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Improving Photovoltaic Technology by Nanomaterials: a Brief Review

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Abstract

Nanomaterials have unique opto-electronic properties that can aid in the progress of current photovoltaic technology in various aspects and aid in the global transition towards renewable energy sources. In this brief review we discuss how might these materials contribute to newer designs of photovoltaic cells that surpass common Silicon cells and render this technology more efficient and more cost-effective. The types of nanostructures that we discuss are: nanotubes, nanowires, nanorods, graphene and nanotextures.

Keywords: Photovoltaics, Nanomaterials, Nanotubes, Nanowires, Graphene.

1. Introduction

The extensive use of pollutant fossil fuels is considered as the main cause of the worsening impacts of climate change that we witness today. This critical situation makes it necessary to explore alternative clean energies such as solar energy, also known as photovoltaic (PV) energy. This clean energy has been for long the subject of extensive research and development, and of governmental incentives to widen its use, which resulted in a considerable growth of PV-power generation in the last decade, as it is shown in Fig. 1. The annual global PV-power generation was raised by 22% in 2021 to exceed 1000 TWh for the first time [1]. According to the International Energy Agency [1], this level should accelerate more to attain 7400 TWh by 2030 in order to meet the Net Zero carbon neutrality roadmap. To satisfy these objectives, PV devices should be more efficient and more competitive against common fossil fuels in order to implement itself in the general public.

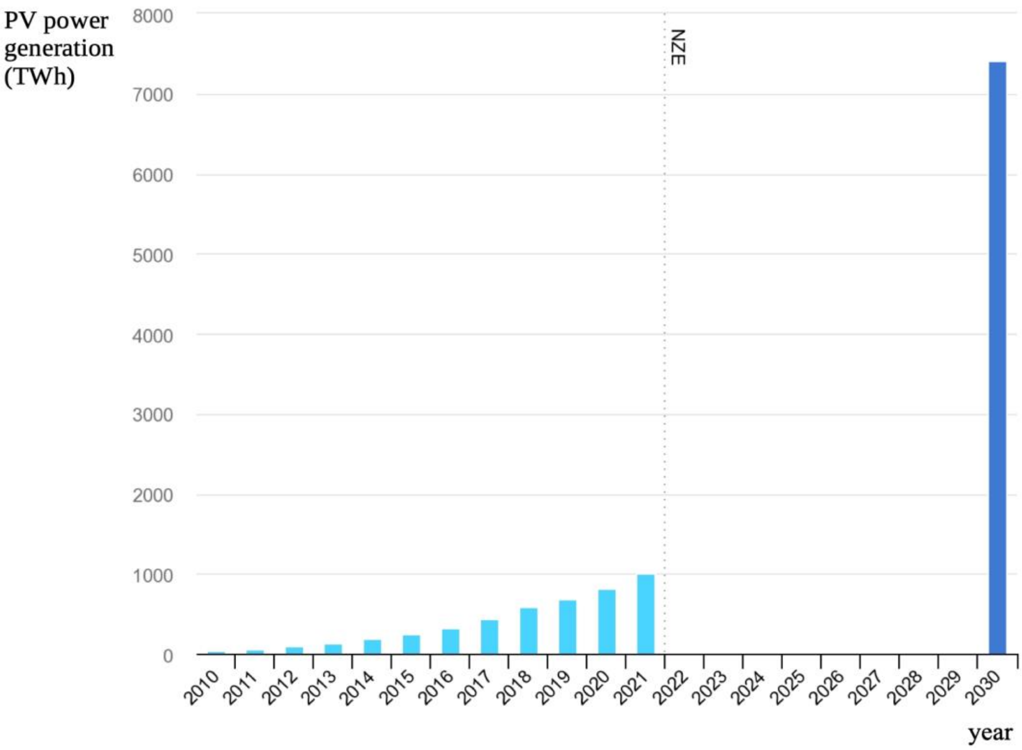

Fig 1. Evolution of PV-power generation from 2000 to 2021 and aimed growth for 2030 according to the Net Zero roadmap set by the International Energy Agency [1].

PV cells convert solar energy (in the form of light photons) to useful electric energy without any emissions during the process. The basic PV cell consists of a photoactive layer sandwiched between two charge-conductive layers (known as electrodes) and possibly charge-transport layers in certain designs, as shown in Fig. 2. In a simplified concept, electric current is generated when photons excite the electrons of the photoactive layer, making them travel through the external circuit to reach the cell again to finish what is known as the photovoltaic effect.

