Low-power humidity sensor for RFID applications

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Abstract

Wireless sensors incorporated in RFID systems are important in several industrial, consumer and logistics applications. By extending RFID tags to sensing applications, the products become smarter. Application areas for these smart tags include: health care (verification of the environmental conditions during transport or in storage of e.g. diapers, bandages, etc.), food monitoring (food quality during transport, storage and sales) and construction industry (e.g. building material).

In this paper, a small, very low power and low cost humidity sensor tailor made for passive RFID applications is presented. The sensor consists of a glass chip substrate with a sub-micron interdigitated gold electrode structure covered with a humidity sensitive polyimide layer. The humidity absorbed by the sensing layer is measured capacitively. Finite element modeling and analytic calculations were used to determine the design of the interdigitated electrodes and the optimal thickness of the polyimide layer. A read-out electronics circuit was designed and used to evaluate the sensor. Sensors were fabricated and calibrations have been made to verify their function. The sensor response was close to linear from below 20 to above 90 \%RH and its response time was proven to be at least as short as that of the climate chamber, namely 0.1 \%RH/s. The concept can easily be adapted to measure a range of other parameters such as temperature or the presence of certain substances.

Keywords: humidity sensor, passive RFID tag, e-beam lithography, nanoimprint lithography (NIL)

1. Introduction

RFID sensor network applications are emerging and moving towards commercialization. As they do so, a new level of intelligence and information will start to spread through society: the possibility for a wide number of different actors to accurately, remotely and quickly access information about their environment or the quality of a certain product. A requirement for this to happen is the development of suitable sensors with key requirements being low power consumption and a low price.

RFID (Radio Frequency Identification) systems consist of RFID tags (i.e., transponders) and readers (i.e., interrogators). There are three types of RFID transponders: passive, semi passive and active. Passive RFID transponders do not contain a power source and they operate only when powered by a nearby RFID reader. Active RFID transponders contain a battery and are constantly powered. Semi-passive RFID tags are hybrid implementations of active and passive transponders. RFID tags can be thought of as “electrical bar codes”, which contain identification data, or remote memories.

One functional area of great relevance to many supply chain applications is the ability to monitor environmental parameters using an RFID transponder with built-in sensor capabilities. Parameters of interest may include temperature, humidity, shock, security and tamper detection. Wireless passive systems based on Micro System Technology (MST) for implantable pressure monitoring, and for neural recording have been reported [1, 2]. Wireless sensors are generally important in several industrial and consumer applications and a low-cost humidity sensing RFID tag has the potential of being an important tool in the food and medical distribution chain and storage as well as in the monitoring of indoor and outdoor environment.

For maximum wireless range and remote energy supply, low-power micro sensor systems are essential, making capacitive detection one of the most suitable sensing methods. Interdigitated electrodes with sensing material (e.g. polymer film on top of electrodes) were chosen since it allows for simple batch processing, miniaturization and low-cost. This sensor configuration with polyimide film [3-6] is predominantly used in both university research and commercial applications but is not developed for passive RFID tags.

In this paper, the design, micro fabrication and characterization of a capacitive humidity sensor for very low power applications, in the \textmu W range, is presented.

2. Design and simulations

Within the IntelliSense project [7], whose framework this sensor was developed in, the specifications were chosen such that the sensor could be used with a passive RFID tag. The resulting requirement was a low-power capacitive sensor with a working point of 10 pF at 2 V, 10 kHz and an active sensor area no bigger than 1 mm\^2.

The solution is a set of interdigitated electrodes covered with a sensitive polymer, a generic measurement method suitable for measuring a range of different parameters (humidity, pH, temperature, etc) depending on the chosen polymer (Fig. 1, 2).
Interdigitated electrodes are used in all kinds of applications, in areas like non-destructive testing, telecommunications, chemical sensing and biotechnology [3,5,8,9]. In case of the humidity sensor, the polymer, which functions as a dielectric between the electrodes, absorbs or releases moisture and its dielectric properties (permittivity) change as a function of the relative ambient humidity, thus the capacitance changes.

Polyimide is well suited for the application due to a high water uptake and a high diffusion rate resulting in high sensitivity and short response time. Polyimide experiences a change in dielectric constant from $\varepsilon = 3.0$ at 0% RH to $\varepsilon = 4.2$ at 100% RH [4].

Analytical model and Finite Element Simulations (FEM) in ANSYS and Comsol MultiPhysics have been used for the calculation and simulation of the sensor capacitance. The results from ANSYS, Comsol and the analytic calculations all lie within 10% of each other.

