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Dry-etching and characterization of mirrors on III-nitride laser diodes from chemically assisted ion beam etching

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Abstract

Vertical mirrors have been fabricated with chemically assisted ion beam etching (CAIBE) on OMVPE grown InGaN/AlGaN laser diode structures. AFM measurements show that smooth vertical sidewalls are obtained which exhibit a root mean squared (rms) roughness of only 40–60 Å. The inclination angle of the etched mirrors is within $\pm 2^{\circ}$ of vertical, as SEM studies indicate. Photopumping measurements reveal that the reflectivity of the etched mirrors corresponds to 60–70% of the value for an ideal GaN/air interface. The reduced reflectivity may be due to surface roughness, a slight tilt in the facet angle, and the excitation of higher-order transverse waveguide modes in the laser structure.

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1. Introduction

Gallium nitride and its related compounds AlGaN and InGaN have recently emerged as important semiconductor materials leading to the realization of high-performance light emitters from the UV to the blue and green spectrum. With the demonstration of the first laser diode in this material system [1], the focus of research has been drawn also towards the development of a commercially viable short wavelength laser diode, which would be useful for a variety of applications such as high-resolution, high-speed laser scanners and printers or high-density optical data storage devices. In the meantime, laser operation has been successfully demonstrated from devices grown on various substrates, e.g. A- or C-face sapphire [1–3], $MgAl_2O_4$ [4] or SiC [5] substrates. Still, the currently most advanced devices, exhibiting room temperature continous wave (cw) operation and lifetimes in the order of tens or even hundreds of hours [6], are grown an C-face sapphire substrates. C-face sapphire, however, does not provide a natural cleavage plane, which makes it difficult to obtain high-quality

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mirrors by cleaving [3] and therefore mirrors have to be fabricated by other means such as polishing or dry-etching.

2. Experimental procedure

Chemically assisted ion beam etching (CAIBE) is a highly versatile tool for dry processing of III-nitride-based LED and laser diode (LD) structures [7]. CAIBE is particularly effective in achieving highly anisotropic etch profiles (e.g., smooth vertical sidewalls for LD facets) because of the independent control of the physical and chemical etching components. In such a configuration, a highly dense and uniform ion beam (e.g., Ar^+) is generated with an electron cyclotron resonance plasma source and dual extraction grids, and the reactive species (e.g., Cl_2, BCl_3) are locally injected onto the sample. The independent control of ion energy, ion density, flux of the reactive species, incident angle and substrate temperature enables a wide range of etch rates and etch profiles. Etch rates approaching 100 nm/min have been achieved for MOCVD-grown GaN on sapphire substrates. The etch rates are reproducible and highly uniform across large areas (e.g., 5 cm diameter). Atomic force microscope (AFM) analysis reveals very smooth etched surfaces. A root mean square (rms) surface roughness of 4–5 Å for the as-grown material increases to only 6–7 Å on the in-plane etched surface, which correlates with the surface morphology before etching. It was found that the etch rates for AlGaN decrease slightly with increasing aluminum mole fraction. However, under optimized etching conditions, these etch rates are comparable, with negligible protrusions in etched GaN/AlGaN heterostructure sidewalls. By tilting the substrate and using temperature-controlled CAIBE, smooth vertical sidewalls have been obtained for etch depths up to 2.5 μm. In order to achieve this profile also the sidewalls of the photoresist mask were optimized to be exact vertical with respect to the semiconductor surface. A scanning electron microscope (SEM) micrograph of such an etched facet is shown in Fig. 1a. AFM measurements on the surface of the mirrors exhibit a rms roughness of 50 Å. The greater roughness on the vertical sidewalls compared to the in-plane surface is probably due to roughness from the photoresist mask. The inclination angle of the etched facet is within $\pm 2^\circ$ of the desired ideal vertical angle as also indicated by the SEM micrograph of Fig. 1b.

