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PHOTON RECYCLING FOR IMPROVED ABSORPTION IN THIN FILM ITO/INP HETEROSTRUCTURE SOLAR CELL

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ABSTRACT: In this work, numerical analysis of thin-film indium phosphide heterojunction solar cell is presented and the absorption process of the incident photons is improved by incorporating a photonic bandgap structure (photonic crystal) in the structure. The cell consists of an indium tin oxide forming a heterojunction with indium phosphide (InP). The top indium tin oxide layer is intended to perform as an anti-reflection coating to reduce optical feedback and also eliminates the need for top metal contact as it is highly conductive. A 2D photonic crystal is incorporated at the back of the device to boost the performance of the photovoltaic device through the process of photon recycling. The device is especially promising for space solar projects because of its exceptional radiation hardness. The projected efficiency as calculated at AM 1.5 by the SYNOPSYS RSOFT CAD software is 25.7% with a fill factor of 86.1% is very promising. Finally, the performance of the designed InP solar cell with photonic crystal is compared to the InP solar cell with a metal back reflector.

KEYWORDS: Thin Film, Solar Cell, Heterojunction, Indium Phosphide, Indium Tin Oxide, Photonic Crystal, Anti-Reflection Coating.

I. INTRODUCTION

Compound III-V photovoltaic (PV) materials are essentially used to fabricate devices for space applications because of their high absorption and radiation-resistant property. They have achieved the highest efficiencies (more than 40%) for PV technology in today's solar cell market [1, 2]. Among them, Indium Phosphide (InP) is typically used as absorber material in photovoltaic and high-speed electronic devices. InP has an energy bandgap of 1.34 eV at 300^0K and a higher mean saturation velocity resulting in higher frequency optoelectronic devices. This gives InP solar cells an edge to go beyond the Shockley Queisser (SQ) efficiency limit which is around 33.7% [3] and is best for both space and terrestrial applications. As Indium Phosphide is expensive material research on the fabrication of solar cells made out of it slowed down. In the last few years, not much research is done to enhance the efficiency of a thin film Indium Phosphide solar cell. However, InP has a notable advantage in space-based solar PV applications due to its inherent high resistance to radiation damage. Even for multi bandgap PV systems, it has many useful and important characteristics. Soon after the discovery of such technologically important properties of InP, the development of InP solar cells was at a peak for several years during the middle 1980s. However, despite this potential, the current record-efficiency of InP material solar cells is 24.2% [4-6], much less than that demonstrated by Gallium Arsenide (GaAs) solar cells which are about 28% [7, 8]. In this proposed work the enhancement of the PCE of a radiation-resistant InP thin-film solar cell (TFSC) is demonstrated by implementing a PhC as a wavelength selective back reflector.

1.1. Proposed solar cell design

A heavily doped n-type Indium Tin Oxide (ITO) and p-type Indium Phosphide (InP) are used to form a thin active region (277 nm) of heterojunction solar cells. Here ITO is serving as both anti-reflection coating (ARC) layer (77 nm) and light-trapping structure. It possesses high electrical conductivity and hence eliminates the need for top metal contact. Just below the active layer, there is a layer of p+ InP (160 nm) induces a back-surface field (BSF) preventing recombination at the back-surface. Finally, a PhC (7x7 Ge rods in SiO_2) is incorporated to facilitate the process of photon recycling by reflecting the photons of the desired wavelength into the active layer to increase the photon absorption (figure 1). The thickness of the InP main absorber layer is calculated only after studying the absorption coefficient and optimization of thickness concerning the incident solar spectrum. Thus, the InP solar cell overall thickness is 1.7µm with an active layer thickness of only 0.437µm. The respective parameters of the device are summarized in Table 1.

