Cold isostatic pressing technique for producing highly efficient flexible dye-sensitised solar cells on plastic substrates

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ABSTRACT

One of the biggest challenges for making dye-sensitised solar cells (DSCs) on plastic substrates is the difficulty in making good quality nanoporous TiO$_2$ films with both good mechanical stability and high electrical conductivity. Cold isostatic pressing (CIP) is a powder compaction technique that applies an isostatic pressure to a powder sample in all directions. It is particularly suitable for making thin films on plastic substrates, including non-flat surfaces. Cold isostatically pressed nanocrystalline TiO$_2$ electrodes with excellent mechanical robustness were prepared on indium tin oxide (ITO)-coated polyethylene naphthalate (PEN) substrates in the absence of organic binders and without heat treatment. The morphology and the physical properties of the TiO$_2$ films prepared by the CIP method were found to be very compatible with requirements for flexible DSCs on plastics. This room-temperature processing technique has led to an important technical breakthrough in producing high efficiency flexible DSCs. Devices fabricated on ITO/PEN films by this method using standard P-25 TiO$_2$ films with a Ru-complex sensitiser yielded a maximum incident photon-to-current conversion efficiency of 72% at the wavelength of 530 nm and showed high conversion efficiencies of 6.3% and 7.4% for incident light intensities of 100 and 15 mW cm$^{-2}$, respectively, which are the highest power conversion efficiencies achieved so far for any DSC on a polymer substrate using the widely used, commercially available P-25 TiO$_2$ powder. Copyright © 2011 John Wiley & Sons, Ltd.

KEYWORDS

flexible dye-sensitised solar cells; cold isostatic pressing; plastic substrates; TiO$_2$ films

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1. INTRODUCTION

Dye-sensitised solar cells (DSCs) have been recognised as potentially a low-cost alternative to conventional silicon-based solar cells because of their remarkably high power conversion efficiency and low-cost fabrication processes [1,2]. The highest efficiency for DSC reported to date has exceeded 11% for devices fabricated by high-temperature sintered TiO$_2$ electrodes prepared on F-doped SnO$_2$-coated conductive glass substrates (usually around 500°C) [3]. Recently, DSCs fabricated on flexible, light weight, thin conductive polymer substrates have received much attention because of their potential for a wide range of commercial applications. DSCs based on flexible polymer substrates are suitable for continuous and speedy manufacturing processes such as the roll-to-roll manufacturing process used in the coating industry. However, the thermal instability of polymer substrates above ~200°C prevents any high-temperature sintering process, which is critically important to form high connectivity between TiO$_2$ particles and between the TiO$_2$ film and the plastic substrate. This has led to polymer-based DSCs exhibiting low power conversion efficiencies when compared to the glass-based counterparts, owing to the poor quality of the electrodes. Alternative techniques to improve the performance of polymer-based DSCs have been researched by many groups. Examples of such alternative techniques include low temperature heating (150°C) [4], microwave irradiation [5], hydrothermal treatment [5,6], UV irradiation [7,8] and electrophoretic deposition [9,10]. The conversion efficiencies observed from these studies were close to or less than 4%. Higher efficiencies for a flexible DSC of 6.4% were reported for TiO$_2$ electrodes prepared...
using binder-free, low-temperature TiO₂ paste containing an interparticle binding agent [11]. Another DSC on polymer substrate with a high efficiency of 5.8% was reported for the lift-off technique developed by Durr et al. [12]. However, recent work has focussed on the use of the compression technique to make TiO₂ electrodes on polymer substrates formed by uniaxial pressing [13–15]. Such pressure-based techniques are able to improve the interparticle connectivity, as well as the mechanical adhesion of the TiO₂ films on flexible substrate. The maximum efficiency of 7.6%, as reported, was obtained by uniaxial pressing of TiO₂ on polyethylene naphthalate (PEN) substrates [15]. However, it would be a challenge to achieve high uniformity specially in large size TiO₂ electrode films of approximately 10 μm thick by such uniaxial mechanical pressing. This would require the two pressing platens or rolls to be perfectly parallel and the surfaces of the platens maintained flat with a submicron mirror finish.

