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A review of transparent solar photovoltaic technologies

Alaa A.F. Husain[a,*], Wan Zuha W. Hasan[a,b], Suhaidi Shafie[a,b], Mohd N. Hamidon[b], Shyam Sudhir Pandey[c]

[a] *Department of electronic engineering, University Putra Malaysia, Serdang 43400, Malaysia*
[b] *Institute of Advanced Technology, University Putra Malaysia, Serdang 43400, Malaysia*
[c] *Department of Biological Functions Engineering, 2-4 Hibikino, Wakamatsu-ku, Kitakyushu, Fukuoka 808-0196, Japan*

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ABSTRACT

Energy is essential for economic development and growth. With the rapid growth of development and the drive to expand the economy, society demands more electricity. Coupled with the realisation that unsustainable energy production can have a detrimental effect on our environment. Solar energy is the most prolific method of energy capture in nature. The economic drive to make solar cells more cost effective and efficient has driven developments in many different deposition technologies, including dipping, plating, thick film deposition and thin film deposition. Typically, in order for solar energy to work efficiently and supply energy to a building, a very large amount of space is required, in the form of rooftops or land, in order to install solar panels; these solar panel space requirements are a large impediment to practical usage. This drawback drove researchers to come up with transparent solar cells (TSCs), which solves the problem by turning any sheet of glass into a photovoltaic solar cell. These cells provide power by absorbing and utilising unwanted light energy through windows in buildings and automobiles, which leads to an efficient use of architectural space. There are approximately nine transparent photovoltaic (TPV) technologies under development, and studies regarding these technologies aim to achieve high transparency along with electrical performance that is compatible with solar panels that are sold in the market. The main objective of this review paper is to state all the latest reported technologies from the year 2007 onwards on transparent photovoltaic technologies with at least 20% average transmission. This includes demonstrating the process used in each technology (including the materials and the methods) and explaining its advantages and disadvantages from a performance, aesthetic and financial perspective. Therefore, this study provides a crucial review on the latest developments in the field of TSCs.

1. Introduction

In recent years, the floodgates of research focusing on clean renewable energy have been opened by scientists who consider solar energy to be the most abundant source of energy that can satisfy society's demands, which stem from continual economic development [1–4]. Solar energy is at least utilised in 4 different ways in our daily lives, and this ranges from heating water to producing electricity. Photovoltaic (PV) technologies are at the top of the list of applications that use solar power, and forecast reports for the world's solar photovoltaic electricity supplies state that in the next 12 years, PV technologies will deliver approximately 345 GW and 1081 GW by 2020 and 2030, respectively [5]. A photovoltaic cell is a device that converts sunlight into electricity using semiconductor materials. Semiconductor materials enable electron flow when photons from sunlight are absorbed and eject electrons, leaving a hole that is filled by surrounding electrons. This phenomenon of electron flow by photon absorption is called the photovoltaic effect. The PV's cell directs the electrons in one direction, which forms a current [5,6]; the amount of current is proportional to the number of absorbed photons, which means that PV solar cells are a variable current source. There are approximately 24 models of solar cell technologies that are made from different types of materials and methods [7]. This review paper is primarily interested in transparent solar cells. However, in order to understand the concept of transparent solar cells, it is important to explain the evolution of solar cells starting from the silicon type. The following is a short background on solar cell technologies.

The challenges that face photovoltaic cells are cost, efficiency, and operating lifetime [8]. Researchers are now focusing on finding materials that will overcome these challenges. Silicon was the first material that exhibited good efficiency [9]. It is used in monocrystalline PV cells, which are at least 6% more efficient but also more expensive than

* Correspondence to: Department of Electrical and Electronic Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia.
E-mail address: alaa.a.f.husain@gmail.com (A.A.F. Husain).

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Nomenclature

TSC	transparent solar cell
TPV	transparent photo voltaic
NT-TiO2	Nanotube titanium dioxide
TDSSC	transparent dye synthesis solar cell
DSSC	Dye synthesised solar cell
EPD	Electrophoretic deposition
TFSC	Thin film solar cell
TLSC	Transparent luminescent solar concentrator
QD	Quantum dot
CE	Counter electrode
Pt	Platinum
η	efficiency (%)
T	transparency (%)
P0	PV rated power (kW)
P	instantaneous AC power (W)
Pmax	maximum power output (W) of panel at standard test conditions
AVT	average transmission
PSC	Polymer Solar Cells
FTO	Fluorine doped tin oxide
ITO	Indium-doped tin oxide
TPV	Thin film Photovoltaic

polycrystalline PV cells [10–12]. Monocrystalline cells are more electrically efficient, as they have a perfect crystal structure, whereas polycrystalline cells have a less perfect molecular structure that impedes electron flow but are slightly cheaper to make. However, due to the high cost of silicon, the market requires new materials and processes that can give an equivalent efficiency, while at the same time reducing costs [2]. Therefore, researchers came up with thin film PV cells (TFPV). Thin films reduce the amount of semiconductor material used to manufacture amorphous solar cells, which reduce the cost by more than half [13,14]. In addition, there is the third-generation solar cell, which includes concentrators and organic solar cells [15] such as dye-sensitized solar cells (DSSC) [16,17]. Most solar cell applications are terrestrial [3,18]. One of the main challenges that most of these applications face is the surface area needed to produce enough electricity in the solar panel; the larger the surface area is, the more sunlight a PV can harness. Hence, the idea of transparent photovoltaic (TPV) cells came to solve this challenge of effectively utilising space. This review focuses on technologies related to TPV and their merits. However, before going through transparent solar cell (TSC) technologies, it is essential to understand the concept of the solar cell and dye-sensitized solar cells (DSSC), presented in sections A and B, because they are 2 main structures used to build most PV models.

