Fully Printed and Flexible Carbon Nanotube Transistors for Pressure Sensing in Automobile Tires

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***Abstract*— As the need for an increased supply and diversity of sensors expands, printed electronics have been identified as a promising approach for low-cost, ubiquitous sensor networks. In this paper, we demonstrate the use of a fully printed carbon nanotube thin-film transistor (CNT-TFT) for sensing environmental pressure over a pressure range extending from 0 to 42 PSIg. The transconductance of the CNT-TFT was found to be linearly correlated with environmental pressure at a sensitivity of 48.1 pS/PSI. We also demonstrate the capability of wirelessly transmitting the data measured by the pressure sensor using a simple Bluetooth module. Using the Bluetooth system, we observed the sensor's response over time as pressure was dynamically changed. Finally, we packaged the sensor along with a material thickness sensor (developed in previous work) into a fully printed smart tire sensor system capable of mapping tire pressure and tread depth differentials.**

***Index Terms*— Printed transistor, pressure sensor, carbon nanotube, thin-film transistor, Internet of Things.**

I. Introduction

ONE driving factor that has induced an abundance of recent interest in printed electronics is the expansive internet-of-things (IoT) [1], [2]. To create a smarter and more efficient electronics ecosystem, a variety of connected sensors and systems are being developed. These systems show promise in increasing safety and an overall quality of life [3], [4]. However, in order to be effective and ubiquitous, the electronics must be low-cost and, in many cases, have a flexible or large-area footprint that is inaccessible to traditional electronics platforms.

Printed electronics are perfectly suited to facilitate this undertaking. For one, they are inherently low cost as they can be typically manufactured in an additive process that is accomplished without the need for high temperatures or vacuum systems [5], [6]. Additionally, printed electronics are compatible with a wide variety of substrates, which can enable both flexible and large-area systems [7]. Printed electronic sensors have been shown to be functional for a range of applications comprising pressure sensing [8], [9], biosensing [10], temperature sensing [11], and others [12]–[15]. One general drawback to printed electronics is their low performance when compared to vacuum-processed electronics. In spite of this, the performance is sufficient for many low-cost sensing networks. Ultimately, printed electronics allow for electronic sensors and systems to be compatible with the high-throughput, low-cost manufacturing needed for IoT applications, while also allowing for additional functionalities, such as flexible and large-area substrates.

A recent device that has shown promise in printed electronics is the carbon nanotube thin-film transistor (CNT-TFT). CNT-TFTs have been demonstrated as flexible transistors with performance on par with, or surpassing, competing technologies, namely metal-oxide and organic flexible transistors [16]–[18]. In recent work, we have developed a fully printed and flexible CNT-TFT that exhibits a field-effect mobility of 16.1 $cm^2/(V\cdot s)$ and an on/off current ratio greater than 10^4 [19]. While CNT-TFTs have shown promise for display backplanes [20], [21], logic circuitry [22], [23], and biological sensors [24]–[26], no work has been done to study their use as environmental pressure sensors.

Pressure sensing is a prevalent and active research area [8], [9], [27], [28]. Typically, sensors rely on an induced tactile pressure, as opposed to an ambient, environmental pressure. While these are related, the sensitivity required, as well as the lack of physical touch, keep these two mechanisms from being used interchangeably. The applications for tactile vs environmental pressure sensors are also dissimilar and important to distinguish. Whereas tactile pressure sensors are primarily used in robotics and AI interfacing [29], [30], environmental pressure of a system is of importance for automobile tires [31], [32], embedded blood pressure sensors [33], manufacturing facility monitoring, and weather stations. A low-cost method of monitoring pressure differentials in the ambient environment would be valuable and is of notable interest for IoT applications.

Many types of sensors are capable of monitoring environmental pressure, including sensors using surface acoustic waves (SAW) [34], piezoelectrics [31], resistivity changes [35], and transistors [36]–[38]. Transistor-based sensors are a promising approach due to their electrical output, inherent amplification properties, and well understood

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electronic behavior. While there are many developed sensors capable of quantifying environmental pressure, they are either rigid or costly, limiting their potential use for large-area applications where many low-cost, flexible sensors are required.

