The Thickness Effect of Indium-Phosphide-Oxide Layer on Photon Absorption of Multi-junction Photovoltaic Cells

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Abstract—In this paper we have investigated the thickness effect of the anti-reflective coating (ARC), Indium-Phosphide-Oxide (InPO) on the multi-junction cell based on InP/InGaAs/InGaSb. Different thickness of InPO has been considered to find out the optimum thickness which produces the best photon absorption. Real Time Photonics Simulator has been used to analyze the results of the photon absorption, photon transmission and photon reflection. The thicknesses of the ARC tested are: 30nm, 70nm, 90nm, 100nm, 130nm and 150nm. Comparing the simulation results of each of the cell with different thickness of InPO, our result shows that at a thickness of 100nm the photovoltaic cell has the best photon absorption. Our result shows the increase in photon absorption between 30nm to 100nm thickness of the ARC and then decrease in photon absorption. Thus we see that the ARC with a thickness of 100nm, the photovoltaic cell executes the highest photon absorption in the range of in the range of 400nm – 774nm wavelength of the solar spectrum, thus producing high solar conversion efficiency.

Keywords—photovoltaic, single-junction, multi-junction, anti-reflective coating, indium-phosphide-oxide

I. INTRODUCTION

Photons incident on the surface of a semiconductor will be either reflected from the upper surface, will be absorbed in the material or will be transmitted through the material. For photovoltaic devices, reflection and transmission are typically considered loss mechanisms since photons which are not absorbed by the semiconductor material do not generate electron-hole pairs. When a photon is absorbed it will raise an electron from the valence band to the conduction band. The key factor in determining the absorption or the transmission of the photon is the energy of the photon. Photons falling onto a semiconductor material can be divided into three groups based on their energy compared to that of the semiconductor band gap. The generation rate of the electron gives the number of electrons generated at each point in the device due to the absorption of solar photons. Neglecting reflection, the amount of photons which are absorbed by a material depends on the absorption coefficient ($\alpha$ in cm$^{-1}$) and the thickness of the absorbing material. A good ARC reduces photon reflection intensely compared to simple photovoltaic cell surfaces. The high refractive indices of semiconductors and high reflection losses of the solar cell can be reduced [1] for both silicon solar cell [2, 3] and multi-junction [4, 5] solar cells. The design of the optimum ARC must not be based only on reducing the light reflectance but also make the most of the external quantum efficiency or diminishing the loss of short circuit current due to reflection. In this work, we have analyzed the photon absorption of the cell by using different thickness of the ARC on a multi-junction (MJ) photovoltaic (PV) cell. We have compared the results of the photon absorption, transmission and reflection of the current high efficient MJ PV cell with varying ARC thickness. We have simulated the performance of the cell with an online Real Time Photonics Simulator, PhotnicsRT. We have taken different thickness of the anti-reflective coating, which includes 30nm, 70nm, 90nm, 100nm, 130nm and 150nm. After comparing the results of the simulations, we see a variation of photon absorption of each of the cell tested with different ARC thickness. Our result shows the best performance of PV cell with ARC thickness of 100nm. We found that at a thickness of 100nm the photon absorption at a wavelength of 400nm is 64.4%, 525nm is 96.4%, 600nm is 95% and 700nm is 80.8%. The research on the MJ PV cell carried out by Simon Y. Foo and Indranil Bhattacharya of Florida State University showed that the PV cell based on InP/InGaAs/InGaSb has best photon absorption in the range of 598nm-800nm of the solar spectrum. The photon absorption of their research shows at 400 nm is 69%, at 500nm 81%, 600 nm 80.2% and at 700 nm 71% [7]. However our result shows that with the addition of ARC with a thickness of 100nm the photon absorption is increased.
dramatically increasing the photovoltaic conversion efficiency.

II. ANTI-REFLECTIVE COATING

ARC is a dielectric thin film applied to an optical surface to reduce the optical reflectivity of that surface. The coating for a single layer ARC is designed for normal incidence consists of a single quarter-wave layer of a material, also the refractive index of which is close to the geometric mean value of the refractive indices of the two adjacent media. At the time of this situation the two reflections of equal magnitude arise at the two interfaces, and these reflections cancel each other by destructive interference [8].

\[ \Delta = 2n_1 t. \]  
(1)

Equation (1) shows the optical path difference of the light. Where, \( n_1 \) is the refractive index of the anti-reflective coating and \( t \) is the thickness of the anti-reflective coating.

In Fig. 1, both ray 1 and ray 2 undergo 180° shifts equal to \( \lambda_0 / 2 \), in the meantime both reflections occur at interfaces separating lower-to-higher refractive indexes. As a result the difference in phase between ray 1 and ray 2 comes from only the optical path difference due to the coating thickness \( t \). Now, if the thickness \( t \) of ray 2 falls behind ray 1 by \( \lambda_1 / 2 \), the two rays interfere destructively consequently minimizing the reflected light. At near-normal incidence this requires that the distance 2\( t \) [9]

The mathematical condition for anti-reflective coating is then given by

\[ \Delta = 2n_1 t = \frac{\lambda_0}{2} \]
\[ t = \frac{\lambda_0}{4n_1} \]

The amount of light which is absorbed by a material depends on the absorption coefficient (\( \alpha \) in \( \text{cm}^{-1} \)) and the thickness of the absorbing material. The intensity of light at any point in the device can be calculated according to the Eq. 2.

\[ I = I_0 e^{-\alpha x} \]  
(2)

where, \( \alpha \) is the absorption coefficient typically in \( \text{cm}^{-1} \) and \( x \) is the distance into the material at which the light intensity is being calculated and \( I_0 \) is the light intensity at the top surface. Equation (3) can be used to calculate the number of electron-hole pairs being generated in a solar cell [8].

\[ G = \alpha N_0 e^{-\alpha x} \]  
(3)

where, \( N_0 = \) photon flux at the surface (photons/unit-area/sec.), \( \alpha = \) absorption coefficient and \( x = \) distance into the material.

