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Effective nanostructured morphologies for efficient hybrid solar cells

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Abstract

The increased global demand for low-cost renewable energy sources has motivated scientists and engineers to derive and explore novel methods for converting solar energy into electricity. Among those methods, solar cell is one of the clean technologies that has been adopted to produce electricity. However, low efficiency, high cost associated with the preparation of materials and subsequent device fabrication prevented their extensive use to satisfy the growing demand. Hence the technologies based on silicon, organic solar cells, dye-sensitised solar cells or a combination of these two (hybrid solar cells) were developed, where the latter has gathered advantages from both inorganic and organic materials. In this article, the potential of hybrid solar cells over the other types are reviewed. Nanostructured morphologies with high surface area offer significant energy conversion efficiency. In this direction, industrially applicable electrospun nanofibers are more appropriate when compared to the other nano-fabrication technologies. Furthermore the ability of aligned nanofibers to provide higher solar conversion efficiency is discussed. We have also highlighted the fabrication of various nanostructures such as thin films, quantum dots, nanoparticles and composite nanofibers and juxtaposed their morphology with efficiency.

Keywords: Hybrid solar cell; Conversion efficiency; Nanostructures; Electrospinning

Abbreviations: 1-D, One dimensional; 2-D, Two dimensional; 3-D, Three dimensional; $CH_3NH_3PbI_2Cl$, Methylammonium lead iodide chloride; DSCs, Dye sensitised solar cells; D102, Indoline dye; DTBT, Di-2-thienyl-2, 1, 3-benzothiadiazole; EDT, 1*2-ethanedithiol; e^-, Electron; FF, Fill factor; HOMO, Highest occupied molecular orbital; HSCs, hybrid solar cells; HSPh, 4-bromothiophenol; J_{sc}, Short circuit density; $Li(CF_3SO_2)_2N$, Bis (trifluoromethylsulfonyl) amine lithium salt; LUMO, lowest unoccupied molecular orbital; MDMO-PPV, Poly [2-methoxy-5-(3′,7′-dimethyloctyloxy)-1,4-phenylene-vinylene]; MEH-PPV, Poly [2-methoxy-5-(2-ethylhexyloxy)-1,4-phenylenevinylene]; MoO_3, Molybdenum trioxide; MPA, Mercaptopropionic acid; N719, ruthenium dye; OSCs, organic solar cells; PANI, Poly (aniline); P3HT, Poly (3-hexylthiophene); P3MT, Poly (3-methylthiophene); PCE, power conversion efficiency; PCBM, [6,6]-phenyl-C_{61}-butyric acid methyl ester; PCL, Poly (caprolactone); PDTTTPD, 2,5-di-(thiophen-2-yl)thieno[3,2-b]thiophene and thieno[3,4-c]pyrrole-4,6-dione; PEDOT, Poly(3,4-ethylenedioxythiophene); PCPDTBT, Poly[2,6-(4,4-bis (2-ethylhexyl)-4H-cyclopenta [2,1-b;3,4-b′]-dithiophene)-alt-4,7-(2,1,3-benzothiadiazole)]; PEG, Poly (ethylene glycol); PEO, Poly (ethylene oxide); PMeT, Poly (3-methylthiophene); PSS, Poly (styrenesulfonate); PTB7, Poly[[4,8-bis[(2-ethylhexyl)oxy]benzo[1,2-b:4,5-b']dithiophene-2, 6-diyl][3-fluoro-2-[(-ethylhexyl)carbonyl]thieno[3,4-b]thiphenediyl]]; PV, photovoltaic; PVK, Poly (9-vinayl carbazole); QDs, quantum dots; SCs, solar cells; Spiro-OMeTAD, 2,2′,7,7′-tetrakis-(N,N-di-4-methoxyphenylamino)-9,9′-spirobifluorene; TBP, 4-tert-butylpyridine; V_{oc}, Open circuit voltage.

