A Cathodoluminescence Study of InGaN/GaN Multiple Quantum Well and N Type GaN Structures

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ABSTRACT

A systematic study of the V-pits in 4 periods of InGaN/GaN multiple quantum well structure (MQW) and defects in n type GaN is investigated by room temperature cathodoluminescence. These MQWs were fabricated on a sapphire substrate by using metal organic chemical vapor deposition. The crystal quality is affected by the lattice mismatch between GaN and the sapphire substrates which results in the generation of a high threading dislocation (TD) density in GaN. It is believed that V-defects originate at the InGaN/GaN interface and may cause non-radiative recombination centers thus reducing the quantum efficiency of the structure. The optical emission from these defects is discussed in this paper. The density of V-defects observed in monochromatic CL images is compared to the TD density in n type GaN sample.

Keywords: cathodoluminescence (CL), multi quantum wells, threading dislocations, V-defects

1 INTRODUCTION

Significant progress has been achieved in the fabrication of high brightness light emitting diodes based on $In_{1-x}Ga_xN$/GaN multiple quantum wells (MQWs) grown by MOCVD. However, the crystal quality is affected by the lattice mismatch between GaN and the sapphire substrates. Advances have been made in the introduction of buffer layers but the there is still a high threading dislocation density in GaN, usually in the $10^9/cm^2$ range. The threading dislocation in GaN can also act as an initiation point for the formation of the V-defects observed in the InGaN/GaN MQW [1]. The V-defect or pit consists of a hexagonal inverted pyramid where the sidewalls are $(10\bar{1}1)$ planes. TEM analysis has shown evidence that the V-defects nucleate at TDs [2,3]. Several factors influencing the formation of V-pits at a TD have been reported, such as strain relief, growth kinetics of GaN crystal, masking effect of In atoms trapped at the TD core, In content in the QWs, and the number of wells in the structure [2,3].

The range in size of the V-defects is from 20 nm to several 1000 nm as observed in SEM images. The V-defects originate at the InGaN/GaN interface and may cause non-radiative recombination centers thus reducing the quantum efficiency of the structure. Cathodoluminescence technique can be employed for investigating the optical emission from these pits. Cathodoluminescence is the emission of light from a sample caused by bombardment of the sample with an energetic electron beam.. For a focused electron beam, the CL spatial resolution is mainly determined by the spreading of the incident electrons in the sample and the diffusion of the generated carriers before their radiative recombination [4,5]. There is experimental data demonstrating that the carrier diffusion under electron beam excitation does not significantly affect the image resolution [6]. The lateral spread of the electron beam is approximately equal to the range of the electron beam which is determined by the beam energy.

2 EXPERIMENTAL

A GaN buffer layer was grown on the sapphire substrate prior to the deposition of a 3um undoped GaN layer. This was followed by the deposition of a 1 um Si doped GaN layer. The 4 period $In_{0.12}$ $Ga_{0.88}$ N/GaN structure was then deposited at 810 ºC on the Si doped GaN layer. The well thickness is 2.7 nm and the barrier thickness is 10 nm. A schematic of the structural details of the InGaN/GaN MQW structure identified as MQW-1 is shown in Figure 1. The n type GaN sample identified as NGaN-1 was grown on a sapphire substrate using the same growth conditions used for the n-GaN layer of the MQW sample.

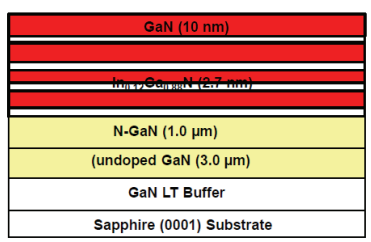
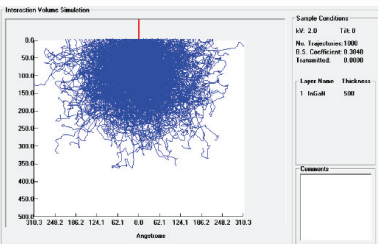


Figure.1: Structure of the MQW sample.

