A Sensor Which Can Be Varied in Humidity Sensitivity
A First Experience Paving the Way to New Chemical Sensors?

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Abstract: During last decades, a number of different sensors have been developing for different analytics to detect. A key aspect of those sensors is that each of them results with a fixed particular sensitivity. Consequently, at occurrence, it is necessary to use a plurality of sensors to arrange measures with different levels of sensitivity. This work intends to investigate the possibility to obtain different sensitivity, in particular with respect to humidity, from one sensor only. To this aim we investigated the resistive flex sensor, which has been already used for other applications but, as far as we know, never investigated for its potential properties as a chemical sensor. Results demonstrated how the resistive flex sensor behaves with different sensitivity values and different sensitivity curves for different bend conditions.

1 INTRODUCTION

Humidity refers to the amount of water vapour in the air. It is so important that can affect meaningfully a number of different aspects of manufacturing (processes in industries), of building structural integrities, even of human comfort. Therefore, its measure can be, somewhat, strategic.

Humidity sensors which have been developed during last decades mainly rely on thermal, acoustic, capacitive or resistive effects (Awang, 2014). The latter, in particular, is commonly based on a comb-shaped thick metal film, with underneath a polymeric film, which "furnishes" a different number of ion current carriers according to the surrounding humidity.

The choice of the humidity sensor depends on the specific application, and has to take into account some parameters related to boundary conditions, such as size, packaging, cost, interchangeability, and some others related to the measurement effectiveness, such as accuracy, repeatability, long-term stability, recovering time, sensitivity (Chen and Lu, 2005).

Our work regards the investigation of a humidity sensor which, with respect to the usually adopted sensors based on the resistive effect, differs in type and offers a changeable sensitivity.

In particular, we investigated the response to humidity of a resistive flex sensor (RFS), with the possibility to change its sensitivity, within a certain range, as desired.

As far as we know, the RFS has never been adopted for humidity measurement purposes and, in addition, it is the first proposal of a humidity sensor able to change its sensitivity of the measure.

2 MATERIALS AND METHODS

2.1 Resistive Flex Sensors

A resistive flex sensor (Figure 1) converts its mechanical bending into a proportional electrical resistance variation. This is due to "isles" of carbon particles (engineered on top of a plastic support and drowned in a binder) which increase their distance with RFS bending, so that the resistance proportionally increases too. This effect is almost reversible, so that the RFS furnish its base resistance when returned to flat conditions (Saggio et al., 2016; Saggio et al., 2009).

Up to now, RFSs have been used in a number of different applications.

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(a)
(b)

Figure 1: (a) Top and (b) lateral view of a resistive flex sensor, manufactured by Flexpoint Inc.

The most investigated application consists in laying RFSs on parts of human skins, so to measure flexions/warpings of joints/segments of the human body. The focus has been for the hand, in measuring fingers (Gentner and Classen, 2009; Saggio, 2012; Saggio, 2014), palm (Rossel et al., 2009; Dalley et al., 2012) and wrist (Howcroft et al., 2011; Kushsairy et al., 2015; Yu et al., 2016). Anyway, RFSs have been used for other body parts too, such as neck (Al-Rahayfeh and Faezipour, 2014), shoulder (Kushsairy et al., 2015), elbow (Kushsairy et al., 2015), torso (Saggio et al., 2016), belly (for foetal movements of pregnant woman) (Borges et al., 2009), ankle (Mazhar and Bari, 2015; Resendiz et al., 2016), lower limb (with a deep vein thrombosis cuff) (Qidwai et al., 2016), and foot (Patil et al., 2016).

Other fields of RFS application involves human-computer interface (Berlia and Santosh, 2014), human-machine interface (Asgar et al., 2013), actuators (Elgeneidy et al., 2016), robots (Mutka et al., 2014), automotive (Persson, 2002) and, even, plants (Shanmugam et al., 2016).

Mechanical and biocompatibility characteristics of RFSs have been already investigated (Saggio, 2012; Saggio et al., 2014), and the interested reader can find a comprehensive review in (Saggio et al., 2016).

