Simplifying Humidity Measurement with Single-Chip Relative Humidity and Temperature Sensor ICs

Introduction

Humidity sensing technology is critical to a wide range of applications, including HVAC and refrigeration, healthcare equipment, such as CPAP machines and ventilators, asset tracking and storage devices for the food and pharmaceutical industries, industrial control systems, meteorological instruments, automotive climate control and defogging, and mobile computing devices. Despite its pervasive necessity and application across many industries, relative humidity measurement is among the more difficult technical challenges in environmental sensing.

Humidity sensing instruments typically rely on measurements of temperature, pressure, mass or a mechanical or electrical change in a substance when moisture is absorbed. A measurement of humidity can then be derived from the calibration and calculation of a given measured quantity. Hygrometers (see Figure 1) have traditionally used human or animal hair to measure humidity as the length of hair changes measurably with humidity. Nowadays, modern electronic humidity sensing devices use temperature of condensation or changes in electrical capacitance or resistance to measure humidity changes with far greater accuracy.

Figure 1. Hair Tension Dial Hygrometer with Nonlinear Scale

Relative humidity sensors in general and those based on capacitive sensing using polymeric dielectric materials in particular have unique application and usage requirements that are not common to conventional (non-sensor) ICs. These requirements include:

- The need to protect the sensor during board assembly, especially during solder reflow, and the need to subsequently rehydrate the sensor
- The need to protect the sensor from damage or contamination during the product life-cycle
- The impact of prolonged exposure to extremes of temperature and/or humidity and their potential effects on sensor accuracy
- The need to apply temperature correction and linearization to the humidity readings

Some of these requirements stem from the natural characteristics of the polyimide films used in capacitive relative humidity sensor ICs. Others are a result of the sensor's open cavity package that exposes the die and the sensor film to the environment. CMOS manufacturing techniques have made possible state-of-the-art capacitive humidity sensors that cost-effectively address the need for protection with innovative covers for the sensing element. Before taking a closer look at these single-chip humidity sensors, let's review some of the basic principles of relative humidity measurement.

Fundamentals of Humidity

The amount of water vapor found in air can vary dramatically, from almost zero to the point of saturation. Insufficient or excessive humidity, or swings between the two, can damage sensitive materials and objects. Humans are also sensitive to humid air, and high humidity can cause discomfort. The human body uses evaporative cooling as its primary mechanism for regulating temperature. When the relative humidity is high, the rate of perspiration evaporating from the skin decreases because the amount of water vapor in the air is already close to saturation.

Humans feel the rate of heat transfer from the body rather than temperature itself: we feel warmer when the relative humidity is high. When humidity is so high that perspiration cannot easily evaporate, the body may overheat, causing discomfort. A combination of high temperature and low relative humidity allows more effective cooling. (See Table 1 for human perceptions of various humidity levels.)

Table 1. Human Perception of Relative Humidity Levels

Dew Point Temp (°F)	Relative Humidity at 90 °F	Human Perception
>75	>62%	Extremely uncomfortable
70 to 74	52% to 60%	Quite uncomfortable
65 to 69	44% to 52%	Somewhat uncomfortable
60 to 64	37% to 46%	Comfortable but humid
55 to 59	31% to 41%	Comfortable
50 to 54	31% to 37%	Very comfortable
<49	<30%	A bit dry

Traditionally, many environments have been controlled based solely on measurements of temperature. In recent years, the measurement of humidity has become equally important. Humidity control is especially important in living, storage and manufacturing sites. Control of temperature and relative humidity is also critical in the preservation of many materials including medications, foods, fabrics and wood products.

Unacceptable humidity levels, especially when combined with temperature extremes, contribute significantly to the breakdown of materials. Heat accelerates deterioration, and high relative humidity provides moisture, which promotes harmful chemical reactions. When combined, these factors can encourage insect activity and the growth of mold. Extremely low relative humidity can also have damaging effects, desiccating sensitive materials and causing them to become brittle. Large fluctuations in temperature and relative humidity also cause damage through expansion and contraction, which helps accelerate deterioration.

Installation and operation of adequate climate controls to meet preservation standards will retard the deterioration of materials considerably. To control humidity and prevent damage or discomfort or to detect events that may have led to product damage in storage or transit, accurate measurement of humidity is vital and, ideally, must be available in a component form that enables easy, cost-effective integration with electronic controls.

