Using nanodiamond particles in photoanode of dye-sensitised solar cell

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In this work, nanodiamond (ND) particles were used as a scattering layer in a photoanode of a dye-sensitised solar cell (DSSC). The thickness of the ND layer was controlled by spin-coating speed. Current–voltage (*I–V*) test results showed that the thickness of the ND scattering layer is an important factor affecting cell efficiency. The best cell efficiency achieved was 6.16% with a spin-coating speed of 2000 rpm, which was 15% higher than the DSSC without the scattering layer.

1. Introduction: Dye-sensitised solar cells (DSSCs) have attracted increasing attention as a device that efficiently converts solar energy to electricity due to the low production cost, low weight, simple fabrication procedure and relatively good energy conversion efficiency [1–4]. A typical DSSC consists of a TiO_2 mesoporous layer on a conductive glass as a photoanode sensitised by dye molecules that convert a photon to an electron, an electrolyte that penetrates through TiO_2 mesoporous film and a conductive glass covered with platinum as a counter electrode [5, 6]. The main challenge in these kinds of cells is to increase the efficiency by using the simplest method. One of the most important techniques to improve the performance of the DSSC is using a scattering mechanism in the photoanode. This mechanism helps to enlarge the photon-travelling path in the photoanode and increase the absorption possibility of photons by dye molecules and consequently increase the photo-electron generation. Some researchers use the core–shell structure in the photoanode as the scattering mechanism. Wang *et al.* use SiO_2 particles as a core and coat a TiO_2 layer by the sol–gel method as a shell material [7]. This structure results in about 50% increase in power conversion efficiency of DSSC. Diamant *et al.* tried various materials as a shell on TiO_2 particles and investigated their effect on DSSC performance [8]. Results show that Nb_2O_5 increases the efficiency by 37.3%. Using a multilayer photoanode is another technique to scatter light in the photoanode and increase DSSC's efficiency. Anatase TiO_2 nanoparticles [9] and a mixture of rutile TiO_2 and ZrO_2 nanoparticles [10] were used as the scattering layer on top of the TiO_2 active layer. By optimising the size and mixing ratio of these particles, an improvement up to 87% in the current density of device can be achieved [10]. Introducing scattering sites in TiO_2 paste help to reduce the processing steps of the photoanode. Spherical voids could act as light scattering sites in the TiO_2 layer. By mixing organic materials such as polystyrene [10–12] and carbon [13] with TiO_2 paste and sintering, these materials burn out and leave voids. These voids act as light-scattering sites and also facilitate the diffusion of ions. By this strategy, the overall efficiency of the device was improved to 25% [4].

Nanodiamond (ND) has a 3.7 eV bandgap and can be used as a semiconductor [14–16]. This high bandgap does not allow this material to efficiently absorb the whole light spectrum and convert it to electron. So, it will be used as a light scattering layer in the photoanode of the DSSC. In this Letter, we evaluate the effect of thickness of the ND layer on top of the TiO_2 as the scattering layer on the efficiency of DSSC.

2. Experimental methods: To fabricate the photoanode of the DSSC, TiO_2 paste (PST-20T, composed of 20 nm TiO_2 nanoparticles; Sharif Solar) was coated on fluorine-doped tin oxide (FTO; Dysol) using doctor blade techniques and sintered at 500°C for 30 min. After this step, a mesoporous TiO_2 structure was achieved. Then a solution containing 0.3 wt.% of ND (HZ-Nanotechnology; produced by the detonation method) in ethanol [17] was prepared and sonicated for 1 h to disperse the ND particles and spin coated on the sintered TiO_2 layer. Spin coating was done at three various speeds, 1000, 2000 and 3000 rpm. By increasing the speed of rotation, the thickness of the layer will be decreased. Sintering of these final photoanodes was done at 500°C for 15 min. After cooling to 80°C, the photoanodes were immersed in 0.3 mM dye solution (N719; Solaronix) in ethanol for 24 h. The platinum paste (PST-Pt; Sharif Solar) was coated on a predrilled FTO glass using doctor blade technique, as a counter electrode. Both electrodes were sealed with 30 µm thick filler polymers (Surlyn; Dyesol) at 120°C for 90 s and filled with the electrolyte (standard iodine-based electrolyte; Sharif Solar) through the predrilled hole.

The active area of each cell is about 0.25 cm^2. The absorption spectrum of TiO_2 and ND layers was analysed by Ultraviolet-visible spectroscopy using a Unicam 8700 spectrometer. The current–voltage characteristics (*I–V*) were measured using a potentiostat under a simulated AM 1.5G light (Sharif Solar) by applying voltage and measuring current. X-ray diffraction (XRD) was used to indicate the crystal structure of ND particles. Scanning electron microscopy (SEM) was used to measure the thickness of the TiO_2 layer and the size of the ND particles.

