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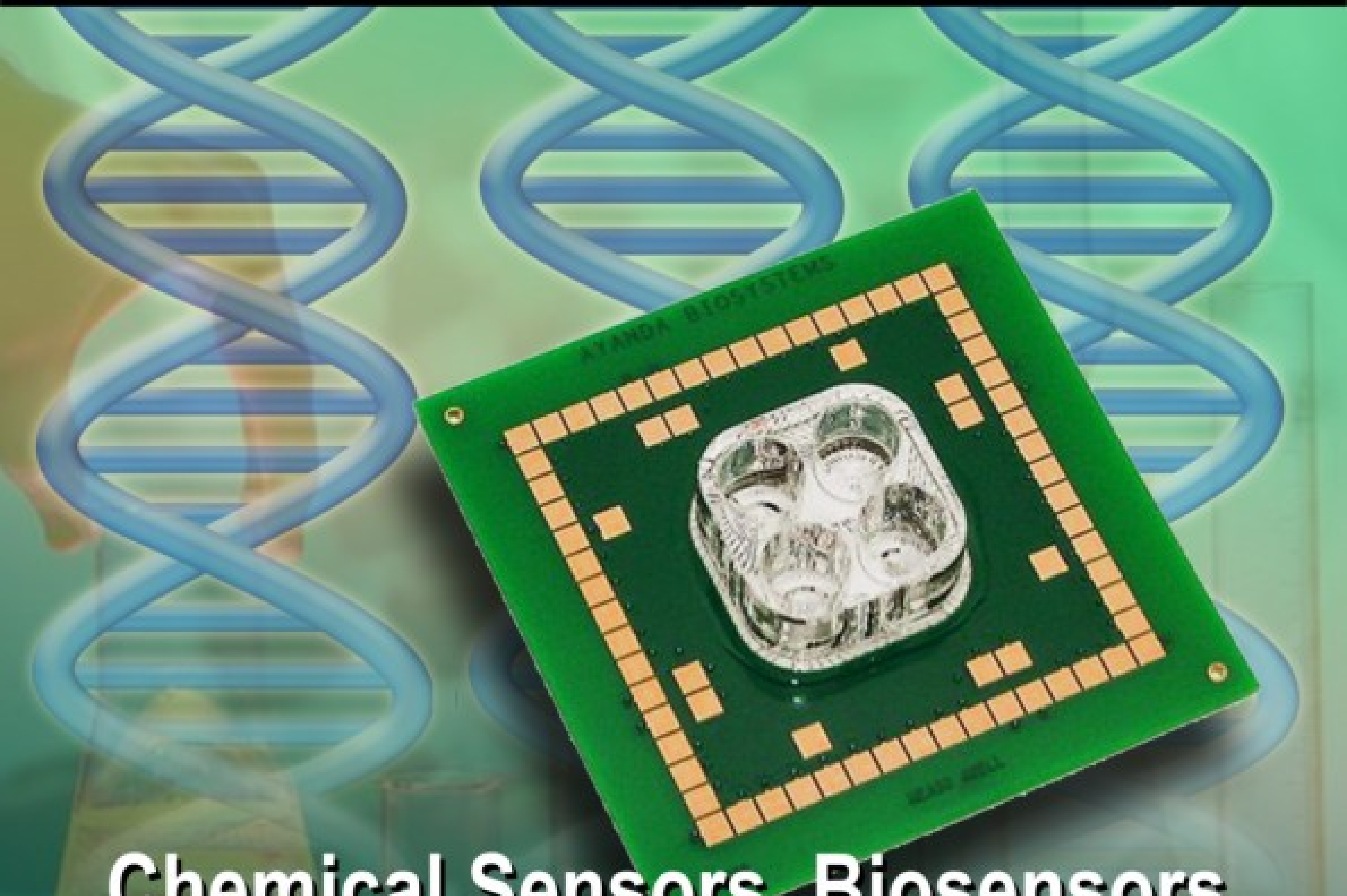

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Poly (3, 4-Ethylenedioxythiophene) - Poly (4-Styrenesulfonate) for Humidity Sensing Using Ink-jet Printing Technique on Flexible Polyimide Substrate

