



# PERFORMANCE MAXIMIZATION OF HYDROGENATED AMORPHOUS SILICON MULTIJUNCTION PV CELL INCORPORATING GAAS JUNCTION

Md. Tafshirul Alam<sup>§</sup>, Md. Ashraful Islam<sup>‡</sup>, Nahid Akhter Jahan<sup>\*</sup>

**Abstract**—In this work, we proposed two different unique hetero-structures of amorphous hydrogenated silicon (a-Si:H) alloying with Ge and C, for solar photovoltaic (PV) use. We explored all the typical figure of merits such as Short circuit current-Open circuit voltage ( $I_{sc}$ - $V_{oc}$ ) characteristics, Fill-Factor ( $FF$ ), Power Conversion Efficiency ( $PCE$ ) of the solar cells at standard test conditions (AM 1.5, 300 K, and solar insolation of 100 mW/cm<sup>2</sup>). The first proposed structure is a slender PIN hetero-structure solar cell (only 393 nm thick P-a-SiC:H/P-a-SiC:H(buffer)/I-a-Si:Ge/N-a-Si:H). Thereafter, for better utilization of solar spectrum we proposed an ultra-slim P-a-SiC:H/I-a-SiGe:H/N-a-Si:H/P-GaAs/N-GaAs multijunction solar cells (only 410 nm). For these duo, a P+ CuAlO<sub>2</sub> transparent conducting oxide (TCO) is used which adheres on the top of window P-a-SiC:H to provide a back surface field-effect for lowering the surface recombination, whereas, a ZnO above the bottom-contact is included to obtain a stabilized ohmic-contact. We optimized both these structures to offer improved efficiency at nominal thickness, at tuned energy gap, at rational impurity-concentrations and doping concentrations of individual-layer. The highest photon PCE from our first heterojunction solar cell is attained as 20.89 % with an a-SiGe:H absorber of 1.66 eV. And the second structure with the inclusion of a GaAs junction (becomes multijunction as a whole) increases the efficiency up to 23%.

**Keywords**— a-Si:H, a-SiGe:H, a-SiC:H, GaAs, heterojunction, multijunction solar cells, PCE, TCO.

## I. INTRODUCTION

AS the oil deficit started in 1973, it created an anxiety and awareness in the whole world about fossil-fuel shortfall, and all the world leaders started to look for alternative renewable sources, among which

PV solar energy remains as prominent one. According to National Renewable Energy Laboratory (NREL), starting from 1971, a looming threat towards biodiversity and environmental imbalance due to unprecedented global warming generated from various green-house-gas (CO/CO<sub>2</sub>) leads to significant interest in this renewable PV cell technologies [1-7]. The past few decades witnessed several and substantial growth in this area. However, commercial price or costing of PV modules and availability of materials have been key concerns. Consequently, PV solar cell technologies that encompass the usage of reduced amounts of low-priced and fewer sophisticated source materials are preferred from the beginning. In PV technologies, wafer-based crystalline silicon solar cells are always considered as the pioneer and achieved relatively high stable efficiencies and reliability, however, the main drawback is the costly module price linked to the considerable amount of fabrication energy, often termed as “gray energy” [5]. Therefore, from ~1975 amorphous silicon (a-Si) was brought together as a material with a budding source for semiconductor devices and emerged as the initial thin-film solar cell material (first a-Si based PV cell provided a PCE of 2.4% in 1976). However, the major drawback of this a-Si is a very large number of defects that are typically suppressed by alloying with Hydrogen, which produces a-Si:H. From 1980 various research teams were formed worldwide to pursue research work on thin-film a-Si:H and received prominent attention especially in south-east Asia (mostly in Japan) and Europe. Mostly due to some notable features, such as: (i) non-lethality to the environment, (ii) outstanding optical absorption coefficient than crystalline Si specially in visible solar spectrum, (iii) lower deposition temperatures (suitably 200-300°C), benefitting the usage of low-priced substrates, and (iv) a potential candidate for manufacturing a large-area-deposition using less demanding growth-technique [3-8]. In addition, it is worth mentioning that the tunability of the energy-gap

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( $E_g$ ) of a-Si composites can be very easily achieved by varying the proportion of elemental-contents (H, C, Ge, and etc.). Together, through the production of a-Si:H alloys (a-SiC:H, a-SiGe:H, etc) it is possible to render better stability and performance enhancement in a-Si:H based solar cell [9-16]. It is witnessed that the a-SiC:H alloy is popularly used as an opening-window layer for mitigating the photosensitive loss due to its broader  $E_g$ . Meanwhile it is found that, a-Si:H and a-SiGe:H composites can be characteristically used as intrinsic and absorber layer because of narrow  $E_g$ . Preferably a-SiGe:H is used as middle cell in multijunction, owing to even more optical absorption coefficient than a-Si:H in every wavelength and hence projected to contribute a vital role in the performance enhancement of a-Si:H based cells. To date the PCE of single junction a-Si:H PV cells is obtained little further than 12% commercially, whereas for double/triple and multijunction PV cells, the PCE reached to 13-16% [6-16]

However, the major impediments towards achieving desired performance from this a-Si:H PV manufacturing is still limited by light involved degradation owing to the continuous generation of new neutral-dangling bond defects (Staebler-Wronski Effect) [12]. It seems that deficiency of scientific understanding and scarce models connecting the properties of material with the cell's performance features are still an obstacle. The scientist are still grappling to reduce this degradation to achieve stable cell, and trying to discover methods for producing better-quality smaller-bandgap bottom-most cell for a double/triple/multi-junctions also through the escalation of the deposition rate by multiple factors. The PV's functionality may also deteriorate if the recombination mechanisms are not addressed correctly, as the collected carrier will intervene the electric field inside the cell. Therefore apposite tunnel-recombination-junction is indispensable to continue the current flow through the cell if it is multijunction. Also a coordination of energy bands of buffer layer with absorber is required for effective charge carrier's transport.