3. Results and discussion: Fig. 1 shows the cross-section of TiO_2 photoanode. As indicated in this figure the thickness of the TiO_2 layer was about 14 µm which is the optimum thickness for the best efficiency [18, 19].

The sintering process of the photoanode was done at 500°C, so the ND particles need to be stable at that temperature. Fig. 2 shows the XRD spectrum of ND powder before and after heating at 500°C for 1 h in an air atmosphere. Results showed that the crystal structure of ND particles did not change. The JCPDS Card No. of ND is 00-001-1249. Butenko *et al.* showed that the ND particles begin to convert to graphite at about 950°C [20].

Fig. 3 shows the SEM image of ND particles. The size of ND particles is about 20 nm. The agglomeration is an intrinsic specification of nanoparticles produced with detonation techniques [15]. So using ultrasonication for dispersion is mandatory.

Since the thickness of the ND layer is very low and the surface of the TiO_2 layer is very rough, it seems that observing the ND layer by SEM is impossible. So we use the schematic view to show the

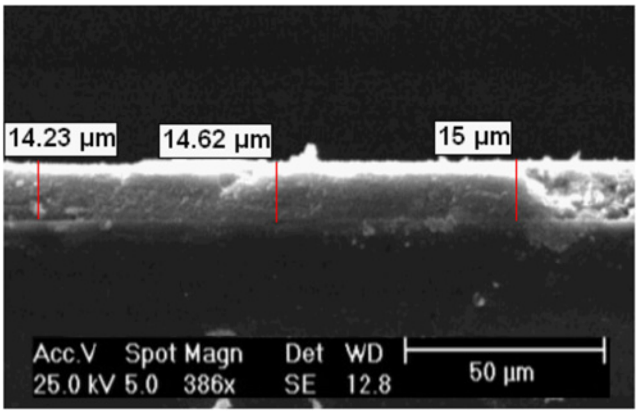

Fig. 1 *Cross-section SEM image of TiO_2 photoanode*

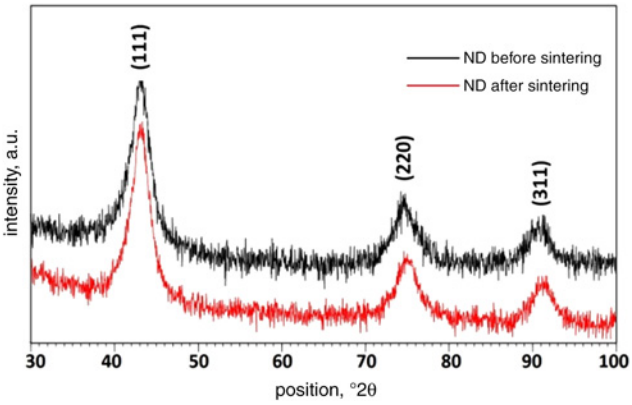

Fig. 2 *XRD spectra of ND powder before (top spectra) and after (bottom spectra) heating at 500°C for 1 h at atmosphere*

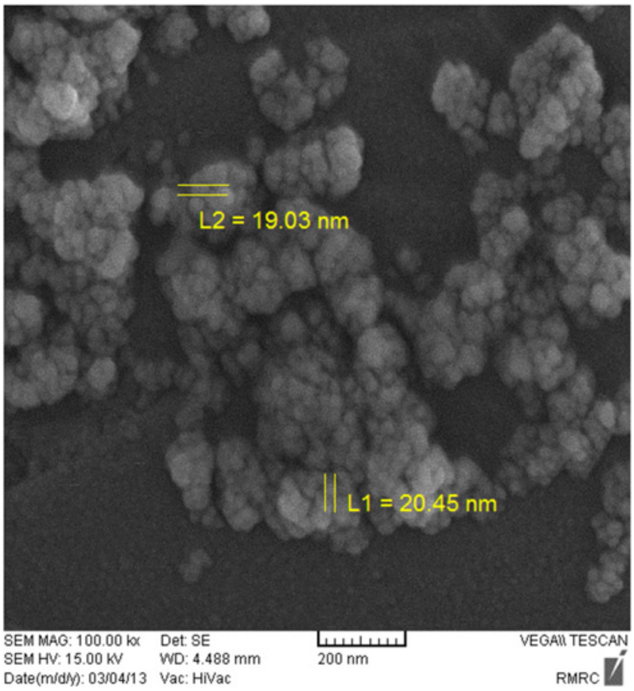

Fig. 3 *SEM image of ND particles*

situation of the ND scattering layer in the photoanode of the DSSC. Fig. 4 illustrates the schematic view of samples and the position of the ND layer in the DSSC.

