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Miniaturised MultiMEMS sensor development

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***Abstract**: Complex systems, from environmental behaviour to electronics reliability, can now be monitored with Wireless Sensor Networks (WSN), where multiple environmental sensors are deployed in remote locations. This ensures aggregation and reading of data, at lower cost and lower power consumption. Because miniaturisation of the sensing system is hampered by the fact that discrete sensors and electronics consume board area, the development of MEMS sensors offers a promising solution. At Tyndall, the fabrication flow of multiple sensors has been made compatible with CMOS circuitry to further reduce size and cost. An ideal platform on which to host these MEMS environmental sensors is the Tyndall modular wireless mote. This paper describes the development and test of the latest sensors incorporating temperature, humidity, corrosion, and gas. It demonstrates their deployment on the Tyndall platform, allowing real-time readings, data aggregation and cross-correlation capabilities. It also presents the design of the next generation sensing platform using the novel 10mm wireless cube developed by Tyndall.*

1. INTRODUCTION

The coming years will see the emergence and deployment of low cost, low power, intelligent wireless sensor networks (WSN) and their use in various applications of environmental monitoring. While large-scale operations like weather stations can use discreet sensors and circuitry, miniaturisation and modularity of the sensing platforms will be necessary for many other applications that require large numbers of remotely deployed monitoring points.

Tyndall is developing miniaturised, wireless capable motes that incorporate customisable sensor interface boards for use in highly modular wireless platforms. The interface boards exist in both 25mm×25mm and 10mmx10mm form factors and allow a combination of different sensors to be connected to computational and RF components [1], [2]. Since discrete sensors are bulky, expensive and consume board area, the use of MEMS-based integrated sensors will allow further miniaturisation of the platform.

2. MULTI-MEMS DESIGN AND FABRICATION PROCESS

A number of different environmental sensors have already been studied and discussed in the literature. Depending on the target application of the sensing platform, which can range from agriculture to IC/systems degradation control, the list of possible configurations to consider must be carefully studied. Often, the solutions are single-purpose sensors aiming at one or two specific parameters only. When low-cost, remote deployment and constant data aggregation from multiple environmental parameters are required simultaneously, miniaturisation of the sensors and conditioning circuitry is essential.

The fabrication of multiple environmental MEMS sensors on one single substrate offers a potential solution to this problem. The fabrication process flow presented on figure 1 is compatible with CMOS technology, as the bottom metal electrode of the MEMS process doubles as the CMOS top metal layer. It enables the development of five different environmental sensors: temperature, corrosion, humidity, gas detection, and gas flow velocity (from left to right on the figure). The possible fabrication of a monolithic MEMS+CMOS sensor die, as well as most of the individual sensor characterisation, has already been described in [3].

The first step of the process flow is the deposition and patterning of a thin metal film on top of native oxide. This is the active sensing layer for temperature, corrosion and gas flow sensors, and acts as the bottom electrode of the humidity sensor. A passivation oxide is then deposited and selectively removed over corrosion and humidity sensors. The third step consists of a conformal polyimide deposition. This polymer layer acts as porous dielectric for the humidity sensor and a sacrificial layer for the fixed-fixed gas sensor element. A second metallic layer is then deposited, forming the top electrode of the humidity sensor and active element of the gas sensor. The silicon substrate is then etched from beneath the gas flow velocity sensor in order to obtain good thermal isolation and improved sensitivity. Finally, the polyimide sacrificial layer is selectively removed.