Regarding all the above-mentioned context, in this work we proposed and investigated two hetero-structures with an intension to explore all the relevant cell-operating features through simulation aiming on maximizing the conversion efficiency. Both of our proposed structures are thin PIN type because thinner the p-i-n cells, lesser the suffering from collection problems, even if the dangling bond defects are increased by the Staebler-Wronski Effect; this is because, in thinner p-i-n-cells, the electric field dominant in the I layer can be boosted, and collection can be prominently enhanced. Our first proposed PIN

heterojunction solar cell is P-a-SiC:H/P-a-SiC:H(thin-buffer)/I-a-Si:Ge/N-a-Si:H with the presence of a p-type  $\text{CuAlO}_2$  on the top that is witnessed as suitable TCO for a-Si:H PV. Afterward we proposed a multijunction cell (P-a-SiC:H/I-a-Si:Ge/N-a-Si:H/P-GaAs/N-GaAs) modifying the former structure by including a GaAs PN junction in the bottom layers to ensure better utilization of the solar spectrum, provided that the  $E_g$  of all the distinct layers of the cell are attuned accordingly. Both our structures are investigated by varying the impurity concentrations, thicknesses, levels of defect, and  $E_g$  of every layers. Although it is argued that the efficiency prospective for a-Si solar cells achieved so far may be somewhat off-putting, we anticipate, the outcome of our investigation will motivate the scientists in this field of interest.

## II. DESIGN-SIMULATION, METHODOLOGY AND MATERIAL DETAILS OF PROPOSED CELL

The commonly used SCAPS-1D simulation program/software (by Prof Marc Burgelman) has been employed for performing modelling and simulation in this work. In this section the structural detail, material used and optical properties of these layers are discussed elaborately. In our both structures, the  $\text{CuAlO}_2$  adheres to the top electrode as TCO and zinc oxide (ZnO) is used just above the bottom electrode. As the a-Si:H intrinsic layer mostly adds to the current production, the optimum design of the cell structure is based on the intensification of light-absorption largely in the intrinsic layer. Whereas, the P and N-type layers are basically for the formation of electric field which is indispensable for separating the generated electrons and hole pairs in the intrinsic-absorber layer to build the PV effect. We analyzed to optimize the performance of the suggested cell through optimization of thickness,  $E_g$ , defect densities and doping concentrations of the window, absorber/intrinsic, and TCO layers for attaining maximum possible PCE at a temperature of 300 K and for solar insolation of 1.5 AM.

Table I and Table II display the properties of all the pertinent design parameters, obtained from previous work/ literatures [13-19], necessary for modelling and calculating the carrier dynamics of a-Si:H based device.

The optimized structural depiction of our proposed PV cells is shown in detail in Fig. 1. As we can see from Fig. 1 (a) that the first proposed optimized structure has a-SiC:H as P-type (20 nm thick) layer at the top, P-a-SiC:H as a thin buffer (3 nm) underneath, a a-Si:H inserted as N-type (30 nm thick). And the intrinsic a-SiGe:H (300 nm thick) is sandwiched in between the P and N-type as the absorber layer. On the very top of the P-type a-SiC:H, a 20 nm of  $\text{CuAlO}_2$  is attached as P-

type TCO connected to the front contact. Besides, a 20 nm of N-type ZnO is included underneath the N-type a-Si:H coupled to the bottom-contact. The total thickness of the entire structure becomes only 393 nm as a whole. A screen-shot of the structure from SCAPS-1D simulation software is shown in Fig. 1 (b).

The layout of second proposed optimized multijunction PV cell is shown in Fig. 1 (c). It is seen from Fig. 1 (c) that this structure comprises of a PIN heterojunction [a 300 nm wide a-SiGe:H intrinsic layer inserted in between the thin P-type a-SiC:H layer (10 nm) and N-type-a-Si:H (20 nm)] attached on top of a GaAs based PN junction [P-type-GaAs (20nm) suitably contacted to N-type-GaAs (10 nm)]. In this structure, also a 20 nm of CuAlO<sub>2</sub> is utilized as P-type TCO joined to the frontal contact and a ZnO is used as a back contact. It is worth mentioning that these front and bottom-contacts not only ease the electrical losses (series resistance) but also the photosensitive losses, particularly the reflection. The overall thickness of our multijunction structure becomes 410 nm only. Fig. 1 (d) provides the screen-shot view of the same structure from SCAPS-1D simulation software.

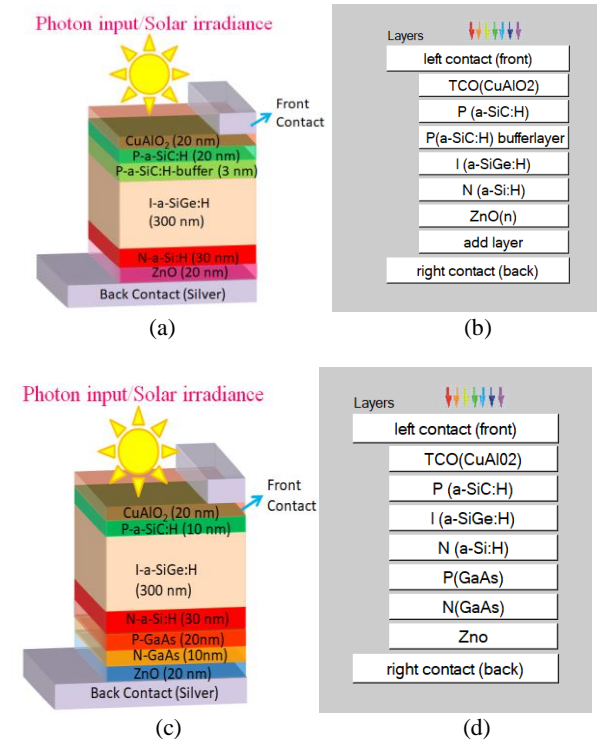


Fig. 1. (a) Schematic depiction of proposed PIN heterojunction PV cell at optimized thickness of all layers. (b) A screen-shot of the layout from SCAPS-1D simulation software. (c) Schematic details of multijunction (PIN-PN) PV cell after optimization and (d) the screen-shot view from software.

