Effect of Thickness and Doping Concentration of Aluminium to the Fabrication of ZnO Photoconductive Sensor

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Abstract. The effect of thickness of aluminium doped zinc oxide (AZO), doping concentration of Aluminium as well as the annealing temperature to the fabrication of AZO photoconductor sensor is the main focused of this research. Silvaco TCAD tool is used to fabricate the AZO photoconductor sensor and to obtain the electrical characteristics of the device by using its simulation software. The device performance was investigated with various thicknesses of AZO film, annealing temperatures and different Al doping concentration. The Al doping was varied $1 \times 10^{17}$ cm$^{-3}$, $1 \times 10^{19}$ cm$^{-3}$ and $1 \times 10^{21}$ cm$^{-3}$, the thickness was varied 0.2 nm, 1.0 nm and 1.2 nm and the temperature was varied from 300°C, 500°C and 700°C. The electrical properties of AZO photodetector were characterized using current voltage (I-V) measurement system respectively. The result shows that by changing the thicknesses of aluminium doped zinc oxide (AZO), and the doping concentration of aluminium in the zinc oxide have greatly improved the electrical characteristics as well as the electrical performances of the photoconductor sensor. Indeed, the post fabrication and simulation process using simulation tools is helpful for the determination of the parameters during the later process of the real device fabrication.

1. Introduction
Aluminium doped Zinc Oxide (AZO) has been studied in various applications such as optoelectronic, photoelectric and transparent electronic devices. All these applications require high work responsitivity, high conductivity and high transparency over the visible range [1]. Since it was discovered, AZO has been researched by many especially on how to improve the properties, their applications and its performance.

There are different techniques used to fabricate aluminium doped zinc oxide active layer. It includes physical and chemical techniques such as spray pyrolysis technique [2], RF Sputtering [3], chemical deposition [4] and others. Besides having to fabricate it hours in a laboratory, AZO can also be prefabricated by using a simulation software via Silvaco TCAD tools. This pre-fabricated or simulation process is very useful that ease the parametric optimization in the later processes. It helps to develop a AZO prototype structure and device in a short time and thus could lower the cost used to fabricate the real device. In this research, AZO structure is designed and analysed using Athena Silvaco TCAD tools.
The AZO structure thickness, doping concentration and temperature were varied and then characterized using current voltage (I-V) measurement in the Atlas, respectively. The reasons why AZO is used in this research is because it is reported to have high transmittance in the visible region, a low resistivity and the optical band gap can be controlled by using Al doping amount [7].

Recently, some researchers investigated the method to fabricate AZO, those methods are spray pyrolysis technique [8], RF Sputtering [9], Sol-Gel Technique [10]. However, these techniques are very costly and require special conditions such as gaseous ambient, lattice matched substrate, other than that it require experimental set up [10] and a lot of time to be spent to fabricate the AZO. However, all these methods were reported to provide high quality AZO. On the other hand, AZO is fabricated virtually using Silvaco TCAD tools in this research. There are several advantages using Silvaco TCAD tools, which is the performance of the aluminium doped AZO can be investigated and different parameter can be varied in this software. In this research, the performance of the AZO photoconductive sensor can be investigated by using the I-V Characteristic. The result can be predicted, and this will be useful information for researchers to conduct the real experiment.

This research focused on simulation analysis of the thickness, doping concentration and temperature of Aluminium to the fabrication of Al-doped ZnO photoconductive sensor using Silvaco TCAD tools. The structure of the AZO is applied for the use in photoconductor sensor. In this research, AZO thickness, doping concentration and temperature were varied and the device characteristic were investigated by the I-V Characteristic.

2. Experimental

For any fabrication purpose using Silvaco simulation software, a general guide for simulation process is provided by the company in order to ease users. With this general flow chart then the summary fabrication process using Atlas used in this study was simplified and shown in Figure 1.

![Figure 1](image-url)

**Figure 1.** Process flow chart for the fabrication of AZO.

In the experimental work, firstly, the thickness of the active layer is varied in order to investigate the best thickness of AZO layer that can minimize resistivity and at the same time forming enough thickness for current flow which does not impede electrons. In this part, both doping and annealing temperature were kept constant. Secondly, doping concentration of Aluminum to the ZnO was investigated with the optimal thickness obtained in the previous investigation. Finally, using the both optimized parameters then after the investigation for annealing temperature is conducted. The summary of fabrication process flow adopted in this study is as shown.
3. Results and Discussion
In this research, in order to further investigate the key role of the AZO layer in our photodetector, AZO layer with different thickness have been prepared and their I-V comparisons characteristics is shown in Figure 2. In this section, the I-V result for both the dark current, \( I_d \) as well as photocurrent, \( I_p \) obtained by changing the thickness of the AZO layer at fixed doping concentration was investigated. It is revealed that in the earlier stage of the thickness addition, the photocurrent \( I_p \) increased as the thickness of AZO increased from 0.2 nm to 1.0 nm. However, it then decreased when the thickness is kept increased above 1.0 nm as can be witnessed at 1.2 nm thickness. Meanwhile, the dark currents, \( I_d \) were reciprocally following the trend in \( I_p \). In general, the decreased in \( I_d \) will results in the increases of \( I_p \) and eventually increased the current gain, \( \text{Gain} = \frac{I_p}{I_d} \). As can also be observed that the photocurrent, \( I_p \) with 1.0 nm AZO coating is the highest among other thicknesses which reaches to as high as 550 nA at -0.6 V of anode voltage. This observation might be associated with the profile of AZO layer being grown. When the thickness is below 1.0 nm, the ZnO may be partially covered with non-uniformly covered film. As it was understood that the role of AZO is to improve the interface between ZnO and electrode, so the photocurrent increases with the increase of AZO thickness. However, when the thickness is above 1.0 nm, the possible rate of the recombination caused by defect trapping and scattering will get larger with increasing AZO thickness, thus the photocurrent will decrease with increasing thickness of AZO film beyond the optimal limit at 1.0 nm. Therefore, 1.0 nm AZO film is the best to collect the photo-generated electrons.

