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# Current Status and Future of III-Nitride Ultraviolet and THz Emitters

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**Abstract**

***Deep-ultraviolet light-emitting diodes (DUV-LEDs) with emission wavelength between 222 - 351 nm were demonstrated which were achieved by developing AlGaN/AlN crystal growth techniques. We succeeded in significant increase of internal quantum efficiency (IQE) and light-extraction efficiency (LEE) and achieved an external quantum efficiency (EQE) more than 20% for DUV-LED. We are also developing unexplored frequency (5 – 12 THz) terahertz quantum-cascade lasers (THz-QCLs) using GaN-based semiconductors. We achieved first observation of inter-subband stimulated emission from GaN/AlGaN QC-structures by current injection.***

## 1. Introduction

The development of new-frequency semiconductor light sources, such as deep-ultraviolet (DUV) light-emitting diodes (LEDs), laser diodes (LDs) and terahertz quantum-cascade lasers (THz-QCLs) are attracting much attentions because of their wide variety of potential applications.

AlGaN DUV-LEDs are attracting a great deal of attention, since they have the potential to be used in a wide variety of applications, such as for sterilization, water purification, UV curing, and in the medical and biochemistry fields, and so on, as shown in Fig. 1.

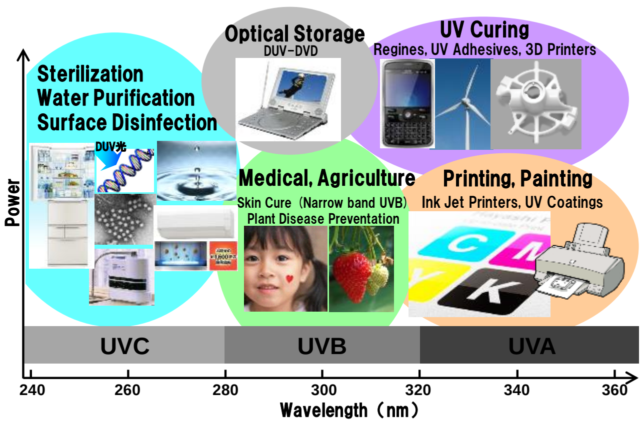


Fig. 1 Potential applications of deep-UV (DUV) LEDs and LDs

As a result of recent developments in AlGaN DUV LEDs, high internal quantum efficiencies (IQE) of more than 60-70 % have been achieved by reducing the threading dislocation density (TDD) of the AlN, by improving the crystal growth technique and/or by the introduction of AlN single crystal wafers. Also we achieved significant increase of electron injection efficiency (EIE) by introducing multi-quantum barrier (MQB) electron blocking layer (EBL). We have demonstrated AlGaN DUV-LEDs with wavelength range between 222 - 351 nm including the shortest wavelength (222 nm) of the AlGaN quantum well (QW) LEDs. We have also developed top level high output power more than 80 mW and external quantum efficiency of 10 %.

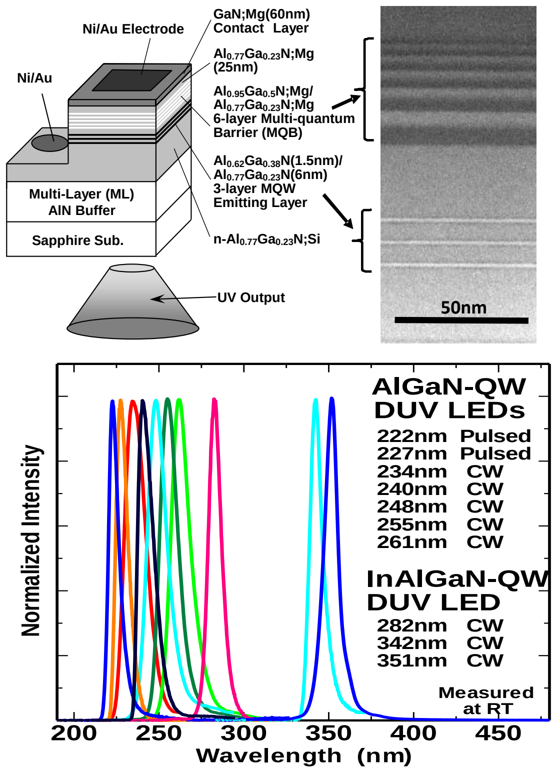


Fig. 2 Schematic structure, cross sectional TEM image and emission spectra of AlGaN and quaternary InAlGaN-based DUV-LEDs

However, the wall-plug efficiency (WPE) of AlGaN DUV-LEDs still remains at 2 - 3 %. The first target for the efficiency of AlGaN DUV-LEDs is to go beyond an efficiency of 20%, which would make them comparable to germicidal mercury lamps. A significant problem is that the light-extraction efficiency (LEE) of AlGaN DUV-LEDs is still quite low because of heavy UV absorption through the p-GaN contact-layer. Clearly, improving the LEE is recent major topic in the development of AlGaN DUV-LEDs.

In this work, we demonstrated an EQE of over 20% in an AlGaN DUV-LED by the significant increase of LEE by introducing a transparent p-AlGaN contact layer and a highly reflective p-type electrode and an epitaxial lateral over growth (ELO) AlN buffer layer on a patterned sapphire substrate (PSS). Recently, we also demonstrated WPE of 9.6 % for an AlGaN DUV LED by integrating a sapphire lens on the backside of sapphire substrate of a flip-chip LED. Also we demonstrated a dramatic LEE enhancement of an AlGaN DUV LED by using highly reflective photonic crystal (PhC) contact layer showing a perfect-reflection property. Using these effects, we aim to develop DUV LED with WPE of more than 20 %, in near future.

