Stimulated emission from InGaN-based resonant cavity light emitting diodes

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ABSTRACT

We have fabricated InGaN-based resonant cavity light-emitting diodes using a method of flip-chip bonding onto a heat-sink, substrate removal, and the incorporation of 2 high-reflectivity (>99%) dielectric mirrors as well as a transparent indium tin oxide contact. The devices exhibit non-linear light-versus-current (L-I) characteristics as well as evolution of cavity modes indicating stimulated emission. The modes are 0.8 nm in width, corresponding to a cavity Q of >510.

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There is no questioning the emerging relevance of GaN-based blue and violet optoelectronic devices in applications such as optical storage, displays, medicine, and lighting. Many of these applications could benefit from a compact, highly directional light source, such as a resonant cavity LED (RCLED) or a vertical cavity surface emitting laser (VCSEL). These devices also yield the added advantages of low-cost arrays and on-wafer testing not afforded by conventional edge-emitting lasers. Recently, there have been some encouraging developments in the fabrication of these vertical structures, such as the demonstration of optically pumped vertical lasers[1,2] and RCLEDs[3], although device performance of the latter still seems to be stymied by failure at low current densities. In this letter we demonstrate both stimulated emission and high current capacity in InGaN-based RCLEDs.

The epitaxial structures were grown by metalorganic chemical vapor deposition (MOCVD) on sapphire substrates and consisted of 5 µm GaN:Si, ten 4 nm $In_{0.1}GaN$ wells separated by 8 nm $In_{0.03}GaN$:Si barriers, a 20 nm $Al_{0.2}GaN$ electron-barrier layer, and 500 nm of GaN:Mg. The devices (Fig. 1) were fabricated to have two top contacts: Ti/Al as an n-contact, and indium tin oxide (ITO) as a p-contact. The use of ITO as a transparent, current spreading contact to p-GaN was explored previously.[4] The ITO was deposited by DC magnetron sputtering in an oxygen ambient from an ITO target. The contacts were annealed at 500°C for 3 minutes to achieve both transparency and conductivity. A dielectric layer was used underneath the ITO contact to define the device apertures, with a diameter of 10 µm. To form the device cavity we incorporated two dielectric DBRs. While several groups have reported reflectivities in excess of 98% using epitaxial mirror growth[5,6], dielectric mirrors still provide an advantage over epitaxial stacks in terms of ease of deposition, higher structural quality (less strain induced cracking), smaller overall thickness, and a wider stopband. The DBRs consisted of 11.5 periods of Ta_2O_5/SiO_2 deposited via electron beam evaporation in an oxygen ambient at 225°C and room temperature for the first and second stacks, respectively. In-situ optical monitoring was used to control the center wavelength of the stack. Each mirror was assessed using a calibration standard in a Perkin-Elmer Lambda-9 spectrophotometer, and found to have a reflectivity in excess of 99.5% over a wavelength range of approximately 70 nm, centered at around 420 nm (Fig. 2).

Following the deposition of the first mirror, the devices were flip-chip bonded to an AlN patterned submount/heat-sink. The sapphire substrate was then removed by laser assisted debonding with a single λ=248 nm, 19 nsec, 565 mJ/cm^2 KrF laser pulse with a 1.6 mm diameter. As discussed previously, the generation of pressure during debonding must be minimized in order to achieve damage free liftoff for thin ($h_f < 5$ µm) devices.[7] Special submount patterns were therefore used to channel cracks away from the devices. After debonding, the samples were immersed in dilute HCl in order to remove gallium droplets produced during irradiation. In order to minimize light scattering at the debonded surface, the devices were polished using colloidal silica and a soft pad. Atomic force microscope (AFM) scans of the polished surface indicated r.m.s. roughness values of around 0.4 nm over a 10 x 10 µm area. We chose this method over dry etching for the improved smoothness and the reduced potential for subsurface damage.[8] Finally, the second DBR was deposited on the polished face to complete the cavity.

The devices were pulse-tested at room temperature, applying voltage pulses ranging from 50 to 500 nsec at both 5 and 10 kHz. Light emission from the devices was uniform over the aperture area. An intensity-versus-current plot (L-I) for a 10 µm diameter aperture device is shown in Fig. 3, taken via a fiber-optic probe into a photomultiplier tube. There is a clear change in the slope of the curve at about 17 mA (22 kA/cm^2), indicating the presence of a stimulated emission component – i.e. amplified spontaneous emission. A second bend in the curve is observed at higher currents (>27 mA) – probably due to device heating.

