THE ROLE OF NANOTECHNOLOGY ON PHOTOVOLTAIC CELLS

ABSTRACT

Advances in the field of Nanotechnology have shown great promise to enhance the photoconversion of photovoltaic cells and hence, improve their electrical output. This breakthrough in terms of efficiency seems meager when compared to the crystalline silicon solar cells. However, Quantum dots Nanocrystals have the potential to achieve higher efficiency because their bandgap can be tuned to absorb a wider range of the electromagnetic spectrum, and also, they can generate multiple excitons through impact ionization process. This Review paper discusses the basic principles of Photovoltaic effects, efficiency and Shockley-Queisser limit, the major drawbacks of silicon-based PV cells, the function of Quantum dots Nanocrystals to improve efficiency and finally the advantages of Quantum dots.

Key words: Photovoltaic effect, Quantum dots, Nanostructures, Bandgap, Multiple excitons

INTRODUCTION

The ever increasing demand for global energy supply, aided by the environment-unfriendly nature of fossil fuels, as well as its depletion and that of other nonrenewable energy reserves, has forced scientific communities to explore the world of renewable energy sources. Of all the renewable energy options of major concern, solar energy is viewed as the future of the world's energy supply backed by the fact that, the sun releases a power output per second of 3.8×10^{20} Megawatts (generally referred to as "the Sun's Luminosity"), several billion times the electric capacity of U.S. utilities. This energy fills the solar system, bathing the earth's atmosphere with a near constant supply of 1.37 kilowatts per square meter (KW/m^2) known as "solar constant" [1]. In theory, all the energies associated with the visible spectrum of light, from near infrared to ultraviolet can be harnessed into a useful electrical energy output.

The energy from the sun can be converted into electrical output through a process known as "photovoltaic effect", using a special type of material known as "solar cells" or "photovoltaic cells" which are made from semiconducting materials, usually silicon. Not all the light energy incident on a solar cell can be converted into electrical power; the light energy must overcome an energy barrier, known as the "Bandgap" for effective conversion. If the energy of a photon is less than the bandgap, it will cause the atoms of silicon in a crystal structure to vibrate about their fixed bond positions and eventually be given off as heat. If the photon energy is greater than the band gap, it can alter the electrical properties of a solar crystal, and the excess energy will be wasted as heat [1, 2]. When hit by an incident light in the form of photons, the cell absorbs energy and generates an electron-hole pair. The electron and hole are then separated by the structure of the device (electrons to the negative terminal and holes to the positive terminal) thus generating electrical power [3]. A potential difference can be set up in the photovoltaic cell by doping a crystal structure of silicon with impurities such as Phosphorus (the Donor dopant) and Boron (the acceptor dopant). This creates a charge imbalance that set up an electric force field also known as the "junction", which prevents a free flow of charges, thus, acting as a diode because, it allow electrons to flow in one direction whose end result is a current of electrons, better known to us as electricity [1, 4, 5].

DRAWBACKS OF SILICON-BASED SOLAR CELLS

The two major disadvantages of silicon-based photovoltaic cells are; low efficiency and high cost of production to meet energy demands. In the first drawback, major energy losses are: surface reflections, charge carrier recombination losses, inability of a cell to absorb photons with energy less than the bandgap, and thermalization of photon energies exceeding the bandgap thereby, wasting excess energy by heating the solar cell. The last two mechanisms alone, amounts to a loss of about half of the incident solar energy in solar cell conversion to electricity. These fundamental losses directly lead to a theoretical efficiency limit famously known as the 'Shockley-Queisser limit' of ~34% for a single junction Photovoltaic cell [6]. This efficiency is a portion of solar energy that can be converted into electricity and the low value suggest that most of the energy from sunlight which strikes the surface of a cell cannot be harnessed into electrical output. Current researches on Photovoltaic systems are aimed at reducing the cost of production using the Thin-film technology of the second generation Photovoltaic systems which is cost effective, and to improve the efficiency past the Shockley-Queisser limit by incorporating Nanostructures into thin-film systems [7].

THIN-FILM TECHNOLOGY

In a quest to circumvent the high cost of fabrication of conventional photovoltaic cells, and to increase efficiency, Thin-Film technology of the second generation solar cells was introduced, most of which; uses amorphous or polycrystalline silicon as the active components which are applied on low-cost substrates/support materials such as glass. The major disadvantage of this technology is low efficiency; this technology was demonstrated to produce about 25% laboratory efficiency, and about ~10% efficient mass-produced PV devices whose efficiency value is comparably low [8].

THE ROLE OF NANOTECHNOLOGY

Two critical explanations of Shockley–Queisser analysis are: (1) photons with energy less than the semiconductor bandgap are not absorbed and thus cannot contribute to Photovoltaic Conversion Efficiency; (2) energetic electrons created by high-energy photons immediately relax to the band edge (i.e. the fraction of energy of photons with energy greater than the bandgap which is immediately lost as heat). Approaches to achieve higher limiting efficiencies attempt to either use the high-energy photons more efficiently, or recover the low-energy photons normally not converted. Nanostructures are explored to eliminate these losses.

