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DEEP ULTRAVIOLET LIGHT EMITTING DIODES (DUV LEDS)

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Abstract. There are a variety of applications for devices that extend into the deep-UV, including biological agent detection and optical storage. The nitride material system is a set of semiconducting compounds that have wavelengths that span a broad range, from yellow to deep-UV. AlGaN has a direct bandgap that extends into the deep-UV range; the device-quality material, is deposited epitaxially using metalorganic chemical vapor deposition on sapphire substrates.

Keywords: *Duv Leds, deep-UV, ultraviolet leds, AlGaN/AlGaN Duv Leds*

1. Introduction to leds

An LED is what's called a "solid-state lighting" technology, or SSL. Stated very simply, an LED is a semiconductor device that emits light as the electricity flows through it.

The primary cause of LED lumen depreciation is heat generated by the LED, so the heat must be removed from the light by conduction or convection.

Without adequate heat sinking or ventilation, the device temperature will rise, resulting in lower light output.

There are a variety of applications for devices that extend into the deep-UV, including biological agent detection and optical storage.

The nitride material system is a set of semiconducting compounds that have wavelengths that span a broad range, from yellow to deep-UV. AlGaN has a direct bandgap that extends into the deep-UV range; the device-quality material, is deposited epitaxially using metalorganic chemical vapor deposition on sapphire substrates.

The most obvious manifestation of its degradation is the gradual decrease in power output when the device is operated at a constant current (i. e. the spontaneous efficiency decreases with time).

The main cause of degradation - a consequence of forward biasing - is the inherent crystal defects; non-radiative recombination centers are formed at these defect sites, thereby impairing the quantum efficiency of the devices.

LED failure is a gradual process; the power output decreases with time, although not necessarily in any well behaved manner. Although the failure of light emitting devices has become considerably less erratic over the past years, there is a variation in reliability between LEDs within a specific batch.

A common approach is to consider the lifetest data as a statistical distribution, and to use its characteristic parameters to describe the device population as a whole.

2. Short leds history

1907: H. J. Round of Marconi Labs discovered that some inorganic substances glow if a electric voltage is impress on them.

1927: The Russian Oleg Vladimirovich Losev independently reported on the creation of an LED, but no practical use was made of the discovery.

1961: Bob Biardand and Gary Pittman (*Texas Instruments*) find out that gallium arsenide (GaAs) give off infrared radiation when electric current is applied. They receive a patent for this diode.

1962: First visible red GaAsP-LEDs was developed by Nick Holonyak ("father of the light-emitting diode") at *General Electric Company*.

1971: The first blue LEDs (GaN) were made by Jacques Pankove at *RCA Laboratories*. Too little light output to be of much practical use.

1993: Shuji Nakamura (*Nichia Corporation*) demonstrates the first high-brightness blue LED based on InGaN.

A light-emitting diode (LED) (Figure 1) is a semiconductor-based p-n junction. When a forward bias is applied, the diode emits light in a very narrow range of wavelengths.

As in other diodes, current flows easily from the p-side (anode) to the n-side (cathode), but not in the reverse direction.

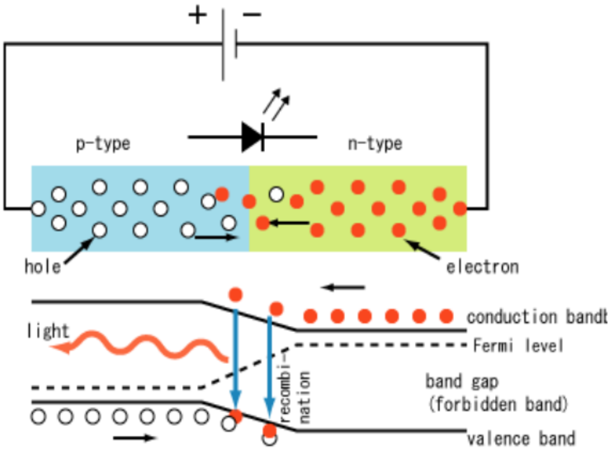

Figure 1. LED principle

3. Led principle

At the barrier layer electrons and holes recombine and energy in the form of a photon is emitting. The wavelength of the light depends on the band gap energy (Table 1).

New materials such as GaN and SiC which have good material properties, attracts increasing attention for use in power devices. Especially, GaN is expected as a material for power devices used in ~700 V from high electrical critical field (~3.3 MV/cm) and realizing high electron mobility (~2000 cm^2/Vs) by using AlGaN/GaN heterostructure.

