Incorporation of Viruses with SWNT-QD Complex in 3D Solar Cell to Improve Efficiency

Tahrim Alam[1], Afrina Zerin Disha[2], Md. Shahriar Iqbal[3], Md. Golam Rashed[4], Sakif Ahsan[5]

[1]Bangladesh University of Engineering and Technology
[2]University of Asia Pacific
[3]University of Dhaka
[4]Ahsanullah University of Science and Technology
[5]Brac University

([1]tahrim.buet@gmail.com, [2]disha@uap-bd.edu, [3]shahriariqbal1988@gmail.com, [4]rashed.ce@aust.edu, [5]palis_1968@yahoo.com)

Abstract- This article describes a novel method of scaling the efficiency of lightweight, flexible 3D solar cells by adding nanostructured material complexes with viruses. The addition of these complexes will help in dissociating exciton and transporting carrier. The dispersion of single wall carbon nanotubes (SWNTs) into poly (3-octylthiophene)-(P3OT) has already shown dramatically improvement of both the electrical conductivity and optical absorption of the polymer. Moreover, CdSe quantum dots (QDs) have been used by several research groups to facilitate exciton dissociation and improve the efficiency of P3OT-based solar cells. The present model proposes to incorporate viruses with the complex replacing the carbon nanotube in 3D solar cell which ensures better electron collection efficiency. The feature of the virus of keeping the nanotube in place, MEG, Wide Angle Light Collection, 3D Photovoltaic Structure, Thin Absorbing Regions, Below Surface Contacts of 3D structures enable in attaining high internal and external quantum efficiency.

Keywords: Quantum Dot; SWNT-QD Complex; MEG; 3D Solar Cell.

I. INTRODUCTION

Energy demand fulfillment is one of the great concerns of current world since all our sources will be evacuated in future. So, researchers are seeking for alternative renewable energy sources which will release the pressure from our current energy sources, such as, oil, gas, coal etc. Renewable energy is the energy which is naturally replenished and sunlight is one of the important sources of natural renewable source. Solar cell, the device which converts sunlight directly to electricity by photovoltaic effect, is an alternative solution for electricity production though a complete suitable model is yet not proposed which will provide maximum efficiency. Solar cell works upon the photoelectric effect theory of Albert Einstein which states that electrons are knocked out energy which is absorbed by semiconducting materials while photons of sunlight hit the solar panel. Thus a potential difference arises which results the flow of electricity. The design of the cell restricts the motion of electrons in one direction only. Major two drawbacks with conventional solar cell are efficiency and cost. To achieve maximum efficiency, the band gap energy of the constitute material should be similar with energy of photon of sun-ray because, if the photon has less energy it will pass through and if the photon has more energy, then extra energy will be wasted as heat. 70% loss of total energy of sun ray occurred due to these two effects [1]. So, recent trend is to increase the efficiency and decrease the cost of manufacturing.

There are three major types of materials used to produce photovoltaic solar cell. In first group, materials are monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium selenide. In second group, materials are made as thin films layer, organic dyes and organic polymers which are deposited on organic substrate. The last group, which is used as electron confining nanoparticles, is made of Nano crystals [2].

Crystalline silicon(c-Si), also known as bulk silicon, is the most rife bulk material for solar cell and is separated in to several categories based on crystallinity and crystal size such as mono crystalline silicon panel, polycrystalline silicon panel and thin film silicon panel. Crystalline silicon is produced in large sheet which is cut in to specific size, which acts as one single cell, to develop a mono crystalline silicon panel. Some conducting metal strips are placed over the entire cell to collect electron from the cell. But major disadvantages are cost and efficiency. This sort of panels is very expensive since they are cut from cylindrical ingots. So it is impossible to cover the entire square module without significant loss of refined silicon. In addition to this, it is capable of converting only 15-18% solar energy to electrical energy [4]. So, efficiency is also a burning question for this kind of panels.

