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Optimization of SWCNTs loading for In_2O_3 based dye-sensitized solar cell application

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ABSTRACT

Background: This paper analyses the structural and electrical properties of In_2O_3 photoanode incorporating with SWCNTs for DSSC application. **Objective:** The most optimum concentration of SWCNTs is analysed for DSSC application. **Results:** Small amount of SWCNTs promote photogenerated electron transfer and reduces charge recombination. **Conclusion:** The optimum SWCNTs concentration in In_2O_3-SWCNTs is 0.1 wt% for DSSC.

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INTRODUCTION

Dye-sensitized solar cells (DSSCs) also known as the Gratzel cells were first introduced by O'Regan and Gratzel in (1991). DSSCs are more desirable than other silicon solar cells due to their low cost manufacturing, simple fabrication and high efficiency energy conversion. DSSCs consist of three main structures: (a) photoanode, (b) sensitizer and (c) electrolyte. TiO_2 is conventionally used as metal oxide semiconductor as a photoanode which exhibits the highest efficiency to date with ~15 % power conversion efficiency (Burschka, J., *et al*., 2013). However, a desirable photoanode material with better DSSC performance is still critical. Therefore, alternative metal oxide semiconductor layers such as ZnO (Abdullah, H., *et al*., 2015), SnO_2 (Mahalingam, S., *et al*., 2015) and In_2O_3 (Abdullah, H., *et al*., 2014) have been used in recent years to improve the cell performance.

The study of the rare earth material of In_2O_3 is less due the slow charge carrier transport and non-porous nature in the morphology of the cell (Gan, J., *et al*, 2012; Sharma, R., *et al*., 2009). In spite of that, In_2O_3 is still used in DSSC as a photoanode layer. This is because when In_2O_3 is used as a dopant in TiO_2 layer, the open circuit voltage (V_{oc}) of the cell increased [8]. Besides that, Chen *et al*. reported that in terms of morphology In_2O_3 halt the growth of TiO_2 grains and showed a smooth surface roughness that could reduce surface reflection and could capture more photon energy (Chen, Y., *et al*., 2008). Although, the photovoltaic efficiency of In_2O_3-based DSSC is still lower than 8 %, it is a critical challenge to increase the cell's efficiency.

Recently, many works on carbon nanotubes (CNTs) have been reported for DSSC application which showed a remarkable cell efficiency [9]. CNTs as a catalyst are used as a composite matrials in the photoanode where it gives a direct pathway for the injected electrons to move easily towards the photo electrode (Chang, W.C., *et al*., 2012). Thus, the CNTs are able to increase the charege carrier transport in DSSCs. In addition, the morphology of the interpenetrating electrodes also increased by introducing CNTs into the photoanode (Razali, M.Z., *et al*., 2015). However, incorporation of high load of CNTs in the nanocomposite will retard the improvement of DSSC cell performance due to serious CNT aggregations (Razali, M.Z., *et al*., 2015).

In this work, we developed In_2O_3-SWCNTs nanocomposite by loading 0.1 wt% and 0.5 wt% of SWCNTs to study on the influence of loading SWCNTs in terms of morphology and photovoltaic efficiency. It is believed that the incorporation of optimum SWCNTs can enhance the In_2O_3-based cell's efficiency. The morphological structure was examined through atomic force microscopy (AFM) and field emission scanning electron microscopy (FESEM). The overall eficiency of the DSSC was determined by the *IV* curve measurement.

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2 Experimental details:

The chemical reagents used in this work are indium chloride ($InCl_3$), 2-methoyethanol, monoethanolamine (MEA) and acid-treated SWCNTs. 2-methoyethanol used as solvent to dilute $InCl_3$ and MEA was added as a stabilizer in the solution. 0.1 wt% and 0.5 wt% of SWCNTs was added in the mixture separately to form 0.1 M of starting solution. The mixture was ultrasonicated at 50 °C for 1 h nad the stirred at 60 °C for 24 h. The heated solution was spin-coated at 1500 rpm for 30 s and repeated for 5 times to coat 5 layers on the ITO substrate. The spin-coated ITO substrate was annealed at 450 °C for 30 min to produce 0.1-SWCNTs-In_2O_3 and 0.5-SWCNTs-In_2O_3.

The fabrication of DSSC photoanode took place by immersing the annealed thin films in N719 dye for 24 h. Meanwhile, the counter electrode was prepared by pasting platinum paste on a clean ITO substrate by screen printing technique. The pltinum paste substrate was annealed at 400 °C for 1 h. The dye immersed thin films and the platinum counter electrode were assembled by sandwiching them together. Idolyte MPN 100 acting as electrolyte is injected into the sanwich layer of DSSC.

