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THE USE OF GRAPHENE IN PHOTOVOLTAIC PANELS

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Abstract*—This paper discusses the advantages of the use of graphene in photovoltaic cells, as well as an analysis of graphene based components. This is contrary to the current use of various compounds of silicon in photovoltaic materials and TCO's as electrodes in solar panels. Graphene is an ideal material for photovoltaics because of its low electrical resistance, compound structure, and its ability to be doped to improve its conductivity. This paper will mainly compare the use of graphene to silicon in a photovoltaic system. The advantages of graphene are mainly due to the efficiency of energy collection from a solar panel.*

The prospect of achieving all of our energy needs through clean solar power is a topic worth discussion and research. The current challenges facing solar technology are that solar panels need to become more efficient, cheaper, and need to have better methods of storing the energy produced. Using graphene in certain components in solar panels may be the answer to one of these challenges, making solar panels more efficient. This paper will analyze different methods by which the efficiency and practicality of current solar panels can be improved using graphene as well as future implications of these enhanced panels in power production.

Key Words—Future Solar Panels, Generation Three Solar Panels, Graphene, n-doped, Photovoltaic, Solar, Solar Cells, Solar Efficiency, Solar Panels

INTRODUCTION

The process of using photovoltaic materials in order to capture energy from sunlight has been around for many years and is improving rapidly towards commercial viability. A major issue of the current solar panel is the efficiency limitations brought on by the use of silicon as the material for the front electrode of the solar panel. Studies have shown that silicon is not an ideal material for the capture of energy from sunlight because of its material characteristics. These limitations have brought us to research better materials/compounds for use in future photovoltaic panels. Our findings have shown that the use of graphene in various parts of the solar panel can help improve power conversion efficiency. Graphene has been found to act as an alternative semiconducting material to indium tin oxide (ITO), resulting in a cheaper and more robust solar panel. Graphene can also work in tandem with other semiconducting materials like amorphous silicon and perovskite out of hopes of increasing the efficiencies of photovoltaic systems. These are various reasons why graphene can act as a good material for helping make solar energy into a more sustainable renewable energy method.

GRAPHENE STRUCTURE

Graphene is often considered a super material because of its various abilities and properties. Graphene is an allotropic material, meaning it is made entirely of one atom, more specifically, carbon. Graphene as a structure is a one atom thick sheet of graphite of indefinite area. As shown in figure 1, this sheet is composed entirely of carbon-carbon bonds where each carbon has four bonds with its neighboring carbons and is located in a hexagonal shape.

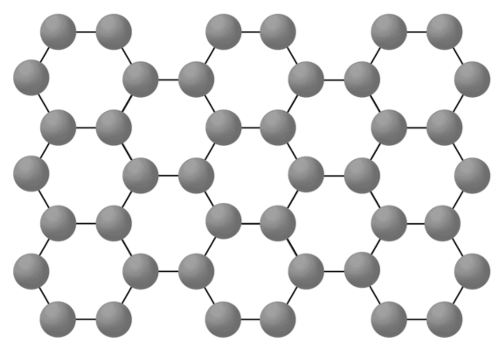

FIGURE 1 [2]
Visual structure of graphene sheet

These bonds are comprised of three sigma bonds that are in the plane of the sheet and one pi bond that is directed out of the page. The pi bond between the carbons in the structure is constantly changing place, making each bond in a graphene sheet essentially uniform in strength and length. These pi bonds are crucial to the fundamental characteristics of graphene, establishing delocalized electrons that are free to travel throughout the structure. These carbon bonds make graphene a very strong material, being over 100 times stronger than the strongest steel manufactured currently. Graphene is also nearly transparent because of its thickness (3.35Å), has a higher electrical and thermal conductivity than copper [3], and has very similar nonlinear optical properties to other photovoltaic materials like gallium arsenide and silicon [4].

The structural and physical properties of graphene make it an ideal material to act as the front electrode of a solar panel. The solar panel would be far stronger than the current silicon based solar panels. Also, a graphene solar panel would be nearly transparent. The transparency of a solar panel would be practical both in the sense of use and actual panel efficiency. Graphene's near transparency would make the prospect of layered solar cells much more viable and help to improve the efficiency of the panel. Graphene's discovery has brought solar power into an even higher echelon of sustainability due to graphene's high abundance and practicality. These benefits, along with the increased energy conversion efficiency because of graphene's inherent conductive abilities, which allows current to flow easier, are major reasons why graphene is an ideal photovoltaic material.

