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Printed single-chip UHF passive radio frequency identification tags with sensing capability

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ABSTRACT

Two printed single-chip UHF radio frequency identification (RFID) tags compatible with EPC Gen 2 protocol capable of measuring temperature and relative humidity are presented. The UHF RFID chip SL900A, which includes an on-chip temperature sensor, is used on both tags to drive the relative humidity (RH) sensors and the RF communication. These tags have been fabricated on polyimide substrate (Kapton HN) which presents a well known humidity dependence. Printed RH sensors consist of an array of 12 serpentine electrodes fabricated by inkjet printing and an array of 6 screen printed interdigitated electrodes, respectively, to achieve a capacitance of around 35 pF far from the capacitive parasites present in the structure. Both tags are able to provide temperature and relative humidity environmental parameters in digital form answering to the inquiries of a RFID reader in a passive energy mode (without batteries). With very low thermal drifts, below 0.05%RH/°C, a RH range of 30% is covered by both tag with sensitivities of 100 fF/RH% for the inkjetted serpentine structure and 54 fF/RH% for the screen-printed one. Therefore, we propose passive RFID tags with a single silicon chip providing a cost-effective solution to monitor environmental conditions based on printing technologies.

1. Introduction

Over the last years, radio frequency identification (RFID) technology has become increasingly attractive due to its advantages of simultaneous tag reading, wider reading range and faster data transfer in comparison with traditional identification techniques (i.e. barcodes) [1]. The development of RFID and the Electronic Product Code (EPC) standard has become a substitute of popular barcodes in packaging. This new trend, known as smart packaging, is able to read not only many packages at the same time but also environmental properties detected by sensors included in the RFID tags. In this sense, a special interest is shown in the capability of tracking the condition of a package through the whole supply chain to certify the product quality has not been degraded. This added value of this technology justifies its higher cost and complexity than traditional techniques [2]. In fact, the field of smart packaging including sensor capabilities opens new challenges in the development of flexible and printed tags compatible with this kind of technologies [3–8]. Furthermore, the opportunity of tracking environmental conditions of objects and the communication between them introduces the paradigm of the Internet of Things (IOT) and Wireless Sensors networks (WSNs) [9,10].

Moreover, great efforts and very valuable advances have been made in the design of flexible and printed sensor [11–13]. Thanks to the requirement of low energy consumption, many gases and humidity printed sensors are capacitive, specifically through changes in the electrical permittivity of some component of the capacitor. Regarding moisture sensors, this transduction mechanism requires the use of chemicals (usually polymers) whose electrical permittivity changes with the relative humidity of the environment. Different approaches have been followed to include the sensing capability in the capacitor. The most frequent strategy has consisted of depositing a sensing layer over the electrodes capacitor [14–16]. Some common polymers are cellulose acetate butyrate (CAB), polymethylmethacrylate (PMMA) and polyvinylchloride (PVC), among others. Another method is to directly use the flexible substrate as sensing element, saving fabrication steps compared with the previous strategy. For this

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purpose, the use of polyimide [13] and photographic paper [17] has already been described. Regarding the physical structure for these capacitors, the most used design is the interdigitated electrodes (IDE) because it presents very interesting features such as one-side access, control of signal strength by changing easily its dimensions, multiple physical effects in the same structure (electric, magnetic, acoustic) and a wide frequency spectrum of use [18]. Recently, a novel serpentine electrode (SRE) has been described by Rivadeneyra et al. whose sensitivity is higher than IDE with the same area [19].

In this regard, several RFID tags with sensing capabilities, sometimes referred as to smart RFID tags, have been already developed following different strategies [20]. Some authors have associated a change in the analogue response of the sensing RFID tag, such as read range or shift of the antenna resonance frequency, to the variation of the monitored magnitude [4,19,21–30]. These strategies can be used as threshold tags [31] but lead to uncertainties in the source of these variations because there are many factors that can interfere in the tag performance, for instance the path loss between antenna and reader or the spatial and temporal fading. In addition, extra circuitry must be added to the reader in order to measure these parameters. Other approaches are based on microcontroller architectures with RFID chips and different types of sensors: temperature, light, moisture content [32,33]; chemical sensing [7,34–38]; printed moisture sensors [4,5,12,13]; pressure [39]; or built-in sensors, typically temperature sensors [40]. There are also some examples of single chip architecture without microcontroller unit already reported [41–43]. The main advantage of this strategy compared to the analogue reading of the tag is the fact that sensor data are directly processed in the RFID tag. Therefore, the sensor digital data can be transmitted to the reader or stored on the RFID tag for future access. In case of data logging, these strategies require the use of a battery to power periodically the tag. Although the extra components increase the cost of the system, the functionalities incorporated justify this higher cost.

