used in blue [134] and UV-A LEDs [135] The micro-pixel LEDs design was further extended to the formation of photonic crystals [136] by the reduction of the size and the period of the array elements [137,138]. An LED design with interconnected micropixels separated by the n-AlGaN contact metal was also shown to be very efficient in achieving the desired uniform current pumping for deep UV-C LEDs, and devices with emission at 255 nm with 1 mW dc and 3.4 mW pulse powers and corresponding maximum quantum efficiencies of 0.14 % and 0.3 % (in dc and pulse pumping, respectively) were demonstrated [53]. Figure 7 shows images obtained from a CCD camera with conventional geometry and micro-pixel designed UV LEDs during cw operation. Changes in color indicate non-uniform emission due to spatial variations in current injection.

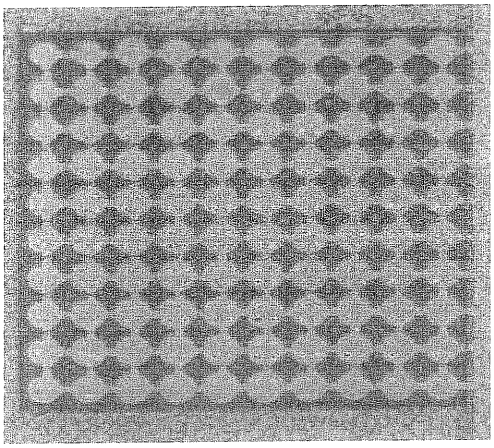


Figure 7. CCD image of a micro-pixel UV LED (total active area of the junction is 220 μm^2) under continuous wave bias condition showing the reduction of lateral current crowding and thereby reducing joule heating.

Thermal management. The DUV LEDs fabricated on sapphire substrates suffer from excessive self heating under continuous wave operation. This is caused by a combination of factors such as poor thermal conductivity of sapphire, higher operating voltages resulting in eddy current losses and low emission efficiencies. Under typical cw (continuous-wave) operation, most of the sapphire-based deep UV LEDs suffer from excessive self-heating due to the relatively higher operating voltages (which result in eddy current losses), low emission efficiencies and poor thermal conductivity of the sapphire (0.35 W cm^{-1} K^{-1}). In an attempt to mitigate the device self heating problem, Chitnis et al. employed flip-chip packaging. In this method, the diced LED chip is mounted in a flip-chip configuration on a high thermal conductivity 175 W/mK insulating AlN carrier with thermo-compression gold bonding. The AlN carrier with flip-chip UV LED is then mounted on a gold-coated header (Fig.8a). Figure 8(b) presents the dc optical power as a function of pump current for the standard and the flip-chip packaged LEDs. As can be seen from the graph, the performance of the device is improved by the flip-chip packaging technique. The saturation current (which is indicative of device self heating) increased for flip-chip package thereby enabling higher output power with higher input drive currents. Also the slope of the curve improved due to better light extraction after flip-chip packaging.

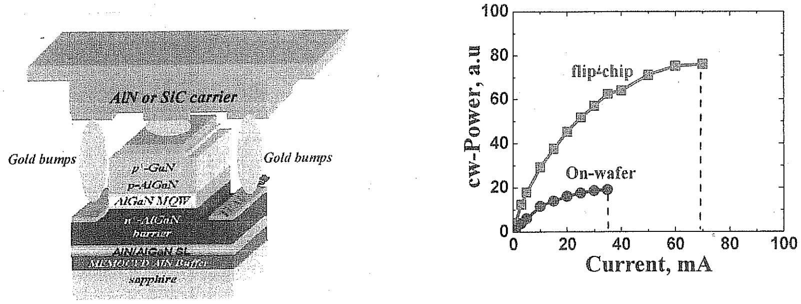
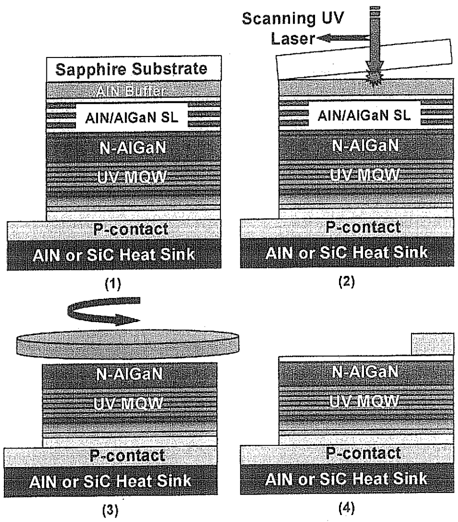


Figure 8. (a) Schematic of a flip-chip packaged deep UV LED, (b) dc output power of standard and flip-chip mounted UV LEDs vs pump current.