FUNDAMENTALS BEHIND SOLAR PANELS

Harnessing Solar Power

Solar power has been around for a long time, but our ability to harness it, and contain it for use in electrical devices is fairly recent. The basic principle of solar power is very similar to Einstein's photoelectric effect but is referred to as the photovoltaic effect. The photovoltaic effect, discovered by Becquerel, is when light is incident upon a surface-the electrons in the valence band absorb the light energy. With increased kinetic energy, these electrons jump to the conduction band and become free electrons. These free electrons are pushed along the material to a junction, called a depletion zone, where there are electron holes on the other side of this zone, and thus creates a flow of electricity through the system, generating electric energy from light energy.

This fundamental concept of inducing current in a material due to light was originally specific to metals in solution because the solution would ionize the plates. This ionization would cause a potential that in turn causes electricity to flow. Over time, materials like amorphous silicon and gallium arsenide became the popular materials used in photovoltaics due to their semi-conductive abilities. These semiconductors have the ability to allow the flow of current after input of a certain threshold of energy into the material. This is better than most metals because the metals require a solution in order to perform as an acceptable semiconductor, having a reasonably low energy threshold.

Current Limitations of Solar Panels

The solar panels that are currently in use and production are often referred to as thin-film solar cells. These cells are typically produced with amorphous silicon as the photovoltaic material for the solar panels and are designed to have a thickness up to about ten micrometers. This is a major improvement over the previous technology in terms of cost savings. Thin film solar panels also suffer because silicon has a poor absorption coefficient, especially in the infrared spectrum and decreasing the thickness of the solar panels only makes the panel less proficient at absorbing the longer infrared wavelengths.

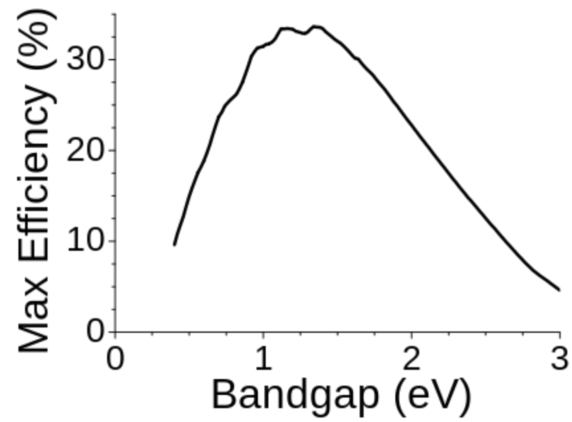

FIGURE 2 [5]
Graph showing relationship between p-n junction band gap energy and max efficiency of solar panel

Currently, solar panels are around 20% efficient for light energy conversion with a limitation of 33.7% due to the Shockley-Queisser limit for single p-n junction cells. This is a key fundamental limitation to solar energy and one that can be overcome but not with the current generation two solar panels. This limitation is caused by many factors. One of these factors is the energy band gap between the p-n junction which has an optimal efficiency of 1.34 eV. Also, reflection losses, series resistance for the structure of the panel, angle of the light incident on the panel, and absorption coefficient of the p-junction of the material. These limitations are especially applicable for silicon, which has an energy band gap of 1.1 eV, a poor conductivity, and a poor absorption coefficient in the infrared spectrum.

Another fundamental limitation to solar power conversion efficiency is the carrier mobility in a material. In a conductor, the carrier mobility is the same as the electron mobility in the material, which is how quickly an electron will travel through the material when experiencing an electric field. In a semiconductor, this is very similar, except for the added effect of hole mobility. Hole mobility is how quickly an electron hole moves through the material when put under an electric field.

While this was a huge issue at first with inorganic materials like silicon, doping has been applied to help improve carrier mobility. Doping is the process of adding impurities to the material in order to create an imbalance in the chemical structure of the material and helping establish free electrons and electron holes. Doping is also a very promising method of improving carrier mobility. The improvement of carrier mobility implies the decrease of internal resistance. This is crucial to photovoltaics because one of the best ways to improve efficiency is to decrease internal resistance. Shown below is the minimal impact that doping has on the transmittance, which in turn describes absorption, assuming constant reflection incident to the surface. In general, light has three methods of travel when in contact with a surface, transmit through, absorb, or reflect off. In the graph below, reflection has been held constant, transmittance is shown, so we can then determine that absorption has remained relatively unchanged.

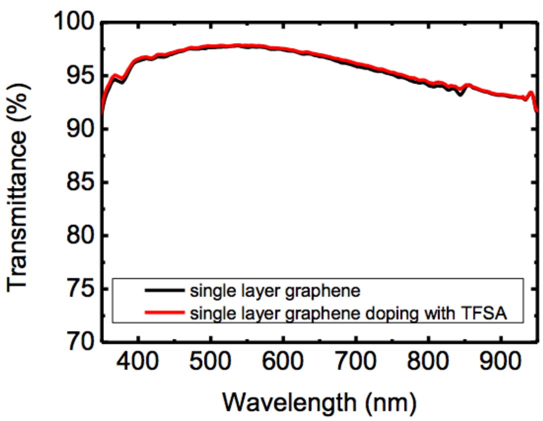

FIGURE 3 [6]
Graph showing the minimal impact on absorption that doping has.

