Fabrication of Low-Loss GaN/AlN Waveguides for Nonlinear Optics

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Abstract

Nonlinear optical phenomena have well-established applications in many areas, such as optical telecommunications. Through the fabrication of low loss waveguides at micron length scales, such nonlinear phenomena can be scaled for use in integrated device applications. The purpose of this research was to fabricate gallium nitride / aluminum nitride (GaN/AlN) waveguides on sapphire substrates that demonstrate low loss and observable nonlinear effects. Because nonlinear effects require very high intensity, mode confinement becomes a very important factor. To increase mode confinement in the fabricated waveguides, a potassium hydroxide (KOH) wet etch is used to undercut the AlN base, increasing mode confinement in GaN. Waveguides were fabricated on sapphire wafers with molecular beam epitaxy (MBE)-grown GaN/AlN layers using standard photolithography and dry etching techniques yielding features ranging from 2-5 μm in width. The waveguides were tested using a femtosecond laser system.

Introduction and Background

Optoelectronic and photonic devices are a class of semiconductor devices that utilize and process light signals. One of the primary components of many of these devices is waveguides that are used to guide the light signals within the device. For device efficiency and information integrity, it is important that waveguides exhibit very low scattering losses. While the guiding properties of waveguide structures are very important to the functioning of such devices, waveguides can also be used to process optical signals through the use of nonlinear optical effects. At very high intensities, such as those provided by a laser, the polarization of the guiding medium interacts nonlinearly with the incident field in ways that are modeled using a power series representation of the electrical susceptibility with terms exceeding linear order. These nonlinearities give rise to many interesting phenomena, such as second and third harmonic generation, sum frequency generation, and Raman shifting. Nonlinear effects are already utilized in macroscale waveguiding structures such as optical fibers. Because nonlinear effects only become pronounced at high intensities, loss and mode confinement become critical properties that must be optimized.

Waveguide Fabrication

The wafers used for manufacturing were 3″ sapphire wafers with various epitaxially grown III-V layers. The two layer types used were; (1) a 500 nm AlN layer with alternating layers of GaN/AlN quantum wells and (2) a 1.4 mm bulk GaN layer on top of 100 nm bulk AlN. A thick layer of silicon dioxide (SiO_2), ~ 1 μm, was deposited on the wafer using pressure-enhanced chemical vapor deposition (PECVD) to act as a more robust mask for the III-V dry etch process. After standard photolithography using a 10x i-line stepper for exposing, the SiO_2 layer was etched using a CHF_3/O_2 dry etch chemistry in a reactive ion etcher (RIE). The III-V layers were etched using an $Ar/BCl_3/Cl_2$ RIE dry etch in an ICP etcher. The samples were finally treated with resist stripper and HF to remove the photoresist and SiO_2 masking layers. With minimal optimization, the process was found to achieve good sidewall smoothness for features ≥ 3.5 μm, but there was noticeable damage during the nitride etch process to 2 μm and 2.5 μm features. Increased sidewall smoothness and reduction in damage to small features could most likely be improved by utilizing a thicker oxide mask layer and further optimization of the III-V etch process.

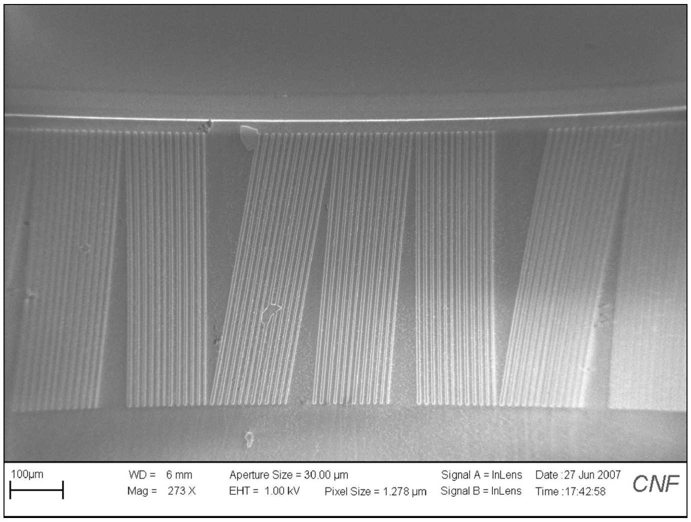

Figure 1: Row of fabricated waveguides.

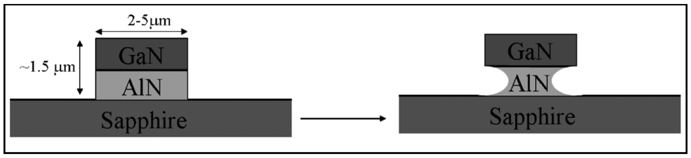

Figure 2: Diagram of KOH undercut.

