

Low Temperature Photoluminescence Measurement of Extremely Thin InGaAs/GaAs Multi Quantum Wells Grown by Molecular Beam Epitaxy

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ABSTRACT: The samples were grown on n⁺ GaAs substrates using molecular beam epitaxy system. The effect of change in the percentage of indium on the optical properties of In_xGa_{1-x}As multi quantum well structures is investigated using the temperature-dependent photoluminescence from 10 K to 300 K. The temperature-dependent PL characteristics there was no shift in peak, arising due to band transition. Hence from the present investigation, it can be concluded that merely changing the composition does not alter the PL characteristics of the **In_xGa_{1-x}As/GaAs** MQW.

In_xGa_{1-x}As multi quantum well (MQW) of 3 nm was grown by using Molecular Beam Epitaxy (MBE) system. The structural studies were done by High Resolution X-ray Diffraction Method (HRXRD). The fringes in the Rocking curves show that the layer homogeneity and high crystal quality was achieved. In addition, the thickness of the quantum well and the In composition of the quantum well layer was obtained from the rocking curve simulation.

KEYWORDS: In_xGa_{1-x}As, multi quantum wells, photoluminescence, HRXRD, AFM, Dark current.

I. INTRODUCTION

Indium gallium arsenide (InGaAs) has been the focus of research interest because it can result in self assembled confined structures such as quantum dots during epitaxial growth. Indium gallium arsenide (InGaAs) is semiconductor composed of indium, gallium and arsenic [1]. It is used in high power and high frequency electronics because of its superior electron velocity with respect to the more common semiconductors silicon and gallium arsenide. InGaAs band gap also makes it the detector material of choice in optical fiber communication at 1300 and 1550 nm.

III-V compound semiconductors have been traditionally grown on (100) substrates because of the wide range of growth conditions which results in good epitaxial layer quality and well-established device processing technology [2]. Doping plays an important role in fabrication of most semiconductor electronic, opto-electronic, and all-optical devices, as it allows to engineer free carrier concentrations in various materials. Group III/V semiconductors are mainly doped either by volume-doping, when the dopant is co-deposited during growth of the doped layer or by delta-doping during which growth of a non intentionally doped layer is interrupted to deposit the "delta layer" [3].

InGaAs/Ga quantum wells, wires and dots have attracted much attention because reduced dimensions lead to modifications in the band structure providing a post-growth possibility to realize new optoelectronic devices based on Indium [5, 6].

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 5, Issue 10, October 2016

II. RELATED WORK

$\text{In}_x\text{Ga}_{1-x}\text{As}$ layers of 3nm thickness were grown on 350 μm thick n^+ -type GaAs single crystal with one side polished using DCA model 450 solid source MBE system at SAMEER, Mumbai. The Indium mole fraction 'x' was varied from 11.5% to 33%. The GaAs substrates were mounted on a molybdenum substrate and were heated to 200⁰ C for two hours. The substrates were heated in preparation for 300⁰ C- 400⁰ C for out gassing. The substrate was then transferred to growth chamber GaAs buffer layer is grown at the oxide desorption temperature. For the growth of InGaAs layer the temperature is taken down by 100⁰ C than buffer layer growth temperature. During the growth, the surface reconstructions shows streaky pattern while spotty pattern indicates 3D growth.

The rocking profiles were obtained using the Material Research Diffractometer. The incident X-ray beam of wavelength 1.5405980 Å was produced at 10 mA and 45kV potential and passed through a four crystal monochromator in symmetric Ge (220) mode to collimate the beam. We have used (004) diffraction with an Ω -2 Θ scan. In this mode of operation, a very high intensity signal can be obtained. We have used a count time of 2 seconds per step

