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Review

Recent progress in graphene incorporated solar cell devices

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ABSTRACT

The atomically thin flat sheet of carbon atoms, 'graphene' showcases several key features that can address emerging energy needs, in particular to enhance the energy conversion efficiency of photovoltaic devices. Here, we review the energy conversion efficiency of graphene incorporated solar cell devices. The various structures of the solar cell devices have been investigated which includes organic, inorganic and hybrid structures. Dye sensitized solar cell with Gr/PEDOT:PSS counter electrode has exhibited 4.5% efficiency, which is comparable to expensive Pt counter electrode based device with 6.3% power conversion efficiency. The Gr/Silicon nano-hole and Gr/Silicon nanowires based Schottky junction devices have revealed high efficiency of 8.71% and 10.30%, respectively. In bulk hetero-junction solar cell devices, GO as electron transport layer has increased performance from 5.9% to 7.5%. The GO/PEDOT:PSS as hole transport layer in planar hetero junction perovskite photovoltaic device of structure ITO/(GO/PEDOT:PSS)/$CH_3NH_3PbI_3$/PCBM have achieved 9.7% efficiency, which is greater than 8.2% of traditional PEDOT:PSS. Though graphene shows great potential for photovoltaic applications, its stability and flexibility are also equally important and have been discussed. The results indicate that utilization of graphene in energy devices yields more efficient results and opens new avenues for future applications.

1. Introduction

Globally increasing energy needs demand for environment friendly, low cost and sustainable solutions for domestic and commercial applications. Different energy resources have been investigated to overcome energy crises faced by the community. Due to low performance, environmental pollution and dearth of resources conventional energy resources are not favorable choice to be used on large scale. Therefore, alternate renewable energy resources i.e. solar, hydel, geothermal and fuel cell energy conversion systems have been discovered, developed and studied. Solar power is a good contender to overcome these energy related issues to address clean and sustainable energy demand.

A solar cell absorbs the light energy and converts it into electrical energy. Since the discovery of photovoltaic effect, different types of solar cells have been fabricated and characterized to gain high efficiency. The performance of a photovoltaic device mainly depends on type of solar cell and material used for fabrication. Currently, Si based first generation photovoltaics dominate the solar energy market for commercial purposes and achieved 11% efficiency (Matsui et al., 2013). Second generation photovoltaics are based on thin-film technology. They have low efficiency as compared to first generation. A more environment friendly and cost effective third generation solar cells includes dye sensitized solar cells (DSSCs), quantum dot solar cells (QDSCs) and organic photovoltaics (OPVs) (Hoppe and Sariciftci, 2004; O'regan and Grfitzeli, 1991; Radich et al., 2011). These devices exhibit low power conversion efficiency, less stability and strength as compared to other generations (Mathew et al., 2014). Therefore, further research is being carried out to enhance the efficiency and stability of photovoltaic (PV) devices.

The basic structure and working principle of a solar cell device is illustrated in Fig. 1. A solar cell mainly comprises of the electrodes, photoactive layer and carrier transport layers. Each part has particular characteristics to be a promising component of an efficient photovoltaic device. The materials having higher transparency, low sheet resistance and high stability are mainly used as electrodes in solar cell. The photoactive layers are generally prioritized for capturing broader spectrum of light, higher charge carrier mobility and enhanced thermal and photochemical stability. Carrier transporters including hole and electron transport layers are used for improved carrier transportation through reduced hole-electron recombination rate.

The device performance of a solar cell is estimated by the fraction of photons absorbed and amount of photocurrent generated i.e. power conversion efficiency

$$\eta = \frac{P_{max}}{P_{inc}} \quad (1)$$

Here P_{inc} is incident photon power and

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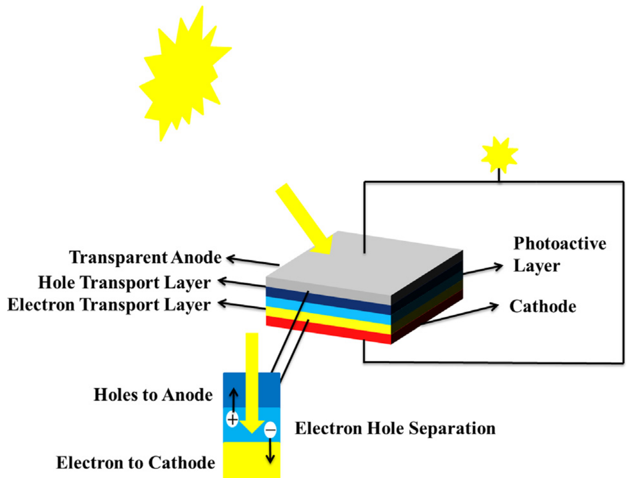

Fig. 1. A solar cell device based on photovoltaic effect comprises of a photoactive layer sandwiched between hole and electron transport layers with front and back electrodes.

$$P_{max} = FF \times V_{oc} \times J_{cc} \quad (2)$$

where FF is filling factor

$$FF = \frac{V_{max} \times J_{max}}{V_{oc} \times J_{cc}} \quad (3)$$

and V_{oc} and J_{cc} denote maximum open circuit voltage and maximum close circuit current, respectively (Green et al., 2015).

