Investigation of Light Extraction Efficiency in AlGaN Deep Ultraviolet LEDs Using FDTD Simulations

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Abstract

Light extraction efficiency (LEE) in AlGaN deep ultraviolet (UV) light-emitting diodes (LEDs) is investigated using three-dimensional finite-difference time-domain simulations. For flip- chip LED structures, LEE is obtained to be <10% due to strong UV light absorption in the p-GaN layer. In addition, LEE of transverse-magnetic (TM) modes is found to be more than ten times smaller than that of transverse-electric (TE) modes, which explains the decreasing behavior of external quantum efficiency of UV LEDs with decreasing wavelengths.

I. Introduction

Recently, deep ultraviolet (UV) light-emitting diodes (LEDs) based on AlGaN materials have drawn increasing attention for various applications such as water purification, sterilization, UV curing, and biomedical instrumentation [1-4]. However, despite rapid progress in increasing the performance of deep UV LEDs, the efficiency of AlGaN-based LEDs with wavelengths corresponding to the UV-C (200 to 280 nm) range is still too low to justify the replacement of current UV lamps. The light extraction efficiency (LEE) of AlGaN-based deep UV LEDs has been thought to be quite low due to UV light absorption in the GaN p-contact layer. The low LEE is one of main limiting factor of the efficiency of AlGaN deep UV LEDs. However, there have been few quantitative studies on the LEE of AlGaN UV LEDs. In this research, we investigate the LEE of AlGaN-based deep UV LEDs using numerical simulations. A three-dimensional (3-D) finite-difference time-domain (FDTD) method with a perfectly-matched-layer (PML) boundary condition is used for the simulation. Using the FDTD simulation, we calculate the LEE of representative deep UV LEDs with flip-chip structures.

II. Simulation Structure

The FDTD computational domains of the flip-chip UV LED structures for our LEE simulations are schematically drawn in Fig. 1. The layer structure of simulated LEDs is basically similar to that of recently reported deep UV LEDs [3,4]. On a sapphire substrate, an AlN buffer layer, an n-AlGaN layer, AlGaN multiple-quantum-well (MQW) active layers, a p-AlGaN electron-blocking layer (EBL) layer, and a p-GaN contact layer are subsequently grown. The thickness of the AlN and the n-AlGaN layer is assumed be 1 and 2 μm, respectively. A p-type electrode reflector exists below the p-GaN layer. For simplicity, the electrode reflector is assumed to be a perfect mirror with 100% reflectance. The absorption coefficient of the GaN layer, which has a strong influence on the LEE, is chosen to be 170,000 cm^{-1} [5,6]. We assume that the LED chip was not encapsulated, and thus it is exposed to air.

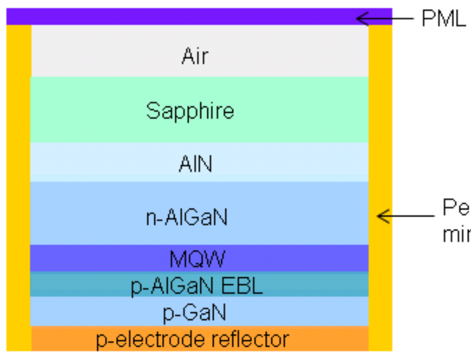

Fig. 1. Schematic side-view diagram of FDTD computational domains of flip-chip UV LED structures.

In the FDTD simulation, a single dipole source is positioned in the middle of the MQW active region. The peak wavelength and the full-width at half-maximum of the spectrum of light emitted from the MQWs is set at 280 and 10 nm, respectively. The dipole source is polarized in the direction either parallel to the MQW plane for the excitation of the transverse-electric (TE) mode or perpendicular to the MQW plane for the excitation of the transverse-magnetic (TM) mode. The distance from the dipole source to the p-GaN layer is fixed at 100 nm. The TE- and the TM-polarized light propagates mainly in the vertical and the horizontal direction, respectively. Therefore, the LEE of the TM-polarized light should be much lower than that of the TE-polarized light.

III. Results and Discussion

Fig. 2 presents our simulated results of the LEE for the

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FC LED structure shown in Fig. 1. The LEE of the TE and the TM mode is plotted as a function of the thickness of the p-GaN layer. As expected, the LEE of the TM mode is much lower than that of the TE mode for all p-GaN thicknesses considered. Depending on the p-GaN thickness, the LEE of the TE mode varies from 4% to 15%, whereas that of the TM mode varies from 0.2% to 1.1%. When there is no p-GaN layer, the LEE of the TE mode is still limited to be only ~15%, which is due to the total internal reflection of light inside the FC LED. The LEE for both modes varies periodically as the p-GaN thickness increases up to 100 nm. This periodic behavior results from the interference of upward emitted light and downward reflected light, and has also been observed in FC or micro-cavity LEDs operating in the visible wavelengths [7-9]. However, the LEE becomes nearly constant when the p-GaN thickness is larger than 100 nm because light is almost completely absorbed in the p-GaN layer for a p-GaN thickness of >100 nm.

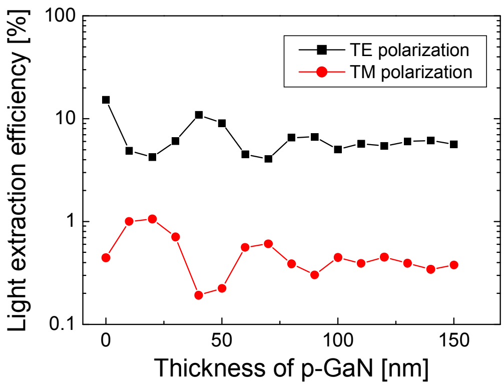

Fig. 2. Simulated results of light-extraction efficiency (LEE) for the FC LED structure shown in Fig. 1. LEE of the TE and the TM mode is plotted as a function of the thickness of the p-GaN layer.

When the p-GaN thickness is larger than 100 nm, the LEE of the TE mode is 5% to 6% and that of the TM mode is 0.35% to 0.45%. That is, the LEE of the TM mode is more than 10 times lower than that of the TE mode. This large difference in LEE between the TE and the TM mode implies that the LEE of UV LEDs may decrease considerably as the emission wavelength decreases. This is because the relative portion of the TM mode increases with decreasing wavelength. According to Refs. [10, 11], the relative portions of the TE mode and the TM mode become equal near ~280 nm. Then, by averaging the LEE of the TE and the TM mode, the LEE at a wavelength of 280 nm will only be ~3% when the p-GaN thickness is >100 nm. The EQE of the deep UV LEDs has been reported to decrease significantly as wavelength decreases, which has been mainly attributed to the decrease in the injection efficiency and the radiative efficiency with decreasing wavelengths. The results shown in Fig. 2 imply that the polarization-dependent LEE can also be responsible for the decrease in the LEE with decreasing wavelengths.

IV. CONCLUSIONS

In this work, the LEE of an AlGaN-based deep UV LED with flip-chip structures was investigated based on FDTD simulations. It was proved that the FDTD method was quite effective to quantitatively evaluate the LEE of deep UV LEDs for each polarization mode. The LEE of deep UV LEDs was obtained to be <10% at best due to strong UV light absorption in the p-GaN contact layer. The LEE of the TM mode was found to be more than ten times lower than that of the TE mode. The presented simulation results are expected to provide some insight into understanding and hence increasing the LEE of AlGaN-based deep UV LEDs.

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