Fabrication and Characterization of Fully Transparent ZnO Thin-Film Transistors and Self-Switching Nano-Diodes

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Fabrication and Characterization of Fully Transparent ZnO Thin-Film Transistors and Self-Switching Nano-Diodes

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Abstract. Fully transparent zinc oxide (ZnO) based thin-film transistors (TFTs) and a new type of rectifiers calls self-switching nano-diodes (SSDs) were fabricated on glass substrates at room temperature by using low resistivity and transparent conducting Al-doped ZnO (AZO) thin-films. The deposition conditions of AZO thin-films were optimized with pulsed laser deposition (PLD). AZO thin-films on glass substrates were characterized and the transparency of 80 % and resistivity with 1.6×10^{-3} Ωcm were obtained of 50 nm thickness. Transparent ZnO-TFTs were fabricated on glass substrates by using AZO thin-films as electrodes. A ZnO-TFT with 2 μm long gate device exhibits a transconductance of 400 μS/mm and an ON/OFF ratio of 2.8×10^{7}. Transparent ZnO-SSDs were also fabricated by using ZnO based materials and clear diode-like characteristics were observed.

1. Introduction

Zinc Oxide (ZnO) have attracted attention as material suitable for use in transparent conductive films because of its wide band gap (E_g = 3.3 eV at 300 K), high electron mobility, rich in natural resources and low cost [1]. Therefore, ZnO can be used for a transparent electron devices on glass or flexible plastic substrates by a low temperature process. Thin-film transistors (TFTs) using ZnO thin-films for the channel layer are a famous application of it [2]. Additionally, low resistivity and transparency materials are required for the transparent conduction in electron devices. In recent years, indium tin oxide (ITO) has been widely applied as a low resistance, conductive material [3]. However, indium is toxic and it is a rare metal. On the other hand, ZnO based low resistance conductive materials are more advantageous than ITO. It is possible to reduce their resistivity by doping them with other n-type dopants, such as indium, gallium, and aluminum (Al) [4-6]. Out of those elements, aluminum has less poison and is rich in mineral resources. In this work, Al-Doped ZnO (AZO) thin-films deposited under optimum conditions were used as the electrodes of ZnO-TFTs.

On the other hand, development of radio frequency devices is active because the areas of goods management and security are employing electronic technology. New types of rectifiers for radio frequency identification (RFID) tags are studied by many groups. It is difficult to form high quality p-type materials from ZnO. As the result, it is difficult to fabricate a p-n junction diode by using ZnO films. One of the new types of rectifiers is called a self-switching nano-diode (SSD). SSD is a kind of rectifier without a p-n junction or a barrier structure so it is possible fabricate it with single material [7]. It has been reported that SSDs using compound semiconductor materials such as InGaAa and GaN [8, 9]. According to M. Y. Irshaid *et al.*, SSDs using ZnO thin-films on a glass substrate have demonstrated at least 51.5 MHz frequency [10]. In this work, fully transparent SSDs were fabricated by using ZnO thin-films as channel layers and AZO thin-films as electrodes.

2. Deposition and Characterization of Al-Doped ZnO

For a purpose of optimizing deposition conditions, AZO thin-films were grown on glass substrates (Corning Eagle XG) by pulsed laser deposition (PLD) at room temperature. A Nd:YAG laser (fourth harmonic, λ = 266 nm) is used for ablation of AZO ceramic target (ZnO-2 wt.% Al_2O_3). The laser repetition rate was 10 Hz and the laser pulse energy density is 2-3 J/cm^2. AZO thin-films with 50 nm thickness were grown under several different oxygen partial pressures (P_{O_2}). The structure of these samples is shown in figure 2. The conditions of P_{O_2} were set in the range of 1×10^{-2} to 1×10^{-5} Torr, and without oxygen. The characteristics of AZO thin-films grown with different conditions were measured by optical transmission measurements, atomic force microscope (AFM), and Hall effect measurements.

Figure 1 shows the optical transmittance from 200 nm to 800 nm wavelength for the AZO films on glass substrates. The photograph in figure 1 shows the fabricated samples. The transmittance increases with increase of the P_{O_2} to 1×10^{-4} Torr. Higher transmittance was observed from a sample grown under 1×10^{-4} Torr of P_{O_2} and it was about 80 % in visible light region. The roughness of AZO thin-films surface was analyzed by an AFM. The roughness of root mean square (RMS) increases with increase in P_{O_2}. The AZO films have a smooth surface with a value of RMS roughness below 1 nm when P_{O_2} is less than 1.0×10^{-4} Torr. Figure 2 shows the variation in carrier mobility, carrier density, and resistivity of the AZO films deposited under different conditions. Carrier mobility is not much changed even when P_{O_2} is changed. Carrier density is stable when P_{O_2} is lower than 1×10^{-4} Torr and its value is around $6\text{-}7\times10^{20}$ cm^{-3}. However, it is decreased when P_{O_2} is higher than 1×10^{-4} Torr. Due to the carrier density, resistivity decreased at higher P_{O_2} but obtained about 2×10^{-3} Ωcm at lower P_{O_2} conditions. From those results, $P_{O_2} = 1\times10^{-4}$ Torr is a good condition for growing AZO thin-films as electrodes by PLD and using it to fabricate transparent electron devices.

