Reduction of the lasing threshold in optically pumped AlGaN/GaN lasers with two-step etched facets

Sergi Cuesta1,∗, Lou Denaix1, Florian Castioni2, Le Si Dang3 and Eva Monroy1

1 University Grenoble-Alpes, CEA, Grenoble INP, IRIG, PHELIQS, 17 av. des Martyrs, 38000 Grenoble, France
2 University Grenoble-Alpes, CEA, LETI, 17 av. des Martyrs, 38000 Grenoble, France
3 University Grenoble-Alpes, CNRS, Institut Néel, 25 av. des Martyrs, 38000 Grenoble, France

E-mail: sergi.cuestaarcos@cea.fr

Received 29 March 2022, revised 16 May 2022
Accepted for publication 19 May 2022
Published 1 June 2022

Abstract

We report a two-step process to obtain smooth and vertical \{10−10\} m-plane facets in AlGaN/GaN separate confinement heterostructures designed to fabricate ultraviolet lasers emitting at 355 nm. The process combines inductively coupled plasma reactive ion etching with crystallographic-selective wet etching using a KOH-based solution. The anisotropy in the wet etching allows the fabrication of flat, parallel facets without degradation of the multilayer ensemble. The optical performance of the lasers is strongly improved (reduction of the lasing threshold by a factor of two) when using the two-step process for the definition of the cavity, in comparison to cavities fabricated by mechanical cleaving.

Keywords: AlGaN, UV laser, etching, lasing threshold, GaN, photoluminescence

(Some figures may appear in colour only in the online journal)

1. Introduction

Ultraviolet (UV) lasers find applications in fields like medical diagnosis and treatment (particularly in the domains of oncology and dermatology), laser lithography, micromachining or three-dimensional printing [1–3]. In this spectral region, the use of excimer lasers is widespread, despite their many restrictions due to the use of corrosive halogen gases. An alternative is frequency conversion based lasers, such as Nd:YAG, although they are limited in terms of flexibility in emission wavelength. To address these issues, there is a strong demand for compact semiconductor UV lasers, and AlGaN has proved to be a promising material for the fabrication of these devices due to its direct ultra-wide-bandgap, wavelength tunability, and feasibility of doping [4–7]. However, the fabrication of AlGaN laser diodes still presents important material challenges. The lattice mismatch in the (Al,Ga)N system results in structural defects (dislocations or cracks) generated by the need to release the accumulated elastic energy [8–11]. Furthermore, the increase of the dopant activation energy with the Al content results in high resistivity layers, which hampers carrier injection [4, 12–16]. Alternative approaches using optical [17–21] or electron-beam pumping [22, 23] are also under consideration.

In order to reduce the lasing threshold, it is crucial to reduce the optical losses. In the case of edge emitting lasers, the fabrication of very smooth and vertical mirror facets is critical to the laser performance [24]. Mechanical cleaving is a common method for the fabrication of lasers [25–27], although it is not practical for mass production and it sets limits to the cavity length. Furthermore, the strain fields due to the lattice mismatch in GaN/AlGaN separate confinement heterostructures (SCH) can result in non-ideal cleaved facets, due to the surface

∗ Author to whom any correspondence should be addressed.
roughness induced by stress relaxation during the cleaving process. Also, mechanical cleaving is difficult to apply when the epilayers are grown heteroepitaxially on substrates whose cleaving planes are not aligned with those of the active layers, e.g. GaN or AlN on c-sapphire.

An alternative method for the definition of the cavity is the use of lithography and etching [28, 29], which grants a precise geometry control, independent of the substrate. However, reactive ion etching (RIE) does not provide the vertical walls required to attain lasing, and a complementary crystallographic selective etching process is required to reduce mirror losses. In this sense, the exposure of AlGaN to TMAH, NaOH or KOH is known to lead to crystallographic selective etching rates [30–34]. Such etching processes have been described also as a method to obtain top-down nanowires with crystallographic smooth \(10-10\) \(m\)-plane sidewalls for photonic applications [35–37], as well as fin-shaped or nanowire-based field effect transistors [38–40].

