Inkjet Printed diF-TES-ADT Organic Thin Film Transistors

Y. V. Li[1,2], D. A. Mourey[1,3], M. A.Loth[4], D. A. Zhao[1,2], J. E. Anthony[4], and T. N. Jackson[1,2]

1. Center for Thin Film Devices and Materials Research Institute,
2. Department of Electrical Engineering, Penn State University. University Park, PA 16802, USA
3. Department of Material Science Engineering, Penn State University. University Park, PA 16802, USA
4. Department of Chemistry, University of Kentucky, Lexington, KY 40506, USA

Solution processed organic semiconductors have potential for very low cost device and circuit manufacturing by printing and similar techniques. Inkjet printing allows digital pattern control and is of particular interest for low-cost products that need to be customized and produced in single or small quantities. We report here OTFTs fabricated with inkjet printed 5,11-bis(triethylsilylethynyl) anthradithiophene (diF-TES-ADT) with 0.35 $cm^2/V \cdot s$ mobility.

DiF-TES-ADT OTFTs fabricated using spin casting have demonstrated mobility > 1 $cm^2/V \cdot s$ and a contact-related microstructure for pentafluorobenzenthiol treated electrodes.[1,2] The OTFTs reported here use untreated contacts, with the solvent system adjusted to provide good wetting of the device surface by the jetted diF-TES-ADT solution. For simple test OTFTs the process begins with an oxidized, heavily doped n-type Si wafer. The heavily doped wafer serves as the substrate and gate electrode for the OTFTs and thermal oxidation provides a simple, high-quality dielectric. Gold source and drain contacts are then deposited by thermal evaporation and patterned by lift-off. Prior to inkjet printing of diF-TES-ADT the substrates are cleaned by UV/ozone with a final ethanol rinse used to remove gold oxide. A Dimatix DMP-2831 piezoelectric drop-on-demand inkjet printer with slightly modified printhead cartridges to allow convenient use of small amounts of printing material was used for the diF-TES-ADT deposition.

DiF-TES-ADT is soluble in a range of organic solvents and has been spin cast to form highly crystalline films from solvents such as chlorobenzene (CB) and toluene.[1,2] However, in inkjet printing, these relatively low boiling point solvents evaporate rapidly resulting in very small, non-uniform crystal domains Trichlorobenzene (TCB) has a relatively high boiling point. however, it does not readily wet our UV-Ozone cleaned device substrates. Mixed solvents can allow control of substrate wetting, hydrodynamic flow in drying droplets, and the structure of the resulting crystalline grains.[3] For this work we used a mixture of TCB and CB for the diF-TES-ADT inkjet printing. A 1 wt% solution of diF-TES-ADT was jetted onto UV/ozone cleaned substrates held at 32 °C. For a typical transistor several drops were printed in a row across the device channel with a drop spacing of 5 µm. For diF-TES-ADT inkjet printed from TCB or mixed TCB/CB, closely spaced drops remain liquid sufficiently long to merge and form a larger drop. With proper control of wetting and drying the large drop will dry with the formation of large diF-TES-ADT crystals including, often, crystals that extend across the transistor channel. After diF-TES-ADT printing the sample was baked at 90 °C for 45 minutes.

Figure 1 shows log(I_D) and $\sqrt{I_D}$ versus V_G for V_D = -40 V (left), and I_D versus V_D for several values of V_G (right) characteristics for an inkjet printed diF-TES-ADT OTFT with t_{ox} = 210 nm, 20 µm channel length, and 190 µm channel width. From these characteristics we extract a field-effect mobility of 0.35 $cm^2/V \cdot s$, a threshold voltage of +3 V, a current on/off ratio of > 10^7, and a sub-threshold slope < 1V/dec.

We have previously reported hybrid organic/inorganic CMOS circuits using p-channel diF-TES-ADT and n-channel ZnO TFTs. [4] In that work, the diF-TES-ADT was deposited in a continuous layer by spin casting and although contact-related microstructure allowed circuit operation, device isolation was limited and single inverter static leakage was in the µA range for both high and low logic levels. Figure 2 (left) shows an optical microscope image of a diF-TES-ADT/ZnO inverter with the OTFT deposited by inkjet printing as described above. This circuit used a 60 nm thick Al_2O_3 deposited by plasma enhanced atomic layer deposition (PEALD), and bi-functional Ti/Au contacts for both the diF-TES-ADT and PEALD ZnO TFTs. For this dielectric the resulting OTFT mobility is lower, near 0.06 $cm^2/V{\cdot}s$, with other characteristics similar to the SiO_2 dielectric test devices. Figure 2 (right) shows inverter switching characteristics and supply current as a function of input voltage for a diF-TES-ADT/ZnO CMOS inverter. Despite the lower mobility, the CMOS inverters work well. The maximum gain is about 40 and the static leakage is sub-pA for both low and high input levels. These results demonstrate good OTFT device and circuit characteristics for inkjet printed diF-TES-ADT.

