

The effect of temperature on the efficiency of dye-sensitized solar cells (DSSC) based on magnesium-doped ZnO nanorods

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ABSTRACT

This study aims to analyze the effect of an optimum temperature of 80°C on the performance of DSSCs based on magnesium (Mg)-doped ZnO nanorods. The synthesis of ZnO:Mg nanorods was carried out using a seed-mediated hydrothermal method with variations. Material characterization included X-ray diffraction (XRD) to analyze the crystal structure, field emission scanning electron microscopy (FESEM) for morphology, UV-Vis spectroscopy for optical properties, and current-voltage (I-V) measurements for photovoltaic performance. The results show that Mg doping in ZnO can modify the energy band gap, enhance visible light absorption, and improve electron mobility. Variations in growth temperature significantly affect the morphological structure of the nanorods and the energy conversion efficiency of the DSSC. The optimum temperature of 80°C yielded the highest efficiency of 1.846%, where the ZnO:Mg nanorods formed were uniform, dense, and well-oriented, resulting in higher DSSC efficiency compared to other temperature variations. These findings confirm that the combination of Mg doping at a growth temperature of 80°C can enhance the performance of ZnO-based DSSCs.

Keywords: Doping; DSSC; growth; magnesium; temperature

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INTRODUCTION

Global dependence on fossil fuels has triggered a policy shift towards a cleaner and more sustainable energy system. This issue has encouraged various countries and international institutions to transition towards a cleaner and more sustainable energy system [1]. One of the renewable and renewable energies is solar energy. Solar energy is utilized as a renewable energy source through solar cells that convert sunlight into electrical energy based on the photovoltaic effect, which is a process in which light absorbed by semiconductors triggers the movement of electrons [2].

One of the devices developed to utilize solar energy is dye-sensitized solar cells (DSSC), which are included in the third generation of solar cells. DSSCs have attracted the attention of researchers because of their advantages over silicon-based solar cells, such as lower

production costs, simple fabrication processes, and good performance in low light conditions [3]. The DSSC structure generally consists of a photoanode, electrolyte, and counter electrode. The photoanode plays an important role because it is where the electron transfer process from the dye to the semiconductor takes place [4].

Semiconductor materials frequently used in DSSC photoanodes are titanium dioxide (TiO₂) and zinc oxide (ZnO). ZnO is a promising candidate because it has a wide band gap (~3.37 eV), high exciton energy (60 meV), good chemical stability, and its nanostructure morphology can be easily controlled through synthetic methods [5]. The ZnO nanorod shape, in particular, has the advantage of a faster electron transport pathway and a high diffusion length, thus potentially increasing the conversion efficiency of DSSCs [6, 7]. However, the use of pure ZnO still has

limitations, especially in terms of dye stability and relatively low conversion efficiency compared to TiO_2 . To overcome this, a widely used strategy is doping with metal elements such as magnesium (Mg) [8].

Mg doping in ZnO can modify the energy band structure, expand light absorption into the visible region, and increase electron mobility. In addition, variations in growth temperature during the synthesis process also affect the grain size, morphology, and crystal quality of ZnO nanorods, which ultimately impacts the performance of DSSCs [9].

Based on this, this study was conducted to examine the effect of variations in growth temperature on the structural, morphological, optical, and efficiency properties of magnesium-doped ZnO nanorod-based DSSCs [6]. With this understanding, it is hoped that optimum conditions can be obtained to improve the performance of ZnO:Mg-based DSSCs as a candidate for renewable energy technology in the future [10].

RESEARCH METHODS

The main materials used are zinc nitrate hexahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) as a Zn source, magnesium nitrate hexahydrate ($\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$) as a Mg doping precursor, hexamethylenetetramine (HMT) as a growth control agent, and N719 dye as a DSSC sensitizer. Fluorine-doped tin oxide (FTO) is used as a conductive substrate, while I^-/I_3^- -based electrolyte is used as an electron transport medium [11].

