The Future of DUV LEDs

−Development of light-extraction technology by nanophotonic structures for practical application of DUV-LEDs−

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Background

The importance of deep-ultraviolet (DUV) light with 200–350 nm wavelength has been increasing in various fields from information, electronic devices to safety and sanitary environment, medical application, such as high-density optical data storage, disinfection of bacteria and viruses, purification of water and air, biosensing, biological and materials analysis, photolithography, prevention of nosocomial infection, and photodynamic therapy. It's becoming an important infrastructure that supports our society. For deep-ultraviolet light sources, gas light sources such as mercury lamps and excimer lasers has been conventionally used. However, the gas light source is short-lived, large in size and requires large power consumption. For such reasons, replacing it with semiconductor solid state light source, which is small in size and power consumption, has been much needed. In addition, as typified by the adoption of Minamata Convention on Mercury in last year, global efforts have been accelerated to reduce or eradicate harmful substances to the human body or environments such as mercury and fluorine. Therefore, the application of deep-ultraviolet light-emitting diodes (DUV-LEDs) with low environmental impacts, high efficiency and long life is strongly desired (Figure 1).

Under these circumstances, the R&D of DUV-LEDs has been very active all over the world. Although the recent performance has been greatly improved, the further improvement in efficiency is necessary for the practical use. The R&D of DUV-LEDs by NICT was adopted as A-STEP (Adaptable and Seamless Technology Transfer Program through Target-driven R&D), the stage for promotion of industry-academia collaborative R&D (feasibility study stage), Seeds Validation. NICT has been engaged in the full-fledged R&D with the aim to apply DUV-LEDs in cooperation with a company, which has been conducting joint research with NICT since December 2013. In this article, we will introduce our efforts towards the efficiency improvement of DUV-LEDs and its application such as the development of significant enhancement technologies in light-extraction efficiency by making use of nanophotonic structures.

The progress and challenges of DUV-LEDs

DUV-LEDs consist of AlGaN-based semiconductors of the direct transition type. Varying the mole fraction of AlN and GaN enables AlGaN-based DUV-LEDs to emit the light with almost full DUV range (210–365 nm). In semiconductor LEDs, if there are high-density defects in the crystal, the electron-hole pairs generated by injection current can easily be changed into the heat through defects without light emission. In AlGaN-based DUV-LEDs, since 10^8 cm^{-2} or more of high-density defects (dislocations) occur on the active layer (Figure 2 (a)) due to the large lattice mismatch in commonly used sapphire (Al_2O_3) substrates, there have been issues of the low internal quantum efficiency and the short lifetime. However, the recent progress of R&D of buffer layer technology and AlN substrates in several groups has brought the significant improvement on these issues. NICT has been conducting R&D of DUV-LED using AlN single crystal substrates in cooperation with Tokuyama Corporation. Since it is possible to reduce the defects (reduction of dislocations) such as less than 10^6 cm^{-2} with DUV-LEDs