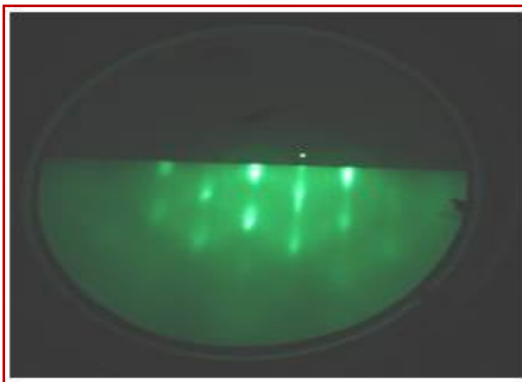


Figure.1. RHEED pattern after the Growth of GaAs buffer layer

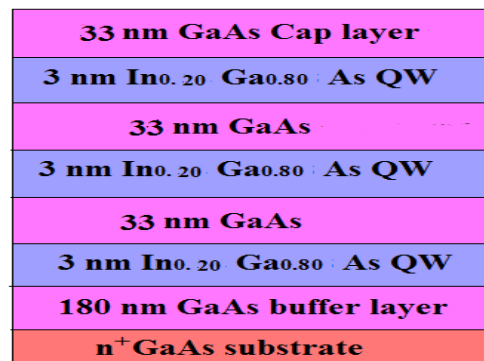


Figure 2: The schematic structure of an $\text{In}_x\text{Ga}_{1-x}\text{As}$ /GaAs MQW.

III. EXPERIMENTAL RESULTS

A. HIGH RESOLUTION X-RAY DIFFRACTION (HRXRD) ANALYSIS

Crystalline properties were analyzed with a PAN analytical X'Pert Pro Material and Research Diffractometer. It provides monochromatic Cu-K α 1 radiation ($\lambda=1.5406$ Å) of 19 arc sec divergence, which is formed by a 1/4⁰ divergence slit, a multi focusing mirror followed by a four-bounce Ge monochromator. Double crystal ω -2 θ scans were measured around the GaAs (004) reflection with a narrow 1/4⁰ receiving slit in front of the detector to diminish diffuse scattered background. For the acquisition of ω -2 θ scans and ω rocking curves (RC), a three bounce Ge (220) analyzer crystal was inserted between sample and detector.

Crystalline properties of grown structures are deduced from high resolution x-ray experiments. Double crystal ω -2 θ scans allow determining layer thicknesses and compounding compositions. Experimental results collected around the (004) GaAs reflection is shown for all examined structures in Fig. 3 to 7 All experimental ω -2 θ scans were simulated in order to determine correct indium compositions and layer thicknesses.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 10, October 2016

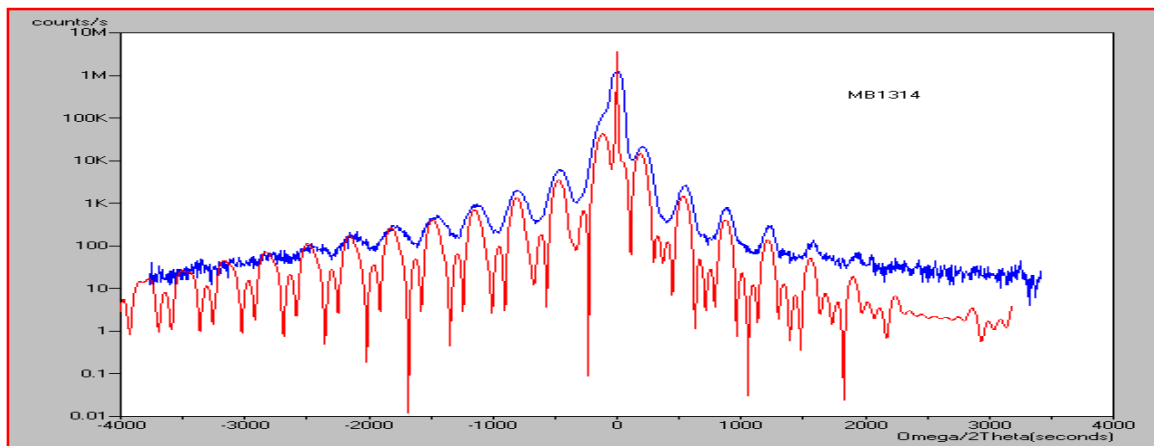


Figure 3: HRXRD scan profile for MB 1314 (11.5% In).

