

A Low-Cost Planar Inkjet-Printed Carbon Nanotube Field Effect Transistor for Sensor Applications

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Abstract—The semiconductor based transistor is the most essential building block of electronic components, computing applications, and sensors. However, the fabrication of this primary electronic element is complex and costly, especially when considering flexible electronics for bio-sensing applications. This paper proposes a planar inkjet-printed carbon nanotube field effect transistor (CNTFET) on paper and polyethylene terephthalate (PET) substrate to reduce the complexity of the system and lower the cost of conventional fabrication schemes. Single walled carbon nanotubes (SWNTs) are being used as semi-conductive ink for an inkjet-printer to facilitate and fabricate two types of transistors. Both thin (0.3 mm gate separation) and thick (0.5 mm gate separation) transistors with wide (4 mm) and narrow (2 mm) channel length have shown nearly linear characteristics of resistivity for a range of applied gate voltages. Our mathematical model based on experimental results shows great usefulness of the proposed inkjet-printed CNTFET for various electronic applications including but not limited to bio-sensors, healthcare measurements, and circuits.

Index Terms—CNTFET, inkjet-printer, paper substrate, PET film, sensor

I. INTRODUCTION

Flexible electronics on paper and plastic bring significant advantages to the products which require shapeability, lightweight, slenderness, and toughness while facilitating low costs and ease of manufacturability. The flexible circuits and systems offer a variety of promising applications including biosensors, biomedical devices, healthcare, photovoltaics, radio-frequency identification (RFID), micro-electromechanical systems (MEMS), digital signature, consumer electronics, automotive, etc. However, fabrication in a cost-effective way and in a laboratory setting at room temperature is an enormous challenge. Conventional clean-room setup for sensor fabrication is too expensive and requires trained personnel to operate. Traditional photolithography and spin coating process results in expensive material loss [1].

The applications of inkjet-printed electronics is a promising research area because of the outstanding features of this technology. Commercial printing cost a lot considering materials and production scale. Electronic wastage is a major concern for our environment due to the rapid development of this industry. The total amount of electronic waste produced each year is hampering our daily livings through environmental degradation [3]. To print flexible electronics, paper is an ideal substrate since it is biodegradable, eco-friendly, contamination

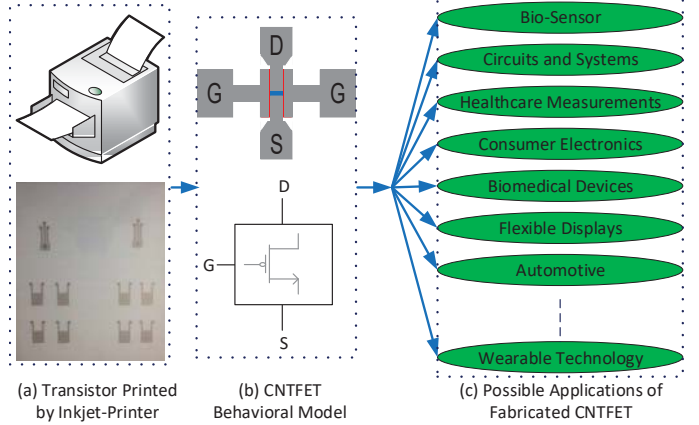


Fig. 1. CNTFETs fabrication and generic applications, (a) fabrication by inkjet-printer, (b) architecture of CNTFET on paper and within a black-box, (c) system level applications.

free, widely available, cheap substrate, fully established in the printing industry, and lightweight [3][4]. However, it is challenging because its surface is rough and porous, has poor chemical and mechanical barrier properties, dissolves materials, and contains impure chemical compounds [5][11]. Fortunately, this rough and porous paper is useful for some applications when coated with a protective barrier that reduces the porous nature. Both active and passive electronic components such as transistor, light-emitting diode (LED), solar cell, energy storage and memory device, sensor, actuator, detector, capacitor, inductor, and resistor are being studied, fabricated, and reported [5][8][10] as paper electronics.

