80. Solar Cells - Recent Developments and Trends

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Abstract

Rapid increase in development of Renewable energy technologies is creating new ways and means for utilization of natural resources. Global environmental concerns and increasing energy demand is coupled with improvement in renewable technology. Of all the renewable energy sources sun is the most inexcusable, clean and free energy source. The power which sun delivers to earth is far more sufficient to fulfil the current energy requirements. Because of these collective properties photovoltaic industry is growing at a very fast pace in market. Solar cells are currently in its third generation and many to follow in the years to come with the aim to increase efficiency and reduce cost. With regard to solar energy development and recent trends the paper reviews 3rd generation solar cells comprehensively.

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1. Introduction

Energy thirst is increasing with tremendous rise in energy demand. Energy is quite essential for both economic and social development. For standard life style, the main challenge for the researchers is to get energy which is sustainable, clean and renewable. It is necessary to divert from the fossils fuels to other sources of energies in order to reduce CO_2 emission and to make environment clean.

Nature is enriched with clean and renewable energy resources like sunlight, geothermal, water, wind, and biomass. All these renewable resources illustrated in fig 1 can provide massive amount of energy to meet global requirements. Among them, solar energy is considered to be quite efficient, environmental friendly and cost effective. Sun is the most incredible source of energy whose radiation falls on earth is about 174,000 terawatts [1]. Energy from single day of sun can satisfy almost 20 years of world's total energy demand. A dramatic growth in utilization of solar energy has been observed in recent years from portable devices to huge power plants.

Solar cells are usually made up of semiconductor material and can be characterized in first, second and third generation. All these generations have their own pros and cons as illustrated in table 1. First generation solar cells are termed as conventional solar cells and are wafer based. Wafer based technology is the most dominant technology in today's world. They have high conversion efficiency but their production is costly as illustrated in table 2. Second generation solar cell is conventional thin film-based that includes amorphous silicon, CdTe and CIGS etc. These solar cells have lower efficiency than silicon based first generation solar cells, but have cheaper production cost. The cost for single watt in case of second generation is much lower than the first generation solar cells. As far as third generation solar cells are concerned they are efficient as well as cost effective in contrast to first and second generation and they are based on emerging thin-films like dye sensitized, perovskite, quantum dot etc. Most of the third generation technologies are not yet commercialized but progress in research will make this generation solar cells commercially viable, stable and cheaper. [2]

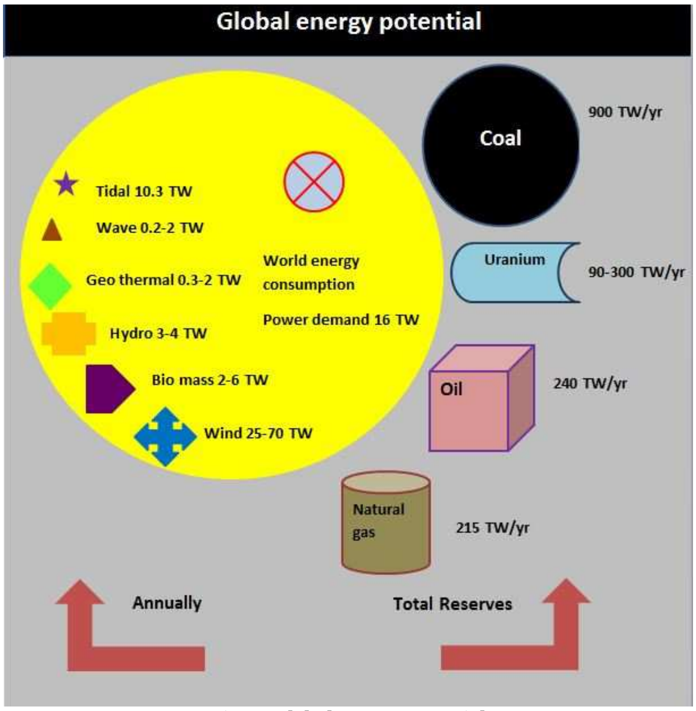

Fig. 1. Global energy potential

Table 1. Pros and cons of 1st, 2nd and 3rd generation solar cells

Solar cell types	pros	cons
1st generation	High conversion efficiency.	High cost. Complex fabrication proces
2nd generation	High value of absorption co-efficient. Occupy both non-vacuum and vacuum process. Low cost raw material. Lower cost production.	Environment Contamination due to fabrication process. Materials are not easily available.
3rd generation	Raw materials are easily available. Easy fabrication. Minimum Cost.	Leakage of Liquid electrolyte. Ru (dye) and Pt (electrode) have High cost.

