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14. ABSTRACT

In this project, we sought to better optimize and understand the two-step etch process for creating GaN-based nanowires which are of interest for nanolasers and other applications. Additionally, we also sought to explore whether an analogous two-step etch approach, could be feasible and developed for traditional III-V semiconductors (e.g. GaAs-based), leading to a top-down process for creating III-V nanowire lasers.

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Report Title

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Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

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Tsai, M.-C., B. Leung, G. Balakrishnan, G. T. Wang, Understanding and Predicting GaN Anisotropic Wet Etch Facet Evolution, 58th Electronic Materials Conference, 6/22-24/16, Newark, DE.

Tsai, M.-C., B. Leung, G. Balakrishnan, G. T. Wang, Chemical Etching of GaN in Hydroxide-Based Solutions: Understanding and Predicting Facet Evolution, 18th International Conference on Metal Organic Vapor Phase Epitaxy, 7/10-15/16, San Diego, CA.

Leung, B., M.-C. Tsai, G. Balakrishnan, C. Li, S. R. J. Brueck, J. J. Figiel, P. Lu, A. A. Allerman, M. H. Crawford, G. T. Wang, Highly Anisotrphic Crystallographic Etching for Fabrication of High-Aspect Ratio GaN Nanostructures, 18th International Conference on Metal Organic Vapor Phase Epitaxy, 7/10-15/16, San Diego, CA.

Wang, G. T., B. Leung, M.-C. Tsai, et al. Nanowires, Nanosheets, and Beyond: Geometry Controlled High Aspect Ratio Nanostructures by Top-Down Fabrication. International Workshop on Nitride Semiconductors (IWN 2016), 10/2-7/16, Orlando, FL.

Number of Presentations: 0.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

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Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

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FTE Equivalent:
Total Number:

Names of Post Doctorates

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FTE Equivalent:
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Scientific Progress

Technology Transfer

III-nitride and III-V nanowires have attracted increasing interest as potential ultracompact and low-power nanophotonic emitters, including nanoscale lasers in the UV-visible-infrared wavelengths. As such, great efforts have been put towards realizing such nanostructures with controlled dimensions, morphologies, and smooth surfaces. There are two main categories for creating nanowires for nanophotonics applications: bottom-up and top-down approaches. The bottom-up approach builds up desired nanostructures starting with individual molecules or atoms. For nanowire synthesis, the bottom-up techniques most commonly include vapor-liquid-solid (VLS) growth and catalyst-free (or "self-catalyzed") growth. These bottom-up approaches have given rise to the production of high quality nanowires, with the lasing demonstrated in a broad range of inorganic nanowires including GaN, CdS, CdSe and ZnO.

An alternative to the bottom-up technique is the top down technique for fabricating nanowires. Compared to bottom-up growth, top-down methods have the potential for superior control of size, placement, alignment, heterostructuring, doping and point defect concentrations, as they are not limited to the narrow growth conditions needed for 1D anisotropic growth. In this case the wires are etched out of a planar semiconductor film. Recently, a two-step dry plus wet etch process was developed at Sandia National Laboratories for the top-down fabrication of high-quality, high-aspect ratio GaN-based nanowires.[1,2] An inductively-coupled plasma etch is first used in combination with a lithographically defined etch mask. This creates tapered pillars with rough and plasma damaged sidewalls, and are not suitable for most optoelectronic applications. Thus, a crystallographically selective KOH-based wet etch is subsequently performed, which results in high-quality nanowires with vertical, smooth sidewalls. Due to the resulting smooth sidewalls, high material quality, and controllable dimensions, this technique has enabled the fabrication and study of GaN-based nanowire lasers and attempts to understand and control their optical properties, including mode, polarization, and wavelength control.[3-11]

In this project, we sought to better optimize and understand the two-step etch process for creating GaN-based nanowires which are of interest for nanolasers and other applications. Additionally, we also sought to explore whether an analogous two-step etch approach, could be feasible and developed for traditional III-V semiconductors (e.g. GaAs-based), leading to a top-down process for creating III-V nanowire lasers.