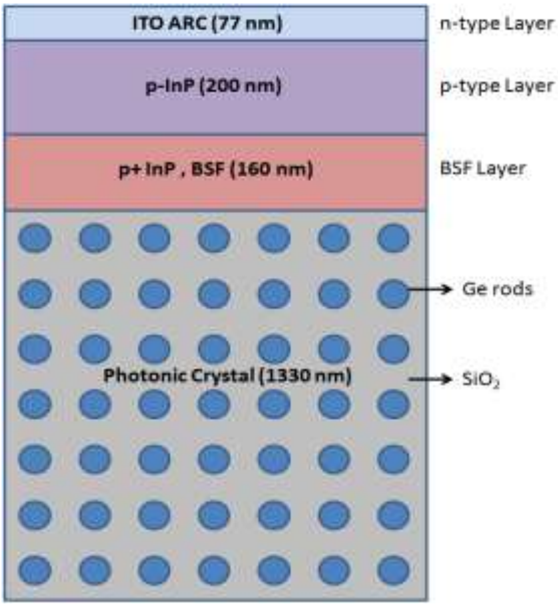

Figure 1. Proposed ITO-InP hetero-junction solar cell with photonic crystal as a back reflector.

Table 1. Proposed solar cell design parameters, materials used, and doping concentration of each layer.

S. No.	Layer	Thickness (nm)	Material	Doping Concentration (per cm^{-3})
1	ARC/n-type	77	ITO	2 x 10^{19} (donor)
2	p-type	200	InP	2 x 10^{17} (acceptor)
3	p+ BSF	160	InP	1 x 10^{19} (acceptor)
4	PhC Back reflector	1330	Ge rods in SiO_2	N.A.

1.2. Inp as promising pv material

InP is an III-V binary semiconductor compound made up of Indium and Phosphorous with a zincblende crystal structure like that of GaAs and all other semiconductors in the III-V group and is second to GaAs as a PV material for improved devices [9]. Due to its attractive electronic and optical properties, InP is chosen as the main absorber material [10]. It has a direct electronic bandgap of 1.34eV and is almost equal to the ideal bandgap achieve by a single p-n junction solar cell with a back-surface mirror at the SQ limit of around 33.7% [3]. It shows impressive chemical, electrical, thermal, and optical properties and therefore is popular in high power devices [8-10]. InP is best suitable for space solar applications due to its low photo-degradation and thermal stability (0.68 W cm^{-1} °C-1), which is far better than the rest of the PV materials such as silicon (Si), making InP solar cells relatively insensitive to heat radiation in contrast to conventional PV materials such as Si [9-11]. Protons and electrons irradiation with high energy creates displacements of atoms also called lattice defects. Complex defects such as vacancy impurity, di-vacancy, interstitial impurity, etc are generated. This induces additional energy states and hence the recombination losses become significant. At concentration $<10^{18}$ cm^3 InP is less vulnerable to crystal defects in comparison to GaAs and has substantially enhanced radiation resistance than GaAs and Si solar cells [11]. The absorption spectrum and absorption depth of the InP depict that the material shows high absorbance for a wider range of incoming spectrum with lesser material especially the photons with higher energy hence TFSCs can be made out of it, making InP a promising material for both space and terrestrial solar applications [12-19]. The major issue with InP is that the material is quite expensive, limiting its application to high-end devices such as space-based solar applications. However, the cost can be greatly reduced by growing extremely thin layers of InP without affecting the PCE of the solar cell. During the last decade the power conversion efficiency of a single junction InP solar cell remarkably improved, however, it is still less than the SQ limit 33%, leaving much space for improvement [19, 20].

1.3. Ito/inp heterostructure and modelling of arc

The energy band diagram of the ITO/p-InP structure was earlier presented in (Botnariuc et al., 1990). The mechanism of current flow within the ITO/InP structures, obtained in different fabrication conditions, was demonstrated in (Andronic et al., 1998) [21]. Hetero-structured solar cells have an edge over conventionally solar cells in terms of better collection efficiency, low radiative losses due to the formation of quantum wells and are cheaper [22]. The reduction of optical feedback (unwanted loss of optical power at the top surface due to specular reflections) is necessary for enhancing the process of absorption in solar cells. The intensity of reflected light from any surface is computed by using the Fresnel equation [23-25]. For a perfect anti-reflection layer coating, the following criteria must be fulfilled by the layer in to minimize the reflections from the semiconductor:

$$n_{arc} = \sqrt{n_o \cdot n_s} \quad (1)$$

$$d_{arc} = \lambda / (4\, n_{arc}) \quad (2)$$

wherein equation 1, 'n_{arc}', 'n_o', and 'n_s' is the refractive index (RI) of ARC, air, and semiconductor respectively whereas in equation 2, 'd_{arc}' is the thickness of the ARC. This is necessary to establish a 180^o phase shift between the reflections from the top surface of the ARC layer and the semiconductor layer. Thus, the two reflected waves are out of phase with each other hence cancels out each other to produce no reflections [26]. Here, Indium-tin-oxide (ITO) is intended to be used as ARC for its appealing electrical and optical properties. The high conductivity and low resistive losses (~104 S/m) of ITO eliminates the deposition of an external metal terminal [27]. It is flexible and highly transparent with a transmittance of > 95% [28-30]. Thus, using the above two equations the value of narc and d_{arc} is calculated as 1.890 and 0.0765µm respectively. The reflection curve and the transmission curve for the ITO layer after the formation of ITO-InP heterojunction are obtained from the simulation is shown in figure 2. The front side ARC layer is advantageous in terms of facilitating both anti-reflection and light trapping. Multilayer ARCs just like double-layer ARCs are a combination of several dielectric layers with different refractive indexes capable to provide multiple dips in the reflection spectra thus reducing surface reflection over a broader range of the incident spectrum. However, their fabrication is complex and relatively expensive [30, 31]. In the proposed solar cell a single layer ARC is used to keep the structure simple and as thin as possible.

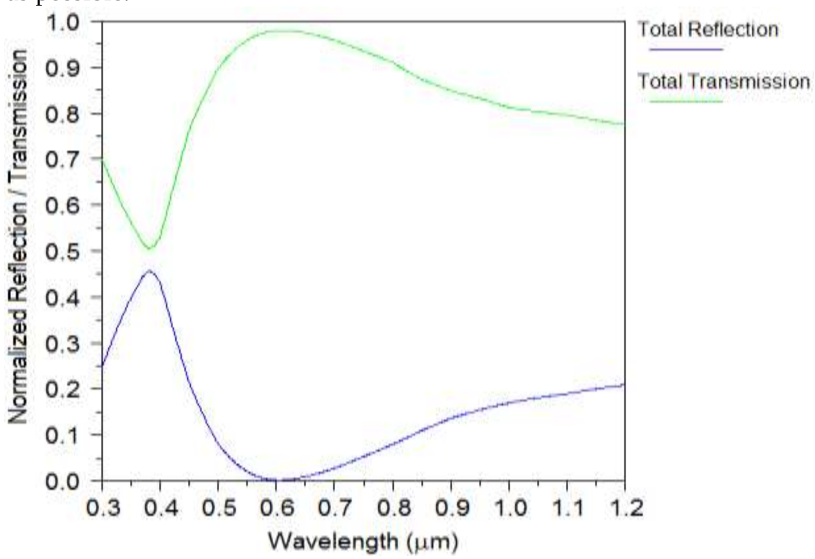

Figure 2. Simulated reflection and transmission curve for ITO ARC layer after the formation of ITO-InP hetero-junction.

1.4. Photon Recycling Through Photonic Crystal

Back metal reflectors or selective wavelength reflectors such as photonic crystals are being incorporated in solar cell design for many years to enhance the PCE of solar cells. Since TFSCs are characterized by a thin absorber layer of less than 10µm, they suffer from insufficient absorption of the incoming solar spectrum. Since the incident wavelength is dependent on the material's absorption coefficient (equation 3), it requires a finite depth (equation 4) before the photon at a specific wavelength is absorbed by the material. More the number of incident photons absorbed successfully, greater will be the excitons generated and hence the short circuit current 'J_{sc}' of the solar cell. The absorption coefficient of a material is given as:

$$\alpha = (4\pi k) / \lambda \text{ cm}^{-1} \quad (3)$$

$$d = 1 / \alpha \text{ cm} \quad (4)$$

Where 'α' and 'k' are the material-dependent absorption coefficient and the extinction coefficient, 'λ' is the incident wavelength and 'd' is the absorption depth. For the proposed structure the efficient absorption occurs at an active layer thickness of 0.36 µm (figure 3).

