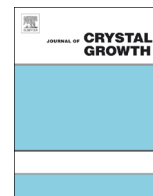




ELSEVIER

Contents lists available at ScienceDirect

Journal of Crystal Growth

journal homepage: www.elsevier.com/locate/jcrysgr

Controlling the compositional inhomogeneities in $\text{Al}_x\text{Ga}_{1-x}\text{N}/\text{Al}_y\text{Ga}_{1-y}\text{N}$ MQWs grown by PA-MBE: Effect on luminescence properties

Pallabi Pramanik^a, Sayantani Sen^a, Chirantan Singha^a, Abhra Shankar Roy^a, Alakananda Das^b, Susanta Sen^b, Anirban Bhattacharyya^{b,*}, Deepak Kumar^c, D.V. Sridhara Rao^c

^a Centre for Research in Nanoscience and Nanotechnology, University of Calcutta, JD2 Sector III Salt Lake City, Kolkata 700098, West Bengal, India

^b Institute of Radio Physics and Electronics, University of Calcutta, 92 A. P. C. Road, Kolkata 700009, West Bengal, India

^c Electron Microscopy Group, Defence Metallurgical Research Laboratory, Kanchanbagh Post, Hyderabad 500 058, India

ARTICLE INFO

Article history:

Received 11 October 2015

Received in revised form

24 December 2015

Accepted 6 January 2016

Communicated by H. Asahi

Available online 13 January 2016

Keywords:

A1. Characterization

A3. Molecular beam epitaxy

A3. Quantum wells

B1. Nitrides

B2. Semiconducting III–V materials

ABSTRACT

$\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}/\text{Al}_{0.55}\text{Ga}_{0.45}\text{N}$ MQWs were grown by PA-MBE using a range of group III/V flux ratios. TEM images indicate sharp interfaces and well/barrier widths of 1.5/2 nm. We observe that small variations of group III/V flux ratio cause dramatic variations in the room temperature photoluminescence (PL) spectra. In addition to band edge luminescence, multiple low energy PL peaks are observed for growths under excess group III conditions, which are absent for near-stoichiometric growth. Temperature dependent PL measurements indicate that at room temperature, emission occurs due to transitions at potential fluctuations generated by the presence of compositional inhomogeneity. These effects are dominant for growth under excess group III conditions due to the presence of a metallic layer on the growth surface during deposition. This can be eliminated by the use of an Indium surfactant during growth, which modifies the diffusion length of Ga and Al adatoms. Under these conditions, the optical properties of MQWs are relatively insensitive to variations in group III to V flux ratio and hence substrate temperature, thus making them suitable for industrial-scale fabrication of optoelectronic devices in the ultraviolet range.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Quantum wells based on AlGaIn alloys have been under focus due to their applications in semiconductor ultraviolet optical sources and other related devices. Research in these structures have made significant progress, with reports of emission in the entire spectral range [1] and high internal quantum efficiencies [2,3]. However UV LEDs based on AlGaIn alloys still show limited power and efficiency levels compared to structures based on InGaIn alloys, and these emission parameters show a large spread and may not significantly increase with use of low defect density templates and substrates. Presence of compositional inhomogeneities has been reported in AlN/AlGaIn MQWs [2,3] for growth by both MBE and MOCVD. Such phenomena are strongly dependent on growth kinetics and thus on substrate temperature. The alloy properties of AlGaIn alloys strongly depend on the deposition method and growth of bulk films by PA-MBE has been studied

extensively. A number of alloy phenomena [4] including long range atomic ordering [5,6] has been reported in these materials, the degree and nature of which can be controlled by the kinetics of growth, specifically the surface mobility of Ga and Al adatoms [7]. This in turn is affected by the substrate temperature and the group III to group V flux ratio. This can be a problem because with the increase of wafer sizes for manufacturing processes, maintaining the uniformity of temperature across the wafer has become technologically challenging. Therefore it is beneficial if the characteristics of the grown structures are relatively insensitive to the employed substrate temperature. This necessitates investigation into the dependence of the optical properties of these MQW structures on the growth conditions.

