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Published in:

Journal of Alloys and Compounds

DOI:

[10.1016/j.jallcom.2019.151803](https://doi.org/10.1016/j.jallcom.2019.151803)

Published: 30/11/2019

Document Version

Peer reviewed version

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Please cite the original version:

Prabakaran, K., Raju, R., Arivazhagan, P., Jayasakthi, M., Sanjay, S., Surender, S., Pradeep, S., Balaji, M., & Baskar, K. (2019). Effects of indium flow rate on the structural, morphological, optical and electrical properties of InGaN layers grown by metal organic chemical vapour deposition. *Journal of Alloys and Compounds*, 811, [151803]. <https://doi.org/10.1016/j.jallcom.2019.151803>

Effects of Indium flow rate on the structural, morphological, optical and electrical properties of InGaN layers grown by Metal Organic Chemical Vapour Deposition

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Abstract

InGaN/GaN heterostructures were grown on c-plane sapphire substrates using metal organic chemical vapour deposition by varying the trimethylindium flow rate as 7, 10 and 14 $\mu\text{mole/min}$. The structural, morphological, optical and electrical properties of InGaN layers were investigated. Crystalline quality, dislocation densities comprising of screw and edge types in InGaN and GaN layer have been analyzed using High-Resolution X-ray Diffractometer (HRXRD). The composition of Indium (In) in the InGaN layers was estimated around 8-10% which was found to be dependent on the In flow rate. The strain between InGaN and underlying GaN layer have been analyzed through reciprocal space mapping studies along the (1 0 -1 5) plane in InGaN/GaN heterostructures. The features of V and trench defects were observed using scanning electron microscopy and atomic force microscopy respectively. The V and trench defect density has been correlated with the pre-existing threading dislocation density estimated using HRXRD measurements. Also the trench defects were observed to be a coalescence of V defects in InGaN layers. The photoluminescence results showed that band edge emission peaks of three different points (primary flat, centre, and Edge) were observed. These peak variations were found to be red shift behavior in all three points. These variations were due to the fluctuations in the Indium composition and corresponding trench & V defects respectively. The Hall measurements exhibit an alteration in semiconducting behavior with respect to V and trench defect surrounded InGaN layers. And also realized that compressive strain in underlying GaN can lead the high sheet concentration compared to the tensile strained underlying GaN layer. It clearly suggests that the V and trench defect surrounded InGaN layers contain the suitable candidates for next generation optoelectronics applications.

Keywords: InGaN, Metal Organic Chemical Vapour Deposition, High-Resolution X-Ray Diffraction, Trench Defect, Red Shift, Hall Measurement;

1. Introduction

The direct band gap of Indium gallium nitride (InGaN)-based alloys can be emerged as a promising material to emit light over the whole visible spectrum depending on the Indium (In) composition. It has a scrupulous properties of tunable energy range 0.7 (InN) to 3.4 (GaN) eV, which covers almost the entire solar spectrum [1, 2]. InGaN has distinctive properties such as high absorption coefficient, high carrier mobility, and high drift velocity that can be used at high temperature and high radiation. Consequently, achieving InGaN is an plethora for applications including the solar cells, blue/green light emitting diodes, laser diodes, Photodetectors, and chemical sensors [1,3-6,7, 8]. However, fabrication of devices based on this material has several material challenges, most prominent being the growth of layer with high indium (In) content. The growth of InGaN layer is not easy above 800°C, [9] due to the high equilibrium vapor pressure of nitrogen over InN [7, 10, 11]. Also, reducing the lattice mismatch between the InN and GaN inorder to obtain the high quality InGaN layer is additional challenge [12, 13]. In spite of an established growth technology for the InGaN based Quantumwells (QWs) by metal organic chemical vapour deposition (MOCVD), the growth of thick InGaN layers on GaN still remains challenging, resulting in layers with high strain and formation of defect microstructures such as In-rich domains, V-defect, InN segregation-defects and trench defects respectively [14-19]. In general, the V-defect appears in InGaN and InGaN based QW structures. These V defects are appears to be hexagonally arranged view with the sidewalls of (1 0 -1 1) planes [20, 21]. This V defects also may be related to the stacking mismatch boundary (SMB) within the InGaN QW structures. Thus, the results of SMB opens up a sample surface into enclosed trench arrangements with the modified luminescence properties [22]. This spectacle of the InGaN based structures is correlated to the lattice relaxation during the growth process. Although, it lacks the morphological, strain relaxation and longer wavelength (green to red) emission of indium

incorporation for InGaN alloys by MOCVD [23, 24]. In this case, the trench defects surrounded InGaN layers are most likely to emit the green spectrum and it may play a deleterious role to the degradation of quality compared to blue spectrum [22, 25]. In order to overcome the issues, the high density trench defects entrenched thick InGaN grown on GaN layer paved an alternative way to improve the optical quality. These kinds of defects may also participate to relieve the local strain in the modified surfaces of InGaN layers. However, these high density trench defects cause the high strain relaxation to adverse the effect of collection of carriers by the polarization fields [26, 27]. The high density trench defects depend on various parameters such as the InGaN thickness, In composition, GaN buffer layer thickness, and miscut of sapphire substrate. In the past literature, F.P.Massabuau and related coworkers investigated the effect of trench defects on InGaN QWs and InGaN layers [17, 22, 26, 28-30]. These studies mainly accessed the resulting of structural and optical properties.

The main aim of this study extended to an optoelectronic application towards the trench and V defects based thick InGaN layers. There is a lack of reports on the investigation of the strain relaxation mechanism, and luminescence properties of trench & V defects surrounded InGaN layers. The mobility limiting scattering mechanism from the V and trench defects based InGaN layers has not been understood clearly. In the present work, the crystalline quality, threading dislocations and In composition (8–10 %) of InGaN/GaN heterostructures were investigated. The V and trench defects formation in the InGaN layers was discussed through the strain relaxation of InGaN/GaN heterostructures. From the photoluminescence spectra, the variation in the band edge emission of each InGaN samples in three different points were analyzed. The mobility, bulk and sheet concentration of the InGaN/GaN heterostructures and related scattering mechanism were studied.