Nanoscale systems exhibit properties which are different from the ones shown by the bulk or thin films of the same compound, and have allowed new ways of approaching solar energy conversion for electricity generation. This was made possible due to the large surface-to-volume ratio of nanomaterials which have various competitive benefits, and also to the fact that objects with a size of ~1–20 nm can exhibit quantization effects, which become more pronounced with decreasing size, and can significantly change material properties such as special conductivity, and specific heat [9].

With the promise shown by the improved properties of nanostructures, Nanotechnology is therefore, aimed at improving conversion efficiency of Photovoltaic systems past the limit set by William Shockley and Hans J. Quisser [6], but still maintaining the cost effectiveness of a Thin-Film Technology so that the overall output would be improved efficiency, at low cost. Nanotechnology therefore, improves the Photovoltaic systems through the following ways:

Semiconductors' Quantization Effect:

Materials at Nanoscale exhibit a Phenomenon called Quantization effect. This is brought about when charge carriers (electrons and holes) in semiconductors are confined by potential barriers to small regions of space (quantum box), where the dimensions of confinement are less than the de Broglie wavelength of the charge carriers. This is achieved when the nanocrystal diameter is less than twice the Bohr radius of excitons in the bulk material (Exciton Bohr radius is the average distance between the electron in the conduction band and the hole it leaves behind in the valence band). These effects would begin to manifest in semiconductors when the length scale is about 25 to 10 nm depending upon effective masses. When charge carriers are confined by potential barriers in three spatial dimensions, it is referred to as Quantum dot (QD). Two-dimensional confinement produces quantum wires or rods, while one-dimensional confinement produces quantum films (also known as quantum wells) [10].

Incorporating this technology into solar photoconversion devices is attracting a great deal of interest from researchers worldwide. Such devices built from nanocrystals that exhibit quantization effect are referred to as “third generation photovoltaics” because new advances in photophysics allows for the possibility of these inexpensive materials to be incorporated into device structures with potential efficiency much higher than the thermodynamic limit for single junction bulk solar cells [10].

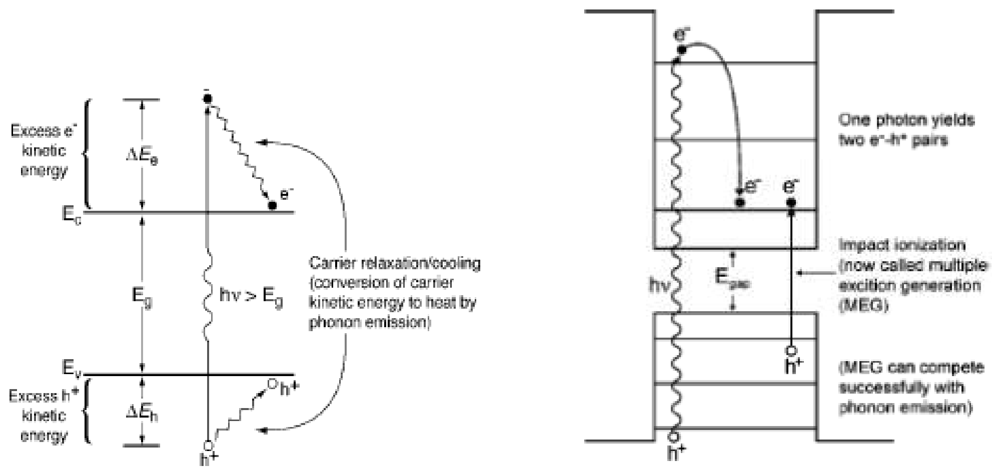
The material systems mostly considered for quantum dots (QD) photovoltaic cells are usually a blend of two or more semiconductors, most prominent of which, are referred to as III/V-semiconductors, and host of other blends such as; Si/Ge or Si/Be Te/Se etc. The prominent advantages of Si/Ge blend over the others are; Higher light absorption in the infra-red spectral region, Compatibility with standard silicon solar cell production (in contrast to III/V semiconductors), Increase of the photo current at higher temperatures, and Improved radiation hardness compared with conventional solar cells [2].

Functions of Quantum Dots (QD)

Quantum dots are tiny particles or nanocrystals of a semiconducting material with diameters in the range of 2-10 nanometers [11]. Quantum dots exhibit unique electronic properties, intermediate between those of bulk semiconductors and discrete molecules, partly as a result of their high surface-to-volume ratios. Because of the relatively few atoms present in Quantum dots (10-50 atoms), where excitons get confined to a much smaller space, on the order of the material’s Bohr radius, it leads to a discrete quantized energy levels more like those of an atom than the continuous bands of a bulk semiconductor. For this reason, quantum dots have been nicknamed or referred to as ‘artificial atoms’ [12, 13, 14].

