The resistive sensors are cheaper to build and have simple readout circuit compared to the other two types [ ].

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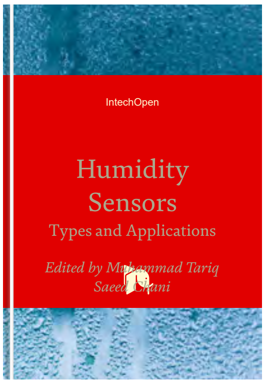

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