Turnstile Diamond Dipole Nanoantenna Based Smart City Compatible Thin Film Solar Cell

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Abstract. A unit cell design of a thin film solar cell incorporating turnstile diamond dipole nanoantenna as a means of light trapping structure is proposed and investigated. Diamond dipole nanoantenna (DDNA) is a transformed version of the conventional dipole nanoantenna whereby the arms of the dipole nanoantenna are replaced by diamond shaped nanoparticles. In contrast to the dipole nanoantenna, DDNA offers larger area for field confinement and it resonates in the maximum solar spectrum range. The reduction of reflection losses along with generation of localized surface plasmons leads to improved photovoltaic characteristics of the thin film solar cell. The suggested TFSC model offers 99% absorption with 1.52 times photocurrent calculated based on finite element approach.

Keywords: Thin film solar cells (TFSC) · Smart city · Plasmonics · Nanoantenna · Surface Plasmon Polaritons · Localized Surface Plasmons · Polarization

1 Introduction

In the growing age of smart cities and Internet of Things (IoT) there has been significant demand of portable, flexible and thinner energy storage devices to cope up the energy requirement of the various appliances [1, 2]. There are many applications where thinner batteries are desired such as smart phones, smart watches and many more. For such applications thin film solar cells (TFSCs) could be a suitable choice if it provides substantial efficiency that can compete with the existing energy storage solutions available in the market [3]. TFSC encounter commercial hurdles despite having a compact design as a consequence of being comparatively less efficient [4].

It has been observed that addition of a suitable resonant light trapping structure to the TFSC design could improve the conversion efficiencies of existing solar cell models

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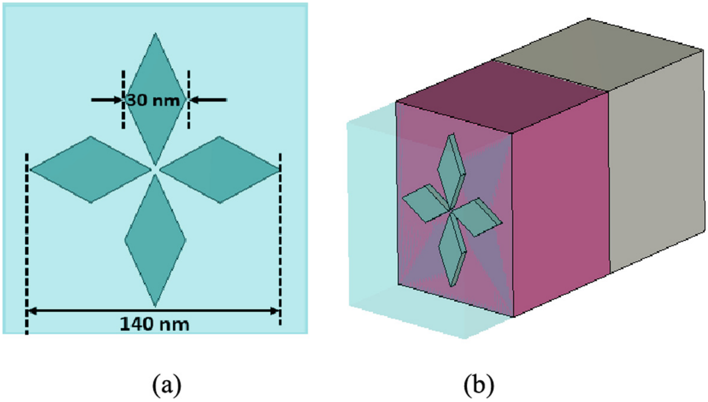

Fig. 1. (a) Dimensions of TDDNA (b) Proposed TFSC unit cell design showing TDDNA on the top of active layer surface

[5]. The common thickness of TFSCs ranges within hundreds of nanometers and some microns [3], under this regime amalgamation of nanotechnology becomes relevant for the quest of higher efficiency. Nanophotonic researchers have proposed various models of TFSCs with increased efficiencies [6, 7]. Researches have reported TFSCs models based on nanophotonics and Plasmonics phenomena such as localized surface plasmon (LSP) and surface plasmon polaritons (SPP) [8, 9]. Surface plasmon polaritons or SPP is the transverse magnetic mode electron cloud oscillation that is excited on the dielectric and metal interfaces. Whereas, localized surface plasmons being the localized form of SPPs that are confined in the proximity in a surrounded submicron region. One of the advantageous features of SPPs and LSPs is high energy confinement in the region where it is excited [10]. Based on these phenomena several TFSC models incorporating nanostructure have been reported [11]. The downscaled version of the conventional antenna which resonates at nanometric wavelength is known as nanoantenna [12] and plasmonic researchers have reported many works where efficient light trapping design for a thin film solar cell is attained by incorporating plasmonic nanoantennas such as Travelling wave antenna [13], needle shape [14], core-shell [15], Euler Spiral [16], Yagi-Uda [17]. Nanoantennas for TFSCs are designed in such a way that its resonance lies within the maximum solar irradiance range. The most desirable attributes of nanoantenna based TFSC are the multi-fold local field confinement and efficient trapping of the impinging sun light. In other words, the nanoantennas increases the effective aperture of a solar cell which results as higher absorption of solar energy. Subsequently, it produces more photocurrent and enhances the conversion efficiency. But there is still significant scope for further performance enhancement as the bandwidth of the nanoantenna are limited.