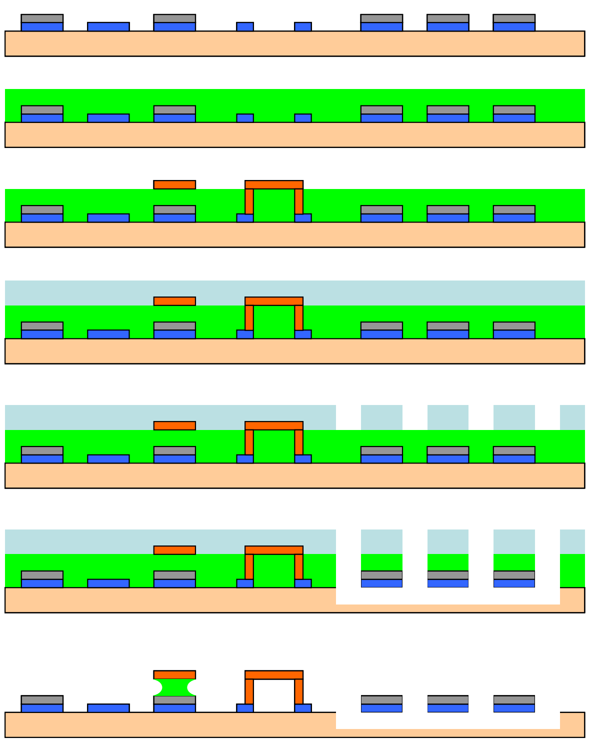

Figure 1: Multiple MEMS sensors fabrication process left to right: temperature, corrosion, humidity, gas, gas flow velocity.

3. Multiple MEMS development and test

3.1 Test settings of multiple MEMS sensors

A test setup has been developed in order to aggregate and correlate data from all sensors over a period of time. Figure 2 shows the MEMS bare die which have been wirebonded in dual-in-line (DIL) packages for testing. They all incorporate three different types of sensors: temperature, humidity and corrosion, as it was not possible to characterise the gas sensors with the setup. As can be seen, different corrosion structures have been tested, consisting of ladders, edge damage detectors, and a combination of triple track and comb pattern [4], [5], and [6]. A non-passivated temperature sensor has also been added to monitor the long-term effects of corrosion.

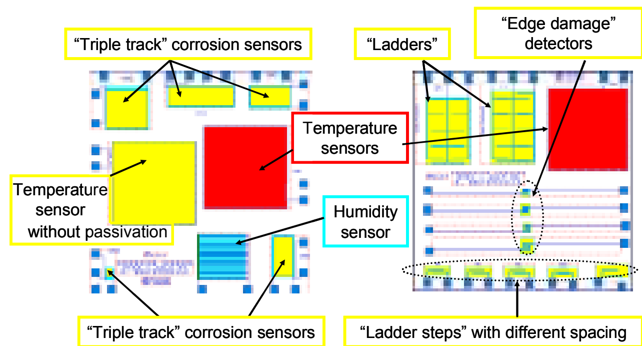

Figure 2: Test structures with multiple MEMS sensors.

Several parameters, such as the sensitivity, stability, and hysteresis of each sensor can be affected by external parameters. It is also important to investigate the isolation of the sensors from these parameters throughout a wide range of values. For the tests described in the following sections, the die have been tested in a TAS HTCL climatic chamber where humidity and temperature has been controlled and monitored with calibrated sensors. Resistance values have been measured using a Keithley 2430 and an Agilent 34411A, and capacitance measurements were read on an Agilent 4284A LCR-meter with a bias of 50mV at a frequency of 100 kHz. The substrates of the die were grounded to avoid parasitic charges.

Extensive testing in different environments and for different biases across the corrosion detectors has been achieved, while the output data collected was both saved and displayed using an Agilent VEE software program.

3.2 Humidity effects on temperature sensors

The resistance R of a metal track varies with the temperature T according to

$$R(T) = R_0\left(1+\alpha\left[T-T_0\right]\right) \qquad (1),$$

where R_0 is the sensor resistance at a known temperature T_0, and α is the thermal coefficient of resistance (TCR) of the material. However, other parameters such as the ambient gas composition and its relative humidity can affect the performance of temperature sensors, and they have to be incorporated to correct the final sensor response.

3.2.1 Effects of humidity on sensor sensitivity and hysteresis

The sensitivity of the sensor given in (1) remains approximately constant over a wide range of humidity from 20%RH to 90%RH, and the hysteresis is negligible. Humidity has no effect on these parameters.

