Fabrication of Differential Amplifiers Using Inkjet Printing and Single Wall Carbon Nano Tubes (CNT)

R. Kamali-Sarvestani*, B. Wright* and K. Triyasakorn*

*Utah Valley University, CS 520-b, Orem, Utah 84058, reza.kamali@uvu.edu

ABSTRACT

In recent years, there were numerous advances for finding new materials in the field of nanotechnology. One of the material that was found applicable as semiconductor is carbon nanotubes (CNT). This paper will focus on the application of single walled carbon nanotubes (SWNT) in fabricating electrical components such as thin-film transistor and capacitor using inkjet printer of Dimatix DMP-2800. In this study CNT was used for fabrication of a differential amplifier in nine steps. Fabricated circuit was tested by adding biasing resistors. Device under test showed the best charactersitic between gate voltages of -5v to -25v.
Threshould voltage was -9 volts and transconductane (g_m) was linear in the working region. This type of differential amplifier is a good candidate for the application of sensors in flexible electronics.

Keywords: *single wall carbon nano tube (CNT), Differntial amplifier, inkject printing, printing electronics, flexible electronics*

1 INTRODUCTION

Flexible electronics is defined as any byproduct of electronic fabrication that can be bent, stretched, compressed, or undergo physical deformation without being damaged [1]. It has numerous applications from flexible touch screen displays to medical devices, biomedical engineering and military applications [2], [3]. Flexible electronics have experienced a high growth rate in the past few years and it is expected that there will be high global market growth from a few billion to hundreds of billions of dollars in the years to come [3].

With continuous advances in the field of nanotechnology and flexible electronics, there is a need to find flexible materials with flexibility to make active components. This paper will report on application of single-walled carbon nanotubes (SWCNT) and inkjet printing to fabricate thin-film transistors (TFT), one of the basic active components in flexible electronics, and a differential amplifier on a paper substrate by a drop-on-demand technique.

SWCNT can be described as a sheet of graphene rolled up into a tube [4]. Its fabrication process requires intense energy sources [5]. Currently, the five main methods used to produce carbon nanotubes are: ARC discharge, laser ablation, chemical vapor deposition (CVD), catalyst chemical vapor deposition (CCVD), and template-directed synthesis, in which ARC discharge, laser ablation and CVD are commonly used [6], [7]. Due to its tube-like structure made of carbon, CNT possesses high electron mobility, high flexibility, and high tensile strength [7], [8], making SWCNT one of the leading materials to be incorporated in future flexible electronics devices and their components, especially as a semiconductor in thin-film field effect transistors [5].

Inkjet printing is a non-contact method in which small droplets of conductive material such as silver nanoparticle ink or functional material are deposited onto the substrate. Inkjet printing is a purely additive process, avoiding production of unwanted material. Due to the lack of byproduct waste and the ability to print on organic substrates such as paper, inkjet printing is both cost efficient and environmentally friendly. The intrinsic qualities of inkjet-printed electronics have promising applications in the field of flexible devices and sensors.

Printing methods for creating flexible electronics have the benefit of low cost, reduced production time, and relatively simple methods of processing [9]. Drop on Demand (DoD) or inkjet fine image printing is environmentally safe technology and currently in use for fabrication of flexible electronics [10], [11]. Compared with the conventional printed circuit board (PCB) process, which uses a subtractive method of etching away metal foil, DoD printing deposits droplets of conductive ink only where desired, eliminating extra costs and waste, and requiring fewer steps than traditional PCB manufacturing techniques [12]. Inkjet printing does not require the use of binders or the creation of stencils employed by other printing methods, and ink can be deposited on low-cost substrates such as paper [9], [12]. Hence, inkjet printing is an environmentally friendly and cost-effective process well suited for flexible electronics.

2 DIFFERENTIAL AMPLIFIER

A differential amplifier amplifies the difference between two separate input voltages [13]. The input signal V_{id} is the difference between V_1 and V_2 [13]. One type of a differential amplifier is a basic MOS differential-pair differential amplifier, which uses a pair of MOSFETs to amplify the difference in voltage between the gate-source voltages (V_{GS}) of both of the transistors [13]. Differential amplifiers have the benefit of less sensitivity to noise and a lack of bypass and coupling capacitors found in discrete-circuit amplifiers [13]. Transconductance is the ratio of current with respect to voltage. The transconductance (g_m) of a MOS-based differential amplifier is calculated using equation 1 [13].

$$g_m = \frac{-V_{od}}{R_D||(R_L/2)V_{id} - R_S V_{od}} \quad (1)$$

In this project minimum feature size for metalic deposition is 20 micro meter. Because of having such a large channel, each transistors has a large drain to source current in the range of a few mili Amper. To avoid common mode effect of such a large drain to source current a diffrential amplifier is very useful. Figure 1 shows the circuit diagram of differential amplifier designed in this project.

