Integrated Temperature, Humidity and Gas Sensors on Flexible Substrates for Low-Power Applications

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Abstract—Temperature, gas and humidity resistive/capacitive sensors on flexible substrates from organic materials, suitable for RFID mobile applications, have been produced and investigated. The sensor implementation solutions are providing simple, versatile and low power temperature and gas detection. The device structure was developed together with the data evaluation strategies based on last generation $\Sigma\Delta$ analog (resistance and capacitance) to digital converters. We demonstrate the possibility of developing gas sensors on humidity sensitive substrates, having temperature corrected responses. The proposed device concept is aimed to evolve towards “flexible & full plastic” implementations.

I. INTRODUCTION

The monitoring of temperature, humidity and ambient atmosphere composition with low cost and low power sensors is of interest for many application fields. Combined/integrated onto radio frequency identification (RFID) transponders, they will allow for the development of smart tags/labels that will, e.g., monitor the environmental conditions encountered during the transportation of perishable/sensitive goods [1]. For doing so, one has to use substrates compatible with the RFID labels and ensure that the chosen sensor solutions are providing simple, versatile and low power gas detection. The proposed device concept is aimed to evolve towards “flexible & full plastic” implementations. Low power humidity and gas sensors on flexible substrates will ask for capacitive readout [2]. Until now the capacitive gas sensors R&D efforts have been directed towards: “on chip (Si)” [3] integrated platforms or “large area plastic sensors” [4]. Nowadays the interest in the field of “integrated on plastic” RFID devices is strongly increasing [5-7] but still no practical solutions are currently available, even if, from the viewpoint of many mobile applications, they will make a lot of sense. Therefore we designed, realized and tested a hybrid prototype, combining the advantages of the Si technologies with the expected benefits from the new-coming “all plastic” and “flexible” electronics; with the demands of intelligent RFID tags in mind we also explored the integration of temperature sensors onto the same substrates. Here we show how it is possible to integrate temperature, humidity and gas sensing by using design concepts based on flexible polymers and last generation capacitance to digital converters. We also demonstrate the possibility of developing sensors on humidity sensitive substrates, having temperature corrected responses.

II. EXPERIMENTAL

A. Sensor platform: design and fabrication

The experimental samples were produced on commercial polyimide combining photolithographic, e-beam evaporation, lift-off, spin-coating, spray coating and casting procedures.

Each sensing platform (Figure 1) consists in a resistor used as temperature sensor and two sets of interdigitated electrodes for the chemical capacitive measurements. The targeted capacitance of the structure with the sensing layer on top was 10 pF.

Figure 1. Sensor platform with Pt thermometer and electrodes.
The total chip area is 14x25 mm². The platforms were manufactured on 4” wafers of 50 µm-thick commercial polyimide (Upilex® 50S from UBE Industries Ltd). E-beam evaporation and a lift-off technique were used to fabricate and pattern the electrical elements. They are made of a 130 nm thick 1.06 Ω/□ platinum film deposited above an adhesion layer of titanium (20 nm). The total resistance of the temperature sensor was about 1 kΩ.

In the last technological step PEUT and PDMS test sensing layers were deposited by drop or spray coating onto the left-hand interdigitated electrodes pair; the right-hand side was kept uncoated to operate as reference during the measurements (Figure 1). The platform layout allows for a large variety of sensitive materials, appropriate to the target analyte which detection is required. The polymers we used are only plain examples, adequate however for the evaluation of the sensor concept and the related measurement and data interpretation strategies.

Sensor readout electronics.

The platform was designed for low power readout electronics. In the experiments we used the dual differential ΣΔ capacitance to digital converter AD7746 and its additional voltage/resistance input (see Figure 2). The data delivered on the I²C bus of AD7746 were accessed by using an I²C to USB adapting microcontroller connected to a PC.

At present the final step of data preparation has been performed off-line, with commercial, non-dedicated, software. This solution allowed for quick sensor tests in different operation conditions and, in the same time, for a straightforward evaluation of the algorithms used to extract the values of the measured parameters (humidity, gas and vapor concentration, temperature). In many tests the first stage of electronics (shown in Figure 2) was kept at the platform temperature in order to simulate real working situations. The data recorded in this way have been compared with those obtained by maintaining the readout electronic at room temperature. The results were very encouraging, no difference, in the limit of the experimental errors, being visible.

III. RESULTS AND DISCUSSIONS

The signals of a PEUT-based chemical sensor at different temperatures and the recorded temperature values are depicted in Figure 3 and the corresponding calibration curves in Figure 4. Figure 5 presents the outputs of a complete sensor system (Upilex® substrate, PDMS sensitive layer, temperature sensor) and the subsequent steps of data extraction. The substrate sensitivity to humidity results in an overall slowly evolving response to the ambient water vapor; the substrate does not respond however to the target gases. The polymer based sensor responds to both VOCs and humidity; the numerical subtraction of the substrate signals reveals, with good accuracy, the behavior of the sensing layer alone. Further corrections, planned to be implemented onto the microcontroller, are based on the temperature sensor inputs, on the polymer and substrate calibration curves for humidity and the actual humidity signal of the polyimide.