Cold isostatic pressing (CIP) is a powder compaction technology used in materials processing engineering, and it applies the same pressure in all directions (as opposed to being reliant on the good shape matching of two flat surfaces). Therefore, high uniformity and high compaction can be achieved, regardless of the shape of the electrode. There are important distinctions between isostatic and uniaxial pressing. In uniaxial pressing, the TiO₂ thin films are pressed by axially loaded punches. In isostatic pressing, the film is vacuum sealed in an elastic mold and pressed in all directions through a liquid medium that can conform to the shape of its compressing objects. Therefore, an important feature of the CIP technique is that it allows non-flat and complex shapes to be pressed, which could be strategic for various types of photovoltaic collectors with different topographies. In this paper, we discuss the potential for using CIP as a new manufacturing method for the preparation of high quality TiO₂ film electrodes on flexible substrates. Morphological, mechanical and photovoltaic properties of such isostatically pressed TiO₂ electrodes on indium tin oxide (ITO)-coated PEN substrates are studied. We report the highest power conversion efficiency achieved so far for any DSC on a polymer substrate prepared with the widely used, commercially available P-25 nano titania powder.

2. EXPERIMENTAL

2.1. Deposition and processing of nanocrystalline TiO₂ films on indium tin oxide-coated polyethylene naphthalate substrates

Titania suspensions of ~30 wt% were prepared by dispersing 5 g of P-25 (Degussa, Hanau, Germany) TiO₂ powder in 99.7% ethanol followed by ball milling [16]. TiO₂ films with different thicknesses were coated by the doctor-blade technique on ITO-PEN (13 Ω/cm) substrates purchased from Peccell Technologies (Kanagawa, Japan) and allowed to dry in air. These TiO₂-coated electrodes were then transferred to a polyethylene envelope (thickness ~80 μm) and sealed under a vacuum of 10⁻¹¹ Torr. Vacuum-sealed electrodes were then pressed at room temperature using a CIP instrument (ABB Autoclave Systems, Columbus, OH, USA) at different pressure ranges varying between 35 and 200 MPa. A schematic demonstrating the preparation of TiO₂ electrodes is shown in Figure 1.

2.2. Characterisation, dye absorption and fabrication of dye-sensitised solar cells

The thickness of the TiO₂ films was measured by a surface profilometer (Dektak 500, Veeco Instruments INC., Woodbury, NY, USA), and the bonding strength between TiO₂ particles in the films evaluated by the nanoscratch technique recently developed by us that uses a nanoindenter (Hysitron Inc., Minneapolis, MN, USA) [16,17]. Six different scratches were made for each film with a controlled dimension of 15 μm in length and 2 μm in depth, and the forces exerted on the indenter in both normal and lateral directions were used for comparison of the film strength. The morphology of the films was studied through an optical microscope, a 3D profilometer (Wyko NT1100 Optical Profiling System) and a scanning electron microscope (FEI Quanta 200 ESEM, FEI Company, Hillsboro, OR, USA). N₂ adsorption–desorption, Brunauer–Emmet–Teller (BET) surface area analysis and Barrett–Joyner–Halenda pore size distribution analysis for unpressed and pressed TiO₂ films were carried out using the Micromeritics Tristar II surface area (BET) and porosity system. The transmittance of TiO₂ films pressed at different pressure ranges was measured by UV–visible spectrophotometry (UV–Vis spectrometer Cary 5000, Genomics, Blackburn, VIC, USA). Dye N719 (purchased from Dyesol Ltd, Queenbeyan, NSW, Australia) was coated on TiO₂ electrodes by immersion in ethanolic dye solutions overnight at room temperature, where the dye concentration was maintained at 0.1 mM. Dye-coated electrodes were then washed in ethanol and dried in flowing nitrogen gas. The amount of dye absorption on TiO₂ electrodes pressed and unpressed by CIP was studied by measuring the optical absorption of the dye de-adsorbed in a 0.1 M aqueous KOH solution.

Dye-sensitised solar cell devices were fabricated by attaching a Pt/ITO/PEN to the dye-coated TiO₂/ITO/PEN electrode. The electrolyte that was composed of 0.04 M I₂, 0.4 M 4-tert-butylpyridine, 0.4 M lithium iodide, 0.3 M N-methylbenzimidazole in acetonitrile and 3-methoxypropionitrile by volume 1:1 was filled in between the electrodes by capillary action. Current (I)–voltage (V) characteristics and incident photon-to-current conversion efficiency (IPCE) of the cells with the configuration of Pt|electrolyte|N719|TiO₂ were studied under irradiation of white light (100 mW cm⁻²) by using an Oriel solar simulator system and monochromatic light. The interfacial electrical properties of the cells were investigated using impedance spectroscopy. This
was carried out by applying negative 0.6 V on the working electrode under a two-electrode configuration, at the dark condition, with the same electrolyte, and by using a multi-channelled potentiostat (Princeton Applied Research, Oak Ridge, TN, USA) coupled with a computer. The charge transfer resistance at the electrolyte–electrode interface was evaluated from EClab software (Bio-Logic, Claix, France).

