Design and Simulation of GaAsN Based Solar Cell with AlGaAs blocking layer for Harvesting Visible to Near-infrared Light

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Abstract

In the present study, the performance parameters of GaAsN dilute nitride-based semiconductor solar cell with and without AlGaAs blocking layers have been investigated in detail by Solar Cell Capacitance Simulator in one dimensional software program (SCAPS-1D). The thickness of absorber, buffer, and blocking layers are varied to achieve the improvement of open circuit voltage, short circuit current, fill factor, efficiency and also to optimize the device structure. The impact of doping and defect densities on the solar cell performance parameters have been analyzed minutely inside the absorber, buffer, and blocking layers. The solar cell thermal stability parameters are also investigated in the temperature region from 273K to 373K. The efficiency of 43.90% and 40.05% are obtained from the proposed solar cells with and without AlGaAs blocking layer, respectively. The present findings may provide insightful approach for fabricating feasible, cost effective, and efficient dilute nitride solar cell.

Keywords: Efficiency, Performance parameters, Photo-generated carriers, SRH recombination and Carrier lifetime.
1 Introduction

Dilute-nitride based solar cell structures have demonstrated much attention due to their potentiality to increase efficiency by adjusting band gap of alloy-based materials [1]. GaAs/GaAsN structure has been designed for the application of space and large-scale power plant. The improvement of the efficiency of this structure is very much necessary for widening the application in different fields [2]. Solar cells are made of a single material (Si), and single-junction (GaAs, CdTe, CuInGaSe) to compound materials, such as perovskite, dye-sensitized, inorganic, quantum dot, quantum well, and dilute nitride based solar cells [3]. Among them alloy based dilute nitride GaAsN compound semiconductor materials solar cell has unique properties.

The alloys of GaAs–GaN provide the opportunity to fabricate GaAsN which recently attract the attention because of their negative and large band bowing (from −7 to −40 eV) largely dependent on compositional properties. The offset of conduction band (> 300 meV) is due to the size and electro-negativity difference among N, Ga and As atoms [4, 5]. The new sub-bands of energy can be constructed in the region of the lower energy of the conduction band by the addition of N inside the GaAs host materials which can be described by the band anti-crossing model. The structural properties of the new sub-band can be controlled properly by changing the amount of the incorporated N atoms inside the host GaAs. The new sub-band widens spectral response up to the infrared range, which contributes to raise the overall performance parameters of the cell [5–7].

The investigation about optical and morphological properties of GaAsN compound solar cell has been performed by different research groups [8–12]. The theoretical maximum efficiency of about 30.10% and 29.00% has been reported for optimized GaInP/GaAs/GaInNAs and GaInNAs solar cell [13]. The maximum conversion efficiency has been determined to be 24.94%, when a hetero-structure configuration of p-GaAs/p-GaAsN/n-GaAs is employed n-GaAs as buffer layer, [14]. Another numerical study has achieved efficiency of 15.9% for the device structure of n⁺ - GaAs/n⁺-GaAsN/p-GaAsN [15]. The reported efficiency is much lower than the expected value in dilute nitride solar cell. The introduction of various defects in GaAsN during the incorporation of N atoms that reduces the number of generated photoelectrons causes this low efficient. The scattering of alloy and non-homogeneity of N atoms reduces the electron mobility and minority
carrier lifetimes with enhanced nonradiative recombination of the flowing photo-generated carriers towards the electrodes and restricts to increase performance of GaAsN/GaAs solar cell [7, 11]. The solar cell with AlGaAs blocking layer can significantly increases the open circuit voltage and consequently increase the efficiency [16]. In order to optimize the performance parameters of GaAsN cell, it is very much essential to investigate doping as well as quantum efficiency ($QE$), defect density, and the variation of different layer’s thickness of the cell structure in presence of the AlGaAs blocking layer.

