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# Optimization of Selective Electrophoretic Deposition and Isostatic Compression of Titania Nanoparticles for Flexible Dye-Sensitized Solar Cells

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ABSTRACT

Flexible photoanodes on PEN/PET based substrates for dye-sensitized solar cells (DSSC) by using electrophoretic deposition (EPD) method for the formation of titania nanoporous layer with titania nanoparticles (P-25) were produced. Considering commercially available titania nanoparticles containing both anatase and rutile phases, the undesired rutile nanoparticles, for DSSC applications, were almost eliminated from the coatings by selective pH adjustment of the EPD solutions without any binders. The coating characteristics and the selective coating capabilities of prepared ethanol and isopropanol based EPD solutions and their acetylacetone additive (as surfactant) alternatives were investigated using zeta potential measurements and mean colloid size analysis. As a subsequent complementary process, deposited films were compressed using Cold Isostatic Pressing (CIP) with an alternative clamping-effect pressure profile in order to increase the interparticular coherence and the overall adherence of the film onto substrates. Having obtained a 14–16 μm film thickness values, cells were assembled with active area values of $0.5 \times 0.5\,cm^2$, $1.0 \times 1.0\,cm^2$ and $2.5 \times 2.5\,cm^2$ and solar measurements were conducted, resulting in up to 4.22%, 4.13% and 4.00% efficiencies, relatively, under AM 1.5 conditions.



## 1. Introduction

Dye-sensitized solar cells (DSSC) are one of the cost effective and versatile alternative for common p-n junction solar cells. Unlike p-n junction photovoltaics, its unique working principle provides efficient low radiation solid state [1–6] light harvesting properties. Remarkable efficiency values of 10.1% [2,6], 11% [6] and 12% [8] have been reported for conventional dye sensitized solar cells during the past few years.

The fabrication of DSSC on flexible polymeric substrates is possible and relatively efficient such that some commercial applications were introduced [9–11]. The most challenging part of such fabrication is the deposition and formation of titania meso/nano-porous thick film on polymeric substrates. Alternatively, several different methods such as screen printing/doctor blade using volatile pastes and formation of titania thick film using electrophoretic deposition to fabricate dye sensitized solar cells on flexible substrates, using N719 dye as sensitizer, are studied.

Deposition of titania layer via doctor blade method had been conducted by Jingzhen Shao et al. [12] with subsequent CIP giving an efficiency of 2.87% at 300 MPa compression with the final titania layer thickness of 3.20 μm. Weerasinghe et al. [13] also used doctor blade method with subsequent CIP technique and reported 6.30% efficiency value with 12.30 μm thickness; while, Peiris et al. [14] reported 4.39% efficiency with subsequent static mechanical compression. Similarly, Ke et al. [15] reported 4.92% efficiency using doctor blade and mechanical compression techniques applied on titania beads.

Utilization of electrophoretic deposition technique was reported to have highly promising results. Chen et al. [16] reported 4.57% efficiency using anhydrous ethanol and acetylacetone colloidal solution for EPD technique with subsequent mechanical compression. Prepared colloidal solution contained 3 g/L solid to liquid ratio with 1:3 ST-41 (Ishihara Sangyo, Japan) to P-25 (Degussa, Germany) weight ratio. Applied voltage values for EPD were in the range of 5 to 25 V. Similarly, Yin et al. [17] conducted EPD applying 1.6 V/cm electric field using a mixture of

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ethanol/isopropanol/butanol as colloidal solution media with subsequent mechanical compression of 100 MPa. Assembled cells exhibited 5.76% efficiency, pointing the remarkable effect of compression on coated electrodes. Chiu et al. [18] reported 6.63% efficiency values using P-90 (Degussa, Germany) for EPD colloids with titania to isopropanol ratio of 0.25 g/100 mL. The deposition of P-25 and P-90 nanoparticles on titanium foils for the fabrication of back illuminating DSSC was reported to be conducted by EPD method. The concentration of EPD solution was 6 g/l of P-25 and P-90 nanoparticles yielding a maximum obtained efficiency value of 6.50% [19].

There are also studies on not only titania nanoparticles but also titania nanotubes coated by EPD method. Kim et al. [20] synthesized titania nanotubes using commercial P-25 titania nanoparticles suspending 1 ml of nanotube precipitates in 30:70 methanol and distilled water solution at 40 V of applied voltage for 60 min. The coating is conducted on fluorine doped tin oxide (FTO)-glass substrates, resulting in 6.71% efficiency. Also, EPD coating of titania nanoribbons which are synthesized from commercial anatase particles treated with NaOH in autoclave exhibited 0.87% efficiency [21]. Another nano-ribbon EPD process was carried out by mixing 1.5 g of nanoribbons with 30:70 ethanol: DI water solution with an adjusted pH value of 9 by tetra-methyl ammonium hydroxide [22]. Additionally, apart from $TiO_2$, the use of EPD method is extended to fabricate MgO coated $SnO_2$ photoanodes for DSSC suggesting efficiencies above 7.00% [23]. There is also an application of EPD method in order to fabricate counter electrodes by deposition of multi-walled carbon nanotubes using graphite sheets as EPD electrodes reporting an efficiency value of 7.03% [24].