3. RESULTS AND DISCUSSION

3.1. Morphology, transmittance and porosity of TiO₂ electrodes on polyethylene naphthalate

Figure 2 illustrates the surface morphology of (a) unpressed and (b) CIP-pressed (200 MPa) TiO₂ films observed by an optical microscope. The three-dimensional surface topographies of the same films measured by the profilometry are shown in the same figure (c and d). TiO₂ films prepared using ethanolic P-25 slurry exhibited a high level of cracking that was formed during the air drying process because of the absence of any binder in the TiO₂ slurry. The degree of such macroscopic cracks was found to be highly dependent on the thickness of the TiO₂ layer. However, the cracked regions were filled by TiO₂ powder under the CIP compression, resulting in a uniform, crack-free film after CIP. Surface morphology of these electrodes was also studied by scanning electron microscopy, and SEM images of (a) unpressed and (b) pressed TiO₂ films are shown in Figure 3. A highly compact structure was observed for the isostatically pressed films, compared with the more porous morphology observed for the unpressed films. Aggregates of up to a few microns in size were observed on the surface of unpressed films, but they were absent from the surface after CIP compression. De-aggregation of P-25 powder during the CIP process is the most likely explanation for the absence of the large TiO₂ aggregates and the more compact structure. TiO₂ films prepared using P-25 powder on ITO-PEN substrates were usually opaque and showed very poor adhesion with the substrates because of the presence of large aggregates in the film [16]. However, with the de-aggregation by the CIP
compression, the pressed films became more transparent and showed increased light transmittance with higher pressure (Figure 4(A)). Figure 4(B) demonstrates the effect of CIP pressure on the transparency of TiO$_2$ films.

N$_2$ adsorption–desorption isotherms of the TiO$_2$ films before and after CIP compression are shown in Figure 5(a) and (b). Both films exhibit the typical IUPAC-type H3 pattern with the presence of the observed hysteresis [18]. Such loops are usually observed for aggregated particles. The sharp decrease in the adsorbed N$_2$ volume at the maximum relative pressure for the pressed film indicates that the porosity has significantly decreased because of the compression. As can be seen in the inserts in Figure 5, both unpressed and pressed films exhibit a mesoporous structure containing pores of diameters mainly between 2 and 50 nm [19], whereas a bimodal pore size distribution is observed for the unpressed film with most pores between 20 and 45 nm. The pore size of the films was found to decrease dramatically after compression as observed in the inserts of Figure 5. Furthermore, the film thickness was dramatically reduced after CIP compression (Figure 6). The magnitude of film thickness reduction is about 50% under CIP pressure between 70 and 200 MPa. In contrast, no significant change in the BET surface area between the pressed films (56.7 m$^2$/g) and the unpressed films (54.0 m$^2$/g) was observed.

3.2. Mechanical stability of the isostatically pressed TiO$_2$ films

During the fabrication of flexible DSCs by using low-temperature processing methods, the formation of good electrical contacts between the particles in mesoporous TiO$_2$ films and between TiO$_2$ films and the ITO layer is essential for achieving high power conversion efficiencies. For glass-based DSCs, these can be achieved by sintering around 500 °C to form a neck between adjacent particles, improving both electrical conductivity and mechanical stability of the film. Therefore, mechanical strength of the porous TiO$_2$ film on the plastic substrate is a useful indication of the
Figure 3. Scanning electron microscopic images of the surface of TiO2 films (a) before and (b) after compression by cold isostatic pressing.

Figure 4. (A) Appearance of the TiO2 films on an indium tin oxide (ITO)-coated polyethylene naphthalate (PEN) substrate as-printed (a) and after cold isostatic pressing (CIP) compression at 200 MPa (b) when the films were laid on a wooden bench. (B) Variation of the transmittance of the 12-µm-thick TiO2 films on ITO-PEN substrates processed at different CIP pressures.
interparticle connectivity. Improved mechanical stability of TiO₂ films also increases flexibility of the electrodes significantly and avoids difficulties associated with sealing the plastic-based DSC devices. Mechanical integrity and adhesion of TiO₂ electrodes on ITO-PEN substrates were assessed by bending deformation. Cold isostatically pressed TiO₂ electrodes on ITO-PEN substrates exhibited robust connectivity between particles in the film, as well as much improved adhesion with the plastic substrate compared to the unpressed films.