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Abstract: A fully reversible and repeatable flexible capacitive humidity sensor is realized from design concept to reality via an ink-jet deposition system. The humidity sensor is ink-jet fabricated with aqueous Poly (3, 4-ethylenedioxythiophene) - poly (4-styrenesulfonate), PEDOT: PSS ink and Toluene suspended nano Ag particles of 5 nm sized solution. The humidity is monitored by changes in the sensor's effective inter-digitated electrodes capacitance. The humidity sensor exhibits sensitivity with resolution and accuracy of 0.0067 nF/ %RH and 1% RH, respectively, towards the relative environmental moisture concentrations of 32% RH to 100% RH. A fast absorption time of < 1 second and desorption time of approximately 3 second for the humidity sensor is observed. *Copyright © 2009 IFSA.*

Keywords: Flexible substrate, Humidity sensor, Conducting polymer

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1. Introduction

Humidity monitoring is critical in many applications from environmental monitoring that is exposed to radioactive radiation [1]; performance assessments of scientific instruments, optical imaging system and sub-systems of Very Large Telescope Interferometer (VLTI) environmental conditions [2]; measurement biases calibration in astrometry [**Error! Bookmark not defined.**]; to monitoring of munitions. Product stability, in particular, is critical to safe handling and storage of munitions as well as mission readiness [3]. Real time eco-friendly environmental monitoring in IT assets is also highly sought in IT data industry [4]. Typically, commercial humidity sensors functionality based on changes in a materials resistance as a function of water absorbed by the material in equilibrium with the ambient environment. Examples include the aqueous Poly (3, 4 - ethylenedioxythiophene) - poly (4-styrenesulfonate), commonly referred to as PEDOT: PSS. PEDOT: PSS soaked textiles employed for humidity, temperature and strain sensing via its resistance changes has been reported [5]. Porous silicon is also adopted in implementing relative humidity sensor with support vector machine (SVM) technique to minimize the sensor hysteresis and nonlinearity [6]. Typically these sensors have a limited response time (in minutes). These sensing response times, cost of affordability, ease of fabrication and physical robustness and flexibility limitations of the current technology are addressed by the reported humidity sensor.

PEDOT: PSS films have been screen printed [7], dip coated [8], and spin coated [**Error! Bookmark not defined.**] successfully for use in anti static coating [9], flexible light emitting diodes [10] as well as electroluminescent display [11]. In this article, the application of the aqueous PEDOT: PSS is extended to capacitive humidity sensing as opposed to its typical use based on resistance changes for other sensing applications. Since the humidity sensor operates on capacitive changes, therefore any resistance variation of the piezoresistive polymer layers due to the surrounding thermal effects is minimized, which is one of the advantages of the sensor design. The humidity sensor's interdigits sense the microscopic dielectric constant changes due to moisture content of the surrounding area of the interdigits sensing electrodes. A major benefit of the capacity sensing design is the response time (<1s) of the sensor. The sensor's sensitivity to moisture concentration is investigated from 32% RH to 100%. The fabricated humidity sensor exhibits repeatable capacitive responses with the varying environmental moisture contents, both increasing and decreasing of the chamber humidity. The response time observed is fast and rapid in the order of sub-second.

2. Device Realization

The interdigits humidity sensor layout is as shown in Fig. 1. The inner capacitive sensing elements are designed to measure the maximum amount of dielectric constant changes due to the surrounding moisture content. This design will have improved sensitivity when compared to the standard parallel plate humidity sensor design because of additional capacitive fringes effect arises from the inter-digitated fingers.

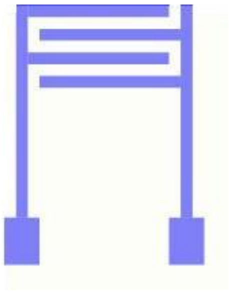

Fig. 1. Humidity sensor design layout, where interdigits are the capacitive sensing structure and connection pads located at the bottom of the structure.

A flexible polyimide Kapton (DUPONT) film of 52 micron thickness is used as the base substrate. The flexible membrane is first pre-cleaned by boiling it with 0.3 μS/cm de-ionized water and Micro-90 cleaning detergent from Cole Palmer Inc. for 1 hour and followed by ultra-sonification for an additional 1 hour. The pre-clean cycle is repeated for 3 cycles. The humidity sensors are deposited via Dimatix ink-jet deposition system. The material of the electrodes consists of Toluene suspended nano Ag particles of 5 - 10 nm average size purchased from NanoMastech Inc. The humidity sensor structure is finalized by the deposition of the electrically conductive~~,~~ aqueous PEDOT: PSS solution from Sigma Aldrich. The humidity sensor is next passivated with an aqueous polyimide top encapsulation layer except the interdigitated structure. The aqueous polyimide passivation layer thickness is approximately 25 microns. The humidity sensor structural layout is as shown in Fig. 2.

