Transparent, Scalable, and Flexible Piezoelectric Pressure Sensors

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ABSTRACT

Present-day touchscreens are capable of mapping the spatial locations of applied pressures, but not the magnitude of applied pressures. As a result, a light and a hard press are currently interpreted similarly. Incorporating pressure sensitive materials into flexible displays can lead to functionality that adds another dimension to the machine-user interaction. Additionally, the integration of such elements on flexible and transparent thin polymer layers has an enabling potential to realize smart and interactive displays at unprecedented resolution and functionalities. We report a scalable monolithic integration scheme for the realization of such devices and the validation of functionality by using a novel Zinc Oxide (ZnO) device that acts as a dual transistor and a pressure sensor simultaneously, thereby allowing seamless integration onto displays without the need to place additional addressing electronics.

Keywords: Pressure, sensors, transistors, flexible, piezoelectric

1 INTRODUCTION

Zinc oxide (ZnO) is a wide-bandgap (3.3 eV) transparent semiconductor that can be deposited by a variety of methods[7]. Thin-film transistors utilizing ZnO as the active channel material have been fabricated using sputtering [1][2], pulsed laser deposition[3], atomic layer deposition[5], hydrothermal growth[6], sol-gel coating[4], and others. However, the method currently used for deposition of ITO for the capacitive touchscreen technologies is sputtering. It is critical for any emerging technology to be compatible with the existing manufacturing methods. In addition, sputtered ZnO TFTs with mobilities as high as 70 $\frac{cm^2}{V \times s}$ have been demonstrated by Fortunato et al [2]. Therefore, sputtered ZnO promises to be an excellent candidate as touchscreen material. Furthermore, with the increasing interest in flexible electronics, a scheme for fabrication of the device on a flexible substrate is desirable. Here, we report a method for integrating the ZnO pressure sensors on a flexible substrate.

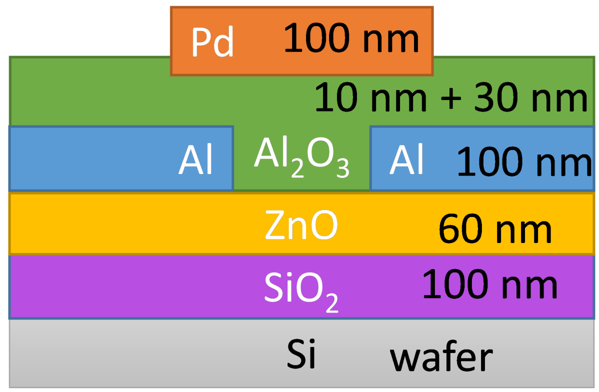

Figure 1: Device structure prior to transfer to flexible substrate

2 EXPERIMENTAL

For the flexible pressure sensors that we are currently working towards, the device structure shown in Figure 1. The fabrication proceeds as follows. First, a Si wafer is cleaned using standard RCA cleaning process and a 100nm-thick SiO_2 layer is grown on the Si wafer by using dry thermal oxidation at 1000°C. Next, a 60-nm thick ZnO layer is deposited using RF sputtering from a ZnO target on a AJA ATC ORION 8 RF sputtering system. The sputtering power is 100W, pressure is 2 mT, and the gas flow was Ar = 10 sccm and N2 = 10 sccm. The base pressure was on the order of 10^{-8} Torr. Next, a protective Al_2O_3 layer is deposited on top of the ZnO to passivate the material and protect it from atmospheric moisture. The 10-nm thick Al_2O_3 layer is deposited by plasma-enhanced atomic layer deposition (PEALD) at 100 °C. The source/drain mask pattern is applied to the substrate using conventional photolithography, and vias are etched through the Al_2O_3 layer. A 100 nm thick aluminium film is grown by electron-beam evaporation and patterned by liftoff. For a top-gate device configuration, another layer of 30 nm thick Al_2O_3 is grown by PEALD as the protective layer. Finally, the gate layer of 100 nm thick palladium is deposited via electron-beam

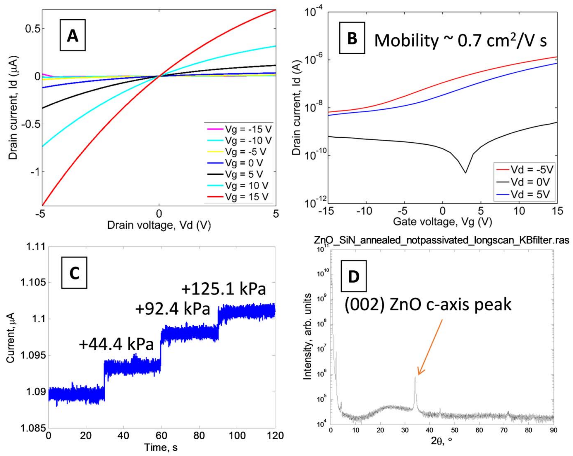

Figure 2: Electrical characteristics of ZnO TFT pressure sensor. a) Id-Vd curve. b) Id-Vg curve. c) Current as a function of time as various pressures are exerted on top of the device. d) XRD pattern of ZnO layer showing the preferred c-axis orientation of the film perpendicular to the channel.