Emission from the devices was centered between 400 and 410 nm. A pulsed spectrum for a 10 µm aperture device is shown in Fig. 4, taken with a CVI SM240 integrating diode array spectrometer. Cavity modes are clearly present and spaced 4 to 5 nm apart, as expected for a cavity length of approximately 5.5 µm. The spectral linewidth of the modes is around 0.8 nm, from which we calculate a cavity Q of >510, although heating of the device during the pulse may be causing frequency chirping (broadening) of the spectrum. However, the linewidth remains the same as the pulse width is varied from 50 to 500 nsec, indicating that any heating would have to be very rapid (<50 nsec). Finite element modeling of larger-area edge-emitting devices indicates that in the first 20 nsec the temperature rises by approximately 35°C.[9] Two other peaks of note are visible in the spectrum. The first is a low-intensity peak at around 500 nm. We believe this to be a result of constructive interference with an air-gap cavity formed between the AlN submount and the first dielectric DBR. The second peak, at a shorter wavelength emission of approximately 380 nm – corresponding to the InGaN barriers – appears at higher current densities for some devices. This peak increases in intensity with higher current injection while the intensity of the primary peak at 400 nm saturates. Most likely this is carrier leakage due to heating, which contributes to the second kink in the L-I characteristics at 27 mA.

Spectra at injection levels below the knee in the L-I curve were taken using a liquid nitrogen-cooled CCD array and a 0.5 m scanning monochromator with an integration time of 10 seconds. Fig. 5 shows the evolution of the spectral characteristics of a 10 µm diameter aperture device with increasing injection current. The emergence of the cavity modes, particularly in the transition across the knee in the L-I characteristics from 17 mA to 20 mA of injected current, is a clear indication of amplified spontaneous emission.

The difference in slope between L-I curves taken at peak and valley wavelengths further demonstrates the presence of a stimulated component in the emission.

Based on the gain characteristics derived from edge-emitting lasers fabricated at UCSB[10], we estimate that the threshold current densities for a VCSEL with 99.5% reflectors should be approximately 12 kA/cm^2. As the spectral characteristics of our devices do not seem to indicate lasing (i.e. we were not able to observe spectral narrowing) the implication is that the internal losses in these structures are higher than in the edge-emitters. Possible loss mechanisms that would be more significant in vertical devices include scattering from rough interfaces, absorption in unpumped wells, dispersion losses due to a long, weakly guided cavity, and heating.

In conclusion, we have fabricated robust InGaN-based RCLEDs. Non-linear L-I characteristics and the emergence of narrow cavity modes evidenced stimulated emission. We expect that as we reduce the losses in the structures, these devices can be pushed past threshold to lasing.

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FIGURE CAPTIONS

Fig. 1. Cross-section schematic of the RCLED device structure.

Fig. 2. Normalized reflectivity of an epitaxial DBR.

Fig. 3. Typical L-I characteristic for a 10 µm diameter aperture device, pulsed for 50 nsec at 5 kHz.

Fig. 4. Spectral characteristics for a 10 µm diameter aperture device, pulsed for 200 nsec at 50 kHz.

Fig. 5. Spectra taken at 12, 15, 17, 20, 22, 25, and 27 mA for a 10 µm diameter aperture device, pulsed for 50 nsec at 5 kHz. The integration time of the CCD was 10 sec.