In this research work, we propose $p^+\text{-GaAs}/p\text{-GaAsN}/n\text{-GaAs}$ and $p^{++}\text{-GaAs}/p^+\text{AlGaAs}/p\text{-GaAsN}/n\text{-AlGaAs}/n^+\text{GaAs}$ solar cell structures to investigate the short circuit current ($J_{sc}$), open circuit voltage ($V_{oc}$), fill factor ($FF$), efficiency ($\eta$) as performance parameters, and $QE$ by the SCAPS-1D with and without AlGaAs blocking layer. This research demonstrates the modeled $p\text{-GaAsN}$ solar cell with AlGaAs blocking layer can achieve the improvement of $V_{oc}$ and $\eta$.

### 2 Device structure and simulation

Figure 1 illustrates the schematic structure of $p^\text{-GaAs}/p\text{-GaAsN}/n\text{-GaAs}$ (Cell 1) and $p^{++}\text{-GaAs}/p^+\text{AlGaAs}/p\text{-GaAsN}/n\text{-AlGaAs}/n^+\text{GaAs}$ (Cell 2), respectively.

![Fig.1 Designed and optimized structure of solar cell (a) Cell 1: $p^+\text{-GaAs}/p\text{-GaAsN}/n\text{-GaAs}$ and (b) Cell 2: $p^{++}\text{-GaAs}/p^+\text{AlGaAs}/p\text{-GaAsN}/n\text{-AlGaAs}/n^+\text{GaAs}$.

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Table 1: Physical parameters of different layers required in the device modeling.

| Parameters (unit) | GaAs          | GaAsN         | AlGaAs        |
|-------------------|---------------|---------------|---------------|
| Conductivity      | p⁺/p⁺ // n/n  | p             | p⁺/n          |
| Thickness, W (nm) | 2/20/1000/1000| 2000          | 5/5           |
| Bandgap, $E_g$ (eV) | 1.42 [14, 18] | 1.33 [14] | 1.81 [19, 20] |
| Electron affinity, $\chi$ (eV) | 4.07 [14, 18, 21] | 4.071 [14, 22] | 3.74 [19, 20] |
| Dielectric permittivity (relative), $\varepsilon_r$ | 12.5 [14, 23] | 12.38 [14] | 12.1 [20, 24] |
| Effective conduction band density, $N_C$ (cm⁻³) | 4.33×10¹⁷ [14, 22, 25] | 4.66×10¹⁷ [14][22] | 6.52×10¹⁷ [24] |
| Effective valence band density, $N_V$ (cm⁻³) | 1.28×10¹⁹ [1, 3, 7] | 1.39×10¹⁹ [1] | 1.12×10¹⁹ [24] |
| Mobility of electron, $\mu_n$ (cm² V⁻¹ s⁻¹) | 8500 [14, 18, 21] | 6538.46 [14, 22] | 2300 [19, 20] |
| Mobility of hole, $\mu_p$ (cm² V⁻¹ s⁻¹) | 400 [14, 18, 21] | 397.72 [14, 22] | 150 [19][19] |
| Concentration of donor, $N_D$ (cm⁻³) | 1.0×10¹⁶ / 1.0×10¹⁸ [14] | 0 | 1×10¹⁷ [26] |
| Concentration of acceptor, $N_A$ (cm⁻³) | 5.0×10¹⁹ / 5.0×10¹⁹ [14] | 1×10¹⁶ | 1×10¹⁷ [24] |
| Defect type | Donor/ Donor/ Acceptor/ Acceptor | Donor | Donor/ Acceptor |
| Energetic distribution | Gaussian | Gaussian | Gaussian |
| Bulk defect density, $N(t)$ total (cm⁻³) | 1.0×10¹⁴ | 1.0×10¹⁴ | 1.0×10¹⁴ |
| Characteristic energy (eV) | 0.10 | 0.10 | 0.10 |
| Reference energy (eV) | 0.71 | 0.665 | 0.905 |
| Capture cross section of electron for acceptor defect (cm²) | 1.0×10⁻¹⁷ | - | 1.0×10⁻¹⁷ |
| Capture cross section of hole for acceptor defect (cm²) | 1.0×10⁻¹⁵ | - | 1.0×10⁻¹⁵ |
| Capture cross section of electron for donor defect (cm²) | 1.0×10⁻¹⁵ | 1.0×10⁻¹⁵ | 1.0×10⁻¹⁵ |
| Capture cross section of hole for donor defect (cm²) | 1.0×10⁻¹⁷ | 1.0×10⁻¹⁷ | 1.0×10⁻¹⁷ |

