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RESEARCH ARTICLE

Engineering

Novel Design of polycrystalline CdTe/Si Tandem Solar Cells Using SiO2/TiO2 Distributed Bragg Reflector

Nuevo Diseño de Celdas Solares Policristalinas CdTe/Si Tandem Usando Reflector de Bragg distribuido SiO2 / TiO2

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ABSTRACT

In this paper, a polycrystalline cadmium telluride/silicon ($CdTe/Si$) solar cell based on SiO_2/TiO_2 distributed Bragg reflector (DBR) is proposed and investigated using calibrated simulations with experimental data of previous fabrication device. At first, by inserting the SiO_2/TiO_2 DBR, the conversion efficiency is increased by about 25% compared with the conventional $CdTe/Si$ solar cell with similar dimensions. In addition, the carrier lifetime of absorber layer can provide an improved conversion efficiency of 15% compared with the $CdTe/Si$ conventional solar cell. The obtained open circuit voltage, short circuit current density, fill factor and conversion efficiency of proposed solar cell structure were about $1.2V, 39.5mA/cm^2, 0.95$ and 28.5% under global AM 1.5 conditions, respectively. The results strongly confirm that the polycrystalline $CdTe/Si$ solar cell based on SiO_2/TiO_2 DBR seems to be the most optimal choice for converting the solar energy in high efficiency photovoltaics systems.

keywords: Novel design; $CdTe/Si$; SiO_2/TiO_2; Tandem Solar Cells; Distributed Bragg reflector (DBR).

RESUMEN

En este artículo, se estudia una célula solar de telururo de cadmio policristalino/silicio ($CdTe/Si$) basada en el reflector Bragg distribuido (DBR) SiO_2/TiO_2 utilizando simulaciones calibradas con datos experimentales de dispositivos fabricados previamente. Al principio, al insertar el SiO_2/TiO_2 DBR, la eficiencia de conversión aumenta aproximadamente un 25 $\%$ en comparación con la celda solar convencional $CdTe/Si$ con dimensiones similares. Adicionalmente, la vida útil del portador de la capa absorbente puede proporcionar una eficiencia de conversión mejorada de 15% en comparación con la celda solar convencional de $CdTe/Si$. El voltaje de circuito abierto, la densidad de corriente de cortocircuito, el factor de llenado y la eficiencia de conversión de la estructura de la celda solar propuesta fueron de aproximadamente $1.2V, 39.5mA/cm^2, 0.95$ y 28.5% bajo condiciones globales de AM 1.5, respectivamente. Los resultados confirman que la celda solar policristalina $CdTe/Si$ basada en SiO_2/TiO_2 DBR es una opción más óptima para convertir la energía solar en sistemas fotovoltaicos de alta eficiencia.

keywords: Nuevo diseño; $CdTe/Si$; SiO_2/TiO_2; Celda solar Tandem; Reflector Bragg Distribuido (DBR).

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1 | INTRODUCTION

Generally, the photovoltaics (PV) can convert the solar energy to generate electricity direct from the sun light by means of crystalline materials, multiple-junctions, or polycrystalline thin films. The polycrystalline thin films reduce the cost and materials needs because of the much lower materials usage, however polycrystalline thin films such as cadmium telluride (CdTe) have several potential advantages [1, 2, 3, 4, 5, 6, 7]. CdTe absorber layer has a high absorption coefficient, direct band gap 1.45 eV that significantly corresponds with the sun light spectra and long-term performance stability [8, 9].

On one hand, the CdTe layer thickness reduction of solar cells is an attractive prospect due to limited availability and the rising price of telluride. Although, the CdTe solar cells have disappointed crystalline Silicon solar cells, but the CdTe cells is also simply manufactural by different techniques such as the closed space sublimation, molecular beam epitaxy, close-spaced sublimation (CSS) deposition, electrodeposition, spraying deposition, vapor transport deposition, screen printing techniques, Chemical bath deposition (CBD), vacuum evaporation, or CSS methods [10, 11]. The efficiency of CdTe solar energy has increased but further gains in efficiency will continue to be beneficial over the past few years. The National Renewable Energy Laboratory (NREL) reports record efficiencies of 23.5% for cell efficiency; and 22.1% for module efficiency at the lab condition for cadmium sulfide/cadmium telluride (CdS/CdTe) solar cells that have increased by only 5.2% during the last 20 years [12, 13]. Therefore, Improved efficiency helps to reduce the cost of the cells since the same area or number of panels can provide more energy.

