Superluminescent Light-Emitting Diodes (SLEDs) Operating at Ultra-High Ambient Temperatures

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Abstract **– SLEDs are attractive light sources for various applications in the visible and near-infrared spectral region. Some applications require operation at ultra-high ambient temperatures of up to 150°C. We show that the electro-optical device performance at such challenging conditions is limited by the thermal degradation of the material gain and by the non-radiative Auger recombination processes that are strongly increasing with temperature. Still, with proper design choices, several milliwatts of optical output power can be generated at ultra-high chip temperatures.**

I. Introduction

Superluminescent light emitting diodes (SLEDs) are efficient light sources that emit broadband light with several tens of milliwatts of output power into single-mode fibers. SLEDs typically operate at wavelengths from 400 nm to 1700 nm with broadband emission of 5-150 nm FWHM. The electro-optical performance is based on amplifying spontaneous emission (ASE) through stimulated emission along an optical waveguide [1]. These characteristics make them attractive light sources for various applications, including biomedical imaging, fiber optic gyroscopes or fiber sensing. Typical temperature ranges of operation cover -40°C to +85°C, but there has been also some recent interest in SLEDs operating at ultra-high ambient temperatures of up to 150°C even.

In this presentation, we discuss the electro-optical performance of SLED devices with an emission wavelength of 800-900 nm operating at ultra-high ambient temperatures beyond 100°C. Under these conditions, the main limitation for the achievable output power is given by the thermal degradation of the material gain and, even more so, by the strongly increasing non-radiative Auger recombination processes. Consequently, ex-facet output power levels of more than 1 mW can be hardly achieved with standard SLEDs operating at 110°C or higher. This limitation can be overcome by using reflective SLEDs (R-SLEDs) [1] with optimized epitaxial layer structures. These devices can generate decent output powers of several milliwatts at ambient temperatures up to 140°C and with Gaussian-shaped ASE spectra having a bandwidth of 10-20 nm FWHM.

II. Epitaxial Layer Design and Material Gain

The epitaxial layer structure of SLEDs operating in the near-infrared wavelength range from 800 nm to 900 nm relies on (Al)GaInAs active-region layers grown on a GaAs substrate. The SLEDs under consideration consist of compressively strained quantum-well (QW) layers. Quantum barrier layers with relatively high bandgap energy are used to provide deep quantum wells. This should keep the carriers (particularly electrons) well confined in the active layer and lower the effect of thermionic emission of carriers out of the QWs, which would reduce the SLED's efficiency at high-temperature operation.

SLEDs operate in the so-called ASE regime below lasing threshold. As a result, the carrier density in the active-region layer(s) is not clamped so that, for a fixed junction temperature, the output power is basically determined by the material gain for a given pump level or a given carrier density. On the other hand, it is well known that, for a fixed pump level, the material peak gain degrades severely with increasing junction temperature. Fig. 1 shows that the peak material at a junction temperature of 120°C is approximately only half of the peak gain at 20°C. Moreover, the peak gain, and thus the ASE spectrum may shift by more than 30 nm to longer wavelengths over the large temperature range. This wavelength shift must be considered when designing the ASE spectrum for the correct wavelength position at the foreseen high-temperature operating condition.

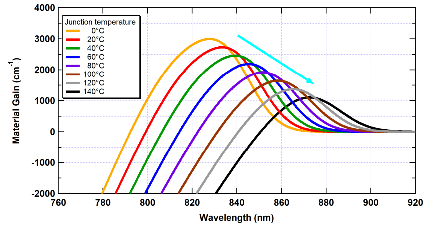

Fig. 1. Spectral dependence of the TE material gain for one quantum well with a fixed carrier density of $5 \cdot 10^{24}$ m^{-3} at various junction temperatures.

III. Auger Recombination

The efficiency of SLEDs suffers severely from non-radiative Auger recombination losses, as has been already pointed out by Piprek because of its generally higher and non-clamped carrier concentration compared to laser diodes [2]. Moreover, the Auger losses increase with increasing junction temperature. The temperature dependence of the Auger coefficient can be well described by an Arrhenius-type equation of the form

$$C_n = C_p \equiv C(T_j) = C_0 \cdot \exp\left(E_a / k_B \cdot \left(1/T_0 - 1/T_j\right)\right), \qquad (1)$$

assuming same Auger coefficients for electrons (C_n) and holes (C_p) [3]. In (1), C_0 is the Auger coefficient at room temperature T_0 = 298 K, E_a the activation energy, and T_j the actual junction temperature. For high activation energies, the Auger coefficient increases enormously with increasing junction temperature, as shown in Fig. 2. For an activation energy of 250 meV, the Auger coefficient is a factor of ten higher at a junction temperature of 120°C compared to room temperature.

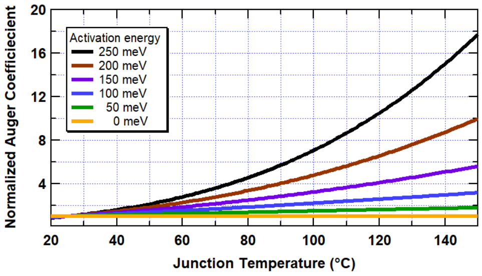

Fig. 2. Normalized Auger coefficient C/C_0 as function of the junction temperature for various activation energies from 0 up to 250 meV.