3.2.2 Humidity isolation of the temperature sensor

The die were placed in the chamber at constant temperature, while humidity was ramped up and down from 20%RH to 90%RH. The response of the sensor gives temperature according to (1), and it can be compared to the actual temperature inside the chamber. The error is then calculated and is not negligible, showing a dependency on humidity of the sensor. A model of the error is then constructed for each temperature value. Figure 3 gives an example of such a model at a fixed temperature of 25°C.

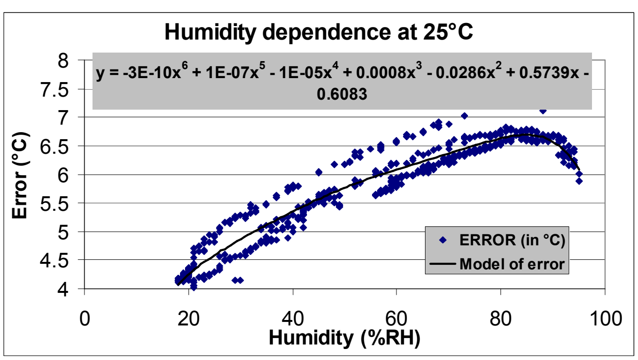

Figure 3: Humidity dependence of temperature sensor at 25°C.

The error can be corrected using the model in order to correlate temperature and humidity effects. We can see on figure 4a that the correction reduces the average error from 20% to a more acceptable value of 5%. An example of the corrected sensor characterisation taking humidity into account is presented on figure 4b. It shows that the measured values are closer to reality after treatment.

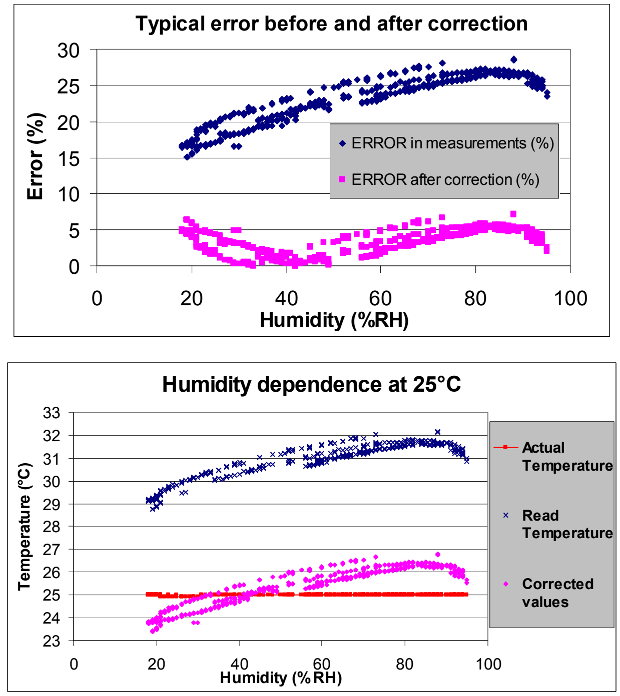

Figure 4: (a) Correction of the error due to humidity; (b) Effects of temperature correction on measurements.

3.2.3 Compensation of humidity effects

From equation (1),

$$\Delta T_{meas} = \frac{R_{meas}-R_0}{\alpha R_0} = aR_{meas} - b \qquad (2)$$

The actual temperature obtained after correction for humidity effects is given by:

$$T = \Delta T_{meas} - corr\,, \qquad (3)$$

where the typical correction for the effects of humidity on the temperature sensor performance is

$$corr = 3.10^{-10}T^6 + 10^{-7}T^5 - 10^{-5}T^4 + 8.10^{-4}T^3 - 0.03T^2 + 0.57T - 0.61 \qquad (4)$$

