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Using Plasmonic Metal Nanoparticles to Enhance Solar Cell Efficiency – Bangladesh Making Significant Progress in Renewable Energy Technology

S. M. Nayeem Arefin*, Shahriar Islam*, Jawad Hasan*, Mustafa Mohammad Shaky*, Fatema Fairooz* and Mustafa Habib Chowdhury*,[1]

Abstract *–The booming economy of Bangladesh in recent times has created a significant need for energy. Consequently, the increasing demand for power generation has led Bangladesh to become more reliant on fossil fuels. This paper highlights the current situation of the power sector in Bangladesh, proposes practical steps that can be taken to tackle the increasing energy demands and discusses the current state of research taking place in Bangladesh regarding the development of photovoltaic solar cells and the potential for thin-film solar cells to effectively harness solar energy. The use of different kinds of plasmonic metal nanoparticles (NPs) such as core-shell NPs, NP dimers made of metallic alloys and hybrid bow-tie shaped NPs with thin-film solar cells are discussed. These nanoparticles are found to significantly improve the efficiency of thin-film solar cells. The societal, environmental, and health impact of shifting from traditional fossil fuel-based energy resources towards harnessing renewable energy, primarily solar energy using thin-film solar cells is also discussed. The paper concludes with a discussion on the economic sustainability of using such proposed high efficiency thin-film solar cells so that such technologies may help lead Bangladesh towards a cleaner, greener and more secure future.*

Keywords *– Bangladesh, plasmonics, renewable energy, solar cells, thin-film solar cells.*

1. INTRODUCTION

Bangladesh has recently emerged as a country with a thriving economy with one of the highest gross domestic product (GDP) growth in 2019 [1]. It is expected that this growth will continue and so the demand of power will increase exponentially. Unfortunately, Bangladesh is still predominantly dependent on fossil fuels to produce electricity. This dependency will create major problems as the natural gas reserve in Bangladesh is estimated to dry out by 2026, as reported by British Petroleum (BP) [2] and the severe impact on the environment of the fossil fuel will make the situation even more difficult.

Solar energy harnessed by photo-voltaic (PV) devices has the potential to address the problem as it provides a greener alternative to the traditional fossil fuels and its cost can be compensated over an extended period of time as it requires almost no cost after installation. Solar energy is abundant in nature and Bangladesh is particularly blessed with a suitable geographic location to harness solar energy for energy applications in large industrial scales [3].

However, two of the major challenges of current photovoltaic (PV) technology is the relatively high cost of production, installation and the relatively low energy conversion efficiency of PV devices such as solar cells. Commercially available solar cells have an efficiency that is less than 30% [4]. It is absolutely crucial to reduce the cost of the solar cell and increase solar cell efficiency in order to have large scale implantation in Bangladesh. It is observed that a significant portion of the cost of a solar cell made of crystalline silicon (Si) is the material cost of Si itself as it comprises almost 40% of the total cost of a solar cell [5]. Thin-film solar cells (TFSC) have the potential to reduce this cost significantly as it uses a very thin layer of Si (not more than 3 μm) compared to 1st generation solar cells (substrate thickness around 180 μm) and thus saves a lot of the expensive bulk material [6]. However, this reduction of material also reduces the volume of the absorbing layer and thus the efficiency (*i.e.*, electricity generation capacity) is also reduced. To increase the light absorption and current generation efficiency of TFSCs, different light trapping technologies such as anti-reflection coating, surface texturing *etc.* have been studied [7]. Among them, the usage of various metallic nanoparticles (NPs) has shown favorable results in increasing the opto-electronic performance of solar cells through harnessing the unique phenomenon of surface plasmon resonance (SPR) [8]. These metal NPs (*e.g.*, silver, gold, aluminum, copper, *etc.*) are characterized by localized surface plasmon resonance (LSPR) modes that come into play when these nanostructures are excited by sunlight (*i.e.*, stimulated by an incident electromagnetic radiation). This leads to increased light absorption and scattering by such metal NPs (called plasmonic metal NPs) at certain resonant frequencies (or wavelengths) [9], [10]. These plasmonic metal NPs can be coupled to solar cells to increase the light absorption and current generation efficiency of such "plasmonic" solar cells [10], [11].

Along with homogenous metallic NPs, various hybrid NP systems have shown promising results in significantly increasing solar cell performance [12]-[14].

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Recent studies highlight a number of such hybrid nanostructures that include: (i) NPs consisting of a plasmonic metal core that is surrounded by a thin dielectric/insulating shell layer; (ii) single or multiple "plasmonically coupled" metal NPs made up of alloys of different plasmonic metals; (iii) hybrid bow-tie shaped NPs that can be used to confine light into a small region on the surface of the solar cells where spherical metal NPs can be selectively placed to significantly enhance the TFSC performance. All these techniques contribute to significantly improve light absorption and current generation efficiency of the solar cell. Thus such "plasmonic solar cells" with a higher current conversion efficiency can lead to fewer solar cells needed to produce a specified amount of electricity, and thus potentially significantly reducing the price and increasing the accessibility of the "green energy" in developing nations like Bangladesh.

2. PRESENT SITUATION AND PROSPECT OF SOLAR ENERGY IN BANGLADESH

2.1 Current State of the Power Sector and Solar Energy Potential of Bangladesh

The majority of electrical power generated is through the use of non-renewable energy sources like natural gas and other fossil fuels. With the rising energy requirement than ever before, as Bangladesh strives towards her development goals by opening new industries in different sectors, providing a reliable electrical energy supply is of the utmost priority. It is of critical importance to highlight, analyze, and predict the current trends of electrical energy generation in Bangladesh. Figure 1 highlights the current electric energy generation capacity sorted using different types of resources from 2018-19 [15]. From Figure 1, it can be clearly observed that the overwhelming generation of electricity depends on the use of non-renewable energy sources (92.51%) and renewable energy generation makes up a very small percentage (1.37%) in the total generation capacity. For the year of 2019 in Bangladesh, electrical generation capacity using gas as the fuel accounted for 57.36% (10877 MW) of the total installed generation capacity followed by oil (furnace oil and diesel) with a percentage of 32.239% (6140 MW), imported power with 6.12% (1160 MW), coal with 2.76% (524 MW), hydro with 1.21% (230 MW) and lastly solar PV which only accounted for 0.16% (30 MW) of total generation capacity [15]. The current annual production of gas in Bangladesh is at 0.97 Tcf (trillion cubic feet) (2018) with 11.47 Tcf of reserves remaining [16]. Considering the yearly growth and production rate, natural gas reserves in Bangladesh will last up to 2026 [17]. In order to tackle this problem, coal generation power plants are expected to play a key role in power generation in Bangladesh [18]. This can bring about adverse effects on the environment, and decrease the already low air quality in the country. In 2019, Dhaka city has repeatedly been ranked as the city with the worst air quality, with an air quality index (AQI) score ranging from 242 to 252 [19].

The geographical location of Bangladesh gives it a distinctive advantage if PV solar cells can be used to harness solar energy for electricity generation. This is because Bangladesh has roughly 300 days a year with an average of 7 to 10 daylight hours with an average Global Horizontal Irradiance of 5 kWh/m^2 in these days [22]. A study conducted estimates that the total grid-connected solar PV potential in Bangladesh could be up to 50 GW [20], which is many folds above the current and even future energy demands of Bangladesh. Hence, among the different forms of renewable energy sources available, solar energy has the highest potential and feasibility for energy production in Bangladesh and can potentially replace fossil fuels in the future to meet the country's energy demands.