Table 1

Color	*Wavelength (nm)*	*Semiconductor material*
Infrared	>760	GaAs, AlGaAs
Red	610-760	AlGaAs, AlGaInP
Orange	590-610	GaAsP, GaP
Yellow	570-590	GaAsP, GaP
Green	500-570	InGaN, GaN
Blue	450-500	ZnSe, InGaN
UV	<400	GaN, AlN, AlGaN, AlGaInN

The attention of researchers focused on reducing contact resistance of AlGaN/GaN HEMT and improving surface morphology by using carbide[1] electrodes even in some problems. The high contact resistance cause higher electrical power loss, and 40% of the electrical

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[1] The motivation for selecting carbide electrodes is that carbon has high melting point to endure being annealed at high temperature and high chemical resistance. TiC/TiN electrodes was deposited by RF sputtering as stacked electrodes on AlGaN/GaN substrate with changing Ti/C ratio to optimize the ratio, the passivation layer on AlGaN/GaN was SiO_2 deposited by tetraethylorthosilane (TEOS), and the contact resistance was measured by TLM patterning. The interface

power loss in breakdown voltages under 1000 V could be reduced if the specific contact resistance (Ωcm^2) decreases from $10^{-5}\Omega cm^2$ to $10^{-6}\Omega cm^2$. Also conventional ohmic contact electrodes have rough surface morphology which causes the misalignment and reduces reliability.

4. Examples of led assembly

An LED lamp contains power conversion electronics (AC/DC), driver IC for the LEDs, a heat sink for thermal management and optics to optimize light quality. Since LED bulbs are intended to be form factor-compatible with current incandescent and compact fluorescent lamps (CFL) bulbs, they will have an AC/DC power supply circuit so they can operate from standard bulb "sockets." (Figure 2.)

For other applications, Figures 3 and 4 represent two other types of LED assemblies.

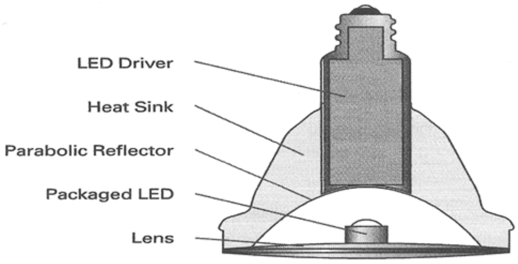

Figure 2. Typical residential LED lamp construction

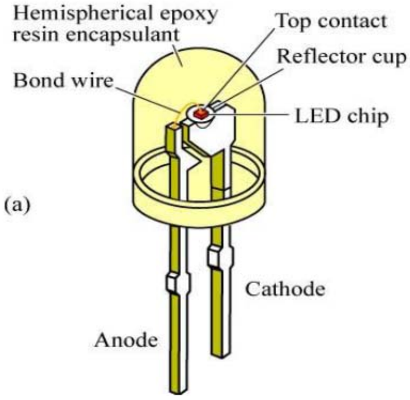

Figure 3. One of the LED types (after [1])

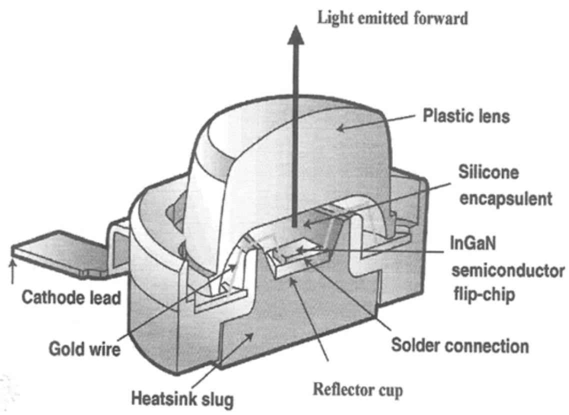

Figure 4. Another LED type with plastic lens (after [1a])

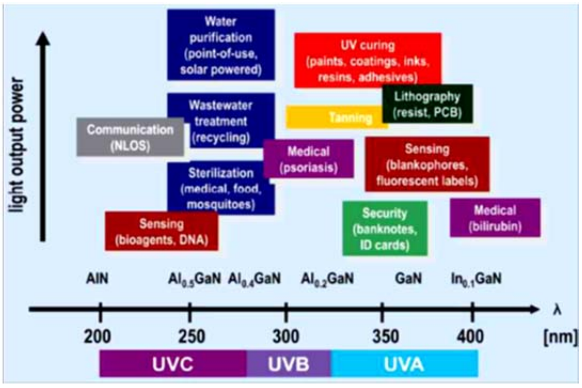

Figure 5. Potential applications for UV LEDs [3]

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layer was observed by TEM, and the surface morphology was measured by AFM and SEM. If the ohmic contact resistance is lower than conventional ohmic contacts, by some treatment to substrates or different methods in more elaborate study, carbide electrodes could have good morphology and low contact resistance without gold and contamination to other substrates including Si substrate.

5. Applications

- Illuminations with high brightness
- Visual signal application
- Automotive lighting
- Flashlights
- Optical measurement systems
- LCD backlit screens
- Grow lights

6. Disadvantages

- High initial price
- Temperature dependence
- Shock resistance
- Parallel ray emission
- No mercury needed
- Color rendering
- Current-regulated power supplies

7. Advantages

- Efficiency
- Direct colour generation
- Small size
- Fast switch time
- Frequent on-off cycling
- Easy dimming
- Cool light without IR
- Lon lifetime

8. Ultraviolet leds

Researchers today are under increasing pressure to quickly develop innovative technologies and new materials that meet the rapidly changing needs of society. The R&D mission is to contribute to the healthy development of society by delivering such innovative technologies and new materials through continuous inquiry and ceaseless effort.