2. Experiments

Three $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ heterostructures were grown on a 2-inch c-plane sapphire substrate using MOCVD system (Aixtron 200/4 RF-S) by varying In composition in InGaN layers. The MOCVD system consists of a horizontal reactor with Radio Frequency (RF) heating. Trimethylgallium (TMGa) and Triethylgallium (TEGa) have been used as the gallium precursor in GaN and InGaN layers respectively. Trimethylindium (TMIn) and ammonia (NH_3) were used as precursors for In and nitrogen (N_2) respectively. Hydrogen (H_2) has been used as the carrier gas to grow GaN layer. On the other hand, N_2 has been used as the carrier gas to grow InGaN layer, as H_2 affects the In incorporation by reducing the lifetime of In adatoms. Prior to material growth, sapphire substrates were thermally cleaned under H_2 ambient at 1050°C for 10 min to remove the native oxide on the surface of the substrate. Subsequently, 30 nm thick GaN nucleation layer (NL) was grown on the sapphire substrate at 500°C with V/III ratio of 3453. GaN–NL was recrystallized at 1010°C for 1 min. GaN layer with the thickness of $1.3\ \mu\text{m}$ was deposited at 1020°C with a V/III ratio of 614. Hereafter, it is called as GaN/sapphire templates. Three variant thick InGaN (60–75 nm) layers were grown on GaN at 750°C for 15 min. Among the three samples, only the TMIn flow was varied about 7, 10, and $14\ \mu\text{mole}/\text{min}$ to alter the In content in the InGaN layer. The corresponding V/III ratio of InGaN layers was 4585, 4996 and 5356, these samples were named as A, B, and C respectively. All other growth parameters remained identical throughout the experimental process. The crystalline quality of grown samples was characterized by PANalytical X'Pert Pro MRD high-resolution X-ray diffractometer (HRXRD) resolution $0.0001^\circ/0.36\ \text{arcsec}$ Ge-(220) monochromator with Triple (Xe) axis and pixel detector. The ω - 2θ scans from HRXRD analysis directly express the In composition from the (0 0 0 2) plane. The thickness and composition of InGaN layers were determined by epitaxy smooth fit software. The Reciprocal Space Mapping (RSM) on (1 0 -1 5) plane was performed to investigate the strain relaxation between the InGaN and GaN layers in the $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$

heterostructures. The surface morphology of InGaN layers was analyzed using Atomic Force Microscopy (AFM- Park XE-100, curvature of cantilever tip <10 nm, along with the position sensitive photo detector (PSPD) vertical and lateral resolution:~0.1 nm and ~30 nm) and Scanning Electron Microscopy (SEM- Carl Zeiss EVO 18, LaB6 filament, 10 kV with secondary electron detector, point to point Resolution: ~10 nm) respectively. The luminescence emission of InGaN layers was analyzed by photoluminescence (PL-Spectra-Physics, Spectral Resolution: ± 0.1 nm) with an excitation wavelength of about 244 nm. The electrical characterizations of the samples were performed by room temperature (300 ± 0.5 K) hall measurements in a Van der Pauw configuration with tin-indium alloy dots as ohmic contact (ECOPIA, HMS 5000). A magnetic field of 0.55 ± 0.03 Tesla (T) perpendicular to the sample was applied.

3. Results and discussion

3.1 Structural Studies

Figure 1 HRXRD (0 0 0 2) ω -2 θ scan of (A) $\text{In}_{0.08}\text{Ga}_{0.92}\text{N}$ (B) $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}$, and (C) $\text{In}_{0.1}\text{Ga}_{0.90}\text{N}$ layers

From the ω -2 θ scan for (0 0 0 2) diffraction in respect of InGaN/GaN heterostructures, the thickness and In composition of the InGaN layers were estimated (Figure 1). The high-intensity peak in figure 1, denotes the GaN layers whereas the low-intensity peak corresponds to InGaN layers. Moreover, the single peak obtained for InGaN ascertains that the absence of InGaN secondary phase formation. It can be seen that the position of the peaks in the InGaN layers shifts to lower angle with increase in the In mole fraction. From the analysis, the thickness of InGaN layers of the sample (A, B, C) was found to be 70 nm, 60 nm and 75 nm $\pm$ 2 nm respectively. The best fitted (Epitaxy smooth fit software) In composition of the InGaN layers was found to be around 8%, 9% and 10% $\pm$ 0.5% respectively. The In composition fluctuation was around $\pm$ 1-3% for all the three InGaN/GaN heterostructures, which is attributed to the thermodynamic driving force that anticipate the occurrence of solid-phase miscibility gap [31]. Furthermore, the indium segregation over the screw dislocations may also be one of the reasons for composition fluctuation [32]. The X-ray rocking curve analysis was performed on (0 0 0 2) and (1 0 -1 5) planes of GaN and InGaN layers. The full width at half maximum (FWHM) values of high intense (0 0 0 2) symmetric plane were obtained as 344, 342, 318 arc-sec whereas for (1 0 -1 5) asymmetric plane the values were 288, 309 and 305 arc-sec for the underlying GaN layers. The FWHM values of (0 0 0 2) symmetric plane of InGaN layer were obtained as 790, 897, and 857 arc-sec whereas for (1 0 -1 5) asymmetric plane, FWHM values as 1574, 1798 and 1687 arc-sec for InGaN samples. The threading dislocation (TD) with edge (edge+mixed type TDs) components (D_{edge}) corresponding to (1 0 -1 5) plane and screw (screw + mixed type TDs) components (D_{screw}) corresponding to (0 0 0 2) plane have been estimated from HRXRD rocking

curve widths of the InGa_N and Ga_N layers respectively [33, 34]. The TD density ($D_{\text{edge}} + D_{\text{screw}}$) have been calculated from the below equations [13, 35],

$$D_{\text{edge}} = \frac{\beta^2}{4.35|b_{\text{edge}}|^2} \quad D_{\text{screw}} = \frac{\alpha^2}{4.35|b_{\text{screw}}|^2} \quad (1)$$

Where D_{edge} is the edge dislocation density, D_{screw} is the screw dislocation density, α and β are referred to FWHM value measured from rocking curve diffraction peaks of (0 0 0 2) and (1 0 -1 5), respectively. Here b_{edge} and b_{screw} represents the length of the burger vector of the a -axis (edge) and c -axis screw dislocation density [36].