Currently, PV solar cells account for a very small percentage in generation capacity for the national supply grid in Bangladesh (0.16%) [15]. However, there has been a growing market for PV cells in the form of microgrids. Despite the relatively high cost of PV solar cells, it has successfully been adopted for generating electricity in rural areas. These rural PV solar systems are also referred to as microgrids (small electrical grids to supply electricity in places where the national grid cannot reach). Rural areas in Bangladesh and most other developing (or third-world countries) still lack access to reliable electricity which impedes socio-economic development and growth in these areas [21].

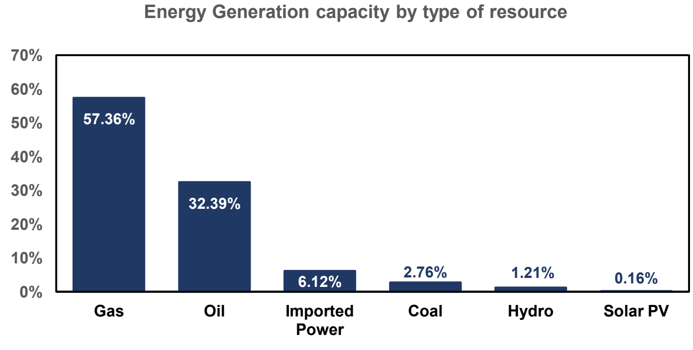

Fig. 1. Energy generation capacity of Bangladesh in 2018-2019 by type of resource [15].

2.2 Current Research and Development Work on Solar-Cells in Bangladesh

Significant efforts have been made in theoretical and practical research and development (R&D) work based on PV cells and solar energy in Bangladesh. A significant portion of these works directed their focus on the development of rural electrification, local transportations, *etc.* Research groups also focused their study on the improvements of PV cells and modules, which will help people both in Bangladesh and globally. Improvements of critical modes (oscillatory stability) within the power system can be achieved via the integration of PV systems to the current power system [23]. Additionally, replacing the existing grid with a smart grid with PV integration can minimize the power shortage problem in Bangladesh [24]. Unlike the conventional solar tracking algorithms and techniques, Ahmed and Rony (2014) suggested a sensor-less and simple mathematical algorithm that uses linear quantization techniques to derive the sun's optimal azimuth and altitude that can be used to track the sun [25]. Similar work has been done to determine the optimum angle for maximum incident power under the climatic conditions of Bangladesh [26]. Later, an idea of using reflectors (fixed directed mirrors or aluminum foils) to concentrate sunlight onto PV panels was proposed by Ahmed *et al.* (2014), so that each of the panels receives more power individually [27]. Furthermore, Hasan *et al.* (2018) propound the use of proton exchange membrane fuel cell (PEMFC) with an upgraded PV system to solve black out problems in base transceiver station (BTS) at telecom sites in Bangladesh [28].

The use of plasmonic NPs to enhance the performance of TFSCs has also gained traction in Bangladesh over the last few years. Works have been done towards increasing the opto-electronic performance of TFSCs using various NPs (Ti and Pt) placed on top of an ARC (anti-reflection coating) or spacer layer (TiO_2) [29]. The use of textured surfaces like back reflectors, ring shaped apertures and gratings have been investigated to explore their light trapping and guiding properties [30], [31]. The possibility of integrating plasmonic nanostructures (Au and Ag) of various shapes with organic solar cells has also shown potential towards increased light absorption compared to basic organic solar cells [32].

2.3 Current Thin-film Solar Cell (TFSC) Technologies

Research has been conducted on various methods through which the opto-electronic performance of thin-film solar cells can be increased, namely, utilizing a metal layer to create a reflective surface on the back surface of the solar cell, employing nano-pyramidal surface textures on the front and back of the solar cell, and using plasmonic metal NPs [10], [33], [34]. The difference in refractive index between silicon and air is very high which leads to the reflection of a significant portion of the incident radiation from the interface of the two mediums (silicon and air), which is known as strong Fresnel reflectivity [35], [36]. To reduce this phenomenon, the use of anti-reflection coatings (ARC) on thin-film solar cells have been proposed [37]. While these ARCs improve the performance of thin-film solar cells, their fabrication is complex and costly due to the expensive equipment involved and the precise control that is required during synthesis, thereby increasing the cost of fabrication substantially [38]. Attempts have been made towards increasing the opto-electronic performance of solar cells using nanostructures like nanopillars, which reduces the Fresnel reflectivity by acting as an additional medium between air and the substrate [39]. But this method leads to an increase in surface recombination and a reduction in the amount of charge carries which ultimately contributes to less current generation [38]. Approaches towards employing surface textures like surface grating has been reported to aid in increasing the optical absorption of solar cells. However, these surface textures are usually fabricated on the micron scale (10-15 microns in thickness) which is considerably large when comparing with the thickness of TFSC and is therefore not suitable for use in 2nd generation TFSC [40]. Furthermore, surface texturing using NPs with high aspect-ratio results in higher surface defects thus increasing the chances of recombination of electron-hole pairs [41].

2.4 Plasmonic Thin-film Solar Cells (TFSCs)

A promising method of increasing the performance of TFSCs is using the LSPR property exhibited by plasmonic metal NPs when incident electromagnetic radiation (*e.g.*, sunlight) matching the plasmon resonance wavelength excites the metal NPs [42]. This research group has conducted extensive computational studies based on Finite-Difference Time-Domain (FDTD) simulations of the effect of using different plasmonic metal NPs and nanostructures to enhance the opto-electronic performance of thin film "amorphous Silicon" (a-Si) solar cells [9]-[13]. The results from these studies showed that TFSCs coated with a layer of homogenous metal NPs exhibit increases in the absorption of light into the solar cell substrate and subsequently results in higher photocurrent generation. It was also shown that the extent of light absorption into the solar cell substrate was influenced by the size and shape of the plasmonic metal NPs [10], [11]. The next sections outline some of the recent research that was conducted by this research group investigating the use of different plasmonic hybrid/multi-particle NP structures such as core-shell NPs, plasmonic NPs made of alloys of different metals and hybrid bow-tie shaped NPs to increase the performance of TFSCs.

3. PLASMONIC NANOSTRUCTURES AND CONFIGURATIONS

3.1 Simulation Setup and Parameters

Commercial grade simulation software such as FDTD Solutions and DEVICE developed by the Lumerical Inc. were used by this research group to perform the simulations with the following configurations and parameters:

Optical Absorption Enhancement Factor (g): Optical Absorption enhancement factor is the ratio of the power absorbed by Si TFSCs with the presence of the different types of plamonic NP and the power absorbed by Si TFSCs without any NP [12]. This unitless ratio gives an idea of how much more or less light is absorbed by the absorbing layer of the solar cell due to the effect of the plasmonic NPs. In the simulations, two detectors (power and field monitors) were placed at two different locations in the absorbing substrate of the solar cell, and the difference of the power recorded between the two detectors was used as the power of the light absorbed in the TFSC. Industry standard test conditions (STC) like temperature (300K) and air mass coefficient (AM 1.5G) were maintained for all simulations.

Short circuit current density (J_{SC} in A/m^2): Short circuit current density gives the idea about how much electricity is produced within a specific region of a solar cell and is calculated as discussed previously [12]-[14].

Open circuit Voltage (V_{oc} in volts): The open circuit voltage was determined to calculate the normalized open circuit voltage and output power of the solar cell and is calculated as discussed previously [12]-[14].