It is often reported that the fabrication of UV laser cavities includes a wet etching step, most often with TMAH [21, 22, 24, 41, 42] or KOH [29]. However, the question remains if this process can lead to comparable or improved mirror facets with respect to mechanical cleaving, or to what point it might limit the device performance. In this work, we report an optimized two-step etching process, involving inductively coupled plasma (ICP) RIE followed by wet etching in AZ400K (KOH containing developer), to fabricate smooth, vertical facets in AlGaNS/GaN SCHs designed to operate as electron beam pumped lasers. We compare the laser performance of etched structures with that of mechanically cleaved cavities from the same wafer, to assess the improvement of reflectivity obtained through the etching process. We show that the lasing threshold almost halved by using the two-step etching process. This improvement is due to the fact that wet etching reveals chemically and atomically smooth \(m\)-plane facets, whereas the stress associated with mechanical cleaving, combined with the strong strain fields in these heterostructures, results in a partial relief of elastic energy by creation of nanofaceted surfaces.

### 2. Sample structure

This study focuses on two GaN/AlGaN laser structures which were grown by plasma-assisted molecular beam epitaxy on free-standing GaN substrates. In both architectures, described in figures 1(a) and (b), the active region consists of a 10-period GaN/Al\(_{0.1}\)Ga\(_{0.9}\)N multi-quantum well (MQW) inserted in an Al\(_{0.1}\)Ga\(_{0.9}\)N/Al\(_{0.2}\)Ga\(_{0.8}\)N waveguide. The layer thicknesses indicated in the figures were confirmed by x-ray diffraction (XRD) measurements. The design labeled ‘SCH’ is a separate confinement heterostructure (SCH) with chemically sharp heterointerfaces, whereas ‘GRINSCH’ refers to a sample in which the Al\(_{0.1}\)Ga\(_{0.9}\)N/Al\(_{0.2}\)Ga\(_{0.8}\)N interfaces are graded along 35.2 nm in order to implement a graded-index separate confinement heterostructure (GRINSCH). Such graded layers pursued an enhanced diffusion of the carriers generated in the top cladding layers towards the MQW. A more detailed explanation of the growth conditions and benefits of the GRINSCH can be found in our previous work [43], which contains simulations of the band diagram of both samples.

To visualize and validate the sample structure, the samples were analyzed using scanning transmission electron microscopy (STEM) in a probe-corrected TFE Titan Themis microscope operating at 200 kV. With this purpose, lamella specimens were prepared using a Ga\(^+\) beam in a Zeiss Crossbeam 550 focused ion beam (FIB) scanning electron microscope (SEM). The voltage was progressively decreased from 30 to 2 kV in order to reduce beam damage and to obtain a sample thickness of about 70–90 nm. The panels on the left side of figures 2(a) and (b) present a cross-section image of a lamella extracted from the SCH and the GRINSCH samples, respectively, observed using high-angle annular dark field (HAADF) detector. The contrast of the image is due to the chemical composition, with dark contrast being observed in areas that are more Al rich (lower atomic number) and bright contrast in areas that are Ga rich (higher atomic number). At this scale, the MQW is hardly discernible due to the small QW width in comparison to the barriers, so that there is not enough chemical contrast with the inner cladding layers. In order to increase the signal-to-noise ratio, atomic-scale STEM-HAADF images were obtained by acquiring and aligning a stack of 40 frames of the area of interest, with a pixel size of approximately 23 pm and a pixel time of 200 ns. The zoomed images presented on the right side of figures 2(a) and (b) clearly reveal the contrast between the GaN quantum wells and the Al\(_{0.1}\)Ga\(_{0.9}\)N barriers.
3. Mirror fabrication

In order to define the optical cavity of the laser structure, we need high reflectivity facets. Here, the facets were implemented by ICP etching followed by crystallographic selective wet etching. The dry etching step was performed in an ICP-RIE system using a Cl₂/BCl₃ (10/25 sccm) chemistry optimized for GaN (etching rate = 215 nm min⁻¹). The radiofrequency (RF) power was 220 W, the ICP power was 990 W, the sample temperature was 50 °C and the pressure in the chamber was 10 mTorr. In a first approach, positive photoresist (AZ-5214E) was used as a mask for the definition of the cavities. In that case, an etching depth of 1 µm was easily obtained, but the etched sidewalls form an angle of 50° with the direction normal to the surface. To reduce this tapering, a second approach consisted in the implementation of a SiO₂/Ni (500 nm/150 nm) hard mask. For this purpose, a SiO₂ layer was deposited by chemical vapor deposition. Then, AZ-5214E was used as negative photoresist to define the cavities by photolithography, followed by electron-beam evaporation of Ni and lift off. Finally, the SiO₂ mask was patterned by ICP-RIE using a CF₄/CH₂F₂ chemistry (25/25 sccm, RF power = 125 W, ICP power = 600 W, pressure in the chamber = 5 mTorr). The SEM image in figure 3(a) presents a tilted view of the GRINSCH structure after dry etching. The top dark layer corresponds to the SiO₂/Ni hard mask. With this mask, the facet angle was reduced to 15°. The mask was removed by washing in HF.