Use of Indium as a surfactant for bulk GaN and AlGaIn growth has also been studied previously by several groups. It has been reported that for AlGaIn alloys grown by PA-MBE at 730 °C, for a flux of 0.08 ML/s Indium content is ~0.01% [8] as measured by RBS, which signifies that Indium is not significantly incorporated in the alloy at this substrate temperature. This may be due to the higher bond strength of Al–N compared to In–N, leading to the

* Corresponding author. Tel.: +91 9903212063.

dissociation of In–N bonds to form nascent N, which in turn reacts with impinging Al flux [8]. It was reported that a 1 ML thick self regulated Indium film can be formed [8] by controlling the Indium arrival rates and substrate temperature. Indium improves the surface morphology of GaN [9,10] and also reduces stacking faults [11] and screw dislocations [12]. AFM studies show removal of Ga-droplets with the use of Indium surfactant [12]. P-type doping [13] and the reduction of point defect density by reduction of yellow luminescence [9,10,14,15] is also facilitated by using In flux during the growth of AlGa_xN alloys. For MQWs, the improvement of the interface quality by modifying the growth kinetics using Indium as a surfactant during the growth of quantum structures has been shown to cause reduction in width of the intersubband absorption peak [16]. Although the effect of Indium flux during growth on the optical properties of AlGa_xN MQWs was postulated [2], a systematic study on this is necessary. In this paper we investigate the effect of the kinetics of growth including the role of Indium as a surfactant, on the optical properties of AlGa_xN MQWs.

We address MQW structures employing AlGa_xN alloys in both the well and barrier layers, which are more appropriate for use in optical emitters such as LEDs and LDs. In LED structures, the requirement of n-type contact layer with band-gap comparable to the barrier layer limits the AlN mole-fraction in the barrier layer to 50–60%, since donor incorporation is difficult for higher Al content. The well alloy composition along with the thickness, control the emission wavelength. In this paper we have chosen ~35% AlN mole fraction for emission at ~300 nm.

2. Experimental methods

A VEECO Gen 930 MBE was used for deposition of III-Nitride materials on c-plane sapphire substrates without any backside coating. The substrates were degassed at 500 °C at a vacuum level of 10^{-9} T prior to deposition. All growths were conducted using PA-MBE process with an RF source for nitrogen activation. The depositions were carried out using a nitrogen flow rate of 1.7 sccm but with varying plasma powers for different growth steps. Typically, the growths were carried out in three steps, starting with the nitridation of the sapphire, i.e. exposure of the Al₂O₃ surface to nitrogen plasma at a substrate temperature of 800 °C [17]. For this step, a plasma power of 400 W was employed, and the termination point determined by observation of the typical AlN RHEED pattern. Subsequently, the plasma power was reduced to 350 W for the AlN buffer layer growth.

The initial nucleation steps were carried out using a modified MEE (migration enhanced epitaxy) process, where excess group III (Al) flux was employed for a short period of time, T_{on} followed by exposure of the deposited film to the nitrogen plasma for a period T_{off} . During Al deposition, the RHEED pattern becomes dim and diffuse, but on exposure to the nitrogen it regains its brightness and streaky behavior. At the end of the AlN buffer layer deposition, (typically 60–80 nm) the RHEED pattern becomes streaky with sign of 2×2 surface reconstructions. A thicker (~150 nm) AlN layer was subsequently deposited using nearly stoichiometric (III/V~1) conditions. The active region of the deposited samples consists of a bulk Al_{0.35}Ga_{0.65}N layer (~320 nm thick), onto which a set of 20 quantum wells are grown, with well composition the same as that of the underlying bulk film, and barrier containing nominally 55% AlN mole fraction.

The control of alloy composition in AlGa_xN materials grown by PA-MBE has been discussed extensively in the literature [7], and has been shown to depend strongly on the disparate desorption properties of Al and Ga and hence on the substrate temperature employed. For growth of Al_{0.35}Ga_{0.65}N at 800°C under stoichiometric conditions, the required Al and Ga beam equivalent

pressures (BEP) were determined to be 4.7×10^{-8} T and 4.6×10^{-7} T respectively, for an RF power of 350 W and a nitrogen flow rate of 1.7 sccm.

Typically III-Nitrides are grown in the excess group III condition, as this leads to smooth surfaces. However, under these conditions, the growth surface is coated with a metallic layer of excess Ga and Al during deposition [18,19]. In this work, a series of samples were grown with group III to group V ratio ranging from unity to as high as 1.12. The RHEED pattern observed during the growth of group III to group V ratio of unity was streaky and bright whereas the pattern at high group III to group V ratio (1.12) was observed to be dim and diffuse indicating the presence of a metallic layer on the growth surface. The effect of this variation of growth kinetics on the structural and optical properties of the MQWs has been studied in this work.

