A Novel "Green" Fully-integrated Ultrasensitive RFID-enabled Gas Sensor Utilizing Inkjet-printed Antennas and Carbon Nanotubes

L. Yang*, D. Staiculescu, R. Zhang, C.P. Wong, and M. M. Tentzeris
Georgia Institute of Technology, Atlanta, GA, 30332, U.S.A.

Abstract

In this paper, the integration of a flexible RFID tag with an inkjet-printed Single Walled Carbon Nanotube (SWCNT) film in a chipless sensor node for toxic gas detection was introduced for the first time. The whole module is realized on a "green" low-cost paper substrate. Carbon nanotube composites change their electric properties (e.g. resistance, dielectric properties) in the presence of very small quantities of toxic gases like ammonia and nitrogen oxide. The RFID tag is designed for the 868 MHz UHF band. When NO_x gas is present, the resistance of the SWCNT film will drop, resulting in the decrease of the backscattered power which will be detected by the RFID reader to realize the reliable toxic gas detection in a non-invasive way.

Introduction

The increased environmental awareness requires more and more applications that use simple, organic, recyclable solutions, fully integrated on flexible substrates for ease of use for almost all applications, including body area networks for medical systems, tracking for pharmaceutical and food industries, toxic pollutants detection, supply chain, space and many more. This demand is further enhanced by the need for lightweight, reliable and durable wireless RFID-enabled sensor nodes [1]. The choice of paper as the substrate material presents multiple advantages and has established paper as one of the most promising materials for UHF RFID applications: it is widely available, recyclable, and the high demand and the mass "reel-to-reel" production make it the cheapest material ever made. Furthermore, the expensive and very polluting batteries need to be replaced in many applications, thus necessitating the emergence of low-cost power scavenging solutions. Energy forms like solar, thermal, vibrational and pressure can be scavenged to power the sensor nodes for various applications. Previous work has demonstrated the successful development of a fully inkjet-printed RFID module on paper [2]. The next challenge is to integrate the sensor and the scavenger on the paper substrate as well. The application of interest for this work is wireless sensing of toxic gas. Single-Walled Carbon Nanotube (SWCNT) composites were found to have electrical properties highly sensitive to extremely small quantities of gases, such as ammonia (NH_3), carbon dioxide (CO_2), nitrogen oxide (NO_x), etc. at room temperatures with a very fast response time [3].

This paper presents, for the first time, a chipless CNT-based RFID-enable sensor node for gas sensing applications, fully printed directly on paper substrate. The printed SWCNT is from Carbon Solutions, which were dispersed in dimethylformamide (DMF) solution for the inkjet printer. The impedance of the SWCNT film forms the sensor part. The antenna was printed first, followed by the 20 layers of the dispersed SWCNT as a load. The expected backscattered power variation from the RFID is 5% due to the impedance change in the presence of NO_x. The gas detection is easily realized in a noninvasive way realized by just detecting this power level variation from the RFID reader's side.

978-1-4244-3647-7/09/$25.00 ©2009 IEEE

Inkjet-printed SWCNT

As a direct-write technology, inkjet printing transfers the pattern directly to the substrate. Due to its capability of jetting one single ink droplet in the amount as low as 1pl, it has widely drawn attention from the industrial world as a more accurate and economic fabrication method than the traditional lithography method.

A SWCNT ink solution was developed for the first time ever as the first step to enable the SWCNT to be inkjet printed. The sample SWCNT powder was dispersed in DMF, a polar aprotic solvent. The concentration of the ink was 0.4mg/ml. The diluted solution was purified by sonicated for 12 hours to prevent aggregations of large particle residues. This is important to avoid the nozzle clogging by SWCNT flocculation during the printing process. Dimatix Materials Printer DMP-2800 equipped with DMCLCP-11610 printer head was used to eject the SWCNT ink droplet onto a flexible substrate. Four devices with 10, 15, 20 and 25 SWCNT layers were fabricated to investigate the electrical properties. Fig. 1 shows the fabricated samples.

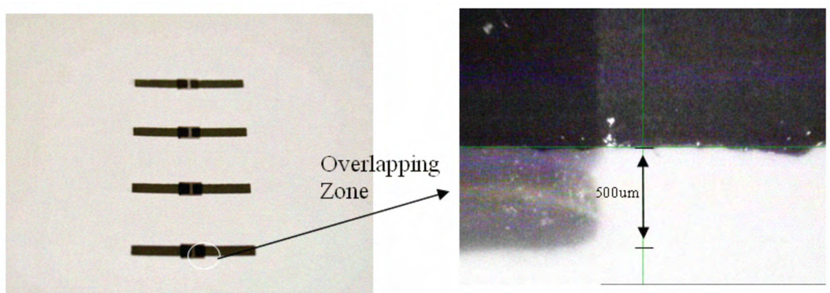


Fig. 1. Photograph of the inkjet-printed SWCNT films with silver electrodes.

