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Two-photon photoluminescence and current images of bulk GaN and InGaN green LEDs

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GaN and related materials have attracted a great deal of interest in recent years for its applications in light emitters/detectors in the green to ultraviolet (UV) wavelength regions [1]. Even though GaN based laser diodes and light emitting diodes (LEDs) are now available in the market, the fundamental properties of GaN are still far from fully understood, especially the defect formation and distribution mechanisms of GaN and their relationship with the luminescence. Our recent studies shows that GaN possesses large two-photon absorption coefficients, even at infrared (IR) wavelength close to midgap energy [2]. This indicates that two photon confocal photoluminescence images and two-photon optical-beam-induced-current (TP-OBIC) microscopy can be applied on the GaN studies and imaging.

Confocal laser scanning microscopy provides a significant improvement in axial resolution over conventional epi-fluorescence microscopy by eliminating out-of-focus fluorescence using a spatial filter in the form of a confocal aperture. Combining two-photon induced fluorescence with laser scanning microscopy, Denk *et al.* [3] achieved high axial/depth discrimination even without a confocal aperture in front of the photodetector, due to the quadratic dependence of the two photon absorption on the laser intensity. Strong fluorescence is only induced in the vicinity of the focal point. The background scattering light and autofluorescence of the sample in the two-photon-excited system is also lower. The use of infrared wavelength leads to a deeper penetration depth in most materials, providing an opportunity to image inside samples.

Our experiments were performed with an inverted microscope and a galvano-mirror based scanning system. A Kerr-lens-modelocked Ti:sapphire laser provided IR laser pulses of 150 fs tunable between 700-800 nm. Band-pass filters were used to select specific spectral band for photoluminescence (PL) image. Figures 1(a) and 1(b) show typical two-photon PL images taken from the edge of a Hall measurement sample with two circle-shaped defects. The excitation wavelength was 720 nm. A 10X objective was employed to focus the laser beam onto the GaN layer. The valence band carriers was photoexcited into conduction band by strong two-photon absorption and the subsequent luminescence was collected by the same microscope objective, separated from the input laser beam by a dichroic beamsplitter, and directed into a photomultiplier (PMT) tube. Due to the large wavelength difference between the IR excitation pulse and the PL light, the luminescent photons can be easily separated from the pump laser beam. Combining with the strong two-photon absorption in GaN, large signal-to-noise ratio can thus be easily achieved. Also due to the IR excitation wavelength, no UV optics are required in the excitation set-up, except for the necessary PL measurements. Figure 1(a) shows the image taken with a 365-nm wavelength interference filter with a 10-nm bandwidth in front of the PMT tube, corresponding to the GaN band-to-band luminescence wavelength at room temperature. Figure 1(b) shows the image taken with a 550-650 nm wavelength bandpass filter, corresponding to the wavelength of the below-bandgap yellow luminescence. Figure 1(c) shows an reference image taken with the transmitted 720-nm beam through the sample. Figure 1(a) indicates excellent lateral uniformity in the measured sample except on the areas around these two circle-shaped defects. It's interesting to note that the area emitting weak bandgap luminescence corresponds to the area emitting strong yellow luminescence. The yellow photoluminescence of GaN has been though to compete with the edge photoluminescence. Such competition, however, has never been conclusively demonstrated [4].

Figure 2 shows example two-photon PL and TP-OBIC images of a green LED dice with a sapphire substrate. The IR laser beam was focused through the sapphire substrate at the InGaN active layer with a wavelength of 760 nm to avoid any possible two-photon excitation in n-doped and p-doped GaN layers. The PL images were taken with a green bandpass filter while a high-sensitive current amplifier was used to detect the photocurrent (PC) in TP-OBIC images. The most pronounced features in the PL and PC images are the bright spots covering all over the LED. These spots have the sizes ranging from 5 μm to less than the resolution of the objective, which is on the order of 1.3 μm. The locations of the bright spots on PL and TP-OBIC images show strong correlation, indicating the same physical origin. Similar bright spots were also observed in electro-luminescence images. Since we have avoided any excitation in the p-doped layer, these bright spots should not originate from the p-doped layer. Possible mechanisms include InGaN island formation due to the strain relaxation between InGaN and GaN layers and

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composition inhomogeneity and immiscibility of the InGaN ternary alloy layer [5]. More detailed studies will be presented.