In this paper, a novel approach of nanoantenna based TFSC performance enhancement is presented in which a diamond dipole is used in turnstile manner. Turnstile positioning aids the performance by making the design polarization insensitive whereas the diamond shape increases the light confinement area. The efficacy of the solar cell

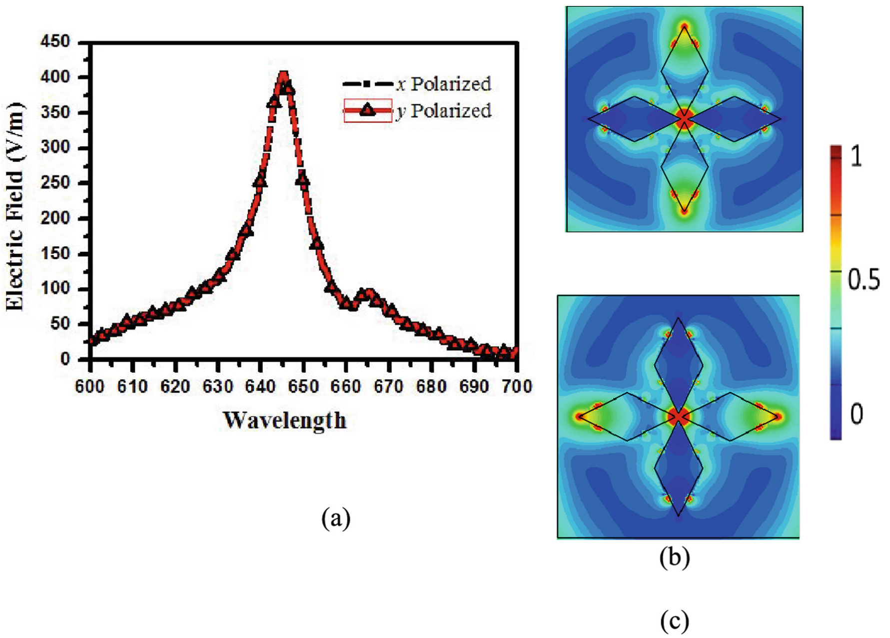

Fig. 2. (a) Electric field enhancement at the centre of the TDDNA and (b), (c) shows the distribution of electric field with respect to both the orthogonally polarized light component

as a whole is improved by higher localization of energy and light being more tightly focused by the adding the nanoantenna to the design.

2 Design Parameters and Computational Details

Similar to the conventional solar cell design, the unit cell (Fig. 1) has three layers. Amorphous Silicon as the absorber layer is sandwiched between the top Indium tin oxide (ITO) made anti-reflection coating (ARC) and bottom cathode which is made of silver. The ARC layer also serves as transparent anode whose thickness is calculated as 80 nm by considering λ wavelength light impinging normally to cancel the reflected light by maintaining 180° phase shift. Due to the fact that it is almost in the middle of the sunlight spectrum, as irradiance is at its highest, 600 nm wavelength light is taken into calculation.

$$h = \frac{\lambda}{4n_{ITO}} \tag{1}$$

The cathode layer and absorber layer both have thickness of 400 nm. As proposed modification, the turnstile dipole nanoantenna is positioned on the top surface of the

