AlGaN-Based Deep Ultraviolet Vertical-Cavity Surface-Emitting Laser

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***Abstract*— An optically pumped AlGaN-based vertical-cavity surface-emitting laser (VCSEL) in the deep ultraviolet (DUV) range (<280 nm) is demonstrated. The lasing wavelength is 275.91 nm with a threshold power density of 1.21 MW/cm^2 and a linewidth of 0.78 nm. The lasing is believed to be benefited from high internal quantum efficiency (IQE) of the AlGaN-based multiple quantum wells (MQWs) and improved fabrication processes.**

***Index Terms*— AlGaN, VCSEL, DUV.**

I. Introduction

GaN-BASED vertical-cavity surface-emitting lasers (VCSELs) are attracting much interest due to their advantages of circular far field distribution, low power consumption, single longitudinal mode emission, temperature-insensitive properties, and two-dimensional integration capability [1]. It can be used in various potential applications, such as high-resolution printing, displays, visible light communication, miniature atomic clocks and so on [2].

However, GaN-based VCSELs still face many challenges. The lower refractive index contrast between nitrides, comparing with dielectric materials, results in several tens pairs of nitrides needed for the nitride distributed Bragg reflectors (DBRs) [3]–[5]. But the stress accumulated in the nitride DBRs can cause a lot of cracks in the epilayer. For the cavity with double dielectric DBRs [6], [7], substrate removal combined with precise control of cavity length is necessary, resulting in complicated fabrication processes. In addition, quantum confined Stark effect (QCSE) orientated from the polarization of nitride reduces the radiative recombination efficiency between electrons and holes. In addition, low-resistance p-type nitride is still difficult to obtain for electrically pumped VCSELs.

Despite these difficulties, GaN-based VCSELs have been demonstrated in a wide spectral range [2]. It has been reported from 363 nm [8] to 498.8 nm [9] for the optically pumped GaN-based VCSELs. For the electrically pumped GaN-based VCSELs, lasing from 402.3 nm [7] to 565.7 nm [10] has been demonstrated. Among various laser light realized by nitride materials, deep ultraviolet (DUV) laser has many potential applications, such as disinfection, medical treatment, biological sensing, lithography, and laser cutting. However, neither optically pumped nor electrically pumped VCSEL has ever been reported in DUV range (<280 nm). The shortest wavelength of VCSELs reported is 363 nm [8].

Since the bandgap of $Al_xGa_{1-x}N$ alloy varies from 3.4 eV to 6.0 eV [11], with increasing Al composition x. AlGaN based VCSEL is expected to work in the DUV range. Many edge-emitting lasers (EELs) lasing in DUV range have been reported by employing AlGaN epilayer [12]–[15]. However, there are only a few reports of VCSEL in the sub-400 nm regime [8], [16]–[19]. The specific challenge in VCSELs compared with EELs is the different length of the gain region. For VCSELs, the gain region is usually only several tens of nanometers, while it can be several millimeters for EELs. Thus, EELs are much easier to lase. There are many issues need to be overcome in order to achieve AlGaN-based VCSEL lasing in DUV range. First, it is difficult to obtain high crystal quality AlGaN epilayer, especially with high Al composition. Al atom has a low surface migration velocity, resulting in high dislocation density [20]. Second, strong optical absorption exists in both the DBR material and the AlGaN epilayer [21], which increases the lasing threshold. Third, the substrate removal of AlGaN epilayer is more difficult than that of GaN epilayer because of the higher bandgap and the higher decomposition temperature of AlGaN. Fourth, the rough AlN or AlGaN surface after substrate removal increases the optical scattering loss, making lasing even difficult [22], [23].

In this work, we successfully fabricated an optically pumped AlGaN-based VCSEL using a cavity with double dielectric DBRs consisting of alternative SiO_2 and HfO_2 layers. Laser

Manuscript received January 5, 2021; revised January 14, 2021; accepted January 15, 2021. Date of publication January 19, 2021; date of current version February 24, 2021. This work was supported in part by the National Key Research and Development Program of China under Grant 2017YFE0131500 and Grant 2016YFB0400803, in part by the Science Challenge Project under Grant TZ2016003, in part by the National Natural Science Foundation of China under Grant 61704140, in part by the Natural Science Foundation of Fujian Province of China under Grant 2019J05023, and in part by the Youth innovation Foundation of Xiamen, China under Grant 3502Z20206055. The review of this letter was arranged by Editor Z. Ma. *(Corresponding authors: Hao Long; Baoping Zhang.)*

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Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LED.2021.3052725.