On the other hand, single junction CdS/CdTe solar cells have relatively low efficiency because they can't absorb low energy photons. In order to overcome the limitations of their low efficiency, tandem solar cells can be used, where the complete solar cell induced by two sub cells [14, 15, 16, 17]. Several different types of tandem solar cells have been experimentally demonstrated for better photon absorption and improved efficiency including III-V/Si solar cells [18, 19], Perovskite/Si tandems [20], CdTe/CIS [21, 22] and CIGS/CIGS [23].

In addition, the distributed Bragg reflector (DBR) is based on the fundamental principal of reflection and transmission of light at interface of multiple layered alternating dielectric pairs. The simplest DBR is composed of a stack of two different layers with different refractive indices. Recently, a CdS/CdTe solar cell based on Si/SiO2 DBR with conversion efficiency of 21.02% is presented [24].

In this work, we propose and investigate a polycrystalline cadmium telluride/silicon (CdTe/Si) solar cell based on SiO_2/TiO_2 DBR using calibrated simulations with experimental data of previous fabrication device. The aim of the numerical modelling is to check whether the CdTe/Si solar cell based on SiO_2/TiO_2 DBR is working properly or not by using the SiO_2/TiO_2 DBR. The paper is organized as follows. In section 2, we have described the device structure model and validation. The results and discussion are presented in section 3. In section 4, we finally conclude.

2 | DEVICE STRUCTURE MODEL AND VALIDATION

Generally, numerical analysis is a fundamental approach to predict of the solar cell performance and ensure the viability of the anticipated structure [2]. The efficiency of the proposed solar cell structure was modeled using the Silvaco ATLAS Device software package [25]. The fundamental and primary equations of interaction of optical and electrical during the solar cells operation and modeling are electrostatic potential, carrier densities, Poisson's equation, the continuity equations and transport equations. Poisson's equation relates the electrostatic potential to the space charge density as [25]:

$$\nabla \cdot (\epsilon\psi(\boldsymbol{r},t)) = -\rho(\boldsymbol{r},t) \tag{1}$$

where ψ, ρ and ϵ are electrostatic potential, local charge density and local permittivity, respectively. The continuity equations for electrons and holes are respectively defined by [25]:

$$\frac{\partial n}{\partial t} = G_n - R_n + \frac{1}{q}\nabla \cdot \boldsymbol{J}_n \tag{2}$$

and

$$\frac{\partial p}{\partial t} = G_p - R_p - \frac{1}{q}\nabla \cdot \boldsymbol{J}_p \tag{3}$$

where n, p, J_n, J_p, G_n and G_p are electron concentration, hole concentration, electron current density, hole current current density, electrons generation rates and holes generation rates, respectively. R_n and R_p are the recombination rates and q is the magnitude of electron charge.

The drift current densities for holes and electrons based on energy balance transport model can be written as [25]:

$$\boldsymbol{J}_n = qD_n\nabla n - q\mu_n n\nabla\psi + qnD_n^T T_n \tag{4}$$

$$\boldsymbol{J}_p = -qD_p\nabla p - q\mu_p p\nabla\psi + qpD_p^T T_p \tag{5}$$

where T_n and T_p represent the electron and hole carrier temperatures. The parameters μ_n and μ_p are the electron and hole mobilities respectively . The coefficients $D_n and D_p$ are the thermal diffusivities for electrons and holes respectively . The rate of creation of electron–hole pairs as a function of position within a solar cell is [25]:

$$G(x) = (1-s)\int_\lambda (1-r(\lambda))f(\lambda)\alpha(\lambda)\exp(-\alpha x)\,d\lambda$$

where s is the grid-shadowing factor, $r(\alpha)$ is the reflectance, $\alpha(\lambda)$ is the absorption coefficient, and $f(\lambda)$ is the incident photon flux that is obtained by dividing the incident power density at each wavelength by the photon energy.

TABLE 1 The device parameters of solar cell for the simulations.