Fill factor (unitless): The fill factor (FF) determines the maximum output power capacity of a photovoltaic cell and as such is used to calculate the output power of a photovoltaic cell. It is the ratio of the power at maximum power point by the product of short-circuit current (J_{SC}) and open circuit voltage (V_{oc}).

Analysis of Electromagnetic Near Fields (NF): The near-field enhancement is the ratio of the electro-magnetic (EM) field distribution in a TFSC in the presence of the plasmonic NP and in a TFSC without the presence of the plasmonic NP [12]-[14]. It is a pictorial representation of the enhancement of the EM field in the vicinity of the plasmonic NP when incorporated in the TFSC.

3.2 Studies of plasmonic core-shell nanoparticles in TFSCs

Apart from homogenous plasmonic NPs (made of a single metal), various composite plasmonic NPs (made of two or more materials) such as core-shell NPs (where the core is the inner material and shell is outer layer material) has shown promising results in improving TFSC performance. From the early 90s, researchers have started to synthesize multilayer NPs to improve and tune their optical and chemical properties based on different applications. Subsequently these NP got coined into the term of 'core-shell' [43], [44]. Core-shell NPs have some distinctive advantage due to the nature of their composition. Figure 2 shows a composition of core-shell NP where the core is made of metal and shell is made of a dielectric (insulating) material.

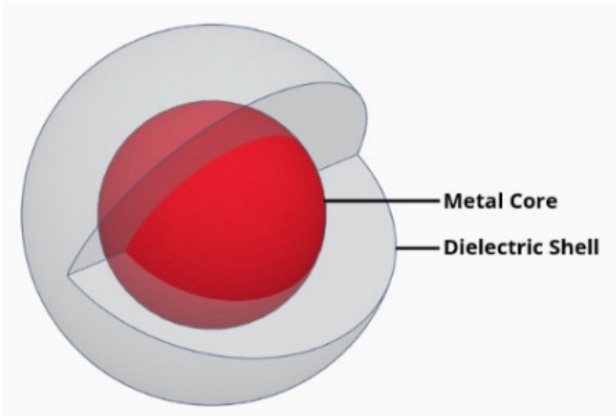

Fig. 2. Meta core-dielectric shell nanoparticle composition.

3.2.1 Advantages of using core-shell NP in photovoltaic applications

For PV applications, metal core and dielectric shell NPs are particularly suitable due to its metal-dielectric interface which can support surface plasmon resonance (SPR) even when embedded inside the light absorbing substrate of the solar cell [9]. So, with core-shell (metal core and dielectric shell) NPs, the particles can be placed on the top as well as inside of the absorbing substrate. Moreover, the dielectric shell can provide much needed chemical and electrical isolation which is crucial for the stability of the NPs as the metallic NPs show the tendency to get oxidized easily [12]. Additionally, by changing the material (*i.e.*, metal), size of the core, thickness of the shell layer, and shape of the particle, the amount of light absorbed and scattered by these plasmonic metal NPs can be tuned as well as the wavelength of the plasmon resonance peak. The high permittivity of the shell provides electrical isolation which is particularly helpful for the metallic core to avoid becoming a new center of electron-hole recombination while still providing LSPR [45]. Furthermore, a new configuration was proposed namely 'sandwich configuration' that comprises both homogenous and core-shell NPs where the core-shell NP is embedded inside the absorbing substrate and a homogenous metallic NP is placed on the top of the substrate, as shown in Figure 3 [12]. It is observed that this particular configuration can significantly increase the performance of the TFSC.

3.2.2 Results and Analysis of Using Core-Shell NP

Figure 4 shows the optical absorption enhancement (g) and short-circuit current density (J_{sc}) comparison between different nanostructure configurations with respect to that of a bare silicon substrate. The percentage increases outlined in Figure 4 are all done with respect to the bare silicon substrate (traditional solar cells that contains no plasmonic NPs). The inset outlines the two parameters considered. It can be seen that highest optical absorption enhancement (g) (42.30%) and J_{sc} (36.33%) is observed for sandwich configuration. This percentage increase corresponds to a g value of 213.45 and a J_{sc} value of 9.321 mA/cm^2, when compared to that of a bare Si substrate with no plasmonic NPs (g=150, J_{sc}=6.837 mA/cm^2) [12]. The percentage increase of other performance parameters such as V_{oc} (0.66%), FF (0.14%) and efficiency (36.4%) were also found to be the highest for sandwich configuration, when compared to the bare Si substrate [12]. This means 42.30% more light will be absorbed by the Si absorbing layer and 36.33% more current will be produced and 0.66% greater open-circuit voltage difference will be generated resulting in 0.14% increase in the FF, which ultimately translates to a 36.4% increase in efficiency exhibited by the Si solar cell embedded with the sandwich configuration of the NPs in comparison with bare Si solar cell. This can lead to potential overall improvements in the opto-electronic performance of the solar cell. It is to be noted that the efficiency values presented are percentage increase in efficiency of the different plasmonic metal NP coupled Si solar cells when compared to a bare Si solar cell. This might not reflect the true efficiency of any real device because the p-n junction, doping concentration and contacts were not considered in the simulations.

Figure 5 shows the optical near-field enhancement image for the “sandwich” configuration of the core-shell NP embedded inside the Si absorbing layer and the homogeneous NP on top of the Si absorbing layer of a TFSC. It is seen that strong EM field enhancement is occurring in the vicinity of NP on the top and also the core-shell NP inside the substrate as seen by the substantial regions in yellow and red colour that represents EM field enhancements of well over 10-fold compared to a bare Si substrate.

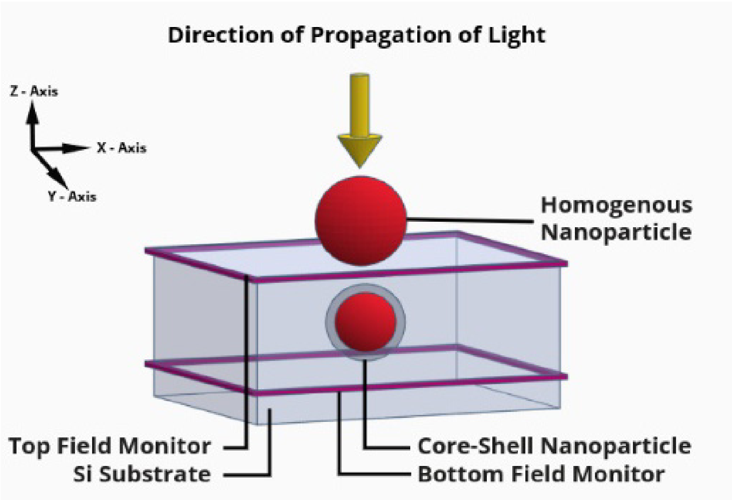

Fig. 3. Simulation setup showing frequency domain field and power monitor placements for “sandwich” configuration of homogenous NP and core-shell NP coupled to a solar cell.

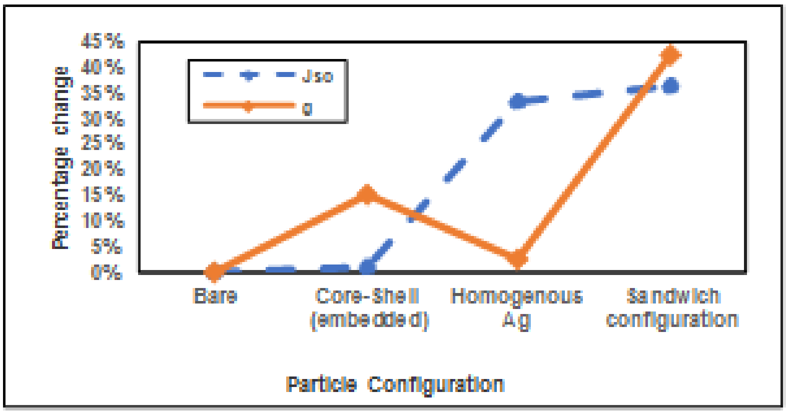

Fig. 4. Optical absorption enhancement (g) and short-circuit current density (J_{sc}) comparison between different nanostructure configurations with respect to that of bare Silicon substrate [12].