3.3 Temperature effects on humidity sensors

The capacitive humidity sensors fabricated at Tyndall are based on two metal electrodes of area *A,* separated by a porous polyimide layer of thickness *d*. The dielectric constant ε_r of the polymer is a function of humidity, and the typical response of the sensor is given by:

$$C(\%RH) = \frac{\varepsilon_0 \varepsilon_r (\%RH) A}{d} \quad (5)$$

3.3.1 Temperature effects on hysteresis

It has already been demonstrated that use of polyimide as the active sensing layer will lead to a hysteresis effect, as its water absorption and desorption rates are different. However, temperature changes will not amplify this effect. This simplifies the compensation model of temperature effects on the humidity sensor [7].

3.3.2 Temperature effects on sensitivity

It has already been proven that temperature affects the sensitivity of capacitive humidity sensors, and that these effects can be compensated [7]. In order to correct the sensor response, the data obtained from the humidity sensor during the previous tests was used to calculate its sensitivity for different fixed temperatures, when humidity is ramped up and down. Figure 5 shows the evolution of the capacitance response for different temperatures from 10°C to 70°C.

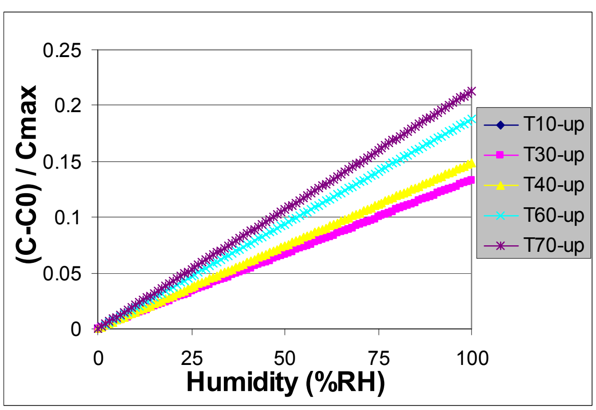

Figure 5: Humidity sensor response at various temperatures.

The sensor sensitivity can be calculated and plotted against temperature, as shown on figure 6. It is clear that temperature has an effect on the sensitivity, as a difference of 25fF per %RH is attained between 20°C and 70°C.

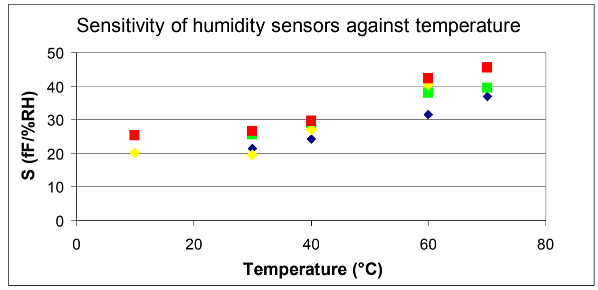

Figure 6: Sensitivity of humidity sensors as a function of temperature.

A model of the sensitivity against temperature can then be constructed for all dies, and the fitted curves are third order equations. The temperature compensation equation for the sensor presented in figure 5 is given by:

$$S = -0.0003T^3 + 0.047T^2 - 1.448T + 30.134 \quad (6)$$

3.3.3 Temperature isolation of the humidity sensor

The temperature isolation of the humidity sensor is not perfect as the sensor response is modified during temperature transitions at fixed humidity. As can be seen on figure 7, the response follows temperature changes, as if humidity increased. It appears that the sensor response is not following the actual humidity in the chamber when a high temperature transition occurs.

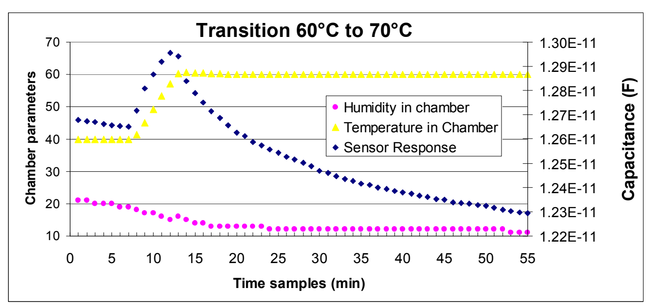

Figure 7: Temperature transition affecting sensor response.

