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Time resolved study of laser diode characteristics during pulsed operation

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Under pulsed operation, time dependent spectral and electro-optical measurements on GaN-based laser diodes show a considerable red shift in the emission wavelength and a decreasing voltage drop across the device. These changes appear on a rather short time scale in the microsecond range. During a 3.7 microsecond long pulse, a temperature increase of approximately 50 K is obtained using different experimental methods. This value agrees well with numerical simulations based on the thermal properties of the material.

1 Introduction Violet-blue laser diodes based on GaN are ideal light sources for a wide range of applications such as optical storage devices, laser printing, spectroscopy, sensing and projection. For optimization of these devices, a comprehensive knowledge about the various effects taking place in the laser diode is inevitable. Since pulsed measurements are frequently used to determine the characteristics of the 'cold' laser diode without excess heating, we investigated the transient behavior of the device during the pulse. Time resolved electrical and optical laser characteristics are presented, giving a detailed insight in the dynamic behavior of laser diodes under pulsed operation.

2 Time resolved optical spectrum The investigated laser diode was fabricated by OSRAM Opto Semiconductors. It was grown on SiC-substrate without ELO-techniques by metal organic chemical vapor deposition and consists of a 560 nm thick AlGaN:Si cladding, followed by a 120 nm GaN:Si waveguide, three $In_{0.1}Ga_{0.9}N/GaN$ quantum wells with GaN:Si barriers, an $Al_{0.2}Ga_{0.8}N$ electron blocking layer, a 100 nm thick GaN:Mg upper waveguide, and a 400 nm thick AlGaN:Mg upper cladding layer. Contacts are deposited on a p-GaN contact layer on top of the 1.5 µm wide ridge and on the n-SiC backside. The cleaved facets are coated with high reflectivity coating ($R \sim 98\%/70\%$) [1, 2].

Using a common optical spectrum analyzer, all wavelengths occurring during the pulse are added up and appear as broad peaks in the spectrum. Wavelengths being present in the spectrum for a short time yield small peaks, whereas wavelengths emitted for a longer period show up as larger peaks. Thus, the shape of the spectrum depends on the pulse width. To identify the real emission wavelengths together with their intensity, a setup for measuring the spectrum at each point in time during the pulse is used. For the measurement, the light of the temperature stabilized laser diode is colli-

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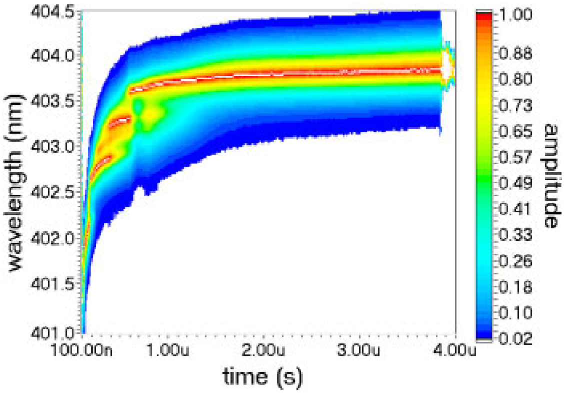

Fig. 1 (online colour at: www.interscience.wiley.com) Time resolved optical spectrum of a laser diode under pulsed operation.

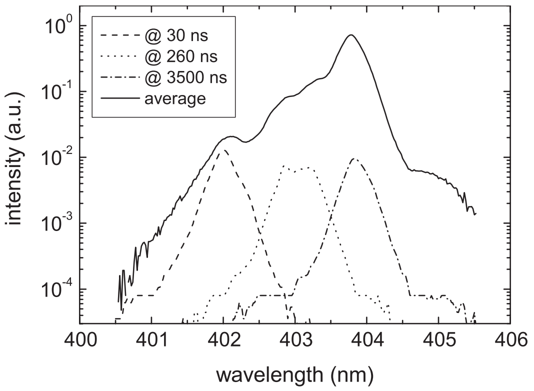

Fig. 2 Optical spectrum of a pulsed laser diode at different points in time during the pulse, compared with the average spectrum.