KOH Undercut

In order to increase the nonlinear effects in the waveguides, an undercut in the lower AlN layer of the bulk GaN/AlN waveguides was created. The undercut would reduce the cross-sectional area of the AlN layer, which would cause the mode to be confined more strongly in the GaN layer, reducing mode volume. Previous research [1,2] had indicated that KOH solutions were capable of selectively etching AlN over other III-V compounds. Waveguides fabricated in the bulk GaN/AlN sample were treated in heated AZ400K developer for 30 minutes at 90ºC ± 5ºC. The solution selectively etched the AlN over the GaN such that a noticeable undercut was formed. A rough scanning electron microscopy (SEM) measurement showed the etch rate to be very approximately 20 nm/min.

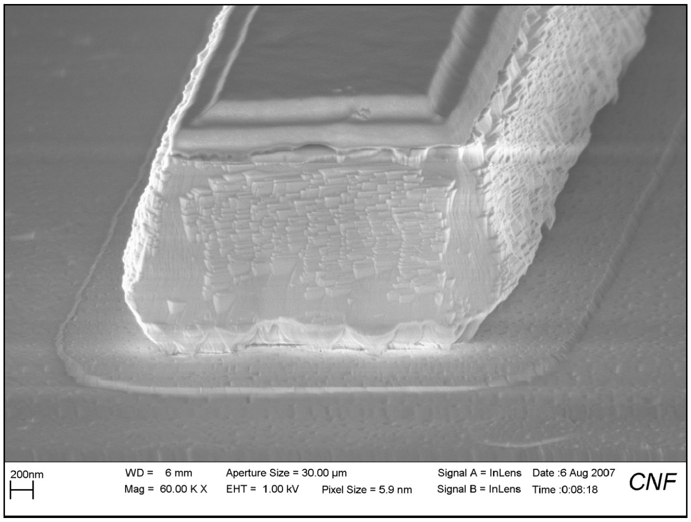

Figure 3: Profile of bulk GaN/AlN waveguide with KOH undercut.

Testing Results and Conclusions

Testing the fabricated waveguides was accomplished using a bright white light source generated by nonlinear interaction of a pulsed fiber laser with a photonic crystal fiber. The laser was coupled to the waveguide by focusing the beam through a lens and the output was observed using a CCD. Only qualitative data could be taken due to equipment and time limitations. The CCD was used to capture various mode profiles for qualitative comparison of waveguides with different material composition and fabrication processes. Comparison of mode profiles in the three tested samples is shown in Figure 4. All fabricated waveguides were shown to support guided modes, but exhibited visible scattering loss. Due to the conservative undercut and significant surface scattering at the facet, there was no concrete difference in mode confinement between the bulk GaN waveguides with and without undercutting, but the initial results show enough potential to warrant further study.

Acknowledgements

I would like to thank Dr. Farhan Rana and Jahan Dawlaty, as well as everyone in the Rana Group, for their help in this project. I would like to thank the entire CNF staff for their assistance in making the technical side of my project possible. I would also like to thank Melanie-Claire Mallison, Lynn Rathbun, the NSF, and the National Nanotechnology Infrastructure Network Research Experience for Undergraduates Program for coordinating this program and giving me this opportunity.

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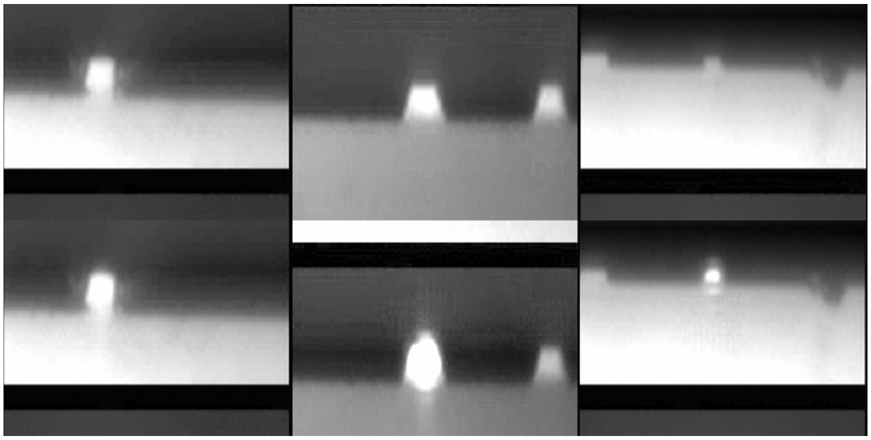

Figure 4: Guide and mode profiles. From left to right: Bulk GaN/AlN with undercut, Bulk GaN/AlN without undercut, Bulk AlN with GaN/AlN quantum wells.