Post growth, the samples were characterized by XRD, TEM, optical transmission and temperature dependent PL studies to evaluate their structural and optical properties. The TEM studies were carried out in cross-sectional mode using Tecnai 20 G2 (200 keV) analytical TEM instrument. Photoluminescence measurements at room and low temperatures were carried out using a 10 mW He–Ag laser (Photon Systems) emitting at 224 nm using a 2 mm diameter spot size.

3. Results and discussion

Fig. 1(a) shows the schematic of a typical sample studied in this work. A cross sectional TEM image of the grown structure is presented in Fig. 1(b). The various layers indicated in the drawing (Fig. 1(a)) can be observed in the cross-sectional TEM image. The quantum wells are clearly visible indicating excellent interface qualities, and the fact that the quality is consistent throughout the 20 pair stack shows a high degree of uniformity during the deposition process. The thickness of the wells and barriers has been found to be 1.5 nm and 2 nm respectively. The AlGa_xN MQWs were studied by HRXRD at the Indus Synchrotron facility at RRCAT, Indore [unpublished] and the thicknesses of the well and barriers are very similar to the results obtained from TEM, while the interface quality improved with the presence of Indium flux.

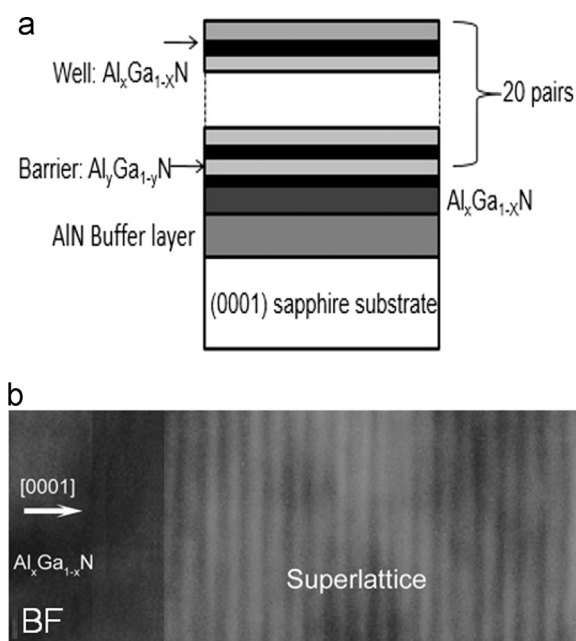


Fig. 1. (a) Schematic of investigated AlGa_xN MQW samples and (b) a typical cross-sectional TEM image.

During the growth, care was taken to maintain identical growth conditions for the bulk AlGaIn layer and the material employed in the quantum well region. This allows the determination of alloy composition of the well material using optical transmission studies, which is dominated by the absorption in the thick bulk AlGaIn layer. A control sample B1 was grown under identical conditions as the previously described samples, but the deposition process was terminated after the bulk AlGaIn layer. Comparison of the optical absorption studies carried out on a typical MQW sample and B1 indicates that the two thick AlGaIn films are nearly identical in composition (band gaps 4.32 eV and 4.34 eV), as shown from the overlapping absorption edge (Fig. 2(a)). The room temperature photoluminescence spectrum obtained from sample B1 is shown in Fig. 2(b), which indicates a single peak at 4.0 eV with a degree of asymmetry indicating a shoulder at longer wavelength (~ 3.6 eV). An interesting feature is the strong red-shift of the luminescence peak compared to the optical absorption edge (4.32 eV), which has been reported earlier and linked to the presence of compositional inhomogeneities in the AlGaIn film at the nanometer scale [20].

The alloy fluctuations at the nanometer scale for bulk AlGaIn materials grown by PA-MBE have been studied extensively by several groups [3–6, 20]. Two different alloy phenomena have been identified as the source of these effects. For growths carried out in excess group V conditions, the limited mobility of the Al adatoms give rise to a category of alloy fluctuations [21], which however also lead to an extremely rough and faceted surface morphology making the conditions unsuitable for the growth of MQW structures. For smooth surface morphology, excess group III conditions are typically employed, which leads to the presence of a metallic layer on the growth surface. The presence of this metallic layer has been linked to the presence of long-range chemical

ordering, as well as strong chemical inhomogeneity at the nanometer scale [6]. The effect of such phenomena on the optical properties of quantum wells employing AlGaIn alloys for both well and barrier materials are found to be very complex, as can be observed in Fig. 3.

