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Design and characterization of a low thermal drift capacitive humidity sensor by inkjet-printing

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ABSTRACT

Small, low-cost and flexible humidity sensors were designed, fabricated by using an inkjet-printing process, and fully characterized. Based on the principles of the capacitor and the ability of a polyimide to absorb humidity, the sensor was fabricated by printing silver interdigitated electrodes on a thin polyimide film of 75 μm thickness. After modeling, the total area of the printed sensor was optimized to be 11.65 mm^2. A relative humidity sensitivity of 4.5 fF/%RH and a thermal coefficient of −0.4 fF/°C were measured at 100 kHz, whereas the sensitivity and the thermal coefficient were 4.2 fF/%RH and −0.21 fF/°C, respectively, at 1 MHz. This latter result implies that it could not be necessary to include thermal compensation to use this sensor depending on the required accuracy and the chosen frequency. This work shows a reliable, fast, simple and low-cost manufacturing process to make small humidity sensors with low thermal drift and high temporal stability. These sensors could be easily integrated into inkjet-printed RFID tags for monitoring of environmental humidity in diverse applications.

1. Introduction

In recent years, printed and flexible electronic devices have become increasingly attractive due to their potential low-cost per surface area, mechanical flexibility and feasibility of large scale processing. The main advantage of printed electronics is a simplified manufacturing process, which results in lower cost processes and shorter cycle time.

On another front, today there is a very strong and growing demand in world trade for humidity sensors. In fact, the field of smart packaging including sensor capabilities opens new challenges in the development of flexible and printed humidity sensors compatible with this kind of technologies. An important additional advantage of printed sensors is the possibility of integrating them with printed radio frequency identification (RFID) tags. There is a lot of interest at present in converging RFID tags and sensing capabilities that are able to save and store the acquired information related to both identity and measured parameters, see for example Refs. [1–3]. The introduction of RFID and the Electronic Product Code (EPC) standard as a substitute of popular barcodes in packaging has advanced markets in intelligent packaging. It will be possible to read not only many packages at the same time but also environmental parameters extracted from sensors incorporated into the containers. There is a special interest in the capability of tracking the condition of a package through the whole supply chain to certify that products in their packages have not been endangered because of being exposed to wrong environmental conditions.

Great efforts and very valuable advances have been made in the design of flexible and printed humidity [3–6] and other gases sensors [7–9]. Related to the requirement of low energy consumption, the classic transduction mechanism of these humidity sensors is capacitive, specifically through changes in the electrical permittivity of some component of the capacitor and the dielectric thickness. This requires the use of chemicals (usually polymers) whose electrical permittivity changes with the relative humidity of the environment. One of the most frequently used structures for capacitive sensors is based on planar interdigitated electrodes (IDE) due to its compactness, high contact area and relative ease of manufacturing [10–12].

Different fabrication processes have been used to develop this kind of sensors, such as gravure, screen printing and inkjet-printing; and different strategies have been applied to include the sensing capability in the capacitor. The most common approach has been to deposit the sensing layer over the IDE capacitor [13–15]. Some frequently used polymers are cellulose acetate

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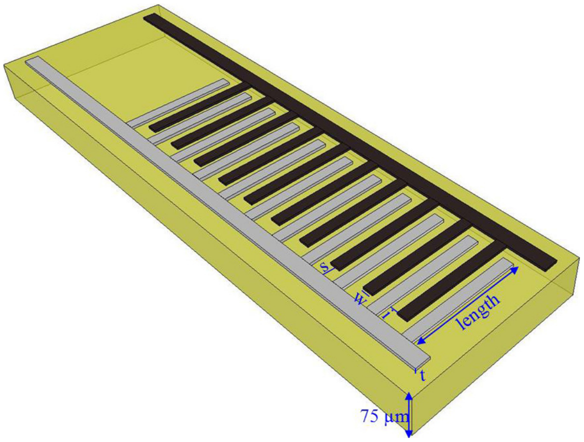

Fig. 1. Layout of the designed IDE sensor (w = width, s = distance, i = interspacing, t = thickness).

butyrate (CAB), polymethylmethacrylate (PMMA) and polyvinylchoride (PVC), among others. Another possibility is to use the flexible substrate as the sensing element. In this case, polyimide [6] and photographic paper [5] have already been described, saving fabrication steps compared with the former approach. Despite all the previous work, these capacitive sensors have a high thermal drift as one of the main challenges to be overcome in order to obtain an accurate humidity measurement. Differential measurements with reference capacitors (not sensitive to humidity) [2] or including additional temperature sensors [16,17] are some of the used strategies to reduce the interference due to thermal drift. Both solutions imply the addition of other devices, consuming more area and energy.

