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Printed electrodes structures as capacitive humidity sensors: A comparison

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ABSTRACT

This work discusses about four planar printed capacitive sensors with different geometrical layouts, fabricated by inkjet printing on a flexible substrate and used as humidity sensors. In particular, we show a comparison among interdigitated electrodes, meandered electrodes, spiral electrodes, and serpentine electrodes in terms of fabrication yields, sensitivities to relative humidity as well as thermal drift taking into account frequency dependencies. In addition, numerical simulations have been performed to further investigate the characteristics of these sensors. All sensors present similar behavior in frequency with humidity. Taking into account sensitivity within the same sensing area, the highest value is achieved by serpentine electrodes, followed by spiral electrodes, interdigitated and meandered electrodes, in this order. The best configuration will be dependent on the specific application and its requirements.

1. Introduction

Capacitive structures are widely used in electronics to address many different applications [1]; they are especially interesting in the field of sensors due to their characteristics, such as low energy consumption, non-intrusive and non-invasive, no radiation and fast response [2,3]. The most common sensing capacitive structures are the parallel plate (PP) and the interdigitated electrode (IDE). PP is characterized by the simplicity of its geometry and the ease of calculation and modelling.

IDE sensors are a particular case of planar capacitive structures where the sensor electrodes are placed in a co-planar plane [4]. The planar structure allows to access the device from only one side [5], which is particularly useful when the access to an material under test (MUT) is limited or the other side should be open to the ambient. The advantage of this kind of structures is the fact that they can be fabricated on a substrate by deposition of a layer without including any step of micromachining. That allows compatibility with any kind of technology. Furthermore, this geometry has been used to fabricate with multiple materials and following different manufacturing process, from integration in semiconductor dices to printing on flexible substrates [6–8]. This additional feature makes planar capacitive sensors an attractive option for applications in material characterization [5], non-destructive testing (NDT) [9], proximity/displacement measurement [10], intelligent human interfacing [11], and imaging [12,13]. Many efforts have been devoted to the theoretical modelling of the planar capacitive structures. Igreja and Dias [14] presented a theoretical model of the capacitance of IDE structure. These capacitors have also been simulated using different simulations tools [15–17]. Some authors have analysed other designs such as spiral electrodes and concentric rings in order to improve the performance of this design [7,18,19]. Other structures such as rectangular-shaped [20] and comb-shaped sensor arrays [21] were studied, showing that desired linearity and sensitivity can be achieved by the optimal selection of a set of structural parameters. Zeothout et al. [22] analysed a rectangular shaped planar sensor using a numerical method and also compared its performance according to different material properties and boundary conditions.

On the other hand, flexible electronic devices manufactured by printing techniques have become increasingly attractive thanks to their feasibility of large scale processing, potential low-cost per

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surface area and mechanical flexibility. Great advances have been achieved in the design of flexible and printed humidity sensors [23–26] as well as sensors for other gases and vapours [27–29]. The classical transduction mechanism of these humidity sensors is capacitive due to the requirement of low energy consumption, in particular, through changes in the electrical permittivity of some structural layer of the capacitor or the dielectric thickness. Different printed techniques have been used to manufacture capacitive printed devices and different approaches have been followed to add the sensing capability into the capacitor. The most common strategy has been to deposit a sensing layer over the electrodes [16,30,31] such as cellulose acetate butyrate (CAB), poly(methyl methacrylate) (PMMA) or polyvinylchloride (PVC), among others. Another possibility has been to select a flexible substrate as sensing element saving fabrication steps, in this sense, polyimide [26] and photographic paper [25] have already been used. One of the main interfering factors to obtain an accurate humidity measurement is temperature. In order to compensate this dependence, several strategies have been already described such as differential measurements with reference capacitors (not sensitive to humidity) [32], including additional temperature sensors [33,34] or using a sensitive layer with very low thermal drift [35,36]. This latter alternative does not require additional devices, and therefore, less area and energy is consumed.

In this work, we will show the design, fabrication and characterization as humidity sensor of four different coplanar electrodes comparing and contrasting their characteristics. In this regard, we present the design, fabrication and characterization of capacitive humidity sensors which uses the flexible substrate as sensitive element. These capacitors have been printed with silver nanoparticles ink by inkjet-printing on a polyimide thin film. In the context, this paper discusses planar printed capacitive sensors in terms of fabrication yields, sensitivity to relative humidity as well as thermal drift taking into account frequency dependencies. Further investigations of the sensor designs have been carried out using a numerical method. The differences among these planar capacitive sensors are pointed out as well as their advantages and disadvantages of the different electrodes designs.