Unlike conventional fabrication schemes, the inkjet-printing shows a great promise for targeted film deposition and high-scale production. Since the efficiency of material utilization is approximately 100%, it is perfectly suited for expensive nanomaterials used in fabrication. Through inkjet-printing, a sensor can be fabricated on thin flexible substrate which offers low-cost and disposable (i.e. green technology) products. In addition, carbon nanotubes (CNTs) are being used in the research area due to their superior conductivity, thermal adjustment, chemical functionality, and strong mechanical strength [6]. CNTs have potentials to directly apply onto flexible substrates to easily get electronic circuit patterns [7].

In this paper, a cost-effective way of CNTFET fabrication

using our office inkjet-printer is proposed. Two types of FETs are fabricated and tested to show their effectiveness in using circuits and systems. Our fabricated FETs can be used both in-house and external environment, depending on the applications and requirements. Even though, more research is required to adjust these newly printed CNTFETs with existing systems and commercial fabrication in large scale. Fig. 1 shows a generic target of our fabricated transistors, (a) fabrication through inkjet-printer, (b) planar architecture printed on paper and transistor within a black-box, and (c) target applications of printed CNTFETs. In Section II, the inkjet-printing process is described. Section III discusses the proposed design, materials choice, and fabrication. Section IV includes the experiments and test results. The mathematical model using MATLAB curve fitting is shown in Section V. Finally, we conclude this paper in Section VI.

II. INKJET-PRINTING PROCESS

The inkjet-printing process is a technique of reproducing digital images by dropping beads of ink onto paper, plastic or different substrate by the use of the printer's piezoelectric function. Usually, a printer driver translates information into readable data and sends the data to the printer, where voltages induce ink dispersion onto the substrate. Spooling temporarily saves data for later use and then stepper motor loads paper from feed tray into the printer with precise increments and ensures the accuracy of ink deposition through the print head using a thermal bubble. Tiny resistors heat up around 500°F due to current flow, which causes ink to form a bubble. The bubble expands enormously and bursts, causing ink to be pushed out of the nozzle. Thus, a vacuum is created that pulls in more ink from the cartridge. Little electrical charges cause piezo crystals to vibrate. The internal vibrational development drives ink out of the nozzle, while the outward development pulls ink from the cartridge.

Changing software settings and choosing nanoparticle inks allows an inkjet-printer to be used for printing circuits and electronic components on paper, plastic or other substrates. This fundamental inkjet-printing process and required inks (nanomaterials) to print flexible electronics are widely described in [2][5]. The inks are in the liquid state consisting of a solute dissolved or otherwise dispersed in a solvent. After printing, a curing process is required, where the solvent evaporates and leaves behind the solute. This improves circuit quality. For accurate narrow injection, it is also important to coordinate between the surface strain of the ink and the surface energy of the substrate in addition to tuning the printing parameters such as drop separating, printing rate, and temperature [5].

III. CNTFET DESIGN AND FABRICATION

Inkjet-printed CNTFETs are printed by layers of conductive materials onto a substrate to attain the same functionality as standard FETs. For this design, three major electrical behaviors are considered to choose materials which are dielectric, semiconductor and conductor. The dielectrics are widely

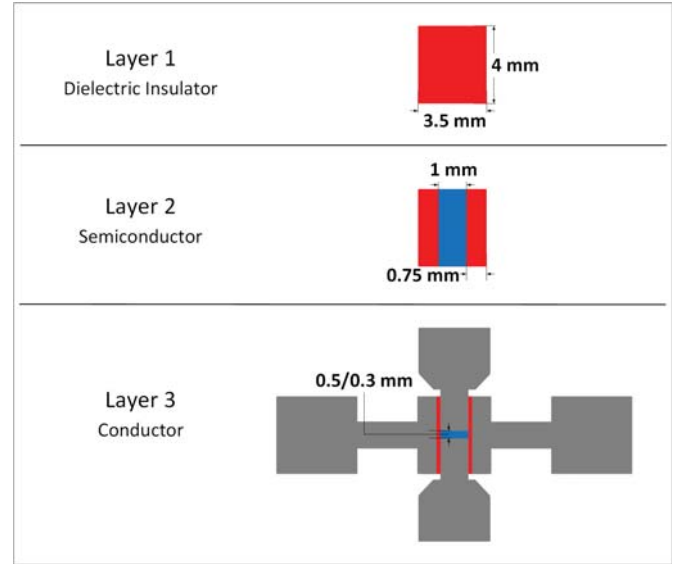


Fig. 2. Paper/PET film based CNTFET design and printing process in layers with respective dimensions.