2. Third Generation Solar Cells

2.1. Nano-crystalline Solar Cells

These kind of solar cells consist of a substrate with nano-crystals coating. The substrate is typically made up of a semiconductor material such as silicon and nano-crystals are generally based on Si, CIGS or CdTe. Thin film solar cells are in improving aura ever and henceforth extensive research is being carried out on them since their birth. The p-i-n amorphous Si thin-film solar cell's efficiency is dependent on illumination of p-side rather than the n-side. So, a large amount of work has been done on the p-side window layer. Advancement in this context was the p-type hydrogenated nano-crystalline Silicon, which consisted of amorphous silicon matrix and nanocrystals of silicon. The results obtained were quite good as they showed high electrical conductivity, doping efficiency, mobility and low absorption coefficient [3]. Amorphous-Si nanocrystals have been prepared using different techniques such as Field induced lateral crystallization (FILC), Metal Induced Crystallization (MIC), Plasma Enhanced Chemical Vapour Deposition Processes (PECVD), etc. These processes have their own pros and cons. Low temperature crystalline growth processes such as Aluminium Induced Crystallization (AIC) [4] have also been employed. Nano-crystalline thin film silicon solar cells are fabricated using different power pressure combinations and different concentration in order to analyse the light induced degradation and efficiency. They are fabricated using active layer of nano-sized crystallites implanted in amorphous silicon matrix homogenously, which resulted in 5% degradation ratio and have great stability against light soaking. Initially they went through degradation but subsequently they stabilize after 10 hours of light soaking and their efficiency degraded only about 2.9 % [5]. The hydrogenated nano-crystalline silicon intrinsic layer has a low bandgap and is not prone to light degradation under red light illumination, so it's very useful in the photovoltaics world. But, it has some setbacks, such as high rate deposition and large-area uniformity. The critical one is its susceptibility for the impurities. It is more sensitive to oxygen and nitrogen, for which they form weak donors in it. The loss in the quantum efficiency due to the presence of Oxygen can be compensated by the addition of boron for large wavelengths. But, if its concentration is increased above certain limit, it causes lower quantum efficiency for small wavelengths [6]. Boron is used as a dopant in p-type amorphous nano-crystalline silicon cells, which has high conductivity and low absorption of light in visible region. The thin films of such materials were deposited on a substrate at 150^0C using PECVD [7]

Table 2. Solar cells efficiency, NREL (2016)

Solar cell type	Efficiency
1st generation	
Mono Crystalline Si solar cell	27.6
Multi Crystalline Si solar cell	21.3
2nd generation	
Amorphous Si	23.3
GaAs cell	29
CdTe	22.1
CiGS	22.3
3rd generation	
DSSC	11.9
perovskite	22.1
Organic cell	11.5
Quantum dot solar cells	11.3
Multi junction solar cell	greater than 40

Table 3. Comparison of 1st, 2nd and 3rd generation solar cells

Characteristics	1st generation	2nd generation	3rd generation
Raw material cost	Low	Medium	Low
Finished material cost	High	High	Low
Fabrication cost	High	Medium	Low
Energy payback period	High	High	Low
Efficiency	High	Medium	High

2.2. Dye Sensitized Solar cells:

Dye sensitized solar cells (DSSC) which is Inspired from natural photosynthesis process have been the effective replacement for Solid state p-n junction devices. The conversion efficiency ranges from 11 to 15%. It is cheap because it can be easily extracted from natural resources. Introduction of nano-sized structure and different particle size have been experimented to obtain high photo-current and photo-voltage. Also experiments have been performed to replace expensive metals like copper with cheap metals like platinum.