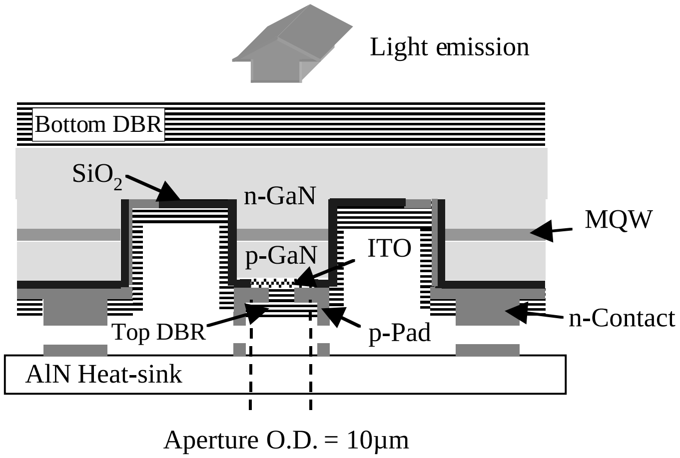

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Fig. 1

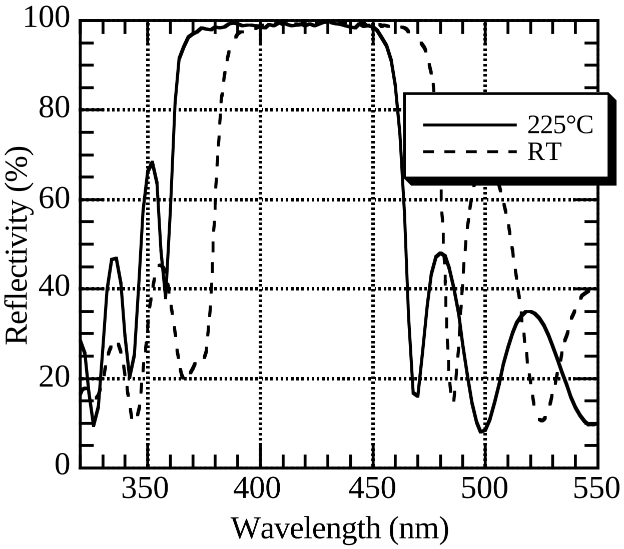

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Fig. 2

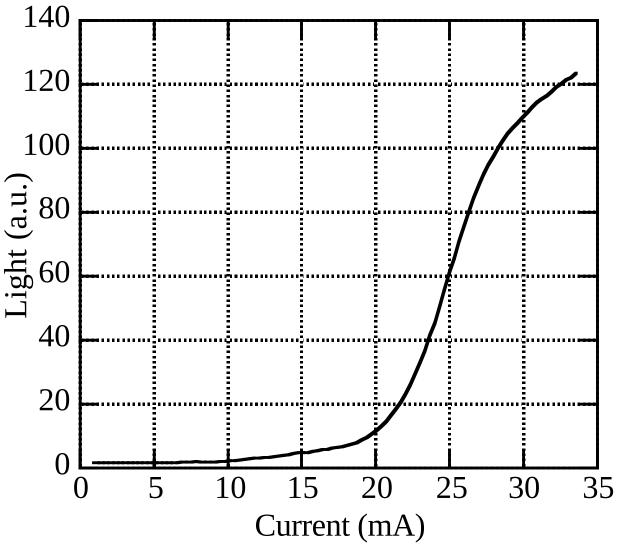

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Fig. 3

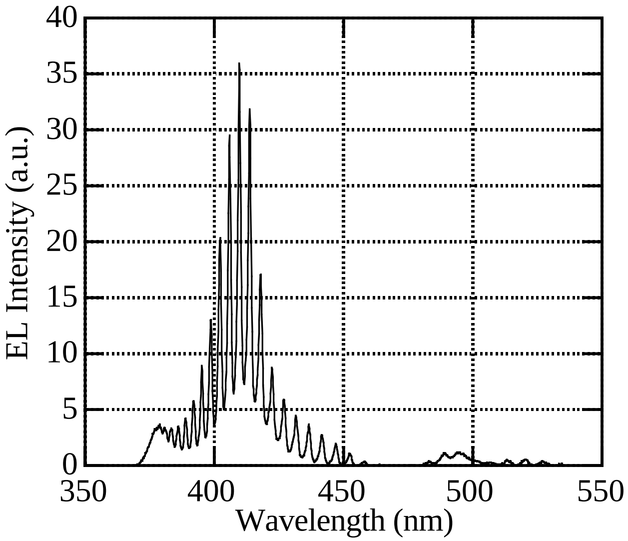

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Fig. 4

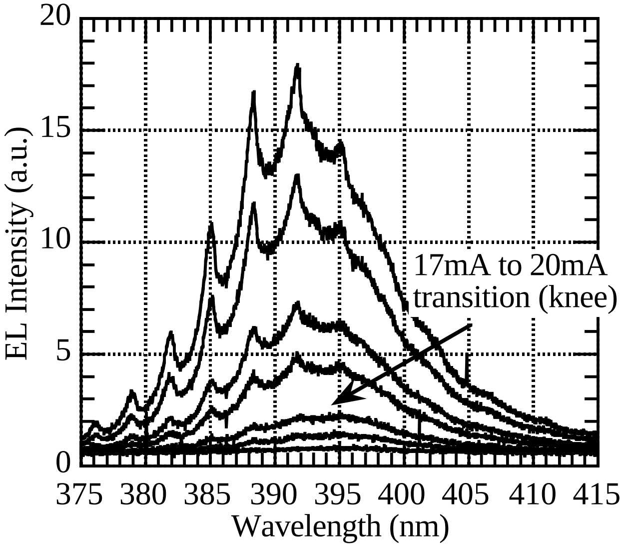

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Fig. 5