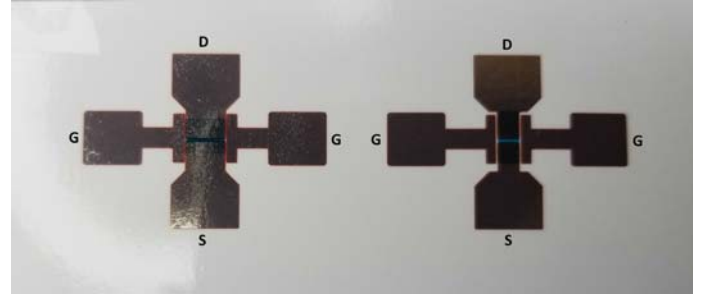


Fig. 3. CNTFETs fabricated on PET film substrate, (a) thick (0.5 mm gap) and (b) thin (0.3 mm gap). Where D = drain, S = source, and G = gate.

used as electric insulators which have the opposite effect of conductors, ideally zero electric charge flow. In this design, paper and PET film substrate are the dielectrics. Those are very poor conductors and will prevent unwanted shorting between routes. Carbon nanotube nanoparticle ink is chosen as the semiconductor due to its outstanding high thermal and electrical conductivity. SWNTs are strong, flexible, have large band gaps and exceptionally high electron mobility. CNTs made from graphene which is transparent, light, non-toxic, flexible, and equivalent to the thickness of an atom. This makes it an ideal semiconductor for flexible sensor applications. Silver (Ag) is selected as the conductor for this design because it has the highest conductance among all metals. It also has a low resistivity and is available as nanoparticle ink for printing. Even though Ag has a higher chance of corrosion than copper or gold and expensive than copper but still is the best choice for perfect routing.

EasyPC CAD tool is being used for layout design. Then three steps fabrication process are followed which is shown in Fig. 2. Layer one and two shows the dimension of dielectric and semiconductor respectively. Gate separation is shown in

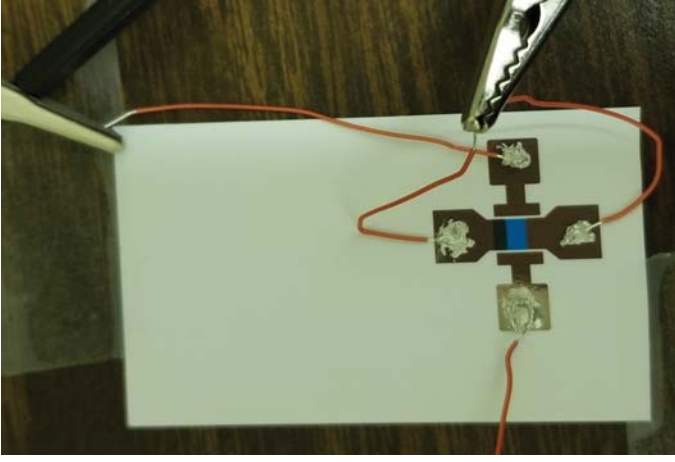


Fig. 4. Fabricated CNTFET on paper substrate in testing using a single channel source meter.

layer three. For this design, 0.3 mm and 0.5 mm gate separation are considered. At first for layer one, the paper or PET film is provided to the printer. The output was then fed back to the printer with proper orientation and perfect alignment for layer two. Finally, repeating the same process maintaining correct positioning for layer three. The simplicity of planar design makes it a highly unique device. The CNT channel will be affected by the applied electric fields at the gate terminals. CNTs are naturally p-type which means it's lattice is positively charged and electrons are the minority carrier. Both wide and narrow channel CNTFETs are fabricated on paper and PET film substrate. Fig. 3 shows wide and narrow CNTFETs on PET film substrate.

