A Carbon Nanotube Inkjet-Printed Hybrid Circuit for Non-Conventional Computing

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Abstract—**Inkjet-printed technology offers a cost-efficient, low-energy, minimal footprint, and adaptable form of alternative computing. Inkjet-printed sensors and circuits use minimal waste, are often biodegradable and can be revised and/or reprinted in an additive manner. This report introduces a transistor-inspired inkjet-printed element with simulated CMOS hybridization as an early form of a more dynamical and non-linear computing element. Although the presented device has low functionality, the research efforts result in a step toward hybridized electronics that may be used for non-Von Neumann computing. The inkjet printed element was made by layering silver and carbon nanotube nanoparticles on paper and polyethylene terephthalate substrates in a way that mimicks the structure of a transistor. A mathematical modeling of the carbon nanotube element was made in MATLAB, then used in PSpice for analog behavioral modeling. The output was validated and used to design a hybridized linear dynamical circuit. Experimental data and simulation results show these early designs have usefulness in circuits and systems fabrication.**

Keywords—**microfabrication, flexible electronics, CNT, inkjet printer, linear dynamical circuit, paper-based, additive manufacturing**

I. Introduction

Inkjet-printed (iJP) paper-based electronics are a low-cost, minimal-process, eco-friendly alternative to printed circuit board (PCB) based circuits that may be implemented as a micro-fabrication unit in space, along with similar units like the 3D printer. This enables a method of localized additive manufacturing and creation of irregular-surface/hybridized electronics [1], [2]. According to the electronics industry road-map, the research of this field is rapidly moving towards integrating inkjet-printed and CMOS-process technology into reliable and hybridized nano-electronics, further supporting the efforts of this report [3], [4]. All outputs of this work strongly supports this next-generation technology.

The primary area of investigation in this report regards research and development of flexible, low cost, biodegradable inkjet-printed sensors for environmental variable detection and human-interaction feedback. A secondary goal was to research and develop inkjet-printed non-linear devices, since they are an integral mechanism to active circuitry, including filters, op-amps, logic units, and may be used as sensors or input to hardware-based machine learning designs. Inkjet-printed circuits are made by printing layers of nanoparticle inks with desired electrical properties onto polymer or semipermeable paper substrates. The result is a plethora of sensing applications that vary according to material choice and circuit structure. This method is especially beneficial for low-process and small-footprint circuit manufacturing, such that it may be used as a micro-fabrication unit in space. The minimal approach and streamlined process of inkjet printed sensors fabrication makes the design and testing feedback process fast. Inkjet printed circuits are also inexpensive to fabricate. The only equipment needed for non-hybrid iJPC technology is the inkjet printer, substrate, design file, and ink cartridges containing the appropriate nanoparticles. There is effectively zero waste byproduct and emission during iJPC technology, since the materials used are largely biodegradable [5].

Conversely, there are shortfalls of inkjet-printed circuits that harm them from being largely commercialized. The print quality of drop-on-demand printers is variable between samples due to ink viscosity, material interaction and uneven curing [1], [6], [7]. Layering is an issue since there is no complete uniformity from printing. The gate bleeds through the insulating layer, shorting with the semiconductor. Another limitation is with the variety of commercially available nano-particle inks. The semiconductor's properties, barring some forms of graphene, are depletion-mode materials (p-type) and thus cannot achieve complimentary pairs for logic gates or higher forms of computation like arithmetic logic units [8], [9]. Some n-type materials are being researched but have not reached the market. Additionally, paper substrates are sensitive to environmental conditions such as oxygen, humidity and temperature. These limitations make reliability and repeatability a challenge.

In this paper, a linear dynamical circuit design with simulation is presented for the inkjet-printed CNT element shown in Figure 1. A previous work conducted for this element was completed and characterized in [10], [11]. In Section II, the CNT element design, fabrication, testing and mathematical modeling are described. Section III discusses the analog behavioral modeling (ABM) development in PSpice with validation based on mathematical modeling. Section IV includes the linear dynamical circuit analysis using developed ABM and a small-signal modeling of the equivalent circuit. The signal analysis using MATLAB is shown in Section V. Finally, conclusion and future research are in Section VI.