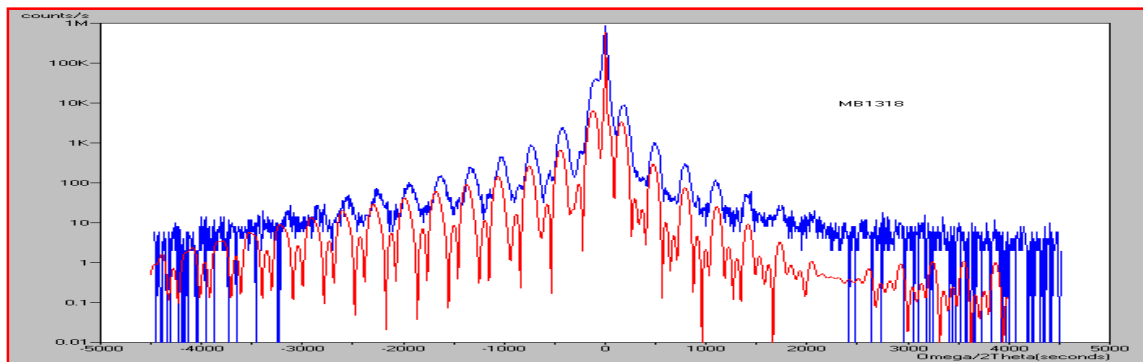


Figure 4: HRXRD scan profile for MB 1318 (15% In).

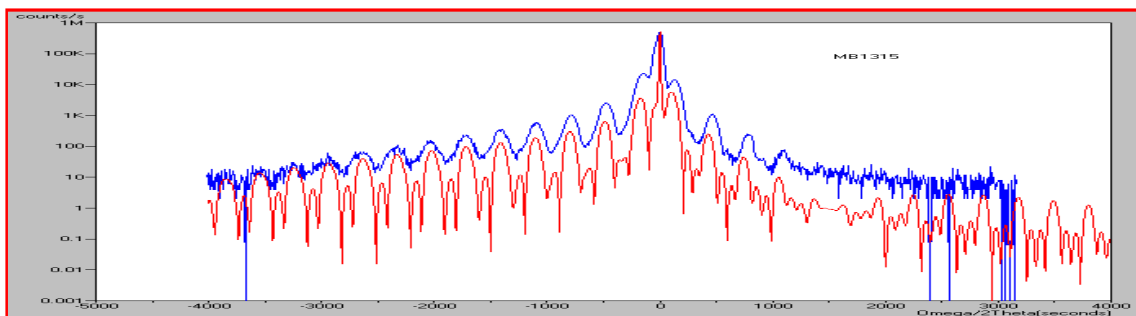


Figure 5: HRXRD scan profile for MB 1315 (20% In).

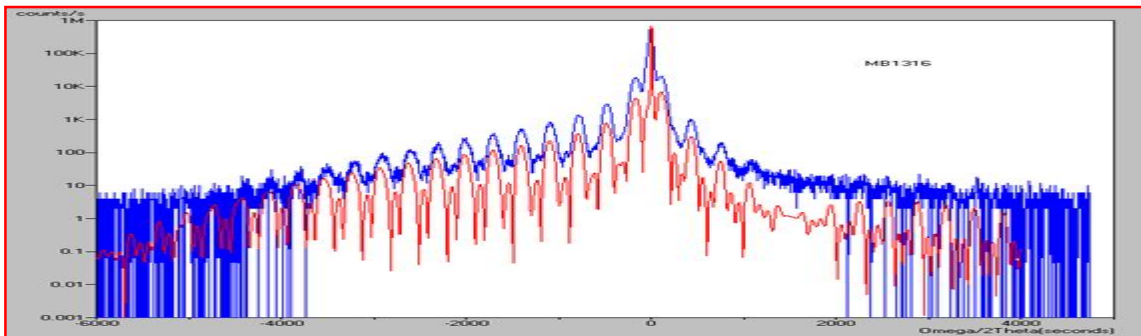


Figure 6: HRXRD scan profile for MB 1316(25 % In).