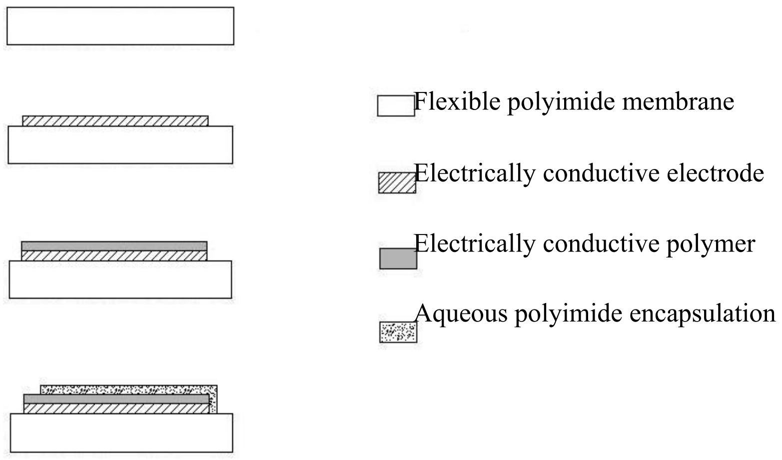

Fig. 2. Humidity sensor structure according to process flow.

Finally, the sensor is annealed for approximately 4 hours inside a Blue-M annealing oven at 180° C with forming gas. The forming gas composition used is 3% H_2 with the balance of N_2 gas. The Blue-M oven is first evacuated to remove moisture and oxygen before it is being refilled with the forming gas at a very low flow rate. The forming gas is used as an atmosphere for annealing processes inside the Blue-M oven, and is also worked as a hyper-sensitization gas to eliminate moisture, solvents, and contaminants, from the deposited films. It would also reduce oxidation of the deposited electrically conductive films.

Each interdigits finger width is measured 0.3 mm W x 0.7 mm L, with a cross sectional area of 0.21 mm^2 and resistivity equal to 0.0033 Ω. The deposited thickness via the ink jet technique is approximately 0.7 micron. Gold wires with a 0.0007 inch diameter are used to connect the sensor into the data acquisition system according to the electronic schematic setup given in Fig. 3.

Since the humidity sensor is capacitive based, the sensor capacitance equation is determined by the standard equation given in Equation (1). The dielectric permittivity of the hollow area between the interdigit sensing elements is a function of the moisture content. As the dielectric permittivity varies with the surrounding humidity, the actual sensor output capacitance is therefore increasing or decreasing in real time. This can be inferred from Equation (1).

$$C(\%RH) = \frac{\varepsilon_{\%RH} * \varepsilon_o * A}{d}, \tag{1}$$

where C is the sensor capacitor at % RH; $\varepsilon_{\%RH}$ is the relative dielectric permittivity, as a function of moisture concentration; ε_o is the permittivity of vacuum; A is the total effective cross sectional area of the interdigits sensing electrodes; d is the distance between the sensing electrodes.

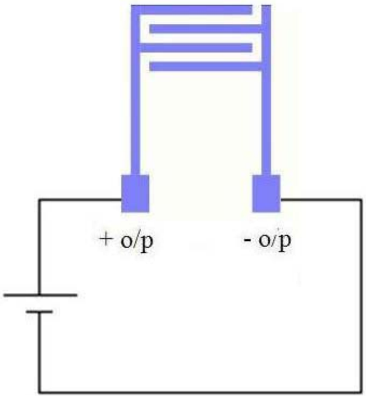

Fig. 3. Schematic diagram of the humidity sensor.

The sensor characteristics equation is determined by the standard equation given in Equation (2), below.

$$C_C(\%RH) = C_s(@55\%RH) + S*[\%RH(C_m) - \%RH(C_s@55\%RH)], \tag{2}$$

where S is the sensitivity measured in nF/%RH; C_c (%RH) is the calculated sensor capacitance output; C_s(@55%RH) is standard capacitance value measured at 55% RH; %RH (C_m) is the measured relative humidity value; %RH (C_s) is the standard relative humidity value measured at 55% RH. The sensor output is consequently measured to be directly proportional to these increasing humidity changes.