The as-dry-etched samples did not display laser emission under optical pumping, which is explained by the imperfection of the optical cavity due to the tilted facet [26, 44].
modelled by van Deurzen et al [24], short wavelength emitters based on cavity optics have a high sensitivity to boundary imperfections. Therefore, a crystallographic-selective wet etching process is required to further reduce the facet tilt. The wet chemical etching of AlGaN in KOH-based solutions is highly anisotropic [33], and can be used to reduce the tapering.

For the optimization of the wet etching process, initial tests were performed on a 4 µm-thick GaN-on-sapphire template grown by metalorganic vapor-phase epitaxy (MOVPE). The layer was first dry-etched following the above-described procedure, with the result shown in figures 3(b) and (c) after removal of the hard mask. Then, the sample was dipped in a deionized water solution of AZ400K developer (KOH-based developer from AZ Electronic Materials USA Corp.), AZ400K:H2O = 1:4, stabilized at 65 °C. Figures 3(d)–(i) show the resulting facets after 2, 6 and 10 h of chemical treatment. The images reveal how the facets evolve under wet etching. In a first step, the areas that were damaged during the dry etching process are rapidly removed, and we observe the emergence of nanofacets at the sidewalls (figures 3(d) and (e)), mostly c-(0001) and m-[10−10] planes. Increasing the etching time, the vertical facets become larger and the presence of (0001) nanofacets is restricted to the part of the sidewall closer to substrate (figures 3(f) and (g)). For longer etching time (figures 3(h) and (i)), vertical facets are obtained. Figure 3(j) is a top-view of the resulting facets, showing the straight morphology of m-[10−10] planes and the roughness of a-[11−20] planes due to the presence of m-[10−10] nanofacets.

The shape that results from the etching process is explained by the Wulff-Jaccodine model [45], which can predict the 3D geometry over time [46–48]. This geometrical model, which can be considered the inverse of a growth model, idealizes the crystal facets as mathematical planes, neglecting real surface structures. It considers that facets with slow etch rate appear in concave geometries, leading to better quality etched planes than in convex areas. In KOH-based solutions, AlGaN m-[10−10], a-[11−20] and c-(0001) planes have etching rates with orders of magnitude slower (nm s−1) than those of semipolar and (000−1) planes (µm s−1). Therefore, vertical facets are exposed, particularly those with the slowest etching rate, i.e. m-[10−10] planes [49].

This experiment was useful to visualize the process leading to smooth m facets. However, for device fabrication, the method should be accelerated. Therefore, for the fabrication of the laser mirrors, we have used non-diluted AZ400K stabilized at 80 °C, with the results illustrated in figures 4(a) and (b) (GRINSCH sample). Note that the facets are vertical and there is no significant differences in the etching rate for the various layers in the stack.
To assess the optical performance of the etched laser structures (cavity length $L = 0.3 \text{ mm}$), we also prepared a series of laser bars with cavity lengths between 0.5 and 1.5 mm by mechanical cleaving along $m\text{-}\{10\text{–}10\} \text{ planes, for both SCH and GRINSCH. The profile of the cleaved bars were imaged by SEM (see figure 4(c)) and atomic force microscopy (AFM) (see figure 4(d)), showing that the mechanical cleaving leads to tilted faceting due to the stress relaxation of the AlGaN/GaN heterostructure. The root mean square (rms) roughness of the facet at the level of the heterostructure is in the order of 20 nm, while the rms roughness of the facet generated at the level of the GaN substrate is in the order of 0.4 nm. Top-view SEM images of the etched facet (see figure 4(e)) and cleaved facet (see figure 4(f)) provide further evidence of the higher quality of the etching process (straight facet) in comparison with the mechanically cleaved facet, whose irregularities are clearly visible at the scale of the image. Lasing was demonstrated in cleaved laser bars (labeled S1 and S3 in [43]), but the enhanced roughness at the heterostructure can surely produce significant light scattering when operating at short wavelengths [24].