The reported power e fficiency of TiO_2 film has over 10%. Its fabrication involves the pre-treatment of photo electrode which is made up of $TiCl_4$, an anti-reflecting layer and light scattering layer. Adhesion and mechanical strength of the nano-structure are enhanced by $TiCl_4$. Thickness of TiO_2 layers is varied in order to have transparent nano-crystalline structure and it plays crucial role in enhancing the efficiency of the cell. Optimal thickness of TiO_2 layer signifies photo current and photo voltage. The top coating and covering increases the photocurrent and the anti-reflecting coating increases the Quantum efficiency up to 94%. All these factors collectively contribute to the total efficiency of the dye sensitized solar cell. Thickness of TiO_2 nano-crystal contributes significantly in cell design [8].

The TiO_2 particles ranging from 10-30 nm are sintered together on photo anode of dye sensitized solar cells. The Nano porous structure increases the effective surface of the electrode and the layer of dye increases the absorption of light. The light is scattered by large size particles but it also decreases the effective size of the electrode [9]. As a standard, Platinum based electrode is used as a counter electrode in dye sensitized solar cell which provides maximum efficiency but it is quite expensive. However, carbon electrode can be an alternate which are cheaper and have comparable conversion efficiency [10].

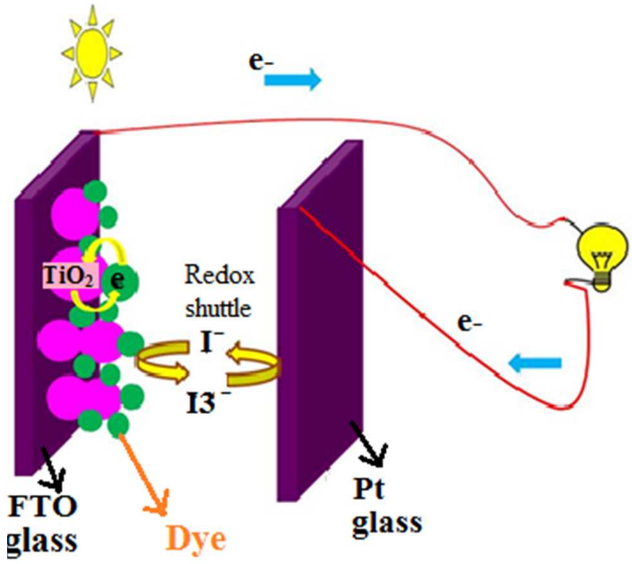

Fig. 3: DSSC (dye sensitized solar cell)

The DSSC using Ruthenium dye (N719) has reported an overall efficiency of 10 % claimed by Gratzel Group. Six different morphologies were investigated by the group. It comprises of Nano particles layer, mixture of nanoparticles with light scattering particles on conducting glass with different thicknesses and sequences. The conversion efficiency of N719 improved from 7.6% to 9.8% by using multilayer structure. This efficiency is further enhanced to 10.2% by using anti reflecting coating. Hence, overall performance of the solar cells can be improved by balancing the surface area and light scattering particle [11].

The DSSC can be manufactured from different naturally occurring dyes for instance using black Rice, Rosa, Capsicum, Kelp and Xanthine. Upon performance investigation it is found that black rice has better (OC) open circuit voltage, (SC) short circuit current and fill factor [12].

2.3. Organic Solar Cell

Using organic materials in fabrication of solar cell is one of the best approaches as it offers the properties like flexibility and low cost fabrication on a large scale. During the past 30 years' research on the organic solar cells has been developed by the introduction of sophisticated device structure and improved materials [13]. The organic solar cell is a bulk-heterojunction device which composed of a glass substrate which is coated by the blocking layer of electron (3,4-ethylene- dioxythiophene, styrene sulfonate), photoactive layer, conductive oxide transparent layer (indium-tin-oxide layer) and some time there is a hole blocking layer (TiO_x, $CsCO_3$ or LiF) and a metal electrode [14].

The organic solar cells consist of an active layer between transparent and metal electrode. There are four layers of organic solar cell having glass as substrate, the transparent cathode of ITP placed on a glass substrate, ITO is coated on the substrate which is basically a mixture of polymers like 3,4-ethylenedioxythiophene and styrene sulfonate. An active layer made up of conjugated film that is used to transmit or absorb the light. Banana flower extract is also an alternative for active layer which is rich in anthocyanin, acting as donor of electrons [15].

