Fabrication and optical characterization of GaN waveguides on (-201)-oriented $\beta - \text{Ga}_2\text{O}_3$

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Abstract: Gallium nitride (GaN), a wide-bandgap III-V semiconductor material with a bandgap wavelength $\lambda_g = 366$ nm (for Wurtzite GaN) and transparency window covering the visible spectrum, has a large number of applications for photonics and optoelectronics. However, the optical quality of this material suffers from growth imperfections due to the lack of a suitable substrate. Recent studies have shown that GaN grown on (-201) $\beta - \text{Ga}_2\text{O}_3$ (gallium oxide) has better lattice matching and hence superior optical quality as compared to GaN grown traditionally on $\text{Al}_2\text{O}_3$ (sapphire). In this work, we report on the fabrication of GaN waveguides on $\text{Ga}_2\text{O}_3$ substrate, followed by a wet-etch process aimed at the reduction of waveguide surface roughness and improvement of side-wall verticality in these waveguides. The propagation loss in the resulting waveguides has been experimentally determined to be 7.5 dB/cm.

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References and links
Introduction

Gallium Nitride (GaN), a wide-bandgap (band-gap energy of 3.4 eV for Wurtzite GaN) semiconductor with high electron velocity and chemical and thermal stability [1], has attracted immense research interests for its many commercial applications, such as solid-state lighting, high-power and high-frequency electronics, and blue semiconductor lasers [2–5]. Similar to other III-V semiconductor platforms [6–8], high-optical-quality GaN is also expected to become a suitable candidate for integrated nonlinear photonic circuits for a wide range of applications spanning from all-optical signal processing to quantum computing. Integrated nonlinear optical waveguides based on GaN can exhibit correlated photon pair generation through spontaneous nonlinear optical processes, thus representing potentials for on-chip quantum sources in the visible and telecommunication spectral ranges. Despite the commercial production of GaN devices, this material still lacks a suitable substrate that would allow for a reduction of structural defects, such as high densities of threading dislocations (TDs) and grain boundaries [9–11]. These defects act as non-radiative recombination centers [12], thus deteriorating the optical quality of the epitaxially grown GaN layer. Recent studies have shown that GaN grown on (−201) β − Ga2O3 has a much lower lattice mismatch of 4.7% as compared to 14% for GaN grown on Sapphire...
Waveguides represent building blocks of any integrated photonic circuit. The first step in this study, we report on the realization of integrated optical waveguides based on GaN on (-201) β − Ga2O3. Using the parameters of the grown GaN wafer, we performed the design of rib waveguides for the C-band telecommunication wavelength range centered around 1550 nm. The design served as the guideline for the subsequent waveguide fabrication, followed by the wet-etch post-processing and experimental measurement of the propagation losses. This is the first, to the best of our knowledge, report on the realization of GaN integrated optical waveguides on Ga2O3 substrate. Passive optical waveguides represent key building blocks of integrated photonic circuits, and we believe that this work can act as a stepping-stone in the realization of integrated optical devices based on GaN on β − Ga2O3 for nonlinear photonics and optoelectronics applications.

Wafer growth

GaN was epitaxially grown on (-201) β − Ga2O3 with the use of triethylgallium and ammonia as source gases at 400 mbar in a MOCVD (Metalorganic chemical vapor epitaxy) chamber. An approximately 9-nm-thick GaN buffer layer was first grown on top of a (-201) β − Ga2O3 (we will further use the notation Ga2O3 for the sake of brevity) at the temperature of 500 °C. On top of the buffer layer, the growth of a 3.5-µm-thick GaN epitaxial layer of higher optical quality has been performed at 1100 °C.

A detailed comparison of the material properties of the resulting wafer and commercially available GaN grown on Al2O3 (Sapphire) has been reported in [13, 14]. The XRD rocking curve (RC) showed a superior GaN quality with a small full width at half maximum (FWHM = 330 arcsec), which is a typical FWHM value of high quality GaN wafer [14]. XRD RC results indicated low threading dislocation density (TDD), dominated by screw and mixed type dislocations [13]. The TDD and the type of dislocations were confirmed by atomic force microscopy (AFM) and transmission electron microscopy (TEM) analysis (TDD was on the order of 108 cm² [13, 14]). To the best of our knowledge, this is the best RC FWHM value for GaN obtained for materials grown on a Ga2O3 substrate. X-ray diffraction measurements have shown a much lower value of the lattice mismatch (only 4.7%) between Ga2O3 and the GaN film, compared to the 14% of lattice mismatch between Al2O3 and GaN [13]. The photoluminescence study reported in [13] has confirmed that the GaN on Ga2O3 wafer has higher photoluminescence yield than GaN grown on Al2O3. AFM measurements have shown the root mean square (RMS) surface roughness as low as ~ 0.3 nm over 400 µm², and ~ 0.17 nm over 25 µm², indicating a significantly smoother surface compared to that of the commercial state-of-the-art GaN grown on sapphire [13, 14]. The XRD, TEM and AFM results indicated that the (-201) β − Ga2O3 is the best orientation for GaN growth. We used the GaN on Ga2O3 wafer, characterized in [14], in our experimental studies reported hereafter.

