Wireless microsensors system for monitoring breathing activity

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***Abstract*— A portable, non-invasive and easy to operate wireless system has been developed for monitoring the breathing activity of patient. The system is composed of a capacitive microsensor (airflow-humidity sensor) integrated on a silicon chip and of a Negative Temperature Coefficient thermistor; both are coupled to a Radio Frequency wireless link. The sensitive part of the microsensor is an array of interdigitated metallic electrodes covered by 100 nm-thick dense anodized aluminum oxide layer. The breath water vapor is adsorbed over the interdigitated electrode and changes the sensor characteristic capacitance. This modulated signal is then digitized and either stored in a memory or directly transmitted to a monitor through the short distance RF link. Full size of the microsensor is less than 1 cm² and can be easily implemented in a classical adhesive bandage. This microsystem is proposed for monitoring sleep-disordered breathing as well as breathing rhythm of athletes during effort.**

Keywords— **Breath monitoring, capacitive & temperature microsensors, alumina adsorption, wireless set-up.**

I. INTRODUCTION

Building bridges between the medical and the engineer world, to sense human life parameters has been from always a constant care to help diagnoses. As breath is one of the vital parameters, several systems to monitor respiration have been developed: thermistors, thoraco-abdominal band, nasal prongs and pneumotachograph. The gold standard pneumotachograph is very invasive and cannot be used for a daily check, making a justification for challenger measurements.

Following this idea, airflow can be detected by change of temperature, humidity or CO_2 concentration in breathed air [1]. The thermistor is the most spread sensor for oro-nasal flow. It shows nevertheless a long time-constant response and a certain inability to detect change in volume exhalation [2], [3] expected in other phenomena than apneas. Pressure transducer at the end of nasal prongs, assessing indirectly the ventilation, authorizes detection of the complete range of events appearing in SAHS (sleep apnea-hypopnoea syndrome): apneas, hypopneas and flow limitations.

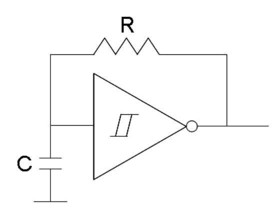
To achieve at the best all the requirements – low hysteresis, high range, resistance against chemicals, short time response, no drift, no degradation - we chose to focus on miniaturized humidity sensors, and especially ceramic-based. Even if the trend is to use porous materials [4], we demonstrated a change of 2 orders of magnitude in capacitance for dense alumina sensing materials. Combined with a classical NTC (negative temperature coefficient) thermistor, the ambition of our system is to improve comfort and reliability of patient assessment during sleep.

II. PRINCIPLE OF OPERATION

A. Set-up description

The key element in our sensor interface is the insertion of a microsensor in an oscillating circuit, translating the capacitance or temperature change to an oscillation frequency shift. The goal of this interface is to visualize and save in a file the variations of the sensing element.

Those variations are, in fact, capacitance or resistance modulations. An easy way to detect and send both small capacitance (ΔC) or resistance (ΔR) variations can be made by placing, respectively, the capacitive microsensor and the NTC thermistor (bead type, nominal value 100 kΩ) in an oscillator loop. A Schmitt trigger oscillator 74HC14™ performs the translation ΔC or ΔR to Δf. The frequency of this oscillator directly depends on C and R values.



$$f \cong \frac{1}{0.8 R.C} \quad (1)$$

Fig. 1: Electrical assembly schematic - oscillation frequency sensitive to R and C (R fixed and C variable or inversely).

The modulated signal (FM) is processed into a 8051 microcontroller and then transmitted by Radio Frequency (RF) link compatible ZigBee at 2.4 GHz. The processing firmware runs and performs a frequency counter function. The results of the counting are then sent to a PC Serial Port using an RS232c interface (Fig. 2). Data are sent on a PC through a serial port, plots them on the screen and also can perform recording in a data file.