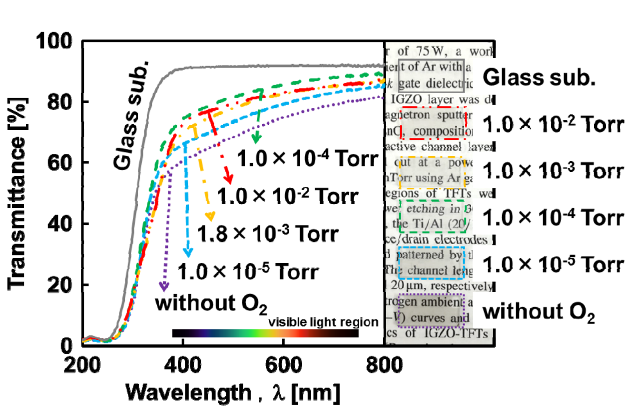

Figure 1. Optical transmittance for the AZO thin-films on glass and the photograph of text as seen through the samples.

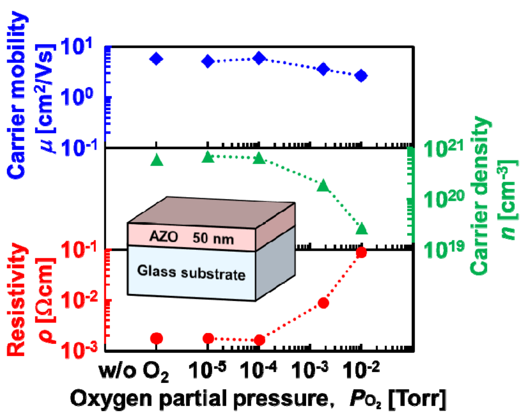

Figure 2. Carrier mobility, density, and resistivity of the AZO thin-films on glass and the structure of the samples.

3. Fabrication and Results of ZnO Thin-Films Transistors

In this work, transparent electron devices were fabricated with unheated process for application to flexible substrates. All the temperatures of the device processing were under 170 °C. Figure 3 shows a schematic diagram of a fabricated top-gate type ZnO-TFT. All layers of this TFT were grown by PLD. ZnO channel layer with a thickness of 40 nm was grown on a glass substrate under optimized P_{O_2} of 6×10^{-3} Torr. We previously reported that HfO_2 gate insulator layer grown at the high P_{O_2} is useful for a small hysteresis in the I_D-V_{GS} curves. The 50 nm thick HfO_2 gate insulator was deposited by PLD at P_{O_2} of 1×10^{-2} Torr. The electrodes were formed by 100 nm thick AZO thin-films at P_{O_2} of 1×10^{-4} Torr. A photograph shows ZnO-TFTs using metal for electrodes and using AZO in figure 4. From the comparison, the transparency of these two kinds of ZnO-TFTs are very different.

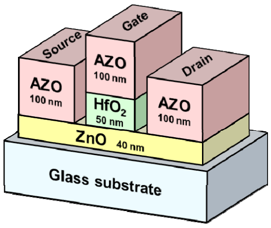

Figure 3. Schematic view of a top-gate ZnO-TFT fabricated in this work.

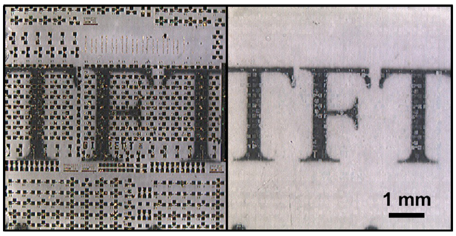

Figure 4. A photomicrograph of ZnO-TFTs using metal (left) or AZO (right) electrodes on glass.

A typical source-drain current (I_{DS})-voltage (V_{DS}) characteristics of a 2 μm gate length (L_G) device are illustrated in figure 5. The gate voltage (V_{GS}) was changed from -1 V to 7 V at 1 V steps. The device exhibits a maximum drain current of 1.4 mA/mm and a transconductance (g_m) of 400 μS/mm. Figure 6 shows the transfer characteristics (I_{DS}-V_{GS}) of the ZnO-TFT. V_{DS} was set to 8 V. The threshold voltage of this ZnO-TFT is 0.5 V and it has an ON/OFF ratio of 2.8×10^7, subthreshold voltage swing ~ 0.3 V/decade. From there results, we succeeded in fabricating transparent ZnO-TFTs reaching a practical level by using AZO thin-films as electrodes.