1.1. Photovoltaic principles

The semiconductor material in a PV cell absorbs light (photons), and this displaces electrons to form pairs of electrons and holes, which are guided in one direction, creating a current. The semiconductor is doped to be a p-n junction with a potential difference, which will drive current flow vertically through the cell in one direction, so it can be harvested as electricity. The diffusion length is one of the important factors that affect the efficiency of the solar cell. Photons must have energy (hv) equal to or more than the energy band gap (E_{gap}) of the semiconducting material [4,19]. In summary, a photovoltaic cell is a device that converts sunlight into electricity using semiconductor materials; it has the same working principle as a semiconducting diode. The semiconductor material, such as silicon, has the property to eject electrons when sunlight is absorbed; the PV's cell then directs the electrons in one direction, which forms a current, as illustrated in Fig. 1 [5,20,21].

1.2. Dye-Sensitized Solar Cells (DSSC): Operational Principal

Since O'Regan and Grätzell reported the fabrication of DSSC in 1991, with efficiencies of 7 – 8%, it became a promising energy generating device [22–24]. DSSC is convenient to fabricate, low cost, and has a high power-to-conversion efficiency. These properties attract scientists' and researchers' attention [25]. An ideal DSSC contains a combination of dye-sensitized transparent conducting substrate, semiconductor film (such as titanium dioxide (TiO_2), zinc oxide (ZnO), tin dioxide (SnO_2), Niobium pentoxide (Nb_2O_5)), electrolyte and counter electrode (CE) [26–30]. The elements of DSSC are clear in Fig. 2 [31]. The heart of the DSSC is the mesoporous oxide containing TiO_2 nanoparticles as a roadway for the electrons to cross from the cathode to the anode, the diameter size of the particles range between 10 and 30 nm, while the thickness of the film is 10 µm approximately, and it is doped with a dye for absorbing the photons. The TiO_2 layer is deposited on a glass coated with transparent conducting oxide (TCO) or fluorine-doped tin oxide (FTO); these are the commonly used substrates [22–33]. The dye knocks out electrons from the photons to the conduction band [19] which result in oxidation of the dye. The dye recovers the lost electrons from the electrolyte; this operation is called iodide/triiodide redox system Eq. (1). The I^- loses electrons to the dye and forms $3I^3$ triiodide. The Triiodide returns to be iodide by gaining electron from the cathode, which is covered with platinum as a catalyst, then the electrons flow from the semiconductor side to the counter electrode side forming a flow of current [31]. The components of DSSC are discussed in more detail below:

$$I^- + \quad 2 \quad e^- = 3 \quad I^- \tag{1}$$

1.3. Semiconductors

Around 80% of solar cells in the world are made using silicon-based materials [34]. The markets favour cost reduction in the material and manufacturing process. Therefore, alternative cheaper materials are required. Semiconducting metals with a wide band gap, able to act by photosynthesis through the use of an organic dye to produce pairs of electrons-holes, has become a good alternative to the conventional inorganic semiconductor-based solar cells. [35] Such semiconductors include titanium dioxide (TiO_2) [36], zinc oxide (ZnO) [37–39] and tin dioxide (SnO_2) [40–42] which are very useful for solar energy applications [43,44]. Semiconductors are crystalline solids, they are neither metals nor insulators, their proprieties are determined at low

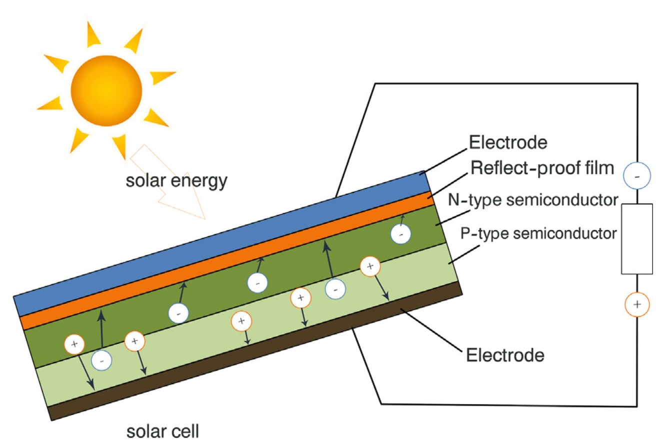

Fig. 1. Si Solar Cell [20].