This graph shows the effects of doped graphene on its light transmittance. This is important to note because the doping is able to reduce resistance of the sheet but would be troublesome if the doping significantly affected the material's absorption.

These are a few of the limitations that currently plague generation two solar panels, most of which are mainly relevant to the design of solar panels. These limitations, such as the maximum efficiency due to the Shockley-Queisser limit and the limited carrier mobility in photovoltaics can often be overcome through the use of graphene in the design of these solar panels. Graphene's ability to overcome these setbacks that are fundamental to solar energy help improve the sustainability of solar energy. By improving the possible efficiency of a solar panel, solar energy can be a more effective process of harnessing energy.

New Photovoltaic Developments

The theory of the photovoltaic effect has had a few developments as of recent in order to improve the efficiency of solar panels. These developments include the concept of a nonlinear photovoltaic (NPV) effect, the impurity photovoltaic (IPV) effect, tandem solar cells, and tunable work functions. These developments are currently relevant to silicon and semiconductor based photovoltaics because of their unusual requirements but can also find application in graphene solar panels because of the similar nonlinear optical and chemical properties of these materials.

The nonlinear photovoltaic effect is developed in order to help recapture energy lost to two-photon absorption. Two-photon absorption is the simultaneous absorption of two photons in a material, typically exciting a molecule to a higher energy state. While this is a similar effect to the standard photovoltaic effect, its energy release is proportional to the wavelength of light, making it much weaker than the energy obtained from the photovoltaic effect at lower wavelengths of light [7]. The method of recapturing this energy is through the two photon-photovoltaic effect. This effect is similar to the photovoltaic effect but can only occur in specific nonlinear optical materials. This process has a much greater influence on higher intensity light because of its nonlinear characteristics. The NPV effect has mainly been studied in silicon and other metalloid compounds because of their unusual optical properties. That being said, recently, there have been measurements into the third order nonlinear optical properties of graphene showing that it acts similarly to amorphous silicon and gallium arsenide [8].

The impurity photovoltaic effect is another process very similar to the photovoltaic effect, where the only difference is the use of impurity traps in the band gap of the semiconductor. The band gap of a semiconductor is essentially the threshold energy that the material requires in order for it to start the flow of current through the depletion across the p-n junction. Shown in Fig.4, these impurity traps develop a two-step process for the excitation of electrons from the valence to the conduction band.

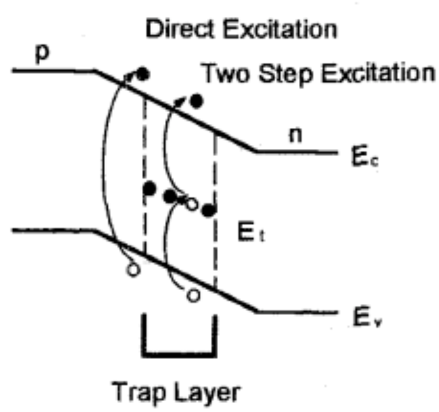

FIGURE 4 [9]
Diagram showing the difference between the PV effect and the IPV effect on the excitation of valence electrons

These impurity traps are created by doping the semiconductor and have very strict requirements in order to accurately alter the energy band gap of the material. This alteration is necessary for the IPV effect to be effective at increasing optical absorption of light energy [9].

Tandem solar cells are not currently a popular design structure due to their added costs for production. They are used in the ISS where the benefits of efficiency and the reduction in weight make tandem use reasonable. The general design of tandem solar cells is the use of multiple solar panels put on top of each other that are composed of different materials in order to improve the absorption spectrum of the system [10]. These solar cells are connected in series and result in higher output voltage to the system because of the setup. Tandem solar cell research is a useful development in photovoltaics because the concept can work with all forms of photovoltaic types and is able to overcome the theoretical Shockley-Queisser limit explained earlier. Tandem solar cells will become a much more economically reasonable design as manufacturing costs for photovoltaic devices drop.

Tunable work functions have been established since the use of doping in semiconductors and their ability for tuning is entirely dependent on the material used. A work function is defined as the amount of work required to take an electron from the surface of a material to just off of the surface of the material. This energy function has the ability to be tuned by the use of doping the semiconductor at its surface. This is very relevant to graphene because its work function of about 4.3 eV is less desirable compared to that of indium tin oxide's work function of 4.7 eV. This discrepancy in work function can be adjusted through the use of doping on the surface of a graphene oxide sheet. Shown below are various doped devices with heavily varying work function energies [11]. These varying work functions provide an easily feasible way of increasing the efficiency of a solar panel by optimizing the work function energy.