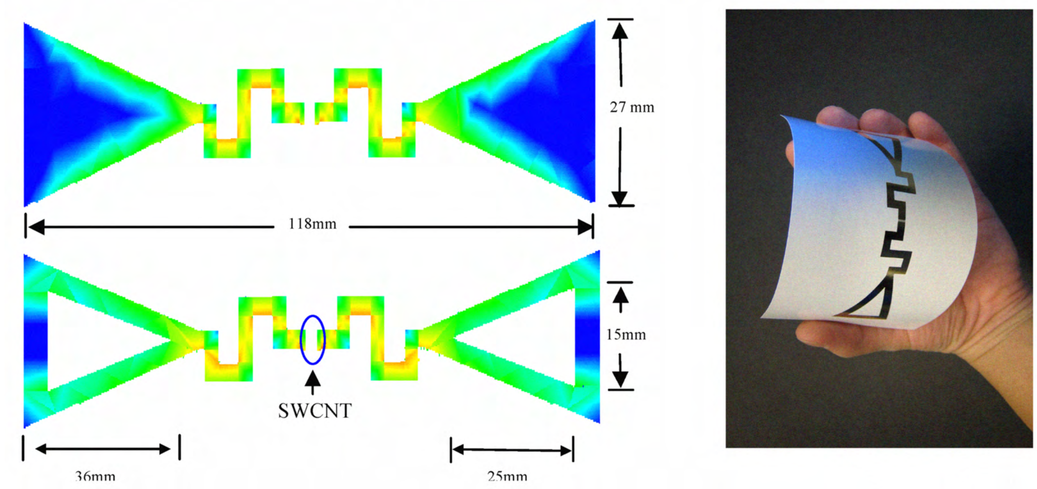
Antenna Design and Measurement

A passive RFID system operates in the following way: the RFID reader sends an interrogating RF signal to the RFID tag consisting of an antenna and an IC chip as a load. The power reflection coefficient of the RFID antenna can be calculated as a measure to evaluate the reflected wave strength.

$$\left|s^2\right| = \left|\frac{Z_{load} - Z_{ANT}^*}{Z_{load} - Z_{ANT}}\right|^2 \qquad (1)$$

where Z_{Load} represents the impedance of the load and Z_{ANT} represents the impedance of the antenna terminals with Z_{ANT}^* being its complex conjugate. The same mechanism can be used to realize RFID-enabled sensors. The inkjet-printed SWCNT film functions as a tunable resistor with a value determined by the existence of the target gas. The RFID reader monitors the backscattered power level. When the power level changes, it means that there is variation in the load resistance, therefore the sensor detects the existence of the gas.

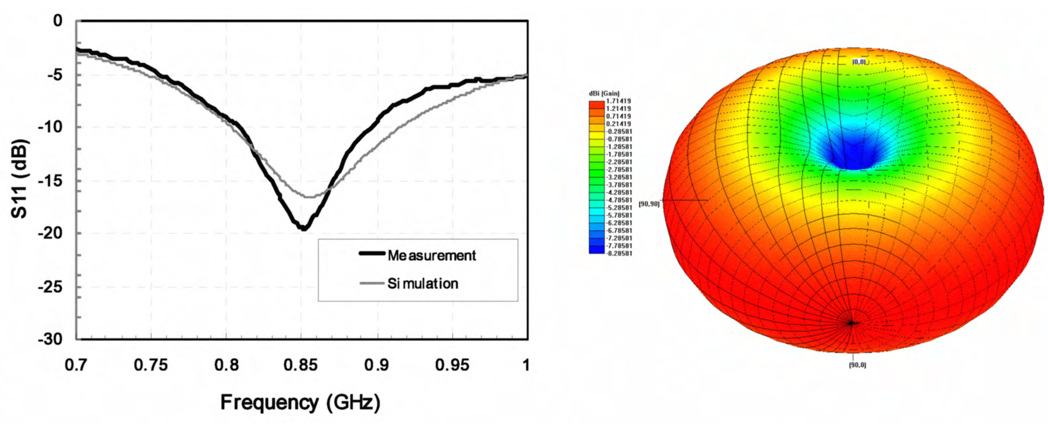
To verify the performance of the proposed topology, a bow-tie meander line dipole antenna was designed and fabricated on a 100um thickness flexible paper substrate with dielectric constant 3.2. The nature of the bow-tie shape offers a more broadband operation for the dipole antenna. Since conductive ink has become the major cost of an RFID tag after introducing the paper-based substrate into the low-cost RFID tag design methodology, it is naturally desirable to minimize the amount of ink used per antenna in the mass production. This is achieved by reducing the printing area in the weakest current density region, which is the dark area in the bow-tie shape as shown in Fig. 2. The SWCNT film was inkjet printed in the center.