4. Optical characterization

Photoluminescence (PL) measurements were performed under pulsed excitation using an Nd:YAG laser ($\lambda = 266 \text{ nm}$, 0.5 ns pulse width and 8 kHz repetition rate). The laser beam was shaped into a 100 $\mu\text{m}$ wide stripe using a cylindrical lens. In length, the variation of the laser intensity was <10% over 1 mm. The samples were pumped perpendicular to the top surface, with the laser stripe perpendicular to the cavity mirrors. The PL edge emission was collected through a Jobin Yvon HR460 monochromator and detected by a UV-enhanced charge-coupled device (CCD) camera. Lasing threshold measurements of samples SCH and GRINSCH were performed for different cavity lengths (0.5, 0.75, 1.0 and 1.5 mm) of mechanically cleaved laser bars and for 0.3 mm-long etched mesa cavities. All the measurements were performed at room temperature with the samples mounted on a copper holder.

Figures 5(a) and (b) show the PL spectra for a 0.3 mm-long GRINSCH cavity with etched facets and a 1 mm-long cavity with mechanically cleaved facets, respectively. The narrow line at 355 nm emerging from the p-type cleaved facet is visible at the scale of the image. Lasing was demonstrated in cleaved laser bars (labeled S1 and S3 in [43]), but the enhanced roughness at the heterostructure can surely produce significant light scattering when operating at short wavelengths [24].

The power density threshold is the pumping power density required to compensate the optical losses in the structure, including the internal ($\alpha_i$) and mirror ($\alpha_m$) losses. Therefore, the dependence of the threshold ($P_{th}$) on the cavity length ($L$) can be expressed as:

$$P_{th} = k (\alpha_i + \alpha_m) = k \left( \alpha_i - \frac{1}{2L} \ln \left( \frac{R_1 R_2}{R_1 + R_2 - 1} \right) \right),$$

where $k$ is a proportionality constant and $R_1$ and $R_2$ are the reflectivity of the two cavity mirrors. In our case, we can assume that both cleaved facets are identical ($R_1 = R_2 = R$). In the case of long cavities, the contribution of the mirror losses becomes negligible compared to the internal losses. On the contrary, the mirror losses become dominant in short cavities.

In the figure 5(d), the cleaved cavities follow the tendency described by equation (1) (dashed-lines in the graph). The fact that data follow the $1/L$ dependence indicates that the cavity losses are dominated by mirror losses. The etched
cavities, with a length of 0.3 mm, are significantly shifted with respect to that trend, showing a much lower lasing threshold than cleaved cavities. As the internal losses are expected to be the same in both cleaved and etched cavities, coming from the same sample wafer, the different lasing threshold is due to the improved reflectivity of the mirrors in etched cavities.

The stimulated emission of the heterostructure develops on the fundamental mode of the waveguide formed by AlGaN layers due to amplification in quantum wells, which is due to the effective absorption of higher-order modes in the GaN substrate material. Therefore, in the first approximation, the reflection coefficient can be estimated as the reflection coefficient of a plane wave incident perpendicularly on the plane of the Fabry–Perot resonator. Assuming that the reflectivity of the etched facets is close to its ideal value, \( R_i = 21\% \), defined by the refractive index contrast between GaN (\( n_{\text{GaN}} = 2.6915 \)) [51] and air at the emission wavelength (\( \lambda = 355 \text{ nm} \)) following Fresnel equations, we can estimate the reflectivity of the mechanically cleaved mirrors to be \( R_{\text{cleaved}} \approx 3.2\% \). This reflectivity value is the maximum obtained from the cleaved facets, since it was extracted from the lowest lasing threshold in the various cavities. Along the cleaved facets, the lasing threshold varies typically by \( \pm 13\% \), which is explained by the inhomogeneity of the facet roughness. Therefore, the value of \( R_{\text{cleaved}} \approx 3.2\% \) must be understood as an upper limit of the reflectivity of the cleaved mirrors.