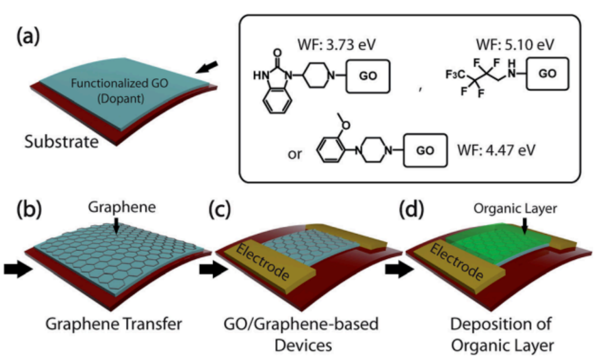

FIGURE 5 [11]
Diagram showing the various doping methods of graphene oxide and the possible work function energies received

These new methods are some of the ways that researchers have been trying to improve the efficiency of currently manufactured solar panels. All of these research developments into photovoltaic systems are improving the sustainability of solar energy by displaying farsighted possibilities for solar energy and where it can develop. With these improvements into theory and design, the use of thin film amorphous silicon solar panels made currently are approaching their maximum efficiency and thus brings the movement towards other materials such as graphene.

GRAPHENE ENHANCED SOLAR PANELS

Graphene enhanced solar panels show promising future potential. While graphene alone doesn't provide a complete solution to solar power inefficiencies, it helps improve many of the weaknesses accompanying solar energy. Graphene's electrical conductivity acts as a zero band gap conductor [11]. Graphene's mechanical strength also allows the strength of a solar panel to be greatly increased; significantly stronger than current thin film solar cells. The implementation of graphene will also result in a possibility of thinner solar cells because of graphene's thickness, making them more applicable on the micro-scale. While graphite has a dark color, because of graphene's thickness, it is almost entirely transparent, which increases the prospect of tandem solar cells mentioned earlier. Also, graphene's absorption spectrum differs from most other photovoltaic materials. While Silicon works well in the visible light spectrum and above, it drastically suffers in the near-infrared to IR spectrum [10]. Shown below is the absorption spectrum of graphene oxide.

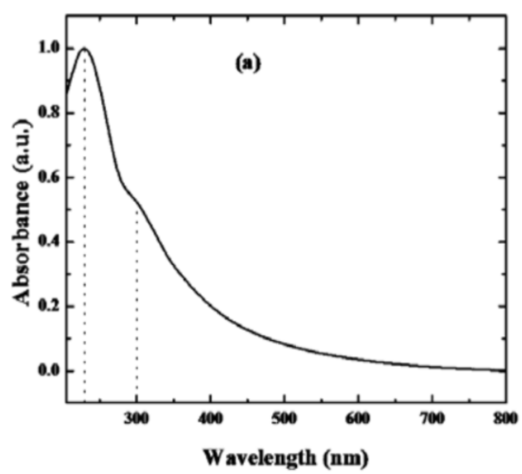

FIGURE 6 [10]
Graph showing the Wavelength (nm) v. Absorbance of graphene oxide, clearly showing high absorbance in the infrared spectrum

There are many different ways in which a photovoltaic system would be improved in terms of both efficiency and cost with the implementation of graphene in certain components.

Graphene as the Front Electrode in a Tandem Solar Cell

There are currently solar cells called tandem cells, which use multiple layers of solar cells, bonded by an electron extracting intermediate layer (IML) to capture the broadest spectrum of light possible. The tandem cell being analyzed is a perovskite ($CH_3NH_3PbI_3$) and silicon tandem cell. The efficiency of converting light to electrical energy of perovskite and silicon cells in tandem is theoretically much higher than a single silicon based solar cell. This is because with perovskite and silicon cells in tandem in the same solar panel, efficiencies higher than the Shockley-Quiesser limit can theoretically be achieved because of the broader absorption spectrum of the two materials in tandem.