The hysteresis characteristic is given by Equation (3)

$$\text{Hysteresis value} = C(32\%RH \Rightarrow 99\%RH) - C(99\%\ RH \Rightarrow 32\%\%RH) \tag{3}$$

where, the hysteresis value is obtained under 1 pF. The hysteresis of the measured condition indicates between ±3% RH (standards) at each humidity point.

The humidity sensor is tested cyclically inside a temperature and humidity controlled Blue-M Vapor-Temp environmental chamber, from 32% RH to 100% RH at constant room temperature of 26° C. The humidity sensor contact pads are externally wired to the exterior of the environmental chamber enclosure. The humidity sensor capacitance is measured by a Triplett 9015 digital multimeter. The moisture is increased steadily while being monitored by the standard pre-calibrated Fisherbrand Traceable* [12] Temperature/Humidity Meter. The sensor's capacitance measurement is measured by applying 1.0 Vrms at 20 kHz at 25° C by HP E3630A constant current power supply. The moisture ramping rate is regulated and monitor with a mini-pump variable flow meter by Control Company. The experimental setup is as illustrated in Fig. 4.

3. Results

Arrays of 11 by 11 individual humidity sensors are fabricated and annealed. The individual humidity sensor is measured 6 mm x 4 mm and is as illustrated in Fig. 5.

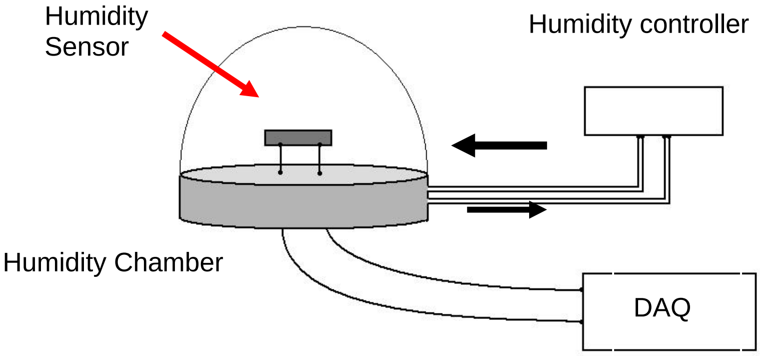

Fig. 4. Experimental setup schematic.

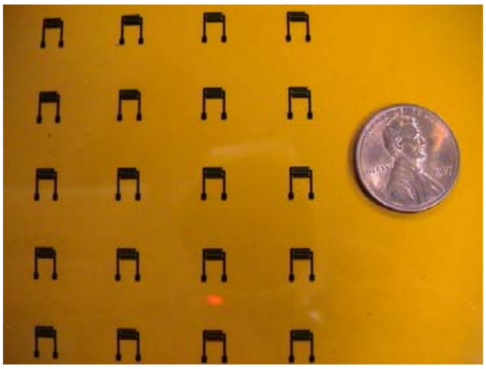

Fig. 5. Fabricated humidity sensor on flexible polyimide substrate.

As the moisture concentration is ramped up and down in the environmental chamber, the ink-jetted humidity sensor response exhibits hysteresis as shown in Fig. 6. The chamber is cycled from normal room humidity, which is approximately 32% relative humidity, RH, to 100% RH at constant chamber temperature. The experimental test results measured for the humidity sensor indicates a sensor accuracy of ± 1% RH, with resolution of 0.0067 nF/ %RH according to the collected experimental data. By comparison to the dip coated thick film PEDOT: PSS impedance based humidity sensor [13], with a fast absorption time of < 30 seconds and desorption time of 5 minutes; and 600 °C calcined TiO_2 based humidity sensor [14], with its rapid absorption time of > 100 seconds and desorption time of 190 seconds, the reported ink jetted humidity sensor is found to have a quick absorption time of < 1 second and desorption time of approximately 3 seconds with a standard USB National Instrument DAQ acquisition system.

In addition to the fast absorption and desorption time of the ink-jet printed humidity sensor compared to commercial sensor, it is found that the accuracy of the ink-jet printed sensor is also comparable or slightly better than the commercial sensors as summarized in Table 1. The sensor also has relatively faster and better responses to moisture content when compared to any of the commercially available tested humidity meters (613 Acurite Digital Indoor Humidity Monitor with Temperature with ± 1% RH accuracy, Fisher Scientific Traceable* [15] Thermometer/Clock/Humidity Monitor with ± 4% RH accuracy, Fisherbrand Traceable* [**Error! Bookmark not defined.**] Temperature/Humidity Meter with 0.1% resolution, ± 3% RH accuracy).

