DEVELOPMENT OF GALLIUM NITRIDE-BASED MEMS STRUCTURES

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ABSTRACT

The fabrication of MEMS structures has generally depended on the ability to carry out highly selective, deep lateral and vertical etching of the component materials. This is particularly problematic in gallium nitride (GaN) and the associated AlGaN and InGaN materials, which are all noted for their chemical inertness.

We report here a method for producing MEMS in this material system based on backside-illuminated photoelectrochemical (BIPEC) undercut wet etching. We also discuss resonance spectra of structures fabricated by this method, including cantilevers and membranes.

INTRODUCTION

A great variety of materials have been used in the fabrication of MEMS structures, chosen based on characteristics as diverse as strength, toughness, electrical breakdown, piezoelectricity, cost, and ease of fabrication. We present results demonstrating the viability of a material that has been growing in popularity in the electronic and optoelectronic communities – Gallium Nitride – for consideration also as a MEMS material. Gallium Nitride (GaN), along with its epitaxial alloys Indium Gallium Nitride (InGaN), and Aluminum Gallium Nitride (AlGaN) is exceptionally chemically inert, highly piezoelectric, transparent to wavelengths in the visible spectrum, strong, and tough. The composition of the $Al_xGa_yIn_{1-x-y}N$ determines the direct bandgap within the range from 0.9 to 6.3 eV, and permits the lattice constant to be in the range a_0 = 3.11Å to a_0 = 3.54Å. Piezoelectric coefficients can range from -1.1 to -2.0 pm/V for d_{33}[1]. Taken together, these properties suggest a variety of possibilities for strain-engineered piezoelectric MEMS Recent work at UCSB has even demonstrated the viability of growing this wurtzite material in crystallographic orientations other than c-plane, resulting in different charge distributions and piezoelectric coefficients[2, 3]. Taken together, these properties suggest wide possibilities for a new class of sensors, actuators, strain-tunable electronic and optical devices.

However, this family of nitride semiconductors has a strong, highly ionic bonding character, which precludes micromachining of the material by conventional wet etching processes. However, photoelectrochemical wet etching has been demonstrated to be an effective etchant in this system, being optically and electrically controllable, as well as both dopant and bandgap selective [4-7]. We have recently developed another etching geometry known as backside-illuminated photoelectrochemical (BIPEC) undercut etching[8], demonstrated its effectiveness at producing deep undercuts[9], and created and measured simple cantilevers fabricated using a similar, BIPEC based process[10]. Images and spectra of those cantilevers are shown in Figures 1 and 2. In this paper we have extended the technique to enable the fabrication of very low aspect ratio (1E-4) structures, in this case membranes 1 μm thick and 1 cm in diameter.

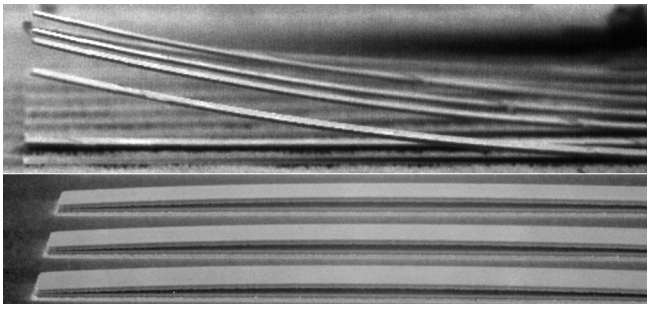

Figure 1. SEM side-view images of two cantilevers. The top cantilevers are composed entirely of GaN, and demonstrate that the material as grown contains a strain gradient which, when relaxed, causes the cantilevers to curve upward. The bottom image shows cantilevers which have been topped with a small layer of InGaN, which counteracts this strain, and causes a downward curvature.

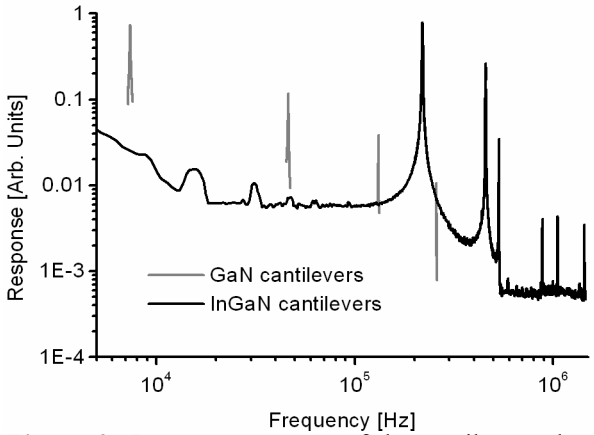

Figure 2. Resonance spectra of the cantilevers shown in figure 1, measured with a commercially available

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vibrometer. First order resonance peaks correspond to quality factors as high as 786.