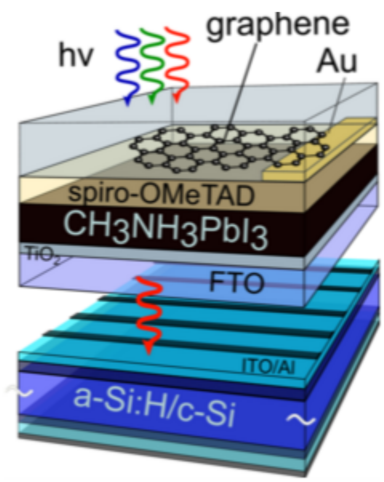

FIGURE 7 [12]
Diagram showing the tandem solar cell with the perovskite layer in black and the silicon layer in blue

The perovskite absorbs much of the blue and green spectrum of visible light, while the silicon absorbs much of the red spectrum, causing an increased number of electrons to be excited from the expanded spectrum of absorption. As seen is Figure 7, the perovskite layer, with a graphene based front electrode, is on top of the silicon layer and it absorbs much of the blue and green spectrum, but allows 64.3% of optical transmission below the band gap of the perovskite to be absorbed by the silicon, with a standard ITO front electrode. The front electrode on the top layer must, in a tandem cell, have an excellent optical transmission, or transparency, in order for certain wavelengths of light to make it across the first band gap to the bottom electrode. The standard transparent front electrode used in silicon solar cells is an ITO electrode. The reason that an ITO front electrode is not able to be used on a perovskite layer is because the ITO layer deteriorates the topmost hole transport layer of the organic perovskite cell during the ion bombardment process used for depositing the ITO layer onto the perovskite. This means that TCO electrodes such as ITO are not compatible with perovskite and an alternative must be found. The alternative is a graphene front electrode, which has an excellent optical transmission of 97.4%. Also, graphene is highly conductive, having a sheet resistance of only ~300 ohms/sq, making it an excellent electrode as well. This experimental data shows that graphene can be an excellent electrode in solar cells, especially in organic tandem cells where electrode transparency is key and TCO electrodes are not an option. [12] This increase in efficiency that is possible with graphene-electrode tandem solar cells would make solar power more sustainable. This is because more solar energy could be harvested per square foot, therefore shrinking the size of solar farms to needed to produce the same amount of energy as solar farms utilizing silicon only solar panels. This decrease in the amount of solar panels needed would also then reduce the amount of materials needed to build a solar farm, further making these graphene-electrode tandem cells a more sustainable option. This increase in efficiency also opens up the possibility of powering individual homes from a smaller solar panel area, maybe from a few panels, showing promise for deployment of these panels in areas of the developing world without a power grid.

N-Doped Graphene Photovoltaic Material

There has been research into the prospect of using graphene as a photovoltaic material. Graphene on its own is not suitable as a photovoltaic material because it has no band gap, but when doped with nitrogen atoms, a band gap can be created in graphene. An experimental solar cell has been made using an N-doped graphene photovoltaic material in order to test the photovoltaic response of graphene, and the plausibility of using it as a photovoltaic material in future cells. The N-doped graphene is created on 99.9% copper foils in a 1000-degree Celsius furnace where a mixed gas of CH_4, NH_3, Ar, and H_2 is circulated through in order to trap nitrogen atoms in the graphene structure. The copper foil is then wet etched using an $FeCl_3$ solution, so that it can be attached to any surface. This leaves behind N-doped graphene photovoltaic material. The N-doped graphene photovoltaic material then has aluminum electrodes deposited onto its surface using a thermal evaporation method. This method is performed by using heat to evaporate a solution that contains dissolved aluminum ions, leaving behind aluminum metal. These aluminum electrodes provide a circuit-path for electrons excited by sunlight in the photovoltaic material to flow through.

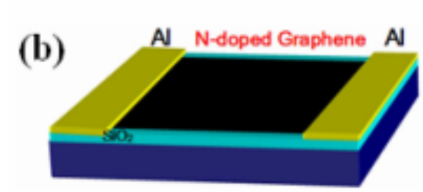

FIGURE 8 [13]
The simple N-doped graphene cell with aluminum electrodes

The structure of the solar cell made by depositing Al electrodes on the N-doped graphene photovoltaic material is shown in Figure 8. The cell was then tested for photovoltaic response in a high vacuum chamber with a pressure of 10^{-7} Torr, using an infrared lamp utilizing a light intensity of .32mW/mm^2.