Digital Object Identifier 10.1109/LED.2021.3052725

lifted off (LLO) process was used to remove the sapphire substrate. After LLO, the sample was polished to achieve an atomically smooth surface. The measured VCSEL lasing wavelength is 275.91 nm with a line width of 0.78 nm and a threshold power density of 1.21MW/cm^2.

II. Experiments

The structure was grown on a nano-patterned sapphire substrate (NPSS) using AMEC Prismo HiT3 metal organic chemical vapor deposition (MOCVD) platform. A 4 μm AlN buffer was firstly grown. Then a 200 nm AlN/$Al_{0.6}Ga_{0.4}N$ superlattice (SL) transaction layer with average Al composition of 80% was grown on the AlN buffer at 1100 ° to act as a "dislocation filter" [20], [24], [25]. A 1.2 μm n-type $Al_{0.6}Ga_{0.4}N$ layer with Si doping concentration of 8×10^{18}cm^{-3} was grown on the SL layer at the same temperature. The active region is consisted of 5 pairs of $Al_{0.4}Ga_{0.6}N$ (2 nm)/$Al_{0.5}Ga_{0.5}N$ (6 nm) multiple quantum wells (MQWs). Finally, a 60 nm p-type $Al_{0.6}Ga_{0.4}N$ cladding layer was grown on the top of MQWs.

The cavity fabrication began with the deposition of a 15.5-pair HfO_2/SiO_2 (34.8 nm /47 nm) bottom DBR. The DBR was etched into a series of 200 × 200 μm^2 squares by buffered oxide etcher (BOE) solution, after a lithography process. Patterned DBR could enhance the following bonding strength. The photoresist was removed, and the structure was then inversed and bonded onto a glass by adhesive bonding. The sapphire substrate, AlN buffer, and AlN/AlGaN SL were removed by means of LLO with a 248 nm KrF excimer laser. Then, the exposed surface was thinned and smoothed in the chemical mechanical polishing (CMP) process, and the epilayer broke spontaneously at the area without DBR underneath. The epilayer thickness after polish was 140∼700 nm estimated by an optical interferometer. A 7.5-pair HfO_2/SiO_2 top DBR was deposited on the sample to finish the VCSEL fabrication. The fabrication process and a top view of a DUV VCSEL are shown in Fig.1. The sample surface morphology was measured by using an atomic force microscope (AFM). Photoluminescence (PL) measurements were performed, using a 240-nm laser with 5 ns pulse duration and 20 Hz repeat frequency. A Helium cycle cooling system was used in the temperature dependent (TD) PL measurements.

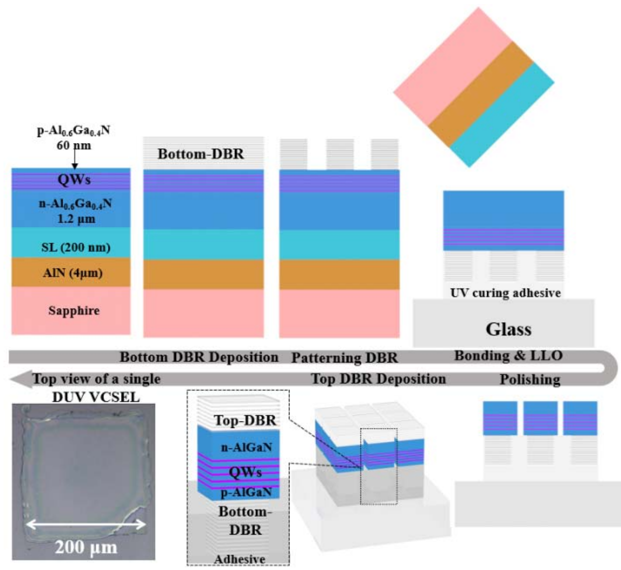

Fig. 1. DUV VCSEL fabrication process and device top view.

