# High Temperature and Large Bandwidth Blue InGaN/GaN Micro-LEDs

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**Abstract:** InGaN/GaN micro-light-emitting diodes with the highest bandwidths at very high temperatures (3.2 GHz at 290°C) are demonstrated. Differential carrier lifetime analysis is undertaken to understand recombination-related effects on the modulation response.

## 1. Introduction

InGaN/GaN micro-light-emitting diodes (micro-LEDs) are of recent interest for applications in visible light communication (VLC), where high data rates using optical links over short distances are becoming increasingly crucial for the future of optical communications technologies [1,2]. These micro-LEDs can be used in faster chip-to-chip optical links and potentially eliminate power-hungry SerDes circuitry [3] by their inherent low ability to operate at temperatures compatible with that of silicon processors (e.g., Tj~105-125°C). Furthermore, utilizing such links in extreme environments is desirable for sensing applications. Recently, high-speed micro-LEDs have demonstrated data transmission of >14 Gb/s at temperatures of 235°C [4], showing they are much less sensitive than GaAs and InP lasers to operating temperature. This is most likely due to favorable carrier dynamics in the InGaN active layers. Carrier dynamics in high-efficiency blue LEDs have been studied in previous works at temperatures up to 200°C, but analysis for micro-LEDs designed for high-frequency operation is lacking [5].

This paper measures high-speed micro-LEDs at elevated currents, 5 kA/cm$^2$, and very high temperatures up to 290°C to test their bandwidth limitation and better understand the effects of temperature and high current density on efficiency and carrier dynamics. High modulation bandwidths (>3 GHz) are demonstrated under extreme temperatures. Additionally, the small signal response of the electrical and optical characteristics of the micro-LEDs are measured and fit to a small signal equivalent circuit to extract lifetimes at different temperatures.

## 2. Experiment

The III-nitride LED structures are grown on sapphire substrates as previously described by [1]. The blue-emitting (~424 nm) active layer is designed for high-speed operation. The epitaxial layers are fabricated into top-emitting micro-LEDs, with an emitting area corresponding to circles with 32-micron diameters. The electrical contacts are designed to test individual devices with GSG probes for high-frequency operation. The underlying carrier dynamics and transport mechanisms of micro-LEDs are essential for understanding modulation response and its potential tunability for achieving higher bandwidths for VLC applications. A standard method of evaluating carrier dynamics in micro-LEDs is time-resolved photoluminescence (TRPL); however, for reasons outlined in [6], testing the device under electrical injection provides more accurate information on differential lifetime information that relates closely to the bandwidth [7]. For this reason, the devices are tested under electrical injection and fit our s-parameters to a small-signal circuit model [7].

The experimental setup to analyze the micro-LED impedance and modulation response is shown in Figure 1(a). The micro-LED chips are contacted with a high-speed, high-temperature GSG probe, and a variable DC bias is applied. A 20 GHz Anritsu vector network analyzer (VNA) is used to measure the impedance and modulation response of the device, where the micro-LED output is free space coupled into an ultra-fast PIN detector with a trans-impedance amplifier (TIA) for signal amplification [1]. The S21 and S11 parameters of the setup are calibrated with a high-speed vertical cavity surface emitting laser (VCSEL) and an impedance standard, respectively. The micro-LED rests on a ceramic heater for temperature control, where the surface of the LED chip is also measured using a type-k thermocouple. The quoted temperatures are the heater temperatures, and the LEDs are 90°C and 30°C cooler at a heater temperature of 290°C and 80°C, respectively. The LED is DC-biased, and the detector is replaced with a standard Si photodiode to measure the static characteristics. The radiative efficiency (or internal quantum efficiency) is calibrated using low-temperature (8K) photoluminescence with a cryostat on unprocessed sections of the LED structure. Previous measurements have shown it is accurate for III-nitride emitters [8].