Most of the organics have poor conductivity as they have strong covalent bond. But they have the advantage of simple fabrication process, low cost material and abundance on the earth crust. The highest efficiency that has been reported till date is11%. There are also some drawbacks like the life time and technical limitation and low stability. [16] The encapsulation of the device requires packing material which is costly. [13]

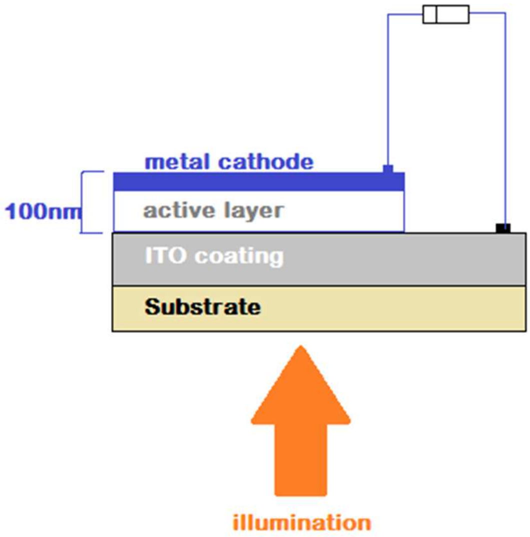

Fig. 4: schematic layout of organic solar cell

2.4. Polymer Solar Cell

This type of solar cell is made up of polymers and repeating structural units of large molecules. As compared to silicon based solar cells they are flexible, lightweight and inexpensive.

Deformable mechanisms including Cu films that are deposited over Kapton substrates and rupturing of the substrate up to an elongation of 50-60% are now used in the polymer solar cells. When Cr adhesion layer was used between Cu and Kapton, only few micron cracks were observed in their microstructure after rupturing [17].

A new material, PbS is now used as a nano crystal due to its broad absorption range in the quantum regime. Because of the high electron affinity, the probability of charge separation is also increased. The intrinsic charge carrier mobility disturbs the performance of MEH-PPV((2-Methoxy-5-2-ethylhexyloxy)-P-Phenylenevinylene) significantly. Hence the use of Plastic solar cell such as PbS: MEH-PV is highly suitable to solve this problem. It also shows that Nano crystals having symmetric XYZ geometry can be used to make effective PV solar cells [18].

Organic solar cells are used extensively nowadays due to its solution based manufacturing which allows the possibility of quick orthogonal shaped multi layers formation. These materials have the capability to overcome the problem of low power conversion efficiency (PCE). By using these materials along with triple junction instead of single junction, the efficiency of the polymer solar cells can be enhanced to 11% which is a great achievement [19].

The combination of conjugated polymer and fullerene bisadduct is a new candidate for polymer based solar cells. Bulk heterojunction organic solar cells consist of conjugated polymers and fullerene, which work as a donor and acceptor respectively. They are cheap, flexible and a very good alternative to Si solar cells. Fullerene bisadduct can increase the (OC) open circuit voltage of organic SCs. The combination of these two provides good alternative in terms of efficiency, cost and performance. [20]

β-diketonato ruthenium complexes are used as a photosensitizer for solar cells. These complexes have ability of high absorption in a broad range of visible light and this property is strongly preferable for efficient conversion of light energy. The energy conversion efficiency approached to 6% with acetylacetonate complex, which is comparable with dithiocyanate complex having highest efficiency till date [21].

2.5. Multi-junction Solar Cells

The single junction solar cells absorb only certain portion of wavelength and hence unable to get advantage of whole light spectrum. The infrared radiations could not be absorbed and ultraviolet could cause thermalization due to the interaction of high energy photons with electrons. So, in order to take more advantage of the coming photons the idea of multijuncition solar cells was introduced. The top layer of such solar cell is used for the absorption of smaller wavelengths (those with high energy) and subsequent layers are for the absorption of larger wavelengths (those with low energy) [22]. During the course of development and improvement of the multi-junction solar cells, the most important step was the introduction of these cells to the Concentrator Photovoltaic. It not only enabled multi-junction solar cells to be cost effective but also to reach a record efficiency of about 41% [23]. The concentrator photovoltaic cells were then tested and modified to have more and more sunlight on it. Experiments were made to find precise optical design to eliminate the irregularities in the concentrator [24]. The concentrator multijunction cells perform better than planar junction cells. Many experiments are being carried out to compare the performance of these cells on the basis of the electrical and thermal properties of the cells. Such experimentations showed that the vertical multijunction cells are better in many respects than that of planar solar cells [25].

