Photoelectrochemical undercut etching for fabrication of GaN microelectromechanical systems

A. R. Stonas
Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106

N. C. MacDonald and K. L. Turner
Mechanical Engineering Department, University of California, Santa Barbara, California 93106

S. P. DenBaars and E. L. Hu
Department of Electrical and Computer Engineering, University of California, Santa Barbara, California 93106 and Materials Department, University of California, Santa Barbara, California 93106

(Received 13 June 2001; accepted 10 September 2001)

The authors have developed a wet, band-gap-selective, photoelectrochemical etching process capable of producing cantilever microelectromechanical systems from InGaN/GaN heterostructures. Fabricated cantilevers were successfully actuated, and resonance spectra were measured. The as-grown strain gradient in the GaN film was found to relax upon removal, resulting in upward curvature of the cantilevers. This curvature was shown to be reversible with the integration of strained InGaN layers on the top surface of the cantilever. All photoelectrochemical wet etching was conducted using a benchtop lamp-and-filter arrangement, employing GaN and InGaN films as filters. © 2001 American Vacuum Society. [DOI: 10.1116/1.1415508]

I. INTRODUCTION

Gallium nitride (GaN), indium gallium nitride (InGaN), and aluminum gallium nitride (AlGaN) have electrical, optical, and mechanical properties of importance for making microelectromechanical systems (MEMS). The highly ionic bond character results in high spontaneous polarization, as well as strong piezoelectricity. The high bond strength results in a high bandgap, which means that applications requiring optical transparency or high-temperature operation may be possible. The material system is most typically grown with a high lattice-mismatch on sapphire (~16.6% to GaN), and the addition of varying indium or aluminum compositions can further change the strain state. Thus one would expect that strain-engineered MEMS might be possible. However, until recently, none of these properties could be easily exploited, for the simple reason that appropriate etching techniques to form group III-nitride material into MEMS were not available.

Due to the extraordinary chemical inertness1 of the group III nitrides, for many years practical etches in the group III nitrides were largely confined to dry etching techniques such as reactive ion etching, inductively coupled plasma, or reactive ion beam etching. Several problems with such physical etches were quickly discovered. Etch damage was quite prevalent, and rapid etch rates and steep sidewalls were difficult to achieve.2,3 No lateral etch technique existed.

An alternative path was found in 1996 when Minsky and Hu applied the process of photoelectrochemical etching (PEC) to GaN, finding reasonable etch rates, and avoiding the possibility of ion-bombardment damage.4 In recent years, several groups have contributed to the development of this technique, with promising results. Since the original article, various photoelectrochemical etching regimes have been shown to be capable of rapid,5 smooth,5 dislocation-selective,7 dopant-selective,4,8 or band-gap-selective etching.4,9 Etch geometries have also been found to use either dopant- or band-gap selectivity to produce deep undercuts.8,9 This article describes the further extension of this etching technique to precisely control band-gap-selective PEC etching for the production of III-nitride heterostructure MEMS. We also discuss initial mechanical characterization of various heterostructure MEMS cantilevers.

II. SAMPLES AND APPARATUS

All experiments were conducted using in-house grown metalorganic chemical vapor deposition samples. Substrates consisted of c-plane sapphire. On this was grown a “tem-

Fig. 1. Schematics of the two basic sample types used in these experiments. (a) Homogeneous GaN cantilever structure and (b) structure capped with an InGaN quantum well stack.
plate” of 1–2 μm GaN, followed by a 50 nm sacrificial layer nominally In_{0.12}Ga_{0.88}N, and another 1–2 μm of GaN. All layers were grown nominally undoped, although an unintentional background doping of at least 1 × 10^{16} cm^{-3} is expected. A schematic of this sample is shown in Fig. 1~\textsuperscript{a}.

Experiments conducted used heterostructure cantilevers employing the same structure as above, followed by an In\textsubscript{x}Ga_{1-x}N quantum well section consisting of a 32 nm lower cladding (x~0.03), a 4 nm quantum well (x~0.09), a 10 nm upper cladding (x~0.03), and a 10 nm GaN cap layer. A schematic of this sample is shown in Fig. 1~\textsuperscript{b}.