If the application of this multiple sensing platform requires a fast accurate response, a correction will be necessary. However, for typical applications in environmental monitoring which do not demand to follow fast changes, this type of compensation is not critical, as the sensor response corrects itself relatively quickly.

3.3.4 Multiple measurements and compensation

By combining the temperature value obtained after correction with equation (4) and equation (6), it is possible to give ΔRH as a function of the measured capacitance C and the measured resistance R.

3.4 Corrosion sensors

The ambient conditions inside the climatic chamber are not particularly highly corrosive as there is no other gas than air, and no salts that could accelerate corrosion of the structures. Therefore, accelerated tests such as the ones described in [4] and [8] were required to test our sensors before they can be deployed outdoors using the Tyndall wireless platforms.

Subsequently, combinations of triple-track, comb and ladder corrosion monitors were characterised while using humidity and temperature sensors for correlation purposes. For the triple-track structures, the middle resistor was grounded, while the structures on each side were inversely biased. As the middle line corrodes and opens, its resistance incrementally increases, until it is fully corroded and becomes an open circuit. This type of device can monitor corrosion kinetics and corrosion rate variations. The ladders demonstrate a gradual response as electrolytic corrosion occurs. The gradual corrosion is here forced by the different gaps between the ladder rungs.

Examples of corrosion data are shown in figure 8 for two triple-track/comb pattern structures, and in figure 9 for a typical ladder.

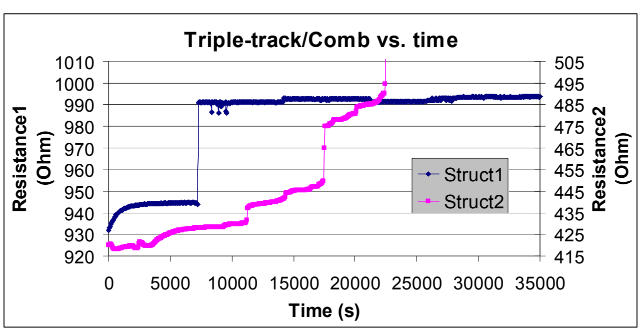

Figure 8: Resistance monitoring of two triple-track corrosion sensors during testing at 60°C, 70%RH, 3V bias. Left axis corresponds to Struct.1.

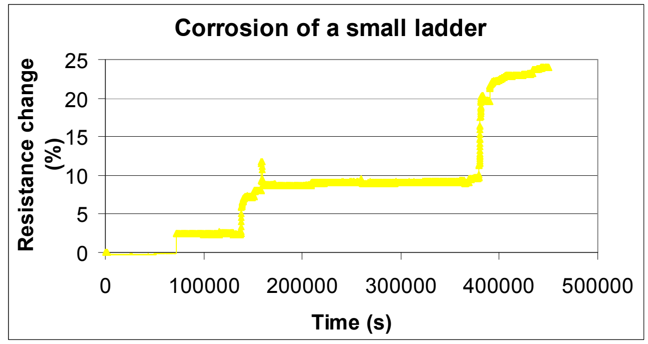

Figure 9: Resistance of the middle line of a ladder at 60°C, 70%RH, 5V bias.

As can be seen on figure 8, the different structures react in an incremental step fashion, and the shortest line is fully corroded before the longest one. Figure 9 shows the same type of sensor response. Only one voltage bias has been used here under fixed ambient conditions. A change of 25% in the line resistance is obtained after 125 hours. We expect extensive tests in more corrosive environments to show that corrosion rates can be better investigated with this type of structure.

Corrosion monitors are very useful to give early warnings of corrosive environment, and change of corrosion rates. Their output response can be correlated with measured parameters such as temperature and humidity (and later gas detection) in order to detect the presence of possible other factors. This has not been possible in the environmental chamber, but will be achieved in the near future.