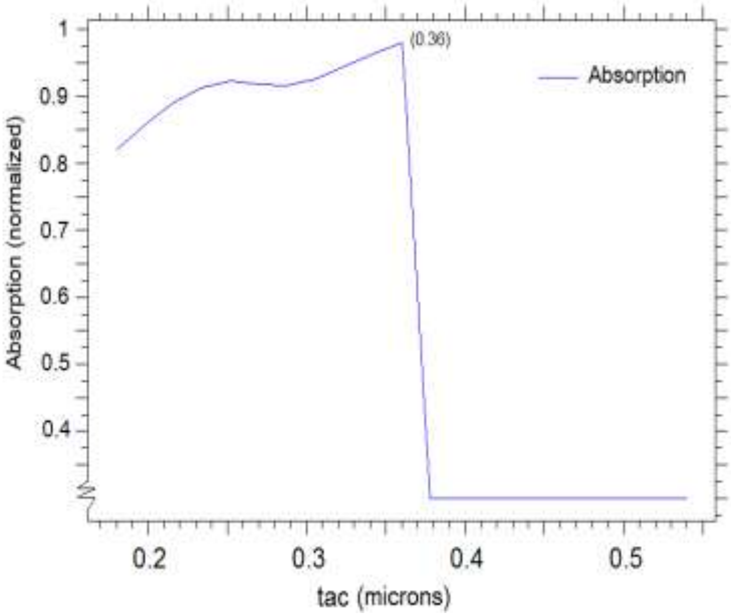

Figure 3. Optimized active layer thickness using the Rsoft CAD tool. In the graph, 't_{ac}' is the active layer thickness. Maximum absorption is achieved at 0.36µm.

A further enhancement in the PCE of the TFSC can be achieved by using a PhC as a selective wavelength reflector [32-34]. Usually, in TFSCs there is still a range of incident photons that passes through the cell unabsorbed by the active layer. However, trapping the light inside the active region for a much longer time can greatly enhance the absorption process. One way to achieve this is to reflect the photons again into the active region which increases the optical path length (OPL) for the successful absorption of the incoming photons. This method of enhancing absorption is termed as photon recycling [35]. Typically, a metallic back reflector such as Aluminium (Al) or Silver (Ag) is coated having reflectance more than 90%. However, this semiconductor-metal interface gives rise to unwanted surface plasmon optical losses. Metallic surfaces also have limited diffraction capabilities and high degradation rates as they are corrosive [36, 37]. The proposed design consists of a tuned photonic bandgap crystal consisting of a 7x7 2D cubic lattice (Ge rods in SiO_2) in place of the conventional metallic coating. The selection of these two materials facilitates cost-effectiveness and the ease of fabrication. The contrast between the dielectrics of the materials, the radius of rods, and the period are optimized such that it must introduce a photonic bandgap (PBG) in the desired range of wavelength. Thus, the prohibited modes can be computed by solving the below Maxwell's equation:

$$\nabla \times \frac{1}{\epsilon(r)} \nabla \times H(r) = \left(\frac{\omega}{c}\right)^2 H(r) \quad (5)$$

where 'H' is the magnetic field, '∈' is the structure permittivity, 'c' is the free space velocity of light and 'ω' is the operational frequency. Here, the Plane Wave Expansion (PWE) method is used for the computation of PBG, and the bandgap is computed as:

$$\text{Bandgap value} = a / \lambda \quad (6)$$

where 'a' is the period of the PhC and 'λ' is the operating wavelength. The PhC's period and rods radius are optimized by Multi-Variable Optimizer and Scanner (MOST) feature of RSOFT CAD software (figure 4) and found to be 190 nm and 38 nm, resulting in the TE bandgap range of 662 nm to 1000 nm which in turn is selected in compliance with the absorption spectrum of ITO-InP solar cell without back reflector (figure 5(a) and figure 5(b)) at 700 nm wavelength of photons.

