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Characterization of etched facets for GaN-based lasers

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Abstract

Dry-etching of laser facets is commonly used for (InAl)GaN/sapphire-based structures since the epitaxial planes of the nitride layers are rotated with respect to the substrate planes making cleaving impractical. To achieve steep and smooth facets by chemically assisted ion beam etching, a 3-layer resist system is developed for patterning. Characterization by scanning electron microscopy and atomic force microscopy shows facets with root-mean-square roughnesses of 7 nm and inclination angles of 2–4°. Optically pumped lasers yield low threshold excitation densities for fully doped separate confinement heterostructure lasers. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

In InP and GaAs material systems laser facets are formed by cleaving the epitaxial layers and the substrate along a mutual cleavage plane. Since lattice mismatch between sapphire (corundum structure) and GaN (wurtzite structure) is partly accommodated by a 30° rotation of the GaN unit cell relative to the sapphire surface [1], the fabrication of cleaved facets in GaN based devices grown on *c*-plane sapphire is more difficult. A variety of approaches have been published to overcome this problem including dry-etching [2,3], growing on different substrates, that allow cleaving [4,5], sawing [6] and polishing [7].

An additional problem in GaN based lasers is the relatively low refractive index $n = 2.5$ of GaN which leads to a reflectivity $R_0 = (n-1)^2/(n+1)^2$ of only 18% (at 410 nm) even for a perfect smooth facet. Scattering losses reduce the facet reflectivity according to $R = R_0 \exp - (4\pi n\,\Delta d/\lambda)^2$ [4], with Δd being the root-mean-square (rms) roughness. Due to the short emission wavelength λ the surface smoothness requirements are more stringent for GaN lasers than for near-IR lasers. Typical etched facets display several nm roughnesses resulting in a significant reduction of reflectivity, for example, by a factor of two for 10 nm rms roughness. In this paper, we report on the fabrication of laser facets by chemically assisted ion beam etching and on the characterization of the etched facets.

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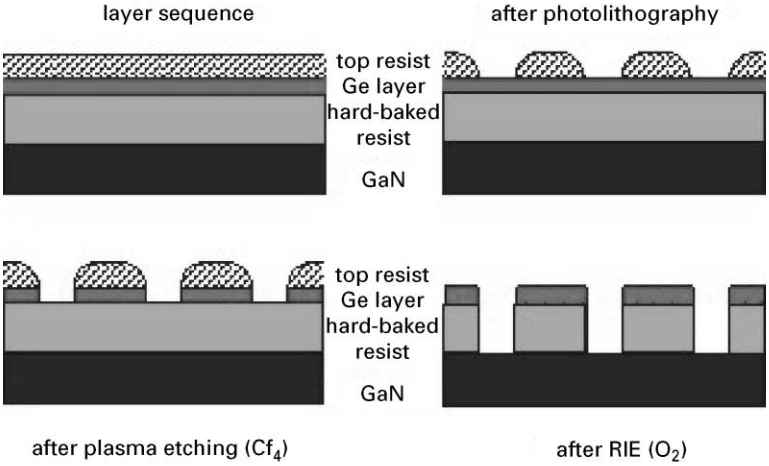

Fig. 1. 3-layer resist as patterning system for CAIBE etching of GaN laser facets.

2. Experimental procedure

Fully doped GaN-based separate confinement heterostructures (SCH) are grown in a horizontal MOVPE reactor (AIXTRON AIX 200 RF) on *c*-plane sapphire substrates. To achieve vertical facets in GaN bulk material, it is crucial to have the sidewalls of the patterning mask also vertical and free of large-scale striations. So the samples are patterned with a 3-layer resist system consisting of AZ4533, Ge and AZ1512 (Fig. 1). Etching of the Ge interlayer is performed using reactive ion etching (RIE) with CF_4 at 400 W and then the pattern is transferred into the second resist layer by an O_2-RIE-system. As chemically assisted ion beam etching (CAIBE) is a very effective tool in achieving highly anisotropic etch profiles we use a TECHNICS PLASMA CAIBE—system to etch the laser facets. Ar and Cl_2 are used as physical and chemical etching components, respectively. A detailed description of the etching process is given elsewhere [8]. The facets are characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM).

3. Results and discussion

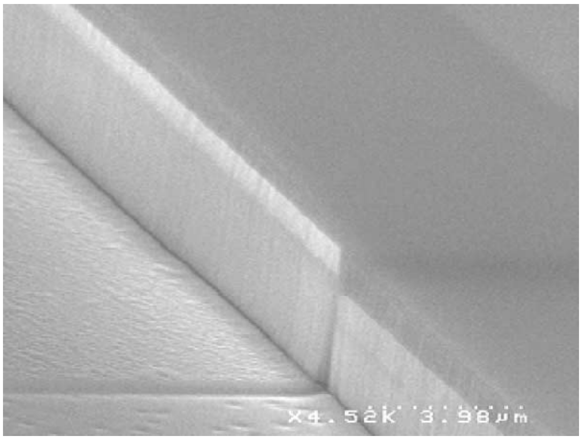

Fig. 2. SEM micrograph of an InGaN/GaN laser facet etched by CAIBE. The structure is still covered by the patterning resist.