Constituting a part of the solar spectrum, ultraviolet (UV) light has a shorter wavelength than blue light and is well known as being the cause of sunburn and other skin problems.

Since DNA has an absorption peak in the 260 nm range, devices generating light in this range are the best suited for sterilization applications[2] [2].

Benefits of UV LEDs: (i) *Compactness;* (ii) *Robustness;* (iii) *Low cost of ownership (system level);* (iv) *Environmental-friendly composition.*

The development of gallium nitride (GaN) has led to the main breakthroughs in LED technology due to its wide electronic band-gap, making it suitable for high-power, high frequency, and high temperature applications [4-6]. Continual improvement in the fabrication of high-quality bulk III-nitride crystals and their epitaxial layers has led to the recent advancements of GaN based light emitting diodes (LEDs) [7]. While much of the focus has been placed on visible light emitting diode technology for display and solid state lighting, scientific focus has turned towards the shorter-wavelength ultraviolet (UV) devices due to their technological importance.

Aluminum Gallium Nitride (AlGaN)/Gallium Nitride (GaN) based deep ultraviolet (DUV) light emitting diodes (LEDs) with emission wavelengths between 200-280 nm enable

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[2] Conventionally, mercury lamps have been used for such applications, especially in the fields of medical care, water purification and food sanitation, due to their ability to emit DUV light in the 254 nm range. However, the use of mercury lamps poses several problems in terms of environmental impact, not the least of which is that they contain mercury, an environmental load substance. They also have a short life of approximately 2,000 hours, and require a high operating voltage. In recent years, on the back of the growing trend toward mercury-free products and heightening energy-conservation requirements, the possibility of DUV-LEDs has prompted their development as a substitute for mercury lamps.

key emerging technologies such as water/air purification and sterilization, covert communications and portable bio-agent detection/identification systems for homeland security, and surface and medical device sterilization. These devices produce a large amount of undesired heat due to low quantum efficiencies in converting electrical input to optical output. These low efficiencies are attributed to difficulties in the growth and doping of $Al_xGa_{1-x}N$ (x~0.7-1) materials and UV absorbing substrates leading to excessive joule heating, which leads to device degradation and a spectral shift in the emission wavelength. With this regard, effective thermal management in these devices.

Depends on the removal of this heat and reduction of the junction temperature. This is achieved by decreasing the package thermal resistance from junction-to-air with cost-effective solutions. The use of heat sinks, thermal interface materials, and high conductivity heat spreaders is instrumental in the reduction of the overall junction-to-air thermal resistance.

9. Deep uv leds

Within the past ten years, a wide variety of group III-Nitride-based photonic and electronic devices have opened a new era in the field of semiconductor research. Fueled by their great potential which extends beyond the capabilities of Si technology, they have become of great commercial importance. The direct and large bandgap nature, intrinsic high carrier mobility, and the capability of forming heterostructures allow them to dominate photonic and electronic device market such as light emitters, photodiodes, or high-speed/high-power electronic devices.

High mobility III-V or Ge channel materials are one of the promising directions for performance improvement as well as reducing power consumption. Even though there are many challenges to the 10 nm technology node or beyond, the improvement of gate stack/channel interface properties and introduction of heterogeneous process integration for new channel materials with higher electron and hole mobility should enable aggressive V_{DD} scaling, thereby reducing power consumption.

There are plentiful ongoing endeavors to push emission wavelength into the deep UV regime for numerous applications including bio-aerosols sensing, air and water purification, and high density data storage. One of the most defining features of the nitride material system is the lack of high-quality bulk GaN or AlN substrates. To date, all commercially available III– nitride LEDs are grown heteroepitaxially on foreign substrates such as sapphire and SiC. Si has also received some attention as the substrate for low-power LEDs due to its clear advantages of low cost and high quality. Many efforts have been devoted to developing high-quality buffer layers to accommodate the mismatch in lattice constant and thermal expansion coefficient between the epilayers and substrates. The presence of a high density of threading dislocations and large residual strain in the heteroepitaxial structures, along with strong piezoelectricity and large compositional fluctuation of the nitride alloys, give rise to some unique electrical and optical characteristics of current III–nitride LEDs [8].

Nitride-based semiconductor materials InN, GaN, AlN and their alloys attract great attention due to their promising applications in optoelectronic devices such as light emitting devices (LEDs) and laser diodes (LDs) [9]. Depending on the alloy composition, these systems could in principle cover a wide wavelength range from red through yellow and green to blue [10].

III-Nitride based DUV LEDs are prospective candidates to replace the conventional bulky, expensive and environmentally harmful mercury lamp as new UV light sources, used in the applications of water and air purification, germicidal and biomedical instrumentation systems, etc. Due to the lack of native substrates and poor carrier injection, AlGaN-based deep UV LED is suffering from low optical power and low overall efficiency, which prevents the availability of low cost, high efficiency deep UV LED on the market.