Table 1. Dislocation densities of Ga_N and InGa_N layers in the InGa_N/Ga_N Heterostructures

Samples	Ga _N layers			InGa _N layers		
	Screw dislocations (10^8cm^{-2})	Edge dislocations (10^8cm^{-2})	TDs using HRXRD (10^8cm^{-2})	Screw dislocations (10^{10}cm^{-2})	Edge dislocations (10^{10}cm^{-2})	TDs using HRXRD (10^{10}cm^{-2})
A	2.37	4.39	6.76	0.12	1.29	1.41
B	2.34	5.04	7.38	0.16	1.68	1.84
C	2.05	4.94	6.99	0.14	1.48	1.62

In the case of InGa_N alloy, one can derive the value of the burgers vector b_{screw} and b_{edge} using the equations given below,

$$c_0^{\text{In}_x\text{Ga}_{1-x}\text{N}} = x.c^{\text{InN}} + (1-x).c^{\text{GaN}} \quad (2)$$

$$a_0^{\text{In}_x\text{Ga}_{1-x}\text{N}} = x.a^{\text{InN}} + (1-x).a^{\text{GaN}} \quad (3)$$

Where $a^{\text{GaN}} = 0.3189$ nm, $c^{\text{GaN}} = 0.5185$ nm and $a^{\text{InN}} = 0.3537$ nm, $c^{\text{InN}} = 0.5706$ nm are the relaxed lattice constant values of GaN and InN respectively [37-39]. The relaxed values of lattice constant a_0 and c_0 values are 0.3218, 0.3221, 0.3225 and 0.5231, 0.5237, 0.5242 nm respectively for various (7, 10 and 14 $\mu\text{mole/min}$) flow rates of InGa N layer using Vegard's law (Eqs. 2 and 3). Thus, we have calculated the TD density of GaN and InGa N layers of the three samples (table 1). As shown in table 1, for InGa N and Ga N layers, the majority of the dislocations were edge-type dislocations which are introduced from the (1 0 -1 5) plane. The InGa N TD densities are in the range between 1.41×10^{10} and $1.84 \times 10^{10} \text{ cm}^{-2}$. More TDs were generated at the $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}/\text{GaN}$ interface which propagates towards the InGa N layer leading to the deterioration of crystalline quality. The Ga N buffer layer TD density (10^8 cm^{-2}) is correlated to the literature. The TD of InGa N layer is increased by the order of two times, when compared to the literature [40]. We observed that, the TD density values do not follow the approximate In composition of samples A-C, due to the additional defects generated during the relaxation process. The strained states and the In composition present in InGa N layer became more inhomogeneous. In addition, this method of investigating the dislocation density in Ga N and InGa N layer does not lead to underestimation in its actual values [41]. The Ga N and InGa N lattice constants c , a and strains were obtained by HRXRD measurement using the lattice spacing d_{0002} and d_{10-15} in the equations 4-7 given below [42]

$$2d \sin(\theta) = n\lambda \quad (4)$$

$$\frac{1}{d_{hkl}^2} = \frac{4(h^2 + hk + k^2)}{3a^2} + \frac{l^2}{c^2} \quad (5)$$

$$\text{Out-of plane strain } (\varepsilon_{zz}) = \frac{c - c_0}{c_0} \quad (6)$$

$$\text{In-plane strain } (\varepsilon_{xx}) = \frac{a - a_0}{a_0} \quad (7)$$

Where c , a are the measured experimental out-of plane and In-plane lattice constants and c_0 , a_0 are the relaxed out-of plane and In-plane lattice constants respectively. The GaN and InGaN in-plane lattice constants, out-of plane lattice constants and strains are shown in table 2. From the table, the positive and negative sign indicates the tensile and compressive strain.

Table 2 Lattice constants, in-plane and out of plane strain for InGaN and GaN layers in the InGaN/GaN heterostructures

Samples	GaN		InGaN		GaN		InGaN	
	Lattice constant c_{GaN} (Å)	Lattice constant a_{GaN} (Å)	Lattice constant c_{InGaN} (Å)	Lattice constant a_{InGaN} (Å)	In-plane strain (ε_{xx})	Out-of plane strain (ε_{zz})	In-plane strain (ε_{xx})	Out-of plane strain (ε_{zz})
A	5.1860	3.1972	5.2444	3.2692	0.0026	0.0002	0.0159	0.0025
B	5.1879	3.1874	5.2518	3.3312	-0.0005	0.0006	0.0341	0.0029
C	5.1824	3.1849	5.2668	3.2904	-0.0012	-0.0005	0.0203	0.0046

The inplane lattice parameters of $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}$ are high compared to the other InGaN layers (sample B and C). When the In composition in InGaN layer is increased, the in-plane and out-of plane strain is found to exhibit tensile strain. The underlying GaN layers are responsible for inducing a change in the in-plane and out-of plane strain in top of InGaN layer. It is an indication of change in crystalline quality, resulting from an inhomogeneous distribution of the In content. It is worth to note that, for an $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}$ layer a high tensile strain is experienced due to an alteration of the lattices [43]. Figure 2 shows 2θ - ω scan of (0 0 0 2) diffraction in respect of GaN/sapphire templates. In this work, it was observed that, sample B (GaN/sapphire

template) possess high intense twinned forms of cubic GaN (1 1 1) (JCPDS card no.882364) [44]. Wu.X.H et.al [36] explained, the near-interfacial region of the GaN layer consists of a combination of cubic and hexagonal phases, which was simulated by a high density of stacking faults and inversion domains controlled by Shockley and Frank partial dislocations. Furthermore, these similar factors may be induced by the irregular arrangement of stacking faults (SFs) in the GaN/sapphire templates [45]. It revealed that, stacking faults density leads to the strain modifications on the GaN buffer layer [46].

Figure 2 HRXRD of (0 0 0 2) 2θ-ω scan of (A) GaN/sapphire (B), GaN/sapphire and (C) GaN/sapphire templates

Figure 3 (A-C) shows the RSM for (1 0 -1 5) plane of samples A, B, and C respectively. Upon Increasing the In composition in InGaN layers the contour shapes in the RSM are found to be irregularly broadened along the Q_x and Q_y directions with respect to the GaN layer which is

attributed to the mosaic structure of the layers. Here the percentage of strain relaxation (R) and defined as [24],

$$R = \frac{a_{InGaN} - a_{0GaN}}{a_{0InGaN} - a_{0GaN}} \times 100 \quad (8)$$

The result explicitly shows that partial relaxation occurs for $In_{0.08}Ga_{0.92}N/GaN$, $In_{0.09}Ga_{0.91}N/GaN$ and $In_{0.1}Ga_{0.9}N/GaN$ heterostructures and relaxation values were observed to be around 2.7%, 4.2% and 3.5% for the samples A, B, and C respectively. These relaxation values are included in the estimation of In composition using the epitaxy smooth fit software of the (0 0 0 2) plane in ω -2 θ scans.

