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Chapter

III-Nitride Nanowires: Future Prospective for Photovoltaic Applications

Soumyaranjan Routray and Trupti Lenka

Abstract

Photovoltaic (PV) technology could be a promising candidate for clean and green source of energy. The nanowire technology provides extra mileage over planar solar cells in every step from photon absorption to current generation. Indium Gallium Nitride ($In_xGa_{1-x}N$) is a recently revised material with such a bandgap to absorb nearly whole solar spectrum to increase the conversion efficiency copiously. One of the major technological challenge is in-built polarization charges. This chapter highlights the basic advantageous properties of $In_xGa_{1-x}N$ materials, its growth technology and state-of-the-art application towards PV devices. The most important challenges that remain in realizing a high-efficiency $In_xGa_{1-x}N$ PV device are also discussed. III-Nitride nanowires are also explored in detail to overcome the challenges. Finally, conclusions are drawn about the potential and future aspect of $In_xGa_{1-x}N$ material based nanowires towards terrestrial as well as space photovoltaic applications.

Keywords: III-nitride, polarization charges, efficiency, InGaN/GaN, nanowires, stress, strain

1. Introduction

Photovoltaic (PV) technology is the most emerging way of harnessing huge amount of energy from sun light as compared to solar thermal and photo electro-chemical cells [1]. PV devices convert incident photons from sunlight to electricity upon exposed to light. PVs are popular because of its compactness and can be used anywhere for different application [2]. Additionally, involvement of nanostructures further boost the performance of solar cell. Over the past decade, nanostructured solar cell has become hot topics within research community due to its potential to enhance the spectral response of cell. Although, first generation silicon wafer based solar cell leads the current global PV market, however this conventional technology do not have any further scope to improve efficiency and reduce cost [3]. Additionally, it is also not recommended to use Silicon based solar cell for space application due to its low radiation tolerance. Second generation thin film technology such as hydro-genated amorphous silicon (a-Si: H), CIGS, and CdTe could not line-up with wafer-based silicon due to use of rare earth elements and low stability [4, 5]. Furthermore, highly efficient compound semiconductors based third generation solar cell have a demerit of high cost which limits its use in terrestrial applications. Hence, the hunt for low cost high performance solar cell are still unachievable. In the meantime, involvement of nanotechnology could bring a ray of hope for future generation

solar cell. Nanowire (NW) geometry has remarkable advantages over planner geometry due to optical, electrical, and mechanical effects. New charge separation mechanisms, low defects and low cost also add more mileage to this journey. Looking towards the current scenario, existing PV technologies aren't the solid foundation for the future projection of the renewable energy generation. None of the existing technology can satisfy global energy demand in future [2, 5]. Moreover, if the material or technological limitations restrict the future roadmap of PV technology, then the incorporation of new efficient materials and transpose of technology will be an assurance against high cost and low efficiency solar cells. Newly explored $In_xGa_{1-x}N$ material brings an bunch of opportunities for future PV technology, having capability to absorb full solar spectrum using a single absorber material. One of the major properties of InGaN material is its tunable bandgap from 0.6 to 3.4 eV by changing 'In' content [6–10]. It also has easy growth of nanowire and nanorod structures with proven technology [11–14]. It is a direct bandgap material where photon absorption and direct interband transition can be occurred without interference of phonons to conserve momentum. Additionally, high absorption coefficient of 10^5 is an additional benefit for good absorption with thin layer. Hence the cost can be minimized as well as recombination rate can also be minimized. InGaN also possess a high saturation velocity and a low effective mass of charge carriers, which ensures the more carrier separation along the junction. High radiation tolerance of InGaN are always appreciated for harsh environments. Moreover, InGaN solar cell do not contain any toxic elements such as arsenic, cadmium or phosphorous as used in MJ solar cell. Thus, it is evident that $In_xGa_{1-x}N$ is an extremely allegiant PV material that can enable several photovoltaic devices [15, 16]. It is required to explore state-of-art of different InGaN based PV technologies and new possibilities of InGaN as a hopeful material for future technology [17, 18]. Hence, in this chapter a scope of III-Nitride and its progress with nanostructures have been discussed in order to explore more on future generation solar cell.

