Nano Energy (2014) **9**, 212–220

Available online at www.sciencedirect.com

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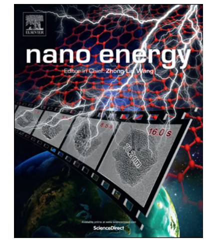

RAPID COMMUNICATION

Highly conductive, non-permeable, fiber based substrate for counter electrode application in dye-sensitized solar cells

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Received 1 June 2014; received in revised form 18 July 2014; accepted 19 July 2014
Available online 1 August 2014

KEYWORDS
Dye sensitized solar cells;
Counter electrode;
Carbon nanotubes;
Adhesion;
PEDOT

Abstract
3rd Generation photovoltaic systems such as dye-sensitized solar cells offer almost limitless material base that can be tested in variety of combinations with unique cell designs. One of the key challenges that remains with the dye-sensitized solar cells is to reduce their fabrication cost without compromising the performance. Such a target can only be achieved by fabricating inexpensive and abundantly available materials with simple and rapid preparatory methods that could deliver robust characteristics within the cell. With this motivation, we report here successful implementation of a highly conductive flexible fiber based substrate in dye-sensitized solar cell which is fabricated by coating a low temperature single walled carbon nanotube ink over a laminated fiber sheet. The substrate exhibited extraordinary durability under severe mechanical stability test conditions, reasonable overall efficiency (6.0±0.3%) and charge transfer resistance ($3.3 \pm 1.6\ \Omega\ cm^2$).
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Dye-sensitized solar cells can be potentially fabricated through a high speed, roll to roll fabrication line by implementing flexible substrates such as transparent conducting oxide (TCO) coated flexible polymer sheet e.g. indium doped tin oxide polyethyleneterephtalate (ITO-PET) and indium doped tin oxide polyethylenenaphtalate (ITO-PEN) or flexible metallic

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http://dx.doi.org/10.1016/j.nanoen.2014.07.013
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sheets such as titanium (Ti) or stainless steel (StS) [1]. For transferring the traditional glass based geometry to the flexible DSSC, most of the experiments have been performed on these afore mentioned substrates [2-11]. However, each type of these flexible substrates have their pros and cons. For example, the opaque metallic sheets can be used as a photoelectrode (PE) because they can handle high temperature sintering process that is critically required to obtain high quality TiO_2 film [12] whereas the disadvantage associated with implementing a metal photoelectrode is the reverse illumination which affects the overall efficiency due to the absorption of light by the semitransparent catalyst layer and electrolyte [1]. Another drawback of using inexpensive metal sheets such as StS is their corrosion in the presence of iodine based redox couple either used as PE or counter electrodes (CE) [13-15]. Hence one of the immediate needs for this technology is to find alternative choices for substrates that could be composed of inexpensive and abundantly available materials similar to the cheap metals and could give high conductivities as well as robust mechanical characteristics. With this motivation, we report here about successful implementation of a non-permeable and highly conductive fiber based substrate (FBS) in dye-sensitized solar cell which is fabricated by coating a low temperature curable single walled carbon nanotube ink over a laminated fiber sheet. The substrate exhibited extraordinary durability against liquid penetration as well as severe mechanical stress, reasonable efficiency (6.0±0.3%) and low charge transfer resistance (3.3±1.6 Ω cm^2) when tested as counter electrode in dye-sensitized solar cells.

The examined fiber based substrate (FBS), known as 'Ensocard Pharma TR', supplied by Stora Enso Oy (Figure 1a) was identified through a wide series of tests (see Experimental methods section) that established its high resistance against the liquid penetration. The basic structure of FBS is illustrated in Figure 1b whereas its composition was explored through optical micrograph (Figure 1c). The FBS is composed of three layers of bleached fibers kraft pulp (Sulfate pulp) [16] along with the chemi thermo mechanical pulp [17,18] which are sandwiched by compressing between two very thin layers of PET polymer coatings (Figure 1b and c). The fiber layers provide mechanical strength and necessary stiffness and at the same time good flexibility to the composite whereas the double sided polymer coating ensures high stability against water or moisture and does not allow them to penetrate inside the substrate.