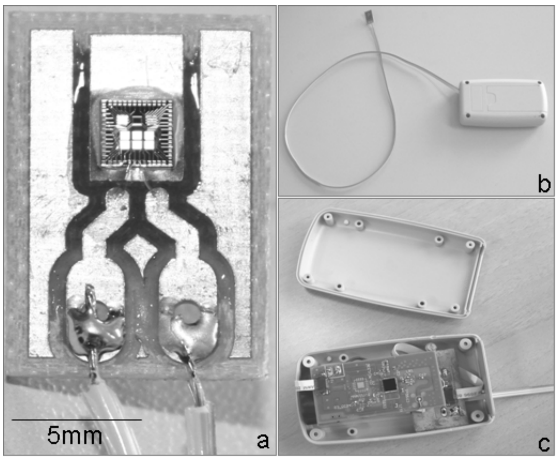


Fig. 2: (a) Interdigited capacitor wire-bonded and glued on an epoxy support; (b) and (c) 24 hours-autonomous embedded module.

B. Microsensor fabrication

For the microsensor, the goal is to use a thin ceramic material as humidity-sensitive layer. Starting from a silicon wafer, wet thermal oxidation produces a reliable 400 nm-thick insulating layer. A 1 µm-thick aluminum is evaporated and patterned by lift-off afterwards as interdigitated fingers and contact pads. Finally, a 100 nm-thick hydrophilic layer is obtained by anodization using boric acid/ammonium hydroxide in ethylene glycol as electrolyte and a current density of 2 mA/cm² [15]. As we use a neutral solution (ammonium borate) in which aluminum oxide is quite non soluble, alumina layer is considered as a barrier layer, instead of a porous layer.

The sensitive part is thus an array of interdigitated metallic micro-electrodes separated by a spacing of 2 µm. The breath water vapor is adsorbed over the interdigitated electrodes (capacitor), and the formed water layer drastically changes the microsensor characteristic impedance.

III. Results

Different situations have been tested to establish sensitivity of our full set-up. In order to understand capacitive change of the interdigitated humidity sensor alone, its behavior under various climatic conditions was analyzed in an ESPEC SH-261 climatic chamber. Measurements were performed after waiting 30 min at every measurement point to have constant humidity in the chamber (Fig. 3).

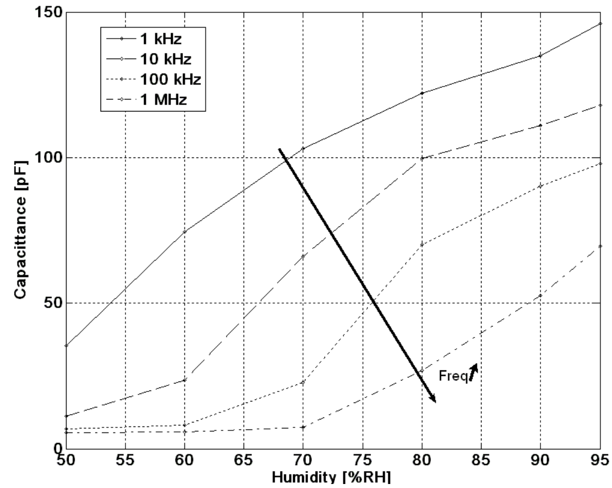


Fig. 3: Capacitance measured at 4 frequencies at 35°C under various humidity levels. The capacitance is formed by 2 interdigitated sensors put in parallel and made of 50 fingers, 2 µm-width separated by 2 µm.

Variations from 11 pF at (35°C,50% RH) up to 118 pF at (35°C,95% RH) are observed at 10 kHz. A complete cycle at constant 20°C with successive increase and decrease of humidity level leads to a small drift of 1.7%.

Our microsensor exhibits a sensitivity of 1 pF/%RH up to more than 5.5 pF/%RH, as defined in (2), when humidity level increases from 50% to 90% RH (Fig. 4).

$$S = \frac{\Delta C}{\Delta RH} \quad [pF/\%RH] \tag{2}$$

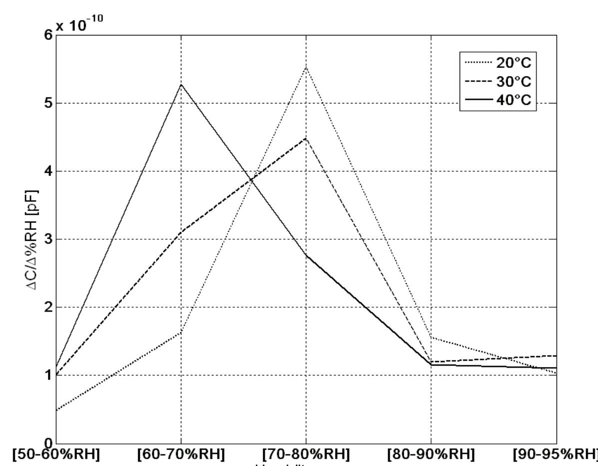


Fig. 4: Sensitivity versus relative humidity (RH) for different temperatures at 10 kHz.