* Indicates the variable parameters.

For designing the Cell 1 and Cell 2, a 20 nm p⁺-GaAs and 2 nm p⁺⁺-GaAs layers are used as the cap layer with acceptor density $N_A = 5.0\times10^{19}$ cm⁻³. A highly doped 1000 nm n-GaAs and n⁺-GaAs with doping concentration $1\times10^{16}$ cm⁻³ and $1\times10^{18}$ cm⁻³ are also used as buffer layers for Cell 1 and Cell 2, respectively. The p-GaAsN layer of 2000 nm with $N_A = 1\times10^{16}$ cm⁻³ is employed as the absorber layer for both Cell 1 and Cell 2. The silicon doped GaAs layers are
also considered as a substrate for both the proposed solar cells. The additional n-AlGaAs layer (above the buffer layer) and p⁺-AlGaAs layer (below the cap layer), each thickness of 5 nm, are also used in Cell 2 as blocking layers to improve the performance parameters. The simulation and investigation are performed by the Solar Cell Capacitance Simulator one dimensional simulation software (SCAPS-1D). The SCAPS-1D provides the opportunity to solar cell researcher to analyze device structure of maximum seven layers. It is a very useful tool used to perform electrical characterizations and spectral response of solar cell. It enables to analyze the tunneling effect, energetic distribution of the defects, carrier generation and recombination [17]. The solar cells are illuminated under 100 mW/cm² (1sun) with global air mas AM 1.5 G solar spectrum at operating temperature 300 K, considering ideal condition for the series (Rₛ) and shunt (Rₛₘ) resistances. The simulation parameters are adopted from previously studied research works as presented in Table 1.

3 Results and Discussion:

3.1 Energy band diagram of designed solar cell

![Energy band diagram of designed solar cell](image)

Fig. 2 Energy band diagram of the designed solar cells at a bias voltage of 0V for (a) Cell 1 and (b) Cell 2.

This research has been done by the numerical simulation to analyze p-GaAsN based solar cell that demonstrates enhancement of conversion efficiency with minimal absorber layer thickness.
Total device structure and different layers’ thickness as well as doping concentration are necessary to be optimized to fabricate a high efficiency solar cell in view to reduce fabrication time and cost, thus enhance production throughput. The thermodynamic equilibrium band diagram of $p^+\text{GaAs}/p\text{GaAsN}/n\text{GaAs}$ and $p^{++}\text{GaAs}/p^{+}\text{AlGaAs}/p\text{GaAsN}/n^+\text{AlGaAs}/n^+\text{GaAs}$ dilute nitride structures, performed by SCAPS-1D simulator, are schematically depicted in Figs. 2(a) and 2(b), respectively. The band diagram structure mainly depends on the band gap energy ($E_g$), electron affinity ($\chi$), and density of doping and defect of the adjacent layers. The value of $\chi$ for GaAsN absorber and GaAs layers are assumed to be 4.071 eV and 4.07 eV for Cell 1 and Cell 2, respectively, while for AlGaAs, $\chi$ is 3.74 eV [1, 7]. The energy difference between the conduction band minima ($E_c$) and the valence band maxima ($E_v$) is illustrated as $E_g$ for each layer. The position of Fermi energy level $E_F$ with respect to $E_c$ and $E_v$ changes due to the variation of operating temperature, density of doping, number of free carriers (electrons and holes), and their effective masses. The position of $E_F$ moves toward $E_c$ in n-type from the mid-gap position, while it moves away from $E_v$ in p-type semiconductor. However, the better $\eta$ is achieved for Cell 2 with AlGaAs blocking layer.

