

A Comparison of Relative Humidity Sensing Technologies

Introduction

Commercially-available, high-volume sensors for measuring water vapor as relative humidity (RH) or water activity (a_w) can be classified by the transduction scheme that they use to convert water vapor concentration into an electrical signal:

- Capacitive
- Resistive (DC resistance or AC impedance)
- Advanced resistive (piezoresistive)

A key component that allows these sensors to be cost-effective is the use of a solid state sensing film that interacts with water vapor to produce a repeatable electrical measurement.

Other sensor types such as mass-change (bulk and surface acoustic wave) or optical (non-dispersive infrared) devices are available but not as widely used because of their cost and complexity, and therefore, are not considered further in the scope of this applications note. See Reference 1 for more information on these sensors.

How Sensing Films Work

Transduction of water vapor concentration into an electrical measurement by the sensing film is a three-step process consisting of:

- Physical and chemical interaction of water vapor molecules with the film surface
- Surface and bulk modifications of the film due to water vapor accumulation on and diffusion into the film
- Electrical measurement of a key electrical or mechanical property of the film that changes due to its interaction with water vapor.

Commercial RH sensors utilize sensitive films made from polymers or porous ceramics that employ chemical adsorption at the film surface. Adsorption involves a weak interaction between water molecules and the surface of the sensing film through van der Waals forces or acid-base

interactions, depending upon the type of film material used. Van der Waals forces are a low energy balance between molecular attractive and repulsive forces involving reaction energies on the order of 0–10 kJ/mole. Acid-base interactions involve proton or electron pair interaction between a target gas and molecules of the sensing film with reaction energies usually less than 40 kJ/mole. After adsorption, and depending upon the structure of the film (i.e., its affinity for water and/or its bulk porosity), water may become absorbed into the bulk through diffusion or capillary action. Because of the low energies involved, adsorption reactions are fully reversible. Reversible reactions are essential if the sensor is to continue working after its first exposure.

Materials for Sensing Films

The ideal sensing film material will have a high sensitivity to water vapor with a linear response from 0% to 100% RH, short response time, high selectivity (i.e., low or no cross-sensitivity), and high long-term stability. Sensitive films are fabricated from three material types: porous ceramics, polymers, and polyelectrolytes.

Porous ceramic films are formed on substrates using thick film screen printing, vapor deposition or direct anodization of an aluminum or silicon substrate. Thick films are usually printed onto an alumina substrate as a paste or conductive ink with film thickness greater than 10 microns.

Dopants can be added to the mixture as reaction catalysts to promote the dissociation of adsorbed water into hydrogen and hydroxyl ions. The hydroxyl ions decrease the bulk resistivity which can be measured as an AC impedance. Alumina and porous silicon films can also be formed by directly modifying the top layers of the substrate through anodization (for alumina) or electrochemical etching (for silicon). Changes in capacitance or conductance can be measured, and are a function of the amount of water that is absorbed into

the film due to diffusion through the bulk, or by capillary transport of water into the film's pores.

Polymers are essentially electrical nonconductors, with bulk resistances eighteen orders of magnitude greater than metals. When they are used as a sensing film for water vapor sensors, only their electrical dielectric and mechanical properties such as mass increase due to water uptake or dimensional changes caused by polymer swelling can be used as a transduction scheme. The dielectric constant of a polymeric film with water uptake will be a combination of the dielectric constants of the polymer and water as a function of the volumetric fraction of water diffused into the film. Polymer swelling initially involves adsorption and diffusion of water molecules into the film's bulk, followed by conformational and configurational (shape and orientation) changes of the polymer chain backbone and radical group branches to accommodate water molecules. This results in dimensional changes in the polymer film which are proportional to water uptake. Swelling can be measured by piezoresistive strain gauges embedded in a deformable microstructure attached to the film with the microstructure designed to act as a mechanical amplifier. A direct resistive measurement of the swelling polymer can be made if a conducting material, such as carbon powder, is homogeneously dispersed throughout the bulk of the polymer film. Swelling will cause the conductive pathways between carbon particles to increase, resulting in an increase in the film's bulk resistance. The bulk resistance is measured as AC impedance to prevent film polarization.