The dissertation [11] is focused on improving the efficiency of deep UV LEDs, by improving the base template epilayers, specifically silicon doped n-type AlGaN electron cladding layer on which the subsequent quantum well and other device layers are grown. Approaches such as short period superlattice (SPSL) nAlGaN and silicon modulation doping nAlGaN are shown to effectively decrease the threading dislocation density (TDD) from $1.2x10^9$ cm^{-2} to 3×10^8 cm^{-2}, followed by the improvement of sheet resistance to 53Ω/□. The improvement of crystal defect density is believed to contribute to the increase of internal quantum efficiency (IQE) and thus the overall device efficiency. Deep UV LED on a wafer device employing proposed silicon doping modulation technique shows light emission peak at 281 nm and yields 25% improvement of the optical power due to the dramatic reduction of the dislocation density as well as the overall efficiency.

There are some other issues that cause the degradation of the recombination efficiency. Currently, most of the Nitride-based LED devices with crystal structures grown along c-orientation exhibit spontaneous and strain-induced piezoelectric fields which can cause degradation in device performance, especially the combination efficiency, due to the reduced recombination probability of the electrons cloud and holes cloud in the active region, which is also known as quantum confine stark effect (QCSE). H.-C. Chen has demonstrated that the use of semipolar or nonpolar sapphire substrate is effective in reducing the QCSE phenomenon; however, the device optical power was low, due to the existence of high threading dislocation in the active layer. To further reduce the defects density, a high quality AlN template is prerequisite for the development of the high power DUV LED on semipolar or nonpolar sapphire substrate.

Sapphire will likely be the substrate of choice for deep-UV LEDs due in part to its transparency. Milliwatt UV LEDs with emission wavelengths as short as 250 nm have emerged in the past several years. Further improvement in LED performance is expected in the near future as the heteroepitaxy of AlGaN materials on sapphire is refined. AlN is a much closer lattice and thermal match for High-Al content AlGaN heterostructures. If bulk AlN or AlGaN becomes commercially available, these materials would be the best choice as the substrate for deep UV LEDs.

The lack of low-cost, large-size, and flawless GaN wafers remains an obstacle. This obstacle must be overcome before III−nitride LEDs grown on GaN substrates have an impact on the development of high-brightness and cost-efficient solid-state lighting sources.

By alloying and forming heterostructures with AlN or InN, GaN has wide wavelength coverage ranging from entire visible spectral range in addition to the infrared and deep ultraviolet (1771 nm ~ 200 nm, 0.7 eV ~ 6.2 eV) ranges. The high thermal and chemical stability of GaN give those devices the advantage of operating in hostile environments. Like most wide bandgap semiconductors, the nitrides exhibit superior radiation hardness compared to the other smaller bandgap counterparts such as Si or GaAs, allowing them to be incorporated into demanding space applications. For these reasons, the research on group III-Nitride semiconductor materials has attracted much attention in both the consumer and defense industries.

A wide variety of group III-Nitrides materials system has opened a new era in the field of semiconductor research for the past decade. They have become of great commercial importance fueled by their potentials that extend beyond the capability of Si technology. The direct and large bandgap nature, intrinsic high carrier mobility, and the capability of forming heterostructures allow them to dominate the photonic and electronic device markets such as light emitters, photodiodes, or high-speed/high-power electronic devices. MOCVD has become the dominant technology for epitaxial growth of epitaxial III-nitrides due to its versatility.

III-Nitride compounds exhibit superior electronic properties with direct band gaps of 0.7 eV (InN), 3.4 eV (GaN), and 6.2 eV (AlN), which cover the entire energy range of solar spectrum as well as visible lights. Besides, III-nitride compounds are formed with a special polar wurtzite lattice structure, which lacks a center of inversion symmetry and produces a large spin splitting by intrinsic spin-orbital interaction. By engineering the band structure of III-nitride compounds, one can fabricate III-nitride nanostructures for the applications of high-efficient lighting sources, sustainable solar cells, and high-speed spintronic[3] devices.