In Fig. 3(a) the room temperature PL spectra from a series of MQW samples is presented. These samples, as described in Fig. 1(a) are identical in every way except for the group III/V flux ratio employed during growth, which ranges from unity (i) to as high as 1.12 (iv). It should be mentioned that under excess group III conditions, the growth was carried out with a metallic adlayer on the growth surface, as indicated by a diffuse and dim RHEED pattern mentioned earlier. As can be clearly observed, the presence of this adlayer significantly changes the room temperature PL properties of these otherwise identical samples.

The sample (i) grown under group III/V ~ 1 shows a clear single peak at 315 nm. As the group III/V flux ratio increases, multiple peaks can be observed, with the main band-edge peak in the range 306–315 nm, and multiple distinct and sharp peaks at higher wavelengths, which dominate over the near-band edge peak in intensity. At the highest group III-flux, the peak at 352 nm is 2.5 times the intensity of the band-edge peak at 306 nm. We attribute the additional low energy peaks to the presence of the metallic group III layer on the growth surface during deposition of the MQWs which strongly modifies the growth kinetics by enhancing the lateral diffusion of adatoms [22]. It should be mentioned here that SEM images of the top surface of these samples do not show the presence of any inclusions or “droplets”. For (ii) and (iii), this metallic layer containing both Al and Ga atoms is relatively thin and flat. However, it can be expected that the alloy composition of this layer is not uniform due to the variation of the diffusivity of the Al and Ga adatoms, that lead to localized and large-amplitude compositional fluctuations in the metallic layer, which is in turn replicated in the localized large-amplitude fluctuation of the alloy composition of the AlGaIn layer upon nitridation. Thus the well and barrier material alloy compositions are not uniform but show strong inhomogeneity and a resultant variation of the band gap at the localized level. This in turn leads to the observation of multiple peaks arising from these localized regions. For very high group III to V (as in iv), the composition of some of these islands nearly reach that of GaN, which leads to a strong peak at 352 nm.

An interesting observation can be made in Fig. 3(a) that the peak at room temperature for (i) is found to be red-shifted compared to that of the bulk AlGaIn film shown in Fig. 2(b).

This cannot be explained from quantum confined Stark effect phenomena as the wells are very thin, thus reducing the possibility of spatial separation of the electron and hole wave functions [23]. Low temperature PL measurements carried out on this sample and comparison of the results with that obtained from sample B1, a bulk AlGaIn film, provide a better understanding of this phenomena. Fig. 3(b) shows that with the reduction in temperature from RT to 4 K, the intensity of the MQW peak at 313 nm increases significantly. However, a new peak, unobserved at room temperature, appears at ~ 285 nm and dominates the spectra at low temperature. We attribute these phenomena to the presence of compositional inhomogeneities in the sample (i), which leads to a fluctuation of bandgap at the localized scale. At higher temperatures, the electron hole pairs created throughout the material travel to these localized minima, and recombine from there, creating a red-shifted peak. As the sample cools down, this transport is arrested leading to the recombination from the material as a whole, which generates the peak at the shorter wavelength that dominates the spectrum. Thus at 4 K, we identify the peak at 285 nm to be from the overall MQW structure, and the peak at 310 nm from localized minima. This peak at 285 nm is

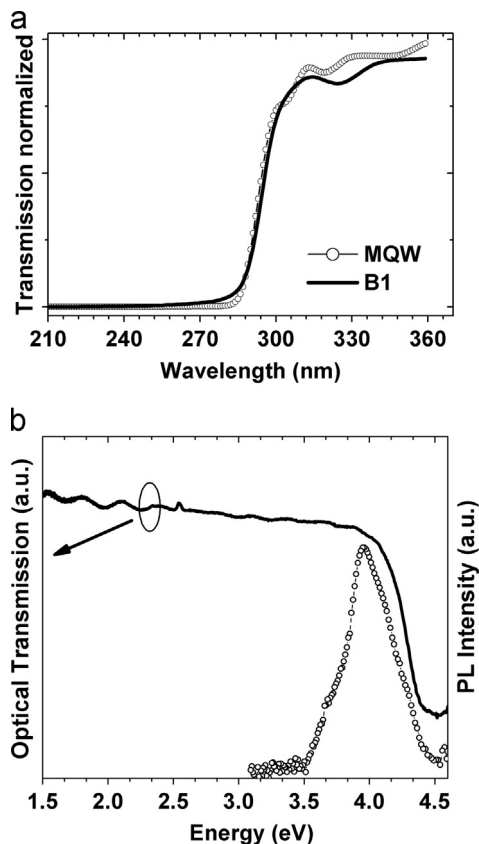


Fig. 2. (a) Comparison of optical transmission spectra obtained from MQW samples as shown in Fig. 1(a) and sample B1; (b) Room temperature PL and optical transmission spectra from B1.