The filter used for etching GaN cantilevers was a ~2 μm thick template; the filter used for etching the InGaN/GaN heterostructure cantilevers was ~2 μm of template material, followed by ~50 nm of In_{0.11}Ga_{0.89}N, in turn followed by a 10 nm cap layer.

All etching was conducted in a benchtop system that has been described previously.\textsuperscript{8} Filtered spectral intensities of ~3 mW/cm\textsuperscript{2}/nm were used, no external bias was applied to the platinum cathode, and the chemical portion of the etch consisted of a 1:3 solution (~2.2 M) of KOH:H\textsubscript{2}O.

III. EXPERIMENTS AND OBSERVATIONS

Samples were patterned using optical lithography into rows of cantilevers, each row attached to a supporting base. Cantilevers ranged in length from 25 to 375 μm and in width from 1 to 175 μm. E-beam deposition and lift-off was used to transfer this pattern into a Ti/Au layer 305 nm thick. The back side of the sapphire substrate then underwent a similar process, in which the areas which were to remain fixed to the substrate were coated with the same Ti/Au masking layer. The metal mask was left on the GaN material to facilitate subsequent mechanical measurements (see Fig. 2).

At this point the samples were ready for PEC etching. An initial, unfiltered, front-side-illuminated etch transferred the front-side pattern through the GaN/InGaN structure. In this nonselective etch step, the hole-dependent etch proceeded regardless of material composition, masked by the opaque metal overlying the GaN surface.

A subsequent, band-gap-selective, back-side-illuminated etch undercut those areas which had no metal on the back. Band-gap-selective etching requires that illumination take place through the higher band gap sapphire and GaN to selectively create electron–hole pairs in the lower band gap InGaN. These photogenerated holes drive the chemistry of the etch. Ideally, selectivity would be accomplished by using a tunable optical source and adjusting the wavelength of the incident light to fall above that of the sacrificial layer, but

![Fig. 2. Process basics: First the top and bottom masks are deposited on the sample, then a mesa is etched using the top mask as the delimiter, then the undercut etching is delimited using the back-side mask. This permits rapid, simple processing.](image1)

![Fig. 3. Transmission spectra of the two filters used in these experiments.](image2)

![Fig. 4. Samples after etching. (a) GaN cantilevers, curved upwards by the relief of intrinsic, as-grown strain gradient and (b) similar cantilevers topped with InGaN, curved downwards by the compressive strain intrinsic to InGaN growth on GaN.](image3)

![Fig. 5. Resonance modes peaks of GaN cantilevers superimposed on the resonance spectrum of InGaN/GaN cantilevers. The InGaN cantilevers are shifted to higher frequencies, and the greater degree of constraint results in a more complex mode spectrum.](image4)
below that of the InGaN/GaN cantilever structure. For these experiments we took the simple expedient of growing our own filters for insertion between the light source and the substrate to be etched.

For the simple, GaN cantilevers, a filter composed of 2 μm GaN grown on sapphire was sufficient to produce the desired undercut, with etch rates of approximately 2.5–5 μm/min. The InₙGa₁₋ₙN/GaN cantilevers, however, required a filter which would transmit light above the band gap of the sacrificial layer (x ~ 0.12), but not above the band gap of the quantum well structure (x ~ 0.03 and x ~ 0.09). A different filter was therefore formed by growing a 50 nm InₙGa₁₋ₙN layer on top of the 2 μm GaN-on-sapphire (x nominally ~ 0.105). The high lateral etch rates of up to 5 μm/min were maintained even with this more absorbent filter. Figure 3 shows transmission spectra of the two filters used in these experiments.