Waveguide design and fabrication

Waveguides represent building blocks of any integrated photonic circuit. The first step in determining the suitability of GaN grown on Ga2O3 for integrated photonic applications is to attempt the realization of waveguides in such a wafer. Using Lumerical Mode Solutions, we designed a rib waveguide with the material parameters corresponding to those of the grown GaN on Ga2O3 wafer and the target operation wavelength 1550 nm. The effect of chromatic dispersion was taken into account by using the reported chromatic dispersion characteristics of GaN [15] and Ga2O3 [16]. Fig. 1 shows the dimensions of the designed waveguide along with the simulated electric field distribution of the fundamental TE mode for the waveguide width of 1.5 µm. We obtained from the simulations the values of the effective refractive index, \( n_{eff} = 1.964 \), and effective mode area, \( A_{eff} = 3.80 \mu m^2 \), for the fundamental TE mode of the waveguide shown in Fig. 1. We fabricated the designed waveguide structures using standard electron beam lithography followed by dry etching and post-processing. The steps of the fabrication process are outlined in...
Fig. 1. Electric field distribution of the fundamental TE mode in the designed GaN-on-$\text{Ga}_2\text{O}_3$ waveguide.

Fig. 2. Schematic representation of the fabrication process. The PECVD deposition of a 400-nm-thick layer of SiO$_2$ on top of the GaN wafer was followed by an e-beam evaporation deposition of a 50-nm-thick layer of Chromium. After that, a 200-nm-thick layer of HSQ was spin-coated and patterned by e-beam lithography. The HSQ mask was then used to imprint the waveguide profile into Chromium, and the chromium was then used as a mask for etching the SiO$_2$ layer. GaN was finally etched through the SiO$_2$ mask.
Fig. 2. The GaN on Ga$_2$O$_3$ wafer was first cleaned with acetone and isopropanol, and then was blow-dried with Nitrogen gas. After that, a 400-nm-thick layer of SiO$_2$ (Silica) was deposited on top of the wafer by Plasma-Enhanced Chemical Vapor Deposition (PECVD) technique, and then 50 nm of chromium was deposited by e-beam (electron beam) evaporation. Following these steps, a 200-nm-thick layer of HSQ e-beam resist was spin-coated and pre-baked at 170 °C. The waveguides were then patterned using 100-kV Jeol 9500 electron beam lithography system with a dose of 950 µC/cm$^2$. In order to make sure that the fabricated structures have the dimensions as per the design (the waveguide width around 1.5 µm), we left some room for fabrication errors by defining the waveguides with slightly different widths within the range of the desired value, from 1.3 to 1.7 µm, with the increment of 0.1 µm. After the e-beam patterning, the e-beam resist was developed in MIF 300 (2.38% tetramethylammonium hydroxide) for 10 min, then rinsed in de-ionized water, and cured on a hot plate at 170 °C for 1 hour. The e-beam-patterned HSQ mask was then used to transfer the waveguide pattern into chromium by Inductively Coupled Plasma in combination with Reactive Ion Etching (ICP-RIE). A Trion etcher was used for etching the chromium layer with an optimized recipe with the following parameters: 20 sccm of chlorine and 10 sccm of argon at the pressure of 50 mT, with the ICP and RIE powers of 200 and 80 W, respectively. The chromium mask was then used to transfer the waveguide pattern into silica with an Oxford 100 ICP-RIE system using 20 sccm of difluoromethane (CH$_2$F$_2$) and 80 sccm of helium at the pressure of 4 mT, 3000-W ICP and 60-W RIE powers. The silica mask was finally used to transfer pattern into GaN.

Fig. 3. SEM images of three GaN ICP-RIE experimental trials. Each scale bar represents 1 µm. The etching recipes and parameters for each of the trials are summarized in Table 1.