Parametrics	CdS	CdTe
$m*n/m_o$	0.171	0.25
$m*p/m_o$	0.7	0.7
Dielectric Constant ϵ/ϵ_o	10	9.7
Electron Affinity [eV]	4.3	4.28
Electron Mobility μ_e $[cm^2/Vs]$	350	500
Hole Mobility μ_h $[cm^2/Vs]$	50	60
Electron/Hole Density n, p $[cm^{-3}]$	10^{16}	10^{14}
Band Gap Energy E_g [eV]	2.42	1.45
Effective Density of States $N_C[cm^{-3}]$	2.4×10^{18}	8×10^{17}
Effective Density of States $N_V[cm^{-3}]$	1.8×10^{19}	1.8×10^{18}

As mentioned above, solar cell operation is modeled by a set of coupled, non-linear, partial differential equations. The computer-aided design (CAD) produces numerical solutions of these equations by calculating the values of unknowns on a mesh of points within the device. An internal discretization procedure converts the original, continuous model to a discrete non-linear algebraic system that has approximately the same behavior. The set of partial differential equations, the mesh and the discretization procedure determine the non-linear algebraic problem that must be solved. The two-dimensional Silvaco ATLAS Device software is suitable for solving self-consistent these equations [25]. For higher accuracy in modeling of the mobility, recombination and carrier lifetimes; the concentration and field dependent mobility model, Shockley-Read-Hall recombination model and SRH concentration-dependent Lifetime were considered.

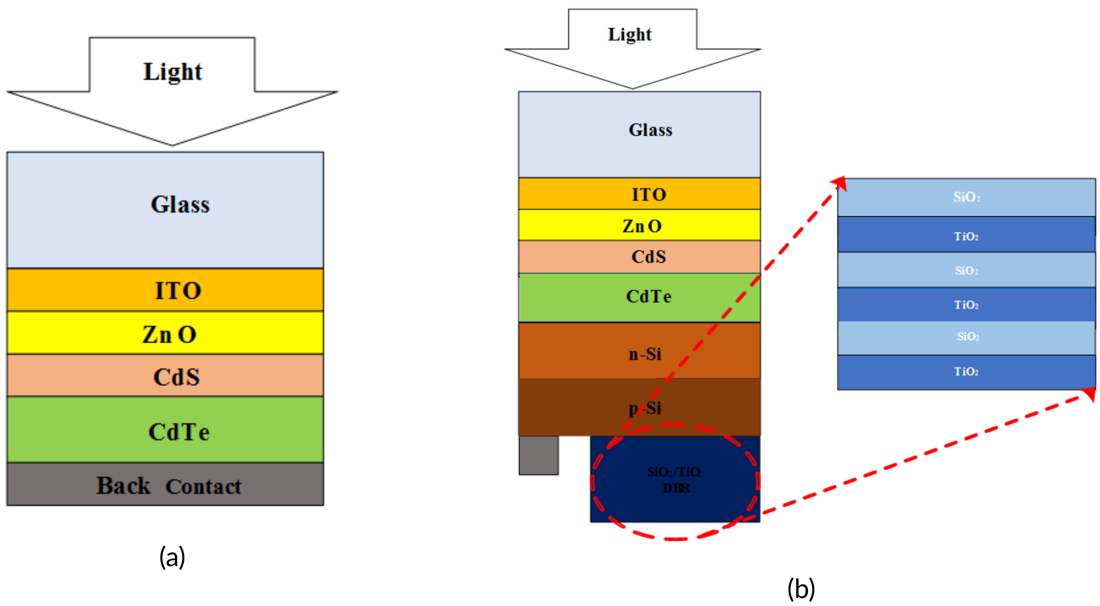

FIG. 1 The cross–sectional views of the previous experimentally-fabricated CdTe solar cell (Glass/ITO/ZnO/n-CdS/p-CdTe/Al), tandem CdTe/Si solar cell (Glass/ITO/ZnO/n-CdS/p-CdTe/n-Si/p-Si /Al) and tandem CdTe/Si solar cell based on SiO_2/TiO_2 DBR.

