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Cite as: AIP Conference Proceedings **2115**, 030467 (2019); https://doi.org/10.1063/1.5113306

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Optical Characterization of InAlN/AlN/InGaN/GaN/ Sapphire High Electron Mobility Transistor Structures

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Abstract. Photoluminescence (PL) and Photoluminescence Excitation (PLE) measurements are performed on MOVPE grown InAlN/AlN/InGaN/GaN/Sapphire High Electron Mobility Transistor Structures. Features associated with InAlN barrier layer, InGaN channel layer and GaN buffer layer are clearly seen in the PL spectra. A blueshift of PL features with excitation intensity is observed which is claimed to be the signature of 2-dimensional electron gas formed in InGaN layer. By comparing the integrated intensity of PL peaks recorded at 7K and room temperature, it is confirmed that the optical quality of InGaN and GaN layers is superior when compared with that of InAlN barrier layer in the HEMT structure. It is also seen that the PLE features of InGaN channel layer are considerably red shifted with respect to PL features of the same layer. It is explained by considering the screening of polarization induced electric field causing a blue shift in case of PL measurements.

INTRODUCTION

The quest for high efficiency bright light emitting devices and high speed electronic devices has led to a substantial research on wide bandgap semiconductors. Group III nitrides, including AlN, GaN, InN, and their alloys, are favorable candidates for specific applications in ultra-violet, blue and green regions of the electromagnetic spectrum as light emitters and photodetectors. This is particularly evident from the revolution it brought to the field of solid-state lighting after the discovery of high luminous efficacy white light emitting diodes.[1] Gallium nitride, on the other hand, emerges as the most promising material for the design of high frequency and high power electronic devices employed in cellular communication, guided missiles, radars and solid-sate power amplifiers in satellite communication.[2,3] Out of all the possible III-V alloys, $In_xGa_{1-x}N$ alloy system is notably important owing to the flexibility to engineer its bandgap which allows for InGaN based devices to be operated over a very wide spectral range.[4] A remarkable insensitiveness against dislocations and high saturation velocity of electron in $In_xGa_{1-x}N$ alloy makes it a suitable choice in high electron mobility transistor (HEMT) applications.[5] In order to fully exploit these attributes, optimum incorporation of indium into the layer is very crucial.[6] However, several issues pertaining to the epitaxial growth of InGaN have stymied the potential of InGaN based HEMT devices. Large lattice mismatch in InN and GaN, phase segregation, compositional inhomogeneities are some of the major bottlenecks which have limited the operational capabilities of InGaN based devices.[7]

Recently, an enhancement in the carrier confinement due to InAlN/AlN/InGaN/GaN heterostructure has attracted a lot of attention for possible applications in next generation HEMT devices.[8] Strong spontaneous and piezoelectric polarization induced discontinuities at the InAlN/InGaN hetero-interface result in enormous charge carrier density due to the formation of 2-dimensional electron gas (2DEG) at the interface.[9] However, an in-depth investigation of 2DEG in nitride heterostructures is a challenging problem. Photoluminescence spectroscopy being a contactless technique can provide useful information about the formation of 2DEG in HEMT structures.[10] In this

DAE Solid State Physics Symposium 2018
AIP Conf. Proc. 2115, 030467-1–030467-4; https://doi.org/10.1063/1.5113306
Published by AIP Publishing. 978-0-7354-1851-6/$30.00

article, PL and PLE spectroscopy techniques are used to study the formation of 2DEG in InAlN/AlN/InGaN/GaN/Sapphire HEMT structure.

EXPERIMENTAL DETAILS

InAlN/AlN/InGaN/GaN/Sapphire HEMT structure used in this study is grown by Metal Organic Vapour Phase Epitaxy (MOVPE) technique. The schematic layer design of the HEMT structure is shown in Table 1.

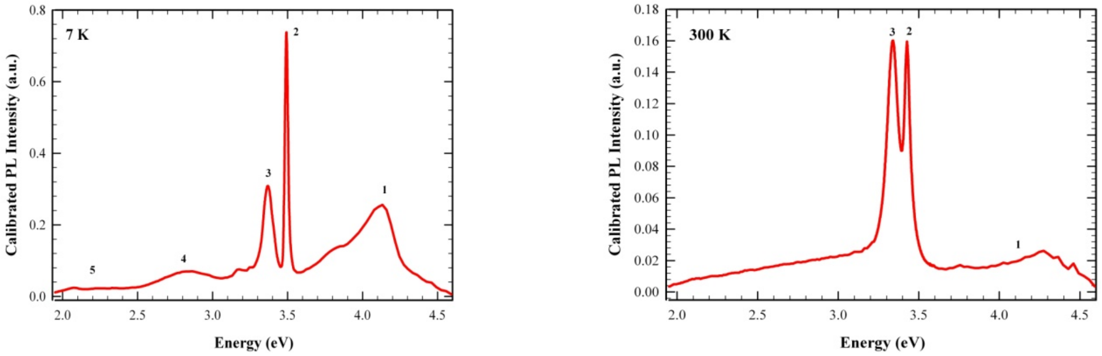
Table 1. Layer details of MOVPE grown HEMT structure