Figure 3 RSM of the (A) $In_{0.08}Ga_{0.92}N$ (B) $In_{0.09}Ga_{0.91}N$ and (C) $In_{0.1}Ga_{0.9}N$ (1 0 -1 5) diffraction

3.2 Morphological Studies

The surface morphology of InGaN/GaN heterostructures observed using SEM (Figure 4 (A-C)). The schematic view of various dimension of trench and V-defects present in the InGaN/GaN heterostructures are shown in Figure 4 (D). Hexagonal or V shaped-defects of different sizes and “trench defects” were observed on the surfaces for all the InGaN layers. As can be seen from the figure, the trench defects are observed which seems to be a coalescence of V defects in InGaN layer. The smaller V-defects are marked by an arrow in Figure 4 (A). This kind of defect occurs due to a combination of growth and collapse processes in the InGaN layers. The smaller V-defect is also known as the thermally eroded pit and is purely dependent on the growth temperature of InGaN layers [47].

Figure 4 SEM micrographs of the (A) $\text{In}_{0.08}\text{Ga}_{0.92}\text{N}$ (B) $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}$ and (C) $\text{In}_{0.10}\text{Ga}_{0.90}\text{N}$ Layers and (D) Schematic view of trench and V-pit formation in InGaN layers

Figure 5 Average density of the trench and V defects observed using SEM

SEM images also shows the crack like regions, which are surrounded by V-defects in figure 4 (A-C). The diameter of V defects was observed in the range of 50-120 nm. The average density of V and trench defects are found to be 9.6×10^8 , 6.6×10^8 and 7.1×10^8 cm⁻² and 0.8×10^8 , 1.4×10^8 , and 1×10^8 cm⁻² (Figure 5) for the grown of InGa_N layers with In flow rates of 7, 10 and 14 μmole/min, respectively. Figure 5 shows the variation in V and trench defect densities of the InGa_N layer in the same order as exhibited by the pre-existing TD defect density. This suggests that, the V and trench defect in the InGa_N layer depends on the pre-existing TD in the Ga_N layer for all the samples. Particularly in sample B, the V-defects density dramatically decreases and trench defects density increases concomitantly. A rather high crack like defects was also observed while compared to the other two samples [24, 26, 48]. These kinds of crack like defects were certainly to mediate the high density trench defects from the similar factors observed in literature [49]. Thorough discussion of such defects in SEM will be further categorized and are

discussed by AFM. It is understood that the high density of trench defects found in the $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}$ layer may contribute to dislocations at the $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}/\text{GaN}$ interfaces and also within an InGaN layer. At this interfaces, the misfit dislocation plays an important role in inducing SFs in the InGaN layers with respect to the GaN layer [45, 50]. This caused high-density surface defect leading to the strain relaxation which is consistent with the HRXRD analysis which shows high values of strain relaxation measured in RSM of sample B [24]. Hence, low-density of V defect and high density trench defect plays a dominant role for the strain relaxation mechanism. The V and trench defect kinetic effects were realized by the reduction of Ga incorporation and/or spatial In segregation in the InGaN layer [51].

Figure 6 (A-C) shows the surface morphology along with line profile over an area of $10\mu\text{m}^2$ as a function of In content based on AFM measurements. It was found that the 3D island growth and surface roughness (R_{rms}) of InGaN layers were about 4.8 nm, 5.4 nm and 7 nm respectively. In addition, it was found that large width of 3D islands is ~100 nm, while the smallest width of 3D islands is ~50 nm. Similarly, the minimum height of 3D islands was found to be 5 nm and a maximum height of ~10 to 25 nm were observed for samples A, B, and C respectively. It was also observed that, the distribution of 3D island was without obvious flat zones on the surface. In this phenomenon, while increasing the Indium flow rate, more indium incorporation occurred which results in increasing the misfit strain in the layer, this accelerate the formation of 3D islands [24]. Figure 6 clearly shows that there is a random change in the surface morphology of InGaN samples grown by MOCVD. It emphasizes that the non-uniformity in InGaN/GaN interface roughness which is manifested from the 3D surface roughness [52, 53].

Figure 6 AFM ($10\mu\text{m}^2$) images with line profile of (A) $\text{In}_{0.08}\text{Ga}_{0.92}\text{N}$ (B) $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}$, and (C) $\text{In}_{0.1}\text{Ga}_{0.9}\text{N}$ layers

Figure 7 AFM ($2\mu\text{m}^2$) images with V defects line profile of (A) $\text{In}_{0.08}\text{Ga}_{0.92}\text{N}$

(B) $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}$ and (C) $\text{In}_{0.1}\text{Ga}_{0.90}\text{N}$ layers

Furthermore, the line profile in the AFM ($2.0 \mu\text{m}^2$) images of figure 7 (A - C) clearly indicates the reverse behavior of the V-defects. The densities of the V-defects are same as the initial TD density in GaN/sapphire interfaces. The V defect density depth and widths were observed from AFM images shown in table 3. It is clear from table 3 that the smaller V-defects are connected to the edge TDs and the bigger V-defects are connected to screw or mixed TDs [54]. It's worth to note that, the AFM images revealed reasonable changes in the V-defect density with an increase in In content in all the InGaN samples. This provides additional evidence that the aforementioned generation of V defects is strain mediated.

Table 3 V- defect width, depth, density, and density estimated using AFM images

Samples	V-Defect width (nm)		V-Defect depth (nm)		V-Defect Density (10^8 cm^{-2})	
	Small	Big	Small	Big	Small	Big
A	63-70	90-117	7.28-8.29	10.14-10.67	0.75	1.0
B	62-74	102-125	6.73-8.42	10.33-12.02	0.75	0.5
C	63-70	86-102	6.10-9.25	11.06-11.35	0.5	0.75

The trench defects are marked by a circle (Figure. 7(A-C)). The AFM images revealed a V and trench defect density around 10^8 cm^{-2} . The average diameters of trench defects are 230, 270, and $225 \text{ nm} \pm 10 \text{ nm}$ for the samples A, B, and C respectively. From the trench defect line profile, it is confirmed that the surface defect is present in InGaN layer (Figure 8 (A-C)). It

shows the difference between the height of enclosed trench defects and the height of the surrounding areas in the InGaN layer.