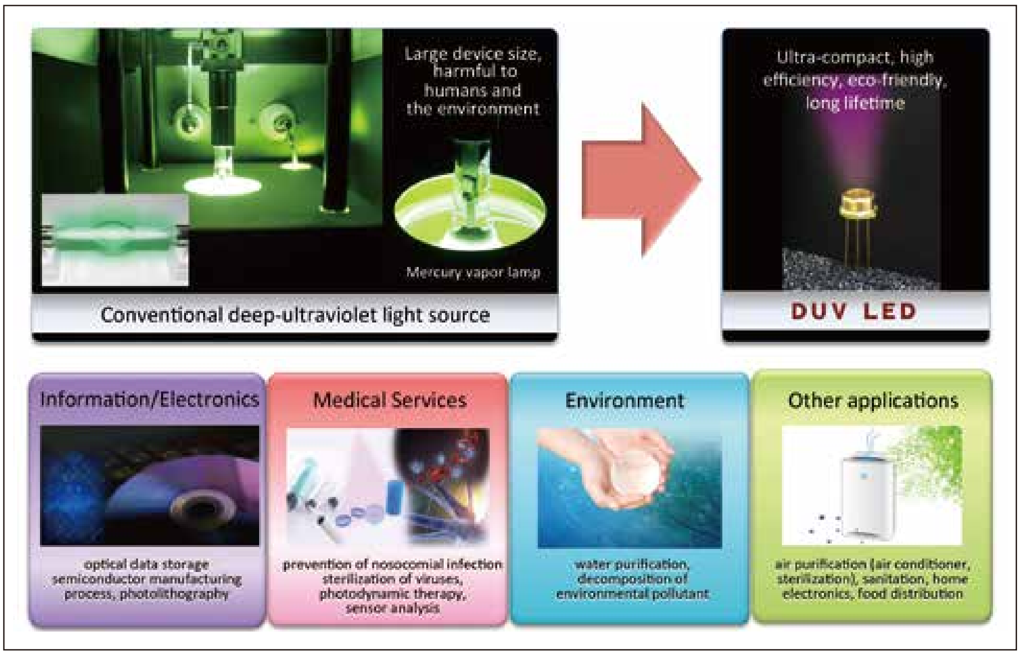

Figure 1 The impact and the applications of DUV-LEDs

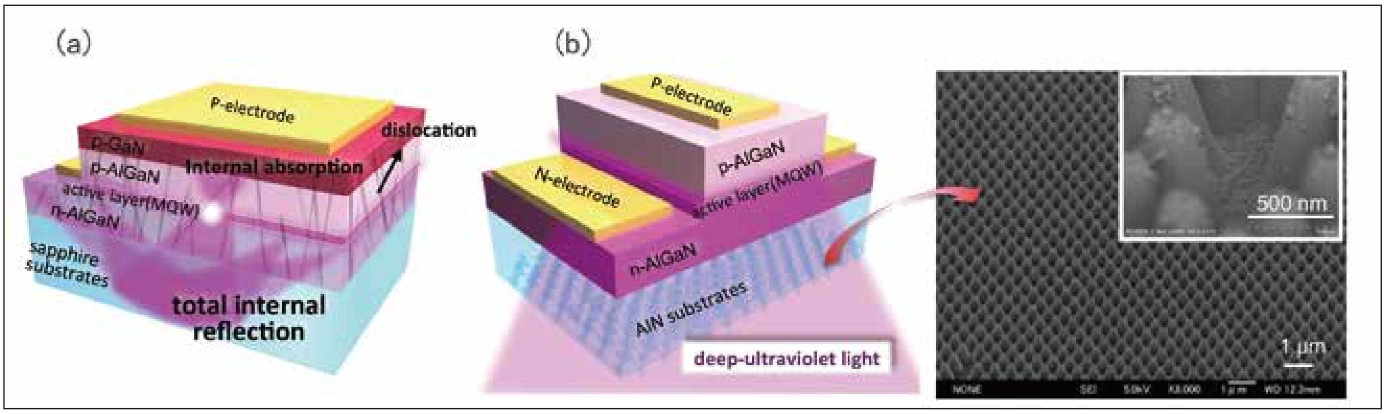

Figure 2 The device structure of AlGaN-based DUV-LEDs
(a) Schematic diagram showing problems of conventional DUV-LEDs (high-density dislocation defects, very low light-extraction efficiency)
(b) Schematic diagram of light-extraction structure with nanophotonic structure and its picture by Scanning Electron Microscope

on AlN substrates, AlN substrates has high advantages in the lifetime and the reliability.

The current biggest factor that inhibits the efficiency improvement in DUV-LEDs is the problem of the very low light-extraction efficiency. This is a particular problem of DUV-LEDs. It is difficult to extract the light due to the internal absorption in the p-type GaN contact layer and the total reflection at the substrate interface. Therefore, most of the light emitted in the active layer change into thermal energy (Figure 2(a)). Especially, with AlN single crystal substrates, since the refractive-index is large (n = 2.29 @265 nm) compared to sapphire's, the critical angle get small (25.9 degrees). Thus, you can extract the only small amount of light. The results of theoretical calculation by 3D finite-difference time-domain (3D-FDTD) method, with absorption in p-type GaN layer considered, showed that the efficiency of light extraction from the flat surface (light extraction surface) of AlN substrates was just only about 4%. In other words, this problem is the main cause of very low external quantum efficiency in DUV-LEDs. With that being said, the improvement of DUV-LEDs depends on how to improve the light-extraction efficiency.