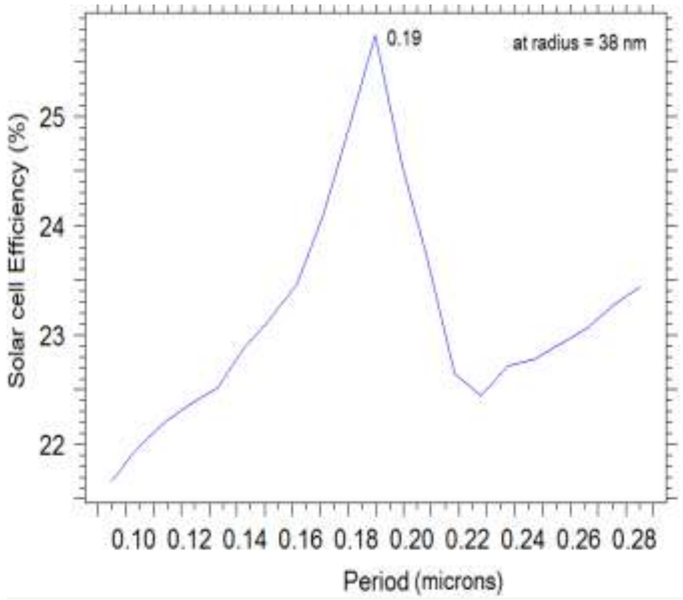

Figure 5. The optimized value of the lattice period of PhC for maximum PCE is found to be 0.19µm.

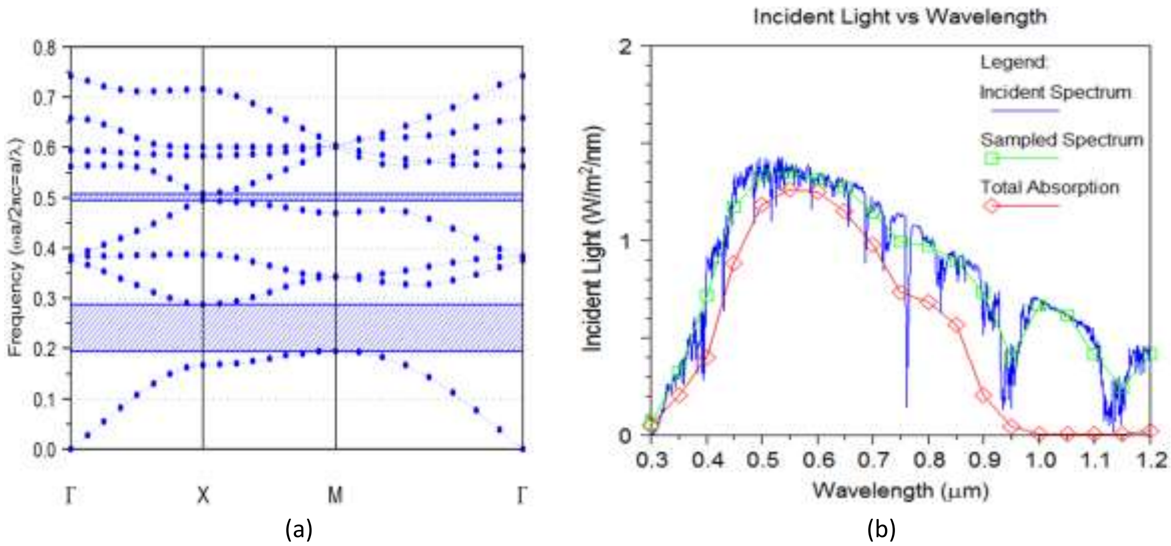

Figure 4. (a) Bandgap graph of designed PhC at a free-space wavelength of 700nm, (b) Absorption spectrum of ITO-InP solar cell without PhC.

1.5. Power Conversion Efficiency Calculation

The energy contained by a photon at any wavelength is given by:

$$E(\lambda) = h\nu = \frac{hc}{\lambda} \text{ eV} \quad (7)$$

Where 'c' is the speed of light in free space, 'λ' is the wavelength, and 'h' is the Planck constant. The total number of incoming photons at incident solar spectrum S (λ) is therefore given as:

$$n_s(\lambda) = \frac{S(\lambda)}{E(\lambda)} = \frac{\lambda}{hc} S(\lambda) \quad (8)$$

The absorption spectra of each layer is added up to get the total absorption:

$$A(\lambda) = \Sigma A_i(\lambda) \quad (9)$$

The absorption spectrum is thus computed by the simulation tool and the absorption of the photons by each layer can be determined as:

$$n_i(\lambda) = \frac{S(\lambda)Ai(\lambda)}{E(\lambda)} = \frac{\lambda}{hc} S(\lambda) A_i(\lambda) \quad (10)$$

S(λ) is the same as the total J_{sc} which can be represented alternately as:

$$J_{sc} = \int_{\lambda min}^{\lambda max} (J_n + J_p + J_d) d\lambda \quad (11)$$