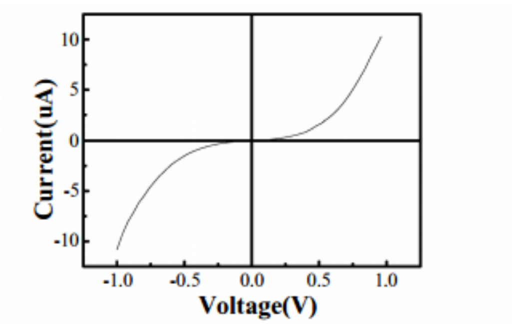

FIGURE 9 [13]
The IV curve of N-doped graphene

The results of this experiment show that the N-doped graphene did in fact display semi conductive properties because its current/voltage (IV) curve was non-linear, as shown in Figure 9, which is indicative of it being a semiconductor. This proves that the N-doping of graphene does successfully open up a band gap in the graphene and allow it to be used as a photovoltaic material. Also, at the junctions between the N-doped graphene and the Al contacts, Schottky barriers are formed. A Schottky barrier is potential energy barrier that is formed at metal-semiconductor junctions, further proving that the N-doped graphene exhibits semi conductive properties. Schottky barriers only allow for current to flow in one direction, much like a diode, and are dependent on the barrier height. Due to the process used to create the N-doped graphene, the barrier heights may be different at different at each Al/graphene junction, causing a difference in the value of the Schottky barriers. When the panel is unilluminated, the amount of electrons coming from the graphene into aluminum equals the amount of electrons flowing from aluminum to graphene for unit time of the respective Schottky barriers, causing an electron balance. However, when the N-doped graphene cell is illuminated, the electron balance is broken and more electrons flow from the N-doped graphene into the aluminum contacts, causing an electrical current at the contacts. Due to the difference in barrier height at the different junctions, the electrical current is allowed to flow, and the photovoltaic effect is achieved. The amount of current produced by the graphene increases as the temperature of the graphene increases as shown in Figure 10.

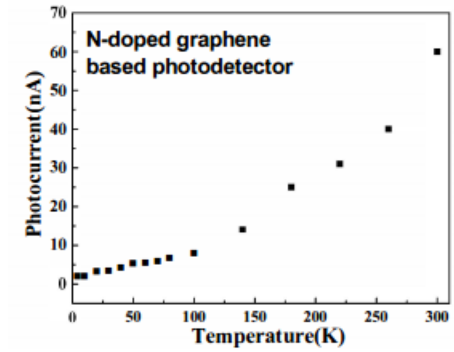

FIGURE 10 [13]
The current produced by the photovoltaic effect of N-doped graphene plotted against the temperature

This experimental solar cell using N-doped graphene has shown that graphene can display photovoltaic properties when doped with the proper materials. However, conversion efficiency and manufacturing cost of these cells will need to be improved with more research if this is to be a practical method of solar power generation. [13]

The Use of Graphene Electrodes in Flexible High Efficiency Organic Solar Cells

There are many potential uses for flexible solar cells and other similar optoelectronic devices, from making portable solar systems, to increasing the practicality of solar power in certain areas, to computing applications of micro optoelectronic devices. Also, flexible solar cells can be mass produced through a low-cost method of manufacturing called roll-to-roll processing. Commonly used current solar cell technology is not practical for flexible solar cells. This is because the silicon crystals commonly used in photovoltaic materials are not thin or flexible with their crystalline structure. Also, the indium tin oxide (ITO) electrodes commonly used on these solar cells are impractical for flexible solar cell technology. This is because ITO electrodes are chemically and mechanically unstable, in addition to indium being an expensive material. This is why many researchers are looking to graphene as a suitable replacement for ITO, especially to produce flexible solar cells. Graphene shares many of ITO's desirable electrode qualities, such as high transparency and high conductivity. Graphene, unlike ITO, is a chemically and mechanically robust material, and has future potential for low processing costs. Since silicon cannot be used in flexible solar cells, organic polymers are used as the photovoltaic material. These types of solar cells are referred to as polymer solar cells (PSC). There are two types of PSC's used with graphene electrodes: anode-based PSC's and cathode-based PSC's. The cathode-based PSC is essentially an inverted anode-based PSC. However, cathode-based PSC's have a power conversion efficiency (PCE) of about 6.9%, which is higher than the 6.1% PCE of anode-based PSC's. The reason for this is that with a cathode-based PSC, a back electrode of an easily oxidized, low work function metal such as Al or Ca isn't needed, since there is an inverted semiconducting metal electron transporting layer on the opposite side. For this reason of a higher overall PCE, only cathode-based PSC's will be discussed. Cathode based PSC's have a structure in the order of Graphene/ZnO/PTB7:$PC_{71}BM$/MoO_3/Ag.