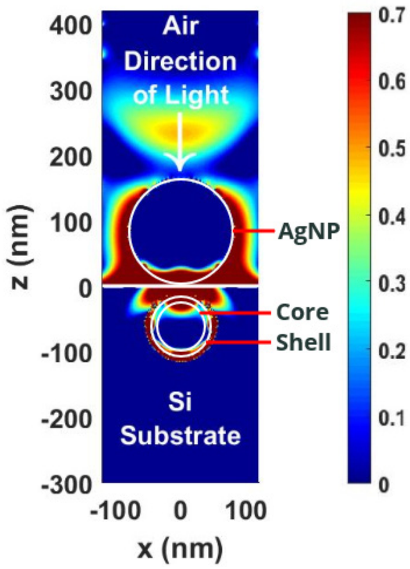

Fig. 5. Optical nearfield enhancement as a result of incorporating homogenous plasmonic NP on top of the substrate and a plasmonic core-shell NP embedded inside the substrate, in "sandwich" configuration.

3.3 Studies of Plasmonic Alloy Bimetallic Nanoparticles in TFSCs

The second set of recent investigations conducted by this research group includes FDTD simulation studies by placement of two plasmonic NPs placed side by side with a clearly defined inter-particle spacing whereby the material of the NP is composed of either an alloy (comprising a mixture of more than one kind of metal) or a homogeneous metal. These two metal NPs are placed on top of a Si absorbing layer of a TFSC as shown in Figure 6. A hybrid bimetallic NP system represents two metallic NPs considered as a single entity [46]. Alloys are created when two or more different metals are combined to form a new material by independently varying the composition of each metal in the alloy [47].

3.3.1 Motivation of alloy bimetallic for solar cell application

The justification for using alloy NPs was to be able to harness the favourable optical and chemical properties of different plasmonic metals within one NP and thus utilize a broader section of the solar irradiance spectrum to enhance the performance of TFSCs [14]. In some instances, two different metallic NPs (of either alloys of single metal) were placed next to each other to better harness multiple wavelengths of the solar spectrum as well as attaining the most stable condition in terms of chemical reactivity and optimized optical properties. It is well known that plasmonic coupling can occur efficiently between neighbouring metal NPs thus leading to strong optical absorbing properties. Varying the combination of metal, composition of each metal in a NP, interparticle distance between metals in bimetallic entity showed that multiple regions of the solar irradiance spectrum has been utilized which were previously not possible and significant enhancements were observed in the Si TFSCs modified by such bimetallic hybrid NPs systems [14].

3.3.2 Results and analysis of using alloy bimetallic NPs with Solar Cells

The graphical representation in Figure 7 shows the percentage change for optical absorption enhancement (g) and short-circuit current density (J_{sc}) for different NP configurations that were incorporated on top of the Si absorbing layer of TFSCs. From the simulation results plotted in Figure 7, it can be observed that an alloy bimetallic NP configuration comprised of two alloy NPs in close proximity where each of the alloy NPs consist of Gold (Au) -the inert metal, with composition of 10% mass and Aluminium (Al) –chemically instable yet with excellent optical properties, with composition of 90% mass. There is a significant change in g (17%) and J_{sc} (25%) for single alloy NP in comparison to bare Si configuration. The alloy-alloy bimetallic/ dimer NP system when coupled to the Si absorbing layer of a TFSC showed the maximum increase in the values for g (22%) and J_{sc} (51%) in comparison to bare and single alloy configuration [14]. A similar trend is also observed for V_{oc} (0.43%), FF (0.09% increase) and efficiency (53% increase). This significant percentage change is observed when two alloy NPs are placed in the bimetallic/dimer configuration due to the plasmonic hybridization [14].

3.4 Studies of Bow-tie Hybrid Nanoparticles in TFSCs

In order to observe and improve the optoelectronic performance of the thin-film silicon (Si) photovoltaic cells, recently this research group performed computational studies on the use of different configurations of hybrid bowtie-based plasmonic metallic nanostructures [48], [13]. Figure 8 shows the bow-tie configuration where the hybrid nanostructures were designed with two triangular cross-sectioned pyramidal nanostructures (equilateral triangle cross-section in x-y plane) and one spherical NP in such a way that both of the triangular NPs were facing each other with one of the apex of their vertices and a spherical NP placed in between. These nanostructures were studied by varying the side lengths and pitch sizes of the triangular NPs, while keeping their height of the triangular NPs and the diameter of the spherical NPs constant.

The main goal of this study was to design pyramidal NPs that can concentrate a significant portion of the incident light (*e.g.*, sunlight) between their apex points (like a magnifying glass concentrating sunlight at a specific point on a paper). The design involved placing a single spherical NP at the point where the light from the sun was concentrated by the triangular NPs. This is done to expose the spherical NP to a maximum amount of incident light (both the direct light hitting the spherical NP and the light concentrated by the triangular NPs). When there is significant spectral overlap between the plasmon resonance of the spherical NP and the scattering resonance of the pyramidal NPs, a high concentration of the incident light occurs in and around the hybrid NPs which can then be plasmonically coupled to the absorbing (Si) substrate of the TFSC below. Increased absorption of this incident light by the absorbing Si substrates can lead to increased electron-hole pair production in the absorbing layer.

These studies involved designing hybrid plasmonic nanocomplexes comprised of: (i) two Al triangular and one Ag spherical NPs, which was named Al-Ag-Al nanocomplex and secondly, (ii) two Ag triangular and one Au spherical NPs, which was named Ag-Au-Ag nanocomplex. The idea was to match/overlap the maximum scattering intensity of the plasmonic triangular NPs with the plasmon resonance (extinction spectra) of the plasmonic spherical NPs that are placed in between the triangular NPs [13]. Figure 9 highlights the percentage increase in J_{SC} values of different NP configuration obtained from FDTD simulations. The results from the graph show that these hybrid bowtie-based plasmonic nanostructures coupled to Si substrate show superior performance in the light coupling efficiency and electrical current generation within the Si absorbing layer of the TFSCs when compared to the bare Si substrate and Si substrate coupled to only spherical NPs[13], [48]. Among the two bowtie nanocomplexes considered, the superior results were obtained with Al-Ag-Al nanocomplex in J_{SC} (5.81% increase), V_{OC} (4.53% increase), FF (0.87% increase), and efficiency (11.58% increase).

It is to be noted that the recent plasmonic solar cell research of this research group described above are simulation results, and steps are being taken to practically implement such “plasmonic solar cells” for testing. It is expected that fabrication of such plasmonic solar cells will not pose a major technological challenge due to the advanced stage of fabrication technology of Si due to its widespread use in the electronics industry. In general, wet chemistry method can be used to manufacture metallic NPs while Stöber process has been shown to be capable of synthesizing dielectric shell layers [49]. The NPs can be embedded by depositing a silver film through thermal evaporation, followed by thermal annealing in nitrogen to create NPs, while the substrate layers (above and below the NPs) can be created through plasma enhanced chemical vapor deposition [50].