Our hypothesis concerns the possibility to adopt RFS as a chemical sensor too, an idea that, as far as we know, was never investigated. This hypothesis relies on the fact that mechanical changes with bending induce physical changes of the “isle” of carbon particles distribution (Saggio, 2012) that can induce different chemical interaction with the surroundings (Saggio et al., 2014), so that the RFS with different bending can behave differently with respect to external analytics.

The RFS we adopted is manufactured by Flexpoint Inc. (Draper, UT, USA) In particular, we selected the 0.005x0.3x3 inch (thickness, width, length) type. Three different versions are available, with overlamination (polyamide or polyester) as a protective layer on-top of the sensible part but, for our purposes, we adopted the bare-one, that is, with no protective layer.

2.2 Electronic Circuitry

We configured the RFS as a variable resistor in the feedback path of an OpAmp (TL082 by Texas Instruments), as schematized in Figure 2, so to obtain a sensitivity changed by the RFS alone, without any influences due to the electronics (the latter behaving with a constant sensitivity).

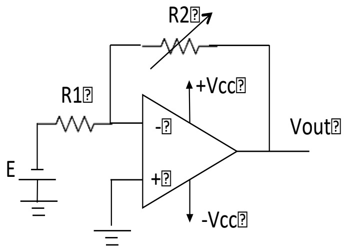


Figure 2: Reading electronics for the resistive flex sensor’s (R2) outputs. The RFS behaves in feedback of an OpAmp.

Supply was sourced by a constant voltage batteries (E=1.2V; Vcc=+/-8.4V). We provided a series limiting current resistor R1 (10KΩ) too.

2.3 Measuring Setup

In order to investigate differences in sensitivity of the RFS under different bending curvature, we realized three different mechanical arrangements for the RFS, fixing it on a planar, 35mm and 20mm in diameter structures, respectively (Figure 3 shows the case of 20mm in diameter arrangement for the RFS), so to investigate more and more bending conditions.


(a) (b)

Figure 3: (a) Lateral and (b) side view of the RFS placed on a 20mm diameter support.

The measuring set-up was realized as shown in Figure 4. The humidity was generated by means of two-channel mass flow controllers (MFCs) (SLA5850S by Brooks Instruments), specifically calibrated for nitrogen, obtaining a 0%-100% of humidity range. One MFC fluxed different concentration of nitrogen, the other channel contributed to form the humidity by

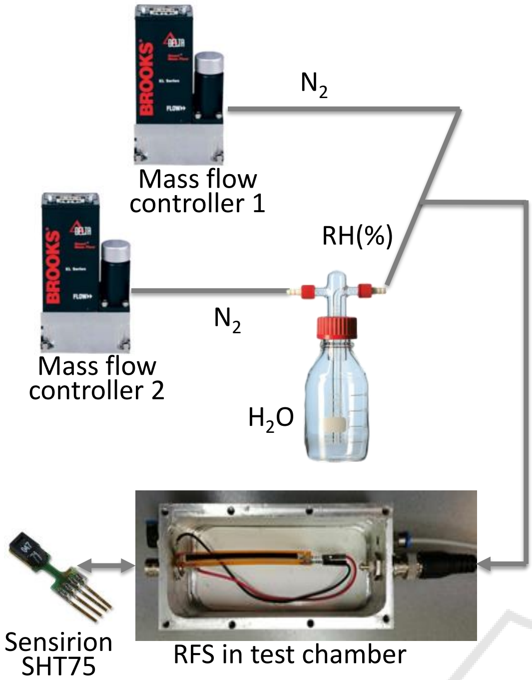


Figure 4: Set-up to investigate the different sensitivity of the RFS for three different bending conditions.

bubbling water.

The RFS was placed inside of a climatic chamber, time by time in a different bending condition as detailed before, at a constant temperature of 25°C. Inside the chamber the temperature and humidity was monitored using a commercial temperature-humidity sensor (SHT75 by Sensirion), with operating range 0≤RH%≤100 and -40°≤T≤123.8°, for relative humidity and temperature, respectively.

3 RESULTS AND COMMENTS

Figure 5 illustrates the sensor's output, as a dynamic voltage responses in the case of flat configuration, when different RH% values are flown into the sensor cell.