In this work, we present the design, fabrication and characterization of a capacitive humidity sensor which uses the flexible substrate as sensitive element. This capacitor has been printed with silver nanoparticles by inkjet-printing on a polyimide thin film. Our aim has been to obtain a very small device with optimized dimensions based on numerical simulation, minimal fabrication steps and a very low thermal drift without additional components, useful in many applications. Furthermore, we have analyzed the influence of the number of printed layers on the sensor performance.

2. Materials and methods

2.1. Sensor design

The devices analyzed in this study are planar IDE capacitors which allow more direct interaction between the sensor and the surrounding environment compared to other structures [13]. The usual approach for providing humidity (or other gases) sensitivity is to deposit a sensing layer on this structure with some humidity-dependent electrical property. The variation of this property with the humidity produces changes in the capacitance of the whole device. But here, we have skipped this deposition step and directly used the flexible substrate made of polyimide as the sensing element to simplify the fabrication process (Fig. 1). The polyimide is a well-known chemical whose electrical behavior shows a high sensitivity to the relative humidity. Specifically, the relationship between the electrical permittivity of this polyimide and the relative humidity has already made it interesting to test it as a humidity sensor [6]. This relationship is given by:

$$\varepsilon_r = \varepsilon_{r0} + \alpha \cdot RH(\%) \qquad (1)$$

where $RH(\%)$ is the relative humidity in percentage and ε_{r0} and α are material dependent parameters. This relative permittivity also depends on frequency and temperature among other parameters which could interfere with the measurement of the humidity. These dependences must be also analyzed in order to obtain a complete overview of the sensor behavior and to try facing them to improve the sensor performance.

Table 1
Physical dimensions of the capacitive interdigitated structure.

Parameter	Value	Description
Length	1.6 mm	Length of each finger (*y*-axis)
Width	50 µm	Width of each finger (*x*-axis)
Thickness	420/900 nm	Thickness of electrodes (1/2 layers) (*z*-axis).
Number	32	Total number of fingers of the larger electrode
Interspacing	50 µm	Distance between consecutive fingers (*y*-axis)
Distance	50 µm	Distance between fingers of one electrode and the backbone edge of the other electrode (*x*-axis)

The optimization of the sensor dimensions may potentially introduce more sensors into the devices, saving manufacturing materials and area. For this purpose, we used COMSOL Multiphysics 4.2a (www.comsol.com, COMSOL, Inc. USA) to optimize the design. This is a powerful interactive environment for solving problems based on partial differential equations with the finite element method. This software has previously been used to calculate distributions of potential field in this type of structures [18,19].

The total capacitance is determined by the integral of the electrostatic energy density, W_e, through the equation:

$$C = \frac{2}{{V_{\text{port}}}^2} \int_{\Omega} W_e d\Omega \qquad (2)$$

where V_{port} is the value of the applied voltage in the port of the sensor. The other electrode is connected to ground. The electrical parameters of the substrate given by the manufacturer and the printed and cured conductive silver ink according to our characterization were included in the numerical simulator [20].

Several parametric analyses were performed varying the fundamental geometrical parameters of the IDE such as the number of fingers, the gap width between two consecutive fingers and their dimensions (width, length and thickness of each finger). In order to optimize the area, we fixed the finger width to the minimum diameter landed drop (in our case 50 µm) and the gap between fingers also to 50 µm. This gap could be reduced below the drop diameter value to increase the capacitance value but this reduction will lead to a strong possibility of short-circuit between electrodes due to printing errors. The parametrical simulations showed that the thickness of the fingers hardly affects the capacitance value in this structure. In this work, we have also tested structures with one and two printed layers. As shown below, their thicknesses are under 1 µm in both cases implying extremely long simulation times because of meshing issues. Due to this fact, we set the thickness of the IDE to 5 µm for all the simulations to drastically reduce the computational time. Then, we extrapolated the value of the capacitance for the thickness of 1 layer and 2 layers according to Fig. 2 where the slope of the curve is 0.019 pF/µm.

According to previous considerations, we manufactured the sensor following the specifications from Table 1 for a targeted nominal capacitance (for one printed layer) of 2 pF since they presented the best compromise between capacitance and area. Finally, the capacitance predicted by COMSOL Multiphysics for this structure was 1.949 pF with only one printed layer in a dry atmosphere.

The designed IDE area was 11.65 mm^2 (L = 1.85 mm × W = 6.3 mm) composed of 63 fingers (32 fingers for one electrode and 31 for the other one) with 50 µm width