We note that while the second, releasing, etch must be photoelectrochemical, the mesa-defining etch has no such requirement. Samples processed using 100 nm SrF₂ as a dry etch mask, and reactive ion etched in 10 mTorr of Cl₂ at 200 W, showed no appreciable mechanical differences from those wet etched in both steps. The wet etching was generally simpler and faster, however, with etch rates of up to 2 μm/min for the conditions described. The dry etch conditions used resulted in etch rates of ~0.1 μm/min.

When the two types (GaN vs InGaN/GaN) of sample were processed, the resulting difference was quite remarkable (Fig. 4). Figure 4(a) shows the dramatic upward curvature of the GaN cantilevers, while the InGaN/GaN cantilevers in Fig. 4(b) exhibit an opposite curvature, with the tips curving downwards into the sapphire substrate. The lattice constant of the sapphire substrate is ~2.4 Å, while the in-plane lattice constant of GaN is ~3.2 Å. It is expected that
GaN grown on sapphire should be compressively strained, but this alone would not account for the dramatic upwards bowing of the released cantilever structures. We believe that there is a gradient in the strain of the material, in the direction of growth. As the GaN grows away from the sapphire substrate, there is some reduction in the number of threading dislocations in the material, and a corresponding change in the compressive strain. The upwards curvature of radius 1.5 mm would correspond to a strain gradient of 665 m$^{-1}$. Effects of the metal remaining on the top surface of the cantilever are expected to be negligible, due to the small thickness and low Young’s modulus.

Figure 4(b) shows that the addition of the InGaN material on top of the cantilever structure produces a reversal in the curvature, with the cantilever curving downward with a radius of ~7 mm. A simple calculation of the expected curvature shows that the structure is not in its fully relaxed state ($r \sim 4.1$ mm). Clearly the small gap left by the sacrificial layer is insufficient, and the cantilever tip is being pushed downward with some force.

IV. MECHANICAL TESTING

A commercial Vibrometer system (Polytec OFV 501 Interferometer/Polytec OFV 3001 Vibrometer) was used to characterize the resonance modes of the resulting cantilever structures. An ac signal of 3.5 V was applied between the metal on top of the cantilever and the ground plane of the chip carrier, which was bonded to the back of the sapphire substrate with silver paint. By this technique, cantilever response could be measured as a function of excitation frequency. The GaN cantilevers had mode peaks with well-defined spacings, and fitted closely (<2% error) with values calculated based on the modes expected. Figure 5 shows superimposed the complete spectrum of the InGaN/GaN resonance modes, and the peaks of the GaN resonance modes. It is clear that the mode structure, in addition to being of higher frequency for the more constrained system, as one would expect, is also more complicated. The assumed mode indices are listed, and unidentified modes are indicated with a “?”.

A study was also done to evaluate the general shape of the first-order vibration modes of each type of cantilever. The amplitude of oscillation is plotted in Fig. 6, measured as a function of the distance from the tip of a 375 $\mu$m long cantilever. Figure 6(a) is measured from a GaN cantilever, which is free at the tip, and Fig. 6(b) corresponds to a cantilever whose tip is pinned. It is clear that there is virtually no motion at the end of the tip of the cantilever, indicating that the modes of this cantilever correspond to the even-numbered modes of a similar free cantilever. This is consistent with the higher frequencies observed.

V. SUMMARY AND CONCLUSIONS

We have presented a complete process for fabricating GaN-based MEMS by using a band-gap-selective photoelectrochemical release etch, and verified its effectiveness by producing several GaN and InGaN/GaN cantilevers. Curvature of these cantilevers was found to be controllable by the application of a thin (~46 nm) InGaN layer, which dramatically altered not only the shape, but also the resonance mode spectrum of the cantilevers. The sacrificial layer was successfully removed without apparent damage to this strain-tuning layer, demonstrating that a high selectivity is maintained in the undercut etch.

ACKNOWLEDGMENTS

The authors would like to acknowledge fruitful discussions with the UCSB GaN community, and the financial support of The Innovative Microwave Power Amplifier Consortium, sponsored by the Office of Naval Research (ONR Award No. 14-96-1-1215), under the direction of Dr. J. C. Zolper.