Fig. 1 shows the cross–sectional views of the previous experimentally - fabricated CdTe solar cell type (Glass/ITO/ZnO/n - CdS/p-CdTe/Al), tandem CdTe/Si solar cell (Glass/ITO/ZnO/n - CdS/p-CdTe/n-Si/p-Si/Al) and tandem CdTe/Si solar cell based on SiO_2/TiO_2 DBR as proposed to achieve higher efficiency. The device parameters for the simulations are similar to that mentioned in Ref. [2] and are given in Table 1.

TABLE 2 The comparison between the experimental results of open circuit voltage (VOC), short circuit current density (JSC), fill factor and cell efficiency with the simulated ones for conventional cell.

Parametrics	Conventional cell	Simulated cell
V_{OC} (mV)	985	988
J_{SC} (mA/cm^2)	22.2	22.14
Fill factor	0.830	0.823
Efficiency $(\%)$	18.12	18

In brief, the conventional cell consists of substrate of glass, 50 nm indium-tin-oxide (ITO), 50 nm CdS and 300 nm CdTe. The device parameters of proposed tandem CdTe/Si solar cell based on SiO_2/TiO_2 DBR are same as tandem CdTe/Si solar cell except that the three pair of SiO_2/TiO_2 served as DBR with their refractive index 1.46 and 2.25, respectively. The geometric thickness of each layer is $d = \lambda/4n$, where n is the real refractive index and λ is the light wavelength that travelling inside the DBR material.

It is worth noting that the simulations are calibrated and tuned using experimental value measured. Table 2 compares the experimental results of open circuit voltage (VOC), short circuit current density (JSC), fill factor and cell efficiency with the simulated ones. As seen, the simulated results are quite close to the experimental data [2].

3 | RESULTS AND DISCUSSION

Figs. 2 and 3 show the voltage dependent current density and output power for tandem CdTe/Si solar cell and conventional CdTe solar cell under global AM 1.5 conditions, respectively.

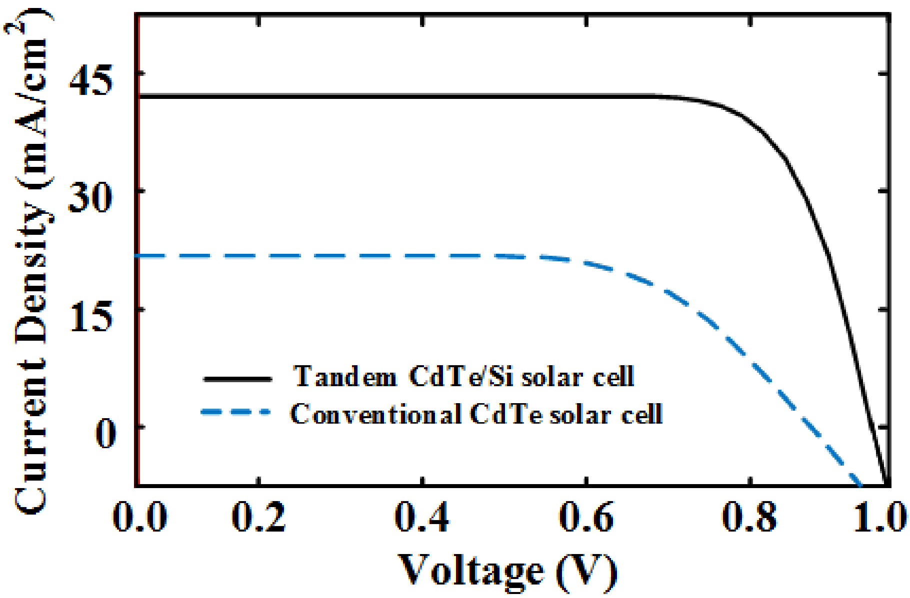

FIG. 2 The voltage dependent current density for tandem CdTe/Si solar cell and conventional CdTe solar cell under global AM 1.5 conditions.

