Fully-Printed, 5G-Powered Wireless Sensing Modules for Perpetual IoT

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***Abstract*—The reported research investigates the layer-by-layer deposition of conductor, semiconductor and dielectric inks for the realization of low-cost, flexible and conformal RF switches. The study looks into types of contacts—Schottky or ohmic—between different materials, as well as new methods to realize channels with µm lengths. Multiple transistors were printed on rigid and flexible substrates, demonstrating non-linearity and a promising RF switching behavior.**

***Index Terms*—flexible electronics, printed transistors, carbon nanotubes, smart skin**

I. Introduction

With the massive increase in the number of Internet of Things (IoT) devices to be deployed in the next couple of years, the demand for fully autonomous, environmentally-friendly, flexible and conformal solutions is rapidly expanding. Previous works described the successful implementations of mm-wave harvesting and backscattering systems supported by commercial components that were difficult to find and mount, besides being expensive [1]–[3]. Additive manufacturing technologies (AMTs) have proven to be a main contributor to the realization of extremely low-cost, flexible wireless electronics on a variety of substrates. Inkjet printing, a part of AMTs, allows the layer-by-layer deposition of any type of ink based on a "Drop on Demand" (DOD) manner. Conductors such as silver nanoparticles (SNPs), semiconductors like carbon nanotubes (CNTs) and dielectric polymers like PVP, PMMA and SU8, can all be deposited at room temperature using a low-cost inkjet printer. The objective of the research proposed here is to investigate the possibility of building active devices using the layer-by-layer ink deposition technique. The realization of fully-printed active devices, more specifically transistors and diodes, introduces a low-cost, rapid and flexing-friendly solution [4].

Fig. 1 shows the side view of a Schottky diode and a thin film transistor (TFT) comprised of conductors, semiconductors and dielectrics. For the Schottky diode, a metal–semiconductor junction is formed between a metal (anode) and n-type semiconductor (cathode), creating a Schottky barrier. Whereas for the TFT, an ohmic contact is required between the source/drain and the channel, followed by a dielectric layer that separates the channel from the gate.

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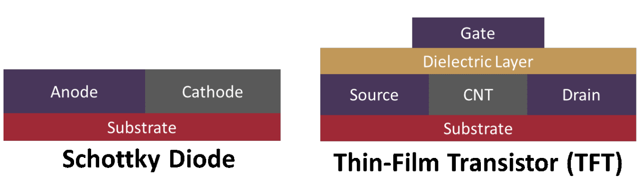


Fig. 1. Side views of a Schottky diode and a thin film transistor (TFT).

II. Project Outcome

In order to achieve switching using a printed transistor in the GHz bands, several criteria need to be met:

- The channel realized by the semiconductor film has to form an ohmic contact with both the source and the drain, in order to eliminate the resistance of Schottky barriers at these interfaces.
- The use of dielectric materials with high dielectric constant k in order to increase the gate capacitance. An alternative is to print a very thin dielectric layer between the channel and the gate to enable switching at low biasing voltages. For this reason, the first experiment was conducted following the bottom-gate approach using a silicon wafer coated with $100\,\mathrm{nm}$ SiO_2 as shown in Fig. 2a. Two sets of transistors were printed using single-wall carbon nanotube (SWCNT) ink purchased from Sigma Aldrich. The electrodes for the first set were made interdigitated to increase the width of the channel while the second set targets a shorter length. Those transistors were tested under varying gate to source biasing voltages using the Keithley 2612B source meter unit to produce the IV curve shown in Fig. 2b. It can be observed that the printed transistor shows a slight non-linear behavior, specially at high applied gate-to-source biasing voltages.

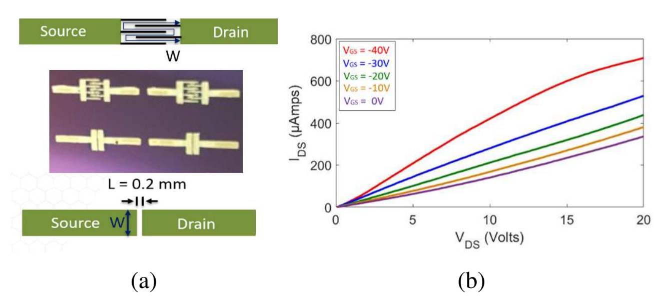
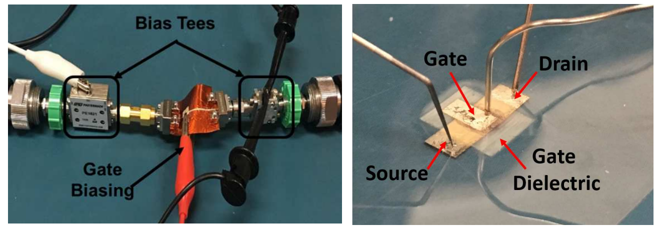


Fig. 2. (a) Printed transistors on SiO_2 coated silicon wafer using silver nanoparticle ink (SNP) for the source and drain and single wall carbon nanotubes (SWCNTs) ink for the channel (b) Measured IV curve for one printed transistor under varying gate-to-source biasing voltages.