Several groups have also started research efforts aimed at developing deep UV LEDs with vertical conduction [15-16]. For this work the deep UV LEDs are grown over



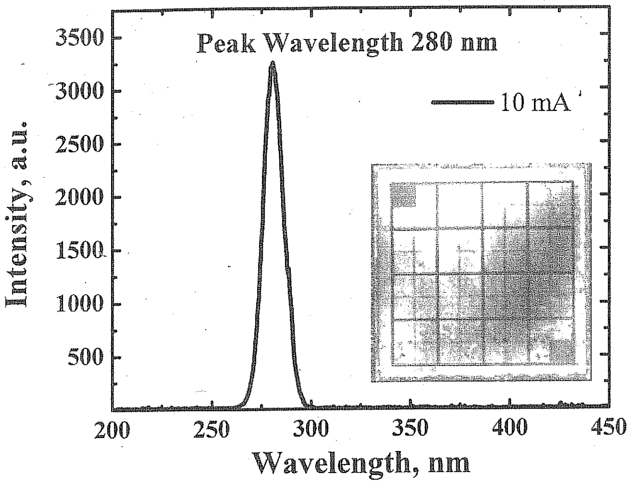


Figure 9 (a) Schematic of the formation process of vertically conducting deep UV LED by removing the sapphire substrate by laser assisted lift-off,
(b) Electroluminescence spectrum of a vertically conducting 280 nm LED (inset) n-AlGaN surface of the LED structure after the removal of sapphire by laser lift-off and AlN and superlattice layers by lapping and polishing.

sapphire substrates with a GaN buffer layer. This buffer layer allows the liftoff of the sapphire substrates and a backside n-contact resulting in a vertical conduction geometry. However the use of GaN buffer layer degrades the overall quality of the LED epilayers leading to performance levels well below those for lateral geometry devices. The first successful fabrication of a large area vertical conduction 280 nm deep UV LED over sapphire with AlN buffer layers has been fabricated by Asif Khan et al. For this vertical geometry deep UV LED, laser lift-off was used to remove the sapphire substrate and form a backside n-contact to achieve vertical conduction (Figures 9 (a) and (b)). Similar to their visible counterparts the vertical geometry devices provide an excellent vehicle to produce large area deep UV LED lamps. They are expected to have much higher output powers due to the ability of sustaining much higher pump currents (as high as 1 amperes) and a substantial increase in the light extraction efficiency.

Light extraction. Enhancing light extraction from an LED is an important factor to improve the device performance. The low light extraction from a nitride based LED is caused by the large difference in refractive indices between the GaN (refractive index is 2.5) and the air space (refractive index is 1). Due to this, a major portion of the light generated in the active layer of the LED is reflected back into the device. Various methods have been employed to reduce the problem of light trapping in the DUV LEDs. Order et al. achieved increase of 340 nm LED output power using photonic crystals. The optical power was reported to increase from 44.5 to 86.6 μW. Khizar et al. reported on the fabrication of 280-nm AlGaN based DUV LEDs on sapphire substrates with an integrated microlens array. Microlenses with a diameter of 12 μm were fabricated on the sapphire substrate by resist thermal reflow and plasma dry etching. LEDs were flip-chip bonded on high thermal conductive AlN ceramic submounts to improve the thermal dissipation and the emitted UV light was extracted through the sapphire substrates, and 55% increase of output at 20 mA dc driving was reported. Khan [139] reported the development of UV transparent planar Fresnel microlenses over sapphire substrates. These lenses were formed on sapphire using a SiO_2-based coating material patterned by direct e-beam writing. A vertical step-like profile of each ring was achieved through multiple exposures so that each ring had a maximum thickness of 560 nm graded in 4 steps to zero thickness. Lens design was optimized for 280 nm wavelength with 4π maximum phase shift and it was found to work well for a visible LED providing 2π maximum phase shift.