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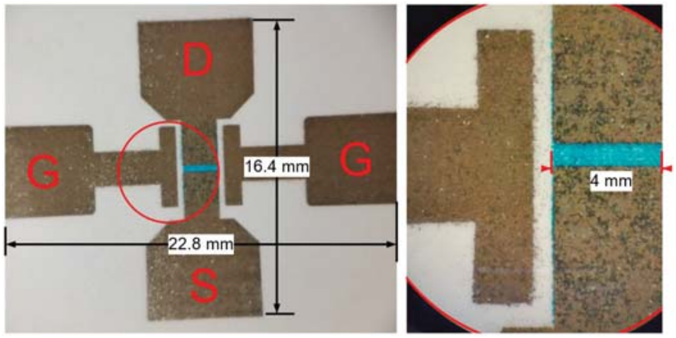

Fig. 1. Narrow-channel iJP CNT element characterized in [10], [11].

II. Inkjet Printed CNT element

The inkjet printed CNT element of Figure 1 was designed, printed, cured and tested in-house using a Brother MFC-J5910DW, an office-quality inkjet printer. A simple image editing software (Microsoft Paint) was used to design the element in two layers (silver and CNT) to be inkjet-printed on paper and polyethylene terephthalate (PET) substrates. Three types of materials were considered based on their electrical properties, fabrication simplicity and accessibility. In our design, the dielectric is paper and PET film substrate, the semiconductor is single walled carbon nanotube (SWCNT) and the conductor is silver (Ag). The carbon nanotube inkjet ink was purchased from Millipore Sigma while the silver nanoparticle ink was purchased from Mitzubishi Paper Mills Limited. At first, the paper or PET film substrate as an insulator was fed into the printer by which it printed the first layer (silver) pattern for signal routing. The paper was then fed back into the printer to print the semiconductor (SWCNT). Referring to Figure 1, we note the channel width as a variable of interest. Thus, two channel widths were considered: 4 mm for the wide channel (0.5 mm gate separation) and 2 mm for the narrow channel (0.3 mm gate separation). After printing, inks were cured with a hot-plate at 120°C for 10 minutes to anneal the ink. Silver epoxy was used for contact points to connect with leads. Further details of materials choice and the printing process are described in [11].

A. Testing and Modeling

After preparing the samples, the CNT-based elements were tested using a Keithley 2635A System Measurement Unit (SMU) to obtain its I-V characteristics. All the test results were collected for V_{DD} = 20 V and analyzed for further validation and implementation. The initial step was to develop a mathematical model, create analog behavioral model blocks in PSpice using a mathematical function and then use that block to complete the PSpice schematics. A mathematical model was developed using a MATLAB curve fitting tool for all the printed elements. Second-order polynomials were chosen because they provided more than 99% accuracy while not over-fitting data. The formula that represents all the iJP devices is a quadratic as seen in Fig. 2. Testing procedure details and mathematical modeling are explained more in depth from supporting work [11]. Coefficients of the PET film CNTFET are also shown in Figure 2.

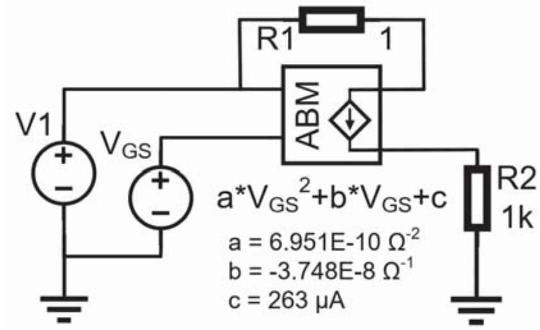

Fig. 2. Minimal implementation of PSpice schematic development with ABM block.

III. Analog Behavioral Modeling in PSpice

Behavioral modeling is the process of developing a model for new or existing devices which represent the same characteristics as the device's practical behavior. This modeling process is widely used in the analog domain. PSpice schematic was used to create an equivalent model of the experimental element. The ABM block with terminals was generated and is shown in Figure 2 as a black box, which represents the mathematical model defining the printed elements with different coefficients. The narrow channel iJP element on PET film was considered for ABM development as it had the highest performance in [11].