IV. CNTFET TESTING

The silver epoxy was used for contact points on top of the fabricated transistor due to its high quality electrical and mechanical contacts. The silver epoxy paste is commonly used in bonding semiconductors and other microelectronic circuit devices. The reasons for choosing silver epoxy paste are excellent screening characteristics, high bond strength, low contact resistance, very low thermal stress, low thermal impedance, and support of a wide variety of temperatures (-65°C to 250°C).

Characterizing transistor I-V properties is the most crucial part to understand their electrical behavior for the target applications. Primary I-V tests could include drain current, on resistance, transfer characteristics, gate leakage, breakdown voltage, and threshold voltage. For our proposed work, drain current and on resistance were tested and measured using a Keithley 2635A (single channel) System Source Meter and a power supply. Traditional FET testing requires a combination of several instruments including a high precision ammeter, voltmeter, and voltage sources. However, it is time-consuming to program and integrate multiple instruments together and then manually record results. Keithley System Measurement Unit (SMU) has a current resolution up to 0.1 fA and also

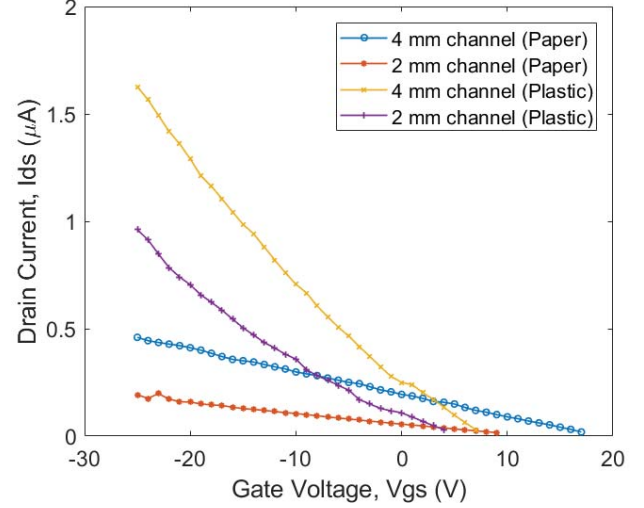


Fig. 5. I_{ds} vs V_{gs} characteristics curve of Paper and PET film CNTFETs.

limits the current flow to protect the device from getting damaged. Recording result of tests is easy through an embedded software interface, TSP Express, where the data is output to either laptop or mobile device. Results can be exported in either graph or excel file. Fig. 4 shows the test setup of a CNTFET on paper substrate.

Fig. 5 shows the plots of experimental data for paper based and PET film based CNTFETs. From the figure, it can be observed that the larger channel length CNTFETs allows more current than the smaller channel length CNTFETs up to a certain gate voltage. For both cases, PET film based CNTFETs are providing three to four times more current than paper based CNTFETs from -25V to $+4\text{V}$. For gate voltage more than $+4\text{V}$ the amount of current through PET film based CNTFETs is lower than the amount of current through paper based CNTFETs. Also, the amount of current through the channel can be controlled from applied gate voltage for various types of applications. PET film based transistors provide better performance compared to paper based transistors because the paper surface is rough and porous. It can be improved by controlling the channel length and width of the fabricated CNTFETs.

V. CURVE FITTING MODELING

A mathematical curve fitting approach is used to extract the I_d - V_{gs} characteristics (shown in Fig. 5) of the printed CNTFETs one-by-one. Fig. 6 shows the experimental data and corresponding fitting model plots for paper wide, paper narrow, PET film wide, and PET film narrow CNTFETs, respectively. The MATLAB curve fitting tool was utilized to fit and optimize the model parameters. The corresponding mathematical representation is shown in equation (1), where a , b , and c are constant coefficients.

