Inkjet Printing of Zinc Oxide Based-Semiconductors for Thin Film Transistors

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Abstract:

Ink-jet printing is widely used in arts and our daily lives. It consists of creating digital images by propelling droplets of ink onto a substrate. This technique can also be used to produce thin film electronics at a fairly low cost. The objectives of this project were to develop ink-jet printed thin film transistors from zinc oxide-based solutions, and explore their morphological and electrical properties. Zinc oxide precursors were directly printed onto a silicon/silicon dioxide (Si/SiO_2) substrate by controlling the substrate temperature and drop spacing. These variables had a strong effect on the film thickness and its electrical performance. After printing, the samples were annealed to evaporate the solvent and react the chemical precursors to form the semiconductor layer. Transistor I-V testing was done by landing source and drain probes directly onto the printed structure and using the Si substrate as a bottom gate. The devices showed field-effect electron mobility between 0.001 and 0.024 $cm^2V^{-1}s^{-1}$. Further work is needed to optimize the processing so that zinc oxide-based transistors can be applied in roll-to-roll processing of circuits with moderately good performance for large-area displays.

Introduction:

The transistor became the heart of modern electronics after its invention in the 1940's thanks to its unique property of generating a greater output current than the one inputed, as well as its low production cost, wide range of applications, and reliability. Transistors need a semiconductor layer to perform the critical switching or amplifying function. Zinc oxide (ZnO), an inorganic material, has shown promising semiconductor properties, and is non-toxic and inexpensive [1]. Therefore, making thin film transistors (TFTs) out of ZnO is an important research topic. Ink-jet printing is a very efficient solution-based process in that the active layer of the transistor is only formed in the channel region, and no additional process is needed for patterning [2]. Consequently, material wastage, production costs and possibly fabrication time are all reduced. Here, we report our investigations on methods of optimizing the electrical performance of ink-jet printed ZnO transistors.

Experimental Procedures:

A ZnO solution was made of zinc acetate dihydrate ($ZnAc_2$•$2H_2O$) mixed with 2-methoxyethanol to form a 0.5 M solution. Ethanolamine was added as a stabilizing agent in the solution. The TFT bottom gate was made out a doped silicon wafer of thickness 550 μm with a 200 nm thick thermally grown SiO_2 layer. The Si/SiO_2 substrate was cleaned with acetone and isopropanol and treated with an oxygen plasma reactive ion etch with a Technics West PEII-A Plasma System. The ZnO precursor was inkjet printed with a Fujifilm Dimatix-2800 printer onto the prepared substrates that were maintained at temperatures of 50ºC or 60ºC with drop spacings of 5 μm, 10 μm or 15 μm. The printed liquid was then pre-baked for 10 min at 100ºC before being annealed for one hour at 480ºC. Morphological characterization was done with an Olympus LEXT OLS4000 interferometer, and three-point probe measurements were performed to electrically characterize the devices, shown in Figure 1.

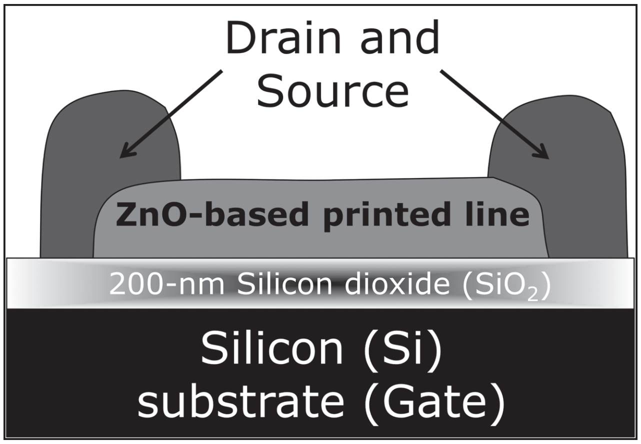


Figure 1: Cross-section of a ZnO ink-jet printed transistor.

