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Design and Analysis of Light Trapping in Thin Film GaAs Solar Cells using 2D Photonic Crystal Structures at front surface

Nikhil Deep Gupta, Vijay Janyani, *Senior Member IEEE*

Abstract–**The paper proposes a design using 2D Photonic Crystal (PhC) structure based thin film hetero-junction GaAs solar cell with a periodic pattern extending from top Transparent Conducting Oxide (TCO) to inside the p-AlGaAs window layer placed just above the active layer of GaAs material. The paper presents the theoretical optical study and optimization of all the required parameters. The paper presents the optical optimization study for thin active layer cell in the generalized manner for 50 nm active layer and then the performance of the proposed structure is compared with Lambertian limits and the planar cell, taken as reference. It has been predicted that these wavelength scale periodic structures greatly enhances the performance of the cell. The improvement in the performance is basically accounted for the better diffraction capability, impedance matching, trapping of high wavelength photons and reduction in reflections from the top due to the PhC structure. The parameters have been optimized and calculated by means of rigorous coupled wave analysis (RCWA).**

Keywords **–Photonic Crystal Structures, Thin film solar cells, Photonic light trapping, GaAs based devices, Diffraction**

I. INTRODUCTION

Photovoltaic (PV) technologies basically suffer from the problem of low efficiency to cost ratio. The most part of the cost in a solar cell is basically contributed by the thickness of the absorption layer. Thus reducing the thickness of the active layer without compromising with the efficiency might provide wider acceptance to the PV technologies. During past decades, thin film technologies have shown that they have the capability to provide the solution to this problem [1], [2]. Thinning down the active material analyzed in this paper, i.e., Gallium Arsenide (GaAs) is all the more important because of its high cost. GaAs has several peculiarities, such as being a direct band gap material etc., which make it a special material for solar cell applications [3], however due to their high cost they are commonly not being preferred for terrestrial applications.

Although, thin film technologies, superficially, seem to have all the solution of the bulk solar cells, but they suffer from the problem of low efficiency as a large fraction of available spectrum is lost due to incomplete absorption. Thus, in order to improve this absorption, certain kind of light trapping technique must be introduced, in which the optical mean path length of the incident photons in the active layer virtually becomes more than the absorption depth required to absorb those photons and thus, eventually they could be absorbed and that too without practically increasing the solar cell thickness. Yablonovitch and Cody [4, 5] first introduced this concept for materials having very weak absorption and derived analytical solutions for light path enhancement possible with ideal Lambertian light-trapping, later extended by Green [6], for any degree of absorption in the active material.

Based on these solutions [6], Fig.1 has shown the comparison of Lambertian light trapping and a bare cell efficiency for GaAs active material of particular thickness without any kind of light trapping structure (LTS) for ideal conditions. One could easily analyze from the figure that an optimized LTS in a thinner cell could provide the same efficiency that could otherwise be achieved with a much thicker cell and thus could reduce the overall cost of the device. Thus, a design of low loss near to ideal LTS is very much a requirement for achieving high efficiency thin film GaAs cell, having values close to the Shockley-Queisser (S-Q) limit [7]. The material parameters used in the figure are taken from [8].

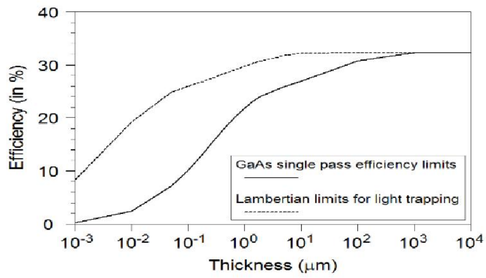

Fig. 1 Cell Efficiency versus active layer thickness graph for GaAs based solar cell using AM1.5 solar spectrum [9]. Ideal case has been considered without assuming any kind of loss.

Usually single layer planar Anti-Reflective Coating (ARC) at the top and metallic layer at the bottom as back reflector (BR) have been used for light trapping in the solar cells [1]. However, practically till date due to the shortcomings of the above mentioned structure [10, 11], it could not achieve even half of the value suggested in [4, 6]. Due to the reason, several new LTS have been proposed, ranging from using randomly roughened surfaces [12] to plasmonic metallic structures [13]. Researchers have also explored for novel structural schemes including ordered (eg. Photonic Crystals, PhC) dielectric LTS designs [3, 14, 15]. Although in case of random LTS,

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Nikhil Deep Gupta is a Ph.D. Scholar with department of Electronics and Communication Engineering, at Malaviya National Institute of Technology, Malaviya Nagar, JLN Marg, Jaipur, Rajasthan – 302017, India (e-mail: nikhildeep.gupta@gmail.com)
Vijay Janyani, a *Senior Fellow of IEEE,* is an Associate Professor with department of Electronics & Communication Engineering, at Malaviya National Institute of Technology, Malaviya Nagar, JLN Marg, Jaipur, Rajasthan – 302017, India (e-mail: vjanyani.ece@mnit.ac.in)

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enhancement could be achieved over broad spectrum, these structures are difficult to be engineered, rescale and reproduce. The periodic LTS has the advantage that the geometrical parameters could be easily varied and the whole structure could be fully engineered using modern lithography techniques, which is also one of the key motivation for this work.