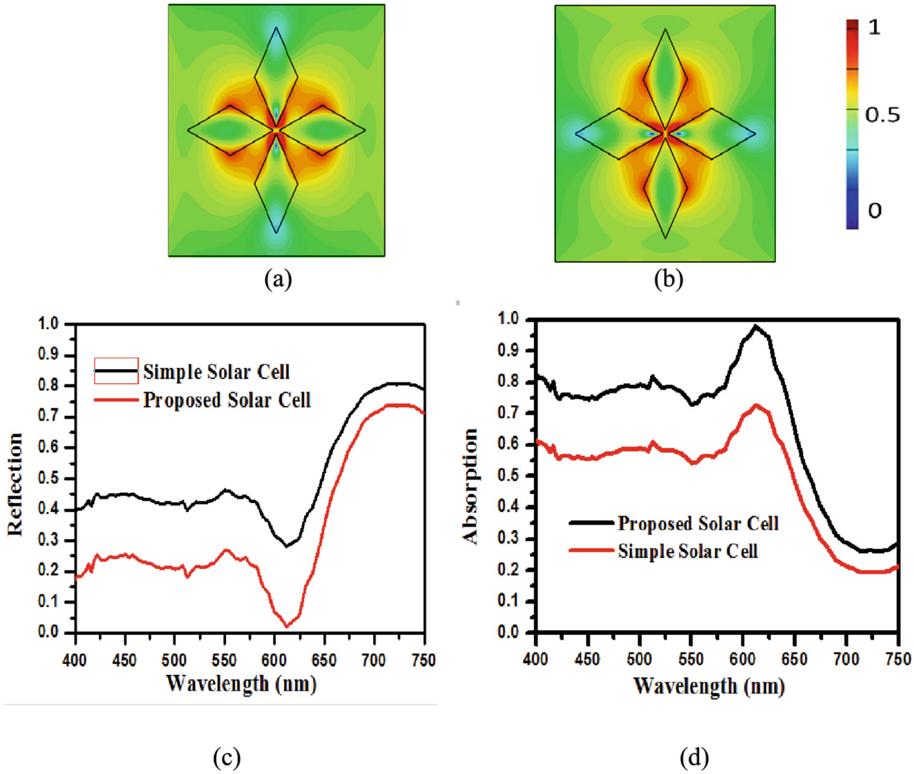

Fig. 3. (a), (b) shows the tangential component of the magnetic field and (c), (d) shows the comparison between the proposed solar cell and simple solar cell in terms Reflection and absorbance as a function of wavelength respectively.

amorphous silicon layer. Figure 1 depicts the design parameters of the proposed unit cell of TFSC.

Computational Domain

The time domain solver of CST Studio Suite [18] is used to conduct the presented study. The computational domain is discretised into mesh cells with 12 × 12 × 12 nm^3 being the largest and smallest mesh cell of 2 × 2 × 2 nm^3. The dispersive behaviour of silver at optical frequency is taken into consideration by including the Drude model is used [19], the permittivity of silver is modelled as:

$$\varepsilon_{Ag} = \varepsilon_0 \left\{ \varepsilon_\infty - \frac{f_p^2}{f(f + i\gamma)} \right\} \tag{2}$$

In the above equations, $\varepsilon_\infty = 5$, ε_0 is the permittivity of free space, f_p plasma frequency 2.175 PHz and γ is 4.35 THz as the collision frequency. All the above parameters are according to the Johnson and Christy model [20].

This design is surrounded by perfectly matched layers from the top and bottom and periodic boundaries at the sides. For excitation A uniform plane wave with 1 V/m is used and is made to incident from the top of the design. Results stated by the authors have been re-implemented using the same approach in order to test the simulation method, and the acquired results are under acceptable [8, 9].

Proposed Methodology for Fabrication

The active layer of amorphous silicon could be grown using the plasma enhanced chemical vapor deposition technique. The layer of ITO can be grown by using sputtering and the combination of layer-by-layer technique with top-down method could be used to fabricate the nanoantenna. The authors on the basis of available literature believe that the design is physically realizable.

