Journal of Sensor Science and Technology
Vol. 21, No. 2 (2012) pp. 83-89
http://dx.doi.org/10.5369/JSST.2012.21.2.83
pISSN 1225-5475/eISSN 2093-7563

A Simple Capacitive Sensor Array Based on a Metal-Insulator-Metal Structure

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Abstract

A simple array of metal-insulator-metal capacitive elements was proposed for a potential application in humidity sensing platforms. We fabricated meso-scale sensors with different sizes(large-size: 2.7 x 2.7 mm^2 ; mid-size: 1.5 x 1.5 mm^2 ; small-size: 0.7 x 0.7 mm^2) and characterized the performance of each design. Polyimide films were utilized as a humidity-sensitive layer. Capacitance changes of the polyimide layer were measured with respect to water absorption. The device showed sensitivity in the full range of relative humidity (RH) with excellent linearity(correlation coefficient > 0.994). This array structure exhibits unique advantages including easy fabrication process, high batch productivity, and high structural compatibility with various substrate materials. It is anticipated that this device structure will be potentially useful in unique applications including mapping spatial humidity variations over a meso-scale area and implementing flexible humidity sensing element arrays.

Keywords : Relative Humidity(RH), Humidity Sensor, Capacitive Sensor, Sensor Array, Polyimide

1. INTRODUCTION

Humidity sensors are used to measure and control humidity in many areas. Capacitive detection method is a widely used technique to measure relative humidity(RH) [1-8]. Generally, capacitive humidity sensors are comprised of a pair of electrodes and a humidity-sensitive insulating layer, made from materials such as polymer[9-12], metal oxide[13, 14], and semiconductors[15, 16]. The large dielectric constant of water, compared to those of many insulators, causes a detectable change in capacitance upon water absorption by the insulator.

There is a large need for monitoring the relative humidity over a meso-scale surface (about 50 cm^2 - 100 cm^2) in many areas of industrial manufacturing, small-volume environmental control, and agricultural soil monitoring[17-21]. It is considered that capacitive sensors offer potential advantages for this application including simple device structure and compatibility with array implementation.

In this research, a capacitive humidity sensor structure was demonstrated with a simple fabrication process for a potential application in a two-dimensional array implementation. Polyimide was used as the humidity-sensitive insulating layer because the change of its dielectric constant is linearly proportional to the amount of water absorbed[22]. Also, it has high inertness to many interfering chemicals. To verify the sensor operation, we measured capacitance changes due to humidity variations and frequency characteristics of the fabricated sensors.

2. SENSING PRINCIPLE

The dielectric constant of a majority of polymers is generally less than 10 at room temperature. That of water is about 80[23, 24], and as such causes a large change in capacitance upon absorption by a polymer. Looyenga's equation for the dielectric constant of a water-absorbing polymer is given by[24, 25]:

$$\varepsilon = \left[\gamma\left(\varepsilon_{H20}^{1/3} - \varepsilon_P^{1/3}\right) + \varepsilon_P^{1/3}\right]^3, \qquad (1)$$

where γ is the volume of water in the film, and ε_P and $\varepsilon_{\mathrm{H2O}}$ are the dielectric constants of the polymer and the water, respectively. Equation (1) assumes that the water vapor absorbed by the polymer can be considered as finely

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(Received : Feb. 3, 2012, Accepted : Feb. 15, 2012)

dispersed isotropic particles[26]. Treated as a parallel plate capacitor, the capacitance is given by:

$$C=\varepsilon A/d \ , \tag{2}$$

where A and d are the capacitor area and the distance between the plates, respectively. This capacitance is affected both by the dielectric constant ε and the polymer thickness d. Any capacitance change due to the polymer swelling is neglected because the volume expansion coefficient of the polyimide is relatively small[27].

