Printed Humidity Sensors And Their Application

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Abstract—We have developed a new type of printed capacitive humidity sensors with stacked parallel-plate electrodes. A polymer sensing material with extremely low hysteresis and a grid top electrode design that ensures the sensor's rapid response to humidity changes were used in the sensors. Screen printing, flexo printing and inkjet printing were used to print the sensors with a capacitance value of 400-2730 pF and a sensitivity of 1.2-11.4 pF/%RH obtained, depending on the printing methods. The sensitivity of the printed sensors was found to decrease with a raised temperature, and the temperature effects were attributed to the water sorption in the sensing polymer and its relationship with temperature. A method of calibrating the temperature of the sensors was thus proposed and implemented. With the obtained capacitance value over 400 pF, low-cost electronic circuit PCB boards were designed and fabricated to attach the printed sensors, resulting in standalone and functional humidity sensing units. Each of the humidity sensing units is equipped with light energy harvesting, capacitance measurement, and wireless data transmission, as well as the calibration capability for converting measured capacitance to relative humidity. The units were successfully applied in the building management of commercial office buildings.

Keywords-humidity sensors; printing; filed application.

I. INTRODUCTION

Printing on flexible substrates is an emerging technology for sensor fabrication. With the combination of new solution-based functional materials and cost-effective printing processes, the technology enables large, flexible, stretchable, lightweight devices that were not possible using traditional semiconductor processes [1][2]. Various sensors were fabricated with the technology, and some of them have been commercialized with a great success. Printed glucose sensors alone, for example, already have annual sales of multi-billion US dollars. Many other printed sensors, such as temperature sensors, organic photodetectors, pressure sensors, humidity sensors have either found practical applications or showed promising future.

In our work of applying printed and flexible humidity sensors in high performance building management, we need sensors that have a capacitance value of several hundred pF and can be measured with a low-cost DC circuit. But, the existing printed sensors normally have a capacitance value of several pF and sensitivity in fF/%RH range, and the sensors need a complicated instrument to analyze [3][4]. We therefore proposed parallel-plate structure with a grid top electrode to achieve high capacitance and high sensitivity, and studied the fundamental characteristics and temperature effect of the obtained sensors in detail. With these, we were able to bring the printed humidity sensors to standalone sensing units that can harvest light energy, perform humidity measurement and transmit data wirelessly at regular interval.

In Section 2, experiment details are provided and in Section 3, the results with discussion are presented. In Section 4, the work is concluded.

II. EXPERIMENT

Cellulose acetate butyrate with 12-15 wt% acetyl and 36-40% butyryl content was used as sensing material with ethylene glycol diacetate as its solvent. Silver flake-based ink was used for screen printing electrodes and PET films for substrates. Silver nanoparticles-based ink was used for flexographic printing and inkjet printing. An EKRA X1-SL screen printer, the flexo unit of Testacolor 171 from NSM-AG, and a Dimatix 2800 inkjet printer from Fujifilm Dimatix were used to print the sensors.

The capacitance of the printed sensors was measured with Agilent 4284A LCR meter for dynamic monitoring, and a battery-powered circuitmate capacitance meter (called as DC meter here) from Beckman Industrial co was used in the detailed study of the sensors at various temperatures and under various water vapor pressures. For the packaged sensors, the measurement was done by the PCB boards automatically and periodically. The capacitance-humidity-temperature characterization was carried out in a Burnsco B-Series environmental chamber.

III. RESULTS AND DISCUSSION

In this work, we proposed a new type of printed capacitive humidity sensors with stacked parallel-plate electrodes to achieve a high capacitance value and high sensitivity. Figure 1 shows the structure of the sensor. A solid conductive silver film is first printed on a flexible substrate PET film as the bottom electrode, followed by printing a layer of sensing material to cover the electrode with a large margin. Then, a grid-shaped top electrode is printed on the material. A capacitance value of over 400 pF as shown in Figure 2 was obtained for all the printed sensors when cellulose acetate butyrate is used as the sensing material. No hysteresis effect was observed from the sensors.

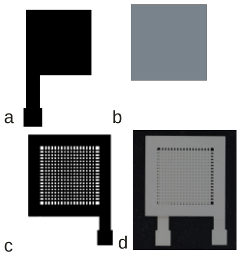

Figure 1. Design of a capacitive humidity sensor and the printed sensor. (a), bottom layer electrode; (b), sensing material layer; (c), top layer electrode; (d), printed sensor.

The sensor performance depends on the thickness of the sensing material (as seen in Table 1), and the achievable film thickness depends on the printing method. Screen printing is

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only good for printing thick films, and the best sensor performance is 435 pF and 1.2pF/%RH. Flexo printing can print thinner films, 725 pF and 1.8pF/%RH can be achieved. Inkjet printing can very thin films, 2730 pF and 11.4 pF/%RH was achieved. As screen printing is suitable for volume fabrication at low cost, the process was used for printing all the sensors used for study and application.