TABLE I  
PERTINENT PARAMETERS OF MATERIALS USED IN PN AND PIN CELLS [16-18]

Parameters	n-a-Si:H	I-a-SiGe:H	p-a-SiC:H	p-a-SiC:H (buffer)	p-GaAs	n-GaAs
$E_g$ (eV)	1.8	1.66	1.90	1.90	1.42	1.42
$\chi$ (eV)	3.8	4	3.7	3.7	4.07	4.07
$\epsilon_r$	11.9	14	11.9	11.9	12.88	12.88
$N_c$ (cm <sup>-3</sup> )	$2.5 \times 10^{20}$	$3 \times 10^{20}$	$1 \times 10^{20}$	$1 \times 10^{20}$	$4.7 \times 10^{17}$	$4.7 \times 10^{17}$
$N_v$ (cm <sup>-3</sup> )	$2.5 \times 10^{20}$	$1.45 \times 10^{20}$	$1 \times 10^{20}$	$1 \times 10^{20}$	$7.0 \times 10^{18}$	$7.0 \times 10^{18}$
$\mu_n$ (cm <sup>2</sup> /Vs)	$2.0 \times 10^1$	$2.0 \times 10^1$	$1.0 \times 10^1$	$1.0 \times 10^1$	$8.5 \times 10^4$	$8.5 \times 10^4$
$\mu_p$ (cm <sup>2</sup> /Vs)	$2.0 \times 10^0$	$2.0 \times 10^0$	$1.0 \times 10^0$	$1.0 \times 10^0$	$4.0 \times 10^3$	$4.0 \times 10^3$
$N_D$ (cm <sup>-3</sup> )	$8.0 \times 10^{18}$	0	0	0	0	$1.0 \times 10^{20}$
$N_A$ (cm <sup>-3</sup> )	0	0	$3.0 \times 10^{18}$	$2.8 \times 10^{18}$	$1.0 \times 10^{20}$	0

TABLE II  
PERTINENT PARAMETERS OF MATERIALS APPLIED AS TCO AND HTM IN THE STRUCTURES [18]

Parameters	ZnO (n)	CuAlO <sub>2</sub>
Thickness (μm)	0.02	0.02
$E_g$ (eV)	3.37	3.60
$\chi$ (eV)	4.35	2.500
$\epsilon_r$	10	60.000
$N_c$ (cm <sup>-3</sup> )	$2.22 \times 10^{18}$	$2.20 \times 10^{18}$
$N_v$ (cm <sup>-3</sup> )	$1.78 \times 10^{18}$	$1.80 \times 10^{19}$
$\mu_n$ (cm <sup>2</sup> /Vs)	$1.00 \times 10^2$	$2.00 \times 10^0$
$\mu_p$ (cm <sup>2</sup> /Vs)	$5.00 \times 10^1$	$8.60 \times 10^0$
$N_D$ (cm <sup>-3</sup> )	$1.00 \times 10^{20}$	0
$N_A$ (cm <sup>-3</sup> )	0	$3.80 \times 10^{18}$

#### A. The characteristic features of a-Si:H and a-SiC:H for PV cell uses

Silicon is very suitable for thin-film solar cell technology, for instance, appropriate band-gap (1-1.5 eV), large absorption coefficient, reproducible, widely available, non-toxic, low recombination rate of excitons and large diffusion length. And a lot of research has already been done on Si. As an absorber, Si can be deposited in a number of forms as a thin film: in the form of amorphous Si (a-Si) with no grains, μ-crystalline Si with grain size less than 100 nm and poly crystalline with grains of 0.1 μm to several μm. In the first two forms, the material features are significantly unique, while the poly crystalline Si behaves almost the same way as the bulk.

It is detected that the dangling bond defect density of a-Si is significantly reduced by alloying with Hydrogen; which makes a-Si:H (defect reduces from  $10^{21}$  cm<sup>-3</sup> to  $10^{16}$  cm<sup>-3</sup> or even more less). Another most important optical properties of a-Si:H is its absorption coefficient which is more than  $10^4$  cm<sup>-1</sup> for light energy higher than the  $E_g$ , which infers that 1000 nm thickness is required to absorb photons of all energy higher the  $E_g$ . The  $E_g$  (mobility gap) typically can be varied from 1.7 to 1.8 eV for a stable quality of a-Si:H. Though, the  $E_g$  (optical) can be increased linearly with H concentration in it [20].

The alloying with C (a-SiC:H) outcomes in broadening the  $E_g$  and it can be broadened to up to 2 eV [21-24]. However, the insertion of C increases the dangling bonds and therefore it is not rather used as absorber. This a-SiC:H is preferably used as opening-window layer in typical a-Si:H based PIN solar cell, due to its pronounced conductivity, and appropriateness for capturing wide range of photons [24]. Here, the thickness, optical and electrical properties are the key constraints that should be adjusted for maximizing the desired performance of typical PIN heterostructure.