	Composition (x/y)	**Thickness**
$In_yAl_{1-y}N$	0.14	10 nm
AlN	-	2 nm
$In_xGa_{1-x}N$	0.04	12 nm
GaN	-	2 μm
AlN	-	50 nm
Sapphire		300 μm

Optical properties of the sample are probed using a combination of spectroscopy techniques viz. PL and PLE measurements. PL is excited with a DPSS UV laser operating at 266nm and collection is done through 0.55m monochromator using a photomultiplier tube detector. Conventional lock-in technique is employed wherein a chopper operating at 180Hz chops the incoming laser beam and thus serves as a reference signal for the lock-in measurements. For temperature dependent PL measurements, the sample is placed in a closed cycle helium cryostat where the sample temperature can be varied from 7K to room temperature. Excitation power dependent PL measurements are also performed with the help of a circularly variable neutral density filter. For PLE measurements, Xe arc lamp with 0.32m monochromator is used as the light source; emission from the sample is then dispersed with the help of a ¼ m monochromator and detected by a photomultiplier tube.

RESULTS AND DISCUSSION

Figure 1 (a) shows the PL spectrum of InAlN/AlN/InGaN/GaN/Sapphire HEMT structure recorded at 7 K. Three distinct peaks labeled as 1, 2 and 3 appear at 4.11, 3.49 and 3.36 eV respectively along with well-known blue luminescence (BL) band at ~2.8 eV (feature-4) and yellow luminescence (YL) band at ~2.1 eV (feature-5) in 7 K PL spectrum. From the peak energy, feature-2 is assigned as exciton recombination in GaN. However, peak energy of feature-1 and feature-3 does not match with the bandgap energy of InAlN (5.03 eV) and InGaN (3.31 eV) respectively. To identify the origin of these two features, PL measurements are also performed at room temperature and the spectrum is shown in Fig. 1 (b). At high temperatures, the non-radiative recombination centers get thermally activated; hence intensity of all the PL peaks is drastically reduced. The values of integrated PL intensity at two temperatures for the three peaks are summarized in Table 2. The fall in the integrated intensity of peaks 2 and 3 appear to be rather small. On the other hand, no traces of YL and BL are observed and the overall intensity of peak 1 falls significantly when temperature is raised to room temperature. A dramatic fall in the integrated intensity of peak 1 indicates that it might be associated with some defect feature in the InAlN barrier layer. However, temperature dependence of peak 1 over the range of 10-300K indicates that the particular peak is composed of three features and they keep appearing in different temperature range according to the respective activation energy (to be reported elsewhere).[11] This is the reason why a blue shift of peak 1 with rise in temperature is seen for InAlN layer. In reality, the features dominating the PL feature of InAlN layer at 7K and 300 K are different. These features can be associated with some defect levels in InAlN layer. However, InAlN layer is grown at a lower temperature of 790°C which is needed to avoid the degradation of InGaN layer. It makes the crystalline quality of InAlN to be very poor. It is therefore expected that the layer is composed of multiple domains consisting of large compositional fluctuations. This is expected due to a limited velocity of adatoms on the growing surface. More work on the assignment of features related to InAlN layer is in progress.



(a) (b)

FIGURE 1. Photoluminiscence spectra of InAlN/InGaN/GaN HEMT structure at (a) 7K and (b) 300K.

TABLE 2. Summary of the integrated PL intensity of three PL features marked in Fig. 1

Temperature (K)	Peak 1	Peak 2	Peak 3
7	0.066 ± 0.005	0.0162 ± 0.0002	0.0189 ± 0.0001
300	0.0073 ± 0.0003	0.0083 ± 0.0001	0.0114 ± 0.0001