III. SIMULATION AND RESULTS

The thickness of the ARC considered are, 30nm, 70nm, 90nm, 100nm, 130nm and 150nm. And the thickness of the other layers of the cell was 100nm respectively. The PV cell based on InPO/InP/InGaAs/InGaSb was exposed in solar radiation at an angle of 45°and at a wavelength of 400nm – 775nm. Fig. 2 shows the structure of the PV cell InPO/InP/InGaAs/InGaSb having 1.35eV, 1.1eV, and 0.5eV bandgap respectively. The performance of the cell has been simulated with an online simulator, PhonicsRT [10]. The aim of our work is to show the thickness effects of the ARC on the photon absorption of the MJ PV cell. We are concerned about the optimum thickness of the ARC which would produce maximum photon absorption and minimum photon reflection. Subsequently, the higher photon absorption would enable the creation of superior number of mobile holes and electrons. The result of the simulations are shown below:
In Fig. 3, the curve 1 represents absorption, curve 2 reflectance and curve 3 transmittance. The photon absorption is 55.59%, 62.57%, 60.57%, 50.6% at 400nm, 500nm, 600nm, and 700 nm respectively.

In Fig. 4, the curve 1 represents absorption, curve 2 reflectance and curve 3 transmittance. The photon absorption is 88%, 88.3%, 79.8%, 65.36% at 400nm, 500nm, 600nm, and 700 nm respectively.

In Fig. 5, the curve 1 represents absorption, curve 2 reflectance and curve 3 transmittance. The photon absorption is 74.9%, 96.6%, 91.2%, 76.3% at 400nm, 500nm, 600nm, and 700 nm respectively.

In Fig. 6, the curve 1 represents absorption, curve 2 reflectance and curve 3 transmittance. The photon absorption is 64.4%, 95.4%, 95.1%, 81.6% at 400nm, 500nm, 600nm, and 700 nm respectively.

In Fig. 7, the curve 1 represents absorption, curve 2 reflectance and curve 3 transmittance. The photon absorption is 44.9%, 76.6%, 92.1%, 89.9% at 400nm, 500nm, 600nm, and 700 nm respectively.

In Fig. 8, the curve 1 represents absorption, curve 2 reflectance and curve 3 transmittance. The photon absorption is 42.8%, 64%, 94.9%, 85.1% at 400nm, 500nm, 600nm, and 700 nm respectively.

Analysing the results of all the simulations of different thickness of the ARC, we see that, the ARC with 100nm thickness shows the best performance of all other thickness we have tested. Also, the photon absorption of the MJ PV cell based on InPO/InP/InGaAs/InGaSb executes the maximum photon absorption when we used InPO of thickness 100nm. The photon absorption at a wavelength of 400nm is 64.4%, 525nm is 96.4%, 600nm is 95% and 700nm is 80.8%. The four layers, InPO/InP/InGaAs/InGaSb PV cell, have the best photon absorption in the range of 400nm – 774nm of the solar spectrum.
significantly. The photon absorption of our four layers of 100nm thickness of our ARC we have tested. With the use of the optimum thickness of the ARC the optical loss of the cell has been minimized contributing to higher cell efficiency. The researchers at Florida State University designed a triple junction PV cell based on InPO/InP/InGaAs/InGaSb with the best photon absorption in the range of 598nm – 800nm of the solar spectrum. On the other hand, in our work we have shown how the use of ARC of 100nm thickness the photon absorption increases significantly. The photon absorption of our four layers InPO/InP/InGaAs/InGaSb PV cell at a wavelength of 400nm is 64.4%, 525nm is 96.4%, 600nm is 95% and 700nm is 80.8%. This result is better in comparing to the PV cell InP/InGaAs/InGaSb and any other thickness of ARC other than 100nm of InPO/InGaAs/InGaSb PV cell. The MJ PV cell based on InPO/InP/InGaAs/InGaSb has much better photon absorption in the range of 528nm – 710nm of the solar spectrum. Thus, in this paper we have shown how the photon absorption increases with the use of optimum thickness of ARC on MJ PV cell.

IV. CONCLUSION

The use of ARC of 100nm thickness of the MJ solar cell based on InPO/InP/InGaAs/InGaSb has shown to produce the greatest photon absorption than any other thickness of the ARC we have tested. With the use of the optimum thickness of the ARC the optical loss of the cell has been minimized contributing to higher cell efficiency. The researchers at Florida State University designed a triple junction PV cell based on InPO/InP/InGaAs/InGaSb with the best photon absorption in the range of 598nm – 800nm of the solar spectrum. On the other hand, in our work we have shown how the use of ARC of 100nm thickness the photon absorption increases significantly. The photon absorption of our four layers InPO/InP/InGaAs/InGaSb PV cell at a wavelength of 400nm is 64.4%, 525nm is 96.4%, 600nm is 95% and 700nm is 80.8%. This result is better in comparing to the PV cell InP/InGaAs/InGaSb and any other thickness of ARC other than 100nm of InPO/InGaAs/InGaSb PV cell. The MJ PV cell based on InPO/InP/InGaAs/InGaSb has much better photon absorption in the range of 528nm – 710nm of the solar spectrum. Thus, in this paper we have shown how the photon absorption increases with the use of optimum thickness of ARC on MJ PV cell.

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