Fig. 2 shows a SEM micrograph of the etched facet of a GaN based laser structure. Contrary to samples that we etched using a single layer resist mask, the facets show no large-scale striations. Experiments clearly show, that the observed inclination angles strongly depend on the setup/alignment of the SEM-system. To achieve reliable results, AFM measurements are used to determine the facet angle. A special sample holder for the AFM was designed, which allows to tilt the sample up to 45° against the horizontal and perform AFM measurements across the facet. The cross-sections of the facet (Fig. 3) show no undercutting behavior of the facet with inclination angles of 2–4°.

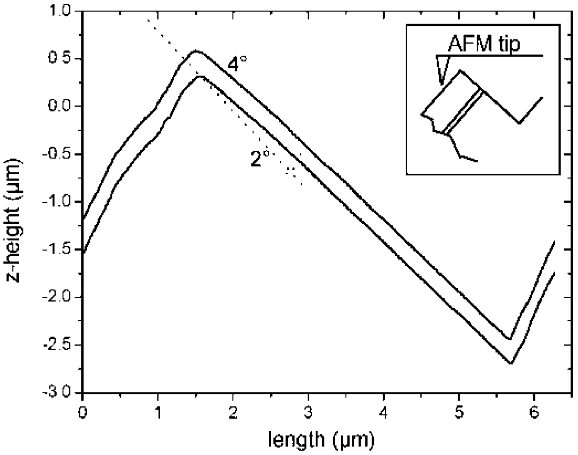

Fig. 3. AFM cross sections of CAIBE etched laser facets. The inclination angles are 2° and 4°. As the aspect ratio is different from one, the visible angles appear to be 10 to 15°.

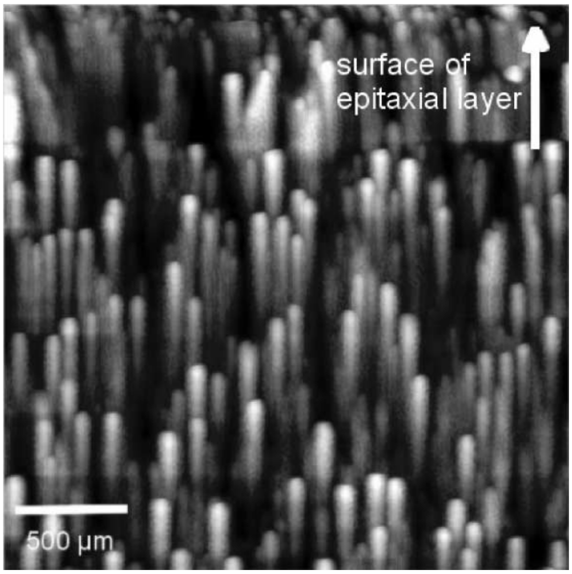

Fig. 4. AFM micrograph of a dry-etched facet. The depicted area is $2.5 \times 2.5\,\mu m^2$ with a rms roughness of 7 nm.

Fig. 4 is an AFM image of a dry etched InGaN/GaN laser facet, showing a rms roughness of 7 nm. Numerical calculations based on the method of Stocker et al. [4] give a reflectivity of about 14% corresponding to 78% of the value of an ideal GaN/air interface ($R = 18\%$ at 410 nm) for this rms roughness. This result fits well with the calculations performed by Kneissl et al. [2], but neglects the reduction of reflectivity due to inclination angles of the facets. Taking the tilt angle of 2–4 into account will reduce the reflectivity by another 50%[9].

The rod-like morphology of the facet indicates that dry-etching of the facets using chemically assisted ion beam etching reveals a pronounced defect structure. Calculating the visible defect density of the material after etching from the AFM micrograph, one will end up with a defect density of about $10^{10}\,cm^{-2}$. A potential source for the observation of these defects is threading dislocations in the epitaxial layer. However, since the density is much higher than that expected from MOVPE grown nitrides [1], an etching induced defect formation cannot be ruled out as a potential cause.

Laser cavities of 400 µm length with etched facets are used to perform photo pumping experiments (measurements performed by Hangleiter and Heppel: TU Braunschweig). Although the reflectivity of the facets is smaller than 10%, optically pumped laser operation of the InGaN/GaN laser structure is achieved for excitation densities of $600\,kW/cm^2$. Spectral analysis of the emission of the GaN based laser structure show a peak wavelength of 414 nm with a full-width at half-maximum (FWHM) of 0.4 nm.

4. Summary

In summary, fully doped SCH GaN based laser structures are grown on sapphire and processed to Fabry-Perot resonators using a 3-layer resist system particularly developed for etching of laser facets. Employing the 3-layer resist system striations occurring from mask erosion are significantly reduced and CAIBE etched facets show rms roughnesses of 7 nm and inclination angles below 4 °. The resonators reveal lasing at reasonably low threshold excitation densities.

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