A PSpice schematic was developed based on the ABM to validate the mathematical modeling and ABM usability. This basic circuit schematic with ABM building block is shown in Figure 2. While CNTs have been shown to perform as n-type or p-type by doping, all the printed devices were p-type due to the nano-particle ink properties. Thus, the source terminal was connected with primary voltage supply (V_{DD}), the drain terminal was connected with the ground and gate voltages (V_{GS}) were applied at the gate terminal. V_{GS} was used as a dc sweep voltage. The PSpice simulation result is shown in Figure 3. The simulated I_{DS} versus V_{GS} curve matched the experimental result as seen from the image.

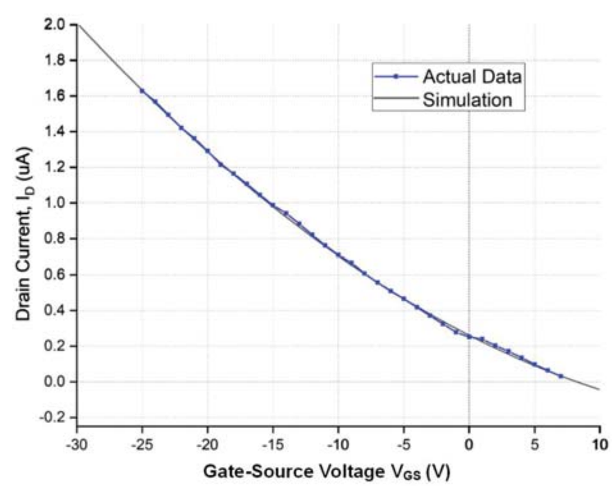

Fig. 3. The Id versus Vds curve of ABM PSpice simulation for PET film based CNTFET compared to experimental results.

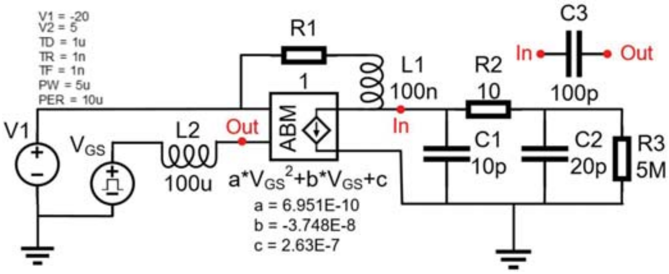

Fig. 4. Linear dynamical circuit using ABM (PET; CNT; narrow channel).

IV. IJP Element Linear Dynamics Using ABM

A simple RC circuit model was designed for the simulation work using the narrow channel iJP CNT. The printed element's ABM was used to build the circuit as shown in Figure 4. This image also shows testing frequency and voltages, where V2 refers to V_{GS}. Its characteristics were found to be quasi-linear because the printed iJP elements partially performed non-linearly. The nonlinear effect was so small that the overall effects could be negligible. Thus, the developed circuit shows linear dynamic behavior which could be useful for different applications requiring a flexible variable resistor.

Figure 5 shows the linear dynamic voltage signal across resistor R_2. The voltage signal looks periodic but there is a non-linear effect available in the signal which can be voltage-controlled. The output also shows a combination of multiple signals where each signal is continuous for a small amount of period before interference by the next signal. It goes on continuously during circuit operation. This is useful in analog mixing circuits for communication. Figure 6 represents the I-V curve across resistor R_2. Although this is not an ideal characteristic of linear dynamical circuits, the results were quasi-linear. The effect of its nonlinear coefficients was so small that the overall effects are negligible. Thus, the linear dynamical circuit shows linearity with a combination of multiple signals, which can still be useful based on the applications and variations of the signal by controlling signal parameters.

