Review on Metallic and Plastic Flexible Dye Sensitized Solar Cell

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Abstract. Dye sensitized solar cells (DSSCs) are a promising alternative for the development of a new generation of photovoltaic devices. DSSCs have promoted intense research due to their low cost and eco-friendly advantage over conventional silicon-based crystalline solar cells. In recent years, lightweight flexible types of DSSCs have attracted much intention because of drastic reduction in production cost and more extensive application. The substrate that used as electrode of the DSSCs has a dominant impact on the methods and materials that can be applied to the cell and consequently on the resulting performance of DSSCs. Furthermore, the substrates influence significantly the stability of the device. Although the power conversion efficiency still low compared to traditional glass based DSSCs, flexible DSSCs still have potential to be the most efficient and easily implemented technology.

1. Introduction of dye sensitized solar cell
The prosperity of human society largely relies on safe energy supply, and fossil fuel has been serving as the most reliable energy source. However, as a non-renewable energy source, the exhaustion of fossil fuel is inevitable and imminent in this century. To address this problem, renewable energy especially solar energy has attracted much attention, because it directly converts solar energy into electrical power leaving no environment affect. Among all the organic solar cells, dye-sensitized solar cells (DSSCs) are the most efficient and easily implemented technology [1].

Dye-sensitized solar cell (DSSC) has been under intense investigation since the first publication reported by O’Regan and Grätzel in 1991[2]. The possibility to produce these solar cells at low cost and their relatively high energy conversion efficiency, reaching 10.3% ± 0.34% (value for a 1cm² cell) [3] make such devices promising alternatives for cheap electricity compared to the classical silicon-based photovoltaic panels. Unlike silicon solar cells, electrons and holes in a DSSC are transported in two different phases, Titanium dioxide (TiO₂) and electrolyte respectively. Thus, the chances of recombination in the cell become low. In addition, DSSCs have been proved to perform better than conventional solar cells, without significant change in the power conversion efficiency, in diffused light and at moderate temperature – up to 50°C. Moreover, these cells can be made on flexible substrates and thus find applications on curved surfaces like clothes, bags, car tops, etc. Transparency of these cells and their performance under the diffused light make these cells more attractive for indoor applications and as panels on windows and doors.

In this review, we focus our study on operation principal and configuration of flexible DSSCs, cost overview of flexible DSSCs, recent achievement in flexible DSSCs and stability issues related to metal and plastic DSSCs.

2. Operation principle and structure of flexible dye sensitized solar cells
The DSSCs is a new type of photovoltaic solar cell composed of a dye-modified wide band semiconductor electrode, a counter electrode, and an electrolyte containing a redox couple (I⁻/I₃⁻). When a DSSC is illuminated by sun light, the dye molecules absorb light and become excited. The absorption of light by the dyes is followed by the injection of an electron from the excited state of the dye to the conduction band of the semiconductor and its subsequent transfer to the transparent oxide. Finally the electron flows through the external circuit. The oxidized dye is simultaneously reduced by a redox mediator in the electrolyte and returns to the ground state. The electrons that flow through the
external circuit arrive at the counter electrode and have an effect on the reverse reaction of the redox couple. Radiant energy is converted to electricity by this process [4 - 6].

The DSSCs fabrication can be switched from traditional glass substrates to either flexible plastic or metal and can be fabricated in different combinations. As indicated in Figure 1, the flexible DSSCs can be prepared in three basic configurations. There are key challenges associated with each type of configuration. For instance, the whole cell assembly can be fabricated on transparent conducting oxide coated flexible plastic sheets like traditional glass based DSSC as Figure 1(a) if the materials could be deposited or coated using low temperature paste or inks. On the other hand, metals also can be used as either counter electrode or photo electrode as figure 1(b) and 1(c). As all know metal can stand high temperature, the high temperature deposition of paste or ink in not the issue, but configuration must be different from conventional DSSCs assembly which is the counter electrode on top and photo electrode on bottom of the DSSCs fabrication. However, this configuration needed careful optimization to achieve maximum output power since the cell is illuminated from the counter electrode side and the light is absorbed by semi-transparent catalyst and electrolyte. In case the metal used as counter electrode, low temperature paste or ink deposition needed to be coated on plastic photo electrode.