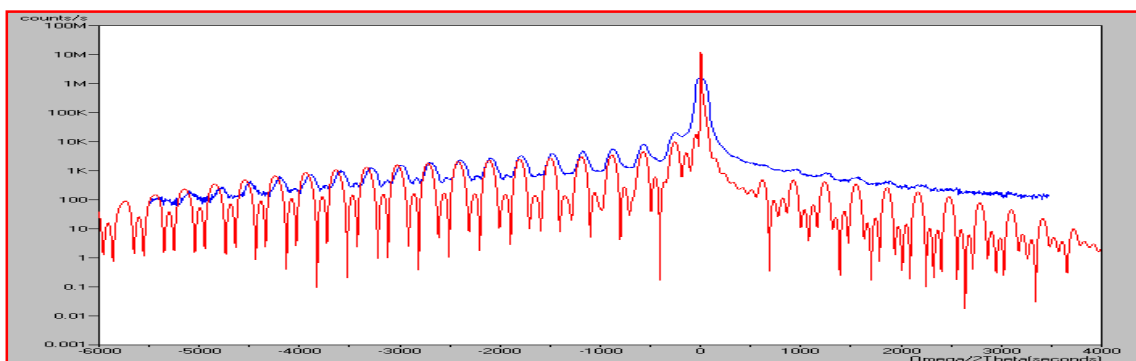


FIGURE 7: HRXRD SCAN PROFILE FOR MB 1317(33 % IN)

The position of this peak cannot be explained by any of the MQW satellites, apart from the fact that it is too intense for a satellite. We attribute the presence of this intense peak to the thick GaAs layer capping the MQW. The GaAs cap has the same in-plane lattice parameter as the partially relaxed MQW. This means that this layer is tensilely strained ($\epsilon_{\parallel} > 0$) and its perpendicular lattice parameter a_{\perp} is smaller than a_s . That is why it diffracts at an angle slightly higher than the GaAs bulk and can be distinguished from the GaAs substrate.

Since the diffraction peak reflects the lattice constant in the growth direction, the largest splitting between the substrate peak and the zeroth satellite peak means the highest indium content [4].

From the interval of the satellite peaks, the period length of samples were determined using the formula [7].

$$L = \frac{(L_i - L_j)\lambda}{2(\sin \Theta_i - \sin \Theta_j)}$$

Where L_i and L_j are the diffraction orders, Θ_i , Θ_j are the corresponding Bragg angles of the satellites and λ is the X-ray wavelength used. In the present investigation the interval for all the samples is found to be approximately equal to 38.5 nm whereas the targeted period was 36 nm.

In composition in InGaAs MQW was estimated as follows. First, the lattice constant of InGaAs well was estimated from the equation, [8].

$$a_{\perp} = \frac{L_W + L_B}{L_W} a_{\perp mqw} - \frac{L_B}{L_W} a_{GaAs}$$

Here, $a_{\perp mqw}$ is the lattice constant of MQW region. The values of $a_{\perp mqw}$ for each sample were estimated from the position of the 0th satellite peaks in XRD profiles. The lattice constant a_{GaAs} is 0.56533 nm. L_W and L_B are the designed well width and the designed barrier width, respectively.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 10, October 2016

Next, the lattice constant of InGaAs a_0 was calculated using the relationship of the elastic deformation of the epitaxial structure, which was expressed by [8].

$$a_0 = a_{\parallel} \left(1 - \frac{C_{11}}{C_{11} + 2C_{12}} \frac{a_{\parallel} - a_{\perp}}{a_{\parallel}} \right)$$

Where C_{11} and C_{12} are the elastic stiffness constants of InGaAs, which were obtained from the composition weighted mean values between the values of GaAs and cubic InAs. The lattice constant in the plane a_{\parallel} was equal to a_{GaAs} . Then, the In composition ' x ' was estimated by assuming the Vegard's law [9].

$$a_0 = (1 - x)a_{GaAs} + x a_{InAs}$$

Where a_{InAs} is the lattice constant of InAs whose value is taken as 0.60583 nm.

Sample	From Design						From XRD measurements		
	T _{well} (s)	T _{Barrier} (s)	L _W (nm)	L _B (nm)	period (nm)	Targeted Indium %	period (nm)	a _{well} (nm)	Indium (%)
1314	10	110	3	33	36	11.5	38.5	0.56869	9
1318	10	110	3	33	36	15	38.5	0.5691	10
1315	10	110	3	33	36	20	38.5	0.5701	12.5
1316	10	110	3	33	36	25	38.5	0.5717	16
1317	10	110	3	33	36	33	38.5	0.5918	19

Table 1: The design values and the analytical results of XRD measurements.