AFM and FESEM analysis were done to study the morphology of 0.1-SWCNTs-In_2O_3 and 0.5-SWCNTs-In_2O_3 films. *IV* curve measurement evaluated the photovoltaic properties of the DSSC via Linear Sweep Voltammetry unit under 1.5 AM.

RESULTS AND DISCUSSIONS

3.1 Structural and morphology characterization:

The In_2O_3-SWCNTs thin film upper surface was viewed in AFM. Fig.1 (a) and (b) shows AFM images of the films loaded with 0.1 wt% and 0.5 wt% of SWNTs, respectively. From the 3D view of the images it is clearly seen that the texture of the films become rougher when higher concentration of SWCNTs added in the nanocomposite. The average roughness (R_a) values display the morphologies with a uniform surface structure. The AFM characterization confirm that the low concentration of SWCNTs (0.1-SWCNTs-In_2O_3) has a low value of R_a around 3.21 nm. Average roughness increased to 10.22 nm at high loading of SWCNTs in the nanocomposite (0.5-SWCNTs-In_2O_3). Table 1 lists the R_a. The AFM result signifies that rougher surface of the photoanode can bounce the incident light falling on the surface and indirectly reflects back (Chang, W.C., *et al*., 2012; Kathirvel, S., *et al*., 2013). On the other hand, smoother surface helps to absorb more photon energy from the sun directly on the surface of the metal oxide (Chang, W.C., *et al*., 2012).

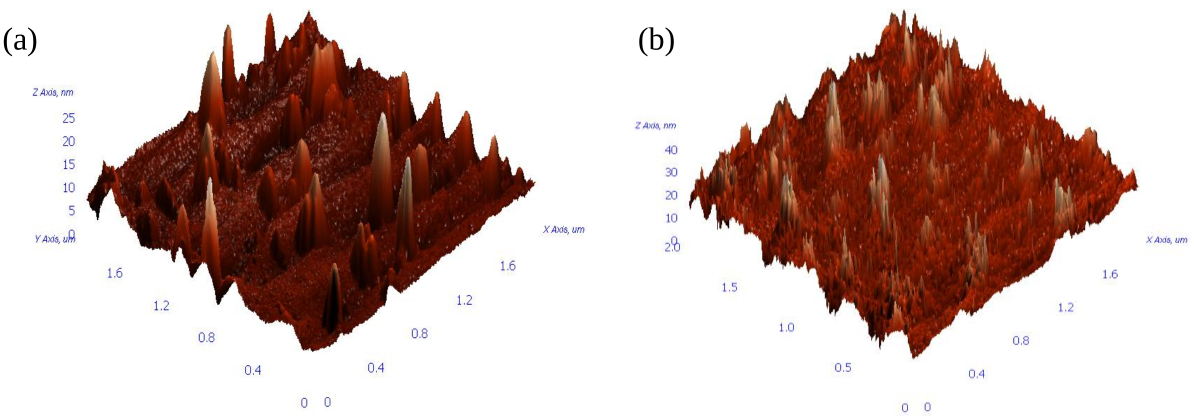

Fig. 1: AFM images of In_2O_3-SWCNTs with SWCNTs amount of (a) 0.1 wt% and (b) 0.5 wt%

Table I: Average roughness of 0.1-SWCNTs-In_2O_3 and 0.5-SWCNTs-In_2O_3

Amount of SWCNTs (%)	R_a (nm)
0.1	3.21
0.5	10.22

Fig. 2 (a), (b), (c) and (d) demonstrates the FESEM images of the surface morphologies of the In_2O_3-SWCNTs loaded with 0.1 wt% and 0.5 wt% of SWCNTs, respectively. The arrangement of SWCNTs in the porous nature of In_2O_3-SWCNTs (Fig. 1(a)) is clearly seen. The octahedron In_2O_3 nanoparticles are more in Fig. 1 (a) than in Fig. 1 (c) indicating that high loading of SWCNTs (0.5-SWCNTs-In_2O_3), causes the In_2O_3 nanoparticles to scatter farrer from each other. The serious aggregation of SWCNTs decreases the photovoltaic efficiency in the cell by decreasing the charge collection in the photoanode (Mehmood, U., *et al*., 2015). Moreover, a high amount more SWCNTs penetrating into the In_2O_3 nanoparticles is seen in Fig. 1 (d). This serious SWCNTs around the nanoparticles inhibit the injected electrons to be transmitted directly to the photoanode. In addition, Kim and Park supported the this statement where, high concentration of CNT has low transmission in DSSCs (Kim, Y.W. and S.H. Park, 2013).