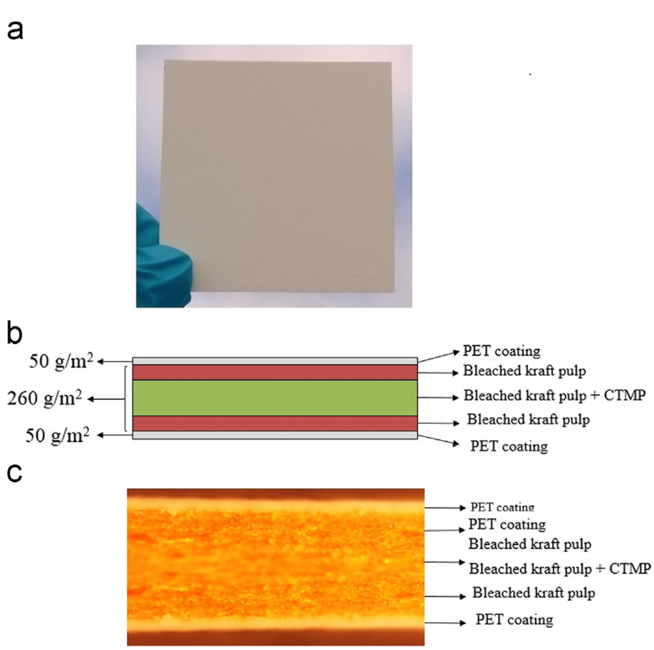

Figure 1 (a) Fiber based substrate 'Ensocard Pharma TR'. (b) Illustration of the components of the substrate. (c) Optical microscope image. Fiber layers were stained with Arcidine Orange (N,N,N′,N′-tetramethylacridine-3,6-diamine.

Like the ITO-PET or ITO-PEN polymer sheets, the FBS can withstand only up to around 160 °C which restricts the use of high temperature based ink or paste of the desired materials over this FBS substrate as well. Therefore a low temperature based aqueous SWCNT ink was applied [19] (see Experimental methods section). The deposition scheme is shown in Figure 2(a–d) where the active area (patterns) was defined through tape mask (Figure 2a) and the aqueous SWCNT ink was spread over the active area of the substrate through a disposable pipette (Figure 2b). Then the substrate was placed over the preheated (120 °C) hotplate and in less than 5 min, upon solvent drying (Figure 2c), the FBS was transformed into a highly conductive substrate (Figure 2d). The sheet resistance of the deposited SWCNT film could be easily reduced from 30 Ω/sq to 5 Ω/sq by decreasing the concentration of surfactant particles from 0.1 to 0.05 g respectively, without compromising the adhesion of the film on the substrate (see Experimental methods section).

One of the major challenges associated with low temperature carbon compounds based inks/paste is their mechanical stability over the deposited substrates which is also rarely reported in the literature [8,19,20]. Therefore for this study, the mechanical durability of the deposited SWCNT film was examined through the substrate bending and tape adhesion tests.

SWCNT coated FBS stripe, as shown in Figure 3(a), was bended (10 times each) over very small bending radii (ranged from 2.5 cm to 1.5 cm) and its sheet resistance (R_{SH}) was regularly measured. These results are summarized in Figure 3(b–d). Marginal changes i.e. (1.4%) in the R_{SH} was observed when the substrate was exposed to 2.5 cm and 2 cm bending radii (Figure 3b and c). Slightly higher (2.3%) change in R_{SH} was observed when the substrate was further bended over severely lower bending radius (1.5 cm, Figure 3d). Moreover, the net change in R_{SH} from the very first relaxed value (of 2.5 cm bending radius) to very last relaxed value (of 1.5 cm bending radius) was only 5.2%. Additionally no visual cracks in SWCNT film were appeared ensuring the high adhesion of deposited SWCNT film.

The mechanical stability of deposited SWCNT film was further examined through severe tape adhesion tests where the layer was subjected under the heavy (2 kg) rolling through a round metallic disk under two types of pressure sensitive tapes (3M Removable i.e. Tape 1 and 3M Magic i.e. Tape 2, Figure 4a-d). The initial sheet resistance (R_{SH}=6.2 Ω/sq) was marginally (1.6%) increased upon first time tape removal (Figure 4b). This increment was almost maintained in further three consecutive tape adhesions and pulls and was again further changed to 1.6%. Hence the

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