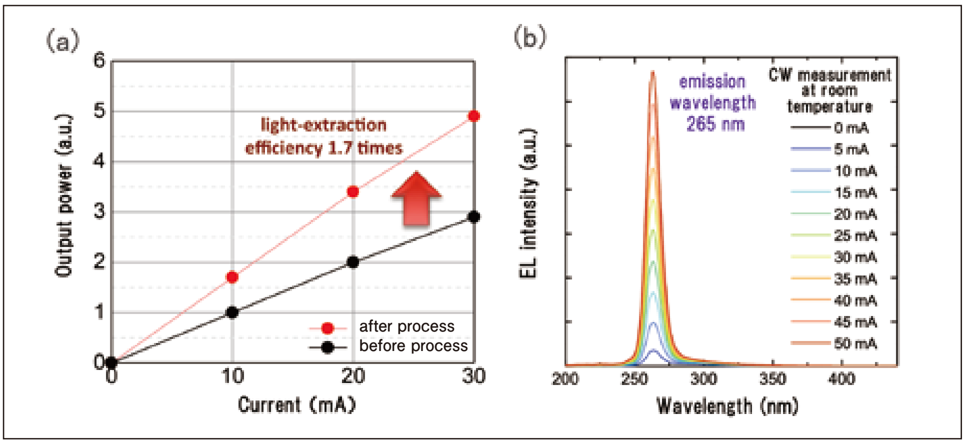

Figure 3 The emission characteristics and the performance improvement results of DUV-LEDs
(a) The improvement of the output power of DUV-LEDs with nanophotonic structure
(b) Emission spectra for each driving current

Performance improvement of DUV-LEDs by nanophotonic structure

The biggest issue preventing performance improvement and practical application of DUV-LEDs is their limited light-extraction efficiency. Currently, we have achieved the highest light-extraction enhancement of DUV-LEDs on AlN substrates in the world. We achieved the high light-extraction efficiency with the reduction of total internal reflection on AlN substrates by proposing and developing new light-extraction structure. The remarkable enhancement of light-extraction is caused by the multiplier light enhancement effects of periodic convex structures at the wavelength scale and smaller fine round convex structures (Figure 2(b)). Not only improvement of the light-extraction efficiency but light output uniformity between devices, manufacture cost, and yield rate are also considered in this unique structure. We achieved the fabrication of light-extraction nanophotonic structures with high precision and high uniformity for DUV-LEDs on AlN substrates. When compared to the devices without the nanophotonic structures, the relative emission intensities of DUV-LEDs recorded with the structures were as high as 1.7 or more (Figure 3). Also, the standard deviations of enhancement between devices were less than 0.03, and we highly achieved the reduction of the dispersion of output power between devices, which is essential for practical use. In fact, we fabricated a prototype of 265 nm DUV-LEDs in collaboration with Tokuyama Corporation and achieved the output power of more than 30 mW. And furthermore, for the reliability measurements, the lifetime for the 50% power reduction at 150 mA was estimated to be over 6,000 hours in 265 nm DUV-LEDs.

Future prospects

These results are expected to bring significant progress toward the improvement of efficiency and reliability, and the practical use of DUV-LEDs. In the future, using nanophotonic structure, we will further improve the light-extraction efficiency and develop the mass production and low cost technology such as nano-imprint technology. By these technologies, we will develop DUV-LEDs that has a high competitive advantage in both performance and cost.

The industrial uses of DUV-LEDs in various fields are expected, and there is a chance that the LED grows into a huge market. Ultimately, by the realization of mercury-free, ultra-compact, highly efficient, and long lifetime DUV solid light sources opening the possibility of new DUV applications, we would like to contribute to build lively, safe and secure and environmentally-friendly society.