We have also performed single-photon confocal PL images. Two-photon excitation clearly exhibits better spatial resolution and reveals more interesting features not observed before. With two-photon excitation technique that is much less susceptible to scattering and absorption, LED devices with multilayered heterostructure can thus be easily imaged and studied without much sample preparation. This work is sponsored by National Science Council of Taiwan, R.O.C. under Grant No. 892112-M-002-003.

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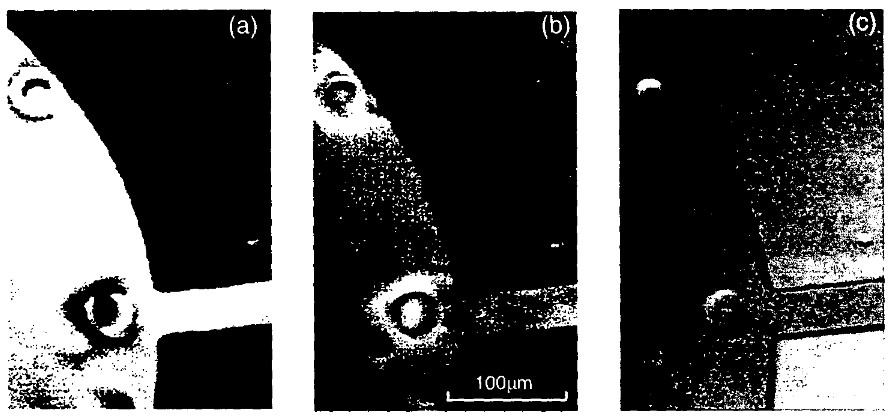

Figure 1. Two-photon confocal photoluminescence images of a GaN Hall measurement sample (a) with a 365 nm filter, (b) with a 550-650 nm bandpass filter. (c) Comparison transmission image. The excitation wavelength was 720 nm.

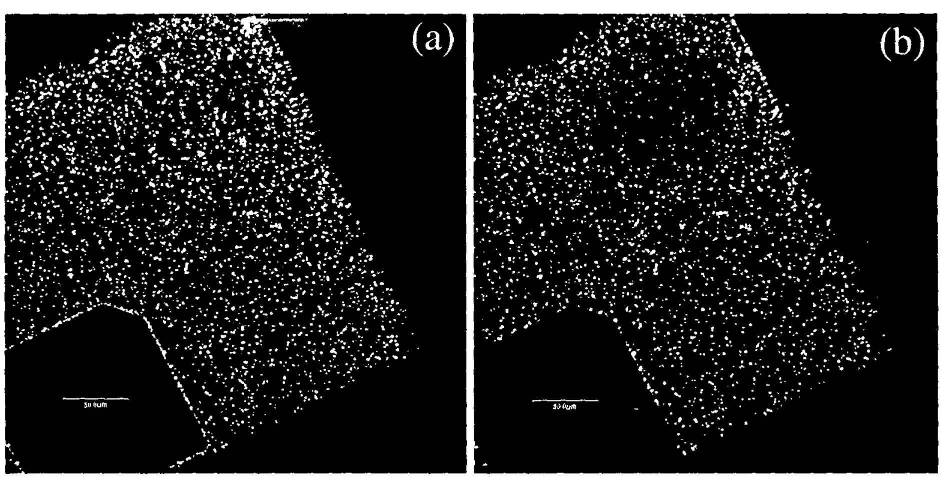

Figure 2. (a) Two-photon confocal PL image and (b) two-photon OBIC image of a green LED. The excitation wavelength was 760 nm. A green filter was used in the PL image.