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A Carbon Nanotube-based Sensor for CO_2 Monitoring

Keat G. Ong and Craig A. Grimes*

Department of Electrical Engineering & Materials Research Institute, 208 Materials Research Laboratory, The Pennsylvania State University, University Park, PA 16802

* Author to whom correspondence should be addressed. E-mail: cgrimes@engr.psu.edu

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Abstract: A carbon dioxide (CO_2) sensor is fabricated by depositing a thin layer of a multi-wall carbon nanotube (MWNT) – silicon dioxide (SiO_2) composite upon a planar inductor-capacitor resonant circuit. By tracking the resonant frequency of the sensor the complex permittivity of the coating material can be determined. It is shown that the permittivity of MWNTs changes linearly in response to CO_2 concentration, enabling monitoring of ambient CO_2 levels. The passive sensor is remotely monitored with a loop antenna, enabling measurements from within opaque, sealed containers. Experimental results show the response of the sensor is linear, reversible with no hysteresis between increasing and decreasing CO_2 concentrations, and with a response time of approximately 45 s. An array of three such sensors, comprised of an uncoated, SiO_2 coated, and a MWNT-SiO_2 coated sensors is used to self-calibrate the measurement for operation in a variable humidity and temperature environment. Using the sensor array CO_2 levels can be measured in a variable humidity and temperature environment to a ± 3% accuracy.

Keywords: Carbon dioxide, carbon nanotube, resonant circuit, wireless, remote query.

Introduction

Carbon nanotubes, molecular-scale tubes of carbon with high mechanical strength and unique electrical properties, have seen considerable interest in recent years for applications including, to name a few, field emission devices [1], nano-electronic devices [2-5], actuators [6], and random access memory [7]. Carbon nanotubes have successfully been used as oxygen [8] and methane [9] gas sensors.

In this paper we report, apparently for the first time, application of multi-wall carbon nanotubes (MWNTs) to carbon dioxide sensing, based upon the measured changes in MWNT permittivity with

CO_2 exposure. The transduction platform used in this work is a planar, inductor-capacitor resonant-circuit (LC) sensor [10,11]. A thin layer of a MWNT-SiO_2 composite is placed upon the inter-digital capacitor of the LC sensor; as the permittivity of the adjacent layer changes so does the sensor resonant frequency which is remotely monitored using a loop antenna [10]. The passive nature of the LC sensor enables long term monitoring without battery life-time issues, and the wireless nature of the platform enables monitoring of CO_2 from within sealed, opaque containers such as food or medicine packages. High levels of CO_2 within such containers are widely used as a determinant for contamination [12,13]. In addition to food quality monitoring CO_2 sensors are important for industrial process control [14], monitoring air quality [15], etc.

Most CO_2 sensors available on the market today operate by measuring the impedance of a capacitor coated with a CO_2-responsive material such as heteropolysiloxane [16], $BaTiO_3$ [17], $CeO/BaCO_3/CuO$ [18], Ag_2SO_4 [19], and Na_2CO_3 [19]. These CO_2 sensors offer a high degree of accuracy and reliable performance, but require hard-wire connections between the sensor head, power supply, and data processing electronics which precludes many monitoring applications.

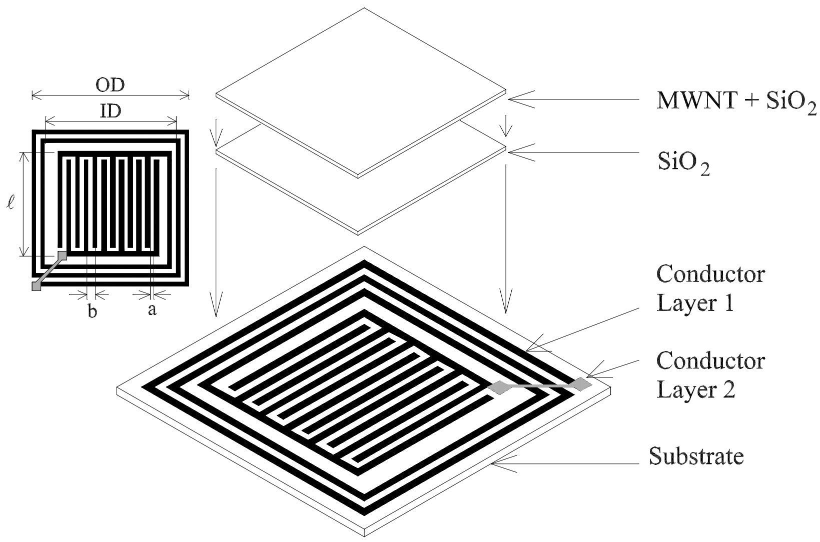

Figure 1. The schematic drawing of the CO_2 sensor. A planar inductor-interdigital capacitor pair is photolithographically defined upon a copper clad printed circuit board. The capacitor is first coated with a protective electrically insulating SiO_2 layer followed by a layer of CO_2 responsive MWNT-SiO_2 composite.