The lattice mismatch is given by

$$\frac{\Delta a}{a} = \frac{a_L - a_S}{a_S}$$

Where a_S is the lattice constant of the substrate and a_L are lattice constants of the strained layers.

Sample	Indium targeted (%)	Lattice mismatch
1314	9	0.00653
1318	10	0.00725
1315	12.5	0.00902
1316	16	0.01185
1317	19	0.04743

Table 2: Lattice mismatch for different indium compositions.

The table 2 shows that mismatch increases with increasing indium mole fraction. The identical results were observed by Young-Hoon Kim et al for InGaN/GaN MQW [7].

B. PHOTO LUMINESCENCE CHARACTERISTICS (PL)

A variety of photoluminescence (PL) experiments were performed, including low-temperature PL to investigate the bandgap of the materials. In the present study we have investigated photoluminescence PL for few samples in order to identify their energy-level structure. The PL measurements were made at 10 K using a liquid-nitrogen-cooled Ge-diode detector. The 807.0 nm line of an NdYAG pump laser was used for excitation and the spectra were recorded using a standard lock-in detection technique. The PL measurements were done at Tata Institute of fundamental research centre Mumbai. The composition dependent optical characterization of the $In_xGa_{1-x}As/GaAs$ MQW structures was performed using photoluminescence system [10].

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 10, October 2016

At very low temperatures (In present case 10 K) the carriers cannot overcome the small barriers created by the bandgap fluctuations and they become confined locally in space at a lower energy than the majority of the film. This causes the luminescence peak energy dependence on bandgap to shift away from the theoretical bandgap dependence with temperature (towards lower energies) at very low temperatures. In an ideal material with no carrier localization at low temperatures the bandgap changes with temperature are governed by the Varshni model.

$$E_g(T) = E_g(0) - \frac{\alpha T^2}{\beta + T}$$

Where $E_g(T)$ the bandgap at temperature T is, $E_g(0)$ is the bandgap at 0 K, and alpha and beta are constants defining the shape of the dependence.

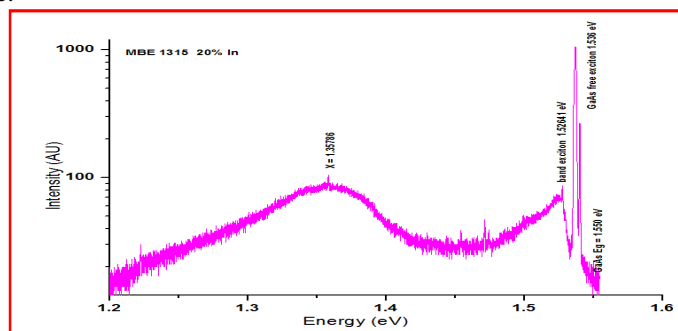


Figure 8: $In_{0.20}Ga_{0.80}As/GaAs$ MQW PL spectrum at temperature 10 K.

In this Figure the spectrum of the emission intensity versus photon energy is given. The PL spectrum of the sample at a temperature of 10 K with nominal Indium compositions $x = 0.20$ is shown in Figure 8. The Figure shows that there is a peak at $E_g \sim 1.35 eV$ which represent the band to band transition and is assumed to have originated from the active region of the structure. It is also observed that there is a band edge at $E_g \sim 1.55 eV$, $GaAs$ free exciton is observed at $E_g \sim 1.536 eV$ and a band excitation at $E_g \sim 1.526 eV$. This part of the spectrum arises due to the $GaAs$ substrate.

Similar results were observed for the other samples having different Indium composition having same well and barrier width (same period of the well). There was no shift in peak, arising due to band transition. Hence from the present investigation, it can be concluded that merely changing the composition does not alter the PL characteristics of the $In_xGa_{1-x}As/GaAs$ MQW.

C. DARK CURRENT MEASUREMENTS

Dark current is a measure of device quality. The lower the dark current, the better the signal-to-noise ratio, thus smaller absolute and relative signals can be detected. The dark current can also affect solar cell properties. In the present investigation these measurements were done using Model 2400 Source Meter SMU Instrument at Thin Films Laboratory, Birla College of Arts, Commerce and science; Kalyan.