The cathodoluminescence (CL) studies were conducted using a Gatan MonoCL4 Elite system installed on a Carl Zeiss 1550 field emitter scanning electron microscope All CL measurements were performed at 300K and a focused electron beam was raster scanned over an area equal to 5.4 µm x 5.4 µm. The images and spectra for the MQW sample were acquired at several electron beam energies: 2, 3, 5, and 10 keV. The CCD detector and the 150 l/mm dispersion

grating were used to acquire the emission spectrum from a 5.4 µm x 5.4 µm area. The PMT detector was used for acquiring the monochromatic CL images with a band pass of 10 nm. The images and spectra for the n type GaN sample were acquired at 5 keV. The CL generation volume depends on the electron beam energy used during the analysis. Thus the increase in beam energy allows the measurement of the emission spectra from larger depths in the structure. Monte Carlo simulation of the electron beam in the InGaN/GaN structure as a function of beam energy was used to determine the size of the interaction volume and the results are shown in Figure 2. The corresponding electron beam current ranged from 0.026 nA at 2 keV to 0.15 nA at 10 keV.



Beam Energy (keV)	Penetration Depth (nm)
2	30
3	50
5	120
10	450

Figure 2: Monte Carlo simulation of a 2 keV electron beam in InGaN. The table shows the electron beam penetration depth in InGaN at various beam energies.

3 RESULTS AND DISCUSSION

One of the two objectives of this paper is to study the optical emission as a function of electron beam energy from the small pits found in MQW-1 sample. The second objective is to correlate the density of V-pits in the MQW to the density of threading dislocations found in the n-GaN/GaN structure.

3.1 CL Emission from MQW Structure

Figure 3 shows the parallel CCD spectrum acquired from sample MQW-1 at a beam energy of 2 keV. At this beam energy the depth of emission is approximately 30 nm which lies within the MQW layer. The CCD spectrum showed a peak at 452.2 nm associated with the near band edge emission of InGaN.

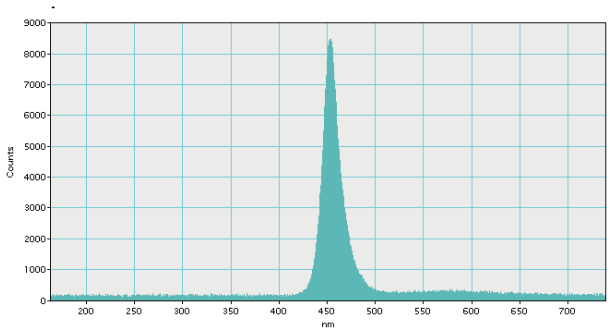


Figure.3: Parallel CCD spectrum of MQW-1 acquired at 2 keV.

It is observed that the near band edge emission peak for GaN was not detected even though there are several GaN barrier layers in the MQW structure. The corresponding SEM and cathodoluminescence monochromatic images are shown in Figure 4.

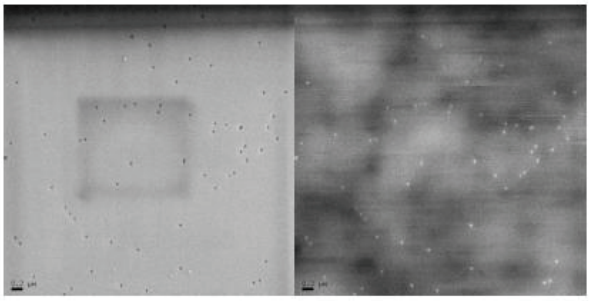


Figure 4: Plan-view SEM image and corresponding monochromatic CL image at 452.3 nm.

It is also observed that there exist bright spots in the CL image corresponding in location to the small V-pits in the SEM image. Also a darker circular area surrounds the bright spot in the CL image. The bright spot indicates that there is optical emission from InGaN within the pit. This is in contrast to experimental findings of others in which dark spots in CL image associated with the V-defects were found thus suggesting that there is no luminescence from the defects [7]. The InGaN monochromatic CL spot at the center of the V-pit is brighter than the image of the surrounding MQW structure. One possible explanation is that there an optical enhancement effect at the V-pit. Another possibility is that more wells are being stimulated in the pit than in the surrounding defect-free areas. At 2 keV the beam penetration depth is about 30 nm which means that half of the InGaN wells are being stimulated. However, if the GaN barrier layer in the pit is thinner then more wells are being stimulated by the incident electron beam. This explanation is supported by previous TEM studies conducted on cross-sections of V-pits that have shown thinner GaN barrier layers in the V-pits. The dark circular area surrounding the central bright spot may be due to non-radiative recombination centers. The results are in agreement with other work suggesting that V-defects may be associated with localized exciton recombination process [3]. However, the authors found out that the excitonic recombination from the V-defects give rise to a long wavelength shoulder in the CL spectra. Other authors have demonstrated that V-pits shift the CL emission to shorter wavelengths [8]. CL spectra with a band pass of 1 nm acquired from several V-pits on this sample showed that the near band edge emission peak from InGaN did not shift and no shoulder on either side of the peak was observed.