CNT-TFTs offer a unique platform that combines the fabrication advantages of low-cost, and flexible printed electronics with the sensing advantages of CNTs and transistors. Additionally, CNTs have been demonstrated to be robust to mechanical strain and harsh environments [39]. Unlike peer technologies, such as organic TFTs, CNT-based devices can operate at higher temperatures and thus in a greater variety of environments. This is critical for some applications, specifically automobile tire pressure sensors.

In this work, we demonstrate a fully printed CNT-TFT as a pressure sensor that is capable of detecting environmental pressure across a range of 0 to 42 PSIg. The most pronounced sensitivity stems from a correlation between the transconductance of the transistor and the environmental pressure. We also demonstrate the combination of the printed pressure sensor with a fully printed material thickness sensor [13] for a comprehensive, integrated, smart tire sensor package. Lastly, we develop a low-cost sensor measurement unit which demonstrates the capability of communicating data wirelessly from the sensor, simulating a real-world sensing environment. Using this system, we are able to analyze the sensor's response to pressure changes over time. To our knowledge, this is the first fully printed transistor-based environmental pressure sensor demonstration and it opens up a novel, fully printed platform for future sensing applications.

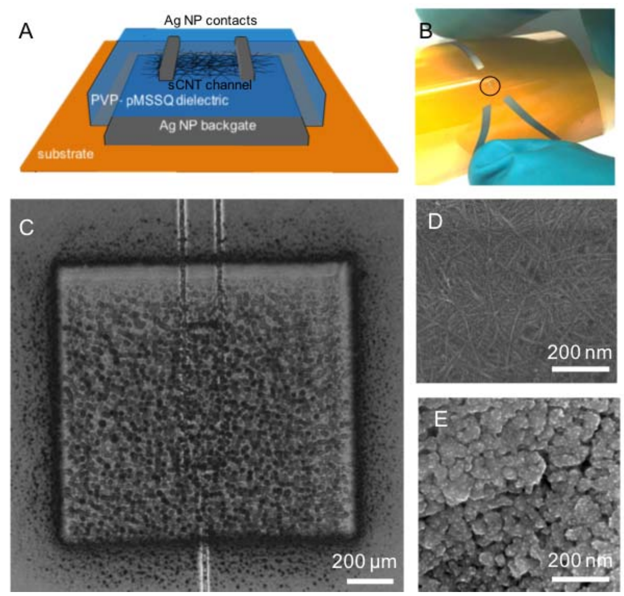

Fig. 1. Fully printed CNT-TFT structure and morphology. (A) Schematic of the fully printed, bottom-gate, top-contact CNT-TFT. (B) Photograph of the sensor on a Kapton substrate being flexed, with the active device area circled. (C) Optical image at 2.5x zoom of the complete device. SEM images of (D) the CNT thin-film channel and (E) the printed Ag NP source, drain, and back gate.

II. Experimental

The pressure sensors are printed on a substrate, either glass or flexible Kapton, using an Optomec 300 Aerosol Jet Printer. The aerosol jet printer operates through atomizing liquid electronic ink and then using N_2 gas (atomizer flow) to deliver the aerosolized ink to a deposition nozzle. The aerosol is then guided down to the substrate by a secondary N_2 gas (sheath) flow in an annular fashion that prevents the ink from contacting the nozzle sidewalls and clogging.

The substrate was prepared by first ultrasonicating in acetone and isopropyl alcohol for 5 minutes each followed by a rinse in DI water. Lastly, the substrate was subjected to an O_2 plasma at 100 W for 4 minutes at 0.9 mBar to remove any organic contamination and to promote ink adhesion.

Next, a silver nanoparticle (Ag NP) back gate was printed onto the substrate using a commercial silver nanoparticle ink consisting of silver NPs (20 wt %) dissolved in xylene (procured from UT Dots Inc.). Prior to printing, the ink was mixed with terpineol at a ratio of 9:1 to prevent ink overspray. The back gate was printed using a 20 and 15 sccm sheath and atomizer flow, respectively. The ultrasonic current used to excite the ink into an aerosol was held at 420 mA and the speed of the print head was set at 3 mm/s. To form a continuous and conductive film, the back gate was sintered in an oven at 200 °C for one hour.