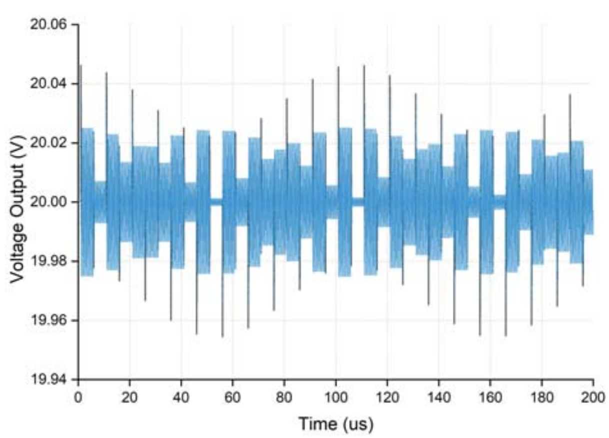

Fig. 5. Voltage response across resistor R_2 (V_{R2}) showing a linear but dynamical and periodic response.

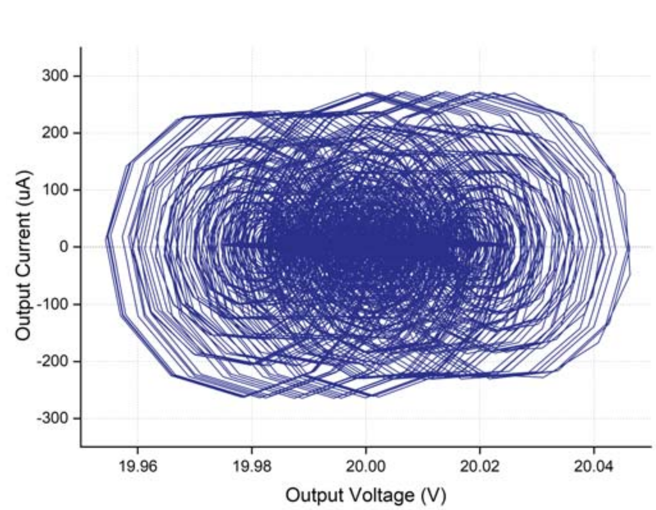

Fig. 6. Current vs. voltage across resistor R_2 of the linear dynamical circuit.

A. Small Signal Modeling of Linear Dynamical Circuit

Small-signal modeling is done to simplify and represent the linear dynamical circuit behavior in mathematical equations. Those equations have been formulated using a MATLAB program to analyze the circuit's behavior. An equivalent small-signal model designed to resemble "Chua's circuit", which shows chaotic behavior, is seen in Figure 7. Circuit solutions are represented by the equations (1) to (3) where Ids represents the iJP element model shown in the equation from Figure 2.

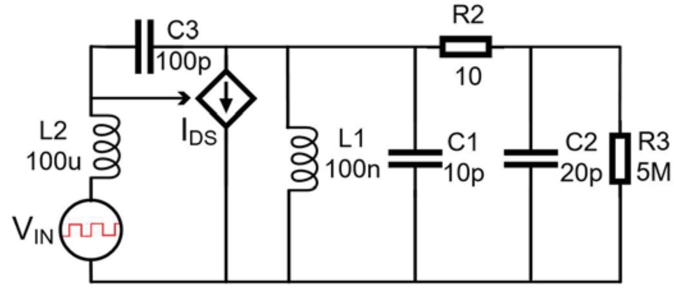

Fig. 7. Small signal model of linear dynamical circuit.

$$\frac{dV_1}{dt} = -\frac{V_1}{R_2C_1} + \frac{V_{GS}}{R_2C_1} + \frac{i_L}{C_1} - \frac{I_{ds}}{C_1} \tag{1}$$

$$\frac{dV_{GS}}{dt} = \frac{V_1}{R_2C_2} - \frac{V_{GS}}{C_2}\left(\frac{1}{R_2} + \frac{1}{R_3}\right) \tag{2}$$

$$\frac{di_L}{dt} = \frac{V_1}{L} \tag{3}$$

V. Signal Analysis in MATLAB

A MATLAB program was used to analyze the linear dynamical signal. Figure 8 shows the frequency spectrum of V_{R2}. Inkjet printed circuits typically operate in the low-frequency range (i.e. kHz range). Thus, the test spectrum