There are several parameters involved in designing the sensor, like electrode dimensions (spacing, length, number, etc) and polymer layer properties (thickness, processing, etc.). The most important of these is the ratio between the thickness of the polymer layer and the electrode periodicity, characterized by the distance $d$ from one electrode to the next (Fig. 1). For the best possible sensitivity, the dimensions of the finger electrodes need to be correlated with the thickness of the polymer so that the main part of the electric field lines lie within the polymer (Fig. 3). If too thin a layer is used, the permittivity change of the polymer will not affect the total capacitance to the desired extent. Too thick a layer will on the other hand react more slowly to a changing environment i.e. in case of the humidity sensor the time for water to diffuse through the polymer will be increased. Literature and simulations show that 95% of the electrical field lines are within the polymer when the thickness of the polymer is at least half the electrode periodicity (Fig. 4) [3,5,9].

The viscosity of the polyimide placed certain limits on the thickness that could be evenly spin coated onto the wafer. Initial tests indicated that a 3 µm thickness could be achieved and suitable dimensions of the fingers were found to be 300 nm in width and 700 nm gap in between fingers making the total periodicity $d = 2(\text{g+\text{w}})$. Substrate permittivity $\varepsilon = 4.5$, polymer permittivity $\varepsilon = 3.0$.

3. Fabrication

The sensors were fabricated on 4-inch Pyrex wafers, initially coated with 200 nm Au using a 15 nm thick Ti adhesion layer. E-beam lithography (JEOL JBX-9300FS) was used to pattern the designed interdigitated structure, with 300 nm wide fingers and 700 nm gap in between fingers, onto the wafers. The gold and titanium layers were dry etched using ion milling (Oxford Ionlab 300).

A 50 nm plasma enhanced chemical vapor deposited (PECVD) silicon nitride layer was deposited on the wafers using an STS PECVD, decreasing the
risk of voltage breakthrough and improving the mechanical stability of the fingers. During the process development stage, the wafers were protected with photoresist and diced prior to cleaning and spin coating of the polyimide. Polyimide PI2723 (Dupont Co.) was spin coated onto the wafers, to form a 3 µm thick layer. The polyimide was annealed in a nitrogen atmosphere at 450 ºC.

The sensor was initially glued, wire bonded and tested on FR4 and aluminum oxide substrates. However the humidity and temperature sensitivity of the substrates turned out to be highly influential on the sensor, adding signals in the order of 0.1 pF. The solution for independent testing of the sensor was to mount contacts directly onto the sensor pads using conductive glue thus removing the substrate altogether (Fig 5).

The influence of the substrate on the sensor read out shows the need for a reference sensor. This reference sensor is to be used together with the sensor on the final RFID tag to subtract signals from temperature fluctuations and other sources of noise from the substrate. The requirements on the reference sensor are that it is insensitive to humidity yet in every other aspect identical to the actual sensor. This was accomplished by sealing off a humidity sensor using layers consisting of 200 nm silicon oxide and 1500 nm silicon nitride on top of the polyimide layer and cover these with a glob top (Fig 6). The silicon dioxide layer relieved stress between the polyimide and the thick and hard but brittle silicon nitride layer. The silicon oxide and silicon nitride were deposited using PECVD.

Fig. 5. Sensor mounted directly on a pair of contacts.

Fig. 6. Sketch of multi layer sealing of the reference chip. Layer thicknesses are not drawn to scale. Glob top thickness is in the range of mm.

4. Measurements

The final sensor was tested in a climate chamber (VCL7010) using a test sequence for temperature and humidity (Fig. 7). Measurements showed that any attempt to take out the analog sensor signals from the climate chamber through cables to an external A/D-converter suffered severely from the humidity and temperature sensitivity of the cables themselves and thus a hermitically sealed box with measurement electronics (Smartec UTI sensor-to-time signal converter with Atmel ATmega48 microcontroller used for data handling) was designed and fabricated for use inside the climate chamber. Sockets through the box wall made it possible to plug in the sensor.

The sensor read out was compared with the humidity sensor of the chamber for one climate cycle (Fig. 8). The noisy character of the graphs is due to the humidity tune-in behavior of the climate chamber and is not due to sensor accuracy. When the two curves are compared one can see that our sensor follows the VCL7010 sensor closely in almost every point. It can also be seen that the sensor is at least as fast as the climate chamber at 0.1 %RH/s. Furthermore, measurements showed that the sensor has a wide measurement range, being virtually linear from 20 to 90% RH (Fig 9).

The reference sensor’s insensitivity to humidity
was tested and confirmed (Fig 10). A slight temperature
dependence was noted, underlining the need for the
reference sensor in applications. The operating point of
the sensor was around 9 pF with a 1 pF measuring
range.

5. Conclusions

A small, low-power and potentially low-cost humidity
sensor for passive RFID applications has been
constructed using a sub-micron interdigitated electrode
structure with spin-coated polyimide.

The next step in the sensor development is to
adjust the wafer process for a scaled-up, low-cost batch
production. The focus is on replacing the slow and
costly e-beam lithography with nano-imprint
lithography, but a new design will also reduce the total
chip size to obtain an increased number of chips per
wafer. Smaller size is also an asset in RFID tag
applications.

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