Additional SEM and monochromatic CL images were acquired at 3, 5, and 10 keV. The images are shown in Figure 6. The bright spots in the InGaN monochromatic images were observed at 3 and 5 keV; but not at 10 keV. The

dark circular area centered at the pit was observed at all beam energies.

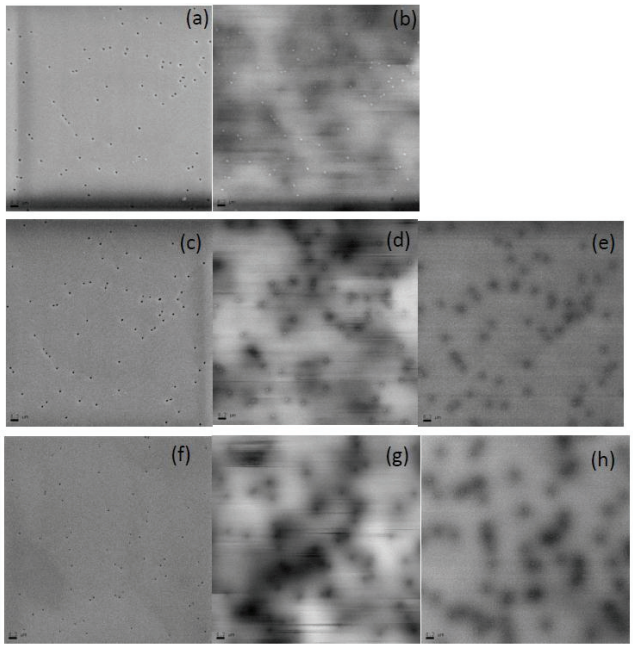


Figure 5: A set of plan-view SEM and monochromatic CL images. (a) and (b) represent the SEM and InGaN monochromatic images at 3 keV; (c) and (d) and (e) represent the SEM , InGaN and GaN monochromatic CL images at 5 keV; (f) and (g) and (h) represent the SEM, InGaN and GaN monochromatic CL images at 10 keV.

At 10 keV bright spots corresponding to the GaN near band edge emission were observed in the CL monochromatic image. No shift was observed in the emission wavelength of InGaN as a function of beam energy for the acquired spectra.

3.2 CL Emission from N Type GaN

The dark spots observed in CL images of GaN are associated with TDs that act as non-radiative recombination centers. CL data was compared to rocking curves acquired by HRXRD, a technique in which the FWHM of the (102) asymmetric peak is used to estimate the edge TD density in GaN films [9]. The TD density is proportional to the square of the FWHM (arcsec^2). The (102) rocking curve on three GaN samples was obtained by high resolution XRD performed on a PANalytical Diffractometer. The three GaN samples were also analyzed in the Gatan CL system using a focused electron beam at 5 keV. CL images were acquired and the density of dark spots was measured on each sample. A plot of the TD density measured by CL versus FWHM^2 is shown in Figure 10. The plot shows a linear relationship between the CL and XRD dislocation density measurements.

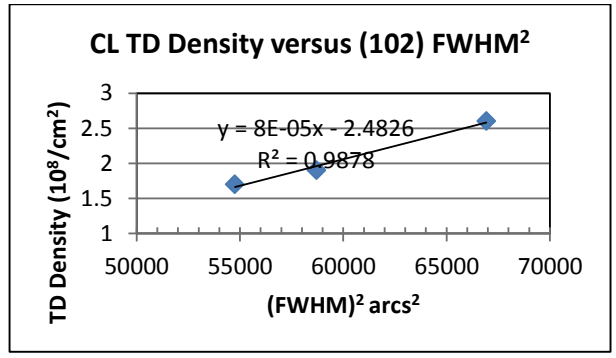


Figure 6: Plot of CL TD density versus XRD (102) FWHM^2

N-GaN-1 sample was first analyzed in the Bruker Icon AFM and then in the Gatan CL system using a focused electron beam at 5 keV. The CL images were acquired from a 5.4 µm x 5.4 µm area, identical to the area analyzed on the MQW sample. AFM, SEM, and monochromatic CL images were acquired and are shown in Figure 7.