The general sensor structure is shown in Figure 1, and consists of a printed inductor-capacitor resonant circuit that is first coated with a protective, electrically insulating SiO_2 layer [20], followed by a second layer consisting of the CO_2 responsive MWNT-SiO_2 mixture with the SiO_2 matrix acting to physically bind the MWNTs to the sensor. As the sensor is exposed to CO_2 the relative permittivity ε_r' and the conductivity (proportional to ε_r'' [21]) of the MWNTs vary, changing the effective complex permittivity of the coating and hence the resonant frequency of the sensor. The relationship between the CO_2 adsorption and the complex permittivity is discussed within the Results & Discussion.

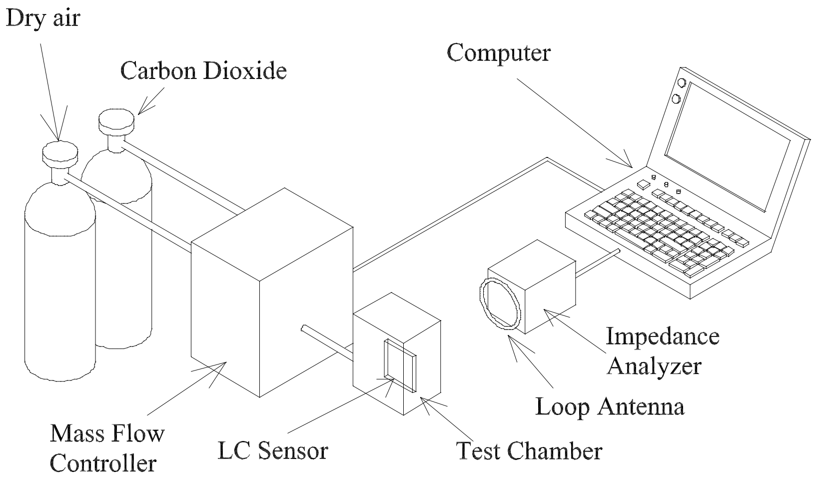

Figure 2. Experimental setup for testing the CO_2 sensor. The sensor is placed inside a sealed Plexiglas chamber, and monitored via a loop antenna. An impedance analyzer is used to measure the impedance spectrum across the terminals of the antenna, and a mass-flow controller is used to control the flow rates of different gasses. A computer controls the devices via the GPIB interface.

As shown in Figure 2, the response of the CO_2 sensor is obtained by directly measuring the impedance spectrum of a sensor-monitoring loop antenna. The impedance of the loop antenna is removed from the measurement using a background subtraction, obtained by measuring the antenna impedance without the sensor present. A typical background-subtracted impedance spectrum is shown in Figure 3, where the resonant frequency f_0 is defined as the frequency at the real impedance (resistance) maximum, and the zero-reactance frequency f_Z is the frequency where the imaginary impedance (reactance) goes to zero. By modeling the sensor with an RLC circuit and performing standard circuit analysis, the complex permittivity, $\varepsilon_r' - j\varepsilon_r''$, of the coating material (both the MWNT-SiO_2 and SiO_2 layers) are calculated from the measured f_0 and f_Z as [10,11]:

$$\varepsilon_r'' = \frac{\sqrt{f_0^2 - f_Z^2}}{4\pi^2 f_0^3 L \kappa \varepsilon_0} \tag{1}$$

ε_0 is the free space permittivity ($\varepsilon_0 = 8.854 \times 10^{-12}$ Farads / meter), ε_s is the relative permittivity of the electrically lossless substrate (that is $\varepsilon_s = \varepsilon_s'$), κ is the cell constant of the interdigital capacitor, and L is the inductance of the spiral inductor in Henry's. The cell constant κ and inductance L can be calculated from the sensor geometry using [22-24]:

$$\kappa = \frac{\ell(N_C - 1)K\left[(1-(a/b)^2)^{1/2}\right]}{2K[a/b]} \tag{2}$$

$$L = 1.39 \times 10^{-6}(OD + ID)N_L^{5/3} \log_{10}\left(4\frac{OD+ID}{OD-ID}\right) \tag{3}$$

where a, b, ℓ, OD, and ID are the dimensions of the sensor defined in Figure 1, N_C is the number of fingers in each capacitor's electrode, N_L is the number of the inductor turns, and K is the elliptic integral of the first kind.