The GaN was etched with Plasmatherm PT770 ICP-RIE system. In order to optimize the etching recipe, we used systematic parameter sweep which involves varying one etch parameter at a time, while keeping the rest of the parameters unchanged, which resulted in the optimization of the parameter values. Fig. 3 shows scanning electron microscope (SEM) images of the outcomes of three etch trials with different parameters, as outlined in Table 1. A Zeiss Ultra 55 SEM was used with an acceleration voltage of 3 keV for cross-section imaging of the cleaved GaN waveguides. The etch rate of GaN, selectivity (defined as the ratio of the etch rate of GaN to the etch rate of silica), and side wall verticality (defined as the sidewall angle with respect to the normal to the substrate's surface) were measured using SEM imaging of the resulting waveguide cross-sections. As the RIE power was increased from 25 W [trial (a) in Table 1] to 80 W [trial (b) in Table 1], the sidewall verticality has been improved from 75 to 79°, and the etch rate increased from 150 to 275 nm/min. On the other hand, the selectivity reduced from 5:1 to 4:1, due to the increased influence of the physical (non-selective) etching mechanism because of the higher DC bias between the generated plasma and GaN surface [17]. As the next step in adjusting the etching recipe, ICP power was reduced from 400 W [trial (b)] to 250 W [trial (c)], which resulted in a slight reduction of the etch rate, but improved the selectivity from 4:1 to 8:1 due to the reduced plasma density [17]. The final optimized etch recipe has the following parameters: 5 sccm of argon, 8 sccm of boron trichloride (BCl$_3$), and 20 sccm of chlorine (Cl$_2$) at the overall pressure of 5 mT, with the ICP and RIE powers of 250 and 80 W, respectively. These parameters yielded
Table 1. Etching parameters and properties of the etch profile, namely, the etching rate, selectivity compared to silica, and side wall angle, presented for the three trial etching recipes with the resulting SEM images shown in Fig. 3.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Etching parameters</th>
<th>Etching rate of GaN (nm/min)</th>
<th>Selectivity to silica</th>
<th>Side wall angle (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Ar:BCl₂:Cl₂ = 5:8:20 sccm, P= 5 mT, RIE = 25 W, ICP = 400 W</td>
<td>150</td>
<td>5:1</td>
<td>75</td>
</tr>
<tr>
<td>(b)</td>
<td>Ar:BCl₂:Cl₂ = 5:8:20 sccm, P= 5 mT, RIE = 80 W, ICP = 400 W</td>
<td>275</td>
<td>4:1</td>
<td>79</td>
</tr>
<tr>
<td>(c)</td>
<td>Ar:BCl₂:Cl₂ = 5:8:20 sccm, P= 5 mT, RIE = 80 W, ICP = 250 W</td>
<td>250</td>
<td>8:1</td>
<td>79</td>
</tr>
</tbody>
</table>

The GaN etch rate of 250 nm/min, selectivity 8:1 compared to PECVD Silica, and the sidewall verticality of 79°.

The SEM images reveal some bump-like structures on the front surface of the waveguides [see Figs. 3 (a) and 3 (b)]. These are an artifact of SEM, most probably arising from charging. Another possible reason of some of these features is imperfections associated with cleaving the GaN sample.

It has been reported in multiple studies that plasma etching induces roughness on the etched surface due to the physical bombardment of the surface caused by the accelerated ions [18,19]. Wet-chemical etching does not involve any ion bombardment, and hence there is no plasma-induced surface roughness expected from this process. A wet-chemical post-processing step involving chemical etching of plasma-damaged top surface of GaN waveguide can reduce the ICP-caused roughness, and hence the light scattering as it propagates through the waveguide. The optical propagation losses are thus expected to be lower in the post-processed samples. These arguments served as the motivation for the wet-chemical postprocessing of our GaN waveguides.

**Wet-chemical post-processing and surface roughness measurements**

We used in our study two well-known wet etchants suitable for GaN, KOH [20] and TMAH [21]. TMAH has shown more reduction in the waveguide sidewall roughness as compared to that observed with KOH. ICP-RIE-etched GaN waveguide samples were wet-etched in 25% solution of TMAH at 80 °C for 5 min, and then were rinsed in de-ionized water. Anisotropic etching property of the TMAH solution improves surface morphology by preferentially etching the side slopes until the slopes are removed entirely, resulting in a smooth and vertical surface [21]. In the case with our samples, Ga-polar (0001) plane was nearly unaffected by the etchant, whereas N-face plane was etched rapidly, which resulted in nearly vertical etch facet. After the wet etch, the remaining silica mask was stripped by treating the sample with 10% hydrofluoric acid (HF) for 3 min and rinsing it with de-ionized water. Fig. 4 summarizes the overall fabrication process showing SEM cross-sectional images of (a) etched silica mask, (b) GaN waveguide after plasma etching, (c) GaN waveguide after post-processing using TMAH, and (d) the final GaN waveguide after stripping silica mask.

