Temperature Measurement of Visible Light-Emitting Diodes Using Nematic Liquid Crystal Thermography With Laser Illumination

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***Abstract*—In this letter, we present a new configuration with laser illumination to measure the temperature of visible light-emitting diode (LED) chips using nematic liquid crystals. This method is applied to measuring the junction temperature of multiquantum well (MQW) LEDs in InGaN–GaN–sapphire structure. A color filter is inserted in the optical path to attenuate the overwhelming LED light. A high-power laser beam is used as the sensing light to enhance the contrast of the thermal image on LED chips. This technique is nondestructive and can be performed in real-time during device operation. One objective is to investigate the effect of the junction temperature on the electrical and optical performance of the LED devices. For the LEDs measured, the conversion efficiency decreases by 67% when the junction temperature rises from 22 °C to 107 °C. The new measurement configuration is a valuable tool to study the thermal performance of GaN-based LED devices and subsequently to investigate the degradation on electrical and optical performance due to junction temperature increase.**

***Index Terms*—Conversion efficiency, GaN, junction temperature, light-emitting diode (LED), liquid crystal, sapphire, thermal measurement, thermography.**

I. Introduction

It IS well established that the operating temperature of semiconductor devices affects not only the efficiency but also the reliability of the devices [1]–[3]. Accurate junction temperature measurement of light-emitting diode (LED) devices is important in revealing how the LED conversion efficiency changes with the junction temperature. Industries have been using case temperature, which is the temperature on a reference location of the package, as a parameter to measure efficiency [1]. While this method is useful for practical purposes, it does not provide physical insight as to how the efficiency degrades with temperature because the junction temperature is unknown. It is the junction temperature, which is the temperature on the quantum well, at which the injection of electrons and holes takes place to produce photons.

Several thermal measurements of LED devices during operation have been reported. Using micro-Raman spectroscopy, a temperature measurement with 1-μm spatial resolution and 10 °C temperature accuracy in InGaN–GaN LED devices was recently performed [4]. Similarly, a microscopic measurement of high junction temperature of InGaN–GaN LEDs was conducted with electroluminescence [5]. Raman spectroscopy and electroluminescence are indirect temperature measurement methods. The nematic liquid crystal thermography in this study, on the other hand, uses a more direct measurement technique [6], [7]. This technique has been known for many years. It can yield high temperature accuracy and high spatial resolution. The temperature accuracy is within ± 1°C. It is also relatively easy and its application cost is low. However, in applying this technique to LEDs, great difficulty exists. The LED light during operation would easily overwhelm the illumination light in the existing microscope commonly used in the setup. Thus, the microscope light reflected from the LED chip surface that carries the temperature information is lost. To overcome the difficulty, a new configuration is established where a high-power laser diode of 660 nm in wavelength is employed as the new illumination source to sense the temperature. A color filter is inserted in the optical path to block the LED light. Junction temperatures of blue LEDs have been successfully measured. This method can be extended to measuring green and red LEDs using near infrared laser beam. The LED conversion efficiency can now be measured at different junction temperatures. This information can help identify the cause of temperature dependence of conversion efficiency, such as the leakage of carriers over the quantum well and nonradiative recombination through defect or impurity states. It also offers useful information on how severely the conversion efficiency is reduced as junction temperature increases.

II. Experiment Setup and Results

The physical structure of the InGaN–GaN LED and measured electrical characteristics are presented in Fig. 1. The device is fabricated on a sapphire substrate and composed of multiple layers. The material composition and thickness of each layer are given in Table I. The actual chip of 380 $\times$ 330 μm is attached to a copper transistor outline (Cu TO)-type package using silver epoxy. The cathode and anode contacts are connected to the package by gold wires. The contact geometry consists of a square inner contact for n-GaN layer and circular one for p-contact. The lid of the TO package is not used. Optical power was measured by an optical power meter with silicon photodiode sensing head. The peak emission wavelength was about 470 nm. After the electrical and optical power measurements were carried out, nematic liquid crystal thermography measurement was performed using the new configuration. Since the p-GaN layer is very thin, 0.5 μm, we can approximate the temperature on the surface as the temperature at the junction. Calculated temperature results support this approximation [6]. In general, the

Manuscript received October 17, 2003; revised March 10, 2004.

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Digital Object Identifier 10.1109/LPT.2004.828361

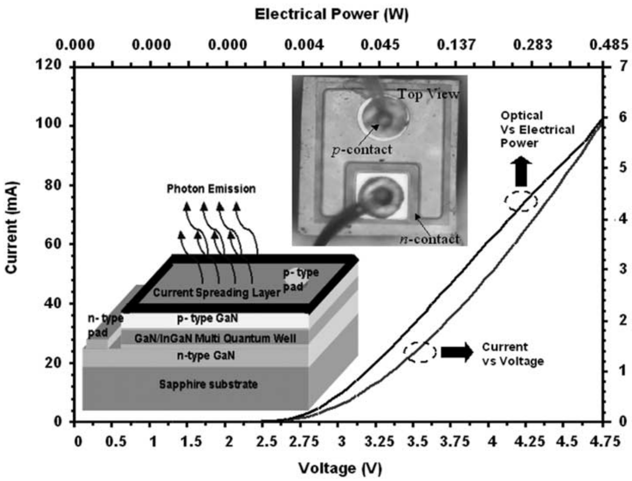

Fig. 1. InGaN–GaN–sapphire device structure with electrical and optical measurement results. The device chip is attached to a copper TO-type package that is mounted to a copper plate.