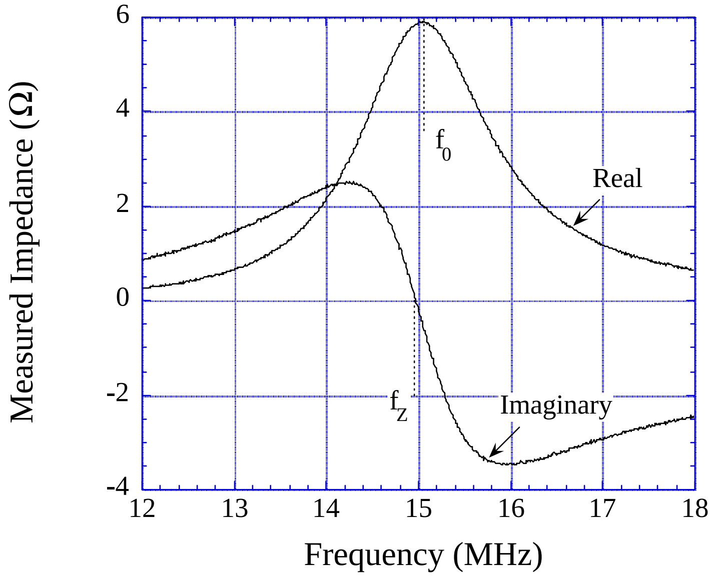

Figure 3. An illustrative measured impedance spectrum of the sensor-perturbed antenna, after subtracting the background antenna impedance. The resonant frequency f_0 is defined as the maximal of the real portion of the impedance, and the zero-reactance frequency f_Z is the zero crossing of the imaginary portion of the impedance spectrum.

Experimental

Preparation of nanotubes

The MWNTs used in this work were prepared by pyrolysis of ferrocene and xylene under Ar/H_2 atmosphere over quartz substrates in a two-stage reactor [25]. Approximately 6.5 mol% of ferrocene was dissolved in xylene and continuously fed into a tubular quartz reactor. Ferrocene has been shown to be an excellent precursor for producing Fe catalyst particles, and xylene was selected as the hydrocarbon source. The liquid feed was passed through a capillary tube and preheated to ~175^{0}C prior to its entry into the furnace. At this temperature, the liquid exiting the capillary was immediately volatilized and swept into the reaction zone of the furnace by a flow of argon with 10% hydrogen. The MWNTs grow perpendicularly from the surface of the quartz reactor tube. After the reaction, the pre-heater and the furnace were allowed to cool to room temperature in flowing argon, and the MWNT sheets collected. Precise details of the fabrication process are described in [25].

The resulting MWNTs were characterized by field-emission scanning electron microscopy, and shown in Figure 4. These studies confirm the collected material consists of highly aligned MWNTs with the dominant tube diameter in the range 20-25 nm with length 50 µm. The MWNT clumps were placed in toluene and then sonicated for 30 minutes to disperse the individual nanotubes, rinsed with isopropanol, and then allowed to dry. The nanotubes were then dispersed in a liquid SiO_2 solution (20 wt% SiO_2 nanoparticles dispersed in water, from [20]) such that a nanotube to SiO_2 dry-weight balance of 2:3 was obtained. The resulting solution was pipetted onto the inter-digital capacitor of the sensor.

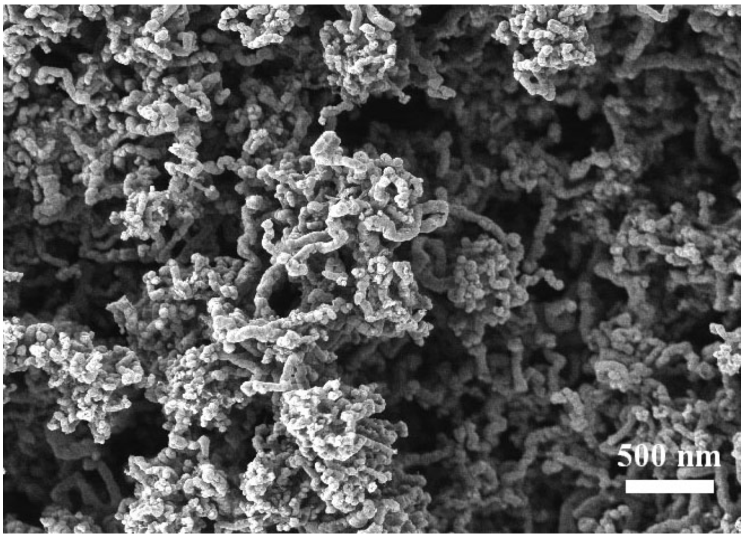

Figure 4. The SEM image of the as-fabricated carbon nanotubes. The carbon nanotubes are about 25-50 nm in diameter, and 50 µm in length.