PhC based solar cells have generated lot of interest during the past decade, as they allow controlling and manipulating the light matter interaction as per requirement. Several studies have been done on the subject including PhC as a single low loss dielectric back reflector [16, 17], PhC as a diffraction grating [3, 15, 18, 19], designing PhC within the absorbing material itself [20, 21]. However, most of these studies are based on Si active material, using PhC LTS either at the back (except few) of the ARC or at the back of the active layer. Thus, there is a need to explore the effect of PhC LTS at the top, which can work both as ARC and to maximize coupling of incident light, for thin GaAs solar cell.

In this paper, we have optically optimized and analyzed the effectiveness of the LTS consisting of PhC structure at the top, extending through the top Indium Tin Oxide (ITO) and p-AlGaAs window layer followed by GaAs active layer of just 50 nm thickness having back window layers of n-AlGaAs. Single layer planar BR of Aluminum (Al) is placed at the bottom. Here, the PhC structure not only helps in index matching for the incident light, but also helps in the coupling of the incident light to the absorbing layer and at the same time helps in increasing the optical path length for high wavelength photons through diffraction and thus contributes for the improvement in absorption almost throughout the solar spectrum. Moreover, the PhC LTS also increases the escape angle for the outward moving photons, thus also helps in the angular performance enhancement of the device.

The Maxwell equations are used to optimize and analyze the effect of the PhC structure [22], and to solve these equations and to calculate absorption in the active layer, rigorous coupled wave analysis (RCWA) numerical method is used [20, 18, 23]. The optical performance of the structure has been analyzed through calculating absorption in the active area and reflectance from the top surface through quantum efficiency and I-V curve measurements [24, 25]. We have also reported the angular performance of the device with reference to the incident angle and also shown the absorption enhancement in the device. Then we have analyzed and compared the performance of the device with that of the Lambertian efficiency as well as with planar reference structure having single planar ARC and BR. It has been observed that the overall relative cell-efficiency enhancement of 127% and 26% can be achieved with proposed PhC LTS as compared to the single pass efficiency and the planar cell respectively. This clearly shows the effect of the PhC LTS in the performance enhancement of the cell, however, still the results achieved are under the Lambertian limits.

II. Proposed Structure Design

The proposed PhC LTS based thin film GaAs solar cell has been shown schematically in Fig. 2. The planar cell without PhC LTS having a single planar ARC of ITO of same thickness as that used for PhC structure has been used as a reference cell for comparison. The sunlight is assumed to be incident from top of the structure, perpendicular to the plane of PhC periodicity. The solar spectrum is considered to be the terrestrial AM1.5 spectrum [9]. The medium surrounding the device is considered to be air. 2D PhC LTS at the top has a hexagonal lattice arrangement, as it would provide better diffraction as compared to the square assembly [26]. The PhC structure is considered to be having air holes in the ITO background followed by Al(0.8)GaAs window layer. Active layer of GaAs is placed below this window layer. Al(0.35)GaAs back window layer is placed below the active layer followed by the Al BR. In this paper, the wavelength dependent material parameters are considered for GaAs and AlGaAs [8], Al [27] and ITO [28].

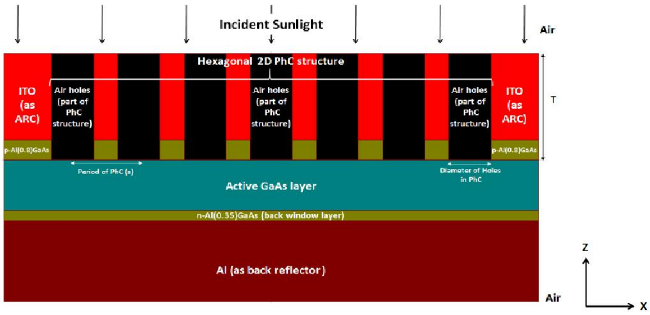

Fig. 2 Schematic diagram of the proposed thin film GaAs cell (x-z direction, side view) with PhC LTS at the top assisted by Al Back reflector

Thin AlGaAs window layers, having higher band gap and heavily doped, are placed in contact with the active layer, as they serve an important purpose to deflect minority carriers away from the contacts to reduce front and back surface recombination, owing to their higher band gap [1, 16, 29]. The Al BR is considered to be as close as possible to be an ideal metallic reflector. ITO has been used at the top, as its refractive index (RI) is close to the square of the product of RI of air and Al(0.85)GaAs, the condition required for a material to provide good impedance matching to minimize reflections from the top [3, 28]. Moreover, ITO also fulfills the requirement that the PhC structure should have minimum absorption together with large refractive index contrast, in order to provide large diffraction.

The device shown in Fig. 2 has 2D PhC structure where a represents its period having circular air holes of radius R and etching depth, T, extending from the top ITO layer till the p-Al(0.8)GaAs layer. Here, the PhC has been used at the top, instead of back [20, 21], to create a structure more feasible from fabrication point of view as it is easier to design PhC structure at the top without actually disturbing the epitaxial layers beneath. Also, there is no need to fill the holes in the structure, just in order to allow the layers to be deposited at the top. Thus, higher index contrast could be achieved within PhC design.

III. Theoretical Numerical Approach and Efficiency Calculation

During the simulation, absorption, reflection and transmission has been calculated by RCWA method [30, 31]. It represents the electromagnetic fields as a sum over coupled waves. A periodic permittivity function is represented using Fourier harmonics. Each coupled wave is related to a Fourier harmonic, allowing the full vectorial Maxwell's equations to be solved in the Fourier domain. The diffraction efficiency is then calculated at the end of simulation. The commercially available RSoft's DiffractMod software has been used, based on RCWA method to perform the 3D simulation analysis [32].