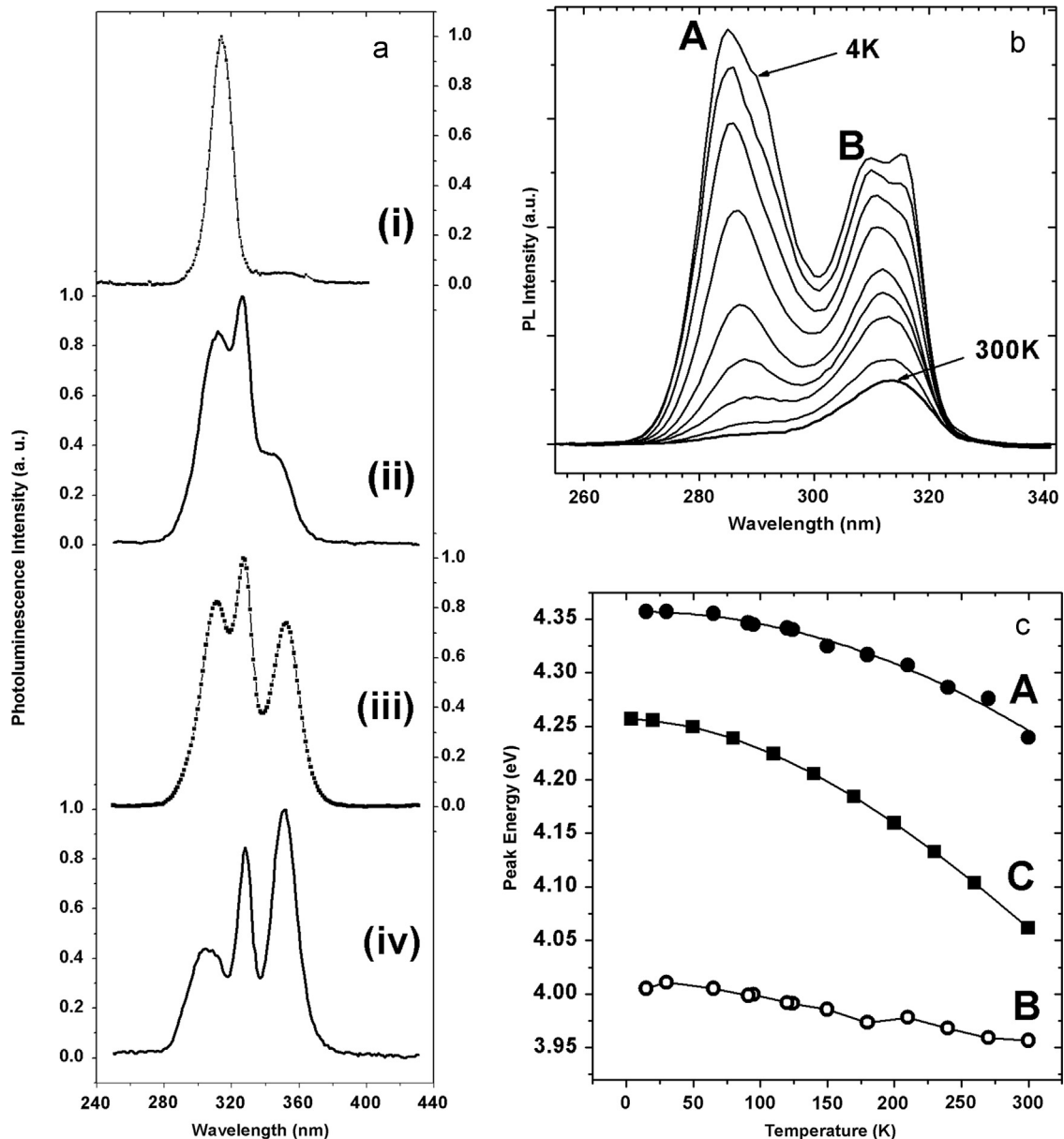


Fig. 3. (a) Room temperature PL spectra of AlGaIn MQW samples grown with increasing III/V flux ratio (i–iv); (b) Temperature dependent PL spectra of an AlGaIn MQW sample grown stoichiometrically; (c) Temperature dependence of the energy of PL peaks A and B of the AlGaIn MQW shown in Fig. 3(b) and bulk AlGaIn film B1 (C).