2. Planar, nanodisk and nanowire III-nitride solar cells

In the present context mainly different geometry of III-Nitride GaN/InGaN material based solar cell are considered, such as planar, nanodisk and nanowire types. Theoretically, it is anticipated that power conversion efficiency more than 40% could be achievable with GaN/InGaN junctions [19, 20]. However, practically achievable efficiency is quite low [21, 22]. One of the major challenges is the association of in-house defects with InGaN layer at higher 'In' content. Which in turn leads to stuck of immobile charges (known as polarization charges) along interfaces and reduces minority lifetime. Recently III-Nitride nanowires (NWs) are proposed as stand-alone PV devices due to enhanced light trapping, defect and stress-free growth [23, 24]. In general, two widely used structure for nanowire solar cell are (i) axial junction and (ii) radial junction. Axial junction is also known as nanodisk (ND) whereas radial junction is known as core-shell-shell (CSS) solar cell. Vapor–liquid–solid (VLS) technique is one of the popular methods to grow the GaN/InGaN nnaowires [23]. The fabricated NWs have hexagonal cross-section with {0001} orientation of top facet and {1–100}/ {10–10} orientation alongside walls of NWs [23]. Literature shows the comparative analysis of planar and circular NWs reported by Y. Zeng *et al.* [25] and B.M. Kayes *et al.* [26] with achievable conversion efficiency of more than 33% and 50% for Si and GaAs respectively. Additionally, ND and NW SCs are reported by Christesen *et al.* [27], which shows comparative better performance in CSS-NW SCs. The analysis in literature taken circular cross-section into consideration for NWs but in practice,

III-Nitride NWs possess either hexagonal or triangular cross-section. Hence, in this chapter, a scope has been taken to analyze the CSS-NW and ND type SCs with hexagonal crystallographic orientations as per the fabricated devices. The chapter also emphasis on effect of polarization induced electric field with a different 'In' compositions of $In_xGa_{1-x}N$. The schematic of planar, ND and CSS-NW SCs as shown in **Figure 1** and simulated using VICTORY 3D Luminous TCAD. Optical and electrical properties are solved using Poisson's equation, drift diffusion, and photo generation-recombination models. All the structures are designed with *n*/*i*/*p* junctions, which helps to reverse the electric field and match with polarization-induced electric field [28, 29]. A uniform 40 nm and 100 nm thickness are taken for n- and p-GaN layer of three structures. Thin Ni/Au (5 nm/5 nm) layer is used as contact for all three considered cells. Incorporation of Ni layer may reduce series resistance and hence enhance fill factor (FF) of the solar cell. The thickness of intrinsic InGaN layer is varied from 6 nm to 200 nm to optimize the thickness in planar, ND and CSS-NW solar cell. The surface recombination velocity of 10^5 cm/s is taken into consideration for all three structure. The minority carrier lifetime is as follows [29].

$$\tau_{n/p} = \frac{1}{\sigma_{n/p} \times \vartheta_{thermal} \times N_{defect}} + \frac{1}{C_{n/p} \times n} + \frac{1}{C_{Augur} \times n^2} \tag{1}$$

Where $\sigma_{n/p}$ is the capture cross sections of electron or hole, thermal velocity of carriers, $\vartheta_{thermal}$ ($\approx 10^7$cm/s), the defect density (cm^{-2}), N_{defect}, electron capture coefficient for acceptor or donor, $C_{n/p}$, and n is the free electron concentrations.

All the material parameters for GaN and InGaN with different compostion can be found from [30]. The interpolation method is used to calculate all parameters for $In_xGa_{1-x}N$ composite alloys. Defect density in the order of 10^{17}, 10^{14} and 10^{12} are incorporated for planar, ND and CSS-NW SCs respectively [31].

The model developed by Romanov *et al.* [32] and Mastro *et al.* [33] are implemented here to calculate polarization charges along InGaN/GaN heterointerfaces and is expressed as,

$$P_{total} = P_{Lz'}^{pz} + \left(P_L^{sp} - P_T^{sp}\right) cos\varphi \tag{2}$$

Where P_L^{sp} and P_T^{sp} are spontaneous polarizations for top and bottom layer respectively, $P_{Lz'}^{pz}$ is the piezoelectric polarization along the interface which solely depends on strain profile, φ is the angle between planes and basal plane. Angle φ is