The simple equivalent model of a humidity sensor is a parallel connection between a capacitance and a resistance. Therefore, the total complex impedance can be expressed as:

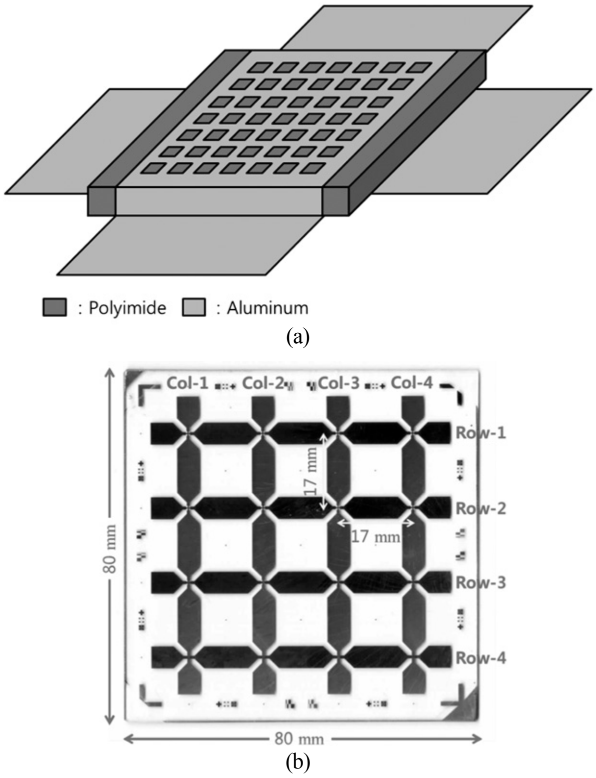
$$Z = R_P/(1 + j2\pi f R_P C) \ , \tag{3}$$

where C, R_P, j and f are: capacitance, leakage resistance, imaginary component, and measurement frequency, respectively. According to equations (1) and (2), the capacitance increases with increasing humidity as the total permittivity increases. Consequently, the total impedance value decreases as the humidity increases as in equation (3).

3. DEVICE FABRICATION AND MEASUREMENTS

Capacitive humidity sensors were implemented using simple fabrication processes. Fig. 1 (a) shows the structure of a single capacitive sensing element composed of a humidity-sensitive dielectric layer(polyimide) sandwiched between two parallel plate electrodes(aluminum). The holes provide access for the water vapor to the polyimide layer. We fabricated sensors of different sizes(large-size: 2.7 x 2.7 mm^2; mid-size: 1.5 x 1.5 mm^2; small-size: 0.7 x 0.7 mm^2) and characterized the performance of each design.

This device structure is excellent for two-dimensional array implementation by serially connecting each device. Fig. 1 (b) shows a photograph of the array. To map a humidity variation, each sensor can be activated by individually addressing two signal lines accordingly. For example, the capacitance measurement with a sensor in the middle can be performed via Col-2 and Row-2, while the rest of the devices are electrically floated and not operating to minimize any electrical interference and parasitic components.



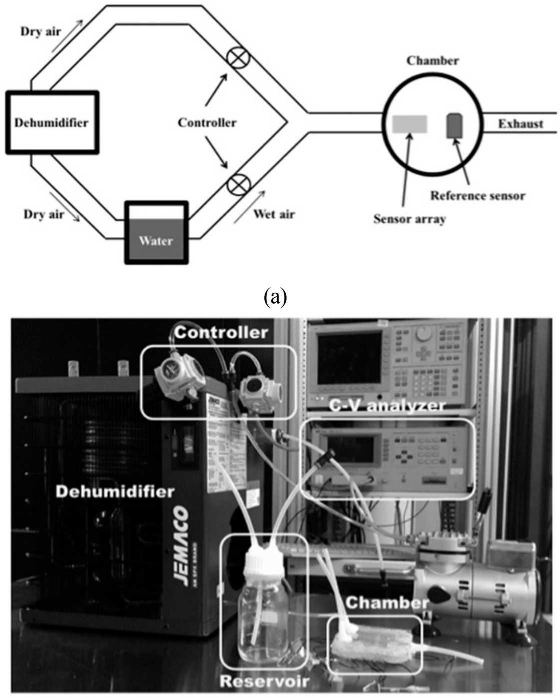
(a)

(b)

Fig. 1. (a) Structure of a single parallel plate capacitive humidity sensor comprised of a humidity-sensitive polyimide layer and two aluminum electrode layers. (b) Sensor array for mapping a humidity distribution.

