Review of ZnO Transparent Conducting Oxides for solar applications

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Abstract. Solar energy is a renewable clean energy and photovoltaic is one of the most effective ways to use sunlight currently. Transparent conductive films such as ITO, AZO and so on as the window layer are widely used in HIT and other high efficiency silicon-based heterojunction solar cells. The Zinc oxide conductive thin film (ZnO) has a high transmittance at 800-1200 nm and a low resistivity, and has the potential to replace ITO film. However, it is limited by the preparation method. The resistivity of the film itself is very high, about 1E-3Ω·cm. And the average optical transmittance in the 300-1200 nm wavelength range is less than 80%. Furnace annealing can play a key role in the elimination of stress, film of repair, recrystallization and grain growth, reducing the interface defects, improving the interface properties, and film photoelectric performance is improved. In the other hand, doping is necessary for achieve a high properties ZnO film.

1. Introduction
The thin film solar technologies apply transparent conducting oxides (TCOs) in improving the performance of the solar cells. In modern technology, the creation of the TCOs is done by using metallic oxides and sometimes sulphides. This is because these types of metals have high levels of electrical conductivity. The chemicals used also have high levels of thermal and chemical stability. One of the metals that are used as TCO is Zinc Oxide. Zinc Oxide (ZnO) is a band gap semiconductor which belongs to the II-VI semiconductor group. The n-type class of doping is used in zinc oxide because of the favorable properties. Some of the properties that make Zinc Oxide a good semiconductor include the good transparency, the mobility of the electrons, the wide bandgap and the strong room temperatures. According to Adewoyin, 2018, the properties of the TCOs are dependent on the deviations of the stoichiometric nature and the type of impurities which exist in the host.

2. Status and prospect
To modulate the chemical properties of the semiconductors, doping is performed. Doping is basically the introduction of the impurities into the semiconductor. The doping material is known as the extrinsic semiconductors. The process of obtaining the thin films of Zinc Oxide is carried out by various processes. The process of deposition is carried out by various methods such as thermal evaporation, molecular beam epitaxy. Scientists also apply the Pulsed laser deposition (PLD) method in the obtaining Zinc Oxide thin films. The PLD method is preferred in the production because it allows the advantage of allowing deposition at low temperatures. The deposition also takes place in a controlled system of reaction through which there is high deposition rates. The properties of the process allow the control of the composition and the properties of the film. Recently, this method has been applied in organic tests and other forms of hybrid tests [2].
The method of deposition allows the manipulation of the properties of the thin films. Tovar et al., 2017, carried out a test on the “structural and optical properties of ZnO thin films prepared by laser ablation using target of ZnO powder mixture with glue.” In this study, the researchers deposited ZnO thin films using the PLD method to two different targets. The researchers used one pure ZnO powder as the target substrate while the other substance that was used in the test contained Cyanoacrylates and Zinc Oxide Mixtures. Cyanoacrylates are a group of metals that are used in the industrial applications such as coatings and adhesives and other sealants. The study then compared the test physical and chemical properties of the thin films deposited on either mixture. The structural and the optical properties of the two depositions were then compared. The research found out that thin films of zinc which had been grown with the Cyanoacrylates glue had better properties compared with the traditional target materials. This study hence recommended that the CA glue material should be used in the creation of the CdTe solar cells as an interreflective layer compared to the traditional cells [3].

Different metal oxides function differently in the solar cells. The metal oxides are used in the solar cells as transparent conduction oxides. They control the open voltage in the solar cells. In a study conducted by Adewoija, 2017, it was noted that kesterite Cu2ZnSnS4 (CZTS) perform differently under various metal oxide influences. The study used fluorine doped tin oxide (FTO), aluminum-doped zinc oxide (AZO) and indium tin oxide (ITO) in the study. The researchers looked at the conversion efficiency and noted that ITO was the best performing device because it had an efficiency of 9.98%. This was followed by AZO which had a conversion rate of 8.41% and FTO which had a conversion rate of 5.91%. The study hence concluded that the AZO substance and the FTO substance have better stability of the thermal components. The device performance hence varied with the different metal oxides. The researches further investigated other factors that contribute to the optimization of the performance of the devices. The researchers looked at the thickness of the TCO film in relation to the efficiency of the device. It was observed that the performance of the device did not improve when the thickness of the metal was increased by 0.025 with the ITO component. The researchers however noticed a deterioration of the performance of the device when the thickness of the metal was increased in AZO and FTO. This was mainly associated with the degree of resistance that is created by the increased thickness of the compounds. This study was different from the study conducted by Martin Tovar et al., 2017, on the impact of thickness on the conductivity where he had noted that the thickness does not influence the performance of the device [1].

Figure 1: Transmission spectra of superstrate glass coated with ZnO deposited at different substrate temperatures
The researchers of this property also investigated the impact of bilayers of TCO on improving the performance of the device. The study followed evidence from previous studies which indicated that having a double layer of the component of the material improves the performance of the device. The researchers introduced a double layer to the oxides. They observed that the creation of a double layer of the oxide has positive impact on the performance of the light element. The double layers had improved electrical performances compared to a single layer. A bilayer increased the optical properties of the two oxides and hence improved the performance of the bulbs. However, an increase in the thickness of the

It is evident that different metals and oxides perform differently and hence some are preferred to be used as conductors while others are not. Researchers have embarked on determining the advantages of some metal oxides over others. Warasawa et.al carried out an investigation on the advantages of using amorphous indium zinc oxide films for a layer of solar cells. The researchers investigated the advantages of using this compound over the conventional Ga-doped zinc oxide which is used in the solar cells. In the research, the electrical properties of the Indium Zinc Oxide (IZO) were distanced from the thickness of the film. The IZO components have a higher rate of mobility and a lower rate of resistance. To prove that the IZO should be taken into the window layer, the researchers investigated these properties and compared it with the properties of Ga-doped zinc oxide [4].