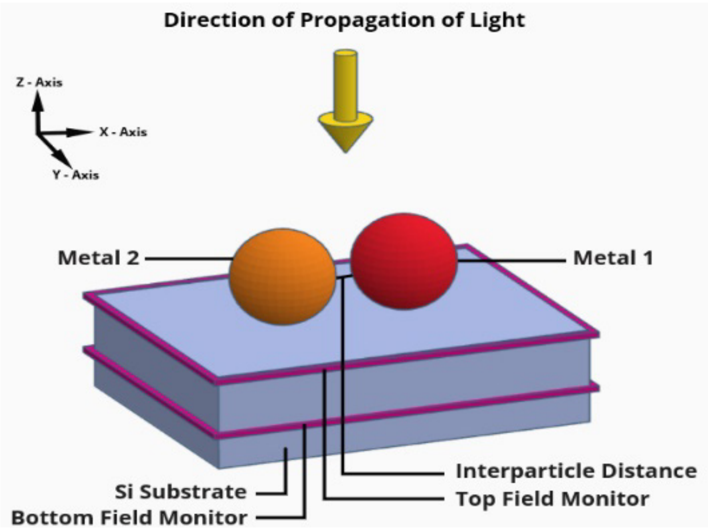

Fig. 6. Simulation schematic showing the plasmonic alloy bimetallic nanoparticle configuration.

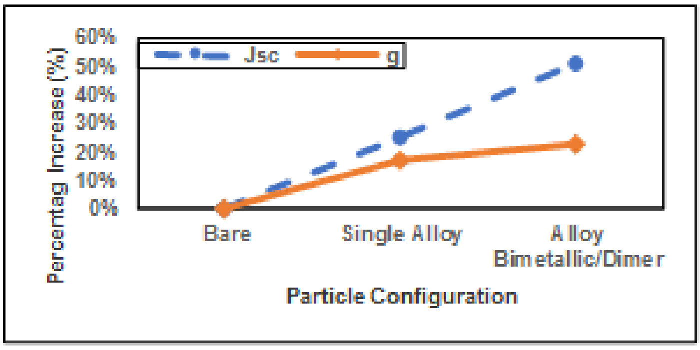

Fig. 7. Percentage change comparison for optical absorption enhancement factor (g) and short circuit current density (J_{sc}) for different nanoparticle configurations [14].

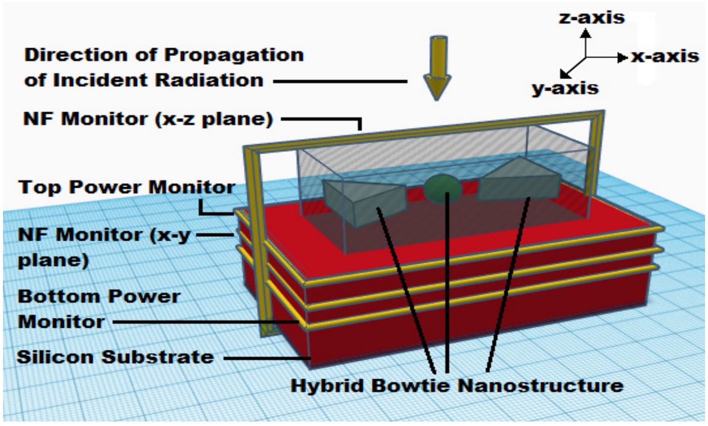

Fig. 8. Simulation setup for optical absorption enhancement and near-field analysis of the bow-tie hybrid nanostructure.

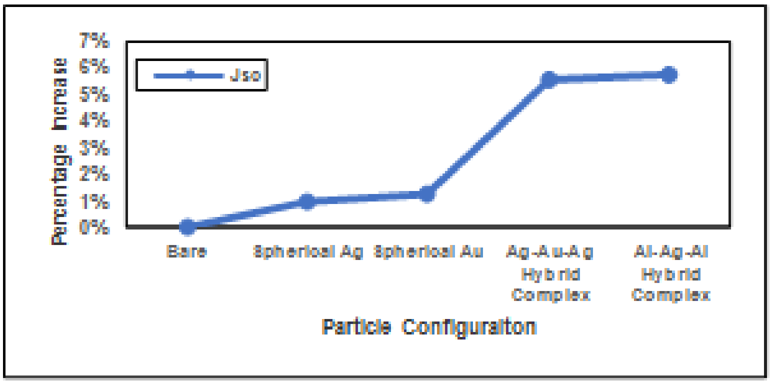

Fig. 9. Percentage change comparison for short-circuit current density (J_{sc}) for different nanoparticle configurations [13].

4. IMPACT OF HIGHER EFFICIENCY THIN-FILM SOLAR CELLS ON SOCIEY, HEALTH AND CULTURE IN BANGLADESH

The continuous rise in the quantity of greenhouse gases (GHG) have led to an increase in the Earth's average temperature, the rise of sea-levels and is causing global climate change. A significant source for GHGs can be attributed to power generation plants (mainly fossil fuel powered plants) operated around the world [51]. According to 'Global Climate Risk Index 2020' report published by Germanwatch, in the period from 1998 till 2018, Bangladesh ranked seventh in the long-term climate risk index. The power generation plants are responsible for 52% of carbon dioxide (CO_2) emissions of the country [52]. If emission levels from these plants are not brought down, adverse environmental, health and security issues may arise in Bangladesh. With the current rate of use of natural gas for energy generation and plans to further increase usage to meet the increased energy demands, natural reserves of gas are projected to be depleted by the next decade [17]. While it may be true that gas-fired power plants are more environmentally friendly than coal-fired power plants, due to diminishing natural reserves [17], substantial investments should be made in the renewable energy sector to mitigate the health hazards and environmental pollution created due to the use of fossil fuels.

The operation of solar panels during their lifetimes (raw materials extraction and manufacturing) produce several magnitudes lower CO_2 emissions than fossil fuel power plants [53]-[56]. Also, no harmful pollutants are released during its operation. Second (2^{nd}) generation or thin-film solar cells (TFSCs) require a lower amount of materials than crystalline solar cells and so TFSCs are more ecologically friendly than traditional soar cells. Due to reduction of thickness of the light absorbing layer of TFSCs, they also tend to be elastic, increasing the flexibility in the location for deployment. This can lead to reduction in space requirement for deployment and more robust structures to withstand adverse environmental conditions like cyclones and nor'westers that are common in Bangladesh. Increasing the efficiency of TFSCs by the proposed incorporation of different plasmonic metal NPs can potentially reduce the cost and amount of PV cells required to power specific rural, urban or industrial areas of Bangladesh.

In order to tackle the problems of power generation (of Bangladesh) stated throughout this paper, the government would be advised to follow in the steps of countries (Germany, Iceland, Kenya, Morocco, China, U.S.A. *etc.*) that have been successful in adopting renewable energy practices [57]. The policies used to realize their energy goals need to be scrutinized, evaluated and possibly be modified to suit the current situation (socio-economic and political) of Bangladesh. Extreme remote and rural areas in Bangladesh (*e.g.*, Chittagong Hill Tracts) still have no access to electricity (5%) due to the high cost and challenges involved in connecting these remote areas to the national grid [58]. Hence, using stand-alone power systems (*e.g.*, solar homes) or using microgrids appears to be one of the practical solutions to deliver electricity to these areas. Lack of access to electricity in remote areas of the country have impeded the development and growth in these areas and is a hurdle that needs to be overcome for Bangladesh to fully transition into a developing country.