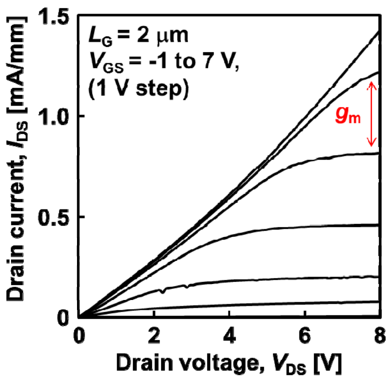

Figure 5. I_{DS}-V_{SD} characteristics at V_{GS} = 1 V intervals for a transparent ZnO-TFT.

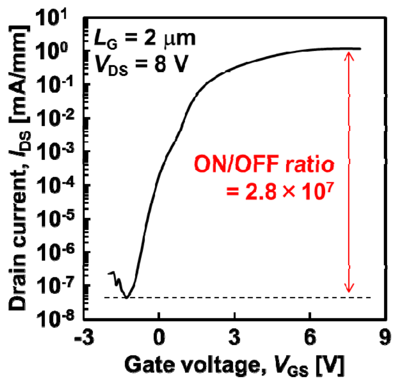

Figure 6. I_{DS}-V_{GS} characteristics with V_{DS} = 8 V of a transparent ZnO-TFT.

4. Fabrication and Results of ZnO Self-Switching Nano-Diodes

The fabrication process of ZnO-SSDs is very similar to that of ZnO-TFTs. A 40 nm thick ZnO thin-film is used as a channel layer. The carrier density of ZnO thin-films using in this work is 2.7×10^{18} cm^{-3} and carrier mobility of 4.4 $cm^2V^{-1}s^{-1}$ were obtained from Hall effect measurements. A simple structure of a ZnO-SSD shown at the inset of figure 7. Trenches on a 50 μm square ZnO channel layer were fabricated by electron beam lithography and wet chemical etching by using a diluted phosphoric acid. The L-shaped trenches were etched through the glass substrate to act as insulation. Ohmic electrodes were formed by 100 nm thick AZO thin-films.

Figure 7 shows the current-voltage (I-V) characteristics of a fabricated ZnO-SSD. The ZnO-SSD has a channel with length (L) of 1.8 μm and width (W) of 300 nm. Clear diode-like characteristics were observed. The ZnO-SSD was measured in the range of -40 V to 40 V. The SSD had a high

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breakdown voltage and the turn-on voltage was estimated to be about 24 V. Figure 8 shows a comparison of the sample's current in *I-V* characteristics for the device with and without ZnO-SSD. The current of the ZnO-SSD is lower because the area of SSD channel is smaller than normal channel. Rectification ratio (γ) was defined with a forward current (I_F, V = 40 V) divided by a reverse current (I_R, V = -40 V) and the γ of 2.6×10^1 was obtained from a fabricated ZnO-SSD. Fully transparent ZnO-SSDs are realized from achievements of fabricating transparent ZnO-TFTs.

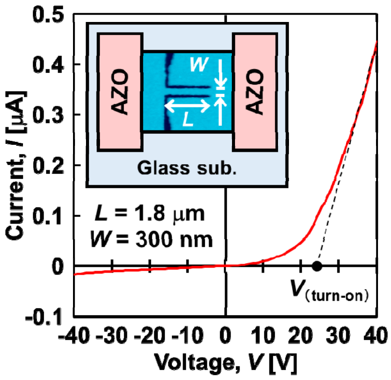

Figure 7. Schematic of a transparent ZnO-SSD fabricated on glass and its *I-V* characteristics.

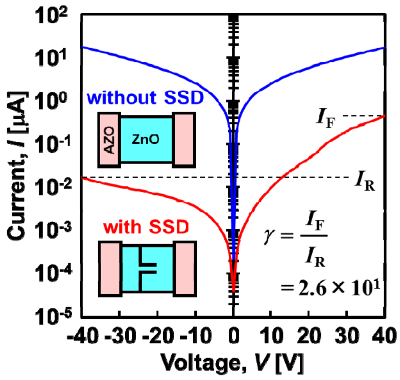

Figure 8. A comparison of performance between devices with SSD and without SSD.

5. Summary

Fully transparent ZnO-TFTs and SSDs were fabricated using AZO thin-films as transparent electrodes on glass substrate at room temperature. We optimized the deposition conditions to grow low resistance AZO thin-films with PLD. A 50 nm thick AZO thin-film on a glass substrate had resulted in a transmittance of 80 % in visible light region and a resistivity of 2×10^{-3} Ωcm. A transparent ZnO-TFT with the AZO thin-film as electrodes showed a clear pinch-off characteristic with an ON/OFF ratio of 2.8×10^7 and a g_m of 400 μS/mm. A new type of rectifier called SSDs with clear diode-like characteristics were fabricated using ZnO based transparent materials.

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