III-Nitride semiconductor-based DUV LEDs are emerging as an enabling technology for diverse military, homeland security, industrial and commercial markets, and space exploration. Current technology allows to fabricate AlGaN-based DUV LEDs with wall-plug efficiency (WPE) between 1-2%, which is substantially lower that WPE for visible and near UV LEDs. Significant R&D efforts are under way, including DARPA's "Compact Mid-Ultraviolet Technology" (CMUVT) program, to improve materials quality, device fabrication and light extraction to increase WPE of DUV LEDs by more than order of magnitude. The paper [12] presents an overview of the latest news in the development of DUV LED technology with the main focus on novel device designs to increase quantum efficiency and improve UV light extraction and reliability of devices emitting in the range of 230 nm 340 nm. Novel QW design has been implemented to suppress polarization effects and phonon engineering approach to increase electron trapping in the active layer of the devices. Very narrow (< 3 nm) and deep (total energy band offset > 0.4 eV) quantum wells were used to suppress Stark effect and increase radiative recombination. Active region of DUV LEDs was embedded inside a deep potential well (larger than the energy of optical phonon) to increase electron-LO (longitudinal-optical) phonon scattering and accelerate cooling of hot injected electrons. This allowed increasing electron capture into the active region without using conventional electron "blocking layer" commonly used in visible LEDs. It was developed and incorporated UV-transparent p-type cladding layers to reduce optical losses due to strong absorption in the top p-AlGaN cladding layer and p^+-AlGaN or p^+-GaN contact layers. Combination with new type of ohmic contact reflecting in DUV spectral range allowed to significantly improve light extraction and increase output power of DUV LEDs by 2 times in the range of 275 nm -- 300 nm, and 2.5 times in the range from 310 nm to 340 nm. Improved quality of epitaxial layers and device fabrication technology enabled to increase reliability of DUV LEDs and fabricate devices with peak emission wavelength in the range of 270 to 280 nm with lifetime exceeding 10,000 hours for continuous wave (CW)

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[3] Spintronics, or spin electronics, involves the study of active control and manipulation of spin degrees of freedom in solid-state systems.

operation. Reliability data for DUV LEDs operating under high current (up to 400 mA) in the pulsed operation mode are presented. A new device fabrication technology was developed, primarily to reduce ohmic contact resistance for very high Al-contant DUV LEDs with peak emission wavelengths shorter than 250 run. This resulted in the reduction of the forward bias from >; 20V to less makes these devices suitable for CW operation. We will also present recent results of space qualification of 250 260 nm DUV LEDs for space applications, which include reliability testing up to 26,000 hours (CW mode), shake and bake, and radiation hardness.

Focusing on three growth fields, namely, “information and electronics,” “environment and energy” and “life and healthcare”, the researchers are proceeding now with the development of a high-performance deep ultraviolet light emitting diode (DUV-LED).

Deep ultraviolet (DUV) light has an even shorter wavelength and is not contained in the solar spectrum. DUV light also exerts strong sterilization ability, destroying the nucleic acids - DNA and RNA - of germs and viruses (Figure 5).

In order to realize DUV LEDs almost all research groups employ AlGaN or AlInGaN multiple quantum wells (MQWs)-based pn-junctions over sapphire substrates. However, with the recent availability of improved AlN substrates, Crystal IS and Hexatech reported DUV LEDs over bulk AlN. The use of sapphire was primarily dictated by the substrate transparency requirements for the emitted light.

Researchers from Japan and the USA have reported [13] the first fabrication on hydride vapour phase epitaxy (HVPE) aluminium nitride (AlN) substrates of aluminium gallium nitride (AlGaN) light-emitting diodes (LEDs) that emit at the deep ultraviolet (DUV) wavelength of 268 nm.

There is much interest in shrinking the wavelength of AlGaN LED emissions to the DUV range around 265 nm for air and water purification. This range is an absorption maximum for DNA, and hence 265 nm DUV can be used to disrupt biological agents such as bacteria. Most work on AlGaN LEDs for this wavelength range is carried out on sapphire substrates. However, large lattice mismatches lead to dislocations in the active material region that emits the light, reducing energy efficiency to a couple of percent.

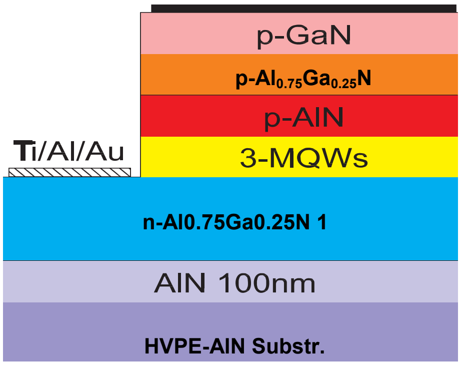

Figure 6. Schematic structure of a 268 nm DUV-LED

HVPE was used to grown thick 250 nm AlN layers on c-plane physical vapor transport (PVT) AlN substrates. Chemical mechanical polishing (CMP) was used to prepare the HVPE AlN surface for the subsequent epitaxy of the LED structure. After CMP, the root-mean-square surface roughness was less than 0.2 nm. The device layers were grown using metal-organic chemical vapor deposition (MOCVD) in an Aixtron AIX200/4RF-S reactor (Figure 6).

The active region consisted of a three-period multi-quantum well (MQW). The p-type layers were an AlN electron-block layer, an AlGaN cladding layer, and a GaN contact layer. Although GaN absorbs DUV, the researchers felt that it was needed to provide a suitable ohmic contact with the nickel/gold p-electrode. Unfortunately, p-type doping becomes even more difficult as the aluminium content of AlGaN is increased.

X-ray analysis showed that the layers of the device were strained pseudomorpically to the underlying AlN, except for the final p-GaN, which was almost completely relaxed due to the large lattice mismatch. The 400μm x 600μm LED devices were produced using photolithography, dry etching, and metal evaporation.

