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Design Status and Loss Mechanisms of AlGaN Deep-Ultraviolet VCSELs

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Abstract. Vertical-Cavity Surface-Emitting Lasers (VCSELs) based on Aluminum Gallium Nitride (AlGaN) structures for Deep Ultraviolet (DUV) emission have great potential for use in sterilizers, photolithography, and solar-blind detectors. Unfortunately, the creation of high performance Ultraviolet C (UVC) VCSELs has been hampered by both physical and structural problems that make them difficult to manufacture. In this paper, I examine the design status of DUV VCSELs based upon AlGaN and identify the factors affecting their performance; specifically, they have reduced internal quantum efficiency in Quantum Wells, poor mirror reflectivity, as well as loss of light due to absorption and scattering, occurring within the microcavity. Device design factors that will either limit or benefit VCSEL designs include: AlGaN Multiple Quantum Wells, Distributed Bragg Reflectors and the Microcavity Structure. Other factors relating to minimizing optical losses with fabrication processes will also be discussed in this paper, including substrate removal, Chemical Mechanical Polishing and Surface Smoothing. A review of the most recent UVC (~275-278 nm) and Ultraviolet B (UVB) (~310 nm) device demonstrations will be used to illustrate existing performance deficiencies as well as the disparities between optically pumped and electrically driven devices. Finally, future areas of research are proposed which include: polarization engineering, control of cavity detuning, development of low loss dielectric mirrors compatible with current injection devices and improvements in P-type conductivity using tunneling injection techniques.

Keywords: Deep-ultraviolet VCSEL, AlGaN, Optical loss, Quantum wells, Distributed Bragg reflectors

1. Introduction

Semiconductor light sources that emit in the deep ultraviolet (DUV) range have a variety of different uses, many of which require very small size and broad area or narrow spectral output, such as sterilizing a wide range of surfaces and for robust sensing capabilities that are blind to light in the solar spectrum. At wavelengths between 200 and 280 nm, ultraviolet C (UVC) light is commonly produced using AlGaN-based devices as this material system provides a means to create high-performance devices based upon wide bandgap materials that have produced a variety of different UVC LED applications and many emerging laser technologies. vertical-cavity surface-emitting lasers (VCSELs) are ideally suited for this application because of their unique advantages over edge-

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emitting lasers, such as producing a circular beam or profile, having the ability to facilitate on-wafer testing of multiple devices simultaneously, and being available to produce scalable arrays in two-dimensional geometries. While many of the advantages of VCSEL are well established within the infrared and visible wavelength ranges, transitioning to the UVC region has proven very difficult, and most demonstrations have been achieved through optical pumping and not by direct electrical injection. The main challenges are a combination of material and device issues, such as the dramatically decreased internal quantum efficiency observed in AlGaN quantum wells when operating in the strong polarization field regime, the challenges in developing high reflectivity and low loss mirror structures for operation in the UV wavelength range, and the optical losses present within the microcavity regions of the VCSEL devices. High aluminum content significantly affects the epitaxial growth of devices. High-density dislocations and low adatom mobility also create device performance issues. Additionally, AlGaN with high aluminum content is difficult to electrically inject into devices due to poor p-type conductivity (high resistivity) and therefore, results in poor current spread within the device. This paper presents an overview of the status of AlGaN DUV VCSELs in terms of design and loss mechanisms, and will revolve around three areas of device physics: performance of quantum well structures; designs of distributed Bragg reflectors (DBRs); and cavity loss mechanisms. Methods to minimize optical loss per production methods (e.g., substrate removal and substrate smoothing) are discussed, and indications of device structure performance limitations are illustrated from recent testing in the ultraviolet B (UVB) and UVC spectral regions. Finally, directions for future research geared towards creating UVC VCSEL devices that can be efficiently electrically injected are discussed [1-3].