blue-shifted compared to the PL peak of the bulk sample as shown in Fig. 3(c), where the peak positions are plotted as a function of temperature. While the peak for both the bulk as well as the MQW (at 285 nm) shows strong blue-shift with reduction in temperature, the peak at 313 nm, the only one to be observed at room temperature, remains relatively invariant.

The observed data indicates that the room temperature PL observed from AlGaIn MQWs is strongly affected by the group III/V flux ratio, showing fundamental changes for relatively small variation in growth conditions. This is a concern that must be addressed for growth on to large substrates in industrial systems, which invariably show variations in growth conditions across the wafer, typically from the variation of substrate temperature across the surface. A deposition method that is relatively insensitive to these fluctuations is therefore of importance in the large scale development of UV LEDs, photodetectors and other devices. With that in mind, we have investigated the effect of Indium on the growth of AlGaIn MQWs, at a deposition temperature (800 °C) where the sticking coefficient of Indium is negligibly small, that is,

it does not incorporate into the material but affects the growth kinetics.

A series of MQW samples were grown under exactly the same conditions as that presented in Fig. 3, the only change being that a flux of Indium (1.88×10^{-7} T) was made incident during growth. PL measurements were carried out using similar conditions as in the previous MQW samples and the results are shown in Fig. 4. It can be observed that, with the introduction of Indium flux the nature of the PL spectra significantly changes and a single peak at 311 nm can be observed for all the samples grown under different group III to V flux ratios. Additionally, for samples grown under nearly stoichiometric conditions, a shoulder can be observed at shorter wavelengths, corresponding to the transition from the overall quantum well, as discussed previously. As the group III to group V flux ratio increases, weak secondary peaks are observed as in Fig. 3(a), but significantly lower in intensity.

The main peak, as shown in Fig. 4, is slightly blue-shifted compared to the sample grown without the Indium flux (313–315 nm vs 311 nm), but is still red-shifted compared to the

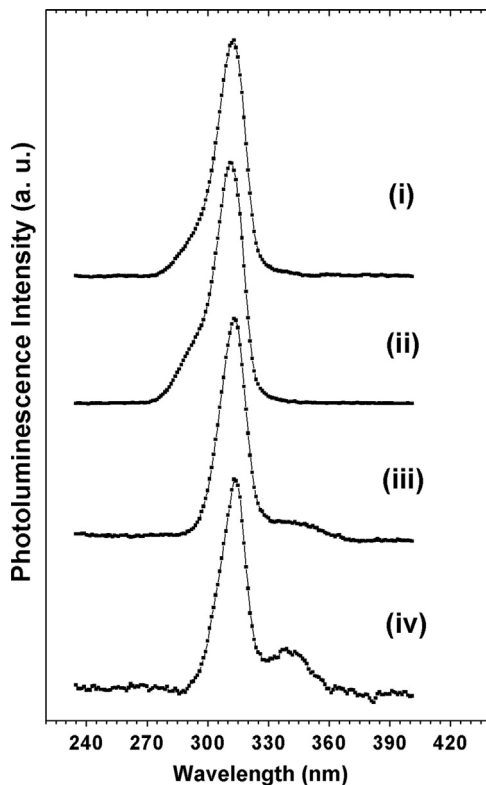


Fig. 4. Room temperature PL spectra of AlGaIn MQW samples grown with increasing III/V flux ratio (i–iv) in the presence of an Indium flux.

absorption edge. Therefore it is clear that potential fluctuations are still present in this film, however their amplitude has significantly reduced. In other words, the specific large fluctuations that gave rise to the low energy peaks (328 nm, 352 nm) for sample grown in excess group III without the Indium flux has been selectively removed. It is therefore clear that the presence of Indium negates the presence of large amplitude compositional inhomogeneities that arise from an excess group III flux. Since the incorporation of Indium at 800 °C is expected to be minimal, we believe that Indium modifies the surface diffusion properties of Ga and Al adatoms, specifically increasing the surface mobility of Ga [24–26]. This will reduce the possibility of formation of Ga-rich clusters in the metallic layer present on the growing surface, thus in turn reducing the amplitude of potential fluctuations. This eliminates the secondary low energy peaks that are observed (Fig. 3(a)) in samples where growth was carried out without the presence of Indium. The alloy fluctuations are in line with observations made by monochromatic cathodoluminescence mapping [26].