The PVT-AlN was removed using mechanical polishing to reduce the amount of DUV absorption. Some of the HVPE-AlN was also removed, and the researchers estimate that the thickness of this layer after polishing was 170 μm. Fortunately, the HVPE-AlN absorbed far less of the 265 nm-wavelength radiation than does the PVT-AlN substrate. Below 300 nm wavelengths, the transmittance of the PVT-AlN substrate was effectively zero.

By contrast, the HVPE-AlN allowed as much as 62% of the 265 nm radiation through. “This value is close to the ideal value when surface reflection is taken into account,” the researchers comment. The intrinsic absorption of HVPE-AlN was measured at 10/cm for 265 nm UV. Without removal of the PVT-AlN, LEDs produced little external radiation and none detectable below 300 nm.

10. Some recent studies

Paper [14] discusses physics, design, fabrication, performance, and selected applications of DUV LEDs. The analysis reveals the relative contributions of electrical injection, internal quantum efficiency, and light extraction efficiency to the overall DUV LED performance. The calculations show that the reduction of the dislocation density at least below value of 2×10^8 1/cm^3 is necessary for reaching high DUV LED efficiency. Better light extraction has been achieved using an innovative p-type transparent sub-contact layer and reflecting ohmic p-type contact resulting in nearly tripling DUV LED power. At high power dissipation, temperature rise might be significant, and data showing the power degradation with temperature increase and the results of the detailed 1D and 3D analysis of thermal impedance of DUV LEDs. As an example of DUV LED application, the paper reports on microbial disinfection using 19 watt 275 nanometer DUV LED.

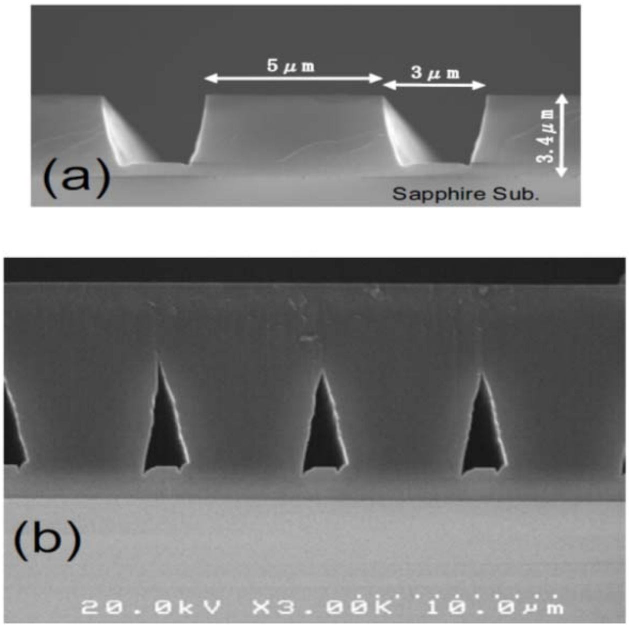

Figure 7. Cross-sectional high-resolution scanning electron microscope (HR-SEM) images of *(a)* an AlN stripe structure and *(b)* an ELO-ALN template [26]

Recently, the development of high efficiency 230-350 nm-band DUV LEDs or laser diodes (LDs) has been attracting considerable attention, because of their wide range of potential applications. AlGaN and InAlGaN alloys are very attractive for realizing high-efficiency DUV LEDs and LDs [15, 16]. Several groups have reported Al-GaN-, InAlGaN-, or AlN-based DUV LEDs, such as 333−350 nm AlGaN LEDs [17 - 19], 240−280 nm AlGaN multi-quantum-wells (MQWs) LEDs [20-22], quaternary InAlGaN MQW LEDs [23, 24] and a 210 nm AlN LED [25].

However, the efficiency of AlGaN-based DUV-LEDs with wavelength below 360 nm is much lower than that of InGaN-based blue LEDs. In order to realize high efficiency AlGaN-based DUV-LEDs, the development of low threading dislocation density (TDD) AlN template is quite important.

The maximum output power of Al-GaN-MQW DUV-LED of the 273 nm LED was 2.7 mW under room temperature (RT) continuous wave (CW) operation. The external quantum efficiency (EQE) may be significantly improved by eliminating the abnormal AlN nucleation on the epitaxial lateral overgrowth (ELO)-AlN template. Figure 7 shows cross-sectional high-resolution scanning electron microscope (HR-SEM) images of (a) an AlN stripe structure and (b) an ELO-AlN template. DUV LEDs based on group III-Nitrides have numerous potential applications in water and air purification, food sterilization, ultraviolet curing, chemical and biological sensors, and medical instrumentation. However, DUV LEDs, with peak emission wavelength between 250 and 320 nm, are prone to self-heating. This rise in temperature during normal operation leads to early saturation of the light output power of these devices at relatively low injection currents and degrades their external quantum efficiency. Furthermore, this high heat dissipation also decreases the reliability of these devices and shorten their life span. Consequently, thermal management of high power LEDs is a crucial area of research and development. Thermal impedance quantifies the rise in the junction temperature of a device per unit of power dissipated. Lower thermal impedance of a device will result in higher dissipation of the heat energy and lower junction temperatures. In thesis [26], the junction temperature and thermal impedance of square-geometry and micro-pixel AlGaN/AlGaN DUV LEDs are measured using the electroluminescence (EL) peak position shift and forward voltage shift methods.