Here, the number of harmonics, M plays an important part in determining the accuracy of the result, as it is used to expand the refractive index and field in Fourier space. The greater the number of harmonics used, the more accurate the simulation will be but for that more simulation time and memory are required. Thus, a convergence study on the number of harmonics has been performed with different harmonics to see how the simulation results change. The results become almost stable for M become equal or more than 5, thus for the simulation analysis we have considered M to be equal to 5.

In order to solve the simulation equations, the structure has been considered as multilayer periodic structure which is decomposed into stacks of layers having with a vertically homogenous region. This approach not only facilitates physical insights into the problem but also provides important numerical advantages [20]. The algorithm considers the structure to have horizontally Periodic Boundary Conditions (PBC). The multilayer structure has been designed in the vertical direction (z direction), having periodic structure in x-y direction. For simulation purpose we have used only a single period of the structure in x-y dimensions, considering PBC.

As the motive of the study is to demonstrate the optical effect of PhC LTS and mechanism behind the light trapping in these structures, we have not got into the details of the charge carrier collection. Since the work is mainly concerned with the optical rather than transport properties of the cell, internal quantum efficiency has been set equal to one. Rather, we have tried to incorporate the electrical losses by incorporating the loss in collection efficiency and through shadowing effects. To calculate the solar cell efficiency, we have calculated the total optical absorption spectrum, $A(\lambda)$ of the entire device through RCWA method, which is the sum of the absorption spectra within each layer, $A_i(\lambda)$ as $A(\lambda) = \sum_i A_i(\lambda)$. Here, we have considered absorption in the active layer as the only useful absorption, in order to consider only the useful charge carriers. Considering the above spectra, the number of absorbed photons at a wavelength λ within each layer is therefore given as:

$$n_i(\lambda) = \frac{S(\lambda)A_i(\lambda)}{E(\lambda)} = \frac{\lambda}{hc} S(\lambda)A_i(\lambda) \quad (1)$$

where, $S(\lambda)$ is a specific incident spectrum [9], and $E(\lambda)$ is the energy of the incident photon, equivalent to hc/λ, where h is Planck's constant and c is the velocity of light in free space. The combined number of electron-hole pairs generated at a wavelength λ and collected by the electrodes is given as [1]:

$$n_{e-h}(\lambda) = \sum_i \eta_s \eta_i n_i(\lambda) = \frac{\lambda}{hc} \sum_i \eta_s \eta_i S(\lambda)A_i(\lambda) \quad (2)$$

where, η_s and η_i represent the shadowing effects and collection efficiency respectively. Here, 90% collection efficiency is considered based on the prior results [33], whereas shadowing effects are considered to be 6.6% [29]. Thus, the total number of electron-hole pairs collected by the electrodes is:

$$N_{e-h} = \int_\lambda n_{e-h}(\lambda) d\lambda \quad (3)$$

For our simulations the above integral is taken over from 300 to 1000 nm (in steps of 1 nm). Lower value of the wavelength has been decided as the photon flux below this value is small in the standard AM1.5 solar spectrum, whereas the upper limit has been decided considering the band gap of the GaAs material at room temperature, which is about 1.432 eV [34]. The absorption is considered to be ceased above this band gap. Using the above equation, short circuit current density, J_{sc} could be calculated as $J_{sc} = qN_{e-h}$(in A/m^2), where q represents the electronic charge and V_{oc}, open circuit voltage is obtained from $V_{oc} = (kT/q)ln(J_{sc}/J_{s0} + 1)$ (in V), where k is the Boltzmann's constant, T = 300 K, and J_{s0} is the reverse bias saturation current. Using these calculated values of J_{sc} and V_{oc}, the solar cell efficiency, η could be measured as:

$$\eta = \frac{\Gamma_f V_{oc} J_{sc}}{P_{in}} \quad (4)$$

where Γ_f is the fill factor of the cell, calculated as $\Gamma_f = (V_m.J_m)/(V_{oc}.J_{sc})$ and $Pin = \int S(\lambda)d\lambda\ (W/m^2)$, represents the total incident power, whereas V_m and J_m represent the voltage and current density at the maximum power point.

In this paper, we have compared our results with that of the Lambertian limits in solar cells. These limits were first derived considering the three main assumptions [4, 5], as follows:

1. The device has Lambertian scattere either at the front or back, which randomized light with isotropic distribution at each energy value, neglecting material intrinsic losses.
2. The active material is considered to have weak absorption for solar spectrum range. This condition is given as,
$$4n^2\alpha t << 1 \quad (5)$$
where n is the refractive index, α is the absorption coefficient and t is the thickness of the active layer.
3. Parameter t is much larger than the wavelength inside it, λ/n, which makes ray optics argument suitable for analysis.