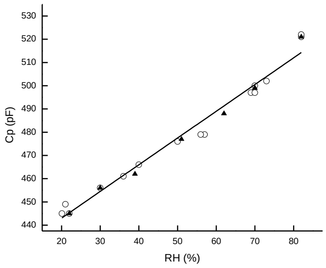
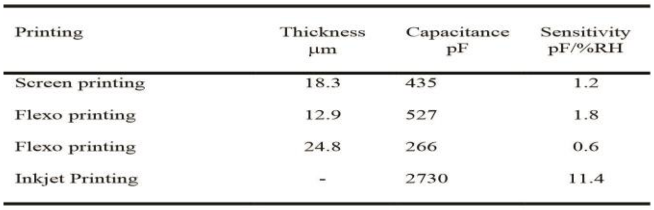


Figure 2. Measured capacitance of a humidity sensor as a function of chamber humidity. (o) measured when humidity was changed ascendingly; (Δ) measured when humidity was changed descendingly.

TABLE 1. EFFECT OF THE SENSING MATERIAL ON SENSOR PERFORMANC



Printing	Thickness µm	Capacitance pF	Sensitivity pF/%RH
Screen printing	18.3	435	1.2
Flexo printing	12.9	527	1.8
Flexo printing	24.8	266	0.6
Inkjet Printing	-	2730	11.4

The performance of the printed humidity sensors was fund related to environment temperature. Figure 3 shows the capacitance-RH plots of a sensor at seven different temperatures. At each of the studied temperatures, the capacitance (Cp) of the sensor responds linearly to the relative humidity (RH) changes. The sensitivity of the sensor - the slope of the Cp-RH plot at each testing temperature was obtained by linearly fitting the corresponding Cp-RH data, and are shown in Figure 4. The sensor sensitivity decreases with increasing temperature, from 1.5 pF/% RH at 5 °C to 1.0 pF/% RH at 45 °C.

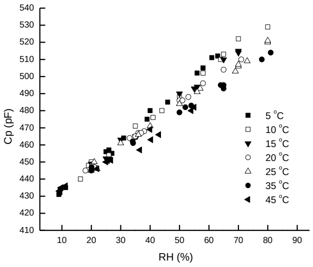


Figure 3. The capacitance-relative humidity relationship of a printed sensor at various temperatures.

The further study at various constant water vapor pressures showed that the capacitance of the sensors decreases with increasing temperature at a constant water vapor pressure, and it increases with increasing water vapor pressure. The reason is that the capacitance change is directly proportional to the water solubility in the sensing material. From the measurement, the sorption of water in the sensing materials was estimated to be from-2.9 KJ/mol to -3.0 KJ/mol.

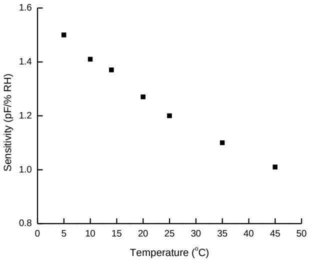


Figure 4. The sensitivity-temperature dependence of a printed relative humidity sensor.

With a capacitance value over 400 pF and a sensitivity above 1 pF/%RH, the printed sensors are acceptable for the measurement with a simple DC circuit in practical field application. A Credit-Sized Printed Circuit Board (PCB) for measuring the sensor's capacitance was thus designed and fabricated for applying the sensors in building management. Figure 5 shows a fully packaged humidity sensor that directly gives humidity reading as a standalone sensing unit. An EnOcean's STM 332U device was incorporated in the PCB for light energy harvesting, data processing and wireless communication. The harvested energy from room light and sun light in day time provides sufficient energy for powering the sensor measurement and data transmission uninterruptedly 24 hours a day. The packaged sensors were successfully deployed in the humidity monitoring and control of an office building. In the application, the sensors were programed to provide humidity data very 5 mins.

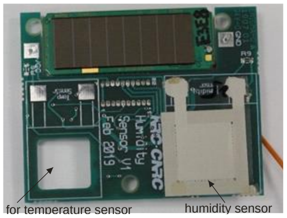


Figure 5. A packaged humidity sensor with self-powering and wireless communication capabilities.

IV. CONCLUSION

Printed capacitive humidity sensors with stacked parallel plates were developed to achieve a high capacitance of over 400 pF and a high sensitivity of over 1.0 fF/%RH. By printing a thin layer of the sensing polymer, the capacitance value and sensitivity of the sensors can be substantially increased. It was found that the capacitance reading and sensitivity of the sensors decrease at elevated temperature, due to the intrinsic decrease of water sorption in the sensing polymer. The printed sensors were packaged with simple DC circuits and energy harvesting units as standalone sensing units for practical field application. They were successfully deployed in an office building for dynamic control.

REFERENCE

[1], S. Khan, L. Lorenzelli, and R. S. Dahiya, “Technologies for printing sensors and electronics over large flexible substrates: a review”, IEEE Sensors, 15, pp. 3164-3186, 2015.
[2], Y. S. Rim, S. -H. Bae, H. Chen, N. D. Macro, and Y. Yang, “Recent progress in materials and devices toward printable and flexible sensors”, Adv. Mater. 28, pp. 4415-4400, 2016.
[3], F. J. Romero, A. Rivadeneyra, A. Salina-Castillo, A. Ohata, D. P. Morales, M. Becherer, and N. Rodriguez, “Design, fabrication and characterization of capacitive humidity sensors based on emerging flexible technologies”, Sens. and Actuators B 287, pp. 459-467, 2019.
[4], A. Rivadenenyra, J. Fernadez-Salmeron, M. Agudo-Acemel, J. A. Lopez-Villanueva, L. F. Capitan-Vallvey, A. J. Palma, “Printed electrodes structure as capacitive humidity sensors: a comparison”, Sens. and Actuators B 244, pp. 56-65, 2016.

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