Sensor Fabrication

A 2-cm square sensor was fabricated by photolithographically patterning a square spiral inductor and an interdigital capacitor on a Printed Circuit Board (PCB), see Figure 1. An ≈ 150 µm thick layer of SiO_2 (confirmed by SEM imaging) followed by an ≈200 µm thick layer the MWNT-SiO_2 mixture were then coated onto the capacitor of the sensor, with a resulting sensor cross section as shown schematically in Figure 5.

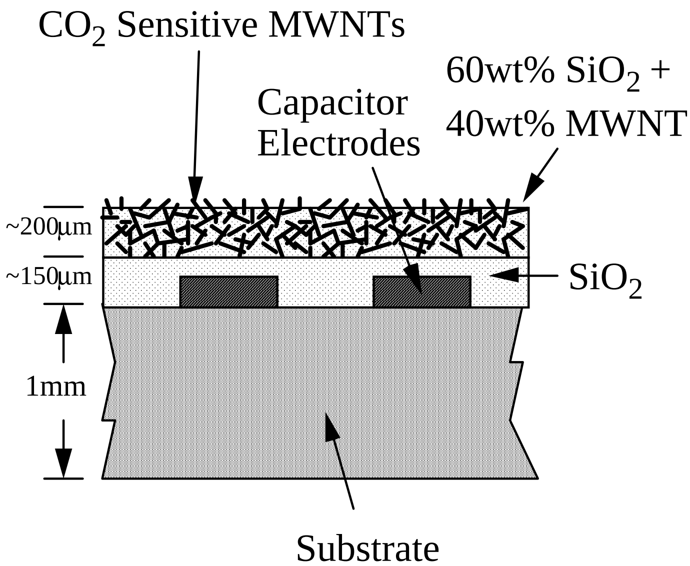

Figure 5. Cross sectional view of the interdigital capacitor. An electrically insulating 150 µm-thick SiO_2 layer is first applied to protect the sensor, followed by a 200 µm MWNT-SiO_2 gas-sensing layer.

Experimental Setup for Sensing CO_2

The testing facility is schematically depicted in Figure 2. The sensor was placed inside a sealed Plexiglas test chamber, and monitored with a single-turn 16 cm diameter loop-antenna located approximately 15 cm from the sensor. Test gas concentration was controlled with a mass flow controller (MKS Instruments Multi Gas Controller 647B). The antenna impedance was measured with an impedance analyzer (Hewlett Packard 4396B), with the cable length removed from the measurement using an HP85033D calibration kit. A computer was used to control the mass flow controller and the impedance analyzer via a GPIB interface, as well as analyzing and processing the measurements.

Results and Discussion

CO_2 Detection

Figure 6 shows the response of the CO_2 sensor as it is alternately cycled between dry air (~80% N_2 and 20% O_2) and pure CO_2; the humidity level in the chamber was 0% RH, and the temperature was 23˚C. There is an increase in values of ε_r' and ε_r'', 0.040 (0.91%) and 0.035 (4.40%), respectively, as the gas is switched from CO_2 to dry air. The change in the complex permittivity magnitude $|\varepsilon_r|$ is 1.02%. The change in the complex permittivity is reversible, with no hysteresis observed.

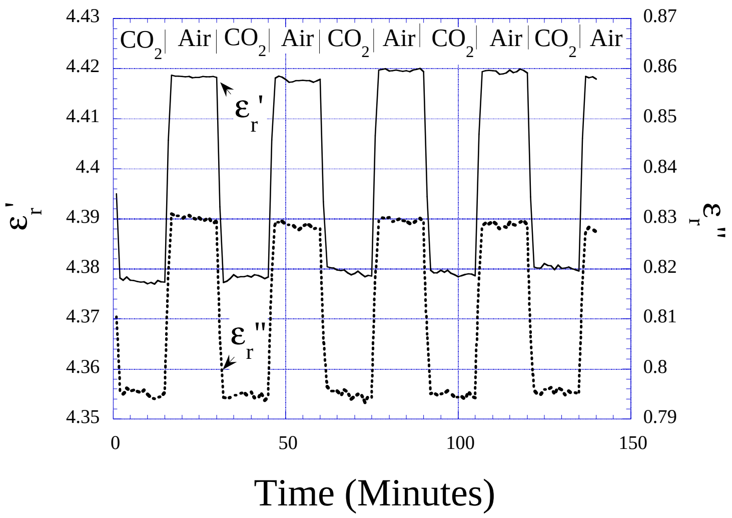

Figure 6. Measured ε_r' and ε_r'' values when the sensor is cycled between pure CO_2 and dry air. The changes are reversible, without hysteresis between increasing and decreasing CO_2 concentrations.