Polycrystalline solar panels are consisting of a series of cells in lieu of one single cell used in mono crystalline panel. The key feature is that, these panels are made of square ingots, so the waste minimization of c-Si is possible which reduced the cost of the panel in comparison to mono crystalline cell.
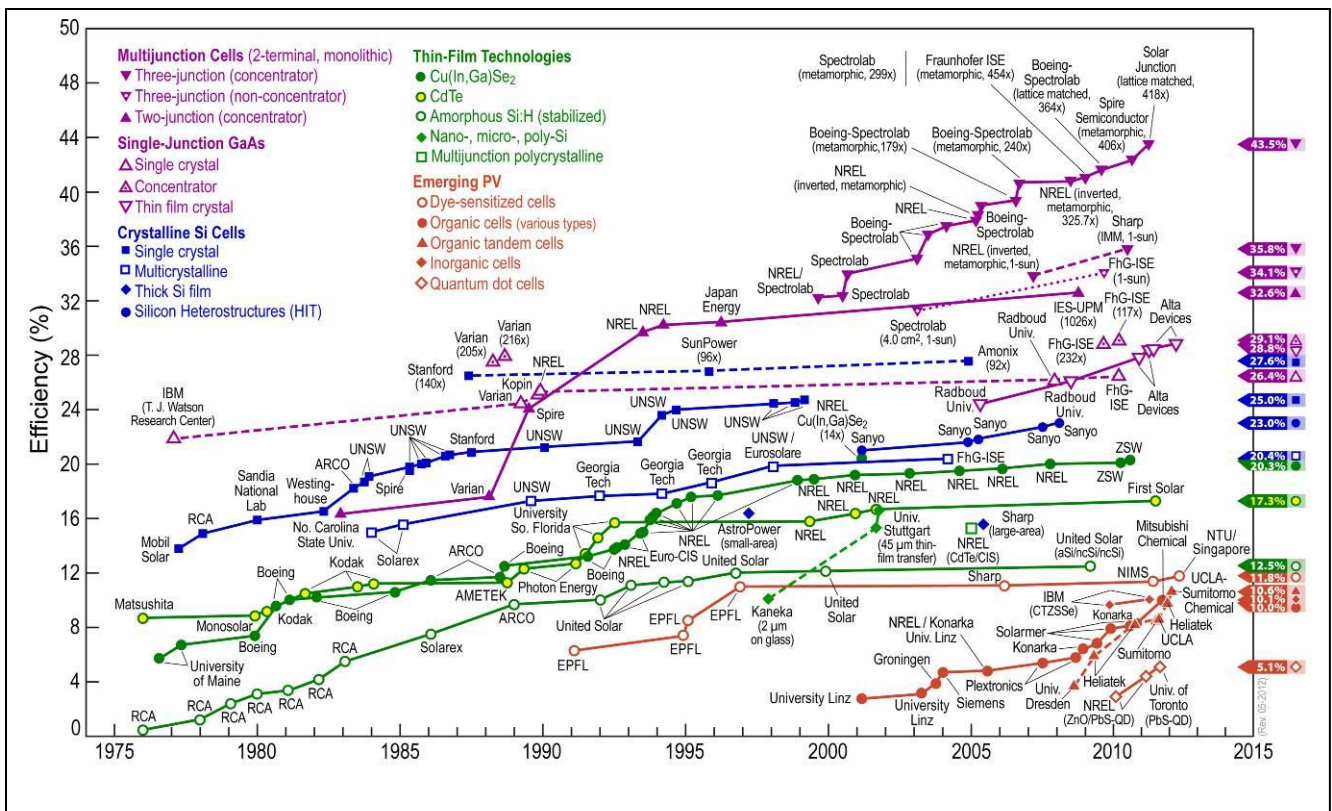
Fig 1: Best Research-cell efficiency [3]

But the efficiency is still poor; it can convert only 12-14% of solar energy to current [4]. Another type of polycrystalline panel is made by ribbon silicon, where thin films of silicon is drawn from molten state and get the polycrystalline structure after solidification. Though the cost is reduced, but this cell depicts very poor efficiency. Cost reduction is possible by using metallurgical grade silicon (UMG silicon), which cost one-sixth of poly silicon.

Thin film technologies have arrived to reduce the cost of panel price. Amorphous Silicon (A-Si), Cadmium Telluride (CdTe) and Copper Indium Gallium Selenide (CIGS) are three thin film technologies. Since the film is attached to another structural material (conducting metal strip), some mandatory parts of crystalline cell are not required here. CdTe is the most attractive among these kinds, as the cost of CdTe is 30% less than CIGS and 40% less than A-Si [4]. Though thin film technologies have some advantages like low cost and versatility, but the efficiency, as well as, corresponding area consumption per watt production is not satisfactory.