Figure 8. Trench defect line profile of (A) $\text{In}_{0.08}\text{Ga}_{0.92}\text{N}$ (B) $\text{In}_{0.09}\text{Ga}_{0.91}\text{N}$, and (C) $\text{In}_{0.1}\text{Ga}_{0.9}\text{N}$ layers corresponding to Figure 7

3.3 Optical Studies

Figure 9 Emission spectrum measured the InGaN wafer at three points (PF, Centre and Edge)

Optical properties of InGaN layers are investigated using PL with increasing the TMIn flow rate. The InGaN layers emission spectra are shown in figure 9. In this consequence, edge and primary flat (PF) emission spectra are fitted by Gaussian distribution function and the corresponding centre peaks were approximated. From the figure 9, sample A, the emission of InGaN layers were observed at 425 nm, 438 nm and 421 nm for PF, centre and edge of the wafer respectively. We observed a fluctuation in sample A, PF to center (13 nm) and the large variations from centre to the edge (17 nm) of the wafer. Sample B emission was located at 442 nm, 461 nm and 449 nm respectively. From PF to centre, the emission variation was only at 19 nm and 12 nm variations occurred from centre to edge. Furthermore, the sample C emissions were observed at 455 nm, 478 nm and 459 nm respectively. It was inferred that, from PF to centre the large variation at 23 nm and from centre to edge it occurred at 19 nm difference. It is clearly shown that, the band edge emission variation is in each InGaN layer. It worth the note that centre of InGaN wafer, linear and predominant red shift emission was observed to be around 438 nm (2.83 eV), 461 (2.69 eV) nm and 478nm (2.59 eV) nm for the samples A, B, and C respectively (Figure 9). These emissions may be ascribed to relatively high “In” incorporation leading to high carrier recombination’s which forms In(Ga)N quantum-dot like structures on the InGaN layer inside the trench defects when compared to the other regions reported in the literature [55, 56]. Thus, it was observed that, as the indium flow rate increases there was significant decrease in the luminescence intensity due to increasing the incorporation of In along with the spatial fluctuations with respect to V and trench defects. Likewise, the remarkable changes in edge (421 to 459 nm) and PF (425 to 455 nm) wafer emissions were also observed the red shifts for samples A-C respectively. It concluded that, the red shift of all samples may be attributed to the Quantum confined stark effect (QCSE) as an effect of the polarization [57]. This

red shift behavior of InGaN (samples A-C) layers is owed to the tensile strain. Additionally, it shows that, the emission intensity is reduced, since the omnipresent V defects are induced and reduces the In incorporation in InGaN layer. Thus, it acts as a nonradiative recombination center. On the other hand, it shows that the PL peaks at 500-650 nm may be attributed to deep-level impurities and/or lattice defects emission [58, 59]. The above noticeable luminescence peak variations corroborates the indium composition percentage attained by HRXRD.

3.4 Hall Measurement Studies

To study the electrical properties of the InGaN/GaN heterostructures, hall measurements were carried out using the Van der Pauw technique (dimension of 10 mm²) at room temperature. In the present work, we grow a nearly semi-insulating (sheet concentration – $2.01 \times 10^{13} \text{ cm}^{-2}$ and resistivity - 0.31 ohm-cm) GaN Buffer layer before the growth of InGaN layer. The results of mobility, bulk and sheet concentration, resistivity of the InGaN layer were shown in table 4. The mobility of InGaN (8, 9 and 10 %) is lower than the GaN layer, which is usually more than 300 cm²V⁻¹s⁻¹ at room temperature [20, 60]. This behavior suggests that, more alloy scattering centers are being created when more indium was added to alloy, resulting in lower mobility. In contrary, there was a conflict between the hall mobility and rms surface roughness values to explain the interfaces of InGaN/GaN heterostructures. A rather high bulk ($5.64 \times 10^{16} \text{ cm}^{-3}$) and sheet concentration ($1.1 \times 10^{13} \text{ cm}^{-2}$) along with resistivity (3.74 ohm-cm) of sample B were obtained when compare to other two InGaN based samples. The observed bulk and sheet concentration was found to be varied in comparison with the classical behavior. Where the classical behavior corresponds to the increase in mobility in monotonically with decrease in the carrier concentration. Based on the obtained information from table 4, it is well inferred that the compressive strain in underlying GaN can lead the high sheet concentration compared to the

tensile strained underlying GaN layer [61]. In this work, the dislocations may play a dominant role in determining mobility, resistivity, bulk and sheet concentration. It is concluded that, the transport mechanism contains both defect centers and the conduction band which explains the phenomenon while increasing the In composition [62]. The conduction in the defect centers is diffusive process, owing to the small but finite overlay of the localized electron wave functions of the defect centers or hopping. Hence, the defect band related mobility is likely to be small when compared to the conduction band mobility in the available literature [62, 63]. It results in altering the semiconducting behavior of all the InGaN layers.

Table 5 Hall Measurement Studies of InGaN/GaN heterostructures

Samples	Mobility cm²/volt sec	Bulk concentration cm⁻³	Sheet concentration cm⁻²	Resistivity (Ohm-cm)
A	21	2.26×10 ¹⁶	4.5×10 ¹²	0.007
B	27	5.64×10 ¹⁶	1.1×10 ¹³	3.74
C	91	4.80×10 ¹⁶	9.5×10 ¹²	1.43

4. Conclusions

In the present work, MOCVD was used to grow the InGaN/GaN heterostructures and the structural, morphological, optical and electrical properties were investigated. The thickness and composition of InGaN layers have been estimated using HRXRD. The influence of different kinds of defects (V and trench defect) on the degradation of the crystalline quality of InGaN layers was examined by SEM and AFM. It was concluded that, the occurrence of V and trench defects depends on the pre-existing dislocations. The V and trench defect density was correlated with the strain relaxation of InGaN /GaN heterostructures. In addition, higher tensile strain in the

In_{0.09}Ga_{0.91}N layer was observed due to the lattice parameter alteration in the GaN layers. Furthermore, an increase in the surface roughness of InGaN layers was estimated using AFM when the In composition was increased which represents the non-uniformity in the InGaN/GaN interface roughness. PL result confirms the incorporation of In with increase in In flow rate. The luminescence properties of the InGaN samples were understood by the fluctuations in the In composition and red shift of the emissions with respect to the formation of V and trench defect. The hall measurements of the InGaN/GaN heterostructures shows more alloy scattering centers and also reveals alteration in the semiconductor behavior with respect to V and trench defect surrounded InGaN layers. From the obtained results, it gives an additional comprehension of the scientific information of the present work in respect of the structural (crystalline quality, composition, layer thickness, lattice constants, strain parameters and reciprocal space mapping), morphological (features of V & trench defect, roughness and related width, depth density), luminescence (emissions of three different points- PF, Centre, Edge) and electrical (mobility, bulk & sheet concentration and related scattering mechanism) properties of InGaN layers were studied compare to the other studies [24,26,60]. These kinds of results help further to development of next generation optoelectronics devices (longer wavelength light emitting diodes etc) based on V and trench defects surrounded InGaN layers.