Silicon (Si), the famous electronics semiconductor, is also the standard material in photovoltaics. In its crystalline form (crystalline-Silicon, c-Si), this material offers a fair conversion efficiency of ~16% for commercial modules [2]. Several PV technologies have emerged after this technology, but c-Si devices remain the most popular with 95% of the global share of PV devices [3]. Despite this prevalence, Si devices have some technical drawbacks, like their low optical absorption in the infrared region which means that not all the light energy is exploited, and also the limited maximum theoretical efficiency at 29% [4]. In addition, ITO –the standard electrodes material– is costly and brittle [5], which does not allow the realization of flexible PV devices.

Economically, PV energy does not yet make a cost-effective choice for most people, and particularly in developing countries like Algeria [6]. This will deter the general public from purchasing this clean energy source in favour of the cheaper –but non sustainable– traditional sources.

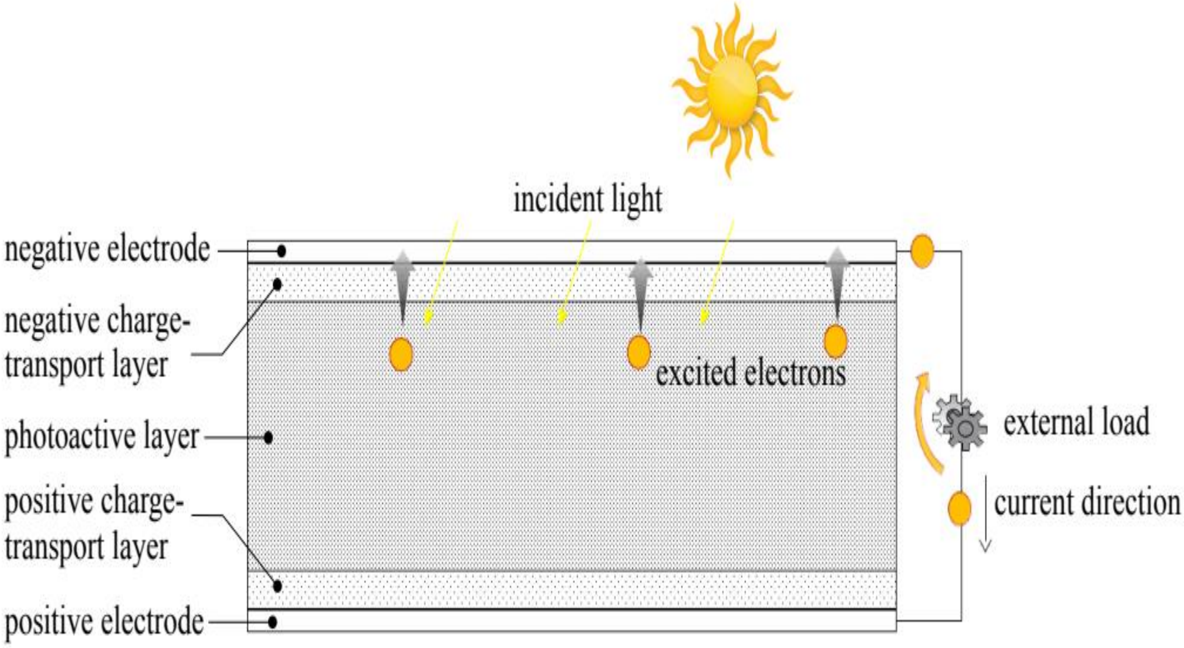

Fig 2. General schematic illustration of a PV cell.

Amongst many investigated solutions to these limits in conventional cells, the most interesting is the use of nanotechnology. Nanomaterials are characterized by having one dimension or more in the order of the nanometer, and one nanometer equals one part from a million in a single millimetre. This infinitesimally small dimensions provide unique physical properties that do not exist in the bulk form of the material. Various fields of science are exploiting these novel materials, including electronics and energetics.

2. Uses of Nanomaterials in Current PV Research

This section discusses the main types of nanomaterials, their interesting properties, and how they are incorporated in the latest research PV devices. Extending these designs to consumers world is dependent on the drop of nanomaterials' production costs and the applicability of laboratory procedures to the industry.