In summary, we conclude that in these strongly strained heterostructures, cleavage causes surface roughness due to stress relaxation that translates in boundary imperfections for the optical cavity. Therefore, the implementation of a two-step etching process for the fabrication of the laser mirrors has proved to be beneficial for the laser performance.

5. Conclusions

We have developed a two-step process combining ICP-RIE and KOH-based crystallographic selective wet etching for obtaining vertical and smooth facets in AlGaN/GaN SCH designed to implement UV lasers emitting at 355 nm. Lasing threshold measurements under optical pumping proved that the mirror losses play a dominant role in the device performance of mechanically cleaved cavities. Such losses can be significantly reduced by using the two-step etching process, which leads to a reduction of the lasing threshold to almost half.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This work is supported by the French National Research Agency via the UVLASE program (ANR-18-CE24-0014), and by the Auvergne-Rhône-Alpes region (PEAPLE Grant).

ORCID IDs

Sergi Cuesta  
https://orcid.org/0000-0003-0262-5875

Eva Monroy  
https://orcid.org/0000-0001-5481-3267

References

[1] Savage N 2007 Ultraviolet lasers Nat. Photon. 1 83–85
[2] Wang X, Jiang M, Zhou Z, Gou J and Hui D 2017 3D printing of polymer matrix composites: a review and prospective Composites B 110 442–58
[3] Tottonchy M B and Chiu M W 2014 UV-based therapy Dermatol. Clin. 32 399–413, ix–x
[4] Amano H et al 2020 The 2020 UV emitter roadmap J. Phys. D: Appl. Phys. 53 503001
[5] Kirste R, Sarkar B, Reddy P, Guo Q, Collazo R and Sitar Z 2021 Status of the growth and fabrication of AlGaN-based UV laser diodes for near and mid-UV wavelength J. Mater. Res. 36 4638–64
[6] Hasan S M N, You W, Sumon M S I and Arafain S 2021 Recent progress of electrically pumped AlGaN diode lasers in the UV-B and -C bands Photonics 8 267
[7] Zhang Z, Kushimoto M, Sakai T, Sugiyama N, Schowalter L J, Sasaoka C and Amano H 2019 A 271.8 nm deep-ultraviolet laser diode for room temperature operation Appl. Phys. Express 12 124003
[8] Wang T-Y, Tasi C-T, Lin C-F and Wuu D-S 2017 85% internal quantum efficiency of 280-nm AlGaN multiple quantum wells by defect engineering Sci. Rep. 7 14422
[9] Martens M et al 2014 Performance characteristics of UV-C AlGaN-based lasers grown on sapphire and bulk AlN substrates IEEE Photonics Technol. Lett. 26 342–5
[10] Einfeldt S, Kirchner V, Heinke H, Dießelberg M, Figge S, Vogeler K and Hommel D 2000 Strain relaxation in AlGaN under tensile plane stress J. Appl. Phys. 88 7029
[11] Thai Q M, Cuesta S, Denai L, Hermelin S, Boisron O, Purcell S T, Dang L S and Monroy E 2021 Optical net gain measurement on Al_{0.54}Ga_{0.46}N/GaN multi-quantum well (arXiv:2108.00460 [cond-mat]) (https://doi.org/10.1364/OE.454381)
[12] Bougerol C, Robin E, Di Russo E, Bellet-Amarlic E, Grenier V, Ajay A, Rigutti I and Monroy E 2021 Solubility limit of Ge dopants in AlGaN: a chemical and microstructural investigation down to the nanoscale ACS Appl. Mater. Interfaces 13 4165–73
[13] Blasco R, Ajay A, Robin E, Bougerol C, Lorentz K, Alves L C, Mouton I, Amichi L, Grenier A and Monroy E 2019 Electrical and optical properties of heavily Ge-doped AlGaN J. Phys. D: Appl. Phys. 52 125101
[14] Collazo R, Mita S, Xie J, Rice A, Tweedie J, Dalmau R and Sitar Z 2011 Progress on n-type doping of AlGaN alloys on AlN single crystal substrates for UV optoelectronic applications Phys. Status Solidi c 8 2031–3
[15] Mehneke F, Trinh X T, Pinge H, Wernnicke T, Janzén E, Son N T and Kneissl M 2016 Electronic properties of Si-doped Al_{x}\text{Ga}_{1-x}\text{N} with aluminum mole fractions above 80% J. Appl. Phys. 120 144502
[16] Kinoshita T, Obata T, Yanaagi H and Inoue S 2013 High p-type conduction in high-Al content Mg-doped AlGaN Appl. Phys. Lett. 102 012105
[17] Hjort F et al 2021 A 310 nm optically pumped AlGaN vertical-cavity surface-emitting laser ACS Photonics 8 135–41
[18] Kirste R, Guo Q, Dyceus J H, Franke A, Mita S, Sarkar B, Reddy P, LeBeau J M, Collazo R and Sitar Z 2018 6 kW/cm² UVC laser threshold in optically pumped lasers achieved by controlling point defect formation Appl. Phys. Express 11 082101
[19] Jayaprakash R, Kalaitzakis F G, Christmann G, Tsagaraki K, Hocevar M, Gayral B, Monroy E and Pelekanos N T 2017 Ultra-low threshold polariton lasing at room temperature in a GaN membrane microcavity with a zero-dimensional trap Sci. Rep. 7 5542