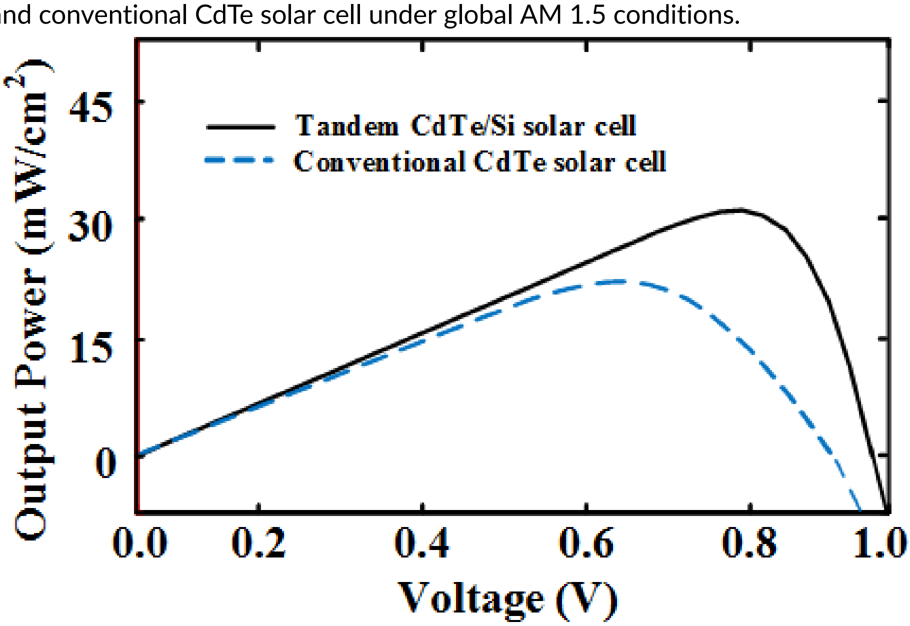

FIG. 3 The voltage dependent output power for tandem CdTe/Si solar cell and conventional CdTe solar cell under global AM 1.5 conditions.

As seen, The obtained open circuit voltage, short circuit current density, fill factor and conversion efficiency of tandem CdTe/Si solar cell are 1000 mV, 37.2 mA/cm2, 0.94 and 23.5% under global AM 1.5 conditions, respectively. In comparison to conventional CdTe solar cell with 18% efficiency, a 30% relative enhancement in the conversion efficiency value for tandem CdTe/Si solar cell.

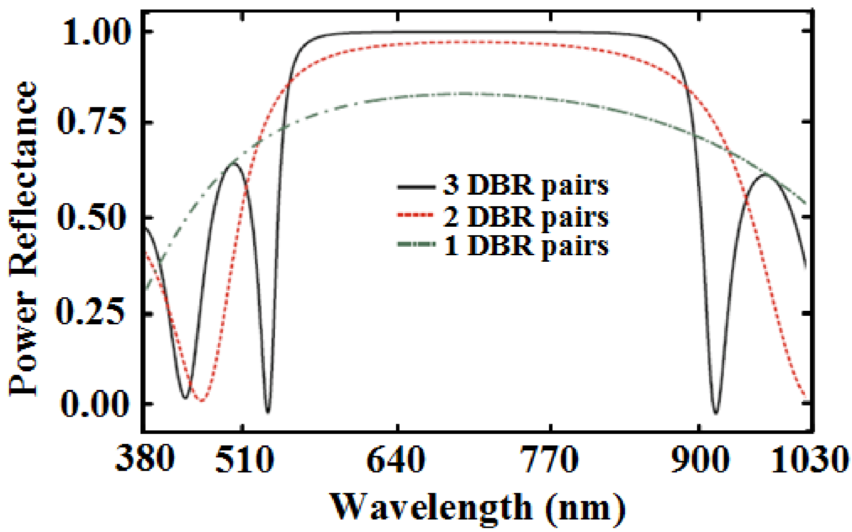

FIG. 4 The power reflectance comparison of the SiO_2/TiO_2 DBR as a function of number of pairs.

