Ultrafast Integrated Humidity and Temperature Sensor Based on Carbon Nanotubes, and a Sensor Controller System

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ABSTRACT

An integrated, resistive-type temperature and humidity sensor made of Brewer Science's electronics-grade, aqueous carbon nanotube ink and an attendant sensor controller system was demonstrated. The sensor consumes little power and is fully printed and flexible, which allows it to be conformally mounted on any surface. The sensor resolution is ~1% for relative humidity and <0.5°C for temperature and has a response time of ~200 ms. The sensor can easily detect moisture and temperature from a human finger. The humidity sensor is highly sensitive to human breathing as well and can be used in multiple medical applications such as real-time monitoring of breathing for patients with sleep apnea. The sensor controller has two decoupled outputs for direct, high-speed measurements of relative humidity and temperature, and it can directly measure absolute humidity. This technology features sensor interchangeability and a wireless readout capability.

Keywords: Temperature and humidity sensors, carbon nanotubes, sensor controller, sensor resolution, response time.

1 INTRODUCTION

Temperature and humidity (T&H) sensors have been extensively used in various areas and are proving useful in multiple new areas. Their usability ranges from monitoring the weather in mobile electronic devices to monitoring the temperature of electronic chips for maximizing chip life and performance. Humidity sensors can be used in the automotive industry for passenger comfort control and fuel/air mixture control in the engine to improve engine efficiency. In medical applications, humidity sensors are used in patient care in ventilators, respirators, and anesthesia machines. Handheld breathing (humidity) sensors can be used effectively for real-time monitoring of breathing (pattern, rate) for patients with sleep apnea or other pulmonary-related diseases and for sedated or anesthetized patients during certain imaging and surgical procedures.

Sensor response time is a critical parameter in several areas such as medical, automotive, and electronics applications. Faster sensors deliver information faster, prompting faster actions to overcome a problem or avoid the loss of life or damage to expensive equipment. Existing state-of-the-art sensors, which are mostly capacitive and/or silicon-based [1, 2], have relatively long response times, usually 5 s to 30 s, which may be too long for some of the applications mentioned above.

Existing commercial sensors come as a chip (not flexible) and cannot be mounted conformally on surfaces. This limitation hinders their usability in many recently emerging flexible electronics applications. A sensor that is very fast to respond, is fully flexible, and can monitor both temperature and humidity with a single, miniature unit would be very appealing to the current sensor industry. A carbon nanotube (CNT)-based printed, flexible T&H sensor provides this opportunity.

CNTs have large surface area for absorption of heat and moisture. The heat/moisture absorption/release mechanism is much faster in these resistive-type sensors than in existing capacitive-type sensors [1, 2]. Thin films of CNTs provide faster absorption and release of moisture and heat, providing the sensors with fast response and improved sensitivity. In addition, functionalized CNTs can act as better absorbers of moisture. CNTs are hole-doped [3], and electron transfer from moisture to CNTs reduces hole concentration, thereby reducing the electrical conductance [4, 5]. The excellent thermal conductivity of CNTs allows faster heat transfer, giving a fast response to heat. Heat can cause reduction of band gap or electron hopping through CNTs [6], both of which increase the electrical conductance.

In this paper, we demonstrate a fully printed, flexible, integrated, resistive-type T&H sensor using an electronics-grade, functionalized CNT ink and an attendant sensor controller system. These sensors are miniature in size, use very low power, and can be battery-operated. Our miniature sensor controller has onboard power, decoupled humidity and temperature outputs, and wireless readout capability. Our sensor and the controller system offer the following features:

i) Ultrafast response time of 200 ms, more than 100 times faster than existing state-of-the-art sensors
ii) Fully printed and flexible sensor
iii) Low power consumption – can be operated with low-drain and thin film batteries
iv) Integrated humidity and temperature measurements with a single sensor unit
v) Fast response to human breathing – useful for multiple medical and human interface applications
vi) Direct absolute humidity readout capability.

