A 3μm Channel, Ink-Jet Printed CNT-TFT for Phased Array Antenna Applications

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***Abstract* — A top-gate CNT-TFT with a channel length of 3μm was fabricated via ink-jet printing on a flexible substrate. The source and drain were designed to contain triangular ends in order to facilitate fabrication of channel lengths less than 5μm. Output characteristic (Ids-Vds) was measured to observe the electrical behavior, and an on/off ratio over 1000 at Vds = 2V was achieved.**

***Index Terms* — Carbon nanotubes, thin-film transistor, phase shifter, phased array antenna, conformal antenna.**

I. Introduction

The ink-jet printing technique on flexible substrates for the fabrication of a thin-film transistor (TFT) has been gaining a lot of attention in the industrial sectors, as well as academia over the last few years [1]-[4], owing to the unique advantages that the technique provides, such as low-cost, high throughput, and ability for mass production. However, regardless of these efforts, there are challenges that still need to be overcome. One of the biggest challenges for ink-jet printing until now is the length scaling of the device. Compared to the other conventional fabrication methods, ink-jet printing has shown its limitation in the length scaling to about 10 μm, mostly due to the difficulty in controlling the size and shape of the ink droplets.

Meanwhile, carbon nanotube (CNT) has been regarded as one of the promising materials for TFT applications due to its excellent electrical characteristics as a semiconductor [5]-[6]. For this material, one of the popular methods for deposition is droplet-evaporation [7], which involves the use of CNT solution. This indicates the possibility of printing CNT, but application for ink-jet printing has been considered difficult due to the frequent clogging of CNTs in the ink-jet heads.

The phased array antenna (PAA) is one of the most widely used structures for steering radio frequency (RF) beams. Utilizing ink-jet printing, we have previously developed and demonstrated a light-weight and conformal PAA system on a flexible Kapton substrates [8, 9]. This structure consists of ink-jet printed antenna elements and a phase-shifting network, as shown in Fig 1. By controlling the ON/OFF states of the printed TFT switches in the phase shifter, which changes the phase of the RF signal in each line, desired steering angles of the propagating RF signal are realized.

Printed CNT-TFTs have already been explored as switches in the phase shifting network with this purpose [8]-[9], and improving the performance of the switches is expected to widen the operating frequency range of antenna array.

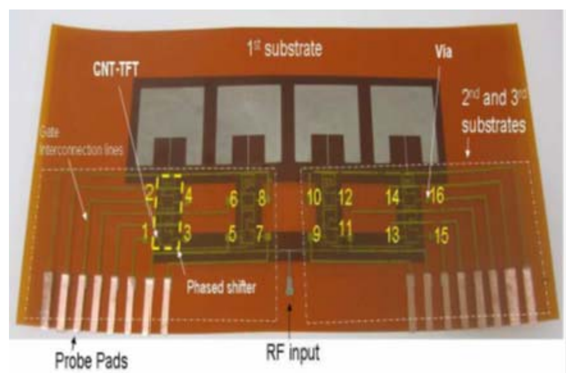

Fig. 1. Picture of a 2-bit 1x4 PAA system containing CNT-TFT switches in the phase shifting network. (Ref [8])

II. Fabrication Process

We used Fujifilm Dimatix Materials Printer (DMP-2800) to fabricate the CNT-TFT. The volume of the ink droplet was 10pL, and the droplet size was estimated to be 25μm in diameter. Kapton was used as a substrate. First, we printed the Source (S) and Drain (D) layers with silver nanoparticle ink. The printed S and D regions were sintered for 15 minutes at 150°C. The tips of the source and drain were point-shaped, as shown in Fig. 2. A zoomed in image of the printed tip is shown in Fig. 3.

The presence of such a pointed structure helps in reducing the channel length of the TFT. Such reduction in channel length is made possible due to the necessity of printing only a few drops at the end of the tips. It is widely known that a shorter channel length TFT has better performance [2]. Therefore, such a pointed structure, with a short channel length, is expected to improve the CNT TFT performance.

Also, this structure is advantageous in reducing the parasitic capacitance, due to the reduction in the overlapping area between the S-D and the gate layers.

After defining the S and D regions with the short channel, the CNT ink was printed on top. The CNT ink was prepared by mixing 99% pure semiconducting single walled CNT Powder (source: Nanointegris, Inc) with 1-Cyclohexyl-2-Pyrrolidine (CHP), followed by 4 hours of sonification [10]. A water-based CNT ink is more widely used, but according to our experience, it tends to clog the nozzle quite often. This happens because during the synthesis process, surfactants are used to make CNTs easily dissolvable in water, but usually the concentration of the CNTs in the solution is high, causing frequent clogging in the ink-jet head nozzles. This problem has been thought to be one of the reasons that hamper consistent printing of the CNT-based devices.

