Cadmium Selenide and Cadmium Telluride Based High Efficiency Multijunction Photovoltaics for Solar Energy Harvesting

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***Abstract*—Developments in solar energy depend on the growth and application of new materials towards the goal of cost-effective solar power. Cadmium Selenide (CdSe) and Cadmium Telluride (CdTe) based multijunction tandem solar cells show great promise for high efficiency next generation cells. In our work we have performed a comparison of solar energy absorption of CdSe/CdTe cell with the existing single and multijunction cells. With an anti-reflective coating of Silicon Di Oxide (SiO2) the CdSe/CdTe cell has shown significant photon absorption in the range of 300-2000 nm. A theoretical efficiency of 34.6% has been achieved under terrestrial AM 1.5, 1 sun condition.**

***Index Terms*—cadmium selenide, cadmium telluride, multijunction, silicon di oxide**

I. Introduction

In recent years, solar technology has been a trending topic both domestically and globally. Multi junction solar cells have reached the highest efficiency over 40% under ideal conditions [1]. So far, multi-junction solar cells are the most efficient of all solar cells. These cells are made of two or more p-n junctions with different bandgaps. Each junction in the cell absorbs a different part of the solar spectrum. When photons strike the top of a solar cell, they are absorbed if the energy is greater or equal to the bandgap otherwise absorption doesn't take place. If the photon's energy is greater than the bandgap, the extra energy from the photon will be dissipated as heat. A well designed multi junction solar cell should be able to convert most of the light spectrum into current so that this can be used to drive external loads. Alloys of group III-V element of the periodic table have been used for fabricating such multi-junction cells. However alternative materials are being examined which can yield impressive results in the near term and be able to provide high efficiency necessary to warrant further research effort.

This paper presents new and possible application of group II-VI materials in a dual junction photovoltaic cell based on 1.74eV Cadmium Selenide and 1.44eV Cadmium Telluride with an anti-reflective coating of Silicon Di-Oxide. In the recent years, wide bandgap II-VI compound materials have considerably been utilized in the electronic applications [2]. Our dual junction CdSe/CdTe cell has achieved a theoretical efficiency of 30% (AM1.5, 1sun condition). An AM1.5 efficiency of 34.6% is anticipated when a single layer anti reflective coating of SiO_2 is applied. In this paper we have shown that our dual junction cell has the highest photon absorption than any other existing single and dual junction cells in the range of 300nm-2000nm. Real Time Photonic Simulator has been used to perform the simulations of photon absorption, transmission and reflection [3].

II. Multijunction Photovoltaic Cells

A. Group III-V Materials

The high efficiency of multijunction concentrator cells has the potential to revolutionize the cost structure of photovoltaic electricity generation. The most efficient present-day multi-junction photovoltaic cells are made of GaInP, GaAs and Ge layers on Ge substrate. A metamorphic $Ga_{0.44}In_{0.56}P/Ga_{0.92}In_{0.08}As/Ge$ 3-junction solar cell has reached a record efficiency of 40.7% at 240 suns under AM1.5 direct, low-AOD, 24.0 W/cm^2, 25°c [1]. The essential distinctive feature of III-V multijunction cells is the very wide range of subcell and device structure bandgaps that can be grown with high crystal quality, and correspondingly high minority-carrier recombination lifetimes. This is true for lattice-matched multijunction cells, but all subcells must have the same crystal lattice constant. Dislocations and other structural defects have a serious deleterious effect on the electronic properties of III-V alloys such as GaInAs and GaInP, which are commonly used in III-V MJ cells.

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B. Group II-VI Materials

Current researchers argue that II-VI semiconductors are more efficient and less expensive than III-V materials [2], [4] and [6]. Both group III-V and II-VI materials have substantial relative advantages and drawbacks with respect to one another for use as the absorber materials in solar cell. Lattice mismatches over 15% and dislocation densities above 10^6 cm^{-2} have little effect on the properties of II-VI devices [4]. Efficiency calculations, assuming lattice matching not to be required for II-VI materials, indicate that the highest efficiency three junction II-VI cells should have efficiencies 3-8% (absolute) higher than those of the highest efficiency three junction II-VI cells [4]. For a CdTe solar cell of proprietary design, EPIR has calculated efficiency above 26% [4]. The firm also believes that a maximum efficiency of more than 30% is achievable for optimized two junction CdTe/Si solar cells in which both the CdTe and Si act as solar energy absorbers. These detailed calculations indicate that the upper limits of energy conversion efficiencies of solar cells employing group II-VI semiconductor materials such as CdTe rival those of present solar cells using corresponding group III-V semiconductor materials such as Gallium Arsenide (GaAs), but with much greater manufacturability and significantly lower cost.

