Origin of power fluctuations in GaN resonant-cavity light-emitting diodes

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Abstract: Resonant-cavity light-emitting diodes (RCLEDs) with multiple InGaN/GaN quantum wells have been grown on sapphire substrates. The emission was through the substrate, and the top contact consisted of a highly reflecting Pd/Ag metallization. The peak emission wavelength was measured to be 490 nm. Under constant current biasing, the intensity was observed to fluctuate irregularly accompanied by correlated variations in the voltage. To investigate this further, emission from the RCLED was focused through a GaAs wafer onto a Vidicon camera. This gave a series of infrared, near-field images, spectrally integrated over a wavelength range from 870 nm to 1.9 μm. Flashes from point sources on the RCLED surface were observed, indicating that short-lived, highly localized "hot spots" were being formed that generated pulses of thermal radiation. It is proposed that this phenomenon results from the migration of metal into nanopipes present in this material. The filled pipes form short circuits that subsequently fuse and are detected by bursts of infrared radiation that are recorded in real time.

OCIS codes: (160.6000) Semiconductor materials; (230.3670) Light emitting diodes; (160.3380) Laser materials.

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1. Introduction

GaN LEDs are finding uses in displays, general lighting, data communications, high-power transistors, data storage, and many other applications [1,2,3]. However, growth of the GaN material is still far from perfect, because the material generally contains a large number of threading dislocations [4,5]. Although the devices can work fairly well in the presence of such defects [6], the dislocations tend to compromise reliability [7]. In lasers and LEDs, metal migration through dislocations has been attributed as a major failure mechanism [8,9]. Various techniques are currently being applied in an effort to reduce the number of defects. These include epitaxial overgrowth [10], bulk crystal growth [11], and the inclusion of layers grown at low temperature [12]. In this paper, we observe failure in resonant-cavity light-emitting diodes (RCLEDs) that we attribute to metal migration along dislocations. This process forms short circuits that subsequently overheat in response to the high current density. This may not result in immediate device failure, but it produces output power fluctuations. After many fluctuations, the devices tend to fail because of a residual resistance left after the short circuits have fused. Here, in contrast to the studies mentioned previously, we observe the failure in real time by monitoring the diode at infrared wavelengths.

2. Sample structure

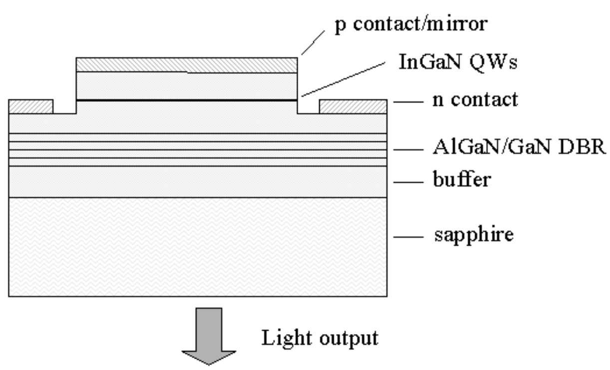


Fig. 1. Schematic of sample structure.

Two structures were investigated, both based on the generic design shown in Fig. 1 and grown by MOVPE. Sample A had a 4-μm GaN buffer layer on the sapphire substrate, 17 $Al_{0.1}Ga_{0.9}N$/GaN λ/4 mirror pairs, and a 3λ cavity layer containing three InGaN/GaN quantum wells consisting of 3-nm-thick wells and 10-nm-thick barriers. The peak wavelength of emission of the quantum wells was at 490 nm. The top *p*-doped GaN layer was coated with Pd/Ag/Ni/Au (3/100/30/300 nm thick) to create a high-reflectivity *p* contact. The *p* contacts were not alloyed after deposition, because non-alloyed contacts preserve their high reflectivity and ensure that the metals do not diffuse into the GaN. The *p* contact was defined by wet etches of $KI:I_2$ (4:1) diluted with 80 parts deionized water, followed by $HCl:HNO_3$ (3:1) diluted with four parts deionized water. A mesa was defined by reactive ion etching (RIE) in a PlasmaTherm 790 series etcher. $SiCl_4$ gas was used as the etchant, at a pressure of 20 mTorr and 225 V dc for 50 min. This etched the top 450 nm of GaN to expose the intracavity *n* layer, which was then covered in Ti/Al/Pt/Au (200/50/30/300 nm thick) to form the *n* contact. The device diameter was 150 μm.

Sample B had a similar structure but was grown in a different reactor. It had 10 mirror pairs and 10 quantum wells with 1-nm-thick wells and 8.5-nm-thick barriers. Processing and metallization were the same as for sample A.

The sapphire substrate was thinned, and the devices separated by dicing. They were then packaged at Infineon in a thin shrink small outline package (TSSOP) for handling.