Following the Ag back gate printing, a commercial polymer-based dielectric xdi-dcs (procured from Xerox) consisting of PVP and a pMSSQ additive was printed using the same aerosol jet printer. The sheath and atomizer flow were kept at 20 and 35 sccm, respectively, with an ultrasonic atomizer current of 480 mA. The speed of the printing was found to be optimum at 6 mm/s. After printing, the polymer dielectric was cured on a hotplate at 80 °C for 30 minutes and then 140 °C for 1 hour.

Next, the semiconducting channel was printed using a semiconducting, single-walled CNT ink (sCNTs, S100 CNT ink procured from NanoIntegris). The CNTs are dispersed in toluene using a proprietary polymer. The concentration of the CNTs within the toluene was diluted to 0.01 mg/ml. The printing parameters used were a sheath flow of 40 sccm, an atomizer flow of 23 sccm, and an ultrasonic atomization current of 470 mA. The speed of the print head was set at 1 mm/s with two layers being printed. After printing, the CNTs were rinsed with toluene to remove excess polymer used in the CNT sorting process and placed in an oven at 150 °C to drive off excess solvent.

Finally, source and drain contacts were printed to complete the bottom-gated, top-contacted transistor using the same ink and printing parameters for the printed Ag back gate. The final product was a fully printed transistor with a dielectric thickness of approximately 1 μm and a channel length and width of 150 and 500 μm, respectively. Various images of the device are shown in Fig. 1. All the printing parameters described were optimized in our previous work [19], [16].

The electrical characterization of the device was carried out using a B1500A semiconductor device analyzer from Agilent Technologies. Electrical measurements were performed in a pressurized environment using a custom-built pressure chamber, designed by Ability Engineering, with shielded triaxial electrical inputs to allow for low-noise electronic

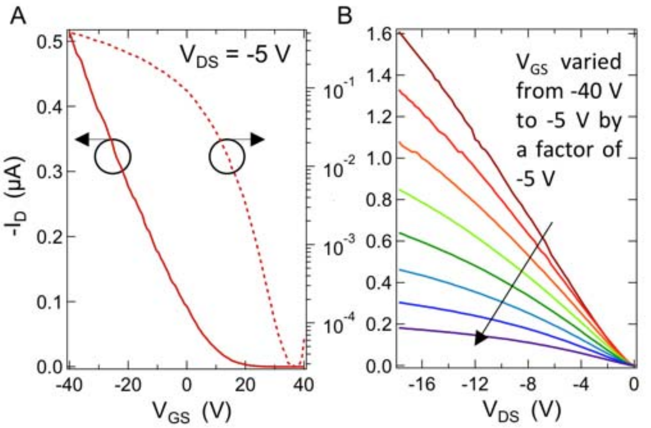

Fig. 2. Transistor characteristics of the fully-printed CNT-TFT pressure sensor under ambient conditions. The transfer and subthreshold curves are shown in (A) and the output curves are shown in (B). For the transfer and subthreshold curves, the drain to source voltage (V_{DS}) was held at −5 V. For the output curves, the gate to source voltage (V_{GS}) was modulated from −40 V to −5 V by a factor of −5 V. The device had a a channel length and width of 150 and 500 μm, respectively.

measurements. The pressure of the system was modulated using nitrogen gas and monitored using a digital pressure gauge.

III. Results and Discussion

A CNT-TFT supported on a glass substrate was first electrically characterized in air (ambient pressure and temperature). The device exhibited a notable on-off ratio of 10^4 and an on-current of 1 μA/mm at a gate-source voltage $V_{GS} = -40$ V and drain-source voltage $V_{DS} = -5$ V. The transistor characteristics, including the transfer, subthreshold, and output plots can be seen in Fig. 2.

Following the primary electrical characterization, the transistor was placed in a custom-built pressure chamber. I_D-V_{GS} sweeps were performed at various pressures to experimentally measure the electrical modulations due to changes in environmental pressure. Once the sensor was placed in the chamber, the pressure was ramped up to 42 PSIg by directly pumping N_2 gas into the chamber. A maximum pressure of 42 PSIg was chosen for these experiments in order to both maintain safe operation with the given custom chamber and to demonstrate the sensor's relevance to automobile tires, which typically operate around this pressure range. After a 3-minute stabilization time, 5 serial electrical measurements were then averaged to take into consideration sweep-to-sweep variation. Next, gas was released from the chamber to reduce the barometric pressure by 3 PSI, to 39 PSIg, and 5 more serial electrical measurements were taken. This process was repeated until the pressure in the chamber had reached equilibrium with atmospheric pressure (14.7 PSIa or 0 PSIg).