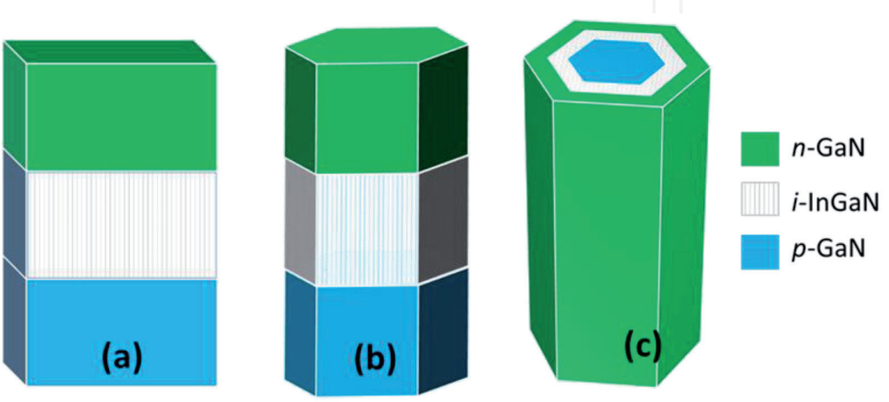


Figure 1.
Schematics of n-i-p *heterojunctions with (a) planar (b) nanodisk (ND) and (c) CSS-NW based solar cell [29].*

considered as 0° for polar {0001} facet and 90° for nonpolar {1–100}/{10–10} facets [33]. Finally, material parameters are incorporated into VICTORY 3D Luminous TCAD to simulate solar cell.

Vertical illumination of light source on the front surface of the device is consider during all analysis as shown in **Figure 1**. Transport of carriers and separation mechanisms in the device depends solely on its geometrical structure. Here, carrier transport in planar, ND and NW type solar cell are explored with the help of energy band diagram. **Figure 2(a)** shows that tilt of energy band along *i*-InGaN region is not in favor of carrier collection due to detrimental polarization effect along {0001} orientation of planar Solar cell. Similarly, ND type solar cell also suffers from polarization effect due to axial growth along {0001} orientation. Hence height of barrier along the junction increases in case of planar and ND solar cell as shown in **Figure 2**.