On the basis of these assumptions, it has become possible to quantify the absorption is terms of $\alpha(\lambda)t_{eff}$, where t_{eff} is the effective path length for the photon inside the active layer for the given structure. Using the same assumptions, the absorption in the single photon pass, $A_s(\lambda)$ case through planar slab without considering reflection losses on the basis of the product $\alpha(\lambda)t_{eff}$ can be given as,

$$A_s(\lambda) = 1 - e^{-\alpha(\lambda)t} \quad (6)$$

The same equation (6) is used to calculate the single pass efficiency limits shown in Fig. 1. Now, as per Yablonovitch hypothesis, the maximum enhancement that could be achieved in case of planar cell surrounded by an isotropic medium is given as $4n^2/sin^2\gamma$ where $sin\gamma$ is 1 for the isotropic case. Thus, here the absorption calculated by equation (6) is modified as:

$$A_{LLY}(\lambda) = 1 - e^{-4n^2\alpha(\lambda)t} \quad (7)$$

These calculations have been done considering ideal cases. Here, LL_Y denotes absorption in case of Lambertian limit [4] We have denoted this light path enhancement calculated as per Green's derivation using the terms LL_G. Unless, otherwise stated, in the later sections Lambertian limit means the modified limit predicted by Green in [6]. We have also calculated the absorption enhancement factor, F, which is defined as [20],

$$F(\lambda) = \frac{A(\lambda)}{A_s(\lambda)} = \frac{A(\lambda)}{1 - e^{-\alpha(\lambda)t}} \quad (8)$$

This enhancement factor has been calculated with reference to the single pass efficiency (considering losses).

IV. STRUCTURE OPTIMIZATION

This section demonstrates the details of the optimization study of the proposed structure. In order to keep the practical issues in mind, where various parameters affect each other while designing an opto-electronic device, we have used contour maps to show the optimization of these photonic structures. The optimization of the 50nm thin active layer device includes the optimization of the period, *a* of the PhC structure together with its radius, *R* or diameter of the circular air holes, *D*, (which in turn also defines the fill ratio for background material) and the thickness of these PhC structures, *T*, which includes the optimization of the thickness of front ITO background layer thickness and beneath Al(0.8)GaAs window layer. The optimization process used in this paper has been inherited from [21, 35].

Initially to start the simulations studies, the active material layer thickness has been kept fixed at a particular value (here 50nm for demonstration purpose). The non-patterned back window layer of Al(0.35)GaAs has been set to 10nm as per the studies performed earlier, as thicker window layer might degrade the performance of the device [36]. The thickness of the planar metallic Al BR has been fixed to 80 nm, found out through optimization procedure as mentioned above, to maximize reflections from BR towards active layer. First, a contour map for the cell efficiency has been calculated by varying simultaneously the values of *a* and *D* of the air holes for optimizing the PhC structure. Contour map for cell efficiency between *a* and *D* has been shown in Fig. 3.

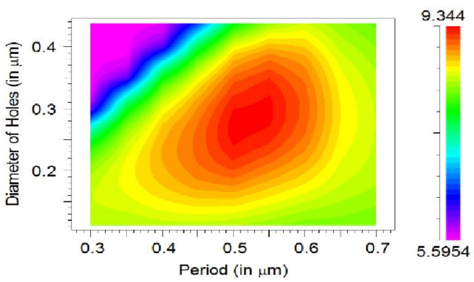

Fig. 3 Contour map representing the optimization of diameter of the air holes with reference to lattice constant (*a*) of the PhC structure. Various colors represent the calculated efficiency for the proposed 50nm based cell.

The figure shows that the optimal value of *a* has been found out to be 500nm and the value of *D* has been found out to be about 275nm, thus providing the ratio of *D/a* to be around 0.55. This ratio ultimately defines the filling ratio for the optimal patterning of the PhC design. This value of *a* is supposed to maximize the coupling of the incident light from the PhC to the absorption layer, and thus produces a dense distribution of absorption peaks for the desired wavelength range. Thus, PhC structure here maximize diffraction of photons towards the absorption layer, having minimizing absorption of useful photons in the front LTS and diffraction in air.

In order to perform this diffraction function, PhC structure period is required to be larger than the wavelength of light in the active layer, i.e. $a > \lambda/n(\lambda)$, where $n(\lambda)$ is the refractive index of active material at that particular wavelength. As per the GaAs material parameters used [8], this condition is basically satisfied for value of *a* equal to around 200nm. However, for a particular thickness active material using PhC diffraction grating, there is several diffraction resonances are created within the entire solar spectrum which basically overlaps and leads to overall efficiency improvement [15, 19]. Let, for a layer thickness of t_{Act}, all these resonances should take a round phase of change of $2m\pi$, so that $k_{\perp} = m\pi/t_{Act}$, where k represents the photon momentum and *m* represents a particular mode. The wavelength of diffracted resonant mode is given by [3, 17]:

$$\lambda = \frac{2\pi n(\lambda)}{\sqrt{G_x^2 + G_y^2 + (m\pi / t_{ACT})}} \quad (9)$$

where *n* is the refractive index of ITO/Al(0.8)GaAs and G_x, G_y are the components of reciprocal lattice vectors ($G_x = i(2\pi/a)$; $G_y = j(2\pi/a)$). The diffraction resonances occur for integer values of *i, j* and *m* and exhibit peaks in the absorption for wavelengths near the band edge for values of period larger than ~ 350 nm as clearly shown in the Fig. 3.

It has been previously shown [20] that when *a* is very small (in our case more than 200nm but less than 350nm), only low wavelength photons could couple to the active layer, whereas patterned PhC layer appeared as uniform for high wavelength ones, where refractive index of the PhC layer is marked by the effective refractive index of the patterned layer. Although, at this PhC pattern reflections from the top and diffraction in the air has been minimized, the light trapping is limited only to low wavelength regime where solar flux is weak. However, it does not mean that we could go for very high values of *a*, as increasing its value improves the light trapping of high wavelength photons but also increases diffraction in air. Thus, there is a need to have an optimal value of *a* which could not only reduces the reflections from the top and diffraction in air but also improves the light trapping of the high wavelength photons. Simulation results have shown the PhC LTS provides most effective guiding and diffraction resonances for 500nm.