2.1 Nanotubes

The use of nanotubes (NTs) represents an important research branch in photovoltaics. The most interesting class of these one-dimensional structures are carbon nanotubes (CNTs), which have great electronic and optical properties and can perform various roles inside PV cells. In Si cells, CNTs are used as a thin film interfaced with Si layer. If CNTs are treated to have semiconducting behaviour, this interface will form a p-n junction. For metal-behaviour CNTs, this interface will form a Schottky junction [7]. CNTs:Si-junction devices have reached an efficiency of 18.9% recently by using Nafion-doped CNTs [8]. In organic PV cells, CNTs can be incorporated in the polymer matrix of the photoactive layer with small concentrations (~4%) to act as electrons donors or as electron acceptor. Alternatively, CNTs films can be used as an organic charge-transport layer [9]. Incorporating single walled CNTs into PEDOT:PSS hole transporting layer was shown to yield an efficiency of 14.6% [10], which is an excellent value for organic cells.

CNTs films combine high transparency and high conductivity [11], which are essential properties for transparent electrodes. Perovskite devices with CNTs electrodes achieved 18.9% efficiency recently [12]. CNTs' flexibility allows to produce ITO-free electrodes in foldable devices with good durability (compare in Fig. 3 the lifetime of PV cells based on ITO-electrodes and those based on CNTs-electrodes).

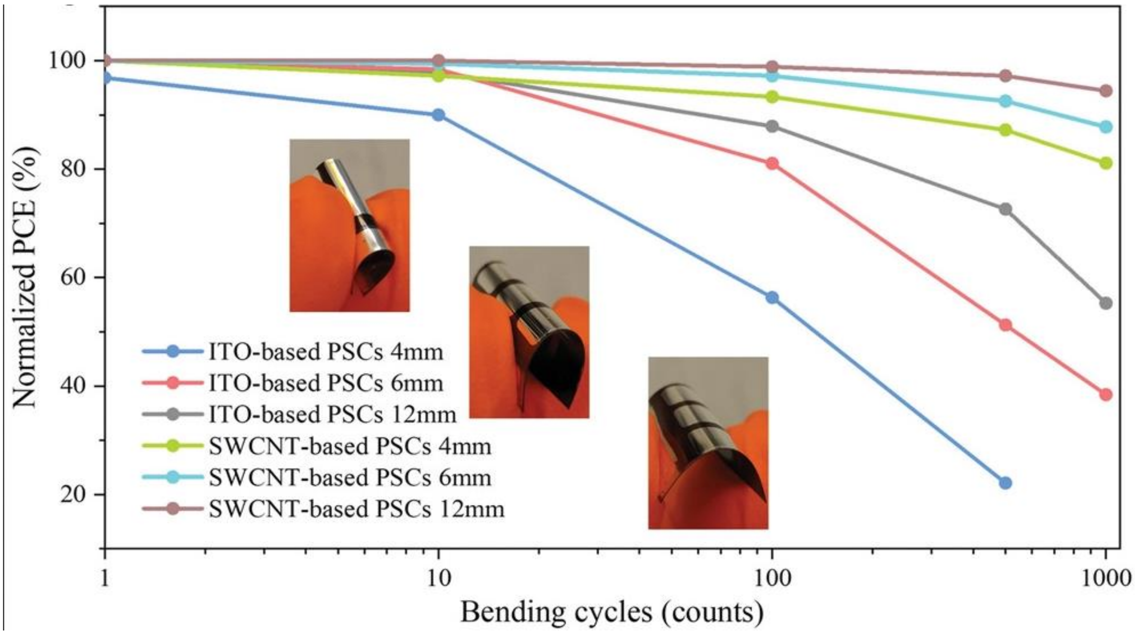

Fig 3. Comparison of bending-cycles effect on the efficiency of flexible Perovskite PV cells based on ITO-electrodes and single walledCNTs-electrodes (with the bending radius of 4, 6, and 12 mm) [12].

TiO2 NTs also possess some interesting properties for PV technology. Their hollow structures provide greater surface areas compared to other nanostructures and give more efficient charge generation and better infiltration and contact with the interacting matrix [13]. TiO2 NTs receive particular focus in dye-sensitized solar cells, where their performance is enhanced by different procedures, like increasing their diameter or doping treatments [14].

2.2 Nanowires and Nanorods

Nanowires (NWs) are one-dimensional nanostructures with elevated aspect ratios, while nanorods (NRs) are less elongated quasi one-dimensional structures. Both of these structures are solid and not hollow like NTs. NWs offer excellent charge transfer and optical properties [15], which are higher than nanostructures with aspect ratios approaching 1:1 [16]. Silicon NWs (SiNWs) are much used in PV research for their superior optical characteristics than bulk Si [17].