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1. Introduction

The solar cells based on semiconducting nanostructures are promising for future-generation photovoltaic devices due to their advantages such as easy processing, scalability and cost effectiveness. Solar cells are mainly categorized (Wu and Zhang, 2010) into three different types such as inorganic solar cells are first generation (Gur et al., 2005; Garnett and Yang, 2008; Kempa et al., 2008; Tian et al., 2007; Luther et al., 2008), organic solar cells (OSCs) and dye-sensitised solar cells (DSCs) Grätzel, 2001; Law et al., 2005; Tan and Wu, 2006 are second generation (Ma et al., 2005), and hybrid solar cells (HSCs) are considered for third generation (Gur et al., 2007; Huynh et al., 2002; Greene et al., 2007). The power conversion efficiency (PCE) of first and second generation solar cells were ~25% (silicon) and ~20% (copper indium gallium di-selenide) at lab scale (Green et al., 2010) respectively. However, the cost (Si) and availability (e.g.: In) of materials within the next 50 years or more are the matters of concern when it comes to large scale industrial production (Green et al., 2001) to meet the current demand. In the recent past, DSCs became a focus of interest due to their conversion efficiencies in the presence of thin absorbers such as dyes or solid state hole conductors depicting efficiencies of 11.4–15% (Han et al., 2012; Zhang et al., 2013; Yella et al., 2011; hardin et al., 2012; Shi et al., 2012). $CsSnI_3$ perovskite was shown to function efficiently as a hole conductor in solid-state DSCs, delivering ~10.2% (Chung et al., 2012; Snaith, 2012). Although, typical DSCs offer considerable PCE they suffer from durability, corrosion and leakage problems. On the other hand, OSCs continued to attract researchers' attention due to their promising features such as economic production, flexibility and lighter weight (Ma et al., 2005). The OSCs include devices with bulk heterojunctions (Yu et al., 1995) and tandem layers consisting (Kim et al., 2007; Blom et al., 2007; Dennler et al., 2009) of various types of conjugated polymers, fullerene derivatives or carbon nanotubes. Notably though solution processable tandem layered solar cells (bulk heterojunctions) consisting of semiconducting polymer and fullerene derivatives have produced an efficiency of ~6.5% (Kim et al., 2007). Organometallic halides based perovskites have shown to produce ~10.9% where solution processable meso-superstructures were developed (Lee et al., 2012). As an alternative to the OSC, HSC comprises the advantages of inorganic, organic materials, which are originated from the concept of organic polymer bulk heterojunctions. When it comes to the advantage of HSCs over OSCs the former possesses higher carrier mobility and the onset of absorption at shorter wavelengths. Moreover, the recent progress in semiconducting nanostructures (nanoparticles/nanorods and nanofibers) in combination with organic nanomaterials (fullerenes, CNT. etc.) open new opportunities to enhance the power conversion efficiency and as a results a widespread commercialization (Xiang et al., 2009). The HSCs made with either ZnO (Beek et al., 2005) or TiO_2 porous metal oxides in combination with polymers yielded efficiencies of ~1% and ~1.4%, respectively (Boucle et al., 2007; Ravirajan et al., 2004). Basically, in HSCs the photo-conversion process occurs at the interface and consequently photogenrated charge carriers are seperated due to the internal electric field. Notably the wide band gap ($TiO_2 \sim 3.2$ eV; $ZnO \sim 3.3$ eV) metal oxide semiconductors cannot absorb solar light lower than the band gap energy. In order to increase the absorption CdSe has been introduced in HSCs (Sene et al., 2000). Well-controlled and good quality films were grown on electrolytic PMeT leading to a *pn*-heterojunction (PMeT/CdSe). However, the efficiency of such a hybrid organic–inorganic junction was as low as ~2.7%. In the same year, Nguyen et al. (2000) fabricated a HSC with PMeT and CdS, where the constituent materials were doped with various anions or metals, respectively. Among these combinations, the best reported efficiency for $PMeT(PF_6^-)/CdS(Sb)$ was ~3.5%. Nanocomposite based HSCs have been considered in the last decade (Huynh et al., 2002) as a promising alternative, where the nancomposite acts as the photoresponsive materials. In the year 2009, Oosterhourt (Oosterhout et al., 2009) and his coworkers fabricated a HSCs with P3HT as donor and ZnO as acceptor, which depicted an efficiency of about 2%. Notably though the efficiency of the hybrid polymer solar cells depends on the 3-D morphology (Oosterhout et al., 2009) of ZnO. By given the difficulty and numerous combination of materials, this review highlights HSCs based on different nanostructures such as thin films, quantum dots, nanoparticles and composite nanofibers. The potential advantages of HSCs over other types of solar cells are also discussed. A quick analysis of nanostructure based HSCs has been reviewed in this article.

1.1. Why do we need hybrid solar cells?

HSCs have the potential to become a leading technology of the 21st century in converting solar energy into electricity due to their easy processability which leads towards printable devices in a roll-to-roll fashion at high speed and low cost. Solar cells can be fabricated based on a composite of *n*-type inorganic nanomaterials and *p*-type conjugated polymers. On the other hand, composite of *n*-type organic materials and *p*-type inorganic semiconductor is also feasible (Chavhan et al., 2010). Further to this bi-layered structures are introduced in the fabrication of hybrid solar cells (Chavhan et al., 2010; Cantu et al., 2011, 2010). The inorganic semiconductors have high electron mobility together with good physical and chemical stabilities, whereas the conjugated polymers are known for their flexibility and low cost accompanied by large area processability (Beek et al., 2004, 2005; Bouclé et al., 2008; Lin et al., 2009). However, the PCE of polymer-based solar cell is poor (1–3%), less stable and sensitive to environmental conditions such as moisture. A simple mechanical combination of these two materials may not be a final solution but the synergy effect that can be expected might boost