Facilitating electricity in these rural areas can bring about development and growth. It can also lead to the development of communication pathways (cell phone towers, roads, radio, *etc.*), thereby connecting the remote populace to the rest of the country and the world (via the internet). It also works to reduce the feeling of alienation and neglect of the people living in such remote areas of Bangladesh (*e.g.*, indigenous minority tribes living in the hill tracts and the people living in the alluvial land areas) where it is almost impossible to have access to grid electricity. The proposed access to electricity will make such rural and minority communities feel as being accepted as a citizen with equal facilities as the vast majority of people living elsewhere in the country. This can prevent or discourage such estranged communities from indulging in terrorism and other illegal measures to express any form of dissent.

Efforts should not only be made to provide electricity to these remote and rural areas via microgrids but also the possibility of using such grids to provide electricity in areas which have an unreliable electrical connection (frequent outages, faulty transmission lines, *etc.*) should also be explored. The biggest hurdle in adopting PV solar panel technology is the high initial cost investment needed. The cost of these PV crystalline solar cells can be reduced substantially if TFSC technology is used. Increase in TFSC efficiency using the proposed plasmonic NPs can potentially further reduce the cost of operation and installation of the solar cells. Implementation of solar energy can give rise to a cultural movement and massive paradigm shift of the minds of the common people. Hence, Bangladesh can also have bright prospects to be a part of a multi-billion-dollar solar cell industry and become a market leader like it is in the ready-made garments (RMG) industry. This revolution can pave Bangladesh towards a greener and sustainable future because this will not only protect the environment and provide electricity but also create new employment opportunities for large number of people.

5. IMPACT OF HIGHER EFFICIENCY THIN-FILM SOLAR CELLS ON THE ENVIRONMENT AND ECONOMIC SUSTAINABILITY IN BANGLADESH

The majority of carbon dioxide (CO_2) emissions in Bangladesh (52%) can be attributed to the power sector [52]. Many countries have invested heavily in renewable energy sources to reduce their carbon footprint and meet their carbon goal according to the Paris Climate Agreement 2016. In 2018, 26.1% (26614 TWh) of the world’s electricity production was generated from renewable energy sources and globally, the new installed capacity of renewable sources was greater than the installed capacity of traditional sources and nuclear power combined [17]. Since 2008, the price for PV solar modules have gone down by a factor of about 5 [59], while their efficiency has been improved, making PV solar cells widely adopted globally for power generation.

According to PSMP (Power System Master Plan prepared by the Government of Bangladesh) 2016 [18], proposed plans to increase the generation capacity in Bangladesh point to an alarming scenario where the dependence of foreign imports of fuel for power generation would increase, thereby decreasing the energy security in Bangladesh and lead to an increase in the already high carbon dioxide emission (CO_2) from the power sector due to the increase in fossil fuel power plants. Adopting a scenario more geared towards the use of renewable energy sources such as PV solar systems would be better for the environment as PV solar systems have lower CO_2 emissions (approximately 40g CO_2 eq/kWh for PV systems compared to an approximately 1000g CO_2 eq/kWh for coal, 640g CO_2 eq/kWh for natural gas-fired combustion turbine (NGCT) and 460g CO_2 eq/kWh for natural gas-fired combined-cycle systems) [53]-[56]. This would also decrease the dependency on foreign imports of fuel (such as coal, natural gas) and therefore can potentially increase energy security in Bangladesh.

Traditional or 1st generation PV solar cells are the predominant type of solar cells that are available in the market. Crystalline (monocrystalline and polycrystalline) Si (with a typical thickness of the cut wafers of approx. 180 μm) makes up the bulk of the material used in these 1st gen cells and is the main contributor to the high price [60]-[62]. To find an alternative to using high quantities of Si, the 2nd generation of solar cells (also called TFSCs) were developed. The absorbing layer in TFSCs are usually only a few microns (μm) thick and so a considerable amount of expensive material can be saved in their fabrication. The primary focus of this paper is on enhancing the opto-electronic performance of a-Si (amorphous silicon) TFSCs by utilizing the plasmonic properties of different kinds of metallic nanostructures coupled to the solar cells. Potentially higher efficiency and thus lower amounts of expensive absorbing materials used can lead to more affordable solar panels and also can significantly reduce the amount of space needed to mount the solar modules. This can potentially lead more widespread adoption of renewable energy with significantly lower carbon emissions compared to fossil fuels and can also save much needed agricultural land for installing such solar panels on a large industrial scale.

For PV solar cells to become a major sustainable competitor in the power generation market, the materials involved in the manufacture of these cells must be abundant, affordable and have a much lower environmental impact than its traditional counterparts. Additionally, the engineering complexity of fabrication should be such that the costs associated should not be prohibitive for widescale deployment in developing countries like Bangladesh. Hence, the cost of one unit of electrical energy generated via PV systems must be equal to or lower than the cost of one unit of grid electricity. While 1st generation crystalline PV cells now cost much lower than they did in the past, it is still relatively expensive for widespread deployment and use in developing countries like Bangladesh. That is why extensive research is being done in developing efficient TFSCs (2nd generation cells) which are significantly cheaper than crystalline Si solar modules [63]. As with the advancement of technology, the price of solar electricity is getting lower but significant work remains to be done to reduce the price even further, for example, via the potential use of plasmonic nanostructures as described in this paper. Despite the relatively limited availability of raw materials (*e.g.*, Te, In, Ge, Cd, Ga, *etc.*) involved in fabrication of PV devices, the growth of TFSCs market should be sustainable to provide Terawatts of renewable energy by the mid-21st century [63].

6. CONCLUSION

This paper outlines the current state of the energy sector of Bangladesh and its challenges to meet the increasing energy demands resulting from thriving economic growth. It also underlines the extent of Bangladesh's reliance on fossil fuels and its ramification on the environment and society. Being fortunate to have favorable solar irradiance due to the geographic location, Bangladesh is well positioned to implement large a scale PV industry to address the current and future energy demands provided that the cost of PV cells can be reduced. To this end, thin-film solar cells have been proposed that require less absorbing material (*e.g.*, silicon) and thereby potentially reducing their fabrication cost. However, due to the reduction of the absorbing layer, the light absorption and current generation efficiency of TFSCs decreases. To overcome this challenge, the use of plasmonic metal nanostructures like core-shell NP, alloy-bimetallic NP and, hybrid-bowtie NP configurations to increase TFSC efficiency have been outlined. The optimal configuration of each NP configuration mentioned above has been shown (via numerical simulations) to significantly increase the opto-electronic performance of TFSCs. The proposed benefit of such higher efficiency combined with low cost of these cells can facilitate both small and large scale deployment of TFSCs. This in turn can aid in bringing electricity to remote areas and rural communities of the country that are outside the current coverage area of the national grid. This in turn can aid in significant infrastructure development, education improvement, economic growth, clean environment and better health of the people thus fulfilling the promise of a "golden" Bangladesh.

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REFERENCES

[1] Asian Development Bank, 2020. *Bangladesh: Economy*. Retrieved from the World Wide Web: https://www.adb.org/countries/bangladesh/economy.

[2] Tetra Tech ES, Inc., 2020. *Challenges in the development of variable renewable energy in Bangladesh*. Arlington, VA: USAID.

[3] Kannan N. and D. Vakeesan, 2016. Solar energy for future world: A review. *Renewable and Sustainable Energy Reviews* 62: 1092-1105.

[4] Green M.A., Dunlop E.D., Levi D.H., Hohl Ebinger J., Yoshita M. and Ho -Baillie

A.W., 2019. Solar cell efficiency tables (version 54). *Progress in Photovoltaics: Research and Applications* 27(7): 565-575.