The performance of the device primarily depends upon the material used for device fabrication. Therefore, a variety of materials have been investigated for device fabrication and characterization. Among these, two dimensional (2D) materials for their fascinating electronic, photonic, mechanical, optical and thermal properties with versatile applications in electronics and optoelectronics are of most importance. Graphene (Gr), a carbon layer having hexagonally packed honeycomb structure, with superlative characteristics manifested favorable photovoltaic applications. Graphene can capture broader spectrum and absorbs 2.3% of irradiated light (Bonaccorso et al., 2010). Ultra high carrier mobility (μ = 20,000 cm^2/Vs) and low sheet resistance makes Gr a perfect choice as photo anode replacing Indium doped Tin Oxide (ITO) (Chen et al., 2008; Rowell and McGehee, 2011).

Similarly, large surface to mass ratio (2630 m^2/g) facilitate charge collection and release process, improving photovoltaic performance (Peigney et al., 2001). Facile chemical activity and functionalization of Gr has promising applications as photoactive layer in solar cells (Gupta et al., 2011; Liu et al., 2008; Yan et al., 2010). Enlarged chemically active surface area modifies the catalytic activity of counter electrode and facilitates charge transfer mechanism. The chemically functionalized Gr exhibited low sheet resistance, enhanced charge transfer activity and increased current density (Roy-Mayhew et al., 2010). Furthermore, Gr/semiconductor Schottky junctions accelerate the carrier separation and diffusion process. Therefore, chemical properties of graphene have also contributed to enhance photovoltaic technology (Zhang et al., 2013b).

Since, Gr and its various composites can be a better choice to address the current demand of more efficient materials for solar cell applications and are consider as potential candidates for as electrodes i.e. transparent anode (Fathy et al., 2016; Gomez De Arco et al., 2010; Hsu et al., 2012; Huang et al., 2012; Lee et al., 2011a, 2011b; Li et al., 2011; Tung et al., 2009; Wang et al., 2008; Wang et al., 2011b), transparent cathode (Bi et al., 2011; Park et al., 2012; Yin et al., 2010b; Yin et al., 2014), catalytic counter electrode (Chen et al., 2013; Kavan et al., 2011a; 2011b; Kavan et al., 2010; Li et al., 2011; Lin et al., 2011; Roy-Mayhew et al., 2010; Yu et al., 2013), photoactive layer (Gupta et al., 2011; Liu et al., 2008; Yan et al., 2010), Schottky junction (Li et al., 2010b; Lin et al., 2013) and carrier transporter (Guo et al., 2010; Kim et al., 2011; Li et al., 2010a; Liu et al., 2012; Tang et al., 2010; Wang et al., 2010; Yang et al., 2010; Yun et al., 2011; Zhou et al., 2011). Fig. 2 illustrates the application of graphene incorporation in various solar cell technologies.

1.1. Graphene as transparent conducting anode

Transparent conducting anode can serve as a window to photoactive layer and as an ohmic contact in photovoltaic devices (Liu et al., 2012). The high transparency (Transmittance (Tr) > 90% (Rowell and McGehee, 2011)) and low sheet resistance (Rs < 10 Ω/□ (Rowell and McGehee, 2011)) are prerequisites for transparent conducting anode. Conventionally used contacts Indium doped Tin Oxide (ITO) and Fluorinated Tin Oxide (FTO) are reported to have highest cost among all components of dye sensitized solar cells (Kalowekamo and Baker, 2009). Apart from cost, limited flexibility and stability also restrict the use of these transparent conducting substrates (Bonaccorso et al., 2010). Therefore, several materials such as metallic nanowires (Li et al., 2011b, 2011a) and carbon nanotubes (Lin et al., 2011) have been fabricated and employed to overcome these limitations, but their surface characteristics limit large scale applications.

On the other hand, graphene owing to its high transparency and low sheet resistance, is one of the best materials to be used as transparent electrode to enhance the PV performance. Despite the fact that best combination of sheet resistance and transmittance is not achieved yet, graphene based transparent conductors have been implemented in organic photovoltaics (Gomez De Arco et al., 2010), inorganic

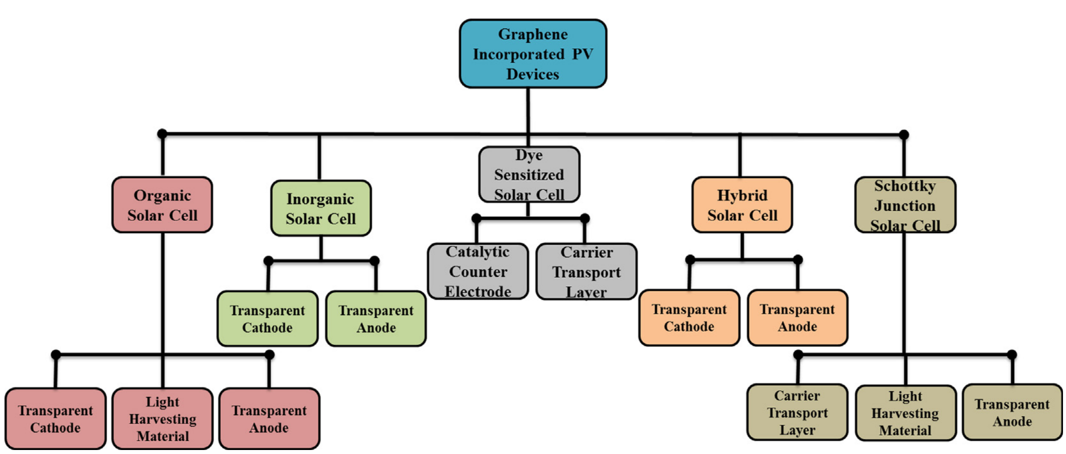

Fig. 2. Schematic illustration of graphene incorporation for various photovoltaic device applications.