As seen in Figure 6 both ε_r' and ε_r'' of the MWNTs are lower when the sensor is exposed to CO_2 and higher when the sensor is exposed to dry air containing ~80 %N_2 and 20 % O_2. We believe that the change in ε_r'', which is directly proportional to the conductivity $\sigma = 2\pi f\ \varepsilon_0\varepsilon_r''$, is due to the adsorption and/or the insertion of gas molecules into either the core or surface of the MWNT that introduces defects and lowers the electrical conductivity [26]. As CO_2, N_2, and O_2 have a relative low ε_r' value

(~1) compared to the MWNT graphene layer (ε_r'~15), the effective ε_r' of the exposed MWNT layer decreases as more gas molecules are adsorbed. Since CO_2 has two lone pair of electrons with Π-type C=O bindings [27] and N_2 is an inert diatomic molecule that only reacts to graphene at high temperature [28], the adsorption capacity of CO_2 is much higher than N_2 at room temperature. Hence, there is a decrease in ε_r' and ε_r'' when the sensor is exposed to CO_2. While O_2, which has two lone-pair of electrons in the anti-bonding Π orbital [29], has similar adsorption behavior as CO_2 it is not present in sufficient quantity to completely counter the N_2 effect. Our observations on ε_r'' (conductivity) decreasing with gas adsorption are consistent with those reported elsewhere [26,28,30,31].

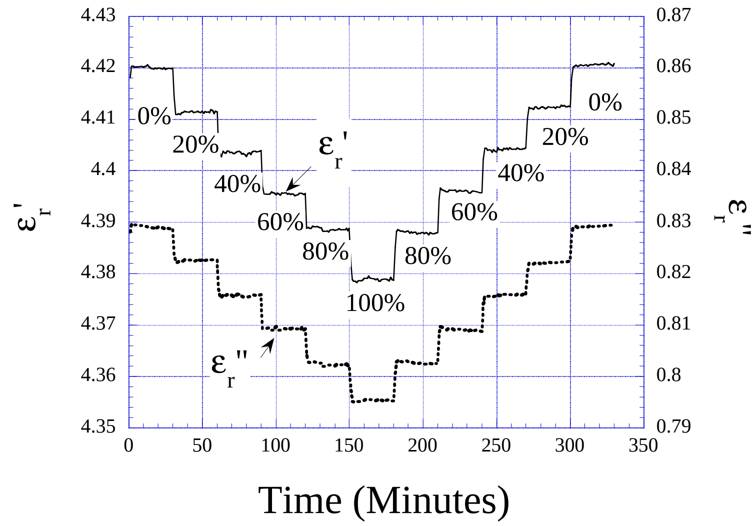

Figure 7. Measured ε_r' and ε_r'' values when the sensor is exposed to CO_2 concentrations varying from 0% (volume) to 100% and then back to 0%. The shifts are linear, with $\Delta\varepsilon_r' = -0.0004043/\%CO_2$ and $\Delta\varepsilon_r'' = -0.0003476/\%CO_2$.

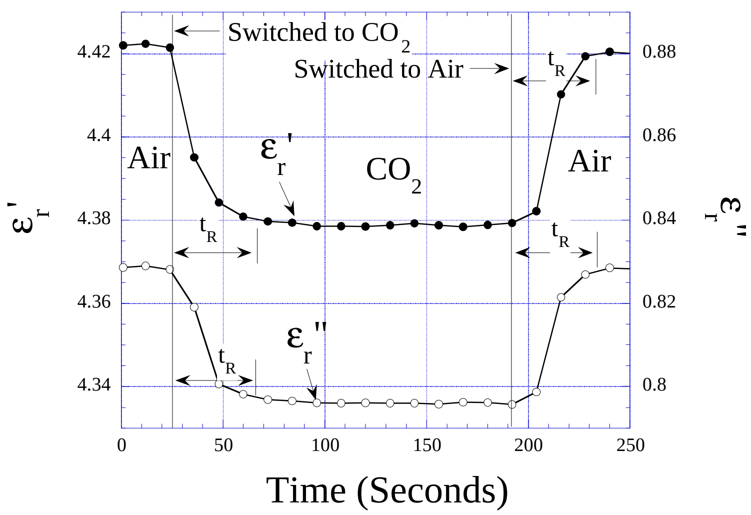

Figure 8. Change in ε_r' and ε_r'' when the gas is switched from air to CO_2, and then back to air. The response time t_R, can be determined from the figure as less than 45 seconds.