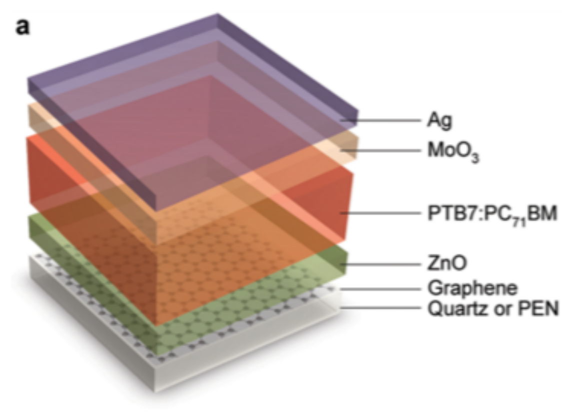

FIGURE 11 [14]
Structure of cathode-based PSC

The graphene electrode is just behind the outer, protective covering of the solar cell. In cathode-based PSC's it is necessary to have an electron transporting ZnO layer deposited directly on the surface of the graphene or else photo-response is negligible. The next layer is the polymer photovoltaic material PTB7:$PC_{71}BM$, where the electrons are actually excited from the light and ejected through the ZnO layer and into the graphene electrode. The next layer is the MoO_3 layer, which is an essential layer in improving the efficiency of this solar cell. This MoO_3 layer prevents recombination between the back Ag electrode and the PTB7:$PC_{71}BM$ photovoltaic layer, thus forcing the electrons to flow in one direction more effectively, and create a stronger electrical current, and therefore improving the PCE of the solar cell. The MoO_3 layer can be treated with a process called annealing, which is heating the layer up to a high temperature, 150 degrees Celsius, holding it at that temperature, and allowing it to slowly cool. This increases the mechanical flexibility of the MoO_3 layer, and also improves its electronic qualities. The current density of non-annealed MoO_3 compared to annealed MoO_3 is 2.6 mA/cm^2 and 16.1 mA/cm^2 respectively. Also, the open current voltage of MoO_3 is improved from .57 V to .68 V after the annealing process. The annealing process applied to MoO_3 is essential to improving the PCE of flexible PSC's. Finally, these solar cells display extreme durability when being bent and flexed.

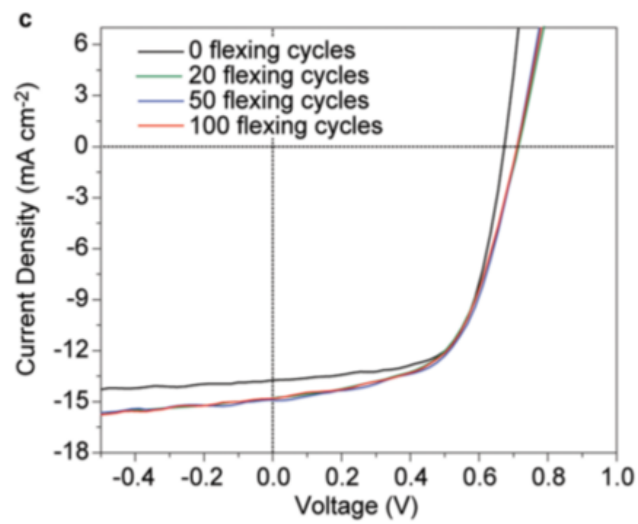

FIGURE 12 [14]
Graph displaying the changes in current density vs. voltage curves at a different number of flexing cycles

As shown in Figure 12, after 100 cycles of flexing the PSC at a flex radius of 5 mm and a strain of ~4.3%, the PSC showed no significant loss in PCE. The future is bright for applications of flexible PSC's, with the experiment cited above having produced a record setting cathode-based graphene electrode flexible PSC with a PCE of 7.1%. This is highly competitive with non-flexible ITO electrode PSC's, which have a PCE of 7.6%. [14] The durability of these flexible PSC's give them a long life span for the applications in which they are used. This makes these flexible PSC's a sustainable product, because once built they will last for a long time before more resources need to be used to produce new ones. Another reason why graphene electrode PSC's are sustainable is because they are not made from rare elements such as indium that need to be extracted from the Earth, the primary ingredient in both the electrode and the polymer photovoltaic material is carbon, one of the Earth's most abundant elements. The flexibility of these panels has potential applications in collapsible solar panels that can become portable and be used for smaller applications, such as powering single homes in third world countries without a power grid.

Ethical Issues

Graphene components in solar panels show much promise in increasing the efficiency and applications of solar panels. One of the largest ethical dilemmas based around this new technology is whether it will be worth investing time, money, and resources into the continued research and testing of graphene based solar cells based on the probability that this investment will yield successful, safe, and sustainable results. Based on the extraordinary electrical, and in some applications such as flexible PSC's mechanical, properties of graphene, we believe that graphene is an extremely promising substance to improve the currently stagnating conversion efficiencies of solar panels.