3. Results

When some of the RCLEDs were biased, it was noticed that the output was unstable; that is, the light output flickered in intensity, or would suddenly go to zero. Occasionally, the output power would suddenly increase again to a former level. These effects were captured during a light-current-voltage measurement, as illustrated in a typical result shown in Fig. 2.

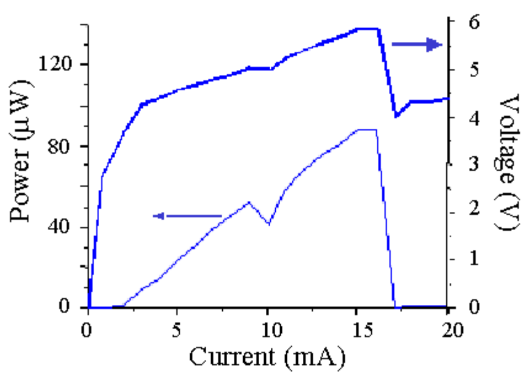
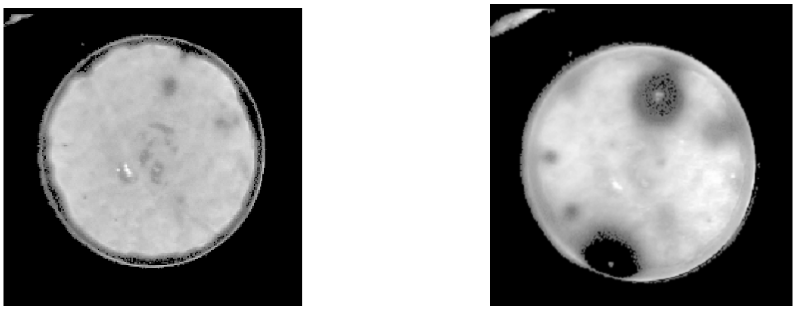


Fig. 2. LI curve for circular contact RCLED showing unstable light output.

These curves are different every time they are measured; that is, the light or voltage may drop or increase at any arbitrary moment. However, a clear correlation is seen between light output and voltage. When the light drops, the voltage also drops; when the light increases, the voltage also increases. This suggests a short-circuiting effect where short circuits are first created and then destroyed in a fuse-like process.



(a) (b)

Fig. 3. Near-field image of sample B (a), before and (b), after degradation.

After the device is run for some time at high bias levels, near 40 mA, degradation of the near-field image may be observed, as shown in Fig. 3. Two large dark areas are clearly visible at the top and the bottom of the image, with two lesser dark spots to the left. If migration-related short circuits were fusing, then it follows that they would be accompanied by a highly localized, significant increase in temperature. The power in a blackbody spectrum increases with temperature to the power of 4, and moves to shorter wavelength with temperature. To investigate the presence of strong blackbody radiation, a long-wavelength-pass filter was inserted into the imaging system, as shown in Fig. 4. In this arrangement, only radiation at wavelengths between 870 nm and 1.9 μm will be detected. No precise determination of temperature can be made, as any thermal spectrum with significant power in this range will be detected. Since the devices normally emit in the blue-green region of the spectrum ($450 < \lambda < 520$ nm), the filtered images were dark with the exception of infrared flashes from transient hot spots.

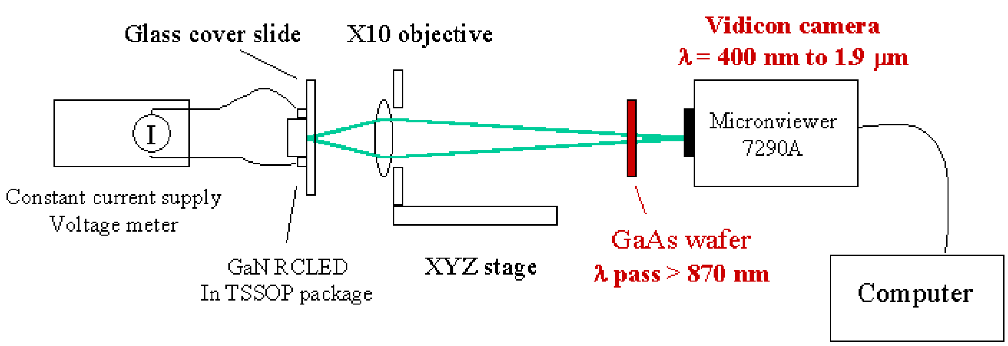


Fig. 4. Setup for imaging the thermal signatures of defect-related short circuits on circular contact RCLEDs. Because of the GaAs wafer, the green emission is blocked and the only wavelengths reaching the camera were infrared, between 870 nm and 1.9 μm.