Characteristic transfer curves for each of the experimentally measured pressures are shown in Fig. 3a. The first notable shift was a significant change in the on-current (current at a $V_{GS} = -40$ V and $V_{DS} = -5$ V) in the device. Normalized on-current vs. pressure can be seen in Fig. 3b. The trend occurs as an exponential drift upward as the pressure increases.

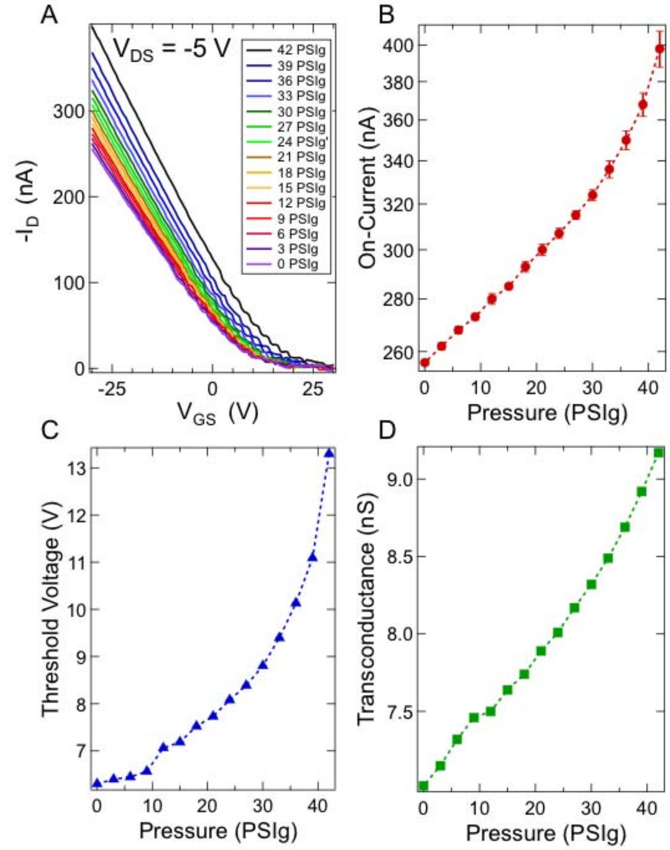

Fig. 3. Modulation of electrical parameters of the CNT-TFT corresponding with environmental pressure change. (A) Characteristic transfer curves for each PSIg measured at a drain to source voltage (V_{DS}) of −5V. (B) On-current, (C) threshold voltage, and (D) transconductance with respect to the environmental pressure.

Additionally, the on-current was found to be extremely stable, with the 5 serial measurements exhibiting an average standard deviation of 1.41 nA (or 0.4 %) for all applied pressures.

To ascertain which electrical performance metric was exhibiting the greatest and most consistent sensitivity to pressure changes, the threshold voltage and transconductance were extracted from the characteristic transfer curves at each pressure value. These metrics are plotted with respect to pressure in Fig. 3c and 3d. Both proved to be positively correlated with the environmental pressure, with transconductance yielding the most linear dependence. The threshold voltage had an increasing exponential trend, which is primarily attributed to the repeated tests. For some printed TFTs, the equilibrium threshold voltage will drift towards 0 V as the device is continuously swept. By sweeping the device, mobile and trapped charges are being redistributed throughout the dielectric layer and interface, and over time this will bring the equilibrium threshold voltage closer to 0 V. Hence, this parameter change may be less induced by pressure, and more so induced by repeated I-V measurements. Therefore, the transconductance is found to be a more reliable choice to use when extracting pressure data.