Techniques for Measuring Humidity

Humidity can be quantified in a number of ways, but the most important measurement for maintaining atmospheric quality is relative humidity. This is the ratio of actual water vapor present in air to the amount of water vapor that would be present in air at saturation when the air cannot absorb any more moisture. Absolute humidity, on the other hand, is defined as the mass of water vapor dissolved in a total volume of moist air at a given temperature and pressure.

The saturation level is generally called the “dew point” or “frost point,” depending on the temperature. The relative-humidity value can change significantly with even slight variations in temperature. For example, a 1 °C change in temperature at 35 °C and 75 percent relative humidity will introduce a change in relative humidity of 4 percent. This is because a higher temperature increases the ability of air to absorb moisture, and a lower temperature decreases the ability of air to absorb moisture.

The capacity of air to absorb moisture increases with higher temperatures, and thus the relative humidity of air decreases as the air is heated. When moist air is cooled, its capacity to absorb moisture decreases, while the relative humidity increases. As a result, the amount of water vapor in air needed to reach the dew point increases with temperature. The dew point at 10 °C, for example, corresponds to a relative humidity of 31 percent at 32 °C.

In principle, the measurement of relative humidity is straightforward. In practice, however, it is not a trivial task. Some types of humidity sensing instruments have poor accuracy and exhibit measurement drift over time. They may also suffer from contamination issues or hysteresis. Regular calibration is required for many traditional instruments, which is both inconvenient and expensive.

The best-known instrument for humidity measurement is the psychrometer, although it is more commonly known by its use as the “wet-bulb/dry-bulb” method. A psychrometer consists of two thermometers, one with an ordinary dry bulb and the other with a moist cloth covering the bulb, called the wet bulb. Evaporation from the moist cloth lowers the wet bulb thermometer's temperature.

The wet-bulb thermometer will show a lower temperature than the dry bulb if the air is not saturated with water vapor. A lookup table is used to derive the relative humidity from the two temperature readings. This can be automated with a microcontroller (MCU), but the disadvantages of a psychrometric sensor include slow response time and large physical size as well as the maintenance issues of keeping one thermometer bulb wet and ensuring good airflow around it.

The most accurate method for humidity measurement in use today is the chilled mirror hygrometer. This technique uses an optoelectronic mechanism to detect condensation on a mirror surface that is maintained at an accurately measured temperature and cooled until condensation forms. The condensation scatters the transmitting LED's light, which results in a sudden drop in the output of the receiving phototransistor. The temperature at which condensation forms provides the dew point from which the humidity value can be calculated. By using a microcontroller-managed feedback loop, it is possible to continuously track the dew point. However, the mirror must be kept clean and have a way of clearing condensation once it has been detected. Because of the mechanical systems they require, chilled-mirror hygrometer instruments are bulky, often expensive and impractical for use in high-volume consumer, automotive and residential applications.

Mechanical hygrometers can be made much smaller but typically exhibit poor accuracy – often in the range of ±10 percent. The most common example uses a piece of animal hair kept under tension. As humidity increases, the hair becomes more flexible and stretches. This change can be measured by a strain gage as the hair stretches with increasing moisture levels.

Electronic Humidity Sensing Technology

Electronic humidity sensors overcome many of the problems of size and cost that plague older techniques, although many conventional designs have significant limitations. To measure humidity, the most commonly employed techniques rely either on a change in resistance or capacitance of a hygroscopic material. This type of sensor has become the solution of choice for mainstream applications because technology advances are turning it into an accurate, compact, stable and low-power alternative.

A capacitive sensor consists of two electrodes separated by a dielectric. Typically, as the water vapor in the air increases, the sensor's dielectric constant follows, producing an altered capacitance measurement that corresponds to the humidity level. A resistive sensor consists of two electrodes separated by a conductive layer. In this case, the conductivity of the sensing layer changes in response to variations in humidity.

New techniques for producing thin films have made these types of sensors, accurate, stable and easy to manufacture in large quantities. The choice of material assures fast response times with little hysteresis. A polyimide film, which can be fabricated in thicknesses of less than 5 µm, can respond to changes in humidity in less than 10 seconds while providing excellent stability.