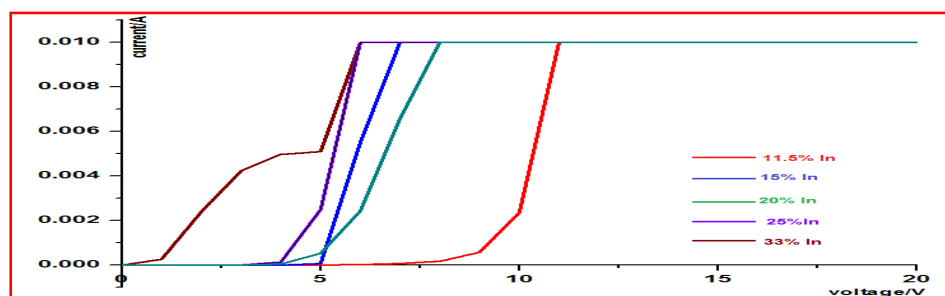


Figure 9.: Dark current vs. voltage plot for $In_xGa_{1-x}As/GaAs$ MQW for different targeted indium composition. Maximum device bias of each curve is +20 V.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 10, October 2016

When reverse bias voltage is applied it is found that the breakdown voltage decreases as the composition of indium increases. Figure 9 shows the dark current-voltage characteristics of the five samples in this study with forward bias,

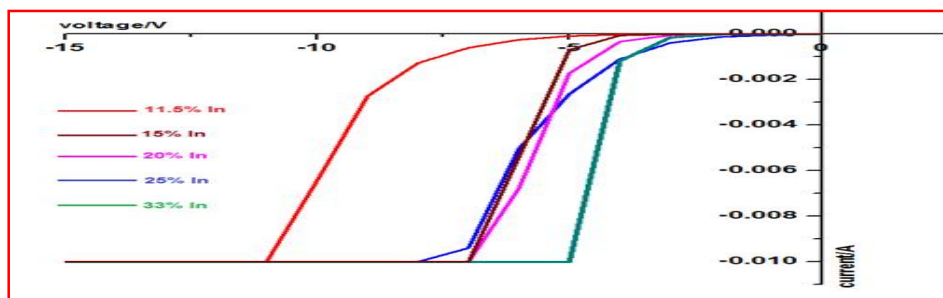


Figure 10: Dark current vs. voltage plot for $In_xGa_{1-x}As/GaAs$ MQW for different targeted indium composition. Maximum device bias of each curve is -15 V.

Figure 10 shows the same current data plotted versus applied voltage in reverse bias. The voltage where the ideal diode I-V curve changes from the ideal shape to an exponentially increasing function is referred to as the crossover voltage. It is observed that the crossover voltage decreases as the composition of indium goes on increasing.

D. ATOMIC FORCE MICROSCOPY (AFM) STUDY

Literature on surface morphology studies is very limited for strained $In_xGa_{1-x}As/GaAs$ MQW structures. It is necessary to understand the effects of strain relaxation on the surface of such structures. A contact-mode atomic force microscope (AFM) was used to investigate sample surface morphology. AFM measurements were made IIT Mumbai (Department Of Physics) using a Digital Instruments Nanoscope. The surface morphology of $In_{0.10}Ga_{0.90}As/GaAs$ MQW sample is shown in Fig. 10.

The root-mean square (rms) surface roughness is shown in Table 3

Sample	Indium (%)	Surface roughness (nm)
1318	10	0.88
1315	12.5	1.11
1316	16	1.43
1317	19	1.78

Table 3: Surface roughness for $In_xGa_{1-x}As/GaAs$ MQW different indium composition.

Table 3 shows that the rms surface roughness increases on MQW structures grown on GaAs buffer layers with increasing InAs mole fraction in the InGaAs wells.