Three photomasks were designed for fabricating the electrode patterns and polyimide patterns using the CADENCE mask layout software. A borosilicate glass was used as the base substrate for the fabrication of the sensor device. Then, 400 nm thick aluminum was deposited onto the glass substrate by an electron-beam evaporator as a bottom electrode. In order to make the sensing layer, we used polyimide(Polyzen 150P, Picomax, S. Korea). The polyimide was coated onto the glass at 3000 rpm for 20 seconds and then cured for 30 min at 150 °C, then patterned using a photolithographic process. The polyimide was finally cured at 250 °C for 3 hours to make a 1.2 μm thick film. Finally, an 800 nm thick aluminum layer was deposited by electron-beam evaporation and patterned by a lift-off process. The array is based on a simple structure involving serial connection of the devices.

As shown in Fig. 2, we prepared a measurement system to characterize the sensor performance. The measurement system is composed of a dehumidifier for dry air and a reservoir for water-saturated air. Two flow controllers are used to generate a 100 cm^3/min flow of a mixture of dry and water-saturated air to perfuse into a measurement chamber. A commercial humidity sensor(HygroPalm21, Rotronic, USA) was used as the reference device to monitor the actual relative humidity.



(a)

(b)

Fig. 2. Relative humidity (RH) measurement setup comprised of a sensor chamber and a sample gas channel of mixed dry and water-saturated air: (a) schematic and (b) photograph of a measurement system.

4. RESULTS AND DISCUSSION

A C-V analyzer(590, Keithley) was used to measure the capacitance change of the fabricated sensors. A rectangular voltage signal(50 mV magnitude at 100 kHz) was applied. Fig. 3 shows the sensor chamber used to measure 2-dimensional humidity variation. A sensor chamber consisted of two inlets and one outlet to produce humidity distribution. Fig. 4 shows the sensor array operation. As shown in Fig. 4(a), (b), capacitance values of the eight sensors were scanned in a dry condition(20 %RH) and wet condition(90 %RH). As shown in Fig. 4(c), (d), the four sensors located at the left and right side of the row were exposed to water-saturated air to show the capacitance changes, respectively. This demonstrates the concept of mapping spatial variation of humidity with the proposed simple sensing element array.

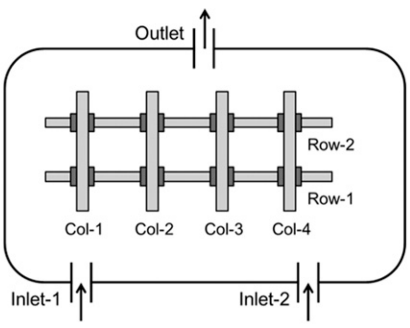
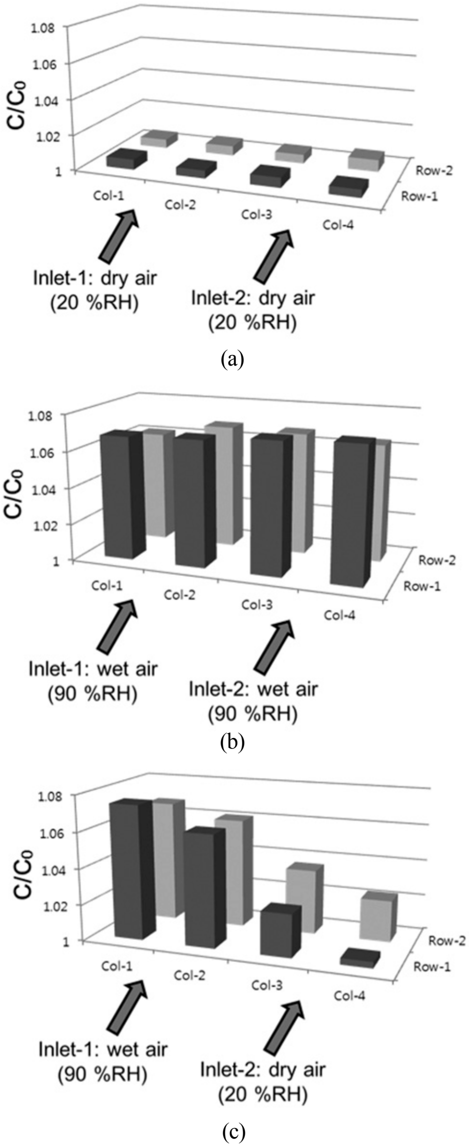