### B. The impact of a-SiGe:H compound in thin-film PV cell

Adding of Ge content in a-Si:H lessens the  $E_g$ . By changing the germanium molar fraction, the optical  $E_g$  of the a-SiGe:H film are typically customized from 1-1.7 eV. It is worth noting that as the fraction Ge is increased the quality of the layer may decrease, unless special precautions are made while the fabrication. Remarkably, for almost every wavelength, the a-SiGe:H's absorption coefficient is greater than the a-Si:H (more than  $10^5 \text{ cm}^{-1}$ ). Also the a-SiGe:H alloy exhibits greater photo-conductivity comparing to the a-Si:H. Hence, it is likely that a-SiGe:H can result in an improved short circuit current owing to its amplified absorption ability. This eventually attains us a drop in the minimum thickness of absorber layer [24].

In addition, a proper absorber layer at the juncture of P (P-type) and I (Intrinsic-type) is imperative for diminishing the recombination at P-I territory and thus plays a dynamic role in carrier transport across the heterojunction. In this perspective, this P-I edge of p-a-SiC:H/I-a-SiGe:H can be a suitable match for our proposed cells.

### C. The insertion of GaAs PN junction in thin-film PV cell and its characteristics

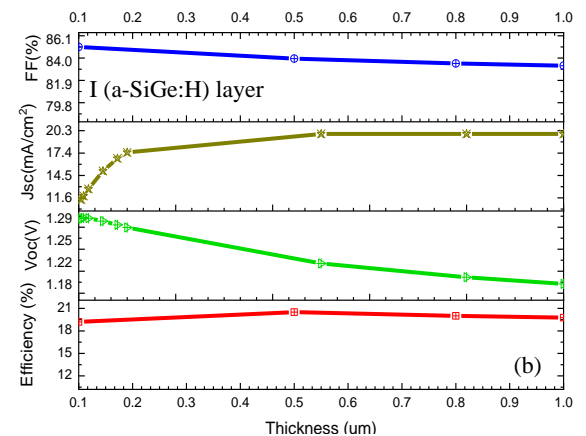
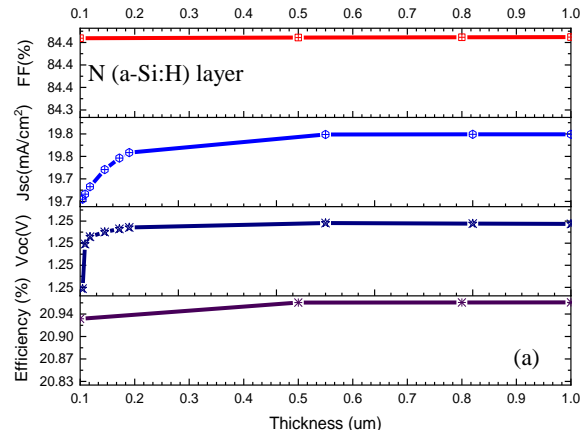
As compound semiconductor GaAs is a well-known name and commonly used, particularly for multijunction solar cells. The atomic structure of this III-V compound is very similar to that of Si. It offers acceptable lattice matching with Si as well. In reference to Si, some notable features of GaAs are: (1) high absorption coefficient, (2) band gap is 1.42 eV, which is ideal for single junction absorption, (3) more radiation hardness than Si (less degradation in light exposure) (4) very high radiative recombination. For regularly used GaAs the doping is usually done by replacement with atoms of Si and C (doping is obtained by diffusion or by hosting controlled amount of dopants while the growth) [24].

Static energy gap is a main limiting factor for single junction solar cell. In order to cover the whole spectrum range of sun energy, tandem or multijunction cells are employed. In order to make multijunction solar cells, we need materials with different  $E_g$ . In case of a-Si:H, this

band variation is achieved by appropriate alloying with Ge and C (discussed in section A and B). Multijunction can be produced either as double junction (tandem) or as triple junction and can be realized in two ways: (1) individually making all junctions and then mechanically attaching them on the top of each other or (2) monolithically making all junctions together. In previous case, the benefit is that each junction can be optimized independently. It is found that GaAs based multijunction already has provided efficiency larger than 40% [25]. Therefore, we introduced GaAs junction in our P-a-SiC:H/I-a-SiGe:H/N-a-Si:H to see the impact on overall efficiency.

## III. RESULTS AND DISCUSSIONS

It is identified that an effective PV cell needs the following qualifications: (1) uniform illumination current in every junction (2) reduction in series resistance along with recombination and reflective loss. The former qualification can be ensured by tuning all layers at suitable  $E_g$ , varying the thickness, doping densities and defect densities [16-22]. The latter is achieved by employing techniques like suitable TCO, buried contact, point contact or back contact solar cells. So far, the efficiency limit of single and double heterojunction a-Si:H based solar cell is seen as 14.6%.





