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# Near-field cathodoluminescence studies on *n*-doped gallium nitride films

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Near-field cathodoluminescence (NFCL) has been used to characterize hydride vapor phase epitaxy grown *n*-GaN films. This technique can obtain high resolution luminescence images and perform local measurements of the diffusion length for minority carriers in different parts of the sample. NFCL contrast observed in round growth hillocks at the sample surface, with a diameter of less than 10  $\mu\text{m}$ , is compared with that observed by conventional cathodoluminescence in scanning electron microscope (CLSEM) techniques. In particular NFCL images reveal features not detected by CLSEM which is explained by the fact that under near field conditions the signal arises from a depth of only several tens of nanometers and is then directly related to the surface hillocks. Diffusion lengths of about 0.4 and 4  $\mu\text{m}$  have been found for the holes in different regions of the samples at room temperature. The order of magnitude of these minority carriers diffusion lengths is in good agreement with previous measurements performed at different GaN samples with other techniques. The NFCL contrast and the differences in the measured diffusion lengths are discussed and explained by variations in local trap concentrations. © 2002 American Institute of Physics. [DOI: 10.1063/1.1487440]

## INTRODUCTION

Due to the increasing interest in the GaN-based materials for applications in blue light emitting diodes, lasers, or high power and high temperature devices, the luminescence properties of GaN have been often investigated in the past years. One of the techniques used to perform these investigations is cathodoluminescence (CL) in the scanning electron microscope (SEM) which has been useful to obtain spatial resolved luminescence information, allowing to correlate extended and point defects with the different luminescence bands, e.g., Refs. 1–6. In this work near field CL (NFCL) is applied to characterize *n*-type gallium nitride films. With this technique a higher spatial resolution than with the standard CLSEM technique is normally achieved. The NFCL resolution depends mainly on the optical fiber aperture rather than on the signal generation volume in the material.<sup>7–9</sup> The NFCL technique is more surface-sensitive, from a surface layer of the order of tens of nanometers, than standard CL. This is due to the nonpropagating nature of the waves which are detected when measuring in the near field regime, where there is an exponential decrease of the signal.<sup>10</sup> The diffusion length of the minority carriers (holes) of the sample was also measured by means of the NFCL signal.

## EXPERIMENT

The samples under investigation were hydride vapor phase epitaxy GaN films grown on (0001) sapphire. The films consisted of an 8  $\mu\text{m}$  thick GaN buffer layer and two 2  $\mu\text{m}$  thick GaN epilayers. The lower layers were undoped and the upper one was Si doped with a carrier concentration of  $10^{18} \text{ cm}^{-3}$ .

The NFCL system used for this work was similar to the one described in Ref. 8. A scanning probe microscope (SPM), with a scanning near-field optical microscopy (SNOM) head, was fixed onto the sample mount of a Cam-Scan S2 SEM. The tip was a glass fiber tapered by heat pulling and then covered with aluminum, leaving the very end uncoated by cutting about 10 nm of the tip end by means of focused ion beams. The tip-sample separation was controlled with subnanometer accuracy by using the method introduced in Ref. 11. The CL signal, generated in the sample by the SEM electron beam, was collected in the near-field regime with the fiber tip and measured with a Hamamatsu extended S20 photomultiplier. The measurements were performed by scanning the sample under static tip and electron beam (probe scanning mode) or by locating the tip at a position while scanning the electron beam (beam scanning mode) as described in Ref. 8. All measurements were carried out at room temperature. The acceleration voltage used was 15 kV for the probe scanning mode and 15, 20, or 25 kV for