III. Design of Dual Junction Cadmium Selenide and Cadmium Telluride Cell with ARC

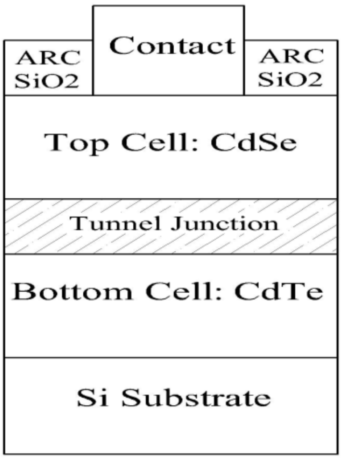

Figure 1. Design of CdSe/CdTe dual junction cell.

In this paper we have designed a monolithic dual junction cell based on group II-VI materials. The cell is comprised of two layers. The bottom layer is made up of CdTe semiconductor material with bandgap energy of 1.44eV and the top layer is made of CdSe having bandgap energy of 1.74eV higher than the bottom CdTe. In order to achieve a high performance the bandgap of the top layer of a multijunction cell should be 1.6-1.8 eV [5]. 1.74/1.44 eV creates the perfect combination of bandgaps which further results in high photon absorption of the solar spectrum. These cells can be grown on large area Si substrates by high-vacuum deposition techniques as the bandgap of Si is more optimal than that of Ge for two-junction (2J) or 3J cells [4]. Cadmium Telluride has been widely used for PV applications because of its bandgap and its high optical absorption co-efficient [6]. Cadmium Selenide (CdSe) is also being developed for use in opto-electronic devices and also tested for use in high efficiency solar cells [7]. To reduce the amount of sunlight lost, an Anti-Reflective Coating (ARC) of Silicon Di Oxide (SiO_2) with a refractive index of 1.46 is put on top of the cell. A good ARC is vital for solar cell performance as it ensures a high photocurrent by minimizing reflectance [8]. The thickness of the ARC is chosen so that the wavelength in the dielectric material is one quarter the wavelength of the incoming wave. For a quarter wavelength anti-reflection coating of a transparent material with a refractive index n_1 and light incident on the coating with a free-space wavelength λ_0, the thickness d_1 which causes minimum reflection is calculated by:

$$d_1 = \frac{\lambda_0}{4n_1} \tag{1}$$

Reflection is further minimized if the refractive index of the anti-reflection coating is the geometric mean of that of the materials on either side; that is, glass or air and the semiconductor. This is expressed by:

$$n_1 = \sqrt{n_0 n_2} \tag{2}$$

where n_0 is the refractive index of the surrounding material, n_1 is the optimal refractive index of the anti-reflection layer and n_2 is the refractive index of the semiconductor.

Inclusion of SiO_2 on top of our solar cell has significantly increased the photon absorption and as well as the overall efficiency. An efficiency of 34.6% is achieved under terrestrial AM1.5, 1 sun illumination. The best performance of the cell is observed with the ARC thickness of 100nm.

IV. Comparison and Analysis of CdSe/CdTe Cell with Other Single and Dual Junction Cells

Photons incident on the surface of a semiconductor will be either reflected from the top surface will be absorbed in the material or will be transmitted through the material. Reflectance is the ratio of the energy reflected from the surface of the interface to the total incident energy. There is a reflection of light at the interface between the first layer of a solar cell and the incident medium, air. There is also a reflection at the interfaces between the individual layers within the solar cell. All these processes result in a total reflectance between the solar cell and air. So, a part of the incident energy that can be converted into a usable energy by the solar cell is lost by reflection. R is the total reflectance.

The values of Reflectance (R), Transmittance (T) and Absorptance (A) are calculated by the following equations,

$$R = |r|^2 \tag{3}$$

$$r = \frac{E_r}{E_i} \tag{4}$$

$$T = |t|^2 \times \frac{n_{sub}}{n_{sup}} \tag{5}$$

$$t = \frac{E_t}{E_i} \tag{6}$$

E_r is the reflected electric field amplitude; E_i is the incident electric field amplitude and E_t is the transmitted electric field amplitude. n_{sub} is the refractive index of the substrate and n_{sup} is the refractive index of the superstrate. From Fig. 2 it is seen that for this cell transmission is almost zero. The only considerable loss is the loss from reflection. So,

$$A = 1 - R \tag{7}$$

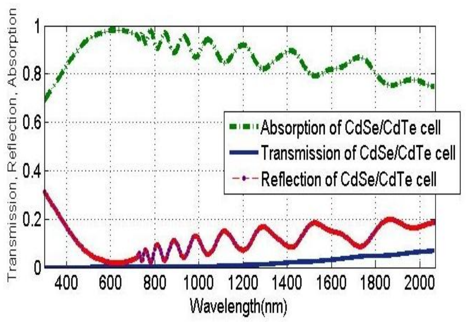

Figure 2. Photon absorption, reflection and transmission of CdSe/CdTe cell.