2. Core structure and theory of DUV VCSELs

2.1. Optical cavity and standing-wave field control

A VCSEL consists of an optical cavity oriented perpendicular to the epitaxial growth direction, formed by two high-reflectivity mirrors, typically DBRs. Maximizing overlap between the optical field and gain medium through placement of the active region in a configuration that achieves maximum standing wave intensity of the optical field will increase the modal gain for the device. The length of the cavity is typically λ/n, resulting in relatively large spacing between longitudinal modes, and allows for single mode operation with good alignment of the cavity resonance to the gain spectrum. While these are also true for DUV VCSELs, the shorter wavelength associated with DUV emission, coupled with the much stronger optical loss mechanisms associated with DUV devices, impose additional constraints on device performance. The general structure of a DUV VCSEL, which is constructed from AlGaN, is shown in Figure 1. The structure includes top and bottom DBRs, the optical cavity, and multiple quantum well active region, with a representation of the standing wave optical field distribution. As indicated in Figure 1, by positioning the MQW region at or near a standing wave antinode, the amount of gain produced will be maximized. Conversely, by positioning the substrate removal interfaces or imperfections in growth at or near standing wave nodes, scattering losses resulting from these interfaces will have a minimized effect upon the cavity quality factor. Although this design approach does not completely eliminate scattering losses, it will reduce their impact on the overall cavity quality factor [4].

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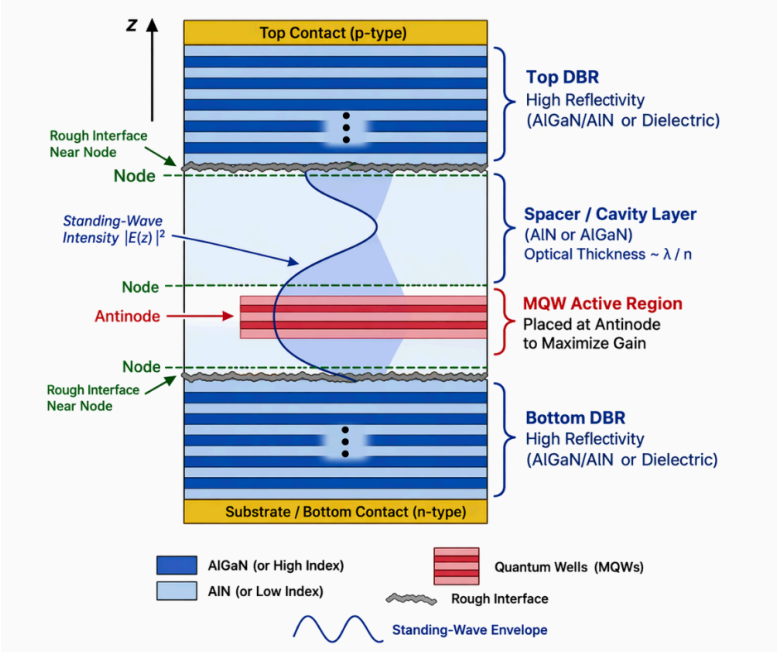

Figure 1. Schematic structure of an AlGaN-based DUV VCSEL

2.2. Quantum wells: QCSE, polarization effects, and gain mechanisms

The active region of DUV VCSELs is typically composed of AlGaN quantum wells that provide the gain for the device. Since wurtzite structure III-nitride materials experience both spontaneous polarization and piezoelectric forces, the active region of the device will generate an extremely strong internal electric field. The strong internal electric fields in the active region create a quantum confined Stark effect (QCSE) within the semiconductor and separate the electron and hole wavefunction, thus reducing their overlap. In turn, this will decrease the radiative recombination efficiency of the device. The strength of the QCSE is dependent on various parameters, including: aluminum composition in the quantum wells, quantum well thickness, and strain within the quantum well structure. To reduce the effects of QCSE on DUV quantum well (QW)s, many VCSEL designers use very thin QWs and high-barrier heterostructures to provide sufficient carrier confinement and maximize wavefunction overlap. However, optimizing these parameters requires that all three of these parameters (confinement, efficiency of radiative recombination, and quality of materials) must be optimized simultaneously. The polarization of the light emitted from VCSEL devices also plays a major role in determining the performance and characteristics of the device. Increasing the amount of aluminum in the AlGaN QW changes the band structure of the semiconductor's valence band from TE polarized light to TM polarized light. Since TM polarized light does not efficiently couple to the surface-emitting geometry used in VCSEL devices, this change in polarization leads to a significant reduction in extraction efficiency and modal gain compared to TE polarized light.