Regarding smart printed RFID tags, Unander et al. [5,12] presented a semi-passive RFID tag with a printed moisture sensor. The sensor solution consisted of a passive RFID tag, a microcontroller, a printed resistor, a printed moisture sensor, and two printed batteries to power the microcontroller. The sensors were defined by conductive silver ink on a plastic film laminated onto cellulose-based substrates. The readout of the sensors was measured by charging and discharging the capacitance. Another similar example was a printed UHF RFID tag which indicated whether the tag had been exposed to a certain degree of humidity [31]. The change of the sensor resistance was used to modulate the properties of a UHF RFID tag antenna by changing antenna input impedance and also introducing or removing ohmic losses in the antenna structure. Both the sensor and the tag antenna are printed horizontally on a paper substrate. Contrary to these strategies, our tags do not require either extra circuitry to obtain data sensor or battery to take measurements.

Here, we present the design, fabrication and characterization of two printed RFID tags with sensing capabilities. Our main aim in this work is to design and fabricate complete systems on plastic foil, integrating printed sensors in printed RFID tags. These passive tags are printed on a flexible substrate. With the aim of testing different sensor structures, each tag includes a different capacitive structure to measure the relative humidity of air. The first tag contains SRE due to their higher sensitivity than the conventional interdigitated IDE [19]. The drawback of this approach is the fact that this sensor is defined by inkjet-printing to achieve better pattern resolution and, therefore, two different printing processes are implicated. In order to easy the manufacturing process, we present the second tag. In this particular case, the sensor is fabricated by screen printing but, due to the lower resolution of this printing technique, the sensor size is significantly bigger in order to get a similar capacitance value. As remarkable features, the architecture is based on printing technologies as fabrication process and with only a single chip architecture, where the sensor data, in digital form, can be reliably delivered to the UHF RFID reader. In addition, the chip used here integrates a temperature sensor, and therefore, these tags provide two environmental parameters in every reading.

2. Materials and methods

2.1. Smart tag architectures

Fig. 1 shows the architecture of the two types of printed tag, including the footprints of the different components required. Both tags present a passive architecture based on SL900A RFID chip [44] (AMS AG, Unterpremstaetten, Austria) compatible with the EPC Gen 2 RFID standard. This RFID chip was chosen due to the integration of a Sensor Front End (SFE) that comprises different sensor conditioning stages and 10-bits Analog to Digital Converter (ADC). This extra circuitry has been used to interface the relative humidity capacitive sensor. Furthermore, it includes an on-chip temperature sensor. In this regard we will be able to measure capacitance values of the humidity sensor and, if necessary, perform thermal compensation to the acquired values.

Two types of printed humidity sensors are presented which are shown in Fig. 1. In both cases, humidity sensors consist of several capacitive elements in parallel to achieve a total capacitance of around 36 pF, well above the parasite capacitance of the RFID chip connections which is about tenths of picofarad. The only difference between these layouts is the footprint of the array of printed sensors, fabricated with different printing techniques, and placed in parallel to sum up a bigger sensor capacitance. The radio frequency interface consists on a typical dipole antenna resonating at 868 MHZ (European Band for RFID UHF) and a RF Surface Mount Device (SMD) inductor used to match the chip input impedance [45].

Temperature value comes from a conversion in the on-chip A/D converter of the SL900A. Two internal voltage references, V_{ref1} and V_{ref2} individually selectable in steps of 50 mV between 160 and 610 mV, set the lower and upper limits of this converter. These limits are defined as $2V_{\text{ref1}} - V_{\text{ref2}}$ and V_{ref1}. The difference between them defines the input voltage range, $V_{\text{ref2}} - V_{\text{ref1}}$, and the limits of operation. These voltage references can be set in the user application and, therefore, a concrete resolution and range can be selected by the user. The minimum resolution is 0.18 °C in a range of 189.9 °C while a resolution of 0.23 °C is obtained with the widest range of 237.2 °C.

The printed humidity sensor is directly connected to the SFE of the RFID chip. To read out the capacitance value, the SFE is configured in capacitance mode. In this mode, an external reference capacitor has to be placed in series with the printed sensor as shown in Fig. 2. The sensor capacitance is excited with a 100 kHz square wave signal whose amplitude is equal to V_{ref1} voltage. This AC signal is generated with a voltage offset of V_{ref1} so the amplitude signal goes from 0 to $2V_{\text{ref1}}$. The input voltage on the ADC associated with the capacitance value is:

$$V_{\text{ADC}} = V_{\text{ref1}} \frac{C_{\text{ref}}}{C_{\text{ref}} + C_{\text{sens}}} + V_{\text{ref1}} \qquad (1)$$

There is no auto ranging capability on the ADC; therefore the reference capacitor has to be properly chosen according to the expected sensor capacitance. According to Eq. (1), the term composed by the division of C_{ref} and $C_{\text{ref}} + C_{\text{sens}}$ governs the input voltage change. At maximum sensing capacitance value ($C_{\text{sens}} \gg C_{\text{ref}}$) the input voltage should be close to V_{ref1} whereas at