The accuracy of an electronic sensor is limited by its drift over time, generally caused by wide variations in humidity and temperature or the presence of pollutants. These factors must be taken into account by system designers when selecting a suitable sensor solution.

To enhance the accuracy of relative humidity measurements, it is helpful to measure ambient temperature and perform temperature compensation on the host (a simple second-order calculation). To determine the dew point or absolute humidity, the ambient air temperature is also required. The ability to measure temperature accurately expands the utility of humidity sensors, and accurate measurement is vital. In the case of a dew-point calculation, a 1 °C error in the measurement of the temperature will produce approximately a 1 °C error in the calculation of the dew point. To achieve the most accurate measurement, it is best if the humidity and temperature measurements are taken as close as possible to each other. Ideally, they will be co-located on the same chip. Such proximity can be difficult to achieve with many traditional electronic sensor designs.

Challenges in Electronic Sensor Design

Many of today's electronic sensor designs use discrete resistive and capacitive sensors, hybrids and multi-chip modules (MCMs), as shown in Figure 2. These legacy approaches suffer from high bill of materials (BOM) costs and component counts, large footprints and the need for labor-intensive customer calibration. A further problem is that discrete sensor solutions are often incompatible with standard surface mount technology (SMT) assembly flows.

Figure 2. Examples of MCM/Hybrid/Module Humidity Sensor Solutions

Discrete and module solutions tend to exhibit high power consumption and demand a large amount of PCB real estate, which can make them difficult to integrate into devices. This is problematic for applications, such as asset tracking, and for use in portable medical devices. Ideally, a humidity sensor should have a monolithic design to enhance reliability and minimize power consumption and size.

A monolithic sensor still has to contend with manufacturing issues. Since the sensor element must be exposed to the environment to perform its function, a humidity sensor is subject to damage and contamination, especially during PCB assembly. The sensor must be kept clean and undamaged. A commonly used technique involves covering the sensor opening with a protective high-temperature tape before PCB assembly and then removing it afterward, but this is a labor-intensive approach that adds production time and cost.

Even if protected, some sensor devices are not compatible with high-volume solder-reflow processes. The extreme thermal cycle of solder reflow can shift the performance of humidity sensors – an effect that is not always included in manufacturers' accuracy specifications. This means that the maximum accuracy can only be achieved if the device is socketed. A socket not only adds an additional component to the BOM cost, but it also increases the cost of labor to install the sensor after the PCB has undergone solder reflow.

The humidity sensor also requires protection during the life of the product, requiring the use of some type of cover or filter, which can impede sensor responsiveness in some implementations. Careful sensor cover design can lessen this issue and even solve the problem of protecting the sensor during manufacture.

State-of-the-Art Sensor Solution with Protective Cover

The Si7005 humidity and temperature sensor from Silicon Labs addresses many of the design and manufacturing challenges posed by discrete, hybrid and modular sensor solutions. The Si7005 humidity and temperature sensor takes the approach of using a hydrophobic cover material as a lifelong protective mechanism for the delicate sensor underneath. The cover, made from expanded polytetrafluoroethylene (ePTFE) hydrophobic filter material, provides protection against dust and most liquids. Its unique structure also allows water vapor to pass through it, ensuring that the filter does not affect sensor response time. Since the optional cover on the Si7005 sensor (shown in Figure 3) is installed at the factory, no time or labor is spent adding and removing protective tape during PCB assembly, and the cover does not have to be engineered into the product design.

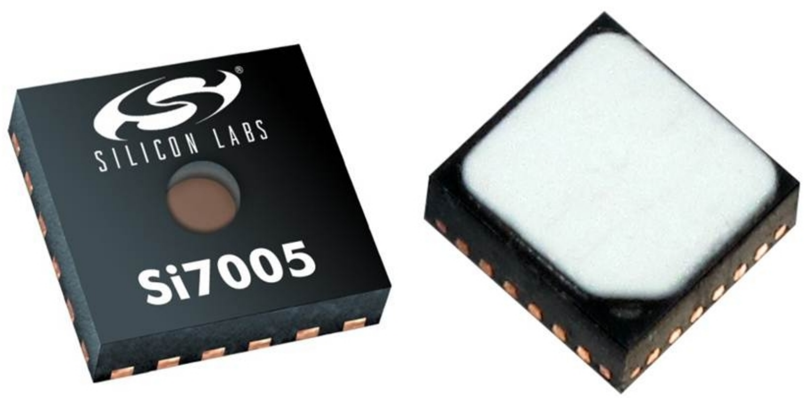

Figure 3. Optional Cover Offers Lifetime Protection for the Si7005 Relative Humidity Sensor