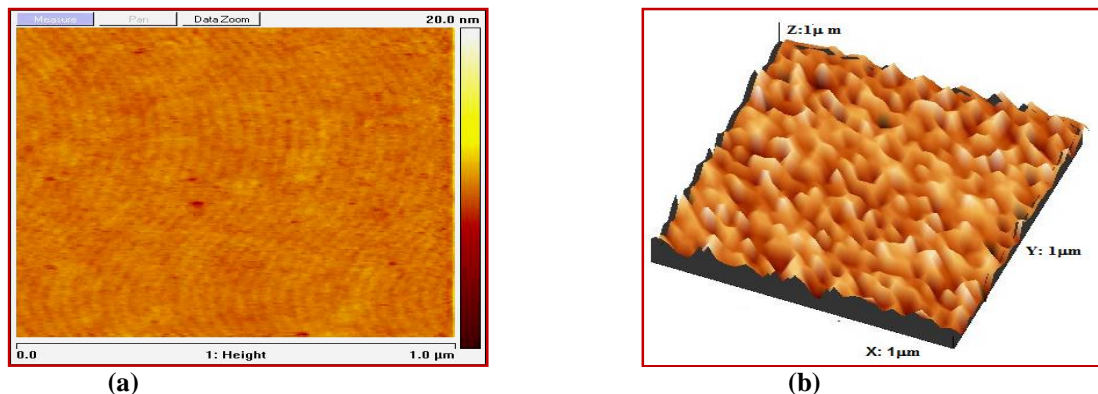


Figure 11: AFM image of $In_{0.10}Ga_{0.90}As/GaAs$ MQW sample (a) 2d image (b) 3D image of the same.

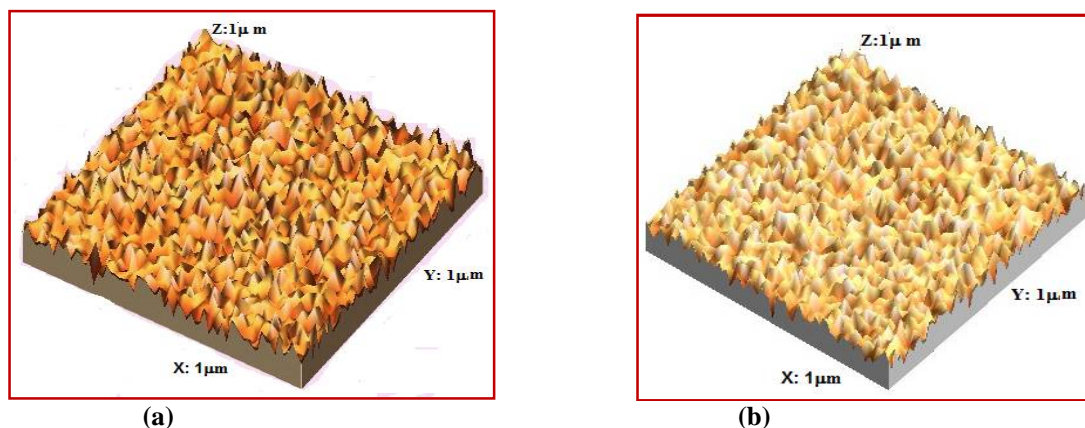


Figure 12: AFM image of $In_xGa_{1-x}As/GaAs$ MQW sample (a) 19% Indium (b) 12.5 % Indium..

IV. CONCLUSION

In summary, we have demonstrated that the $In_xGa_{1-x}As/GaAs$ MQW structures were successfully grown by MBE using solid source. Five samples of different indium composition were successfully grown. For each sample, clear satellite peaks originating from $In_xGa_{1-x}As/GaAs$ MQW structures were observed in HRXRD profiles. From the position of the satellite peaks, the period lengths in MQWs and the lattice constants of $In_xGa_{1-x}As$ layers were determined. The indium compositions in the $In_xGa_{1-x}As$ layers are 9–19%, which were estimated from the values of lattice constant and the elastic constants. As indium percentage increases lattice mismatch increases.

The optical characterization was carried out using Photoluminescence spectroscopy. The low temperature PL measurements were performed at 10 K. In case of PL characteristics there was no shift in peak, arising due to band transition. Hence from the present investigation, it can be concluded that merely changing the composition does not alter the PL characteristics of the $In_xGa_{1-x}As/GaAs$ MQW.

The surface morphology measurements indicate that the surface roughness increases with increase in composition of Indium.

The dark current measurements were done in reverse as well as forward bias. It is observed that the crossover voltage decreases as the composition of indium goes on increasing.

International Journal of Innovative Research in Science, Engineering and Technology

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Vol. 5, Issue 10, October 2016

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