As mentioned earlier, in the case when the incident photons wavelength becomes higher than the period of the PhC LTS, then, instead of behaving as a diffraction grating, the structure behaves as a uniform layer, whose effective index is a weighted average of the refractive index of PhC structure. This behaviour can be quantified by recalling the expression for the effective index of an arrangement of air holes in the ITO dielectric background, that could be given as:

$$\varepsilon_{eff}(f) = \frac{1}{2}\left[f.\varepsilon_{ITO} + (1-f).\varepsilon_{Air} + \frac{1}{f/\varepsilon_{ITO} + (1-f)/\varepsilon_{Air}} \right] \quad (10)$$

The same equation can be used for PhC structure in the p-AlGaAs layer beneath ITO layer. Here, $f = \pi R^2/((\sqrt{3}/2)*a^2)$ is the fill ratio for the hexagonal lattice structure. This provides an information for the effective index matching of the absorption layer with that of the incident medium (which is air in our case). Using the effective data values of parameters used in equation (10), value of *R* could be calculated. The optimization results for *D* has been shown in Fig. 3, showing the optimized value to be about 275 nm, almost validates our simulation results.

Fig. 3 also shows that the cell efficiency is only varied by 1% if the values of *a* and *D* for PhC structure are 10% away from the optimal values. Thus, we could also infer that this structure exhibits good fabrication tolerance with regards to a variation in the parameters of the proposed configuration. Thus, it is possible to fabricate the proposed device using available nano-

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lithography techniques and has the ability to provide optimal results.

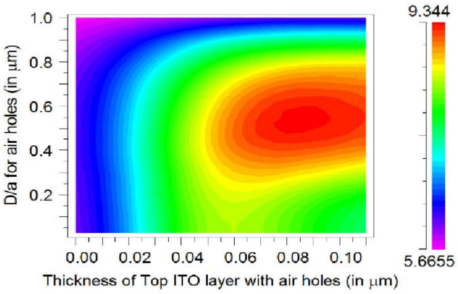

Fig. 4 Contour plot for cell efficiency optimization as a function of thickness of top ITO layer having PhC LTS and *D/a* ratio for the proposed 50 nm active layer cell configuration.

Next, the optimization of the PhC depth in the ITO and p-AlGaAs has been done with reference to the ratio *D/a* as shown in Fig. 4 and 5, respectively. The depth of the PhC LTS should be such that the coupling of light to the active layer should be maximized, with negligible absorption in PhC layer itself and specularly reflected beam from PhC into the air should be minimized. The sum of the reflection coefficient from ITO, p-AlGaAs and air should become zero for the specific value of *T* [15]. This helps in impedance matching between the incident medium and active layer and thus helps in improving the coupling of light to the active layer. From Fig. 4, this optimal value of the PhC structure thickness with ITO background is found out to be around 85 nm, whereas the optimal thickness of the etched PhC pattern in p-AlGaAs window layer has been found out to be 40 nm. However, as suggested in [36], the thick window layers might adversely effect the electrical performance of the cell, thus instead of using 40 nm thickness of p-AlGaAs layer, we have limit this thickness to 20 nm.

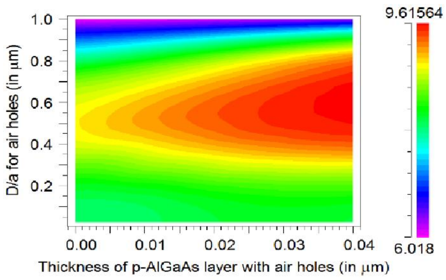

Fig. 5 Contour plot for cell efficiency optimization as a function of thickness of p-Al(0.8)GaAs layer having PhC LTS and *D/a* ratio for the proposed 50 nm active layer cell configuration.

Thus, *T* becomes 105 nm from the top (85 nm in ITO layer and 20 nm in p-AlGaAs layer). From Fig. 4 and 5, one can also find out that there is good tolerance for efficiency around the optimized value of *T* and *D/a* parameters and there is only about 1% decrease in final cell efficiency, for around 10% variation in the optimal values.

Here, optimizing an appropriate etching thickness for the PhC structure plays an important part in the cell efficiency enhancement, as it perturbed the slab guided modes and the PhC grating makes them accessible from an incident radiation [21]. As mentioned earlier, the condition is similar to the diffraction grating, which deflects the normally incident light to the oblique direction and thus increases the path length for that wavelength photons. The diffracted waves propagates at nearly grazing angle within the material, with a large propagation path, thus improves absorption within the active layer within the wide spectral range. Thus, the role of the PhC LTS is to couple the incident radiation field to the guided slab modes, without significantly varying the modes themselves. This completes our design optimization for the proposed 50 nm GaAs active layer cell. The optimized parameters are summarized in Table 1.

