Aluminum-doped Zinc Oxide (ZnO) Inkjet-Printed Piezoelectric Array for Pressure Gradient Mapping

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***Abstract*—Inexpensive and flexible sensors are being designed as inkjet-printed circuits (iPCs) to solve a dynamic range of conditional issues in the biomedical, environmental, civil and industrial fields. The combination of print pattern, material choice and layering structure give iPCs a robust platform for developing products not attainable with printed circuit boards (PCBs). In this paper, a fully printed pressure sensing array was created as a multipurpose device useful for pressure mapping applications; specifically for monitoring and mapping the gait of physically compromised hospital patients. The printed array of gate-less field effect transistors utilizes aluminum-doped zinc oxide (ZnO) as the semiconducting layer due to its piezoelectric properties. Testing shows single nodes in the array detect various levels of pressure, while the entire array acts as a pressure gradient map, depending on the circuit containment method. This paper is concluded with a discussion of testing and research for future applications.**

***Index Terms*—ZnO, piezoelectric, pressure sensor, inkjet printed**

I. Introduction

Inkjet-printed circuits (iPCs) are at the margins of technological exploration in the modern era along with other unique fabrication methods such as 3D printing. Inkjet printers are high precision, non-contact, drop-on-demand, piezoelectric ink dispensers. Replacing the standard inks with nanoparticle inks allows for conductive material to be printed onto substrates in patterns that form passive and active circuitry.

This paper regards the design of a pressure sensing array that uses a piezoelectric material (zinc oxide) to sense pressure differences and a silver pattern layered on top to supply power and provide a route to read the output. With further development, this sensor will be used as a non-invasive method of monitoring patient mobility in the healthcare industry. A pressure mapping will give real-time data to the physician or caretaker and the system may be designed to show anomalies in gait or stress at undesired pressure points. When paired with machine learning, this may also be used to predict events such as falling accidents for the elderly and physical training patients.

A. Inkjet-Printed Circuits (iPCs)

The setup to produce printed circuits is low, making it ideal for both novices and professionals to experiment in small workspaces. Substantial monetary incentives exist with iPCs since initial investments and continual costs are low. The equipment needed to manufacture these are a standard inkjet-printer, substrate, nanoparticle inks, hotplate for curing and CAD software. A good low-volume fabrication setup could cost less than $1,500 depending on the materials and CAD software chosen.

Financial impact from misprints is reduced because new prints are easily made without using substantial amounts of material. Inkjet-printed circuits are also environmentally friendly as there are minimal waste byproducts during it manufacturing, especially compared to PCB fabrication. Likewise, all of the materials used for this pressure sensor array are biodegradable for minimum carbon footprint.

B. iPC Applications

Passive elements have been designed as iPCs with relatively high reliability, leading to printed low-frequency matching and filtering circuits. Antennas and radio frequency identification tags (RFIDs) are obvious applications since they are made by printing conductive pattern onto a planar substrate [1]. Organic thin film transistors (OTFTs) and organic light emitting diodes (OLEDs) have also been designed [10], [11]. Body temperature, heart rate, electrocardiogram, blood pressure, pH, glucose/insulin levels, detection of tissue damage and many other parameters can be detected with printed biosensors [2]. The variability of sensor applications in the biomedical field is a reality that can be attributed to the unique properties of the chosen semiconductor.

For instance, graphene's extraordinarily high surface-to-volume ratio (2600 m^2/g) makes it sensitive to gasses and atoms [3], [4], [5]. An experimental pattern of interdigited silver ink rows with a layer of graphene ink designed in this work's previous study showed sensitivity to carbon dioxide (CO_2) and was applied as a breathing monitor apparatus for hospital patients [6]. Different chiralities of graphene have shown to sense CO_2, oxygen (O_2), nitrogen (N_2), ammonia (NH_3) and carbon monoxide (CO) [7], [8]. It has also been shown to detect carbohydrates, proteins, metabolites and nucleic acids, making it ideal for sensing biomarkers [9]. The applications of inkjet-printed technology are boundless as they are useful for sensing many materials and conditions at remarkably low fabrication costs.

This paper is organized as follows. Section II covers the material choice and fabrication details of the pressure sensing array. Section III explores some behaviors of the pressure sensing array. Section IV concludes the paper with future work considerations.

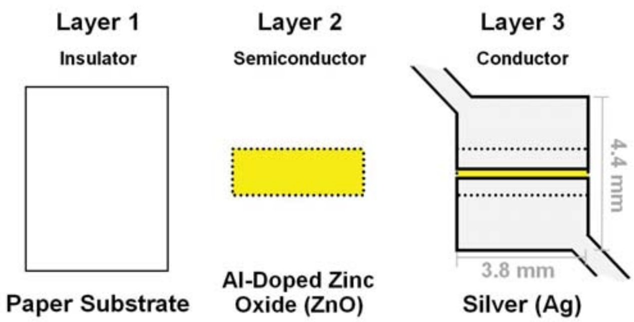


Fig. 1: Fabrication: layering of the dielectric, semiconductor and conductor patterns create a node of the pressure array.