2.6. Perovskite Solar Cells

The perovskite material is attaining attention in photovoltaic industry because of its abundance in nature and ease of fabrication. The main problem with this kind of solar cells is its stability and toxic nature of the lead based perovskite materials. To overcome this problem some other contending metals like tin has been introduced, which is nontoxic and abundant in nature.

The material stability and optical properties of 2D perovskite series MA2CuClxBr4−x were studied and was found that the Br/Cl ratio have significant effect on it. By increasing the Br content the band gap can be reduced. The copper also plays an important role in absorption of the wavelength between 700 nm to 900 nm. It can be deposited using spin coating technique. By increasing the Br/cl ratio, the intensity of green photoluminescence is enhanced and hence can be used as light emitting device. The mesoporous Titania contributes to the power conversion efficiency. The efficiency degrades by combination of low absorption coefficients and heavy mass for the holes. The active cations set aside these issues and promote 2D copper based perovskite hybrid materials. [26]

The lead based perovskite solar cells have high efficiencies but due to toxic nature of lead it cannot be commercialized. For this purpose, Bismuth based perovskite material are introduced because of its non-toxic nature. It consists of double perovskite structure in which Bi3+ is incorporated into $Cs_2AgBiBr_6$. It has indirect gap of 1.96 eV. It is best matched for tandem solar cells. The comparative study of single crystal photoluminescence and powder photoluminescence showed that it has high defect tolerance. It is more stable to moisture and heat than lead. It opens the way of exploration for inorganic and hybrid halide double perovskite structure. [27]

Solid state hybrid organic-inorganic solar cells have been developed in the form of layer structure of titania nano-particle, organometallic halide perovskite and spiroMeOTAD as hole transporter. The cell efficiency was 7% under ambient conditions. The cell efficiency increased day by day by putting it in incubation under ambient condition without being encapsulated [28].

Planer hetrojunction perovskite solar cells were manufactured using low temperature approach. It is observed that its Power conversion efficiency is based on external bias. The power efficiency increased from 1 to 8% when external voltage is adjusted before measurement and after scanning from 3 V to 6 V. By using different material characterization techniques, it is evident that the increase in the power conversion efficiency is encompassed by ion motion under the influence of external voltage. There are some other contributions as well like that of Ferro-electricity or traps but ion motion under external bias plays pivotal role. The reproducibility and stability of the devices improves with decrease in ionic motion, [29]

The lead perovskite based solar cells are emerging because it is economically cheaper and having higher power conversion efficiency upto 17% in most cases. But because of lead toxic nature, it needs to be substituted by some other contending metals. In this case tin is the most suitable. Using Sn based perovskite, CH_3 NH_3SnI_3; high open circuit voltage can be achieved. It has power conversion efficiency of more than 6% but it has stability issues. The problem of stability rises because of the oxidation of tin. It can be reduced by decreasing the doping concentration [30].

2.7. Quantum dot Solar Cells

A quantum dot solar cell uses quantum dots as the absorbing photovoltaic material. Quantum dots have bandgaps that are capable of being tuned across a broad range of energy levels unlike bulk materials [31]. Third generation solar cells also use semiconductor quantum dots (QDs) as light absorber [32].

Fig. 5. Pervoskite solar cell

Semiconductor QDs have numerous advantages like multiple extinction generation, tuneable absorption size, and high optical extinction coefficient. Perovskite QD-sensitized 3.6mm-thick TiO2 film showed maximum external quantum efficiency (EQE) of 78.6% at 530 nm and solar-to-electrical conversion efficiency of 6.54% [33] [34].