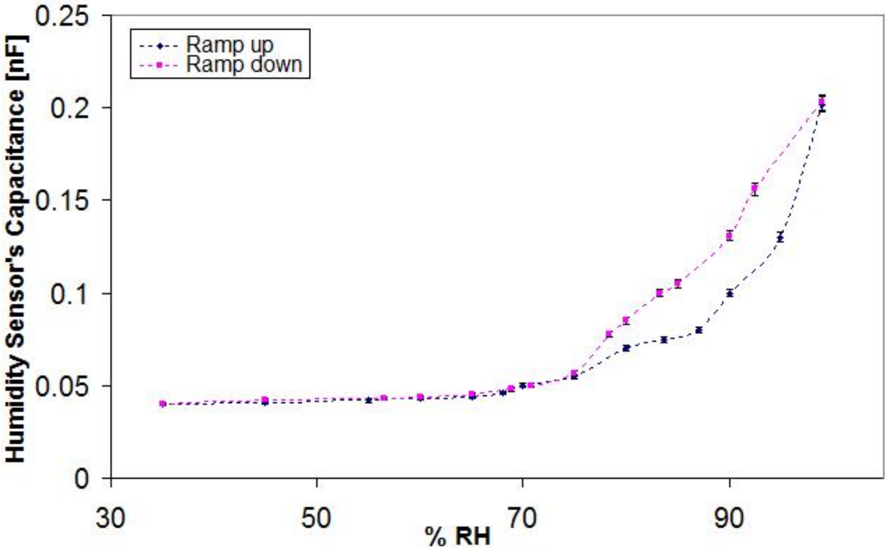

Fig. 6. Ink jet fabricated humidity sensor responses with moisture variation. The error bars indicated on the graph represent variability in sensor response over 10 cycles and they correspond to a sensor accuracy of 1% RH.

Table 1. Humidity sensors response time comparison.

Sensor	Reference	Absorption time (s)	Desorption time (s)	Accuracy (%RH)
Ink-jet Capacitive	This article	1	3	1
PEDOT:PSS Impedance	13	30	300	
TiO2	14	>100	190	
613 Acurite				1
Fisher Sci	15			4
Fisherbrand	9			3

The sensor hysteresis observed is due to the sensing elements refresh rate which is typical of any capacitive humidity hygrometer. The film has a memory of the previous capacitance. The absorption and desorption rate is measured by the response of the chamber humidity ramping control rate. If the measurement time constant is delayed appropriately long enough between the ramping up and down, the observed hysteresis is expected to be minimized. The increase of capacitance with the increase of moisture concentration within the experimental range tested is attributed to the promotion of charge carrier density in the electrically conductive polymer. It is reported and estimated by Tanielian et al. that the adsorption of water molecules on the polymer surface of the interdigits capacitor increases the carrier conduction and generates holes in the vicinity of the semiconducting active layer surface due to their relatively large dipole moment [16]. Furthermore, as the water moisture concentration changes in between the interdigitated structure, the dielectric layer in between these interdigits design will be affected.

It is observed from the author's fabrication processes that the humidity sensor sensing properties of electrically conductive polymer could be enhanced greatly by lengthening the polymerization time. According to experimental results, the sensing properties of conducting polymers could be improved by increasing their orderness degree from amorphous structure.

4. Conclusion

A fully reversible and repeatable flexible humidity sensor is fabricated via ink-jet deposition techniques. The humidity sensor is fabricated from electrically conductive poly (3, 4-ethylenedioxythiophene) poly (4-styrenesulfonate), PEDOT: PSS polymer ink, which forms the interdigits of the capacitive structure, nano particle Ag ink for electrical contact, and an aqueous polyimide encapsulation which is used as the passivation top layer. This fabrication approach of the reported capacitive humidity sensor is not reported previously.

The humidity sensor exhibits a fast response, < 1 second to the changing moistures concentration inside the environmental chamber. The response time is better than any existing humidity sensor available commercially. The resolution and accuracy of the device are 0.0067 nF/ %RH and 1% RH, respectively. However, the inherent humidity capacitive delay/effect is observed as the result of the response time. To our knowledge, a capacitive based humidity sensor designed utilizing PEDOT: PSS polymer thin film fabricated by the Dimatix deposition system is novel, and the first of its kind.