II. Material, Pattern and Fabrication

Three electrical properties of nanoparticle inks are considered for printing circuits: the dielectric, conductor and semiconductor. The dielectric acts as an insulator and needs to have low conductivity. For this paper, the dielectric is the substrate (photo-paper). Glossy photo-paper is plentiful, inexpensive, flexible and compatible with common inkjet printers. Silver (Ag) was chosen as the conductor since its conductance is the highest among metals, it has low resistivity and is readily available as an ink for inkjet printers from retailers like Millipore Sigma.

The semiconductor chosen is important as it defines the electrical, thermal and mechanical properties (i.e. the functionality) of the sensor. The semiconductor used for the pressure array in this paper is aluminum-doped zinc oxide due to its piezoelectric properties.

A. Properties of Al-Doped ZnO

Zinc oxide is a non-toxic, inexpensive and easily accessible crystal. When doped with aluminum, a plentiful and non-toxic substance, the ZnO crystal's electron mobility increases and it acts as a semiconductor. Aluminum has four valence electrons while zinc has two. Aluminum impurities are introduced to the ZnO lattice and an electron from the aluminum transfers to the conduction band of the crystal, increasing n-type electrical conductivity [12].

Zinc oxide is a piezoelectric material, meaning when it is exposed to strain, an electric field is induced across the lattice, allowing more electrons to flow. This is the fundamental attribute of the pressure sensing array. In combination with the semiconducting properties, physical stress can be electrically captured by the Al-doped ZnO. Tests of the pressure sensor array later in the paper gives insight as to how sensitive this material is to applied force and natural vibrations.

B. Circuit Fabrication and Testing Equipment

The sensors are all printed, cured and tested in the BioInspired Integrated Circuits laboratory at the University of Alabama Birmingham (UAB). Ink is printed onto the glossy photopaper substrate using a house-hold inkjet printer that is retrofit to contain the nanoparticle metals. Once all the layers have been printed, the circuit cures on a specialized hotplate. Curing is essential to performance by improving particle uniformity and conductivity.

Fabrication of the sensor is provided in Figure 1. There, the experimental sensor is made by printing the dielectric layer, feeding the paper back through for the semiconducting layer and then repeating for the conductive layer. All iPCs developed in the BioInspired laboratory follow this basic process.

The pressure sensors in this paper were tested using the Keithley 2604B Dual SourceMeter and recorded using the graphical user interface provided by Keithley for this product in the BioInspired Lab facility.

III. Pressure Sensing Array

The piezoelectric-based pressure sensor array is shown in Figure 2. Each node is electrically indistinguishable from one another. Analyzing one node may be generalized for the others assuming the variation of print and curing quality is approximately uniform throughout the device. A voltage applied across the terminals results in an output current at each pin, which are functions of the ZnO resistivities. The carrier mobility of Al-doped ZnO includes a strain variable from its piezoelectric property.

A. Electrical Characteristics

The I-V curve of a single node is provided in Figure 3. This curve was generated by applying the voltage and allowing a short time (<5s) for the current to settle before applying the next voltage. The settling time may be explained as a product of its piezoelectric effect. Applying a voltage means generating a non-zero strain at the moment of voltage change, inducing a small voltage that discharges after a few seconds. A fast voltage sweep shows some non-linearity whereas a slow sweep is more linear. The linearity of the produced I-V curve indicates that each node acts similar to resistor when the imposed strain is zero. For all tests, a high voltage (40 V DC) is supplied for maximal current output.

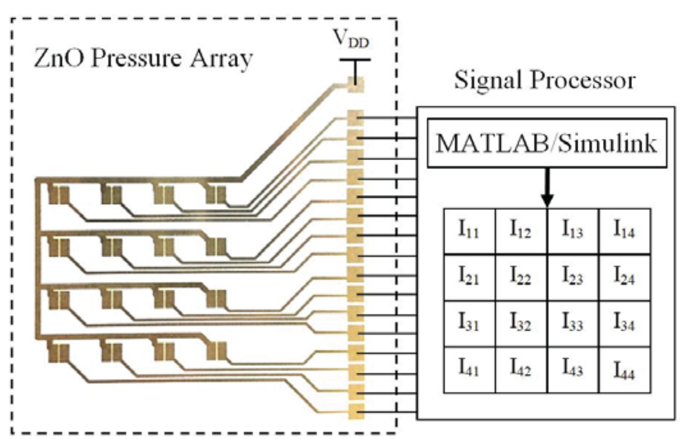


Fig. 2: Prototype Gate-less Al-doped ZnO FET Array with Conceptual Signal Processing Scheme.