Once the humidity microsensor alone has been characterized, the full set-up as described in Section II was tested to measure human breath. To perform such measurements, a rigid plastic tube (Ø = 6 mm, L= 10 cm) helps to conduct exhaled air from mouth or nasal nostril until sensors. Those sensors are wired to the Schmitt trigger oscillator and the data processing unit thanks to soft electrical cables before going down towards the box (Fig 1b).

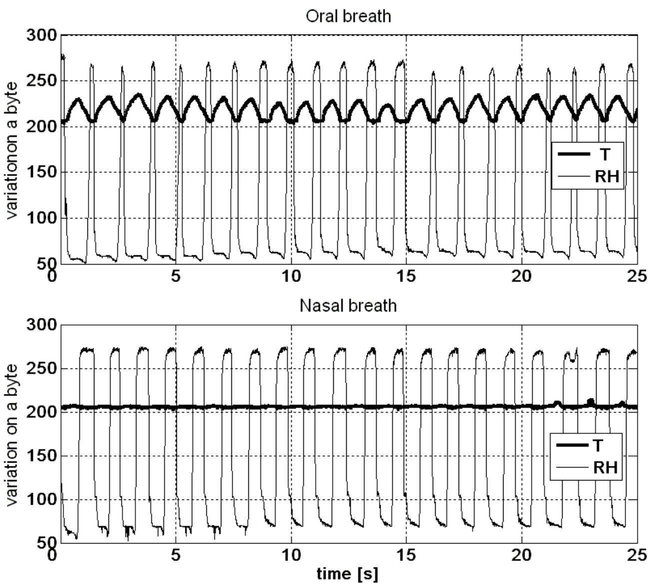


Fig. 5: Variations coded on a byte when human being breaths, respectively, with his mouth and his nose into a plastic tube ended by sensors (T and RH refer, respectively, to the thermistor and the humidity sensor).

Each breathing step is stored both with the thermistor and the humidity sensor as temperature and water vapor concentration changes (Fig. 5). Expirations are recorded as maximum peak values for temperature (negative temperature coefficient) and minimum peak values for humidity. Measurement points are taken every 10 ms, allowing fine plot of the inspiration-expiration cycle.

Defining rise time and fall time as the time needed to reach respectively 90% and 10% of the maximum detected stimulus, breath capacitance measurements show faster answer with, respectively, 150 ms and 250 ms. For temperature both times are approximately equal to 600 ms. If no inspiration arrives to cool or to dry the sensors, the unforced return to the initial value is, respectively, 2 s-long and 15 s-long, showing times incompatible with breathing rhythm.

The fundamental mechanism responsible of the humidity detection is the presence of a chemisorbed layer of hydroxyl ions on which physisorption of water molecules can easily occurs (Grotthus mechanism) [4]. As the first chemisorbed water layer is produced at very low humidity level and is

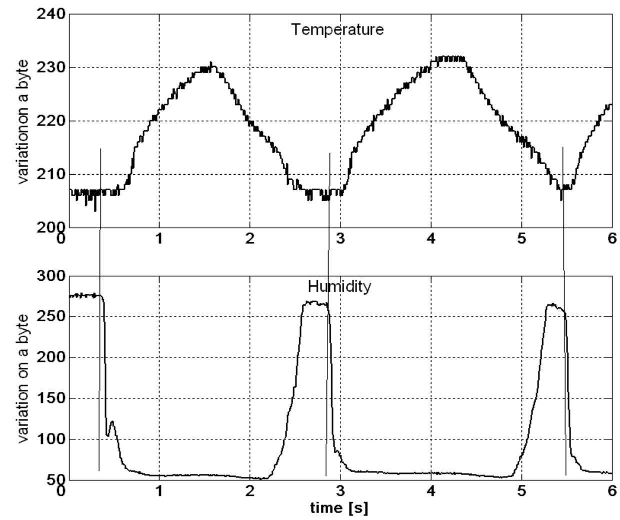


Fig. 6: Variations coded on a byte when human being breaths orally in a plastic tube ended by sensors, respectively, recorded with a thermistor and a humidity sensor.

nearly unchanged with humidity variation because strong bonds formation, oxide surface ever helps in the water-adsorption mechanism.