Polyelectrolytes (PEs) are a special class of modified polymers in which one type of an ionic chemical radical group is fixed to the repeat units of the polymer backbone to form a single-ion conducting material. Biological materials such as DNA, RNA and most proteins are polyelectrolytes. An example of a synthesized PE is sulfonated polysulfone that contains sulfate groups along the polymer backbone as the ionic radical donor. The introduction of water vapor to a PE film under a voltage bias will hydrolyze the ionic

groups, resulting in a flow of ions. Film conductivity can be measured as ionic impedance (i.e., AC resistance) and will vary in proportion to the water vapor concentration present. The measurement scheme is AC-based to avoid polarizing the film over time. Polyelectrolytes that contain strong acidic or basic radical groups in their structure tend to be very hydrophilic polymers that dissolve readily in water. Cross-linking reagents may be added to convert them into a water insoluble compound to ensure long life as a sensing film.

Capacitive and Resistive Sensors

Figure 1 shows a capacitive RH sensor utilizing interdigitated gold electrodes printed onto a ceramic substrate. Typical electrode geometries consist of a 4-mm wide by 10-mm long comb. Each comb contains ten fingers that are 200- μm wide with 100- μm gap spacing. The total capacitance for this geometry is a summation of the fringing capacitances between adjacent fingers, with the alumina substrate and sensitive coating acting as dielectric layers. Capacitive RH sensors have been created with this platform using porous ceramic films such as alumina, porous silicon, and doped glass inks. Several resistive RH sensors are available using this platform design incorporating polymer or doped porous ceramic sensing films.

A leading sensor manufacturer currently offers an AC resistive sensor of this type using a proprietary polyelectrolyte film. This device operates with a recommended 1VAC peak to peak excitation at 5–10 kHz. The specified operating range is 0–100% RH with a ± 1 %RH inherent accuracy over a –40 to 100C temperature range. Sensor t_{90} response time is 10 sec for a step change from 11% to 93% RH to achieve a 90% full response.

Figure 2 shows a parallel plate design configuration currently offered by several manufacturers of capacitive RH sensors. General construction consists of a parallel plate capacitor with two polymer layers. The top polymer layer is a porous film and acts as mechanical filter against sensor contamination from dust, dirt, and oils. An upper electrode of porous platinum is patterned on top of the poly-

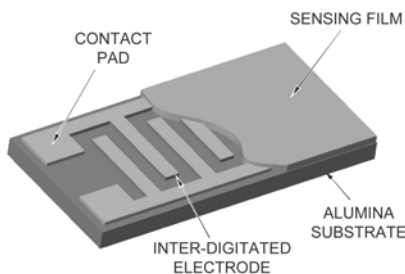


Figure 1. Interdigitated electrode design used in capacitive and resistive RH microsensors.

mer sensing film. A lower electrode layer is located between the sensing film and silicon substrate. Variations of this design exist without the porous polymer filter layer, and with various proprietary electrode geometries to optimize sensor performance. A version of this sensor type is commercially available using a porous alumina film anodically grown on an aluminum sheet metal substrate. A porous gold electrode is patterned on the ceramic film to form an aluminum oxide capacitor that is sensitive to water vapor.

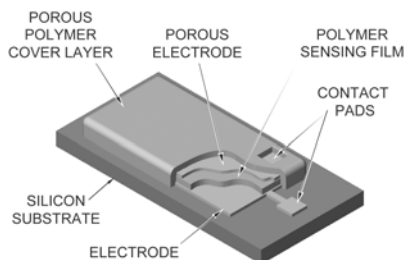


Figure 2. Parallel plate design for capacitive RH microsensors can include a porous polymer cover layer to exclude particulates.

A signal conditioning scheme recommended by several sensor manufacturers for capacitive RH sensors is shown in Figure 3. It is based upon the widely used 7556 Timer IC which contains two 555 CMOS timers. The circuit provides a DC output directly proportional to relative humidity. Timer U1A acts as a fixed pulse generator to trigger the second timer circuit. The pulse width of the second timer IC is controlled by the RH sensor and varies linearly with sensor capacitance. Circuit output from U1B is a pulse width modulated signal that can be measured with a DC voltmeter.

Advanced Resistive Sensors

While capacitive and resistive RH sensors measure the change in dielectric properties or conductivity respectively, Hygrometrix has developed an advanced resistive RH sensor that exploits the volumetric changes in polymeric films due to water vapor (see Figure 4).