2. Materials and methods

(A) Fabrication process

The DMP-2831^{TM} Dimatix printer (Fujifilm Dimatix Inc., Santa Clara, USA) was used for inkjet printing. The selected materials were an ink of silver nanoparticles (U5603 SunTronic Technology, San Diego, USA) on a polyimide substrate (Kapton® HN with 75 μm of thickness, Dupont^{TM}). Table 1 shows the main properties of the used ink and substrate, respectively.

According to the manufacturer of the substrate, the relationship between the relative permittivity (ε_r) and the relative humidity (RH) is given by:

$$\varepsilon_r = 3.05 + 0.008 \times RH(\%) \text{at 1 kHz, } 23^{\circ}\text{C} \quad (1)$$

The first step before printing was to prepare the substrate removing all traces of particles with a cleaning process to ensure the best quality and to avoid failed printings. First, the substrate was immersed in acetone for 2 min to remove dust on the surface, and then was submerged in propanol about 2 min to remove the acetone. After that, the substrate was washed with purified water to eliminate the propanol and finally was dried at 120 °C for 5 min. During the printing process the substrate temperature was fixed at 40 °C and a drop space of 25 μm was settled for 50 μm landed diameter drops. Finally, a sintering step is carried out at 120 °C for 60 min.

In order to know the thickness of the printed layer, the theoretical model given in [37] has been used. According to this model, the amount of used ink is 22.7 nl for one printed layer with a thickness of 460 nm. With that printing and curing conditions, the resistivity of the conductive electrodes were 23 ± 2 μΩ cm [37]. The fabrication time is much shorter than in the case of other sensors because no other sensing layer was needed [16,30,31]. The fabrication process is also simplified because it only required printing one layer on one side of the substrate. In a previous work, we demonstrated that thickness layer does not contribute significantly to capacitance and therefore the definition of electrodes by only one printed layer is enough for a proper sensor performance [35]. A matrix of twenty capacitors of each type was fabricated in order to test the reproducibility of the process.

(B) Physical and electrical characterization

The geometrical characterization, the roughness of printed patterns as well as the thickness of the patterns have been measured using a Wyko NT1100 Optical Profiling System (VEECO, Tucson, AZ, USA), and a Dektak XT^{TM} Stimulus Surface Profiling System (Bruker Corporation, Conventry, UK).

The AC electrical characterization for the different fabricated capacitors has been performed by measuring their capacitance and dissipation factor, using the four-wire measurement technique with a precision Impedance Analyser 4294A and an impedance probe kit (4294A1) (Agilent Tech., Santa Clara, CA, USA). The excitation voltage applied in all measurements was $V_{DC} = 0$ and $V_{AC} = 500$ mV. The frequency sweep of analysis was from 100 kHz to 10 MHz. In all prototypes, one of the end sides has been enlarged to facilitate its connection to any analyser. A SMA (SubMiniature version A) male connector has been glued to these end points using silver-filled epoxy EPO-TEK® H20E (Epoxy Technology, Inc., Billerica, USA). A complete compensation method has been implemented to eliminate the contribution of parasitic capacitances by measuring several commercial capacitances placed in the same configuration as the devices under test with the 16034G surface mount device (SMD) Test Fixture (Agilent Tech., Santa Clara, CA, USA).

The stationary humidity and temperature responses of the sensors have been measured in a climatic chamber VCL 4006 (Vötsch Industrietechnik GmbH, Germany). The humidity deviation in time was ±1% to ±3%, whereas the temperature deviation in time was ±0.3 °C to ±0.5 °C. The data acquisition and analysis have been automated using Labview 2012 software (National Instruments Corporation, Texas, USA). Due to the slow response of the mentioned climatic chamber, the dynamic response has been measured in a customized humidity measurements set-up ($9 \times 3\ \text{cm}^2$), which automatically controls wet and dry airflow inside a small gas cell at room temperature. Two LCR-meters (HP 4284L and Agilent E4980A, Agilent Tech., Santa Clara, CA, USA) have been used to measure the corresponding capacitance values at a frequency of 100 kHz every 5 s. Capacitance and time measurements of the printed sensors have been controlled and recorded using the software Labview 2012. RH and temperature measurements have been also registered by a commercial sensor (SHT15, Sensirion AG, Switzerland) in order to verify the data given by the chambers' displays. In all cases, the capacitors have been placed in the middle of the climatic chambers allowing the atmosphere interaction in both faces of the sensors, printed and non-printed.

(C) Electrodes designs

We have analysed four different electrodes configurations as capacitive sensor. In this section, we present the geometry of each device, pointing out the dimensions and areas of the fabricated capacitors.