(a) (b)

Fig. 2. The RFID tag module design on flexible substrate: (a) current density distribution of the proposed antenna configurations (b) photograph of the fabricated conformal tag.

The simulation and measurement results of the return loss of the proposed antenna are shown in Fig. 3 (a), showing a very good agreement. The tag bandwidth extends from 810MHz to 890MHz, covering the whole European RFID band. The antenna performance is plotted in Fig. 3 (b), which is almost omnidirectional at 868MHz with directivity around 2.01dBi and 94.2% radiation efficiency.



(a) (b)

Fig. 3. (a) Measured return loss of the SWCNT-enabled RFID tag antenna (b) Simulated far-field radiation pattern plot. An omnidirectional radiation pattern can be observed at Φ= 0° plane with directivity 2.01dBi.

As a proof-of-concept benchmarking case, 20 layers of SWCNT were chosen to print on the gap of the fabricated RFID tag. In the air, the film performance is close to an 80Ohm load with -10dB return loss at 868MHz. When NO_2 is present, the return loss will become -13dB, assuming a 20% resistance decreasing. The return loss difference is equivalent to 5% of the energy arriving the RFID tag, which would not be reflected back to the reader, as shown in Fig. 3. By detecting this backscattered signal difference on the reader's side, the sensing function can be fulfilled.

Piezoelectric Scavenger for Active RFID-enabled Sensors

The tag presented in this paper is a passive one. However, state-of-the-art long-range RFID tags are realized by active RFID topologies, which require a power supply. Until now, chemical-cell batteries have been sufficient, but replacing them is a costly nuisance and an environmental disposal hazard, thus making this solution less practical as demand increases. As the next step, extraction of electrical energy from human body movement will be realized by the energy scavenger to power up the active RFID tag module on flexible organic substrate. The preliminary study investigates the feasibility of a piezoelectric scavenger, using a push-button piezoelectric switch. The schematic of the scavenging circuit is presented in Fig. 4. In experiment, the energy harvested from one button pushing, which can be trigged by walking movement, can power an eight-bit encoder to send two words. This proves that the concept is feasible and the next step will be the integration of the scavenger on the paper substrate.

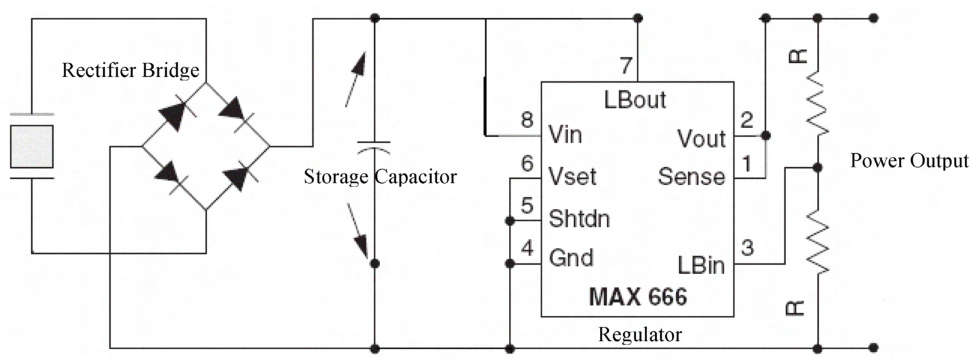


Fig. 4. Piezoelectric scavenger schematic.

Conclusions

The inkjet printing method has been utilized for the first time to deposit SWCNT film on a fully-printed "green" RFID module on paper to form a wireless gas sensor node. Furthermore, the feasibility of a piezoelectric scavenger was successfully investigated to be integrated in the tag. The last step will be the integration of the scavenger on the paper substrate as well. Thus, the major steps have been completed for the development of an energy-independent, trully "green" sensor node to help build the next generation of environmentally-friendly electronics.

References

[1] T. Mishima, N. Abe, K. Tanaka, and H. Taki, "Toward construction of a mobile system with long-range RFID sensors" *IEEE conference on Cybernetics and Intelligent Systems*, vol. 2, pp. 960-965, 2004

[2] L. Yang, A. Rida, R. Vyas, M. M. Tentzeris, "RFID tag and RF structures on a paper substrate using inkjet-printing technology," *IEEE Transaction on Microwave Theory and Techniques*, vol. 55, pp 2894-2901, Dec. 2007.

[3] K. G. Ong, K. Zeng, C. A. Grimes, "A wireless, passive carbon nanotube-based gas sensor," *IEEE Sens. Journal*, 2002, vol. 2, pp 82-88.