2.3. Distributed Bragg reflectors in the DUV regime

Highly-reflective DBRs are necessary for laser oscillation and are main components of VCSEL designs. Selecting mirrors in the deep-ultraviolet can be difficult because semiconductor and dielectric material often have increased absorption at shorter wavelengths. Epitaxial nitride DBRs

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(AlGaN/AlN multilayers) can be designed to have very high reflectivities through the use of specially-designed superlattice structures; however, because the refractive index contrast between layers is low, a large number of periods is needed to obtain the desired reflectivity, which increases the total thickness of the DBR and poses challenges with induced strain-related defects like cracks or other types of defects. Dielectric DBRs can achieve high reflectivities with significantly fewer layers or periods, and they suffer very little from the effects of combined stresses associated with epitaxy. Therefore, dielectric DBRs are the most common type of mirror used in UVC VCSEL demonstrations. However, being electrical insulators, dielectric DBRs complicate current injection methods and require special design considerations, such as substrate removal and wafer bonding, to properly operate in VCSELs. Hybrid configurations of DBR-type mirrors, which are epitaxially grown and dielectric-based DBRs, have been used as well as other forms of reflectors, such as high-contrast gratings. Nevertheless, the application of these techniques in the fabrication of practical UVC VCSELs is still limited, and the challenge of achieving high reflectivity with the ability to inject current through a high-reflectivity mirror is an ongoing problem [5].

2.4. Cavity length, detuning, and optical loss mechanisms

The VCSEL's cavity length affects the resonance wavelength and the distance between the mode of the cavity and the gain peak. When the distance between these two points is as small as possible, the modal gain is maximized, and the lasing threshold is lowered. Precise control of the cavity length is important in DUV VCSELs, especially for small thickness variations, because small changes in cavity length can cause large shifts in the output wavelength due to the short emission wavelength of the device. The main sources of optical loss in DUV VCSELs are absorption and scattering losses. Absorption losses occur due to cavity materials, the DBR, and the doped layers, whilst scattering losses arise from the surface roughness of the cavity and interface imperfections. After the substrate has been removed (such as by laser lift-off), optical scattering losses are significant as the substrate is often removed, leaving behind a rough surface. A practical approach to reducing the scattering loss is to place rough surfaces in close proximity to the nodes of standing wave conditions (where the optical intensity is zero) as described in Section 2.1 and seen in Figure 1. Furthermore, surface smoothing techniques, including chemical mechanical polishing, are often used to reduce roughness on the interface. To reduce absorption losses, the use of highly absorbing materials should be minimized in regions of high optical field intensity, and the region of overlap between the optical field and p-type layers or metallic contacts should be minimized.

3. Key fabrication techniques and optical loss suppression

3.1. Substrate removal and surface planarization

The use of dielectric DBRs on both sides of UVC VCSEL cavities is a common structure, meaning that access to the nitride surface will be necessary after epitaxial growth. Therefore, when growing onto sapphire substrates, the DBR option requires both the removal of the substrate and processes of layer transfer. This means that there is a typical process flow for fabricating UVC VCSELs: starting with the deposition of the bottom DBR, then bonding, then the removal of the substrate, and finally both surface treatment and the deposition of the top DBR. The most widely used method for substrate removal is laser lift-off (LLO). The device consists of a UV excimer laser to decompose a sacrificial layer located at the interface between the sapphire substrate and the nitride epilayer. Once the sacrificial layer is decomposed by the LLO process, the sapphire substrate and nitride epilayer