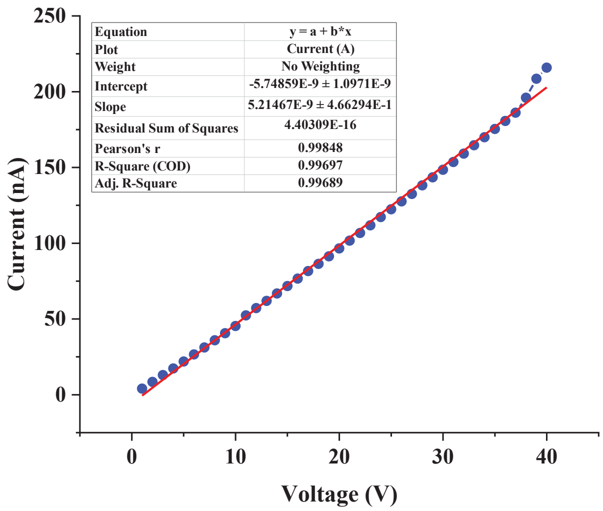


Fig. 3: I-V Curve of the Gate-less Al-doped ZnO FET with Linear Regression.

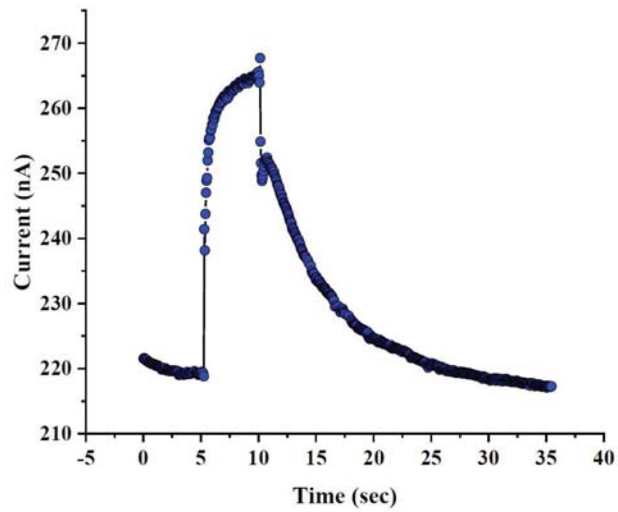


Fig. 4: Current output response versus time when pressure is applied to node I_{11}. The change in current is 50 nA and discharge time approximately 25 sec.

B. Pressure Array Tests

The piezoelectric array was placed in a translucent sleeve for all tests to prevent environmental stimuli from skewing data. This method of protecting the circuit created a slight dependency between nodes nearby each other. This works to the advantage of the pressure gradient mapping application as all nodes have dependencies and there is effectively more sensibility between nodes, increasing mapping variability. In other words, each node is aware of whether its adjacent nodes are exposed to strain. The pressure response of a single node is provided in Figure 4. Note that the rise-time is practically immediate whereas fall-time is long and gradual. It takes time for the material to discharge back to its original state.

Another observation is that while most of the current change is immediate upon external strain, there is a variation based on the magnitude of the strain value. Further investigation is displayed in Figure 5. The minimal strain applied resulted in current change of about 30nA, only half of its maximum current. Gradually increased pressure shows a proportionate rise in current. This means the piezoelectric mapping device is capable of defining varying levels of pressure rather than just a binary output. The gradient mapping is a function of pressure magnitude as expected from the characteristics of the piezoelectric material.

The output current of one node was plotted against time in plot (a) of Figure 6. Pressure was applied to the first node at 5 second and the output current rose 50 nA. After releasing at 10 second, an arbitrary 5 second discharge time was given before applying pressure to the next node in the first row. The process was repeated to produce the plot. Current discharges at the observed node after pressure is released and has slight but noticeable perturbations when the nearby nodes are applied strain. The test was repeated for each node. All plots showed similar response to plot (a) of Figure 6 in that the node of observation showed the most drastic current change and the