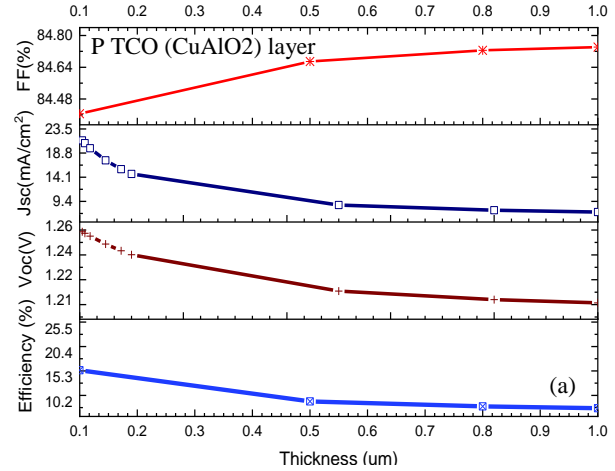
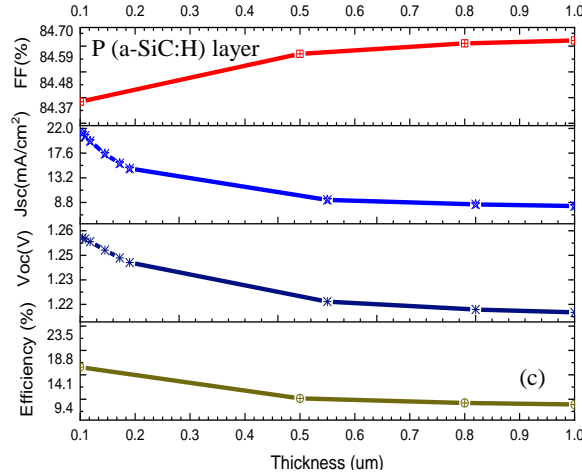


Fig. 1. Fill-Factor (FF),  $J_{sc}$  (short circuit current density), and open circuit voltage  $V_{oc}$ , as a function of thickness varied from 1 nm to 1  $\mu$ m for all P, I and N-layers of our first proposed cells.

In PIN, the P and N-type layers are for the formation of electric field, which is vital for separating the generated exciton pairs in the intrinsic-absorber layer to build the PV effect. We investigated the performance of the proposed cell through optimization of thickness,  $E_g$ , defect densities and doping concentrations of the window, absorber/intrinsic, and TCO layers for achieving maximum possible PCE at a temperature of 300 K and for solar insolation of 1.5 AM. Hence, thickness, doping concentrations and defect densities are considered as key design factors.

At first we have shown the effect of thickness variation on the performance such as FF,  $J_{sc}$ ,  $V_{oc}$  and efficiency of the first proposed double heterojunction PIN cell in Fig. 1. The thickness has been varied from 1 nm to 1000 nm. The simulation-results of Fig. 1 helps us selecting the optimized thickness for each layers, because this is a crucial parameters that decides the cost of overall solar cell. Our results reveal that the PCE shows insignificant variation with thickness for I (a-SiGe:H) and N (a-Si:H) layers although increases slightly and reaches a maximum value by growing the thickness of absorber I-layer and N-layers from 1 to 500 nm. Although it is typical that the light absorption is likely to increase with increasing the region of I; though, it should be noted that much larger thickness would distress the electric field. Hence, we selected the optimized thickness of the I-layer of the PIN cell as 0.3  $\mu$ m (300 nm) and for N layers we picked 30 nm without compromising the efficiency. The P-type a-SiC:H layer shows the opposite trends comparing with the others with the variation of thickness on the performance. The optimized P-layer thickness is found as 20 nm, whereas the best buffer thickness is found as 3 nm.

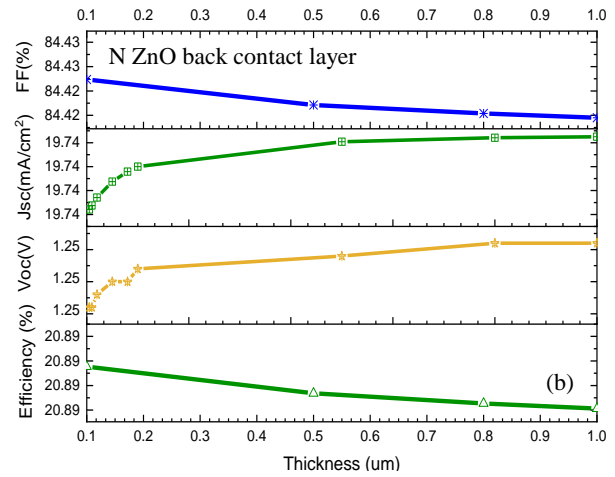
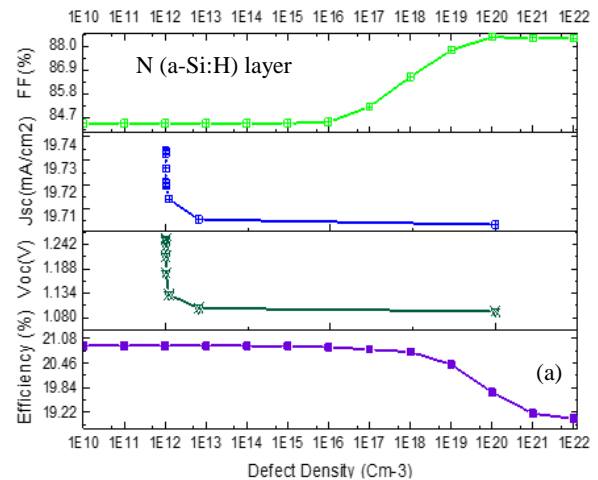


Fig. 2. Fill-Factor (FF),  $J_{sc}$  (short circuit current density), and open circuit voltage  $V_{oc}$ , as a function of thickness varied from 1 nm to 1  $\mu$ m for all P-type  $\text{CuAlO}_2$  as TCO and N-type ZnO as back contact layers.