Dye-sensitized Solar cells (DSSCs) are very attractive to build integrated solar panels since the color of the device can be easily varied by choosing different dyes. Though the cost/performance ratio is very lucrative in comparison to previous cells, the efficiency is poor of this kind.

Quantum dot solar cells (QDSCs) have attracted much interest due to their unique properties. At the very commencement, it is possible to tune the band gap of QDs by controlling their size. So, the absorption spectra of QDs can be tuned to match the spectral distribution of sunlight. Then, due to quantum confinement effect, semiconductor QDs has large extinction coefficients. Next, rapid charge separation is possible since QDs have intrinsic dipole moments [5]. The efficiency of all types of solar cell is presented in Fig. 1 [3].

This paper discusses the theoretical aspects of improving the efficiency of a solar cell by merging CdSe SWNT complex with viruses in 3D solar cell considering the drawbacks of QD and SWNT solar cell. Theoretically it is ensured that upon addition of these features there might be answer improvement in power conversion efficiency which is subjected to experimentation. But, the details speak fairly conclusively in support of the view.

II. PROPOSED METHOD

A. Research Background

This method is based on the principle that conducting polymers are capable of photo induced charge transfer. The polymers which are proposed for this application are poly (3-hexylthiophene)-(P3HT), poly (3-octylthiophene)-(P3OT), and poly (para-phenylenevinylene)-(PPV) [7–10]. These conducting polymers have the ability to generate excitons

upon absorption of photons. The exciton is normally coupled to a phonon; this provides the energy for mobility in the polymer chains [11]. Such intra-chain diffusion of neutral excitons in the polymer is however limited by self-trapping and columbic interactions [8]. Also, it has been shown that the diffusion lengths of excitons are quite low (less than 10nm in most cases before recombination) [11-14]. If a localized potential energy difference exists which is greater than the exciton binding energy (columbic attraction and spatial location on polymer backbone [15]), dissociation into the free electron and hole carriers can occur. This dissociation process usually arises from sufficient localized electric fields, resulting in carrier promotion to a delocalized state, transport by inter-chain hopping, or charge transfer to an electron accepting impurity [11-13]. Transient absorption spectroscopy has shown that such charge transfer effects will take place on the Pico-second timescale in the absence of recombination [16]. The efficiency of the charge transfer process has been described on the basis of zero-point oscillations whereby an on-chain hole can act as a potential barrier for recombination. Such a mechanism is supported by sufficient molecular ordering and interfacial dipole due to differences in electro negativity of the electron acceptor and polymer [12]. The separated hole has carrier mobility through on-chain transport using the highly coupled, p-conjugation network [13].

The overall quantum yield of exciton dissociation is largely influenced by the localized electric field and temperature on the effective carrier mass of the material. This effect is most pronounced in 'heavy' carriers where the poor mobility leads to a higher probability of recombination [13]. In the case of polymeric solar cells, additives are incorporated with a sufficiently high electron affinity to dissociate the exciton into free carriers before recombination which can contribute to the photocurrent in a suitable device structure [17]. The use of nanomaterial as the electron accepting impurities in these polymer systems is currently an area of very active research and appropriate selection should maximize exciton dissociation and promote efficient carrier transport in the device. The most widely investigated nanomaterial for polymeric solar cells have been semiconducting nanocrystals, fullerenes, and single wall carbon nanotubes (SWNTs).

Incorporation of SWNTs into P3OT has demonstrated high open-circuit voltages (Voc), nearly 1.0 V, although the power conversion efficiencies are currently well below 1% [9, 24, 25]. The high electron affinity of QDs and fullerenes enables the dissociation of polymeric excitons, leading to an improvement in these types of devices. Also, since the electrical conductivity of the photoactive polymers routinely employed is low, the QD or fullerene additive is primarily responsible for electron transport to the negative electrode [17]. However, these materials have a low aspect ratio and have therefore necessitated very high doping levels consistently up to 475% w/w which can negatively impact the mechanical properties of the polymer composite [8, 19, 21]. In comparison, the low percolation threshold of SWNTs coupled with their extraordinary SWNTs [26] allow for significant enhancement of electron transport at even very low doping levels [25]. Therefore, if a material which encompasses both

high electron affinity and high se can be utilized as an additive, namely in the form of a quantum dot-single wall carbon nanotube (QD-SWNT) complex, a further enhancement in the conversion efficiency of polymeric solar cells is expected.