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Where J_n and J_p are the current density of emitter, collector and J_d is the photogenerated current. The V_{oc} of a solar cell is given by:

$$V_{oc} = \frac{nkt}{q} \ln \left(\frac{J_{sc}}{J_o} + 1 \right) \quad (12)$$

Where J_o is the saturation current density, the power conversion efficiency of the solar cell thus can be computed by the expression:

$$\eta (\%) = \frac{J_{sc} \times V_{oc} \times FF}{P_{in}} \times 100 \quad (13)$$

II. RESULT AND DISCUSSION

The structure is simulated using "RSOFT's DiffractMOD and Solar Cell Utility" based on RCWA algorithm which numerically analyzes the behavior of the solar cell and to compute the PCE. The method efficiently determines the transmission and reflection from periodic structures [38-40]. The structure is simulated at 100% collection efficiency, considering only optical losses. The resulted PCE is 'η' = 25.74% with 'J_{sc}' = 33.1 mA/cm2, 'V_{oc}' = 0.81 V and a fill factor of 'FF' = 86.17 % (figure 6 (a)). The quantum efficiency curve in figure 6 (b), shows the proposed solar cell quite efficiently converts a large number of photons to electric current. A comparison study is also made with the ITO-InP solar cell without any back reflector and with Al metal as a back reflector. It is found that the incident solar spectrum absorption is increased as compared to the single junction ITO-InP solar cell without PhC which can be seen in figure 7.

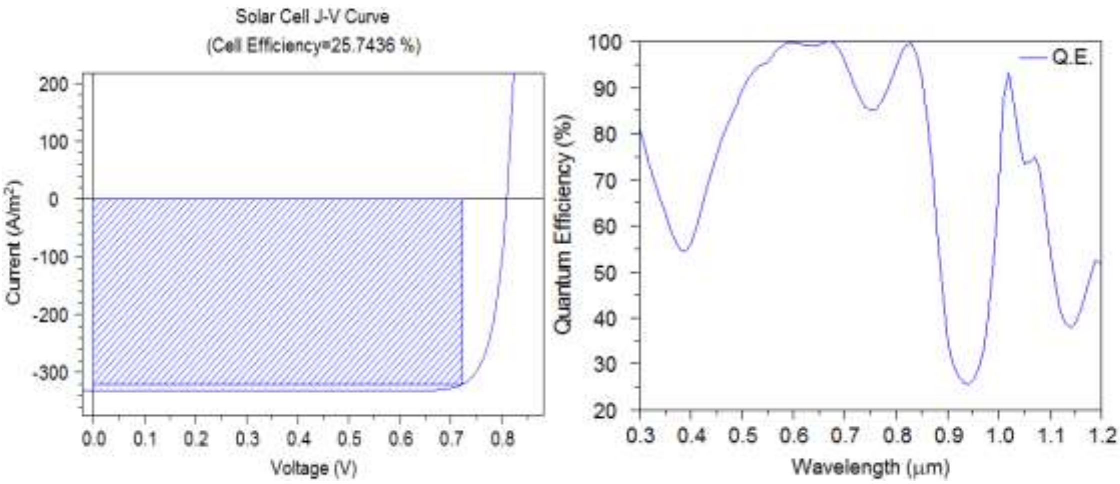

Figure 6. (a) Conversion efficiency and J-V curve of the proposed ITO-InP solar cell structure with FF = 86.1 %. (b) Quantum Efficiency of the proposed ITO-InP solar cell.

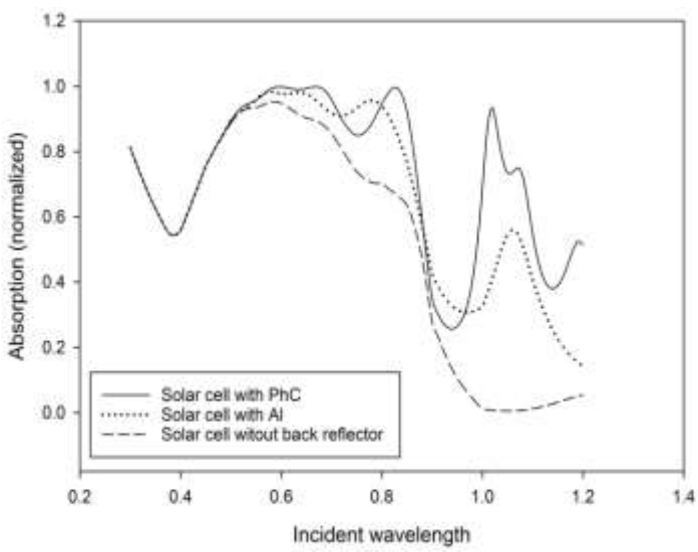

Figure 7. Graph showing the enhancement in the absorption of the incident solar spectrum by PhC back reflector over Al metal back reflector and no back reflector.