[5] Catchpole K.A. and A. Polman, 2008. Plasmonic solar cells. *Optics Express* 16(26): 21793-21800.

[6] Meier J., Vallat-Sauvain E., Dubail S., Kroll U., Dubail J., Golay S., Feitknecht L., Torres P., Fay S., Fischer D. and Shah A., 2001. Microcrystalline/ micromorph silicon thin-film solar cells prepared by VHF-GD technique. *Solar Energy Materials and Solar Cells* 66(1-4): 73-84.

[7] Ferry V.E., Sweatlock L.A., Pacifici D. and Atwater H.A., 2008. Plasmonic nanostructure design for efficient light coupling into solar cells. *Nano Letters* 8(12): 4391-4397.

[8] Hägglund C., Zäch M., Petersson G. and Kasemo B., 2008. Electromagnetic coupling of light into a silicon solar cell by nanodisk plasmons. *Applied Physics Letters* 92(5): 053110.

[9] Ashraf N.I., Shaky M.M., Rifat R.A. and Chowdhury M.H., 2019. Use of plasmonic metal core-dielectric shell composite nanoparticles embedded within the absorbing layer to enhance the efficiency of thin-film solar cells. In *Proceedings of the 2019 IEEE Region 10 Symposium (TENSYMP)* 479-484.

[10] Choudhury S.A. and M.H. Chowdhury, 2016. Use of plasmonic metal nanoparticles to increase the light absorption efficiency of thin-film solar cells. In *Proceedings of the 2016 IEEE International Conference on Sustainable Energy Technologies (ICSET)* 196-201.

[11] Choudhury S.A., Nawshin N. and Chowdhury M.H., 2017. Influence of particle shape on the efficacy of plasmonic metal nanoparticles to enhance the energy conversion efficiency of thin-film solar cells. In *Proceedings of TENCON 2017-2017 IEEE Region 10 Conference* 2393-2398.

[12] Arefin S.M.N, Islam S., Fairooz F., Hasan J., and Chowdhury M.H., 2020. Computational study of “sandwich” configuration of plasmonic nanoparticles to enhance the optoelectronic performance of thin-film solar cells (Article in Press). In *Proceedings of the* 2020 *IEEE Region 10 Symposium (TENSYMP)*.

[13] Shaky M.M. and M.H. Chowdhury, 2019. Use of novel hybrid plasmonic nanoparticle complexes to increase the efficiency of thin-film solar cells. In *Proceedings of the TENCON 2019-2019 IEEE Region 10 Conference (TENCON)* 203-208.

[14] Fairooz F., Hasan J., Arefin S.M.N., Islam S., and Chowdhury M.H., 2020. Use of plasmonic nanoparticles made of aluminum and alloys of aluminum to enhance the optoelectronic performance of thin-film solar cells (Article in Press). In *Proceedings of the* 2020 *IEEE Region 10 Symposium (TENSYMP)*.

[15] BPDB, 2019. *Annual Report 2018-19*. Power Division, Misinstry of Power, Energy and Mineral Resources, Government of Bangladesh.

[16] PETROBANGLA, 2019. *Annual Report 2018*. Energy and Mineral Resources Division, Misinstry of Power, Energy and Mineral Resources, Government of Bangladesh.

[17] Dudley B., 2019. *BP Statistical Review of World Energy*. London, UK: BP Statistical Review.

[18] PSMP, 2016. *Power System Master Plan 2016*. Power Division, Misinstry of Power, Energy and Mineral Resources, Government of Bangladesh.

[19] IQAir, 2020. *Dhaka Air Quality Index (AQI) and Bangladesh Air Pollution - Airvisual*. Retrieved from the World Wide Web: www.iqair.com/us/bangladesh/dhaka.

[20] Mondal M.A.H. and M. Denich, 2010. Assessment of renewable energy resources potential for electricity generation in Bangladesh. *Renewable and Sustainable Energy Reviews* 14(8): 2401-2413.

[21] Kabir E., Kim K.H. and Szulejko J.E., 2017. Social impacts of solar home systems in rural areas: A case study in Bangladesh. *Energies* 10(10): 1615.

[22] Mohammad H., 2013. Achieving sustainable energy targets in Bangladesh. *UN Chronicle* 52(3): 36-39.

[23] Shah R. and N. Mithulananthan, 2009. Interconnection of PV based generator and its impact on Bangladesh power system stability. In *Proceedings of the 2009 1st International Conference on the Developments in Renewable Energy Technology (ICDRET)*. Dhaka, Bangladesh, 17-19 December. IEEE.

[24] Ahmed M., Parvez M. S., Hossain M.M., Pal A.K., Hassan H.M.I., and Iqbal M.S., 2015. Minimization of power shortage by using renewable solar energy through smart grid, perspective: Bangladesh. In *Proceedings of the 2015 3rd International Conference on Green Energy and Technology (ICGET)*. Dhaka, Bangladesh, 11-11 September. IEEE.

[25] Ahmed A. and M.I. Rony, 2014. Towards a novel sensorless dual axis solar tracking algorithm for Bangladeshi PV modules. In *Proceedings of the 17th International Conference on Computer and Information Technology (ICCIT)*. Dhaka, Bangladesh, 22-23 December. IEEE.

[26] Paul S., Khan M.K.A., Adibullah M., and Anzum S.N., 2013. Determination of optimal angle for maximum power of a PV module under Bangladeshi climatic condition. In *Proceedings of the 2013 International Conference on Energy Efficient Technologies for Sustainability*. Nagercoil, India, 10-12 April. IEEE.

[27] Ahmed S., Mia M.M.A., Acharjee S., and Ansary M.A.A., 2014. More efficient use of photovoltaic solar panel using multiple fixed directed mirrors or aluminum foils instead of solar trackers in rural perspective of Bangladesh. *International Journal of Scientific and Technology Research* 3(4): 294-298.