### 3.2 Effect of thickness on PV parameters

The effect of solar cell performance with respect to different layer thickness in Cell 1 and Cell 2 are shown in Figs. 3.
Fig. 3 The effect of solar cell performance with respect to different layer thickness for (a) $p^+$-GaAs layer of Cell 1 (b) $p^{++}$-GaAs layer in Cell 2 (c) and (d) $p^+$-AlGaAs and n-AlGaAs layers, respectively in Cell 2, (e) and (f) p-GaAsN layer in Cell 1 and Cell 2, respectively (g) n-GaAs layer in Cell 1 and (h) n$^+$-GaAs layer in Cell 2. Here the ‘broken lines’ indicate the data for Cell 1 whereas, the solid lines for Cell 2.

Figures 3(a), and 3(b) represents the variation of $V_{oc}$, $J_{sc}$, $FF$ and $\eta$ due to change of the thickness of $p^+$-GaAs and $p^{++}$-GaAs cap layers in Cell 1 and Cell 2, respectively. It is observed that with the increase of the thickness of $p^+$-GaAs from 10 to 100 nm in Cell 1 (Fig. 3(a)), the solar cell output parameters $V_{oc}$, $J_{sc}$, $FF$ and $\eta$ decreases slowly compared to that of Cell 2, where the thickness changes from 1 to 20 nm (Fig. 3(b)). With the enhancement of thickness of the cap layers $p^+$-GaAs and $p^{++}$-GaAs in Cell 1 and Cell 2, respectively, a smaller number of photons is absorbed inside the p-GaAsN layer which results in the decrease of the number of electron-hole pair generation. Hence, the overall performance parameters decrease. This type of degradation in $V_{oc}$, $J_{sc}$, $FF$ and $\eta$ has been reported in previous studies [14, 15]. The effect on the change of the thickness of $p^+$-AlGaAs and n-AlGaAs blocking layers is shown in Figs. 3(c) and 3(d), respectively, for Cell 2 (Fig. 1(b)). It is observed from the results that due to the variation of the thickness of the layer $p^+$-AlGaAs, there is no change of the solar cell output parameters (Fig. 3(c)), while $V_{oc}$, $FF$ and $\eta$ enhances owing to the rise of the thickness of the layer n-AlGaAs in Cell 2 (Fig. 3(d)). The improvement of these performance parameters may be due to the change
of offset voltage (band alignment) with the increase of n-AlGaAs layer thickness [27–29]. Figures 3(e) and 3(f) represent the variation of $V_{oc}$, $J_{sc}$, $FF$ and $\eta$ due to the change of thickness of p-GaAsN absorber layer at 300 K for Cell 1 and Cell 2, respectively. It is obvious from Fig. 3(e) that with increasing the thickness of p-GaAsN layer from 200 nm to 3000 nm, the value of $V_{oc}$ monotonically increases from 1101 to 1105 mV whereas the value of FF sharply increases from 89.58 and reaches a maximum value to 89.85 at around 1400 nm, after that it is monotonically decreases to 83.57 for Cell 2. With rising the thickness of p-GaAsN from 200 nm to 3000 nm (Fig. 3(f)), the values of $J_{sc}$ and $\eta$ increases monotonically from 34.53 to 46.13 mAcm$^{-2}$ and 32.21 to 40.56%, respectively for Cell 1 and 33.72 to 45.57 mAcm$^{-2}$ and 33.25 to 45.23, respectively for Cell 2. The decrease of the values of solar cell parameters is due to the small number of photons absorption at lower thickness and higher recombination rate of free electrons and holes before they move toward the electrodes. A thicker layer enables to enhance the photons absorption and create large number of electron hole pairs, which dominantly enhances amount of the photo-generated current [28, 30, 31]. However, thicker absorber layer increases the solar cell fabrication cost significantly. Hence considering overall consequences, it is necessary to investigate thickness dependency of absorber layer. The thickness dependency of n-GaAs and n$^+$-GaAs layers for the photovoltaic parameters of $V_{oc}$, $J_{sc}$, $FF$, and $\eta$ for Cell 1 and Cell 2 has been investigated as illustrated in figure 3(g) and 3(h), respectively. It is observed that with increasing the thickness of n-GaAs layer, the photovoltaic parameters $V_{oc}$, $J_{sc}$, and $\eta$ decreases constantly for Cell 1 (Fig. 3(g)) while these values show increasing tendency for Cell 2 (Fig. 3(h)). However, the value of $FF$ remains constant for both Cell 1 and Cell 2. The increase of n-GaAs layer thickness may enhance the threading dislocation density, which results in decrease of $V_{oc}$ as well as $\eta$. The presence of AlGaAs blocking layer with the n$^+$-GaAs layer in Cell 2, changes band alignment which enhances the values of $V_{oc}$, $FF$, and $\eta$ as shown in Fig. 3(h) [27–29].