Acknowledgement

The authors acknowledge the Department of Science and Technology (DST/TM/SERI/2K12/71(G)), Government of India for funding the research project under SERI.

References

- [1]L. Sang, M. Liao, N. Ikeda, Y. Koide, M. Sumiya, Enhanced performance of InGaN solar cell by using a super-thin AlN interlayer, Applied Physics Letters, 99 (2011) 161109.
- [2]A. Yamamoto, K. Sugita, A. Bhuiyan, A. Hashimoto, N. Narita, Metal-organic vapor-phase epitaxial growth of InGaN and InAlN for multi-junction tandem solar cells, Materials for Renewable and Sustainable Energy, 2 (2013) 10.

- [3]L. Sang, M. Liao, Y. Koide, M. Sumiya, High-performance metal-semiconductor-metal InGaN photodetectors using CaF_2 as the insulator, *Applied Physics Letters*, 98 (2011) 103502.
- [4]D. Chen, B. Liu, H. Lu, Z. Xie, R. Zhang, Y. Zheng, Improved performances of InGaN schottky photodetectors by inducing a thin insulator layer and mesa process, *IEEE Electron Device Letters*, 30 (2009) 605-607.
- [5]B.W. Liou, Design and fabrication of $\text{In}_x\text{Ga}_{1-x}\text{N}/\text{GaN}$ solar cells with a multiple-quantum-well structure on SiCN/Si (111) substrates, *Thin Solid Films*, 520 (2011) 1084-1090.
- [6]C.-F. Lin, K.-T. Chen, S.-H. Chen, C.-C. Yang, W.-C. Huang, T.-H. Hsieh, InGaN-based solar cells with a tapered GaN structure, *Journal of Crystal Growth*, 370 (2013) 97-100.
- [7]Q. Guo, T. Nakao, T. Ushijima, W. Shi, F. Liu, K. Saito, T. Tanaka, M. Nishio, Growth of InGaN layers on (1 1 1) silicon substrates by reactive sputtering, *Journal of Alloys and Compounds*, 587 (2014) 217-221.
- [8]S. Sanjay, K. Baskar, Fabrication of Schottky barrier diodes on clump of gallium nitride nanowires grown by chemical vapour deposition, *Applied Surface Science*, 456 (2018) 526-531.
- [9]J. Yang, D. Zhao, D. Jiang, P. Chen, J. Zhu, Z. Liu, L. Le, X. He, X. Li, H. Yang, Photovoltaic response of InGaN/GaN multi-quantum well solar cells enhanced by inserting thin GaN cap layers, *Journal of Alloys and Compounds*, 635 (2015) 82-86.
- [10]S. Srinivasan, F. Bertram, A. Bell, F. Ponce, S. Tanaka, H. Omiya, Y. Nakagawa, Low Stokes shift in thick and homogeneous InGaN epilayers, *Applied physics letters*, 80 (2002) 550-552.
- [11]I.h. Ho, G. Stringfellow, Solid phase immiscibility in GaInN, *Applied Physics Letters*, 69 (1996) 2701-2703.
- [12] T.H. Seo, J.P. Shim, S.J. Chae, G. Shin, B.K. Kim, D.S. Lee, Young Hee Lee, E.K. Suh, Improved photovoltaic effects in InGaN-based multiple quantum well solar cell with graphene on indium tin oxide nanodot nodes for transparent and current spreading electrode, *Applied physics letters*, 102 (3) (2013) 031116.
- [13] K. Prabakaran., M. Jayasakthi, S. Surender, S. Pradeep, S. Sanjay, R. Ramesh, M. Balaji, N. Gautier, and K. Baskar, Structural, morphological, optical and electrical characterization of InGaN/GaN MQW structures for optoelectronic applications, *Applied Surface Science*, 476, (2019) pp.993-999.
- [14]Y. Guo, X. Liu, H. Song, A. Yang, X. Xu, G. Zheng, H. Wei, S. Yang, Q. Zhu, Z. Wang, A study of indium incorporation in In-rich InGaN grown by MOVPE, *Applied Surface Science*, 256 (2010) 3352-3356.