![Figure 2. \( I_p \) and \( I_d \) comparison characteristic at different AZO thicknesses.](image)

Figure 3 below shows result of varying doping concentration of aluminium to the ZnO layer in the AZO photoconductic sensor by maintaining the thickness of 1.0 nm. It can be observed that at lower level of doping concentration of 1.0 x 10^{17} \text{ cm}^{-3} and 1.0 x 10^{19} \text{ cm}^{-3} the current increased by the increasing of aluminum doping concentration. In general, when ZnO as a metal oxide is doped with a proper element it will improve the electrical performance of the device by reducing the resistivity of the AZO film. Extrinsic doping such as Aluminium serves as a donor in ZnO lattice. Higher conductivity carrier concentration will also increase the mobility carrier as the Aluminium concentration increases. Increasing the Aluminium concentration into the ZnO, Al ions will create an lot of free electron in ZnO, and in return, electrical conductivity increases.
Al ions in ZnO acts as charge carriers reservoir and as donor impurities. As the Al concentration increases, the Al atom will get closer to the Zn sites, this will lead to the force of charge carriers transport and increase the conductivity. However, for further increased of the Al doping at $1.0 \times 10^{21} \text{ cm}^3$ has caused the light current, $I_p$ decreased. This is mainly because the decreased in the conductivity of the AZO film as the overloaded Al atoms in the lattice will impede the electron (carriers) flow within the crystal. Secondly, this phenomenon is also probably attributed by the difference in the ionic radius of zinc (0.074nm) and Aluminium (0.055nm), thus will cause an increment in resistivity. As mentioned above, Al$^{3+}$ provides extra free electron into the system. In contrast, the increase doping levels affected to increase the resistivity of doped films that may be associated with the addition of insulator Al$_2$O$_3$ concentration [11, 12]. However, the optimum of Al doping level was found at $1.0 \times 10^{19} \text{ cm}^3$ in AZO film.

![Figure 3](image.png)

**Figure 3.** $I_p$ and $I_d$ comparison characteristic at different Al doping in AZO film.

Figure 4 below shows the $I_p$ characteristics when the temperature were varied between 300°C, 500 °C and 700°C and the thickness of the Al-doped Zinc Oxide were kept constant with a thickness of 1.0 nm and the aluminium doping concentration were kept constant at $1x10^{19} \text{ cm}^3$. Result shows that the current $I_p$ increased as the annealing temperature increased which is closely related to the decreases in resistivity of the AZO film. As mostly reported, the resistivity decreases with increasing temperature is actually due to the behavior of the bulk Zinc Oxide semiconductor, and it seems to have exhibited in the case of AZO film prepared in this study. In addition, the decrease in electrical resistivity is also associated with the grain size during the post-annealing process.

Theoretically, grain size increased with increasing annealing temperature. As grain size increased, then the grain boundary to decrease and also improved the crystallinity of ZnO. The improvement in crystallinity improved the mobility of the charge carrier and the current, $I_p$. In this experiment, the results showed that the electrical resistivity of AZO films decreased with increasing annealing temperature from 300°C to 500°C but increased with annealing temperature from 500°C to 700°C. The decrement of resistivity has been represented by the increment of current characteristics in the I-V results.

The current, $I_p$ variation with annealing temperature of the AZO films can be attributed to the increase of oxygen when increasing the annealing temperature that reduces the number of oxygen vacancies (free carrier) in ZnO films. This result is similar to those reported by Asghar et al. [13] and Bouhssira et al. [14] in their study when investigating the effect of annealing temperature on the characteristics of AZO film.
4. Conclusion
In summary, Al-doped ZnO photoconductor have been successfully prepared and simulated using Silvaco TCAD tools. Effect of thickness, doping concentration of Aluminium and the annealing temperature to the fabrication of Al-doped ZnO photoconductor have been investigated by means of the performance of its light current, $I_p$ and the associated dark current, $I_d$. Al–doped ZnO (AZO) photodetector device gave high conductivity of electric current, $I_p$ when the thickness of AZO was at 1.0 nm and the amount of aluminium doping concentration was at $1.0 \times 10^{19}$ cm$^3$. Meanwhile on the effect of annealing temperature variation, the AZO film requires the optimum annealing temperature of 500°C which in turns causing the highest increases of $I_p$ among others. Finally, it can be concluded that we have successfully prepared samples of AZO of good electrical properties which can be used in many opto-electrical applications. Above all, it can also be witnessed that the post fabrication and simulation through Silvaco TCAD tools can be very helpful for the real fabrication process in the later process of photodetector.

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