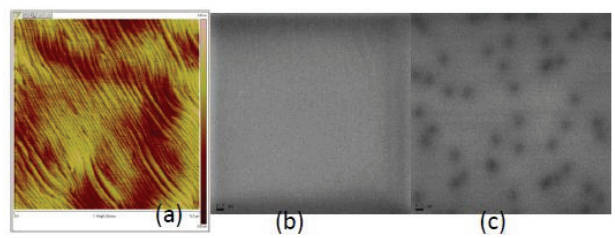


Figure 7: A set of images acquired from sample NGaN-1: (a) AFM image; (b) SEM image; and (c) monochromatic GaN CL image.

The AFM and SEM images showed a smooth surface with no pits. However, the monochromatic GaN CL image showed dark spots corresponding to non-radiative recombination centers, such as TDs. The measured defect (dark spot) density is about 1.8 x10^8/cm^2. This is comparable to the defect density measured in the MQW-1 sample of 2.4 x10^8/cm^2 as shown in Figure 8.

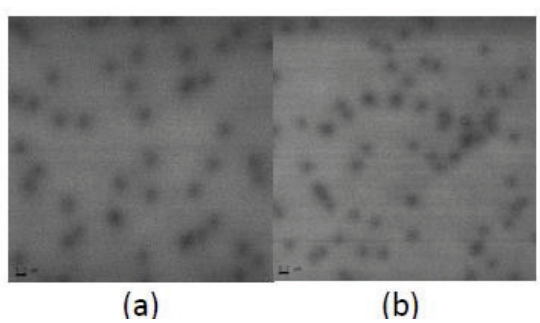


Figure 8: Comparison of monochromatic GaN CL images acquired at 5 keV: (a) NGaN-1; and (b) MQW-1.

The CL data suggest that the defects in the GaN layer act as the origin for the generation of V-pits in the subsequent growth of the InGaN/GaN MQW structure.

4 SUMMARY AND CONCLUSIONS

We have used spatially resolved room temperature CL to study the optical emission from a high PL brightness MQW structure and an n-type GaN. V-defects in the MQW sample were observed in SEM images as well as AFM. The size of the V-pits in the MQW is less than or equal to 100 mm. Electron beam energies of 2, 3, 5, and 10 keV were used to probe optical emission from different depths which also affects the CL spatial resolution. The monochromatic images associated with the near band edge emission of InGaN showed a dependence on the primary electron beam energy, hence penetration depth. The InGaN monochromatic images showed a bright spot surrounded by a dark circular area in the V-pits at 2 keV, 3 keV, and 5keV. The GaN monochromatic images showed a bright spot surrounded by a dark circular area in the V-pits at 5 keV and 10 keV. However, at 10 keV the dark circular area was observed with no InGaN bright spot at the center.

The results at lower energies suggest that there is either an optical enhancement effect at the V-pit or more wells are stimulated in the V-pit than in the surrounding defect-free area due to a difference in GaN barrier thickness. At the higher energies, the electron beam penetrates into the n-GaN layer thus stimulating emission from this layer at the expense of CL spatial resolution. The increase in spatial resolution at 10keV does not explain the lack of the InGaN bright spot at the pit. A bright spot corresponding to the pit is still observed for the near band edge emission from GaN. Further studies will be conducted to determine the origin of the CL emission bright spots within the small V-pits.

Spatially resolved CL was also used to study the optical emission from the n type GaN structure grown with the same conditions as the GaN template for the MQW structure. The SEM and AFM images showed that no pits were present at the surface. However, the monochromatic GaN CL image showed dark spots corresponding to non-radiative recombination centers. The measured defect (dark spot) density is about 1.8 $x10^8/cm^2$. This is comparable to the defect density measured in the MQW-1 sample of 2.4 $x10^8/cm^2$. The CL data suggest that the defects in the n type GaN layer act as the origin for the generation of V-pits in the subsequent growth of the InGaN/GaN MQW structure. The defects in N-GaN are non-radiative recombination centers that may affect the quantum efficiency of the MQW structure. Therefore, improvement in LED brightness can be achieved by reducing the defect density of GaN. This goal can be accomplished by developing new buffer layers or using suitable lattice matched substrates.

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