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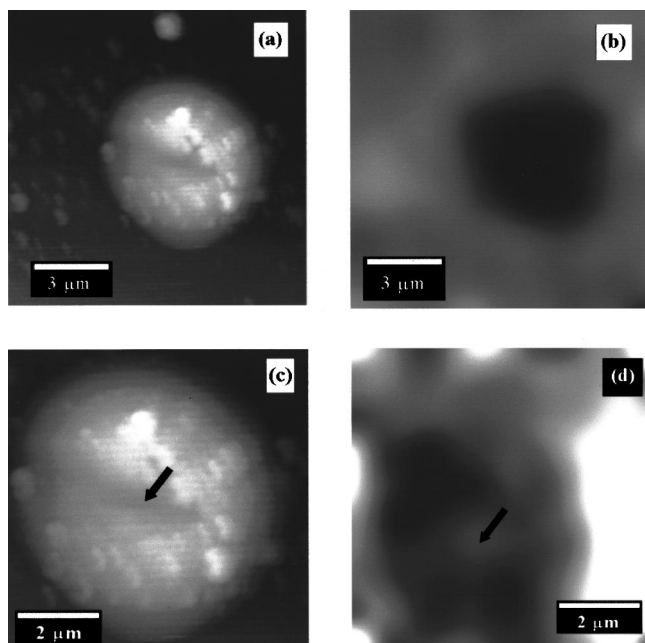


FIG. 1. (a) Topography of a hillock, (b) corresponding panchromatic NFCL image, (c) higher magnification topography image of the hillock, and (d) NFCL image of the area shown in (c).

the beam scanning mode. The study was made on the upper surface of the sample.

### RESULTS AND DISCUSSION

SEM secondary electron images of the sample surface show, as previously reported,<sup>6</sup> a distribution of round hillocks of a size of about 5 μm in a smooth background. Most of the hillocks show an almost circular shape and in some of them a not well defined hexagonal shape is observed. The hexagonal shape, often reported in microscopic observations of the surface of GaN films, is here observed in the relatively few hillocks present with sizes of about 40 μm or higher. The origin of these features has been studied previously, e.g., Refs. 12 and 13 and they are thought to be due to a core of inversion domain or to nanopipes which are the open cores of screw dislocations.

It has been found in a previous SEMCL study of these structures<sup>6</sup> that the small hillocks, with diameters in the range of few microns, do not show CL contrast in the panchromatic imaging mode relative to the film background. On the contrary, the hillocks with sizes of several tens of microns showed a marked CL contrast revealing a particular recombination behavior at the boundary or the center of the hillocks.

Figure 1(a) shows the topography image of one of the small hillocks with a diameter and height of about 7 μm and 200 nm, respectively. Figure 1(b) shows the corresponding panchromatic NFCL image. All the NFCL images were smoothed with a Gaussian filter due to the low signal-to-noise ratio. The hillock shows a well defined NFCL dark contrast that differs from the lack of contrast observed from standard CL measurements for hillocks of the same size. The difference in the contrast from the small hillock in standard CL and the NFCL can be explained by the near-field detec-

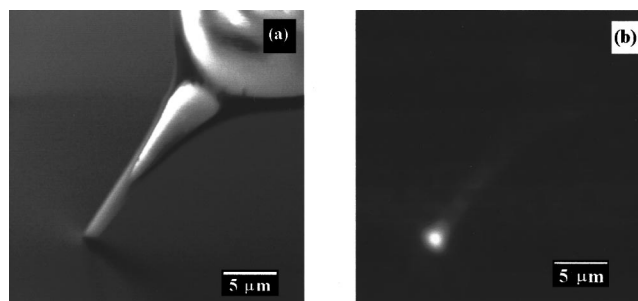


FIG. 2. (a) Secondary electron image of the tip on the sample, and (b) corresponding NFCL image.

tion conditions. In the near-field regime the detection of evanescent waves that have an exponential decay behavior is just from a few tens of nanometers in depth (Ref. 10). The depth investigated in standard CL can be considered to be around the electron range, which in our experiment is 1.2 μm. Thus if the height of the hillock is about 200 nm and its structure is not expanded into the material below it, the SEMCL signal from the hillock would be overcome by the luminescence detected from the matrix, while under NFCL conditions the signal arises mostly from the hillock volume.