2 EXPERIMENTAL

All temperature and humidity sensors in this work were fully printed and flexible and were prepared using Brewer Science's ultralow-metal-content (<10 ppb metal ion content), electronics-grade, aqueous CNT ink. The CNT ink used to make sensors is shown in figure 1. First, discrete temperature and humidity sensors were printed in order to evaluate their performance; they were then integrated into a single unit. Proper design, form factor, and CNT material were implemented to minimize temperature effects on the humidity sensor and vice versa. In addition, the temperature sensor was sealed with a thin filter layer to isolate it from the effects of moisture. All sensing tests were run in a humidity chamber by ramping the relative humidity from 25% to 90% to 25%, and temperature from 20°C to 100°C to 20°C, keeping the other variable fixed. The breathing sensing tests were done by directing the human breathing to the sensor surface using a polyethylene tube. The electrical measurements were done using a Keithley SCS-4200 semiconductor analyzer.

Figure 1: Brewer Science's electronics-grade, aqueous CNT ink used to print the sensors.

3 RESULTS AND DISCUSSION

3.1 Humidity/Breathing Sensor

Figure 2 shows a printed, flexible humidity sensor and its sensing performance. The sensor responds to both moisture and human breathing instantaneously, with a response time of 200 ms. In the near future, the response time should be much shorter than presented here through the use of proper experimental set-up and electronics, which is currently in progress. Power consumption during sensor use was only 30 μW. The sensor showed a 38% drop in conductance with moisture from human breathing, indicating its potential for being useful as a portable breathing monitor in multiple medical applications such as home monitoring of breathing for patients with sleep apnea and pulmonary diseases. The sensor sensitivity was ~0.5% per % RH and showed 18% and 31% change for 25%-70% and 25%-90% relative humidity changes, respectively. Interestingly, the sensor showed a nice response to even moisture from a human finger.

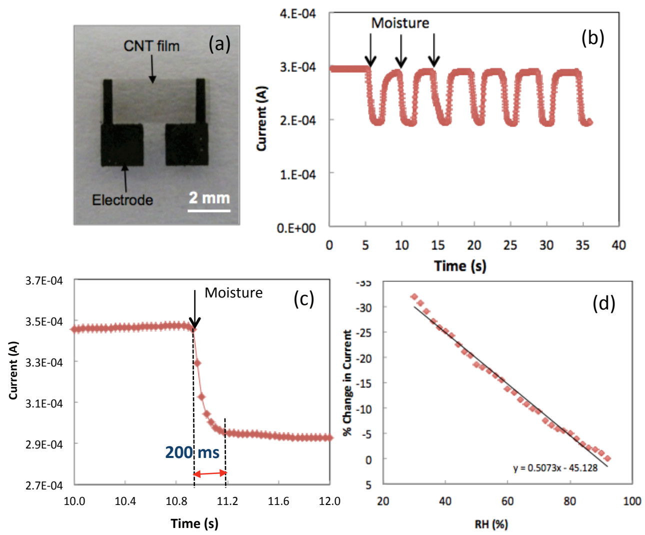

Figure 2: (a) A humidity/breathing sensor. (b) Sensor response to moisture from human breathing. (c) A curve showing the sensor response time. (d) Percentage change in current vs. relative humidity inside humidity chamber. Applied drain voltage = 0.1 V.

To verify the safety of using the sensor during breathing monitoring, we ran simulated tests and monitored the CNT exposure level during the tests. The tests were conducted introducing the CNT monitor at about 1 inch from the sensor while flowing the air at the rate of 2.5 L/min. The air sample was collected for 30 minutes from each of 6 samples, and high resolution transmission electron microscopy (and EDX, if needed) was used to analyze each sample. All the collected samples had no CNT content on them, confirming the safety of the sensor.

3.2 Temperature Sensor

A discrete CNT-based temperature sensor and its sensing performance are shown in figure 3. The sensor responds to heat only but not to moisture [figure 3(b)],

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enhancing reliability and accuracy of the sensor. The sensitivity was ~0.5°C [figure 3(c)], with a temperature coefficient of resistance (TCR) of 0.370. The sensor response time was ~300 ms (not shown), and showed 16% and 29% increase in conductance for ΔT=50°C and 80°C, respectively [figure 3(d)]. The sensor used 50 nW of power during operation.