Fig. 2. Optical image of the source and drain layers printed on Kapton substrate using silver ink.

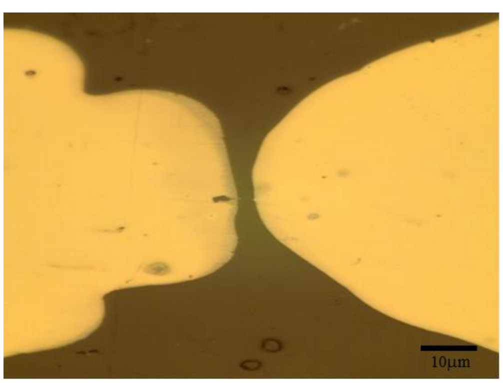

Fig. 3. A zoomed-in microscope image of the point-shaped source and drain tips.

Therefore, we chose to use an organic solution, which is found to be very beneficial to solve this problem. A concentration of 0.01 mg/ml for the solution was found to be proper for this study. With this concentration, clogging problem reduced dramatically while showing good deposition properties. After printing, we carried out the sintering process at 150°C for 5 minutes.

Then, the dielectric layer was printed and sintered at 150°C for 5 minutes. Finally, a silver gate layer was printed, followed by the sintering at 150°C for 15 minutes. The complete structure of the CNT-TFT is shown in Fig. 4.

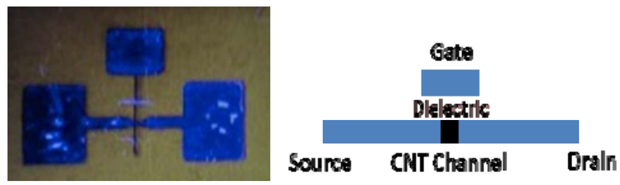

Fig. 4. An optical image of the complete CNT-TFT structure formed by ink-jet printing method (left) and its cross-sectional view (right).

III. Measurement

According to the process mentioned above, we fabricated the CNT-TFT device with a channel length of 3µm, and a channel width of 300 µm.

The output characteristic (Ids-Vds) is shown in Fig. 5. It can be seen that the CNT channel acts as a p-type semiconductor, showing an increasing current when a negative gate voltage is applied. I_{on}/I_{off} at a drain bias voltage of 2V is about 2.89×10^3 at Vgs of -6V.

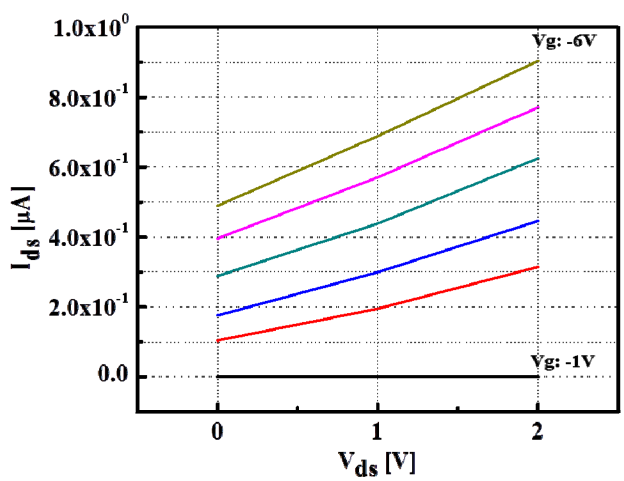

Fig. 5. Output (Ids-Vds) characteristic of the fully printed CNT-TFT.

The Ids-Vds curves indicate the existence of a Schottky barrier between metal electrodes and the semiconductor channel with a slight inflection behavior. The inflection shape of Ids-Vds curve is a common characteristic of the Schottky barrier FET. It is thought that the work function of silver (□ = 4.7eV) is small enough and the barrier is formed for holes in the semiconducting CNT. Without the barrier, more linear shape is expected to exist in the same region [3].

Also, one possible factor affecting the Schottky barrier level is the oxidization of silver. Silver is known to be very easily oxidized in air, and it is possible that the pervasion of oxygen lowers the work function of silver. Similar effect has been reported with H_2 gas pervaded into Pd metal [3]. Further investigation needs to be made for better device performance understanding, and to apply the technique for achieving roll-to-roll manufacturing of devices.

VII. Conclusion

We fabricated a complete top-gated sub 5µm channel length CNT-TFT using ink-jet printing. We could reduce the channel length of the device by printing pointed shapes for the source and drain layers. Then, to prevent the clogging issue of the ink-jet head due to the CNT-ink, we used organic-based CHP solvent with proper concentration. I-V measurements on the fabricated TFTs indicated that CNTs are p-type semiconductor, with the existence of a Schottky barrier in the metal-semiconductor contact.

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