The ideal cascade of energy transitions for an optimal nanomaterial-polymer solar cell would include photon absorption by the components over the entire air mass zero spectrum and dissociation of the excitons by the highest electron affinity material near the exciton [17]. The dissociation process will be based on a sufficient potential energy difference between polymer and nanomaterial energy levels as compared to the exciton binding energy [11].

The work function of metallic SWNTs (M-SWNT) indicates an appropriate potential energy level for exciton dissociation when used in conjunction with the P3OT polymer, CdSe QDs, and S-SWNTs. Although the P3OT's exciton binding energy is relatively high, 0.5 eV [13], each of the nanomaterials discussed would have sufficient electron affinity to dissociate the electron–hole pair based on the difference in potential energy. The efficiency of dissociation and charge transfer from the polymeric exciton relies on the ability to delocalize the electron and eliminate the columbic interactions between the localized hole on the polymer chain and the electron acceptor [12]. Since the QDs rely on a hopping conduction to transport the electrons to the negative electrode [19], an alternative would be a ballistic conductor like SWNTs that transports electrons with minimal columbic interactions.

In comparison to the polymer, dissociation of the exciton from CdSe QDs shows a reduced energy barrier of 0.1 eV [24] and the electron transport through the SWNTs would presumably be most efficient with appropriate coupling of the QDs to the SWNTs. Engineering of a suitable polymeric photovoltaic device requires an understanding of the potential energy levels associated with the components such that the material junctions are tailored to promote efficient photo-conversion into free carriers.

The photo-induced excitons in the polymer are expected to be dissociated by the nearest high electron affinity material, either the QD or SWNT. Ultimately, the holes are transported by the polymer to the positive electrode and the dominant electron path is through the percolating SWNTs to the negative electrode. Additionally, the QDs can produce excitons upon optical absorption [28] and be dissociated by neighboring or chemically bonded SWNTs [26]. In addition to the absorption by the polymer and QDs, it has been shown that semiconducting SWNTs can also absorb light and create bound electron–hole pairs which could contribute to the photoconductivity in these types of devices [30, 31]. The electron affinity of the QDs can be tailored based upon the selection of semiconductor material used [32]. Further control of the energy band gap for the QDs and SWNTs can be achieved by tuning the diameter distribution. Due to the fact that the polymer, QDs, and SWNTs may each absorb in a different spectral region, the possibility exists that these nanomaterials could be combined in such a way as to produce

a series of junctions in a polymeric solar cell which would be analogous to a conventional triple-junction solar cell [38].

B. Method

In the present work, incorporation of the prepared CdSe-SWNT complexes into P3OT with viruses utilizing the tower structures of 3D solar cell would presumably enhance the efficiency. This dramatic improvement takes place even though the viruses and the nanotubes make up only 0.1 percent by weight of the finished cell.