In order to be more quantitative, the bonding strength between the particles in nanoporous TiO₂ films processed at different pressure values was examined using the novel nanoscratch methodology previously developed by us [16,17]. Variations of the normal and lateral displacements, respectively, as a function of indentation time are shown in Figure 7(a) and (b). The forces exerted on the indenter during the indentation and ploughing through the film in both normal and lateral directions were recorded and plotted against time. As observed in Figure 7(c) and (d), higher forces were required to maintain the same indentation depth (1 μm) and the same scratch length (15 μm) for the samples CIP pressed at higher pressure. The maximum normal force observed during the initial indenting and the steady state lateral force during ploughing are plotted against applied pressure in Figure 7(e) and (f). Table I summarises the average force values based on five scratches made on each film. Both the maximum normal force and the steady state lateral force were increased with increasing pressure on the films, indicating the improved film strength due to CIP compression.

![Figure 5. N₂ adsorption-desorption isotherms and pore size distribution (insert figure) of (a) unpressed and (b) cold isostatic pressing-processed TiO₂ films.](image-url)
3.3. Photoelectrical properties of TiO$_2$|dye| electrolyte cells on plastic substrates

The photoelectrochemical properties of TiO$_2$ electrodes on ITO-PEN substrates were investigated by dye-sensitising the electrodes with N719 dye and measuring IPCE and $I$–$V$ characteristics in a sandwiched cell configuration with a Pt-coated ITO-PEN substrate as a counter electrode. IPCE of the cell is defined by the number of generated electrons divided by the number of incident photons [$\text{IPCE} = 1240 \times \frac{1}{I_{ph}}(\lambda I_\lambda)$, where $\lambda$, $I_\lambda$ and $I_{ph}$ are the wavelength (nm), the short circuit photocurrent ($\mu$A cm$^{-2}$) and the incident light ($\mu$W cm$^{-2}$), respectively] [20]. Figure 8 shows the IPCE spectra at the optimum conditions for cells prepared using (a) unpressed and (b) CIP-processed photoelectrodes on plastic substrates. IPCE reached a maximum of 72% around the wavelength of 530 nm, where the adsorbed N719 dye has its peak absorption. To the best of our knowledge, this is the highest IPCE value reported so far for plastic-based DSCs constructed with widely available P-25 TiO$_2$. High performance in IPCE and the broadening of the light absorption spectrum could be correlated with the higher dye absorption observed in the CIP-processed thick TiO$_2$ films (1.27 × 10$^{15}$ molecules/cm$^2$) compared to the unpressed films (5.6 × 10$^{16}$ molecules/cm$^2$). Unlike glass-based DSCs, both the unpressed and CIP-pressed electrodes on plastics showed a dramatic drop in photocurrent at shorter wavelengths (<400 nm) because of UV-filtering effect by the ITO-PEN substrate.

The performance of the cells produced by the CIP technique was evaluated by means of $I$–$V$ characteristics under both white light illumination (air mass 1.5, 100 mW cm$^{-2}$) and dark conditions (Figure 9). The efficiency of the cells increased progressively with the increase of the applied CIP pressure and reached a plateau at around 200 MPa (insert in Figure 9). Table II summarises the results of $I$–$V$ characteristics at optimum conditions. The maximum power conversion efficiency of the CIP-processed electrodes with the optimised thickness is measured to be 6.3% with $J_{sc} = 13.05$ mA cm$^{-2}$, $V_{oc} = 732$ mV and a fill factor of 66% under 1 sun. Significant levels of enhancement in the photocurrent are observed for the CIP-processed electrodes. The current reported here is the highest value reported for any polymer DSCs using P-25 TiO$_2$ power as electrodes. There has been a noticeable increment in the $V_{oc}$ after the films were processed by CIP. This could be due to the reduced charge recombination of the cell resulting from the better connectivity of TiO$_2$ particles due to the compaction of the titania film.