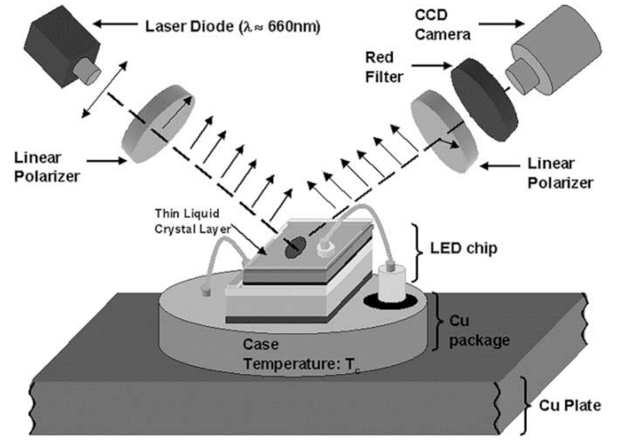

Fig. 2. New nematic liquid crystal thermal measurement configuration using polarized laser diode ($\lambda \approx 660$ nm) beam and a charged-coupled device camera with color filter to study the thermal performance of visible InGaN–GaN–sapphire LEDs. For simplicity and clarity, the optical microscope that images the chip surface is not shown.

TABLE I
LAYERS OF THE LED CHIPS

	p-type GaN	GaN/InGaN MQW	n-type GaN	Sapphire
Thickness (μm)	0.5	0.003	4	100

maximum surface temperature (temperature on the hot spot) cannot be used to approximate the junction temperature. However, when the temperature variation over the chip surface is small, the maximum surface temperature can be used to approximate the junction temperature with acceptable error. For the LED chips studied, the temperature variation over the chip is less than 2 °C, as determined by raising the base temperature while observing how the hot region spreads outward. This small variation is due to the thin current spreading layer on the p-GaN to distribute the current uniformly over the p-region. Since the temperature variation is very small, the maximum temperature is used to approximate the junction temperature with error less than 2 °C.

The nematic liquid crystal thermography is nondestructive and has high spatial resolution limited only by the resolution of the optical microscope. Fig. 2 illustrates the experiment setup for this new configuration. A high-power 660-nm laser diode is used as the illumination source. The laser beam is highly polarized as required by nematic liquid crystal thermography. This means that the electrical field component of the light-wave is in a fixed direction that is often referred to as the polarization orientation. An optical polarizer is used to further increase the degree of polarization of the laser beam. The polarized laser beam is shone onto the sample through the microscope objective lens. If a region of liquid crystal layer on the LED device surface is heated above the transition temperature of the liquid crystal, the liquid crystal layer within that region will change from anistropic to isotropic medium. As a result, the linearly polarized light that enters into and is reflected from the nematic liquid crystal layer will not change the polarization orientation, and the region will appear as dark gray under a polarizing optical microscope that has a cross polarizer. On regions other than the hot regions, the temperature stays below the transition temperature and the liquid crystal layer remains optically anisotropic. The light reflected from these regions will change its polarization orientation. These regions will appear bright under the polarization microscope. On the boundaries between the dark and bright regions, the temperature would equal the transition temperature of the nematic liquid crystal. The rotation on the polarization orientation is due to the optical birefringence of the liquid crystal below transition temperature. Since the InGaN–GaN–sapphire chip is transparent to the laser light, the laser beam does not heat up the LED chip.

The LED light has much higher optical power than microscope incandescent light. As a result, the external light that is reflected from the chip (coated with LC film) is much weaker than the LED light and is overwhelmed by the LED light. Thus, the polarization rotation information on the LED surface needed to identify the hot spot is lost. To overcome this difficulty, LED light must be blocked in the measuring system. A red filter reduces LED optical power by more than 30 dB but passes the 660-nm laser beam. Since the LED device chip is transparent at 660-nm wavelength, the laser beam does not heat up the device. Thus, both blocking of LED light using a red filter and illumination by high-power laser are required to observe clear hot spot. The nematic liquid crystal with 302 K (29 °C) transition temperature was first applied to InGaN–GaN–sapphire multiquantum well (MQW) LEDs. The device in TO-package was mounted on a copper plate that was placed under the experimental setup shown in Fig. 2. The plate has a temperature of 295 K (22 °C) that is also the base temperature of the LED package. Without electrical power applied to the LED, the optical image of the LED is shown in Fig. 3(a). The electrical power was applied and increased gradually until hot spots are recognizable, as exhibited in Fig. 3(b). The smallest distinguishable hot spot is observed when the peak temperature on the device surface just reaches the transition temperature of the liquid crystal used.