Figure 7 presents the shifts of ε_r' and ε_r'' as a function of the CO_2 to dry air volume ratio. The symmetry of the steps indicates the absence of hysteresis with increasing or decreasing CO_2 concentrations. The absolute change in the complex permittivity with CO_2 concentration is linear at $\Delta\varepsilon_r' = -0.0004043/\%CO_2$ and $\Delta\varepsilon_r'' = -0.0003476/\%CO_2$. The response time of the sensor t_R, determined as the time to achieve steady state response after switching gas concentrations, is determined from Figure 8 as approximately 45 s, and was found to be constant with temperature to 43°C, the upper limit tested.

Humidity and Temperature Dependencies

Figure 9a displays the effect of changing humidity, temperature, and CO_2 concentration on the complex permittivity magnitude of the MWNT- SiO_2 sensor coating. Figure 9b is an illustrative real-time measurement showing how the permittivity magnitude of the MWNT CO_2 sensor changes, at CO_2 concentration = 0% and 25%, in response to various humidity and temperature conditions. Due to the strong attraction of the MWNTs for water moisture the response time of the CO_2 sensor suffers a dramatic increase in high humidity environments. Operation at elevated temperatures improves the response time of the sensor as it is cycled between dry and humid environments. Switching from 0% to 100% humidity levels at 23°C, 31°C, and 42°C the response times are, respectively, 22, 16 and 14 minutes. Switching from 100% to 0% humidity levels at 23°C, 31°C, and 42°C the response times are, respectively, 58, 36 and 34 minutes.

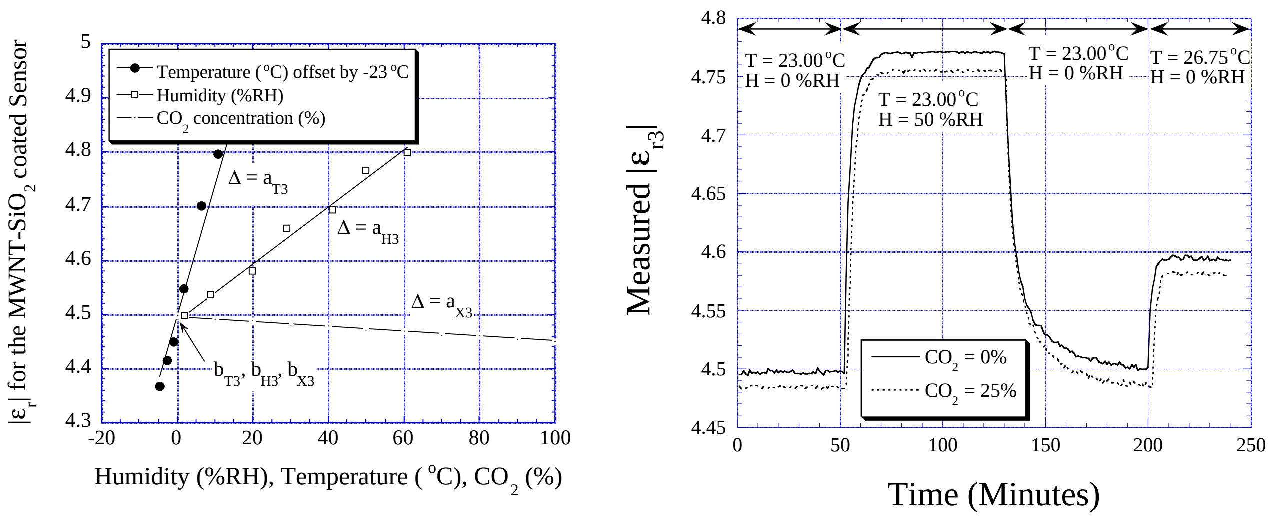

Figure 9. (a) The permittivity magnitude of the MWNT-based CO_2 sensor shifts linearly with CO_2, humidity, and temperature. (b) The permittivity magnitude of the MWNT-based CO_2 sensor, at zero and 25% CO_2 concentration, as it is exposed to different humidity and temperature conditions.

To eliminate the effects of humidity and temperature, a SiO_2-coated sensor and an uncoated sensor are used in addition to the CO_2 sensor, forming a sensor array. The SiO_2-coated and the plain sensors do not respond to CO_2, but both linearly respond in separable ways to humidity and temperature, over the range investigated 0 - 60% RH and 18˚C - 43˚C, as shown in Figs. 9a and 9b. Since their responses to both humidity and temperature are linear, the complex permittivity magnitude of the plain sensor ε_{r1}, and the SiO_2-coated sensor ε_{r2}, can be related to humidity and temperature as:

$$\varepsilon_{r1} = \left(a_{T1}T + b_{T1} / 2\right) + \left(a_{H1}H + b_{H1} / 2\right) \tag{4}$$

$$\varepsilon_{r2} = \left(a_{T2}T + b_{T2} / 2\right) + \left(a_{H2}H + b_{H2} / 2\right) \tag{5}$$

H is humidity in %RH, *T* is temperature in ˚C, while *a* and *b* are coefficients experimentally determined by curve-fitting the data in Figures 10a-10b and listed in Table 1. In our experiment, *T* was offset by -23˚C (i.e. *T* = 0 means *T* = 23˚C in the real world); the offset is required since the sensor is initially calibrated at room temperature (23˚C).