The EL peak-shift method was found to be more reliable than voltage-shift method to predict the thermal impedance for unpackaged devices. On the other hand, for packaged devices, the measurements using voltage-shift method were found to be more accurate than those from peak-shift method. Figure 8 shows (a) a bird's-eye view and (b) a cross-sectional image of the abnormal AlN cores generated on ELO-AlN layer observed by HR-SEM.

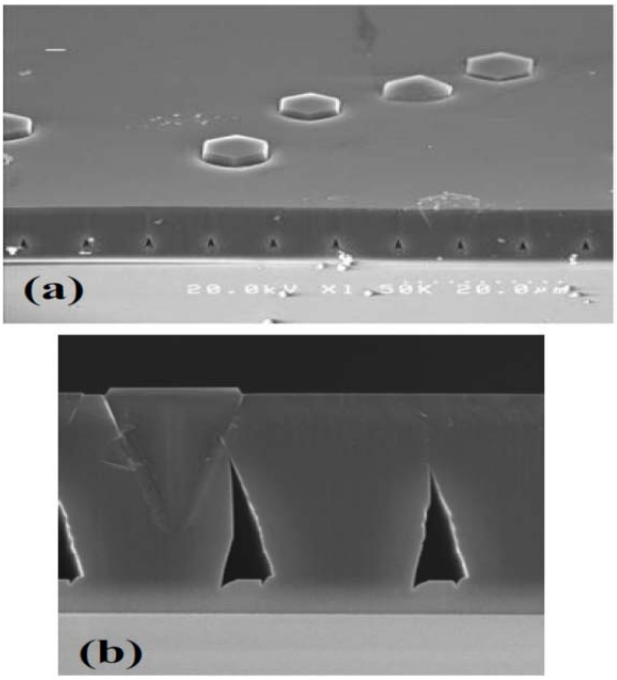

Figure 8. *(a)* A bird's-eye view and *(b)* a cross-sectional image of the abnormal AlN cores generated on ELO-AlN layer observed by HR-SEM [26]

11. Raman spectroscopy

Raman spectroscopy is an optical method that reveals the molecular structure by measuring the inelastic scattering of light. The development of Raman spectrometry has often depended on a serious of newly generated optical techniques. Over the last decade, the laser technology has been developed rapidly. Progress in semiconductor technology has occurred and various ultraviolet solid-state and gas lasers have appeared, and lasers with different properties, such as pulsed or continuous wave, working in single or multi mode have appeared in the commercial market. Different lasers could be suitable only for one particular application. A dedicated spectrometer and special optical components may be required, so in order to implement a DUV Raman system in practice, one has to deal with much optical knowledge.

The temperature rise in LEDs is an important parameter that must be determined for both thermal management and device lifetime/reliability assessment. Commonly used indirect methods of measuring the device temperature either estimate the multiple quantum well (MQW) temperature based on measuring temperature dependent device characteristics (e.g., forward voltage and electroluminescence methods), or they measure the average temperature across the device structure using optical methods such as infrared (IR) thermography and thermo-reflectance. However, none give true insight into the vertical distribution of temperature in these structures. Raman spectroscopy was applied to operating UV LEDs to give the temperature rise in discrete layers within the LED device structure, going from the growth substrate to layers adjacent to the MQWs [27].

A successful application of Raman spectrometry to food analysis generally requires that one has a resonance Raman effect to be active for the target compound. This is so because otherwise Raman is a quite weak effect that is against the possibility to realize high sensitivity detection [28].

12. Failure modes

The most important failure modes detected are [29]: *(i)* the modification of the optical properties of the encapsulation, due to the high temperatures involved, *(ii)* the detachment of the encapsulation layer in low flux white LEDs, that induced a thermal resistance increase and the total failure of the device, *(iii)* the generation of non-radiative recombination centers in UV LEDs, *(iv)* the generation of parasitic path that short the junction.

In [29] a study on DUV LEDs performance and reliability has been reported. The relation between the different radiative emission processes, by evaluating the relative electroluminescence intensity of the three main emission bands of the LEDs has been analyzed in detail. It was also presented an analysis of the mechanisms that limit the reliability of these devices during dc stress: it has been shown that *(i)* Optical power degradation can be ascribed to the increase of the non-radiative recombination rate, and *(ii)* the degradation rate is related to the molar fraction of Al inside the quantum wells (QWs). Capacitance versus voltage (C-V) analysis provided further information on the degradation process, indicating that as a consequence of stress, the charge distribution in the active layer is modified, possibly due to the generation of defective states. Together with reported degradation mechanisms, a failure mode responsible for sudden death of device was found and it has been ascribed to a poor morphology of the LED structure.