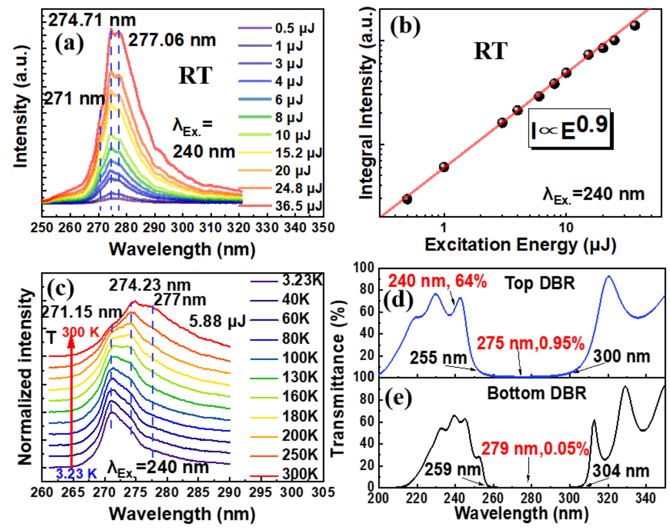

Fig. 2. Excitation energy varied PL measurement results of the as-grown wafer (a). Three peaks at 271, 274.74 and 277.06 nm were observed, which were interference peaks. The emission center is around 274.71 nm. Log-Log plot of the integrated PL intensity (I) as a function of excitation energy (E) (b). I∝E$^{0.9}$ indicates that radiative recombination dominated in the whole PL measurement. TD PL measurement results of the as-grown wafer (c). Top (d) and bottom (e) DBRs transmittance spectra.

III. Results and Discussions

Fig. 2(a) is the excitation energy varied PL measurement results of the as-grown wafer, collected at room temperature (RT). Three peaks can be observed at 271, 274.71 and 277.06 nm, respectively, which were interference peaks from the optical resonance between the AlN/substrate interface and the epilayer surface. And the epilayer thickness could be estimated to be 5.6 μm from these peak positions, in agreement with the structure. The emission center was at 274.71 nm. The integrated PL intensity varied with the excitation energy was depicted in a Log-Log plot, as shown in Fig. 2(b). The integrated PL intensity I was proportional to the excitation energy E, and can be express as the power law [27]–[29],

$$I \propto E^P, \tag{1}$$

where P reflects the recombination type of the sample in the PL measurement. $P > 1$, indicates that the emission is dominated by defect-related nonradiative recombination; $P \sim 1$, indicates that the emission is dominated by radiative recombination; $P < 1$, indicates another nonradiative recombination, Auger recombination, which is more prominent at high injection levels [29], [30]. In Fig. 2(b), $P = 0.9$, which indicates that radiative recombination dominated in the whole PL measurement. It suggests low defect density in the active region.

Fig.2 (c) shows the TD (3.23 K∼300 K) PL measurement results of the as-grown wafer, and all the spectrum

TABLE I
SUMMARY OF LASING WAVELENGTH, THRESHOLD, AND LINE WIDTH FROM PREVIOUS VCSEL RESEARCH RESULTS AND THIS STUDY

Wavelength (nm)	Threshold	Line width (nm)	Active region	Year	Organizations
363[8]	2 MW/cm^2	<0.5	GaN	1996	ATMI & U. Mass.
383[19]	30 mW	<0.1	$In_{0.03}Ga_{0.97}N$ / GaN	2000	Brown U. &Sandia National Labs.
367.5[17]	1 MW/cm^2	1.4	$In_{0.04}Ga_{0.96}N$ / $Al_{0.15}Ga_{0.85}N$	2015	Georgia Tech.
374.9[18]	1.64 MW/cm^2	0.66	$In_xGa_{1-x}N$/ $Al_yGa_{1-y}N$	2016	Georgia Tech.
375[16]	270 kW/cm^2		$In_{0.04}Ga_{0.96}N$ / $Al_{0.15}Ga_{0.85}N$	2019	Georgia Tech.
275.91	1.21 MW/cm^2	0.79	$Al_{0.4}Ga_{0.6}N$/ $Al_{0.5}Ga_{0.5}N$	2020	XMU