It remains to determine the luminescence efficiency of the various samples grown with and without the presence of Indium. Our observations show that the luminescence intensity for samples grown with or without Indium flux increases significantly with decrease in group III to group V ratio. However, at the same time the surface roughness also increases considerably, and since the brightness of the PL peak is dependent on various parameters, including the surface morphology which determines the light extraction; it is difficult to estimate IQE based only on room temperature measurements. The IQE can be calculated by the ratio of the PL intensity measured at room temperature and at 4 K, where the efficiency is expected to be ~100%. This however is difficult in the current measurements due to the presence of multiple peaks at low temperature.

4. Conclusions

In this paper we investigate the effect of growth kinetics on the optical properties of $\text{Al}_{0.35}\text{Ga}_{0.65}\text{N}/\text{Al}_{0.55}\text{Ga}_{0.45}\text{N}$ MQWs designed to emit ~290–300 nm. Even for otherwise structurally identical samples, small changes of group III/V ratio during deposition by PA-MBE drastically modify the nature of room temperature photoluminescence. The results indicate that the nature and magnitude of the fluctuations of the AlGaIn alloys show two distinct regimes depending on the deposition condition. Under moderate group III-rich conditions, the magnitude of the inhomogeneity is relatively small, and a single peak can be observed at room temperature. Higher group III, however, leads to an enhancement of the fluctuation amplitude, and multiple distinct peaks can be observed at significantly longer wavelengths. The use of Indium during growth reduces this effect by modifying the surface diffusion lengths of Ga and Al, and a single peak is obtained. The ability to control these phenomena and make it relatively insensitive to the group III to V flux ratio, and thus the substrate temperature, is important for improving the yield of device structures grown onto large substrates in commercial systems where temperature variation is inevitable across the wafer surface.

Acknowledgments

This work was partially funded by the Department of Information Technology (12(3)/2011-PDD), Government of India. The authors acknowledge Dr. T. K. Sharma of RRCAT Indore, India for XRD measurements. Pallabi Pramanik (09/028 (0823)/2010-EMR-I) Sayantani Sen (09/028 (0921)/2014-EMR-I) Alakananda Das (09/028 (0946)/2015-EMR-I) would like to acknowledge the Council of Scientific and Industrial Research (CSIR) Senior Research Fellowship scheme and Chirantan Singha would like to acknowledge the Department of Science and Technology (DST) INSPIRE fellowship (IF120257) for funding their respective work. Dr. Sridhara Rao would like to acknowledge the Director, DMRL/Group Head, EMG for the electron microscopy facilities.