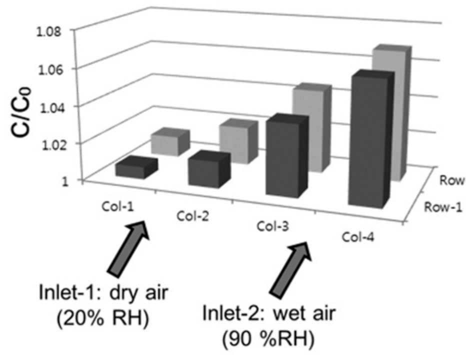
Fig. 3. Schematic of measurement equipment used to measure 2-dimensional humidity variation.



(a)

(b)

(c)



(d)

(C_0: initial capacitance; C: capacitance after 60 min)

Fig. 4. Normalized capacitance response as a function of 2-dimensional humidity variation: (a) all dry condition, (b) all humid condition, (c) inlet-1: wet air, inlet-2: dry air, (d) inlet-1: dry air, inlet-2: wet air.

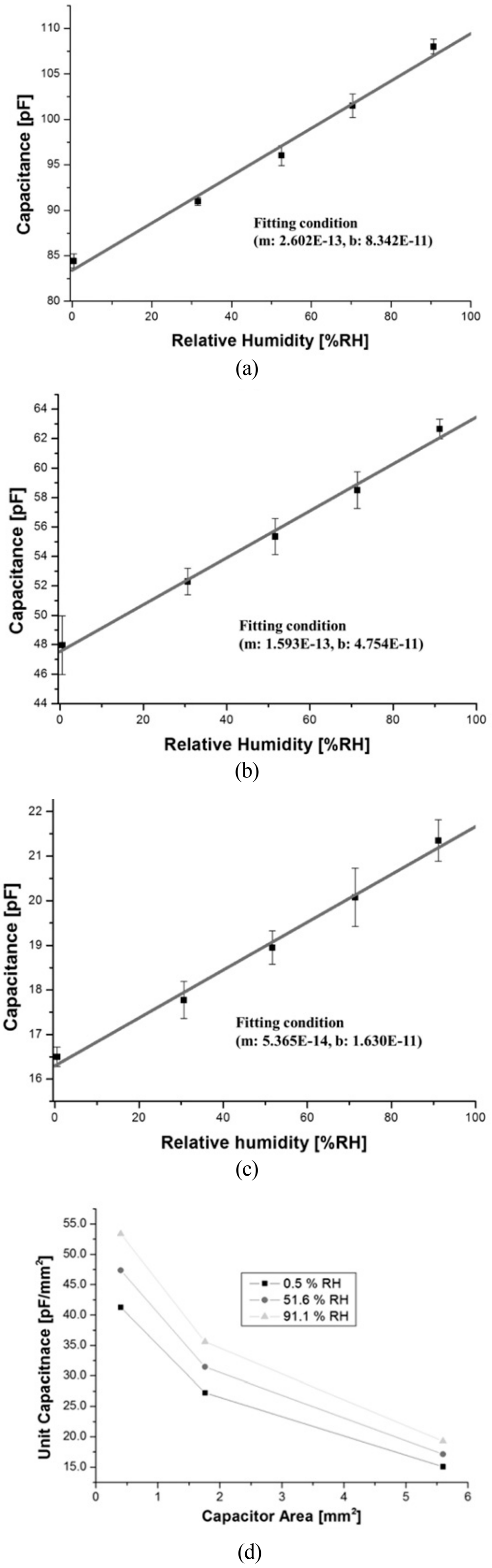
Fig. 5 (a)-(c) show the capacitance changes of three different sensors with respect to the relative humidity. These devices exhibited excellent linearity in the full range of relative humidity. The fitting equation can be expressed as

$$y = mx + b, \qquad (2)$$

where y, m, x, and b are capacitance, slope, relative humidity and capacitance at 0 %RH, respectively.