EXPERIMENTAL

Material was first grown by MOCVD on sapphire. All samples consisted of 1.25 μm unintentionally doped (UID) n-type GaN followed by 1.25 μm of n-type GaN:Si. These first layers are referred to as the template. On this template was grown a sacrificial layer of $In_xGa_{1-x}N$:Si (x~0.17) 50-100 nm thick, and a spacer layer of 1 μm n-type GaN:Si.

For several of our samples, this was followed by a quantum well structure, which was intended to probe the strain state of the material. This consisted of top and bottom claddings of n-type $In_xGa_{1-x}N$ (x~0.03) sandwiching a well of UID $In_xGa_{1-x}N$ (x~0.12).

All intentional doping was nominally 1E18 cm^{-3}. Growth temperatures ranged from 840-900°C for InGaN growth, and 840-1200°C for GaN growth.

After growth, samples were patterned with a square array of circular vias in a metal film (Ø = 25 μm, spacing = 100 μm) deposited using e-beam evaporation with Ti/Pt/SrF_2 (25Å/3000Å/2000Å thick) The first two layers were designed to serve as an inert contact and cathode during later photoelectrochemical etching, and the strontium flouride served as the dry etch mask during the following Reactive Ion Etching (RIE). A chlorine-based RIE was employed, with etch conditions of 5 mTorr pressure, 200W power, for 40 minutes. This transferred the pattern of the SrF_2 through the thickness of the GaN, thus exposing the sidewall of the sacrificial layer.

A 10 second dip in concentrated HCl removed the SrF_2 and exposed the Pt cathode for subsequent BIPEC etching.

The key process in the fabrication of these devices was backside-illuminated photoelectrochemical (BIPEC) wet undercut etching. This was performed in an inexpensive home-made apparatus, diagrammed schematically in Figure 3.

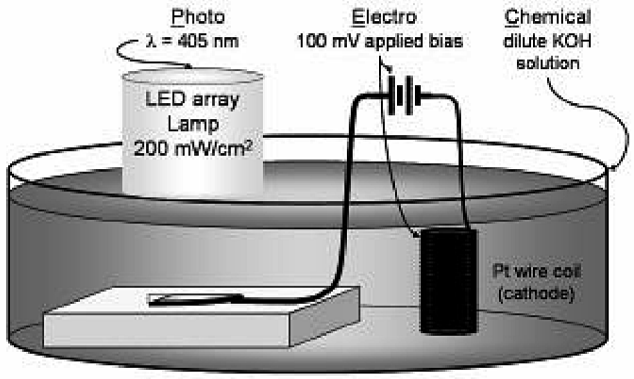

Figure 3. A schematic of the BIPEC system.

The electrochemical portion of the apparatus consisted of a gold wire pressed firmly against the metallized surface of the sample. To this was connected a voltage-controlled DC power supply, the other end of which was connected to a coiled platinum wire, which served as the external cathode. Biases employed ranged from 0-200mV. The electrolyte consisted of a solution of 1:3 KOH:H_2O

The photon source in this case consisted of a home-built LED array, which supplied light at a peak wavelength of 405 nm (FWHM = 15 nm), at an intensity of 200 mW/cm^2. This was used to exploit the bandgap-based selectivity inherent in PEC etching. In this case InGaN had a bandgap below the energy of illumination, and was preferentially etched, leaving the surrounding (higher bandgap) GaN intact.

After undergoing wet etching, the sample was transferred in solution to a methane bath, and was placed in a critical-point dryer to remove the fluid while avoiding stiction effects.

Since the resulting film was wrinkled (due to the release of stresses caused by heteroepitaxial growth) the film had to be stretched in order to be actuated. This was performed by the applicaton of a DC bias of 0-600 V which was added to the 100V AC signal.