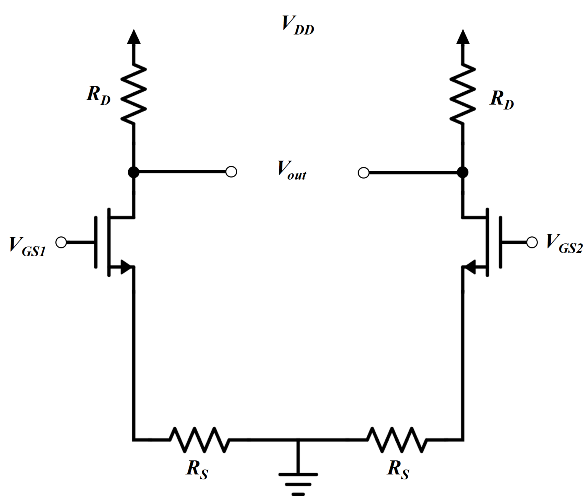

Figure 1. Schematic of a MOS-based differential amplifier.

3 FABRICATION

The differential amplifier was comprised of two TFTs, two 100 Ω resistors, and two 10 k Ω resistors. The TFTs were fabricated using a combination of inkjet printing with a Dimatix DMP-2800 and manually depositing material using a Gibson handheld pico-pipette onto a photo paper substrate (Epson Ultra Premium Photo Paper GLOSSY). The inkjet-printed patterns were created in Microsoft Paint as bitmap image files and imported into Dimatix Drop Manager to create printable patterns. Firstly, the gate was produced by printing a single layer of Mitsubishi Paper Mills silver-nanoparticle ink (model number NBSIJ-FD02) onto the paper substrate with a 10 µm drop spacing. A dielectric layer of graphene oxide water dispersion (Graphenea 0.4 wt% concentration) was then dropped by hand with the pico-pipette directly onto the gate with enough volume to completely cover the tip of the gate. After the graphene oxide was dry, the source and drain were printed with silver nanoparticle ink with a 10 µm drop spacing. The source and drain were printed in the shape of two adjacent T shapes with a separation of 230 µm on top of the graphene layer. The CNT (Sigma-Aldrich Lot# MK0D8389) was first diluted with distilled water at a ratio of 1:9 so that the CNT provided a sufficient resistance (~ 25 kOhm) for use in the TFTs. More concentrated CNT dilutions had a much lower resistance that was unsuitable for use in a transistor. The CNT was then deposited by hand via pico-pipette on top of the source and drain with sufficient volume to cover the gap between them.

The TFTs were incorporated into a differential amplifier circuit as seen in figure 1. The triangular gate pins on the transistors were printed on the same layer as the gate of the TFT with the DMP2800, and the rest of the circuit was printed on the same layer as the drain and source. Two 100 Ω source resistors (R_S) were attached with MG Chemical silver conductive epoxy glue (model #8330-19G) on either side of the ground, and two 10 kΩ drain resistors (R_D) were glued on the two branches attached to voltage source V_D. The epoxy glue was allowed to dry for at least 10 minutes. For some tests, physical wires were also glued to the triangular pins of the pattern to allow the printed circuit to be hooked up to a voltage source and tested. However, for other tests, the physical wires were simply placed on the triangular pins without glue. Figure 2 showes the required layers to fabricate each transistor.

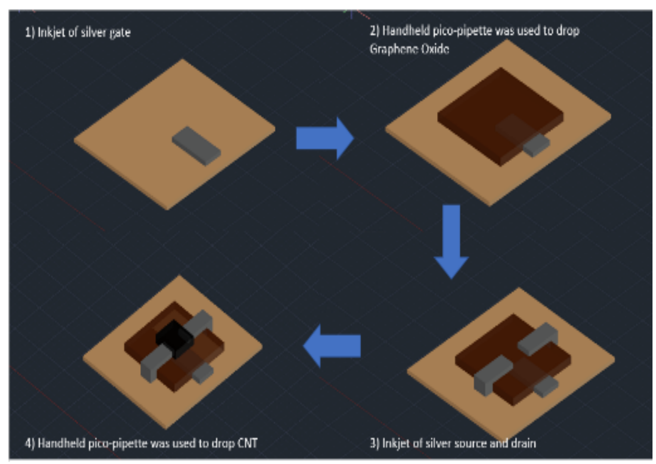

Figure 2. 3D illustration of CNT-TFT fabrication process.