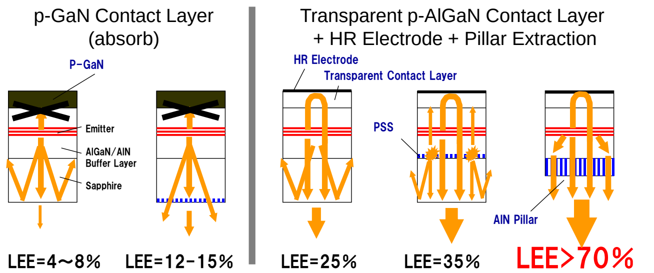


Fig. 3 Schematic LED structures for improving light-extraction efficiency (LEE) of DUV LED and roughly calculated LEE values

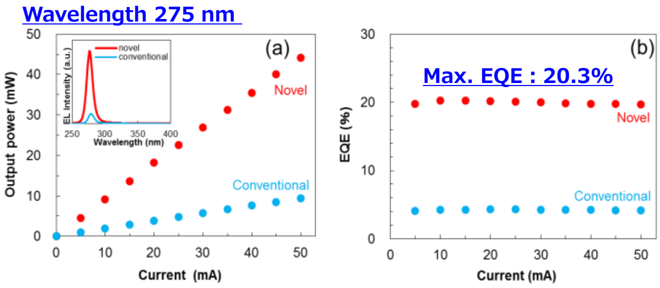


Fig. 4 Current- output power (I-L) and I-EQE characteristics DUV LED demonstrating world top EQE of 20.3%, achieved by improving LEE

Also attracting a great deal of attention are THz-QCLs, which are compact, high-power, narrow line-width THz laser light sources that have the potential to be useful in a variety of applications such as in medical imaging, security screening, wireless communications, etc. We are studying THz-QCLs using III-nitride semiconductors, with which there is the potential to realize QCLs with wide frequency ranges. The electron-longitudinal optical (e-LO) phonon energy ($E_{e\text{-}LO}$) of GaN-based semiconductors is large, being about 90 meV, which is almost three times that of GaAs semiconductors (36 meV). Also the maximum conduction-band discontinuity ($\Delta Ec$) is 1.86 eV for GaN/AlN, which is more than three times that of an InGaAs/AlGaAs (0.6 eV) lattice matched to an InP substrate. Such unique material properties are attractive for developing QCLs operating at previously unexplored frequencies. The current status of the operating frequency range achieved by GaAs-based THz-QCLs is limited to 1.2～5.2 THz. On the other hand, by shifting the e-LO phonon absorption frequency, the operating frequencies of GaN-based THz-QCLs are expected to be in the range 3～20 THz, including the unexplored frequencies from 5 to 12 THz. Moreover, by using the large band discontinuity of GaN/Al(Ga)N superlattices (SLs), it is expected that 1～8μm band infrared (IR)-QCLs will be realized. We fabricated GaN/AlGaN THz-QCLs comprising a pure-3-level system design and conducted the first demonstration of stimulated emission with a III-nitride-based QCL. We achieved stimulated emission with a GaN-based QCL in the unexplored frequency range from 5.4 to 7 THz.

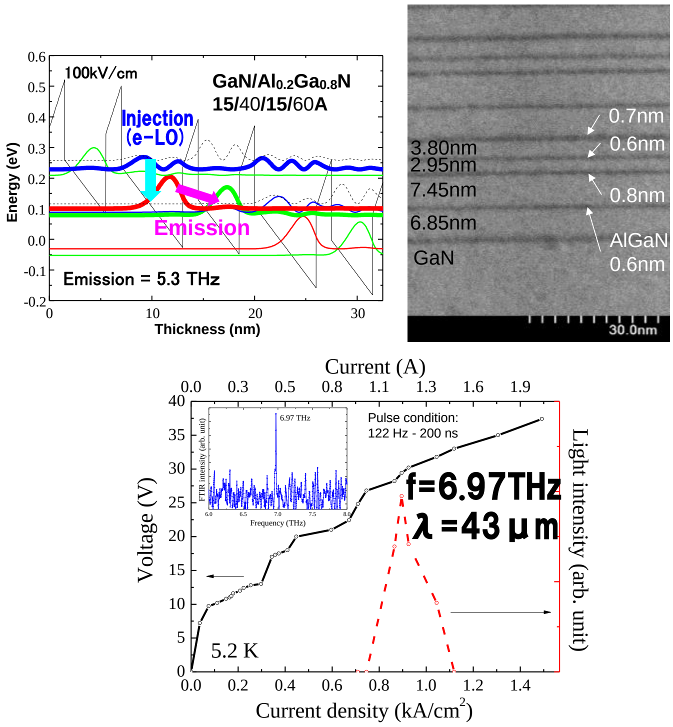


Fig. 5 Quantum structure design, cross-sectional TEM image of fabricated GaN/AlGaN THz-QCL and emission spectrum, I-V and I-L characteristics of the stimulated emission observed from the GaN-based QCL


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