The transconductance shift occurred linearly with the pressure change at a slope of 48.1 pS/PSIg and an R^2 value of 0.98

from 0 to 42 PSIg—a pressure range similar to that of an automobile tire. The sensing mechanism is postulated to be that larger environmental pressures exert a downward force on the sensor, reducing the CNT-to-CNT junction resistances within the thin-film channel, as well as the contact resistance. This would account for a lower channel resistance and therefore a higher transconductance. Another contributing factor is likely that the pressure is modulating the thickness/defects within the printed dielectric, causing greater electrostatic control, and thus greater transconductance at higher pressures. Overall, this linearity over a large sensing range extends the applicability of this sensor to many desirable applications.

Additionally, the sensor maintained a similar shift in transconductance as the pressure was increased from 0 to 42 PSIg. The operation maintained its linearity, and the transconductance increased at a rate of 10.2 pS/PSIg with an R^2 value of 0.82. While there is a significant reduction in sensitivity as the pressure is modulated in the reverse direction, the fact that the direction of the transconductance change is similar is beneficial, and it remains possible that the hysteretic effects could be reduced in future embodiments by reducing charge traps in the dielectric and using double-sided contact interfaces.

To better illustrate the printed pressure sensor's application as a low-cost sensing platform for IoT purposes, a flexible sensor was printed on a polyimide (Kapton) substrate using the exact printing parameters described above and integrated with a low-cost measurement and communication module. The sensor was designed to interface with an Arduino microcontroller and a Bluetooth communication chip to transmit the conductance of the carbon nanotube channel from the inside of the pressure chamber to a mobile phone, as shown in the inset of Fig. 4a. The circuit implemented to measure the change in conductance was a simple voltage divider where the transistor was placed in series with a 1 MΩ resistor and the voltage across the resistor was measured. Due to the simplicity of the measurement circuit, the measured parameter is conductance as opposed to the more complex transconductance. Measuring transconductance would require modulating the gate voltage, which is not conducive to continuous tests, though could be implemented for taking measurements every few seconds rather than continuously. N_2 was pumped into the chamber to bring the total pressure to 42 PSIg. The Arduino system transmitted the measured voltage (average of 10,000 consecutive voltage measurements) every 30 seconds, and after 3 minutes, gas was vented from the chamber to bring the pressure down by 3 PSIg. The relationship between the conductance (after 150 seconds of equilibration) and the chamber pressure is shown in Fig. 4a, along with a picture of the custom built pressure chamber and a schematic of the device (insets).

For a complete smart tire system, the pressure sensor could also be integrated with a fully printed material thickness sensor, which is shown in Fig. 4b and was developed and optimized in previous work [13]. The sensor consists of two millimeter-sized printed conducting electrodes that form a capacitive-based sensor. An oscillating voltage is applied to the sensor and the signal reflectance changes based on the overlaid

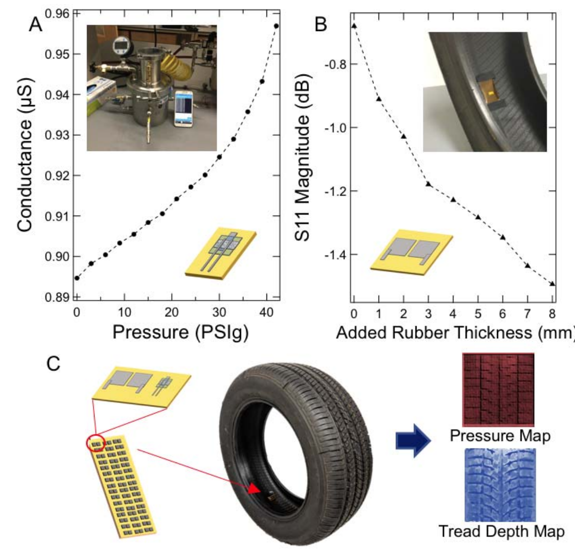

Fig. 4. Low-cost, printed automobile tire sensor demonstration. (A) A fully printed, flexile Kapton substrate sensor's conductance vs environmental pressure measured by an Arduino module and transmitted to a mobile phone with a photograph of the chamber and a schematic of the sensor as the insets. (B) The operation of a fully printed, material thickness sensor at 487 MHz with a photograph showing placement within a tire and a schematic of the sensor as insets. (C) A cartoon schematic with hypothetical implementation of a fully printed and fully integrated tire monitoring system that would allow for pressure and tread depth mapping.

material thickness. The plot demonstrates the signal reflectance change when 1 mm thick plies of rubber are added on top of a 1 cm thick piece of automobile tire. This system is unique in that both sensors (material thickness and pressure) can be fabricated using the same printer and electronic materials.