In order to understand the origin of feature 3, excitation power dependent PL measurements are performed at 7 K and the spectra are plotted in Fig. 2. Evolution of the PL spectra as a function of the excitation power shows a monotonic rise in the PL intensity of all the PL features. It is observed that the peak at 2.2 eV (YL), 2.8 eV (BL) and 3.487 eV (GaN) shows no conspicuous shift with increasing excitation power. However, feature-3 is found to shift from 3.359 eV to 3.380 eV with one order increase in excitation intensity. Such a power dependent blueshift (~21meV) can be explained by invoking the concept of coulombic screening due to excess charge carriers which are injected by the laser beam. It is well established that polarization induced electric field causes tilt in the potential profile of both the channel and barrier regions which in turn causes a redshift in the transition energy. However, owing to the large population of photo-generated excess carriers at high excitation power, the polarization induced electric fields in InGaN channel layer is considerably screened which explains why the PL feature associated with InGaN layer blueshifts with excitation intensity. A blueshift of PL peak is a typical indentifying signature of 2DEG condensed near the interface in InGaN channel layer.

To gain further insight of the 2DEG features, PLE spectrum is recorded at 7 K for the yellow band at detection energy of 2.175 eV as shown in Fig. 3. Several sharp peaks appear above 3.45 eV which are related to the bound and free exciton transitions in GaN buffer layer. For the excitation photon energy below 3.3 eV, two peaks appear at 3.181 and 3.285 eV. Origin of these peaks can be attributed to the carrier excitation in the quantum confined energy levels in InGaN region. Excitation source, being the Xe-arc lamp, is not intense enough to produce a large number of excess photo-generated carriers as would be the case when the sample is excited with a DPSS-UV laser source. A large redshift due to quantum confined stark effect is therefore evitable for the excitation transitions in PLE measurements. Hence, the two peaks appearing at 3.181 and 3.285 eV are associated with the ground and excited states transitions of the 2DEG formed in InGaN layer.

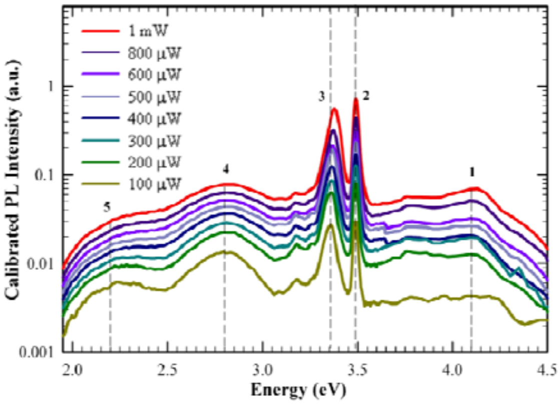


FIGURE 2. 7 K Excitation power dependent PL spectra of InAlN/InGaN/GaN HEMT structure.

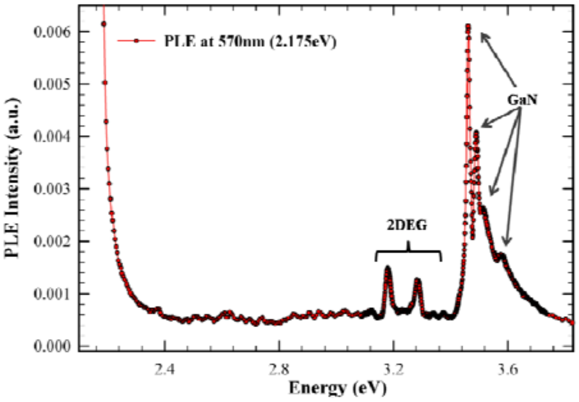


FIGURE 3. 7 K PLE spectra of the same sample recorded at 2.175 eV detection energy.

CONCLUSION

In conclusion, systematic PL and PLE measurements are performed on MOVPE grown InAlN/AlN/InGaN/GaN/Sapphire HEMT structures. Sharp PL peaks originating from different layers of HEMT structures are clearly recorded. A feature associated with 2DEG which is formed due to redistribution of charge carriers in the active region of HEMT structure is identified from excitation power dependent PL measurements. Signature of the same is further confirmed by performing PLE measurements where two features associated with the ground and excited states of 2DEG are clearly seen. However, they are found to be at relatively low energy when compared with the PL spectra of the same sample. The difference is explained by considering the photo-induced screening of the polarization induced electric field in InGaN channel layer.

ACKNOWLEDGMENTS

Authors acknowledge Mr. S. Porwal for his help in optical measurements, Dr V. K. Dixit, Dr. S. K. Khamari, Mr. A. Chatterjee, Ms. Geetanjali and all other members of SML for useful discussions, Dr Rama Chari, Associate Director, MSG, RRCAT, Dr P. A. Naik, Director, RRCAT, and Dr. R. K. Sharma, Director, SSPL, DRDO, New Delhi for their constant support and encouragement during the course of this work.

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