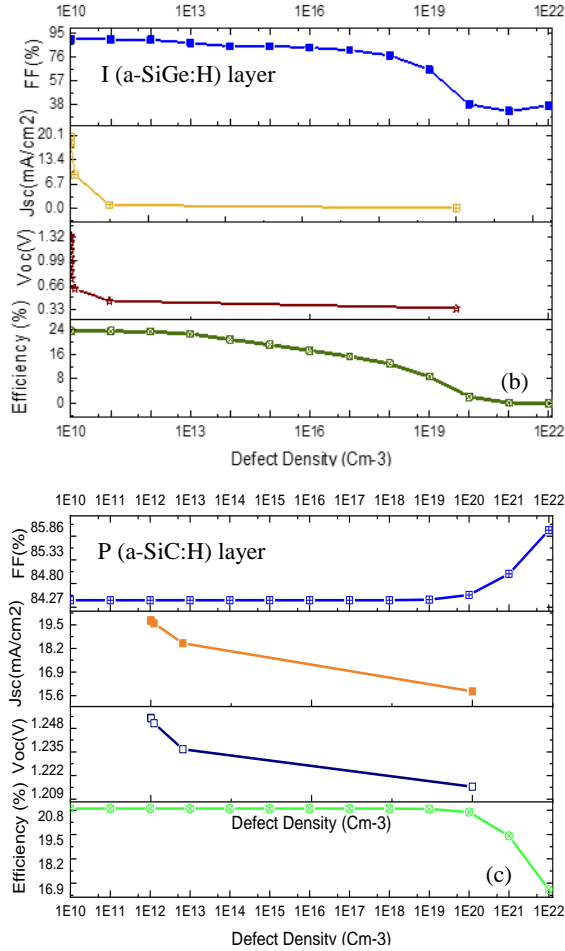


Fig. 3. The effect of the variation of defect densities of each layer on Fill-Factor (FF),  $J_{sc}$  (short circuit current density) open circuit voltage  $V_{oc}$ , and efficiency (%) of the first proposed PIN structure.

Similarly, in order to optimize the thickness of TCO and back contact layer as depicted in Fig. 2, same variation of thickness have been carried out for P-type  $\text{CuAlO}_2$  as TCO and N-type ZnO as back contact layers. From the simulation results, we select the N+ ZnO layer thickness as 20 nm for preserving small series resistance and the optimized thickness of P+-type  $\text{CuAlO}_2$  TCO layer is also found as 20 nm above the P-type a-SiC:H opening for our first proposed heterostructure.

Thereafter we investigate the influence of defect density on every layer of the first proposed structure as shown in Fig. 3. We can perceive from the Fig. 3 that, mostly the defect density of I-a-SiGe:H dominantly disrupts the cell's efficiency by increasing recombination loss, disturbing illumination current by imposing an asymmetric electric-field across the junction. Then for the selection of proper doping densities of the doped layers (P and N) the obtained variations (shown in Fig. 4) are conducted. This variation helped us to decide the suitable donor and acceptors concentrations for our structures.

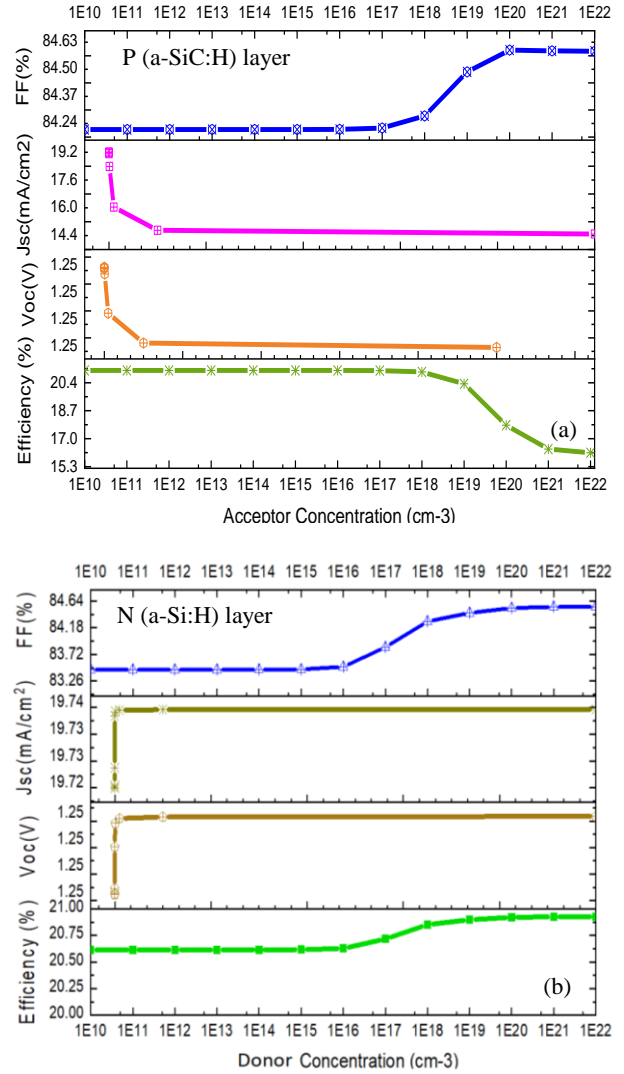
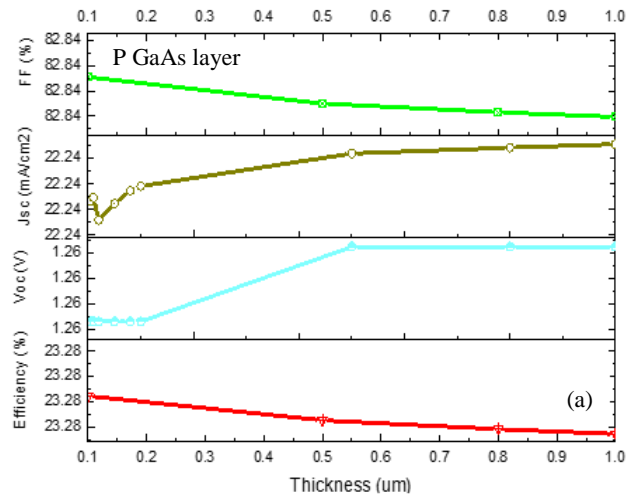


Fig. 4. Fill-Factor (FF),  $J_{sc}$  (short circuit current density) open circuit voltage  $V_{oc}$ , and efficiency (%) as a function of doping concentrations  $N_A$  and  $N_D$  (cm<sup>-3</sup>) of P-(a-SiC:H) and N-(a-Si:H) layers.