SiNWs' physical properties can be controlled by changing their geometry and density in production processes. For instance by changing growth temperature in vapour-liquid-solid (VLS) method (Fig. 4 (a)-(c)) [18], or by varying etch time in metal-assisted-chemical-etching (MACE) method (Fig. 4(d)-(f)) [19]. SiNWs have excellent antireflection properties, and using them on top of textured Si surfaces was shown to reduce the reflectance from ~13% to less than 1% [20].

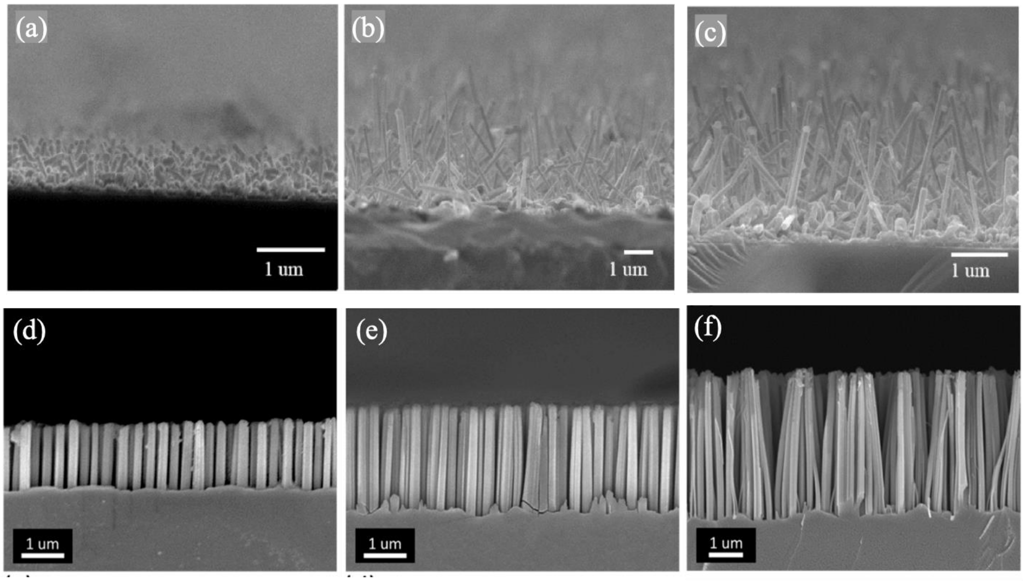

Fig 4. Control of NWs' morphology and density: (a), (b) and (c) The effect of varying growth temperatures in VLS method (450 ◦C, 550 ◦C, and 620 ◦C respectively). Reproduced from [18]. (d), (e) (f) The effect of varying etch time in MACE method (2, 4 and 8 min respectively). Reproduced from [19].

ZnO NRs and NWs possess high electronic properties that make them very interesting for photovoltaics research [21], and in particular for dye-sensitized cells and CdTe cells [22],[23]. Metallic-type NWs, like AgNWs [24] and CuNWs [25], are investigated as substitutes to ITO in flexible and transparent electrodes. To further improve these metal-based electrodes, NWs are doped with graphene, which provides higher conductivity, more flexibility, more protection for metal NWs against oxidation, and lower surface roughness [26],[27].

2.3 Graphene

Graphene is a two-dimensional sheet-like carbon nanomaterial which combines high conductivity with optical transparency. It also offers remarkable mechanical flexibility [28], which allows it to replace fragile ITO electrodes in flexible PV designs. Graphene-based electrodes have actually demonstrated better photovoltaic performance than CNTs electrodes, which is due to their better morphology (allowing greater charge transport) and higher transparency (allowing more light penetration and absorption in the photoactive layer beneath) [17].

In addition to its use as a transparent-electrode layer, graphene can be incorporated into the photoactive layer to perform various functions, such as a light-harvesting material, electron transport layer, hole transport layer, or a Schottky Junction (SJ) layer [30]. Graphene-based SJ PV cells were realised only in 2010 with a modest efficiency of 1.5% [31], but they have been constantly developed since then to reach 13.5% efficiency recently [32]. Also, the latest Perovskite PV cells with TiO2-graphene hole-transport layer demonstrated a 26% efficiency [33], which approaches closely the efficiency of best c-Si laboratory cells [2].