The capacitive sensitivity per unit area of each design is also plotted in Fig. 4 (d) for comparison. The exposed polyimide area(i.e. the hole area not covered by the electrode) have a parasitic capacitance caused by the fringe electric field, although its contribution to the sensitivity is considered less effective than that of the actual capacitor area(i.e. the area covered by electrode). The ratio of exposed area to capacitor area becomes larger as the overall device size increases in our design. Therefore, the unit capacitance becomes smaller with increasing device size.

The frequency characteristics of the sensor were measured with an electrochemical workstation(FAS1, Gamry). A sinusoidal voltage signal(50 mVp-p of 10 Hz - 100 kHz range) was applied. An exemplary Bode plot of a single device is shown in Fig. 5 (a). The characteristic of the total impedance magnitude versus frequency exhibits that of a typical capacitive element. Fig. 5 (b) shows the Nyquist plot in which the imaginary magnitude(i.e capacitive component) and real magnitude(i.e. resistive



(a)

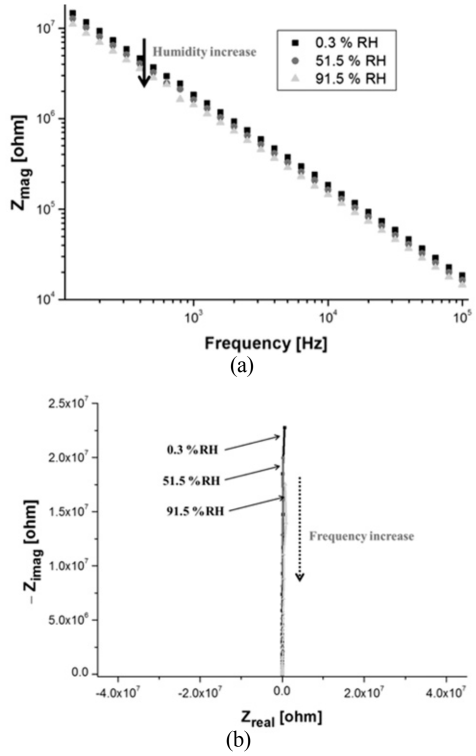
(b)

(c)

(d)

Fig. 5. Capacitance changes versus relative humidity: (a) Large-size(2.7 x 2.7 mm^2). (b) Mid-size(1.5 x 1.5 mm^2). (c) Small-size(0.7 x 0.7 mm^2). (d) Normalized unit capacitance versus actual capacitor area(i.e. the area covered by electrode).

component) are separated. It is obvious that the sensor is considered mostly a capacitive component in the full range of relative humidity because of the nearly straight-lined profiles observed in the plots.



(a)

(b)

Fig. 6. Frequency responses of a large-size sensor (device size: 2.7 x 2.7 mm^2) at relative humidities of 0.3 %RH, 51.5 %RH, and 91.5 %RH. (a) Bode plot. (b) Nyquist plot.

5. CONCLUSION

We proposed a simple capacitive device structure that can be potentially applied to implementing a two-dimensional humidity sensor array over a meso-scale area(about several-hundred square centimeters). Excellent linear sensitivities(correlation coefficient > 0.994) were observed over the wide relative humidity range of 0 %RH - 90 %RH. These devices exhibited frequency responses that were largely capacitive in nature(i.e. imaginary impedance) in a 10 Hz - 100 kHz range. This simple metal-polymer-metal structure is easy to fabricate at low cost and is compatible with various types of substrate materials. It is expected that this platform could appeal to niche application areas including integrated sensing elements on flexible substrates that conform to non-planar surfaces.

ACKNOWLEDGMENT

This work was supported by the second phase of the Brain Korea 21 program in 2011.

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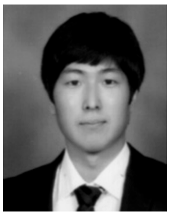

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