Fabrication steps are as follow:

Procedure 1: Load the cartridge filled with silver nanoparticle ink into the Dimatix DMP-2800 printer and change the drop spacing to 10 µm. This drop spacing is essential to maintaining the quality of the print. When the drop spacing is too close, pooling of silver ink can result and the ink may smudge. If the drop spacing is too large, gaps in the printed pattern may be present and the print quality may be too inconsistent. At 10 µm, the result is uniform printing.

Procedure 2: Create the bitmap image files in Microsoft Paint for the three layers that will be printed: the print origin marker, the gates, and the source and drain and rest of the circuit. Import the .bmp files into the pattern editor of the

Dimatix Drop Manager software and save the image files as pattern files that the DMP-2800 can print.

Procedure 3: Load the paper substrate onto the platen of the printer. Turn on the vacuum and let the paper lay flat on the printing surface. Make sure that the paper stays flat, as the printer head can be damage if it collides with an edge of the substrate that is sticking up.

Procedure 4: Print a small cross shape onto the paper and then set the print origin to the center of the cross with the fiducial camera. This will serve as the common print origin for the different printed layers. This step ensures that subsequent layers will line up properly after taking the paper off of the platen to drop the dielectric and semiconductor layers with a handheld pipette.

Procedure 5: Load the designed gate pattern showed in figure 3 into the printer software. Make sure that the design has one elongated part that can be covered with graphene oxide with a triangle on the end that can be connected to a voltage source or other device via epoxy glue. Making sure the print origin is set to the center of the cross, print one layer of the pattern with silver nanoparticle ink.

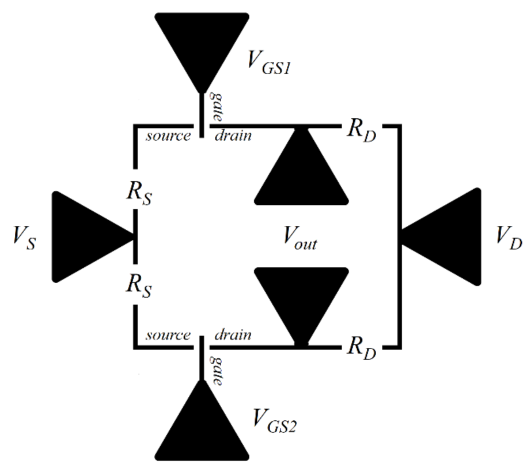

Figure 3. Designed circuit with labels

Procedure 6: Turn off the vacuum and remove the paper. Proceeded to drop graphene oxide onto the elongation part of the silver gate. Graphene oxide will serve as the dielectric for the transistor. Make sure to drop enough graphene oxide to cover the whole elongated section of the pattern but none of the triangle. Let the graphene oxide layer dry until it is of uniform thickness.

Procedure 7: After the graphene oxide has dried, load the paper substrate back onto the printer platen and use the fiducial camera to reset the print origin to the center of the cross. It is worth noting that during this process, students may notice that the print origin has shifted quite a bit, and they may need to move the fiducial camera quite a bit to find the cross again.

Procedure 8: Print the silver source and drain on to the paper substrate along with the wires and triangular pins of the rest of the circuit. Make sure that the two source and drains have an adjacent T shape pattern with the heads of the Ts pointing toward each other. The source and drain should be aligned so that they print directly onto graphene oxide layer with the spacing between them equivalent or smaller than the thickness of the elongated part of the gate. A distance of around 250 pixels was a suitable distance for our experiment.

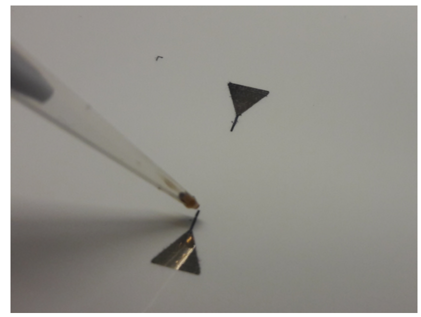

Figure 7. Dropping graphene oxide via pico-pipette

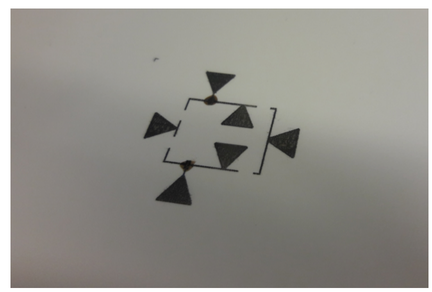

Figure 4. Printed circuit with silver source and drain

Procedure 9: Dilute the CNT with distilled water at a 1:9 ratio. This process is necessary as the undiluted CNT has low resistance that is unsuitable for use in the transistors. By diluting the CNT, the resistance of the solution will increase. At a 1:9 ratio, the resistance is high enough to be used as a proper semiconductor in the transistor. After the solution has been thoroughly mixed, use the handheld pipette to drop a small amount of CNT onto the source and drain, with enough volume to bridge the gap between the two. The volume of the CNT should be small to avoid a randomly oriented network of CNT that could cause an open circuit. Using conductive epoxy glue, attach the four resistors in the gaps of the printed pattern according to the instructions above. The final circuit is illustrated in figure 4.