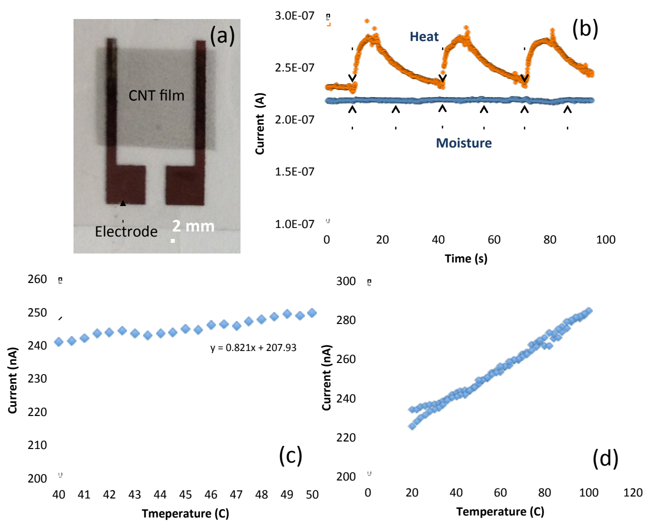

Figure 3: (a) A CNT temperature sensor. (b) Sensor response to heat and moisture. (c) A curve showing the sensor resolution (data interval = 0.5°C). (d) Percentage change profile with temperature of the sensor. Applied test voltage = 0.2 V.

3.3 Integrated Temperature & Humidity Sensor

Discrete temperature and humidity sensors were combined in a single unit to build an integrated T&H sensor. Planar and interdigitated electrode (IDE)-type sensors were built. Figure 4 shows an IDE integrated sensor, in TO-220 package form.

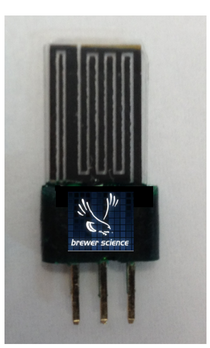

Figure 4: Brewer Science's fully printed, integrated T&H sensor chip.

T&H sensor performance was similar to that obtained using discrete sensors [graphs not shown]. The moisture sensor showed a 41% decrease in conductance for moisture from human breathing whereas the temperature sensor showed a 25% increase in conductance for ΔT = 80°C. Both have an approximate response time of 300 ms.

These CNT-based T&H sensors provide several unique advantages over existing ones in terms of speed, cost, complexity, form factor, etc. These sensors can be built in different form factors – in an integrated form or as discrete temperature and humidity sensors – as well as in different sizes, as needed. Unlike a traditional chip-based sensor, these sensors can be printed directly on the desired device surface, providing greater structural versatility than traditional chip-based sensors.

3.4 Sensor Controller

Figure 5 shows a sensor controller interface prototype with built-in temperature and humidity sensors.

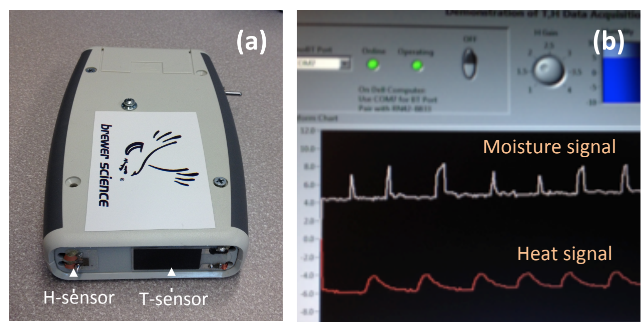

Figure 5: (a) Brewer Science's sensor controller prototype (dimensions: 14 cm x 8 cm x 1.5 cm) and (b) wireless readout of response of attached sensors to heat and moisture from human finger.

The controller has two decoupled outputs for direct high-speed measurements of relative humidity and temperature and is capable of direct measurement of absolute humidity. The sensor controller has sensor interchangeability that makes the system a versatile platform that can sense multiple analytes as well as humidity and temperature. The controller can be wirelessly connected to a computer or tablet for sensing readout. The system implements WiFly®, Bluetooth®, and ZigBee® wireless technology and can be coupled with various operating systems. Both sensors and controller can run with onboard batteries.

4 SUMMARY

Discrete and integrated CNT-based temperature and humidity sensors and a versatile sensor controller interface were demonstrated. The integrated sensor has a low-power design and is fully printed and flexible. The sensor has a resolution of ~1% for relative humidity and <0.5°C for temperature, and it has a response time of 200-300 ms. The sensor sensitivity was sufficient to easily detect moisture and heat from a human finger. The humidity sensor was also very sensitive to human breathing and was able to monitor breathing pattern and rate in real time. The demonstrated sensor controller has two decoupled outputs for direct measurement of relative humidity and temperature and can directly measure absolute humidity. The system can use various wireless technologies for remote sensing readout and can be coupled with various operating systems.

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