The sensor is based upon a patented shear stress principle for measuring water vapor. The vapor-sensing element is constructed from a thin polymer film deposited and bonded to the top surface of four cantilever beams that are bulk micro-machined from the surrounding substrate of a silicon chip. Each microbeam contains an electrically isolated and diffused-in semiconductor strain gauge which measure beam stress by the piezoresistive effect. Semiconductor strain gauges are a well-demonstrated, very mature and stable technology with a proven track record. They have been used for over 20 years in piezoresistive pressure sensors with over 200 million such devices deployed in the automotive industry alone. Adsorption and desorption of water vapor causes the polymer film to expand and contract, inducing a stress in the underlying silicon micro-beam through surface shear stress coupling at the polymer-silicon interface. Behavior of this structure to water vapor is analogous to a classical bimorph structure responding to a temperature gradient in which differences in material thermal expansion cause deflection. Water vapor concentration is transduced and linearly measured as mechanical strain. The process is fully regenerative and reversible, depending solely upon van der Waal adsorption of water vapor.

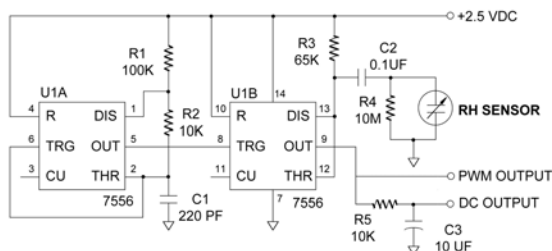


Figure 3. Recommended signal conditioning circuit for capacitive RH microsensors converts frequency into a voltage output.

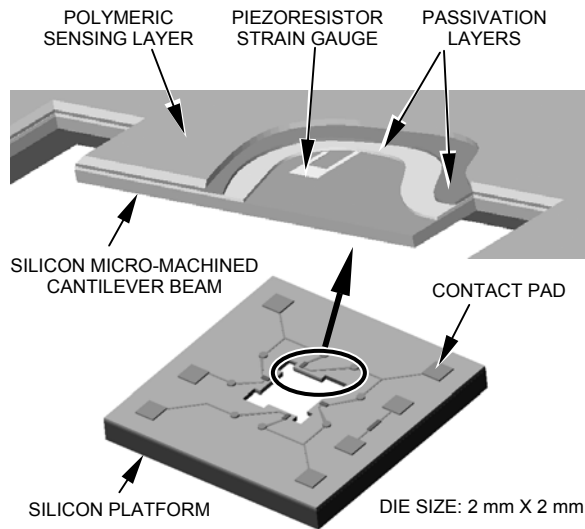


Figure 4. The Hygrometrix RH sensor is an advanced resistive device with four semiconductor strain gauges and full Wheatstone Bridge all on one chip.

It is known that humidity dependent changes of a polymer sensing film could strongly affect the accuracy and long term stability of conventional capacitive and resistive sensors when the sensing film is in direct electrical contact with the electrodes. An advantage of the Hygrometrix sensor design over conventional capacitive and resistive sensors is that the polymeric film is electrically isolated from the sensing electrodes. A nitride and oxide passivation layer separates the polymer film from the strain gauges and associated metallization to ensure long term stability and accuracy.

Signal conditioning for the Hygrometrix RH sensor is very simple because the four embedded strain gauges are electrically connected together into a full Wheatstone Bridge circuit directly on the sensor chip. Bridge excitation is provided by a 1.2 to 2.5V DC voltage source that is external to the device. Sensor output is measured as bridge output voltage that is linearly proportional to the excitation voltage, and ranges from 0 to 72 mV Full Scale (FS) for relative humidity values from 0 to 100%, respectively. With a drive current requirement of only 0.285mA/V, the Hygrotron™ sensor consumes only 0.5 mW of power at 1.25V

excitation. Additional details on the sensor and its operation may be found elsewhere (2).

Sensors Comparison

A side by side comparison of sensor technologies is shown in Table 1 (see next page). Several manufacturers currently offer capacitive sensors using a parallel plate electrode configuration and polymeric sensing film.

The Hygrometrix sensor has several advantages over competing technologies, including:

- A patented sensor transduction scheme based upon the piezoelectric effect that ensures long term sensor stability and accuracy.
- Relative humidity and temperature sensing on the same chip, allowing end users to compute dewpoint temperature.
- Full 0 to 100% relative humidity detection range in condensing environments with very high linearity and fast response.
- Simple, field-proven DC excitation and signal conditioning, similar to circuits found in widely used automotive pressure sensors.
- A surface mount package design based upon industry standards that protects the sensor chip from contamination.