3 Performance of TFSC Incorporated with Turnstile Diamond Dipole Nanoantenna

When the top surface of solar cell unit cell is subjected to excitation in the form of sunlight modelled as per ASTM1.5[21], the nanoantenna placed on top of absorber layer gets excited and receives the sunlight as per its resonance. With its multiple resonance characteristics, the turnstile DDNA confines the light in the gap of the dipole. The distribution of electric field intensity on active layer surface is shown in Fig. 2. Here, it can be seen evidently that the energy confinement is significantly larger than the dipole nanoantenna. This is caused by the phenomena of localized surface plasmons. The distribution of the tangential component of the magnetic field further justifies this phenomenon. To verify this the distribution of the tangential component of the magnetic field is shown in the Fig. 3. By observing Fig. 3, it can be concluded that there is higher concentration of surface current in the gap of the dipole because the current density is directly dependent on the magnetic field component. The main reason of this surface current is the excitation of localized surface plasmons. By comparing, this with the dipole nanoantenna characteristics, it can be said that there is higher LSP excitation in case of turnstile dipole nanoantenna.

The subsequent effect on the field enhancement is monitored by means of a probe which is mounted in the exact center of the dipole gap. The electric field measured by the probe shows resonant characteristics of the turnstile DDNA. In the absence of the nanoantenna, there are no bright spots of energy confinement on the surface or anywhere in the solar cell. But when, the nanoantenna are added to the design, then the composite design functions as a light-trapping structure as a result to the localized surface plasmons excitation. Therefore, minimizing the reflection losses of the thin film solar cell (Fig. 3c). Figure 3(d) depicts the comparison in terms of absorbance of the simple thin film solar cell with the TDDNA embedded thin film solar cell. It can be noted that there is significant increase in the absorption spectra around 640 nm wavelength. It results from the suggested turnstile dipole nanoantenna's ability to trap light.

Optical to Electrical Conversion

In the calculation of the conversion efficiency, it is believed that every absorbed photon is going to result in the generation of one pair of electrons and holes. The effectiveness is best described as [5]:

$$\eta = \frac{\int_{300nm}^{\lambda_g} F_S(\lambda) A_{Si-a}(\lambda) \frac{\lambda}{\lambda_g} d\lambda}{\int_{300nm}^{4000nm} F_S(\lambda) d\lambda} \quad (3)$$

Here, λ_g is taken as 800 nm which is close to the band gap wavelength of amorphous silicon, $F_S(\lambda)$ is the photon flux density referred per the ASTM 1.5 solar spectrum. $A_{Si-a}(\lambda)$ is the absorbance as a function of wavelength. As the losses associated with silver can be assumed negligible then absorbance can be computed as:

$$A_{Si-a}(\lambda) = 1 - R(\lambda) \quad (4)$$

Further, the photocurrent density can be computed as [5]:

$$J_{SC} = e\frac{\lambda_g}{hc}\eta\int_{300nm}^{4000nm} F_s(\lambda) d\lambda = 87.66\ \eta\frac{mA}{cm^2} \quad (5)$$

In order to show the merit of the proposed model, the photocurrent enhancement factor (*PEF*) is calculated as:

$$PEF = \frac{J_{sc}^{na}}{J_{sc}^{SSC}} \quad (6)$$

Here, J_{sc}^{na} and J_{sc}^{SSC} are the photocurrent densities of the unit cell, calculated by using Eqs. (3) and (4) for the solar cell comprising of turnstile DDNA and simple solar cell respectively. The *PEF* for the proposed model is compute as 1.52 which shows the merit of the turnstile DDNA embedded thin film solar cell in terms of photocurrent generation.

4 Conclusion

Compact energy storage systems are one of the major requirements of any smart city. Since smart cities are generally densely occupied and numerous applications such as monitoring vehicles, drones further need flexibility as well. These all parameters could be fulfilled by thin film solar cells. As reliance upon fossil fuels is not considered in internet of things, integration of renewable energy is not only beneficial by environmental point of view but also it is essential for effectively utilizing the space limitation as there would be numerous applications running in the smart city. A solution to overcome the lower efficiency of the existing TFSC has been proposed. Based on the theoretical study and simulation presented, it can be concluded that the proposed design overpowers the conventional thin film solar cell in terms of photocurrent enhancement factor and absorption of sunlight inside the active layer of thin film solar cell. The design exhibits 99% highest absorption with 52% increased photocurrent.

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