In summary, the humidity sensor is designed and recorded capacitively, therefore any resistance variation of the piezoresistive polymer layers due to the surrounding thermal effects is minimized. The interdigits humidity sensor senses the microscopic dielectric constant changes due to moisture content of the surrounding area.

References

[1]. Brenner R, Bingefors N, and Mohn B, Evaluation of a Humidity Sensor for Use in an Environment Exposed to Radiation, *Journal of Testing and Evaluation*, Vol. 35, Issue 5, September 2007.

[2]. F. Puech, S. Leveque, M. Sarazin, and R. J. Mathar, Temperature and humidity environmental conditions in the VLTI, Adv. In Stellar Interferometry, J. D. Monnier, M. Scholler, W. C. Danchi, Editors, 626840. *SPIE Proceedings,* Vol. 6268, 28 June 2006.

[3]. M. Miller, J. Fortner, J. Buswell, H. Chelner, and M. Lossner, Health monitoring of munitions for mission readiness, Collection of Technical Papers - *43rd AIAA/ ASME/ SAE/ ASEE Joint Propulsion Conference*, Vol. 8, 2007, pp. 7769-7776.

[4]. RF Code Inc., Austin and Dallas TX, USA, 2008.

[5]. W. A. Daoud, J. H. Xin, and Y. S. Szeto, Polyethylenedioxythiophene coatings for humidity, temperature and strain sensing polyamide fibers, *Sensors and Actuators B*, Vol. 109, 2005, pp 329-333.

[6]. X. Wang and M. Ye, Hysteresis and nonlinearity compensation of relative humidity sensor using support vector machines, *Sensors and Actuators B, Chem*., Vol. 129, 2008, pp. 274-284.

[7]. P. Harrop, Printing high-volume electrical and electronic devices, *Gatfworld*, Vol. 18, Issue 3, June 2006, pp. 26-28.

[8]. A. K. Cuentas-Gallegos, M. E. Rincon, and G. Orozco-Gamboa, Physical and electrochemical characterization of nanostructured composites formed by TiO_2 templates and PEDOT-PSS films, *Electrochimica Acta*, Vol. 51, Issue 18, 5 May 2006, pp. 3794-3801.

[9]. F. Jonas and J. T. Morrison, 3, 4-Polyethylenedioxythiophene (PEDT): Conductive coatings technical applications and properties, *Synth. Met*., Vol. 85, 1997, pp. 1397-1398.

[10]. Y. Cao, G. Yu, C. Zhang, R. Menon, and A. J. Heeger, Polymer light emitting diodes with polyethylene dioxythiohene-polystyrene sulphonate as the transperant anode, *Synth. Met*., Vol. 87, 1997, pp. 171-174.

[11]. A. O. Patil, A. J. Heeger, and F. Wudl, Optical properties of conducting polymers, *Chem. Rev*., Vol. 88, 1988, pp. 183-200.

[12]. NIST Certifications: A certificate is provided to indicate instrument traceability to standards provided by the National Institute of Standards and Technology (NIST*). Calibration is performed in an ISO 17025 calibration laboratory certified by A2LA.

[13]. C. P. L. Rubinger, C. R. Martins, M.-A. De Paoli, and R. M. Rubinger, Sulfonated polystyrene polymer humidity sensor: Synthesis and characterization, *Sensors and Actuators B, Chem*., Vol. 123, 2007,

pp. 42-49.

[14]. Y. Zhang, W. Fu, H. Yang, Q. Qi, Y. Zeng, T. Zhang, R. Ge, and G. Zou, Synthesis and characterization of TiO2 nanotubes for humidity sensing, *Appl. Surf. Sci*., 2008.

[15]. NIST Certifications: Individually serial-numbered Traceable Certificate is provided from an ISO 17025 calibration laboratory accredited by A2LA; indicates traceability to standards provided by NIST*.

[16]. M. Tanielian, M. Chatani, H. Fritzsche, V. Smid, and P.D. Persans, Effect of adsorbates and insulating layers on the conductance of plasma deposited amorphous silicon-hydrogen, *J. Non-Cryst. Solids*, Vol. 35–36, 1980, pp. 575–580.

Guide for Contributors

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