evaporation and patterned using liftoff with standard photolithography. The device described above is not transparent. However, the device can be made transparent by replacing the electrode layers with transparent conducting oxides (TCOs), such as indium tin oxide (ITO) or aluminum-doped zinc oxide (AZO), as we have previously demonstrated [1]. After the device has been fabricated on the rigid substrate, it can be transferred to a flexible substrate by spin-coating a polyimide layer, etching back the Si substrate up to the SiO2 layer, and spin-coating an additional polyimide layer to achieve a stress-neutral plane for the sandwiched devices. The monolithic integration with Si circuits can be achieved as follows. First, the functional and read-out circuitry, along with the required transistors are fabricated on an SOI wafer. Next, the top Si layer is removed to expose the buried oxide layer (BOX). Next, the ZnO TFT sensor fabrication proceeds as outlined above. Vias are etched to connect the ZnO source, drain, and gate lines to the Si circuit electrodes. The final optional step is transfer to flexible substrate.

3 DISCUSSION AND RESULTS

Reference devices were initially fabricated on glass substrates [1]. The electrical properties of a reference device are shown in Figure 2. The Id-Vd curve in Figure 2a displays n-type semiconductor characteristics and an Ohmic contact. Figure 2b shows the Id-Vg measurement, with an off current on the order of few nA, and an an Ion/Ioff ratio of ≈ 200 in the voltage range of Vg = -15V to Vg = +15V. The mobility of the channel layer

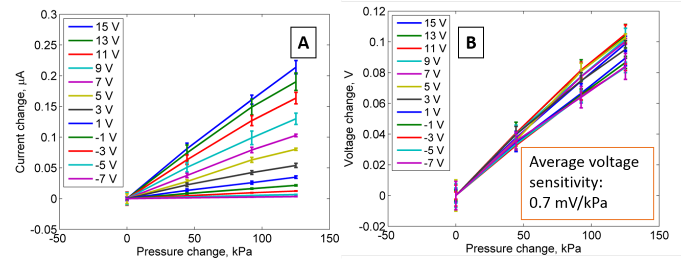

Figure 3: Current (a) and voltage (b) sensitivity of the ZnO TFT pressure sensor at different gate voltage levels Vg.

extracted from the transfer curve (Figure 2b) is around 0.7 $\frac{cm^2}{V \times s}$. Using a pulsed measurement technique, we were able to obtain a stable current measurement as a function of time, shown in Figure 2c. When pressure is exerted on top of the TFT (every 30s an additional new weight is applied), the drain current increases. Pressure sensitivity measurements are shown in Figure 2c. We believe that the following pressure sensing mechanism takes place. Upon application of pressure on top of the ZnO TFT, the vertical electric field inside the channel is created due to the assymetric shifting of ions inside the piezoelectric ZnO material. This electric field effectively changes the channel potential, or, alternatively shifts the threshold voltage. Depending on the direction of applied pressure and the film polarity, this effect could either enhance or decrease the effective gate voltage. The potential change contributes to the drain current allowing well defined gradual changes with incremental pressure increase. Figure 3a shows that the current change is linearly proportional to the applied pressure and also depends on the applied gate voltage. This can be thought of as biasing the device at various gate voltages, and then measuring the current change due to a small perturbation of the gate voltage. This effect can be used in reverse. From the measured changes in currents, using the Id-Vg plot, it is possible to reverse calculate the "effective" gate voltage change. The extracted effective voltage change at various gate voltage biases is shown in Figure 3b, where the voltage sensitivity is estimated at 0.7 mV/kPa and appears to be independent of the gate voltage. This suggests that piezoelectric charge density is much higher than that induced by the gate bias, which supports our proposed mechanism and provides means for developing high resolution pressure sensors.

4 CONCLUSION

Since the voltage sensitivity is an intrinsic property of the film, the current sensitivity can be increased by creating a material with a higher slope of the Id-Vg curve, or, equivalently, a higher mobility. Therefore, there is a potential to increase the sensitivity of the devices by ≈ 100 fold with optimizing the ZnO deposition technique to obtain much higher electron mobilities of $>50\ \frac{cm^2}{V\times s}$ as reported elsewhere [8].

The demonstrated pressure sensor can be easily integrated into an array without the need to place an additional switching element next to every pixel. This would allow the readout circuit to be placed completely off the screen.

The array configuration can be created by adding multiple transistors in parallel on a common source and drain lines, and connecting individual gate lines to control multiple source/drain patterns at once. We are currently working on optimizing the composition and thickness of the dielectric layers and the device functionality on a flexible substrate which we believe could become a competitive alternative to replacing the existing touchscreen pressure sensor technology.

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