3.3 Impact of thickness on the quantum efficiency

The effect of GaAsN layer thickness on quantum efficiency ($QE$) for solar Cell 1 and Cell 2 are demonstrated in Fig. 4.
In this study, the absorber layer thickness has been varied from 0.5 to 2 \( \mu \text{m} \) for both solar cells at the doping density of 1.0\( \times 10^{16} \) cm\(^{-3} \). The thickness of p\(^+\)-GaAs and n-GaAs are fixed at 20 nm and 1000 nm, respectively for Cell 1. For Cell 2, the thickness of p\(^{++}\)-GaAs and n\(^+\)-GaAs are 2 nm and 1000 nm, respectively. The p-GaAsN enables to absorb illuminated lights from 200 to 1300 nm at different depth of the layer as indicated in Fig. 4. With increment of the thickness of p-GaAsN the absorption of light increases which are reported in the earlier studies [8, 31–33]. For achieving maximum efficiency as well as reducing the materials cost, the optimum thickness of p-GaAsN absorber layer is fixed at 2 \( \mu \text{m} \) and 1.5 \( \mu \text{m} \) for these proposed solar cells Cell 1 and Cell 2, respectively.

### 3.4 Influence of doping concentration on PV parameters

In order to investigate the impact of doping density, the acceptor density \( N_A \) in p\(^+\)-GaAs and p\(^{++}\)-GaAs layers is varied from 5.0\( \times 10^{14} \) to 1.0\( \times 10^{20} \) cm\(^{-3} \) for Cell 1 and Cell 2, respectively as depicted in Figs. 5 (a) and 5(b). With increasing \( N_A \), the values of \( J_{sc} \) initially increases for Cell 1 and remains almost constant from \( N_A = 1.0 \times 10^{16} \text{ cm}^{-3} \) up to \( N_A = 1.0 \times 10^{20} \text{ cm}^{-3} \) (Fig. 5(a)), while no change of the value of \( J_{sc} \) observed for the Cell 2 (Fig. 5(b)). In contrast, the value of \( V_{oc} \) rises from 832 mV to 1054 mV and 1058 mV to 1105 mV for Cell 1 and Cell 2, respectively which results in the enhancement of the \( \eta \). The reason for the increase of the \( J_{sc} \) and \( V_{oc} \) in Cell 1 is due to the enhancement of the reverse saturation current and electrical conductivity [15, 34]. At the value of large \( N_A \), recombination of electron-hole pair reduces the number of carrier at the electrode which results in constant \( J_{sc} \) [30, 34]. As shown in Fig. 5 (c), there is no effect of \( V_{oc} \).
$J_{sc}$, $FF$, and $\eta$ on acceptor density in the $p^+$-AlGaAs layer. The value of $V_{oc}$ and $\eta$ increases abruptly as the donor density $N_D$ reaches $10^{19}$ cm$^3$ in n-AlGaAs as illustrated in Fig. 5(d). The similar tendency was observed in the previous studies of [16, 35]. The Figs. 5 (e) and 5(f) represent the effect of $N_A$ inside GaAsN on the output parameters for both Cell 1 and Cell 2. For Cell 1, initially the value of $V_{oc}$ and $FF$ decreases from 1054 to 1046 mV and 88.03 to 84.89 for the range of $N_A$ from $10^{14}$ to $10^{17}$ and $10^{14}$ to $10^{16}$ cm$^{-3}$, respectively. After that it increases up to the value of $N_A = 10^{20}$ cm$^{-3}$ (Fig 5 (e)). While the value of $J_{sc}$ first increases and remains constant up to $N_A = 10^{19}$ cm$^{-3}$, then it decreases at higher density of $N_A$. The overall $\eta$ of the solar Cell 1, initially decreases to minimum value of 40.05% at $N_A = 10^{16}$ cm$^{-3}$, then it rises to 42.36% at $N_A = 10^{19}$ cm$^{-3}$ (Fig 5 (f)). On the contrary, the $V_{oc}$, $FF$, $J_{sc}$ and $\eta$ remain constant up to the value of $N_A = 10^{19}$ cm$^{-3}$ for Cell 2. Then, all the output parameters reduce with increasing $N_A$ density.
Fig. 5: The influence of doping density on the photovoltaic performance parameters (a) p+\text{-GaAs} layer of Cell 1 (b) p++\text{-GaAs} layer in Cell 2 (c) p+\text{-AlGaAs} layer of Cell 2 (d) n-AlGaAs layers of Cell 2 (e) and (f) p-GaAsN layer in Cell 1 and Cell 2 (g) n-GaAs layer in Cell 1 and (h) n+\text{-GaAs} layer in Cell 2. Here the ‘broken line’ indicate the data for Cell 1 whereas, the solid lines for Cell 2.

With the enhancement of $N_A$ density, reverse saturation current reduces which results in small rise of $V_{oc}$. Finally, the value of $\eta$ increases. After the density of $N_A=10^{19}$ cm$^{-3}$, all the solar cell performance parameters ($V_{oc}$, $J_{sc}$, $FF$ and $\eta$) tend to degrade due to the reduction of minority carrier lifetime as well as number of photo-generated carriers inside p-GaAsN absorber layer for both solar cells. From $N_A$ density $10^{17}$ to $10^{20}$ cm$^{-3}$, the $V_{oc}$ increase only 11 mV. A similar phenomenon has been discussed in earlier studies of [28, 34]. The figures 5(g) and 5(h) represent the effect of donor doping density $N_D$ on output parameters. With increasing the donor density $N_D$ in n-GaAs and n+\text{-GaAs} layers for both Cell1 and Cell 2, respectively $V_{oc}$ and $\eta$ increases, while $J_{sc}$ remains constant. The primary reason behind this enhancement of the $\eta$ is the improvement of the electrical conductivity and $V_{oc}$ in n-GaAs and n+\text{-GaAs} layer due to the addition of large number of free electrons [28, 34].
3.5 Impact of defect density on PV parameters

The impact of total density of defect on the photovoltaic output parameters for the different layers of both the solar cells (Cell 1 and Cell 2) are depicted in Fig. 6.
Fig. 6 The impact of total defect density on the photovoltaic performance parameters. (a) $p^+$-GaAs layer of Cell 1, (b) $p^{++}$-GaAs layer in Cell 2, (c) and (d) $p^+$-AlGaAs and $n^-$-AlGaAs layers in Cell 2, (e) and (f) $p$-GaAsN layer in Cell 1 and Cell 2, (g) $n$-GaAs layer in Cell 1 and (h) $n^+$-GaAs layer in Cell 2. Here the ‘broken lines’ indicate the data for Cell 1 whereas, the solid lines for Cell 2.