The Si7005 humidity and temperature sensor uses a polyimide film to detect changes in humidity. This thin, sensitive film is deposited over a metal finger capacitor. A precision bandgap referenced circuit, located on the same die as the humidity sensor, provides temperature measurement. Co-location on the same die ensures that both humidity and temperature are measured in close proximity, providing exceptional measurement accuracy.

The on-die temperature sensor ensures accuracy when the Si7005 device is used around the ambient environment's dew point. If condensation gathers on the sensor, an on-chip heater can be activated to dry the sensor and restore operation once the sensor is above the dew point. The on-die temperature sensor also ensures that the MCU that collects the humidity reading can take this heating effect into account.

The Si7005 sensor's long-term measurement drift due to aging is no more than 0.25 percent of relative humidity per year, which is less than half the drift of many competing devices. The specified accuracy includes an allowance for the effects of solder reflow. As a monolithic solution, the Si7005 humidity and temperature sensor is factory calibrated, eliminating the need for this labor-intensive step to be performed by the customer after PCB assembly.

The Si7005 humidity and temperature sensor takes advantage of additional monolithic integration to ease system design and provide the functions of much larger modules in a single, compact IC package (4 mm x 4 mm QFN). In addition to the sensing elements, the Si7005 device integrates an analog-to-digital converter (ADC), signal processing, non-volatile memory for calibration data, and an I^2C interface. See Figure 4 for chip-level details. This high level of integration improves ruggedness and reliability, reduces cost and development time and simplifies board design. The monolithic design also helps reduce power because the Si7005 sensor's current consumption is, on average, 1 µA when used to perform one temperature and one humidity reading per minute. This makes the device well-suited for power-sensitive applications.

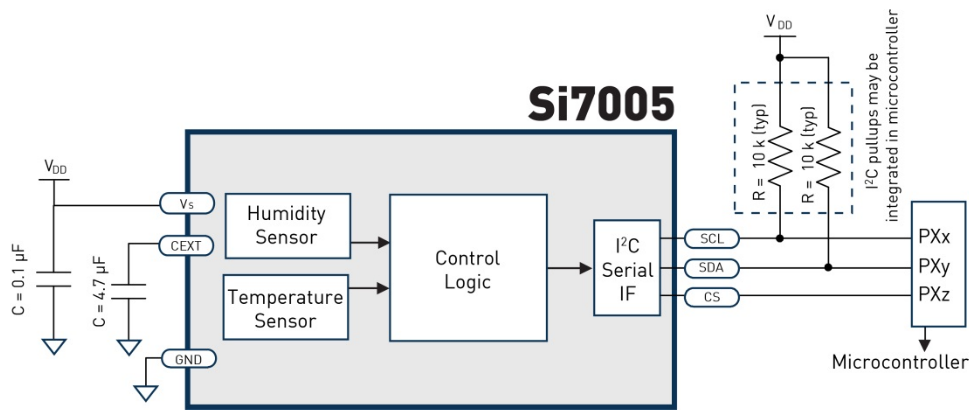

Figure 4. Si7005 Humidity Sensor Provides a Single-Chip Solution for Humidity Measurement

The entire bill of materials for the Si7005 humidity and temperature sensor solution consists of just two bypass capacitors versus the dozens of components often required to implement the same functionality with a discrete solution.

Through the use of monolithic integration and innovative design, the Si7005 humidity and temperature sensor brings cost-effective and compact relative humidity and temperature sensing to a growing range of applications where the effects of moisture in the air must be monitored and controlled with great accuracy and long-term reliability. Humidity sensing technology has indeed come a long way since the days of hair-based hygrometers. For more details about the Si7005 humidity and temperature sensor, please visit www.silabs.com/humidity-sensor.

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