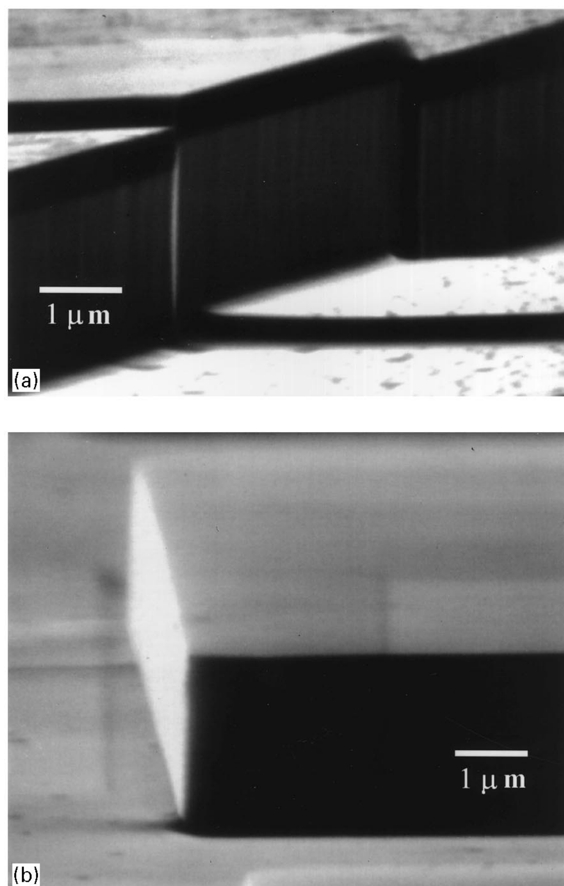

Fig. 1. (a) SEM micrograph of a CAIBE etched facet of an InGaN/AlGaN ridge waveguide laser diode structure with a $Si_xO_yN_z$ isolation layer on top. (b) Sideview of a CAIBE etched mirror of an InGaN/AlGaN laser diode structure as used in the photopumping experiments.

In order to evaluate the optical properties of the etched facets, photopumping experiments were performed on a set of laser diode structures with CAIBE etched facets and different cavity lengths. The samples were grown by OMVPE on C-face sapphire substrate. First, a 4 μm thick GaN film was grown, followed by a 500 nm $Al_{0.07}Ga_{0.93}N$ cladding layer. The active region was formed by

$5In_{0.15}Ga_{0.85}N/In_{0.05}Ga_{0.95}N$-QWs with a well width of 25 Å and a barrier width of 70 Å, embedded in between two 100 nm GaN confining layers. The final upper $Al_{0.07}Ga_{0.93}N$ cladding layer was kept thin (50 nm) in order to permit direct photoinjection of carriers into the active region by a 337 nm nitrogen pump laser. The entire structure was undoped. Subsequently, the two mirrors were etched and in the same step also 100 μm wide mesas were defined to provide the lateral optical confinement. The total etch depth was about 2.5 μm. In addition, on a second set of samples one side of the facet received a high reflective Al-coating ($R = 93\%$), in order to separately determine distributed and mirror losses. As shown in Fig. 2, the threshold power density decreases with the inverse cavity length in both cases. As expected the threshold power density variation depending on the cavity length is less pronounced for the HR-coated samples, because of the overall lower mirror losses. By extrapolating both curves we find the internal losses to be about 40 cm^{-1} with the uncoated mirror reflectivity corresponding to 60–70% of the ideal value for a GaN/air interface ($R = 18\%$).

In order to determine the origin for the reduced reflectivity, numerical calculations were performed based on Igas method [8]. The normalized mirror reflectivity was calculated for the inclination angle of the tilted facet and the surface roughness. As can be seen in Fig. 3a and Fig. 3b the mirror reflectivity deteriorates strongly with increasing tilt angle or surface roughness. For the investigated structure and the measured rms roughness and tilt angles, the mirror reflectivity should be better than 80% compared to the ideal value. This is somewhat higher than the values determined by the photopumping experiment. The discrepancy may be due to the relatively weak optical confinement of the waveguide structure. Experiment and calculations on