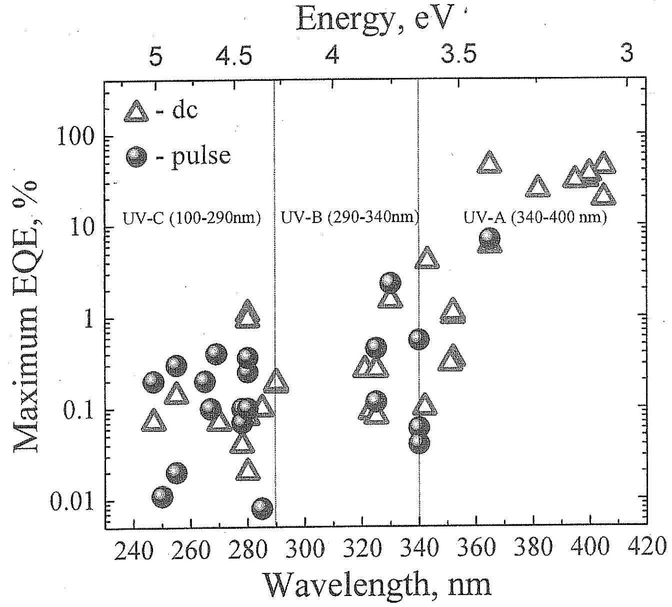


Figure 10. Summarized plot of maximum external quantum efficiency reported for cw (open) and pulse (closed) operations of UV LEDs.

Despite the material and device challenges associated with growth of very wide bandgap III-nitride AlInGaN materials, UV LEDs have advanced from less than 0.1% EQE to 1-10% depending on emission wavelength, over the last 10 years. While the production of these devices is expected to ramp-up, there are great challenges lying ahead. As seen from Fig. 10, the efficiency of deep UV LEDs is still not comparable to that of UV-A devices. An increase of the external quantum efficiency up to ~ 10 % must be achieved via further device optimization. The reduction of defects and improvements in doping in AlGaN layers with high Al molar fraction are of great importance for improving the efficiency of deep UV-C emitters. Native single crystal AlN substrates as well as innovative doping solutions must be considered. Another challenge is the light extraction, where novel encapsulation materials transparent down to ~ 200 nm should be explored.

UV Laser Diodes

The lack of compact solid-state light sources in the blue-violet-UV region of the spectrum has stimulated the development of growth techniques and prompted research on fabrication procedures for nitride-based materials. LDs occupy a specific and important place in this area, and violet (405 nm) emitting nitride based LDs have undergone tremendous progress in the last 13 years with lifetimes exceeding 10,000 hours, thus becoming commercially acceptable [140]. New shorter wavelength LDs might find immediate applications in frontier technologies such as super high-density optical storage systems, since recording densities in the compact disk are proportional to approximately the reciprocal of the wavelength squared. Other important applications include high resolution laser printers, chemical sensing equipment, projection full-color displays, position location systems, bio-agent detection and control, biotechnology applications, fine photolithography, and many more. The semiconductor laser has a number of unique advantages when compared against other coherent light sources, namely high efficiency, robustness, high speed, higher reliability, and potentially lower cost. A semiconductor UV LD would be a welcome replacement for the notoriously unreliable He-Cd gas laser. However, design and manufacturing of LDs itself is a much more complex problem in comparison with LEDs ,and requires even higher quality of materials. Additional challenges present themselves in the device design, namely, the tiny laser cavities require low-loss waveguides with cladding layers featuring abrupt interfaces for optical confinement, as well as structures for channeling the electron and hole currents into the recombination zone. The realization of facet mirrors which are smooth enough to define the laser cavity with very low losses need a special approach, as well.

The first nitride-based injection laser was reported in 1995 by Akasaki and co-workers, a device utilizing an InGaN active layer yielding an emission line at 405 nm.[141] Later in 1996 Nakamura et al. also demonstrated nitride-based LDs [142-143144]. Basically over the next few years rapid and impressive improvements in the performance of those nitride-based lasers were achieved predominantly by Nakamura and his co-workers at Nichia Chemical Industries. Those early works on nitride-based LDs usually covered the blue to near-UV (380-450 nm) spectral range.