2.4 Surface nanotextures

Surface texturization has been for long a standard treatment for c-Si wafers to create microscale textures that enhance light-trapping and reduce reflection. The progress of nanotechnology permitted the realization of nanoscale textures with higher efficacy than microscale textures. Texturization gives a black appearance to Silicon surface, hence the name ‘black Silicon’ (note the colour of nanoholes-textured cell in Fig. 5 (a’)). Different methods for creating nanoscale textures exist, and the most common are MACE method, alkaline etching, acidic etching, electrochemical etching, laser irradiation method and reactive ion etching (RIE) [34],[35]. Each method will result in different nanotextures, for which the geometric properties can be further adjusted by controlling the method’s parameters to optimize the optical characteristics. In this respect, we present in Fig. 5 the examples of nanoholes (realized using nanosphere lithography and RIE process) [36], nanoparaboloids (realized using silica-beads nanosphere lithography and RIE process) [37], and nano grooves (realized using lithography and alkaline etching) [38]. We join as well the corresponding reflectance charts to demonstrate the improvements of textured devices over non-textured reference devices, and to show the influence of nanotextures’ parameters on optical properties.

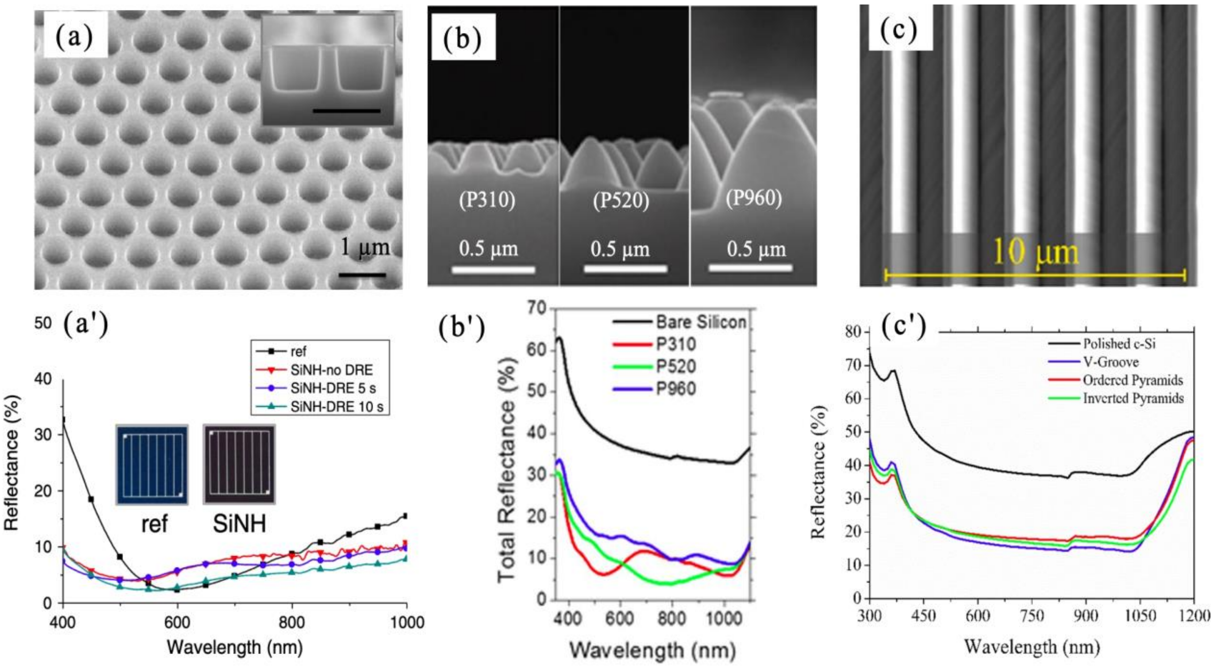

Fig 5. Nanotextured Si surfaces with their respective reflectance charts: (a,a') Si nanoholes with and without damage-removal etching (DRE). Reproduced from [36]. (b,b') Nanoparaboloids using different silica-beads sizes. Reproduced from [37]. (c,c') V-shaped grooves and the reflectance results of other types of nanotextures. Reproduced from [38].

3. Conclusion

In this paper we have reviewed the recent uses of nanomaterials in photovoltaics and the large benefits they can add. The properties of these materials can help to make PV energy more efficient and more competitive against traditional fossil sources, which may contribute in the global transition towards environmentally-friendly energies. The remaining challenge, however, is to improve fabrication and assembly techniques of nanomaterials in large-scale industry, and render these procedures more economical and mores sustainable.

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