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Commentary

Graphene Solar Cells-Will it be the Ultimate Power Converter?

Commentary

Solar cells or photovoltaic (PV) cells involve the direct conversion of light energy into electrical energy. PV cells are basically *p-n* junctions made from layers of semiconducting materials. Under light illumination, either free electron-hole pairs are generated within the bulk of the layers and subsequently separated through the internal electric field across the depletion layer of the junction (in conventional solar cells), or exactions are created and simultaneously separated across a hetero-interface (in excitonic solar cells), thus producing an open-circuited photo voltage [1,2]. Upon connection with an external circuit, an electric current is drawn out and used for powering outside devices. This photocurrent, along with the photo voltage, defines the power that the solar cell can deliver.

In general, solar cells are categorized into 1st, 2nd and 3rd generation PV cells. The 1st generation cells are the conventional ones, made up of crystalline silicon (c-Si) wafers (either single-crystalline or poly-crystalline Si), having efficiency below 20%. 2nd generation includes thin film solar cells (TFSCs), which are made up of layers of amorphous silicon (a-Si), cadmium telluride (CdTe), copper indium gallium selenide (CIGS) etc., having efficiency less than 15%. Although TFSCs have lower power and space efficiency as well as lesser longevity than that of c-Si – based solar cells, but they are considerably cost-effective, and hence highly attractive for volume production. 3rd generation solar cells (also thin film – based cells, popularly known as 'emerging photovoltaics') are still in the research and development stage, but use newer materials and thin film deposition technologies to improve the power and space efficiency of the cells. Most of these cells use inorganic, organic and/or organometallic compounds. Although the reported efficiency of these emerging photovoltaic cells are still considerably lower than the satisfactory level for productive commercial applications, but they promise to achieve the goal of producing low-cost, high-efficient solar cells. Especially, after the advent of Nanotechnology, existing solar cell materials reveal improved and interesting properties at nanoscale against their bulk counterparts, whereas new (yet cost-effective) thin film deposition techniques are invented to produce new types of nanostructured materials for improved solar cell applications. Some of these emerging solar cells include dye sensitized solar cells (DSSCs), hybrid solar cells, organic solar cells (or plastic solar cells), perovskite solar cells, plasmonic solar cells, quantum dot solar cells and graphene solar cells, among others.

Amongst these, graphene-based solar cells are considered to be the most promising one, because of the fact that graphene [3,4] is one of the most attractive and sought after nanomaterials in recent times after the advent of single-layer graphene via a simple mechanical exfoliation method [5]. Graphene, which is the world's first two-dimensional (2D) material, is made of a single layer of carbon atoms that are bonded together in a repeating pattern of hexagons and either freely suspended or adhered to a substrate. Graphene is considered to be the 'wonder material' because of its unique properties. It is the strongest (200 times stronger than steel), thinnest (1 million times thinner than a human hair), most conductive, highly stretchable, extremely transparent, fully flexible, chemically inert and impermeable material. Since graphene is made of carbon, which is abundant and relatively inexpensive material, it offers extraordinarily diverse applications in improving the existing products as well as providing opportunities for developing newer ones.

In general, solar cells require a transparent electrode which should be made up of materials that are conductive and allow light to get through. The conductive Indium Tin Oxide (ITO) is used with a non-conductive glass layer as the transparent electrodes in most TFSCs (especially organic solar cells). But ITO is rare, brittle and thus makes solar panels expensive as well as unstable in terms of longevity. Therefore, benefiting from graphene's excellent conductivity and transparency, cost-effective, yet high-efficient transparent electrodes can be fabricated for solar cells. Although, graphene is a great conductor, but it is not very good at collecting the electrical current produced inside the solar cell, because the electrons in graphene can penetrate any potential barrier, thus making the cell "leaky" even in the open-circuited condition. Hence, researchers paid attention to find appropriate ways to modify graphene to reduce its conductivity at an appropriate level suitable for solar cell and similar electronic applications. Hydrogenated carbon, the so-called 'graphane' [6] and graphene oxide [7] are found to be suitable candidates for transparent electrodes in solar panels. Therefore, many research groups focus on these 'cousins' of graphene as a replacement for ITO in transparent electrodes of solar cells, whereas other groups concentrated on searching novel ways of utilizing graphene in organic and other thin film solar cells to improve the overall performance of the solar cells. The later groups focused on several interesting properties of graphene, such as their tunable bandgap to allow/absorb wide range of solar radiation, high optical absorbance, tunable electronic levels for efficient interfacing with other materials for fast charge transfer, large charge mobility etc., which are highly attractive for photovoltaic applications in terms of efficient light harvesting and charge collections.

