Effects of low energy e-beam irradiation on cathodoluminescence from GaN

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We present cathodoluminescence (CL) studies on low energy e-beam irradiated (LEEBI) metal-organic vapor phase epitaxy (MOVPE) grown GaN films. High intensity LEEBI has been reported to reduce the band-edge photoluminescence intensity of MOVPE grown GaN films. Here we observe similar reduction of band-edge CL intensity with increasing LEEBI dose. The irradiation damage is found to be concentrated in the LEEBI energy dissipation depth by CL depth profiling. We have previously attributed the LEEBI induced reduction of band-edge intensity to the activation of in-grown Ga-vacancies. Here we observe no increase in the relative intensity of defect related yellow or blue CL emission peaks in the LEEBI treated samples. This indicates that blue or yellow emission in undoped GaN is not related to in-grown Ga-vacancies.

1 Introduction

Gallium nitride (GaN) is commonly used in short wavelength LEDs, laser diodes and power transistors [1, 2]. It is a chemically hard material and considered to be well resistant to radiation [3]. Furthermore, GaN films can tolerate high voltages and current densities making them suitable for high power devices. However, degradation of optical quality of GaN films and devices has been observed after low energy e-beam irradiation (LEEBI) with energies in the 5–35 keV range [4–6]. This is surprising since the energy is well below the Frenkel pair generation thresholds of 150 and 500 keV for the N- and Ga-sublattices, respectively. Degradation has been caused by both LEEBI activation of Mg acceptors in p-doped GaN [6] and by cathodoluminescence (CL) measurements with high intensity and dose [4]. The damage formation is thought to involve activation of vacancies, defect migration or clustering of point defects.

We have recently reported on strong reduction of photoluminescence (PL) intensity of GaN/InGaN based QW structures and GaN films after high intensity LEEBI [7–9]. Furthermore, we have shown that the intensity reduction is induced by the activation of in-grown Ga-vacancies typical of metal–organic vapor phase epitaxy (MOVPE) grown GaN [7]. We believe that the in-grown Ga-vacancies are initially passivated by hydrogen and are activated by the breaking of hydrogen–Ga-vacancy complex by the LEEBI treatment.

In this paper we present CL studies on LEEBI treated GaN films. Compared to PL, CL allows measurements with considerably higher carrier densities. This is especially useful when characterizing defect states that are only weakly seen with PL measurements. CL allows also luminescence depth profiling by varying the e-beam acceleration voltage [10, 11]. In the LEEBI treated samples the band-edge CL intensity was found to decrease with increasing irradiation dose and the irradiation damage was found to be concentrated in the LEEBI energy dissipation depth by CL depth profiling. We observed no increase in the relative intensity of defect related yellow or blue CL emission peaks with increasing Ga-vacancy activation. This indicates that blue or yellow emission in undoped GaN is not related to Ga-vacancies.

2 Experimental

Thin film GaN samples were grown on c-plane sapphire (Al₂O₃) by MOVPE. The precursors for N and Ga were ammonia and trimethylgallium, respectively. In all the samples, a 3 μm thick undoped c-plane GaN layer was grown on sapphire with the common two-step method. The samples were exposed to an e-beam using an e-beam lithography tool. The exposure was performed by rapidly sweeping the e-beam on a specific area of the sample surface. The e-beam energy was 5 keV and the dose was varied between 0 and 160 μC cm⁻² by controlling the exposure...
time and the beam current. The e-beam spot size was approximately 2 nm in diameter and the corresponding momentary current density 0–130 kA cm$^{-2}$. CL measurements were performed at room temperature. The CL acceleration voltage was varied from 5 to 25 keV, and the probe current was kept constant at 25 nA. As we used a constant probe current, the CL excitation power density inside the GaN films changed between the measurements. When the CL acceleration voltage was increased from 5 to 25 keV [10, 11] the excitation power density decreased by approximately 65%.

3 Results Figure 1 shows room temperature CL spectra of GaN films irradiated with a 5 keV dose of 0, 40, and 160 $\mu$C cm$^{-2}$. Peaks from GaN band-edge (BE) luminescence at 362 nm, blue luminescence (BL) around 430 nm, and yellow luminescence (YL) around 550 nm can be identified from all the spectra. It can be seen from Fig. 1 that the intensity of all BE, BL, and YL peaks is reduced with increasing irradiation dose. The GaN BE luminescence is reduced by approximately 60% by an irradiation dose of 160 $\mu$C cm$^{-2}$. This is comparable to our previous results, where similar irradiation dose caused GaN band-edge PL intensity to drop 70%. Also in our previous work similar LEEBI treatment was not found to cause any surface contamination that could contribute to the reduction of PL intensity [7–9]. We observed no decrease in the CL signal during or the after the CL measurements, indicating that the CL probe energy was too small to cause further damage to the film [4].

An interesting feature seen in Fig. 1 is that the BL and YL intensities are reduced with approximately the same ratio as the GaN BE intensity. This indicates that the damage induced by the irradiation is not linked with the origins of either BL or YL. We have previously shown that the LEEBI induced reduction of BE PL intensity is linked to the activation of in-grown Ga-vacancies in MOVPE grown GaN [7]. The activation is most likely caused by breaking of hydrogen – in-grown Ga-vacancy complexes by the LEEBI treatment. In the LEEBI treated samples the Ga-vacancy concentration rose to approximately $2 \times 10^{17}$ cm$^{-3}$ from the detection limit of $1 \times 10^{16}$ cm$^{-3}$ by a 5 keV dose of 160 $\mu$C cm$^{-2}$. Keeping in mind the significant concentration of activated Ga-vacancies in the LEEBI treated samples, the behavior of YL and BL band intensities we observe here is in contradiction with previous reports that associate these bands with Ga-vacancies [12–14]. In general, the relation of Ga-vacancies and the YL and BL bands in undoped GaN is not clear [13, 15] as other sources, such as carbon impurities as the source of the YL [16, 17] and Zn as the source of the BL band [15] have also been proposed.

CL measurements allow depth profiling of luminescence intensity by varying the CL acceleration voltage [10]. The energy dissipation depth profile of an e-beam varies greatly with the acceleration voltage. This is shown in Fig. 2a, where the energy dissipation profiles of 5, 10, 15, 20, and 25 keV e-beam are plotted as a function of depth in GaN. The dissipation profiles were calculated with a cubic polynomial approximation [18] of the Bethe–Bloch method [19]. The CL generation is proportional to the energy dissipation of the

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**Figure 1** Room temperature CL spectra of GaN films irradiated with a 5 keV dose of 0, 40, and 160 $\mu$C cm$^{-2}$ measured with 10 keV CL acceleration voltage. BE, BL, and YL denote band-edge, blue, and yellow luminescence peaks, respectively.

**Figure 2** Simulated (a) energy dose and (b) self-absorption corrected BE luminescence generation profiles with CL acceleration voltages of 5–25 keV in GaN.
Low energy e-beam irradiation was shown to reduce the band-edge CL intensity of MOVPE grown GaN films. The irradiation damage was found to be concentrated in the energy dissipation depth of the e-beam by CL depth profiling. We observed no increase in the relative intensity of defect related yellow or blue CL emission peaks in the irradiated films. Our previous results link the irradiation induced reduction of intensity to the activation of in-grown Ga-vacancies in the material. This indicates that blue or yellow luminescence in undoped GaN are not related to Ga-vacancies.

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