were normalized. Three peaks could be observed at 271.15, 274.23 and 277 nm, which were also interference peaks. The emission center varied from 271.15 to 274.23 nm with increasing temperature. The internal quantum efficiency (IQE) of the MQWs was estimated, following the formula, IQE $= I_{RT}/I_{LT}$, where I_{RT} is RT integrated PL intensity and I_{LT} is low temperature integrated PL intensity. Assuming the IQE is 100% at 3.23 K, the estimated IQE at 300 K is ~62%. It is a reasonable high value comparing with previous research results, 85% [31], 69% [32], 50% [33], 55% [34], 43% [35], and 8% [36].

The transmittance spectra of the top and bottom DBRs were depicted in Fig.2 (d) and (e). The bandwidth was ~45 nm for both top and bottom DBRs. The extinction coefficient for HfO_2 and SiO_2 was 0.009 and 0, respectively, at 280 nm. The reflectivities of top and boom DBRs were calculated to be 95.3% and 97.7% at 276 nm.

After LLO, the epilayer was lifted off from AlN/AlGaN SL, and then thinned and polished to remove the degraded crystal produced in LLO. Fig. 3 is AFM surface morphology after polishing. The atomic smooth surface is achieved with root-mean-square (RMS) roughness of 0.96 nm. A flat surface can reduce the optical scattering loss of the cavity [22], [23].

The fabrication of the AlGaN-based VCSEL was finished by the deposition of top DBR. Then, it was optically pumped by a 240-nm laser with 5 ns pulse duration and 20 Hz repeat frequency at RT. The collected emission spectra are shown in Fig. 4(a). With the increasing pumping energy, a lasing peak appeared at 275.91 nm with a linewidth of 0.78 nm. Fig. 4 (b) shows the light output intensity as a function of excitation energy. The threshold power density is 1.21 MW/cm^2 after considering the top DBR reflection (64% transmittance at 240 nm). Table I summarizes the characteristics of previous sub-400 nm VCSELs and this work, which are all optically

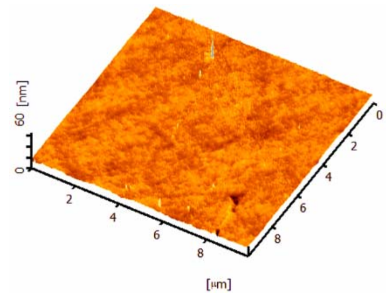

Fig. 3. AFM image (10 × 10 μm^2) of the epilayer after polishing. The RMS roughness is 0.96 nm.

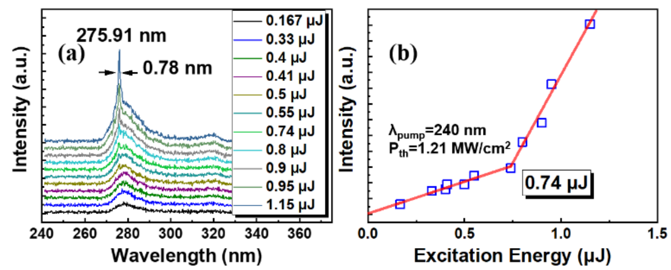

Fig. 4. Laser emission spectra for the AlGaN VCSEL with increasing pumping energy at room temperature (a), light output intensity as a function of excitation energy at room temperature (b).

pumped at RT. As shown in Table I, the shortest wavelength, 363 nm, was reported in 1996 using the GaN layer. Comparing with previous works, this work realized the VCSEL with AlGaN MQWs structure lasing at 275.91 nm.

Our superior lasing character is believed to be benefitted from the good quality of the active region with an IQE of 62%, double-side dielectric DBR structure instead of hybrid DBRs structure to reduce the growth difficulty of the epilayer, and good polishing technique to obtain smooth surface after LLO.

IV. CONCLUSION

Optically pumped AlGaN-based DUV VCSEL was realized with a lasing wavelength of 275.9 nm, a threshold power density of 1.21 MW/cm^2 and a linewidth of 0.78 nm. The lasing is believed to be benefited from high IQE of the MQWs and improved fabrication processes.

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