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separate from each other, generally leaving behind a rough and/or partially damaged surface, especially for Al-containing materials, which have a lower thermal stability than GaN-containing systems. Therefore, accurate and precise control of both the LLO laser parameters and the sacrificial-layer design is essential to preventing any significant damage to the crystalline structure of the active multiple quantum wells. Due to the significant amount of scattering loss caused by rough surfaces, surface planarization must be performed on the optical cavity substrate before removing it from the optical cavity substrate. The degree of planarization affects the Q factor of the optical cavity as well. Planarization of the optical cavity surfaces is accomplished through either chemical mechanical polishing (CMP) or photoassisted chemical etching (PCE). The purpose of CMP is to remove an area of damaged material, to control the thickness of the nitride layer used, and to achieve global planarization of the optical cavity substrate surface. PCE uses illumination with an alkaline solution to perform controlled chemical reactions that remove contaminants on the optical cavity substrate. Since PCE is effective for minimizing surface damage and reducing nanoscale roughness on the optical cavity substrate surfaces, CMP and PCE are often used together, with CMP providing bulk planarization of the optical cavity substrate surfaces and PCE providing a finishing refinement to the quality of the planarized surfaces.

3.2. Process-induced loss mechanisms and suppression strategies

Fabrication methods create more than just surface roughness; they also characterize the optical loss introduced by the process. The most abundant sources of scatter loss are lateral confinement, interface roughness, and the particulate contamination of the dielectric. Therefore, the goal of the fabrication process is to produce a dielectric film that possesses a high density and few defects while maintaining a clean processing environment.

Absorption losses are primarily dictated by the properties of the material and device structure; however, both the selection of fabrication processes as well as the overall design will have a significant impact on absorption losses. Examples of how this occurs can be seen by looking at the use of highly doped p-type layers and metal contacts which will produce a significant amount of absorption at deep UV wavelengths. Thus, to minimize absorption losses, one must design processes to create minimum overlap between the optical modes and the region that will absorb light. These challenges have lead to the development of such methods as thin p-type layers, transparent current-spreading layers and/or alternate current injection schemes, such as tunnel junctions. There are a variety of optical field engineering methods available that relate to cavity design which were discussed in Chapter 2 (Sections 2.4.1-2.4.3). The design and production of UVC VCSELs requires a careful focus on the interface roughness being as small as possible and ensuring there are no added optical losses to the UVC VCSEL due to any of the processes used to make them. A successful manufacturing process for UVC VCSELs also includes a coordinated effort to optimize the substrate removal, surface planarization, and dielectric mirror deposition processes, as well as the minimization of process-induced scattering and absorption losses through both design and production. These aspects of manufacturing UVC VCSELs must all be accomplished in conjunction with the design of the optical cavity so that they operate at low loss and can generate laser output under real-world application conditions [6].

4. Research progress of DUV VCSELs and representative demonstrations

Initially, Hjort et al. presented the first optically pumped AlGaN VCSEL operating at room temperature (310 nm) in 2021 [7]. This key finding verified that VCSELs could be operated in the

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UVB wavelength regime utilizing dielectric DBR-based microcavities, as well as emphasizing the design of the cavity and the mirror reflectivity as critical factors to achieving stable lasing at shorter wavelengths.

While UVB devices have been successfully produced, extending VCSELs for operation within the UVC wavelength regime presents much greater difficulties. The first demonstration of an optically pumped AlGaN-based DUV VCSEL emitting at 275.91 nm was accomplished by Zheng et al., representing one of the first times VCSELs have been created with lasing in the 200−280 nm region (2021) [8]. The device achieved a threshold pump power density of 1.21 MW/cm² and had a line width of 0.78 nm. This study highlighted that achieving sufficient internal quantum efficiency in AlGaN MQWs as well as reducing optical losses in the cavity are both vital to producing UVC lasing.