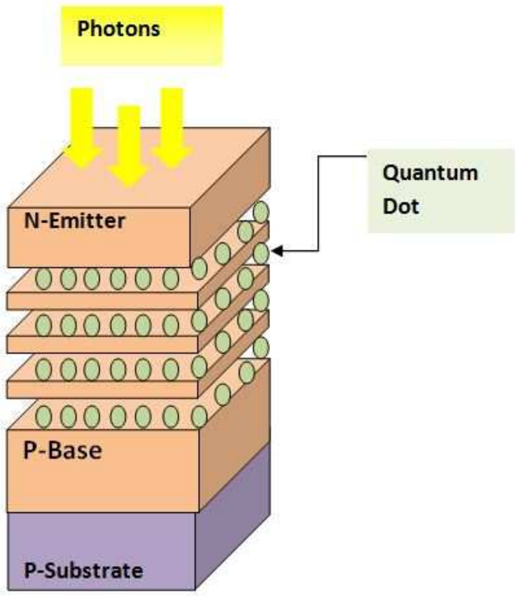

Fig. 6. Quantum dots solar cell

Doping also has impact on QDs. Two methods of selective doping namely modulation and direct doping is used to gain a comprehensive device-level assessment of doping profile and density. It has been clarified that the negative impact of p-type doping on the achievable V_{oc} observed in high quality crystal samples is due to the asynchronous and faster dynamics of holes with respect to electrons. The impact of n-type doping on the photovoltaic characteristics has been addressed under barrier material quality. Improved power conversion efficiency with respect to undoped cells is predicted due to remarkable V_{oc} recovery [35].

Many categories of semiconductor quantum dots have been synthesized, containing groups II-VI, III-V, IV-VI, IV. One approach to enhance efficiency in QD-based PV cells compared to conventional bulk semiconductor-based PV is to create efficient multiple extinction generation (MEG) from a large fraction of the photons in the solar spectrum. Three generic types of QD solar cells that could utilize MEG to enhance conversion efficiency can be defined: (1) photo-electrodes composed of QD arrays that form either Schottky junctions with a metal layer, a hetero p-n junction with a second NC semiconductor layer, or the i-region of a p-i-n device, (2) QD-sensitized nano-crystalline TiO2films, and (3) QDs dispersed into a multiphase mixture of electron- and hole-conducting matrices, such as C60 and hole conducting polymers (like polythiophene or MEH-PPV), respectively. Additional research and understanding is required to realize the potential of MEG to significantly enhance solar cell performance.

3. Conclusion

The importance of photovoltaic increased, with recognition of climatic changes and instability of fossil fuels. A vast research is being carried out on solar photovoltaic technology and a remarkable improvement in both performance and efficiency has achieved. First generation solar cells are most mature solar technology, having long term stability and good performance with efficiency of about 15% to 20%**.** Second generation solar cells are cost effective as compared to first generation with efficiency ranges from 10% to 15 %. Third generation solar cells having efficiency from 15% to 30% are the emerging technology and have enormous potential due to its high efficiency, low cost and easy synthesizing process.

References

[1] Smil *"General Energetics Energy," in the Biosphere and Civilization*, V. 1991, John Wiley, New York, p.240

[2] Mohammad Tawheed Kibria, Akil Ahammed, Saad Mahmud Sony, Faisal Hossain and Shams-Ul-Islam, "Comparative studies on different generation solar cells technology," Institute of Energy, University of Dhaka, Bangladesh.

[3] Ke Tao et al. "Low-temperature preparation of flexible a-Si:H solar cells with hydrogenated nanocrystalline silicon p layer," Vacuum 86, (2012), pp.1477-1481.

[4] Ian Y.Y. Bu. "Room temperature synthesis of nanocrystalline silicon by aluminium induced crystallization for solar cell applications," Vacuum 86, (2011), pp.106-110.

[5] Sumita Mukhopadhyay, Romyani Goswami and Swati Ray, "Light induced degradation in nanocrystalline Si films and related solar cells: Role of crystalline fraction. Solar Energy Materials & Solar Cells," 93, (2009), pp.674–679.

[6] Guozhen Yue, Baojie Yan, Laura Sivec, Yanhua Zhou, Jeffrey Yang and Subhendu Guha, "Effect of impurities on performance of hydrogenated nanocrystalline silicon solar cells," in Solar Energy Materials & Solar Cells 104 (2012) pp.109–112.

[7] E. Fathi, Y. Vygranenkob, M. Vieira and A. Sazonov, "Boron-doped nanocrystalline silicon thin films for solar cells," in Applied Surface Science, 257, (2011), pp.8901–8905.