The dual junction cell was exposed in the range of 300nm-2000nm of the solar spectrum. Fig. 2 shows the absorption, reflection and transmission of the proposed cell. Substantial photon absorption efficiency has been observed in our CdSe/CdTe cell in the range of 300nm to 2000nm both with and without the anti reflective coating. With the anti reflective coating we observed a photon absorption of 68.8% at 300nm, 83.2% at 400nm, 94.2% at 500nm, 97.97% at 600nm, 96.8% at 700 nm, 88.0% at 1000nm, 89.1% at 1400nm, 85.9% at 1700nm and 76.9% at 2000nm respectively in the solar spectrum. An efficiency of 34.6% has been obtained under terrestrial AM1.5 1 sun illumination.

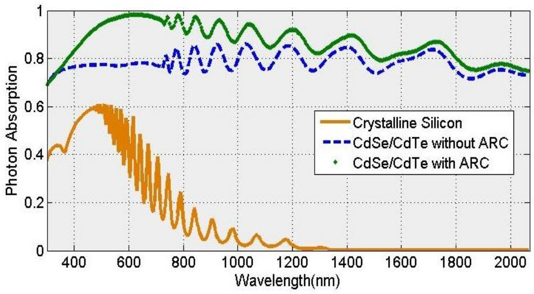

Figure 3. Comparison of photon absorption between crystalline silicon cell and CdSe/CdTe cell with and without ARC.

Crystalline silicon is the most popular single junction solar cell. From Fig. 3 it is seen that our cell has shown better photon absorption efficiency than the c-Si solar cell in the entire solar spectral range.

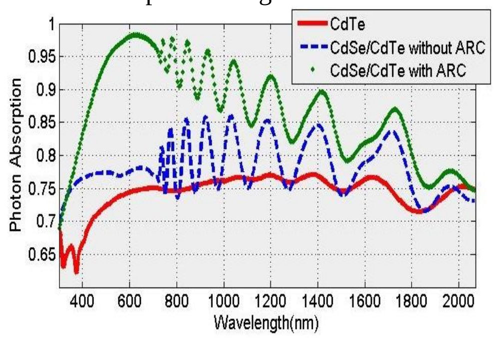

Figure 4. Comparison of photon absorption between CdTe single junction cell and CdSe/CdTe cell with and without ARC.

Cadmium Telluride (CdTe) is the most successful thin film photovoltaic technology to surpass crystalline silicon [9]. The best cell efficiency of CdTe has plateaued at 16.5% since 2001. Fig. 4 shows a comparison of CdTe cell with our dual junction cell with and without anti-reflective coating. The simulation results in Fig. 4 identifiably show that CdSe/CdTe cell has better photon absorption than single junction CdTe solar cell.

A lattice mismatched 1.6eV GaInP and 1.1 eV GaAs grown with an Air Mass Zero(AM0) achieved an efficiency of 23% with dual layer anti-reflective coating [10]. Fig. 5 shows a comparison of CdSe/CdTe cells and GaInP/GaAs. It is clear that the absorption is much higher in our proposed cell.

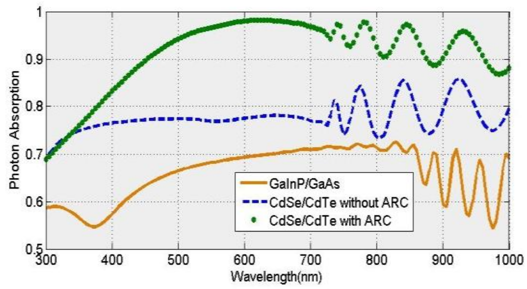

Figure 5. Comparison of photon absorption between GaInP/GaAs cell and CdSe/CdTe cell with and without ARC.

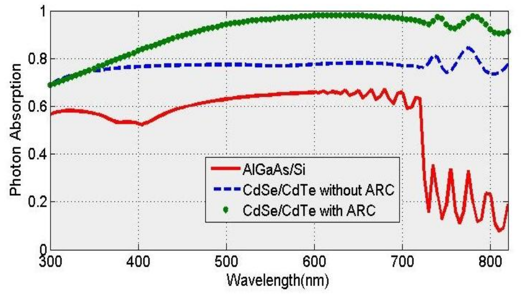

Figure 6. Comparison of photon absorption between AlGaAs/Si cell and CdSe/CdTe cell with and without ARC.

AlGaAs/Si is a monolithic dual junction cell which has an attractive combination of materials for obtaining high efficiency [11]. In Fig. 6, we see that our solar cell executes better performance than this dual junction cell for the entire solar spectrum.