With this example of result, we can worth remarking three important evidences (obtained in all the other occurrences):

- measurements have been randomly performed;
- sensor reproducibility is satisfactory, as shown by highlighting couples of measurements for the same values (50% and 100% of RH);
- the proportion between 100% and 50% responses does not account for linearity.

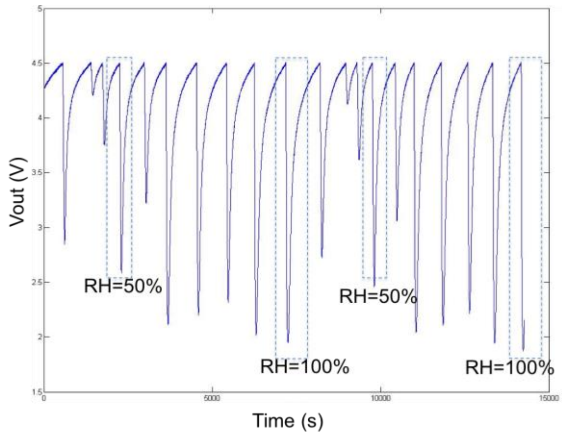


Figure 5: Sequence of dynamic responses in the time (seconds) domain, registered for the output voltage of the sensor system (flex resistance in flat configuration + electronic interface) when different RH% values are flown into the sensor cell.

Figure 6 summarizes all obtained results, as three outputs of the OpAmp voltage versus the relative percentage humidity, Vout vs. RH%, one output for each of the three mechanical configurations imposed to the RFS: flat condition or bending conditions around a 35mm and a 20mm diameter support, respectively.

The three outputs can be summed by three V_{out} vs. RH% fitting curves as:

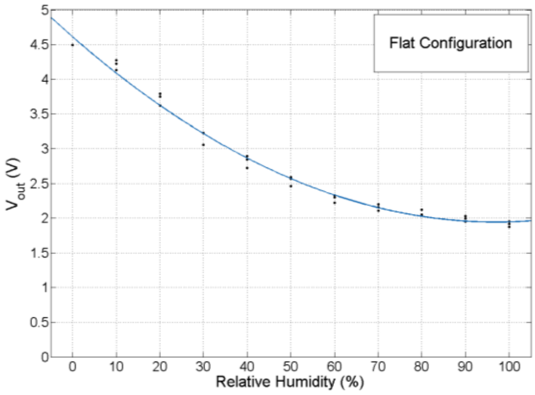
- flat setting:
  $V(RH\%)_{FS} = p1_{FS}\ RH2 + p2_{FS}\ RH + p3_{FS}$ (with $p1_{FS} = 0.00028$; $p2_{FS} = -0.055$; $p3_{FS} = 4.60$, Figure 5a);

- 35mm setting:
  $V(RH)_{35S} = p1_{35S}\ RH + p2_{35S}$
  (with $p1_{35S} = -0.035$; $p2_{35S} = 4.39$, Figure 5b);

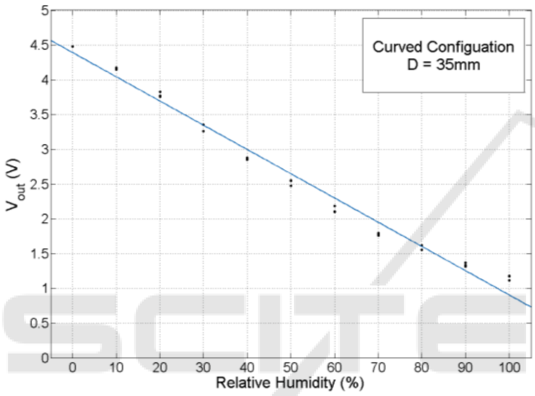
- 20mm setting:
  $V(RH\%)_{20S} = p1_{20S}\ RH + p2_{20S}$
  (with $p1_{20S} = -0.033$; $p2_{20S} = 4.72$, Figure 5c).