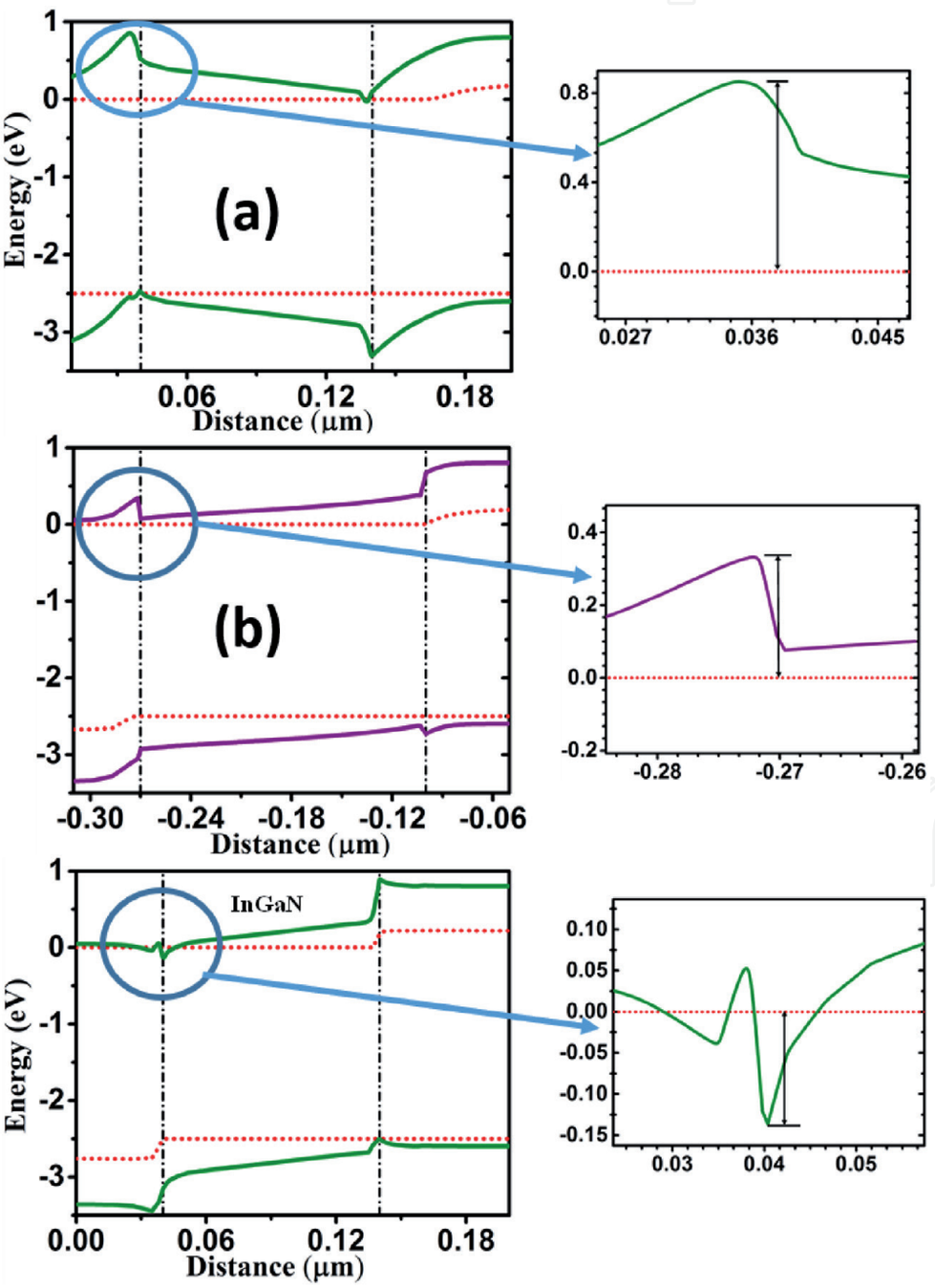


Figure 2.
Energy band diagram of (a) planar (b) ND and (c) CSS-NW solar cell at 100 nm, 150 nm, and 180 nm i-InGaN thickness respectively.

High potential barrier hinders the diffusion of photogenerated carriers to either sides of the contact. Consequently, carrier collection degrades along {0001} interface. Similarly, potential valley is also observed next to barrier along the interfaces, which stocks carriers leading towards low collection.

Thus, with increase in bias voltage, photogenerated carriers accumulate inside the potential valley rather than traveling in *i*-region. In contrast, CSS-NW type solar cells do not show this effect because of radial separation of carriers. Polarization charges have negligible effect on CSS-NW due to nonpolar facets as shown in **Figure 2(c)**. The inclination energy band in CSS-NW solar cell is in favor of carrier collection. Potential barriers are less as shown in **Figure 2(c)**. Hence a hassle-free movement of carriers is possible in CSS-NW solar cell.

Figure 3 shows dependency of short-circuit current density (J_{sc}) on 'In' composition and thickness of i-InGaN absorber layer. In planar structure, diffusion length carriers are quite low due to high density of defects, which consequently leads to a poor J_{sc} . Thus, higher thickness of *i*-InGaN do not contribute more towards current due to low diffusion length of carriers. It is also observed that increase in 'In' composition leads to higher polarization charges [24], which also block some of the diffused carriers before collection. Thus J_{sc} shows a poor performance at higher 'In' fraction as shown in **Figure 3**. However, J_{sc} is high in radial junctions as compared to axial junctions. In order to interpret this result, Shockley diode equation is considered for short circuit current as

$$I_{sc} = q \int_{V_{active}} g(\vec{r}) d^3\vec{r} \tag{3}$$

Where volume of the absorption region is, V_{active} , photo-generation rate, $g(\vec{r})$ and position vector is given by $\vec{a}$. The optical photo generation rate, $g(\vec{r})$ is considered as constant g across the entire NW solar cell, which simplifies the complexity of the model.