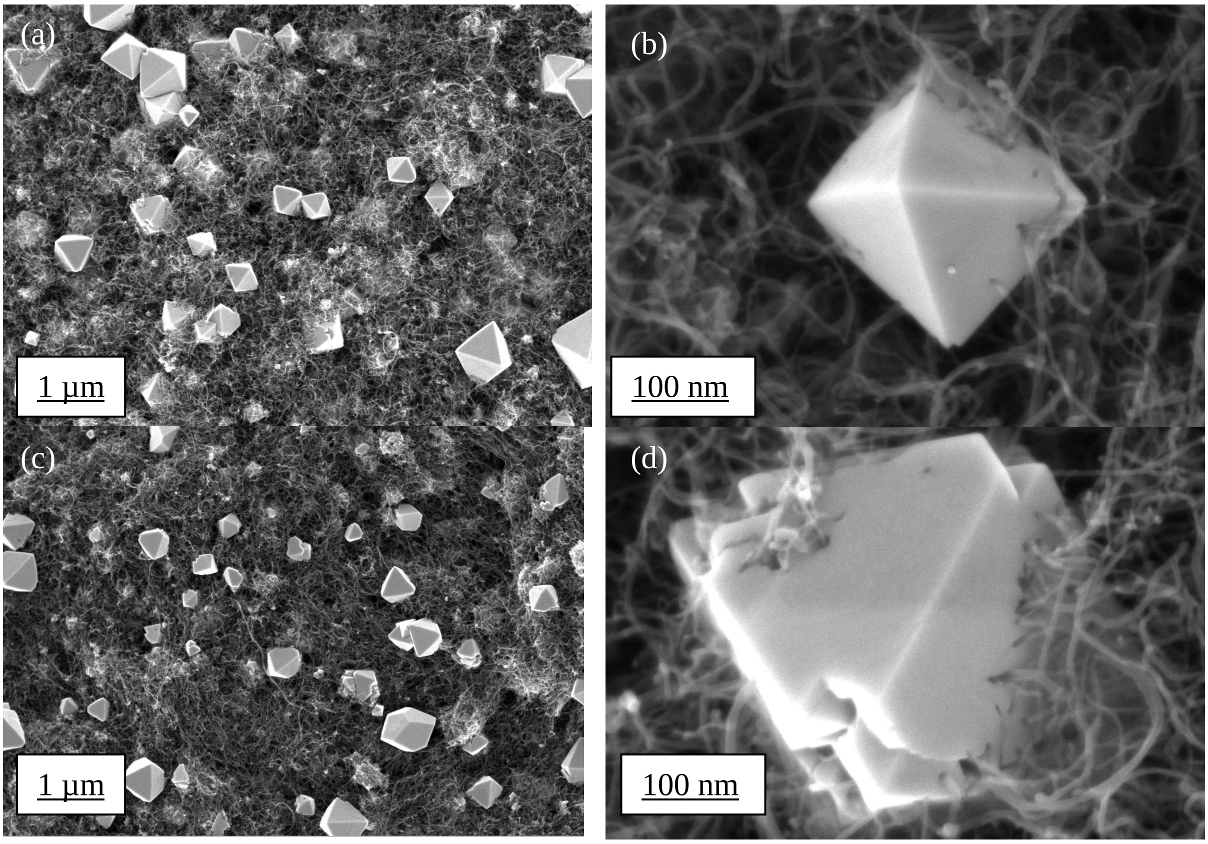

Fig. 2: FESEM images of In_2O_3-SWCNTs with SWCNTs amount of (a) 0.1 wt% in microscale, (b) 0.1 wt% in nanoscale, (c) 0.5 wt% in microscale and (d) 0.5 wt% in nanoscale