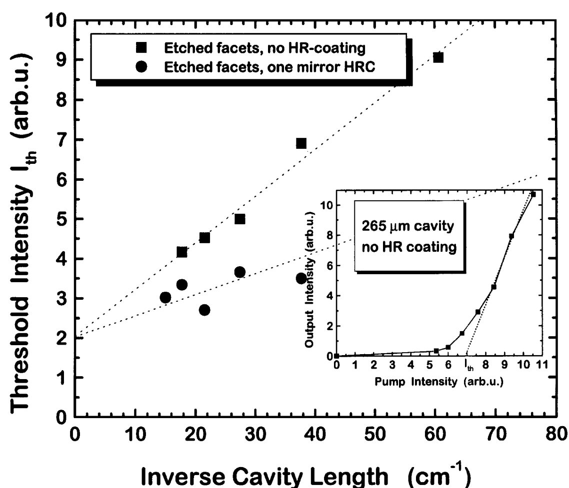

Fig. 2. Measured optical threshold power density I_{th} for optically pumped InGaN/AlGaN laser diode structure vs. the inverse cavity length. The inset shows the optical output power vs. the pump power for a 265 μm cavity laser structure.

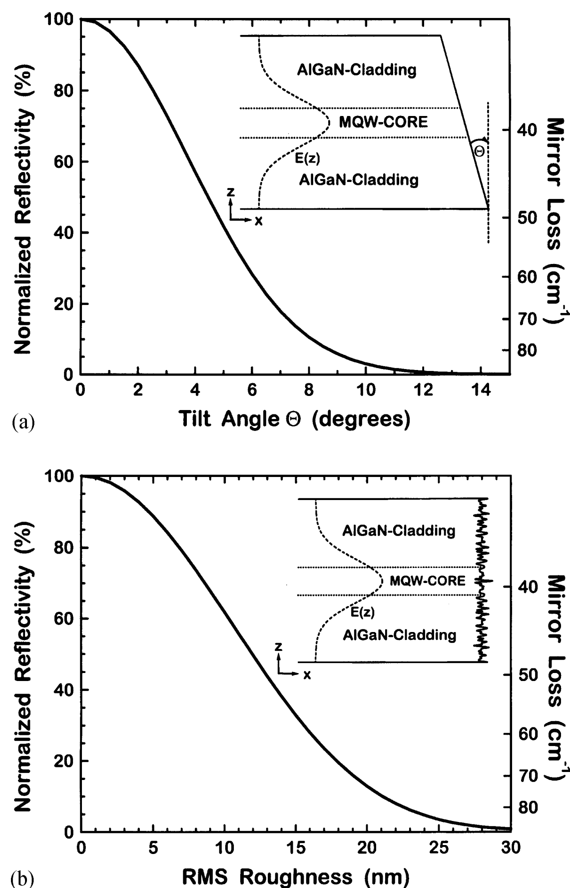

Fig. 3. (a) Calculated normalized mirror reflectivity versus the inclination angle of a tilted facet. (b) Calculated normalized mirror reflectivity vs. the rms surface roughness of the etched facet. The values for the mirror losses on the right axis were calculated assuming a 500 μm cavity.

a similar structure have shown [9] that higher-order transverse modes are supported in a waveguide formed by the entire 5 μm epi-layer structure. As in the present case, the mirrors were etched only down to 2.5 μm of the total structural layer thickness, hence, part of the optical mode is not reflected by the etched mirrors. It can be estimated from the mode profile in this structures that this can account for an additional 20% reduction of the mirror reflectivity, which then would very well match our measured mirror reflectivity.

3. Conclusion

We have shown that high-quality vertical mirrors can be fabricated using CAIBE on OMVPE grown InGaN/AlGaN laser diode structures. Smooth vertical sidewalls have been obtained, which exhibit an rms roughness of only 40–60 Å, with inclination angles of the etched facet within $\pm 2^{\circ}$ of the desired vertical angle. Photopumping experiments show that the reflectivity of the etched mirrors corresponds to 60–70% of the value for a ideal GaN/air interface. The reduced reflectivity may be due to surface roughness, a slight tilt in the facet angle, and the excitation of higher-order transverse waveguide modes in the laser structure.

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