Thus J_{sc} can be expressed as

$$J_{sc} = q \times g \times L_{active} \tag{4}$$

Where, active absorption layer is, L_{active} . It is noteworthy to mention that due to the structural advantages, CSS-NW possess more than two-fold enhancement in active absorption region, which in turn support more photon absorption and high current. Therefore, it is observed that J_{sc} is quite enhanced in CSS-NW case as compared to ND and planar counterparts. It is due to the high absorption region of CSS structure and higher diffusion length of carriers. Depending on the structural advancement, carrier diffusion length, and lifetime, an optimized 180 nm, 150 nm

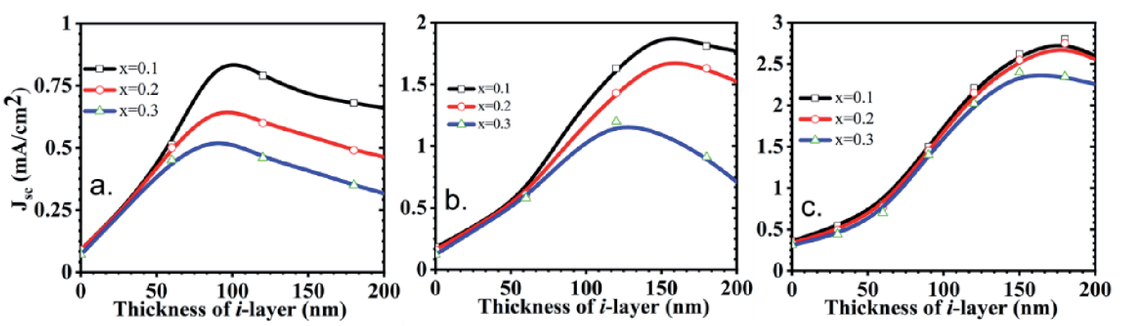


Figure 3.
Short circuit current density (J_{sc}) at 10%, 20%, and 30%, 'In' content for (a) planar (b) Nanodisk and (c) CSS-NW solar cell.

and 100 nm active layers are obtained for CSS-NW, ND and planar structure respectively as given in **Figure 3**.

Figure 4 shows the current density-voltage-power density (J-V-P) curve of n-GaN/i-$In_{0.1}Ga_{0.9}N$/p-GaN planar, ND and NW type solar cell. The optimized thickness of 100 nm, 150 nm and 180 nm i-InGaN is considered for all performance analysis. It shows a higher J_{sc} in CSS-NW as compared to ND and planar structure. It is anticipated that higher current in CSS-NW solar cell is mainly due to higher active absorption region and efficient carrier separation. It is important to highlight that planar and ND type solar cells shows a stair-case type *J-V* curve, which is not there in CSS-NW. It is may be due to low degree of strain relaxation or higher stress generation along the interface which is again related to structural issues of device. Hence, it is always important to engineer the device structure as per the material properties of the absorber layer. High defect density along the interface is also play a major role for low current in planar and ND solar cell. CSS-NW do not possess a staircase J-V curve due to low defect density, low stress and high degree of strain relaxation. It is also observed that the depth of stair-case in *J-V* curve is increasing with higher 'In' contents. Additionally, higher J_{sc} value of 2.82 mA/cm^2 is noted in CSS-NW solar cell (**Figure 5**).

It is also observed that due to high degree of strain relation, low defects density and more active area of absorption, CSS-NW structure can accommodate higher thickness of active InGaN layer (W) region. Moreover, higher thickness of absorber enhances the probability of more absorption of photons from sunlight. In other hand, active region of planar and ND type solar cells cannot be increased due to are limitation of surface recombination arte, polarization induced electric field, low degree of strain relaxation and defect density. V_{oc} of ND type solar cell is seen to be higher than CSS-NW type solar cell which is may be due to the recombination rate along the junction. However, the rate of increase in J_{sc} of CSS-NW structure is comparatively higher than ND and planar solar cell. Similarly, planar solar cell possesses a low as compared