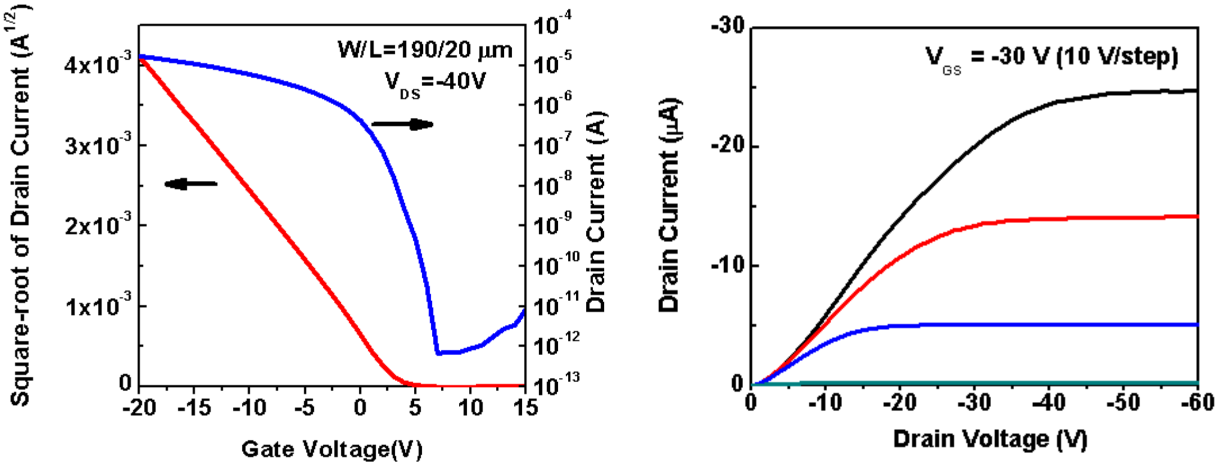

Figure 1: Log(I_D) and $\sqrt{I_D}$ versus V_G for V_D = -40 V (left), and I_D versus V_D for several values of V_G (right) characteristics for an inkjet printed diF-TES-ADT OTFT with t_{ox} = 210 nm and 20 µm channel length.

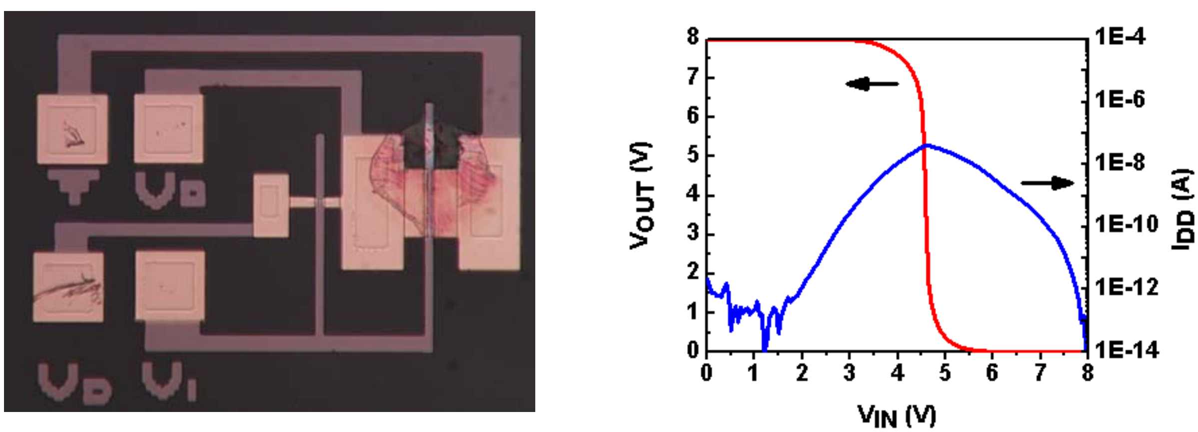

Figure 2: Optical microscope image (left) and inverter switching characteristics and supply current as a function of input voltage (right) for a diF-TES-ADT/ZnO inverter with the OTFT deposited by inkjet printing.

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[2] D. J. Gundlach, et al, "Contact-Induced Crystallinity for High-Performance Soluble Acene-Based Transistors and Circuits," *Nature Materials*, **7**, pp. 216-221 (2008) .

[3] J.A. Lim, H.S. Lee, W.H. Lee, and K. Cho, "Control of the Morphology and Structural Development of Solution-Processed Functionalized Acenes for High-Performance Organic Transistors," *Adv. Funct. Mat*, **18**, pp. 1-11 (2008).

[4] D. A. Mourey, S. K. Park, D. Zhao, J. Sun, Y. Li, S. Subramanian, S. F. Nelson, D. H. Levy, J. E. Anthony, and T. N. Jackson, "High-Speed, Low-Temperature Integrated ZnO/Organic CMOS Circuits," *65th Device Research Conference Digest*, pp. 147-148, (2008).