The most important limiting factor of fabrication of DSSC on polymeric substrates is the incapability of heat treatment of the photoanodes. Therefore, as a pseudo sintering process in order to form solid, mechanically stable films, compression of the substrates takes place. Compression has been used as a completing process for the formation of the films as mentioned previously. Apart from uniaxial compression processes [25,26], cold isostatic process (CIP) has been introduced. Yong Peng et al. [27] reported 4.00% efficiency using doctor blade method for coating and CIP as subsequent process applying 50, 100 and 200 MPa of compression at different durations. As mentioned before, Weerasinghe et al. [13] and Shao et al. [12] applied CIP process in order to provide mechanical stability and increased titania nanoparticle interaction.

The distinctive feature of this work is the utilization of isoelectric point phenomena of dielectric nanoparticles suspended in a charged solutions to develop a highly practical production method for large scale flexible DSSC applications with increased active cell area. Since commercially available P-25 contains two phases of titania which are anatase and rutile, we aimed to obtain low temperature, binder-free and time effective process to coat only anatase particles on the substrate by EPD method. In DSSC, the desired phase of titania is anatase due to its band gap, morphology and dye adsorption

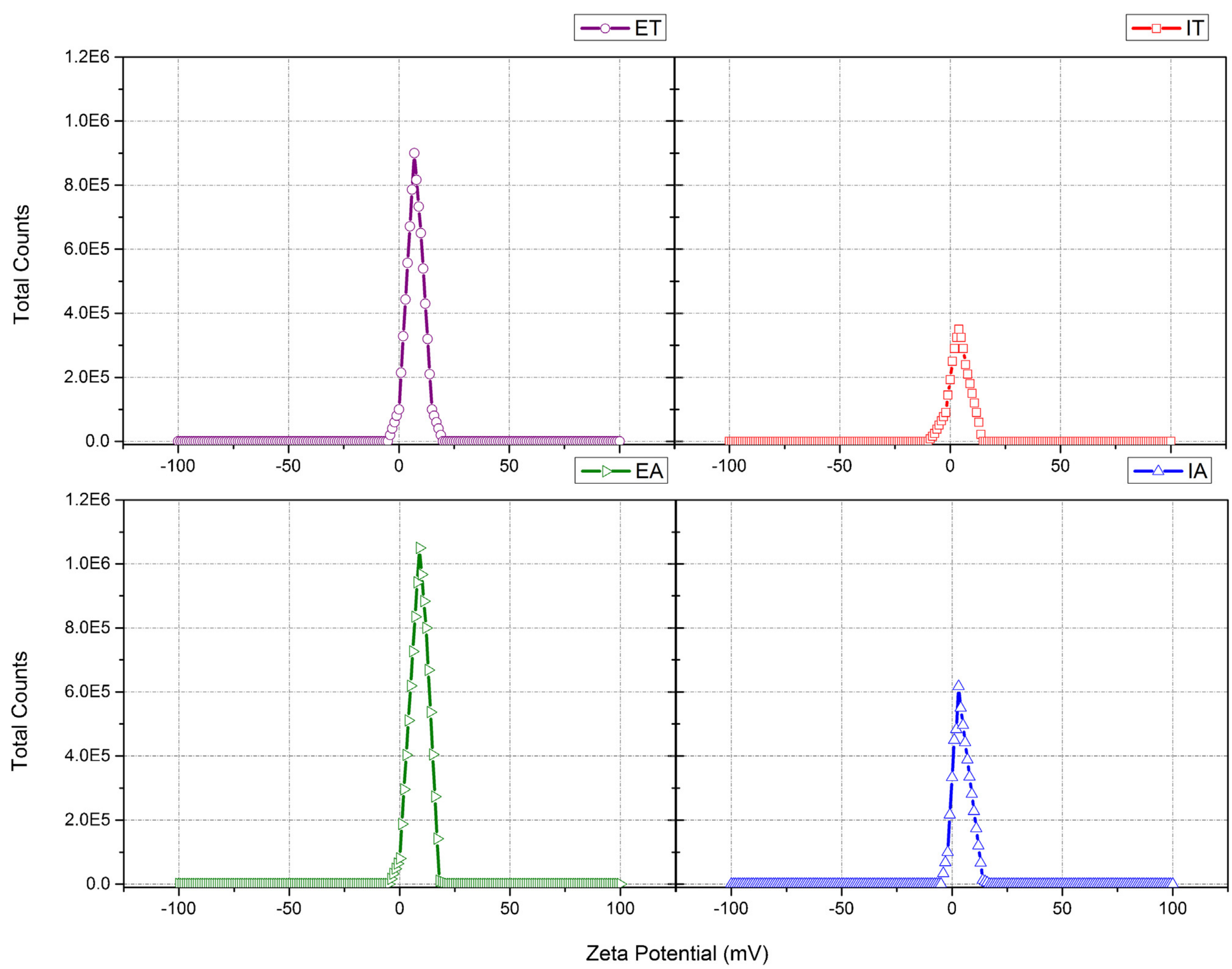


**Fig. 1.** Zeta potential measurements of four colloidal solutions.