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Figure 4. Calibration curves of PEUT-sensor for ethanol and n-propanol at different temperatures. Temperature values have been measured with the integrated Pt thermoresistor of the sensor. The readout electronics was kept at the sensor temperature. From the sensor responses in the background of 50% relative humidity was subtracted the baseline shift due to humidity; it is displayed in the lower panel. In the same panel one also finds the temperature shift of the baseline (exp. data from Figure 3).

Figure 5. The sensor signals, their successive preparation and different level of information subtraction. (Spray-coated PDMS sensing layer on UPILEX® polyimide).

For instance a simple computing algorithm was used to infer the actual values of the humidity and gas/vapor concentration. It makes use of all 3 channel output of the sensor, mentioned above (gas sensing layer & substrate, substrate and Pt thermoresistor) and run as follows:

Calibration stage:

1. The reference capacitances of the sensor capacitive channels are measured in reference conditions (fixed temperature, 0% humidity, absence of the target gas).
2. The integrated thermometer is verified and calibrated if necessary (the Pt thermoresistor deposited and annealed in standard conditions do not normally require for additional calibration).
3. The gas sensing channel (layer together with substrate) is calibrated for the target gas at different humidity levels and temperatures. One obtains calibration curves as those in given in Figure 4.
4. The humidity channel (substrate or substrate with humidity sensing layer), chosen to be insensitive to the target gas, is calibrated for humidity and temperature (calibration curves not shown, because of space lack, but similar to those in Figure 4).

Measuring stage:

1. The actual temperature is measured with the Pt thermoresistor.
2. The output of the substrate is converted to humidity using the corresponding calibration curve. To do this one multiplies the local slope of the calibration curve for the given temperature with the actual value of the substrate response.
3. The output of the sensor channel is converted to target gas concentration in the same way as at the previous point, this time the corresponding slope depends on both temperature and humidity.

If the responses of the sensing elements of the platform are quite linear, then, it is possible to reduce the amount of stored data and interpolation steps required to get the factors used in the evaluation process. So, in the first approximation order, one uses only the linear fits of the real curves; this procedure will reduce each curve to only two parameters: the slope and the intercept of the ordinate axis at the origin. In this case the algorithms can be implemented with only simple mathematical operations (addition and multiplication).

The results of the off-line calculations for the PDMS signals corrected for temperature and humidity are shown in Figure 5 in order to demonstrate the potential of the sensor system to yield the correct values of the ambient atmosphere parameters (target gas, humidity and temperature).

The main obstacle in implementing such sensors for wide ranges of applications is, as almost always in the gas sensing field, the limited selectivity of the sensing layers for the intended target gases. It is not trivial to overcome this inconvenient and one usually has to employ sensor arrays to sample the experimental data. A multivariate analysis step is afterwards required in order to infer the concentration values of the detected gases.

For the capacitive sensors a huge problem is the interference given by the humidity. Due to the high dipolar momentum of the water molecule, this analyte produces large shifts of the effective permittivity values at all sensing materials and by that drastically reduces the response specificity to other target gases. The first results with the sensor platform demonstrate the possibility to remain in the simple frame of a differential capacitive sensor platform, and to eliminate the humidity interference as well.

The design concept of the sensor platform is appropriate for mobile application, powered from small batteries, or for passive detection in conjunction with remote operation on RFID tags. During the tests the average dissipation of the platform alone was less than 10µW at 1 reading/s. For the mobile application it is counting, however, the power consumption of the whole sensor system together with its driving electronics. Suitable exploitation strategies can significantly expand the sensor potential and applicability area.

IV. CONCLUSION

The sensor concept we developed, here including capacitive / resistive platform layout and implementation, sensor readout based on low power analog to digital ΣΔ converters and the measurement strategies with the associated algorithms for the evaluation of the analyte concentrations has successfully passed the test phase.

It was also proved the possibility to simultaneous measure temperature, humidity and gas/vapor concentrations with only one sensor platform; furthermore, the differential structure of the capacitive sensor system allows manufacturing of gas sensors on humidity sensitive substrate. In both investigated cases, that is PEUT and PDMS based sensors, it was possible to extract the specific responses towards the analytes from unwished signals due to ambient humidity even if the responses induced by humidity exceeded with more than an order of magnitude the responses generated by the target gases.

This feature is very useful when designing sensors for RFID tags, which are currently produced on not completely hydrophobic polymeric substrates. Additional efforts for improving the sensitivity and selectivity of the sensing materials/layers employed in capacitive gas/vapor sensors are also stringently required.

REFERENCES