We have measured the variation of voltage, fill factor, efficiency and photocurrent as a function of film thickness and light intensity. The effects of CIP-processed film thickness on photocurrent, photovoltage, fill factor and cell efficiency are shown in Figure 10(a, b). Both fill factor and photovoltage are decreased with increasing TiO$_2$ film thickness. The photocurrent increased with increasing TiO$_2$ film thickness up to about 15 μm and then decreased with a further increase in electrode thickness. The maximum photocurrent and thus the maximum efficiency were found in the CIP-processed device containing a film of ~17.5 μm. The effects of incident light intensity on these parameters for the same device are shown in Figure 10(c) and (d). The fill factor increased and the voltage decreased monotonically with the increase of the light intensity. The efficiency is found to decrease with the increase of light intensity because of the diffusion limitation of the electrolyte. A linear variation of photocurrent against the light intensity is observed for the DSCs prepared with the electrodes processed by CIP technique. Such monophotonic process also demonstrates the better interparticle connectivity of the TiO$_2$ film.

3.4. Electrochemical impedance spectroscopy study

Electrochemical impedance spectroscopy is a useful technique to examine the electrical properties of components and their interfaces in DSCs. Internal resistance of the TiO$_2$ film and the film/substrate interface of the isostatically pressed TiO$_2$ films were studied using electrical impedance spectroscopy. A typical Nyquist diagram for glass-based DSCs normally features three semicircles in the order of increasing frequency and is attributed to the diffusion within the electrolyte, the electron transfer at the oxide/electrolyte interface and the redox reaction at the platinum counter electrode [21–23]. The intercept with the real axis at high-frequency range corresponds to the contact resistance between the TiO$_2$ film and the transparent conducting oxide coating on the substrate or the ohmic resistance of the cell [24]. Impedance spectra obtained for a 15-μm-thick TiO$_2$ electrode processed at different CIP pressure values are shown in Figure 11. Only two distinct semicircles are seen for these cells, as has been observed by others for the polymer substrate-based DSCs [25,26]. A data fitting
model was employed using the equivalent circuit shown in Figure 11. The semicircle corresponding to the high range of frequencies (the left semicircle, with diameter $R_1$) and the middle range of frequencies (the right semicircle, diameter $R_2$) represent the redox reaction at the platinum counter electrode and the electron transfer at the oxide/electrolyte interface within the TiO$_2$ network, respectively. The high-frequency intercept with the real axis is the ohmic resistance ($R_0$) and is related with the sheet resistance of the substrate of the working electrode. The values of $R_0$, $R_1$ and $R_2$ related to Figure 11 are all summarised in Table III. The reduction of the $R_1$ and $R_2$ values with increased CIP pressure illustrates that the charge transfer resistance in the relevant interfaces of the cells has decreased because of the pressure. Similar contraction of the Nyquist plot is observed by Hoshikawa et al., as the calcination temperature of TiO$_2$ electrodes was increased [21], which improved the connectivity.

Figure 7. The variation of (a) lateral displacement, (b) normal displacement, (c) lateral force and (d) normal force of the nanoin dentor on the TiO$_2$ films made at different pressures. A typical measured curve is displayed for each sample. (e) Averaged normal force (at $t = 8$ s) and (f) averaged steady state lateral force ($t = 30$ s) variation against the cold isostatic pressing pressure (the average values were calculated based on five different scratch tests).
Thus, it is likely that compression by CIP has increased the interparticle connectivity of the film significantly.

In the Nyquist plot, higher sheet resistances of substrates lead to larger $R_0$ [21]. A trend of right shift in Nyquist plots for the pressed electrodes (Figure 11) indicates that the compression may have caused some damage to the conductive ITO layer accompanied with the robust film/substrate adhesion observed in the pressed electrodes. Mechanical embedding of aggregated TiO$_2$ particles in the ITO layer on the moderately compressible PEN substrate can lead to such an increase in the sheet resistance of the ITO‐PEN substrate. Furthermore, the effect of film thickness on the charge transfer resistance of the pressed electrodes is shown in Figure 12, and the results are summarised in Table IV. The charge transfer resistance of different interfaces was found to decrease dramatically with the increase of the electrode thickness. Therefore, CIP has enabled the fabrication of thick electrodes with reduced charge transfer resistance in the cell, thereby enabling higher energy conversion efficiency for the plastic‐based DSCs.