V. Efficiency Calculation

Performing a calculation using the Shockley Quisser methodology [12], a two layer cell can reach a maximum theoretical efficiency of 42% and three layer cells 49%. The maximum theoretical limit efficiency of multijunction cells with infinite junctions is 86.8% [13].

The conversion efficiency η of solar cells is calculated as the ratio between the generated maximum power P_m, generated by a solar cell and the incident power P_{in}.

$$\eta = \frac{P_m}{P_{in}} \tag{8}$$

$$P_{in} = \int_0^{\infty} \phi(\lambda) \frac{hc}{\lambda} d\lambda \tag{9}$$

Where, $\phi(\lambda)$ is the photon flux density, h is Planck's constant, and c is the velocity of light. The relation between solar spectral irradiance $I(\lambda)$ and photon flux $\phi(\lambda)$ is given by:

$$I(\lambda) = \phi(\lambda) \times \frac{hc}{\lambda} \tag{10}$$

$$P_{in} = \int_0^{\infty} I(\lambda) d\lambda \tag{11}$$

output power P_m is given by:

$$P_m = E_g \int_0^{\lambda_g} \phi(\lambda) d\lambda (1-R) QE_{op} \eta_g QE_{el} \tag{12}$$

Where, E_g is the bandgap of the absorber layer and λ_g is the wavelength of photons that corresponds to the bandgap energy of the absorber of the cell. QE_{op} is the internal optical quantum efficiency which is the probability of a photon being absorbed in a material; η_g represents the number of electron-hole pairs generated by one absorbed photon. QE_{el} is the electrical quantum efficiency and is defined as the probability that a photo-generated carrier is collected. Here we have assumed that each photon creates one electron-hole pair and electron collection efficiency is 100% i.e. $QE_{op} = \eta_g = QE_{el} = 1$.

$$\eta = \frac{\int_0^{\lambda_g} I(\lambda) A(\lambda) \frac{\lambda}{\lambda_g} d\lambda}{\int_0^{\infty} I(\lambda) d\lambda} \tag{13}$$

In the above equation, $I(\lambda)$ is the solar spectral irradiance of the ASTM AM1.5 [14]. Absorptance of the spectrum $A(\lambda)$ is found from the Photonics RT simulator [3] and for this particular cell λg = 2065nm.

In the efficiency calculation different thicknesses of the cell has been considered to find out the optimum thickness which gives the best efficiency. The thicknesses of the tested cell range from 500nm-5000nm. Fig.7 shows the effect of thickness on overall efficiency.

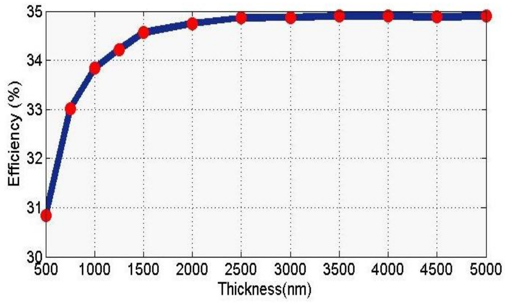

Figure 7. Thickness VS efficiency graph.

Using eq. 13 we calculated the theoretical conversion efficiency (η) of our CdSe/CdTe cell and other single and dual junction cells. Table 1 compares the calculated η values for the single and multi-junction solar cells under 1 sun AM1.5 illumination. The results in Table 1 show that our dual junction group II-VI CdSe/CdTe cell has better efficiency than other single and dual junction III-V solar cells.

TABLE I. Calculated Efficiencies For Different Single And Multijunction Cells.

Solar Cell Type	Cell Example	Efficiency (%)
Single Junction	Crystalline Silicon	6.90
Dual Junction	GaInP/GaAs	31.8
Dual Junction	AlGaAs/Si	22.5
Dual Junction	CdSe/CdTe	34.6

VI. Conclusion

The main challenges in the photovoltaic research are to increase the solar conversion efficiency of the existing solar cells and to make them more cost effective for commercial applications. Single junction cells provide a limited efficiency, whereas in multijunction cells the efficiency reaches to a great extent. In this work we have proposed a dual junction cell based on CdSe and CdTe. We showed the photon absorptance, transmittance and reflectance of this cell. The top layer of CdSe helped to increase the photon absorption in the initial range (300-712nm) of the solar spectrum and CdTe has given boost to the photon absorption in the range of 700nm and beyond. We compared the photon absorptance of the proposed cell with other single and dual junction cells. Finally, we calculated the theoretical conversion efficiency of our cell and compared it with the other cells. The results obtained from the simulations indicate that CdSe/CdTe is a promising cell for future use in multijunction cell applications. A theoretical efficiency of 34.6% suggests that group II-VI CdSe/CdTe cell with this efficiency should be actualizable in near future.

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