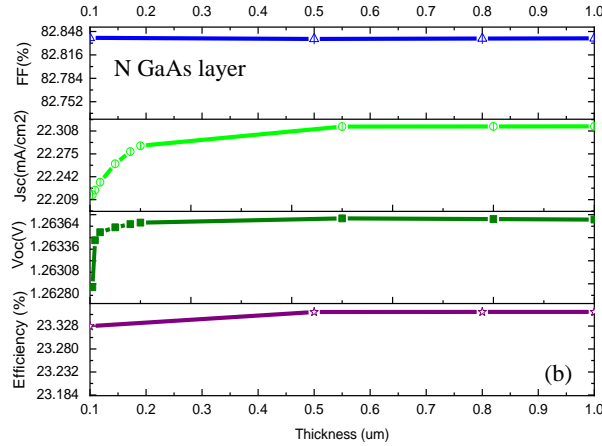


Fig. 5. Fill-Factor (FF),  $J_{sc}$  (short circuit current density), and open circuit voltage  $V_{oc}$ , as a function of thickness varied from 1 nm to 1  $\mu$ m for all P-GaAs and N-GaAs of the second proposed multijunction cell

Next, Figs. 5-7 convey the similar analysis of our simulation results for our second proposed multijunction solar cell which includes GaAs PN junction beneath the former amorphous based Si heterostructure. It is observed from Fig. 5 that both P and N-GaAs shows almost insignificant dependence on thickness although for P-GaAs the efficiency slightly increases with lowering the thickness, while, for N-GaAs the efficiency somewhat increases with increasing the thickness. It is worth noting that in this multijunction structure N-a-Si:H/P-GaAs interface serves as the tunnel recombination junction. Electrons incoming at the N-type from the top of tunnel junction and holes arriving at the P-type from the bottom cell do not contribute in charge generations rather recombine fully and continue the current flowing. Therefore in order to keep low ohmic loss the thickness of P-GaAs is decided 20 nm which is larger than N-GaAs (10 nm).

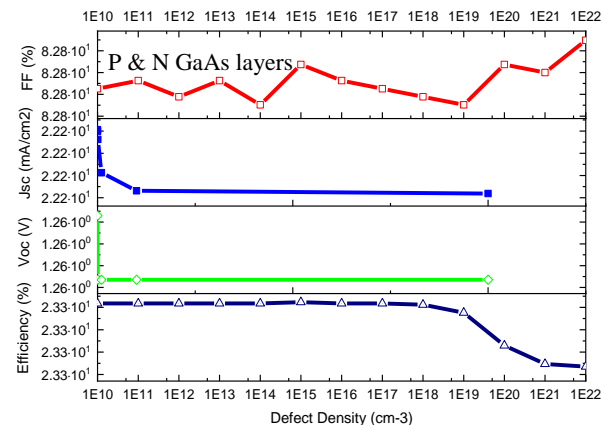


Fig. 6. The variation of defect densities of P and N GaAs layers on the performance parameters (Fill-Factor (FF), short circuit current density ( $J_{sc}$ ), open circuit voltage ( $V_{oc}$ ), and efficiency (%)) of the multijunction cell.

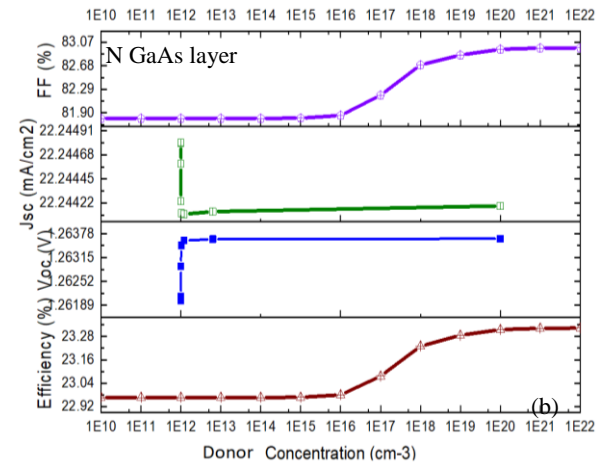
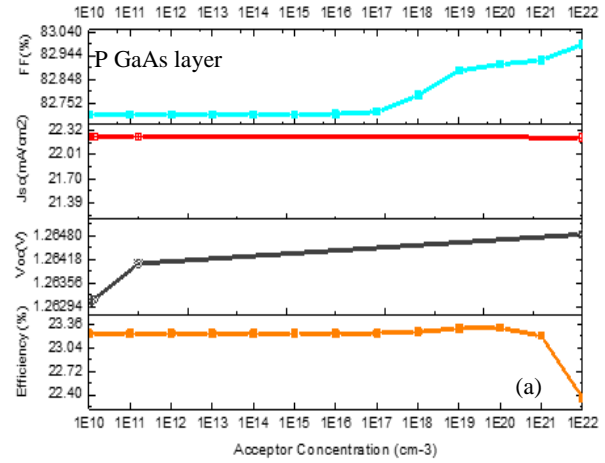
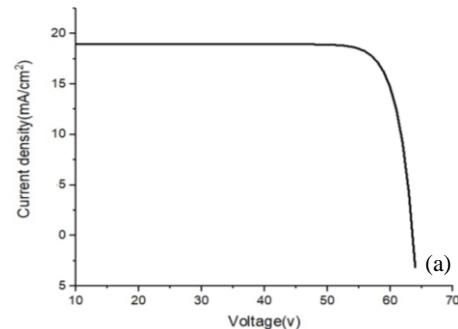


Fig. 7. The variation of doping concentration  $N_A$  and  $N_D$  ( $\text{cm}^{-3}$ ) of P-GaAs and N-GaAs layers on the performance parameters (Fill-Factor (FF),  $J_{sc}$  (short circuit current density) open circuit voltage  $V_{oc}$ , and efficiency (%)) of the multijunction cell.