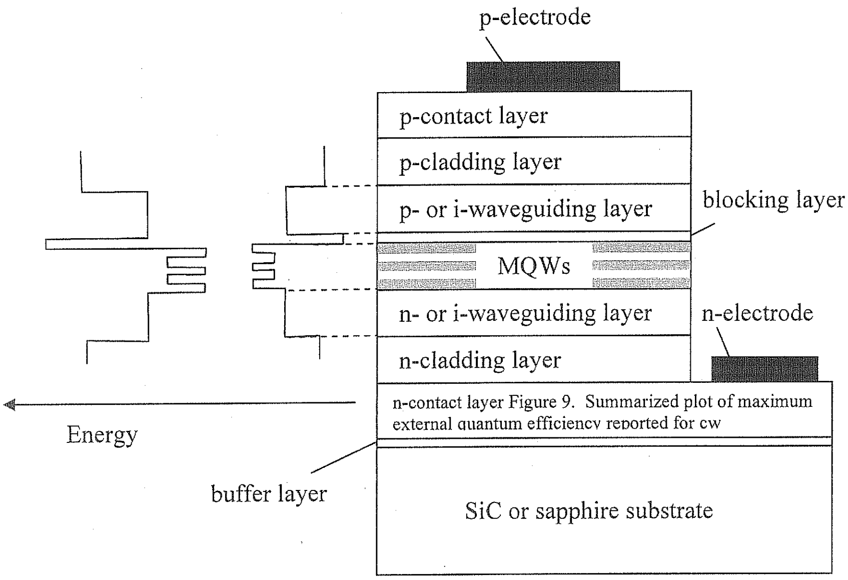


Figure 11. Typical schematic of the UV LD and possible energy band diagram.

Following these developments, LDs have been demonstrated which operate in the near-UV down to 360 nm [145-149]. There are now nitride LDs with various different improvements such as LDs with distributed Bragg reflectors [149,150-152], high-power output [153-155] and even different microcavity design [156,157]. LDs reported by different groups have usually operated at room temperature under both pulsed and cw current injection regimes and the designs are typically based on combinations of the InGaN/GaN/AlGaN heterostructure system. The lasing threshold has been as low as a few kA/cm^2 whereas output powers can typically reach up to several tens of mW, although there are several cases where even hundreds of mW have been emitted. All these LDs were based on optical transitions below the GaN band-gap and the active regions always included at least a small percentage of In. The aluminum content in alloys of AlInGaN or AlGaN was extremely low.

The attention is now focused on the results on LDs where the light emission range has been expanded beyond the GaN band-gap, i.e. with the wavelength shorter than ~ 360 nm. As mentioned earlier in this chapter, the shift of the wavelength towards deeper UV regions has been a challenging task basically due to the problems related with the incorporation of higher amount of Al into the nitride alloys. In this regard, the main problems in LD fabrication are: i) Materials quality; ii) mirror facets; iii) optical confinement; iv) operation lifetime. Let us discuss these issues.

High quality (crack free, low threading dislocation densities) AlGaN materials with relatively high concentrations of Al are necessary since we need to confine sufficient carriers in the quantum well in order to invert the population. In order to invert the electron population very high injection levels are required in comparison with LEDs, and any non-radiative recombination paths will cause serious heating of the material. Such non-radiative losses would result in an increase of the lasing threshold or even the vanishing of the population inversion. High quality mirror facets are necessary in order to obtain reasonable feedback in the cavity. Cleaving of nitrides on substrates which are a different material, especially sapphire, is challenging. The cladding layers should contain a sufficiently high content of Al in order to provide a significant decrease in refractive index and thus effectively confine the coherent light within the active layer. Again, this causes strain and often cracking of the layers. Finally, the reported lifetimes of the UV LDs are quite short, too short from the commercial viewpoint. Hence, no wonder that only a small number of research efforts have been undertaken on UV LDs, and consequently only a few works have been published so far [158-162,[163]]. The reported wavelength region of laser emission spans only from 343 to 360 nm. Obviously there has not been a breakthrough in the UV-LD technology since these optical transitions are still very close to GaN band-gap. The shift of the lasing line towards the UV region has basically been achieved either due to rather small Al-incorporation into alloys or just because of sufficient quantum confinement in very narrow quantum wells.