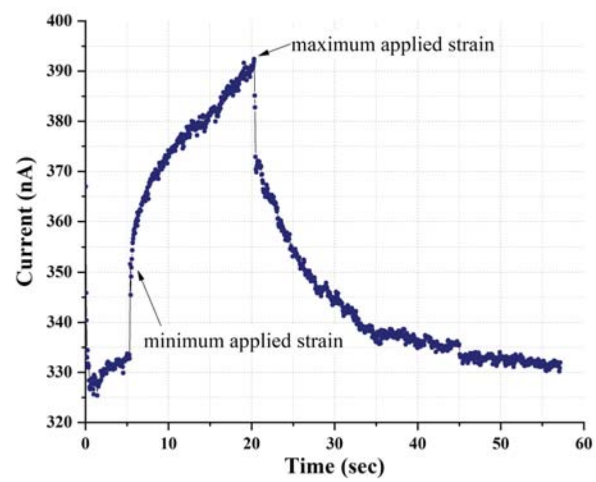
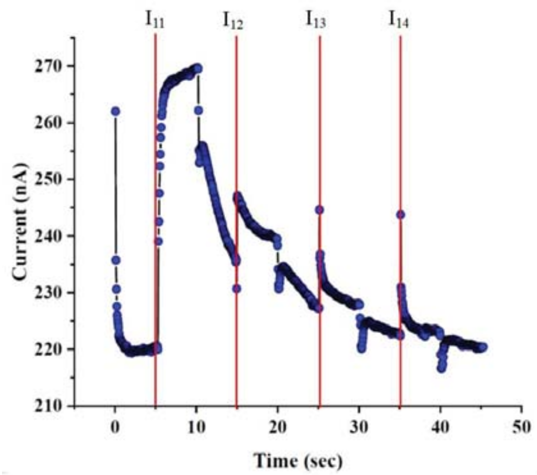


Fig. 5: Current output response versus time when pressure differences are applied to node I_{11}. The change in current is 50 nA and discharge time approximately 35 sec.

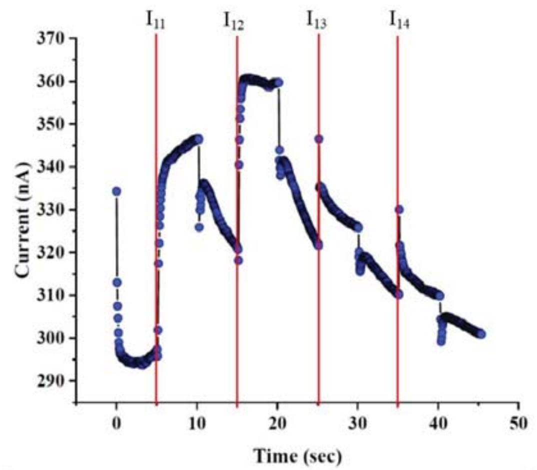
nearby ones has diminishing effects on its output. Plot (b) of Figure 6 is an example of a different node (I_{12}) under the same test conditions. Note that the nearby nodes induce a current flow at magnitudes inversely proportional to the distance from it.

C. Future Tests and Applications

Several tests will be performed to thoroughly characterize the array. One test is the effect of current drift on the device and how to reduce it. Another is a closer look at charge/discharge times. Tests to see the selectivity of all outputs under various mappings will show the effectiveness of the device. All these tests may be repeated for different packaging methods and



(a)



(b)

Fig. 6: (a) Current response vs time of I_{11} when pressure is applied to each node. The change in current is most substantial at I_{11}. (b) Current response vs time of I_{12} when pressure is applied to each node. The change in current is most substantial at I_{12}.

adjusted print patterns in an effort to explore selectivity control and improve current output at reduced voltages.

Aside from the application of this paper, the most straightforward implementation of the array is a fully printed, biodegradable keyboard. The packaging method would change by applying buttons directly over the nodes, avoiding dependencies between keys and making them more selective. Other applications of Al-doped ZnO include anything related to pressure and vibration monitoring. A thorough study of the vibrational responses would be conducted to gauge how sensitive the Al-doped ZnO is to environmental perturbations. Another application being considered is in the biomedical field. R. A work prior to this uses graphene overlayed with an interdigited pattern of silver as a carbon dioxide breathing rate monitor [6]. A similar print has been made with the same silver pattern but ZnO instead of graphene. This is useful as a breathing monitor device, where the difference is that ZnO detects strength of breathing flow while the graphene detects carbon dioxide concentration. Together, these can be used to cross-validate each other and improve the accuracy of the monitoring device.

IV. Conclusion

This paper is a brief look at an application of inkjet-printed circuits produced in the BioInspired Lab at UAB. Al-doped ZnO has semiconducting and piezoelectric properties, making it ideal for pressure-based applications. The printed Al-doped ZnO gate-less FETs arranged into an array create a pressure sensitive canvas. When the containment method is a material covering the entire device, small dependencies between adjacent nodes form. The combination of dependencies between nodes of the array and each node's ability to detect various strain magnitudes makes the setup ideal for pressure gradient mapping applications. Aside from the applications discussed, this pressure array will be implemented into wearables such as a shoe for footprint pressure mapping, which will help doctors observe the mobility of their patients before and after operations. As more is discovered regarding the behavior of this fully printed, planar and biodegradable design, the spectrum of applications will continue to reveal itself.

Acknowledgment

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