[28] Hasan M.M., Hasan N., and Rahman M., 2018. Observation of fuel cell technology and upgraded photovoltaic system for rural telecom system in Bangladesh. *Bangladesh Army University of Engineering and Technology Journal* 2(2): 71-78.
[29] Mahmud T., Reja M.I., and Akhtar J., 2018. Photovoltaic performance analysis of plasmonic solar cell based on Ti and Pt nanoparticles and different spacer layer thicknesses. In *Proceedings of the 2018 International Conference on Computer, Communication, Chemical, Material and Electronic Engineering (IC4ME2)* 1-5. IEEE.
[30] Hossain M.I., Qarony W., Hossain M.K., Debnath M.K., Uddin M.J., and Tsang,Y.H., 2017. Effect of back reflectors on photon absorption in thin-film amorphous silicon solar cells. *Applied Nanoscience*, 7(7): 489-497.
[31] Islam Z. and M.Z. Islam, 2017, December. Plasmonic solar cell with annular apertures and Ag grating supporting fabry-perot modes. In *Proceedings of the 2017 IEEE International Conference on Telecommunications and Photonics (ICTP)* 259-262. IEEE.
[32] Islam M.Z., Snigdha F., and Hasan M.S., 2018, March. Plasmonically-enhanced absorption in organic solar cells with metal nanostructures. In *Proceedings of the 2018 9th International Renewable Energy Congress (IREC)* 1-5. IEEE.
[33] Winans J.D., Hungerford C., Shome K., Rothberg L.J., and Fauchet P.M., 2015. Plasmonic effects in ultrathin amorphous silicon solar cells: performance improvements with Ag nanoparticles on the front, the back, and both. *Optics Express* 23(3): A92-A105.
[34] Isabella O., Vismara R., Linssen D.N.P., Wang K.X., Fan S., and Zeman M., 2018. Advanced light trapping scheme in decoupled front and rear textured thin-film silicon solar cells. *Solar Energy* 162: 344-356.
[35] Lee C., Bae S.Y., Mobasser S., and Manohara H., 2005. A novel silicon nanotips antireflection surface for the micro sun sensor. *Nano Letters 5*(12): 2438-2442.
[36] Lee Y.J., Ruby D.S., Peters D.W., McKenzie B.B., and Hsu J.W., 2008. ZnO nanostructures as efficient antireflection layers in solar cells. *Nano Letters* 8(5): 1501-1505.
[37] Bouhafs D., Moussi A., Chikouche A., and Ruiz J.M., 1998. Design and simulation of antireflection coating systems for optoelectronic devices: Application to silicon solar cells. *Solar Energy Materials and Solar Cells* 52(1-2): 79-93.
[38] Chen H.C., Lin C.C., Han H.W., Tsai Y.L., Chang C.H., Wang H.W., Tsai M.A., Kuo H.C., and Yu P., 2011. Enhanced efficiency for c-Si solar cell with nanopillar array via quantum dots layers. *Optics Express* 19(105): A1141-A1147.
[39] Lin G.R., Chang Y.C., Liu E.S., Kuo H.C., and Lin H.S., 2007. Low refractive index Si nanopillars on Si substrate. *Applied Physics Letters 90*(18): 181923.
[40] Heidarzadeh H., Rostami A., Dolatyari M., and Rostami G., 2016. Plasmon-enhanced performance of an ultrathin silicon solar cell using metal-semiconductor core-shell hemispherical nanoparticles and metallic back grating. *Applied Optics* 55(7): 1779-1785.
[41] Li J., Yu H., Li Y., Wang F., Yang M., and Wong S.M., 2011. Low aspect-ratio hemispherical nanopit surface texturing for enhancing light absorption in crystalline Si thin film-based solar cells. *Applied Physics Letters* 98(2): 021905.
[42] Catchpole K.A. and A. Polman, 2008. Plasmonic solar cells. *Optics Express* 16(26): 21793-21800.
[43] Hoener C.F., Allan K.A., Bard A.J., Campion A., Fox M.A., Mallouk T.E., Webber S.E., and White J.M., 1992. Demonstration of a shell-core structure in layered cadmium selenide-zinc selenide small particles by x-ray photoelectron and Auger spectroscopies. *The Journal of Physical Chemistry* 96(9): 3812-3817.
[44] Zhou H.S., Sasahara H., Honma I., Komiyama H., and Haus J.W., 1994. Coated semiconductor nanoparticles: The CdS/PbS system's photoluminescence properties. *Chemistry of Materials* 6(9): 1534-1541.
[45] Liu F., Qu D., Xu Q., Xie W., and Huang Y., 2011. Plasmonic core-shell nanoparticle-based thin film solar cells. In *Proceedings of the SPIE 8011, 22nd Congress of the International Commission for Optics: Light for the Development of the World* 80114J.
[46] Fairooz F., Choudhury S.A., Ashraf N.I., Mahdi W., and Chowdhury M.H., 2019, February. Use of bimetallic plasmonic nanoparticle complexes for enhancing thin-film solar cell efficiency. In *Proceedings of the 2019 International Conference on Electrical, Computer and Communication Engineering (ECCE)* 1-6. IEEE.
[47] Fairooz F., Arefin S.M.N., and Chowdhury M.H., 2019, December. Use of nanoparticles arrays made of alloys of plasmonic metals of varying compositions to enhance the opto-electronic performance of thin-film solar cells. In *Proceedings of the 2019 International Conference on Innovation in Engineering and Technology (ICIET)* (Article in Press). IEEE.
[48] Shaky M.M., Ashraf N.I., Rifat R.A., and Chowdhury M.H., 2019. Use of hybrid bow-tie based plasmonic nanostructure to enhance the efficiencies of thin film solar cells. In *Proceedings of the 2019 International Conference on Electrical, Computer and Communication Engineering (ECCE)*. Cox's Bazar, Bangladesh, 7-9 February. IEEE.
[49] Chaudhuri R.G. and S. Paria, 2012. Core/shell nanoparticles: Classes, properties, synthesis mechanisms, characterization, and

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applications. *Chemical Reviews* 112(4): 2373-2433.

[50] Santbergen R., Liang R., and Zeman M., 2010. Amorphous silicon solar cells with silver nanoparticles embedded inside the absorber layer. *MRS Online Proceedings Library Archive* 1245.

[51] International Energy Agency (IEA), 2011. *CO2 Emissions from Fuel Combustion.* Luxembourg: Imprimerie Centrale.

[52] World Bank, 2015. *World Development Indicators 2015*. Washington D.C., USA: World Bank.

[53] Hsu D.D., O'Donoughue P., Fthenakis V., Heath G.A., Kim H.C., Sawyer P., Choi J., and Turney D.E., 2012. Life cycle greenhouse gas emissions of crystalline silicon photovoltaic electricity generation: Systematic review and harmonization. *Journal of Industrial Ecology* 16: S122-S135.

[54] Kim H.C., Fthenakis V., Choi J., and Turney D.E., 2012. Life cycle greenhouse gas emissions of thin-film photovoltaic electricity generation: Systematic review and harmonization. *Journal of Industrial Ecology* 16: S110-S121.

[55] Whitaker M., Heath G.A., O'Donoughue P., and Vorum, M., 2012. Life cycle greenhouse gas emissions of coal-fired electricity generation: Systematic review and harmonization. *Journal of Industrial Ecology* 16: S53-S72.

[56] O'Donoughue P.R., Heath G.A., Dolan S.L., and Vorum M., 2014. Life cycle greenhouse gas emissions of electricity generated from conventionally produced natural gas: Systematic review and harmonization. *Journal of Industrial Ecology* 18(1): 125-144.

[57] Council C. and C. Council, 2020. 11 Countries Leading the Charge On Renewable Energy. Climate Council. Retrieved from the World Wide Web: https://www.climatecouncil.org.au/11-countries-leading-the-charge-on-renewable-energy/.

[58] Mondal M.A.H., 2010. Economic viability of solar home systems: Case study of Bangladesh. *Renewable Energy* 35: 1125–1129.

[59] SunShot, 2015. *Photovoltaic System Pricing Trends. Historical, Recent, and Near-Term Projections, 2015 Edition.* Washington, D.C., USA: SunShot, U.S. Department of Energy.

[60] Sarti D. and R. Einhaus, 2002. Silicon feedstock for the multi-crystalline photovoltaic industry. *Solar Energy Materials and Solar Cells* 72(1-4): 27-40.

[61] Green M.A., 2001. Crystalline silicon photovoltaic cells. *Advanced Materials* 13(12-13): 1019-1022.

[62] Terheiden B., Ballmann T., Horbelt R., Schiele Y., Seren S., Ebser J., Hahn G., Mertens V., Koentopp M.B., Scherff M., and Muller J.W., 2015. Manufacturing 100 -thick silicon solar cells with efficiencies greater than 20% in a pilot production line. *Physica Status Solidi (a)* 212(1): 13-24.

[63] Fthenakis V., 2009. Sustainability of photovoltaics: The case for thin-film solar cells. *Renewable and Sustainable Energy Reviews* 13(9): 2746-2750.