Fig 2: Device Structure

The viruses actually perform two different functions in this process. First, they possess short proteins called peptides that can bind tightly to the carbon nanotubes, holding them in place and keeping them separated from each other. Each virus can hold five to 10 nanotubes, each of which is held firmly in place by about 300 of the virus's peptide molecules. In addition of the virus, the coating of titanium oxide produced by viruses over each of the nanotubes which are in close proximity to the wire-like nanotubes that carry the electrons. In addition, the viruses make the nanotubes soluble in water, which makes it possible to incorporate the nanotubes into the solar cell using a water-based process that works at room temperature. The theoretical structure of the device is shown in Fig. 2.
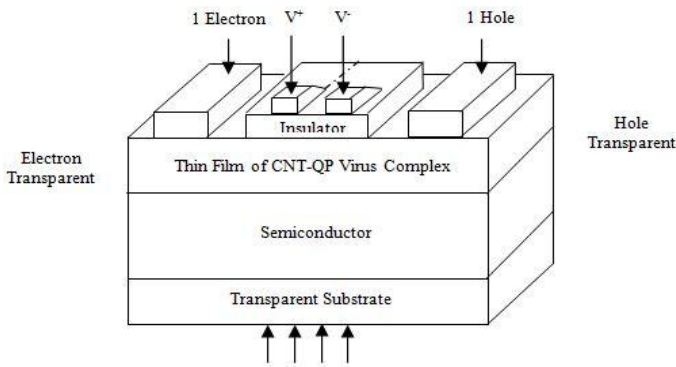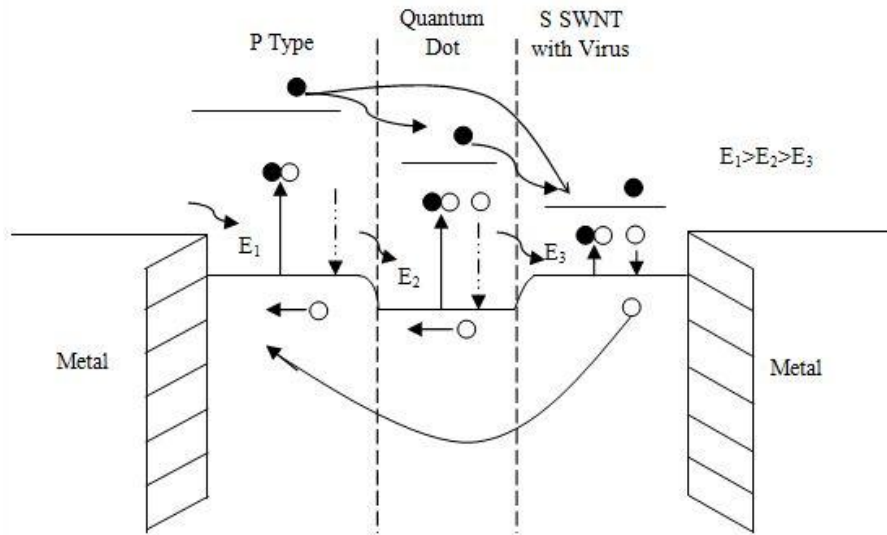
Fig 3: Schematic Illustrating QP SWNT Virus Complex Equilibrated at the Fermi Energy

Previous attempts to use the nanotubes, however, had been thwarted by two problems. First, the making of carbon nanotubes generally produces a mix of two types, some of which act as semiconductors or metals. It is shown that the effects of these two types tend to be different, because the semiconducting nanotubes can enhance the performance of solar cells, but the metallic ones have the opposite effect. Second, nanotubes tend to clump together, which reduces their effectiveness. And that's where viruses are successfully used

to control the arrangement of the nanotubes on a surface, keeping the tubes separate so they can't short out the circuits, and keeping the tubes apart so they don't clump.

The basic physical reason for the improvement in power output is the 3D structures vertical surfaces which can collect much more sunlight during mornings, evenings and winters, when the sun is closer to the horizon. The schematic figure of proposed model is presented in Fig-3.

III. EXPECTED FEATURES

This solar cell makes use of thousands of carbon nanotube 'towers' or 'cones' to trap incident sunlight for longer with the expectation that trapped sunlight would eventually start the electron-ejection process to generate electricity without being reflected. This light, unable to escape, would then lead to a boost in the efficiency rate as more electron-ejecting processes were started.

The novel and unique solar cells capture nearly all of the incoming light. This significant improvement allows for the possibility of higher efficiency rates.

Carbon nanotube array forming the integral part of the solar cell enables to reduce the size and weight of the solar cell.

Trackers on the solar cell unit could be eliminated as the carbon nanotube-based solar cell will, due to its inherent structure, trap sunlight within its array and reduce the amount of incident sunlight reflected back into the atmosphere.

In addition, the carbon nanotube array actually works best at angles not associated with high noon. For example, at high noon, the 3D solar cell had an efficiency rating of 3.5 % but when the angle changed to 45 degrees, the efficiency rating doubled to 7 %. This opens up the prospect of 3D solar cells being used when the light is diffuse, opening up the prospect of being deployed in areas located +/- 35 degrees of the equator that are outside the Sunbelt. Furthermore, by not requiring trackers, the manufacturing costs will be reduced.

IV. CONCLUSION

This paper reviews the theoretical synthesis of the presently available emerging methods which rationally suggests towards a positive enhancement of efficiency. Features like Multiple Exciton Generation, wide Angle Light Collection, 3D Photovoltaic Structure, thin Absorbing Regions, below Surface Contacts of 3D structures will certainly enable in attaining high internal and external efficiency which are subjected to further experimental investigations.

REFERENCES

[1] Dr. V. K. Sethi, Dr. Mukesh Pandey and Ms. Priti Shukla, Use of Nanotechnology in Solar PV Cell, International Journal of Chemical Engineering and application, Vol. 2, No. 2.

[2] Baumann, A., et al., Photovoltaic Technology Review. 2004, University of California at Berkeley: Berkeley, CA. p. 40.

