Inkjet printed electrochemical, organic field-effect transistors

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Background
Conventional inkjet printers can be used to fabricate electrochemical, organic transistors (ECT) on rough flexible substrates, such as photo paper. Printing serves the dual purpose of combined deposition and patterning. The transistors fabricated are normally-on field effect transistors (FETs) which works as a switch on the circuit activated by the voltage that is input to the gate.

Objective
To reproduce a normally-on FET circuit using the printing process developed by Richard Mannerbro, et.al., FET is a multilayered poly(3,4-ethylenedioxythiphene):poly(styrenesulfonate)(PEDOT:PSS) with a 1.3mm² active area channel.

Theory
The thin film FET has three basic elements: (1) an insulating layer (or substrate), (2) a conjugated polymer, and (3) three terminals – the source (S), drain (D), and gate (G) (Figure 1a). The S and D are in electrical contact through the polymer channel, which is conductive when gate voltage (Vg) is 0V; it is therefore "normally-on." The electrolyte separates the G from the S and D on the substrate, and connects the G to the rest of the circuit (Figure 1a). When a voltage is applied at G, a charge is induced between the PEDOT:PSS and the electrolyte. The charge reduces the PEDOT⁺ in the channel region and thereby "closes" the gate (i.e., channel effectively becomes and open circuit by having a high resistance). The resistance of the channel is controlled by the following reaction:

\[ \text{PEDOT}^+ + M^+ + e^- \rightarrow \text{PEDOT} + M^+ + \text{PSS}^- \]  

where M⁺ is a metal cation transferred through the electrolyte from the gate to the rest of the polymer (Figure 1b).

Procedure
1. 4.26 mL of PEDOT:PSS solution  
2. 5.74 mL of Ethylene Glycol  
3. Store polymer in cartridge

Electrolyte
1. 8.21 mL of deionized water  
2. 1.09 gm of poly(sodium 4-styrenesulfonate)  
3. 0.24 mL of Glycerol  
4. 0.30 gm od D-sorbitol  
5. Store electrolyte in separate cartridge

Printing – Epson Stylus C88+
1. Set color of drawing to correct RGB scale in order that it only uses one cartridge in CMYK  
2. Insert HP Everyday Photo Paper, Glossy  
3. Print seven layers a. Between layers of PEDOT:PSS anneal for 5min at 60°C  
   b. Between layers of electrolyte anneal for 3min at 60°C  
4. Print electrolyte on top of PEDOT:PSS once the polymer layers are completely dry

Testing – Output Characteristics
To record the output characteristics, the circuit shown in Figure 2 was reproduced from the literature. In order to produce negative voltage on one end of the circuit, a USB oscilloscope device Analog Discovery 2 from Digilent was used. The measurement was done on the software called WaveForms 2015. The input voltage at the Vᵢ in the diagram was 5mHz, 500mVPP, and +500mV offset square wave so that the maximum amplitude of waves is from 0V to 1V.

Result and Discussion
4-point probe test was conducted on R, R₀, and R, on Figure 2 before applying the input voltage. The results are the following:

\[ \begin{align*}
  R & = 2000 \text{ kΩ} \\
  R₀ & = 1000 \text{ kΩ} \\
  R_{\text{in}} & = 400 \text{ kΩ}
\end{align*} \]

Even though each path on the circuit had high resistances, the expected output was measured on the oscilloscope as shown in the Figure 3. The amplitude of the output was about 0.4V. The input voltage was a square wave that oscillated between 0 and 1V and a frequency of 5mHz and inverted relative to the output. The amplitude of output was lower in magnitude than what was expected, but this can be accounted for in terms of a slower than expected switching speed of the channel.

As the input voltage was applied, a repetitive color change at the active channel was observed as Figure 4 shows. When the Vᵢ = 1V, the channel was blue and the the voltage was 0V, the light blue color returned. This coloration makes sense because PEDOT has a deep blue color. Therefore, this is an apparent indication of the reaction (1) happening at the channel.

Conclusion
In conclusion, the circuit could be reproduced successfully with the expected output. However, more investigation should be done to obtain the full amplitude in output voltage. Also, different active channel areas should be tested to measure the differences in time and output voltage.

Reference