mated and then focussed on the entrance slit of a grating monochromator. At the output slit, the light of the actually selected wavelength is collected by a fast photomultiplier tube. Thus, for this particular wavelength the intensity distribution versus time can be observed on an oscilloscope connected to the photomultiplier tube. Scanning the selected wavelength of the monochromator over the range of the emission spectrum of the laser diode yields a plot as shown in Fig. 1. The pulse width is 3.7 µs at a duty cycle of only 0.05 percent to avoid excess heating. The shown spectrum is normalized to the maximum emission wavelength at each point in time in order to display the wavelength distribution irrespective of the slightly varying output power. Obviously, a strong change of the emission wavelength and the shape of the spectrum is observed during the pulse. As expected, the actual spectra during the pulse look completely different than the spectrum averaged over the entire pulse duration (Fig. 2).

The measurements of Fig. 1 were repeated at different input power levels. For comparison, the time dependent peak wavelength was extracted from the measurement data and plotted in Fig. 3. Depending on the electrical input power, the spectrum shows a wavelength shift between 1.3 nm and 2.2 nm during the pulse. As time progresses, the spectrum shows a mostly continuous tuning; these periods are separated by sudden jumps. We attribute the parts with continuous tuning to a temperature induced shift of the longitudinal modes, which is superposed by the much stronger shift of the gain spectrum. At certain points this leads to mode hopping across several longitudinal mode spacings. The exact mechanism of those jumps is not yet entirely understood and is subject to further investigations.

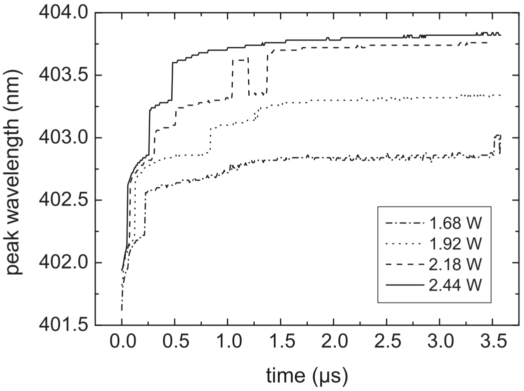

Fig. 3 Time dependent peak wavelength of a laser diode with 1.5 µm ridge width at various electrical input powers.

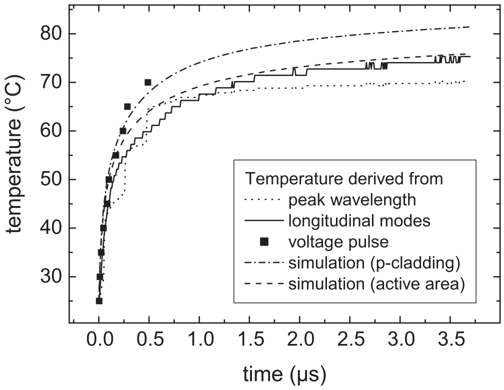

Fig. 4 Temperature evolution inside the laser diode, obtained by different measurement methods and simulations.

From temperature dependent measurements, a shift of the peak emission wavelength due to the shift of the gain spectrum of $\mathrm{d}\lambda_\mathrm{g}/\mathrm{d}T = 0.042\,\mathrm{nm/K}$ is obtained. Scaling the curve of the peak wavelength with this factor yields the temperature evolution, as shown in Fig. 4.

Removing the discontinuities in the peak wavelength results in a smooth curve. This curve corresponds to the shift of the longitudinal modes, for which we calculated a factor of $\mathrm{d}\lambda_\mathrm{FP}/\mathrm{d}T = 0.0155\,\mathrm{nm/K}$ from the change in the effective refractive index [3, 4]. Scaling of this smooth curve with the above factor leads to almost the same temperature evolution as before. For both methods, a temperature increase of approximately 50 K within 3.7 µs is obtained. A large percentage of this increase occurs within only 1 µs.