- In order to achieve low-losses between the source and the drain under gate biasing conditions, the length of the channel has to be in the order of hundreds of nm (thereby enabling quasi-ballistic transport of the carriers over the small gap), a big challenge with the available Dimatix inkjet printer. However, we have been exploring methods relying on surface modifications and wetting conditions [5], [6] to create small channels, in the $\mu\mathrm{m}$ range as shown in Fig. 3. The gap formed between the washed metallic CNTs and wet JSB-40G SNP ink is realized following this concept: the CNT is originally very hydrophobic, however, when formulated as an ink, it is hydrophilic. Therefore, this method suggests printing the first CNT metal electrode and washing the surfactant leaving behind a hydrophobic CNT on the substrate. The next step consists of printing the hydrophilic SNP ink next to it which leads to a repulsion between the CNT metal and SNP electrodes resulting in a very small gap.

The next step was to merge the aforementioned requirements in a single transistor printed design and test its performance at both DC and RF. SNP inks and metallic CNTs were chosen for the source and drain, having demonstrated a low contact resistance with the semiconductor CNT of the channel. For the gate dielectric, the choice of the ink was very challenging. The ion gel electrolyte is a very common type of insulator used in flexible transistors design due to its high capacitance and the ability to exhibit fast switching operation under low voltage biasing. Although we were able to reach currents in the order of mA for a gate bias ranging from -5 to 30V and an I_{ON}/I_{OFF} of more than 10^5 with the printed transistor on Kapton shown in Fig. 4a, large deviations would appear in the results after few days. This was mainly due to the drying of the ion gel. To conduct the RF test, the other side of the Kapton substrate was covered with copper tape for the two-port measurements as shown in Fig. 4a. The switch displayed small changes in transmission under a gate biasing of $10\,\mathrm{V}$ but the transmission was very lossy mainly due to two reasons: the channel resistance is still very high causing an unmatched condition and the ion gel is introducing additional losses. Another ink, xdi-dcs dielectric ink from NanoIntegris, was then investigated to replace the ion gel as an insulating layer. Printing a large number of transistors such as the one presented in Fig. 4b has shown that more than 5 layers are needed to avoid shorting the gate with the source/drain electrodes due to the presence of pinholes. To investigate the printing of Schottky diodes, we have received printed samples on Polyethylene terephthalate (PET) substrate from Tanaka Precious Metals in order to test the contact of CNTs with a variety of metals (Au, Pt, Ni, Pd and Cu). However, we were not able to characterize them properly because the printing was very uneven and the patches displayed broad and numerous gaps. Due to COVID, we were not able to move on with this collaboration.



(a) (b)

Fig. 4. (a) Printed transistor on Kapton substrate connected for RF test (ion gel used for gate dielectric) (b) Printed transistor on PET substrate (xdi-dcs printed as gate dielectric).

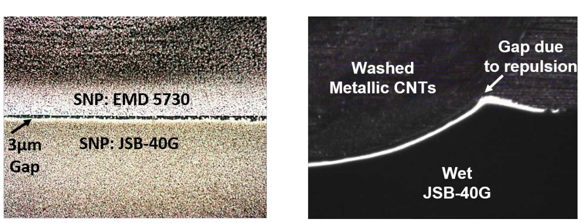


Fig. 3. Few $\mu\mathrm{m}$ gap formed by printing two inks with different wetting properties.

III. Career Plan and Fellowship Impact

I am now on track to finishing my Ph.D. by the end of 2021 and I would love to become a faculty and keep working closely with the MTT-S community. This award was a true honor, it has given me the confidence, motivation and visibility that I needed to keep pursuing revolutionary research and connecting with others in and outside my field. Even though we did not have the chance to attend IMS 2020 in person due to the pandemic, the support of the fellowship allowed me to develop my research and networking skills through extensive meetings with companies and collaborations with teams from different areas.

Acknowledgment

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