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Cathodoluminescence Hyperspectral Imaging of Nitride Semiconductors: Introducing New Variables.

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Cathodoluminescence (CL) hyperspectral imaging—the acquisition of a full optical emission spectrum at each pixel of an image—has become firmly established as a measurement mode in scanning electron microscopy (SEM) [1]. CL is sensitive to the structural, compositional and electrical properties of a sample, and the inherent *multimode* nature of SEM makes it possible to combine CL with other techniques which are also sensitive to one or more of these properties. For example, combining CL hyperspectral imaging with simultaneous X-ray microanalysis has been used to probe composition variations within semiconductors [2] and minerals [3]. In this work we present recent results combining CL hyperspectral imaging with other SEM modes, and also demonstrate the benefits of introducing additional measurement parameters, such as sample applied bias and microscope chamber pressure.

Structural defects are central in determining the performance of electrical and optical devices based on III-nitride semiconductors. To better understand the effect of threading dislocations on carrier recombination in such materials, we have carried out CL imaging together with electron channeling contrast imaging (ECCI), which is sensitive to the lattice distortions associated with such defects. Using this combination of techniques we have shown that both pure edge dislocations and mixed (combination of edge + screw) dislocations act as nonradiative recombination centers in GaN epilayers [4].

Since CL provides information only about *radiative* recombination, it needs to be coupled with other techniques to provide a fuller picture of the different carrier loss mechanisms which limit device performance, an objective we achieved by measuring CL together with electron beam induced current (EBIC). This signal originates within the junction of an electrically contacted device (measured via an external circuit) and is dependent on the *total (i.e.* radiative + nonradiative) recombination. By carrying out both techniques simultaneously on $In_xGa_{1-x}N$/GaN light-emitting diodes (LEDs), we have separated out nonradiative recombination from other loss mechanisms, such as light extraction or electrical contacting issues [5].

These CL/EBIC measurements on contacted LEDs have opened up the possibility of introducing an additional variable into CL imaging: applied bias voltage. Figure 1 shows an example of such measurements for an InGaN/GaN LED device. This capability allows the emission to be imaged under conditions closer to those of a device in normal operation. It also allows us—by imaging at several bias values—to differentiate between the drift and diffusion components of the current, and to probe the influence of the quantum-confined Stark effect in the active region of the LED. Furthermore, comparison with electroluminescence (EL) hyperspectral images yields additional information: for example, in some areas of the LED we see correlations between contrast features in EL and EBIC images which are not present in the CL, implying that they originate in the diode junction or contacts rather than in the active layer itself [5].

Finally, we have demonstrated CL hyperspectral imaging in an *environmental* SEM operating with a variable pressure of water vapor. This has allowed us to measure for the first time such insulating samples as undoped wide-bandgap semiconductors and mineralogical specimens without the necessity to coat them with gold or carbon. This reduces sample charging while having a minimal effect on either the intensity or resolution of the measured luminescence, and without introducing additional background light. Figure 2 shows how this technique allows imaging of an undoped $Al_xGa_{1-x}N$ epilayer, which was otherwise not possible due to charging-related image drift [6, 7].

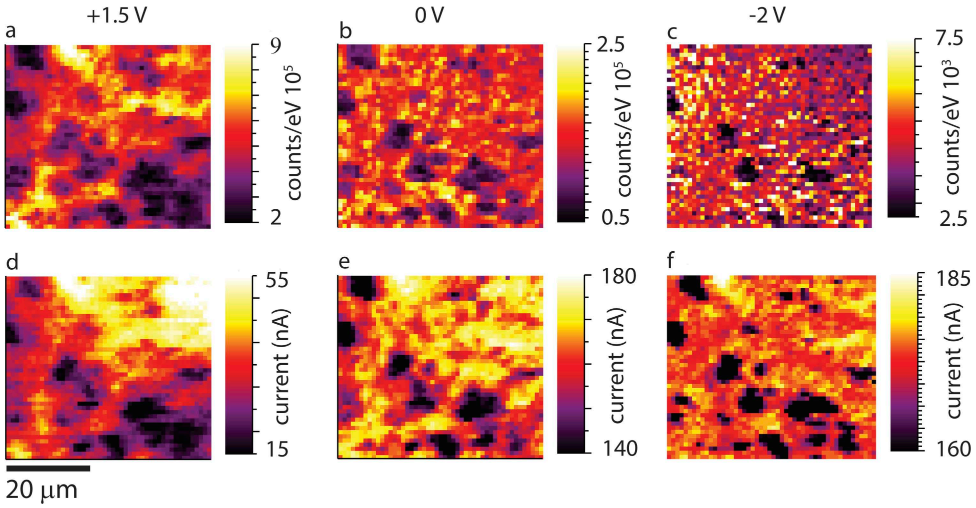

Figure 1. CL intensity (a–c) and EBIC (d–f) maps acquired simultaneously from an InGaN/GaN LED under varying bias. Areas showing as dark in both techniques unambiguously indicate nonradiative recombination.

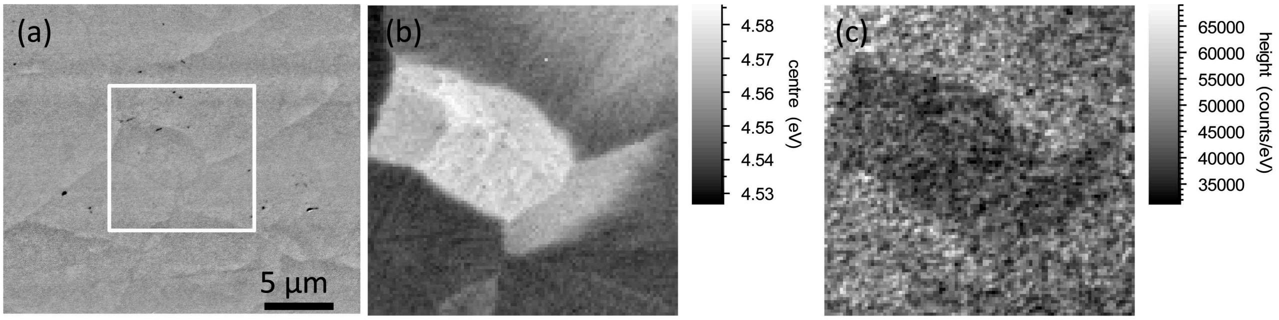

Figure 2. Measuring a non-conducting sample: (a) secondary electron, (b) CL peak energy, and (c) CL intensity images from an undoped $Al_{0.47}Ga_{0.53}N$ epilayer with 0.1 mbar of H_2O in the SEM chamber.

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