[8] Seigo Ito, Takurou N. Murakami, Pascal Comte, Paul Liska, Carole Grätzel, Mohammad K. Nazeeruddin, and Michael Grätzel, "Fabrication of thin film dye sensitized solar cells with solar to electric power conversion efficiency over 10%," in Thin Solid Films, 516, (2008), pp. 4613–4619.

[9] Jorg Ferber and Joachim Luther, "Computer simulations of light scattering and absorption in dye-sensitized solar cells", in Solar Energy Materials and Solar Cells, 54, (1998), pp. 265-275.

[10] Zhong-Sheng Wang, Hiroshi Kawauchi, Takeo Kashima and Hironori Arakawa, "Significant influence of TiO2 photoelectrode morphology on the energy conversion efficiency of N719 dye-sensitized solar cell", in Coordination Chemistry Reviews, 248, (2004), pp. 1381–1389.

[11] Zhen Huang, Xizhe Liu, Kexin Li, Dongmei Li, Yanhong Luo, Hong Li, Wenbo Song, LiQuan Chen and Qingbo Meng, "Application of carbon materials as counter electrodes of dye-sensitized solar cells", in Electrochemistry Communications, 9, (2007), pp. 596–598.

[12] Sancun Hao, Jihuai Wu, Yunfang Huang and Jianming Lin, "Natural dyes as photosensitizers for dye-sensitized solar cell", in Solar Energy, 80, (2006), pp. 209–214.

[13] Harald Hoppea and Niyazi Serdar Sariciftci, "organic solar cells: An overview" in Journal of Materials Research 19(7), July 2004.

[14] Yasemin Uduma,b , Patrick Denk a, Getachew Adama, Dogukan H. Apaydin a, Andreas Nevosad c,Christian Teichert c, Matthew. S. White a, Niyazi. S. Sariciftci a and Markus C. Scharber a, "Inverted bulk-heterojunction solar cell with cross-linked hole-blocking layer," in Organic Electronics Volume 15, Issue 5, May 2014, Pages 997–1001.

[15] Sutikno, Ngurah Made Dharmaputera, and Sri Rahayu, "Journal of Advanced Agricultural Technologies," Vol. 1, No. 2, December 2014

[16] Vivek K. A1 and G. D. Agrawal2, "IJRET: International Journal of Research in Engineering and Technology," eISSN: 2319-1163 | pISSN: 2321-7308

[17] Nanshu Lu, Xi Wang, Zhigang Suo, and Joost Vlassaka, "Metal films on polymer substrates stretched beyond 50%," School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA

[18] Andrew A. R. Watt, David Blake, Jamie H. Warner, Elizabeth A. Thomsen, Eric L. Tavenner, Halina Rubinsztein-Dunlop and Paul Meredith, "Lead Sulphide Nanocrystal: Conducting Polymer Solar Cells," Soft Condensed Matter Physics Group and Centre for Biophotonics and Laser Science, University of Queensland, Brisbane, Australia

[19] Chun-Chao Chen, Wei-Hsuan Chang, Ken Yoshimura, Kenichiro Ohya, Jingbi You, Jing Gao, Zirou Hong, and Yang Yang, "An Efficient Triple-Junction Polymer Solar Cell Having a Power Conversion Efficiency Exceeding 11%," in advanced materials, volume 26, July 2014, pp.5670-5677.

[20] Nichole Cates Miller, Sean Sweetnam, Eric T. Hoke, Roman Gysel, Chad E. Miller, Jonathan A. Bartelt, Xinxin Xie, Michael F. Toney, and Michael, "Molecular Packing and Solar Cell Performance in Blends of Polymers with a Bisadduct Fullerene," in Nano letters, 12(3), Department of Materials Science and Engineering and Department of Applied Physics, Stanford University, United States, 2012, pp. 1566-1570.
http://pubs.acs.org/doi/abs/10.1021/nl204421p?src=recsys

[21] Yoshiaki Takahashi, Hironori Arakawa, Hideki Sugihara, Kohjiro Hara, Ashraful Islam, Ryuzi Katoh, Yasuhiro Tachibana and Masatoshi Yanagida, "Highly efficient polypyridyl-ruthenium(II) photosensitizers with chelating oxygen donor ligands: β-diketonato Bis(dicarboxybipyridine)ruthenium," in Inorganica Chimica Acta, volume310, 2000, pp. 169-174.