The variation of defect densities jointly for P and N GaAs layers on the performance parameters (Fill-Factor (FF), short circuit current density ( $J_{sc}$ ), open circuit voltage ( $V_{oc}$ ), and efficiency (%)) of the multijunction cell is shown in Fig. 6 that reveals almost stable efficiency even at defect density up to  $1 \times 10^{19} \text{ cm}^{-3}$ . Corollary, Fig. 7 (b) gives a clear picture how heavily doped N-GaAs can keep the tunnel junction's electrical loss in control.



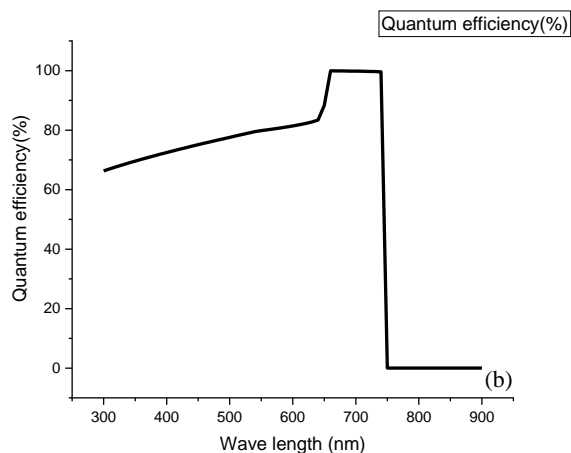


Fig. 8. (a) The I-V characteristics of the optimized PIN (P-a-SiC:H/P-a-SiC:H(buffer)/I-a-SiGe:H/N-a-Si:H) heterojunction solar cell including P<sup>+</sup>-type CuAlO<sub>2</sub> TCO and N<sup>+</sup> type ZnO as back contact layer. (b) The quantum efficiency (QE(%)) of the PV cell as a function of wavelength.

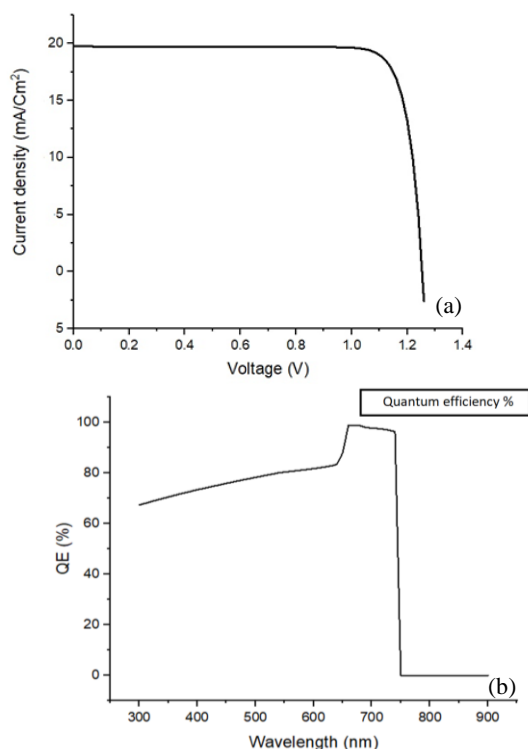


Fig. 9. (a) The I-V curve of the optimized PIN-PN (P-a-SiC:H/I-a-SiGe:H/N-a-Si:H/P-GaAs/N-GaAs) Multijunction solar cell including P<sup>+</sup>-type CuAlO<sub>2</sub> TCO and N<sup>+</sup> type ZnO as back contact layer. (b) The quantum efficiency (QE(%)) of the PV cell as a function of wavelength.

Finally, the optimized I-V curve and internal-quantum-efficiency (IQE) of the first proposed cell of P-a-SiC:H/P-a-SiC:H(buffer)/I-a-SiGe:H/N-a-Si:H double-heterojunction solar cell is depicted in Fig. 8 with maximum efficiency of 20.89%. Then the optimized I-V and IQE curves of the P-a-SiC:H/I-a-

Si:H/N-a-Si:H/P-GaAs/N-GaAs multijunction cell are shown in Fig. 9 with a peak efficiency of 23%. It discloses that by incorporating GaAs PN junction in the multijunction cell, the efficiency has increased from 20.89% to 23%.

#### IV. CONCLUSION

In this work, a methodical analysis on a double heterojunction PIN P-a-SiC:H/I-a-SiGe:H/N-a-Si:H PV cell is designed and simulated using SCAPS-1D simulator. At first place, the PV cell were simulated and optimized with the variation of thickness, defect densities and doping concentrations of P-type aSiC:H as window layer at P-I interface, a-SiGe:H as absorber I and N-a-Si:H layer. The highest PCE is achieved to be 20.89% implementing CuAlO<sub>2</sub> as suitable P-type TCO that provide suitable back surface-fields as well. The same structure with the inclusion GaAs PN junction (becomes multijunction as a whole) increases the conversion efficiency up to 23%.

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