[20] Sellés J et al 2016 Deep-UV nitrile-on-silicon microdisk lasers Sci. Rep. 6 21650

[21] Sato K et al 2020 Room temperature operation of AlGaN ultraviolet-B laser diode at 298 nm on lattice-relaxed Al_{0.6}Ga_{0.4}N/AIN/sapphire Appl. Phys. Express 13 031004

[22] Hayashi T, Kayase Y, Nagata N, Senga T, Iwaya S, Iwaya M, Takeuchi T, Kamiyama S, Akasaki I and Matsumoto T 2017 Demonstration of electron beam laser excitation in the UV range using a GaN/AlGaN multiquantum well active layer Sci. Rep. 7 2944

[23] Wunderer T, Tjeschke J, Yang Z, Teepe M, Batres M, Vancil B and Johnson N 2017 Resonator-length dependence of electron-beam-pumped UV-A GaN-based lasers IEEE Photonics Technol. Lett. 29 1344–7

[24] van Deurzen L, Page R, Protasenko V, Huili X and Jena D 2021 Optically pumped AlGaN double heterostructure deep-UV laser by molecular beam epitaxy: mirror imperfections and cavity loss (arXiv:2109.10515) [cond-mat, physics: physics]

[25] Kang J H, Krüger O, Spengler U, Zeimer U, Einfeldt S and Schowalter L J 1975 Correlation of the anisotropic etching of AlGaAs using modified free energy theorems to predict equilibrium growing and etching shapes Jpn. J. Appl. Phys. 15 2750–6

[26] Stocker D A, Schubert E F, Grieshaber W, Boutros K S and Redwing J M 1998 Facet roughness analysis for InGaN/GaN lasers with cleaved facets Appl. Phys. Lett. 73 1925–7

[27] Nakamura S, Senoh M, Nagahama S, Iwasa N, Yamada T, Matsushita T, Kiyoku H and Sugimoto Y 1996 InGaN multi-quantum-well structure laser diodes with cleaved mirror cavity facets Jpn. J. Appl. Phys. 35 L217–20

[28] Khan F A, Zhou L, Ping A T and Adesida I 1999 Inductively coupled plasma reactive ion etching of Al_{x}Ga_{1-x}N for application in laser facet technology J. Vac. Sci. Technol. B 17 2750

[29] Miller M A, Crawford M H, Allerman A A, Cross K C, Bans A M, Shul R J, Stevens J and Bogart K H A 2009 Smooth and vertical facet formation for AlGaN-based deep-UV laser diodes J. Electron. Mater. 38 533–7

[30] Stocker D A, Schubert E F and Redwing J M 1998 Crystallographic wet chemical etching of GaN Mater. Sci. Eng. B 55 83–7

[31] Palacios T, Calle F, Varela M, Ballesteros C, Monroy E, Naranjo F B, Sánchez-García M A, Calleja E and Muñoz E 2000 Wet etching of GaN grown by molecular beam epitaxy on Si(111) Semicond. Sci. Technol. 15 996–1000

[32] Ng H M, Weimann N G and Chowdhury A 2003 GaN nanotip pyramids formed by anisotropic etching Appl. Phys. Lett. 73 2654–6