Table 1. Regression coefficients of plain, SiO_2 coated, and MWNT-SiO_2 coated sensors.

Coefficients	Plain Sensor	SiO_2-coated Sensor	MWNT-coated Sensor
a_T	a_{T1} = 0.00089523	a_{T2} = 0.00193071	a_{T3} = 0.024175
b_T	b_{T1} = 1.01062	b_{T2} = 1.34392	b_{T3} = 4.49524
a_H	a_{H1} = 0.00011883	a_{H2} = 0.00064168	a_{H3} = 0.0052665
b_H	b_{H1} = 1.01051	b_{H2} = 1.34359	b_{H3} = 4.49472
a_X	0	0	a_{X3} = -0.00045769
b_X	0	0	b_{X3} = 4.49562

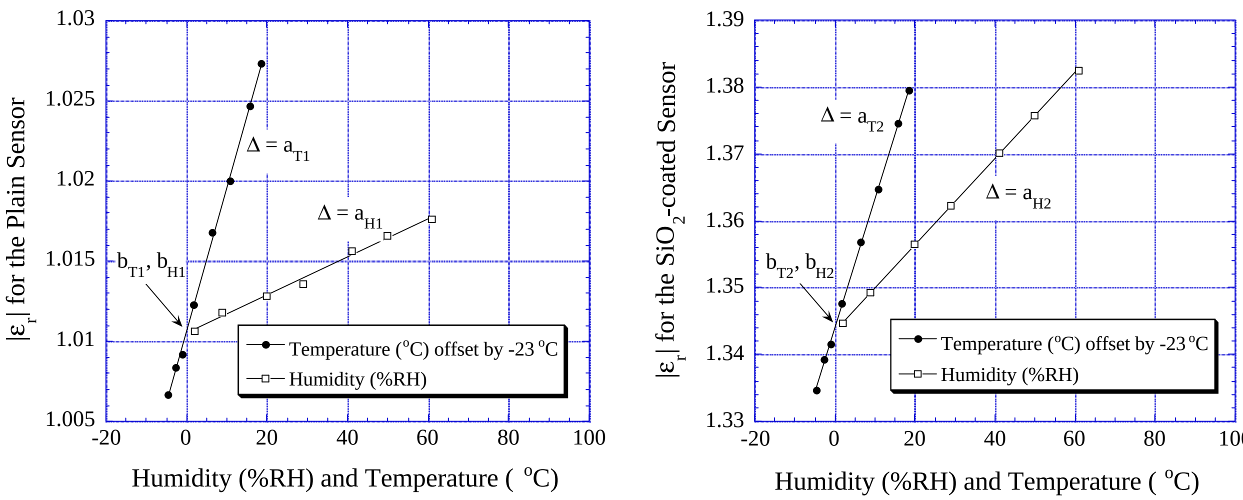

Figure 10. (a) The permittivity magnitude of the plain (uncoated) sensor shifts linearly with humidity or temperature. (b) The permittivity magnitude of the SiO_2-coated sensor shifts linearly with humidity or temperature; note response slopes of Figures 9a, 10a, and 10b are uniquely different.

The humidity and temperature can then be determined by simultaneously solving Eqs. (4) and (5):

$$\begin{bmatrix} T \\ H \end{bmatrix} = \frac{1}{a_{T1}b_{H2} - a_{T2}b_{H1}} \begin{bmatrix} b_{H2} & -b_{H1} \\ -a_{T2} & a_{T1} \end{bmatrix} - \begin{bmatrix} \varepsilon_{r1} - (b_{T1} + b_{H1}) / 2 \\ \varepsilon_{r2} - (b_{T2} + b_{H2}) / 2 \end{bmatrix} \tag{6}$$

For the MWNT-SiO_2 coated sensor the magnitude of the complex permittivity ε_{r3} can be related to humidity, temperature, and CO_2 with the equation:

$$\varepsilon_{r3} = \left(a_{T3}T + b_{T3}/3\right) + \left(a_{H3}H + b_{H3}/3\right) + \left(a_{X3}X + b_{X3}/3\right) \quad (7)$$