As shown in Fig. 6(a), the values of $V_{oc}$, $J_{sc}$ and $\eta$ start to decrease at the total defect density of $5.0 \times 10^{18}$ cm$^{-3}$ while the value of FF shows increasing tendency from $5.0 \times 10^{17}$ cm$^{-3}$ for the $p^+$-GaAs layer in Cell 1. On the contrary, all the solar cell performance parameters ($V_{oc}$, $J_{sc}$, FF and $\eta$) of $p^{++}$-GaAs, $p$-AlGaAs and $n$-AlGaAs layers in Cell 2 remain constant with changing the total defect density as indicated in Figs. 6(b), 6(c) and 6(d), respectively. A similar results was found in the previous report [12, 36]. The value of the total defect density of p-GaAsN layer is varied from $1.0 \times 10^{12}$ to $5.0 \times 10^{18}$ cm$^{-3}$ and the significant impact of the total defect density on the
PV parameters has been represented in Figs. 6 (e) and 6(f). The Cell1 and Cell 2 can endure the total defect density about $10^{14}$ cm$^{-3}$ to obtain $\eta$ of 40.05% and 43.90%, respectively. At the maximum defect density of $5.0 \times 10^{18}$ cm$^{-3}$, both Cell 1 and Cell 2 demonstrate least efficiency of 20.58% and 35.48% respectively. All the PV performance parameters degrade significantly at higher defect densities. The Shockley–Read–Hall (SRH) recombination rate contributes to decrease the PV performance parameters of the p-GaAsN absorber layer due to the existence of high defect density. The SRH recombination decreases the number of photo-generated carriers as well as the $V_{oc}$, thus reduces the $FF$ and $\eta$. The solar cell devices are significantly affected due to the existence of interface and bulk defects that decreases the minority carrier life time and diffusion length [12, 36].

With increasing defect density of the layer n-GaAs in Cell 1, the value of solar cell performance parameters ($V_{oc}$, $J_{sc}$, $FF$ and $\eta$) decreases due to the reduction of the free carriers as well as electrical conductivity, however no variation is observed of the output parameters of n$^+$-GaAs layer in Cell 2 as depicted in Figs. 6 (g) and 6(h). A similar tendency was found in the previous report of [37].

3.6 Effect of temperature on performance parameters:

Considering the thickness of 2000 nm of p-GaAsN absorber layer, the temperature is varied from 273K to 373K of solar Cell 1 and Cell 2 as represented in Figs. 7(a) and 7(b). The temperature dominantly contributes to decrease the value of $V_{oc}$ in Cell 1 and Cell 2 which results in decrease of the overall efficiency. The rise of temperature in Cell 1 and Cell 2 increases the reverse saturation current which also reduces $V_{oc}$ almost linearly from 1099 to 950 mV and 1140 to 1006 mV, respectively. The values of $\eta$ also decreases from 41.97 to 34.37 % and 45.75 to 38.62 % and for Cell 1 and Cell 2, respectively.
The semiconductor materials bandgap, $E_g$, decreases with rising in temperature due to reduction of the bonding energy and the electron-hole recombination processes enhances. Thus, the number electron-hole also reduces due to temperature rise which maintains constant $J_{sc}$ for Cell1 and Cell 2 over the range of temperature that are generated due to reduction of $E_g$ [37, 38]. The $FF$ decreases for the combined effect of the $V_{oc}$, $J_{sc}$, and $\eta$.