Table 1: Summary of the optimized parameters for the proposed 50 nm GaAs active layer cell

S. No.	Parameters	Values (nm)
1.	Anti-Reflection Coating (ITO having PhC structure etched)	85
2.	Thickness of p-Al(0.8)GaAs window layer (having PhC structure etched)	20
3.	Thickness of n-Al(0.35)GaAs back window layer	10
4.	Back reflecting layer of Aluminum	80
5.	Period of the PhC structure at the top (a)	500
6.	Diameter of the air holes etched in PhC structure (D)	275
7.	D/a (ratio)	0.55
8.	Thickness of the PhC structure etched from the top (etched in top ITO and p-AlGaAs)	105

V. RESULTS AND DISCUSSIONS

In this section, we will discuss the performance of the proposed 50nm active layer thin GaAs solar cell with PhC LTS in terms of the calculated absorption and reflection spectra, spectral distribution as per AM1.5 spectra, absorption enhancement as per equation (8) and angular performance with variation in incident light angle. The results are compared with that of the Lambertian limit [4, 6] and ideal and practical single pass efficiency. For better understanding of the performance enhancement in the proposed PhC LTS based design, we have also compared the results with a reference cell.

To start with, we have calculated the absorption spectra for the proposed 50 nm active layer thickness PhC LTS based cell and compare the results with different configurations as mentioned in the preceding para. The calculated absorption graph is shown in Fig. 6, where maximum value is normalized to unity, the case when the entire incident light gets absorbed. Starting from the ideal single pass case, one can observe that the absorption started to dip exponentially after 400 nm and almost drops below 50% after 450 nm. The condition become even worse when we have included the losses, including reflections from the top, collection efficiency losses and shadowing effects in the calculations for single pass case.

Now, consider the case of reference cell having planar LTS. From the figure, one can observe that after 450nm, the absorption in the reference cell has been enhanced as after this wavelength the effect of LTS has come into effect, as the thickness of the active layer in itself is not enough to absorb the entire spectrum beyond this range due to small value of the absorption coefficient. Also, due to the ARC at the top, reflections has also been reduced. Next, taken the case of the proposed PhC LTS based cell, which is shown by dark blue line patterned by open circles in the figure, we can observe that the enhancement in the absorption is achieved for almost the entire incident wavelength range as PhC LTS in our design, functions not only to trap the high wavelength photons but also to maximize the coupling of the incident light by reducing reflections from the top. This has been achieved through PhC

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structures as the patterned structure provides better impedance matching. For patterned structure, the line shape of the resonance broadens for increasing energy, according to the fact that a higher intrinsic absorption produce slower and broader features in the absorption spectra [20, 23]. Here, the absorption enhancement ceases beyond around 670nm as beyond this range, the effect of BR becomes dominant and both the PhC LTS based cell and the reference cell has the same Al BR of equal thickness. From the figure, one can also observe although we could achieve higher efficiency practically with the proposed structure, but still this efficiency under the Lambertian limit efficiency.

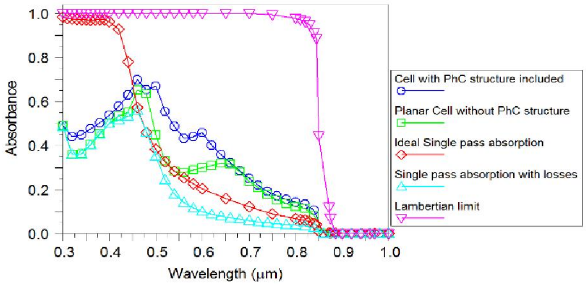

Fig. 6 Calculate absorption spectra for the proposed 50 nm GaAs active layer cell having 2D PhC LTS and its comparison with other proposed structure without any pattern and to Lambertian limit [6].

Next, in Fig. 7, we have demonstrated the absorption enhancement factor, *F*, calculated as per equation (8). The graph clearly shows that there is enhancement in the absorption in the active layer of the GaAs cell due to the proposed PhC LTS and that too spread in the entire incident spectrum range. The enhancement becomes pronounced beyond 450nm for the reason as beyond this value, the LTS effect becomes dominant and is mainly responsible for guiding, coupling and deflecting photons for absorption in the active layer.

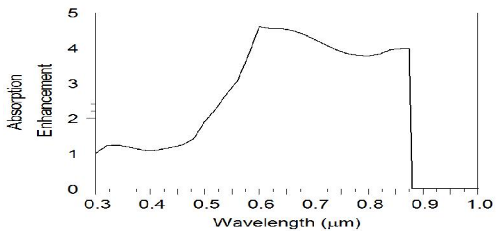

Fig.7 Calculated absorption enhancement graph for 50 nm active layer PhC LTS based cell as per Equation (8).

Calculated reflectance spectra for the proposed GaAs cell has been shown in Fig. 8, in comparison to the reference cell. Here, the reflectance from the structure includes all the diffraction orders, and as can be observed from the figure, this reflectance is always less as compared to the planar reference cell than the PhC LTS based cell. This happens basically as the PhC structure provides both the better impedance matching condition (as the PhC LTS provides the intermediate effective refractive index) and light trapping.

At high wavelengths, the reflection contribution is basically due to incomplete absorption in the active layer, which is nearly complementary to absorbance spectrum. At low wavelengths, there is a residual reflection, but it is evident that the intermediate patterns provide a spectral band of low reflectance, which is broader than that of the reference cell. In the patterned cell there is still diffraction in air due to large number of allowed modes [20]. This diffraction in air could be reduced with small lattice constant value, but as mentioned earlier the period of the PhC structure cannot be reduced to the very small value as this adversely affects the trapping of high wavelength photons.