Another ethical issue about graphene enhanced solar panels is if these solar panels will benefit mankind enough to warrant their development. These graphene enhanced solar panels can benefit developing countries in particular, places that don't have electric grids set up. This is because unlike the main method of solar production in the developed world, which is large solar farms, we cannot set up a solar farm in a small village in a third world country, because of the impracticalities of the cost of doing so and because of the lack of electrical infrastructure to handle the amount of energy that would be produced. This is why smaller scale, high efficiency graphene enhanced solar panels would be perfect for supplying power to rural areas in third world countries without electrical infrastructure. These graphene enhanced solar panels would be highly efficient and perhaps portable because of flexible PSC developments allowing the panels to be at least partially collapsed for shipping. These solar panels would be able to supply electricity for single homes with a small amount of panel area and a relatively cheap cost. Graphene enhanced solar panels have a lot of potential in improving the living conditions of a lot of people by supplying electricity to third world countries, therefore showing just one of their potential benefits to mankind.

The cost of graphene is rather expensive right now, which may bring the sustainable use of such a compound into question, however, one must take into consideration the novelty of graphene and its massive development in such a short period of time. Further improvements into manufacturing graphene substrates will only become cheaper as the demand of graphene increases and more companies begin manufacturing graphene, driving costs down by both competition and new efficiencies in the manufacturing process that will surely be discovered. The element that makes up graphene, carbon, is one of the most abundant elements on Earth, so as we become better at manufacturing graphene, the cost can only go down. The abundance of graphene provides a major argument in accordance with the long term sustainable view of harnessing energy. The use of graphene compared to silicon in a solar panel, while both are expensive, they are costly because of different reasons. Silicon is both a rare and costly element, and requires much modification for use in solar panels. Graphene is costly to produce because of its necessary resolution. This is a major difference between these photovoltaic materials, graphene being a far more sustainable substance.

Also, solar cells with graphene components are both extremely safe and environmentally friendly. Environmental safety is important to the sustainability of solar energy because the poor air quality as a result of the burning of fossil fuels is one of the largest public health crises right now. The more efficient we can make solar panels, the more of our energy will be produced through it, and the less fossil fuels will be burned, making the air safer for everyone to breathe. The photovoltaic effect releases no pollutants in the air, making the process a sustainable one. The harnessing of solar energy provides no negative effects for both short and long term analysis.

Finally, efficient solar cells with graphene are extremely environmentally friendly because it makes the highly environmentally destructive methods of extracting fossil fuels, such as drilling and fracking, less necessary because more of our energy will be produced through renewable solar power. In conclusion, it is clear that using the sunlight that falls on the Earth, that normally goes unused, to produce our energy is a sustainable practice. When considering the likelihood of solar panel efficiency being significantly improved, new applications of solar panels being introduced, the public health safety benefits of replacing fossil fuels, and the environmental destruction widespread solar power will help prevent, we have deemed that the investment into continued research into graphene solar cell components worth it. [15]

FUTURE OF SOLAR ENERGY

While solar energy becomes more and more prevalent in the U.S.A, the need for more efficient panels becomes more and more of a necessity for implementation of solar energy. The future of solar energy is very bright, with increased resolution of manufacturing inaccuracies and improvements in various energy recapture techniques from the photovoltaic effect. These emerging technologies are developed as alternatives to the first generation crystalline cells and second generation thin film solar cells. The alternatives mentioned earlier mainly have to do with the materials being currently used in solar panels. These alternatives include the use of tandem solar cells, perovskite, gallium arsenide and graphene. These alternatives, all mentioned earlier, offer various benefits to the power conversion efficiency of a photovoltaic system.

Tandem solar cells offer a method of bypassing the current radiative transfer limits brought on by the Shockley-Queisser limit. This technology is one of the most unique and valuable methods of improving efficiency because it has no limitation to the amount of photovoltaic devices that can be put in series together and uses multiple materials, including graphene, in the process in order to create a photovoltaic system with a very broad absorption spectrum.

Graphene’s role in the future of solar panels ties in with the use of all the other materials mentioned above. Graphene can be used as an alternative to silicon because of its conductive properties, robustness, and carrier mobility. Graphene can also be used alongside perovskite as a photovoltaic material because their absorption spectrums have little overlap and put together can result in a much broader wavelength.

The manipulation of work functions by doping the electrode of the photovoltaic device is a very promising possibility looking toward the future of solar power. This is especially relevant to graphene, which helps solidify the possibility of optimizing the work function. This will help improve the use of graphene as an alternative to indium tin oxide. This is a very important aspect of the future of solar energy because graphene is a cheaper alternative to the costly indium tin oxide semiconducting material, which is a far weaker material than graphene and can't function in organic photodetectors.

In conclusion, the use of graphene will help bring solar power to the masses. The viability of an inexpensive solar cell is becoming more of a realistic concept with the discovery and further advancement of graphene development. Solar power will eventually compete with the costs of non-renewable energy sources, hopefully within the next generation of solar panels.

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