References

- 1.) Fenner, Ralph and Zdankiewicz, Edward, "Micro-Machined Water Vapor Sensors: A Review of Sensing Technologies," *IEEE Sensors Journal*, No. 1, Vol. 4; Dec. 2001.
- 2.) Hygrometrix Inc. 2004, Application Note No. 2004-1: Implementing the Hygrotron™ Humidity Sensor Into Your Design.

Table 1. Comparison of Relative Humidity Sensing Technologies

| Sensor Type: Film Type: Device Parameter | AC Resistive Poly-electrolyte | AC Resistive Polymer | AC Resistive Porous Ceramic | Capacitive (Parallel plate) Polymer | Capacitive (Parallel plate) Polymer | Capacitive (Parallel plate) Polymer | Advanced Resistive (Piezoresistive) Polymer Hygrometrix HMX2000 | Evaporative Adiabatic Saturation (Wet and Dry Bulb Temp.'s) | Chilled Mirror Hygrometer |
|--|----------------------------------|-------------------------------|--------------------------------|--|--|--|---|--|---------------------------|
| Quantity Measured | %RH | %RH | Dew/Frost Point Temp. | %RH | %RH | %RH and T | %RH and T | Wet & Dry Bulb Temp.'s | Dewpoint Temperature |
| Range Humidity (%RH) Temperature (deg C) | 0 to 100 --- | 0 to 100 --- | --- -80 to 60 | 0 to 100 --- | 0 to 100 --- | 0 to 100 -40 to +120 | 0 to 100 -15 to +185 | 20 to 100 --- | -15 to +93 --- |
| Cost, including signal conditioning | High | High | High | Medium to High | Medium to High | Very low | Low | High | Very high |
| Accuracy (%RH) | +/- 5 | +/- 5 | +/- 3 degC | 5 | 1 to 5 | +/- 3.5 | +/- 1 | 3 to 4 | High |
| Temperature Range (deg C) | -40 to +100 | 0 to +60 | -80 to +60 | -40 to +100 | -40 to +185 | -40 to +120 | -15 to +185 | 0 to < +100 | -15 to +93 |
| Temperature Effect (%RH/deg C) | - 0.4 | 0.6 | n/a | 0.1 | < 0.1 | Not available | Very low | < 0.5 | Very low |
| Long-term Stability (%RH/yr) | Poor to fair | < 2 | Not available | 0.5 | < 1 | < 0.5 | Very good | 0.01 | Very good |
| Response Time (sec) | 15 | 120 | < 5 | 10 | 15 to 60 | 4 | < 10 | 120 to 300 | Medium |
| Hysteresis (%RH at 25C) | +/- 2 | < 1 | Not available | +/- 1.5 | < 2 | +/- 1 | +/- 1 | Poor | Low |
| Linearity (%RH) | Very poor | Very poor | Poor | +/- 2 | 1 | +/- 3 | Less than +/- 1 | Poor | Very good |
| Interchangeability (%RH) | Very poor | Very poor | Poor | Very good | +/- 3 Fair | Good | Good | Excellent | Good |
| Lead Effect | Medium to high | Medium to high | Medium | Very high | Very high | Medium | Low | Medium | Medium |
| Resistance to Contamination | Very good with polymer filter | Very good with polymer filter | Fair | Good | Good | Good | Good | Fair | Fair |
| Resistance to Condensation | Excellent with polymer filter | Excellent with polymer filter | Fair | Excellent | Excellent | Poor | Excellent | Very good | Excellent |
| Cleanability | Good w/ polymer filter | Good w/ polymer filter | Fair | Good | Good | Good | Good | Good | Fair |
| Calibration Ease | Poor | Poor | Fair | Very good | Very good | Excellent | Excellent | Excellent | Very good |
| Size / Packaging | Medium; Non-standard SIP | Medium; Non-standard SIP | Medium to large; Custom probe | Medium; Non-standard through-hole | Medium; Non-standard SIP | Medium; SMD; MEMS and CMOS based | Very Small Standard SMD; MEMS based | Medium to Large; Custom probe | Large; Custom probe |