As far as the recent progress in the graphene solar cell research

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is concerned, in 2010, Li and co-authors from Indiana University reported wet-chemical synthesis of largest and soluble graphene quantum dots with uniform size-distribution, which would open up exciting opportunities to tune the optical and electronic properties of graphenes suitable for photovoltaic applications [8]. Generally, synthesis of uniform size graphenes that are stable and large enough to absorb the entire visible spectrum is highly challenging because of their extremely low solubility and strong tendency of agglomeration into graphitic structure, thus altering the opto-electrical properties of graphenes and preventing efficient interfacing with other materials in photovoltaic devices. The above-mentioned report presented a novel solubilization strategy for the fabrication of large graphene quantum dots with uniform size for efficient use in solar cells as sensitizers.

In 2013, Grossman's group at Massachusetts Institute of Technology (MIT) [9] theoretically showed that stacking of several bi-layers (consisting of a monolayer graphene and a single layer molybdenum disulfide sheet) into a new solar cell can become 1000-times more efficient than Si-based solar cells of similar weight. Although this report is mainly based on theoretical modelling and the first prototype is yet to be realized, but may soon come into existence, thus achieving the potential goal of creating the "ultimate power converter". In the same year, Wang et al. [10] from University of Oxford reported ultra-low temperature solution-processed graphene/TiO_2 nanocomposite thin film perovskite solar cells having relatively higher (~15.6%) efficiency, where graphene nanoflakes provide superior charge collection properties for the fabrication of cost-effective, yet high-efficient solar cells. Also in 2013, Koh et al. [11] from Singapore's A*STAR institute reported that graphene outperforms ITO as transparent electrodes in organic solar cell devices, when stacked with four layers of graphene sheets.

In 2014, another research group from MIT [12] developed a flexible transparent graphene-based electrode for graphene polymer solar cell, having record efficiencies reported so far, which could provide novel means to realize fully graphene-based flexible solar cells. Another breakthrough was reported in 2014, when a researcher group from the University of Cincinnati [13] showed that adding even a small amount of graphene flakes facilitates the exciton dissociation and charge transfer in polymeric solar cells to improve the performance of the cell by as much as threefold the conventional non-graphene variant. This result is significant in the sense that pristine graphene can be used as a charge transporter for improved performance of solar cells. In 2014, an international research group reported, for the first time, that semiconducting polymer thin films' performance, in terms of vertical charge transport (i.e. parallel to thickness), is enhanced considerably when deposited on a single-layer graphene [14]. The importance of this work is that it contradicts the general notion that thinner polymer films conduct better. It was observed that a 50 nm polymer film conducts (vertically) 50 times better than a 10 nm thick film, when deposited on a single-layer graphene. This work would benefit considerably to the emerging photovoltaics because of the fact that enhancement of vertical charge transport in a solar cell is one of the key issues for the improved performance. In the same year, a European collaborative group reported that graphene's dynamical response to photo excitation can be manipulated effectively by tuning the doping levels within the graphene to generate significant amount of 'hot' carriers for superior photovoltaic applications [15]. This breakthrough enables the efficiency of the graphene-based solar cells to be doubled. Technically, the major issue with photovoltaic cells is its efficiency, which is merely 32% for most efficient and hence, most expensive solar cell, thus showing its inefficiency to replace the coal (or more generally non-renewable source) - based electricity. In that respect, utilizing graphene in solar cells to raise the efficiency to a staggering 60% can really revolutionize the renewable energy field to achieve low-cost, clean and environment friendly energy resources.

Recently, in February, 2015, a research group from Indian Institute of Science reported considerable enhancement of light-matter interaction by creating a device consists of a stack of two-dimensional arrays of silver (plasmonic) nanoparticles, each separated by single-layer graphene. The novelty of this work is that, graphene acts as a perfect spacer in the device to produce almost 1 million times higher electromagnetic field enhancement between the nanoparticles, thus enormously boosting the light-matter interaction, which is greatly beneficial for solar cell applications [16].

More encouraging trend on graphene solar cell research is the recent involvement of industries in this field. A Canadian renewable energy company, Sunvault Energy, recently announced to develop graphene-based supercapacitors to incorporate into photovoltaic devices for high efficient energy generation, storage and transfer within one unit [17]. Similarly, a British company, 2-DTech and an Australian company, Dyesol, recently entered into an agreement to develop graphene-based DSSCs, which may revolutionize the solar power conversion [18]. The main objective of this joint-venture project is to carefully engineer the graphene incorporation within the perovskite charge collecting regions of thin film DSSCs to considerably enhance the efficiency. Alongwith energy efficiency, use of graphene will lead to considerable space efficiency as well as cost-effectiveness and durability (by preventing entrance of moisture and external toxic reagents via monolayer graphene incorporation).

Therefore, it will not be an exaggeration to state that the extraordinary and diverse properties of graphene may soon lead to the fabrication of most efficient, cost effective and durable graphene solar cells to make "ultimate power conversion possible" [19].

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