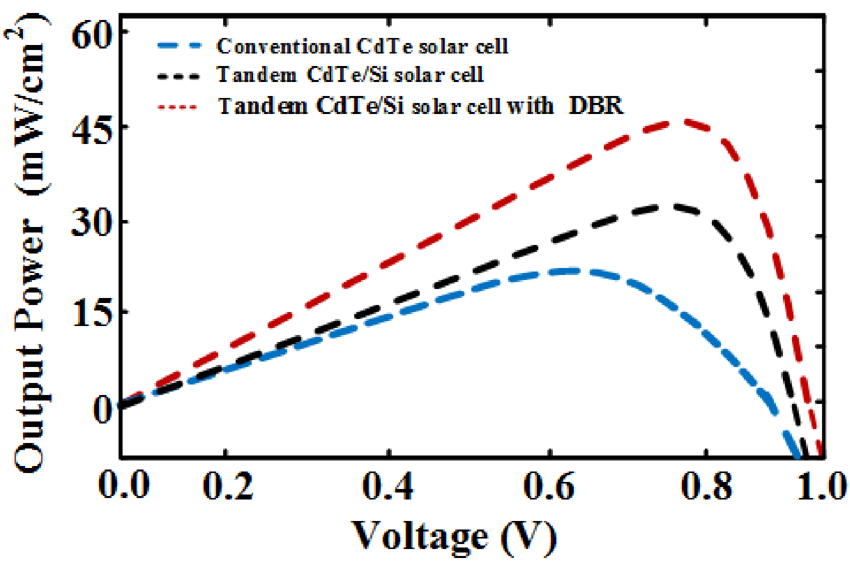

FIG. 5 The comparison between output power characteristics of different structures of solar cells including tandem CdTe/Si with three pair of SiO_2/TiO_2 DBR, tandem CdTe/Si and conventional CdTe cells under.

Although metallic DBRs can act as electrodes but they suffer from a lack of light transparency, whereas dielectric DBRs have high light transparency. In order to achieve better performance, we optimize tandem CdTe/Si solar cell with three pair of SiO_2/TiO_2 DBR. By increasing the number of DBR pairs, large power reflectance values can be achieved due to the periodic nature of the DBRs. The 100% power reflectance at a certain wavelength can be approached with an infinite number of DBR pairs. On the other hand, the required number of DBR pairs to achieve a given reflectance value at certain wavelength decreases with increasing refractive index contrast of the stack of two different layers. The refractive index contrast for SiO_2/TiO_2 DBR is 0.79. Therefore, we optimize the number of SiO_2/TiO_2 DBR pairs. Three different values of pairs, as 1, 2, and 3, are used for this purpose. Fig. 4 shows the power reflectance comparison of the SiO_2/TiO_2 DBR as a function of number of pairs. It is evident that the maximum power reflectance value increases as the number of pairs increases from 1 to 3, whereas a flat stop bandwidth is formed for 3 SiO_2/TiO_2 DBR pairs. The values of maximum power reflectance and stop bandwidth are 99.97%.

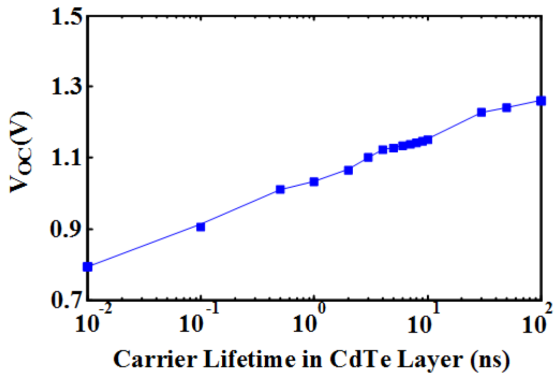

FIG. 6 The comparison of the open circuit voltage as a function of carrier lifetime of CdTe for tandem CdTe/Si with three pair of SiO_2/TiO_2 DBR structure under global AM 1.5 conditions.

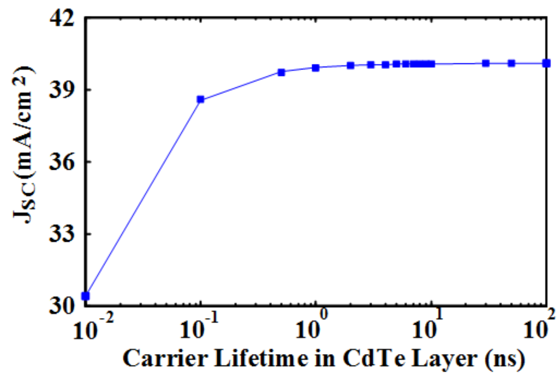

FIG. 7 The comparison of the short circuit current density as a function of carrier lifetime of CdTe for tandem CdTe/Si with three pair of SiO_2/TiO_2 DBR structure under global AM 1.5 conditions.