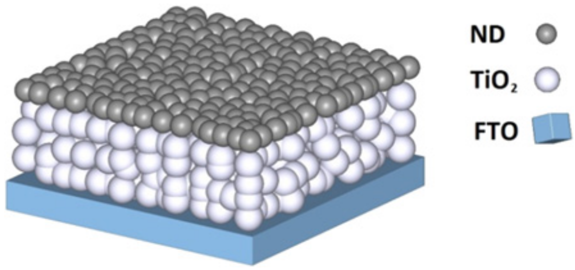

Fig. 4 *Schematic view of samples and the position of the ND layer in the DSSC*

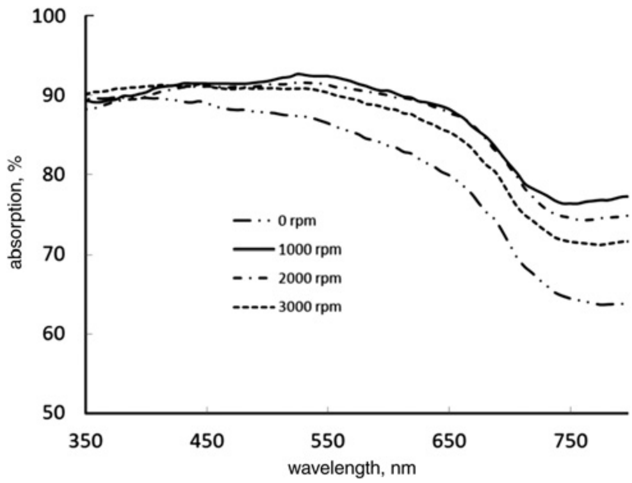

Fig. 5 *Optical absorption spectra of photoanodes with and without a ND scattering layer (0 rpm means TiO_2 without a ND layer)*

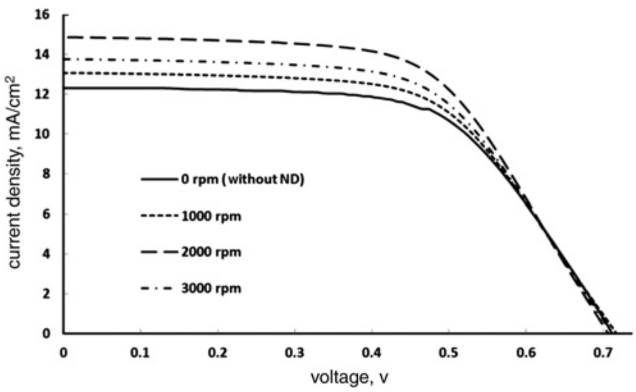

Fig. 6 *I–V curve of DSSCs for various thicknesses of ND scattering layers*

Optical absorption spectra of photoanodes with and without ND scattering layer are shown in Fig. 5. As can be seen from this figure, the absorption of light increases with decreasing the rotation speed of a spin coater. So, increasing the thickness of the ND layer can help to increase the light absorption. On the other hand, the light absorption of photoanodes with a ND layer increases in the large wavelength region of the light spectrum in comparison with the photoanode without the ND layer.

Fig. 6 illustrates the *I–V* curve of the produced cells. The results obtained are summarised in Table 1. It is clear that by increasing the thickness of the ND layer, the J_{sc} increases to an optimum level, 14.48 mA/cm^2. The light scattering effect of the ND layer is the main reason for this phenomenon. After that, increasing the ND layer thickness results in decreasing the J_{sc} and efficiency of the

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Table 1 Photovoltaic performance characteristics of DSSCs fabricated with various spinning speeds

Cell number	Spinning speed, rpm	V_{oc}, V	J_{sc}, mA/cm^2	Fill Factor	Efficiency, %
1	0	0.71	12.40 ± 0.07	0.61 ± 0.01	5.35 ± 0.09
2	1000	0.714	13.00 ± 0.2	0.63 ± 0.02	5.86 ± 0.17
3	2000	0.704	14.48 ± 0.33	0.60 ± 0.01	6.16 ± 0.12
4	3000	0.709	13.44 ± 0.41	0.61 ± 0.01	5.78 ± 0.16

DSSC because of the greater recombination of photoelectrons by electrolytes. Light scattering by ND particles is affected by a graphite-like external shell comprising of sp^2 hybridised carbon atoms and the sp^3 hybridised diamond core [21].

Finally, it should be mentioned that the electron mobility of TiO_2 is less than ND [22], therefore it may be concluded that the transformation of a photoelectron from TiO_2 to ND particles is energetically favourable.

4. Conclusion: Using ND particles in photoanodes of DSSCs results in increasing the current density and efficiency. Results of a light absorption spectrum of photoanodes showed that increasing in light harvesting is the main effect of adding a ND layer to a TiO_2 structure of photoanodes. Under optimum conditions, the efficiency and current density of the DSSC with a ND layer increased up to 15 and 17%, respectively.

5 References

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