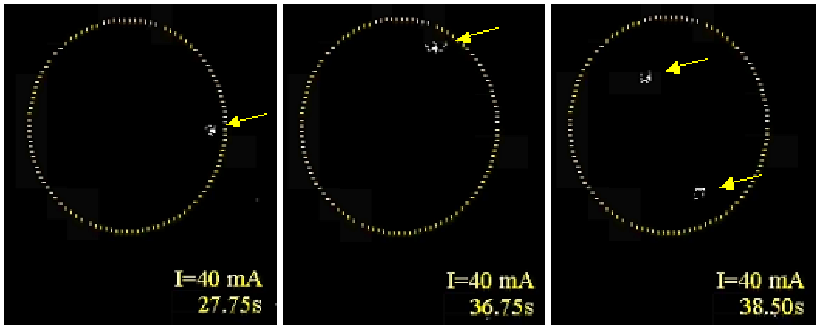


Fig. 5. Device A has transient hot spots that flash for less than 1 s. Dashed circles have been drawn in to represent the outline of the device [432 kB]. The movie shows that flashes start after ~24 s.

The camera was programmed to take images every 0.25 s. Three of these images are shown in Fig. 5, and a typical movie sequence of such images has been published with this article. Usually the image is entirely dark, because the normal visible emission has been blocked. However, at irregular intervals flashes are indeed observed, as indicated by arrows in the figure. These pulses have a duration of just less than 1 s, determined primarily by the size of the heat source and the thermal conductivity of the host material. This indicates that localized short circuiting and fusing are taking place in the material, which results from the contact metal migrating down tubular threading dislocations that are common in this material [see Fig. 6(a)]. After the fusing, the failed point may go open circuit, and so the current passes through the undamaged part of the device, and the device goes back to its high-emission state. Alternatively, there may be a residual resistive short circuit down the sidewalls of the resulting hole in the material. This acts as a parallel resistance, and the light output is not recovered. As the device accumulates more of these, the output drops to unusable levels. Material damage is revealed when the contact metals are removed, as is evidenced by the pitting near the *p*-metal edge in Fig. 6(b). Damage is highest near the edge of the *p* contact, as this has highest current density because of current-crowding effects. The large-scale damage evident in Fig. 6(b) also suggests that not all fusing events are captured in Fig. 5, but only the few hottest events. To capture more events, a more sensitive detector is needed.

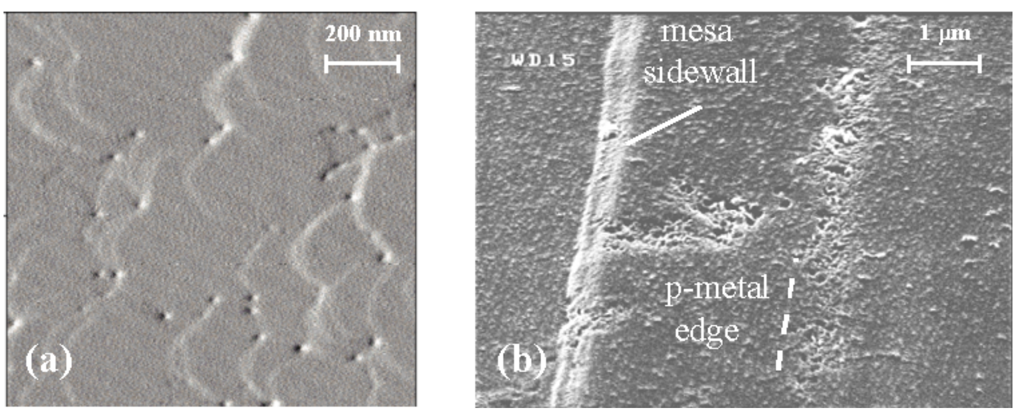


Fig. 6. (a) Typical 1×1 µm AFM image of GaN surface before degradation, showing open core dislocation density on the order of 3×10^{9} cm^{-2} and curved growth ledges. (b) SEM image after degradation and metal removal, showing large-scale surface pitting near the edge of the *p* metallization.

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4. Conclusions

A novel infrared measurement technique has been used to study failure in GaN LEDs. Bottom-emitting InGaN/GaN multiple-quantum-well RCLEDs have been manufactured on sapphire substrates. Instabilities were observed, characterized by irregular but correlated variations in the light output and voltage. During measurement in the infrared, bright flashes were also detected at irregular intervals. We have proposed that this is due to metal migration down threading dislocations that form fuses on the nanoscale. The initial short circuit induces a high current density such that the subsequent temperature increases are sufficient to melt the metal. This may result in an open-circuit or a residual resistance. In the case of the former, the device recovers its normal operation, whereas in the latter case light output and voltage are irrecoverably reduced.

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