Fig. 5 shows a comparison between output power characteristics of different structures of solar cells including tandem CdTe/Si with three pair of SiO_2/TiO_2 DBR, tandem CdTe/Si and conventional CdTe cells under global AM 1.5 conditions. The tandem CdTe/Si with three pair of SiO_2/TiO_2 DBR shows the maximum output power of 45 mW/cm2 under global AM 1.5 conditions. As can be observed, the output power value of tandem CdTe/Si with three pair of SiO_2/TiO_2 DBR increased about 25% and 55% compared to that of the tandem CdTe/Si and conventional CdTe solar cells, respectively.

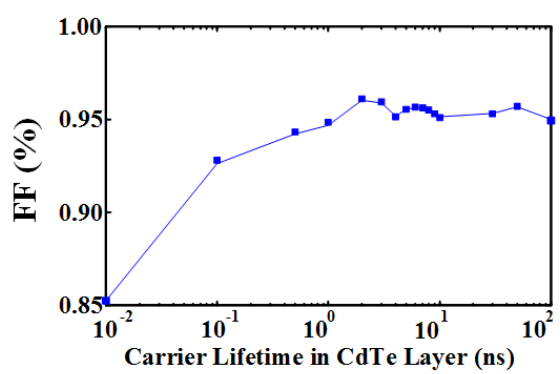

FIG. 8 The comparison of the fill factor as a function of carrier lifetime of CdTe for tandem CdTe/Si with three pair of SiO_2/TiO_2 DBR structure under global AM 1.5 conditions.

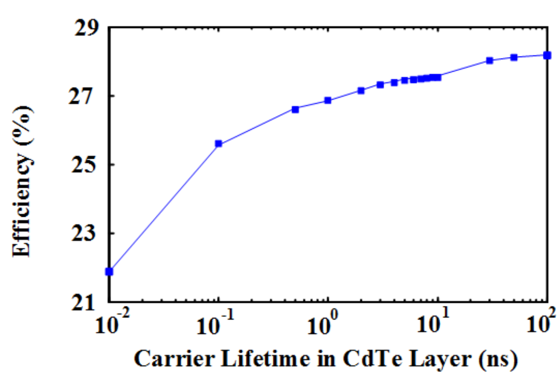

FIG. 9 The comparison of the conversion efficiency as a function of carrier lifetime of CdTe for tandem CdTe/Si with three pair of SiO_2/TiO_2 DBR structure under global AM 1.5 conditions.

In order to investigate whether the carrier lifetime effect was present when the carrier lifetime of CdTe increased, the performances of the tandem CdTe/Si with three pair of SiO_2/TiO_2 DBR with different carrier lifetime were also examined. Except carrier lifetime, all parameters are kept as same in these simulations.

Figs. 6–9 show comparison of the open circuit voltage, short circuit current density, fill factor and conversion efficiency as a function of carrier lifetime of CdTe under global AM 1.5 conditions, respectively.

It is evident that the carrier lifetime of CdTe has a strong effect on the conversion efficiency. Since all carriers generated in the depletion region will be physically collected at higher lifetimes, the conversion efficiency improve with increasing the carrier lifetime. The improved open circuit voltage, short circuit current density, fill factor and conversion efficiency of tandem CdTe/Si with three pair of SiO_2/TiO_2 DBR were 1.2 V, 39.5 mA/cm2, 0.95 and 28.5% under global AM 1.5 conditions, respectively.

4 | CONCLUSION

In this paper, we propose and investigate a polycrystalline cadmium telluride/silicon (CdTe/Si) solar cell based on SiO_2/TiO_2 distributed Bragg reflector (DBR) by using calibrated simulations with experimental data of previous fabrication device. By inserting the SiO_2/TiO_2 DBR, the conversion efficiency is increased by about 25% compared with the conventional CdTe/Si solar cell with similar dimensions. Furthermore, the carrier lifetime of absorber layer can provide improved conversion efficiency of device about 15% compared with the conventional solar cell. With optimized carrier lifetime, a significant enhancement in short circuit current density and output power was noticed with maximum cell efficiency up to 28.5% under global AM 1.5 conditions. The results approve that the polycrystalline CdTe/Si solar cell based on SiO_2/TiO_2 DBR seems to be the most optimal choice for converting the solar energy in high efficiency photovoltaics systems.

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