## 3. Results

Figure 1(b). shows the radiative efficiency (RE) versus current density for several temperatures up to 200°C. As temperature increases, the EQE decreases, and the peak efficiency shifts to higher current densities. The downward shift is more prominent at the lower currents, suggesting an increase in defect (or Shockley-Reed-Hall) recombination. The peak radiative efficiency is estimated to be about 16% at 25°C but drops as speed increases. At 290°C and 5 kA/cm$^2$, the radiative efficiency is ~1%. As for all III-nitride LEDs, the efficiency droop occurs at the highest current densities caused by the dominance of Auger recombination. The decrease in efficiency at the highest currents suggests that Auger recombination also increases with temperature for these LEDs. These efficiencies are lower than LEDs designed for lighting, and there is a clear tradeoff between efficiency and switching speed. The current versus voltage (IV) characteristic is shown in Figure 1(c) for multiple temperatures. There is an expected decrease in resistance with temperature, and the operating voltage at 5 kA/cm$^2$ (or 40.2 mA) is 4.1 V.

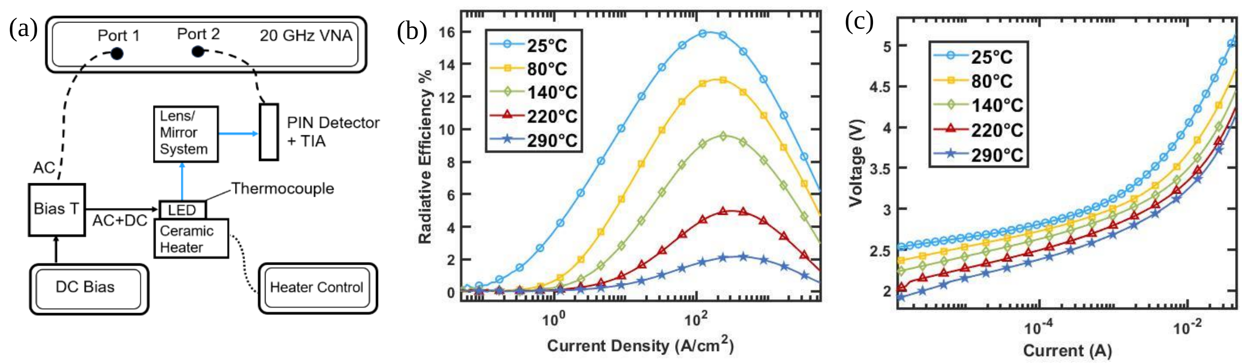


*Fig. 1. (a) Schematic of the measurement setup, (b) radiative efficiency vs current density, and (c) voltage vs current for temperatures ranging from 25 to 200 ℃.*

The modulation bandwidths of the micro-LEDs at the hottest temperatures (290 °C) are shown in Figure 2(a). Also shown in Figure 2(b) is the modulation response for multiple temperatures at the highest applied current density (5 kA/cm$^2$). There is an increase in bandwidth for both increased current and temperatures over the measured ranges. The modulation bandwidth is taken as the -6 dB optical bandwidth. The bandwidth versus current density for all temperatures is shown in Figure 2(c). The drive current is limited to 5 kA/cm$^{2,}$ ensuring the device is not electrically overstressed. Even with this limitation, record bandwidths of 3.2 GHz at 290 °C are demonstrated, which we believe is the highest temperature operation of a multi-GHz optical device recorded to date. These bandwidths can be achieved at room temperature when the micro-LEDs are driven at 12 kA/cm2 current densities. The increase in bandwidth at higher temperatures is an interesting and important phenomenon, whereas, in other materials systems, the bandwidth decreases with rising temperatures [9] Although there are tradeoffs between efficiency and high-speed operation, such devices have demonstrated sub-pJ/bit switching energies [5, 10].