IV. Full 3D Device Simulation and Device Optimization

The electro-optical performance of the SLED chips has been simulated using a full 3D simulation software tool. The simulator has been calibrated using measurement results, obtained from fabricated modules, over the temperature range from 20°C to 120°C. The Auger coefficient C_0 and the activation energy E_a have been used as open parameters for fitting the measured *L-I* characteristics. The fiber-coupled output power values of the modules have been multiplied by factors of 2.2 assuming a realistic fiber coupling efficiency of 45%. This allows a direct comparison with the simulated ex-facet output power from the SLED chip. From our simulations, as shown in Fig. 3, we find that the best agreement with measured *L-I* characteristics is achieved using an activation energy of 250 meV and a room temperature Auger coefficient of 2.4×10^{-42} m^6/s.

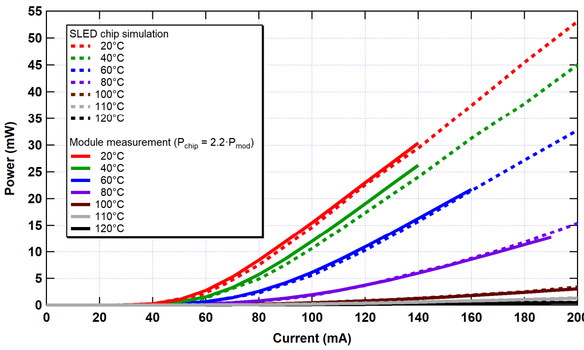

Fig. 3. Comparison of measured (solid lines) with simulated (dashed lines) *L-I* characteristics for various heatsink temperatures from 20°C up to 120°C.

With standard SLED design rules, it appears to be very challenging to achieve an output power of more than 1 mW for heatsink temperatures of 110°C or above. This is mainly due to the Auger loss coefficient that is strongly increased at high ambient temperatures and for high activation energies (see Fig. 2). However, with a continuous reduction of the activation energy from 250 meV (black curve) to 0 meV (orange curve), the *L-I* characteristics can be significantly improved, as shown in Fig. 4, even at high junction temperatures. Having zero activation energy means that the temperature dependence of the Auger coefficient is switched off, resulting in device operation with a constant Auger coefficient C_0. Consequently, the remaining difference between the orange curve (120°C) and the red curve (25°C) is caused by the reduction in material gain and by thermionic loss of carriers from the QWs.

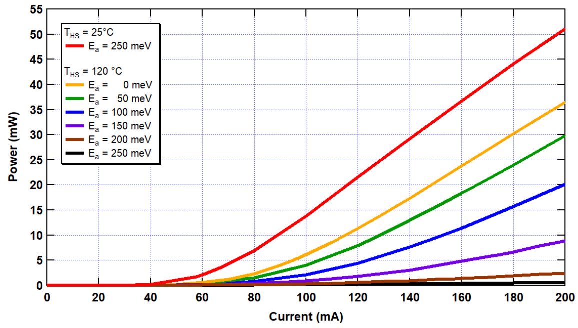

Fig. 4. *L-I* characteristics simulated for various activation energies at a heatsink temperature of 120 °C. The red curve shows is for room temperature (25°C).

A significant improvement for high-temperature operation can be achieved with R-SLED devices [1] with a double-pass amplification process, which results in a significant boost in output power. After additional epitaxial design optimization, optical output power levels of more than 20 mW at 130°C, around 6 mW at 140°C and even 1 mW at 150°C are obtained with low injection currents of 200 mA only, as shown in Fig. 5.

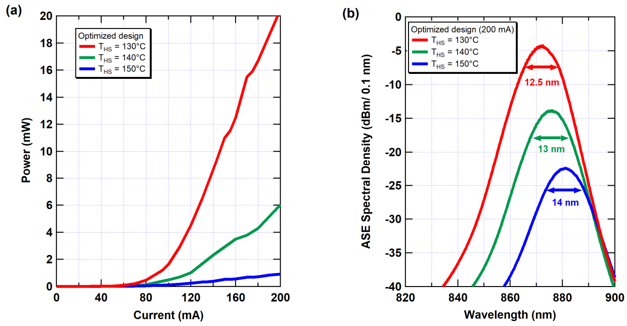

Fig. 5. (a) Simulated *L-I* characteristics for an optimized R-SLED structure for heatsink temperatures of 130°C, 140°C, and 150°C. (b) Gaussian-shaped ASE spectra obtained at an injection current of 200 mA.

V. Summary

We have shown that the electro-optical performance of GaAs-based SLED devices, operating at 800-900 nm and at ultra-high ambient temperatures, is mainly limited by the strong temperature-dependence of the Auger coefficient for high activation energies and, secondly, by the thermal degeneration of the material gain. Consequently, R-SLED designs seem superior in generating several milliwatts of output power at chip temperatures beyond 100°C compared to standard SLED designs.

References

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[2] J. Piprek, “What limits the efficiency of GaN-based superluminescent light-emitting diodes (SLEDs),” *Optical and Quantum Electron.*, 51(12), DOI: 10.1007/s11082-019-2106-3, 2019.

[3] J. Piprek, *Semiconductor Optoelectronic Devices: Introduction to Physics and Simulation*, Academic Press, 2003.