- [15] T. Hoon Seo, J.-P. Shim, S. Jin Chae, G. Shin, B. Kyoung Kim, D.-S. Lee, Y. Hee Lee, E.-K. Suh, Improved photovoltaic effects in InGaN-based multiple quantum well solar cell with graphene on indium tin oxide nanodot nodes for transparent and current spreading electrode, *Applied Physics Letters*, 102 (2013) 031116.
- [16] B.-T. Tran, E.-Y. Chang, H.-D. Trinh, C.-T. Lee, K.C. Sahoo, K.-L. Lin, M.-C. Huang, H.-W. Yu, T.-T. Luong, C.-C. Chung, Fabrication and characterization of n-In_{0.4}Ga_{0.6}N/p-Si solar cell, *Solar Energy Materials and Solar Cells*, 102 (2012) 208-211.
- [17] F.-P. Massabuau, L. Trinh-Xuan, D. Lodié, S. Sahonta, S. Rhode, E. Thrush, F. Oehler, M. Kappers, C. Humphreys, R. Oliver, Towards a better understanding of trench defects in InGaN/GaN quantum wells, *Journal of Physics: Conference Series*, IOP Publishing, 2013 pp. 012042.
- [18] Y. El Gmili, G. Orsal, K. Pantzas, T. Moudakir, S. Sundaram, G. Patriarche, J. Hester, A. Ahaitouf, J. Salvestrini, A. Ougazzaden, Multilayered InGaN/GaN structure vs. single InGaN layer for solar cell applications: A comparative study, *Acta Materialia*, 61 (2013) 6587-6596.
- [19] J. Liu, H. Liang, X. Xia, Q. Abbas, Y. Liu, Y. Luo, Y. Zhang, L. Yan, X. Han, and G. Du, Anomalous indium incorporation and optical properties of high indium content InGaN grown by MOCVD. *Journal of Alloys and Compounds*, 735, (2018) pp.1239-1244.
- [20] K. Prabakaran, M. Jayasakthi, S. Surender, S. Pradeep, S. Sanjay, R. Ramesh, M. Balaji, and K. Baskar, Influence of InGaN interlayer thickness on GaN layers grown by metal organic chemical vapour deposition. *Applied Physics A*, 125(3), (2019) p.206.
- [21] Shiojiri, M., Chuo, C.C., Hsu, J.T., Yang, J.R. and Saijo, H., Structure and formation mechanism of V defects in multiple InGaN/ GaN quantum well layers, *Journal of Applied Physics*, 99(7), (2006) p.073505.
- [22] F. Massabuau, M. Kappers, C. Humphreys, and R. Oliver, Mechanisms preventing trench defect formation in InGaN/GaN quantum well structures using hydrogen during GaN barrier growth, *physica status solidi (b)*, 254(8), (2017) p.1600666.
- [23] H. Woo, J. Kim, S. Cho, Y. Jo, C.H. Roh, J.H. Lee, Y.G. Seo, H. Kim, H. Im, C.K. Hahn, Epitaxial growth of low temperature GaN using metal migration enhanced epitaxy for high-quality InGaN/GaN heterojunctions, *Superlattices and Microstructures*. 120 (2018) 781–787
- [24] J. Liu, H. Liang, X. Xia, Y. Liu, J. Liu, Q. Abbas, R. Shen, Y. Luo, Y. Zhang, and G. Du, Indium Incorporation Induced Morphological Evolution and Strain Relaxation of High Indium Content InGaN Epilayers Grown by Metal–Organic Chemical Vapor Deposition. *Crystal Growth & Design*, 17(6), (2017) pp.3411-3418
- [25] B. Ding, Improving radiative recombination efficiency of green light-emitting diodes. *Materials Science and Technology*, 34(14), (2018) pp.1615-1630.

- [26] S. Rhode, W. Fu, M.A. Moram, F.-P. Massabuau, M.J. Kappers, C. McAleese, F. Oehler, C.J. Humphreys, R. Dusane, S.L. Sahonta, Structure and strain relaxation effects of defects in $\text{In}_x\text{Ga}_{1-x}\text{N}$ epilayers, *Journal of Applied Physics*, 116 (2014) 103513.
- [27] V.C. Su, P.H. Chen, R.M. Lin, M.L. Lee, Y.H. You, C.I. Ho, Y.C. Chen, W.F. Chen, C.H. Kuan, Suppressed quantum-confined Stark effect in InGaN-based LEDs with nano-sized patterned sapphire substrates, *Optics Express*, 21 (24) (2013) 30065–30073.
- [28] F.-P. Massabuau, L. Trinh-Xuan, D. Lodié, E. Thrush, D. Zhu, F. Oehler, T. Zhu, M. Kappers, C. Humphreys, R. Oliver, Correlations between the morphology and emission properties of trench defects in InGaN/GaN quantum wells, *Journal of Applied Physics*, 113 (2013) 073505.
- [29] E. Taylor, F. Fang, F. Oehler, P.R. Edwards, M.J. Kappers, K. Lorenz, E. Alves, C. McAleese, C.J. Humphreys, and R. W. Martin, Composition and luminescence studies of InGaN epilayers grown at different hydrogen flow rates. *Semiconductor Science and Technology*, 28(6), (2013) p.065011.
- [30] F. P. Massabuau, M. K. Horton, E. Pearce, S. Hammersley, P. Chen, M.S. Zielinski, T. F. Weatherley, G. Divitini, P.R. Edwards, M.J. Kappers, and C. McAleese, Optical and structural properties of dislocations in InGaN. *Journal of Applied Physics*, 125(16), (2019) p.165701.
- [31] Y. Huang, A. Melton, B. Jampana, M. Jamil, J.-H. Ryou, R.D. Dupuis, I.T. Ferguson, Compositional instability in strained InGaN epitaxial layers induced by kinetic effects, *Journal of Applied Physics*, 110 (2011) 064908
- [32] H. Lei, J. Chen, and P. Ruterana, Role of c-screw dislocations on indium segregation in InGaN and InAlN alloys, *Applied Physics Letters*, 96(16), (2010) p.161901.
- [33] M.K. Horton, S. Rhode, S., S.L. Sahonta, M.J. Kappers, S.J. Haigh, T.J. Pennycook, C.J. Humphreys, R.O. Dusane, and M.A. Moram, Segregation of In to dislocations in InGaN. *Nano letters*, 15(2), (2015) pp.923-930.
- [34] Moram, M.A., Ghedia, C.S., Rao, D.V.S., Barnard, J.S., Zhang, Y., Kappers, M.J. and Humphreys, C.J. On the origin of threading dislocations in GaN films. *Journal of Applied Physics*, 106(7), (2009) p.073513.
- [35] S. Lazarev, S. Bauer, K. Forghani, M. Barchuk, F. Scholz, T. Baumbach, High resolution synchrotron X-ray studies of phase separation phenomena and the scaling law for the threading dislocation densities reduction in high quality AlGaN heterostructure, *Journal of Crystal Growth*, 370 (2013) 51-56.
- [36] X. Wu, L. Brown, D. Kapolnek, S. Keller, B. Keller, S. DenBaars, J. Speck, Defect structure of metal-organic chemical vapor deposition-grown epitaxial (0001) GaN/ Al_2O_3 , *Journal of applied physics*, 80 (1996) 3228-3237.