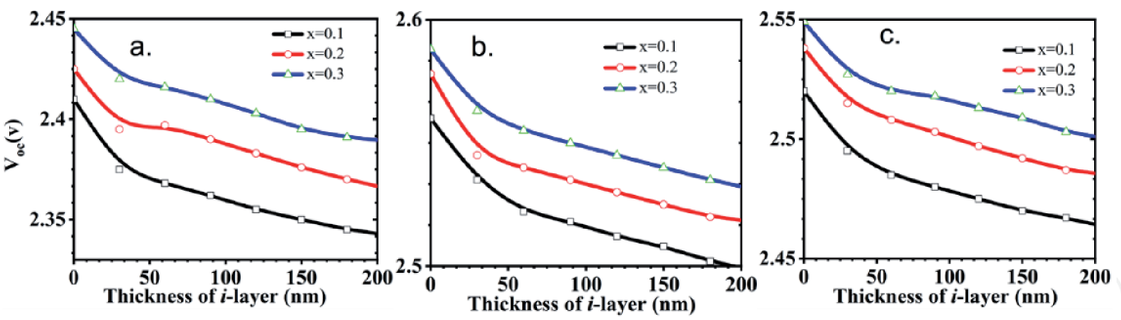


Figure 4.
Open circuit voltage, V_{oc} at 10%, 20%, and 30%, 'In' content for (a) planar (b) Nanodisk and (c) CSS-NW solar cell.

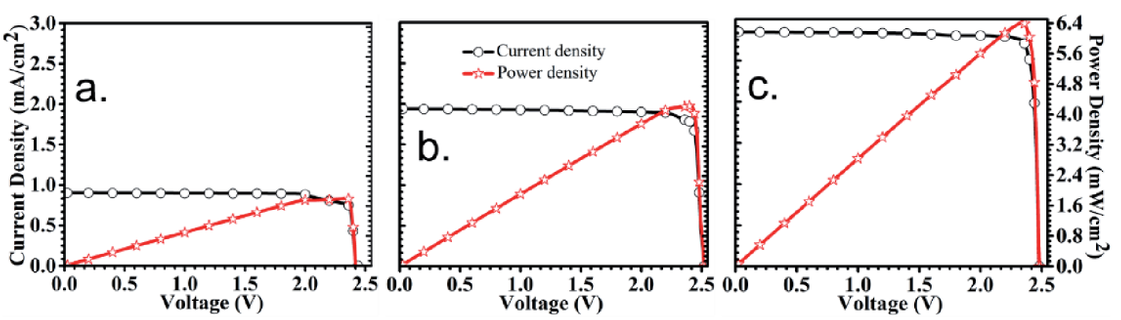


Figure 5.
Current density (black line) – Voltage – Power density (red line) of (a) planar (b) ND and (c) CSS-NW solar cell at 100 nm, 150 nm, and 180 nm i-InGaN thickness respectively.

to ND and NW solar cell. It is mainly due to appearance of staircase type *J-V* curve, which in turn reduces maximum power (P_m) of solar cell. Finally, achievable conversion efficiency (η) of CSS-NW structure is increased by more than 0.5-fold and 2.5-fold, compared to ND and planar type solar cells respectively. More analysis on different types of CSS nanowire is also studied and can found in [34–36].

	W (nm)	**J_{sc} (mA/cm^2)**	**V_{oc} (V)**	**FF (%)**	**Efficiency η (%)**
Planar	100	0.90	2.41	82.7	1.8
Nanodisk (ND)	150	1.93	2.52	87.6	4.28
CSS-Nanowire (NW)	180	2.84	2.47	91.6	6.46

3. Conclusion

In this chapter, the importance of nanowire solar cell with III-Nitride material is explored in a detailed manner. A comparative analysis is carried out with planar, nanodisk and nanowire type solar cell and concluded that nanowire type structure shows a better performance as compared to others. Additionally, it is found that nanowires in InGaN materials are grown either in triangular or hexagonal orientation. The strain relaxation is more in CSS-nanowires which in turns leads to low in-house defect density along the interfaces. CSS-NWs are also able to accommodate higher thickness of intrinsic material due to high carrier diffusion length. Radial separation of carriers also provides more surface area and better control on carrier separation mechanisms. Hence, it is concluded that radial growth of nanowire provides a broad range of opportunity for performance enhancement of solar cell. The similar type of observation are also applicable to LASER and light emitting diodes, where III-Nitride materials are used.

Acknowledgements

The authors acknowledge Dept. of Science and Technology, Govt. of India for financial support for providing the instrumental facility under DST-FIST in Dept. of ECE, SRM Institute of Science and Technology, Chennai, India.

The authors also acknowledge Visvesvaraya PhD Fellowship of MeitY, Govt. of India and TEQIP-II for procurement of Silvaco TCAD tool in Department of ECE, NIT Silchar for carrying out the research work.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this chapter.

Appendices and nomenclature

InGaN	indium gallium nitride
GaN	gallium nitride
CIGS	copper indium gallium selenide
CdTe	cadmium telluride

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