3 Electrical pulse The increase in temperature was confirmed by measuring time dependent current-voltage characteristics. As time progresses, the laser heats up, which leads to a stronger activation of the Mg-dopant in the p-GaN layers [5]. Therefore the resistance of the device decreases during the pulse. This leads to a dynamic reduction of the voltage drop across the device, and a corresponding increase of current.

Figure 5 shows the voltage drop across the laser diode during the pulse on a logarithmic time scale and for temperatures of 25 °C and 50 °C. Due to impedance mismatch between the 50 Ω line and the device, ringing occurred in the early phase of each voltage pulse, leading to the noisy shape of the voltage versus time curves. In order to facilitate the subsequent analysis, the upper of these curves has been smoothed with a polynomial fit. Starting at the initial voltage of the 50 °C-curve (10.8 V) allows us to determine the time after which the 25 °C-curve reaches the same voltage and thus the same temperature, as indicated by the arrows in Fig. 5. Repeating this procedure for a set of temperatures in the range of 25 °C to 70 °C yields the temperature evolution. In this case a temperature increase of 45 K within 0.5 µs is obtained, demonstrating that the fairly large series resistance of the p-region and the p-contact leads to a slightly higher temperature in this part of the laser structure than in and near the active zone.

4 Simulation Solving the time dependent heat equation by means of finite elements simulations (Flex-PDE) yields information about the temperature evolution during the pulse at different points inside the laser. Additionally, the temperature decrease after turning off the pumping current can be obtained, which is not accessible through the proposed measurement methods (Fig. 6). Excellent agreement with the experimental data could be achieved (Fig. 4): The simulated temperature increase in the p-AlGaN layer corresponds to the results measured with the voltage pulse method, whereas the data calculated for the active region confirm the results evaluated from the wavelength shift. Ob-

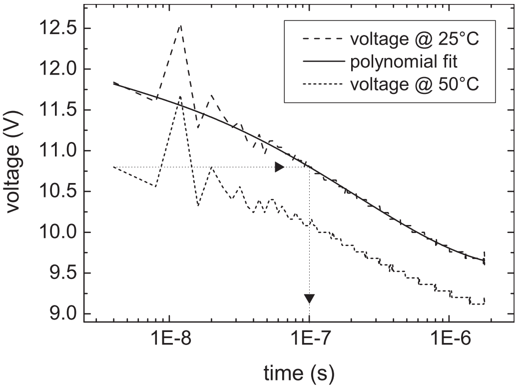

Fig. 5 Voltage drop across the laser diode versus time. By comparison of the voltage pulse at different temperatures, the temperature change can be obtained.

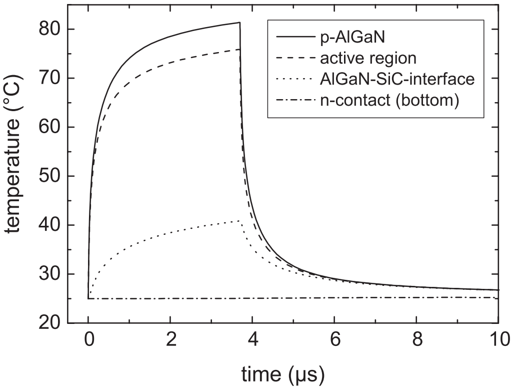

Fig. 6 Simulation of the temperature evolution at different points inside the laser diode, during and after a 3.7 µs pulse.

viously, the temperature increase is confined to a small area below the ridge, as shown by the much smaller temperature change at the n-AlGaN–SiC interface. As expected for such short current pulses, almost no temperature change is noticeable at the n-contact at the backside of the substrate.

5 Conclusion In summary, these experiments reveal a strong dynamic behavior of GaN-based laser diodes in short current pulses resulting from the drastic ohmic heating due to the still poor electrical properties of these devices. Thus, the presented methods represent an important tool for the optimization of the devices towards an improved power budget.

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