Synthesis of Mg-Doped ZnO Nanorods by Seed-Mediated Hydrothermal Method

The synthesis is carried out in two stages, namely the formation of a seed layer and the growth of nanorods. The seed layer is made by dissolving Zn acetate dissolved in ethanol, then coated on the FTO substrate using the spin coating method, followed by heating at a temperature of 350°C to obtain a ZnO seed layer [3]. The growth process uses a substrate

with a seed layer dipped in a mixture of $\text{Zn}(\text{NO}_3)_2$, HMTA, and $\text{Mg}(\text{NO}_3)_2$ with varying Mg concentrations. The growth process is carried out in a hydrothermal oven at varying temperatures of 60°C , 70°C , and 80°C for 8 hours. After the process is complete, the substrate is rinsed with distilled water and dried at room temperature [10].

DSSC Fabrication

The obtained ZnO:Mg photoanode is then immersed in an N719 dye solution for 24 hours so that the dye molecules are adsorbed on the nanorod surface. The substrate is then assembled into a solar cell by adding a Pt/FTO-based counter electrode and an I^-/I_3^- electrolyte [8].

Characterization

The characterization carried out in this study is X-Ray Diffraction (XRD), used to determine the crystal structure and grain size of ZnO:Mg. Field Emission Scanning Electron Microscopy (FESEM) was used to analyze the morphology of nanorods. UV-Vis Spectroscopy was used to measure optical absorption and determine the band gap energy [12, 13]. Energy Dispersive X-ray (EDX) was used to confirm the presence of Mg elements in the ZnO structure [5]. And I-V Characterization was used to determine the photovoltaic performance of DSSCs, such as energy conversion efficiency, short circuit current (J_{sc}), and open circuit voltage (V_{oc}).

RESULTS AND DISCUSSION

UV-Vis Characterization

Figure 1 shows the absorbance curves of ZnO 90°C and ZnO:Mg materials synthesized at several variations of heating temperatures (60°C , 70°C and 80°C) in the wavelength range of 300 – 600 nm. In general, all samples show a strong absorbance peak in the UV region around 300 – 350 nm, which is characteristic of the valence band transition to the conduction

band in ZnO semiconductor materials [8]. In pure ZnO heated at 90°C, the absorbance intensity appears slightly higher than that of the ZnO:Mg sample [14]. This indicates that Mg doping causes a decrease in absorbance intensity, possibly due to changes in the electronic structure and an increase in crystal defects that can affect the light absorption process [15]. For ZnO:Mg samples, increasing the calcination temperature from 60°C to 80°C shows an increasing trend of absorbance in the UV region [10]. This increase indicates that higher heating temperatures can improve the crystal quality or optimize the substitution level of Mg^{2+} ions into the ZnO lattice, thereby improving the optical response [16]. After passing through the wavelength of 380 nm (visible region), all samples show very low and relatively constant absorbance, indicating that the material remains transparent to visible light [12].

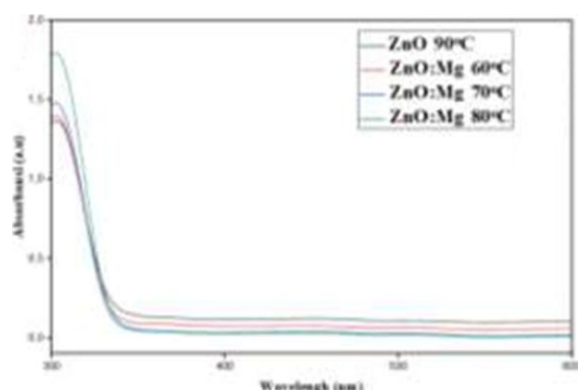


Figure 1. Absorption spectrum of ZnO:Mg samples with various growth temperatures.

Overall, this graph shows that Mg doping and variations in heating temperature affect the intensity of UV absorbance, but do not change the position of the absorption edge significantly [17]. This confirms that the band structure of ZnO is relatively stable, but its optical properties can be tuned through variations in the synthesis temperature and the addition of Mg dopants [18].