IV. Discussion

Thermal oxide between the micro-electrodes fingers as well as alumina anodized fingers themselves permit to reach high humidity sensitivity. Moreover, electrolyte anions trapped on the surface originating from the anodization process increase physical adsorption [5]. Physisorbed water acts on impedance by increasing conductance and capacitance, respectively, because of ionic conduction and higher permittivity of water.

Table I shows a comparison between some sensors reported in literature. We focus especially on capacitive sensing based on adsorption and capillary condensation improved by hydrophilic materials (sensitive to water vapor and other polar organic molecules) as polyimide or alumina. High moisture absorption of polyimide leads to very high sensitivity, nevertheless important drifts are observed beyond 70% RH [6]. Most of humidity sensors based on alumina use the porosity obtained by acid anodization to take advantage of capillary condensation inside pores. Impedance variations as high as three orders in magnitude is found for 10 nm-porous alumina [5]. However, such pores could contribute to a drift in capacitance characteristics caused by narrowing of the pores [7].

Contrary to the permittivity of dry air which is slightly modified in function of humidity levels [11], thermal conductivity is significantly improved for small RH level and high temperature [12]. In [9], Okcan and co-workers present sensitive sensors (46.9 mV/%RH) based on this principle which avoids saturation due to condensation but needs to maintain permanently hot points (around 250°C).

Ref.	***Best sensitivity***	***Sensing layer***	***Transducer***
[6]	3.4 pF/%RH	Polyimide	Capacitive
[8]	30 fF/%RH	Polyimide	Capacitive
[10]	1.1 pF/%RH	Polyimide	Capacitive
Our work	5.5 pF/%RH	Alumina	Capacitive

Table I: Comparison of sensitivity for some humidity sensors presented in the literature.

To sense with an optimized temperature and humidity dynamic, a cold and dry surrounding environment is preferable. Moreover, return to the initial state is accelerated with forced ventilation. Consequence of ventilation is very visible for the temperature sensor. By closing mouth around the tube, airflow heats or cools the sensor and the thermistor shows a 5 times higher dynamic, allowing correct airflow plot only for oral breath. However, humidity measurements are relatively unaffected in both cases even if the saturation plateau during expiration increases for oral breath.

Correct distance between water vapor expired air and the humidity sensor has to be found to avoid saturation by drowning completely the sensor. At this point, all water physisorbed does not increase the capacitance anymore and desorption time becomes longer.

As ambient conditions were favorable (20°C), no difference between oral or nasal temperature expiration is observed [13], but measuring in cold environments would increase temperature sensitivity.

Based on our investigations and in agreement with the literature, we can say that thermistor is less sensitive to respiration, but it avoids the saturation phenomenon. Humidity sensing reveals to be very sensitive and finely correlated with temperature breathing cycle. However, the aperture in front of the sensor has to be optimized to avoid important condensation. In one hand, future works have to define the best sensors positioning taking into account multiple predictable failures in case of oro-nasal breath, liquids running out the nose, movements, local heat due to contact with skin, wet environments, etc. In the other hand, in the purpose of co-integrating electronic circuits and micro-sensors such as temperature and humidity sensors to achieve further miniaturization, previous work has successfully proved the concept for our flow sensors [14] and will be continued. Consequence of anodization step on electronics is now under investigation.

Nevertheless, coupling humidity and temperature sensing is a promising approach to record and alert as well when simple event like apnea occurs or in case of hypopnoea and flow limitations.

V. Conclusions

Taking advantage of miniaturization offered by microelectronic fabrication techniques, a humidity microsensor based on water-adsorption of aluminum oxide has been developed. Coupled with a classical NTC thermistor, an embedded wireless set-up showed fine recording of breath cycle thanks to its remarkable sensitivity. Sleep-disordered breathing as well as breathing rhythm of athletes during effort are potential applications for this microsystem.

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