[3] National Center for Photovoltaics. (2012, 05 15). Best Research-cell efficiency. Retrieved 05 15, 2012, from NREL: National Center for Photovoltaics Home Page: http://www.nrel.gov/ncpv.

[4] Green MA, Emery K, Hishikawa Y, Warta W. Solar cell efficiency tables (version 36). Progress in Photovoltatics: Research and Applicaton 2010; **18**: 346-352

[5] A. Goetzberger, J. Luther, G. Willeke, Solar cells: past, present, future, Sol. Energ. Mat. Sol. Cells 74 (2002) 1–11.

[6] B.A. Gregg, M.C. Hanna, Comparing organic to inorganic photovoltaic cells: theory, experiment, and simulation, J. Appl. Phys. 93 (2003) 3605–3614.

[7] M. Chandross, S. Mazumdar, S. Jeglinski, X. Wei, Z.V. Vardeny, E.W. Kwock, T.M. Miller, Excitons in PPV, Phys. Rev. B 50 (1994) 14702–14705.

[8] W.U. Huynh, J.J. Dittmer, A.P. Alivisatos, Hybrid Nanorod-Polymer Solar Cells, Science 295 (2002) 2425–2427.

[9] E. Kymakis, G.A.J. Amaratunga, Single-wall carbon nanotube/conjugated polymer photovoltaic devices, Appl. Phys. Lett. 80 (2002) 112–114.

[10] S.E. Shaheen, C.J. Brabec, N.S. Sariciftci, F. Padinger, T. Fromherz, J.C. Hummelen, 2.5% efficient organic plastic solar cells, Appl. Phys. Lett. 78 (2001) 841–843.

[11] D.M. Basko, E.M. Conwell, Theory of hot exciton dissociation in conjugated polymers, Synth. Met. 139 (2003) 819–821.

[12] V.I. Arkhipov, P. Heremans, H. Bassler, Why is exciton dissociation so efficient at the interface between a conjugated polymer and an electron acceptor? Appl. Phys. Lett. 82 (2003) 4605–4607.

[13] H. Bassler, V.I. Arkhipov, E.V. Emelianova, A. Gerhard, A. Hayer, C. Im, J. Rissler, Excitons in pi-conjugated polymers, Synth. Met. 135–136 (2003) 377–382.

[14] J.J.M. Halls, K. Pichler, R.H. Friend, S.C. Moratti, A.B. Holmes, Exciton diffusion and dissociation in a poly (p-phenylenevinylene)/C60 heterojunction photovoltaic cell, Appl. Phys. Lett. 68 (1996) 3120–3122.

[15] J. Cornil, D. Beljonne, C.M. Heller, I.H. Campbell, B.K. Laurich, D.L. Smith, D.D.C. Bradley, K. Mullen, J.L. Bredas, Photoluminescence spectra of oligo-paraphenylenevinylenes: a joint theoretical and experimental characterization, Chem. Phys. Lett. 278 (1997) 139–145.

[16] A. Haugeneder, M. Neges, C. Kallinger, W. Spirkl, U. Lemmer, J. Feldmann, U. Scherf, E. Harth, A. Gugel, K. Mullen, Exciton diffusion and dissociation in conjugated polymer/fullerene blends and heterostructures, Phys. Rev. B 59 (1999) 15346–15351.

[17] B. Kannan, K. Castelino, A. Majumdar, Design of nanostructured heterojunction polymer photovoltaic devices, Nano Lett. 3 (2003) 1729–1733.

[18] T. Fromherz, F. Padinger, D. Gebevehu, C.J. Brabec, J.C. Hummelen, N.S. Sariciftci, Comparison of photovoltaic devices containing various blends of polymer and fullerene derivatives, Sol. Energ. Mat. Sol. Cells 63 (2000) 61–68.

[19] B. Sun, E. Marx, N.C. Greenham, Photovoltaic devices using blends of Branched CdSe nanoparticles and conjugated polymers, Nano Lett. 3 (2003) 961–963.

[20] G. Yu, J. Gao, J.C. Hummelen, F. Wudl, A.J. Heeger, Polymer photovoltaic cells: enhanced efficiencies via a network of internal donor–acceptor heterojunctions, Science 270 (1995) 1789–1791.

[21] V. Dyakonov, The polymer-fullerene interpenetrating network: one route to a solar cell approach, Physica E 14 (2002) 53–60.