Results and Discussion:

Increasing the drop spacing strongly influenced the morphological and electrical characteristics of the printed shapes as shown in Figure 2. At a drop spacing of 5 μm, the droplets overlapped forming a very thick film (819 nm), which exhibited no transistor-like electrical properties. At a drop spacing of 10 μm, the film thickness was 563 nm and transistors with channel lengths and widths of 704 μm and 555 μm, respectively, exhibited electron mobility of 0.004 $cm^2V^{-1}s^{-1}$ and an on-to-off current ratio of about 40. Figure 3 shows the output characteristics, which show their Ohmic properties. At a drop spacing of 15 μm, the print thickness was 133 nm. They were better transistors with a channel length and width of 602 μm and 442 μm, an electron mobility of 0.024 $cm^2V^{-1}s^{-1}1$, and on-to-off ratios of 1.1×10^3, with a clear contrast between the Ohmic and saturation regions. Therefore, increasing the drop spacing decreases the film thickness, which improves the electrical performance of the films.

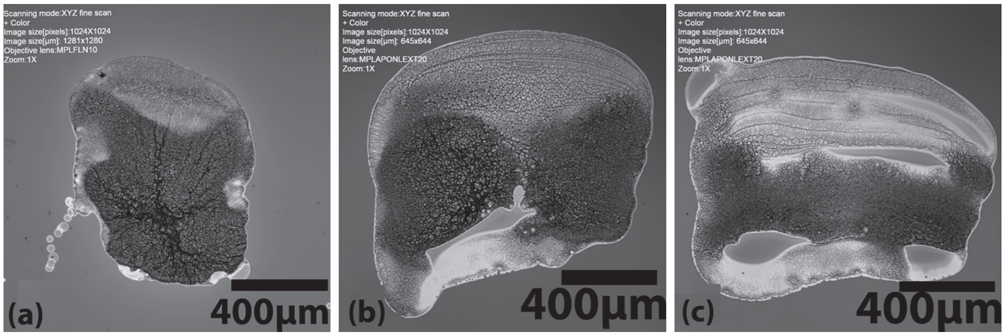
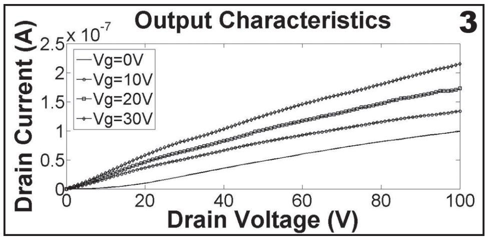


Figure 2: ZnO films printed at (a) 5, (b) 10, and (c) 15 µm. Notice the decrease of solvent (dark regions) from (a) to (c).



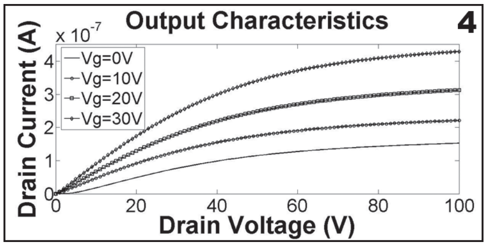


Figure 3, left: A transistor made with 10 µm drop spacing exhibits only the Ohmic region.

Figure 4, right: Optimum printing conditions yield maximum drain current of about 0.45 µA.

Substrate temperature is also an important variable. ZnO films printed at a substrate temperature of 60ºC showed higher electron mobility than those printed at 50ºC. Since the flash point of the solvent used was 40ºC, maintaining the substrate at a higher temperature during the print accelerated solvent evaporation and, thereby, improved the electrical properties of the films. The drain current at a given voltage almost doubles when substrate temperature is increased from 50ºC to 60ºC. Figure 4 shows the output characteristics of prints at 60ºC substrate temperature.

Conclusion and Future Work:

We have fabricated ink-jet printed ZnO TFTs using a precursor at a concentration of 0.5 M. The printed film was then subjected to a pre-bake at 100ºC for 10 min before annealing at 480ºC for 1 h. It was found that the performance of the ZnO TFTs improved as the substrate temperature and drop spacing increased during printing. Both factors affect how fast the solvent is evaporated for better film formation. Further investigation must be done to confirm the trends observed and optimize the performance of the transistors. Also, we would like to print on other substrates besides Si/SiO_2 as well as use nanoparticles or metal solutions for printing electrodes.

Acknowledgments:

This project was supported by the NNIN REU Program funded by the National Science Foundation and NSF Bridge Award # ECCS 1032538. Thanks go to the Lurie Nanofabrication Facility and its staff for the logistical support.

References:

[1] J.J. Schneider et al., Adv. Mater. 2008, 20, 2283-3387.

[2] C. Avis and J. Jang, Electrochem. Solid St., 2011, 14 (2), J9-J11.