As evidenced, we found a non-linear behaviour, with a saturation trend for RH%>80%, when RFS was in flat condition, and almost linear behaviours when RFS was in both bending conditions. In fact, for bending conditions we obtained R-square=0.985, for 35mm diameter of the support, and R-square=0.9855, for the 20mm diameter of the support, respectively.

The sensitivity, expressed as dV/dRH%, calculated on the fitting curve reported above, was confirmed to be linked to the physic deformation of the RFS, since it increases in value with RFS's bending.



(a)



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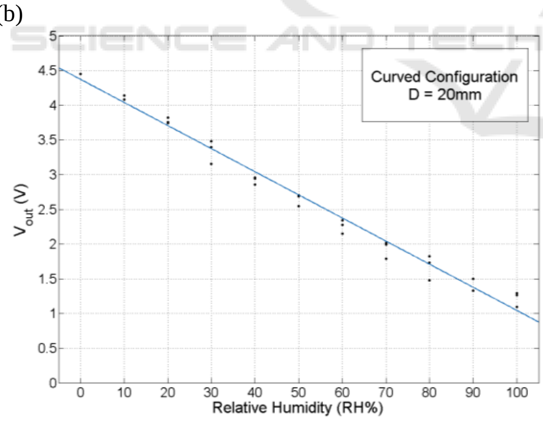
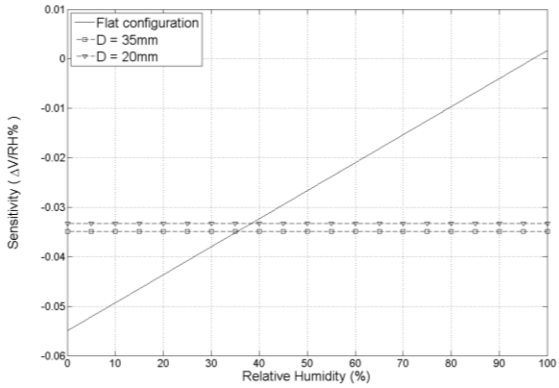


(c)

Figure 6: Vout vs. RH% for RFS in (a) flat, (b) 35mm diameter-support (R2=0.9852), (c) 20mm diameter-support bending condition (R2=0.9855).

According to the results, graphically summed in Figure 7, we can argue that the flat configuration for RFS furnishes higher selectivity, but for humidity within 1%-40% RH% range only; differently, the bending configurations offer a lower sensitivity but it remains almost linear within the overall RH% range.

In particular, in flat condition the sensitivity can be estimated by a linear approximation at low RH% value (less than 10%) as -50mV/%, while in the two bending conditions we obtained -35mV/% and -33V/% for the 35mm and 20mm settings, respectively, within the overall RH% range of variation.



(d)

Figure 7: Overall sensitivity.

4 CONCLUSIONS

Each humidity sensor has its proper sensitivity, that is, the slope of its output characteristic curve which relates sensor's output with respect to relative humidity (RH). Different sensitivities are for different sensors.

Differently, we investigated the possibility to vary the sensitivity of a unique sensor with changing its bending.

The idea was to investigate the characteristic of a resistive flex sensor, which is made of a sensible carbon-based material, engineered on-top of a plastic substrate, which can be bent with no damage.

The resistive flex sensor was measured under different grade of bending, in a climate chamber with relative humidity which was fully-range varied (0%-100%).

The results demonstrated how the resistive flex sensor behaves with different sensitivity and different output-value versus RH% curves, so that we can select the optimal bending to obtain the most useful sensitivity-behaviour, according to specific measure we are interested in.

As far as we know, this work opens to the possibility to realize a new type of chemical sensors which, respect to the currently adopted ones, can offer the added value to mechanically real-time and on-the-use change its selectivity.

This approach could be of great interest for applications needing low-power and reduced dimension, such as bio-medical applications in general and in particular wearable solutions. Also food industry could benefit from this approach when focused on solutions for smart-packaging oriented to quality monitoring and shelf-life assessment.

Future works will investigate change of sensitivity with respect other chemicals (rather than humidity) and change in selectivity, with respect to different chemicals, so to evidence the possibility to paving the way to a new kind of sensor, of which we can change the sensitivity and the selectivity according to the time-by-time necessity.

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