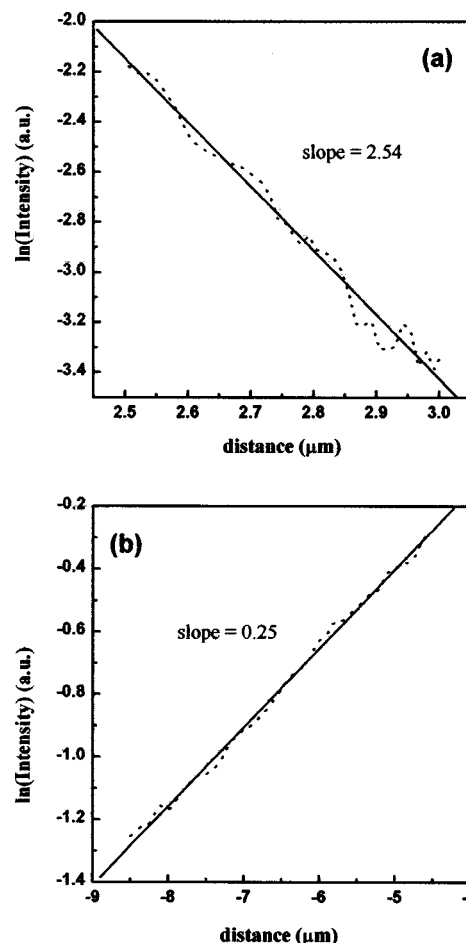


FIG. 3. (a) Semilogarithmic plot of the NFCL intensity vs distance from Fig. 2(b). (b) Semilogarithmic plot obtained at another area within the same n-GaN sample.

The dark NFCL contrast of the hillocks, as seen in Fig. 1, shows the existence of a different defect structure, or different nature of recombination centers, in the hillock than in the matrix. The CL spectra of the films show<sup>6</sup> that the main luminescence band is the broad complex band peaked at about 550 nm that has been often reported for GaN samples and different kinds of defects. Monochromatic SEMCL measurements of large hillocks have shown that in the main part of the hillock, excluding the boundary and the center, there is an enhancement of a weak emission at 430 nm. The fact that the hillocks appear dark in the NFCL image indicates that the dominant 550 nm defect band is markedly reduced in the hillock volume leading to a reduced total luminescence, even although the 430 nm band could be enhanced in this region.

A NFCL image at higher magnification of the hillock shows that the dark central part of Fig. 1(b) is not homogeneous but presents a brighter region in the center [Fig. 1(d)]. The corresponding topography image shows a hole in the center [Fig. 1(c)]. This result agrees with CL observations<sup>1,6</sup> of large hillocks in which an enhanced yellow luminescence was detected in the center. This emission was attributed to some stacking defect.

Figure 2 shows the SE and the NFCL images of an area of the sample recorded in the beam scanning mode with the SNOM probe located at a position. From this image the profile of the NFCL intensity as a function of the distance to the tip was recorded. The profile shows approximately an exponential decrease of the signal [Fig. 3(a)]. From the corresponding semilogarithmic plot and considering that the diffusion length of the minority carriers is inversely proportional to the slope (Ref. 8) a diffusion length of about  $0.4 \mu\text{m}$  was estimated. From similar plots of another region of the sample showing a much higher NFCL intensity a diffusion length of about  $4 \mu\text{m}$  was calculated [Fig. 3(b)]. We have, therefore, obtained different diffusion lengths in different areas in the sample. A smaller diffusion length has been obtained from the region showing lower NFCL intensity. It is known<sup>4</sup> that some defects producing a decrease in the diffusion length of minority carriers also create nonradiative paths for the recombination of electron-hole pairs.

## CONCLUSIONS

NFCL has been used to study growth hillocks in GaN:Si epitaxial films. With this technique, that uses the SNOM mode, the luminescence signal from a region close to the sample surface is detected without the influence of the film matrix. For this reason the luminescence of slightly protruding surface features, as the growth hillocks, can be investigated. Round shaped hillocks of a few microns show a dark contrast relative to the film background. This is attributed to a lower intensity of the yellow band in the volume of the hillock. From NFCL measurements in the beam scanning mode, the minority carrier diffusion lengths in different sample regions was estimated.

## ACKNOWLEDGMENT

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