The basic structure of these near-UV LDs is similar to the ones operating in longer wavelength regions. Figure 10 shows a typical schematic diagram of the LD structure along with the possible energy-band configuration. In all cases the MOCVD growth technique has been employed. Notably, sapphire was used as substrate [158-162] and only Edmond et al.[33] have successively applied SiC substrates. However, in all cases special measures were undertaken in order to reduce dislocation and other defect densities in the layers. A very effective approach for greatly reducing the densities of defects such as threading dislocations employs the use of epitaxial lateral overgrowth or ELOG [164]. With the ELOG approach, a thin film of GaN is deposited over a sapphire substrate, and this film is then coated with an insulator such as SiO_2. Stripes are then etched in the oxide back to the GaN, and then a second nitride growth sequence is undertaken, where the new nitride material only grows up through the stripes. The new GaN film also grows laterally over the SiO_2 surface, and this lateral material can be nearly free of defects, allowing the fabrication of excellent laser structures over it [165]. In the process of fabricating such devices, a few authors successively applied low-temperature deposition for buffer layer or additional interlayer for suppressing crack generation before attempting to deposit the actual LD structure [160-162].

Usually the active LD region consisted of several QWs [159-162]' or even a single QW [158] formed either with GaN [161,162] AlInGaN [158,159] or AlGaN [160] serving as the well material. Typical widths of LD ridges are from 2 to 20 microns whereas cavity lengths vary from 400 to 1500 microns. As an example, a specific LD structure reported by by Iida and coworkers [155-162] is analyzed. The active region of the LD was aligned on the ELOG region to provide material with low-threading dislocation-density. The n-contact layer consisted of a 4 μm thick $Al_{0.18}Ga_{0.82}N$ layer, as well as an additional n-cladding layer. Then, an unintentionally doped $Al_{0.08}Ga_{0.92}N$ waveguiding layer (120 nm), three pairs of GaN (3 nm)/$Al_{0.08}Ga_{0.92}N$ (8 nm) MQW to form the active layer, an unintentionally doped $Al_{0.08}Ga_{0.92}N$ waveguiding layer (120 nm), a p-type $Al_{0.25}Ga_{0.75}N$ (20 nm) electron-blocking layer, a p- $Al_{0.18}Ga_{0.82}N$ (700 nm) cladding layer and p^+-

GaN (20 nm) contact layer were successively stacked. The laser cavity mirrors were formed by cleaving. Similar LD structures have also been successfully applied by other authors. The dopants of Si and Mg are typically used for n- and p-doping, respectively.

Figure 12 illustrates the spectral properties of the LD obtained by Masui et al.[158] namely, electroluminescence spectra at current densities below threshold [part (a)] and above threshold [parts (b) and (c)]. Figure 13 shows typical voltage vs. current characteristics and light output versus current characteristics of the LD under pulsed condition which operated at the wavelength of 350.9 nm [161].

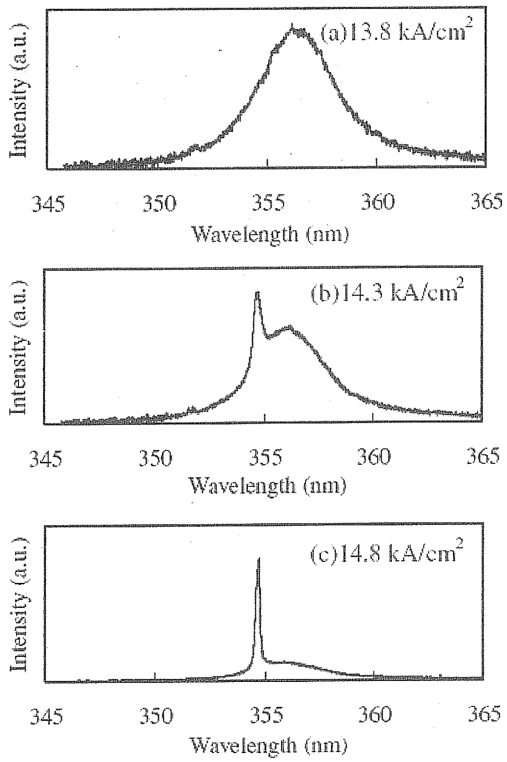


Fig 12. Emission spectra of UV LDs, composed of $Al_{0.09}Ga_{0.91}N$ wave guiding layers and $Al_{0.14}Ga_{0.86}N$/ $Al_{0.09}Ga_{0.91}N$ cladding layers at different current densities