References

- [1] M. Kneissl, T. Kolbe, C. Chua, V. Kueller, N. Lobo, J. Stellmach, A. Knauer, H. Rodriguez, S. Einfeldt, Z. Yang, N.M. Johnson, M. Weyers, *Semicond. Sci. Technol.* 26 (2011) 014036.
- [2] A. Bhattacharyya, T.D. Moustakas, L. Zhou, D.J. Smith, W. Hug, *Appl. Phys. Lett.* 94 (2009) 181907.
- [3] E.F. Pecora, W. Zhang, A. Yu Nikiforov, L. Zhou, D.J. Smith, J. Yin, R. Paiella, L. Dal Negro, T.D. Moustakas, *Appl. Phys. Lett.* 100 (2012) 061111.
- [4] G. Coli, K.K. Bajaj, J. Li, J.Y. Lin, H.X. Jiang, *Appl. Phys. Lett.* 80 (2002) 2907.
- [5] E. Iliopoulos, K.F. Ludwig Jr., T.D. Moustakas, S.N.G. Chu, *Appl. Phys. Lett.* 78 (2001) 463.
- [6] Y. Wang, A.S. Özcan, K.F. Ludwig Jr., A. Bhattacharyya, T.D. Moustakas, L. Zhou, D.J. Smith, *Appl. Phys. Lett.* 88 (2006) 181915.
- [7] E. Iliopoulos, T.D. Moustakas, *Appl. Phys. Lett.* 81 (2002) 295.
- [8] E. Monroy, B. Daudin, E. Bellet-Amalric, N. Gogneau, D. Jalabert, F. Enjalbert, J. Brault, J. Barjon, Le. Si Dang, *J. Appl. Phys.* 93 (2003) 1550.
- [9] F. Widmann, B. Daudin, G. Feuillet, N. Pelekanos, J.L. Rouvire, *Appl. Phys. Lett.* 73 (1998) 2642.
- [10] W.K. Fong, C.F. Zhu, B.H. Leung, C. Surya, B. Sundaravel, E.Z. Luo, J.B. Xu, I.H. Wilson, *Microelectron. Reliab.* 42 (2002) 1179.
- [11] E. Monroy, F. Guillot, B. Gayral, E. Bellet-Amalric, D. Jalabert, J.-M. Gérard, Le Si Dang, M. Tchernycheva, F.H. Julien, *J. Appl. Phys.* 99 (2006) 093513.
- [12] C. Kruse, S. Einfeldt, T. Böttcher, D. Hommel, *Appl. Phys. Lett.* 79 (2001) 3425.
- [13] Y. Chen, H. Wu, G. Yue, Z. Chen, Z. Zheng, Z. Wu, G. Wang, H. Jiang, *Appl. Phys. Express* 6 (2013) 041001.
- [14] C.T. Foxon, S.E. Hooper, T.S. Cheng, J.W. Orton, G.B. Ren, B. Ya Ber, A.V. Merkulov, S.V. Novikov, V.V. Tret'yakov, *Semicond. Sci. Technol.* 13 (1998) 1469.
- [15] C.F. Zhu, W.K. Fong, B.H. Leung, C.C. Cheng, C. Surya, B. Sundaravel, E.Z. Luo, J.B. Xu, I.H. Wilson, *Mat. Res. Soc. Symp. Proc.* 618 (2000) 153.
- [16] P.K. Kandaswamy, F. Guillot, E. Bellet-Amalric, E. Monroy, L. Nevou, M. Tchernycheva, A. Michon, F.H. Julien, E. Baumann, F.R. Giorgetta,

- D. Hofstetter, T. Remmele, M. Albrecht, S. Birner, Le Si Dang, *J. Appl. Phys.* 104 (2008) 093501.
- [17] T.D. Moustakas, T. Lei, R.J. Molnar, *Physica B* 185 (1993) 36.
- [18] G. Namkoong, E. Trybus, K.K. Lee, M. Moseley, W.A. Doolittle, D.C. Look, *Appl. Phys. Lett.* 93 (2008) 172112.
- [19] T.D. Moustakas, A. Bhattacharyya, *Phys. Status Solidi C* 9 (2012) 580.
- [20] A.V. Sampath, G.A. Garrett, R.W. Enck, P. Rotella Jr., H. Shen, M. Wraback, *Phys. Status Solidi C* 8 (2011) 1534.
- [21] C.J. Collins, A.V. Sampath, G.A. Garrett, W.L. Sarney, H. Shen, M. Wraback, A. Yu. Nikiforov, G.S. Cargill III, V. Dierolf, *Appl. Phys. Lett.* 86 (2005) 031916.
- [22] J. Neugebauer, T.K. Zywiets, M. Scheffler, J.E. Northrup, H. Chen, R.M. Feenstra, *Phys. Rev. Lett.* 90 (2003) 056101.
- [23] A. Bhattacharyya, I. Friel, S. Iyer, T.-C. Chen, W. Li, J. Cabalu, Y. Fedyunin, K.F. Ludwig Jr., T.D. Moustakas, H.-P. Maruska, D.W. Hill, J.J. Gallagher, M. C. Chou, B. Chai, *J. Cryst. Growth* 251 (2003) 487.
- [24] S. Keller, S. Heikman, I. Ben-Yaacov, L. Shen, S.P. DenBaars, U.K. Mishra, *Appl. Phys. Lett.* 79 (2001) 3449.
- [25] E. Monroy, B. Daudin, N. Gogneau, E. Bellet-Amalric, D. Jalabert, J. Brault, *Phys. Status Solidi (b)* 234 (2002) 726.
- [26] E.F. Pecora, W. Zhang, A. Yu Nikiforov, J. Yin, R. Paiella, L. Dal Negro, T.D. Moustakas, *J. Appl. Phys.* 113 (2013) 013106.