[22] L. Zheng, Q. Zhou, X. Deng, M. Yuan, G. Yu, Y. Cao, Methanofullerenes used as electron acceptors in polymer photovoltaic devices, J. Phys. Chem. B 108 (2004) 11921–11926.

[23] C.J. Brabec, S.E. Shaheen, C. Winder, N.S. Sariciftci, P. Denk, Effect of LiF/metal electrodes on the performance of plastic solar cells, Appl. Phys. Lett. 80 (2002) 1288–1290.

[24] E. Kymakis, I. Alexandrou, G.A.J. Amaratunga, High Voc PV devices fron carbon nanotube– polymer composites, J. Appl. Phys. 93 (2003) 1764.

[25] B.J. Landi, R.P. Raffaelle, S.L. Castro, S.G. Bailey, SWNT-polymer solar cells, Prog. Photovot: Res. Appl. (2004) in press.

[26] A. Thess, R. Lee, P. Nikolaev, H. Dai, P. Petit, J. Robert, C. Xu, Y.H. Lee, S.G. Kim, A. Rinzler, D.T. Colbert, G. Scuseria, D. Tomanek, J.E. Fischer, R. Smalley, Crystalline ropes of Metallic Carbon Nanotubes, Science 273 (1996) 483–487.

[27] U.E.H. Laheld, G.T. Einevoll, Excitons in CdSe quantum dots, Phys. Rev. B 55 (1997) 5184–5204.

[28] A.L. Efros, M. Rosen, M. Kuno, M. Nirmal, D.J. Norris, M. Bawendi, Band edge exciton in quantum dots of semiconductors with a degenerate valence band: dark and bright exciton states, Phys. Rev. B 54 (1996) 4843–4856.

[29] S. Kazaoui, N. Minami, N. Matsuda, H. Kataura, Y. Achiba, Electrochemical tuning of electronic states in SWNTs studies by in situ absorption spectroscopy and ac resistance, Appl. Phys. Lett. 78 (2001) 3433–3435.

[30] M. Freitag, Y. Martin, J.A. Misewich, R. Martel, P. Avouris, Photoconductivity of Single Carbon Nanotubes, Nano Lett. 3 (2003) 1067.

[31] A. Fujiwara, Y. Matsuoka, H. Suematsu, N. Ogawa, K. Miyano, H. Kataura, Y. Maniwa, S. Suzuki, Y. Achiba, Photoconductivity in semiconducting SWNTs, Jpn. J. Appl. Phys. 40 (2001) L1229.

[32] L.E. Brus, A simple model for the ionization potential, electron affinity, and aqueous redox potentials of small semiconductor crystallites, J. Chem. Phys. 79 (1983) 5566–5571.

[33] Z.A. Peng, X. Peng, Formation of high-quality CdTe, CdSe, and CdS nanocrystals using CdO as precursor, J. Am. Chem. Soc. 123 (2001) 183–184.

[34] A.C. Dillon, P.A. Parilla, J.L. Alleman, J.D. Perkins, M.J. Heben, Controlling single-wall nanotube diameters with variation in laser pulse power, Chem. Phys. Lett. 316 (2000) 13.

[35] E. Kucur, J. Riegler, G.A. Urban, T. Nann, Determination of quantum confinement in CdSe nanocrystals by cyclic voltammetry, J. Chem. Phys. 119 (2003) 2333–2337.

[36] D.H. Son, J.S. Wittenberg, A.P. Alivisatos, Multielectron ionization of CdSe quantum dots in intense femtosecond uv light, Phys. Rev. Lett. 92 (2004) 127401–127406.

[37] B.J. Landi et al. / Solar Energy Materials & Solar Cells 87 (2005) 733–746 745.

[38] W.W. Yu, L. Qu, W. Guo, X. Peng, Experimental determination of the extinction coefficient of CdTe, CdSe, and CdS nanocrystals, Chem. Mater. 15 (2003) 2854–2860.

[39] M.A. Green, Third Generation Photovoltaics: solar cells for 2020 and beyond, Physica E 14 (2002) 65–70.

Tahrim Alam was born in Bangladesh on 3rd September 1986. He completed his under graduation from Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh; in 2011. His research interest is Semiconductor fabrication and characterization, Nanostructured electronic materials, Energy (Li-ion battery, fuel cell, and solar cell) etc.