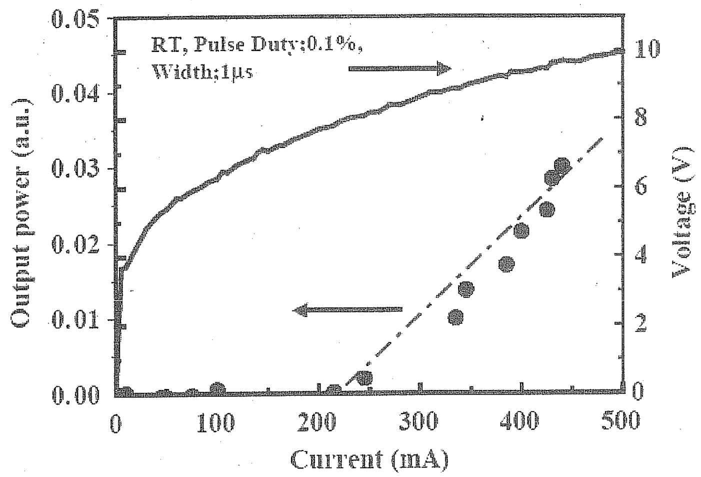


Figure 13.Voltage versus current characteristic and light output versus current characteristic of UV-LD under pulsed condition at room temperature.

The precursor of future practical device designs for injection lasers operating in deeper regions of the ultraviolet must be as a first step the realization of efficient photoluminescence and even stimulated emission in this range using optical pumping. There are now some new materials and improved structures with better quality, and a number of recent results seem to be promising in this regard. There are several reports on lasing in this deeper UV region under photoexcitation in nitride-based MQWs [63,166- 169]. A stimulated emission line at 258 nm was observed in $Al_{0.5}Ga_{0.5}N$/AlN MQWs grown on a bulk single-crystalline AlN template under strong selective photoexcitation of the quantum wells [63,166]. Improvement of crystal quality of the AlGaN MQW structure by a combination of flow-rate modulation epitaxy and a new AlN/GaN multi-buffer layer [169] allowed the authors to achieve lasing at 241 nm at room temperature. Even shorter wavelength lasing (231.8 nm) was reported in AlGaN MQWs grown on a SiC substrate under photoexcitation at 20 K [168]. Figure 14 illustrates typical lasing spectra of a preliminary AlGaN MQW laser under optical pumping with different Al concentrations in the quantum well and the quantum barrier obtained by Takano et al.[169]. More recently, Shatalov et al. [170] reported the first ever room temperature (RT) stimulated emission at 214 nm under pulsed condition using high quality AlN layers that were grown over patterned sapphire substrates by a pulsed lateral epitaxial overgrowth (PLOG) process. Figure 15 shows the stimulated edge-emission spectra from the PLOG AlN film for the E || c and the E ⊥ c polarizations. As seen from Fig. 14, the stimulated emission signal was strongly polarized with E || c [transverse magnetic (TM) mode].

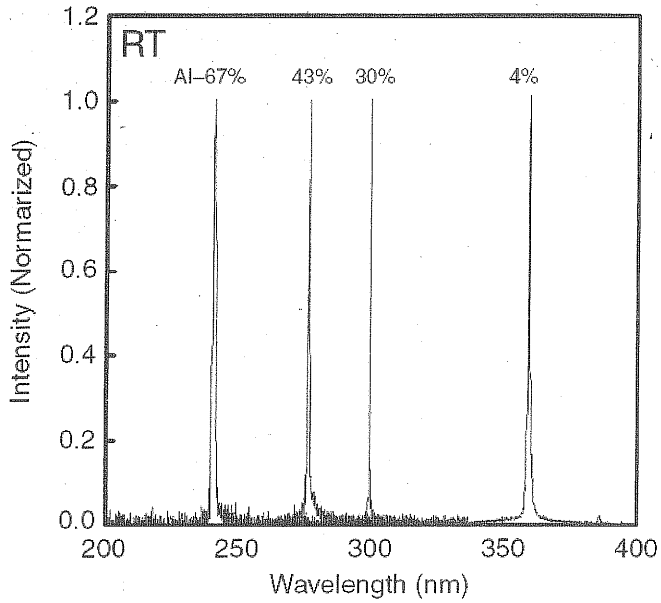


Figure 14. Lasing spectra of 354.5 nm AlGaN MQW laser under optical pumping.