Work defects were observed in both the green and UV LEDs that could potentially reduce the lifetimes of the devices [30]. In the green LEDs, dark defect signals observed using the laser-based localization techniques were used to pinpoint large contact metallization defects. Defects in the contact metallization and at the metal/p-type semiconductor interface may create strong spatial non-uniformities in current injection. This type of defect could create hotspots and non-uniform light emission. Dark defect signals observed in the UV LEDs were determined to be shorting paths. Part of the contact metallization had diffused along dislocation cores to create leakage currents through the quantum wells. It is theorized that failure occurred in the UV LEDs when enough of these leakage paths dominated current injection through the QWs.

For the UV LED it is clear that a dislocation is present at the failure site and that Au has diffused through the QW. However it is still unclear what materials properties the dislocation possessed to segregate itself from surrounding dislocations (size, presence of a micropit). Plan-view TEM can reveals another dimension of structure that is required for this type of failure to take place. One theory might be a cluster of dislocations. A quantitative correlation between increases in leakage current under laser stimulation and time to failure would be beneficial to monitor degradation of the devices. The TIVA / LIVA characterization technique can be a successful tool for III-nitride LED characterization of defects and degradation. This technique can be a powerful tool to predict early failure in commercial devices as well as support the development of in-house semiconductor devices. Further studies characterizing the multiple different defects observed in the UV LEDs and further laser-spotting characterization are expected to fully establish the TIVA / LIVA technique as a viable screening method and reliability technique for III-nitride optoelectronics [30].

13. Reliability

The reliability and output power of AlGaN-based DUV-LEDs fabricated on AlN substrates prepared by hydride vapor phase epitaxy are reported in paper [31]. TEM analysis revealed that dislocation density in LED layers, except the p-GaN layer, was below 10^6 cm^{-2}. DUV-LEDs emitting at 261 nm exhibited an output power of 10.8 mw at 150 mA. The lifetime of these LEDs was estimated to be over 10,000 h for CW operation at 50 mA. No significant acceleration of output power decay at higher operation currents was observed. The estimated lifetime at the operation current of 150 mA was over 5,000 h.

14. Package-reltaed failures, lifetime, and future possible solutions

To dissipate the amount of heat that is generated during operation, the LED die needs to be bonded to a heat sink or substrate, often with a solder attach. If voids in the solder attach create an insufficient thermal path, the resulting hot spots will eventually lead to thermal runaway and failure. Whisker growth caused by electromigration, which can come from internal strain, temperature, humidity, and material properties, usually happens near the bonded surface between the solder and the heat sink and can lead to electrical short circuits. In choosing a die attach material, the following should be considered: *(1)* stress relaxation at the interface; *(2)* excellent adhesion between the bonded surfaces; *(3)* effective heat dissipation as well as high thermal conductivity; and *(4)* CTE matching materials between the bonded surfaces.

Package-related failures can occur in the encapsulant, wire, and phosphor. Wire-bond breakage or detachment and die-attach strength loss are due to overheated epoxy encapsulant. These problems, in turn, cause a delamination between the chip and epoxy. Mechanical stress from lead wires is another failure mechanism, because it can generate open circuits inside the device. Inappropriate pressure, position, and direction applied to a lead wire soldering can accumulate the stress at normal operating temperature, bending the leads toward the body of the LED.

Most of white LEDs use yellow or red/green phosphors, which are susceptible to thermal degradation. When two or different phosphors are mixed, each constituent should have compatible lifetime and degradation behavior to keep the status of color. The color temperature and purity level of phosphors also degrade over time.

New encapsulant materials for future high-power and high efficiency LED packaging should have the following properties: high refractive index, high thermal and UV resistance, low CTE, low modulus, good adhesion, and low moisture permeability. High refractive index is needed to achieve high light extraction. However, this need can be alleviated by using efficient packaging design, such as the multiple small chip mounting and lens/cup design. To take advantages of both epoxy resins and silicone, developing new epoxidized silicone materials is a possible solution for the packaging of high power LEDs [32].

15. Conclusions

The recent results on high efficiency devices clearly indicate a maturation of the technology to the point where the development of systems for air- and water-purification and bio-medical applications is very feasible. Several companies in the US, Japan, Korea, China and Europe are scaling up their production lines. This will certainly lead to large volume LEDs sales and a reduction of their unit price.

There is very little understanding of how the coupled response leads to the heat distribution within the active portion of the LED. Dissertation [33] gives device growth engineers and designers more insight into the impact that doping and the formation of p and n contacts has on the performance of the device. It is not clear at this time how much additional thermal control can be gained by coupling thermal design into the chip architecture as opposed to simply managing the heat loads via the packaging materials. Additional work needs to be done to couple the thermal packaging design along with the optical design for UV LED systems.

With improved performance, the transformative and enabling nature of DUV LED technology has the potential for reducing and, in many cases, eliminating the practice of using antibiotics for preventing infections and developing new testing procedures based on UV fluorescence. Once this expected performance is achieved, the market for DUV LEDs could explode [34].

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