XRD Characterization

Figure 2 shows the X-ray diffraction (XRD) patterns of pure ZnO samples (90°C) and

ZnO:Mg samples heated at various temperatures (60°C, 70°C, and 80°C). All samples display the typical peaks of ZnO with a hexagonal wurtzite crystal structure, indicated by the appearance of diffraction peaks on the (100), (002), and (101) planes [6]. This confirms that Mg doping and varying the heating temperature do not change the basic structure of ZnO [8].

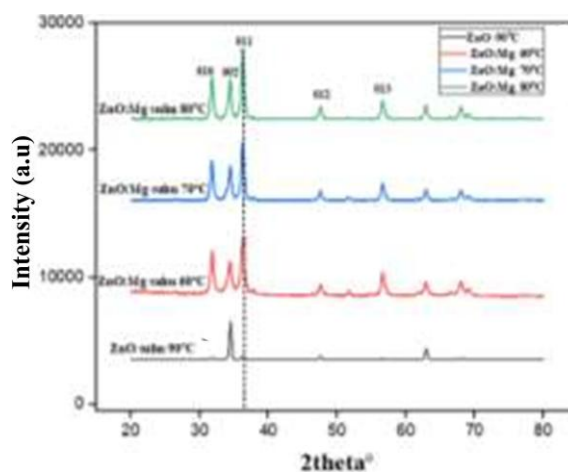


Figure 2. XRD patterns of pure ZnO and ZnO:Mg samples at various temperatures.

In the ZnO:Mg sample, the intensity of the diffraction peaks increases with increasing heating temperature [11]. The sample at 80°C exhibits the highest peak intensity, indicating improved crystallinity and larger crystallite size [19]. In contrast, the sample at 60°C had the lowest intensity, indicating a suboptimal crystallization rate [20]. In addition, the position of the main peak (101) in ZnO:Mg appeared to have shifted slightly compared to pure ZnO [4]. This slight shift indicates the possibility of Mg^{2+} ion substitution (smaller radius) into the ZnO lattice, which causes changes in the lattice parameter (lattice strain) [5]. No new peaks were seen that pointed to the MgO phase or other impurities, indicating that Mg was well dispersed in the ZnO structure and did not form a secondary phase [9]. Overall, this XRD pattern shows that the addition of Mg did not change the crystal structure of ZnO, but affected the crystallization rate and resulted in a slight peak shift due to changes in the lattice parameter [21]. Increasing the heating

temperature also plays an important role in improving the quality of ZnO:Mg crystals [22].

Field Emission Scanning Electron Microscopy (FESEM) Characterization

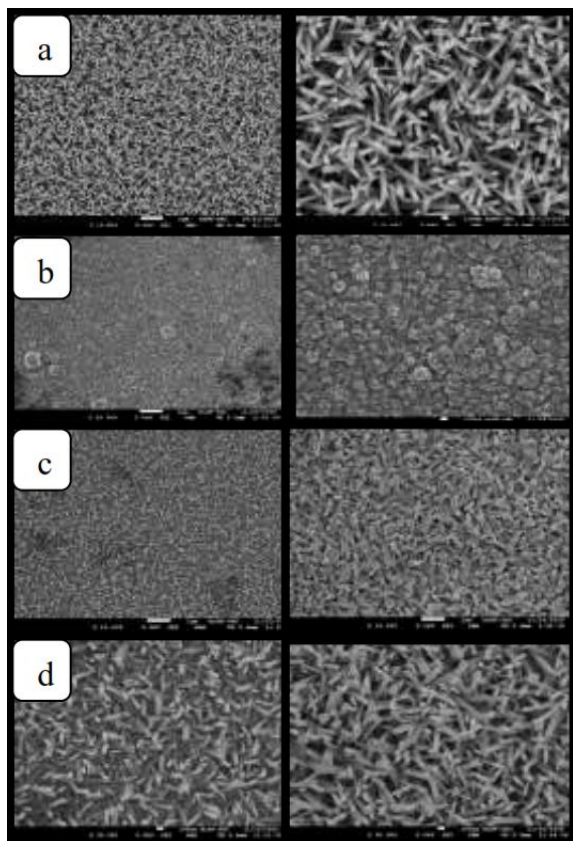


Figure 3. FESEM photos of nanorods (a) ZnO, (b) ZnO:Mg 60°C (c) 70°C (d) 80°C with a magnification of 10,000x and 30,000x.