### 3.7 Enhancement of performance parameter p-GaAsN solar cell

The electrical characteristics ($J$-$V$) curve of the designed p-GaAsN dilute nitride solar cells with and without AlGaAs blocking layer has been demonstrated in Fig. 8 at 300 k under illumination of 100 mWcm$^{-2}$. The solar cell with AlGaAs blocking layer (Cell 2), demonstrates the improved performance parameters $V_{oc}=1105$ mV, $J_{sc} = 44.22$ mAc$^{-2}$, $FF = 89.84$, and $\eta = 43.90$, which is larger than the solar cell without AlGaAs blocking layer (Cell 1) in which $V_{oc} = 1053$ mV, $J_{sc} = 44.80$ mAc$^{-2}$, $FF = 84.89$, and $\eta = 40.05$. The present study proclaims a new insight to obtain the outmost efficiency of 43.90% and 40.05% for Cell 2 and Cell 1, respectively. The optimal PV performance parameters in the present study at 300 K and the comparison of performance of our achieved results with the previously studied values are demonstrated in Table 2 and Table 3, respectively.
Fig. 8 the electrical J-V characteristics of the designed solar cells.

Table 2: Comparison of the performance parameters in present study at 300 K.

| No. | Studied solar cell | GaAsN depth (nm) | $J_{sc}$ (mA/cm$^2$) | $J_{mp}$ (mA/cm$^2$) | $V_{oc}$ (mV) | $V_{mp}$ (mV) | FF (%) | PCE (%) |
|-----|--------------------|------------------|----------------------|----------------------|----------------|----------------|--------|---------|
| 1   | Cell 1             | 2000             | 44.80                | 42.71                | 1053           | 936            | 84.89  | 40.05   |
| 2   | Cell 2             | 2000             | 44.22                | 43.11                | 1105           | 1019           | 89.84  | 43.90   |

Table 3: Summary of the PV parameter of our present study with the previously studied values.

(Expt. = Experimental, Theo. = Theoretical)

| No. | Research Type | Structure       | GaAsN depth (nm) | $J_{sc}$ (mA/cm$^2$) | $V_{oc}$ (mV) | FF (%) | PCE (%) | Ref.   |
|-----|---------------|-----------------|------------------|----------------------|----------------|--------|---------|--------|
| 1   | Theo.         | p-GaAs/p-GaAsN/n-GaAs | 2000             | 30.31                | 930            | -      | 24.94   | [14]   |
| 2   | Theo.         | p-GaAsN/n-GaAsN  | 1500             | 68                   | 790            | 68     | 38.20   | [22]   |
The Table 3 illustrates the comparison of the development of GaAsN solar cell structures by different research groups. The theoretical approaches in the previous study show that the efficiency enhances from 15.0% to the highest 38.20% till now. From the simulation works, we have determined larger $V_{oc}$ and $\eta$ compared to the reported values [13, 14, 22, 28]. The value of $FF$ and $J_{sc}$ obtained from the numerical study is also higher than that in most of the previous reported values. The present study provides the insight for the guideline to obtain outmost efficiency of 40.05% and 43.90% for GaASN solar cell without and with AlGaAs blocking layer.

### 4 Conclusions

Dilute nitride solar cells of p-GaAsN absorber layer, have been designed to exploit absorption of light in the wide range and investigated in detail. The numerical study has been done by SCAPS-ID simulator to analyze the impact of layer thickness, defect and doping density, and temperature variation on the output parameters such as $J_{sc}$, $V_{oc}$, $FF$ and $\eta$. The numerical simulated output indicates that the solar cell containing AlGaAs blocking layers (Cell 2) exhibits an overall efficiency of 43.90% with doping density of $1.0\times10^{16}$ cm$^{-3}$ and defect density of $1.0\times10^{14}$ cm$^{-3}$ in the 2000 nm thick p-GaAsN absorber layer. On the other hand, the solar cell (Cell 1) containing no blocking layers shows the efficiency of 40.05% at the same doping and defect densities of the same absorber layer and its thickness. The present study leads toward the
realization of high-efficiency dilute nitride solar cell for the applications in space and PV industries.

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Declaration of Competing Interest

The authors declare that they have no competing interest related to the financial or personal relationship.

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