[22] Rabi Ibrahim Rabady, "Optimized multi-junction photovoltaic solar cells for terrestrial applications," in Solar Energy, 106, (2014), pp.72–81

[23] Geoffrey S. Kinsey et al, "Operating characteristics of multijunction solar cells. Solar Energy Materials & Solar Cells," 93, (2009), pp.950–951

[24] R.D. Schultz, F.J Vorster and E.E van Dyk, "Performance of multi-junction cells due to illumination distribution across the cell surface,"in Physica B, 407, (2012), pp.1649–1652

[25] Yupeng Xing, Kailiang Zhang, Jinshi Zhao and Peide Han, "Thermal and electrical performance analysis of silicon vertical multi-junction solar cell under non-uniform illumination" in Renewable Energy, 90, (2016) pp.77-82

[26] Daniele Cortecchia, Herlina Arianita Dewi, Jun Yin, Annalisa Bruno, Shi Chen, Tom Baikie, Pablo P. Boix, Michael Grätzel, Subodh Mhaisalkar, Cesare Soci, and Nripan Mathews, "Lead-Free MA2CuClxBr4−x Hybrid Perovskites", DOI: 10.1021/acs.inorgchem.5b01896, 2016.

[27] Adam H. Slavney, Te Hu, Aaron M. Lindenberg, and Hemamala I. Karunadasa, "A Bismuth-Halide Double Perovskite with Long Carrier Recombination Lifetime for Photovoltaic Applications", J. Am. Chem. Soc., 138, 2016, pp. 2138−2141.

[28] Georgia Sfyri, ChalluriVijayKumar, DimitriosRaptis, VassiliosDracopoulos and PanagiotisLianos, "Study of perovskite solar cells synthesized under ambient conditions and of the performance of small cell modules", in Solar Energy Materials & Solar Cells, 134, (2015), pp. 60–63.

[29] Xiaodong Li, Xueyan Wang, Wenjun Zhang, Yulei Wu, Feng Gao and Junfeng Fang, "The effect of external electric field on the performance of perovskite solar cells", in Organic Electronics, 18, (2015), pp. 107–112

[30] Nakita K. Noel, Samuel D. Stranks, Antonio Abate and Christian Wehrenfennig, "Lead-free organic–inorganic tin halide perovskites for photovoltaic applications", in Energy Environ. Sci., 7, 2014, pp. 3061.

[31] Sixto Gim´enez1, Iv´an Mora-Ser´o1,4, Lorena Macor1, Nestor Guijarro2, Teresa Lana-Villarreal2, Roberto G´omez2, Lina J Diguna3, Qing Shen3, Taro Toyoda3,4 and Juan Bisquert1, "Improving the performance of colloidal quantum-dot-sensitized solar cells," in Nanotechnology, 20, (2009), 295204 (6pp)

[32] Jeong-Hyeok Im, Chang-Ryul Lee, Jin-Wook Lee, Sang-Won Park and Nam-Gyu, "6.5% efficient perovskite quantum-dot-sensitized solar cell," Nanoscale, 3, 2011, pp. 4088-4093

[33] Istva´n Robel, Vaidyanathan Subramanian, Masaru Kuno, and Prashant V. Kamat, "Quantum Dot Solar Cells. Harvesting Light Energy with CdSe Nanocrystals Molecularly Linked to Mesoscopic TiO2 Films," in journal of the American chemical society, 128(7), 2006, pp. 2385-2393.

[34] F. Cappelluti·, M. Gioannini, A. Khalili, "Impact of doping on InAs/GaAs quantum-dot solar cells: A numerical study on photovoltaic and photoluminescence behavior," in Solar Energy Materials and Solar Cells, Volume 157, December 2016, p. 209–220

[35] A. J. Nozik, M. C. Beard, J. M. Luther, M. Law, R. J. Ellingson and J. C. Johnson, "Semiconductor Quantum Dots and Quantum Dot Arrays and Applications of Multiple Exciton Generation to Third-Generation Photovoltaic Solar Cells" in Chemical reviews, 110 (11), 2010, pp.6873-6890.