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主　論　文　の　要　旨

論文題目　**Toward high performance of micro-LEDs via sidewall engineering for next-generation display**
(次世代ディスプレイにおけるサイドウォールエンジニアリングによるマイクロLED の高性能化に向けた研究)

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論　文　内　容　の　要　旨

Because of the emerging demand for ultra-high pixel per inch (PPI) display which will play a key role in augmented reality (AR) / virtual reality (VR) applications, called near-eye display, III−nitride based micro-light emitting diodes (μLEDs) that can realize small pixel are attracting strong attention. For the fabrication of μLEDs arrays, top-down process by shaping each pixel with inductive coupled plasma reactive ion etching (ICP-RIE) allows us to realize ultra-small pixel (typically < 10 × 10 μm^2). ICP-RIE dose not seriously degrade the performance of traditional large size LEDs (> 300 × 300 μm^2). However, it makes μLEDs to encounter the sidewall damage, which becomes more and more serious as μLEDs size shrinks, thus leading low external quantum efficiency (EQE). Decreasing EQE with shrinking pixel size makes it difficult to realize high performance and high PPI of μLED display. In this thesis, the influence of sidewall conditions on the performance of μLEDs is systematically investigated. In addition, I propose the solutions how to overcome lowering EQE of μLEDs with shrinking size in this thesis.

Because the sidewall is formed by ICP-RIE etching, the dry etching conditions of ICP-RIE was most important and thus investigated. With high-bias power etching condition, an ion-bombardment is dominant, which makes the plasma induced damage on the etched surface including sidewall. However, it was reported that chemical reaction between Cl_2 etching gas and GaN layer is dominant under low-bias power etching. This chemical reaction not only suppressed the plasma induced damage but also improved the leakage current and ideality factor that are indirectly related to Shockley-Read-Hall (SRH) non-radiative recombination. Moreover, chemical reactions created the rough sidewall through dislocations, increasing the light extraction efficiency via sidewall. Therefore, the LED pixel made by the low etching bias shows high EQE than the LED pixel made by high etching bias. Given that etching by low-bias power is dominantly chemical reactions in ICP-RIE system, it is suitable for realizing high performance μLED and fabricating ultra-small μLED via less etching damage.

For better luminous efficiency, current display system uses various pixel designs such as circular, square, and stripe. Regarding such demand in the display system, variously designed III–nitride μLEDs were quantitatively investigated in this work. Although the mesa size is fixed, the peripheral length can be controlled depending on the μLED design. To clarify the relationship between the peripheral length and sidewall damage, the current density at peak EQE (J_{peak}) was investigated. J_{peak} offered the information of SRH non-radiative recombination since J_{peak} is proportional to it. It was quantitatively confirmed that if the peripheral length of the pixel becomes longer, the J_{peak} and SRH non-radiative recombination rate becomes higher. Usually, LEDs having high SRH non-radiative recombination rate shows low EQE. However, in this experiment, LED having the longest peripheral length showed the highest EQE; This behavior was further investigated by separately analyzing IQE and light extraction efficiency. Undoubtedly, IQE decreased with increasing the peripheral length. On the other hand, light extraction efficiency increased with increasing the peripheral length. This behavior is attributed to the fact that light extraction occurs not only from the top and the bottom but also to the sidewall, indicating that sidewall light emission increased total light extraction efficiency. Consequently, increasing light extraction efficiency not only compensates decreasing IQE but also increases peak EQE. Furthermore, it was confirmed that tetramethylammonium hydroxide (TMAH) treatment removed the lattice distortion that was observed by transmission electron microscopy at the sidewall. Correspondingly, the surface recombination rate is reduced by reducing carrier trap site that is part of SRH non-radiative recombination center, which improved peak EQE.

By systematically and quantitatively investigating the sidewall condition, this thesis guides the pathway how to realize high performance μLED for next-generation display.