In order to confirm the reduction in the sidewall roughness of the post-processed etched waveguide surface, we performed an atomic force microscopy (AFM) analysis of the GaN waveguide sidewall before and after the post-processing, using a Park NX10 AFM to quantify the impact of the wet-etch process on the surface roughness of the GaN waveguides. Fig. 5 shows the 3D AFM plots of the etched GaN sample before [Fig. 5(a)] and after [Fig. 5(b)] the post-processing. To simplify the comparison, we used the same Y-axis scale for both the plots. It
is obvious from the figure that there is a dramatic reduction in GaN surface roughness as the consequence of the chemical post-processing. The AFM data demonstrate the reduction of the root-mean-square roughness more than 4 times after the post-processing: the characteristic size of the sidewall imperfections had reduced from 1.13 to 0.23 nm.

Optical characterization

The fabricated GaN sample was cleaved on both ends and lap-polished for butt-coupling the light into and out of the waveguides. The Fabry-Perot loss analysis [22] has been performed using the optical characterization setup shown in Fig. 6. A tunable cw semiconductor laser, Santec TSL 710, was used as the light source for the Fabry-Perot loss measurement in the wavelength range around 1550 nm. The light from the laser source was first coupled into a single-mode SMF28 fiber, and then was collimated for free-space coupling into the waveguides. The collimated laser beam was then TE-polarized using a half-wave plate and a polarizing beam splitter. The TE-polarized light was then butt-coupled into the waveguide using a 40× microscopic objective mounted on a 3-axis micrometer coupling stage. The light was then coupled out of the waveguide with a 20× microscopic objective. An IR detector was used to measure the optical power at the waveguide output. Measuring the output power as the function of wavelength and performing the Fabry-Perot loss analysis [22], we deduced the value 7.5 dB/cm for the propagation loss of the fundamental TE mode in a 1.5-µm-wide GaN waveguide on Ga2O3. We were unable to observe any light guidance in the waveguides not treated with the chemical post-processing due to their higher propagation loss. This further confirms that the post-processing has improved the quality of the structures.

Experimental studies on GaN slab waveguides have shown a relatively low propagation loss ranging from 0.6 dB/cm to 3 dB/cm [23, 24]. However, a limited number of experimental studies, performed with GaN channel waveguides, have shown the measured values of the propagation loss at 1550 nm ranging from 18 dB/cm to 34.4 dB/cm [25–27] for a variety of substrate materials,
Fig. 5. 3D AFM plots of a $2 \mu m \times 2 \mu m$ region of GaN surface: (a) before the post-processing, (b) after the post-processing.

Fig. 6. Optical characterization setup for measuring the propagation loss by the Fabry-Perot method. The inset displays the image of a guided mode as seen on the IR camera.
such as sapphire, silicon, and aluminum nitride. There is a single study reporting the propagation loss as low as 1 dB/cm for a GaN ridge waveguide on sapphire [28]. However, the reported waveguide structure was largely multimode with the waveguide width of 10 µm, as opposed to the 1.5 µm used in the present study. Our measured propagation loss value of 7.5 dB/cm compares well to these published data, which confirms that Ga$_2$O$_3$ substrate holds promise for the growth of GaN with improved optical quality.

Conclusions

In this work, we report on the design and fabrication of GaN waveguides on Ga$_2$O$_3$ substrate, detailing the growth of the wafer, the design and fabrication of the waveguides, and their subsequent wet-chemical post-processing resulting in the reduction of the surface roughness. The fabricated post-processed waveguide displayed the propagation loss of 7.5 dB/cm which compares well with other available studies. To the best of our knowledge, there is no reports on the realization of GaN waveguides on Ga$_2$O$_3$ substrate. Our experimental effort has confirmed that this substrate material holds a lot of promise for integrated photonic devices based on GaN. The future improvements to the fabrication process can lower the defect density and propagation losses, thus making it possible to exploit valuable properties of GaN in a variety of integrated photonics applications.

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