To demonstrate the hypothetical potential of these integrated sensors, Fig. 4c illustrates how a high-resolution pressure and tread depth map of an entire tire area would be possible. Due to the low-cost nature of printed electronics, a large-area map consisting of both the illustrated material thickness and pressure sensors is feasible and would provide invaluable data about how both tire wear and pressure differentials affect a tire's performance over time. Additionally, the compatibility of both sensors with flexible substrates would allow for a single sheet to be flexed within the inner wall of the tire while still maintaining functional operation. This unique application takes advantage of the low-cost and high-throughput manufacturing capabilities of printed electronics and provides a distinct example of a real-world use for printed sensors.

Another aspect that is important to pressure sensors is the stabilization time of the sensor. The Arduino measurement system was used to output conductance measurements of the CNT-TFT every 30 seconds, while the pressure of the chamber was modulated. The conductance vs. time, with the environmental pressures overlaid, is shown in Fig. 5. There is an obvious and marked shift in just the 1^{st} measurement after a change in pressure, which is taken 30 seconds after a discrete change in pressure. It is also notable that the sensor conductance steadies, with minimal variation, until the next change in pressure after the first 2 measurements. This indicates that the change occurs in a time as short or shorter

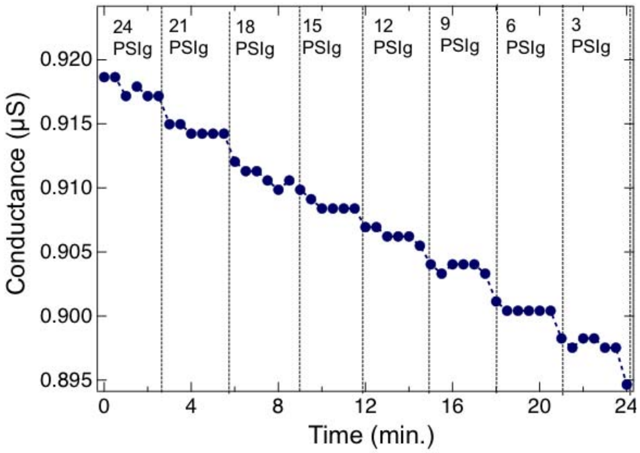

Fig. 5. Conductance changes over time of a printed CNT-TFT pressure sensor. The pressure of the chamber in which the sensor sits is overlaid and ranges from 24 PSIg to 0 PSIg. All values were measured using a voltage divider circuit and an Arduino microcontroller, the values were communicated outside of the chamber using a Bluetooth module.

than 30 seconds and stabilizes within 60-90 seconds. It also speaks to the repeatability of the conductance measurement, which is steady and repeatable over a short time span.

IV. Conclusion

We have demonstrated the operation of a fully printed CNT-TFT-based pressure sensor. The electrical properties of the transistor were measured from within a custom-built pressure chamber. The pressure sensor exhibited a linear change in transconductance over a pressure range that directly corresponds with common tire pressure values. It was shown that the sensor could be integrated with a complimentary material thickness sensor, used to monitor tire tread wear, for a fully integrated smart tire system. Furthermore, we demonstrated the IoT capabilities of these printed sensors and their use in smart tire applications using simple circuitry and Bluetooth communication. The conductance was shown to be directly correlated to the pressure and was communicated wirelessly from the inside of the pressure chamber using a simple Bluetooth module. Overall, this work identifies and evaluates a specific sensing application for fully-printed and flexible CNT-TFTs and presents a unique low-cost method for pressure sensing on non-conformal surfaces.

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Dr. Franklin was the Technical Program Chair for the 2017 75th Device Research Conference and the Subcommittee Chair for Nano Device Technology of the IEEE International Electron Devices Meeting in 2017. Over the years, he has served on organizing committees of symposia for various meetings of the Materials Research Society, the Applied Physics Society, the American Chemical Society, and the IEEE.