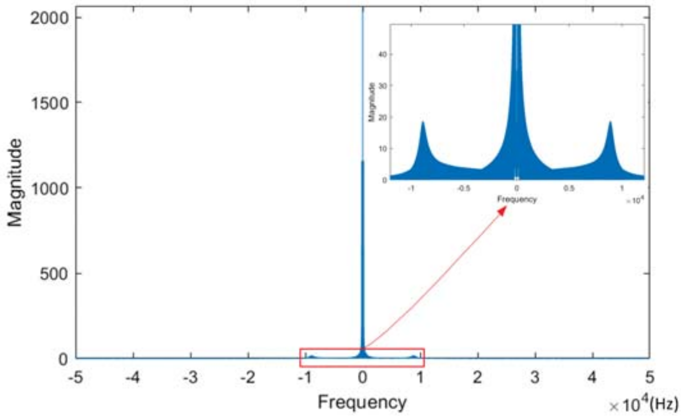

Fig. 8. Frequency spectrum of the linear dynamical signal (V_{R2}).

was under 5 kHz. The zoomed part shows signals are distributed for a wide range, explained by the combination of multiple signals. Figure 9 shows a scatter plot using the peak values of V_{R2}. It is clear from the scatter plot that the signals are distributed with a periodicity to be a linear signal with a combination of multiple signals. Figure 10 represents the histogram plot of V_{R2}. It indicates how multiple signals at low frequencies are mixed together in a linear dynamic fashion.

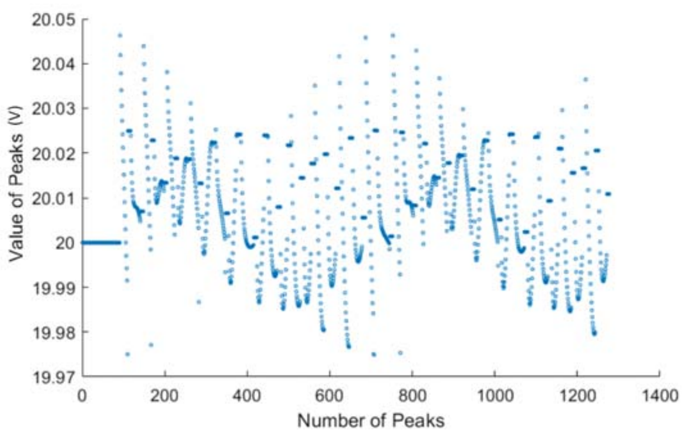

Fig. 9. Scatter plot of the linear dynamical signal using peaks of V_{R2}.

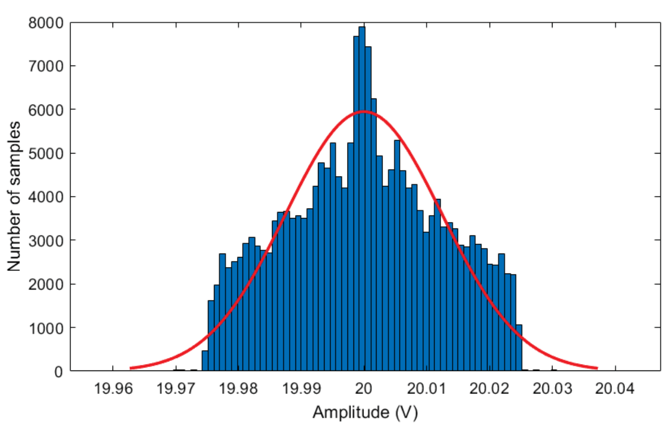

Fig. 10. Histogram plot of the linear dynamical signal (V_{R2}).

VI. Conclusion

The inkjet printing process using nano-particles is a promising emerging technology for micro-fabrication methods in hard-to-access locations. This paper proposes a inkjet-printed, linear dynamical, hybridized circuit design using a regression model of a novel inkjet-printed element that was characterized in previous studies. SWCNT ink was used due to its outstanding electrical and mechanical properties. Further research is required to realize a more non-linear and high-performing element for computing. Also, additional research is essential for improved ink chemistry and better defined electrical properties. Inkjet printed element's regression model was used to develop ABM in PSpice. Then the ABM was used to create a linear dynamical circuit to analyze the printed element's behavior. Experimental results, mathematical analysis and PSpice simulations of this work have demonstrated the usage of an office-quality inkjet printer to develop a circuit element on paper and plastic substrate, with expectations of a more non-linear element after further research.

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