![Figure 1. Different configuration of flexible DSSCs](image)

3. **Cost overview of flexible dye sensitized solar cells**

A key issue in the commercialization of DSSCs is bringing down the production cost further while keeping up a decent efficiencies and lifetime. The total expense of volume DSSCs production principally relies on upon the materials cost and the fabrication methods. The rigid glass substrate is the most costly part in a DSSC which is in excess of 60% of the aggregate expense of all parts in DSSCs[7]. Also, overall cost can be decreased by replaced with cheap and flexible substrates such as plastic, metal or even paper[7;8]. Another advantage of flexible DSSCs is avoiding the cost for inactive materials such as metallic frames, strut and bolts and additional glass encapsulation used in the installation of silicon solar cells [9]. Another favorable aspect for the DSSCs is the cost of its manufacturing tools and equipment. For a 10 MW/year manufacturing capacity, the production costs for glass based DSSCs has been estimated in between $7.25/m² - $ 11.60/m²[7] compared to $ 32/m²[9] production cost for thin film solar cells. Hence, by fabricating DSSCs on light weight and flexible substrates and also implementing roll-to-roll processing, large cost reductions could be expected even be halved compared to glass based batch process DSSCs technology. In case of DSSCs, which is
mostly still in a laboratory scale phase, scaling up to mass production should most likely bring down the cost further through different learning and scale effects in production. The easy and non-vacuum based fabrication equipment for DSSCs may potentially further reduce the overall cost of DSSCs production.

4. Flexible photo electrode

Flexible photo electrode can be fabricated by utilizing fast roll-to-roll fabrication devices. The metal based photo electrode offers an advantage for high temperature sintering processes which is a key requirement for high quality TiO$_2$ nano particle film. These high temperature TiO$_2$ paste have been employed in reverse illumination configuration of DSSCs and has achieved an efficiency of 8.6 % for stainless steel based substrate. However in the case of stainless steel, the stability is a critical problem as the cell can lose performance in couple of hour under sun illumination [22,23]. So far, Titanium is among metal based photo electrode that show good stability under sun [22]. The highest efficiencies been report on Titanium based flexible DSSCs is 9.2 %. On the other hand, the high temperature sintering process cannot be applied on plastic substrates such as polyethylene terephthalate (PET) or Polyethylene naphthalate (PEN) because deformation at 150°C. Transferring the high temperature sintered TiO$_2$ film has been demonstrated through ‘lift off’ process and mechanical compressing. For this technique, efficiency of cell is 7.6 % been achieved. The key issue related to low temperature paste or ink preparation is the weak inter particle bonding between individual TiO$_2$ particles which is basically obtained through high temperature sintering process. Due to that problem, the movement of electron within TiO$_2$ film experiences high resistance and cause lower current compared to high temperature sintering film. Several researchers have been demonstrated different low temperature methods such as chemical sintering, vacuum sealing and pressing, hydrothermal treatment, UV treatment, spray deposition methods. Efficiency level of 2 -7 % has been obtained using those method which is still lower compared to the glass based DSSCs.

| Substrate | Preparation method | Efficiency, η (%) | Reference |
|-----------|--------------------|------------------|-----------|
| Ti$^a$    | Surface treatment  | 9.2              | [24]      |
| StSt$^b$  | Surface treatment and TiO underlayer | 8.6 | [10] |
| W$^c$     | ITO interlayer     | 3.6              | [36]      |
| Zn$^d$    | ZnO nanorod        | 2.4              | [37]      |
| ITO-PEN$^e$ | Mechanical pressing and UV treatment | 7.6 | [11] |
| ITO-PEN$^e$ | Vacuum seal and pressing | 6.3 | [12] |
| ITO-PEN$^e$ | Hydrothermal and mechanical pressing | 5.8 | [11] |
| ITO-PET$^f$ | Electrophoretic deposition and CVD/UV | 3.8 | [25] |
| ITO-PET$^f$ | Spray deposition and UV treatment | 3.3 | [27] |
| ITO-PET$^f$ | Hydrothermal crystallization and autoclaving | 2.5 | [26] |

$^a$Ti: Titanium. $^b$StSt: stainless steel. $^c$W: tungsten. $^d$Zn: Zinc. $^e$ITO-PEN:Polyethylene Naphthalate doped Indium Titanium Oxide. $^f$ITO-PET: Polyethylene Terephthalate doped Indium Titanium Oxide