4 RESULTS AND DISSCUSSION

To test the differential amplifier, V_{GS1} was hooked to ground, and a two-channel DC power supply was used to provide -5 V to V_D and the voltage of V_{GS2} was gradually increased from 0 V to -25 V. The printed circuit was tested on the paper itself, negating the need for a breadboard. V_{out} for each value of V_{GS2} was measured with a handheld digital multimeter and recorded. Test results showed that V_{out} increased as V_{GS2} was increased. The graph suggests an exponential relationship at first while higher voltages show a more linear correlation. Flexibility of the circuit is visiable in figure 5 and the relation between outpout voltage and gate to source voltage is displayed in figure 6.

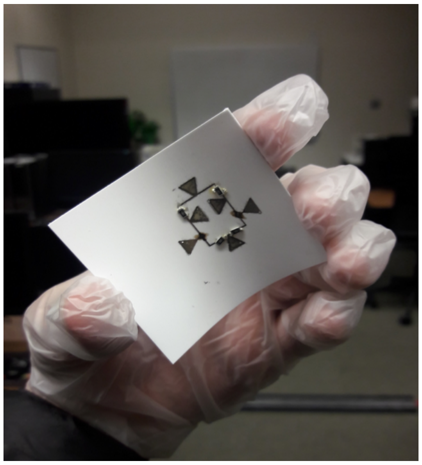

Figure 5. Finished printed product

Figure 7 shows a plot of the data. At V_{GS2} = -25 V, the transistors broke down and no longer amplified the input voltage. Transconductance (g_m) had a linear relationship with V_{id} between -10 V and -17 V. Threshold voltage (V_T) was around -9 V.

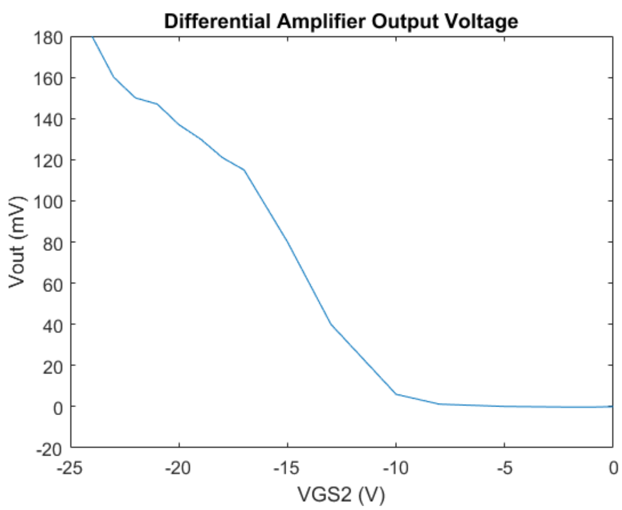

Figure 6. Chart of output voltage of differential amplifier

The device also exhibited properties of a sensor. While testing the voltage, movement such as walking by the workstation or moving a hand near the transistors would cause V_{out} to fluctuate. The fluctuations of V_{out} lessened when the door to the lab was closed. It is possible that the exposed CNT on the top layer of the transistors was acting as a pressure or temperature sensor.

5 ACKNOWLEDGMENT

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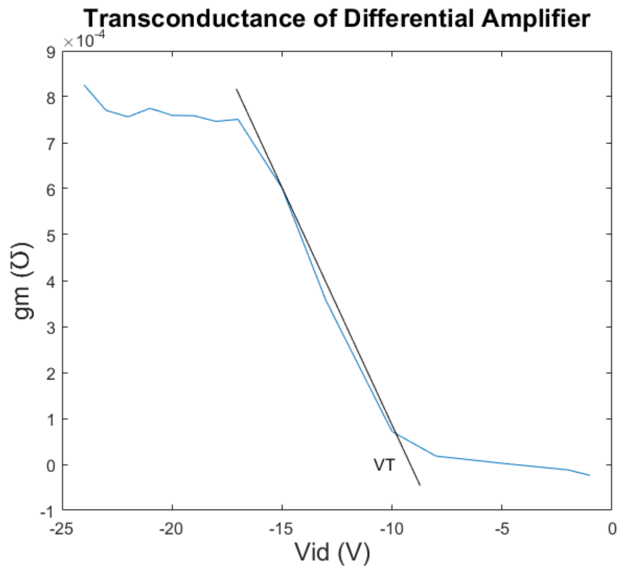

Figure 7. Transconductance of differential amplifier

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