X is the percent volume of CO_2 present, and a_{T3}, a_{H3}, a_{X3}, b_{T3}, b_{H3}, and b_{X3} are coefficients determined from Figure 9a listed in Table 1. Rearranging Eq. (7), the CO_2 concentration can be found as:

$$X = \frac{\varepsilon_{r3} - a_{T3}T - a_{H3}H - \left(b_{T3} + b_{H3} + b_{X3}\right)/3}{a_{X3}} \quad (8)$$

Figure 11 shows application of the sensor array to measurement of 0% and 25% CO_2 atmospheres in a variable temperature and humidity environment; the CO_2 percentage is calculated using Eq. (8) with data from Figure 9b. After a calibration transient due to the different response times of the sensors to changing temperature and humidity levels (primarily dictated by the strong attraction of MWNTs to water vapor), the calculated CO_2 levels in a given humidity and temperature environment are within an error margin of ± 3 CO_2%. However since the periods over which the sensor reports spurious measurement values are clearly discernable, both due to the rapid rate of change and clearly incorrect values (e.g. 120% CO_2), software routines could be readily implemented to keep the sensor tracking nominal steady-state values.

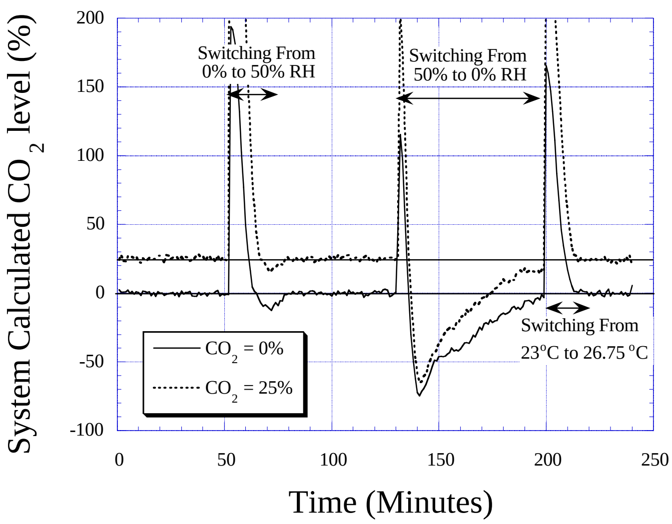

Figure 11. CO_2 concentration determined using measured data as corrected by Eq. 8 with calibration parameters of Table 1; measurements are taken with CO_2 concentration kept at 0% and 25%. Outside of the transient region, upon reaching steady state measured results are within ± 3%. Since the different sensors have different response rates large errors occur when humidity and temperature change, an effect dominated by the slow desorption of moisture from the MWNTs.

Conclusions

Application of multi-wall carbon nanotubes (MWNTs) to CO_2 sensing has been demonstrated. The sensor is reversible, with no hysteresis observed between the cycles of CO_2 and dry air (~20% O_2 + 80% N_2), with a response time of approximately 45 seconds. The MWNTs are used in combination with a passive, remote query sensor platform, therefore no direct wire connections to the sensor are needed for operation, nor is a battery needed to power the sensor. These operational characteristics make the CO_2 sensor attractive for long-term wireless monitoring applications, such as monitoring CO_2 levels in food or medicine packages to check for product spoilage [12,13].

It is found that the complex permittivity of the MWNTs is lower when the sensor is exposed to CO_2 than in dry air. This is due to the relatively higher adsorption capacity of the MWNT for CO_2 in comparison to N_2, which increases the surface defects [26] and lowers the MWNT conductivity. Our observations on ε_r'' (conductivity) decreasing with gas adsorption are consistent with those reported elsewhere [26,28,30,31]. Absorption of CO_2 also lowers ε_r' of the MWNT, as ε_r' of CO_2 is much smaller than that of the electrically conductive MWNT. While O_2, which has two lone-pair of electrons in the anti-bonding Π orbital [29], has similar adsorption behavior as CO_2 it is not present in sufficient quantity to completely counter the N_2 effect.

To eliminate the deleterious effects of humidity and temperature on the MWNT CO_2 sensor, measured values are calibrated against the response of both a SiO_2-coated sensor, and a plain (uncoated) sensor, neither of which respond to CO_2 and both of which uniquely respond to temperature and humidity. Using the described calibration algorithm of Eq. (8) enables CO_2 concentrations to be measured to within ±3 CO_2% in a changing humidity and temperature environment. For operation within 0 - 60% RH and 18˚C - 43˚C the sensors respond linearly to humidity and temperature, therefore a straight-forward linear calibration routine can be used with success. At higher temperatures and humidity levels the sensor responses are non-linear, so a higher-order calibration routine would be needed to maintain sensor accuracy.

Acknowledgements

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