The magnitude of the difference in energy between the highest valence band and the lowest conduction band is a function of the size of quantum dots nanocrystals. This relationship is inversely proportional as a decrease in size of the crystals, results in an increase in energy difference between the highest valence band and the lowest conduction band. This makes quantum dots bandgap tunable depending on its size. The smaller the quantum dots, higher energy is required to confine excitons into its volume, and more energy is released when the crystals returns to their ground state, resulting in a colour shift from red to blue in the emitted light. This unique character makes it possible for quantum dots to emit any colour of light from the same material simply by changing the size of the dots. In this way, it is possible for the electrical and optical properties of quantum dots to be adjusted according to their purpose of use; this is because they are artificial clusters of semiconducting atoms whose electrons' mobility are restricted due to their small size, achievable through quantization of their energy levels resulting into a tunable bandgap and therefore, control of their obsorbance and frequencies [15, 16]. Quantum dots solar cells therefore, are designs that use quantum dots as the absorbing photovoltaic materials whose bandgaps can be tuned into the far infrared frequencies that are typically difficult to achieve with traditional solar cells, thereby making infrared energy as accessible as any other.

Quantum Dots can also be employed in a specialized type of cells called "the hot-carrier cells". In this type of cells, instead of the extra energy supplied by a photon to be lost as heat, it induces the formation of high energy electrons which in turn, results to a high voltage. Studies have shown that, when a photon creates an electron-hole pair, any photon with energy exceeding the threshold energy value known as the bandgap is divided between the electron and hole in a proportion that depends on the band structure. This can result in carriers with kinetic energies in excess of the thermal energy, $E = 3/2\ KT$. In single absorber solar cells, electrons and holes lose this excess energy by inelastic carrier-phonon scattering before they are separated. This thermalization process represents a significant source of irreversible loss [17]. Hot carrier solar cells are therefore envisioned to extract energy from the photogenerated electron-hole pairs, before they cool down to the lattice temperature [18], thereby increasing the portion of the photon energy that can be extracted. Another way to utilize the high energy photon is to generate multiple electron-hole pairs also referred to as Multiple Exciton Generation (MEG). This allows a single photon to produce multiple excitons (electron–hole pairs) achievable only in a semiconductor quantum dots structures. Unlike the bulk semiconductor where high energy photon promotes an electron from the valence band to higher level in the conduction band in which an excited electron (hot carrier) undergoes many nonradiative relaxation before reaching the bottom of the conduction band as shown in figure 1a, the hot carrier however in quantum dots undergoes impact ionization process (carrier multiplication). Therefore, the absorption of a single photon generates multiple electron-hole pairs. Absorption of Ultraviolet photons in quantum dots therefore, produces more electrons than near infrared region as illustrated in figure 1b [10, 19, 20].



(a) Bulk Semiconductor **(b) Quantum Dot**

Figure1. Thermalization of hot carriers in (a) Bulk semiconductor, and (b) Quantum dot, from [10].

Advantages of Quantum Dots Solar Cells

As mentioned earlier, the next generation of solar cells is viewed in terms of high efficiency at low cost, Nanotechnology via the use of Quantum dots has been identified as the way forward to achieving this objective due to their unique quantum properties and vast application. Below are some of the advantages of quantum dots in a solar cell.

i. Unlike bulk semiconductor solar cells, Quantum dots solar cells can be made from simple inexpensive materials using inexpensive laboratory processes.
ii. Quantum dots solar cells have shown promise to attend efficiencies as high as or even greater than their conventional counterparts. This possible higher efficiency is because quantum dots nanocrystals can generate multiple excitons through impact ionization. Therefore, for every photon absorbed, two or more electrons are emitted which contributes to the increased efficiency
iii. Since quantum dots are tunable by either increasing or reducing their sizes or twisting their shapes, their properties can be tailor-made to absorb energy from the sun in regions where conventional solar cells cannot.
iv. Since they can be made from inexpensive materials, they can be mass produced through high-throughput roll-to-roll manufacturing, which ends up lowering the cost of quantum dots

v. Due to their unique discrete properties, quantum dots are versatile, highly efficient in generating electrical current, and are an ethical option for the next generation of solar cells

CONCLUSION

Nanotechnology has shown great promise in the field of renewable and sustainable energy and has offered opportunities to develop low-cost and highly efficient cells via quantum dots nanocrystals. Even though, most of the progress made in this field are still subject to further research, quantum dots have many specifications which make them better suited for solar cells than bulk materials such as crystalline silicon, prominent among the specifications are, inexpensive fabrication process and tunable bandgap. By stacking quantum dots of different sizes in gradient multi-layer nanofilms, solar cells are capable of absorbing a larger percentage of the sun's energy which in turn can provide clean, renewable, sustainable and environment-friendly source of energy, especially in the wake of the world's depleting oil reserve and its negative impact on our planet. Therefore, the future of the world's energy sector depends on solar photoconversion, and improved photconversion can be achieved through nanotechnology where quantum dots are at the forefront of the technology.

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