As seen in Fig. 3(b), two hot spot regions are clearly seen. The hot spots begin to appear near p-GaN contact region. The width of two hot spots is 21 and 35 μm, respectively. As drive power is increased, the size of the hot region expands. In other words, the regions enclosed by the boundary that is at the transition temperature spread outwards from p-GaN contact region toward n-GaN

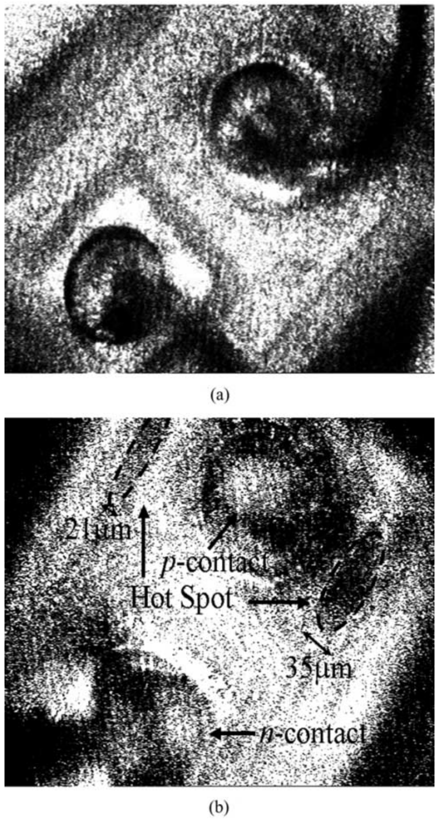

Fig. 3. Image of field-off LED with nematic liquid crystal coating is shown on (a). Hot spot image of InGaN–GaN LED device using nematic liquid crystal with 29 °C transition temperature is shown in (b) and corresponding drive power is 22.4 mW.

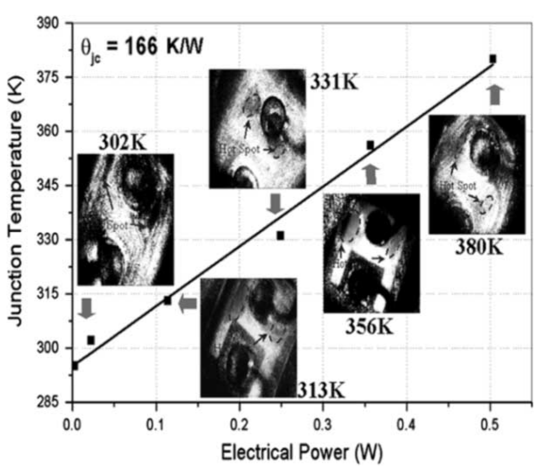

Fig. 4. Results of thermal measurements. The hot spot images obtained using liquid crystals with different transition temperatures and the relationship between junction temperature and electrical power.

contact region. This experiment was repeated with liquid crystals having transition temperatures of 313 K, 331 K, 356 K, and 380 K, respectively. The peak temperatures measured using five different liquid crystals versus drive powers are plotted in Fig. 4. Liquid crystal thermographic images at different drive powers are also included in Fig. 4. It is seen that the hot spots appear at similar locations at different drive powers. These locations are within the regions where the LED light intensity is very high. Using the measured junction temperatures in Fig. 4, we can now determine the conversion efficiency versus the junction temperature. The conversion efficiency is the ratio of measured light power to the electrical drive power. To our surprise, the conversion efficiency is a very sensitive to junction temperature. Since InGaN and GaN have wide energy bandgaps, one would think that the conversion efficiency probably would change little with junction temperature. Our experimental data show otherwise. The efficiency degrades by 67% as the junction temperature increases from 295 K to 380 K, which is quite serious in practical applications.

In Fig. 4, a linear relationship between the junction temperature and drive power is observed. An important thermal performance parameter commonly used in semiconductor devices is the junction-to-case thermal resistance defined as

$$\Theta_{jc} = \frac{T_j - T_c}{P}$$

where T_j is the junction temperature which is also the temperature that we measured, T_c is the case (base) temperature, and P is the electrical drive power. The thermal resistance is simply the slope of the curve in Fig. 4, which is $\Theta_{jc} = 166^\circ$ K/W for the LED devices studied.

III. Summary

We have studied the thermal performance of MQW LEDs in InGaN–GaN–sapphire structure. Peak temperatures on the chip were measured using nematic liquid crystal thermography with laser beam illumination. The junction temperature can be approximated by the surface temperature since the active region of the device is very close to the chip surface. Liquid crystals with transition temperatures of 302 K, 313 K, 331 K, 356 K, and 380 K were used. The measured results exhibit a nearly linear relationship between the junction temperature and the drive power. We believe that this is the first demonstration of the LED junction temperature measurement using liquid crystal thermography. This new configuration is a valuable tool for determining the junction temperature and to further find out how the junction temperature affects the conversion efficiency.

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