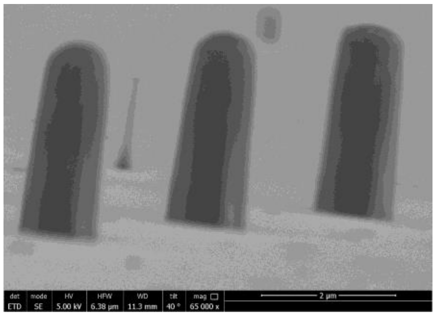

Figure 1. Dry etched GaN pillars showing crystallographic facets

For the dry etch step in top-down fabrication of GaN nanowires, important considerations are the sidewall angle, etch rate, etch selectivity between the mask and GaN, and surface roughness. Examining the choice of mask material, Ni mask was found to provide the best balance between selectivity (Ni: GaN ~ 25:1 vs Cr:GaN ~20:1) and surface roughness (undulations in the Ni mask ~ 20nm). An improved dry etch recipe was then developed with more vertical sidewall angles of ~86° (versus ~81° before optimization) and smoother sidewalls, after performing the process optimization including the ICP/reactive ion etch (RIE) powers, pressure, temperature and gas flow ratios. Plasma etches, compared to wet etches, are generally non-crystallographic in nature, although crystallographic features (facets) are obviously seen after the etch (Fig. 1), which is interesting both scientifically and for nanostructure fabrication processes.

The second step of the GaN nanostructure fabrication process is an anisotropic (crystallographic) wet etch. The wet etch improves upon the dry etch by producing vertical and smooth facets based on the crystallography of GaN, and removing the plasma damage from the sidewalls. Both are crucially important in the fabrication of high performance optical devices. Using general geometric principles of crystallographic dissolution, we put forth a mechanism whereby the tapered GaN pillars transition into vertical, straight nanowires with smooth sidewalls. At corners, semipolar fast etch rate facets in convex geometries appear. These quickly become concave, whereby slow etch rate facets (polar and nonpolar) appear and the fast etch facet (semipolar) disappear. The process repeats until all ledges/steps are removed and only vertical sidewalls remain.

The high anisotropy of the wet etch in GaN greatly aids in the creation of highly vertical, anisotropic structures. In exploring a possible two-step etch approach for creating GaAs-based nanowires, we first considered the differing crystal structure of GaAs (zinc-blende) vs. GaN (wurtzite) as well as known facet etch rates for GaAs wet etches. Based on this analysis, we chose to study the etching of GaAs (111)A and GaAs (100) crystal orientations, where vertical slow etch facets can potentially be exposed. Using e-beam lithography to define Ni dots as a dry etch mask, we developed and optimized an ICP-RIE plasma etch process to first etch GaAs pillars. Results for both [111]A and [100] oriented GaAs nanopillars are shown in Figure 2. Following the dry etch optimization, preliminary wet etching was performed using different etchants. Compared to the KOH-based wet etching of GaN, the wet etch rate of GaAs for all etchants was much faster, leading to much shorter etch times and increased difficulty in controlling the etch. A sulfuric acid and hydrogen peroxide etch yielded the best results, smoothing the as-ICP-etch sidewalls. Further investigation is needed in order to optimize the etch conditions and to determine if crystallographically defined facets can be formed.

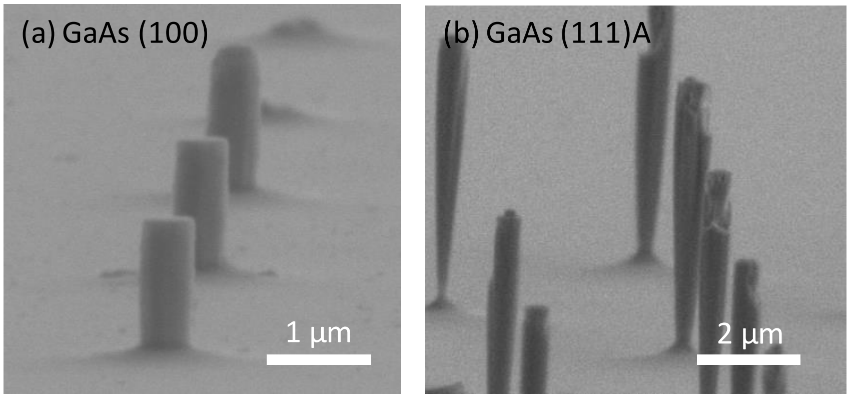

Figure 2. Dry etched GaAs pillars with (a) [100] and (b) [111]A orientation

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Presentations

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