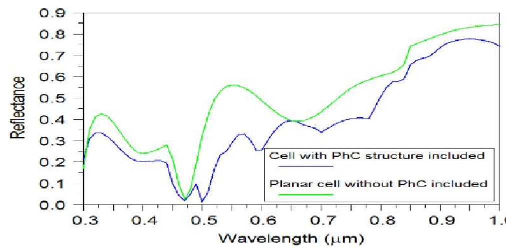

Fig.8 Calculated reflection spectra for the proposed cell with PhC patterning and its comparison with the non-patterned planar solar cell structure.

Next, we have shown the smoothened spectral distribution graph for the proposed PhC LTS cell in Fig. 9. As shown in the previous results, the figure also shows the performance enhancement for the patterned structure as compared to the reference cell and single pass values. Again, one can predict from the figure that, although through this proposed periodic patterning could enhance the efficiency considerable, but still the results achieved are under the Lambertian limits.

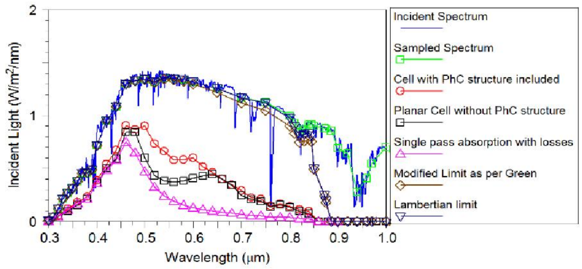

Fig.9 Calculated spectral distribution graph for the considered AM1.5 solar spectrum [9] for the proposed 50 nm active layer cell with PhC LTS and its comparison with the reference cell having same active layer thickness.

The evaluation of the proposed structure has also been done with respect to the incident light angle, and the calculated values over the angular range of incidence as shown in Fig. 10, predicted improved performance of the device as compared to the reference planar cell almost for the entire incident angle range. The result can be attributed to the better diffraction capability and coupling efficiency of the PhC LTS which helps in guiding the light to the active layer for large range of angle of incidence.

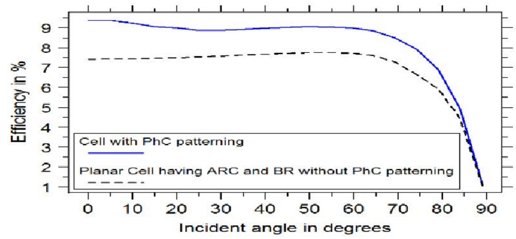

Fig. 10 Incident angle Vs. Cell Efficiency graph for proposed 50nm active layer based GaAs cell structure with and without PhC patterning

It can be noted from the figure that our designed structure is able to perform almost equivalent to the normal incidence up to about 75° or so, retaining nearly 80% of the normal incidence efficiency and shows significant performance enhancement. Thus, we could say that the efficiency enhancement of the considered PhC LTS is rather robust with respect to variations of the orientation and of the incidence angle. This is an important result, as through this we can predict the proposed structure would yield the same efficiency enhancement for direct and diffuse light, without any need of solar tracking.

Now, to have better understanding of the absorption mechanism associate at different incident light wavelength, we have shown in Fig. 11, electric field intensities at 8 different wavelength for TE polarization ranging from 350 nm (high energy photons) to 850 nm (low energy photons. As the main purpose of the PhC LTS is to couple maximum incident light to below active layer, it is required that the structure should provide minimum reflections from the top, should have minimum absorption and also should have maximum diffraction towards the active layer to improve the path length of the incident light. The above mentioned phenomenon can be clarified using the electric field intensities shown in Fig. 11.

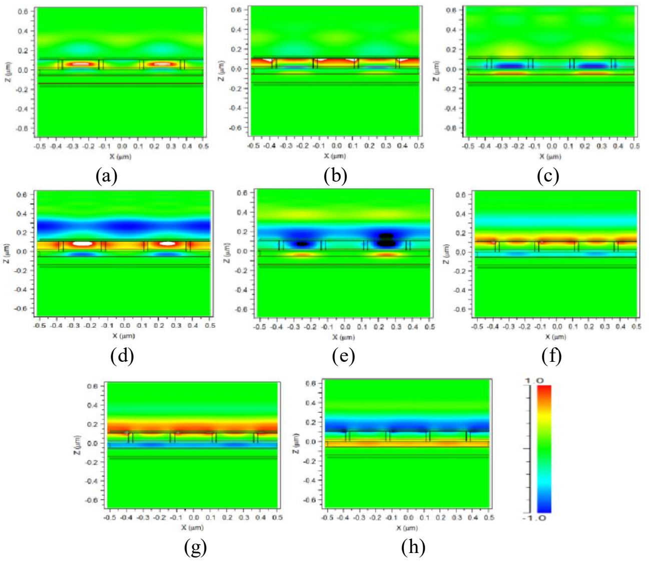

Fig. 11 Electric field intensities for the proposed 50nm active layer PhC LTS based GaAs cell for TE polarization, calculated at the following wavelengths: (a) 350nm, (b) 450nm, (c) 500nm, (d) 550nm, (e) 600nm, (f) 700nm, (g) 800nm, and (h) 850nm. Vertical stack after figure (h) shows the color reference used to predict intensity.

Fig. 11(a) shows the electric field intensity at 350nm. It shows that for high energy incident photons there are considerable reflections from the top surface and most of the light remained in the PhC LTS itself, with only small portion of incident light is coupled to the bottom active layer. This is the main reason for small value of absorption in the proposed cell around 350 nm, as shown in Fig. 6. Fig. 11(b), shows the intensity at 450 nm, indicated that although there are still reflections from the top and resonances in the PhC structure itself, but less than the case at 350 nm and thus, here the coupling of light also get enhanced. Now, Fig. 11 (c), depicts the case around 500nm, which is as per Fig. 6, is among the main spectrum areas of enhancement in absorption as compared to the reference cells. One can easily observed from the figure that here the coupling of the incident light from the incident medium to the active layer becomes stronger having very small concentration of light in PhC itself and reduction in reflections.