3.2 Photovoltaic performance of DSSC:

Fig. 3 shows the *IV* cure measurement for the In_2O_3-SWCNTs-based DSSCs. The efficiency of the cell is strongly depenedent on the loading amount of SWCNTs in the nanocomposite. The V_{oc} is achieved when the there is potential diference between the Fermi level of In_2O_3-SWCNTs and the redox electrolyte. While, the short circuit current density (J_{sc}) (mA/cm^2) is the maximum photocurrent received during light capturing by the N719 molecules (Liberatore, M., *et al*., 2009). The solar energy conversion efficiency (η) and fill factor (*FF*) for DSSC was calculated by equation (1) and (2) (Wen, P., Y. Han and W. Zhao, 2012),

$$\eta = \frac{V_{oc} J_{sc} FF}{P_{in}} \quad (1)$$

and

$$FF = \frac{V_{\max} \times J_{\max}}{V_{oc} J_{sc}} \quad (2)$$

Table 2 tabulates the photovoltaic properties obtained through the *IV* curve measurement. Both the J_{sc} and V_{oc} dropped when a high concentration of 0.5-SWCNTs were added in the nanocomposite to 1.54 mA/cm^2 and 0.32 V, respectively. Besides that, the *FF* and η also decreased for 0.5-SWCNTs-In_2O_3 films to 0.42 and 0.21 %, respectively.

The improvement in J_{sc} and V_{oc} for 0.1-SWCNTs-In_2O_3 films signifies that the charge collection and transport of electrons are enhanced in the DSSC. The highest efficiency was achieved for 0.1-SWCNTs-In_2O_3 films where it is consistent with the porous morphology and smooth surface seen in FESEM and AFM, respectively. Therefore, incorporation of SWCNTs in In_2O_3-based DSSC improves the cell performance but the CNTs concentration should be maintained at 0.1 wt% to achieve the optimum photovoltaic efficiency. A large amount of CNTs will cause the dye molecule and the CNTs to compete with each other for light-harvesting, thus increases the charge transport resistance and produces poor cell efficiency (Yu, J., J. Fan and B. Cheng, 2011). Furthermore, the excess amount of CNTs causes the photoelectrode to be less tranparent with its dark colour, that can decrease the photovoltaic efficiency.

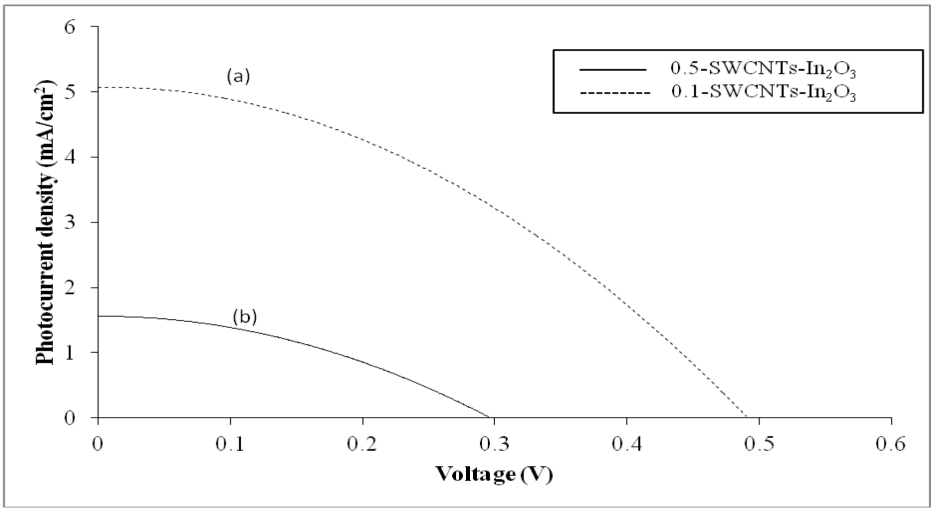

Fig. 3: *J-V* characteristics of In_2O_3-SWCNTs with SWCNTs amount of (a) 0.1 wt% and (b) 0.5 wt%

Table II: Photovoltaic properties of 0.1-SWCNTs-In_2O_3 and 0.5-SWCNTs-In_2O_3

SWCNTs Concentration (wt%)	V_{oc} (V)	J_{sc} (mA/cm^2)	FF	Efficiency (%)
0.1	0.49	5.23	0.45	1.16
0.5	0.32	1.54	0.42	0.21

Conclusion:

In summary, In_2O_3-SWCNTs-based DSSCs were succesfully fabricated. The optimum concentration of SWCNTs in the nanocmoposite is 0.1 wt% where it achieved 1.16 % of solar conversion efficiency with high J_{sc} and V_{oc}. The AFM and FESEM results showed 0.1-SWCNTs-In_2O_3 films have smoother surface structure and porous nature that facilitates the injected electrons to move easily towards the working electrode. The 0.5-SWCNTs-In_2O_3 films have a serious SWCNTs aggregation that inhibiths the cell performance. Hence, the optimum loading of SWCNTs in the nanocomposite of In_2O_3-SWCNTs is 0.1 wt% of SWCNTs that can improve the overall DSSC performance.

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