Table 2. demonstrates the increase in the PCE and fill-factor on increasing the V_{oc} of the solar cell. At V_{oc} = 1V and greater, the efficiency is even higher than the SQ limit of 33%. The constant current shows that the current has now reached to a maximum value as no additional photon recycling is occurring. The performance of the designed ITO-InP solar cell with PhC is compared with the cell without any reflector and after adding an Al metal back reflector (figure 7 and figure 8). It can be observed from the graphs that using PhC can significantly enhance the short circuit current through the process of photon-recycling. This increases the total absorption of the incident solar spectrum and hence the PCE.

Table 2. The table shows the increase in PCE of the solar cell with V_{oc} and an increase in J_{sc} as a result of photon recycling.

S.No.	V_{oc} (V)	J_{sc} (mA/cm^2)	FF (%)	η(%)
1	0.7	32.4	84.5	21.4
2	0.76	32.6	85.5	23.5
3	0.81	33.1	86.1	25.7
4	0.87	33.1	86.8	27.8
5	0.92	33.1	87.4	29.6
6	0.99	33.1	88.1	32.1
7	1.12	33.1	89.1	36.8
8	1.2	33.1	89.7	39.7

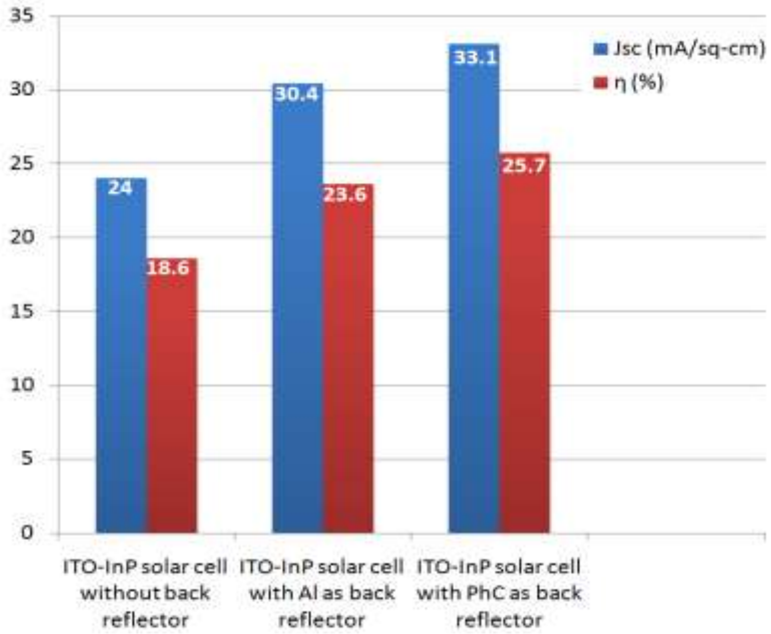

Figure 8. Comparison showing the increase in the J_{sc} and PCE of the solar cell with the use of back reflector at V_{oc} of 0.81V. In the proposed solar cell design, using PhC gives the highest J_{sc} and PCE.

III. CONCLUSION

Thus, by implementing a PBG structure as a back reflector the PCE of the ITO-InP solar cell is substantially enhanced with an added advantage that the cell is radiation-resistant. This shows that the cell is a perfect solution for space solar PV applications where the recombination losses due to radiation and heating become a major problem. Numerical simulation of the solar cell showed that the efficiency is even higher than the record single-junction InP solar cell (22.1%) and the current highest efficiency of 24.2 % [4, 41]. The efficiency achieved with the current structure is 25.7 % with J_{sc} = 33.1 mA/cm2, FF = 86.1 % at open-circuit voltage of 0.81V. The current enhancement as a result of the use of PhC and reduced surface recombination due to the implementation of the back-surface field is very promising. To further increase the photo-current density quantum dots could be embedded in the structure thus leaving much room for future improvements.

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