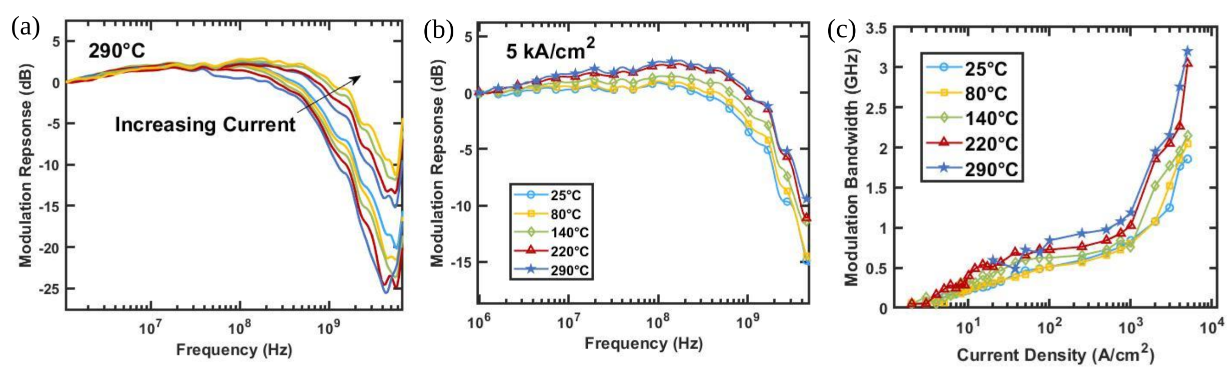


*Fig. 2. (a) Modulation response at 290°C, (b) response from 25°C to 290°C at 5kA/cm$^2$, and (c) bandwidth vs current density from 25°C to 290°C.*

The lifetimes of the LEDs can be determined by fitting the impedance and optical response (S11 and S21 curves, respectively) to a small circuit equivalent model. The small signal LED circuit is given in Reference [7] and includes the relevant resistances, capacitances, and the recombination and escape lifetimes in the active layers. One result of the fit is the determination of the differential carrier lifetimes ($t_{DCL}$), which is the rate of change in the recombination lifetime with carrier density. The differential carrier lifetimes for the micro-LEDs are shown in Figure 3(a) for room temperature and 290 °C). The differential carrier lifetime decreases with temperature and current density. A power-dependent fit is used for further analysis. However, slight variations with current may reveal subtle recombination dynamics that require further study.

Using an analysis similar to Reference [7], the differential carrier lifetimes and radiative efficiency are used to determine the radiative and non-radiative lifetimes of the micro-LEDs and how they respond to temperature. Figure 3(b) shows the radiative ($\tau_{rad}$) and non-radiative ($\tau_{nr}$) at 25 °C and 290 °C. Both lifetimes change with temperature and current. The decrease in $\tau_{nr}$ with temperature is expected as the defects and defect-assisted Auger become more active with temperature. The increase in $\tau_{rad}$ with increasing temperature could have multiple causes. These causes include changes in wavefunction overlap due to polarization fields with temperature and changes in the bandstructure causing changes in matrix elements. A comparison of this data with models that include temperature, such as bandstructure versus temperature, will help discover the causes of these lifetime trends and elucidate possibilities for design and performance improvements.

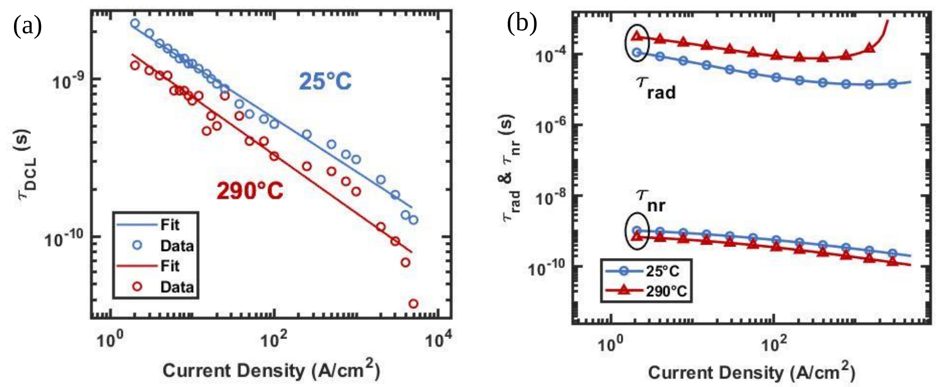


*Fig. 3. (a) Differential carrier lifetimes and fits at 25 ℃ and 290 ℃. (b) Calculated radiative and non-radiative lifetimes at 25 ℃ and 290 ℃.*

## 4. Conclusion

Record bandwidths of 3.2 GHz at 290 °C for III-nitride micro-LEDs are demonstrated. A reduction in both the radiative and non-radiative lifetimes at higher temperatures causes these increased bandwidths.

## 5. References

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