- [37] S. Choi, E. Heller, D. Dorsey, R. Vetry, S. Graham, Analysis of the residual stress distribution in AlGaIn/GaN high electron mobility transistors, *Journal of Applied Physics*, 113 (2013) 093510.
- [38] S. Strite, H. Morkoç, GaN, AlN, and InN: a review, *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures Processing, Measurement, and Phenomena*, 10 (1992) 1237-1266.
- [39] M. Wu, S. Zhou, A. Vantomme, Y. Huang, H. Wang, H. Yang, High-precision determination of lattice constants and structural characterization of InN thin films, *Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films*, 24 (2006) 275-279.
- [40] N. Faleev, B. Jampana, O. Jani, H. Yu, R. Opila, I. Ferguson, C. Honsberg, Correlation of crystalline defects with photoluminescence of InGaIn layers, *Applied Physics Letters*, 95 (2009) 051915.
- [41] R. Chierchia, T. Böttcher, H. Heinke, S. Einfeldt, S. Figge and D. Hommel, Microstructure of heteroepitaxial GaIn revealed by x-ray diffraction, *Journal of Applied physics*, 93(11), (2003) 8918-8925
- [42] M. Moram, M. Vickers, X-ray diffraction of III-nitrides, *Reports on progress in physics*, 72 (2009) 036502
- [43] K.J. Lee, T.S. Oh, T.K. Kim, G.M. Yang, K.Y. Lim, Optical and structural properties of $\text{In}_x\text{Ga}_{1-x}\text{N}$ films on tensile-strained GaIn/Si (111) structures grown by using MOCVD, *Journal of the Korean Physical Society*, 47 (2005) 842-846.
- [44] P. Liu, Y. Cao, H. Cui, X. Chen, G. Yang, Synthesis of GaIn nanocrystals through phase transition from hexagonal to cubic structures upon laser ablation in liquid, *Crystal Growth and Design*, 8 (2008) 559-563.
- [45] H.K. Cho, J. Lee, K.S. Kim, G.M. Yang, Formation of misfit dislocations and stacking faults in high indium content $\text{In}_x\text{Ga}_{1-x}\text{N}$ layers grown by metal organic chemical vapor deposition, *Journal of the Korean Physical Society*, 39 (2001) 165-169.
- [46] Cho, H.K., Lee, J.Y., Kim, K.S. and Yang, G.M., Growth of a GaIn overlayer with low threading dislocation density using stacking faults, *Journal of the Korean Physical Society*, 39(1), (2001) pp.622-626.
- [47] T. Tao, Z. Zhao, L. Lian, S. Hui, X. Zili, Z. Rong, L. Bin, X. Xiangqian, L. Yi, H. Ping, Surface morphology and composition studies in InGaIn/GaIn film grown by MOCVD, *Journal of Semiconductors*, 32 (2011) 083002.
- [48] T. Song, Strain relaxation due to V-pit formation in $\text{In}_x\text{Ga}_{1-x}\text{N}$ / GaIn epilayers grown on sapphire, *Journal of applied physics*, 98 (2005) 084906.

- [49] F.P. Massabuau, S.L. Sahonta, L. Trinh-Xuan, S. Rhode, T.J. Puchtler, M.J. Kappers, C.J. Humphreys, and R.A. Oliver Morphological, structural, and emission characterization of trench defects in InGaN/GaN quantum well structures. *Applied Physics Letters*, 101(21), (2012) p.212107.
- [50] H.K. Cho and G. M. Yang, Generation of misfit dislocations in high indium content InGaN layer grown on GaN. *Journal of crystal growth*, 243(1), (2002) pp.124-128.
- [51] Z. Liliental-Weber, Y. Chen, S. Ruvimov, J. Washburn, Formation mechanism of nanotubes in GaN, *Physical Review Letters*, 79 (1997) 2835.
- [52] Sun, Xiaojuan, Dabing Li, Hang Song, Yiren Chen, Hong Jiang, Guoqing Miao, and Zhiming Li, Short-wavelength light beam in situ monitoring growth of InGaN/GaN green LEDs by MOCVD, *Nanoscale research letters* 7, (2012) 282.
- [53] Q. Li, J. Zhang, L. Meng, J. Chong, and X. Hou, Mobility limitations due to dislocations and interface roughness in AlGaN/AlN/GaN heterostructure, *Journal of Nanomaterials*, 2015, (2015) 8
- [54] Z. Chen, L. Su, J. Shi, X. Wang, C. Tang, P. Gao, AFM application in III-nitride materials and devices, in: *Atomic Force Microscopy-Imaging, Measuring and Manipulating Surfaces at the Atomic Scale*, InTech, 2012
- [55] S. M. Ting, J.C. Ramer, D.I. Florescu, V.N. Merai, B. E. Albert, A. Parekh, D.S. Lee, D. Lu, D. V. Christini, L. Liu and E.A. Armour, Morphological evolution of InGaN/GaN quantum-well heterostructures grown by metalorganic chemical vapor deposition. *Journal of Applied Physics*, 94(3), (2003) pp.1461-1467
- [56] J. Bruckbauer, P.R. Edwards, T. Wang, R.W. Martin, High resolution cathodoluminescence hyperspectral imaging of surface features in InGaN/GaN multiple quantum well structures, *Applied Physics Letters*, 98 (2011) 141908.
- [57] W. Liu, J. Yang, D. Zhao, D. Jiang, J. Zhu, P. Chen, Z. Liu, F. Liang, S. Liu, Y. Xing, and L. Zhang, Energy band tilt in ultra-thin InGaN film affected by the surface adsorption and desorption. *Applied Surface Science*, 456, (2018) pp.487-492.
- [58] K. Prabakaran, R. Ramesh, M. Jayasakthi, S. Surender, S. Pradeep, M. Balaji, K. Asokan, K. Baskar, Electronic excitation induced structural and optical modifications in InGaN/GaN quantum well structures grown by MOCVD, *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 394, (2017) 81–88.
- [59] S. Sanjay, K. Prabakaran, S. Singh, and K. Baskar, Growth of gold-palladium alloy catalyzed gallium nitride nanowires by chemical vapour deposition, *Materials Letters*, 217, (2018) 100-103.

- [60] A. Yildiza, F. Dagdelen, S. Acar, S. Lisesivdin, M. Kasap, Y. Aydogdu, M. Bosid, Stokes Shift and Band Gap Bowing in $\text{In}_x\text{Ga}_{1-x}\text{N}$ ($0.060 \leq x \leq 0.105$) Grown by Metal organic Vapour Phase Epitaxy, *Acta Physica Polonica A*, 113 (2008) 731-739.
- [61] L. Pan, X. Dong, Z. Li, W. Luo, J. Ni, Influence of the AlN nucleation layer on the properties of AlGaN/GaN heterostructure on Si (1 1 1) substrates, *Applied Surface Science*, 447 (2018) 512-517.
- [62] R.J. Molnar, T. Lei, and T.D. Moustakas, Electron transport mechanism in gallium nitride, *Applied physics letters*, 62(1), (1993) pp.72-74.
- [63] J. Liu, H. Liang, B. Li, Y. Liu, X. Xia, H. Huang, Q.A. Sandhu, R. Shen, Y. Luo, and G. Du, Unintentionally doped high resistivity GaN layers with an InGaN interlayer grown by MOCVD, *RSC Advances*, 6(65), (2016) 60068-60073.