[33] Zhang D and Edgar J H 2005 Wet etching of GaN, AlN, and SiC: a review Mater. Sci. Eng. R 48 1–46

[34] Al Taradeh N, Frayssinet E, Rodriguez C, Moranchio F, Sonneville C, Phung L-V, Soltani A, Tendille F, Cordier Y and Maher H 2021 Characterization of m-GaN and a-GaN crystallographic planes after being chemically etched in TMAS solution Energies 14 4241

[35] Li Q, Wright J B, Chow W W, Luk T S, Brenner I, Lester L F and Wang G T 2012 Single-mode GaN nanowire lasers Opt. Express 20 17873

[36] Debnath R, Ha J-Y, Wen B, Paramanik D, Motayed A, King M R and Davydov A V 2014 Top-down fabrication of large-area GaN micro- and nanopillars J. Vac. Sci. Technol. B 32 021204

[37] Behzadira D, Nami M, Westbrock N, Zamani Koupianji M R, Fezzell D F, Brueck S R J and Busani T 2018 Scalable top-down approach tailored by interferometric lithography to achieve large-area single-mode GaN nanowire laser arrays on sapphire substrate ACS Nano 12 2373–80

[38] Im K-S, Sindhuri V, Jo Y-W, Son D-H, Lee J-H, Cristoloveanu S and Lee J-H 2015 Fabrication of AlGaN/GaN Ω-shaped nanowire fin-shaped FETs by a top-down approach Appl. Phys. Express 8 066501

[39] Fatahiah M F et al 2019 Top-down GaN nanowire transistors with nearly zero gate hysteresis for parallel vertical electronics Sci. Rep. 9 10301

[40] Im K-S, Won C-H, Vodapally S, Caulmilone R, Cristoloveanu S, Kim Y-T and Lee J-H 2016 Fabrication of normally-off GaN nanowire gate-all-around FET with top-down approach Appl. Phys. Lett. 109 143106

[41] Tanaka S et al 2021 AlGaN-based UV-B laser diode with a high optical confinement factor Appl. Phys. Lett. 118 163504

[42] Sakai T, Kushimoto M, Zhang Z, Sugiyama N, Schowalter L J, Honda Y, Sasaoka C and Amano H 2020 On-wafer fabrication of etched-mirror UV-C laser diodes with the ALD-deposited DBR Appl. Phys. Lett. 116 122101

[43] Cuesta S et al 2021 AlGaN/GaN asymmetric graded-index separate confinement heterostructures designed for electron-beam pumped UV lasers Opt. Express 29 13084

[44] Iga K, Wakao K and Kunikane T 1981 Mode reflectivity of tilted mirrors in semiconductor lasers with etched facets Appl. Opt. 20 2367

[45] Tsai M-C, Leung B, Balakrishnan G and Wang G T 2016 Room-temperature operation of AlGaN/GaN asymmetric graded-index separate confinement heterostructures designed for electron-beam pumped UV lasers Opt. Express 24 9509–17

[46] Kawano K, Sasaoka C and Amano H 2020 Direct high-speed operation of normally-off GaN nanowire gate-all-around FET with top-down approach Appl. Phys. Express 8 066501

[47] Cristoloveanu S and Lee J-H 2015 Large-area GaN nanowire laser arrays on sapphire substrate Appl. Phys. Lett. 109 143106

[48] Weirauch D F 1975 Correlation of the anisotropic etching of single—crystal silicon spheres and wafers J. Appl. Phys. 46 1478–83

[49] Shaw D W 1979 Morphology analysis in localized crystal growth and dissolution J. Cryst. Growth 47 509–17

[50] Kazanowska B A, Sapkota K R, Gunning B P, Jones K S and Wang G T 2021 Exploring AlGaN nanostructures fabricated via a chemical wet etching Gallium Nitride Materials and Devices XVI ed H Morköç, H Fujikawa and U T Schwarz (United States: SPIE) p 64

[51] Cuesta S, Denaix L, Dang L S and Monroy E 2021 Fabrication of AlGaN/GaN asymmetric graded-index separate confinement heterostructures for UV emission Appl. Phys. Lett. 119 151103

[52] Barker A S and Ilegems M 1973 Infrared lattice vibrations and free-electron dispersion in GaN Phys. Rev. B 7 743–50