Actuation was realized in a home-built vacuum system, connected to a commercially available Polytec OFV 501/3001 Interferometer/Vibrometer. The sample was soldered to a custom printed circuit board, and a glass slide was placed on either side of it. Then a glass window patterned with a gold ring was placed across the slides. Electrical contact was made with solder between a trace on the glass window and a trace on the printed circuit board. This left a gap of ~650 μm between the sample and the gold ring, sufficient for expected electrostatic actuation across the gap. The printed circuit board with the associated glassware was then inserted into a vacuum chamber, connected to electrical feedthroughs, and pumped down to >200 mTorr. The measurement laser was shone through the ring, and reflected from the center of the membrane, back to the vibrometer for measurement of velocity and displacement of the membrane. A multidimensional MEMS motion characterization suite is used to measure the dynamic movement of the device.[11]

Capacitive actuation was conducted at 0-100V AC with DC offsets of 0-600V.

RESULTS AND DISCUSSIONS

A resulting membrane is shown in Figure 4, below. Immediately upon completion of the structure, it was observed that its low aspect ratio and strain-relieved state resulted in a floppy, wrinkled film, similar in appearance to household plastic-wrap.

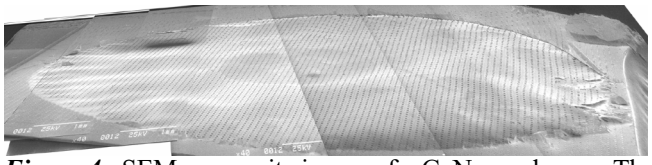

Figure 4. SEM composite image of a GaN membrane. The membrane is 1 micron thick, and 1 cm across. The diagonal lines and image shape are artifacts left from piecing together several SEM images.

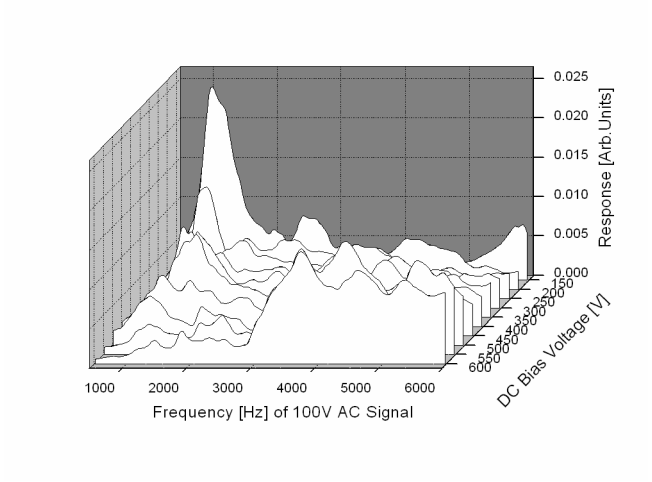

Figure 5. Resonance spectra of the membrane shown in figure 4, for varying DC bias voltages. Resonance frequencies change as a function of applied biaxial strain.

Shown in Figure 5 are a set of response curves, showing the change in position and structure of the membrane as it is stretched tighter by successively greater DC bias. The lowest observed mode begins to diminish, and a more complex set of modes begins to appear at higher frequencies as the tension is increased.

Attempts to use the quantum well as a strain probe have thus far not been successful; we believe that the major limitation is insufficient etch selectivity of $In_xGa_{1-x}N$ to $In_yGa_{1-y}N$ (x>y) in our system.

CONCLUSIONS AND FUTURE WORK

We conclude that the BIPEC process appears to be a viable technique for producing a variety of MEMS devices from the Group-III Nitrides, and continue our efforts to use quantum well probes to measure the strain state of the membrane directly.

There are several processing issues which must be resolved before the beneficial properties of the III-Nitrides can be more fully exploited in MEMS. We are particularly interested in extending the depth of selective undercuts, so that we may produce less porous structures. An illumination source with a narrower FWHM, such as a tunable Alexandrite laser is a possible, though costly, solution. Perhaps a more reasonable solution is the masking of the edges of the quantum well with an inert dielectric, such as SiN.

There are also more fundamental questions which it would be interesting to answer. Perhaps most interesting would be a more thorough study concerning the effects of piezoelectric fields on the electrochemistry of the etching process, particularly taking into account that the strain state changes continuously as the etch progresses. Such research could result in improvements in the selectivity and etch rate of the photoelectrochemical etching process.

A final issue which it could be interesting to explore is the mechanism by which the PEC etching rate and morphology often depend on growth conditions, even when those conditions affect no other measurable material properties. A variety of defects might be the cause, but evidence is still scant in this arena.

Acknowledgements

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