4. INTEGRATION AND DEPLOYMENT

As it has been presented in [2] and [3], Tyndall has developed modular wireless platforms in different formats for deployment in WSN. The multi-sensors dies can then be attached to these platforms as it has already been demonstrated for temperature and humidity on a 25mmx25mm board [1].

On figure 10, the deployment of the present sensors on two Tyndall motes is depicted. The 10mmx10mm version has been made possible thanks to the compatibility of the MEMS process with CMOS technology. Hence, signal conditioning circuitry has been designed on the sensor die, reducing the space taken by discreet components mounted at the back of the 25mm layer.

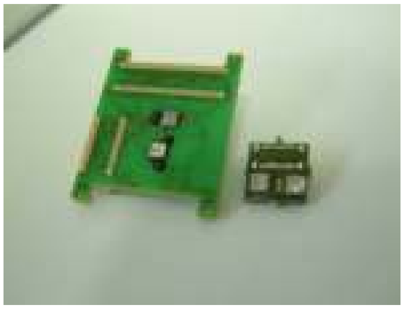

Figure 10: MEMS multi-sensor dies deployed on 25mm (left) and 10mm (right) wireless motes.

Integrating the multi-sensor die described in this paper with the wireless motes will allow deployment and testing in outdoor environments. This will be achieved in the following stages of the project, and will enable data aggregation and cross-correlation between sensors in more various fields.

5. Conclusion

The design, fabrication and test of multiple MEMS sensors on a single die has been presented in this paper. Cross-correlation between different sensors has been investigated in a controlled environment; models that correct for the unwanted effects of temperature and humidity have been developed and validated. Future work will involve gas and gas flow velocity sensor characterisation and deployment of the complete wireless platform in the field.

References

[1] S. Harte, B. O'Flynn, R.V. Martinez-Catala, E.M. Popovici, , "Design and Implementation of a Miniaturised, Low Power Wireless Sensor Node", *Proc. 18th European Conference on Circuit Theory and Design*, pp. 894-897, August 27-30 2007.

[2] J. Barton, G. Hynes, B. O'Flynn, K. Aherne, A. Norman, A. Morrissey, "25mm Sensor-Actuator Layer: A miniature, highly adaptable interface layer", *Sensors and Actuators A-Phys.,*Vol. 132, November 2006, pp. 362-369.

[3] M. Hautefeuille, C. O'Mahony, B. O'Flynn, K. Khalfi, F. Peters, "A MEMS-based wireless multisensor module for environmental monitoring", *Journal of Microelectronics Reliability*, Vol. 48, No. 6, June 2008, pp. 906-910.

[4] N.L. Sbar, R.P. Kozakiewicz, "New Acceleration Factors for Temperature, Humidity, Bias Testing", *Proc. 16th Annual Reliability Physics Symposium*, pp. 161-178, 1978.

[5] P.R.Troyk, R. Frankovic, J.E. Anderson, "Experimental Techniques for Electrical Testing of Microelectronics Coatings", *Transactions on Components, Hybrids, and Manufacturing Technology*, Vol.14, No.2, June 1991.

[6] H.R. Shea, A. Gasparyan, H.B. Chan, S. Arney, R.E. Frahm, D. López, S. Jin, R.P. McConnell, "Effects of Electrical Leakage Currents on MEMS Reliability and Performance", *IEEE Transactions on Device and Materials Reliability,* Vol.4, No.2, June 2004.

[7] C.Y. Lee, G.B. Lee, "Micromachine-based humidity sensors with integrated temperature sensors for signal drift compensation", *Journal of Micromechanical Microengineering*, Vol.13, pp.620–627, 2003.

[8] J.N. Sweet, M.R. Tuck, D.W. Peterson, D.W. Palmer, "Short and long loop manufacturing feedback using a multi-sensor assembly test chip", *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, Vol.14, No.3, September 1991