Enhanced performance has resulted from subsequent advancements in epitaxial growth methods and their related fabrication processes. Zheng et al. (2023) showed that high-quality epitaxial AlGaN structures combined with optimized fabrication methods (such as LLO and CMP) can produce UVC VCSEL emission between 275.91 nm and 277.64 nm, with a threshold irradiance of only 0.79 MW/cm², which at the time constituted a record low for thresholds of this type [1]. This work illustrates the importance of both epitaxial growth quality and the quality of any post-growth surface processing in minimizing optical losses and facilitating efficient lasing operation.

Surface and interface engineering have been shown to have a major impact on device performance in addition to threshold reductions. Zheng et al. (2020) reported the use of PCE following LLO to smooth the AlGaN surface by reducing the root-mean-square roughness from 30.5 nm to 5.6 nm [4]. This reduction improved the quality of the HfO_2/SiO_2 DBR fabricated on the AlGaN substrate and improved the microcavity characteristics of the ultraviolet devices fabricated on this substrate. These results indicate that there is a strong correlation between optical loss suppression in UVC VCSELs and the fabrication processes that result in improved surface quality and reduced scattering.

Overall, current progress in DUV VCSELs indicates that achieving efficient UVC lasing requires coordinated advances in epitaxial growth, cavity design, and fabrication processes. While optically pumped devices have demonstrated feasibility, further improvements in material quality, mirror technology, and electrical injection strategies are required to realize practical electrically injected UVC VCSELs.

5. Conclusion

This paper discussed the physics involved in optically suppressing the losses of DUV VCSELs and also cover the progress made in fabricating these devices. The state of the art in DUV VCSELs has advanced from a theoretical concept to demonstrate experimental capability due to two major advances in technology that have occurred. The technological advances are: Improvements to AlGaN multiple quantum well growth increasing the internal quantum efficiency (IQE); and improvements in the fabrication processes required to minimize optical losses in the DUV VCSEL cavities via substrate removal, post-removal surface planarization, and dielectric DBR integration methods. The experimental results obtained at ~310 nm UVB and ~275-278 nm UVC demonstrate that DUV VCSELs are possible with the appropriate control of the mirror reflectivity and optical losses in the cavity. Nonetheless, these devices are mostly optically pumped, and electrically injected UVC VCSELs have not yet been realized due to a number of challenges, including the poor p-type conduction of Al-rich AlGaN, the inefficient spreading of the injected current, and the difficulty of integrating the electrical injection structure with a low-loss optical cavity.

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To achieve continued progress in developing electrically injected UVC VCSEL devices, there is a need for coordinated optimization of multiple elements in both device design and fabrication. The first aspect is that the active region must include a polarization-aware design. The number of quantum wells and the thickness of the barrier structures should be designed to minimize the quantum confined Stark effect; yet, they must also provide a good amount of TE polarized emission, good optical gain, and good multiple quantum wells barrier thickness uniformity. The second aspect is that the design of the optical cavity should be designed so that the exact amount of detuning can be controlled, and the thicknesses of all of the layers will have uniformity since the resonance range of the DUV cavity will be quite small, and will be very sensitive to post-fabrication variations. The third aspect is that engineering the optical losses should be approached from a system-wide perspective. By using very little absorption, employing low roughness dielectrics for mirrors, employing CMP and PCE for achieving low roughness at all the interface layers, and performing careful engineering of the structure to minimize the effects of residual roughness. The final aspect is that the electrical injection schemes should be based on work that has taken place with DUV LED devices, specifically by using the tunneling method to inject current into the laser structure. However, these methods must be designed specifically to work with the VCSEL laser design, in order to avoid absorbing material or too much metal over the high intensity regions of the VCSEL laser.

If these approaches can be successfully integrated, electrically injected UVC VCSELs have the potential to evolve from laboratory-scale demonstrations to practical, chip-scale ultraviolet laser sources for applications in sterilization, sensing, and advanced photonic systems.

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