These observations are in agreement with previous reports that suggest the stimulated emission from $Al_xGa_{1-x}N$ ($x \geq 0{:}65$) and AlN to be strongly polarized with E || c due to the dominance of the TM optical gain [171,172,173]. This is in contrast to GaN, where the stimulated edge emission signal is transverse electric (TE) polarized ($E \perp c$) due to the dominance of TE optical gain as well as the higher facet reflectivity (lower threshold) for the TE-mode. For comparison we also measured the edge stimulated emission spectra for a GaN layer grown by MOCVD on sapphire. This data presented in Fig.14 confirms the expected polarization differences. Similar difference in polarization properties was also found for $Al_xGa_{1-x}N$ multiple quantum well structures with different Al content.

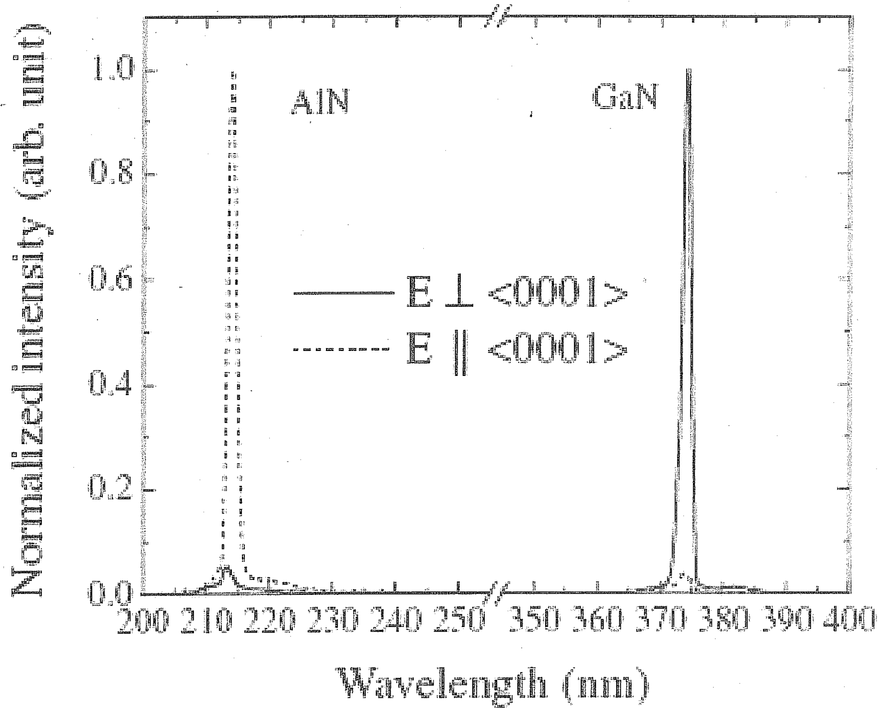


Figure15. Stimulated edge emission spectra of AlN (214 nm) and GaN for TE and TM polarizations.

Thus there are some very promising new approaches and we are entitled to expect in the near future a further shift of the nitride-based UV LD emission towards shorter wavelengths. A fully functional deep UV nitride-based injection laser lies just over the horizon, especially because of the increasing availability of bulk nitride substrates and improvement in growth techniques.

Summary

Driven by the need for efficient, compact and robust solid-state UV optical sources, massive research efforts have been undertaken in the past two decades to develop III-nitride based UV and DUV emitters. Despite several fundamental problems, such as control of heteroepitaxy and doping, high efficiency near UV LEDs, extremely short wavelength UV LED and cw operation of UV LD have been achieved, and several of them have already been commercialized. There are still great many challenges left to be solved and need research focus. Development of alternative precursors for MOCVD growth of AlGaN may improve control of heteroepitaxy and minimize impurity incorporation. Improvements in growth techniques and the availability of nitrides bulk substrates should trigger massive improvement of device performance in the near future. The problem of p-type doping of AlGaN with high Al concentration will likely be the major obstacle for achieving deep UV LEDs with efficiencies as high as 5-10 %. Large difference in Al molar fraction between waveguide and clad layers required for efficient waveguiding in UV LD structures also poses a significant challenge in the growth and strain control of these AlGaN based layers. Alternative concepts for LED and LD device design involving approaches of nanoelectronics and nanophotonics should be considered and these may overcome some of the above fundamental problems.

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