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Inkjet-Printed PEDOT:PSS/ZnO Diodes on a Flexible Polyimide Substrate

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Summary:

Printing techniques offer an innovative and cost-effective approach to fabricating large amounts of flexible and lightweight electronic devices. However, developing a multilayered device such as a diode, which requires precise layer-to-layer alignment, remains a challenge. In this work, we present a fully printed approach for fabricating inkjet-printed pn-diodes on metalized polyimide substrates. The device consists of a pn junction formed by two inkjet-printed layers, namely a n-type zinc oxide (ZnO) and a p-type (PEDOT:PSS), while the bottom copper (Cu) electrode is pre-patterned onto the substrate. The device demonstrated stable rectifying behavior and exhibited promising electrical performance.

Keywords: Printed Electronics, Inkjet printing, pn-diode, Zinc oxide (ZnO), PEDOT:PSS.

Background, Motivation and Objective

Driven by growing research interest in IoT applications and the industry's shift toward greener solutions, the consumer electronics market has seen an increasing demand for flexible electronic circuits [1]. Printed and hybrid electronics have attracted significant attention as cost-effective and high-efficiency manufacturing approaches, well-suited for large-area manufacturing. Inkjet printing technique has emerged as a promising technique due to its key advantages including low-temperature processing, maskless and non-contact deposition, digitally programmable patterning, compatibility with a wide range of rigid/flexible substrates and minimal material waste. Advances in material development and the formulation of functional inks with high-performance properties—such as high mobility—have enabled the inkjet printing of advanced electronic devices, including transistors [2], diodes [3], capacitors [4], and nanoparticle-based microelectromechanical systems (MEMS) [5].

Considering these advancements, research on printed pn-diodes has gained attention due to the ability of printing techniques to selectively deposit a wide range of functional materials, enabling the formation of junctions with diverse material combinations. Among these, oxide semiconductors have shown significant potential to enhance the performance of these structures. In particular, n-type metal oxides are advantageous due to their conduction bands being derived from extended metal s-orbitals, which results in high electron mobility [6]. Consequently, materials such as ZnO, NiO, SnO_2, TiO_2, and In_2O_3 have been employed as n-type layers in printed diode structures for a variety of applications. ZnO, has emerged as a favorable candidate as it combines high carrier mobility, excellent optical transparency, and compatibility with low-temperature processing. Moreover, ZnO has demonstrated reliable performance in inkjet-printed devices and has been successfully integrated with various flexible substrates. However, metal oxides typically exhibit poor performance as p-type semiconductors. To address this challenge, hybrid diode structures have been developed, in which an organic semiconductor serves as the p-type layer. One of the most widely used materials is PEDOT:PSS. Due to the presence of polystyrene sulfonate (PSS), PEDOT:PSS is identified as a stable p-type polymer. As a result, PEDOT:PSS is considered a solution-processable p-type polymer, highly compatible with various substrates making it an ideal candidate for multilayer heterojunction structures.

Description of the Device Fabrication

Here, we present the fabrication of inkjet-printed ZnO/PEDOT:PSS diodes on a polyimide substrate. The device consists of two printed layers and a metal layer acting as a contact. Both printed layers were designed using CAD software, in order to be aligned accurately and were printed in sequence. A low-temperature sintering process at approximately 140°C, was employed after printing each layer. A commercial polyimide (Kapton) substrate, 25µm thick with 9µm copper tracks, served as the base and the bottom electrode after the selective CU patterning. A commercially available ZnO ink was used as the n-type semiconductor while a commercial PEDOT:PSS ink served as the p-type layer. Printing was carried out using a semi-custom Drop-on-Demand (DOD) inkjet printer. Optimal printing parameters for the two inks were determined experimentally, with a droplet spacing of 65µm in both axes to ensure consistent droplet overlap. The final devices—Cu/PEDOT:PSS/ZnO—are shown in Fig. 1a, while Fig. 1b presents detail at the edge of the structure from the optical microscope.

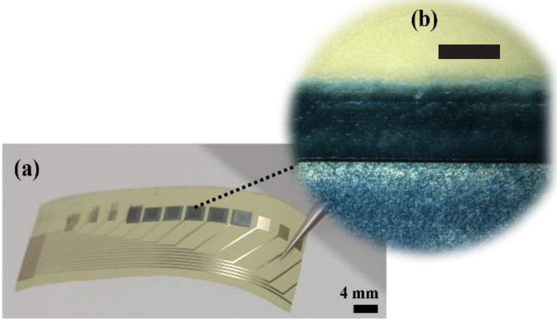

Fig.1 Inkjet-printed PEDOT:PSS/ZnO diode photographs (a); top view (scale bar is 500 µm) (b).

Results

Preliminary electrical characterization was conducted on all printed samples to validate the diode-like behavior of the fabricated ZnO/PEDOT:PSS structures. The measurements were performed using a typical probe station, connected to a Keithley 2612 source meter controlled via a custom LabVIEW interface. All characterizations were carried out at room temperature, and under dark conditions.

Fig. 2 shows three representative I–V curves (1st, 50th, and 100th) from a single ZnO/PEDOT:PSS diode using a double-staircase sweep (+0.2 → +3 V and –0.2 → –3 V) at a constant rate of 0.59 V s^{-1} for 100 measurement loops. The curves exhibit a rectifying behavior characteristic of pn-junction diodes with a low reverse leakage current. A slight hysteresis is indicated, which may be caused by charge trapping. The good overlap of the 1st, 50th, and 100th curves validates device operational stability, which is a major issue in printed electronic components.

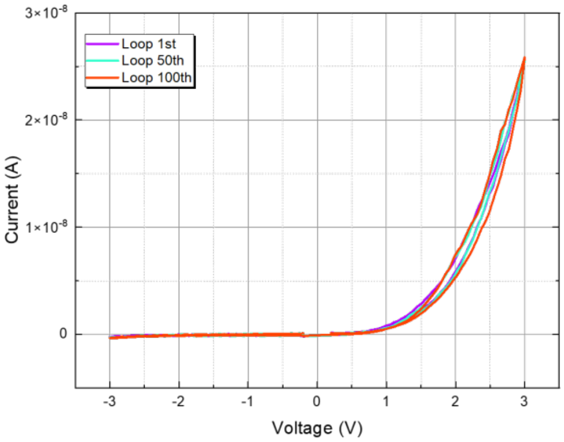

Fig. 2. I–V curves of the printed diode. The curves shown correspond to the 1st, 50th, and 100th measurement loops.

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