Next, Fig. 11 (d) and (e) shows the electric field intensities at 550 nm and 600 nm. Here, too although the coupling of light to the active layer is strong and the absorption is better as compared to the reference cells but still at these regions the reflections are high (which could be accounted due to diffraction in air) and also there is strong resonance in PhC LTS itself. Subsequent, figures shows intensity diagrams at 700, 800, 850 and 875 nm, respectively show that as the wavelength increases, the coupling reduces and the reflections from the front surface becomes dominant.

Thus, on the basis of the above intensity diagrams, one could predict that although the proposed structure have enhanced the performance of the ultra-thin film GaAs cell, but in order to enhance the efficiency even further to take these values toward limiting ones, one has to reduce the reflections from the top even further, improves diffraction of light from the top towards active layer and convert the resonances in the PhC structures instead of losses to useful light, by coupling more and more of this light towards useful active medium. We have summarized the efficiency improvement achieved through the designed and optimized structure, and could be found from Table 2.

Table 2: Summary of the cell efficiency for the optimal structures with 50 nm cell thicknesses (here effi. denotes efficiency).

Active layer thickness (nm)	Single pass effi. with losses (device without LTS)	Proposed Cell effi. with PhC structure at top	Planar ref. cell with-out PhC structure	Total effi. Inc. (%) as compared to bare cell	Improvement in effi. by PhC design as compared to planar structure (%)	Lambertian Limit effi.
50	4.133	9.383	7.432	127.1	26.3	25.855

From the table, one could find that the top PhC LTS based structure having just 50 nm active layer thickness could provide almost 127% efficiency enhancement as comapred to bare cell structure, and could provide about 26.3% efficiency enhancement as compared to the commonly used planar reference cell, which clearly predicts the worth of the PhC periodic LTS for the future ultra thin film device development.

In this paper, we have proposed the detailed optical analysis of the proposed design, but have not considered the electrical transport and the possible presence of defects. In the periodic structures like the presented PhC LTS, and that too placed at the top of a device, these parameters might become crucial. However, the electron transport properties could benefit from the reduced active layer thicknesses. Also, one has to take care of the diffusion properties of the GaAs material, as GaAs has small diffusion lengths, thus increasing the active layer thickness beyond certain value is also not practical in order to achieve S-Q limits, as with increase in thickness, recombination would also increase, thus LTS plays all the more important role for thin GaAs cells. Therefore, a detailed investigation of actual cell architecture including both optical and electrical properties would be very helpful and can be the direction for extending the present work towards real cell structures.

VI. Conclusion

In conclusion, the paper presents an optical design optimization for the 50 nm thin GaAs active layer cell having 2D PhC LTS at the top assisted by the Al BR. The results obtained indicate considerable efficiency enhancement for the proposed structure. The results are also compared with the Lambertian limits for light trapping as well as with those having single pass and reference planar cell and demonstrate the improved performance for the PhC LTS based cell, in terms of absorption, reflection and variation of incident angle. It is interesting to note that the designed structure retains almost 80% of the normal incidence efficiency even for high angle of incidence and thus provides significant angular performance improvement. This improvement in efficiency is basically accounted to the better index matching, trapping of low energy photons and diffraction of incident light to the active layer provided due to the proposed PhC LTS. Also, it has been shown that the device provides good fabrication tolerances, thus it can be practically realized.

VII. ACKNOWLEDGEMENT

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Nikhil Deep Gupta received his B.E. degree from Rajasthan University, Jaipur, India in 2009 in the Electronics and Communication Engineering. He received his M.Tech. from Maulana Azad National Institute of Technology (MANIT), Bhopal, India in 2011 with a Gold Medal. After that, he had worked as Junior Research Fellow at Malaviya National Institute of Technology (MNIT), Jaipur, India in a Defense Research and Development Organization (DRDO), India sponsored project. Since Jan. 2013, he has been doing Ph.D. at MNIT, Jaipur, India. His areas of interest are thin film solar cells and their applications, solar PV systems and its applications, opto-electronics, optical communication, photonic crystals and photonic crystal based devices.

Vijay Janyani is Associate Professor with the Department of Electronics and Communication Engineering at Malaviya National Institute of Technology (MNIT), Jaipur, India. He obtained his Bachelor's and Master's degrees in engineering from Malaviya Regional Engineering College Jaipur with a Silver Medal and Gold Medal, respectively, and PhD from University of Nottingham, United Kingdom under Commonwealth Scholarship Scheme. He is a recipient of various awards such as the Derrick Kirk Prize of University of Nottingham United Kingdom for excellence in research and Career Award for Young Teachers of All India Council for Technical Education (AICTE), New Delhi. He has been a visiting faculty at Asian Institute of Technology Bangkok under faculty secondment scheme of Government of India. He is the coordinator from his Institute of the British Council sponsored Indo-UK collaborative research project on Microstructured Optical Fibers under UKIERI scheme. His current research interests include optical communication, solar cells, photonic crystals, nonlinear optoelectronics, all-optical systems, and numerical modeling.