### 4. CONCLUSIONS

A CIP method has been developed for the preparation of highly flexible DSCs at room temperature on polymer substrates. This technique does not require any additives such as organic binders, interparticle connecting agents in the titania slurry or any high temperature sintering to form necking between particles. TiO$_2$ electrodes were prepared by the simple doctor‐blade technique, using readily available P‐25 titania powder dispersed in ethanol, and were compressed by CIP to build up the connectivity required between the TiO$_2$ particles and the adhesion of the film with the ITO‐PEN substrate. Improved flexibility, higher mechanical stability and better electrical connectivity

<table>
<thead>
<tr>
<th>Pressure applied (MPa)</th>
<th>Maximum normal force (µN)</th>
<th>σ</th>
<th>Steady state lateral force (µN)</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpressed</td>
<td>220</td>
<td>94</td>
<td>153</td>
<td>54</td>
</tr>
<tr>
<td>70</td>
<td>1300</td>
<td>276</td>
<td>961</td>
<td>201</td>
</tr>
<tr>
<td>140</td>
<td>1982</td>
<td>147</td>
<td>1538</td>
<td>139</td>
</tr>
<tr>
<td>200</td>
<td>2383</td>
<td>214</td>
<td>1856</td>
<td>165</td>
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</table>

<table>
<thead>
<tr>
<th>TiO$_2$ electrode</th>
<th>Thickness (µm)</th>
<th>$J_{sc}$ (mA cm$^{-2}$)</th>
<th>$V_{oc}$ (V)</th>
<th>$ff$</th>
<th>$η$ (%)</th>
<th>IPCE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonpressed</td>
<td>12.3</td>
<td>9.79</td>
<td>0.663</td>
<td>63</td>
<td>4.05</td>
<td>43</td>
</tr>
<tr>
<td>CIP processed</td>
<td>17.3</td>
<td>13.05</td>
<td>0.732</td>
<td>66</td>
<td>6.30</td>
<td>72</td>
</tr>
</tbody>
</table>

CIP, cold isostatic pressing; IPCE, incident photon‐to‐current conversion efficiency.
of the film are the most important characteristics of the electrodes produced by this method. Sensitised with N719 dye, flexible DSCs on plastics processed by CIP with optimised thickness have yielded high conversion efficiencies of 6.3% and 7.4% for an incident solar energy of 100 and 15 mW cm\(^{-2}\), respectively.

Figure 10. Dependence of the fill factor, open-circuit voltage, current density and energy conversion efficiency on the TiO\(_2\) film thickness (a, b) and the incident light intensity (c, d).

Figure 11. Impedance spectra of Pt|electrolyte|N719|TiO\(_2\) cells prepared using TiO\(_2\) electrodes (with an initial thickness of 15 µm) processed at different cold isostatic pressing pressure values.
Table III. Electrochemical impedance data of the electrolyte|dye|TiO2 systems processed at different cold isostatic pressing pressure values (TiO2 film thickness for each sample before compression was ~15 µm).

<table>
<thead>
<tr>
<th>Pressure applied (MPa)</th>
<th>$R_0$ (Ω)</th>
<th>$R_1$ (Ω)</th>
<th>$R_2$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unpressed</td>
<td>23.21</td>
<td>80.56</td>
<td>102.34</td>
</tr>
<tr>
<td>35</td>
<td>27.76</td>
<td>30.21</td>
<td>94.39</td>
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<tr>
<td>70</td>
<td>27.06</td>
<td>15.79</td>
<td>39.11</td>
</tr>
<tr>
<td>140</td>
<td>28.94</td>
<td>11.93</td>
<td>23.58</td>
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<tr>
<td>200</td>
<td>29.91</td>
<td>11.51</td>
<td>22.93</td>
</tr>
</tbody>
</table>

Figure 12. Impedance spectra of the electrolyte|dye|TiO2 systems processed with 200 MPa cold isostatic pressing pressure.

Table IV. Electrochemical impedance data of the electrolyte|dye|TiO2 systems of different electrode thicknesses processed with 200 MPa cold isostatic pressing pressure.

<table>
<thead>
<tr>
<th>Thickness of the electrode (µm)</th>
<th>$R_0$ (Ω)</th>
<th>$R_1$ (Ω)</th>
<th>$R_2$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>20.46</td>
<td>47.22</td>
<td>161.5</td>
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<tr>
<td>2.7</td>
<td>23.08</td>
<td>34.99</td>
<td>23.08</td>
</tr>
<tr>
<td>8.4</td>
<td>26.43</td>
<td>14.37</td>
<td>29.65</td>
</tr>
<tr>
<td>16.2</td>
<td>26.7</td>
<td>6.37</td>
<td>11.73</td>
</tr>
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REFERENCES


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