The main goal of doping a semi-conductor is so that the degree of resistance is reduced and the density of the carrier is also increased. The electron mobility is hence the most important factor that the scientists must consider in the determination of the material to select. According to Waraswa, 2010, the indium zinc oxide had a bandgap energy of 3.6eV. The chemical has an amorphous structure and hence it has high reproducibility in different conditions of deposition. It can be deposited without the intentional heating through the sputtering method. The other property that Zinc Oxide holds is that there is high mobility and it has low free-carrier absorbance in the same density. This means that the IZO deposits are the best in solar cells compared to Ga-doped Zinc Oxide. The electrical properties of IZO make it the preferred component in the solar cells [4].

The image below was derived from Waraswa’s study. It details on the relationship between mobility and density of the carrier of different chemicals.

![Figure 2: µ-n relationship for IZO and ZnO:Ga. Dot-dashed and dashed lines show the µ-n relationship for grain-boundary scattering and ionized impurity scattering, respectively.](image)

The performance of the Zinc Oxide as a conductor is also dependent on the size of the particles and the morphology factors of the particles. A study conducted by Zhang et.al investigated the impact of the size of the particles and the morphology of the particles on the properties of ZnO. The study also investigated the magnetic properties that would be changed in case the shape of the ZnO was changed.
It was observed that the change in the shape has great influence on the electrical properties of the ZnO [5].

Researchers have also investigated the other methods that can be used to improve the performance of the Zinc Oxide chemicals. A study conducted by Tsai et.al 2015 revealed that the photovoltaic performance of triple junction solar cells can be improved by the use of ZnO nanorods/TiO2. The study found out that the additional compound increased the performance of the triple junction solar cells and recommended that future solar cells should apply this technique in improving efficiency. The image below is derived from the study. It shows the proposed AR structure in the triple junction solar cells.

Another study focused on the application of the creation of CdTe thin film from a nanowire made up of ZnO arrays. This study was mainly focused on the replacement of the known buffer layers. This means that there is minimum alteration of the structure of the solar cell. The incorporation of the nanowire was found to change the performance of the solar cells while the dimensions of the wire influenced the performance of the device. The shorter wires of approximately 100 nm showed that there was low performance in the cell while the longer wires of approximately 250-2000nm had more functional cells. The researchers were able to produce working devices with up to 9.5% efficiency. This was through the production nanowire cells which had an embedded tip. The study hence concluded that the length of the nanowire influence the properties of performance through the
recombination of the carriers. The study showed an alternative way of creating conductors in film solar cells without doping of Zinc Oxide.

The nanowires have attracted the attention of many researchers as the alternative for the optoelectronic devices. The nanowires work “By constraining carrier transport in two dimensions” which allows the carriers to be moved through the dimension that has not been strained. The arrays give the cell an improved charge through which there is increased mobility of the carriers and there is a reduction of the reflection levels. This allows better optical collection and hence this improves the efficiency of the photovoltaics. The implementation of this prospect is however very challenging because the creation of the nanowire cells on a macroscopic scale is difficult. The nanowires also have high aspect ratio and this causes complexity and hence it is hard to take them up as solar cell fabricators [6].

The ZnO nanowires are used in different solar cells. In a similar study conducted by Mo, et.al, 2017, he identified that the nanowires can be grown and used in CdS quantum dots sensitized solar cells. In this study, a chemical bath deposition (CBD) was used to grow ZnO on the ITO conducive glass. These nanowires were used in the assembly of the CdS quantum dots sensitized solar cells. The research then investigated the growth process and the photovoltaic performance of the CdS quantum. The increase in the growth time increased the average size of the nanowire. This method increases the aspect ratio of the nanowires which in turn increases the efficiency of energy conversion in the CdS quantum. From the study, the best energy conversion rate (η) was 0.401% whereby there was an aspect ratio of 20.56. It was noted that in such a solar cell, the density of the current is increased because there are more electron-hole pairs and there is strong light which traps the effect of ZnO nanowires [4].

In the recent past, scholars have engaged in a research to investigate the impact of various processes on the properties of various metals. These studies have mainly focused on the optical and photovoltaic properties. In a study conducted by Mehrabian, 2015, the optical and photovoltaic properties of ZnS nanocrystals fabricated on Al:ZnO films using the SILAR technique were observed. In this study, the hybrid solar cells were used whereby the structure was fabricated such that the successive ion layer absorption and reaction (SILAR) technique was applied effectively. The ZnS layer was grown on the ITO/AZO to fabricate the cell. It was observed that eh bandgap varied in the narrow range of 3.8-4.0 eV based on the SILAR cycles. The study then examined the properties of the fabricated cells in the illumination of one sun (AM 1.5, 100mW/cm2). The study hence concluded that the SILAR cycles improve the performance of the fabricated photovoltaic cells. The efficiency of the cells was observed to be 3.25% after six cycles of SILAR.

The image below shows the fabricated solar cell.
To control the operations of the solar cells, various techniques are used. One of the aspects that scientists have sought to investigate is the reduction of reflection of light in ZnO/Si heterojunction thin film solar cells. In a study conducted by Fallahazad et al., 2017, it was observed that the surface texturing and nano structure coating is a method of reducing the degree of reflection in the film solar cells [7].

3. Conclusion
In conclusion, from the studies carried out above, it is evident that doping of the ZnO allows the improvement of the efficiency of solar cells. These studies have investigated various properties of ZnO and how they can be changed.

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