5. Flexible counter electrode

Different catalyst layer has been tested by several researchers such as Platinum (Pt), Carbon composites and conducting polymer such as poly(3,4-ethylenedioxythiophene)(PEDOT) and polystyrene sulfonate (PSS). Among all the materials, Pt can be deposited through various low temperature processes such as chemical reduction, electrodeposition and mechanical pressing which is suitable for plastic substrate. For plastic substrate, efficiency level of 5 - 8 % has been obtained using
those methods. In the case of metal based counter electrode, using low temperature methods such as sputtering in preparation of the Pt has been a much better option compared to high temperature treatment [19;20]. This has been thought to be caused by the increased oxidation of the metal surface in high temperatures which would hinder the charge transfer. However, the selection of viable deposition methods for a catalyst in the case of metals is larger than with plastic. For metal substrate such as stainless steel, the best efficiency is 5.3 % been achieved with Pt as catalyst, which is relatively poor compared to glass substrate DSSCs. Furthermore, the DSSC fabricated using stainless based counter electrode with thermal deposition corroded [28]. Ti exhibits good chemical stability with electrolyte compared to stainless steel. The best conversion efficiency of DSSC obtained with Ti based counter electrode is 7.7%. However, to reach lower cost fabrication of DSSC, alternative materials have been investigated such as conducting polymer. Conducting polymers such PEDOT-PSS have been tested as alternative catalyst via spin coating and screen printing on polymer. The best efficiency for these polymers on plastic substrates is about 4.4%. For metal based substrate, with Ti as counter electrode with PEDOT as catalyst, 6.3 % efficiency has been reached. Stainless steel based counter electrode also work well with carbon by applied composite film made of carbon aerogel and poly(tetrafluoroethyelene) and in such case give efficiencies as high as 9.2 %. As corrosion is the main challenge for stainless steel based counter electrode, the next step was to move toward more corrosion resistant metals.

Table 2. Performance of DSSC with different materials as counter electrode and different catalyst

| Substrate | Catalyst | Preparation method | Efficiency, $\eta$ (%) | Reference |
|-----------|----------|--------------------|------------------------|-----------|
| StSt$^a$  | Carbon   | High temperature sintering | 9.2                    | [14]      |
| Ti$^b$    | Pt$^c$   | High temperature sintering | 7.7                    | [29]      |
| Ti$^b$    | PEDOT$^d$ | Electrodeposition   | 6.3                    | [21]      |
| StSt$^e$  | Pt$^c$   | Sputtering          | 5.3                    | [30]      |
| Ni$^e$    | Pt$^c$   | Sputtering          | 5.1                    | [33]      |
| Ni-PET$^f$| Pt$^c$   | Electrodeposition and film transferring | 7.9                    | [15]      |
| ITO-PEN$^g$| Pt$^c$ | Screen print and pressing | 7.2                    | [16]      |
| ITO-PEN$^h$| Pt$^c$ | Electrodeposition | 6.5                    | [18]      |
| ITO-PEN$^h$| Pt$^c$ | Chemical reduction  | 5.4                    | [17]      |
| ITO-PEN$^h$| PEDOT-PSS | Screen printing | 4.4                    | [31]      |

$^a$StSt: stainless steel. $^b$Ti: titanium. $^c$Pt: platinum. $^d$PEDOT: Zinc. $^e$Ni: nickel. $^f$Ni: Polyethylene Terephthalate doped Nickel. $^g$ITO-PET: Polyethylene Terephthalate doped Indium Titanium Oxide. $^h$ITO-PEN:Polyethylene Naphthalate doped Indium. $^i$PEDOT-PSS:

6. Stability of flexible dye sensitized solar cells

DSSCs manufactured on glass substrates have exhibited high efficiencies along with excellent stabilities under 60°C and 80°C accelerated aging test and also in outdoor natural environmental condition. This is mainly due to the excellent resistance of glass against the moisture intrusion as well as the temperature. The case for flexible substrates such as plastic and metallic sheet is totally different. The plastic sheets are permeable for intrusion of water or moisture within the cells. In this case, the selection and suitability of material that could resist moisture is crucial because some component in DSSCs such as N719 dye is known to be hydrophilic which is capable of absorbing water [32]. The plastic substrates also sensitive to UV light [34] as well as harsh volatile solvents such as acetonitrile [35]. Whereas, flexible metallic sheet such as stainless steel are facing corrosion problem from redox couple [28;31].
Long term stability is vital for the success of flexible dye sensitized solar cells. These cells need to stand high humidity and extreme temperature. The UV sensitivity of plastic can also be severe problem for flexible DSSCs compared to glass. In this regard, the integrations of flexible DSSCs need to be reviewed according to its application in different operating conditions. The good news about the DSSCs is its higher relative performance in low light condition compared to Silicon based solar cell. This can broaden the utilization of flexible DSSCs for daily uses such as battery charging of mobile phones, traveling bags, and clothes where both bright light and extreme weather condition are not necessary required for the optimum performance of DSSCs.

7. Conclusion

Overall, DSSCs have been recognized as highly potential solar energy conversion devices. Toward the low cost and roll-to-roll processing of flexible DSSCs, alternative substrate needed to replace conventional glass substrate mainly on plastic and metal substrates. However, stability is the main problem in development of flexible DSSCs for practical applications. Hence, further research needs to be carried put in order to commercialize flexible DSSCs.

8. Acknowledgment

Authors wishing to acknowledge the funding assistance of the Ministry of Education of Malaysia (MOE) under Fundamental Research Grant Schemes (FRGS), grant no. FRG0308-TK-1/2012 and FRG0351-TK-2/2013.

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