Figure 3 shows the morphology of hexagonal ZnO nanorods that have varying diameters in each sample. Changes in synthesis temperature generally greatly affect the morphology, grain size, and level of particle agglomeration [8]. The FESEM results of pure ZnO show that the material has a morphology in the form of rod structures (nanorods) that grow randomly and stacked on each other. While at a temperature of 80°C the most uniform morphology appears, the particle size is relatively homogeneous and also the agglomeration is lower [13]. This condition is often considered as the optimum temperature, because the balance between the nucleation rate and crystal growth is achieved. Increasing the

synthesis temperature can increase particle size, reduce grain boundaries at high temperatures and cause agglomeration if the temperature is too high [14].

Efficiency of Dye-Sensitized Solar Cell (DSSC)

The results of DSSC performance tests are shown in Figure 4 which displays the I-V curves of DSSC samples based on ZnO and Mg-doped ZnO with variations in growth temperatures of 60°C, 70°C, 80°C, 90°C and 100°C [23]. Information on the effect of Mg doping on ZnO was carried out by measuring the I-V under a 400 mW/cm² halogen lamp. The current density value of undoped ZnO is 0.152 mA/cm² and the voltage is 0.347 V. This value is relatively small so it will affect the efficiency of DSSC. The efficiency of undoped ZnO DSSC is 0.104% [5].

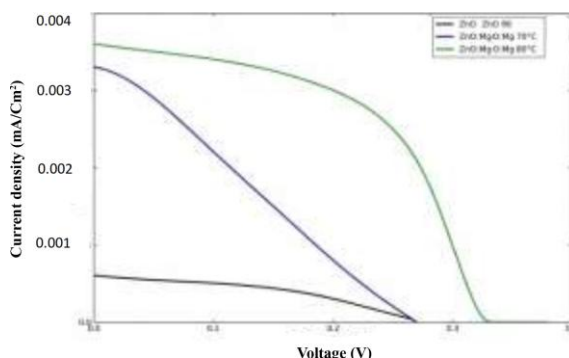


Figure 4. DSSC I-V curve.

Based on the research, the sample that shows the highest current density value with voltage is produced by the ZnO:Mg sample at 80°C, which is 0.458 mA/cm² and 0.596 V, with an efficiency of 1.846%. The increasing growth temperature exceeds the optimum growth temperature, resulting in an increase in crystal defects in the material structure [23]. This condition results in a decrease in the current and voltage density values which have an impact on the efficiency of DSSC [1]. The results of the efficiency calculation are shown in Table 1.

Table 1. Results of the performance measurement of DSSC based on ZnO:Mg nanorods with variations in growth temperature.

Sample name	J_{sc} (mA/cm ²)	V_{oc} (V)	FF (%)	η (%)
ZnO (90°C)	0.152	0.347	7.901	0.104
ZnO:Mg (70°C)	0.576	0.645	9.59	0.891
ZnO:Mg (80°C)	0.458	0.596	27.017	1.846

CONCLUSION

The I-V graph of the ZnO:Mg sample at 80°C shows the largest field area compared to other samples. The larger field area indicates that electron mobility is higher so that efficiency increases. The results of UV-Vis, XRD, FESEM characterization, and I-V testing show a strong relationship between optical properties, crystal structure, morphology, elemental composition, and performance of ZnO:Mg-based DSSCs. Based on the UV-Vis results, the ZnO:Mg sample grown at 80°C shows the highest absorbance, which indicates better light absorption capability than samples at other temperatures. This increase in absorbance is related to the formation of a more effective optical energy level due to Mg doping and optimum growth conditions, thus supporting the electron excitation process from the dye to the ZnO conduction band.

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