$$I_{ds} = a * V_{gs}^2 + b * V_{gs} + c \quad (1)$$

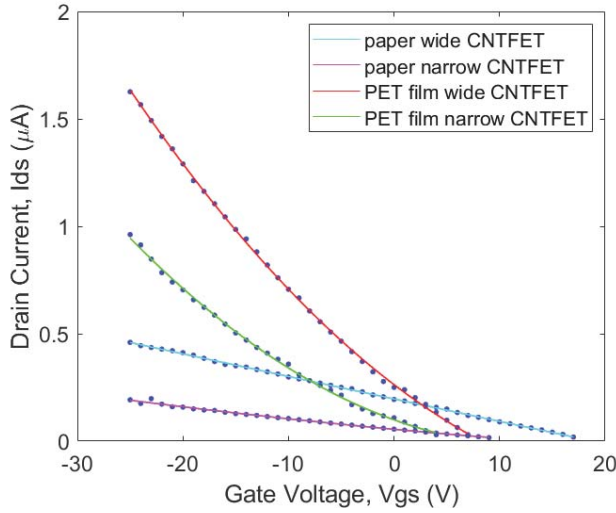


Fig. 6. Curve fitting model for Paper and PET film CNTFET with wide (4 mm) and narrow (2 mm) channel.

The constants are slightly different from each other for all the CNTFETs under test, which is shown in the following regression equations along with their ranges (low to high) of values for all of the constants.

Paper based transistor with wide (4 mm) channel has the following coefficients (with 95% confidence bounds):

$$a = 2.243 * 10^{-12} (-4.027 * 10^{-12}, 8.514 * 10^{-12})$$

$$b = -1.045 * 10^{-08} (-1.054 * 10^{-08}, -1.037 * 10^{-08})$$

$$c = 1.964 * 10^{-07} (1.951 * 10^{-07}, 1.976 * 10^{-07})$$

Paper based transistor with narrow (2 mm) channel has the following coefficients (with 95% confidence bounds):

$$a = 3.568 * 10^{-11} (1.974 * 10^{-11}, 5.162 * 10^{-11})$$

$$b = -4.519 * 10^{-09} (-4.812 * 10^{-09}, -4.227 * 10^{-09})$$

$$c = 5.523 * 10^{-08} (5.328 * 10^{-08}, 5.718 * 10^{-08})$$

PET film based transistor with wide (4 mm) channel has the following coefficients (with 95% confidence bounds):

$$a = 6.951 * 10^{-10} (6.519 * 10^{-10}, 7.384 * 10^{-10})$$

$$b = -3.748 * 10^{-08} (-3.834 * 10^{-08}, -3.662 * 10^{-08})$$

$$c = 2.63 * 10^{-07} (2.581 * 10^{-07}, 2.678 * 10^{-07})$$

PET film based transistor with narrow (2 mm) channel has the following coefficients (with 95% confidence bounds):

$$a = 6.442 * 10^{-10} (5.914 * 10^{-10}, 6.971 * 10^{-10})$$

$$b = -1.77 * 10^{-08} (-1.888 * 10^{-08}, -1.652 * 10^{-08})$$

$$c = 9.932 * 10^{-08} (9.346 * 10^{-08}, 1.052 * 10^{-07})$$

Both first and second order polynomial model is applied to fit the experimental data. The second order polynomial equation shows a better model for all the transistor data because

it fits more with experimental data. Paper wide transistor may seem to be a linear model while all other transistors show a better fitting with a polynomial equation. Overall, it is clear that the graphs have a more second order polynomial trend and the error is minimum with respect to test data points.

VI. CONCLUSION

This paper proposes a flexible electronics fabrication scheme using planar inkjet-printer. Compared to existing technology, inkjet-printer provides an easy process and costs less than a dollar to fabricate a circuit or system on paper or plastic substrate. Intensive testing will be performed for characterization of printed transistors to implement in real-time applications. In this paper, two types of fabricated CNTFETs with wide (4 mm) and narrow channel (2 mm) on both paper and PET film are presented with experimental results. A polynomial fitting model is used to develop mathematical modeling for the transistors. Results from both experimental outputs and mathematical analysis validate the effectiveness of the proposed scheme to develop prototype FETs using inkjet-printer and nanoparticle materials, in particular, CNTs.

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